HIGGS MEASUREMENTS PERSPECTIVE

André David (CERN)

HIGGS MEASUREMENTS PERSPECTIVE *(AND LACK THEREOF)*

André David (CERN)

Rules of engagement

Session I	Session II
I tell you a lot about a lot.	Contents depends on your feedback and interests.

Session I

- I tell you a little about a lot.

Session II

- Contents depends on your feedback and interests.
  - Look for slides with a

Menu of discussion topics

- In my biased preferred order:
  1. EFT and pseudo-observables.
  2. What's in a signal strength?
  3. CMS $H \to \gamma\gamma$ analysis.
  4. The maximum entropy coincidence.
  5. What's inside the CMS combination?
  6. Concrete BSM model searches.
  7. Tensor structure: spin/CP.
  8. More on the m_H combination.
  9. Going off-shell.
  10. HL-LHC extrapolations.
  11. Kappa: BSM interpretations.
  12. Statistics primer.

Part I

"A complete disas… a mess"

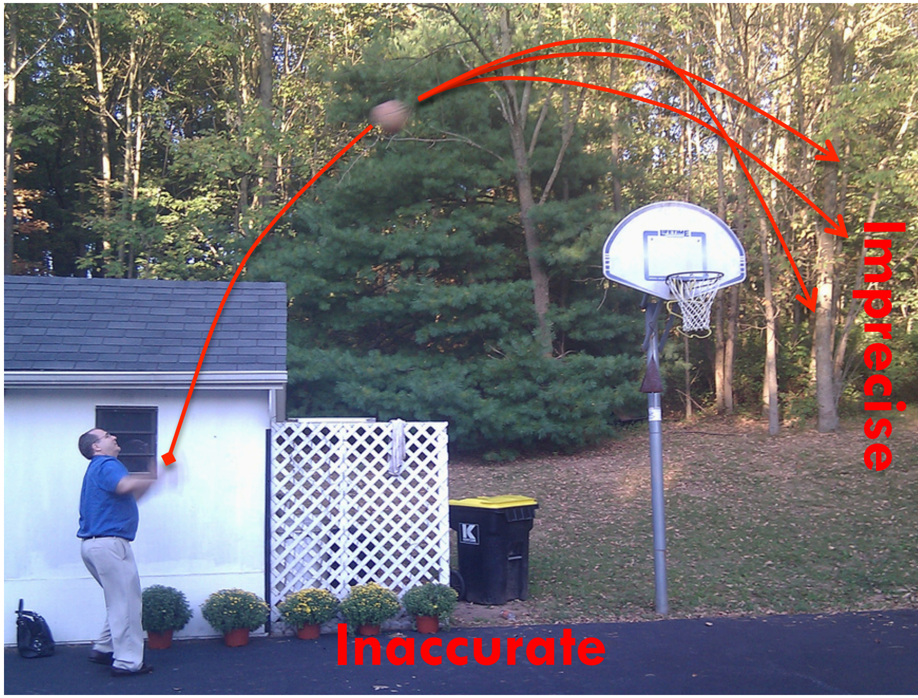
Accuracy vs. precision.

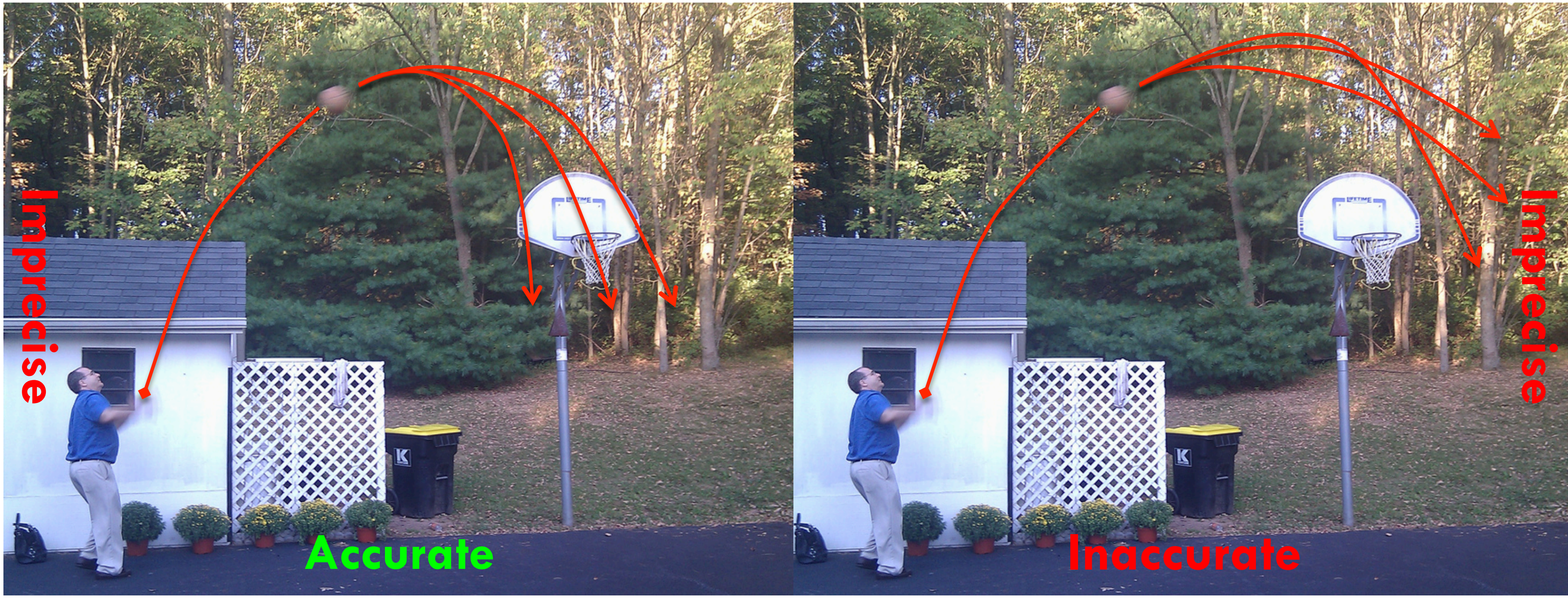
Uncertainty vs. error.

Sources of uncertainty vs. effects of uncertainties.

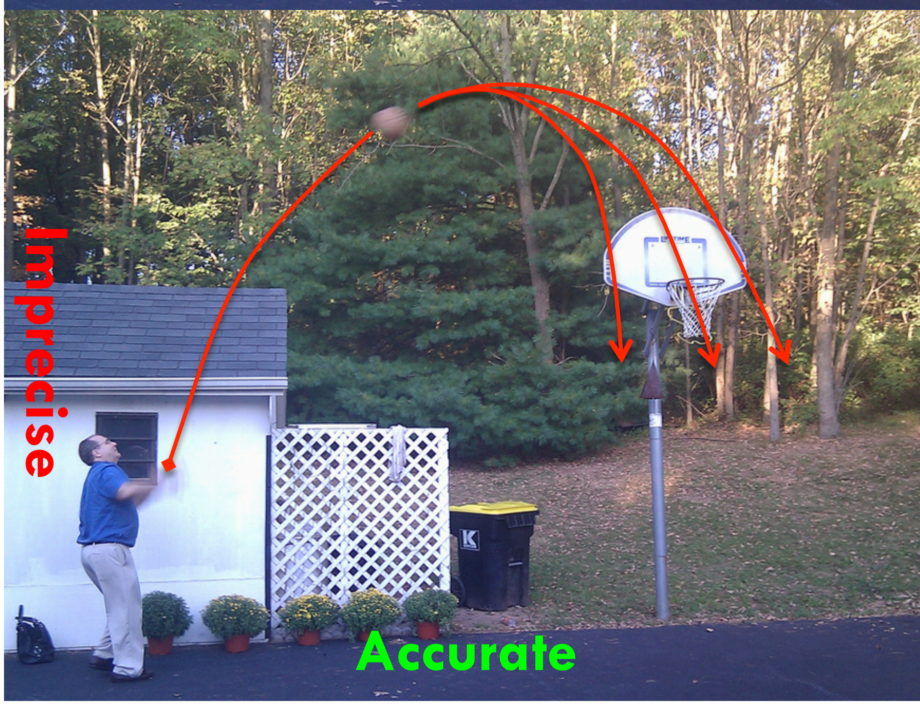
Scale variations vs. "scale uncertainties".

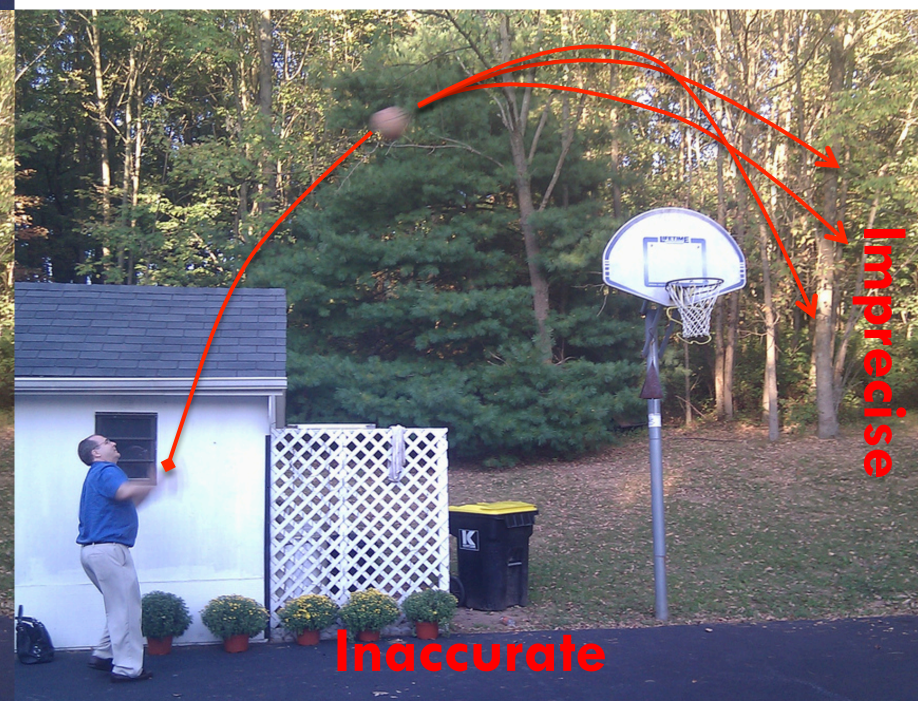
Two words on *accuracy and precision*

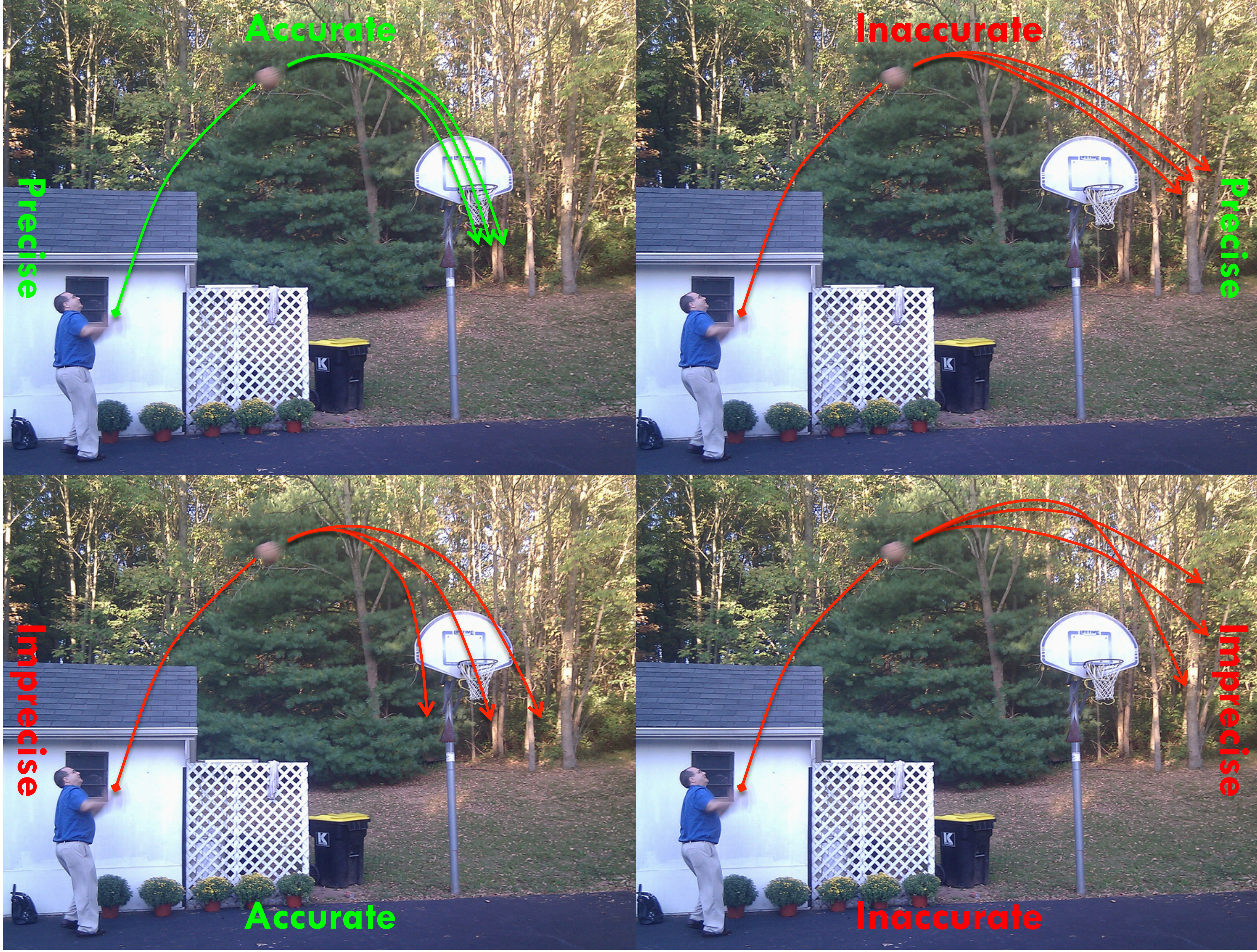

Imprecise
Inaccurate


Imprecise
Accurate
Inaccurate
Imprecise

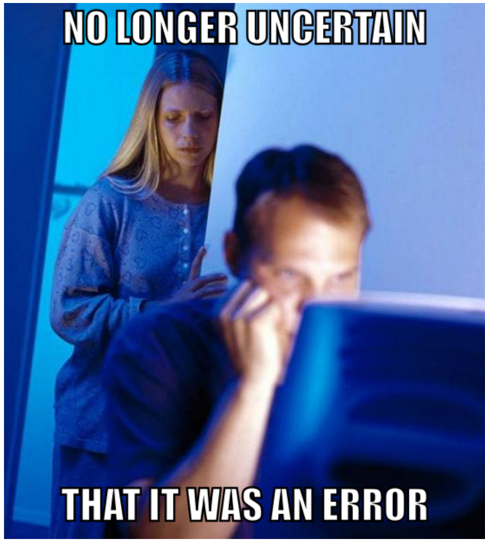

Accurate
Precise


Imprecise
Accurate


Imprecise
Inaccurate

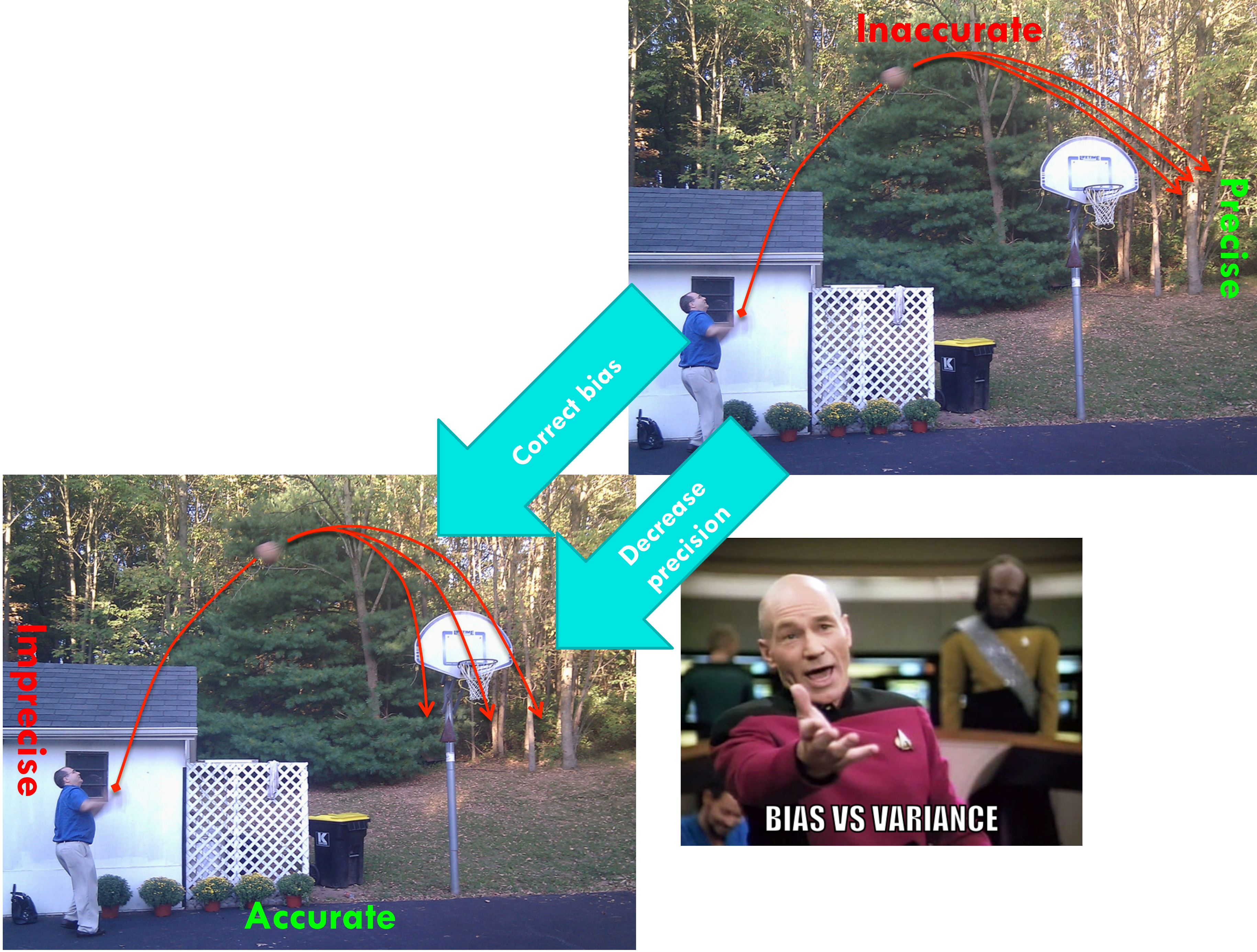

Accurate
Precise
Inaccurate
Precise
Imprecise
Accurate
Inaccurate
Imprecise

Two words on *error and uncertainty*

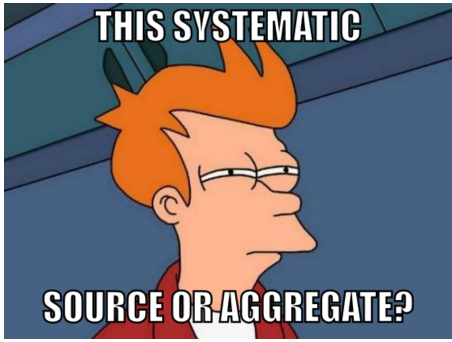


- **Error:** the result of a **bias** or **mistake.**
- **Uncertainty:** the degree to which some thing is not known.

- ***It's a mistake to call errors uncertainties.***
- E.g.:
  - Exp. correct for syst. effects (a bias).
  - Corrections come with added uncertainty.


Inaccurate
Precise
Correct bias
Decrease precision
Imprecise
Accurate
BIAS VS VARIANCE

Two words on *sources of syst. uncertainties*

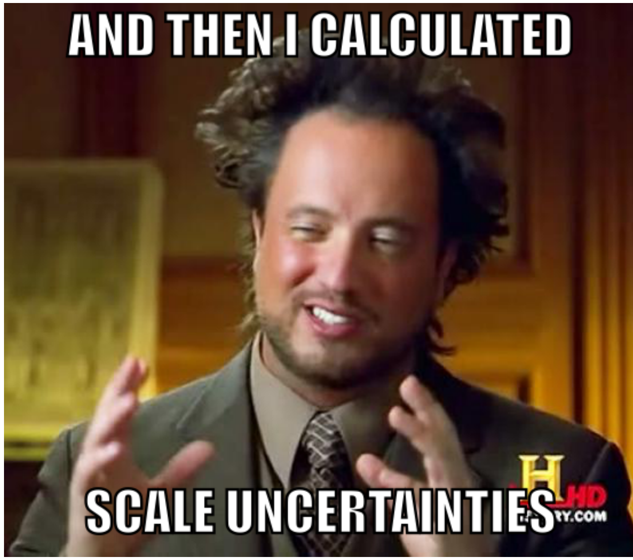


- **Jet energy scale** uncertainty:
  - Makes ggH events move in (out) of 0-jet (1-jet) selections.
  - Reduces (increases) overall acceptance, etc.
- **JES has an effect**, but is **not a source per se.**
- Sources of systematic uncertainty are:
  - Flavor-, time-, p_T-, and η-dependence of JES calibration,
  - Knowledge of the material in the detector, alignment precision, pile-up subtraction, etc.
- **Be mindful to not mix**
  - sources (independent, can be improved, combinable) with
  - effects (aggregate, cannot be improved, uncombinable).
  - *(Theory "uncertainties", which is yet another story.)*

Two words on *scale variations*

- ***There's no such thing as scale uncertainty.***

- There are **scale variations.**
  - Calculations should not depend on them…
  - … and some times they don't.
    - Does that mean the calculation is done?



About who is between what

Cf. Fabio's "Aneesh⟷Fabio⟷André"

Nature


Nature
Theory


Nature
Theory
Theorists
(inside)


Nature
Theory
Phenomenologists
Theorists
(inside)

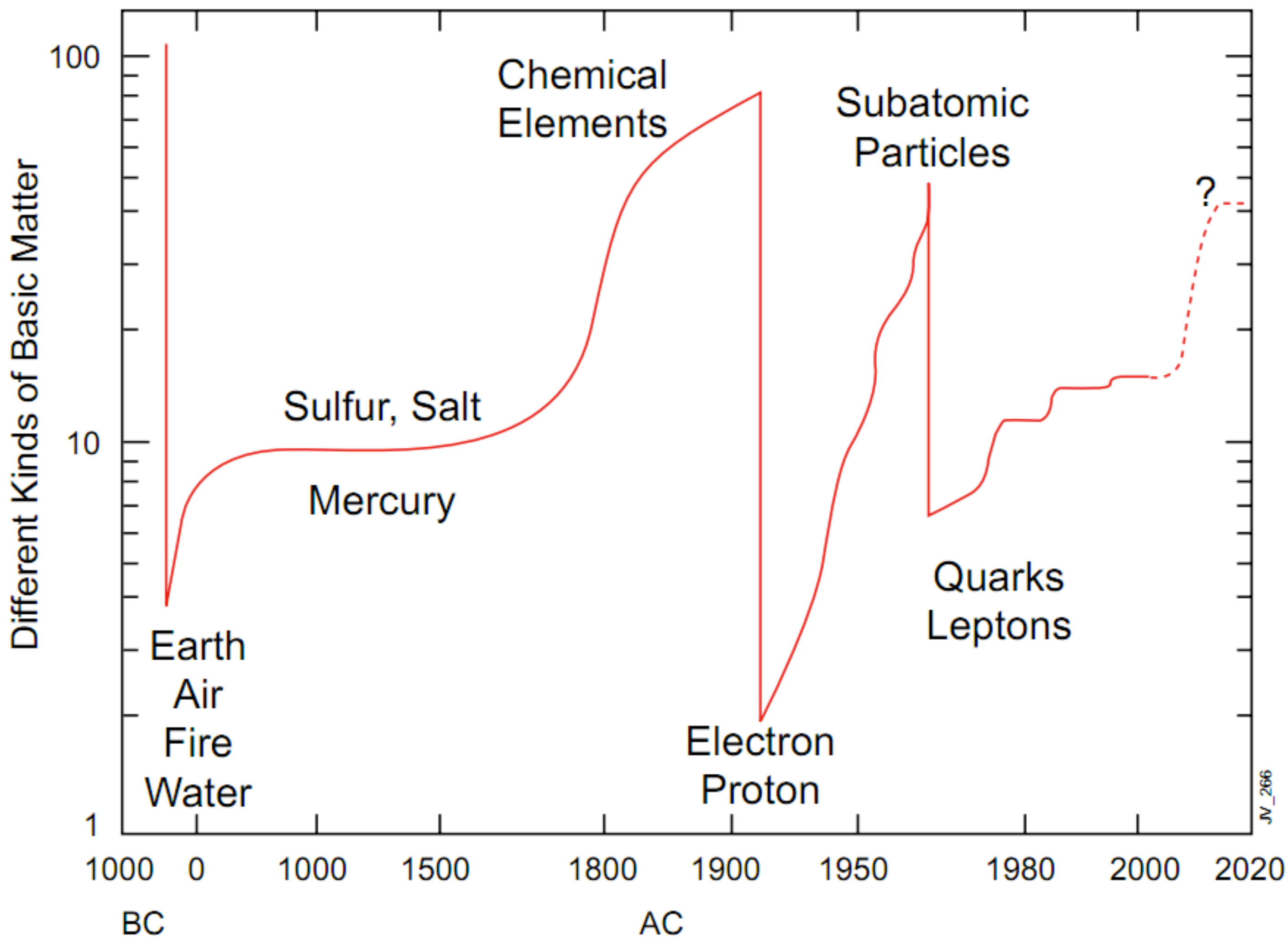

Nature
Nature
Theory
Phenomenologists
Theorists
(inside)


Nature
Experimentalists
Nature
Theory
Phenomenologists
Theorists
(inside)


Nature
Experienced experimentalists
Experimentalists
Nature
Theory
Phenomenologists
Theorists (inside)

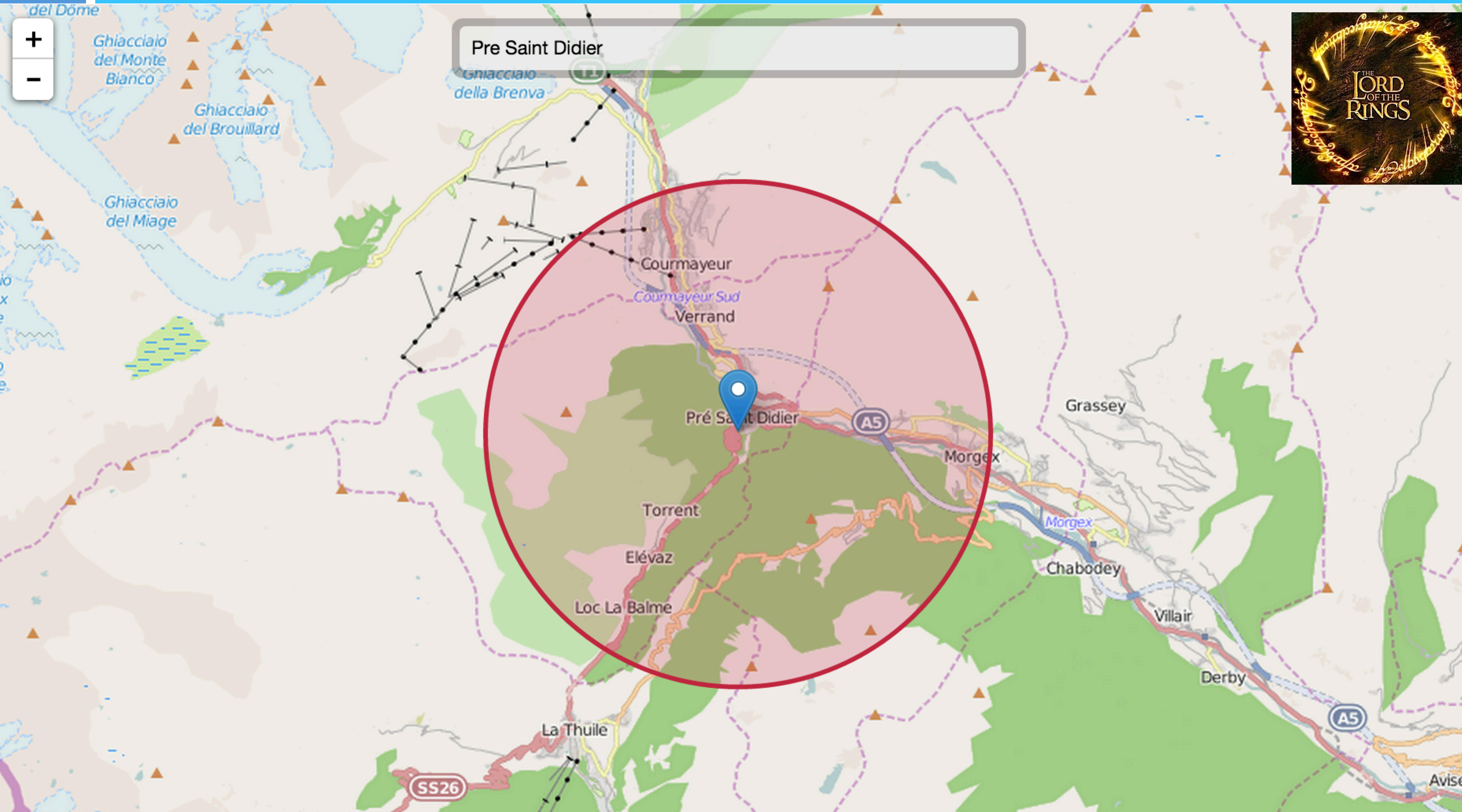
Evolutions & revolutions of the elements

[Plot courtesy of Jim Virdee]



LHC – the lord of the rings

[http://natronics.github.io/science-hack-day-2014/lhc-map/]



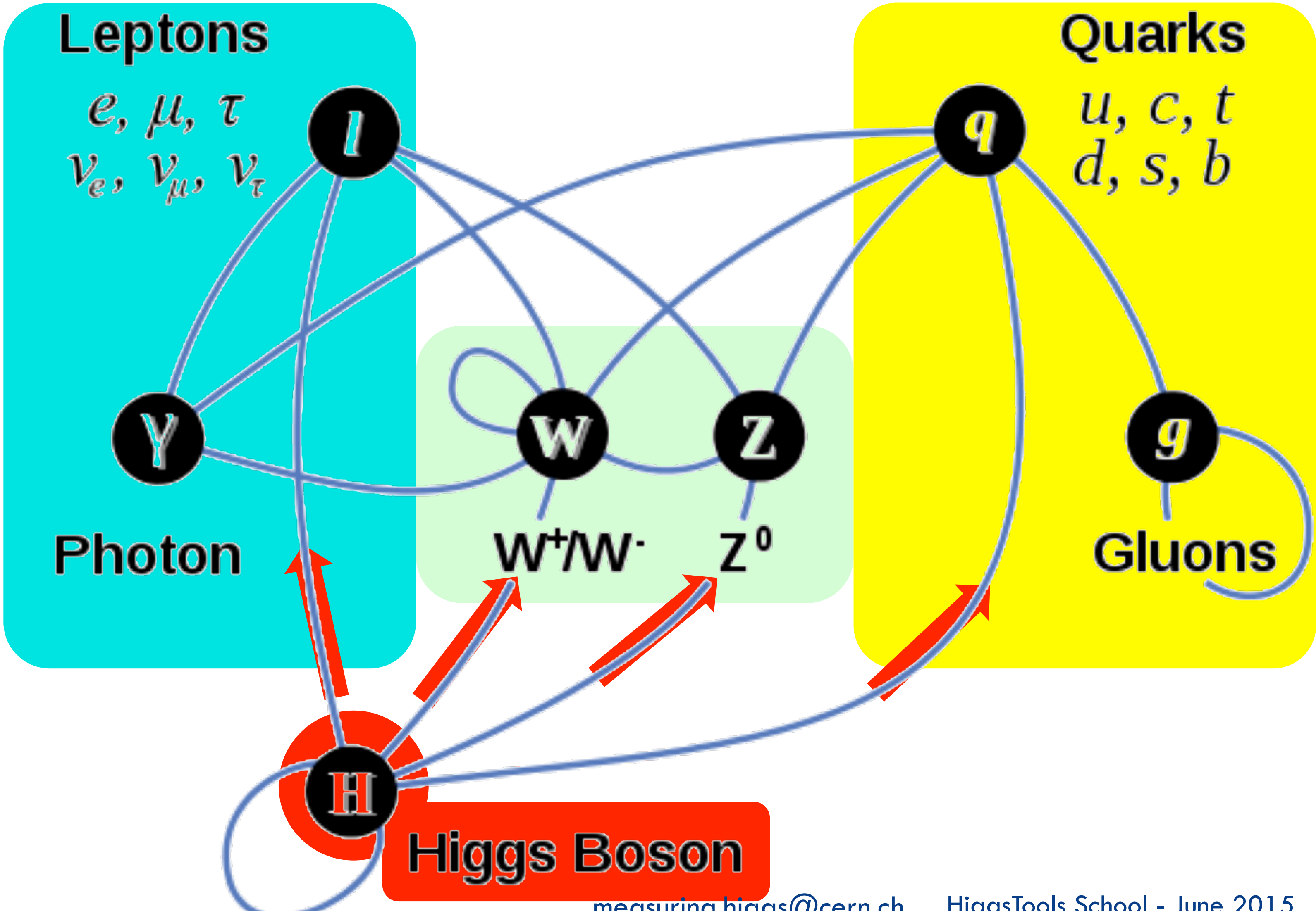
Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \\
&\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac12\partial_\mu H\partial_\mu H - \tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \\
&M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + \\
&g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + \\
&4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \\
&\tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac14 g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - \\
&g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + \\
&igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(\tfrac43 s_w^2 - \\
&1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+ \\
&\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) + \\
&i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt2}\phi^-[m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - \\
&m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac g2\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \tfrac g2\tfrac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 - \\
&M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- - \\
&\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) + \\
&igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) - \tfrac12 gM[\bar X^+ X^+ H + \bar X^- X^- H + \tfrac{1}{c_w^2}\bar X^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar X^+ X^0\phi^+ - \\
&\bar X^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-] + igMs_w[\bar X^0 X^-\phi^+ - \bar X^0 X^+\phi^-] + \tfrac12 igM[\bar X^+ X^+\phi^0 - \bar X^- X^-\phi^0]
\end{aligned}
$$

The Standard Model of Particle Physics

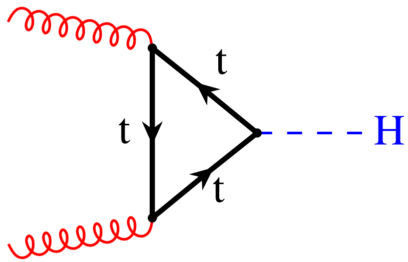
Electromagnetic force – light Weak force – star combustion Strong force – protons and neutrons



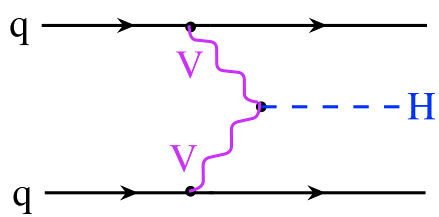
How SM Higgses are born

[http://cern.ch/go/cWH8][http://cern.ch/go/SnJ8]

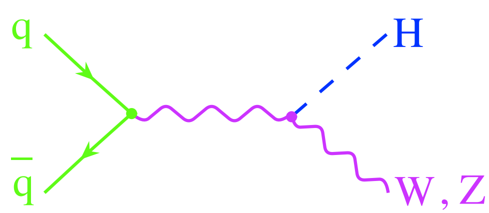
- **Gluon fusion**



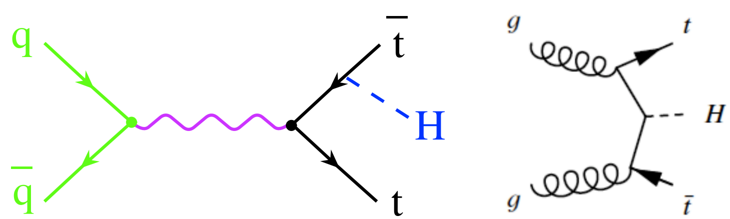
- **VBF**

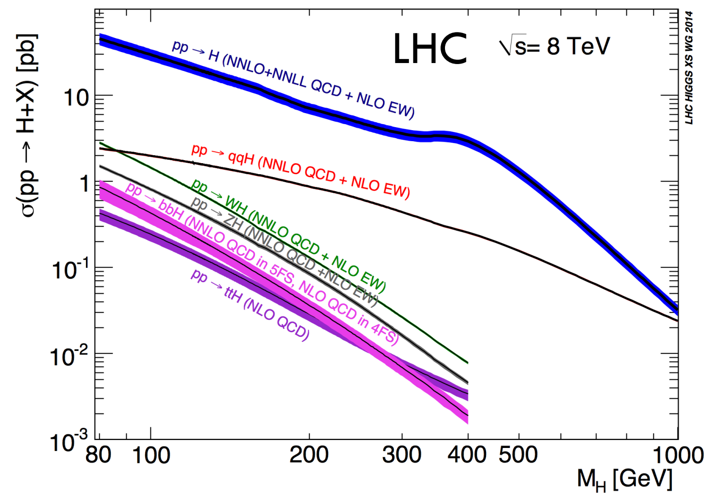


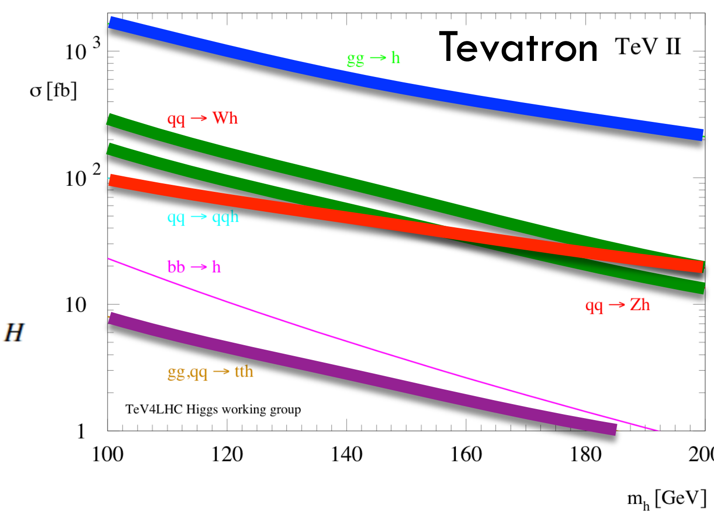
- **WH, ZH**



- **bbH, ttH**



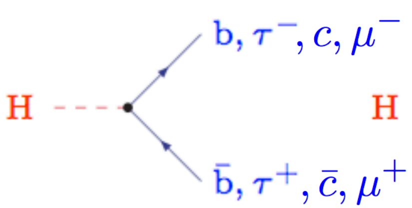


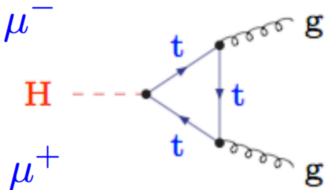


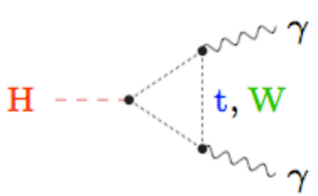
How SM Higgses die

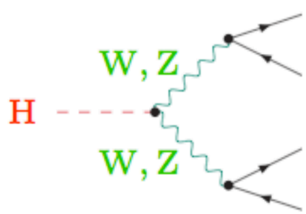
[http://cern.ch/go/qkh6][arXiv:1208.1993][arXiv:1408.0827]

- Couplings and kinematics drive BR ($b\bar{b}$, WW, $\tau\tau$, ZZ).
  - Decays with photons ($\gamma\gamma$, $Z\gamma$) through loops.

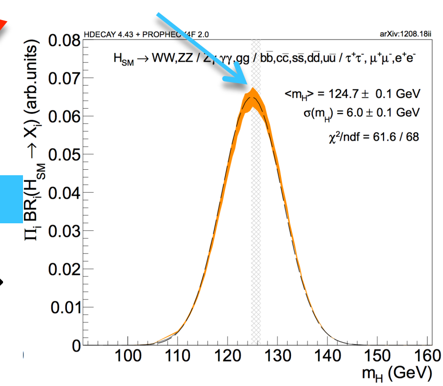


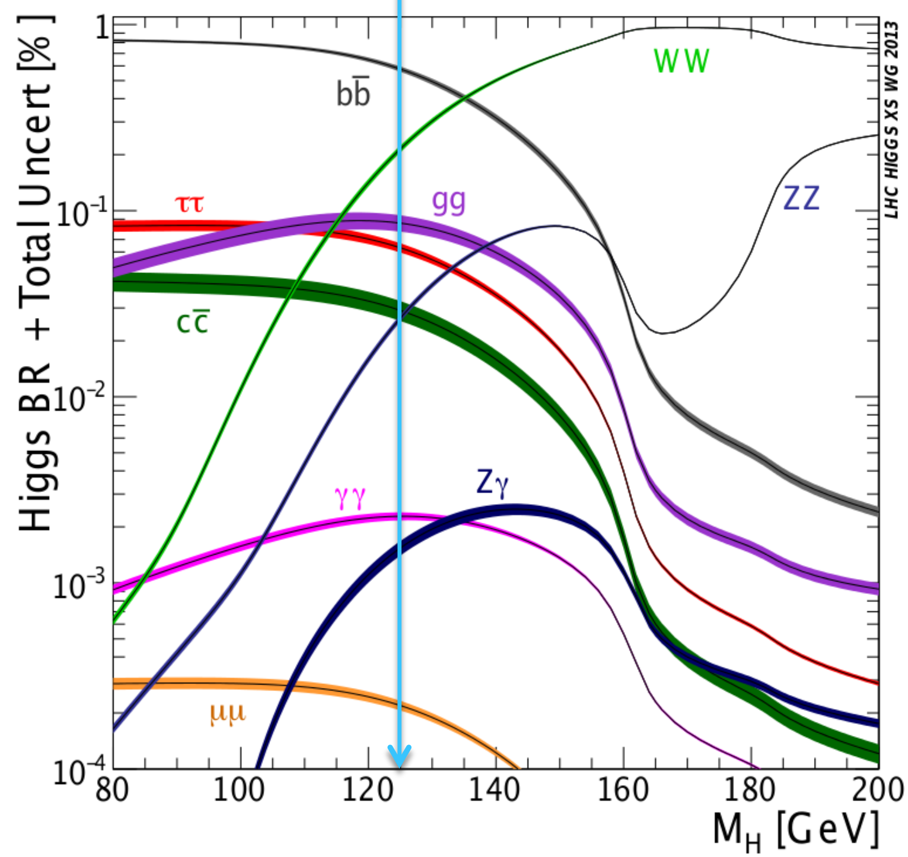






Near to maximal ΠBR_i ⟶





Prato dei Miracoli

[http://goo.gl/K8Lqmu]

Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu][“Scalar meadow”]

Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu][“Scalar meadow”]

2011: nothing else in the horizon

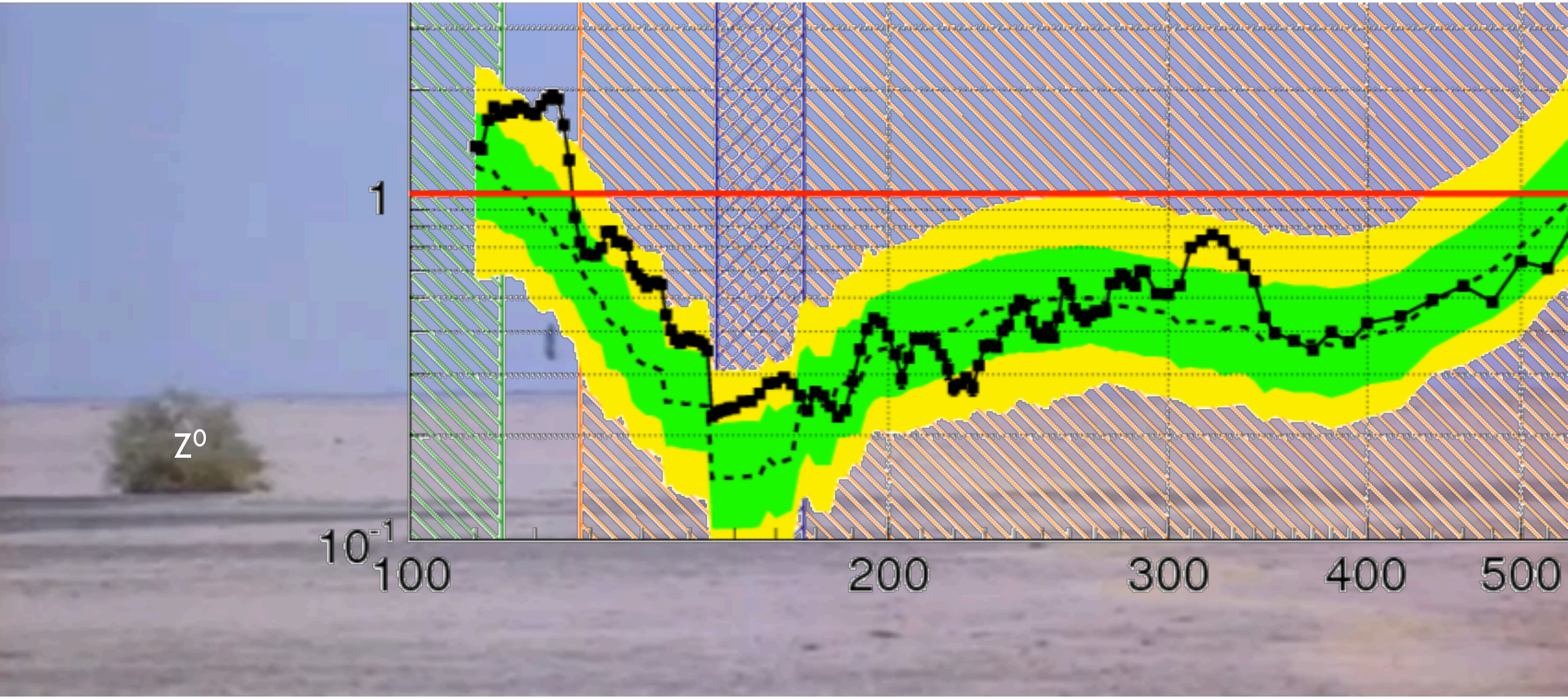
["Lawrence of Arabia" idea from C. Grojean]

- We first saw that we could not exclude a narrow range.

2011: nothing else in the horizon

["Lawrence of Arabia" idea from C. Grojean]

- We first saw that we could not exclude a narrow range.



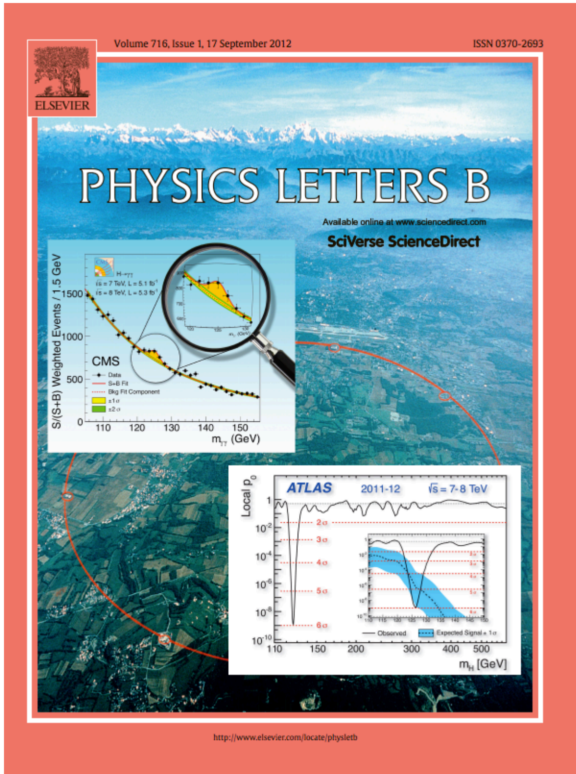
2012: a rider!

["Lawrence of Arabia" idea from C. Grojean]

- We discovered a peak rising from the background.

July 4, 2012
Looking up to a new boson

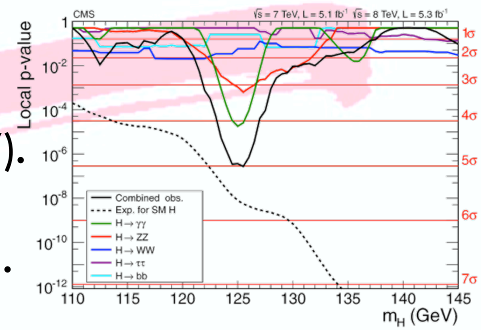
[http://cern.ch/go/q8jx]

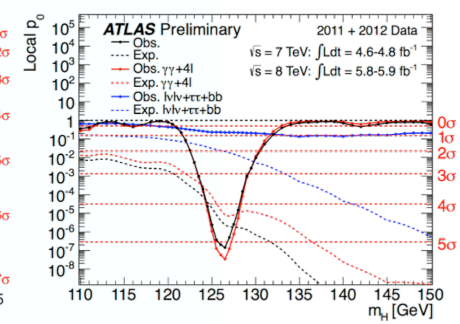


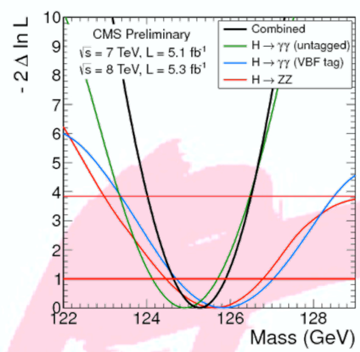
Higgsdependence day recap

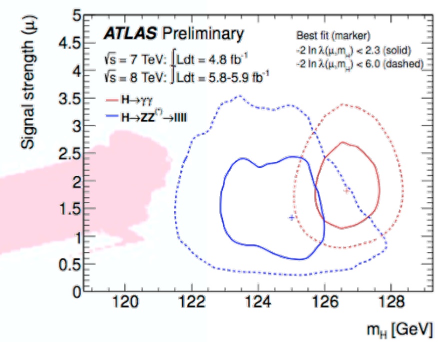
[http://cern.ch/go/q8jx]

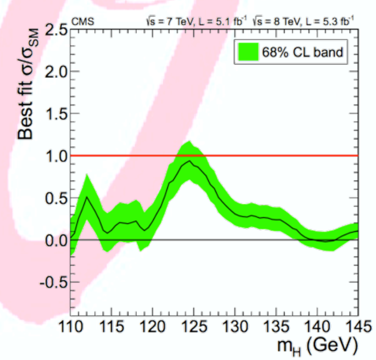
- **Both experiments at 5.0 σ.**
  - One above SM expectations…
    $\sigma_{ATLAS}/\sigma_{SM}$ = **1.2 ±0.3** (at 126.5 GeV).
  - …the other one below.
    σ_{CMS}/σ_{SM} = **0.80 ±0.20** (at 125 GeV).
- Mass
  - ATLAS: min. p-value at 126.5 GeV.
  - CMS: m_X = 125.3 ±0.6 GeV.
- "Proto-couplings" compatible with SM.
- ***"More data needed…"***

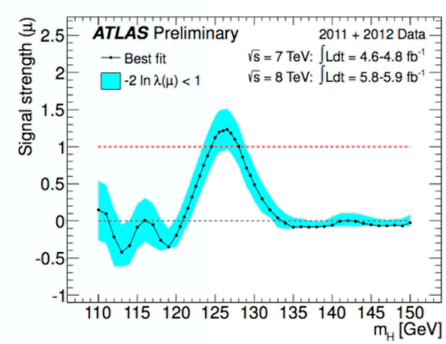


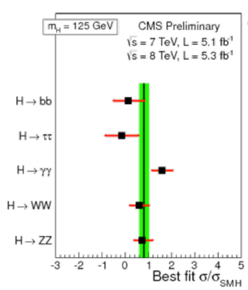


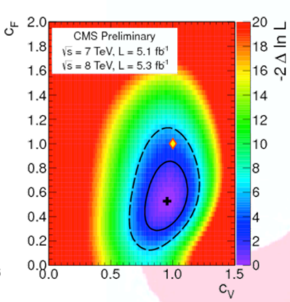


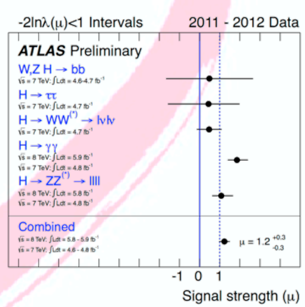












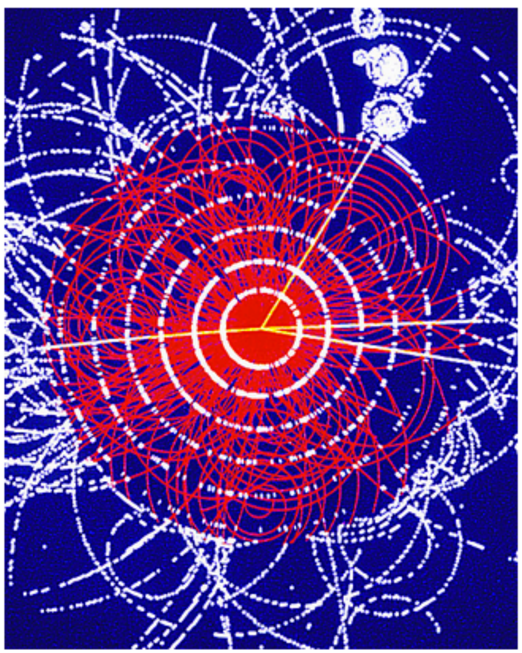
Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

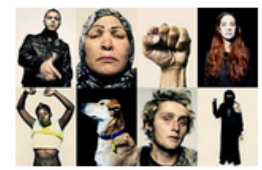
WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

Video

Poll Results

PAST PERSONS OF THE YEAR



2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

2008: Barack Obama

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THE CANDIDATES

18 of 40

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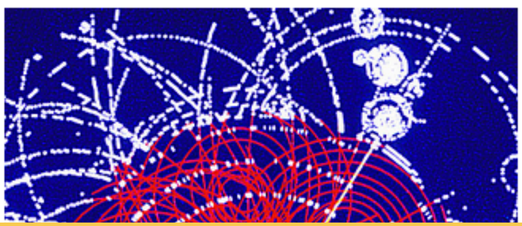

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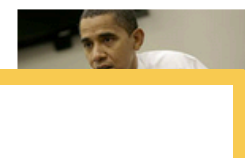
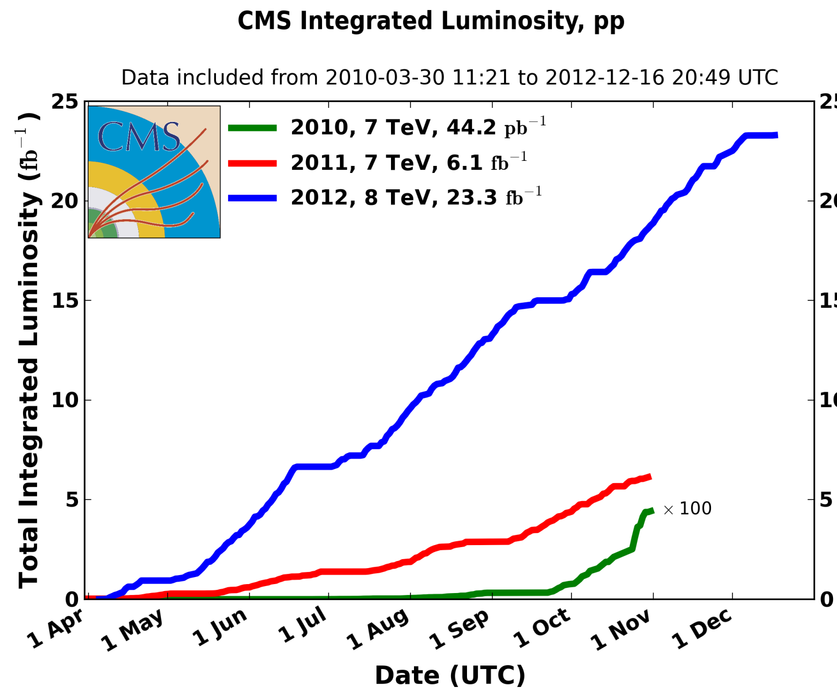
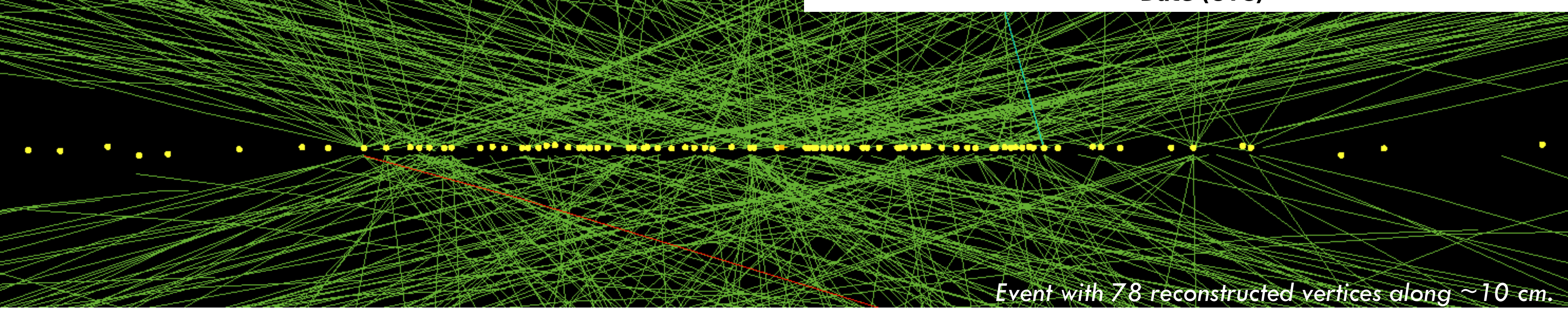


The LHC Run 1: a bountiful harvest

[http://cern.ch/go/K8Tj] [http://cern.ch/go/ZW9S]

- LHC delivered ~30 fb^{-1}.
- **Challenge:** precision physics with ~20 simultaneous proton-proton collisions.





Event with 78 reconstructed vertices along ~10 cm.

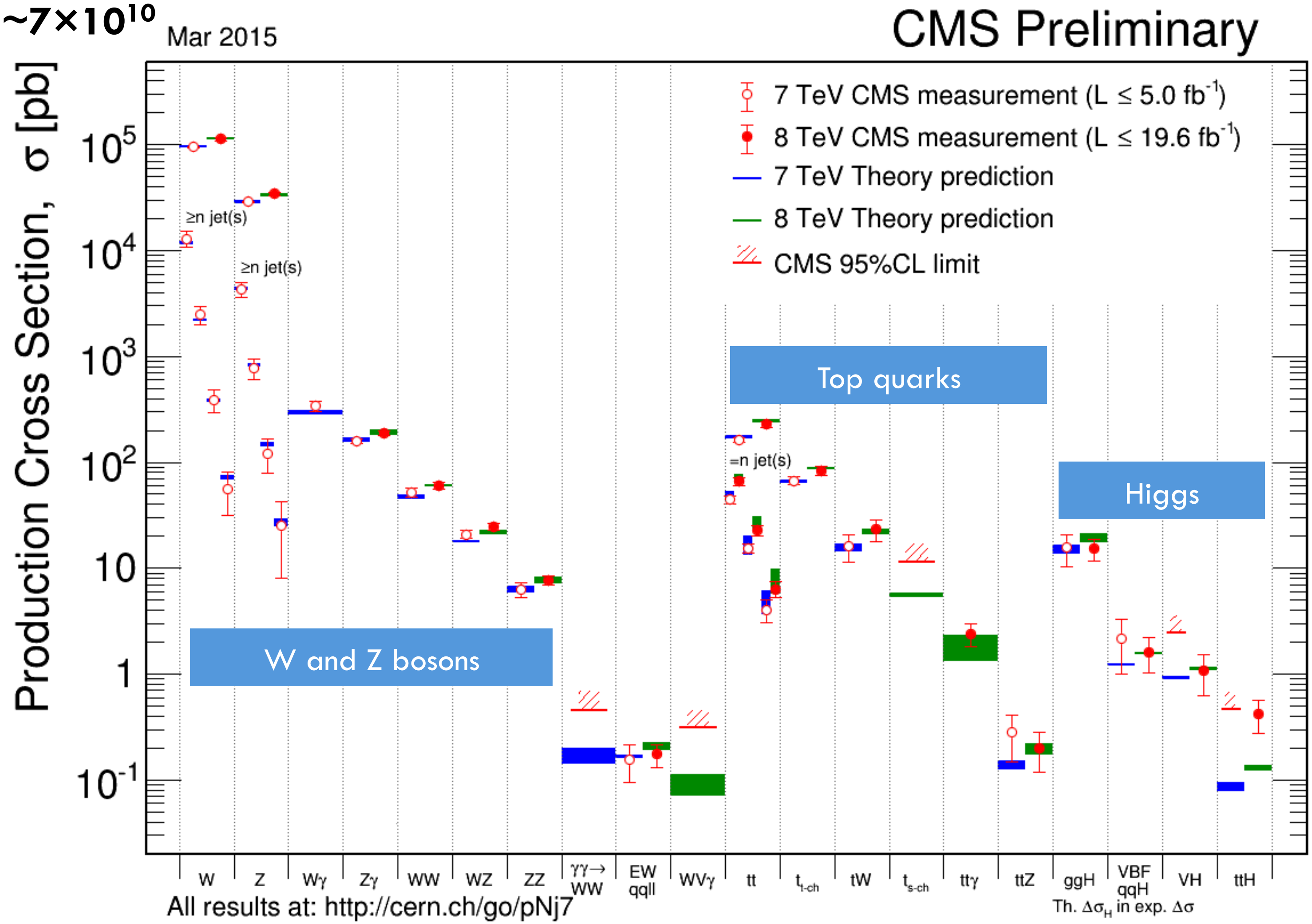
On the shoulders of giants

detector makers & theory calculators

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [http://cern.ch/go/lf9C][http://cern.ch/go/KD8D]

Inelastic collisions: ~7×10^{10}

Six orders of magnitude of EWK, top, and Higgs Physics

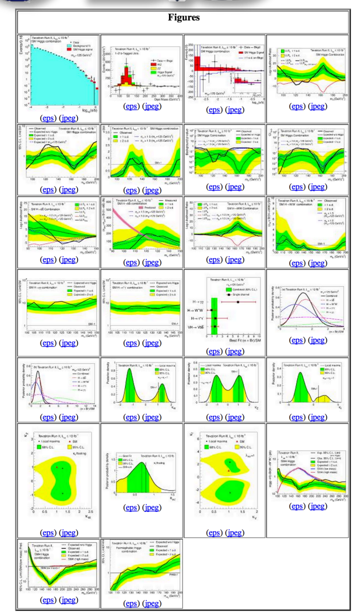


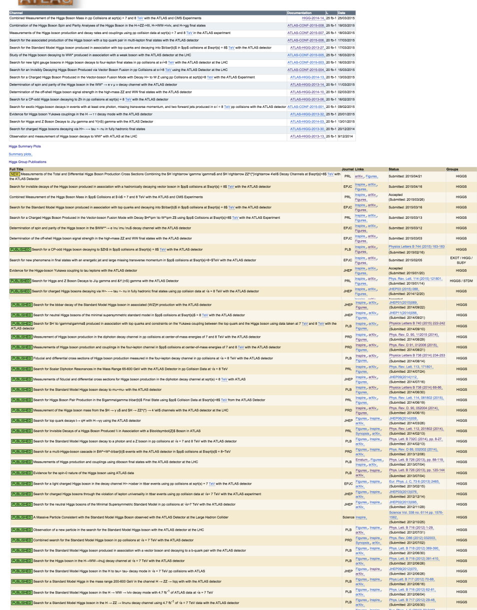
2013: a rider with a gun

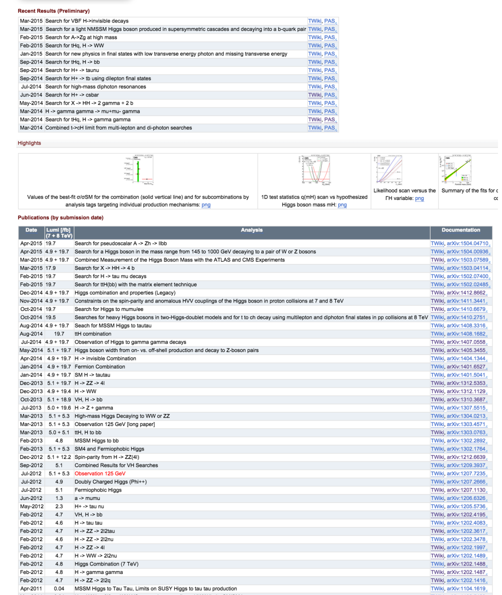
["Lawrence of Arabia" idea from C. Grojean]

- By early 2013 a clear Higgs-like picture emerged.

(self-inflicted) Mission: impossible







- Present a coherent view of (some) present-day Higgs coupling results from LHC (and Tevatron) experiments.
  - Any mistake is the speaker's fault (send email).

Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

★ "seen" ☆ "tried" - "impossible"	$H \to b\bar{b}$			$H \to \tau\tau$			$H \to WW$			$H \to ZZ$			$H \to \gamma\gamma$			$H \to Z\gamma$			$H \to$ inv.			$H \to \mu\mu$			$H \to c\bar{c}$ $H \to HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

- **Still much to explore on the rarer ends.**

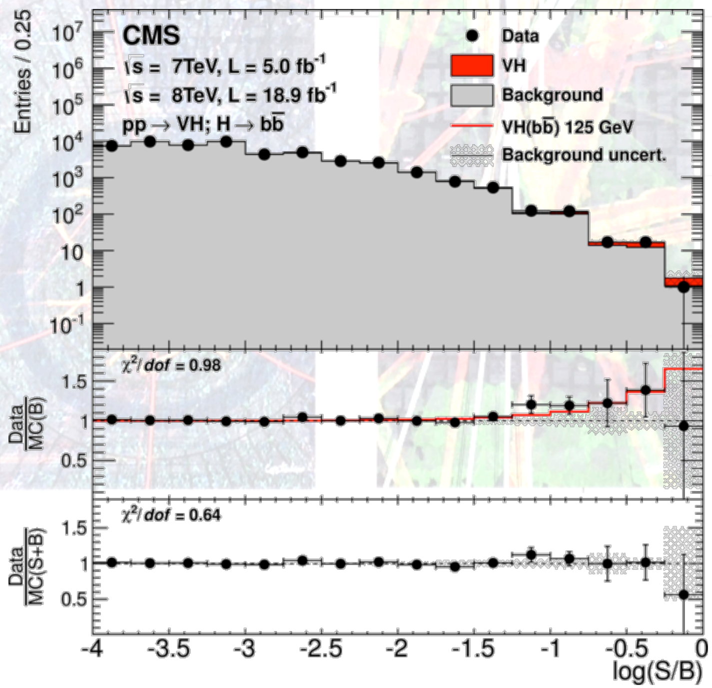
  (to the right and to the bottom) (and outside this picture ☰)

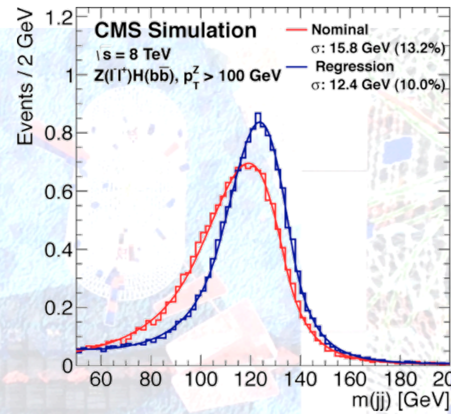
VH, H→b$\bar{b}$ vignettes

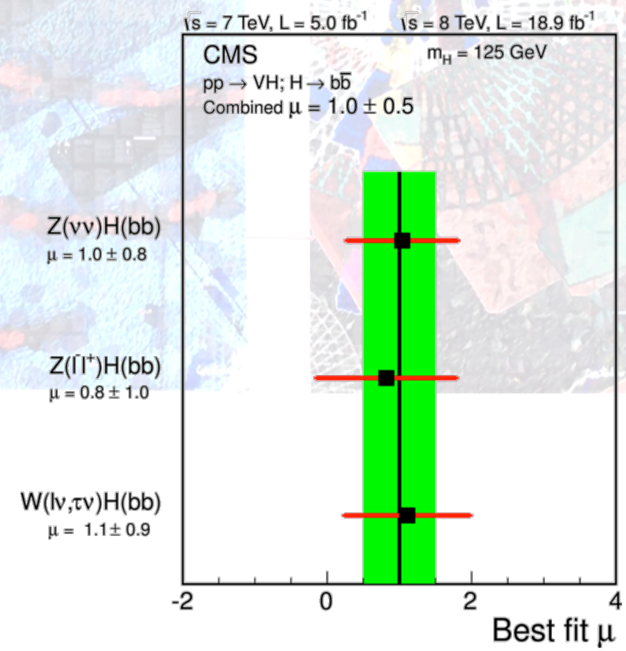
[PRD 89 (2014) 012003]

PRD 89 (2014) 012003

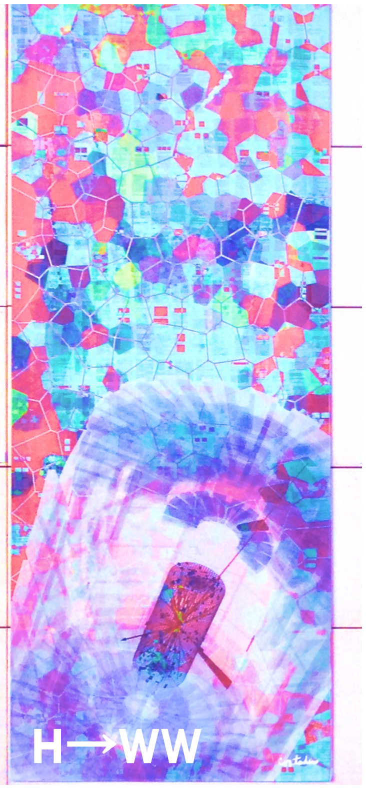
- 2.1σ (2.3σ exp.)
- σ/σ_{SM} = 1.0 ±0.5





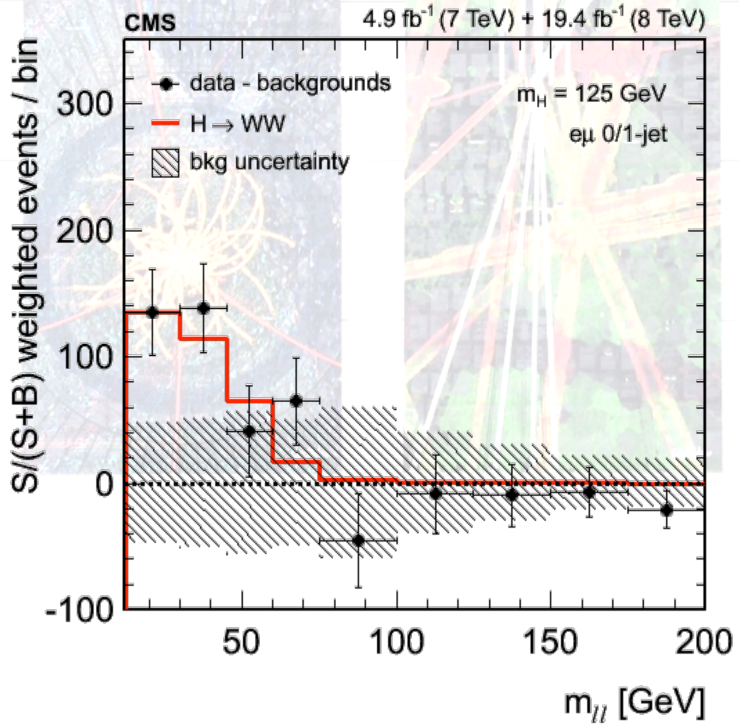


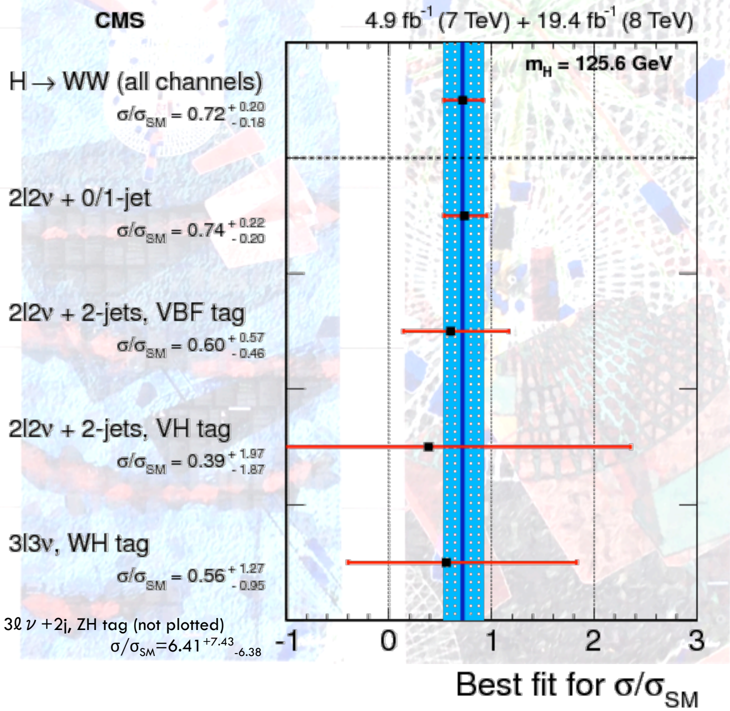
H→WW→2ℓ2ν vignettes



JHEP 01 (2014) 096

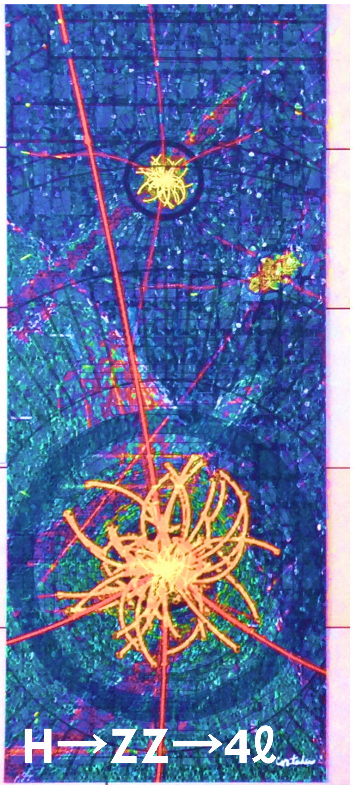
- 4.3σ (5.8σ exp.)
- $\sigma/\sigma_{SM} = 0.72 \pm 0.19$





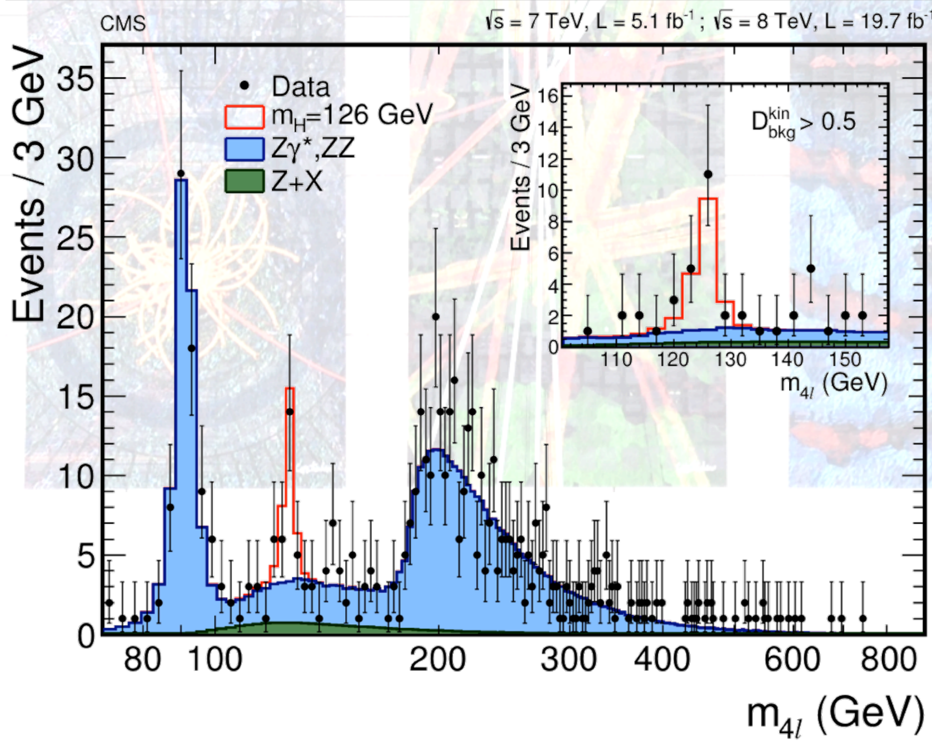
H→ZZ→4ℓ vignettes

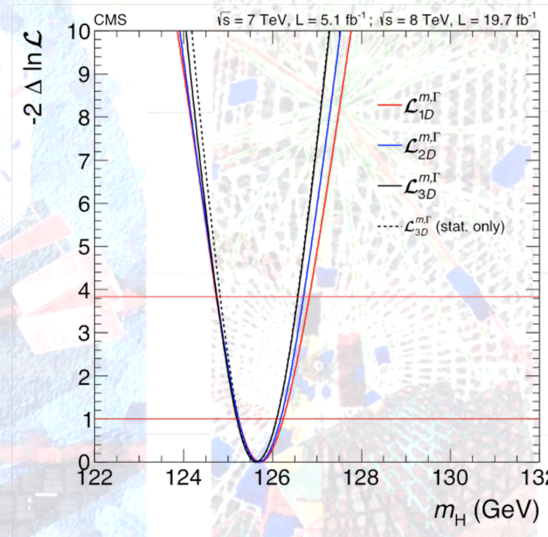
[PRD 89 (2014) 092007]

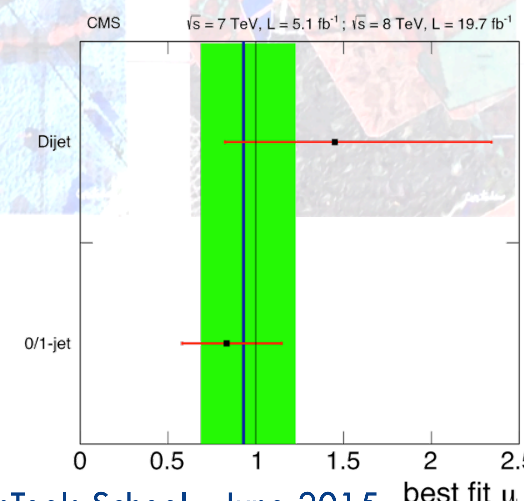


PRD 89 (2014) 092007

- 6.8σ (6.7σ exp.)
- m_H= 125.63 ±0.42 (stat.) ±0.16 (syst.) GeV
- σ/σ_{SM} = 0.93 ±0.25 (stat.) ±0.13 (syst.)

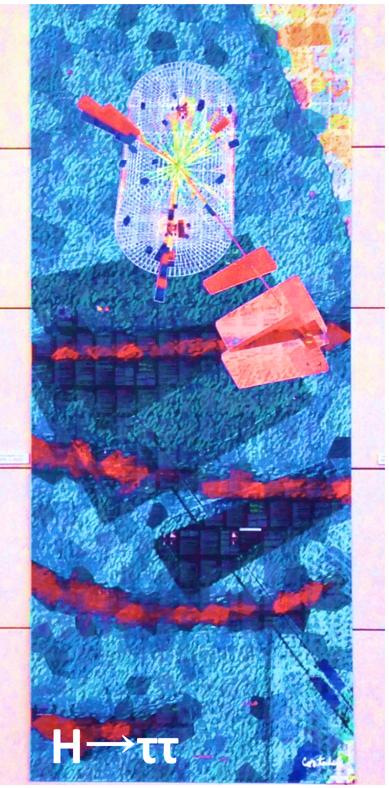






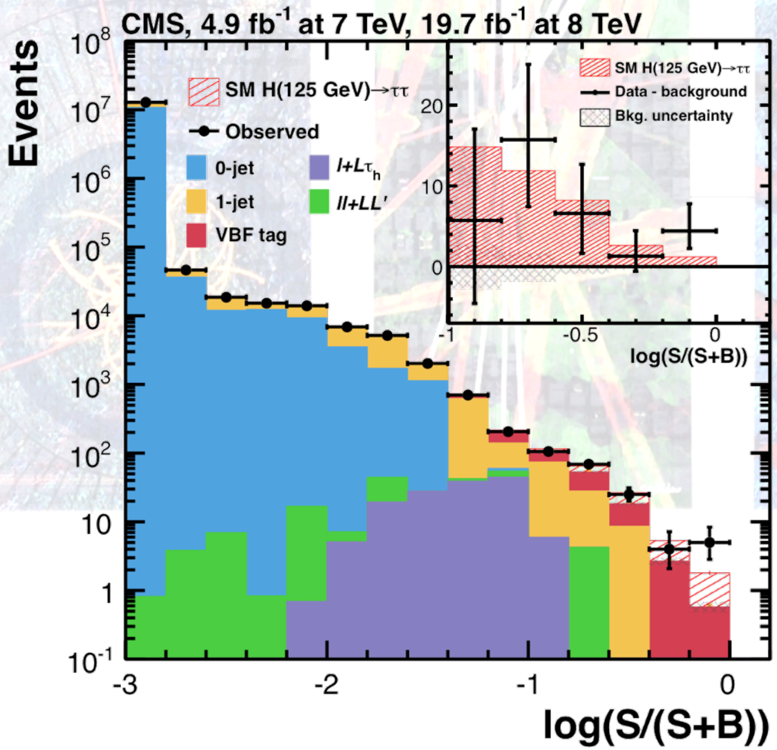
H→ττ vignettes

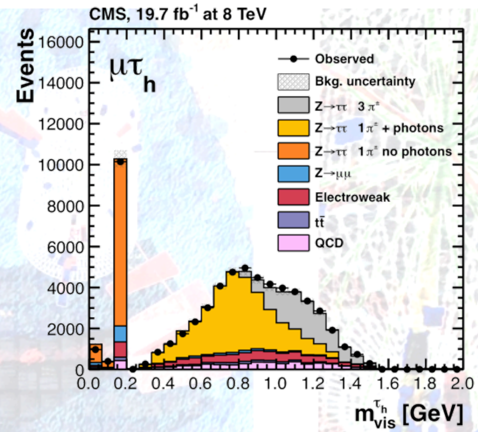
[JHEP 05 (2014) 104]

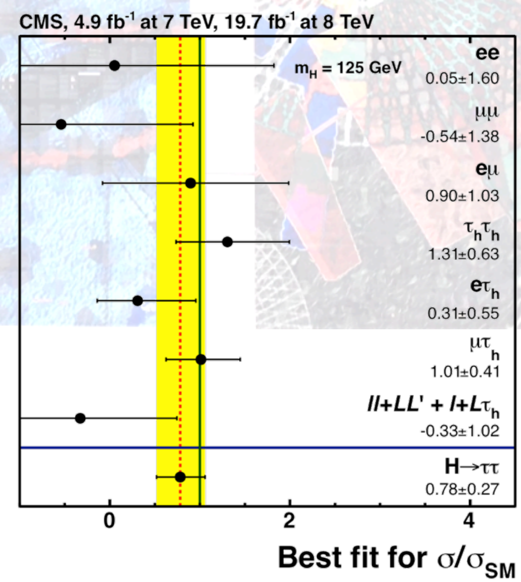


JHEP 05 (2014) 104

- 3.2σ (3.7σ exp.)
- σ/σ_{SM} = 0.78 ±0.27





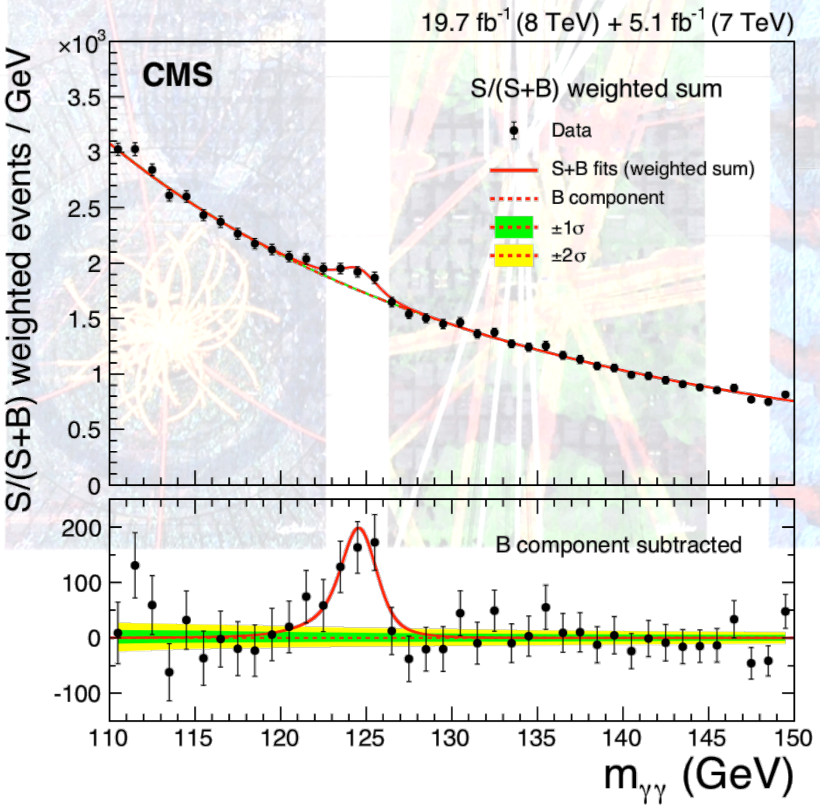


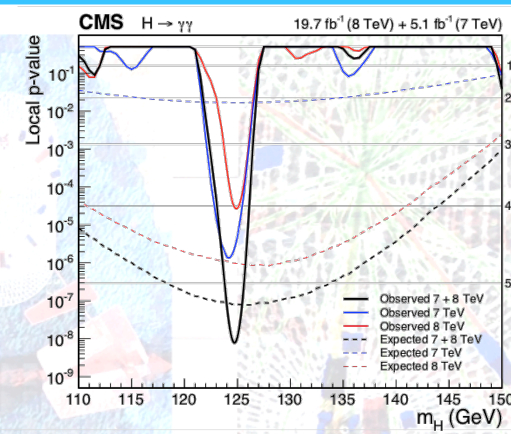
$H \rightarrow \gamma\gamma$ vignettes

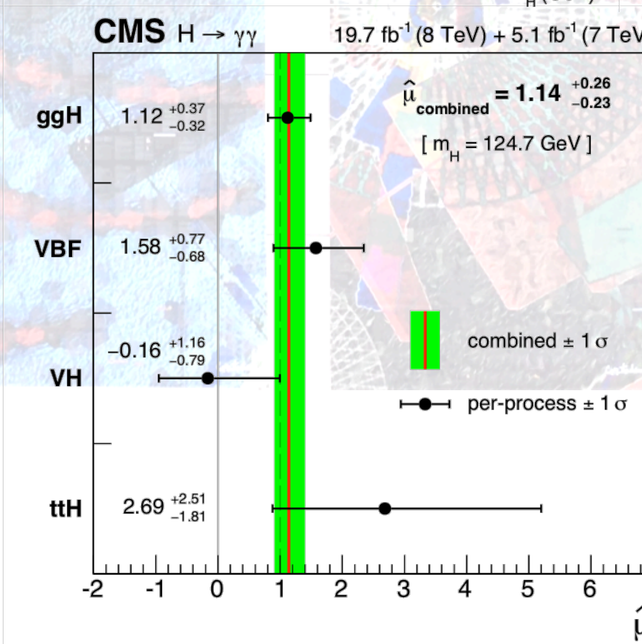
[EPJC 74 (2014) 3076]

- 5.7σ (5.2σ exp.)
- $m_H = 124.70 \pm 0.31$ (stat.) ± 0.15 (syst.) GeV
- $\sigma/\sigma_{SM} = 1.14 \pm 0.21$ (stat.) ± 0.11 (theo.) ± 0.07 (syst.)

EPJC 74 (2014) 3076







Nobel prizes…

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \\
&\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac12\partial_\mu A_\nu\partial_\mu A_\nu - \tfrac12\partial_\mu H\partial_\mu H - \tfrac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \\
&M^2\phi^+\phi^- - \tfrac12\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + \\
&g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + \\
&4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \tfrac12 g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \\
&\tfrac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \tfrac12 g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac14 g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac14 g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \tfrac12 g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac12 ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - \\
&g^2\tfrac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + \\
&igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac23(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac13(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac43 s_w^2 - \\
&1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\tfrac83 s_w^2-\gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt2}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt2}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+ \\
&\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt2}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt2}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt2}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - \\
&m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - \\
&M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + \\
&igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \tfrac12 gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \\
&\bar{X}^-X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \tfrac12 igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{aligned}
$$

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \tfrac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \\
&\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \tfrac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \\
&M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h\left[\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \tfrac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
&A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + \\
&g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \tfrac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2 \phi^+\phi^- + \\
&4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - g M W^+_\mu W^-_\mu H - \tfrac{1}{2} g \tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \\
&\tfrac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - \\
&W^-_\mu \phi^+) + i g s_w M A_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - i g \tfrac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
&\tfrac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \tfrac{1}{4} g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] - \tfrac{1}{2} g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) - \tfrac{1}{2} i g^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \tfrac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - \\
&g^2 \tfrac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m_u^\lambda) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m_d^\lambda) d^\lambda_j + \\
&i g s_w A_\mu \left[-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)\right] + \tfrac{i g}{4 c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (\tfrac{4}{3} s_w^2 - \\
&1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s_w^2 - \gamma^5) d^\lambda_j)] + \tfrac{i g}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d^\kappa_j)] + \tfrac{i g}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1 + \\
&\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) u^\lambda_j)] + \tfrac{i g}{2\sqrt{2}} \tfrac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \tfrac{g}{2} \tfrac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + \\
&i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \tfrac{i g}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m_u^\lambda (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j)] + \tfrac{i g}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - \\
&m_u^\kappa (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j)] - \tfrac{g}{2} \tfrac{m_u^\lambda}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m_d^\lambda}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{i g}{2} \tfrac{m_u^\lambda}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{i g}{2} \tfrac{m_d^\lambda}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{X}^+ (\partial^2 - \\
&M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \\
&\partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + \\
&i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) - \tfrac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H] + \tfrac{1 - 2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \\
&\bar{X}^- X^0 \phi^-] + \tfrac{1}{2c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \tfrac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
\end{aligned}
$$

SM with H = Standard Theory

Standard **Theory** of Particle Physics

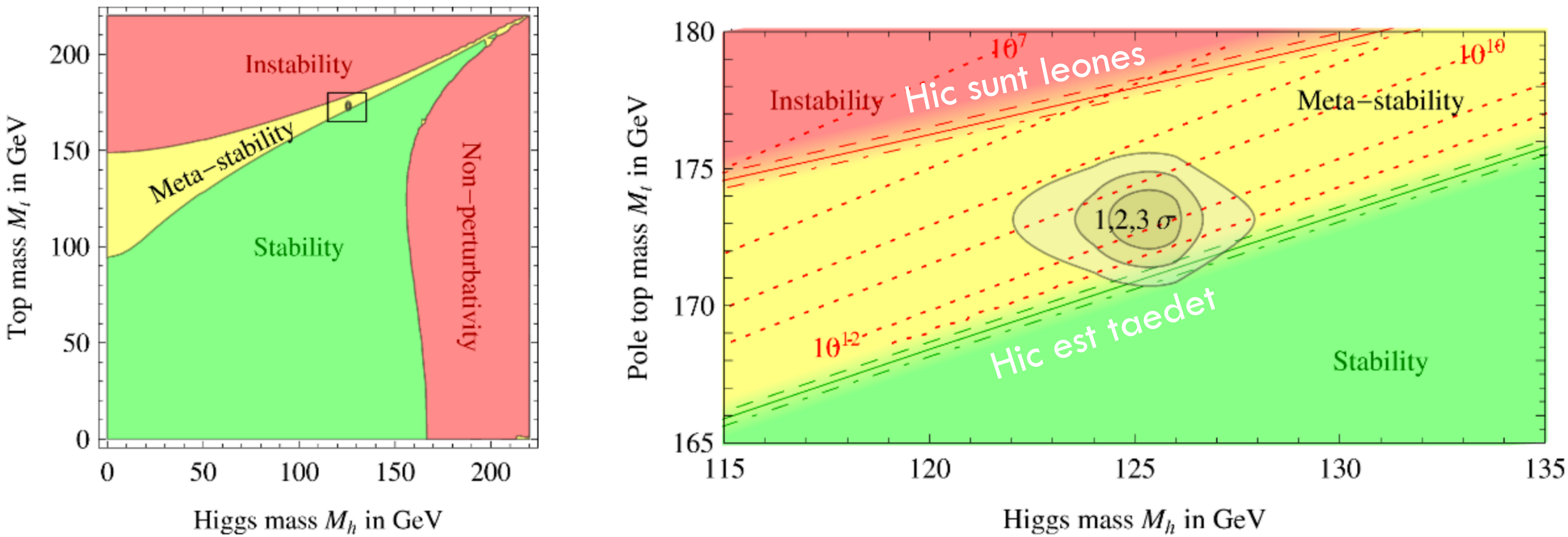
[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4} g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu -$$
$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac12 \partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac12 \partial_\mu A_\nu \partial_\mu A_\nu - \frac12 \partial_\mu H \partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$
$$M^2\phi^+\phi^- - \frac12 \partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2} M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$
$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$
$$\frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + igs_w \quad \ldots \quad) -$$
$$\frac14 g^2 W^+_\mu W^-_\mu[H \quad \ldots \quad +$$
$$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar d_j^\lambda(\gamma\partial + m_d^\lambda)d_j^\lambda +$$
$$igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u_j^\lambda\gamma^\mu u_j^\lambda) - \frac13(\bar d_j^\lambda\gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar u_j^\lambda\gamma^\mu(\frac43 s_w^2 -$$
$$1-\gamma^5)u_j^\lambda) + (\bar d_j^\lambda\gamma^\mu(1-\frac83 s_w^2-\gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar d_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) +$$
$$i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa) + m_u^\lambda(\bar u_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) -$$
$$m_u^\kappa(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda) - \frac g2\frac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d_j^\lambda\gamma^5 d_j^\lambda) + \bar X^+(\partial^2 -$$
$$M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+ X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- -$$
$$\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^- X^0 - \partial_\mu\bar X^0 X^+) + igs_wW^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) +$$
$$igs_wA_\mu(\partial_\mu\bar X^+ X^+ - \partial_\mu\bar X^- X^-) - \frac12 gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ -$$
$$\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

Valid up to ~Planck scale ?

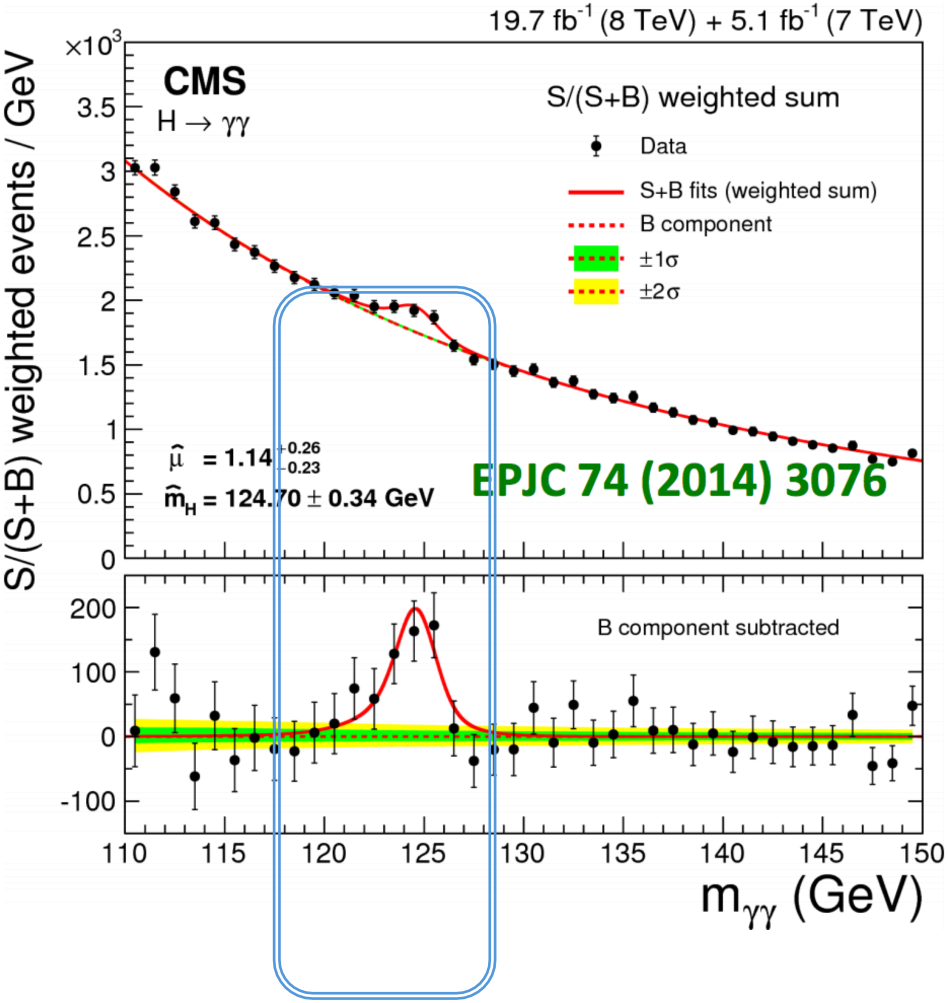
The fate/character of the Universe

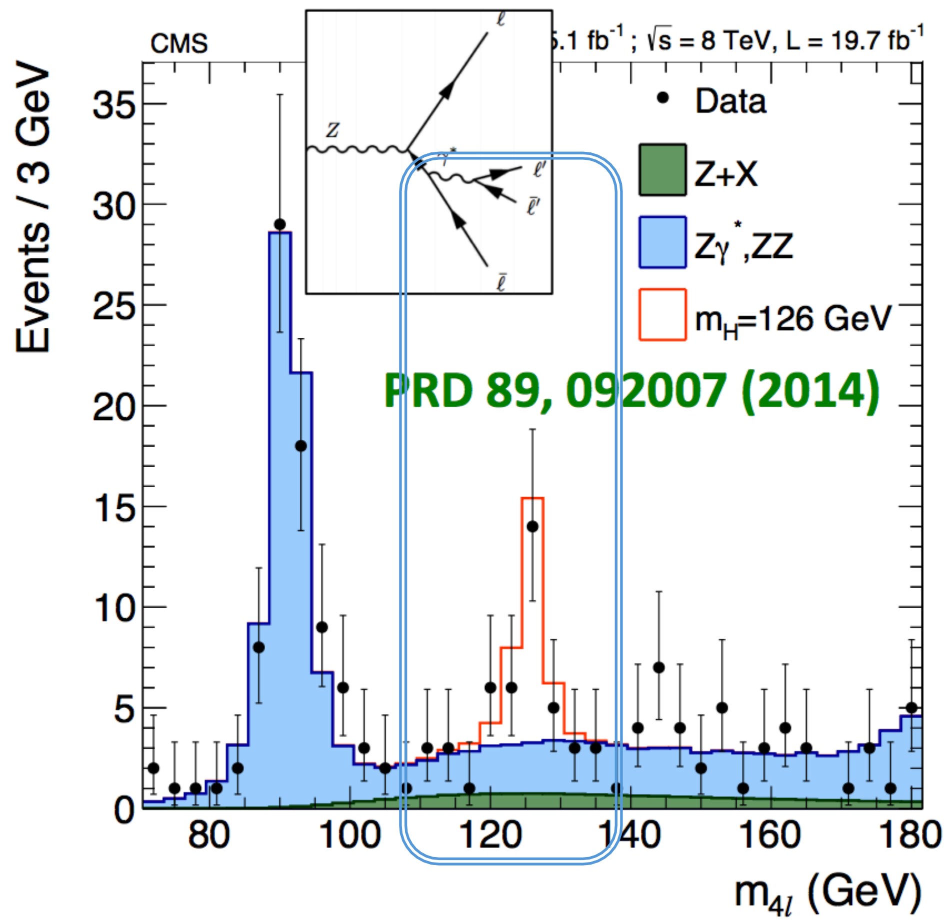
[JHEP 08 (2012) 098]



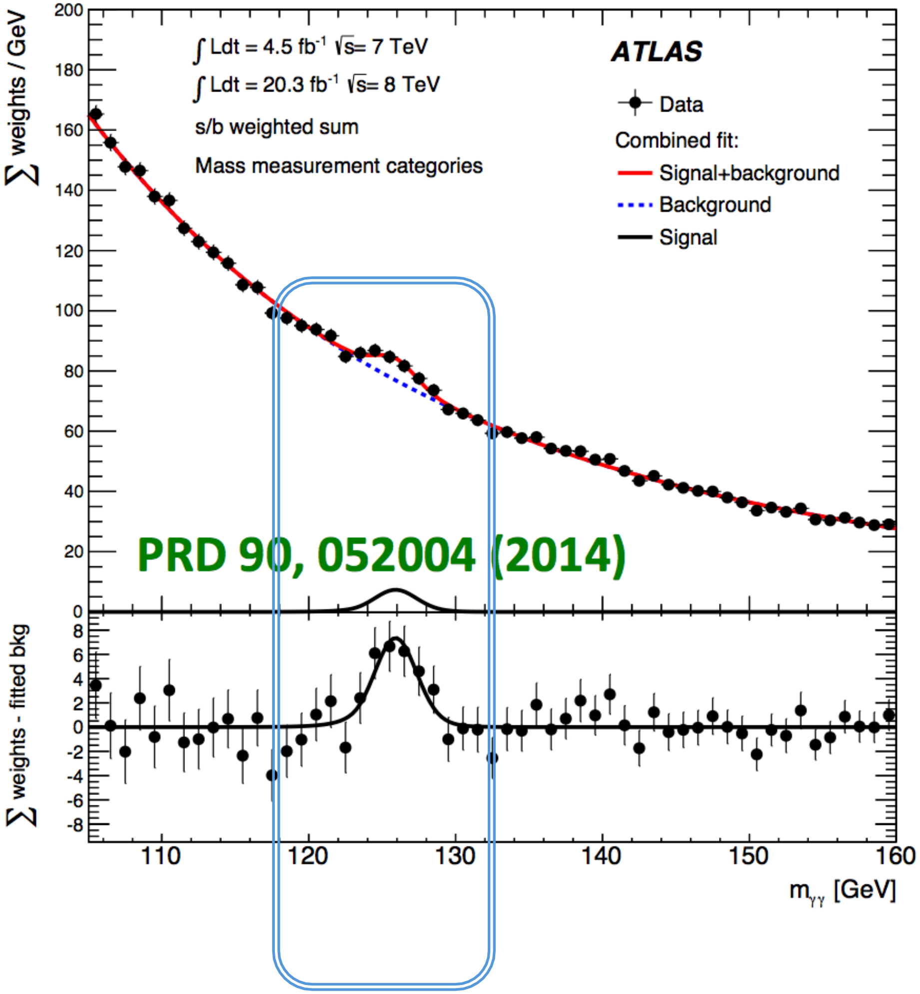
- The SM vacuum stability depends crucially on the masses of the top quark and Higgs boson.

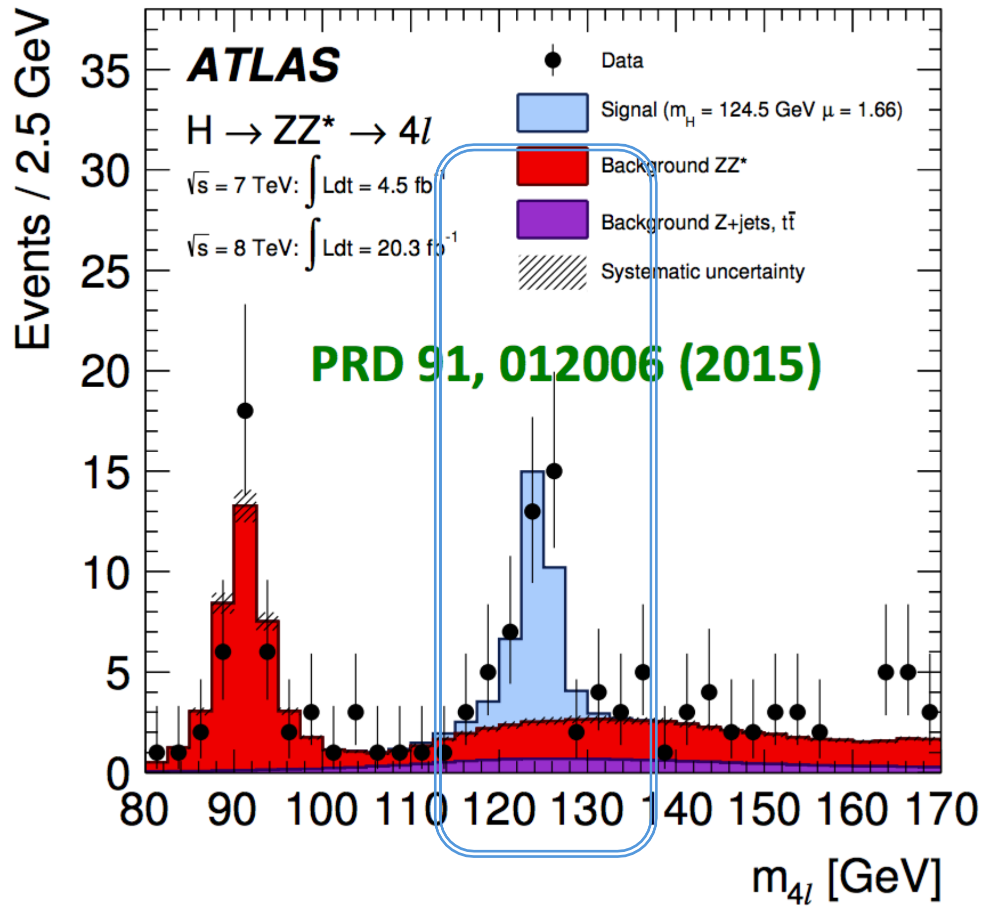
Mass peaks: mass measurements





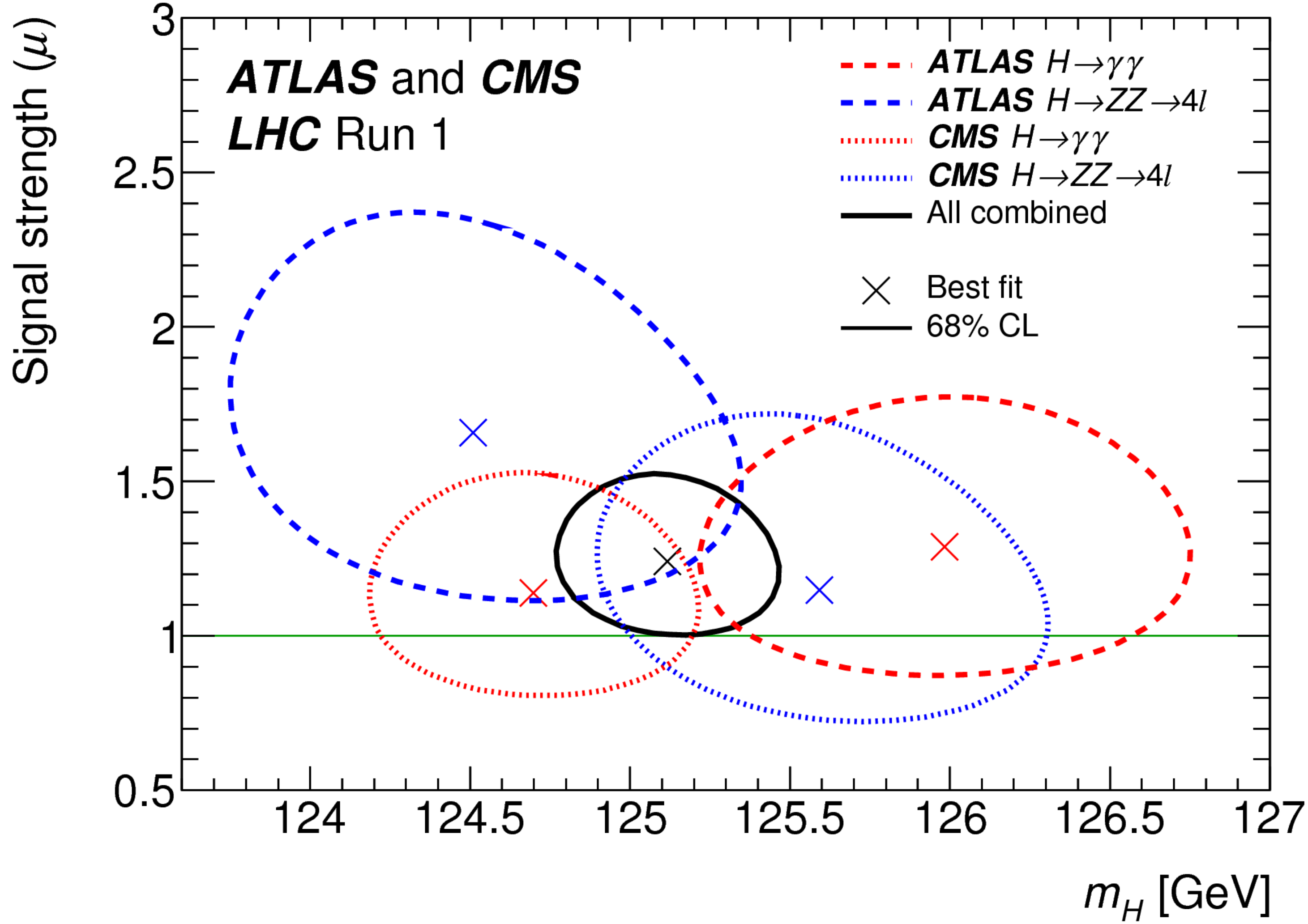
Mass peaks: mass measurements





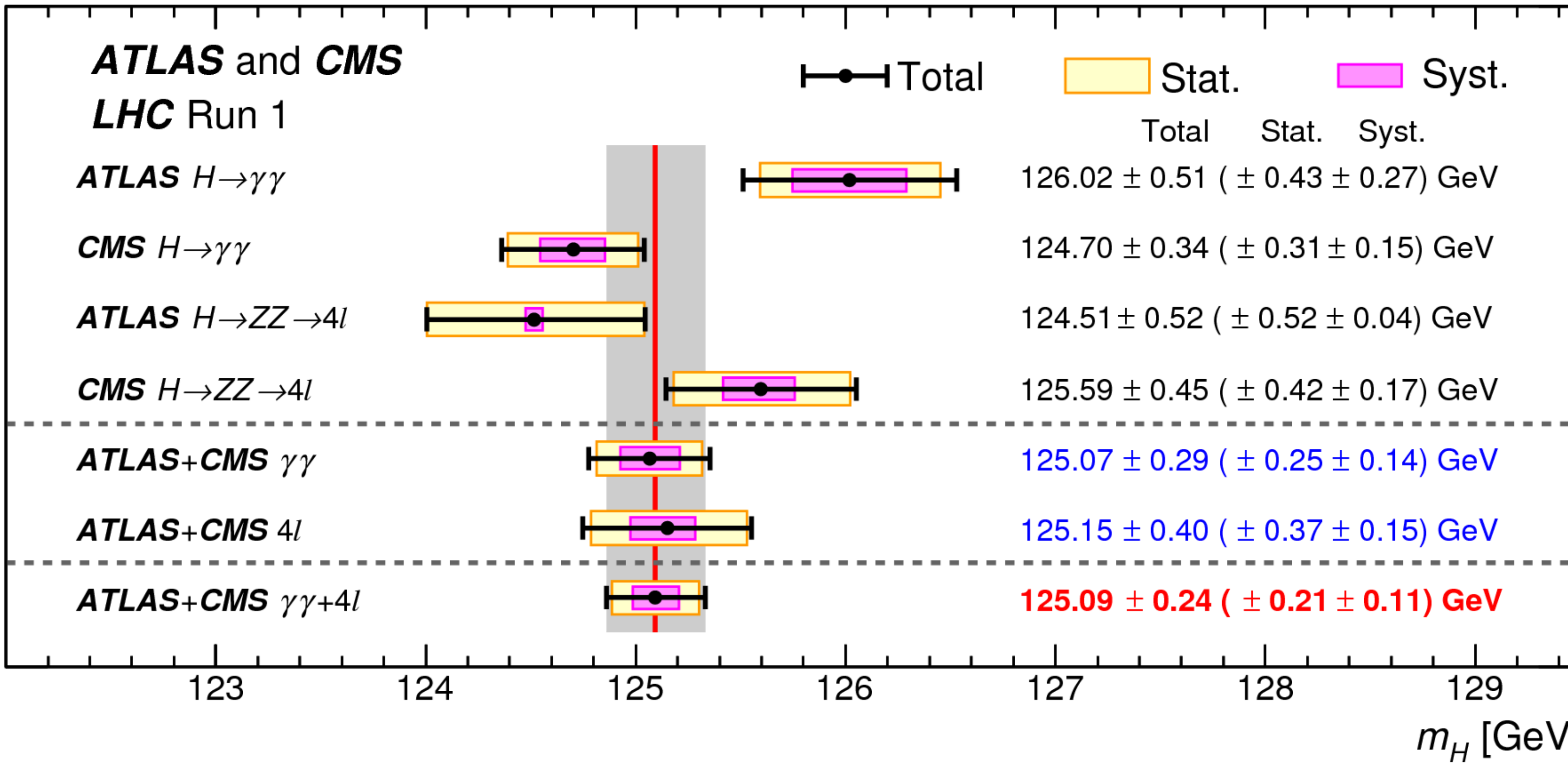
Combined LHC mass measurement

[arXiv:1503.07589]



Combined LHC mass measurement

[arXiv:1503.07589]



Combined LHC mass measurement

[arXiv:1503.07589]

$$\mathbf{m_H = 125.09 \pm 0.21\ (stat)}$$
$$\mathbf{\pm 0.11\ (scale)}$$
$$\mathbf{\pm 0.02\ (other)}$$
$$\mathbf{\pm 0.01\ (theory^{*})}$$
$$\mathbf{GeV}$$

Stat. uncertainty dominates overall.

Energy scale syst. can be improved.

Run 2 will reduce uncertainty !

For the record

- ~5150 authors.
- Found that there are two:
  - Archana Sharma (both CMS)
  - Andrea Bocci
  - Muhammad Ahmad
  - F. M. Giorgi (one CMS, one ATLAS)

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Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of contributors to a single research article.

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$
$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac12 \partial_\mu H\partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$
$$M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$
$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$
$$\frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + igs_w \quad \ldots \quad) -$$
$$\frac14 g^2 W^+_\mu W^-_\mu[H \quad \ldots \quad +$$

Valid up to ~Planck scale ?

$$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j +$$
$$igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac23(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac43 s_w^2 -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac83 s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$
$$m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 -$$
$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) +$$
$$igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac12 gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$
$$\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac12 igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar q^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu -$
$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$
$M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$
$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$
$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$
$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$
$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$
$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$
$\frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$
$W^-_\mu\phi^+) + igs_w$ … $) -$

Valid up to ~Planck scale ?

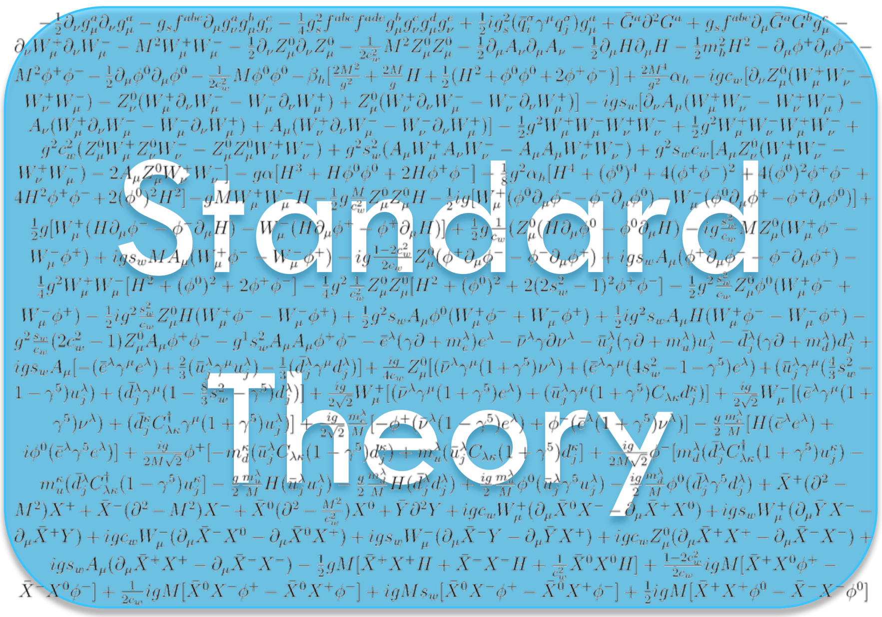
$\frac14 g^2 W^+_\mu W^-_\mu[H$ … $+$
$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$
$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu$ … $)d^\lambda_j +$

But: dark matter, matter-antimatter, etc.

$igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e$ … $s_w^2 -$
$1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\frac{4}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+$
$\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac g2\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) +$
$i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$
$m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac g2\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 -$
$M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0 X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar Y X^- -$
$\partial_\mu\bar X^+ Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar Y X^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) +$
$igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \frac12 gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ -$
$\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$

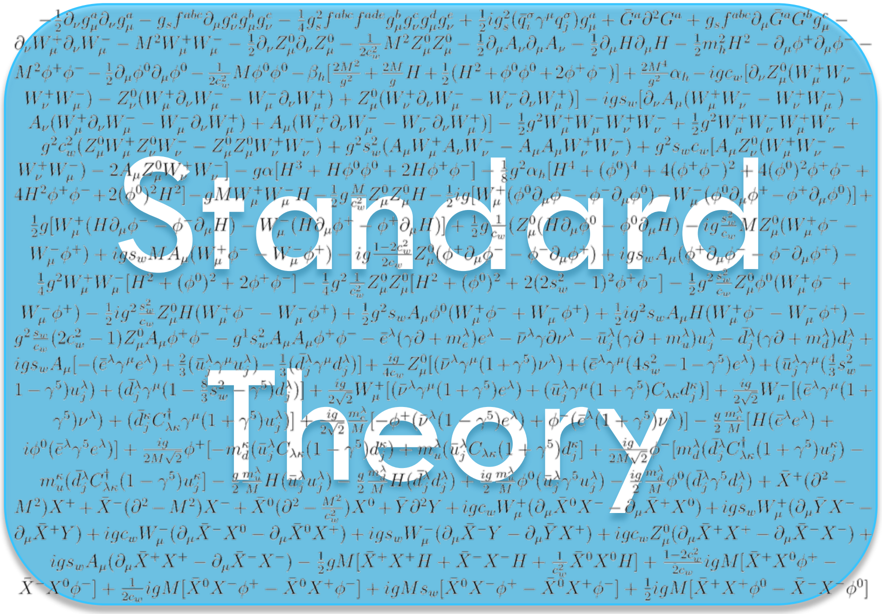
The Next Standard Model

[http://cern.ch/go/dW6z]



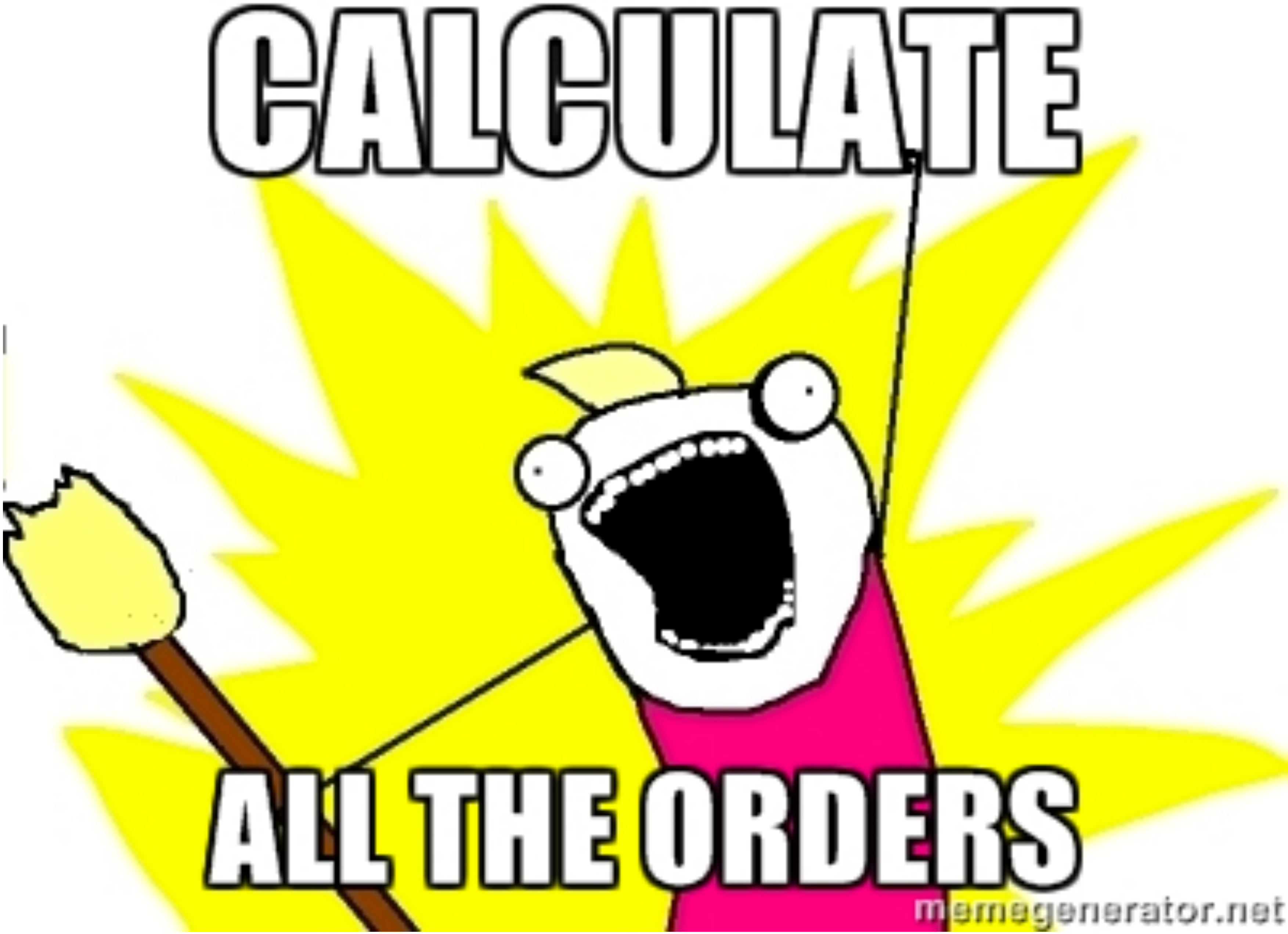
The Next Standard Model

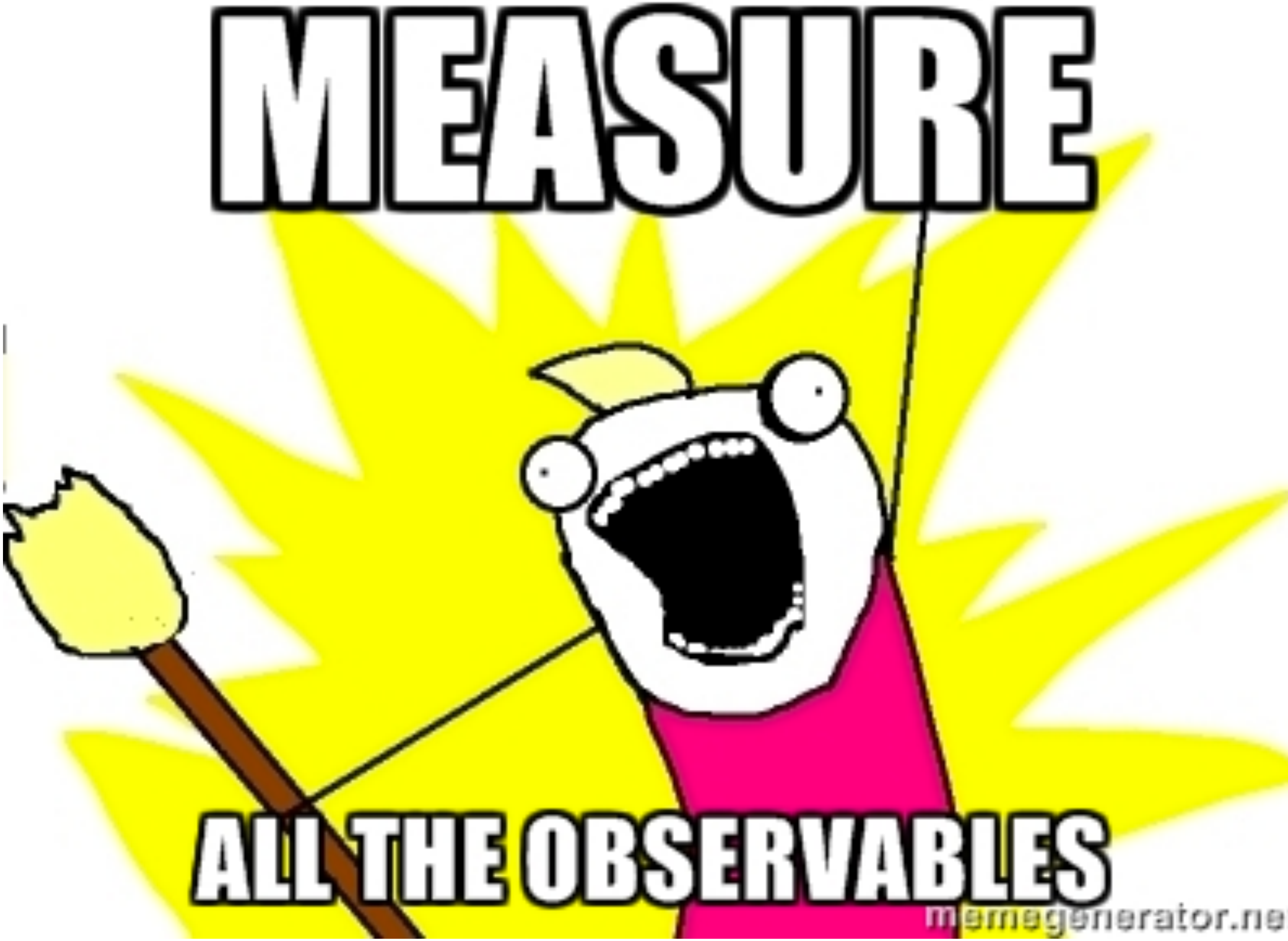
[http://cern.ch/go/dW6z]



+

Something else


CALCULATE
ALL THE ORDERS
memegenerator.net


MEASURE
ALL THE OBSERVABLES
memegenerator.net


EVERY SINGLE
ONE ?
memegenerator.net

Deviations of H(125)

- **Heavy New Physics**
  - Concern of LHC HXSWG WG2
  - Decoupling of heavy d.o.f.
  - Indirect effects, loops, dim-6 operators, etc.

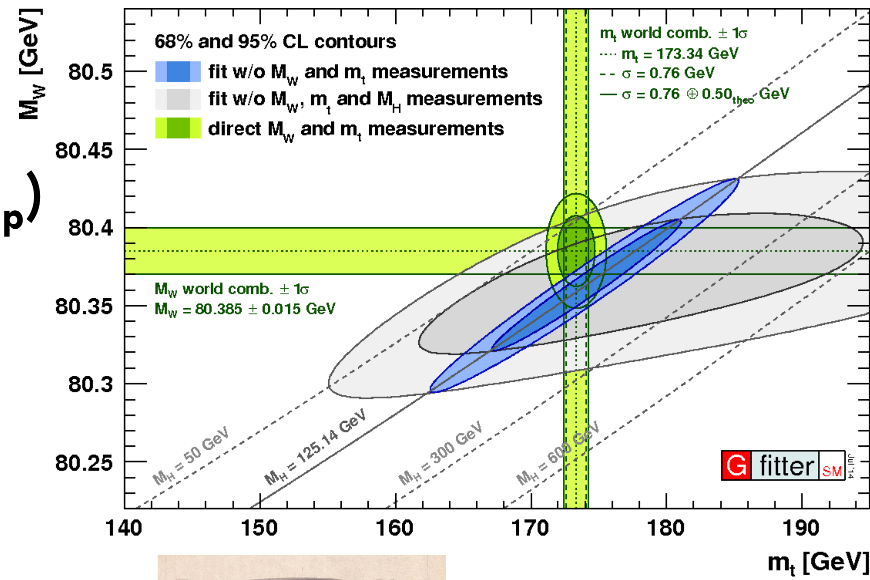
- **Light New Physics**
  - Benchmarks from LHC HXSWG WG3
  - Other states, degenerate states, etc.

Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition $\rightarrow$ EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

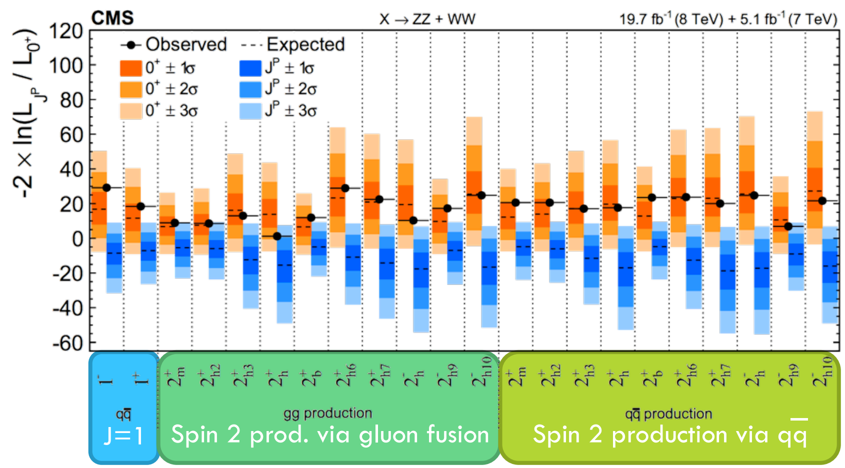
An actual measurement

- **Mass**
  - **Exp. Uncertainties**
  - **SM consistency: (m_H, m_W, m_{top})**
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT



Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- **Spin**
  - **Are we happy now?**
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition ⟶ EFT
- Scalar couplings
  - $\kappa \longrightarrow \kappa(q) \longrightarrow f(q) \longrightarrow$ EFT



Handles on deviations

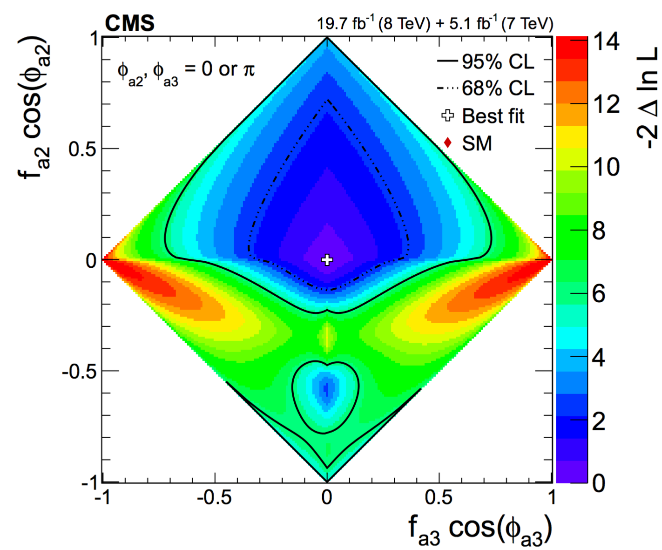
- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- **Charge**
  - **Zero. (That was easy.)**
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

0

Handles on deviations

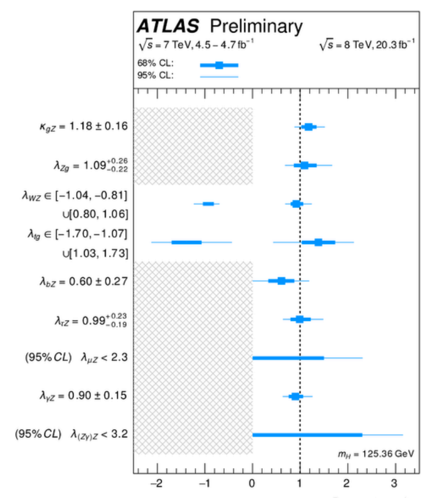
- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- **Parity**
  - **Amplitude decomposition → EFT**
- Scalar couplings
  - $\kappa \longrightarrow \kappa(q) \longrightarrow f(q) \longrightarrow$ EFT

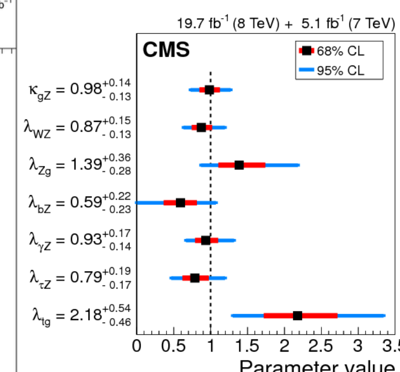
$$\begin{aligned} A(X_{J=0} \to V_1 V_2) \sim\ & v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2} \right] m_Z^2 \epsilon^*_{Z_1} \epsilon^*_{Z_2} \right. \\ & + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} \\ & + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} \\ & \left. + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \end{aligned}$$



Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- **Scalar couplings**
  - **κ → κ (q) → f(q) → EFT**





Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

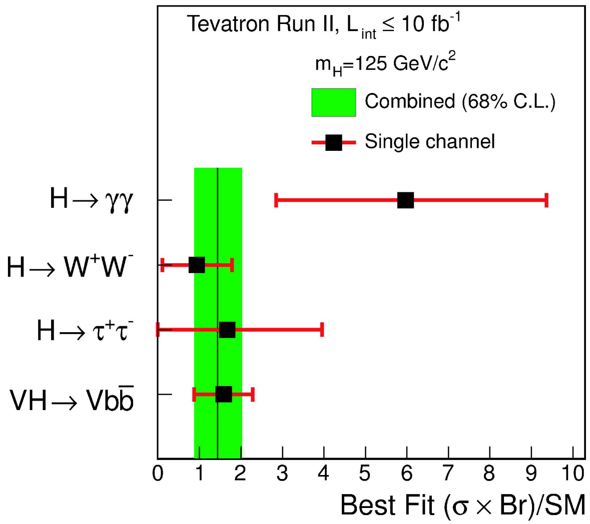
★ “seen” ☆ “tried” - “impossible”	H→$b\bar{b}$			H→$\tau\tau$			H→WW			H→ZZ			H→$\gamma\gamma$			H→Zγ			H→inv.			H→$\mu\mu$			H→$c\bar{c}$ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

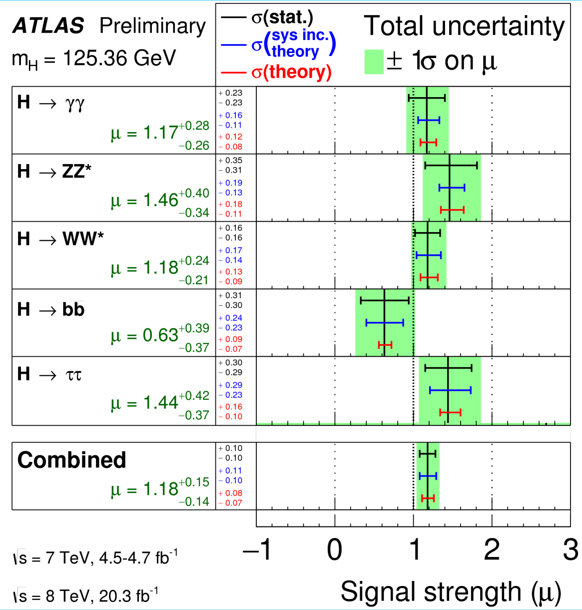
- **Still much to explore on the rarer ends.**

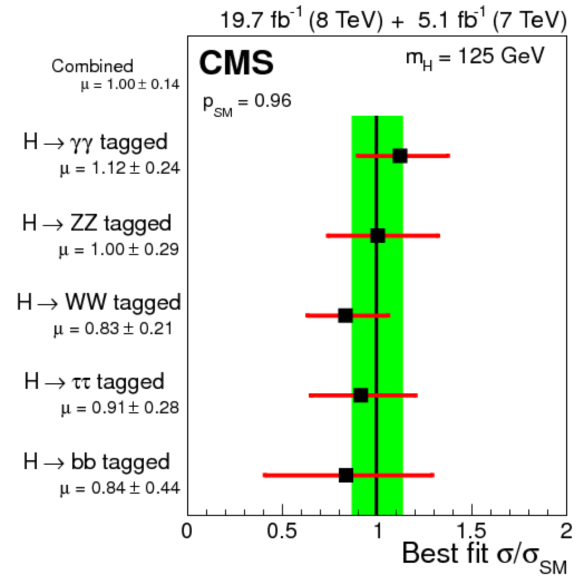
  (to the right and to the bottom) (and outside this picture)

Relative signal strengths

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







	Tevatron	ATLAS	CMS
m_H	125 GeV	125.4 GeV	125.0 GeV
$\mu = \sigma/\sigma_{SM}$	$1.44\ ^{+0.59}_{-0.56}$	1.18 ±0.15	1.00 ±0.14

Naïve LHC average: 1.1 ±0.1

So small that you need a pipette

Particles smaller than the Higgs boson exist?

By PTI | 23 Mar, 2014, 01.52PM IST 1 comments | Post a Comment

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LONDON: There are unknown particles floating around the universe that may be even smaller than the Higgs boson, the 'God particle' discovered in 2012, scientists say.

Ryttov referred to the theories that have been put forward over the last five years for the existence of particles in the universe that are smaller than the Higgs particle.

The so-called techni-quarks can be the yet unseen particles, smaller than the Higgs particle that will form a natural extension of the Standard Model which includes three generations of quarks and leptons.

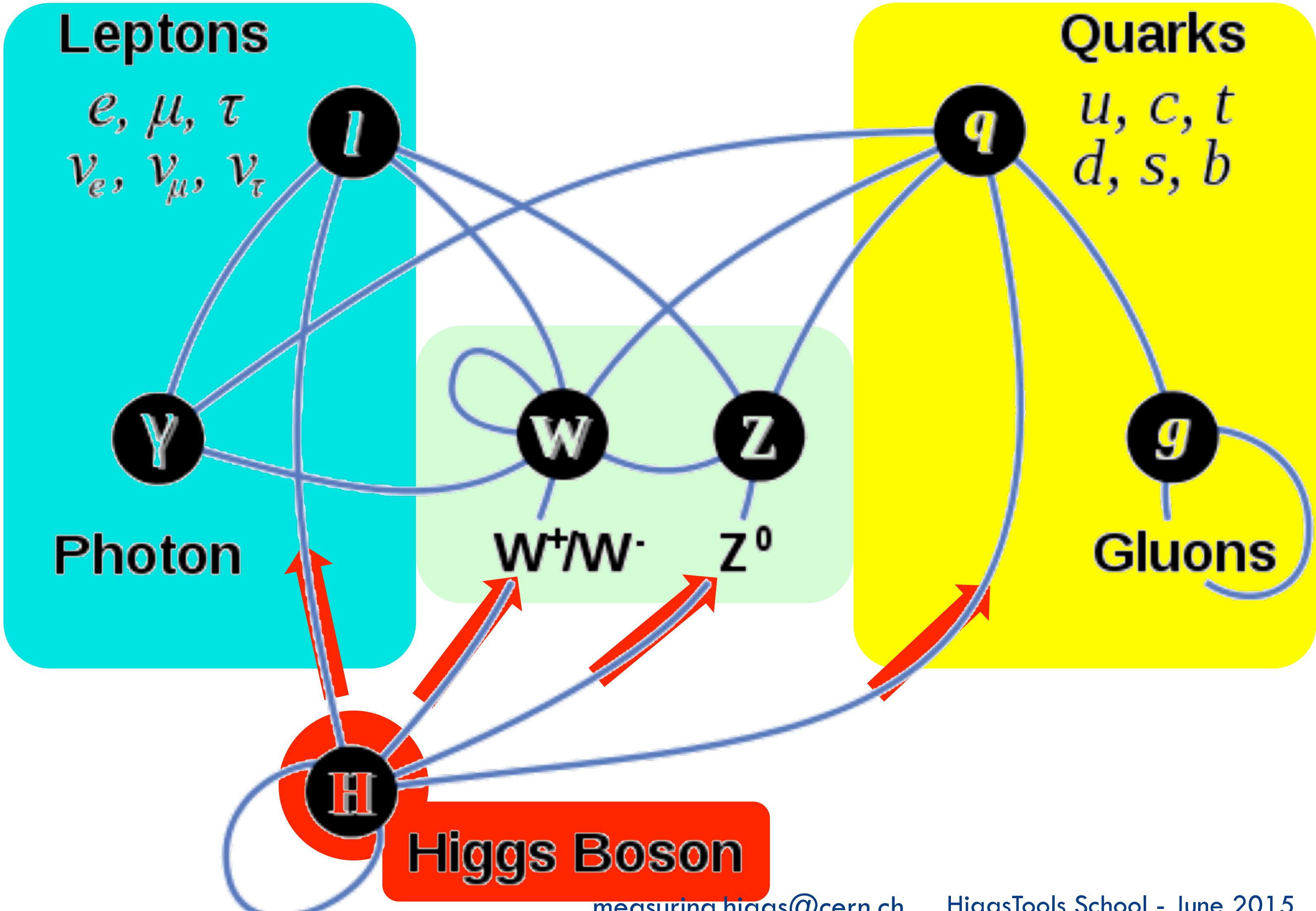
These particles together with the

The Standard Model of Particle Physics

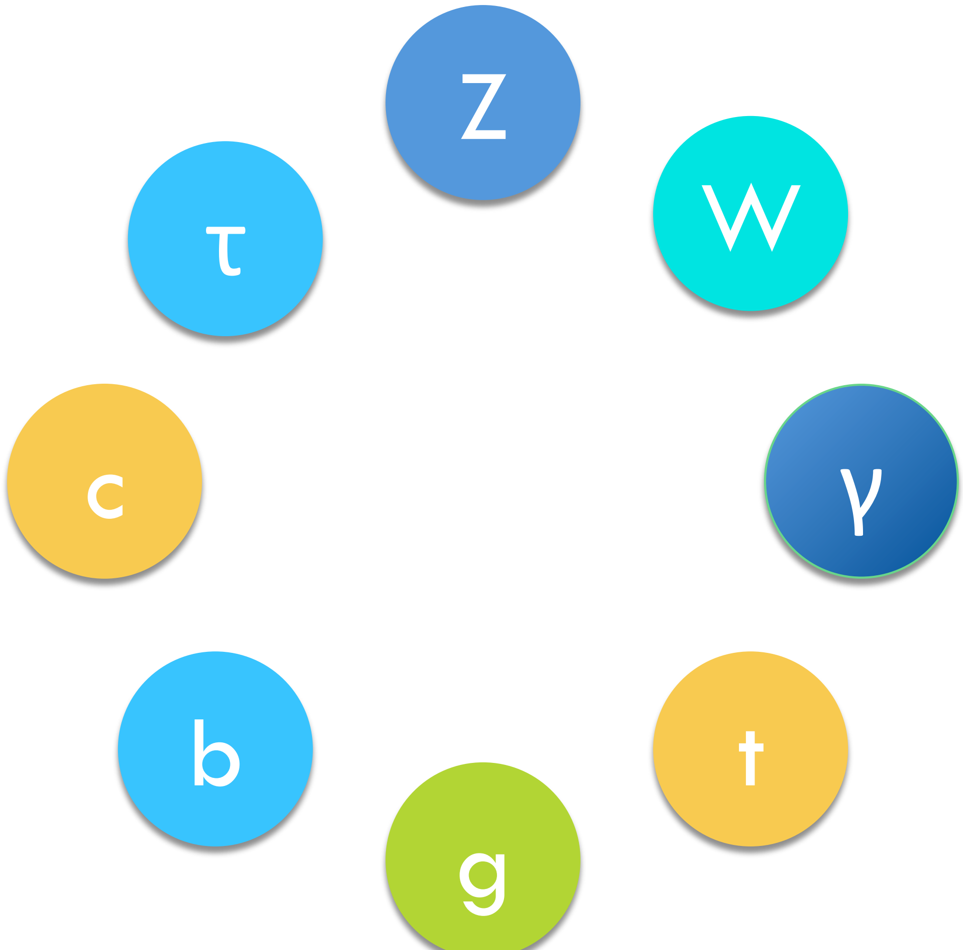
Electromagnetic force – light

Weak force – star combustion

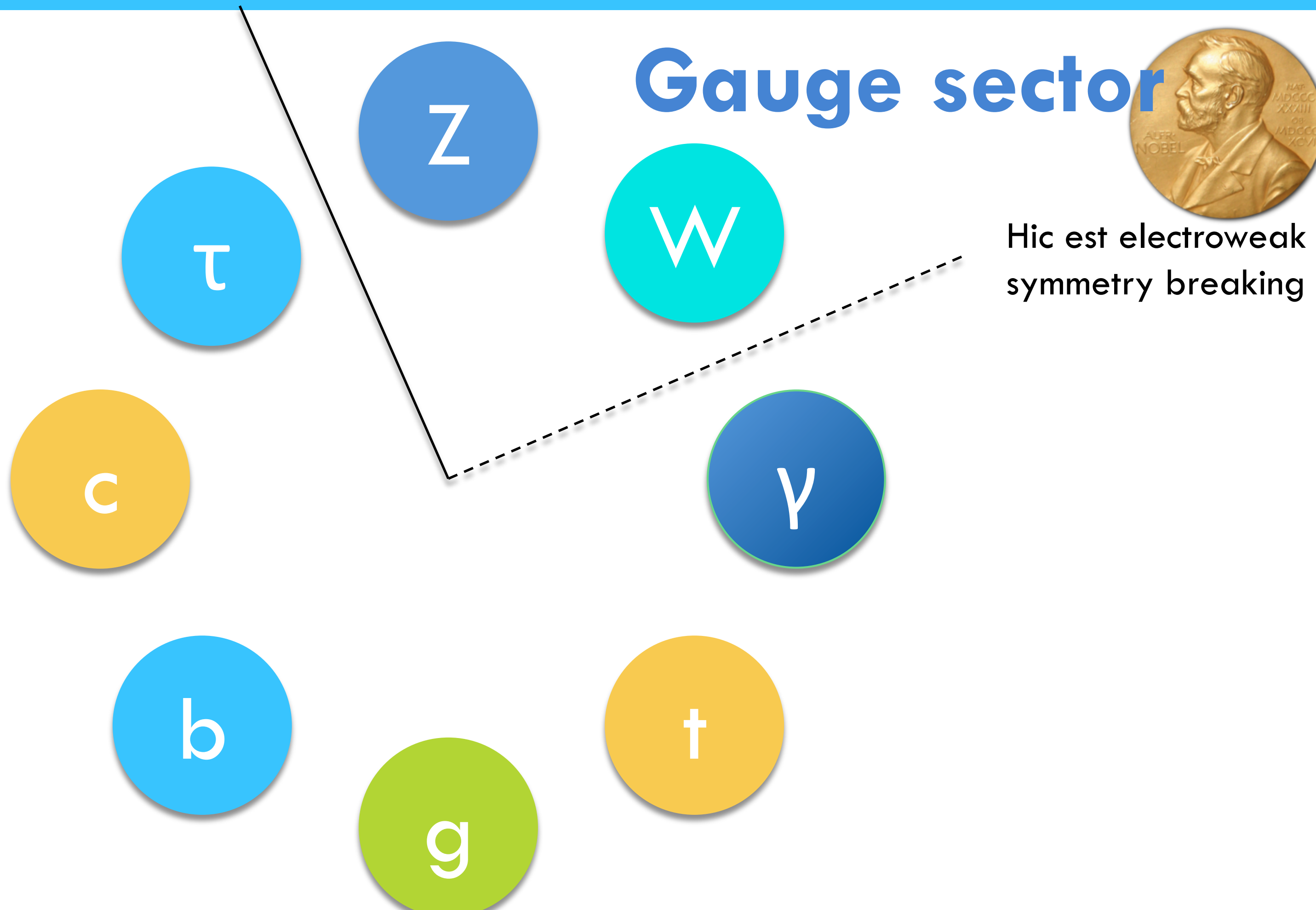
Strong force – protons and neutrons



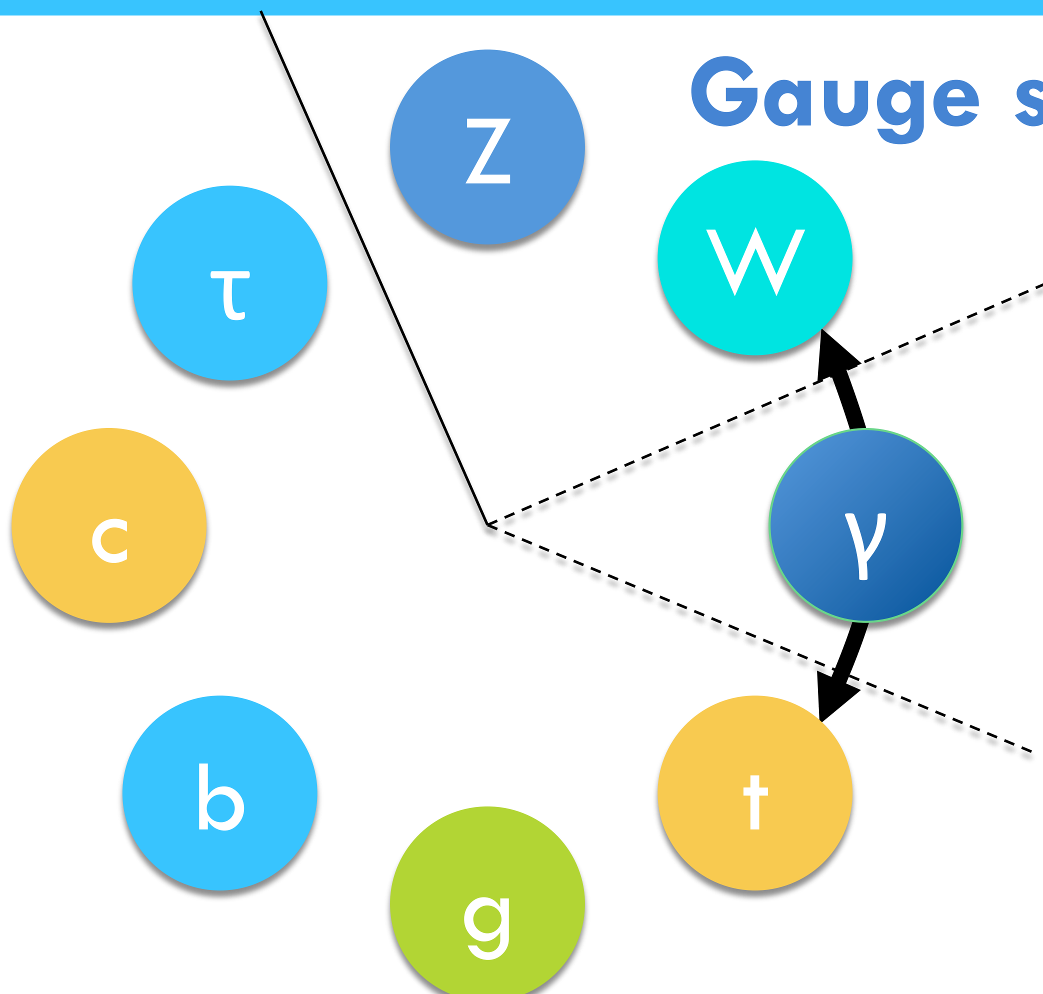
Scalar coupling structure



Scalar coupling structure

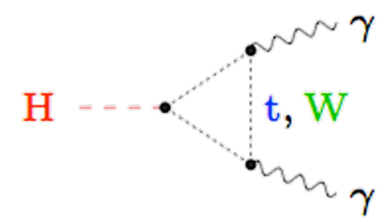


Scalar coupling structure



Gauge sector

Mixed sector

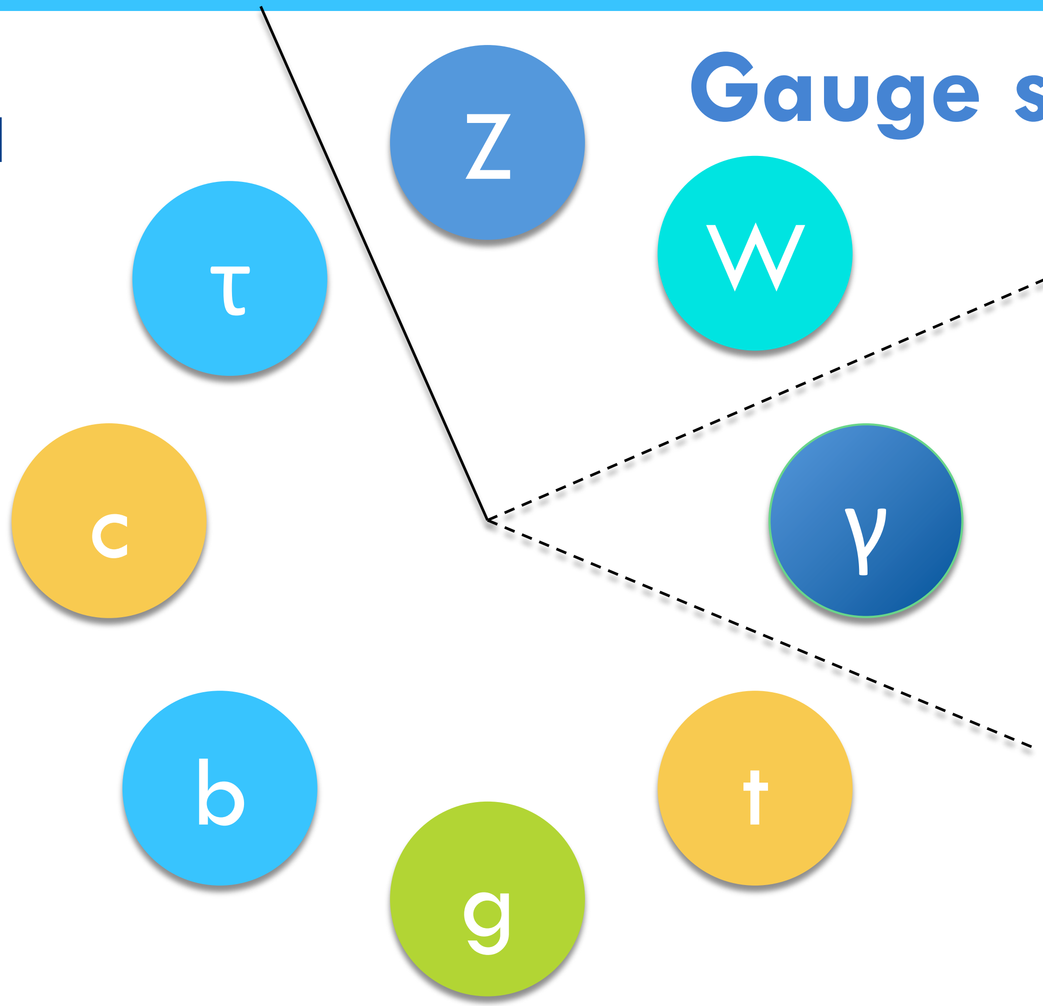


Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure

Yukawa sector

Gauge sector



Mixed sector

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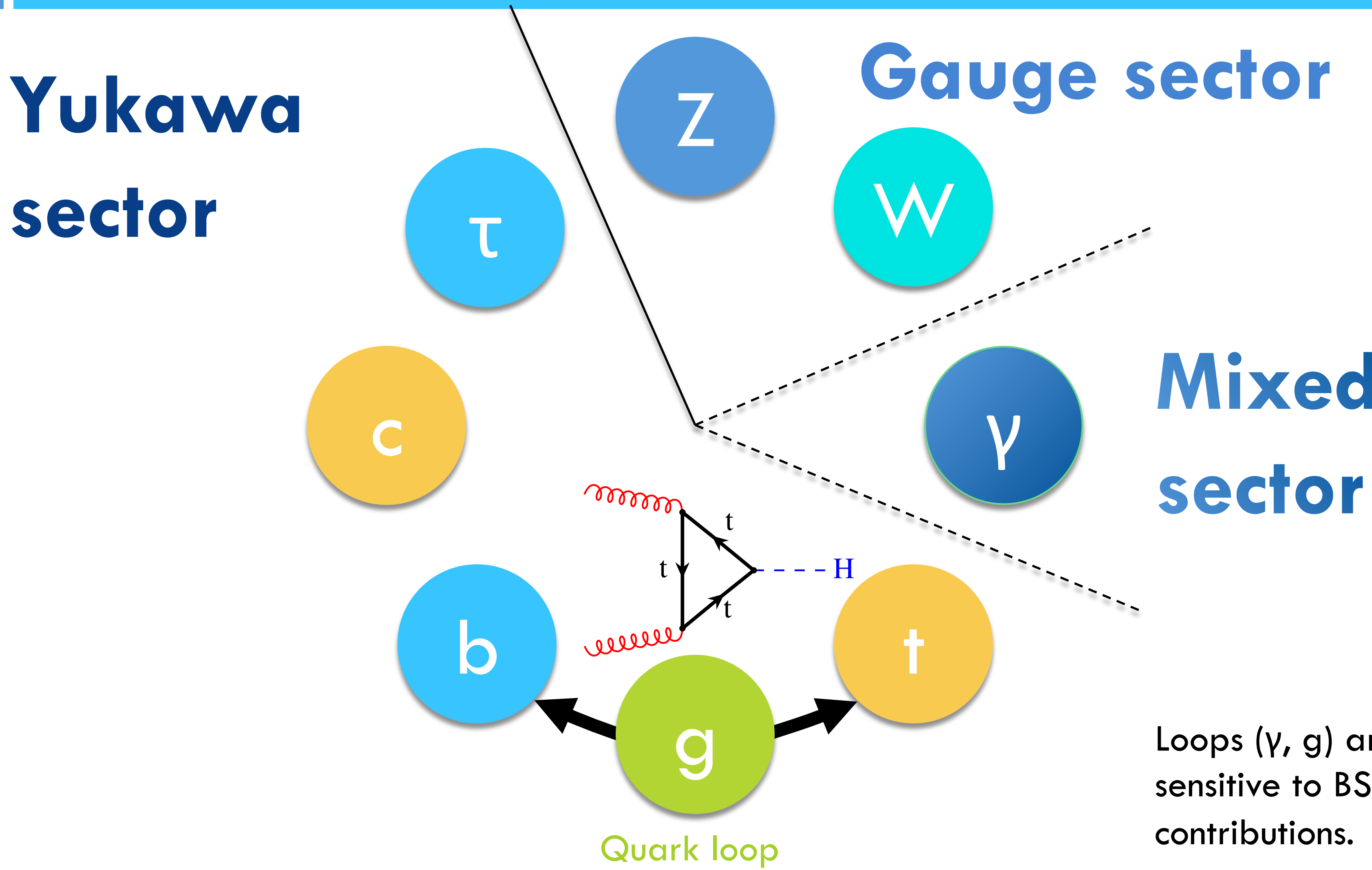
Scalar coupling structure



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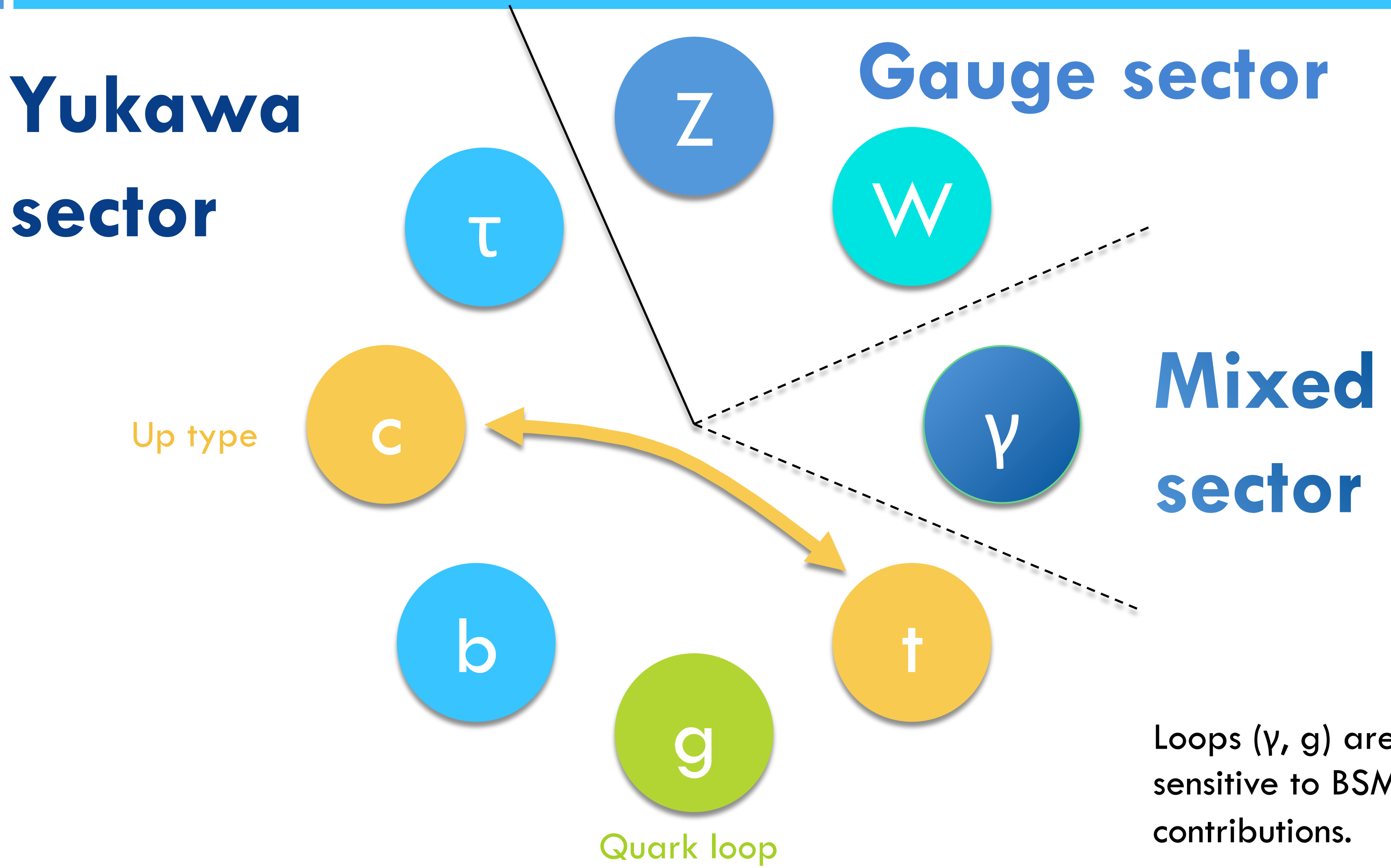

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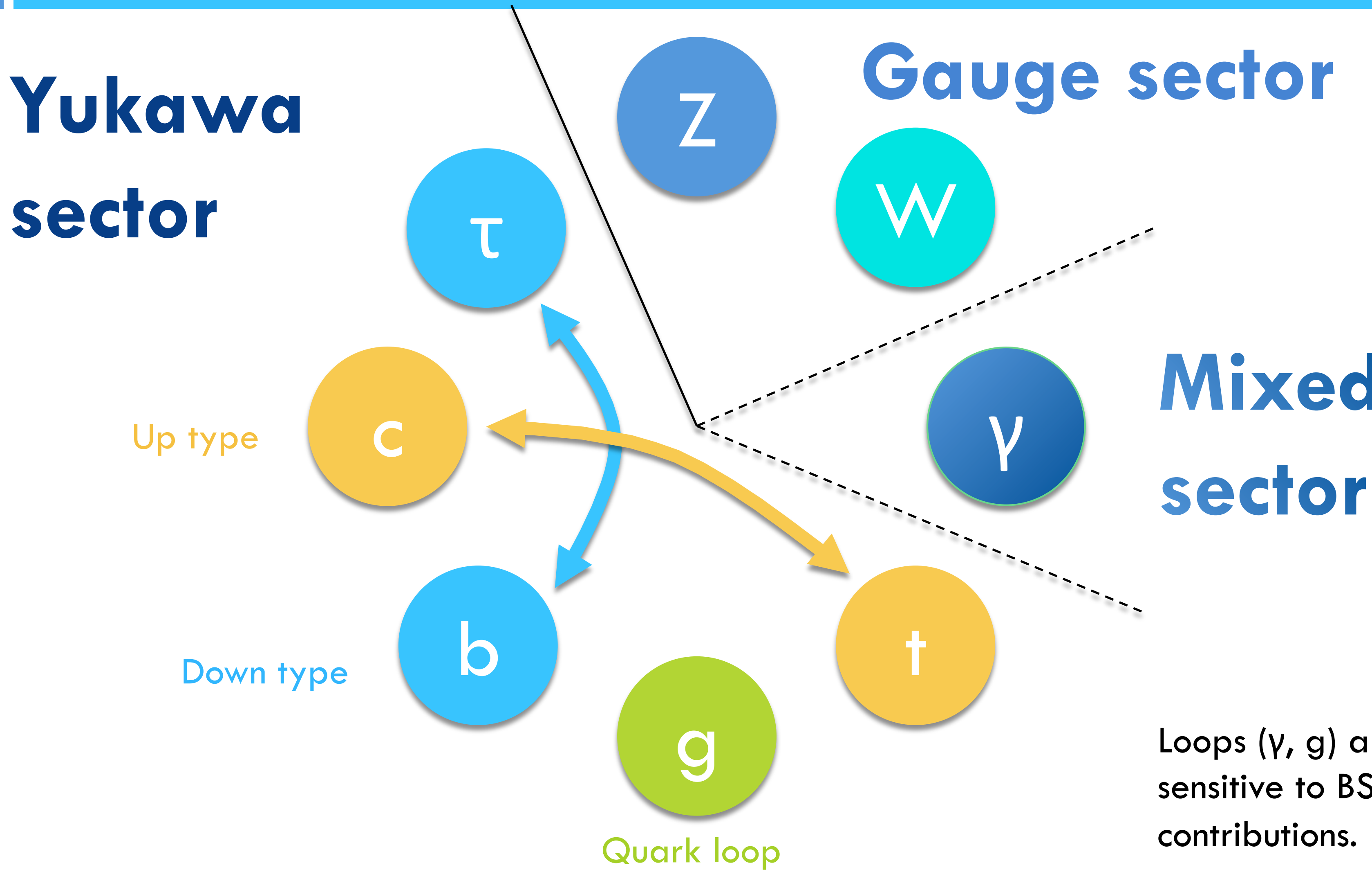

Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{\mathrm{SM}}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{\mathrm{SM}}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{\mathrm{SM}}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{\mathrm{SM}}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{\mathrm{SM}}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{\mathrm{SM}}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{\mathrm{SM}}_{gg}} : \text{ see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{\mathrm{SM}}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{\mathrm{SM}}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{\mathrm{SM}}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma/\Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

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$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

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$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

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$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma_{\mathrm{s\bar{s}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^2 \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to "closest of kin".

Scalar coupling deviations framework

[arXiv:1307.1347]

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$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

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$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

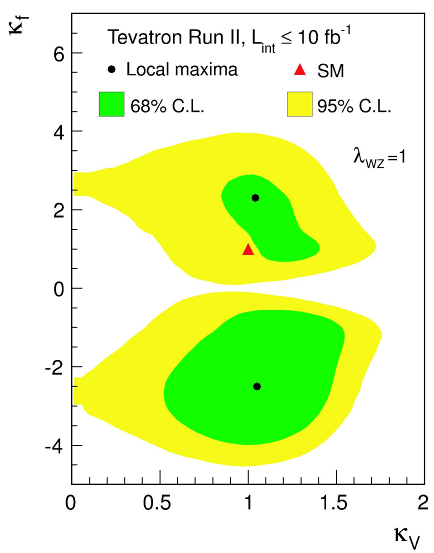
Total width

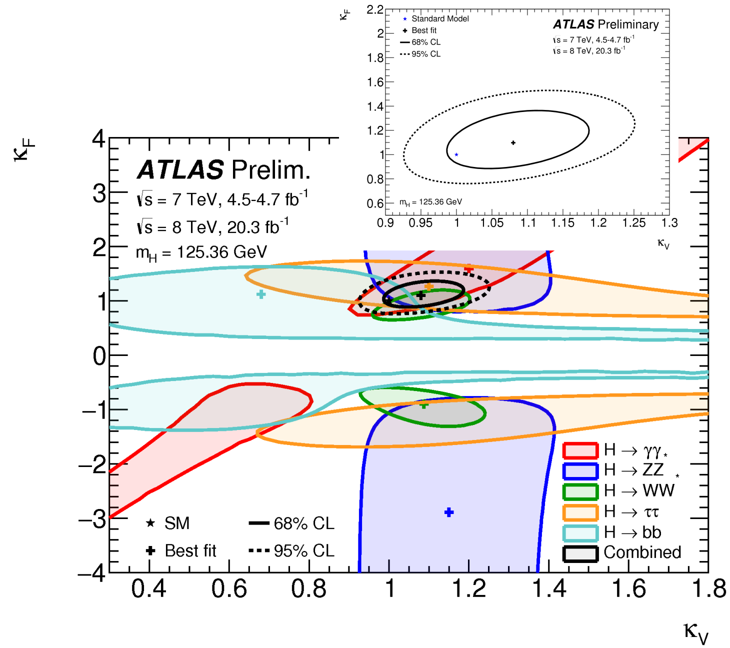
$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

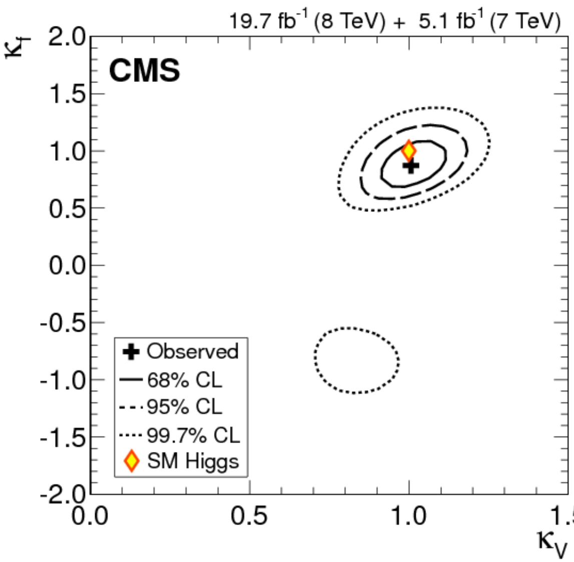
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H.

Weak bosons and fermions

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]



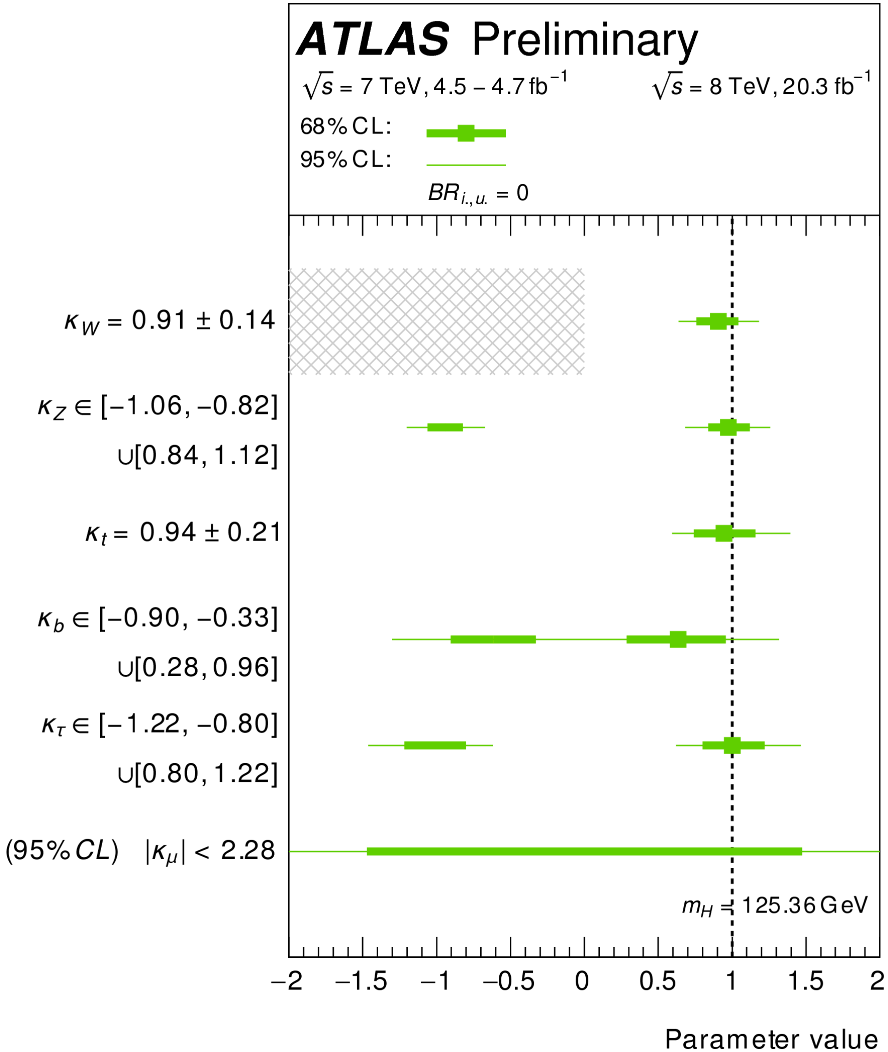


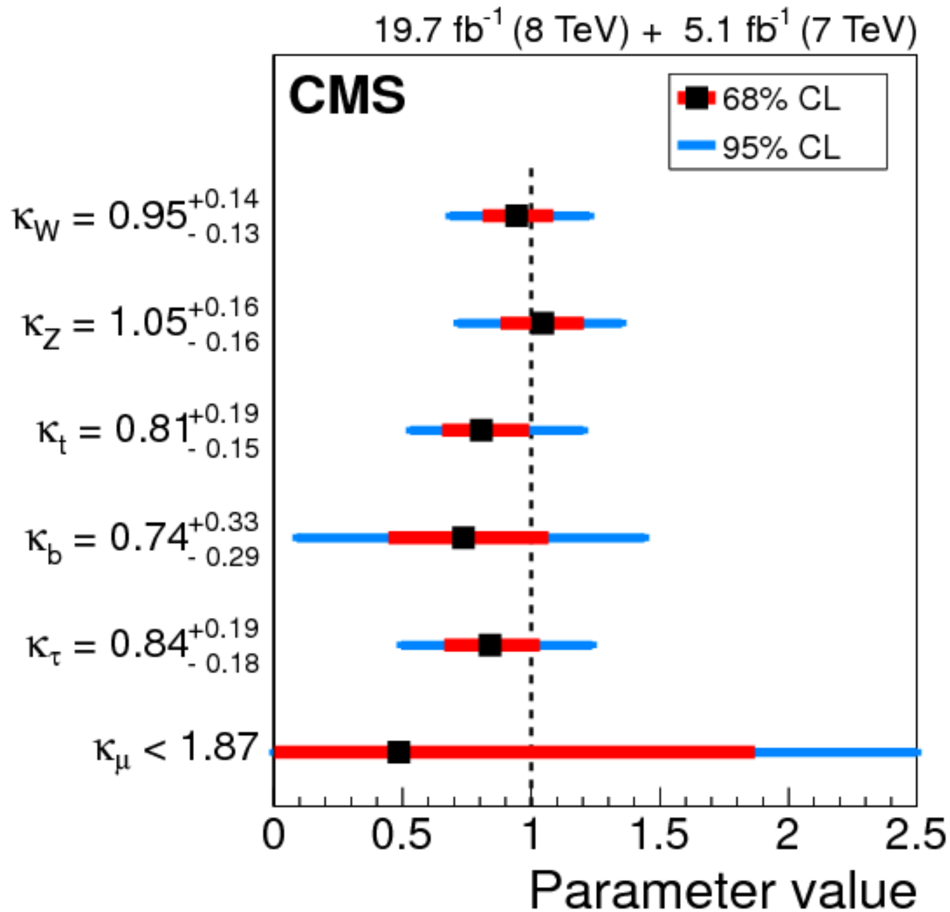


	Tevatron	ATLAS	CMS
p(SM)	-	41%	< 1 σ

Resolving SM contributions

[ATLAS-CONF-2015-007][arXiv:1412.8662]

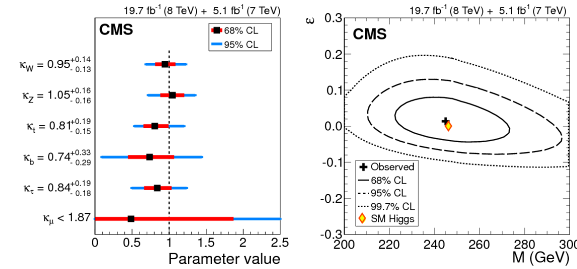


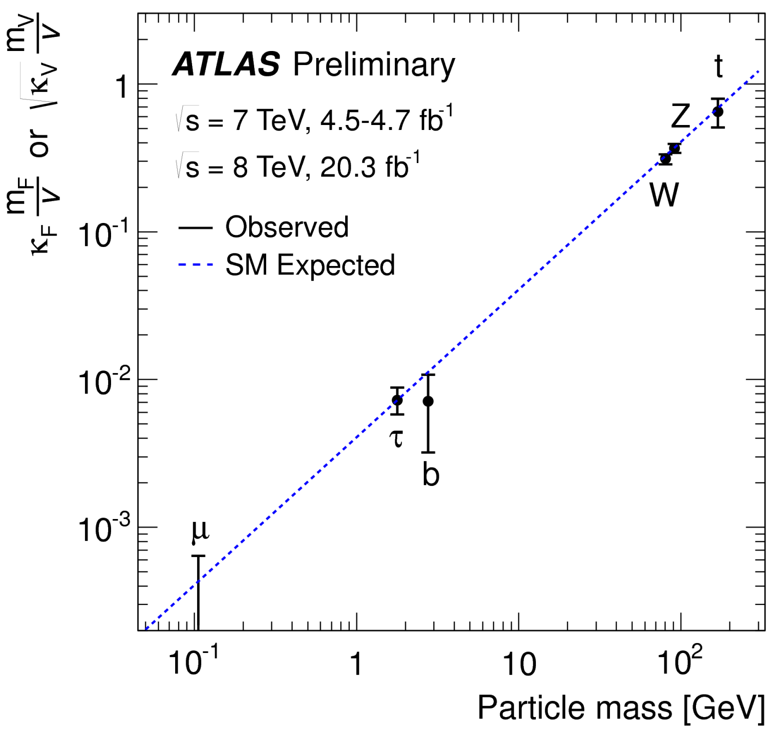


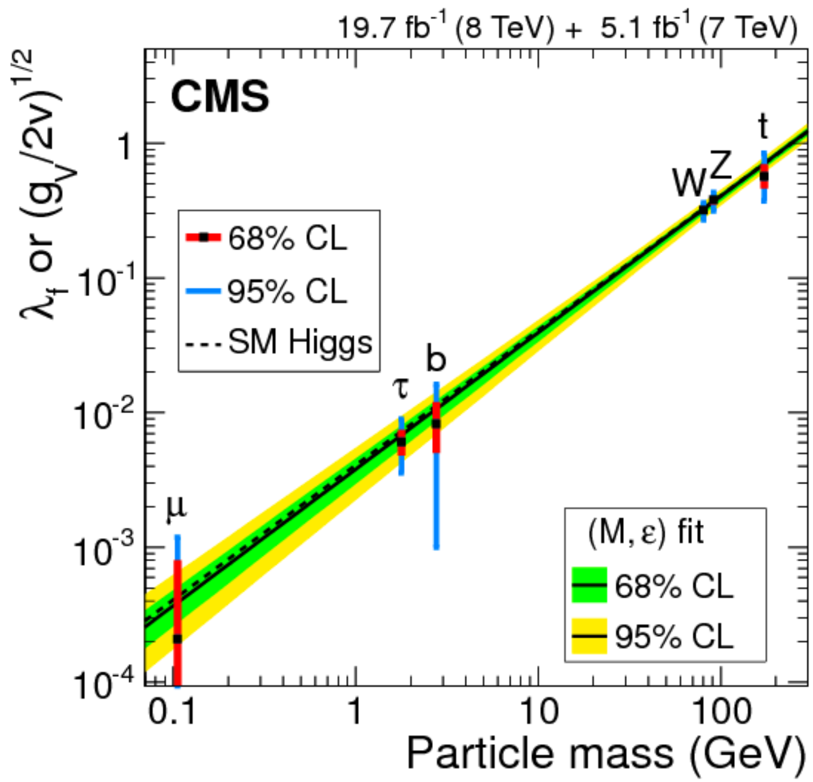
Coupling deviations summaries

[ATLAS-CONF-2015-007][arXiv:1412.8662][arxiv:1207.1693][arxiv:1303.3570]

- Assuming no BSM particles.

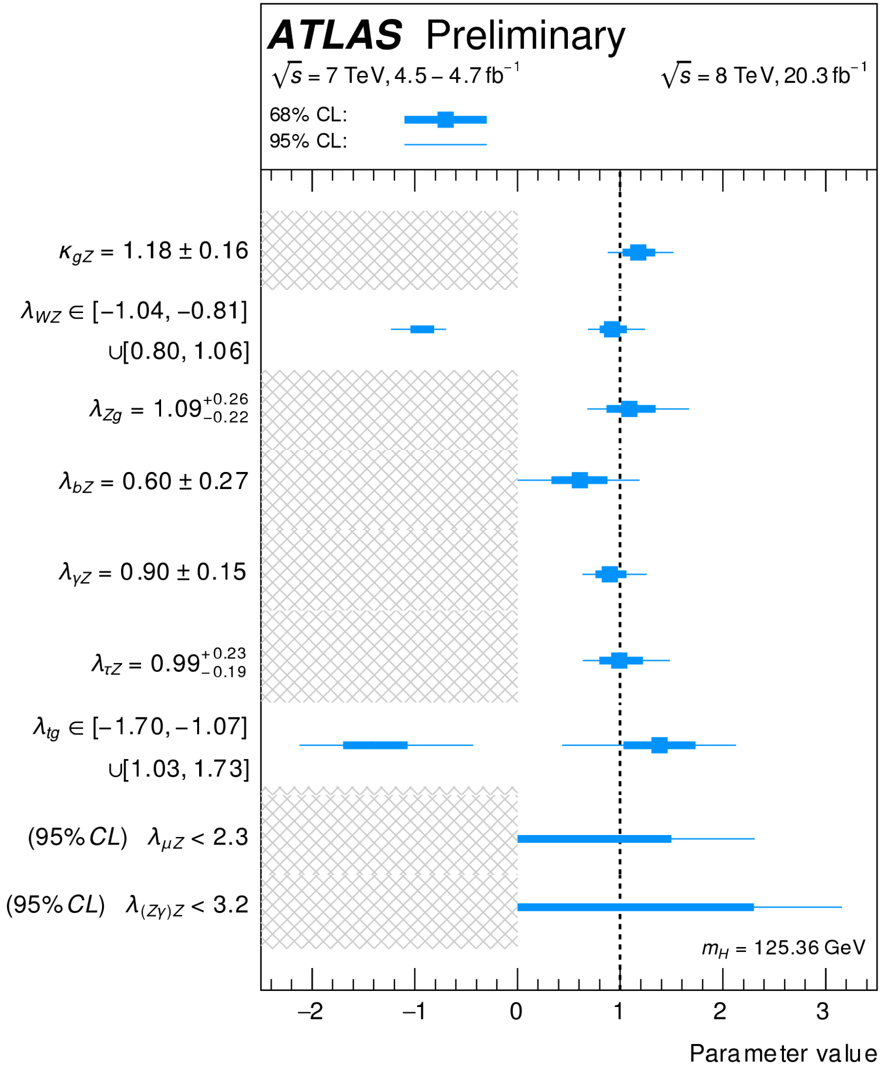


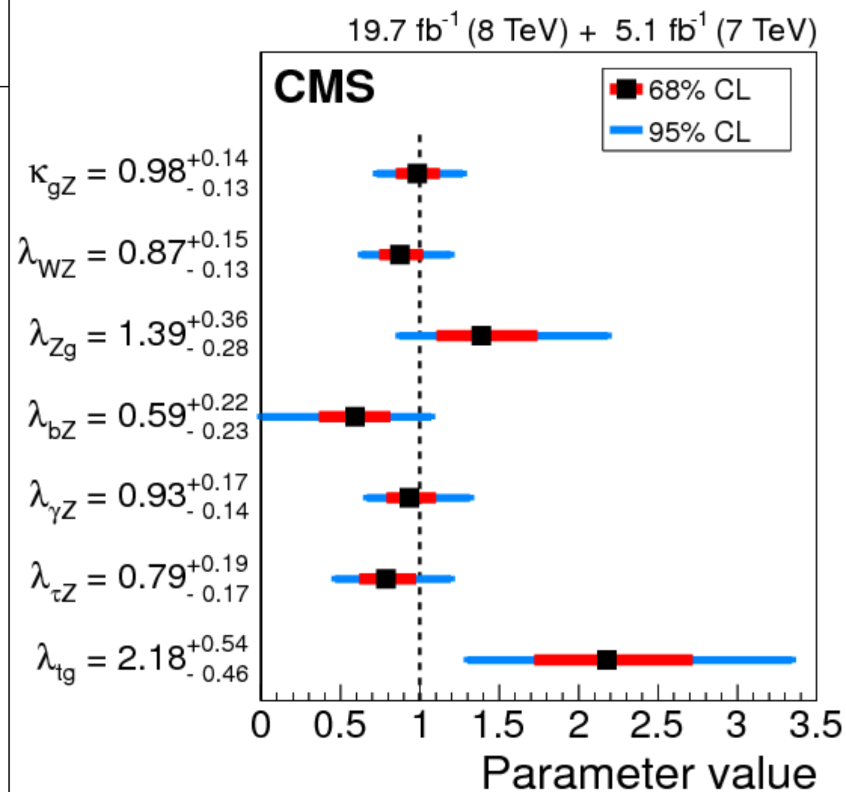




The deviations that we do not (yet) see

[ATLAS-CONF-2015-007][arXiv:1412.8662]





A very long way to go…

Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$H^0 \to WW^*$	seen		
Γ_2	$H^0 \to ZZ^*$	seen		
Γ_3	$H^0 \to \gamma\gamma$	seen		
Γ_4	$H^0 \to b\bar{b}$	possibly seen		
Γ_5	$H^0 \to \tau^+\tau^-$	possibly seen		

H^0 SIGNAL STRENGTHS IN DIFFERENT CHANNELS

Combined Final States	1.07 ± 0.26	(S = 1.4)
WW^* Final State	0.88 ± 0.33	(S = 1.1)
ZZ^* Final State	$0.89\,^{+0.30}_{-0.25}$	
$\gamma\gamma$ Final State	1.65 ± 0.33	
$b\bar{b}$ Final State	$0.5\,^{+0.8}_{-0.7}$	
$\tau^+\tau^-$ Final State	0.1 ± 0.7	

Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$Z \to e^+e^-$	3.363 ± 0.004 %		45594
Γ_2	$Z \to \mu^+\mu^-$	3.366 ± 0.007 %		45594
Γ_3	$Z \to \tau^+\tau^-$	3.370 ± 0.008 %		45559
Γ_4	$Z \to \ell^+\ell^-$	3.3658 ± 0.0023 %		
Γ_5	$Z \to \ell^+\ell^-\ell^+\ell^-$	$(4.2\,^{+0.9}_{-0.8}) \times 10^{-6}$		45594
Γ_6	$Z \to$ invisible	$(2.000 \pm .006) \times 10^{-1}$		
Γ_7	$Z \to$ hadrons	$(6.991 \pm .006) \times 10^{-1}$		
Γ_8	$Z \to (u\bar{u} + c\bar{c})/2$	$.116 \pm .006$		
Γ_9	$Z \to (d\bar{d} + s\bar{s} + b\bar{b})/3$	$.156 \pm .004$		
Γ_{10}	$Z \to c\bar{c}$	$(1.203 \pm .021) \times 10^{-1}$		
Γ_{11}	$Z \to b\bar{b}$	$(1.512 \pm .005) \times 10^{-1}$		
Γ_{12}	$Z \to b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		

The future

["Lawrence of Arabia" idea from C. Grojean]

- We must examine this Higgs to the fullest extent !
  - It may be the only clue to leave the SM oasis and cross the desert.

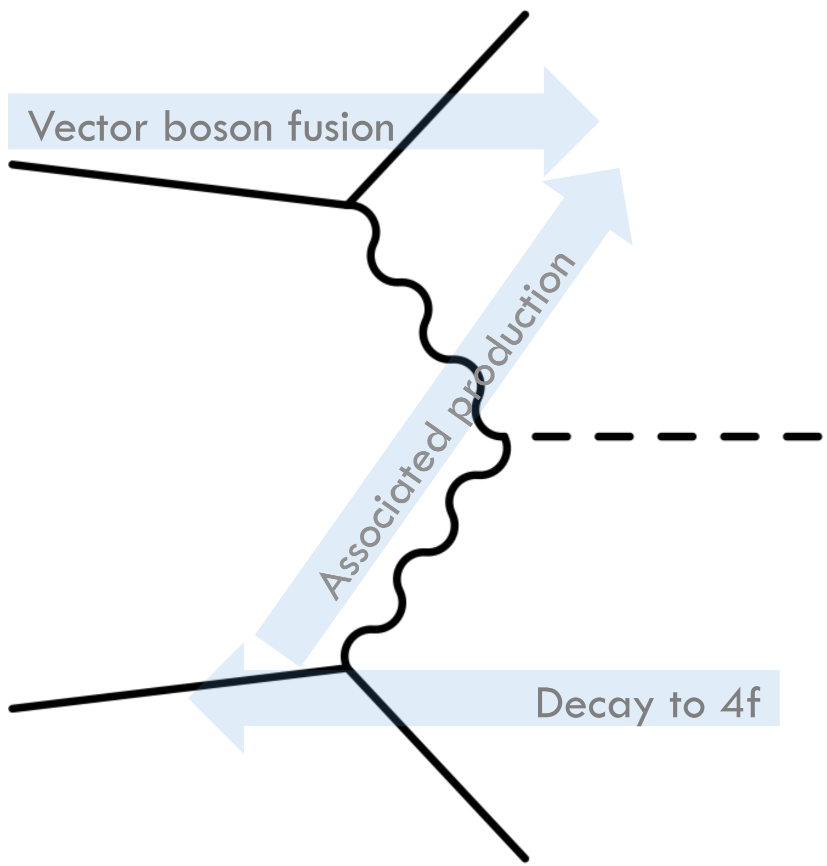
Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu]

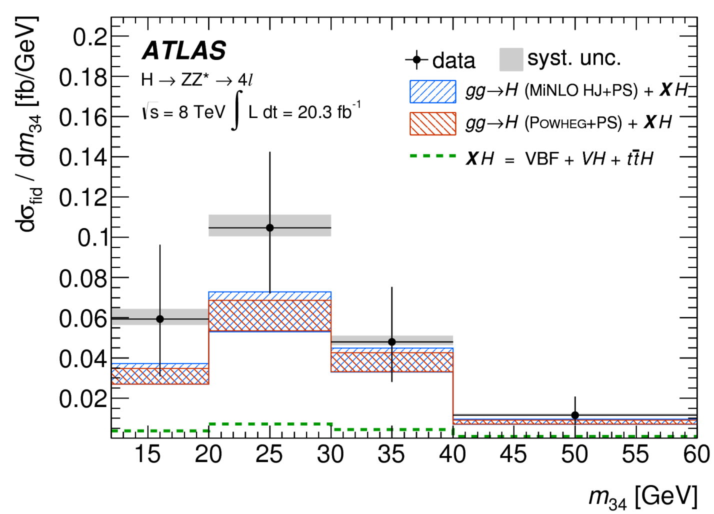
Boson discovery & first measurements

Precision measurements & Searches for deviations

The many facets of HVV



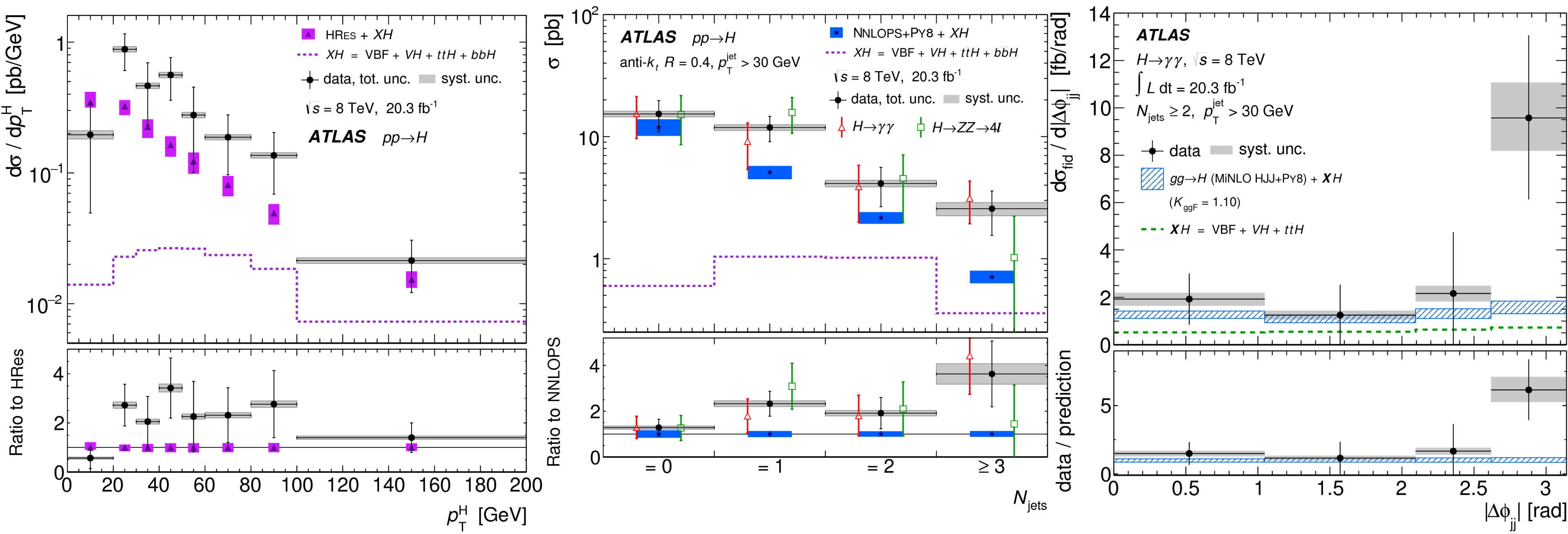
Decay	γ	γ*/Z*	Z
γ	✓	✓	✓
γ*/Z*		? (VBF)	✓ (VH)
Z			✓ (H*)



Differential distributions

[arXiv:1407.4222][arXiv:1408.3226][arXiv:1504.05833]

- Differential picture directly touches fundamental aspects:
  - The loop structure where new particles may be running (p_T shape).
  - The QCD structure of the calculations (N_{jets}).
- ATLAS H→γγ and ZZ results and the adventure of unfolding.
  - Illustrates the power of having more statistics (signal-like excess).



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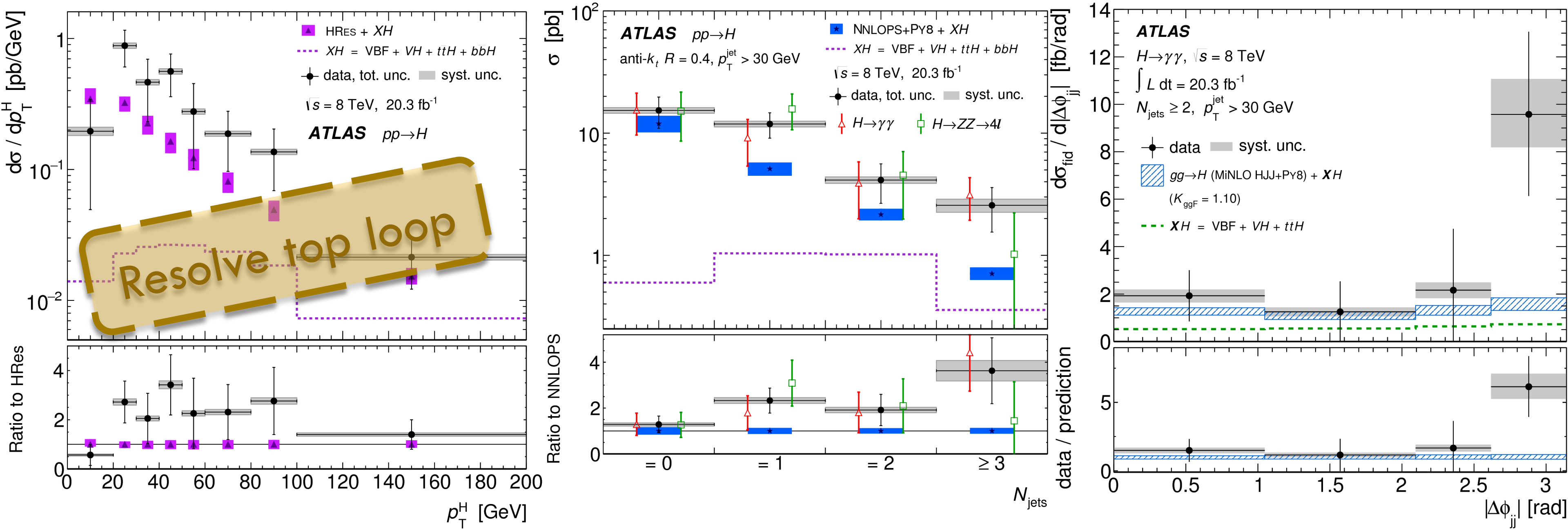

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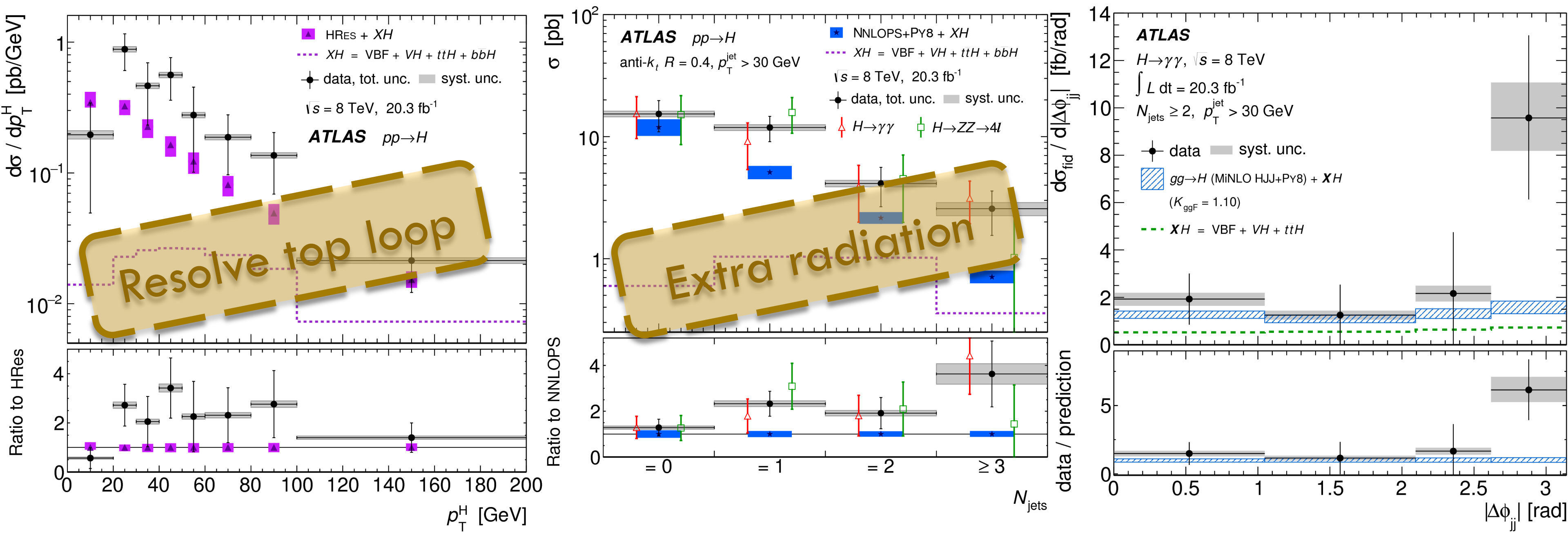

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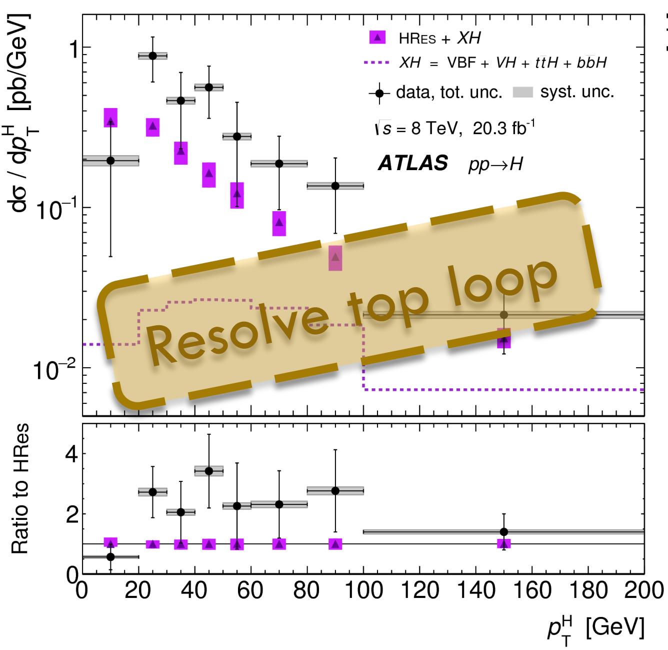
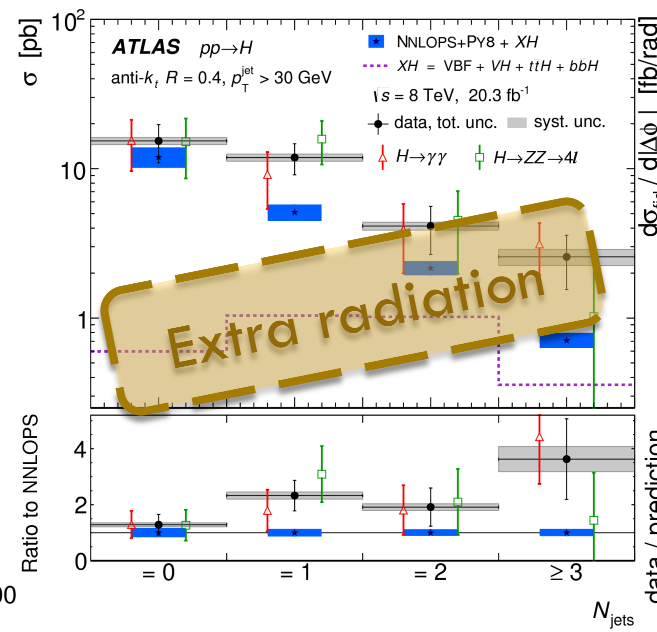
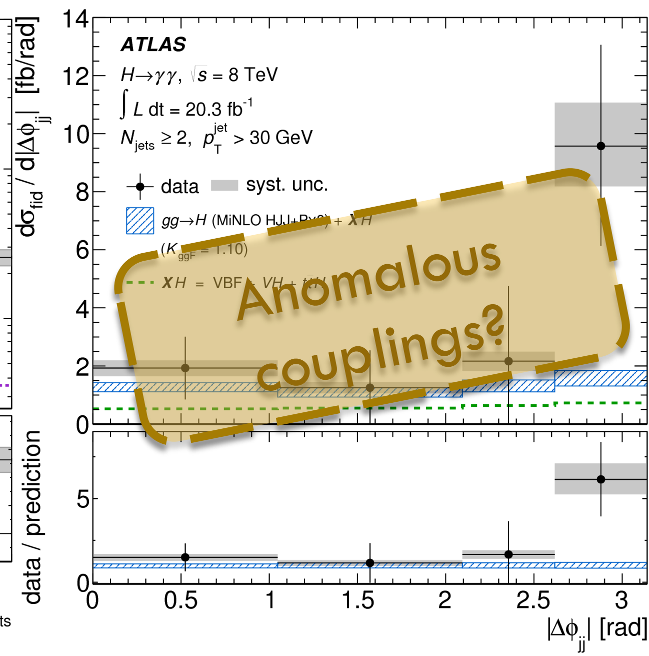


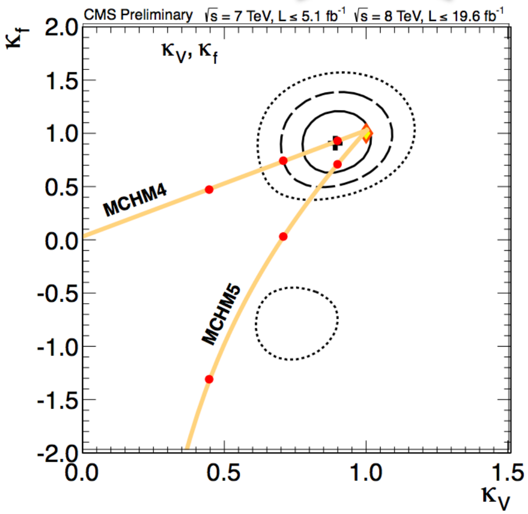




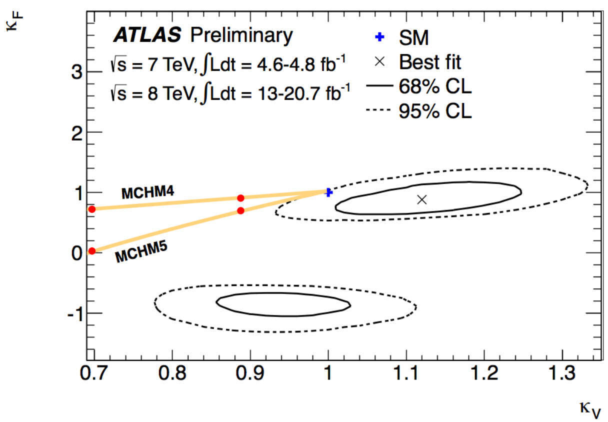
From deviations to EFTs

[http://cern.ch/go/W96V]

- Today we talk about deviations from the SMH.
  - arXiv:1209.0040 or equivalent.
  - **Draw/exclude your own theory. ➔**



- **One (single) nice feature: κ =1 recovers best SMH calculations.**
  - But that's it: we can find deviations, but only roughly fathom their meaning.



Deviations are on a diet

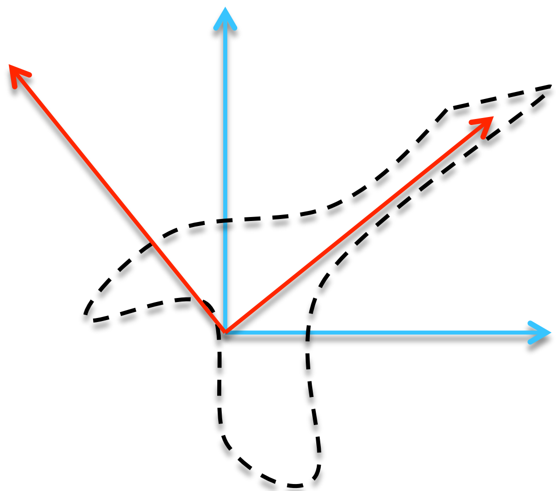
[arXiv:1306.6352]

- SUSY ($\tan\beta = 5$): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$
- Composite Higgs: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

Kappas simplistic, EFT complex

[NPB 268 (1986) 621]

- Instead of just using **experimentally-driven parameters** interpret with **basis of QFT operators** that may encode the fingerprint of **BSM physics.**
- EFT allows for accurate calculations.
  - NLO EWK effects, etc.
  - More sensitive interpretation.
- 2499 dim-6 operators mapped out in 1986.
  - **Which operators to keep?**
  - **What about dim-8?**
  - **What about loop processes?**
- **Where is the interface between experiment and theory?**
  - How to quote results?

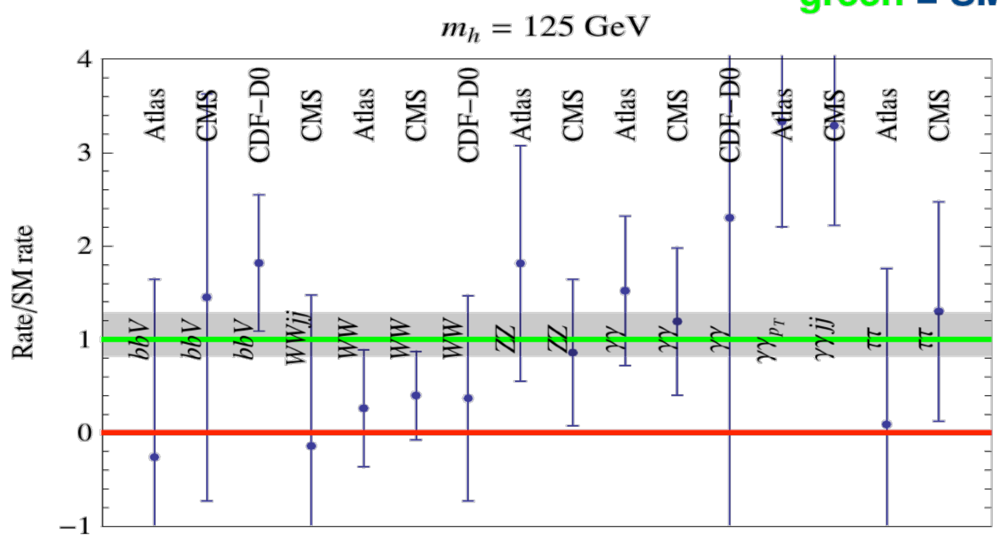


In 2012 some theorists speculated…

[http://goo.gl/CVm6s]

- After Moriond 2012, new fits disfavor the SM and motivate for New Physics

red = no Higgs boson
green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

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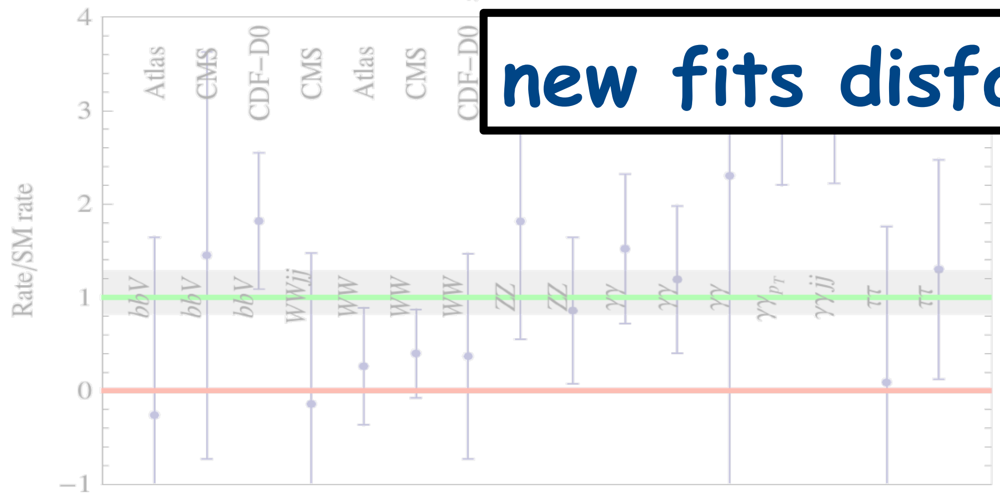
new fits disfavor the SM

new fits disfavor the SM

new fits disfavor the SM



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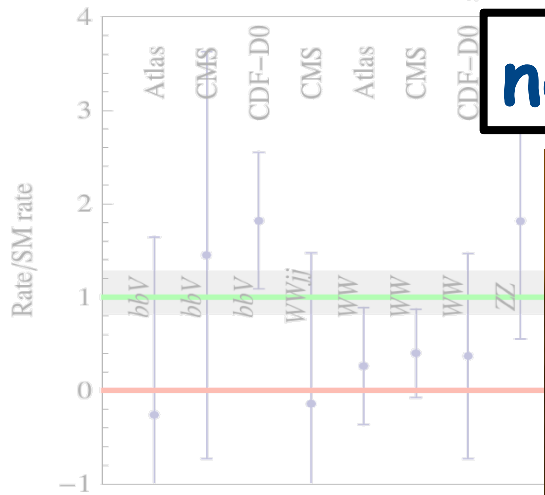
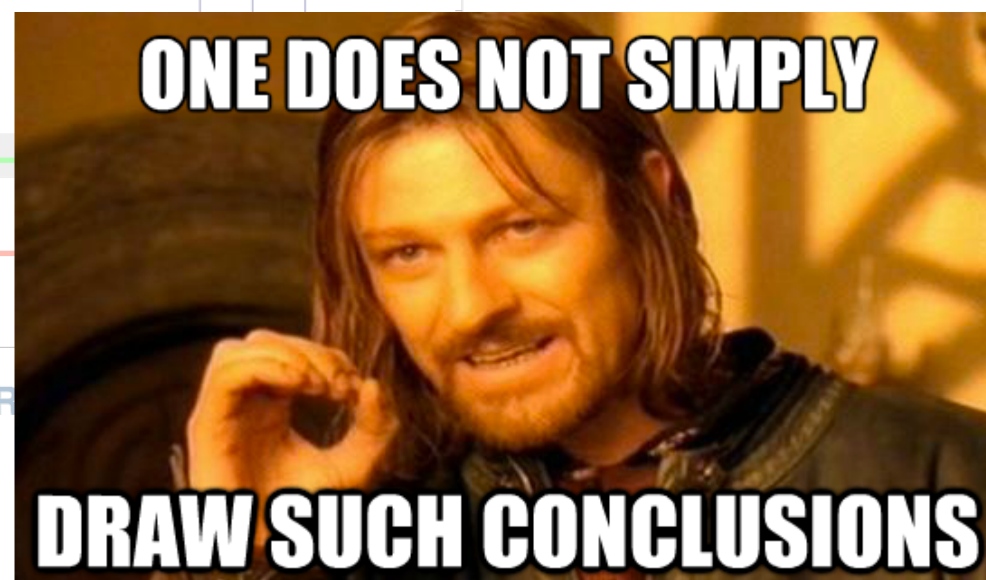


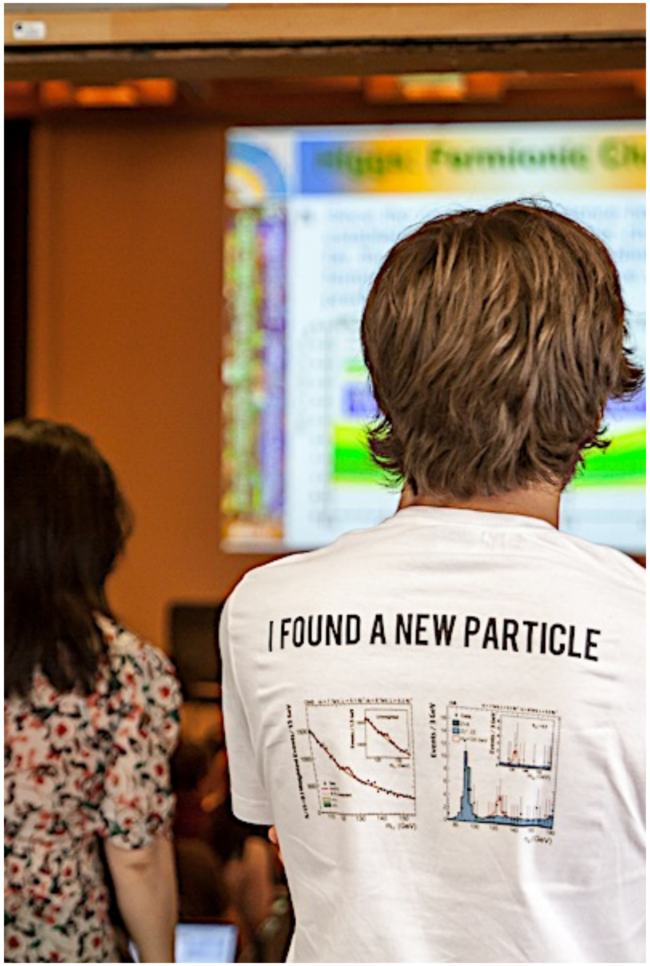
P. Giardino, K. Kannike, M. R



Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu]["Scalar meadow"]

Outlook



- **LHC13: last chance before "direct BSM desert".**
  - Tevatron: Run I → top discovery, Run II → SM precision.
  - LHC 2010: early SUSY and EXO exclusions.
- **Higgs, one way out of the "SM oasis":**
  - From O(10%) to differential.
  - From "seen" to O(%) measurements.
  - From limits on rare things to observations.
  - From conjectures on weird things, to putting limits on them.
  - From ad-hoc κ fits to global EWK/flavour EFT fits.
- **We have a long way to go.**
  All it takes is one deviation.

Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu][“Scalar meadow”]

Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu][“Scalar meadow”]

199 years of patient construction

Prato ~~dei Miracoli~~ scalare

[http://goo.gl/K8Lqmu]["Scalar meadow"]

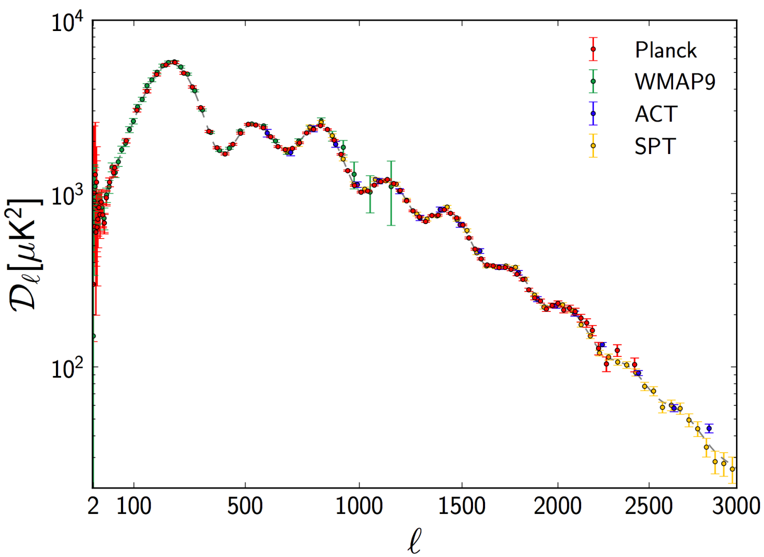
199 years of patient construction

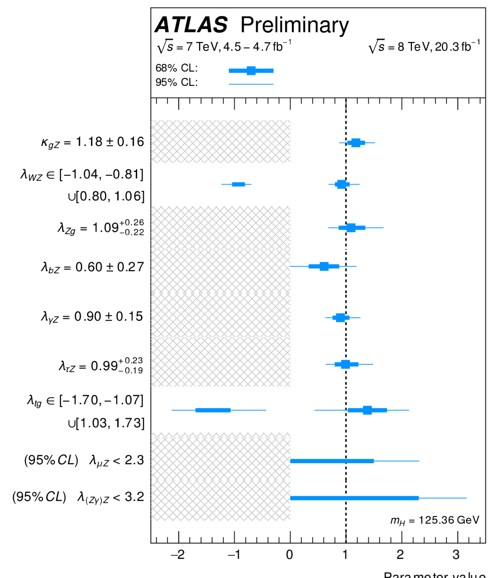
… and 44 years of modern stabilisation work

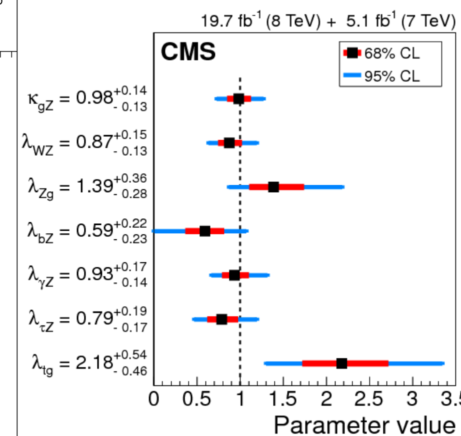
The ~~beautiful~~ ~~boring~~ Universe today

[arXiv:1303.5062][ATLAS-CONF-NOTE-2015-007][arXiv:1412.8662]

- **Up above:** “Simple six-parameter ΛCDM”.
- **Down below:** (Not-as-simple) ~20-parameter Standard Model of Particle Physics.







Looking forward to LHC combination and surprises at higher energy: PeV neutrinos, LHC 13 TeV, …

References

"…and references therein."

- Experiments' pages on Higgs results:
  - ATLAS: http://cern.ch/go/7IDT
  - CMS: http://cern.ch/go/6qmZ
  - Tevatron: http://cern.ch/go/h9jX
    - CDF: http://cern.ch/go/q8NV
    - D0: http://cern.ch/go/9Djq
- Partial list of conferences and workshops:
  - Higgs Days 2013: http://cern.ch/go/6zBp
  - ECFA HL-LHC workshop: http://cern.ch/go/SFW6
  - Higgs EFT 2013: http://cern.ch/go/bR7w
  - Higgs Couplings 2013: http://cern.ch/go/THp9
  - Moriond 2014: http://cern.ch/go/k8FP
  - Bernasque 2014: http://cern.ch/go/Pz7I
  - ICHEP 2014: http://cern.ch/go/8Btf
  - Rencontres du Vietnam 2014: http://cern.ch/go/9ZJJ
  - Zuoz Summer School 2014: http://cern.ch/go/9SHw
  - Higgs Days 2014: http://cern.ch/go/lfP6
  - Higgs Couplings 2014: http://cern.ch/go/HMm6

Part II

Menu of discussion topics

- In my biased preferred order:
  1. EFT and pseudo-observables.
  2. What's in a signal strength?
  3. CMS $H \rightarrow \gamma\gamma$ analysis.
  4. The maximum entropy coincidence.
  5. What's inside the CMS combination?
  6. Concrete BSM model searches.
  7. Tensor structure: spin/CP.
  8. More on the m_H combination.
  9. Going off-shell.
  10. HL-LHC extrapolations.
  11. Kappa: BSM interpretations.
  12. Statistics primer.

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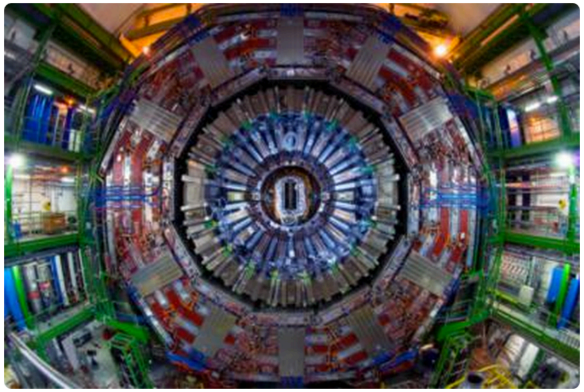
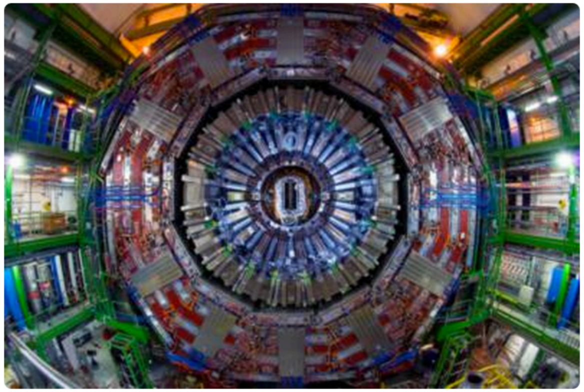
Big Experiments

#WolfAI

ImageIdentify[]

Big Experiments

#WolfAI

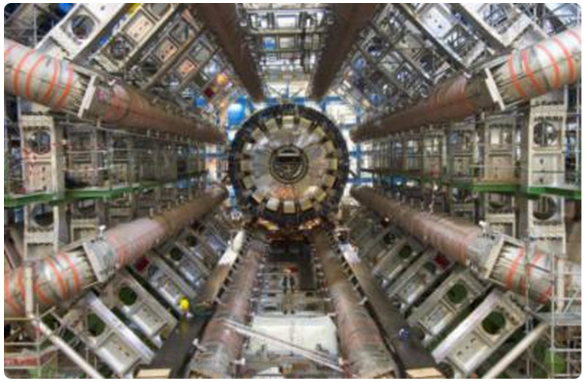
ImageIdentify[]

roulette wheel

Tell ImageIdentify how it did: Great! Could be better Missed the point What the heck?!

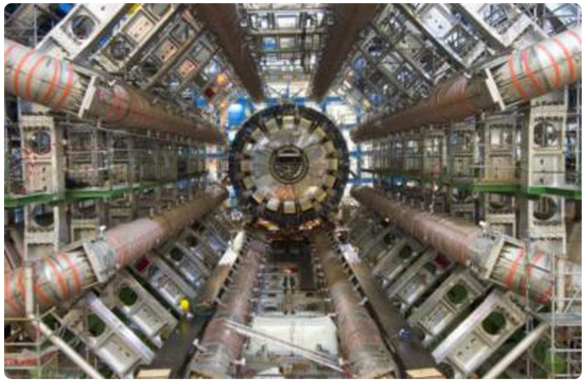
Big Experiments

#WolfAI

ImageIdentify[]

Big Experiments

#WolfAI

ImageIdentify[]

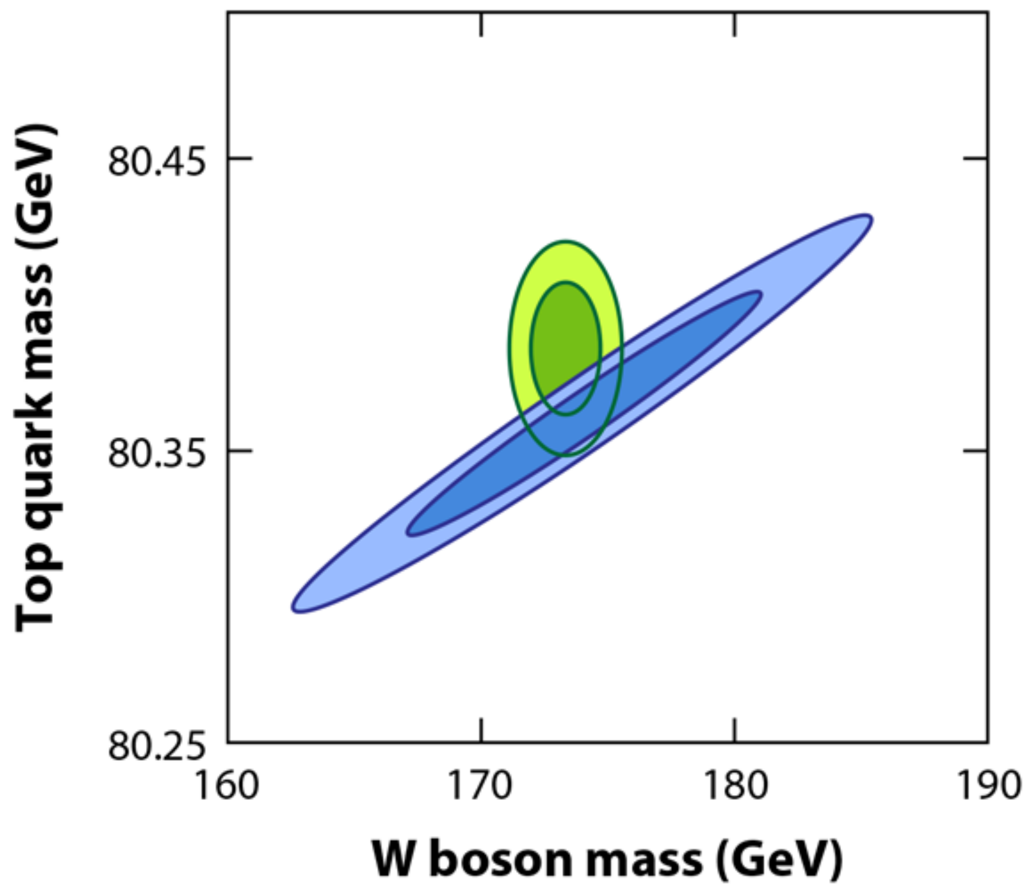
shopping center

Tell ImageIdentify how it did: Great! Could be better Missed the point What the heck?!

ATLAS+CMS m_H in PRL

[PRL 114 (2015) 191803][http://physics.aps.org/articles/v8/45]

- First ATLAS+CMS publication.
  - 0.2% precision.
- PRL Viewpoint by Chris Quigg: "*With LHC Run 2 [we] can look forward to a new round of exploration, searches for new phenomena, and refined measurements. Combined analyses […], such as the measurement of the Higgs boson mass discussed here, will help make the most of the data.* ***We still have much to learn about the Higgs boson, the electroweak theory, and beyond.***"



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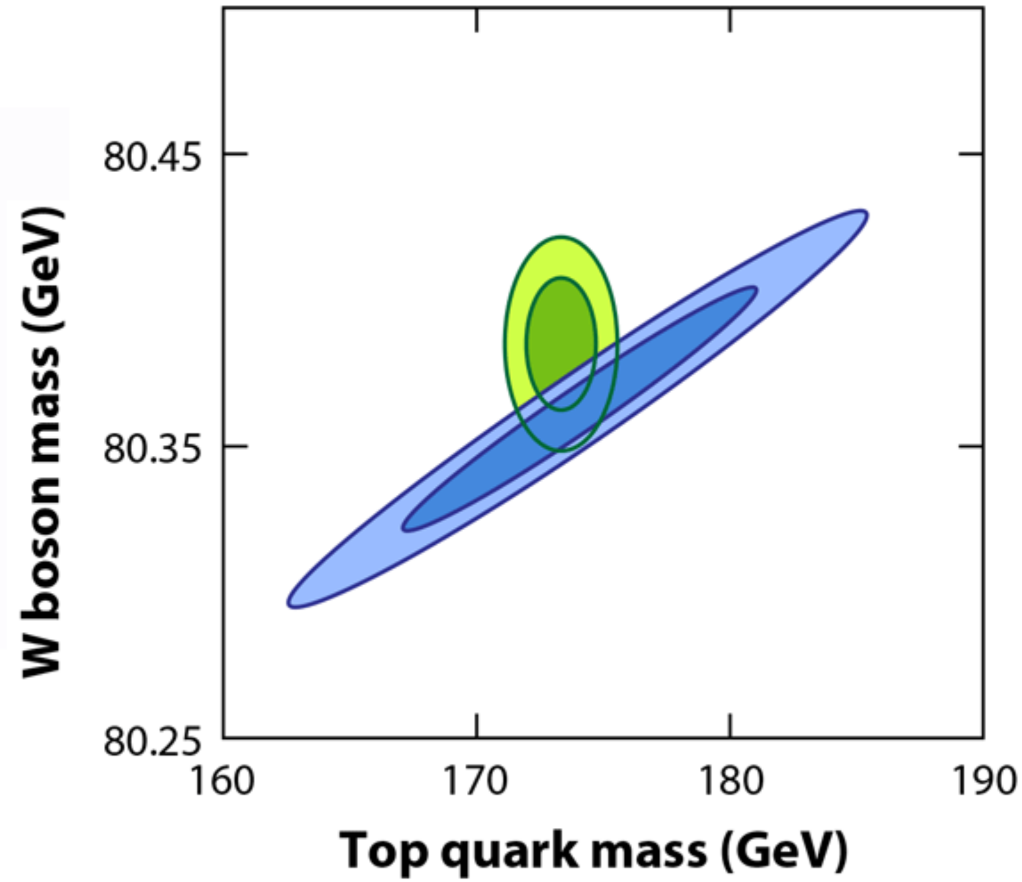


Statistics interlude

What’s in a signal strength

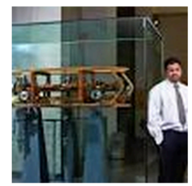
EFT and pseudo-observables

Some things are convention

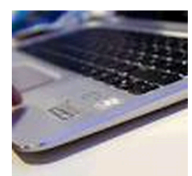
US markets will be affected by '**leap second**' | New York …
New York Post - Jun 27, 2015
Comment(required). June 27, **2015** | 11:10pm ... This "**leap second**" will occur as the clock strikes 8 p.m. in New York. The last time this happened was in 2012, ...

Leap second on June 30 will be 'mini-Y2K'
USA TODAY - Jun 22, 2015
Short on time? Don't worry. This month you'll get an extra second. "**leap second**" will be added on June 30 at midnight Coordinated Universal ...
Will the **leap second** on June 30 break the Internet?
In-Depth - Daily Times - Jun 21, 2015
Explore in depth (11 more articles)

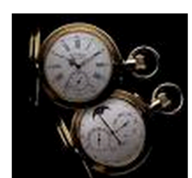
Leap Second 2015: Why This Tuesday Will Be Longer Tl
Chinatopix - 47 minutes ago
Leap Second 2015 — Experts recently announced that Tuesday, June 30, will be longer than usual. Why? Because leap second wil occur.



A **leap second** will be added to time next week but watch …
The Independent - Jun 24, 2015
Thursday 25 June **2015** ... When the last **leap second** kicked in, on a Saturday night in June 2012, websites including Reddit and LinkedIn faltered as servers got ...
What does the **leap second** mean for government IT?
GCN.com - Jun 25, 2015
Explore in depth (8 more articles)



Will the '**leap second**' break the internet?
SBS - Jun 23, 2015
Leap seconds are adjustments to international time that take the slowing of Earth's rotation into account, which changes slightly from day to day.
Leap second: What is the extra second you will get on 30 June?
International Business Times UK - Jun 23, 2015
Explore in depth (3 more articles)



Is the **Leap Second 2015** a danger like Y2K?
TWCN Tech News (blog) - Jun 14, 2015
Many IT companies are dreading over the **leap second 2015**. Most of these companies are considering the leap second as another Y2K-like ...

Some things are convention

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Handling Leap Seconds the OpenBSD Way

Contributed by pitrh on Sun Jun 28 20:17:50 2015 (GMT)
from the bounded leaps dept.

Christian Weisberger (naddy@) let us all know what we need to do to prepare for the impending leap second:

```
As you may have heard, a leap second will be upon us at 23:59:60
UTC on June 30.

The sky will fall, civilization will end, and dinosaurs will roam
the earth again.  Well, maybe not.

Neither the OpenBSD kernel nor OpenNTPD handle leap seconds in any
way.  So what will happen?
```

```
After the leap second, your OpenBSD system's time will be off by,
well, one second.  Gasp, shock.  Let's say you synchronize your
clock with ntpd against a server that does have the correct time.
At the next poll, i.e. within about half an hour, ntpd will notice
the offset and correct it, which will take a few minutes.  That's
it.  (I expect ntpd will drop down to a short poll interval and the
frequency correction will fishtail a bit since it's a differentiator
reacting to a jump.)

Unless you obsessively watch your ntpd, you won't notice a thing.
```

Some things are convention

US markets will be affected by '**leap second**' | New York …
New York Post - Jun 27, 2015
Comment(required). June 27, **2015** | 11:10pm ... This "**leap second**" will occur as the clock strikes 8 p.m. in New York. The last time this happened was in 2012, ...

Leap second on June 30 will be 'mini-Y2K'
USA TODAY - Jun 22, 2015

How does Google handle this event?

We have a clever way of handling leap seconds that we posted about back in 2011. Instead of repeating a second, we "smear" away the extra second. During a 20-hour "smear window" centered on the leap second, we slightly slow all our servers' system clocks (by approximately 14 parts per million). At the end of the smear window, the entire leap second has been added, and we are back in sync with civil time. (This method is a little simpler than the leap second handling we posted back in 2011. The outcome is the same: no time discontinuities.) Twenty hours later, the entire leap second has been added and we are back in sync with non-smeared time.

Leap second: What is the extra second you will get on 30 June?
International Business Times UK - Jun 23, 2015
Explore in depth (3 more articles)

Is the **Leap Second 2015** a danger like Y2K?
TWCN Tech News (blog) - Jun 14, 2015
Many IT companies are dreading over the **leap second 2015**. Most of these companies are considering the leap second as another Y2K-like ...

Some things are not convention

Something is going to happen on June 30th that hasn’t happened in over 2,000 years

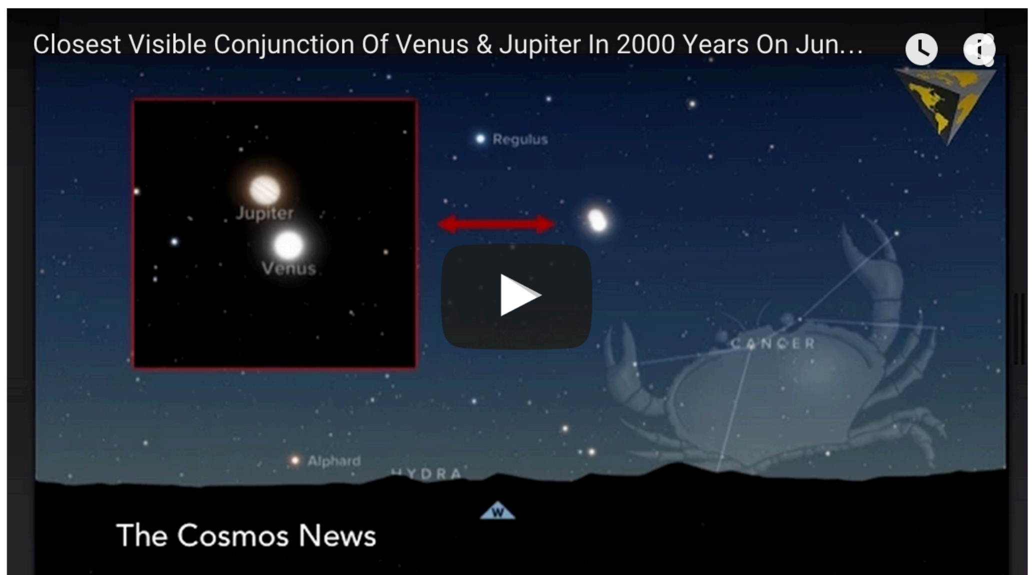
Sunday, June 28, 2015 14:41

EMAIL

(Before It's News)

Sunday, June 28, 2015

Something is going to happen on June 30th that hasn’t happened in over 2,000 years



Some things are not convention

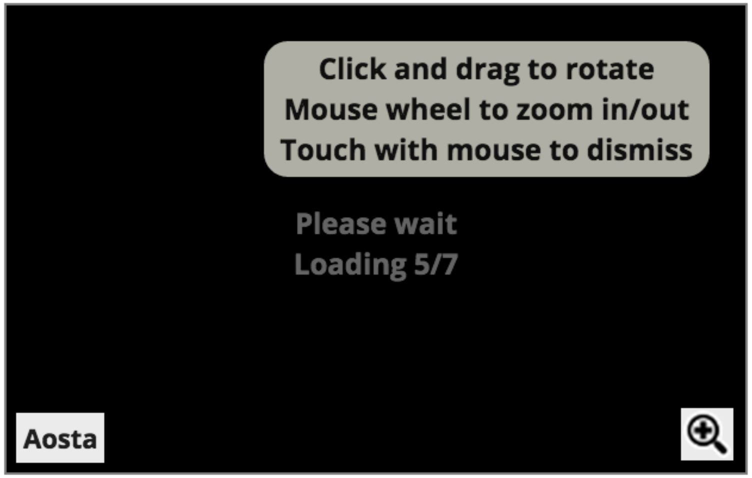
Conjunction between Venus and Jupiter

Wed, 01 Jul 2015 at 06:02 CEST (Tomorrow)
04:02 UTC

Dominic Ford, Editor
From the Conjunctions feed

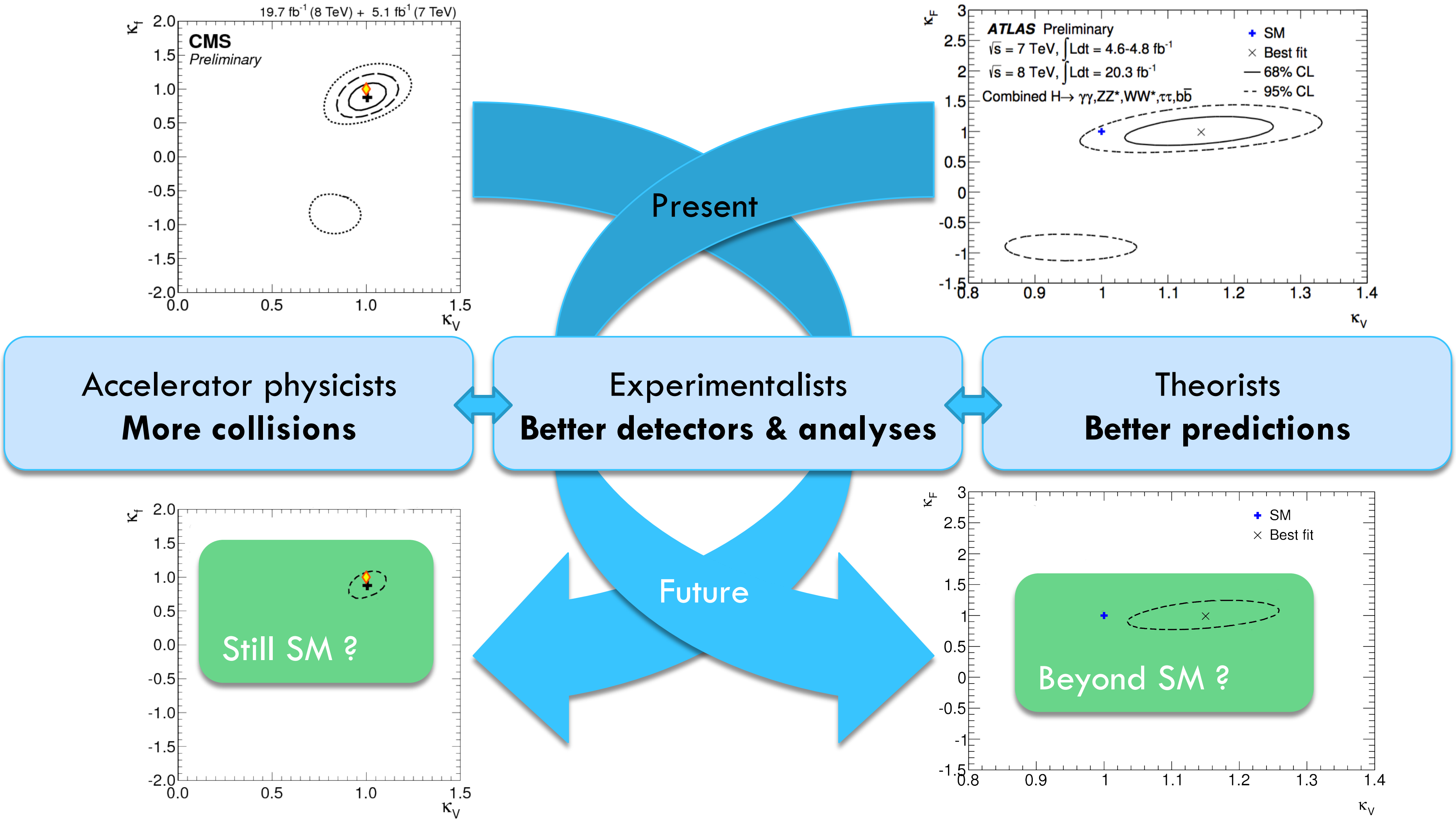
Venus and Jupiter will make a close approach, passing within 0°20' of each other.

From Aosta (click to change), the pair will be difficult to observe as they will appear no higher than 18° above the horizon. They will become visible at around 21:45 (CEST) as the dusk sky fades, 18° above your western horizon. They will then sink towards the horizon, setting 2 hours and 17 minutes after the Sun at 23:37.

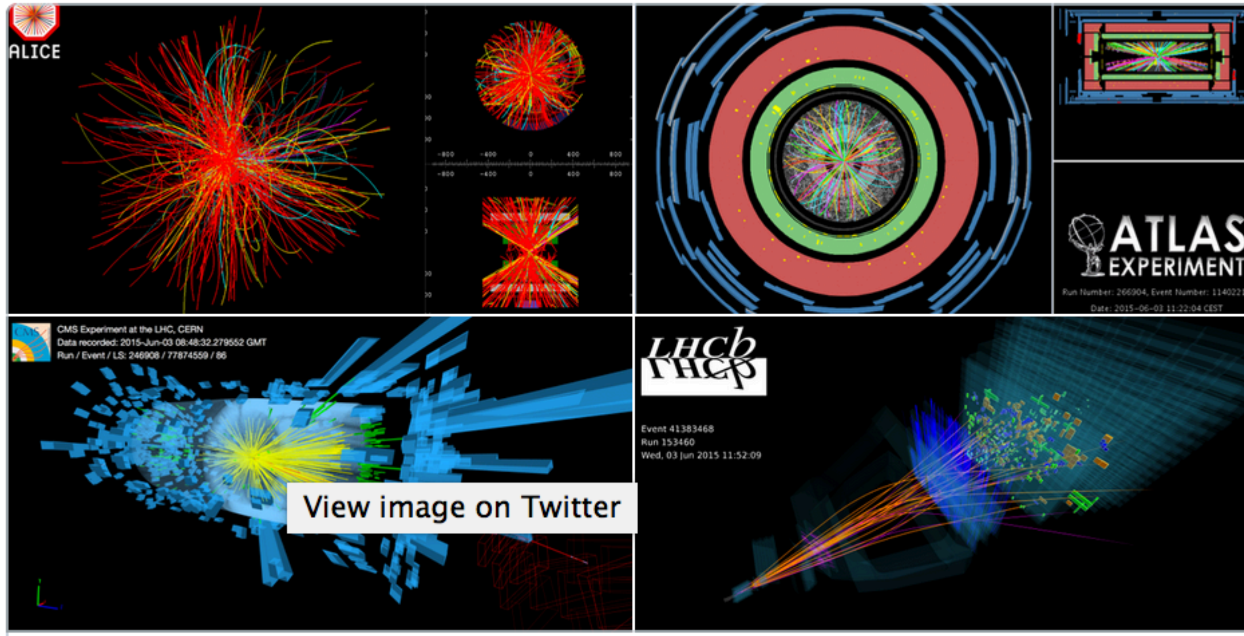


Kappas galore

The future is in precision and accuracy



Back to the #13TeV future



CERN @CERN

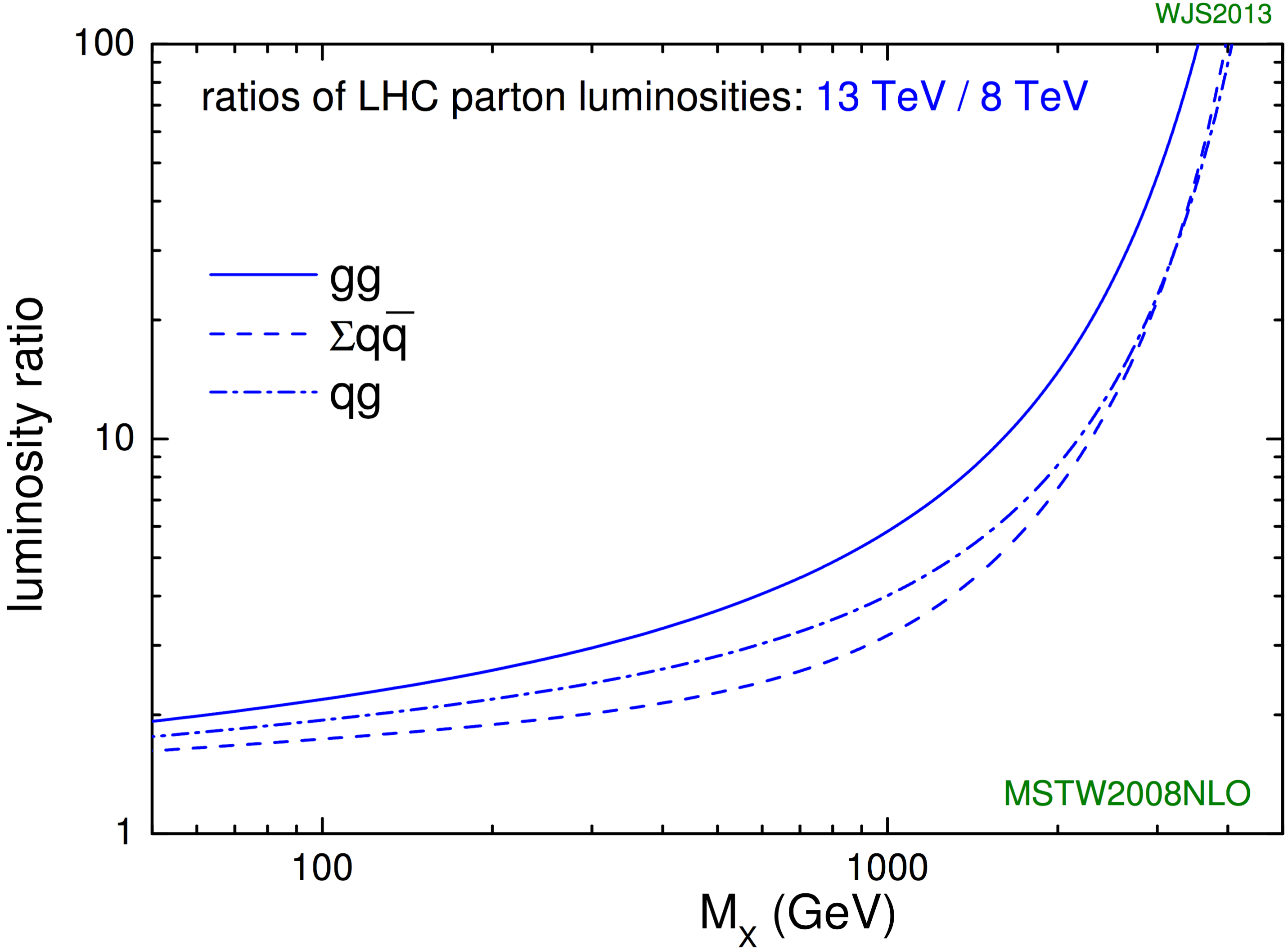
Follow

The LHC experiments are back in business with record energy collisions of #13TeV: cern.ch/go/D7z6

12:41 PM - 3 Jun 2015

853 558

The future is luminous



Back to the #13TeV future

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Science & Environment

Large Hadron Collider turns on 'data tap'

By Paul Rincon
Science editor, BBC News website

3 June 2015 | Science & Environment

The CMS experiment team celebrated when the first collisions occurred

Of pseudo-observables and EFT

Lunch – Waldorf-Astoria style

[http://cern.ch/go/Ns8X]

“Two waiters serve two steel workers lunch, on a girder high above New York City, 1930. (Photo by Keystone/Getty Images)”

4-box summary

Kappas cannot describe many SM deformations.

Fiducial cross-sections are a lot of bins.

Wilson coefficients deeply rooted in TH.

Need to **extend kappas** to something **between the other two.**

Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu -$$
$$\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$
$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h\left[\frac{2M^2}{g^2}+\frac{2M}{g}H+\frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^- +$$
$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$
$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$
$$\frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar e^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar u_j^\lambda(\gamma\partial+m_u^\lambda)u_j^\lambda - \bar d_j^\lambda(\gamma\partial+m_d^\lambda)d_j^\lambda +$$
$$igs_wA_\mu\left[-(\bar e^\lambda\gamma^\mu e^\lambda)+\frac{2}{3}(\bar u_j^\lambda\gamma^\mu u_j^\lambda)-\frac{1}{3}(\bar d_j^\lambda\gamma^\mu d_j^\lambda)\right] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda)+(\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda)+(\bar u_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 -$$
$$1-\gamma^5)u_j^\lambda)+(\bar d_j^\lambda\gamma^\mu(1-\tfrac{8}{3}s_w^2-\gamma^5)d_j^\lambda)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda)+(\bar u_j^\lambda\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda)+(\bar d_j^\kappa C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u_j^\lambda)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda)+\phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda)+$$
$$i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar u_j^\lambda C_{\lambda\kappa}(1-\gamma^5)d_j^\kappa)+m_u^\lambda(\bar u_j^\lambda C_{\lambda\kappa}(1+\gamma^5)d_j^\kappa] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1+\gamma^5)u_j^\kappa) -$$
$$m_u^\kappa(\bar d_j^\lambda C^\dagger_{\lambda\kappa}(1-\gamma^5)u_j^\kappa] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar u_j^\lambda u_j^\lambda) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar d_j^\lambda d_j^\lambda) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u_j^\lambda\gamma^5 u_j^\lambda) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d_j^\lambda\gamma^5 d_j^\lambda) + \bar X^+(\partial^2 -$$
$$M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- -$$
$$\partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) +$$
$$igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \frac{1}{2}gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ -$$
$$\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac{1}{2}igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$$

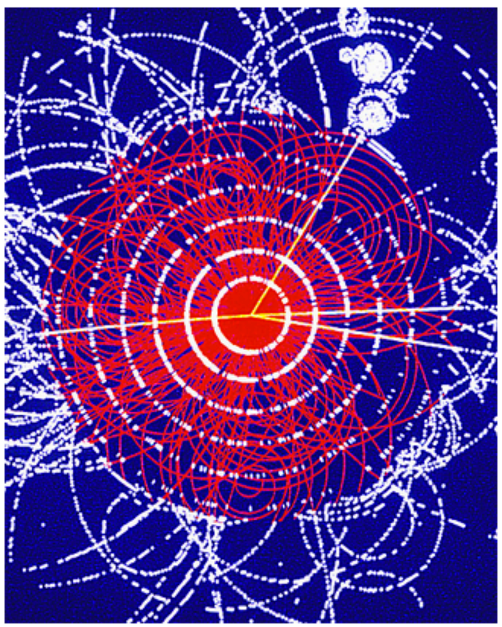
Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

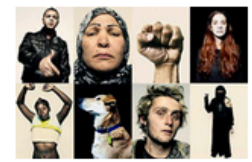
WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

Video

Poll Results

PAST PERSONS OF THE YEAR



2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

2008: Barack Obama

Most Read | Most Emailed

1 Who Should Be TIME's Person of the Year 2012?

2 LIFE Behind the Picture: The Photo That Changed the Face of AIDS

3 Nativity-Scene Battles: Score One for the Atheists

4 The $7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy

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THE CANDIDATES

The Higgs Boson

18 of 40

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SSPL/GETTY IMAGES

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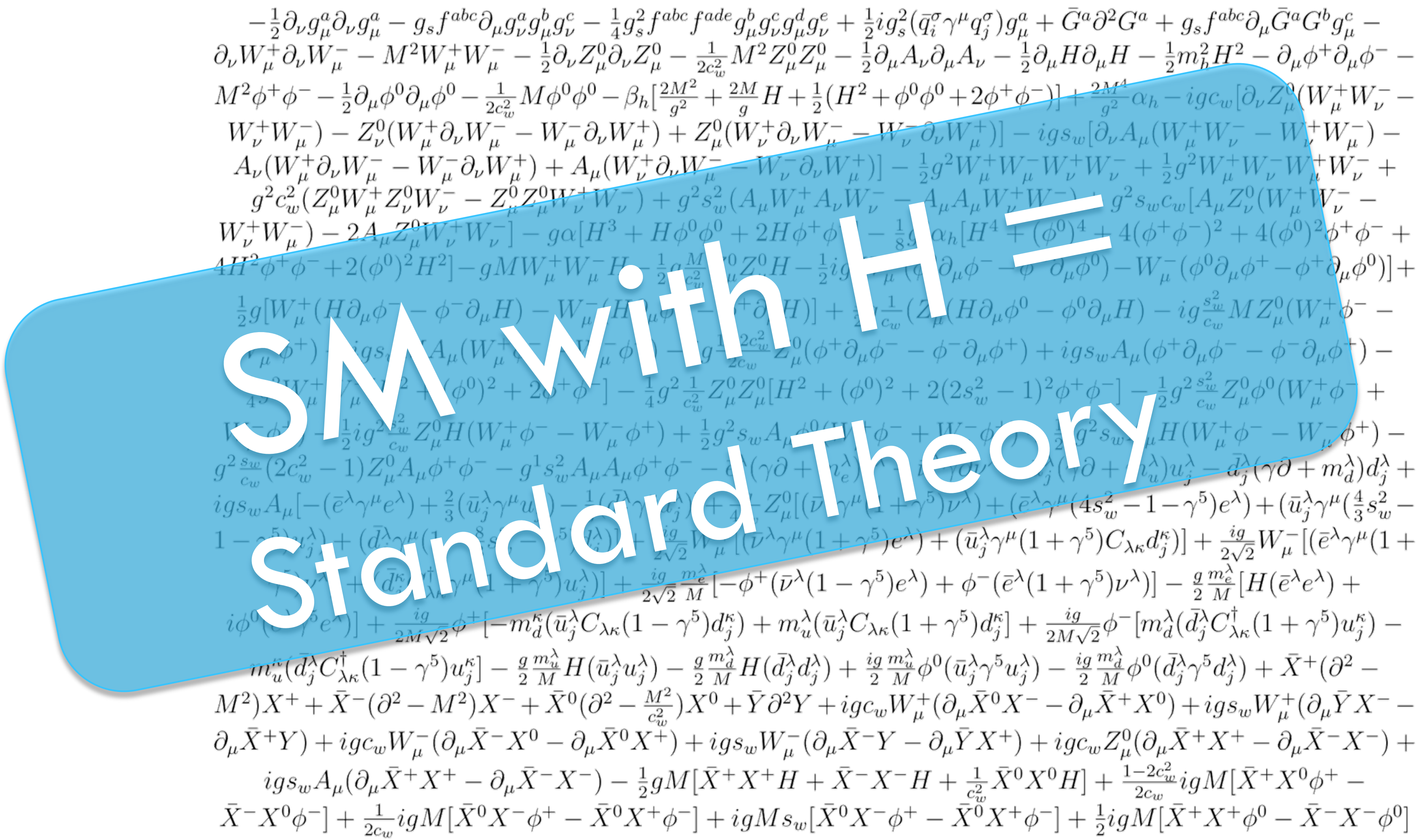
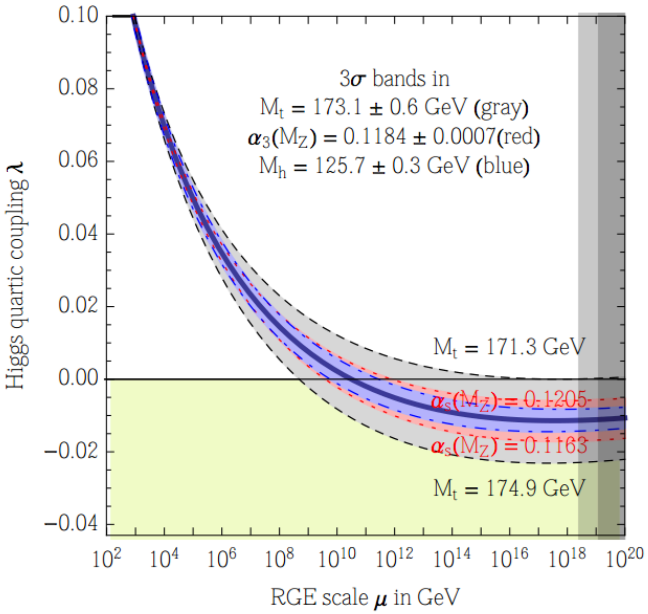
Standard **Theory** of Particle Physics

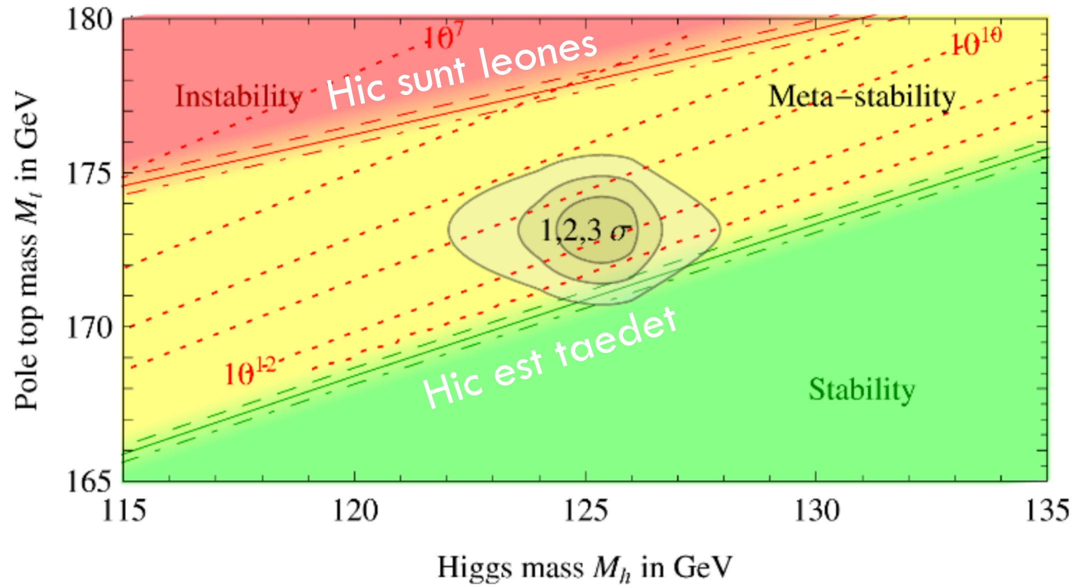
[http://cern.ch/go/dW6z]



The fate/character of the Universe

[JHEP 1208 (2012) 098]





- Standard Theory seems self-consistent up to large scales.
  - …though the Universe might decay.

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$
$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$
$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$
$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$
$$g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$
$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$
$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$
$$W^-_\mu\phi^+) + igs_w \quad \ldots \quad) -$$
$$\frac{1}{4}g^2 W^+_\mu W^-_\mu[H \quad \ldots \quad +$$
$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$
$$g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j +$$
$$igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$
$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$
$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$
$$m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 -$$
$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$
$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) +$$
$$igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] + \frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Valid up to ~Planck scale ?

Standard **Theory** of Particle Physics

[http://cern.ch/go/dW6z]

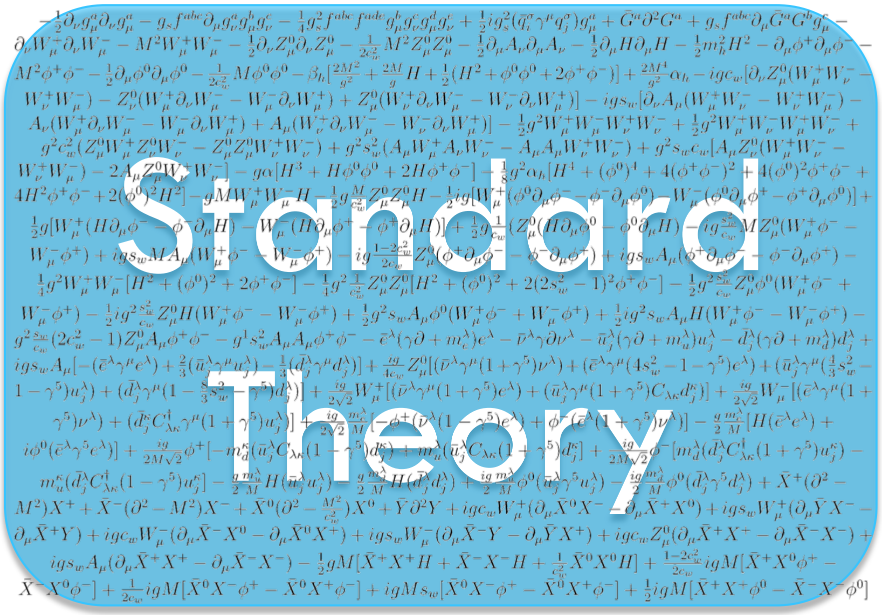
$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar G^a G^b g^c_\mu -$
$\partial_\nu W^+_\mu\partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - \frac12\partial_\mu H\partial_\mu H - \frac12 m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$
$M^2\phi^+\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$
$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$
$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$
$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$
$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac18 g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$
$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac12 ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$
$\frac12 g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$
$W^-_\mu\phi^+) + igs_w$ … $) -$
$\frac14 g^2 W^+_\mu W^-_\mu[H$ … $+$
$W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$
$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu$ … $)d^\lambda_j +$
$igs_wA_\mu[-(\bar e^\lambda\gamma^\mu e$ … $s_w^2 -$
$1-\gamma^5)u^\lambda_j) + (\bar d^\lambda_j\gamma^\mu(1-\frac83 s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt2}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt2}W^-_\mu[(\bar e^\lambda\gamma^\mu(1+$
$\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt2}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar e^\lambda(1+\gamma^5)\nu^\lambda)] - \frac g2\frac{m_e^\lambda}{M}[H(\bar e^\lambda e^\lambda) +$
$i\phi^0(\bar e^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt2}\phi^+[-m_d^\kappa(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt2}\phi^-[m_d^\lambda(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$
$m_u^\kappa(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac g2\frac{m_u^\lambda}{M}H(\bar u^\lambda_j u^\lambda_j) - \frac g2\frac{m_d^\lambda}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar X^+(\partial^2 -$
$M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- -$
$\partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) +$
$igs_wA_\mu(\partial_\mu\bar X^+X^+ - \partial_\mu\bar X^-X^-) - \frac12 gM[\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar X^+X^0\phi^+ -$
$\bar X^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + igMs_w[\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-] + \frac12 igM[\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0]$

Valid up to ~Planck scale ?

But: dark matter, matter-antimatter, etc.

The Next Standard Model

[http://cern.ch/go/dW6z]



The Next Standard Model

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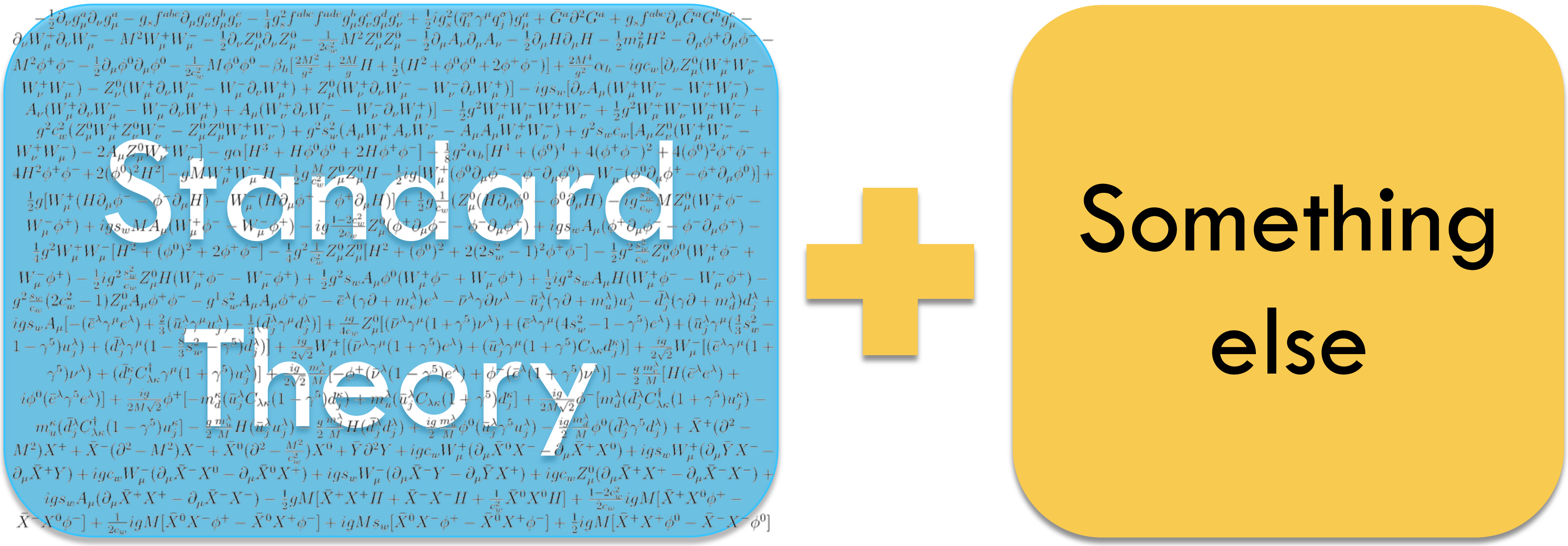

H(125) – looking for “*something else*”

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - J=0 ok for everyone?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

Handles on deviations

- **Mass**
  - **Exp. Uncertainties**
  - **SM consistency: (m_H, m_W, m_{top})**
- Spin
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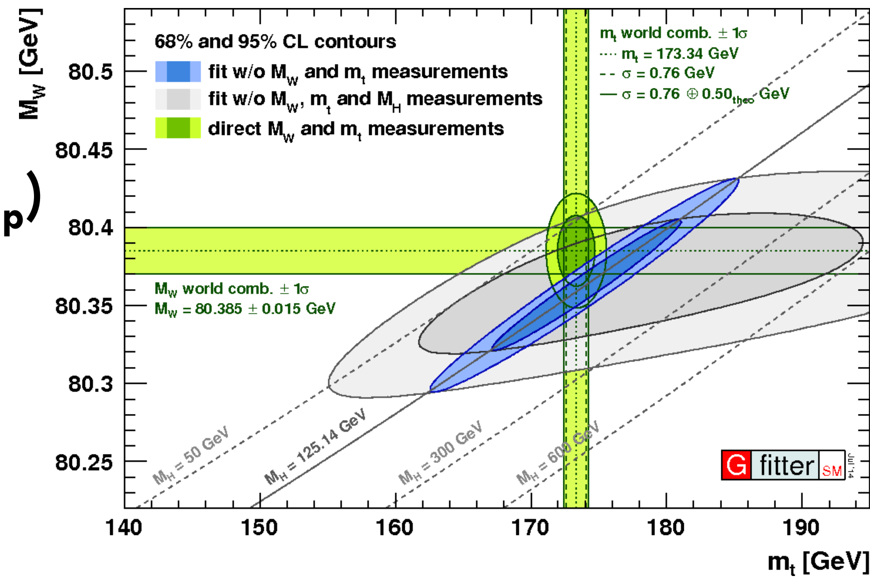

Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- **Spin**
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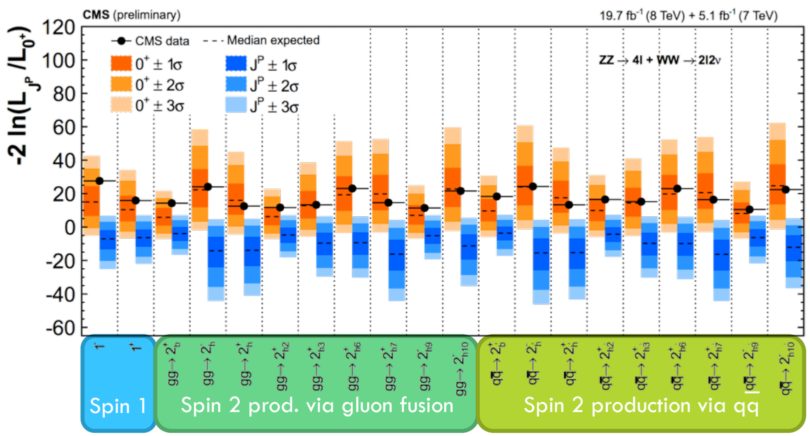

Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - J=0 ok for everyone?
- **Charge**
  - **Zero. (That was easy.)**
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  - Amplitude decomposition → EFT
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0

Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
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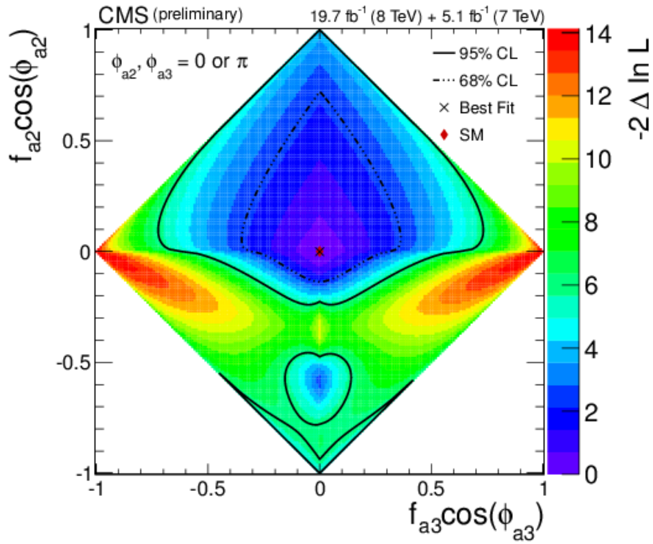
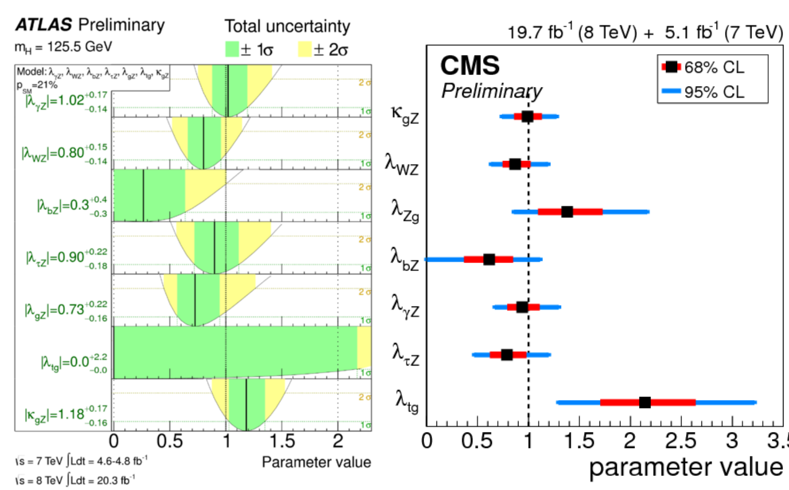
- Charge
  - Zero. (That was easy.)
- **Parity**
  - **Amplitude decomposition → EFT**
- Scalar couplings
  - $\kappa \longrightarrow \kappa(q) \longrightarrow f(q) \longrightarrow$ EFT

$$\begin{aligned} A(X_{J=0} \to V_1 V_2) \sim\ & v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\ & + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ & + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ & \left. + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \end{aligned}$$



Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - J=0 ok for everyone?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- **Scalar couplings**
  - **$\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT**



Kappas: scalar coupling deviations

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\rm ggH}}{\sigma^{\rm SM}_{\rm ggH}} = \begin{cases} \kappa_{\rm g}^2(\kappa_{\rm b}, \kappa_{\rm t}, m_{\rm H}) \\ \kappa_{\rm g}^2 \end{cases}$$

$$\frac{\sigma_{\rm VBF}}{\sigma^{\rm SM}_{\rm VBF}} = \kappa_{\rm VBF}^2(\kappa_{\rm W}, \kappa_{\rm Z}, m_{\rm H})$$

$$\frac{\sigma_{\rm WH}}{\sigma^{\rm SM}_{\rm WH}} = \kappa_{\rm W}^2$$

$$\frac{\sigma_{\rm ZH}}{\sigma^{\rm SM}_{\rm ZH}} = \kappa_{\rm Z}^2$$

$$\frac{\sigma_{\rm t\bar{t}H}}{\sigma^{\rm SM}_{\rm t\bar{t}H}} = \kappa_{\rm t}^2$$

Detectable decay modes

$$\frac{\Gamma_{\rm WW^{(*)}}}{\Gamma^{\rm SM}_{\rm WW^{(*)}}} = \kappa_{\rm W}^2$$

$$\frac{\Gamma_{\rm ZZ^{(*)}}}{\Gamma^{\rm SM}_{\rm ZZ^{(*)}}} = \kappa_{\rm Z}^2$$

$$\frac{\Gamma_{\rm b\bar{b}}}{\Gamma^{\rm SM}_{\rm b\bar{b}}} = \kappa_{\rm b}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\rm SM}_{\tau^-\tau^+}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\rm SM}_{\gamma\gamma}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\rm b}, \kappa_{\rm t}, \kappa_{\tau}, \kappa_{\rm W}, m_{\rm H}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\rm Z\gamma}}{\Gamma^{\rm SM}_{\rm Z\gamma}} = \begin{cases} \kappa_{\rm (Z\gamma)}^2(\kappa_{\rm b}, \kappa_{\rm t}, \kappa_{\tau}, \kappa_{\rm W}, m_{\rm H}) \\ \kappa_{\rm (Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\rm t\bar{t}}}{\Gamma^{\rm SM}_{\rm t\bar{t}}} = \kappa_{\rm t}^2$$

$$\frac{\Gamma_{\rm gg}}{\Gamma^{\rm SM}_{\rm gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{\rm c\bar{c}}}{\Gamma^{\rm SM}_{\rm c\bar{c}}} = \kappa_{\rm t}^2$$

$$\frac{\Gamma_{\rm s\bar{s}}}{\Gamma^{\rm SM}_{\rm s\bar{s}}} = \kappa_{\rm b}^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\rm SM}_{\mu^-\mu^+}} = \kappa_{\tau}^2$$

Total width

$$\frac{\Gamma_{\rm H}}{\Gamma^{\rm SM}_{\rm H}} = \begin{cases} \kappa_{\rm H}^2(\kappa_i, m_{\rm H}) \\ \kappa_{\rm H}^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times \mathrm{BR}) = \sigma \cdot \Gamma / \Gamma_{\rm H}$

Kappas: scalar coupling deviations

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} =$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} =$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa_t$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa_W^2$$

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$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{\mathrm{SM}}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$= \kappa_t^2$$

see Section 3.1.2

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{\mathrm{SM}}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{\mathrm{SM}}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{\mathrm{SM}}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

Kappas do not change shapes. Only overall yields.

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma/\Gamma_H$

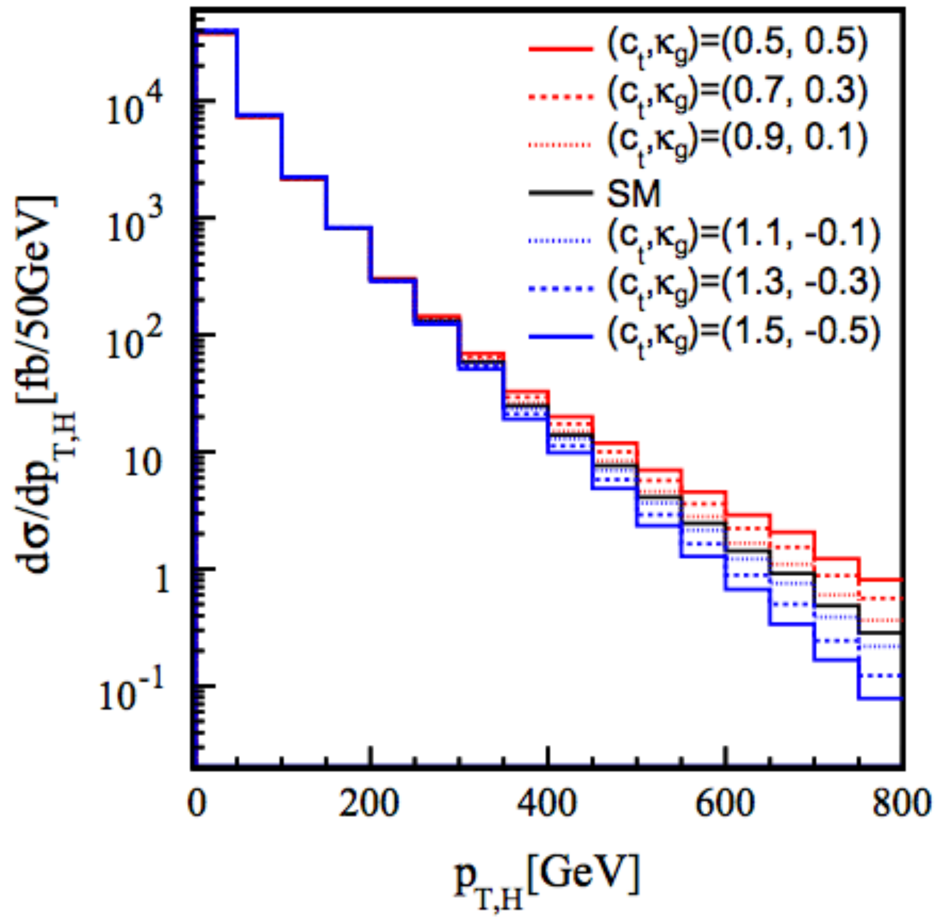
Kappas do not change shapes

[Spannowsky et al. arXiv:1405.4295]

- Scaling the **SM line** would not capture **gluon-gluon-H** vertex effects:

$$\mathcal{L}_{\rm eff} = -c_t \frac{m_t}{v}\bar{t}tH + \kappa_g \frac{\alpha_S}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{a\,\mu\nu} + \mathcal{L}_{\rm QCD}$$

$$\mathcal{M}(c_t,\kappa_g) = c_t\mathcal{M}_{\rm IR} + \kappa_g\mathcal{M}_{\rm UV}$$



Deviations are on a diet

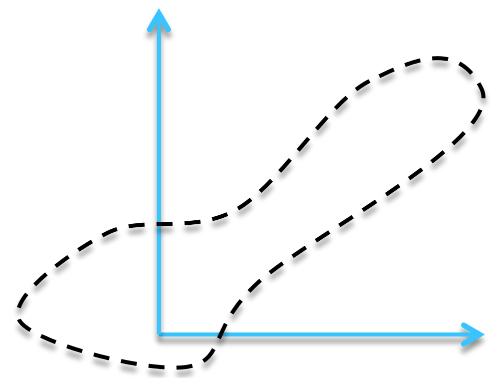
[arXiv:1306.6352]

- SUSY ($\tan\beta = 5$): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\text{ TeV}}{m_A}\right)^2$$
- Composite scalar: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\text{ TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\text{ TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\text{ TeV}}{m_T}\right)^2$$

Effective field theory (EFT): the idea

[NPB 268 (1986) 621] [JHEP 10 (2010) 085]

- **Experimentally-driven set of parameters** vs. basis of QFT operators that may be better aligned with the **Next SM features.**



- EFT allows to perform accurate calculations:
  - NLO EWK effects, etc.
  - More sensitive interpretation.

- >59 dim-6 operators already mapped out in 1986.
  - **Which operators to keep ?**
  - **What about dim-8 ?**
  - **What about loop processes ?**

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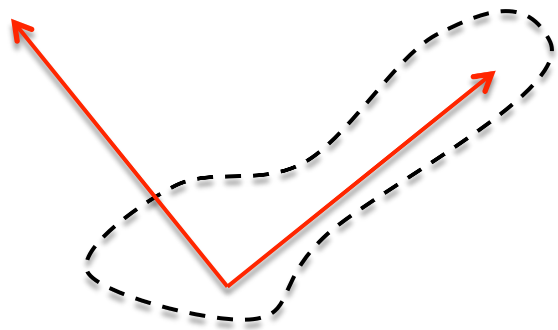

- Experimentally-driven set of parameters vs. **basis of QFT operators** that may be better aligned with the **Next SM features.**
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  - **Which operators to keep ?**
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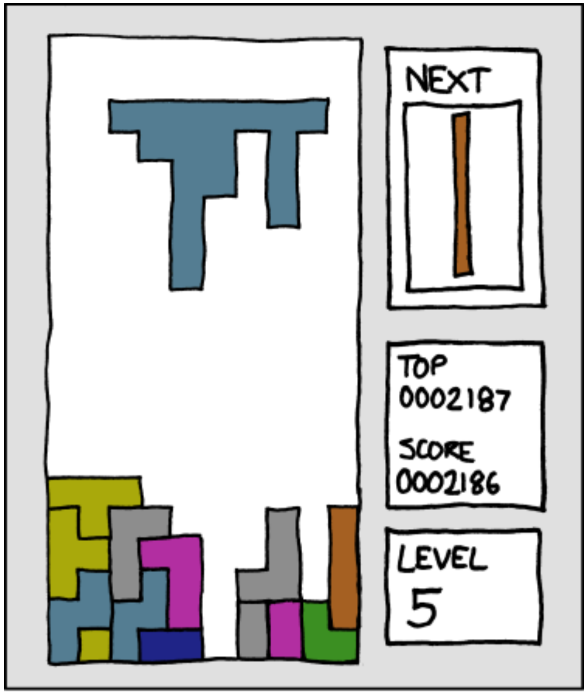
  - **What about loop processes ?**

LHC Higgs Cross Section WG

[http://xkcd.com/888/]

- Experimentalists and theorists joined to produce the best pieces for a common puzzle. ➘
- This talk draws heavily from discussions in and around **WG2**.
  - Special thanks to G. Passarino, G. Isidori, A. Falkowski, M. Duehrssen, M. Trott, F. Riva, F. Maltoni, and C. Grojean.
  - Inaccuracies are still my own.



HEAVEN

Supplementing the Standard Theory

Concrete BSM

- SUSY: MSSM, NMSSM, etc.
- Possibly:
  - Light new physics.
  - Other states.
  - Non-decoupled.
- Specific benchmarks.
  - LHC HXSWG WG3.

EFT expansion

- Add higher-dimensional operators.
- Assumes:
  - Heavy new physics.
  - Indirect effects, loops.
  - Decoupled.
- Generic interpretation.
  - LHC HXSWG WG2.

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Concrete BSM	EFT expansion

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  - LHC HXSWG **WG2**.

Not all EFT are born the same

[http://cern.ch/go/L98Q]

Top-down EFT

- Full theory known:
  - Matching conditions bridge EFT and full theory.

Bottom-up EFT

- Full theory **un**known:
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Top-down EFT

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Bottom-up EFT

- Full theory **un**known:
  - Add operators as theory can calculate and data can discern.

A taxonomy of dim-6 operators

[Trott et al. JHEP 04 (2014) 159]

Class	N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
$1: X^3$	4	2	2	2	2	2	2
$2: H^6$	1	1	1	1	0	0	0
$3: H^4 D^2$	2	2	2	2	0	0	0
$4: X^2 H^2$	8	4	4	4	4	4	4
$5: \psi^2 H^3 + \text{h.c.}$	3	$3n_g^2$	3	27	$3n_g^2$	3	27
$6: \psi^2 X H + \text{h.c.}$	8	$8n_g^2$	8	72	$8n_g^2$	8	72
$7: \psi^2 H^2 D$	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
$8: (\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
$8: (\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
$8: (\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
$8: (\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
$8: (\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
$8:$ All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Table 2. Number of CP-even and CP-odd coefficients in $\mathcal{L}^{(6)}$ for n_g flavors. The total number of coefficients is $(107n_g^4+2n_g^3+135n_g^2+60)/4$, which is 76 for $n_g=1$ and 2499 for $n_g=3$.

EFT questions

- From 2499 dim-6 operators to ~60 operators.
  - **Symmetries** guide the culling:
    - Flavour, ~custodial, CP.
    - Each assumption needs **testing** measurements/observables.

- But to go down from ~60:
  - Guidance from **experimental sensitivity**.
  - Use **complementary information**:
    - LEP, Tevatron, etc experimental constraints.
    - aTGC/aQGC, top quark, EDM searches, etc.

Working out the details

[http://cern.ch/go/6xk9]

"A construction worker crouches over the end of a girder high above the streets of New York. (Photo by General Photographic Agency/Getty Images). Circa 1930"

EFT challenges

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
  $= \mathbf{d4^2} + \text{d4}\times\text{d6}$ $(+\ \text{d6}^2 + \text{d4}\times\text{d8})$ $(+\ \text{d6}\times\text{d8} + \text{d8}^2) + \ldots$
  - Weeding of the negligible, keeping of the sizable.

- Delicate choices because of:
  - Tails of large Q^2 values where dim-8 may not be so small.
  - Where there is no dim-6 tree contribution, dim-8 is leading.

- And let's not forget interferences.
  - Signals and backgrounds are physics processes all alike.

Delicate choices

[Passarino http://cern.ch/go/nT7n]

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
  $= d4^2 + \mathbf{d4 \times d6}\ (+\ d6^2 + \mathbf{d4 \times d8})\ (+\ d6 \times d8 + d8^2) + \ldots$

1	Λ^{-2}	Λ^{-4}	Λ^{-4}	Λ^{-6}	Λ^{-8}

LO: g_{d4}
NLO: $g_{d4}{}^3$
NNLO: $g_{d4}{}^5$
…

If Λ < X TeV, **dim-8** should not be neglected w.r.t. **dim-6**.

Delicate choices

[Passarino http://cern.ch/go/nT7n]

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
  $= d4^2 + \mathbf{d4 \times d6}\ (+\ d6^2 + d4 \times d8)\ (+\ d6 \times d8 + d8^2) + \ldots$

$1 \quad \Lambda^{-2} \quad \Lambda^{-4} \quad \Lambda^{-4} \quad \Lambda^{-6} \quad \Lambda^{-8}$

LO: g_{d4}
NLO: g_{d4}^{3}
NNLO: g_{d4}^{5}
…

If Λ > N TeV, **SM NNLO** should not be neglected w.r.t. **dim-6**.

Delicate choices

[http://cern.ch/go/Ks9T]

- $|\text{dim-4} + \text{dim-6} + \text{dim-8} + \ldots|^2 =$
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$1 \quad \Lambda^{-2} \quad \Lambda^{-4} \quad \Lambda^{-4} \quad \Lambda^{-6} \quad \Lambda^{-8}$

LO: g_{d4}
NLO: g_{d4}^3
NNLO: g_{d4}^5
…

VH, VBF, Hjj can probe very large Q^2, where d4 ~ 0.
Work in progress.
Many ideas.

Towards a conventional basis

[LHCHXSWG-INT-2015-001] [Falkowski http://cern.ch/go/Ks9T]

- Effort in the LHC HXSWG WG2 to **standardize the dim-6 operator language.**
  - Incorporate constraints from **LEP precision data.**
  - Link to **aTGC/aQGC** LHC EWWG.
  - **Basically, any data fit using dim-6 EFT can be “rotated in”.**
- Design choice: align tree-level dim-6 effect with straightforward H(125) experimental observables.
  - **Beyond tree-level, not that simple.**

NLO EFT meets kappas

[Passarino http://cern.ch/go/nT7n]

$\mathbf{H \rightarrow \gamma\gamma}$ *Ad usum Delphini* (does not mean former member of Delphi)

is PTG

$$\Delta\kappa^{\gamma\gamma} = -\frac{1}{2\,s_\theta^2}\left(a_{\phi D} - 4\,s_\theta^2\,a_{\phi\Box}\right)$$

$$\Delta\kappa_{\mathrm{W}}^{\gamma\gamma} = \Delta\kappa \quad \Delta\kappa_{\mathrm{t}}^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{\mathrm{t}\phi} \quad \Delta\kappa_{\mathrm{b}}^{\gamma\gamma} = \Delta\kappa^{\gamma\gamma} + a_{\mathrm{b}\phi}$$

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$$\mathscr{A}\,(\mathrm{H}\to\gamma\gamma) = \kappa^{\gamma\gamma}\,\mathscr{A}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{b}}^{(4)} + 2\,i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AA}}$$

NLO EFT meets kappas

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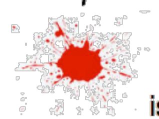
$\mathbf{H} \to \boldsymbol{\gamma\gamma}$ *Ad usum Delphini* (does not mean former member of Delphi)



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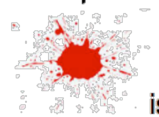

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$$\mathscr{A}\,(\mathrm{H}\to\gamma\gamma) = \boxed{\kappa^{\gamma\gamma}\,\mathscr{A}^{(4)} + \kappa_{\mathrm{t}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{t}}^{(4)} + \kappa_{\mathrm{b}}^{\gamma\gamma}\,\mathscr{A}_{\mathrm{b}}^{(4)}}\ \boxed{+2\,i\,g g_6\,\frac{M_{\mathrm{H}}^2}{M_{\mathrm{W}}}\,a_{\mathrm{AA}}}$$

LHC season 2 premieres next week

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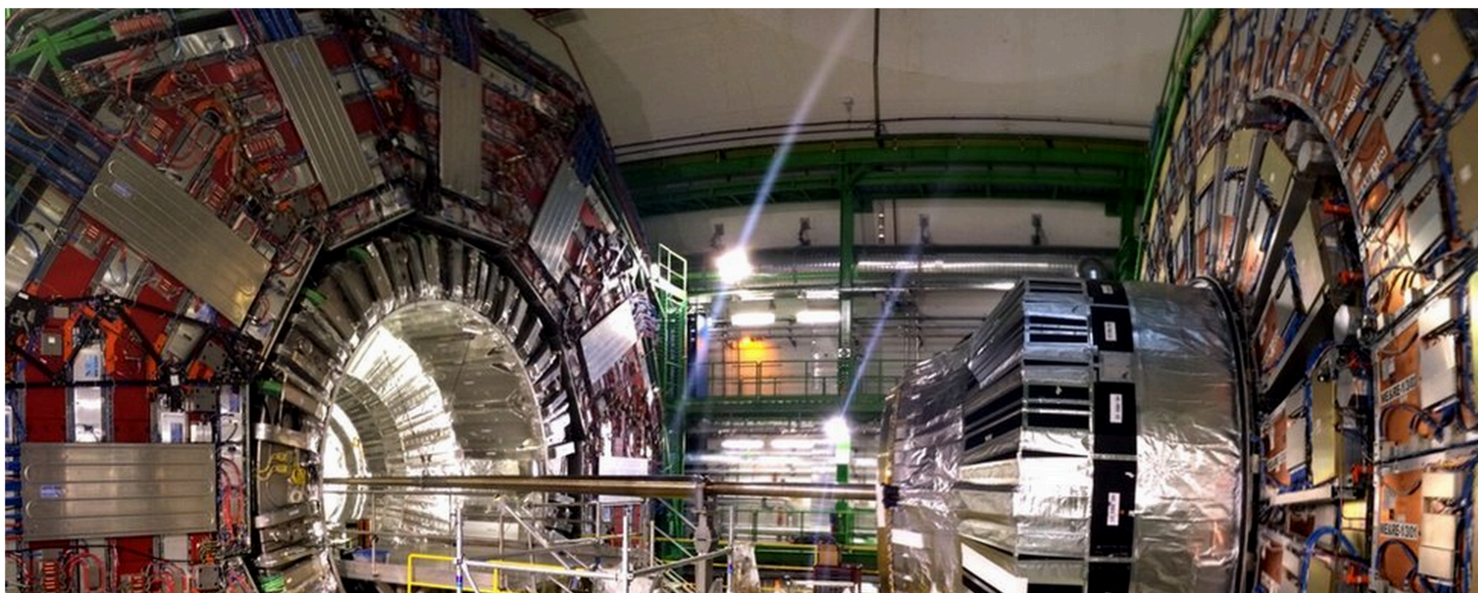
LHC restart: 'We want to break physics'

By Jonathan Webb
Science reporter, BBC News



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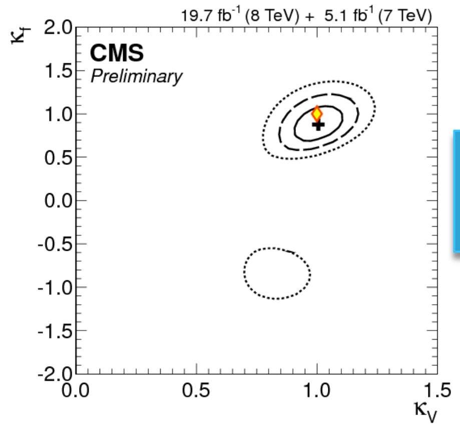
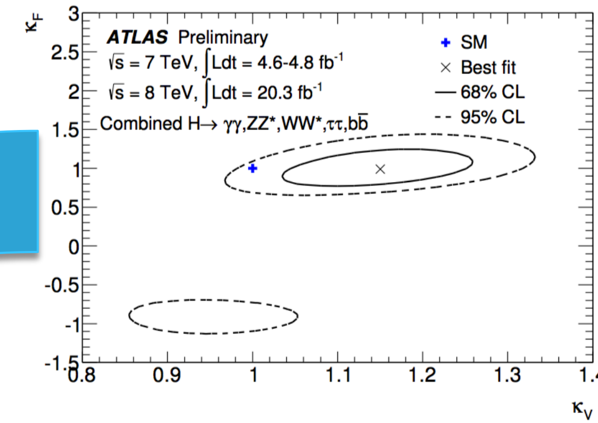
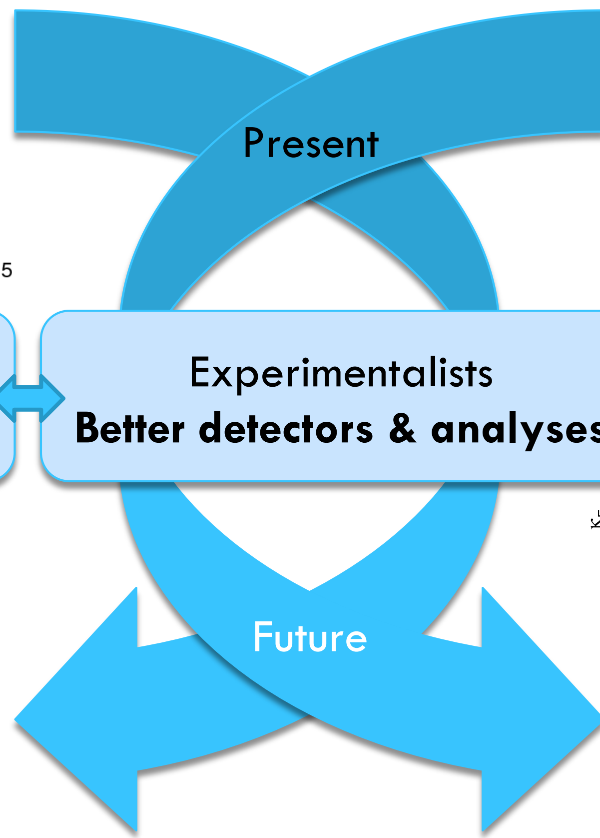
‘We want to find the Next SM’

The future is in precision and accuracy



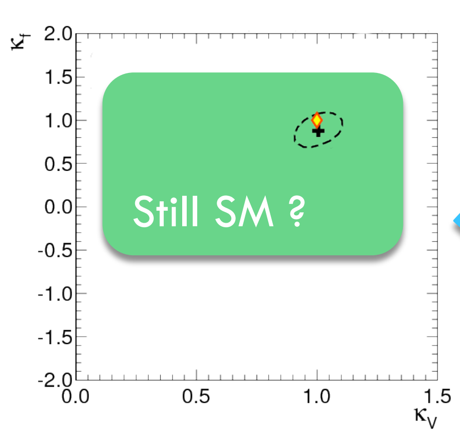


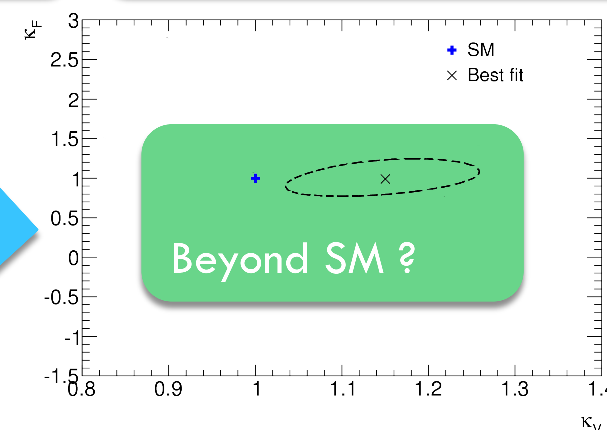


Accelerator physicists
More collisions

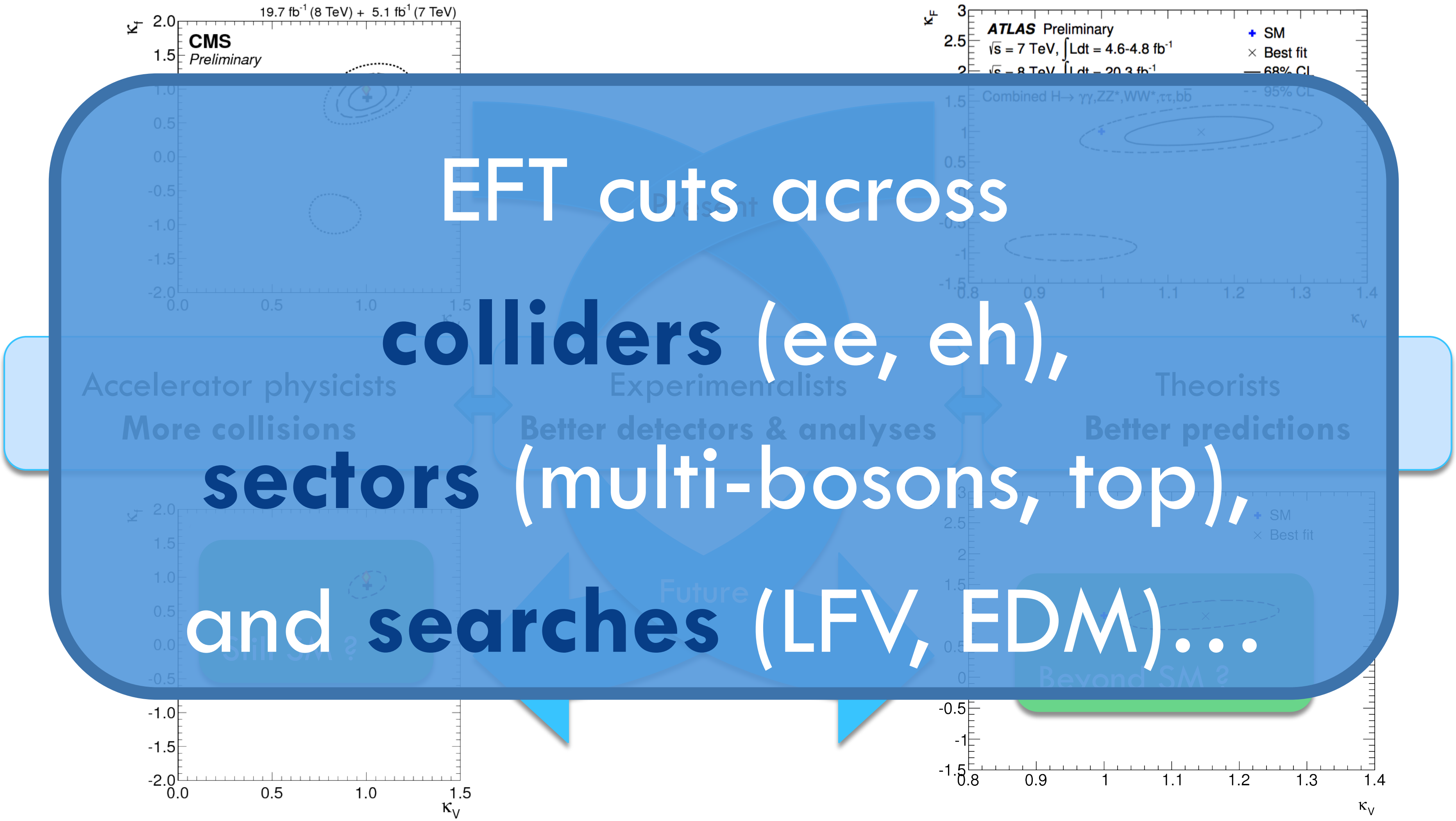
Experimentalists
Better detectors & analyses

Theorists
Better predictions





The future is in precision and accuracy



EFT cuts across

colliders (ee, eh),

sectors (multi-bosons, top),

and **searches** (LFV, EDM)…

Looking for the middle way

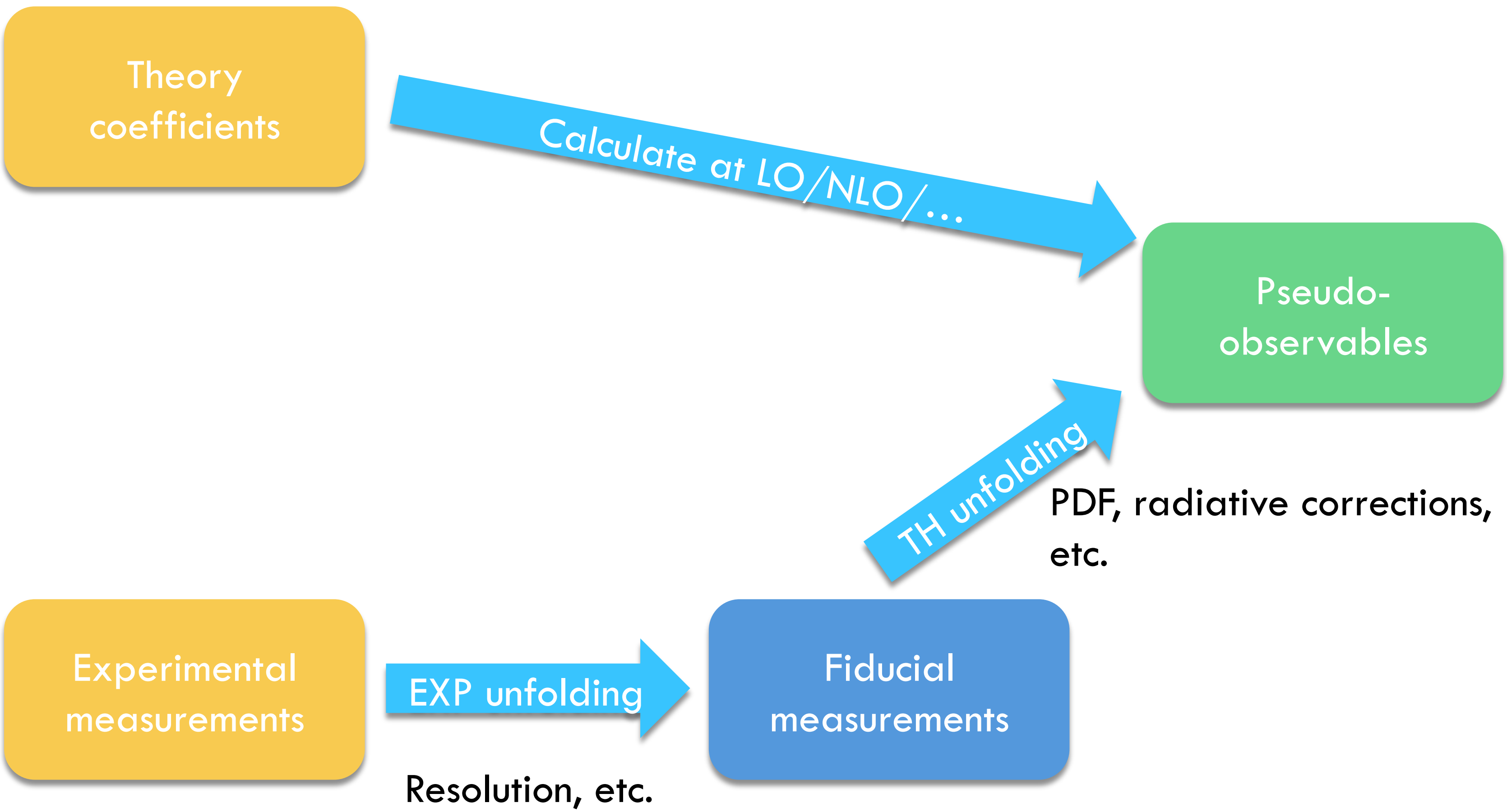
[http://cern.ch/go/6xk9]

"The eleventh most dangerous occupation in America is that of the rivet tosser. ***Insurance companies will not issue life or accident insurance cover to these people.*** *(Photo by Evans/Three Lions/Getty Images). Circa 1950"*

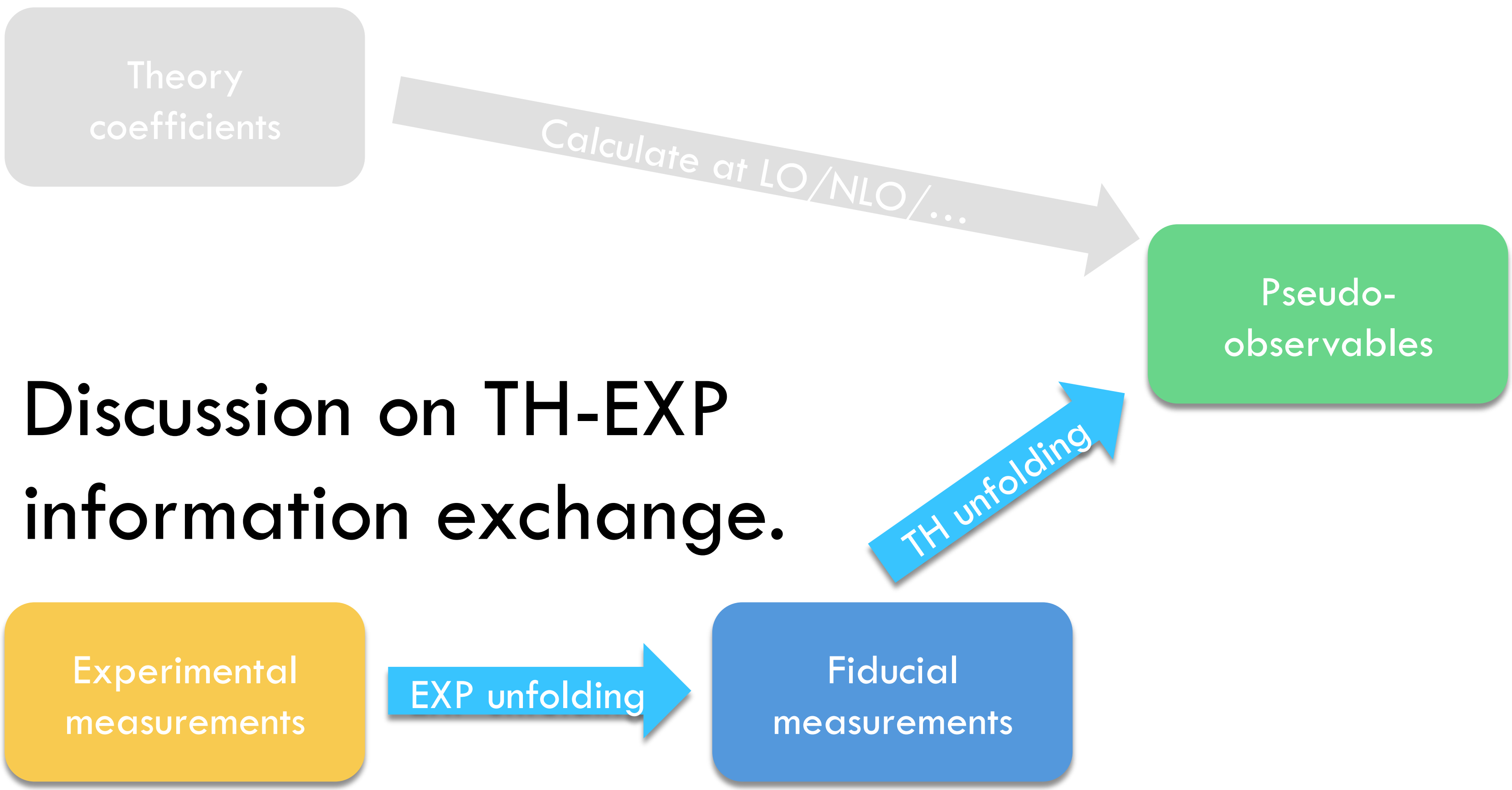
The need for the middle way

- **EFT** is all-encompassing, calculable, and evolving.
  - **But** too costly to redo all analyses if/when higher order calculations become available.
- **Fiducial cross-section** could be produced differentially for many quantities.
  - **But** no physical interpretation of every single bin by itself.
- **The middle way: pseudo-observables (PO).**
  - LEP-inspired scheme where theory and experiment intersect at clearly-defined points.

With some LEP inspiration

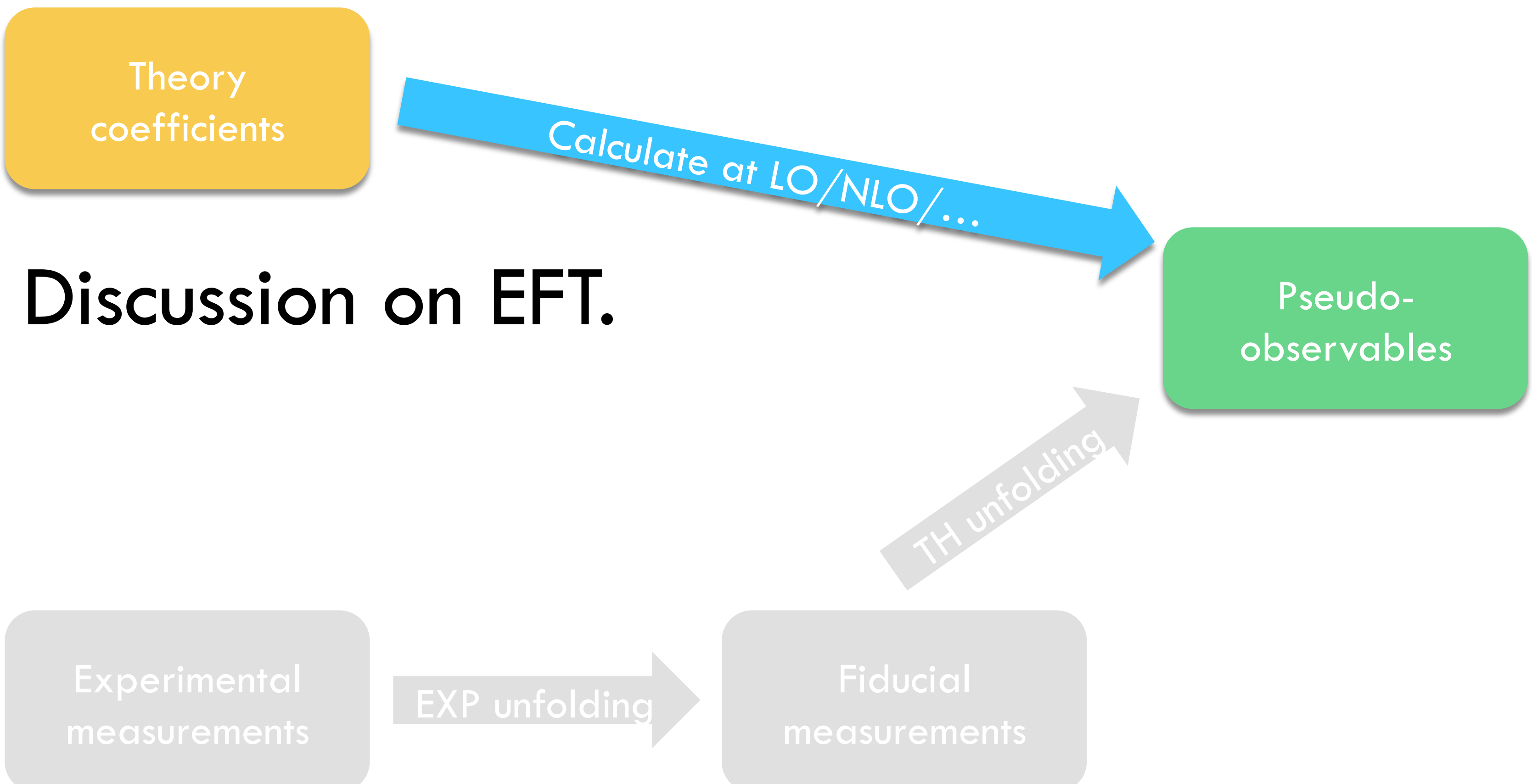


With some LEP inspiration



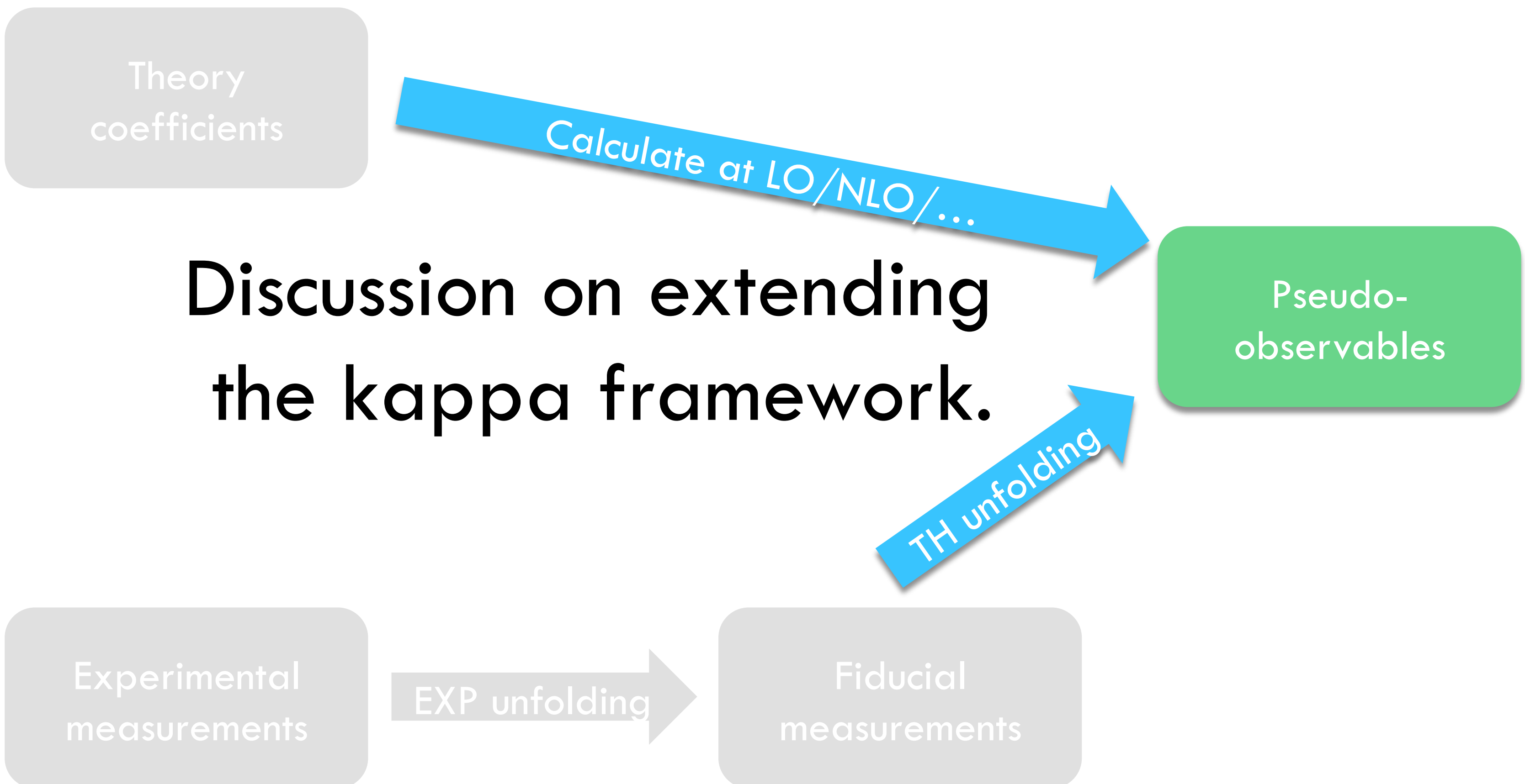
Discussion on TH-EXP information exchange.

With some LEP inspiration



Discussion on EFT.

With some LEP inspiration



Discussion on extending the kappa framework.

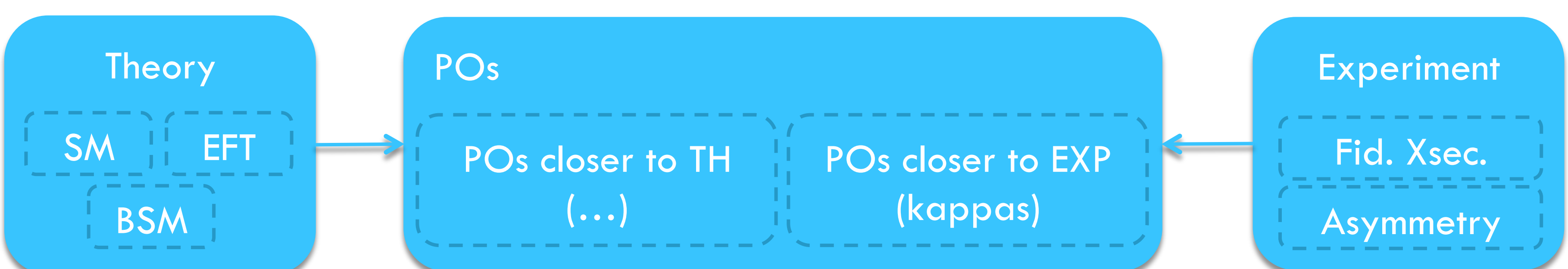
From kappas that fit little stuff…

...to kappas that fit more stuff.

Kappas might have been our first POs

- Kappas **must be extended** to:
  - Differential quantities.
  - Remove some assumptions.
  - Cover smooth deviations from the SM.

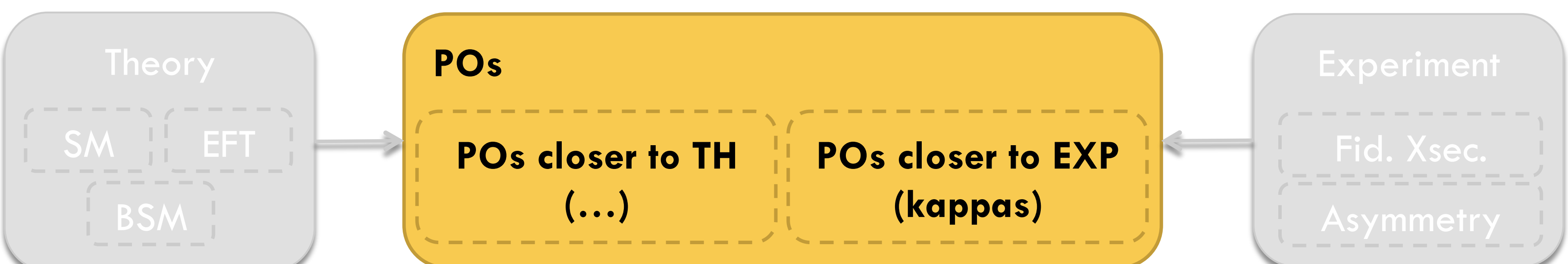
- With better/more POs, kappas may remain as part of the PO framework:



Inspiration for building PO

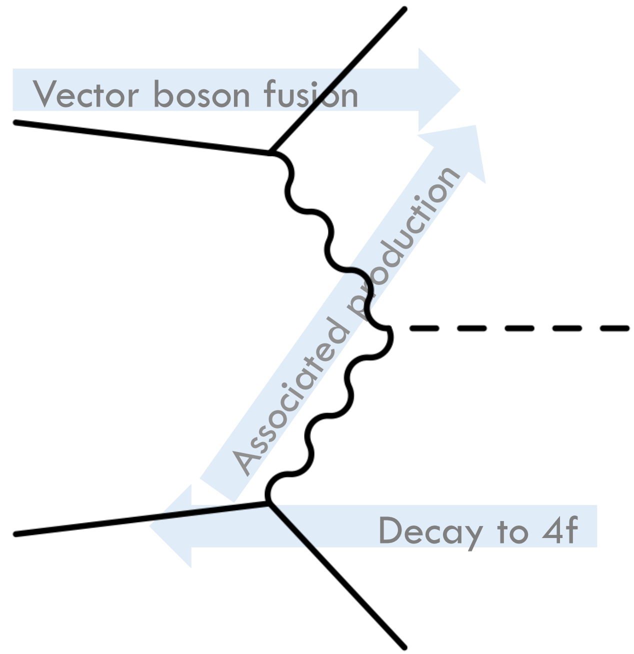
- If we assume that:
  Next SM ~ |dim-4 + dim-6 + dim-8 + … |²

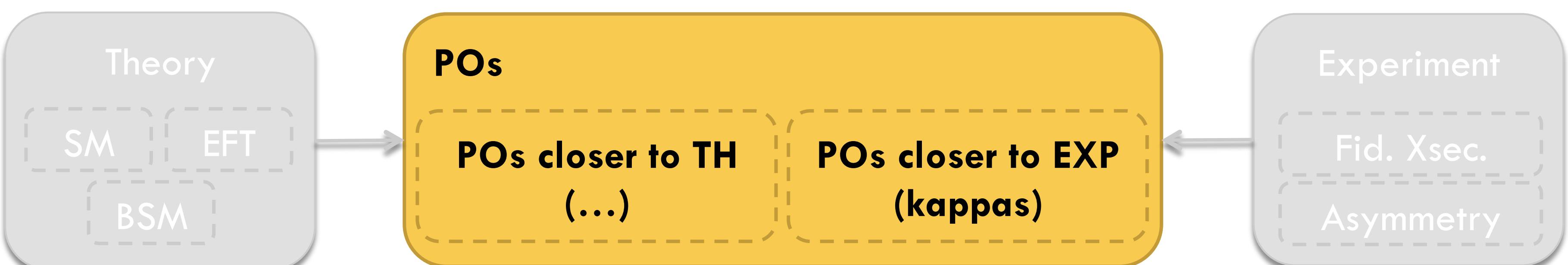
- Then POs can be motivated to parametrize:
  $\delta(\mathrm{PO}_i) \sim (\mathrm{Data} - \mathrm{d4}^2) = \mathrm{d4}\times\mathrm{d6} + \mathrm{d6}^2 + \mathrm{d4}\times\mathrm{d8} + \ldots$



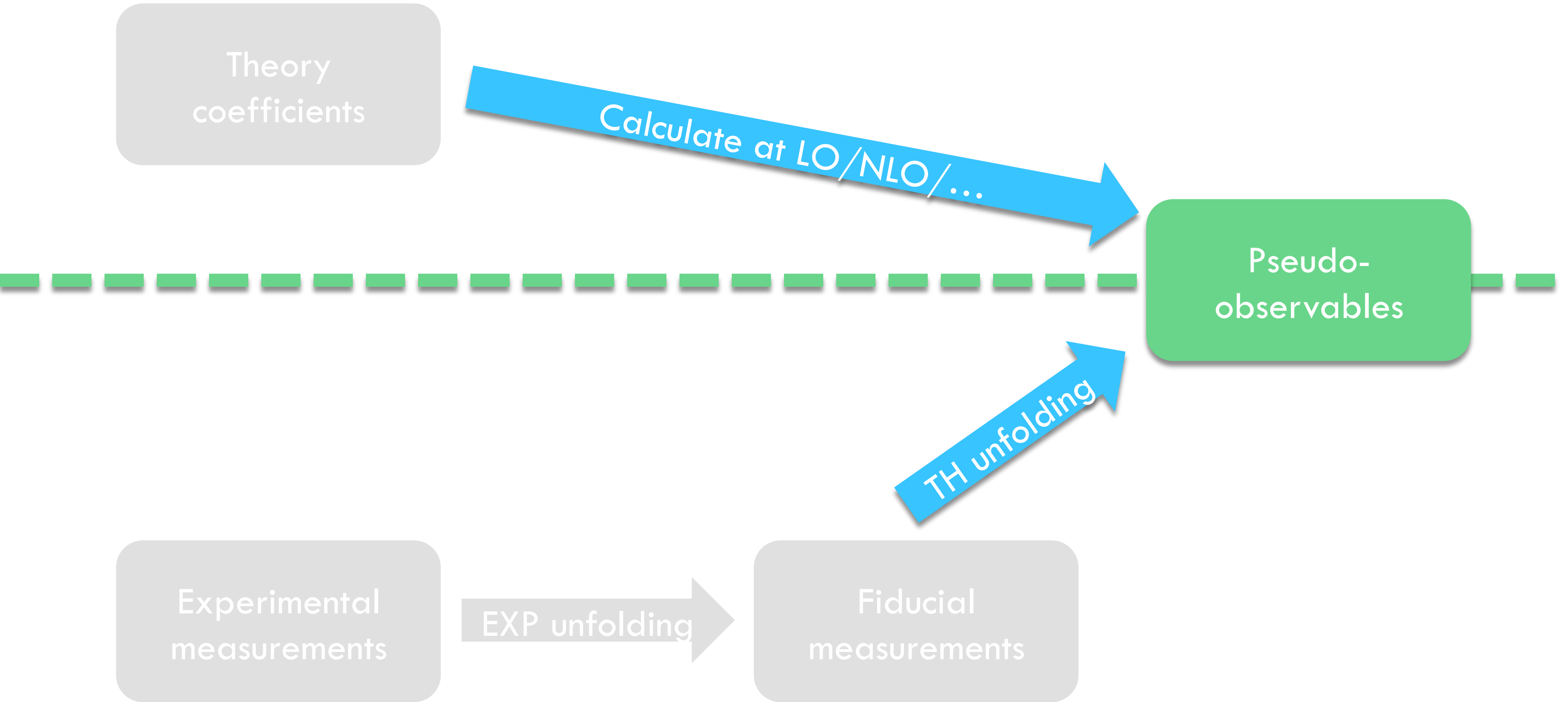
Inspiration for building PO

- Many practical issues to be solved.
- Many conceptual issues to be tackled.
- Many discussions to be held.





The middle way in action



The middle way in action

Theorists refine calculations and interpret against PO.

Theory coefficients

Calculate at LO/NLO/…

Pseudo-observables

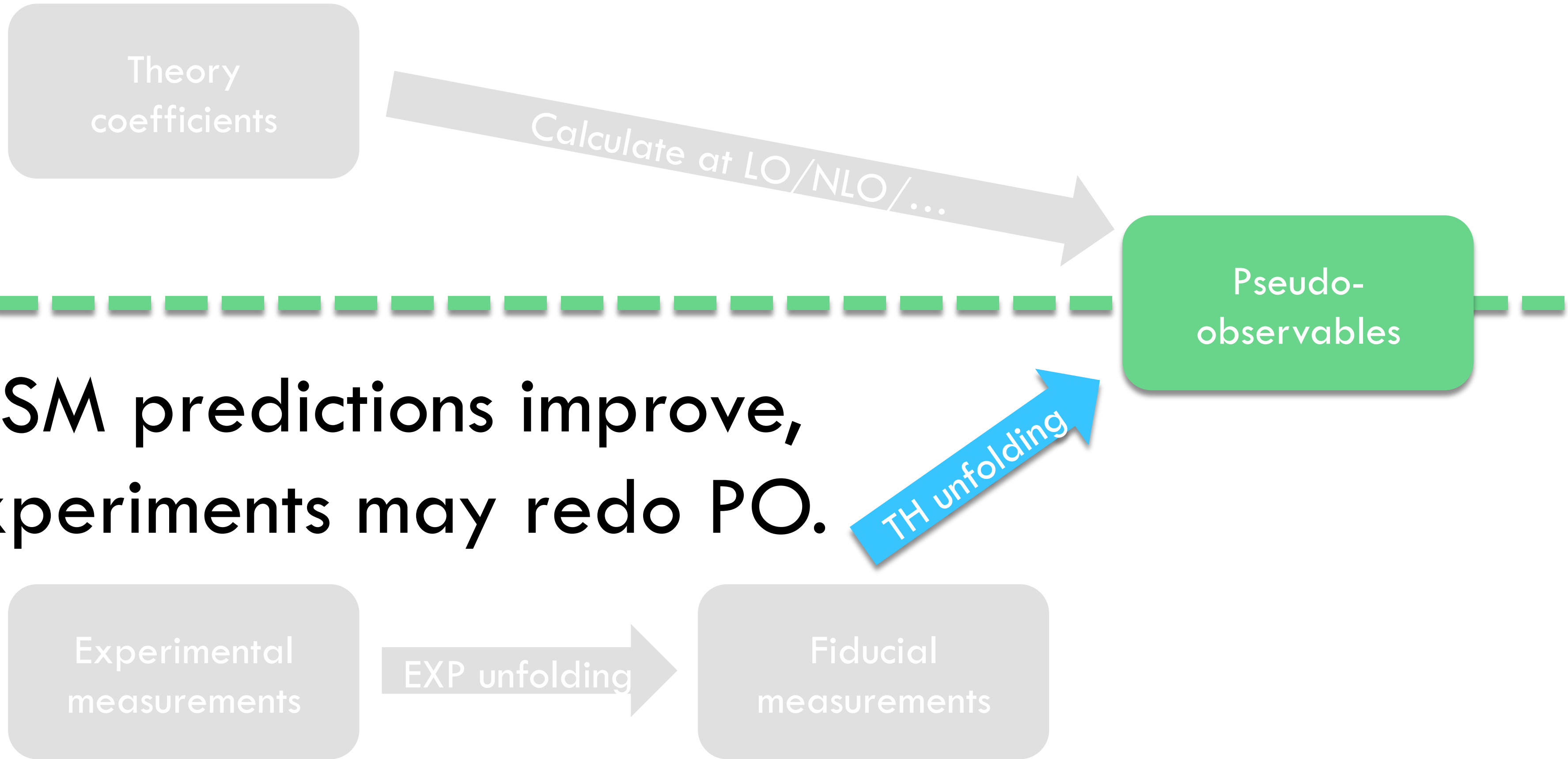
TH unfolding

Experimental measurements

EXP unfolding

Fiducial measurements

The middle way in action

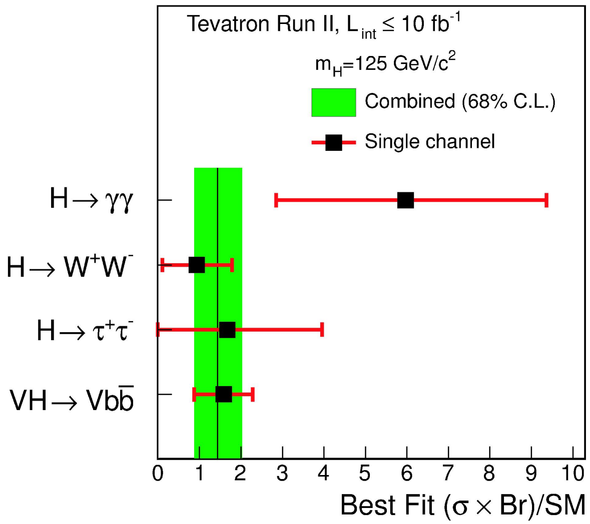


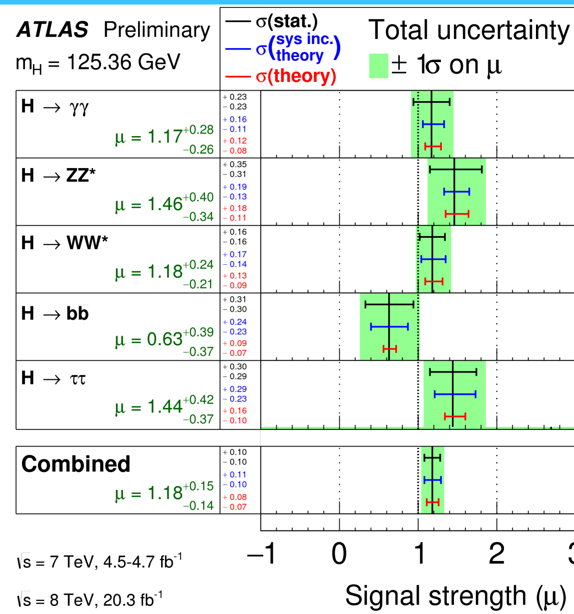
If SM predictions improve, experiments may redo PO.

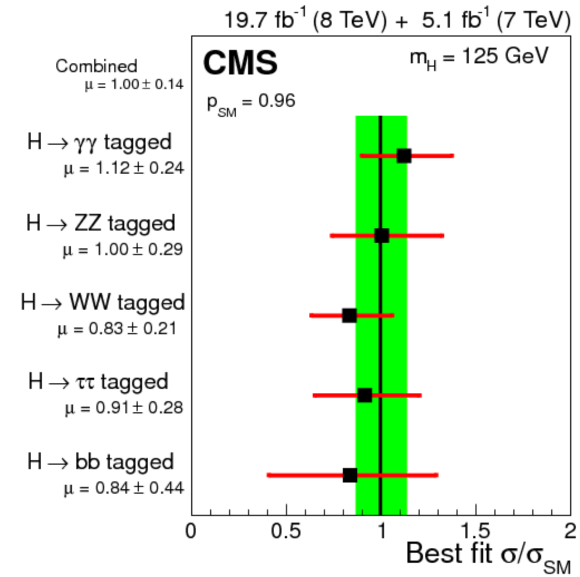
Of signal strengths

Relative signal strengths

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







What's in a “signal strength”?

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

- Deviations are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Production

Decay

- Deviations are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

- **Deviations** are searched relative to SM expectation.
- *Conclusions are only as good*
  as the accuracy and precision
  of the numerator and denominator.

Anatomy of deviations

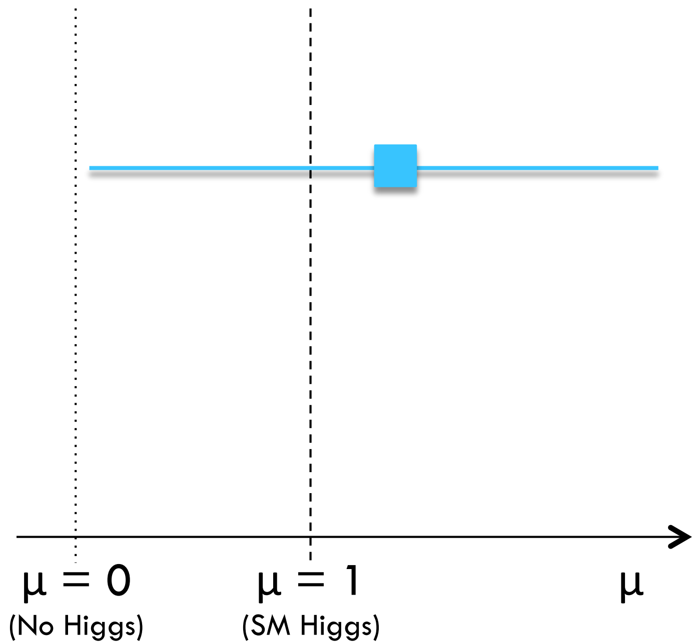
$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

Standard Model

- **Deviations** are searched **relative to SM expectation.**
- *Conclusions are only as good as the* ***accuracy and precision*** *of the* ***numerator and denominator.***

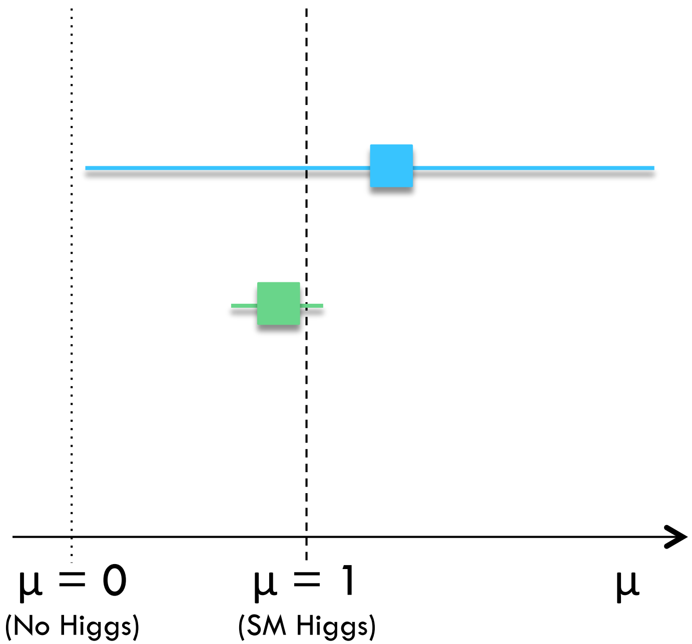
The anatomy of deviations



Imprecise measurement compatible with 0 and 1.
Inconclusive, "more data needed".

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - **$\mu = 1.3 \pm 1.2$ is inconclusive and "more data is needed"**, but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations

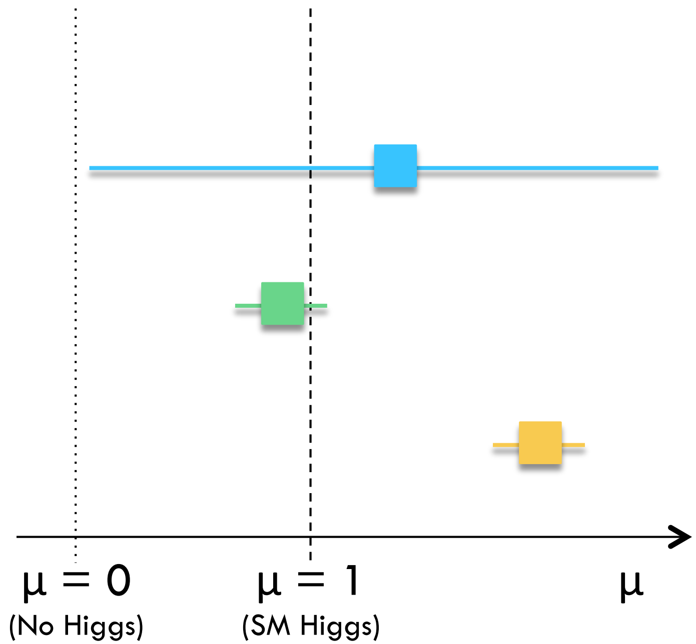


Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

- **μ = 1 means that the data match the SM.**
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 1.3 \pm 1.2$ usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data needed”.

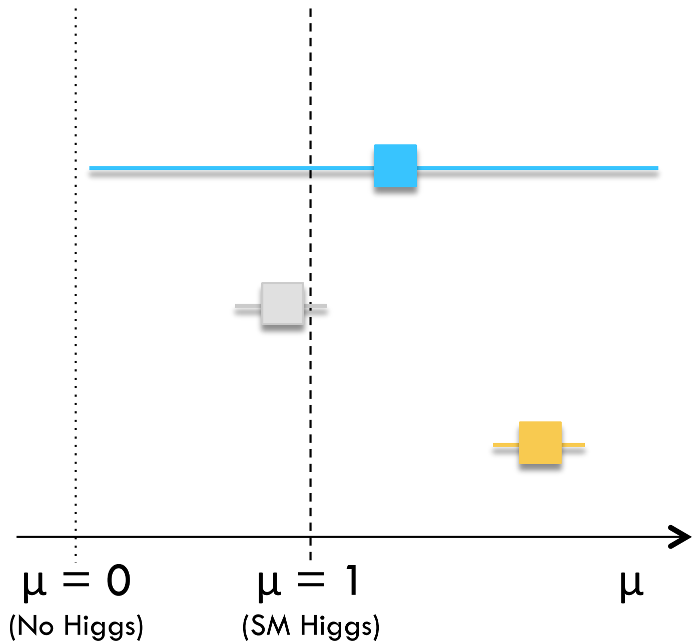
Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation.

“New Physics ⇒ Deviation” but “Deviation ⇏ New Physics”
See, e.g., http://cern.ch/go/W8wW

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means “more data needed”, but
    - **$\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, "more data **or better theory** needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation **or exp./theory bias.**

"New Physics $\Rightarrow$ Deviation" but "Deviation $\nRightarrow$ New Physics"
See, e.g., http://cern.ch/go/W8wW

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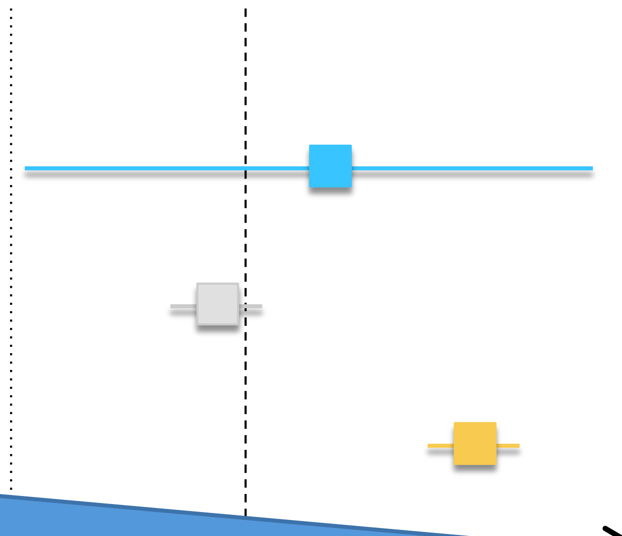
The anatomy of deviations



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"New Physics $\Rightarrow$ Deviation" but "Deviation $\nRightarrow$ New Physics"
See, e.g., http://cern.ch/go/W8wW

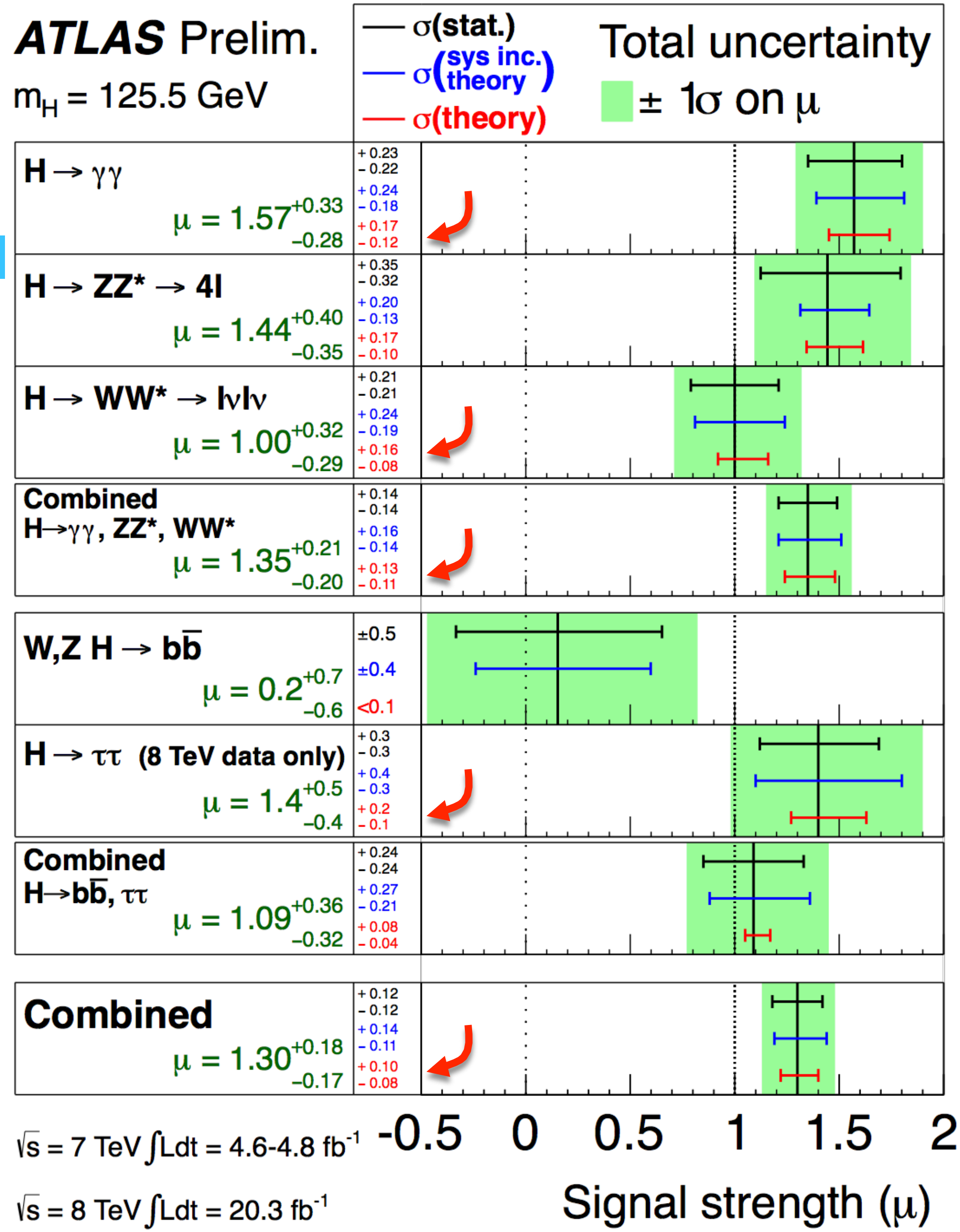
Theory contributes as much to the conclusions as experiments !

- μ = 2.0 ±0.2 could mean

Theory uncertainties

[ATLAS-CONF-2014-009]

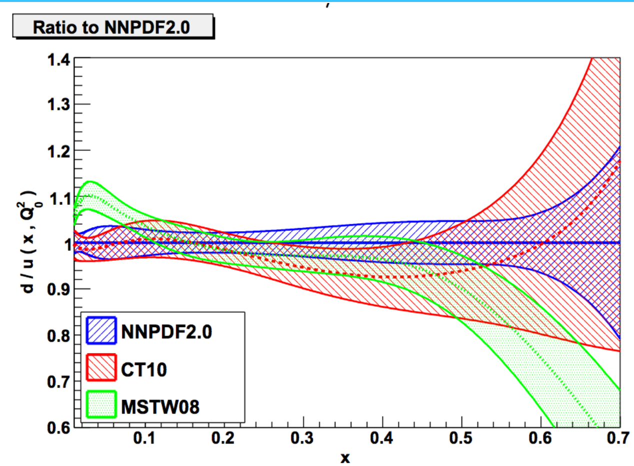
- PDFs not dominating on μ .
  - ggH vs VBF+VH.
  - PDF4LHC prescription too conservative?
    - **Changing soon!**
  - PDG $\sigma(\alpha_s)$ too aggressive?
- NNLO+NNLL not enough to tame large QCD corrections in gluon-fusion?

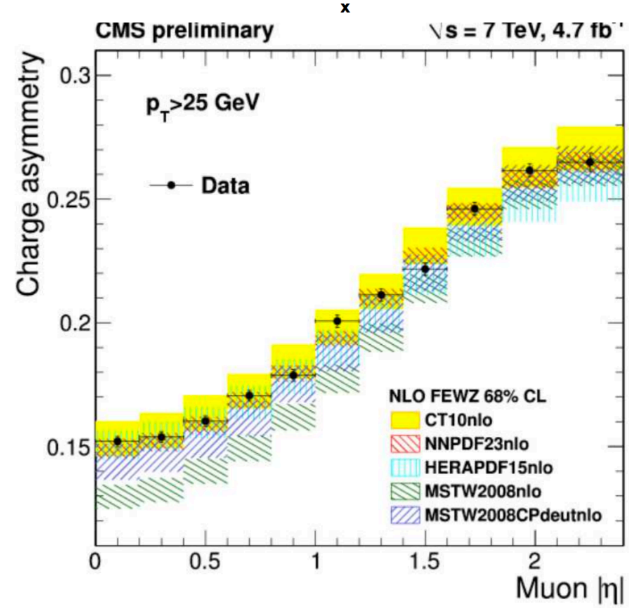


Theory uncertainties: a tale of PDFs

[http://cern.ch/go/V8xJ]

- Long-standing difference in d/u ratio between MSTW and others.
- Neatly resolved by CMS W asymmetry measurements.
- MSWT made parameterization more flexible: case closed.





Theory uncertainties

- Bottom-line for Run2:
  - Consider measurements that constrain PDF fits.
  - For higher orders, more than precision, also a matter of accuracy.
    - Need to work with theorists to get these right, also differentially.

- Or you can try to dodge them with p_T ratios…
  - …but end up needing a lot of data.

Theory uncertainties: MHOU

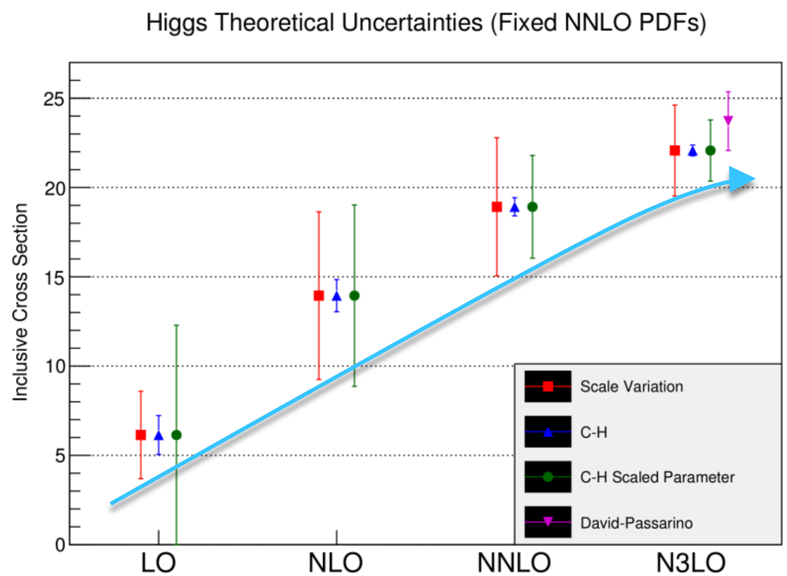
[arXiv:1307.1843][http://cern.ch/go/V8xJ]

- Scale variations are not theory uncertainties.
- **The uncertainty is due to missing higher orders (MHO).**

$$\frac{\sigma_{gg}(\sqrt{s}, M_H)}{\sigma_{gg}^{LO}(\sqrt{s}, M_H)} = 1 + \sum_{n=1}^{\infty} \alpha_s^n(\mu_R)\, K_{gg}^n(\sqrt{s}, \mu = M_H)$$

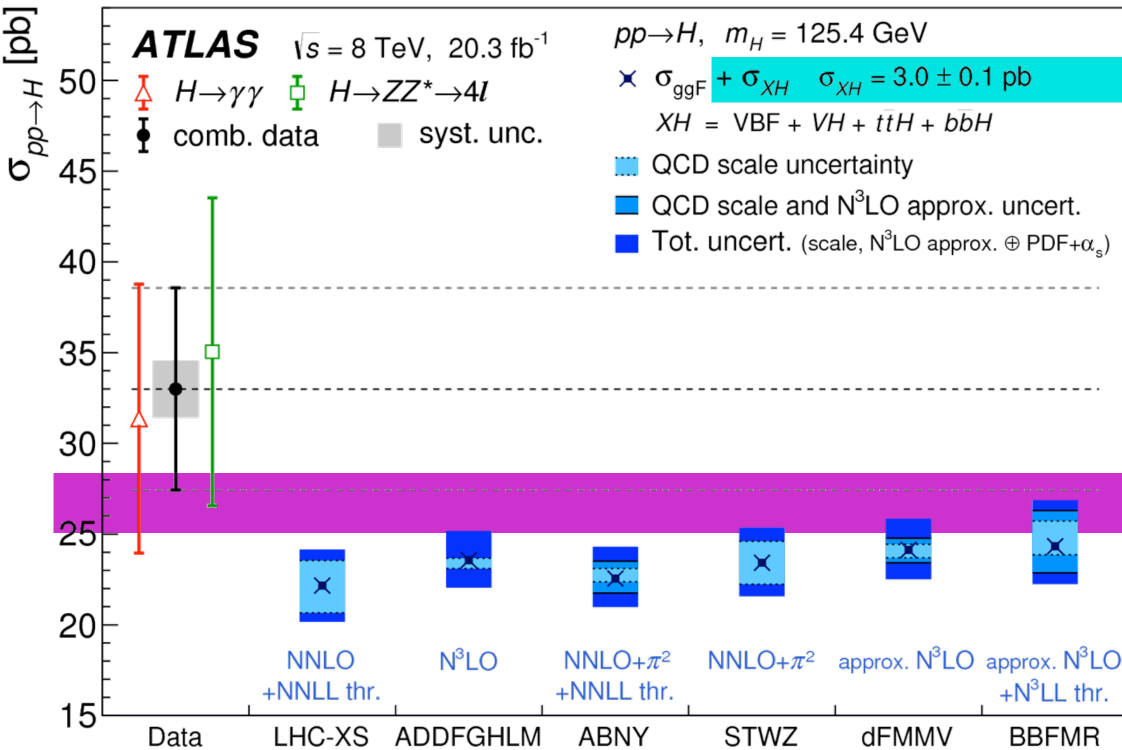
8 TeV	$\mu = M_H/2$	$\mu = M_H$	$\mu = 2M_H$
K_{gg}^1		11.879	
K_{gg}^2		72.254	
K_{gg}^3	168.98 ± 30.87	377.20 ± 30.78	681.72 ± 29.93

- Take gluon-gluon fusion:
  - All series terms are positive.
  - We can try and complete the series instead of **always** being off.



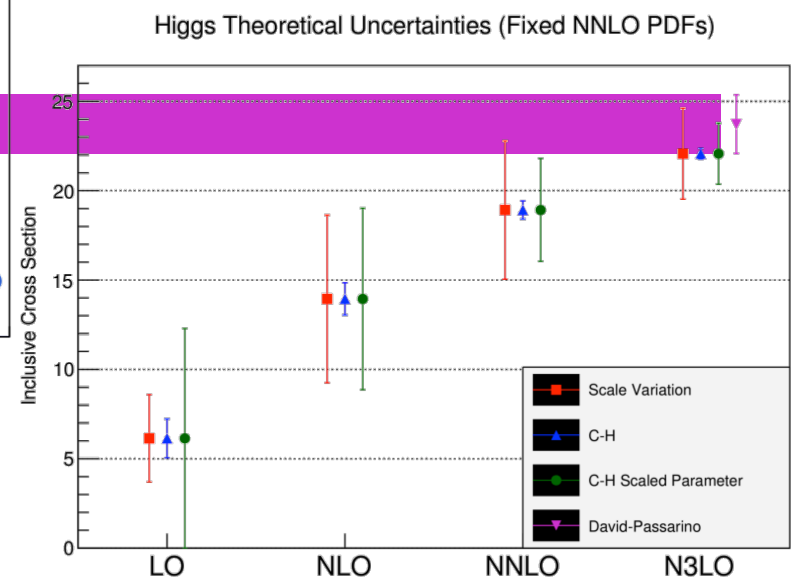
Up, up, and away!

[arXiv:1504.05833]



Name	$\sigma_{gg\to H}$ [pb]
Data$-XH$[a]	30.0 ±5.3 (stat) ±1.6 (sys)
LHC-XS	19.15 $^{+1.38}_{-1.49}$ (scale) $^{+1.44}_{-1.32}$ (pdf)
ADDFGHLM	20.55 $^{+0.04}_{-0.45}$ (scale) $^{+1.60}_{-1.44}$ (pdf)
ABNY	19.54 $^{+0.55}_{-0.14}$ (scale) $^{+1.47}_{-1.35}$ (pdf) ±0.78 (appr.)
STWZ	20.41 ±1.18 (scale) $^{+1.53}_{-1.41}$ (pdf)
dFMMV	21.12 $^{+0.29}_{-0.42}$ (scale) $^{+1.58}_{-1.46}$ (pdf) ±0.56 (appr.)
BBFMR	21.32 $^{+1.39}_{-0.45}$ (scale) $^{+1.60}_{-1.47}$ (pdf) ±1.39 (appr.)

[a] Non-ggF cross section $\sigma_{XH} = 3.01^{+0.05}_{-0.06}$ (scale) ±0.09 (pdf) pb, subtracted from the measured inclusive cross section: 33.0 ± 5.3 (stat) ± 1.6 (sys) pb.



CMS H→γγ analysis

The Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$

$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- -$$

$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$

$$g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$

$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$

$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar\nu^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j +$$

$$igs_wA_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 -$$

$$1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$

$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar\nu^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$

$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$

$$m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 -$$

$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) +$$

$$igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ -$$

$$\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

The Standard Model of Particle Physics

[http://cern.ch/go/dW6z]

$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu -$$

$$\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- -$$

$$M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c^2_w}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) -$$

$$A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu +$$

$$g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$

$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- +$$

$$4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] +$$

$$\frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- -$$

$$W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) -$$

$$\frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- +$$

$$W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) -$$

$$g^2\frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s^2_w A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j +$$

$$igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w -$$

$$1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+$$

$$\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) +$$

$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) -$$

$$m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 -$$

$$M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- -$$

$$\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) +$$

$$igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] + \frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$

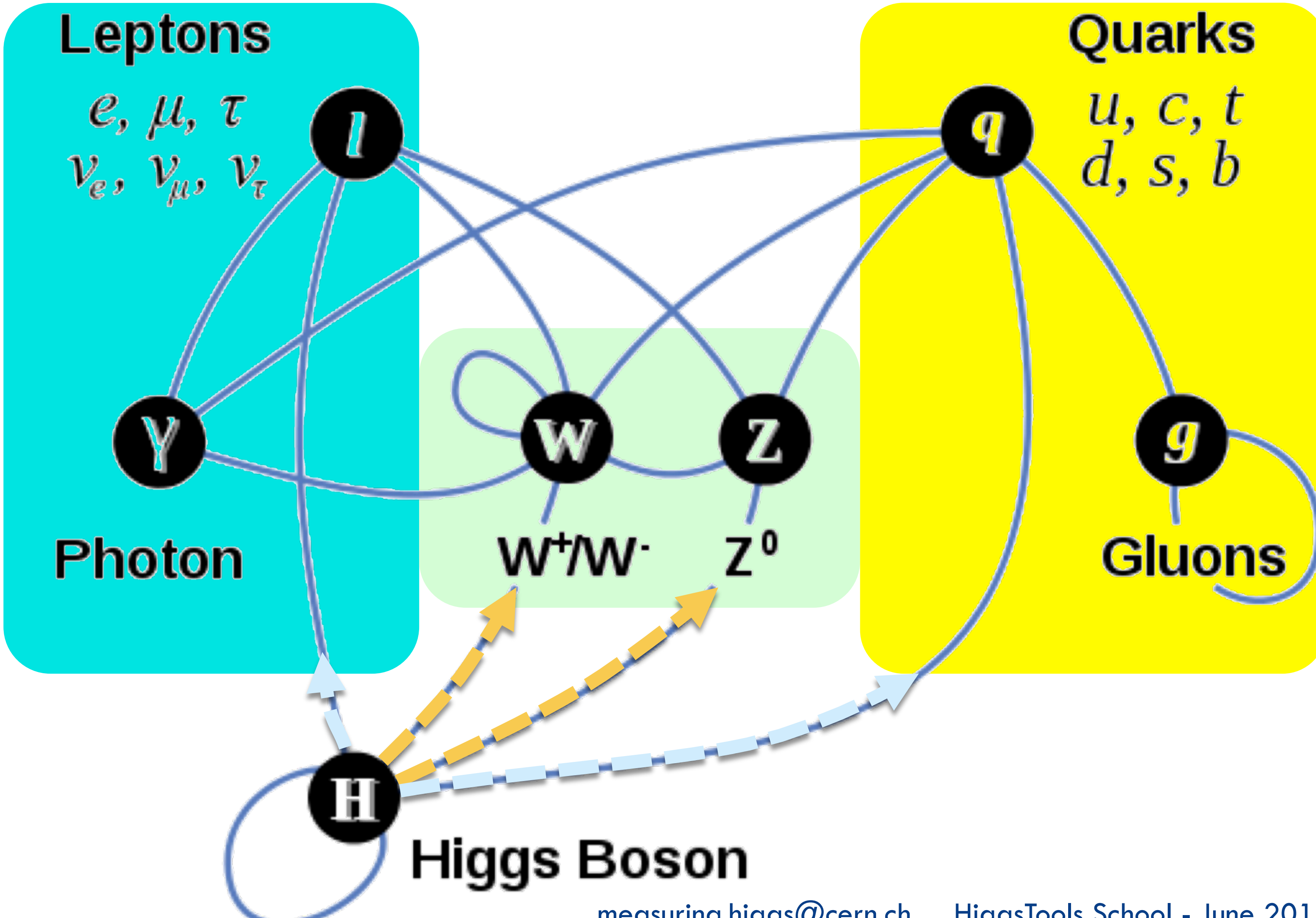
$$\bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

The Standard Model of Particle Physics

Electromagnetic force – light

Weak force – star combustion

Strong force – protons and neutrons



What photons do you see?

[http://cern.ch/go/6pjw]

LIGHT IS A

Particle!

What photons do you see?

[http://cern.ch/go/6pjw]

Photons in High Energy Particle Physics

[Particle Data Group]

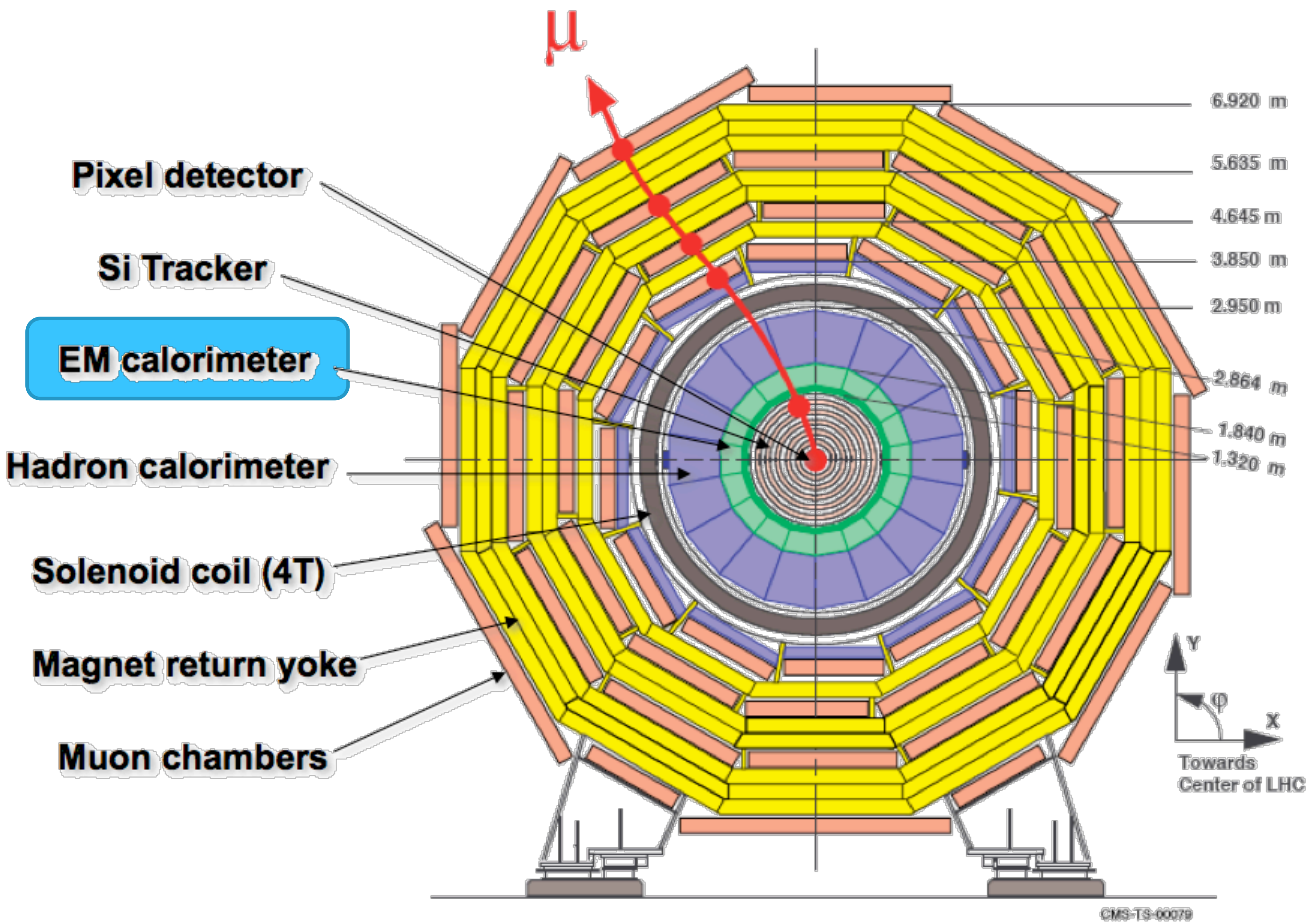
$\boxed{\gamma}$

$$I(J^{PC}) = 0,1(1^{--})$$

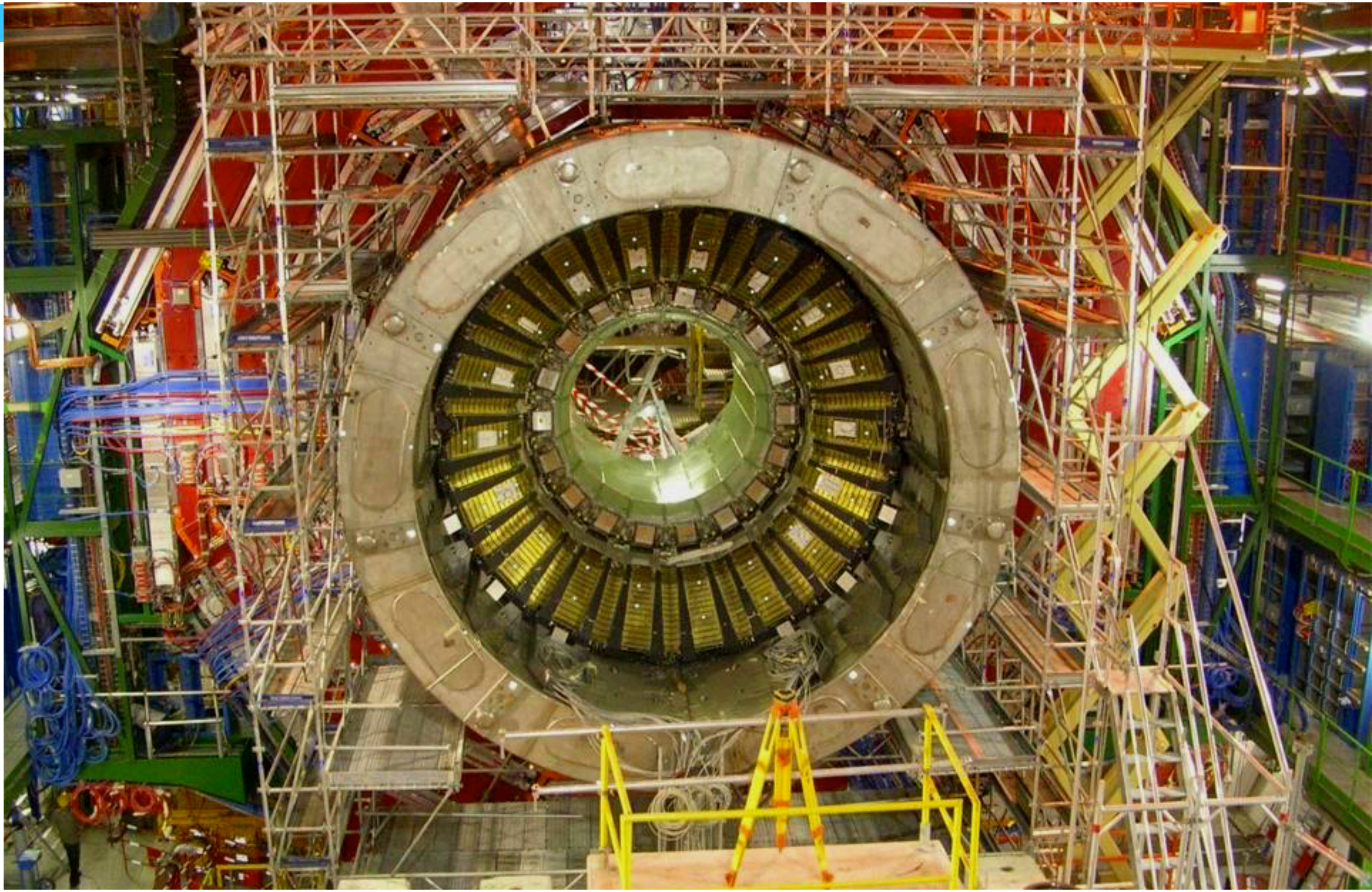
$$\text{Mass } m < 1 \times 10^{-18} \text{ eV}$$
$$\text{Charge } q < 1 \times 10^{-35} \; e$$
$$\text{Mean life } \tau = \text{Stable}$$

- A rather straightforward particle: **massless, neutral** and **stable.**

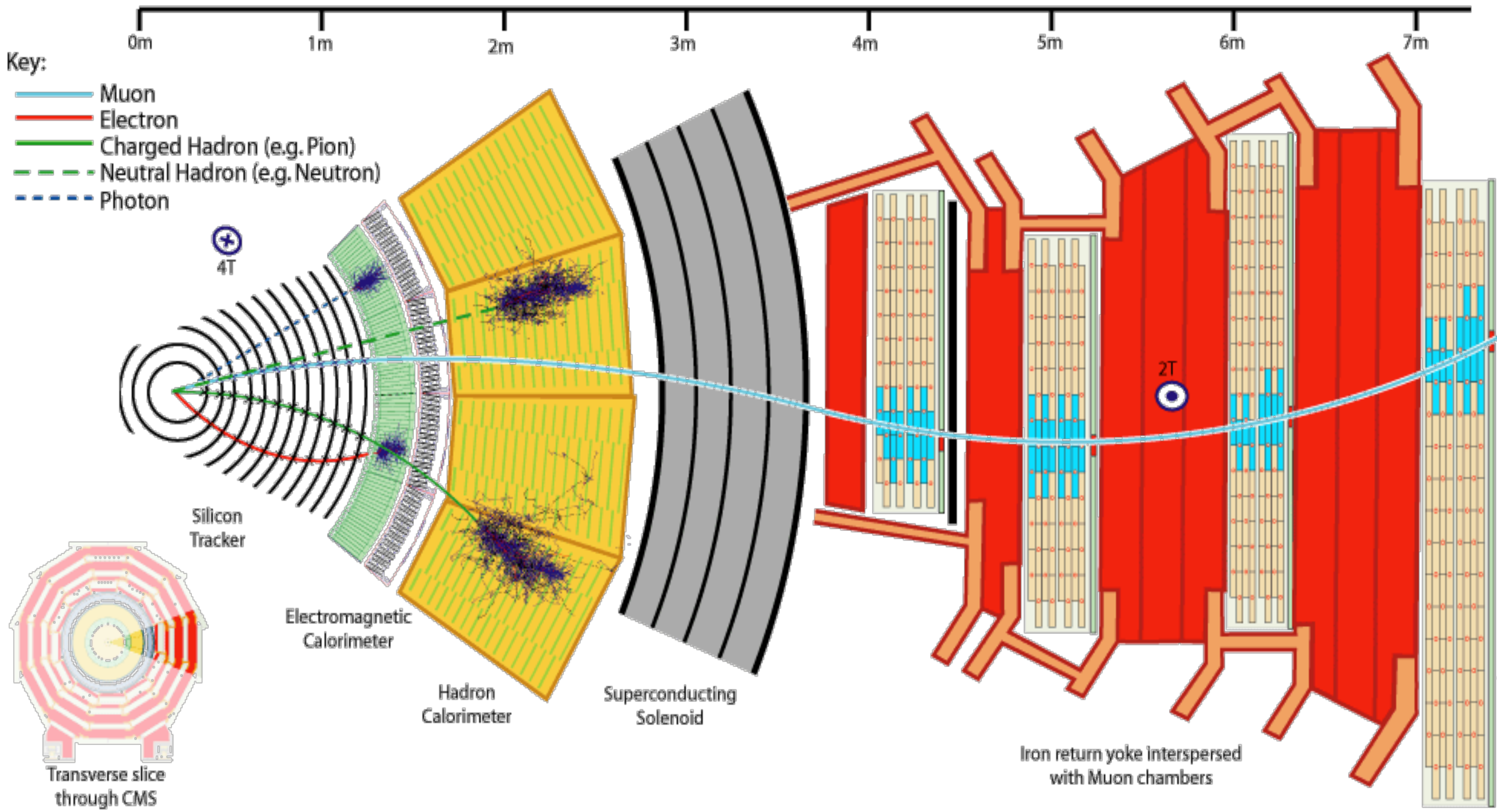
Particle detectors in CMS



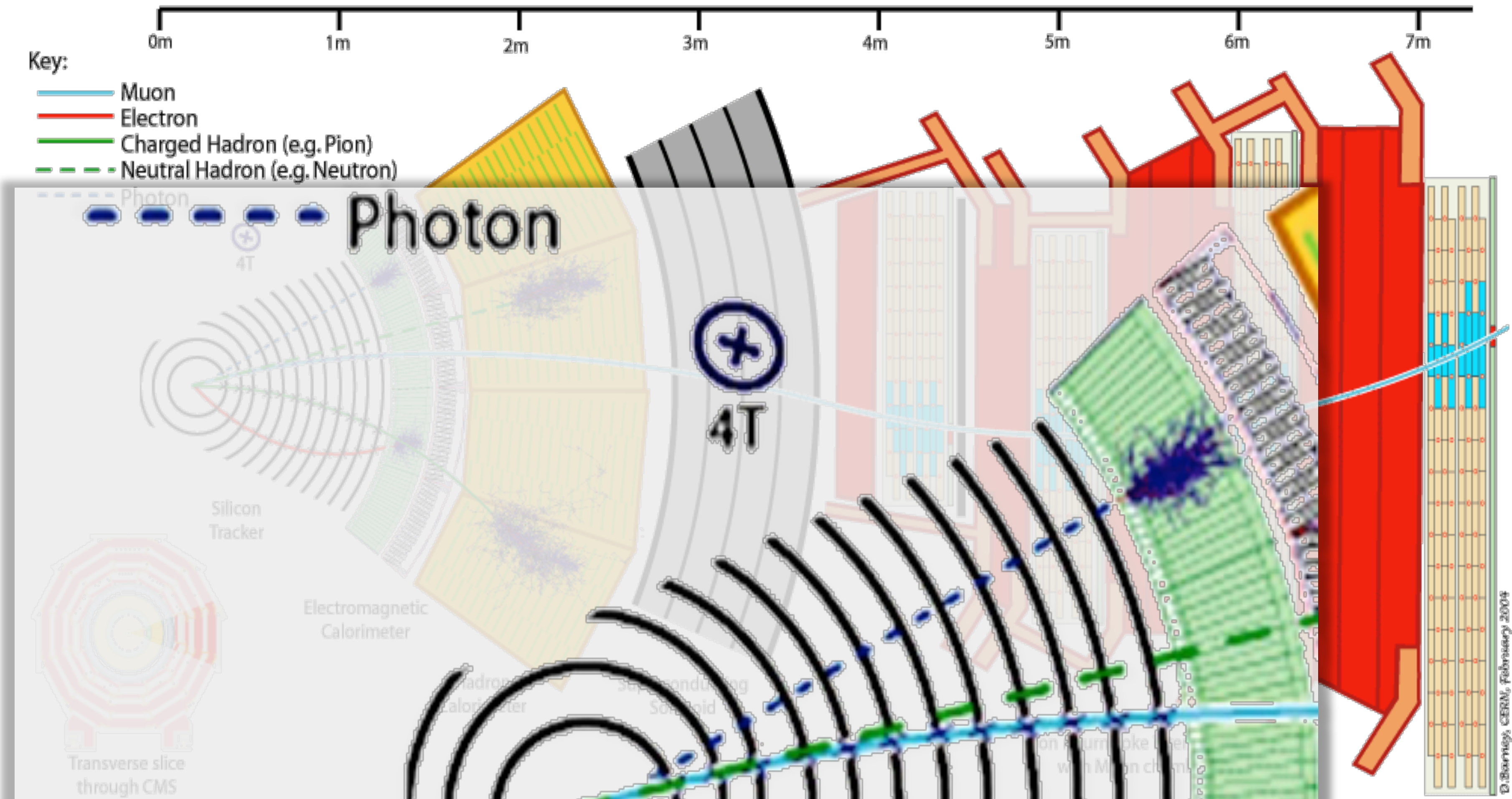
2007: ECAL barrel installed



Detecting particles in CMS



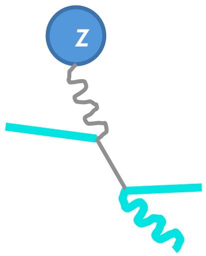
Detecting particles in CMS

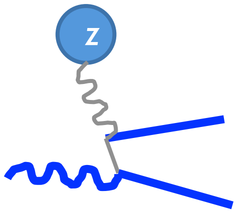


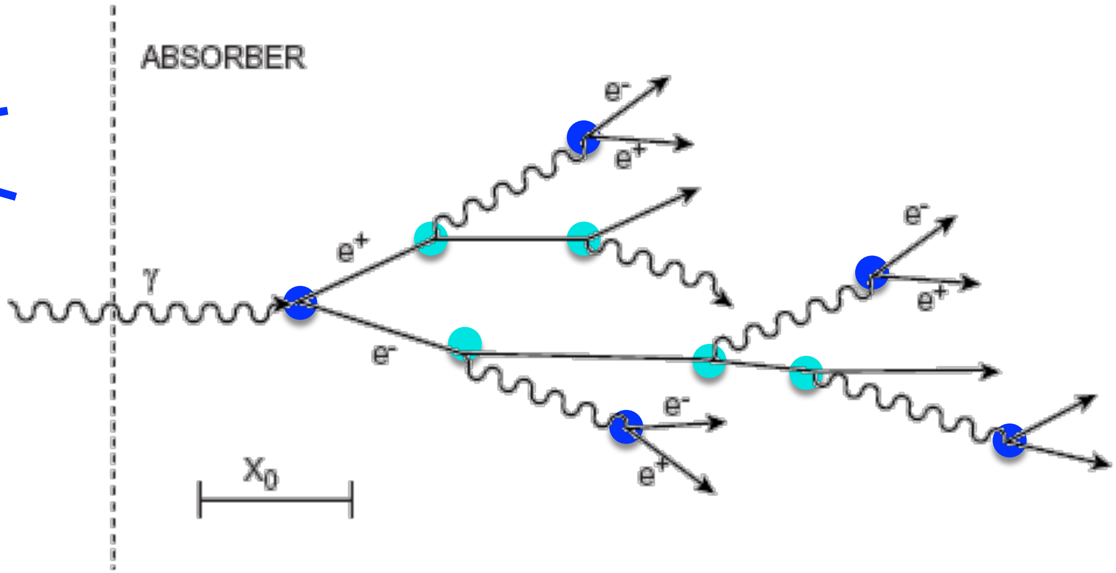
Detecting photons

and electrons and photons and electrons and photons and electrons and photons…

- Electromagnetic showers result from electrons and photons undergoing **bremsstrahlung** and **pair creation** in the presence of nuclei.



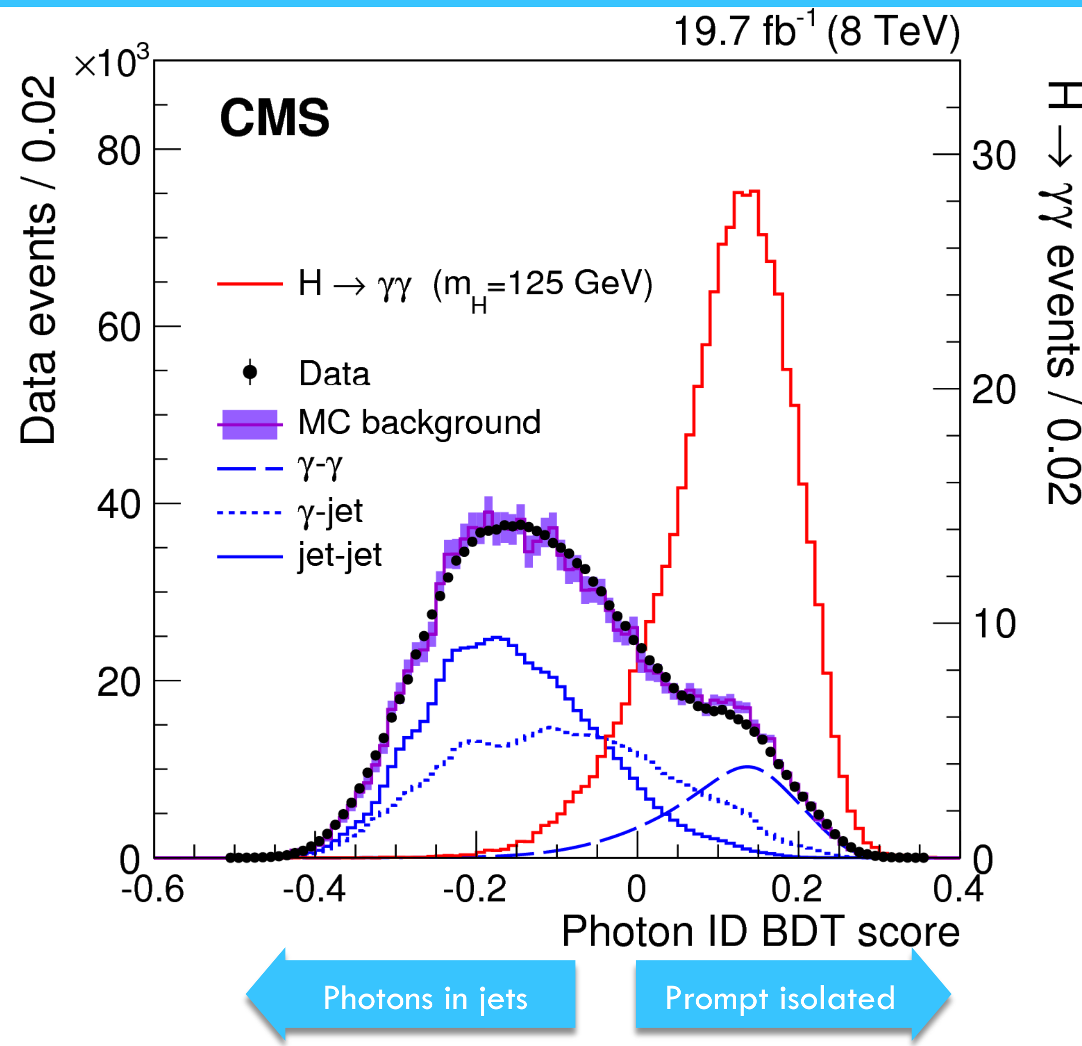




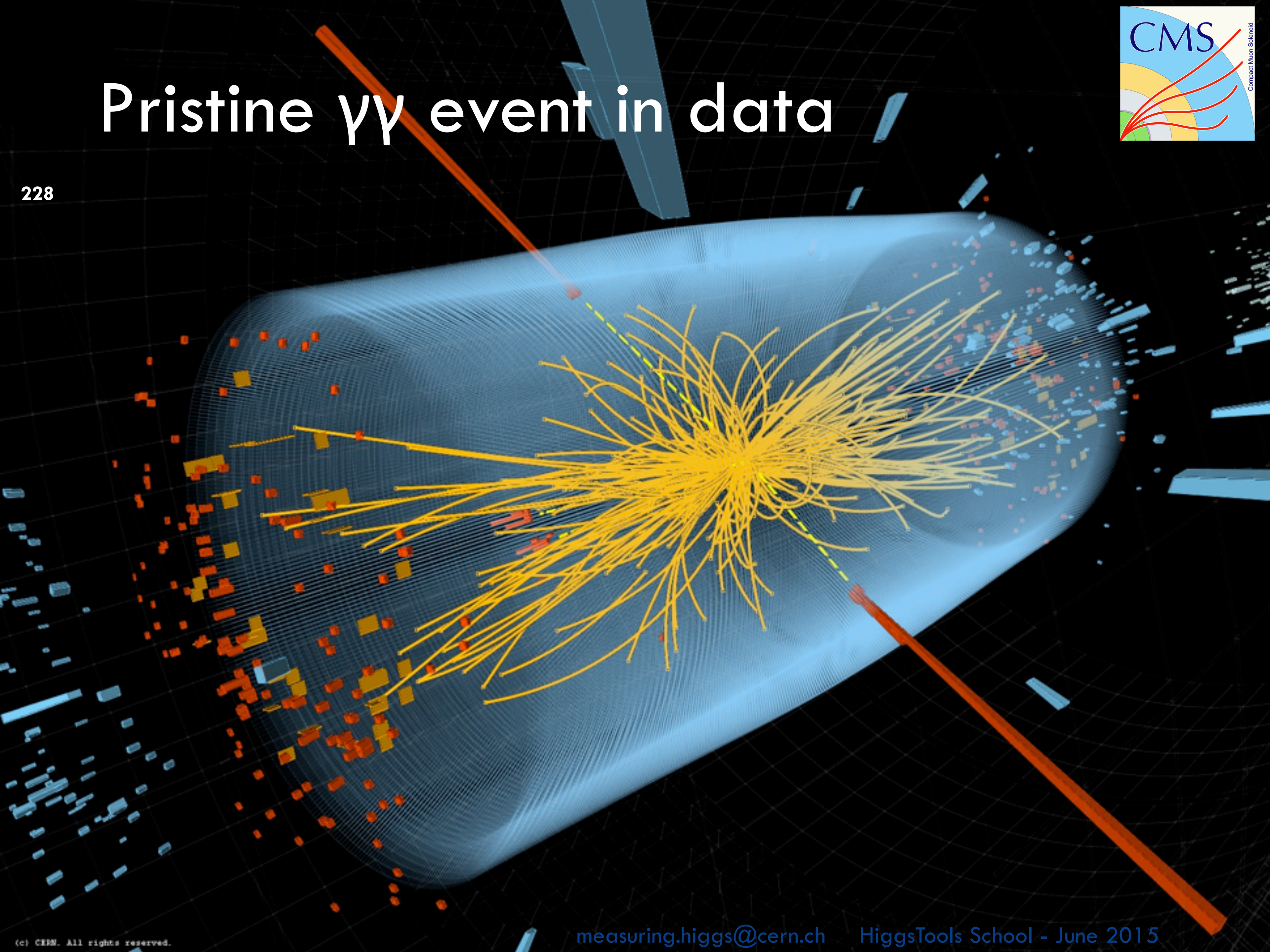
- Showers keep developing until all particles are absorbed.
  - For high energy **electrons**, **bremsstrahlung** is the dominant mechanism.
  - For high energy **photons**, **pair creation** is the dominant mechanism.

Not all showers look the same

- Jets of other particles mimic photons.
  - Overwhelming production of $\pi^0 \rightarrow \gamma\gamma$.
- Photons from $H \rightarrow \gamma\gamma$ segregated using multivariate technique.



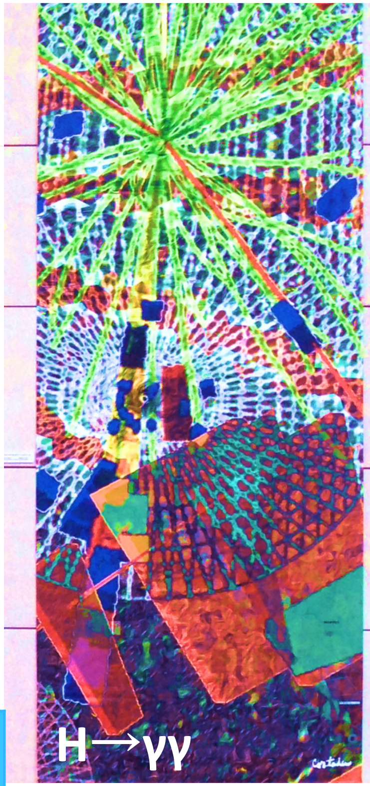
Pristine γγ event in data



Final Run 1 H→γγ analysis

[arXiv:1407.0558, submitted to EPJC]

- **Final calibration** of the CMS ECAL for Run 1 data.
- **Improved simulation/understanding** of:
  - ECAL noise evolution with time.
  - Effect of out-of-time collisions.
  - Amount and distribution of material in front of ECAL.
- **Improved** description of **energy scale uncertainties.**
- **25 event categories** targeting all production modes.
- **New background modeling** considers multiple functional forms simultaneously.



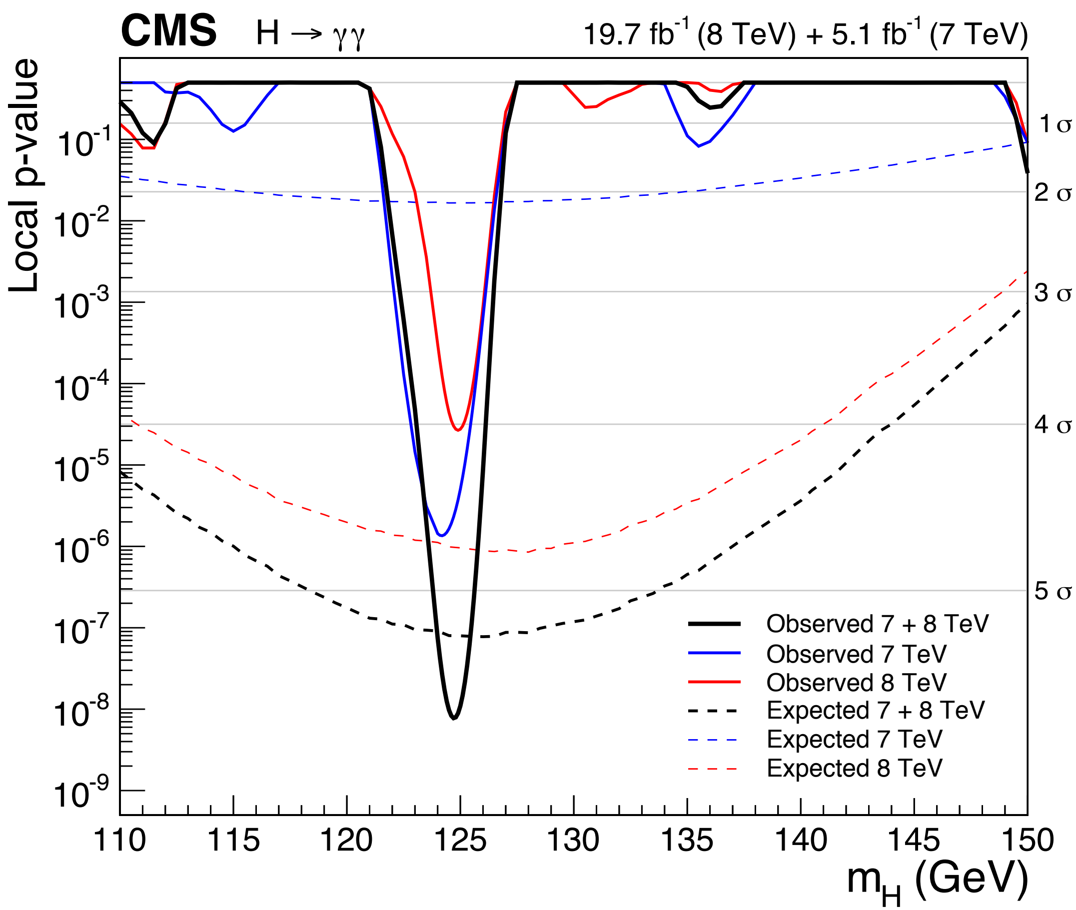
arXiv:1407.0558 (subm. to EPJC)

	Improved energy resolution	New event selection	Background modeling
Improvement on expected sensitivity since preliminary result:	~9%	~9%	~7%

H→ γγ significance

[arXiv:1407.0558, submitted to EPJC]

- Significance: 5.7σ obs. (5.2σ exp.)



H→ γγ significance

[arXiv:1407.0558, submitted to EPJC]

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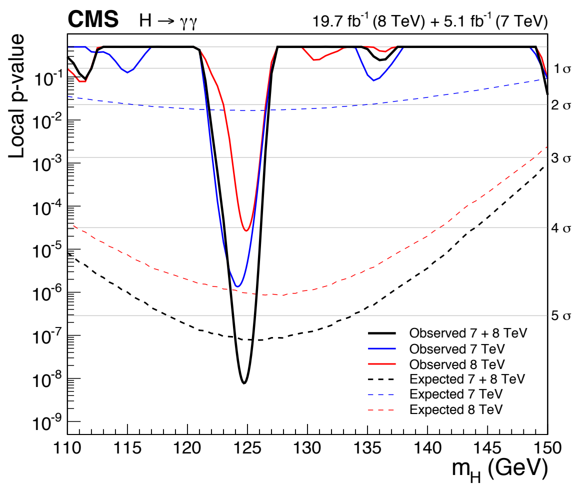
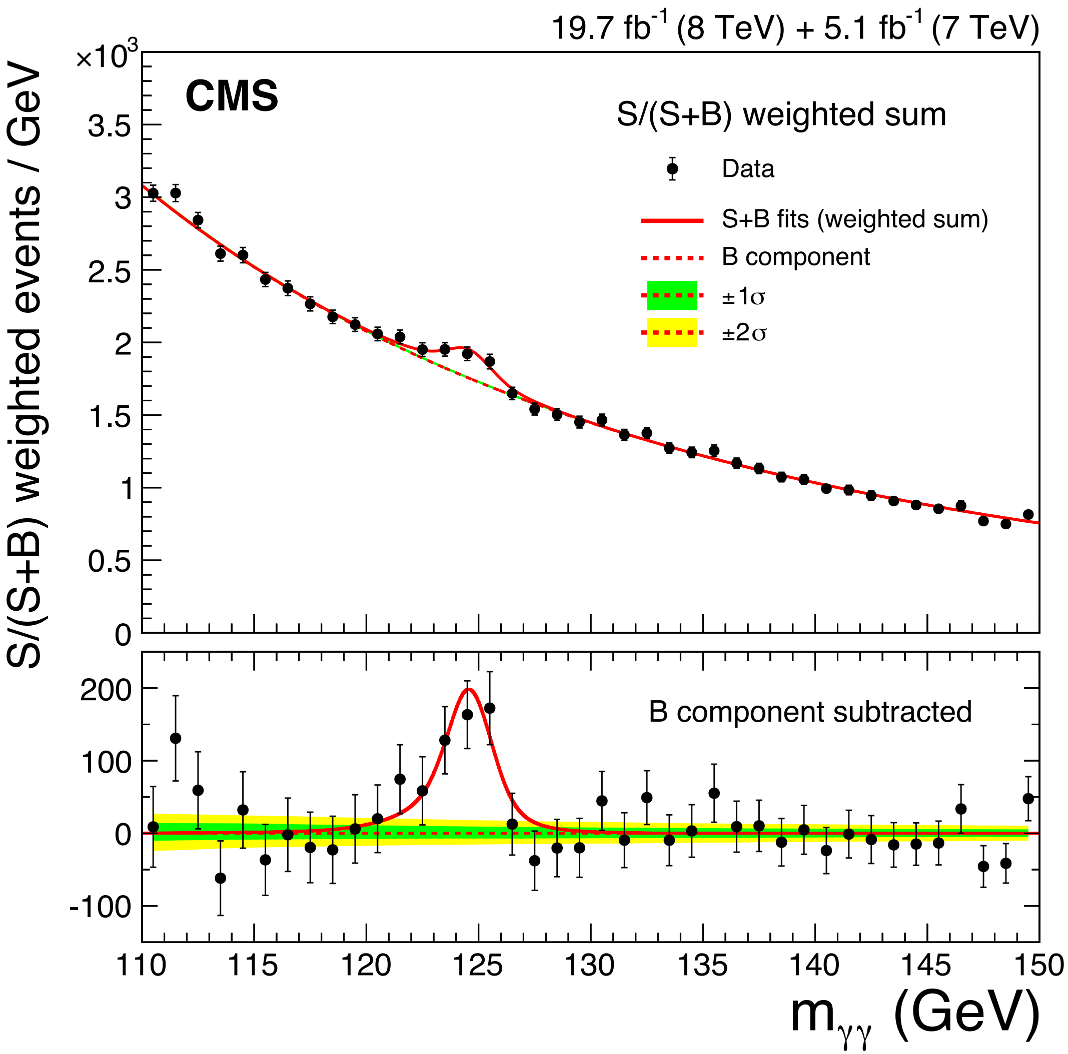
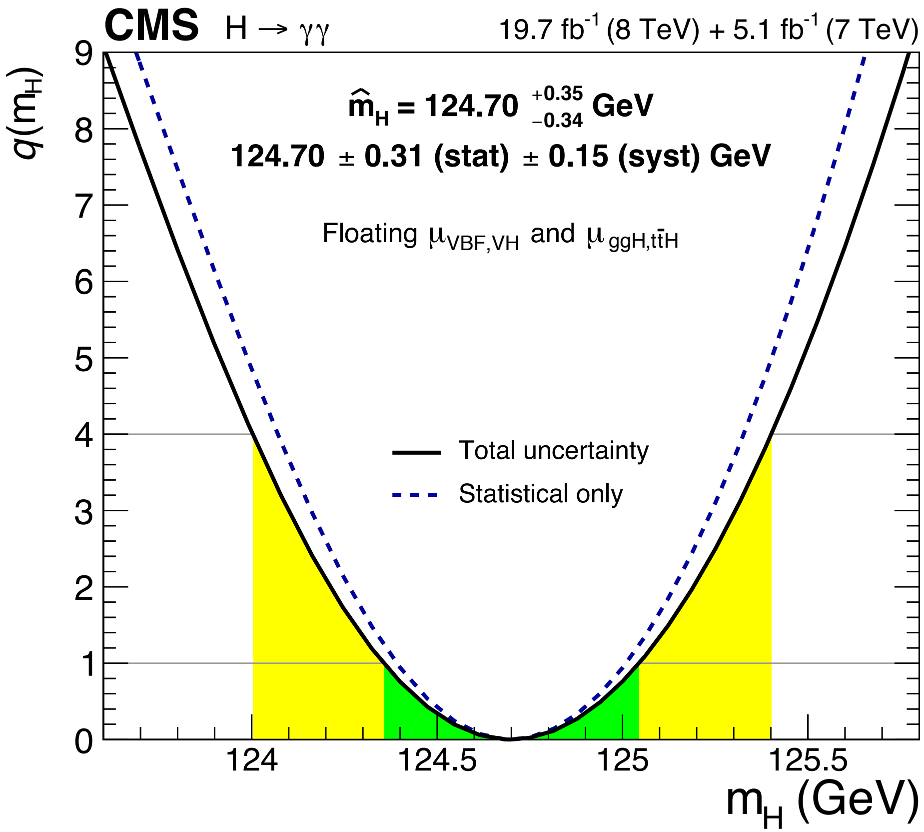




H$\rightarrow$ γγ mass measurement

[arXiv:1407.0558, submitted to EPJC]

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$



H→ γγ mass measurement

[arXiv:1407.0558, submitted to EPJC]

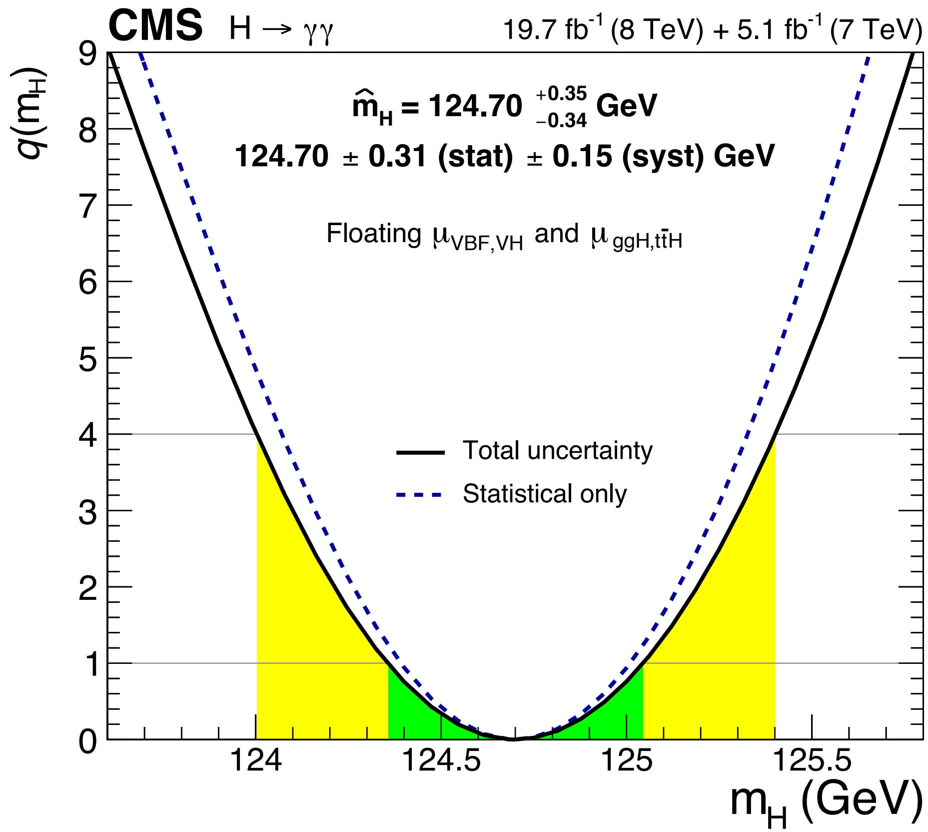
$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$

Calibration

E(γ) scale & resolution correction uncertainty:

±0.05 GeV on m_H

m_Z scale, electrons



$H \rightarrow \gamma\gamma$ mass measurement

[arXiv:1407.0558, submitted to EPJC]

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$

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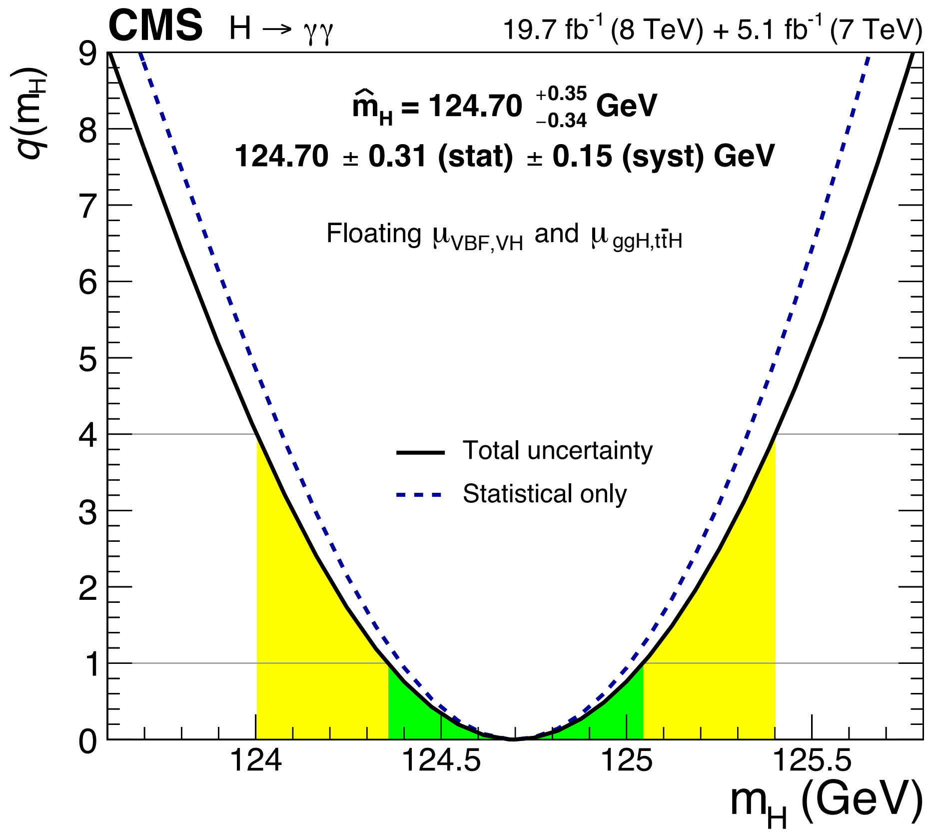
m_Z scale, electrons

m_H scale, electrons



$H\rightarrow\gamma\gamma$ mass measurement

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Calibration

$E(\gamma)$ scale & resolution correction uncertainty:

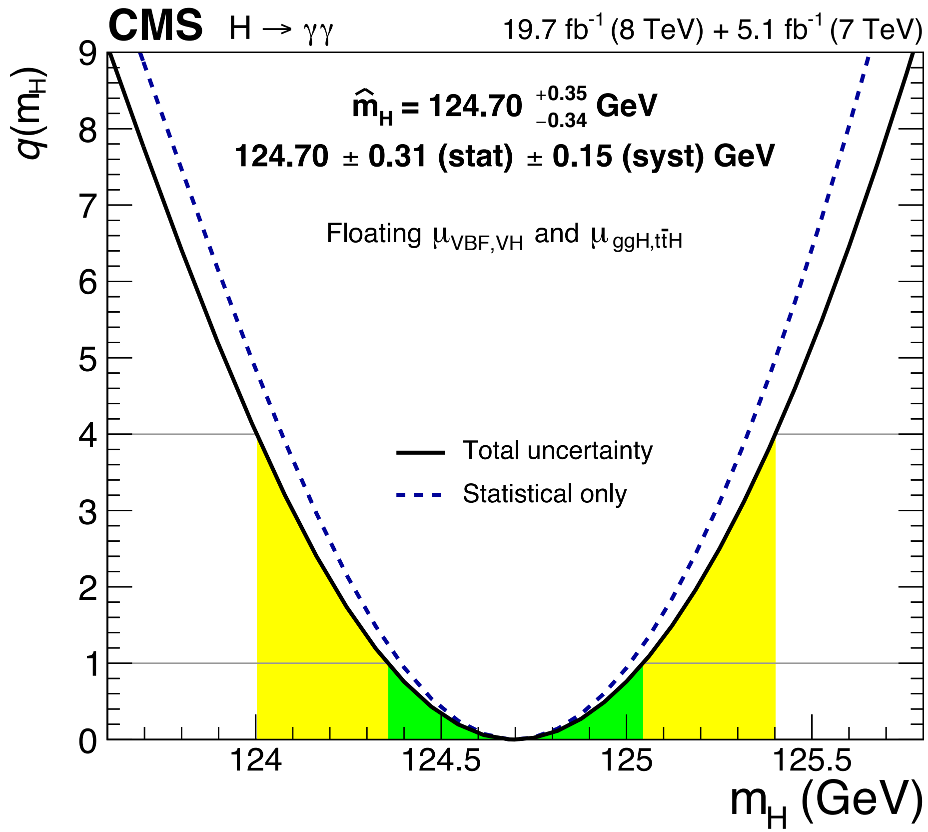
±0.05 GeV on m_H

m_Z scale, electrons

Large p_T Z boson data

Non-linearity uncertainty: **±0.10 GeV**

m_H scale, electrons



H→ γγ mass measurement

[arXiv:1407.0558, submitted to EPJC]

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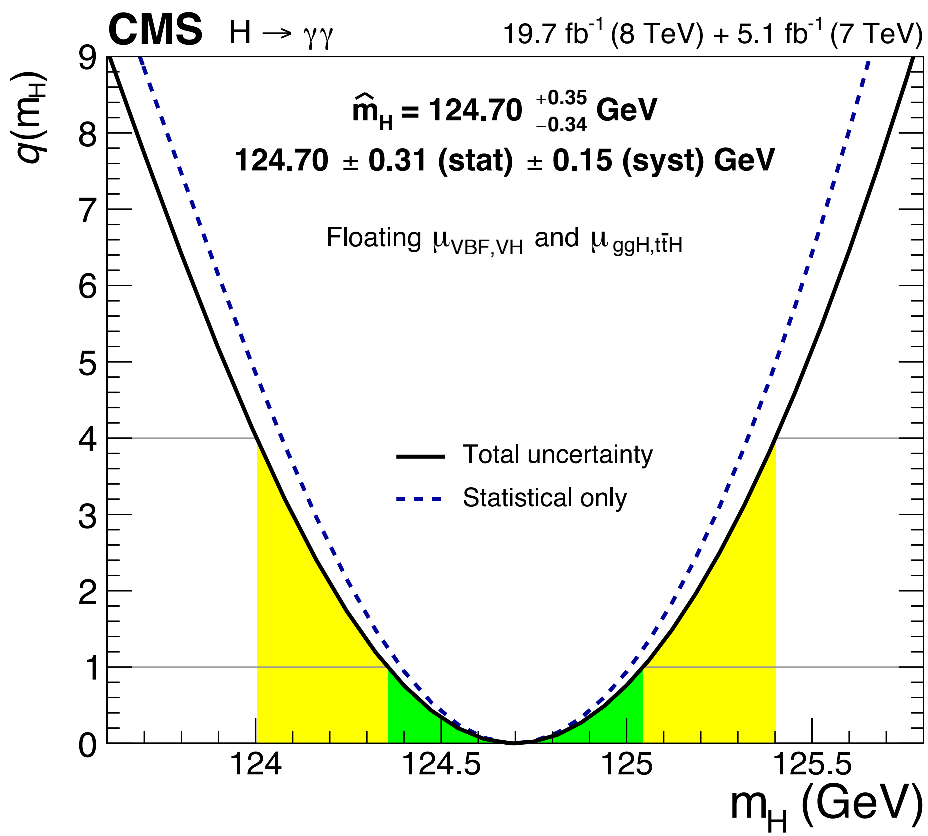
Calibration
E(γ) scale & resolution correction uncertainty:
±0.05 GeV on m_H

m_Z scale, electrons

Large p_T Z boson data
Non-linearity uncertainty: **±0.10 GeV**

m_H scale, electrons

m_H scale, **photons**



H→ γγ mass measurement

[arXiv:1407.0558, submitted to EPJC]

$$m_H = 124.70^{+0.35}_{-0.34}\ [\pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})]\ \text{GeV}$$

Calibration
E(γ) scale & resolution correction uncertainty:
±0.05 GeV on m_H

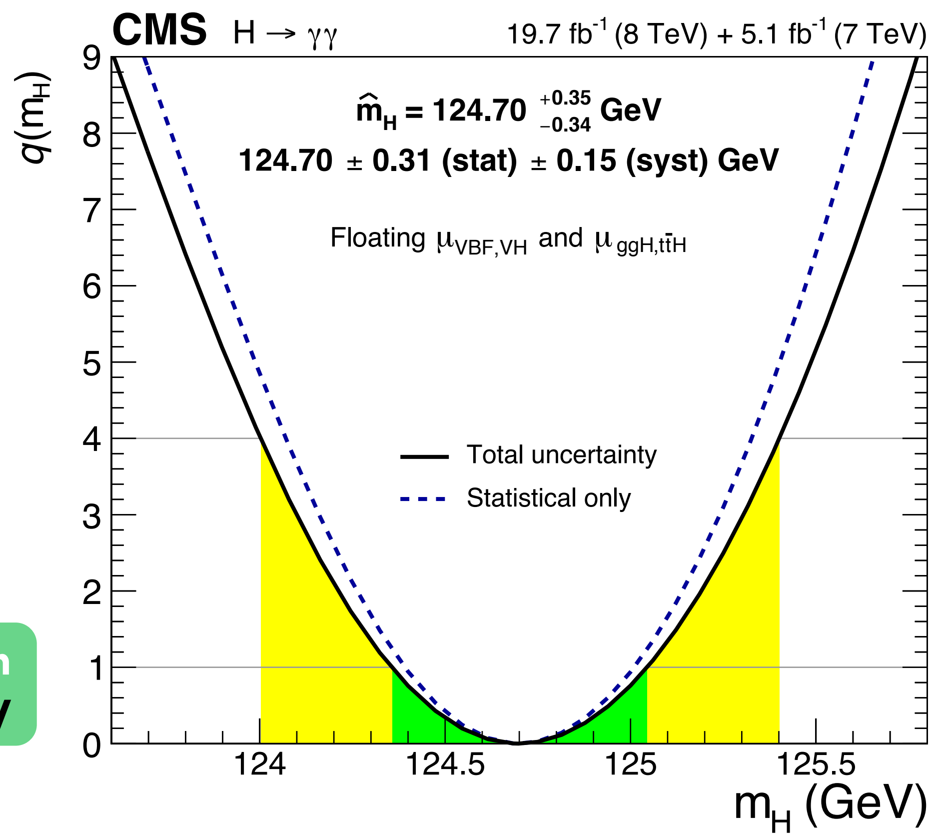
m_Z scale, electrons

Large p_T Z boson data
Non-linearity uncertainty: **±0.10 GeV**

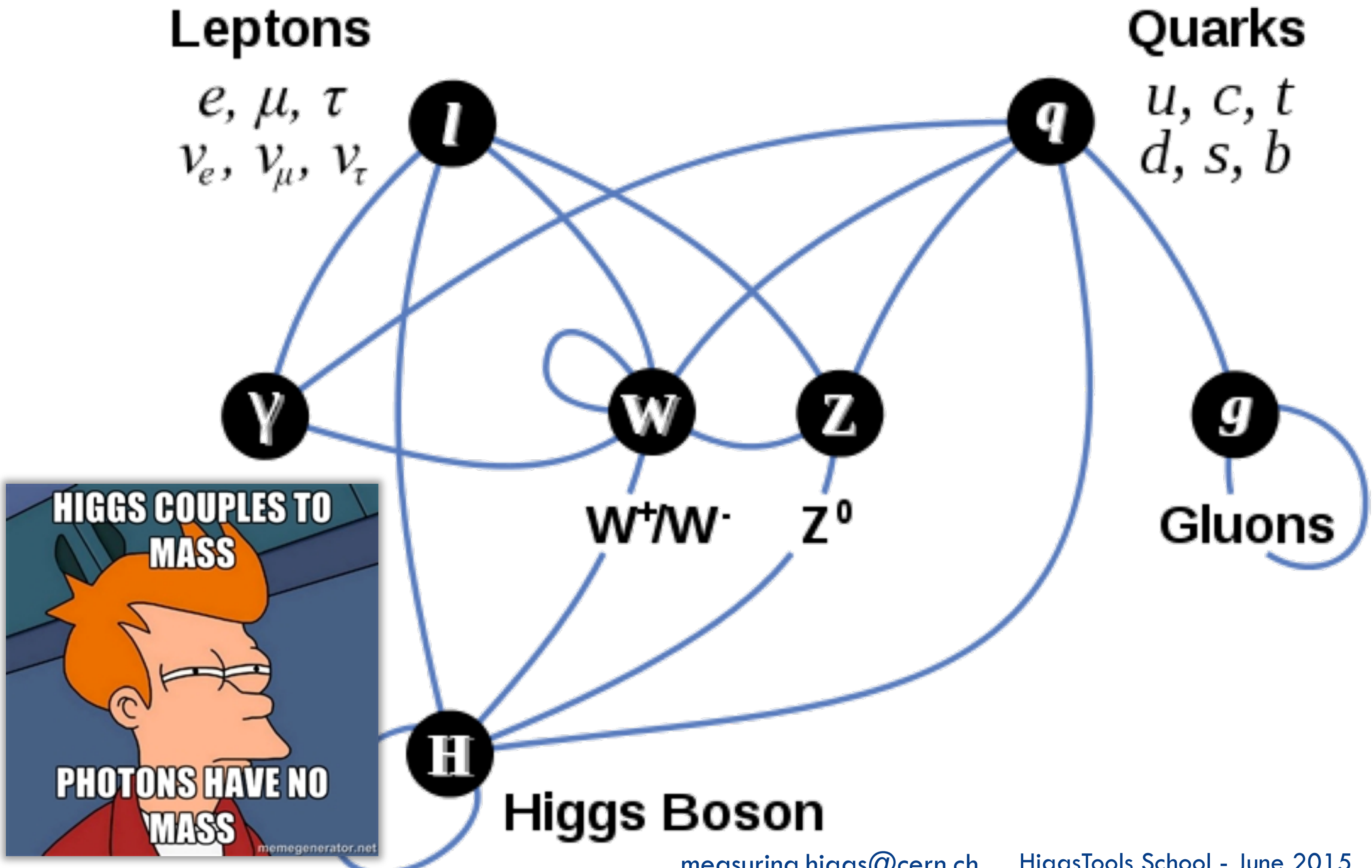
m_H scale, electrons

From simulation
Data-MC electron-photon differences: **±0.10 GeV**

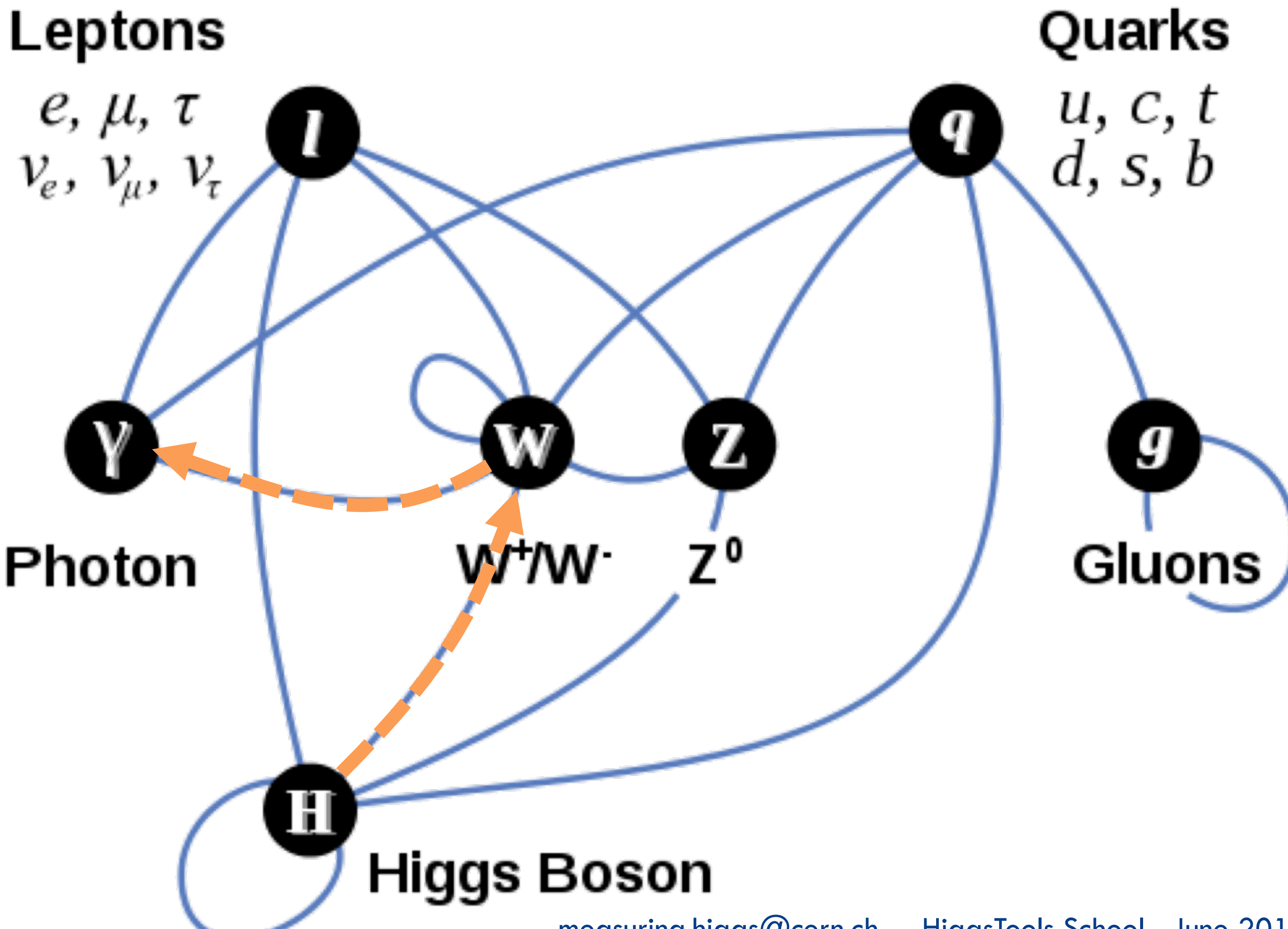
m_H scale, **photons**



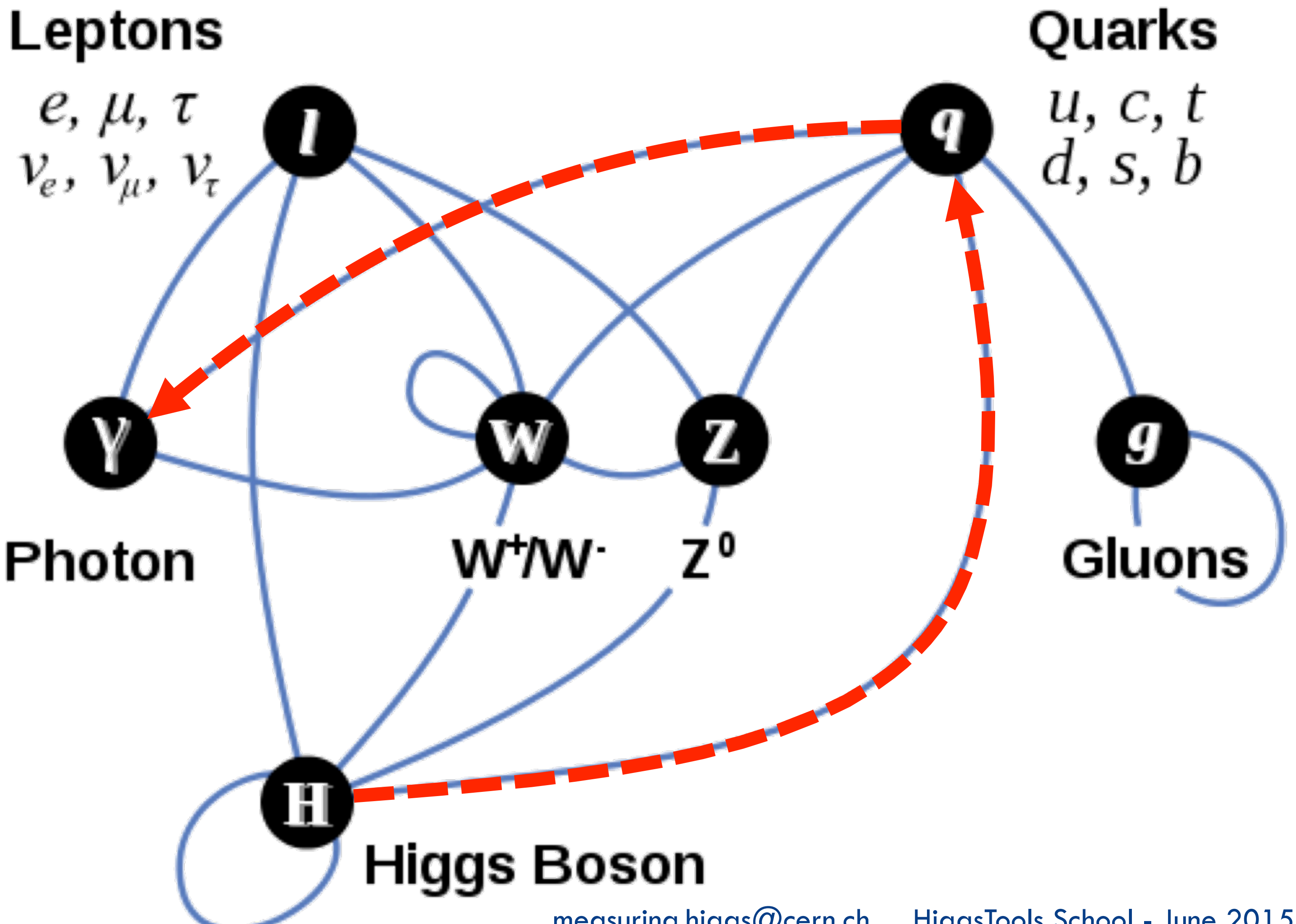
The (missing) path from H to γ



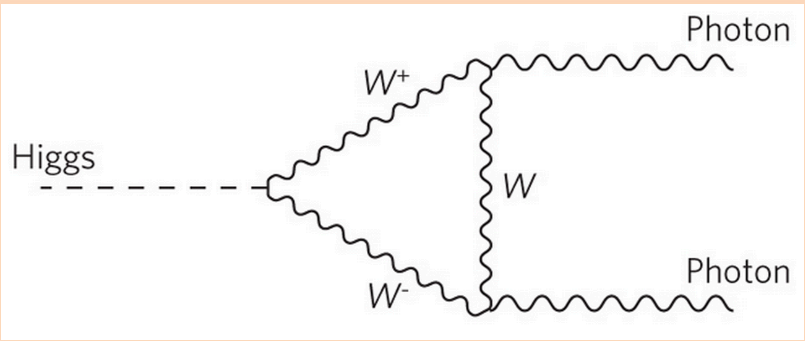
The path from H to γ: W boson

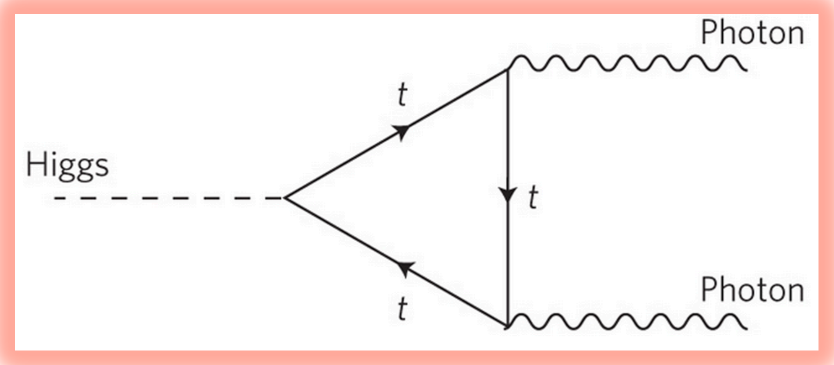


The path from H to γ: **top quark**



To interfere ~~or not to interfere~~



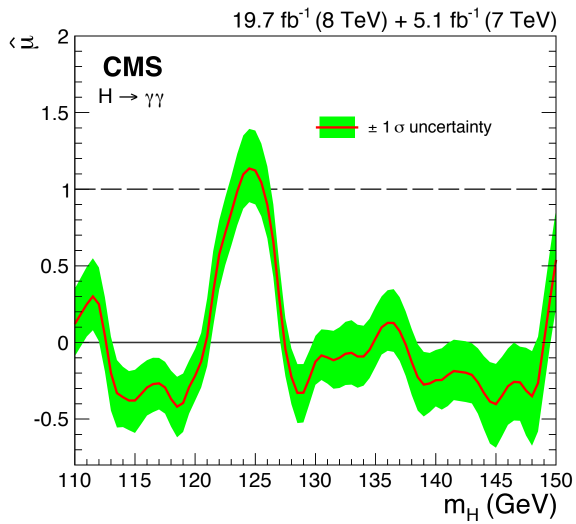


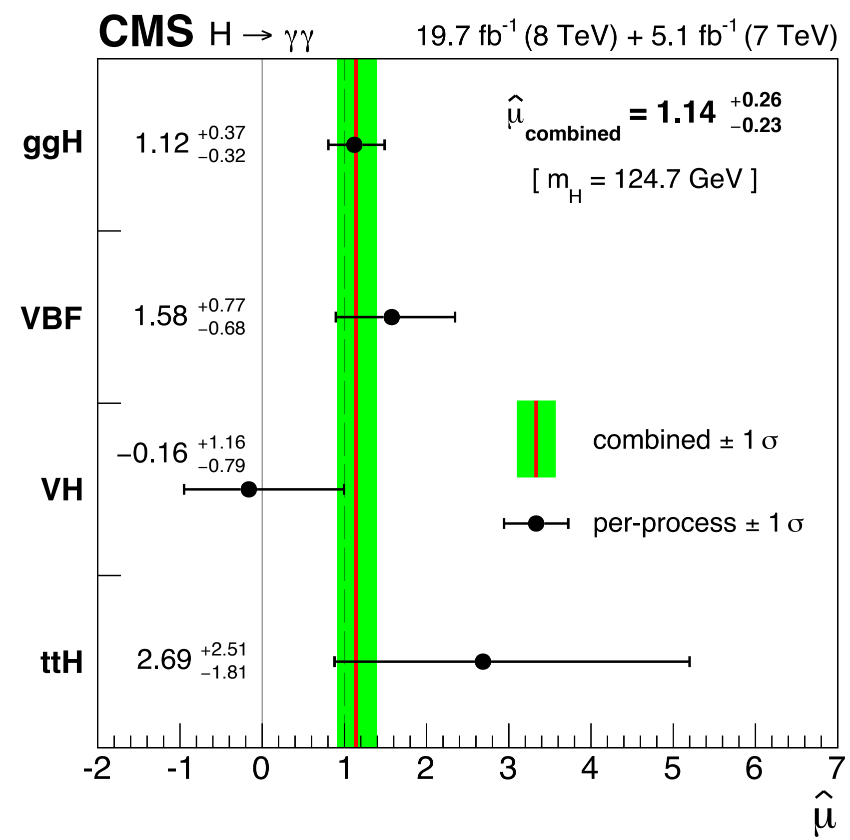
- QM: all possible paths will contribute.
  - Two dominate in the SM: $\Gamma_{\gamma\gamma} \sim |1.26\ A_W - 0.26\ A_{top}|^2$
    - Destructive interference.
    - Decay rate is fixed from W and top couplings.
- New BSM particles could open up new paths…

$H \rightarrow \gamma\gamma$ signal strength

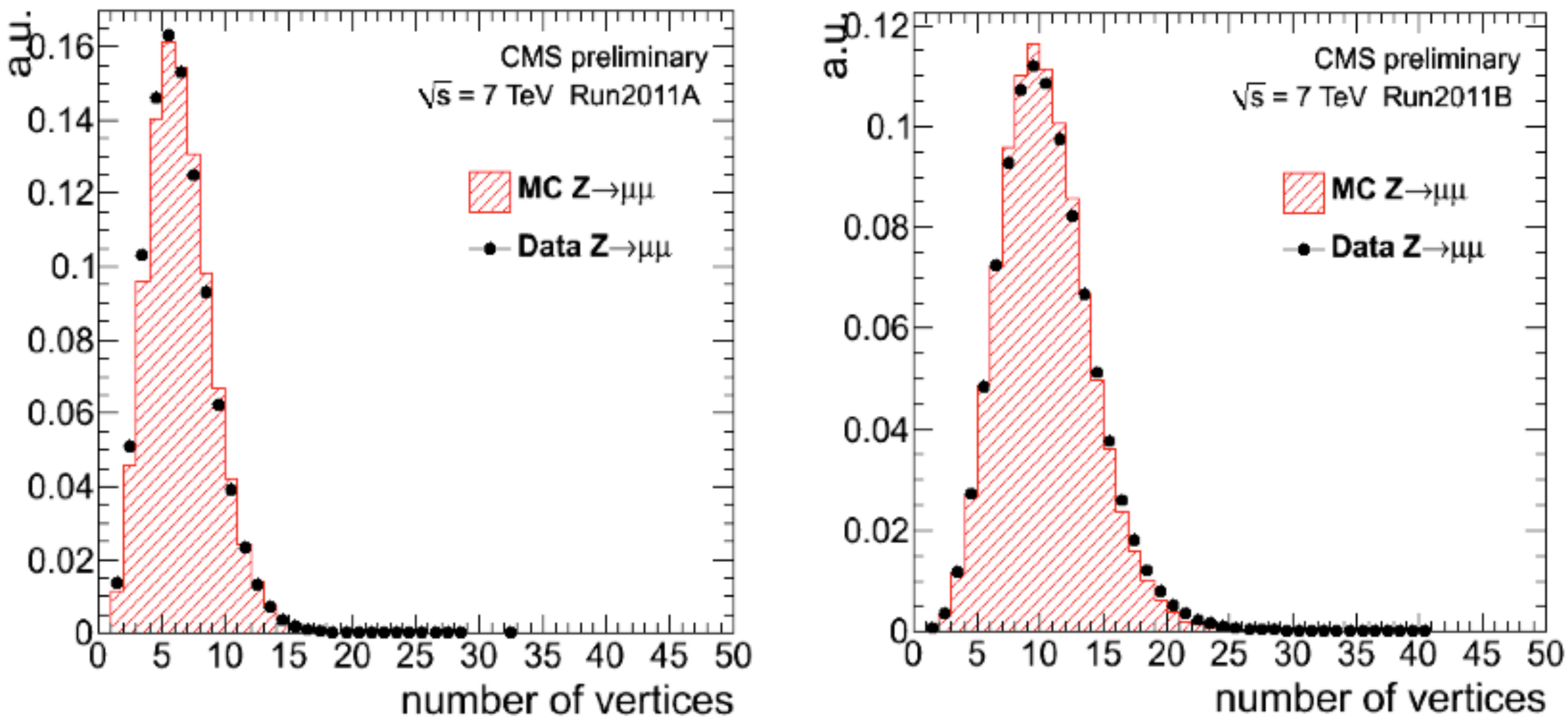
[arXiv:1407.0558, submitted to EPJC]

$$\sigma/\sigma_{\rm SM} = 1.14^{+0.26}_{-0.23}\left[\pm 0.21(\text{stat.})^{+0.13}_{-0.09}(\text{theo.})^{+0.09}_{-0.05}(\text{syst.})\right]$$



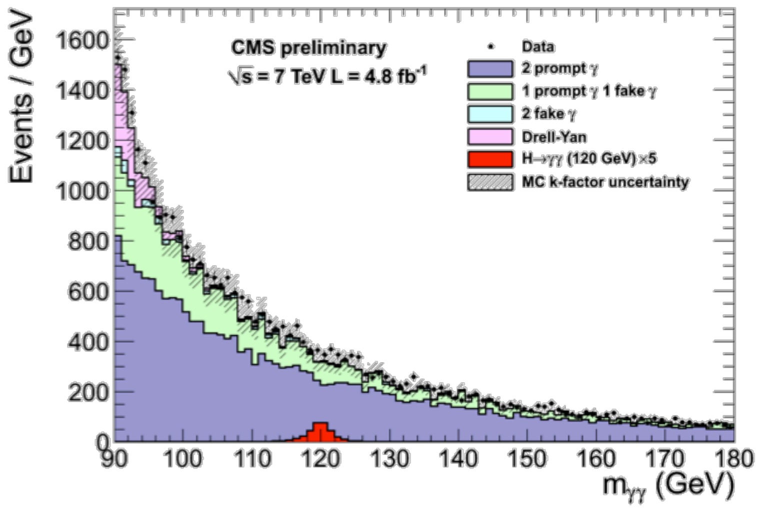


Full 2011 dataset: pileup



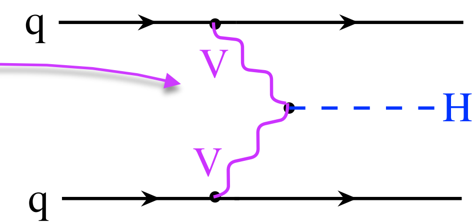
The di-photon channel in CMS

- H → $\gamma\gamma$ one of the most sensitive channels in 110 < m_H < 150 GeV
  - Clean final state: two high p_T isolated photons
  - Narrow mass peak
- H → $\gamma\gamma$ sensitivity driven by mass resolution and S/B
  - Mass resolution
    - * Photon energy
    - * Di-photon opening angle
  - Major Backgrounds
    - * pp → jet + jet , pp → γ + jet with jet faking photon (mainly π^0)
    - * pp → $\gamma\gamma$



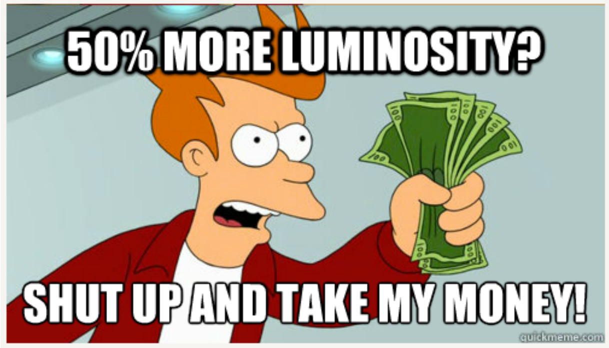
- Multivariate analysis (MVA) techniques used to improve H → $\gamma\gamma$ search sensitivity
  - provides more optimal event classification
- The analysis uses $\int L\,dt$ = 4.76 fb^{-1} of CMS data

Analysis strategy evolution

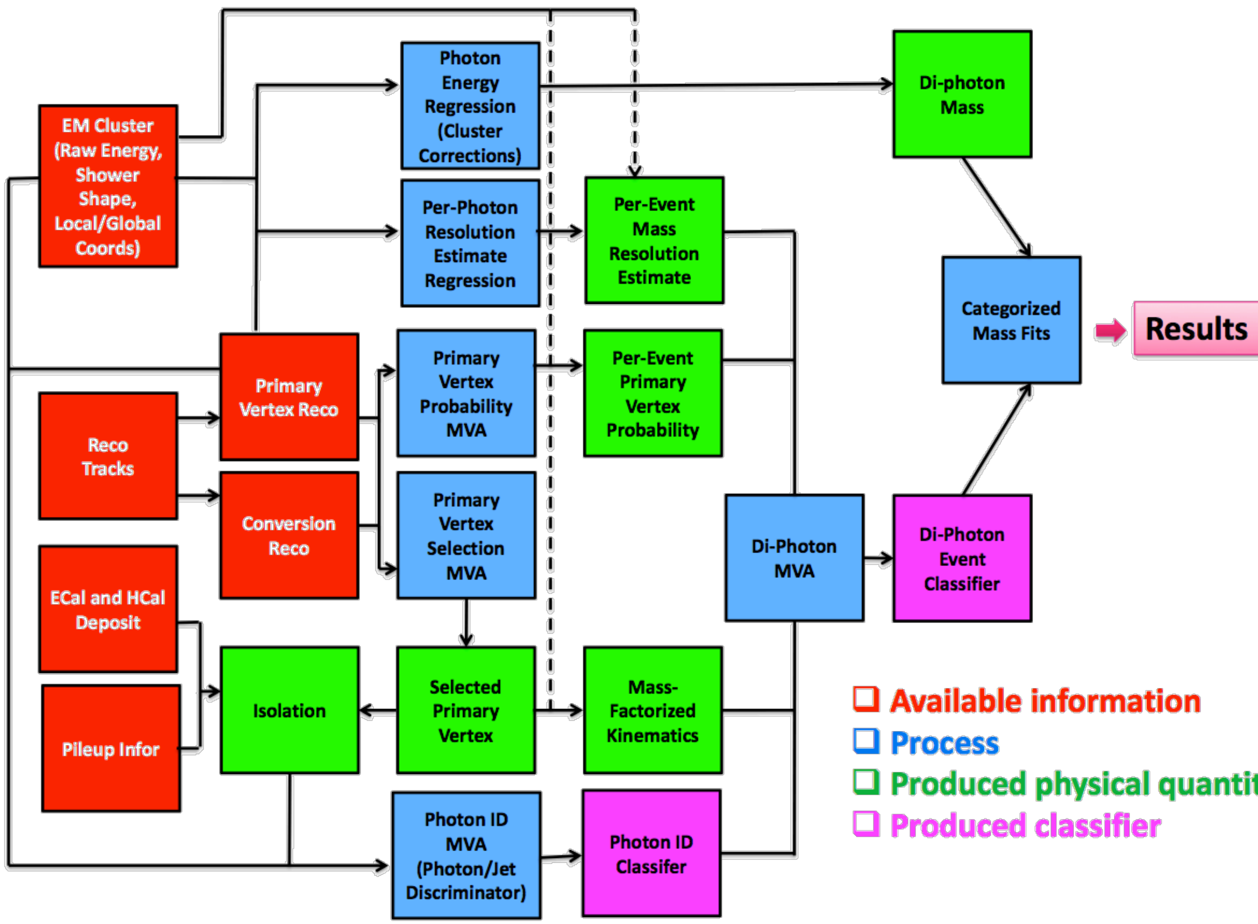


- **Cut-based analysis.**
  [PLB 710 (2012) 403-425]
  1. Di-jet tagged events for VBF production.
  2. Remaining events split by resolution and S/B:
     - Photon pseudorapidity (barrel / endcap).
     - Photon shower shape (unconverted / converted / π^0).

- **Multivariate (MVA) analysis.**
  [CMS-PAS-HIG-12-001]
  - Event-by-event boosted decision tree (BDT) classifier.
  - Sensitivity improvement equivalent to ~ 50% more integrated luminosity.

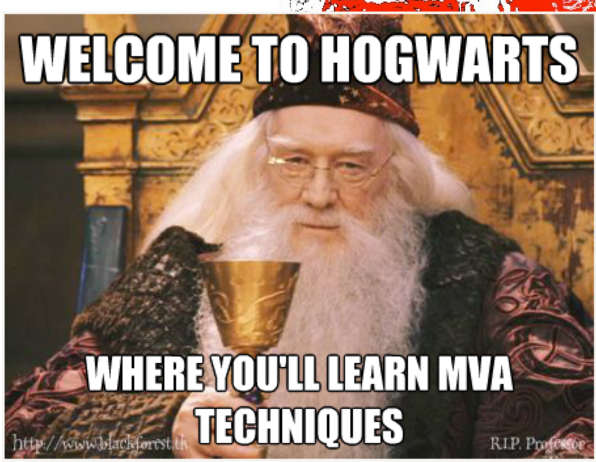


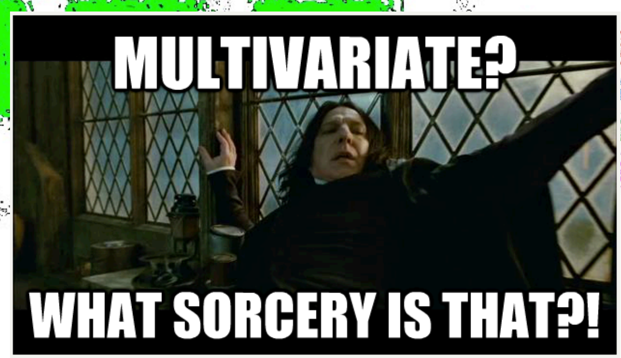
Anatomy of the analysis



- Available information
- Process
- Produced physical quantity
- Produced classifier

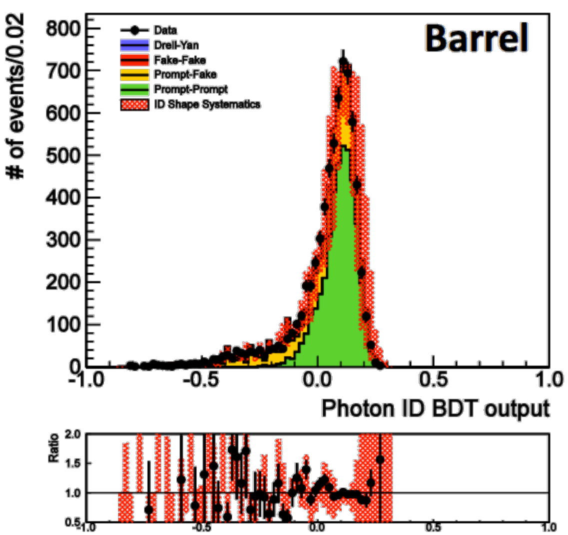
Anatomy of the analysis

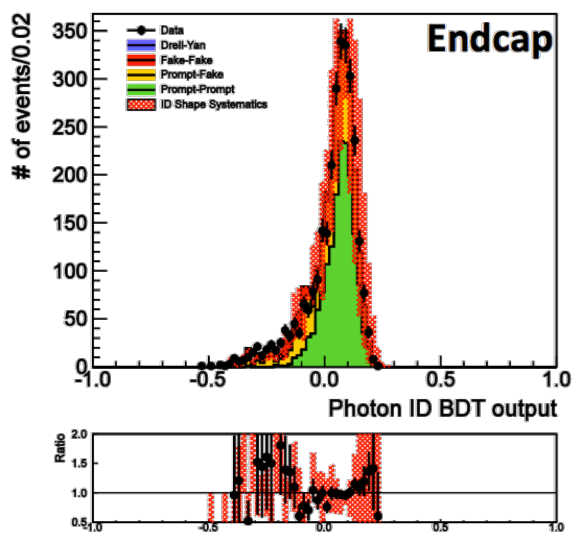




Photon identification

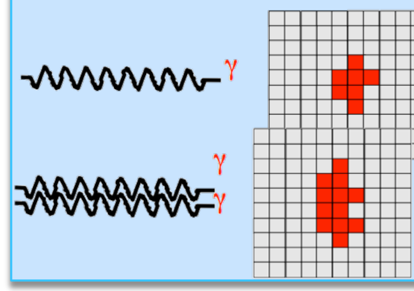
- Photon ID MVA discriminates prompt photon from jet faking photon using a boosted decision tree (BDT) trained on MC simulation events
  - Signal sample: prompt photons from $H \to \gamma\gamma$
  - Background sample: jets from $pp \to \gamma + jet$
- MVA trained separately for Barrel and Endcap
- Uses variables related to shower shape and isolation
- MVA output gives a classifier variable discriminating prompt photons from fakes
- Photon ID MVA output for the leading photon in preselected di-photon events with $m_{\gamma\gamma}$ >160 GeV is compared between data and MC





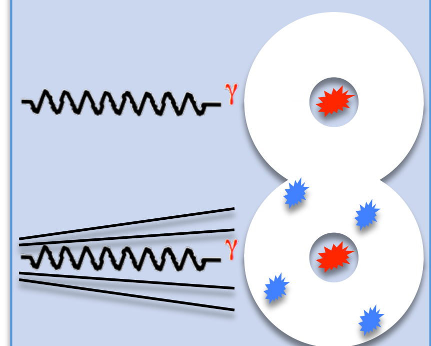
Shower shape

(photon energy distribution)



Isolation

(activity around a photon)



Mass resolution deconstructed

Photon energies

Di-photon opening angle

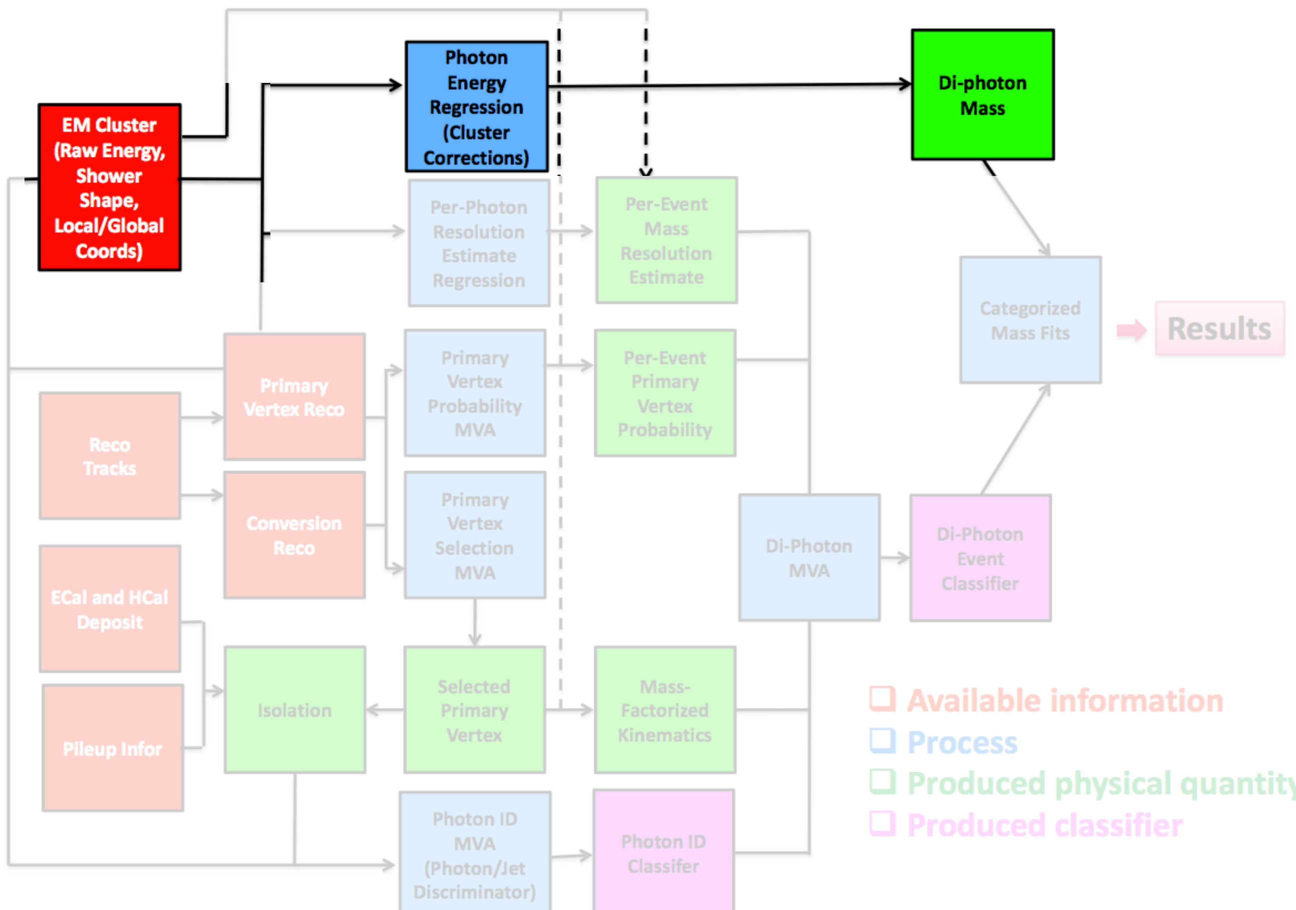
$$M_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}\left(1-\cos(\alpha)\right)$$

$$\frac{\delta M}{M} = \frac{1}{2}\left(\frac{\delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\delta\alpha}{\tan(\alpha/2)}\right)$$

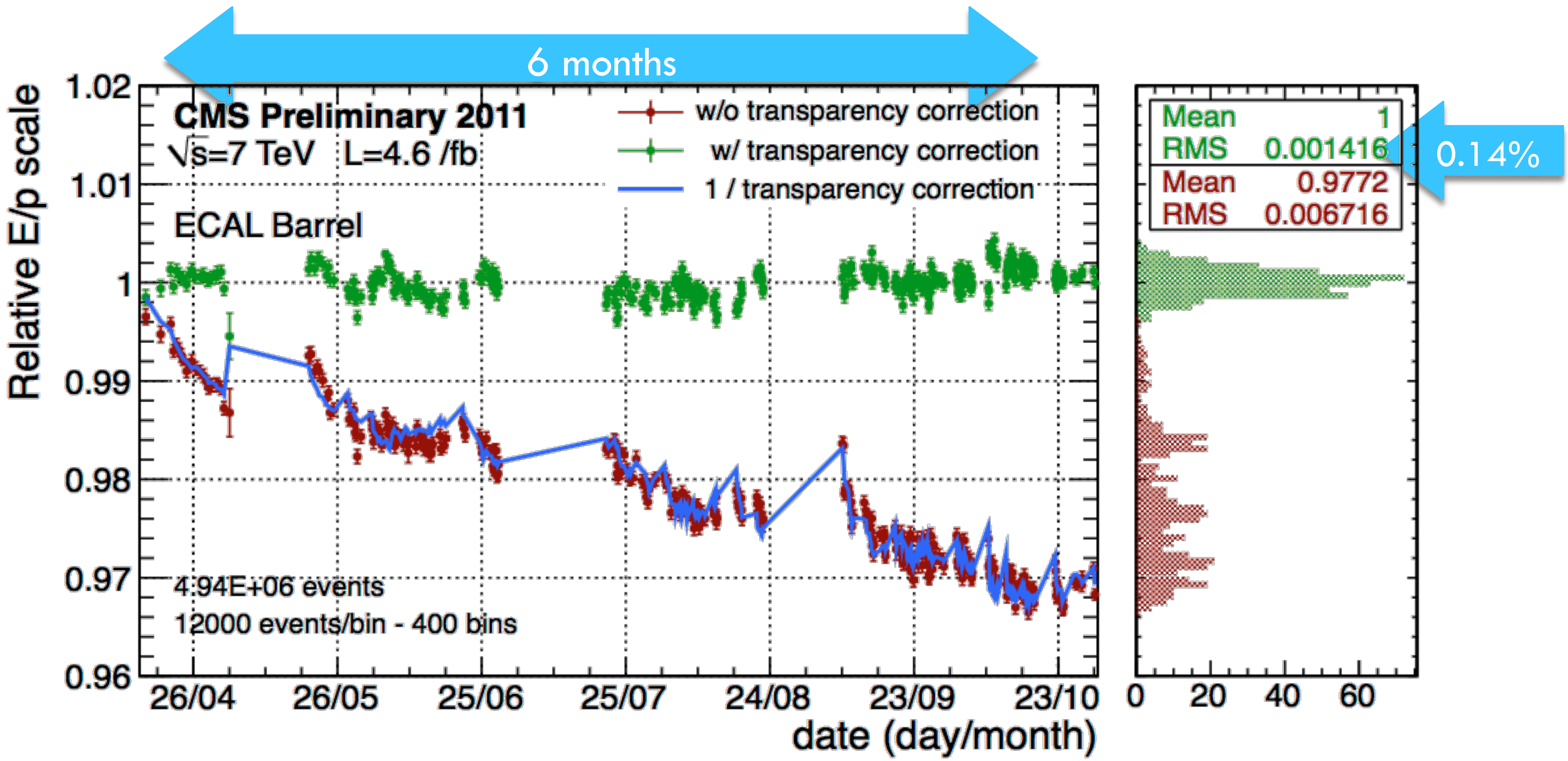
Photon energy resolution

Angular resolution

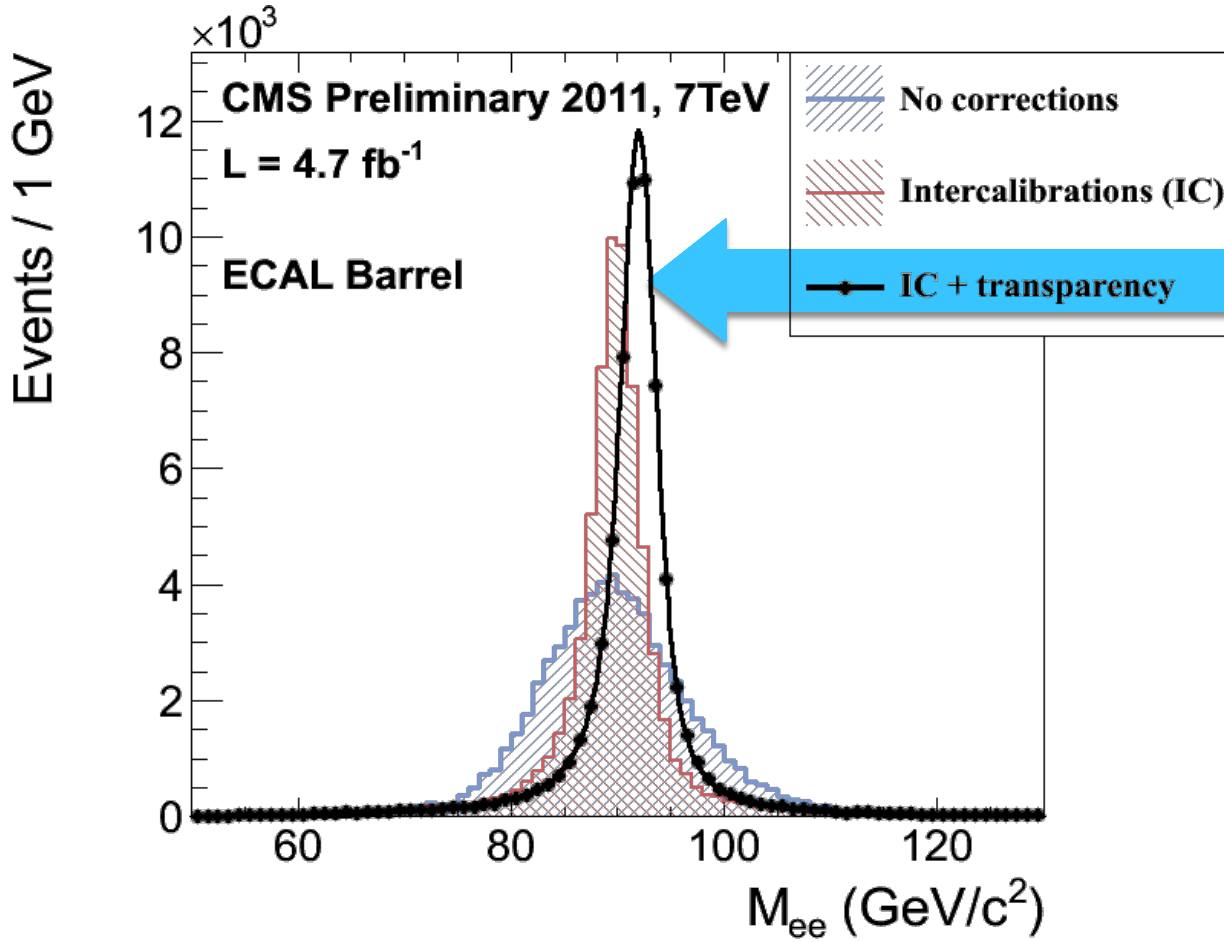
Anatomy of the analysis



ECAL calibration: isolated electrons



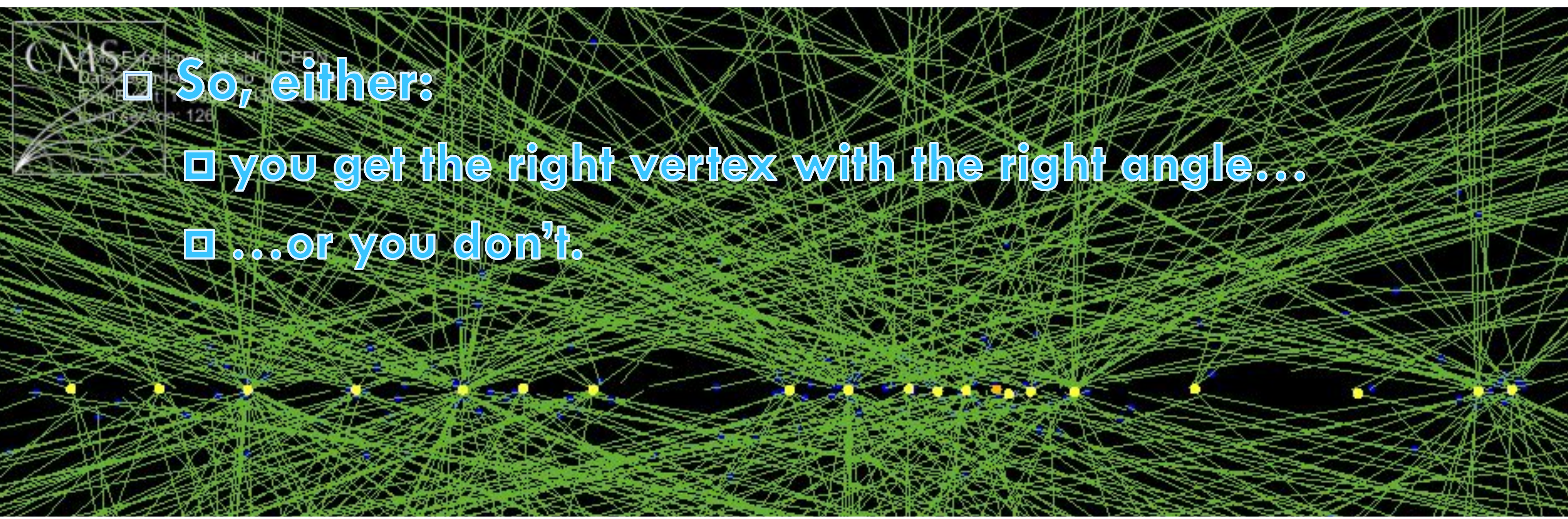
ECAL calibration: Z→ee peak



1.0 GeV resolution

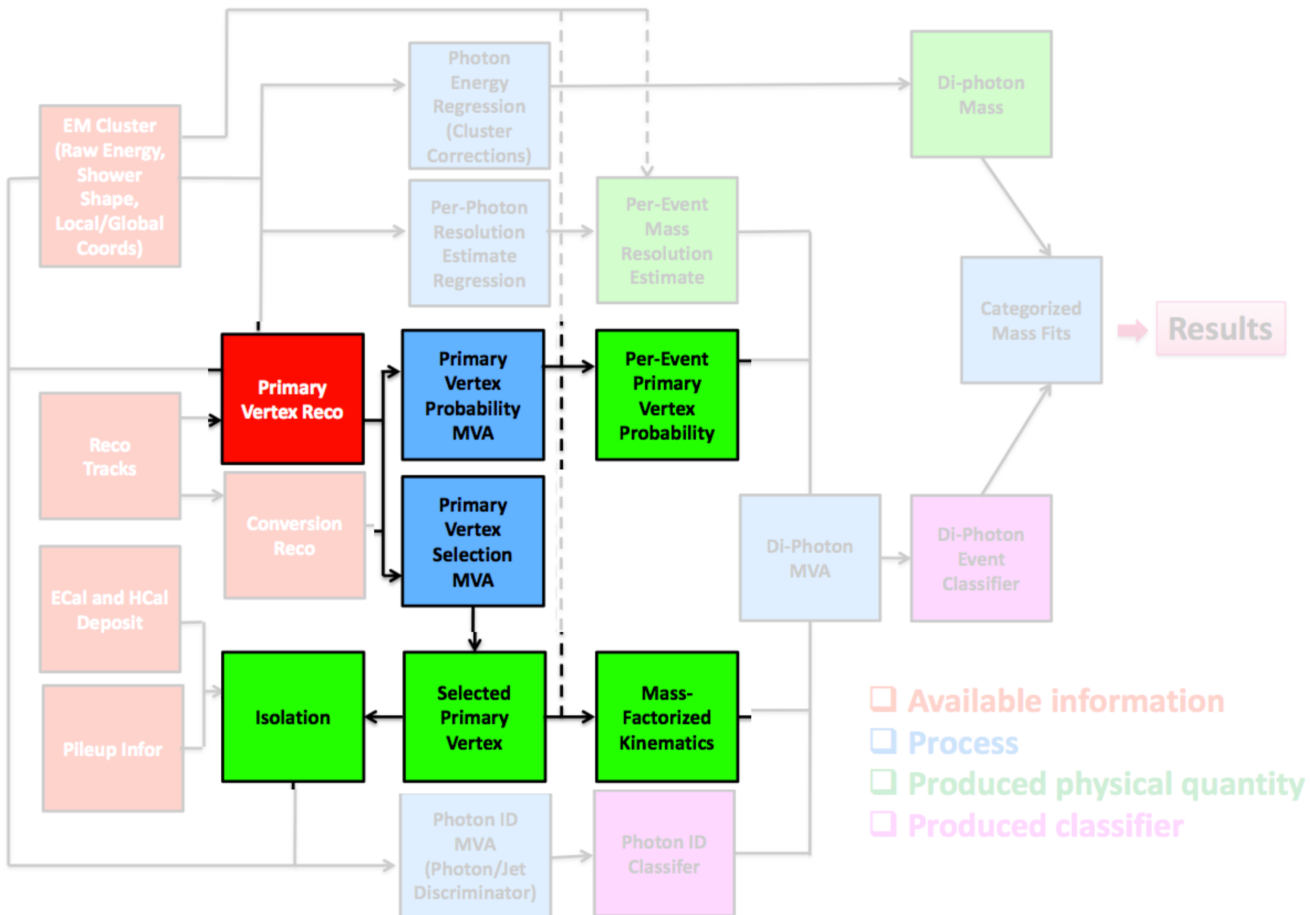
Angular resolution

- Unconverted **photons have no tracks.**
- CMS ECAL is homogeneous, optimized for energy resolution, **no pointing ability.**

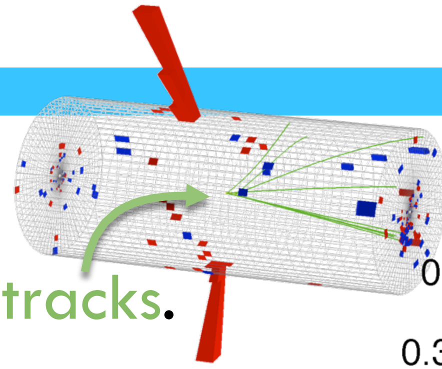


- So, either:
  - you get the right vertex with the right angle…
  - …or you don't.

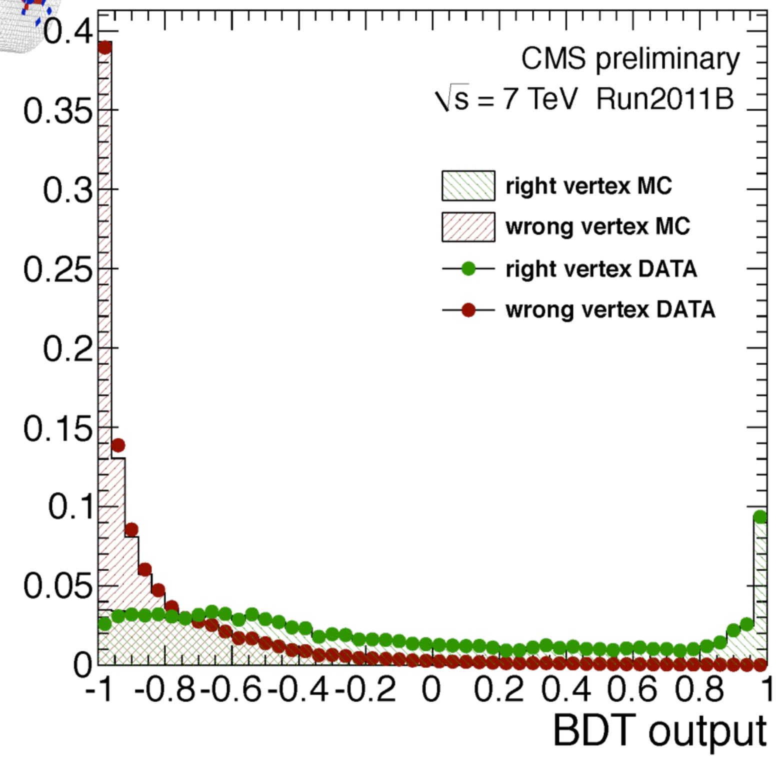
Anatomy of the analysis



Choosing the best vertex

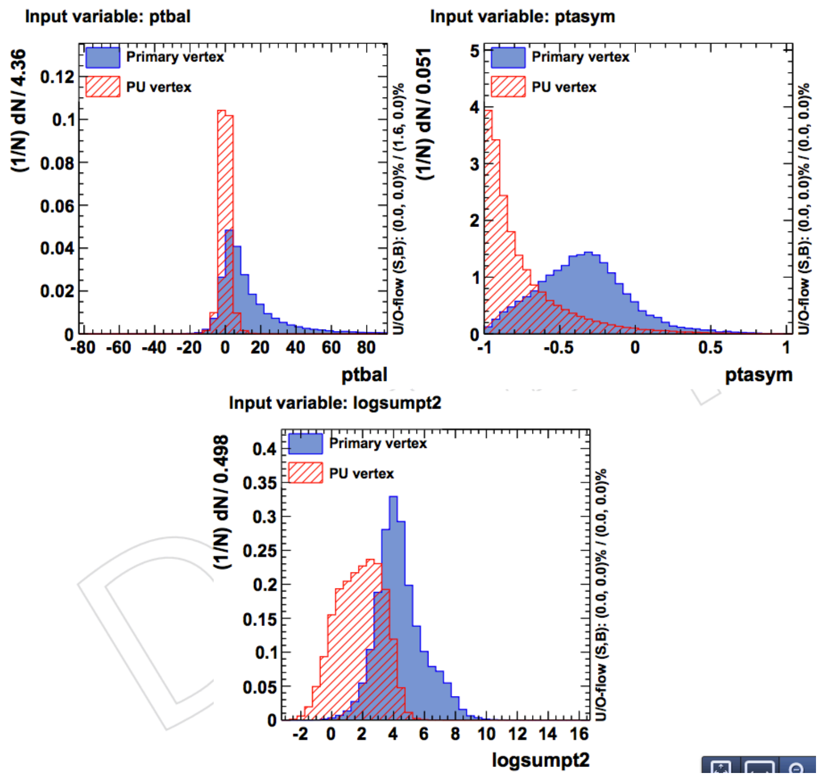


- Main handles:
  - Di-photon recoil tracks.
    - Good at high p_T.
    - Validated with $Z \rightarrow \mu\ \mu$ events. ➔
  - Photon conversion tracks.
    - Validated with γ -jet events.



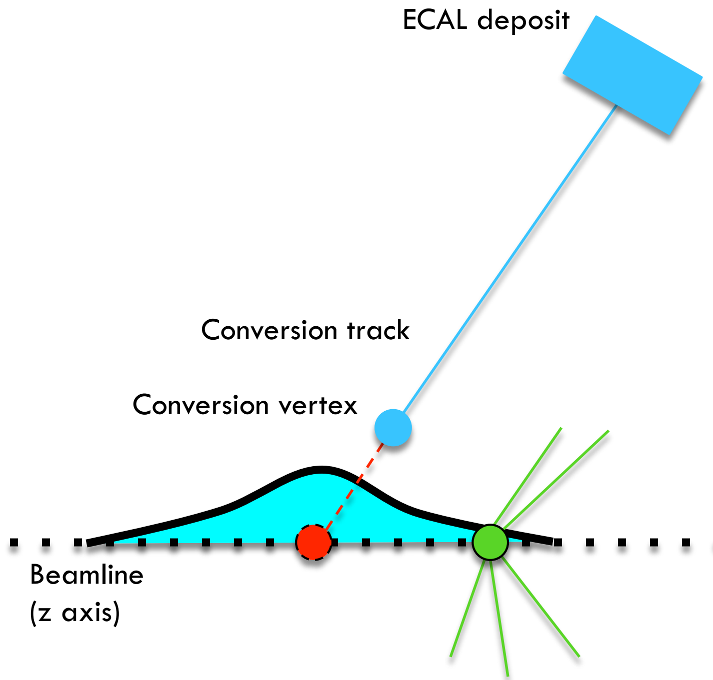
Vertex recoil variables

- *sumpt2*: $\sum_i |\vec{p}_T^{\,i}|^2$.
- *ptbal*: $-\sum_i (\vec{p}_T^{\,i} \cdot \frac{\vec{p}_T^{\,\gamma\gamma}}{|\vec{p}_T^{\,\gamma\gamma}|})$.
- *ptasym*: $(|\sum_i \vec{p}_T^{\,i}| - p_T^{\gamma\gamma}) \,/\, (|\sum_i \vec{p}_T^{\,i}| + p_T^{\gamma\gamma})$.

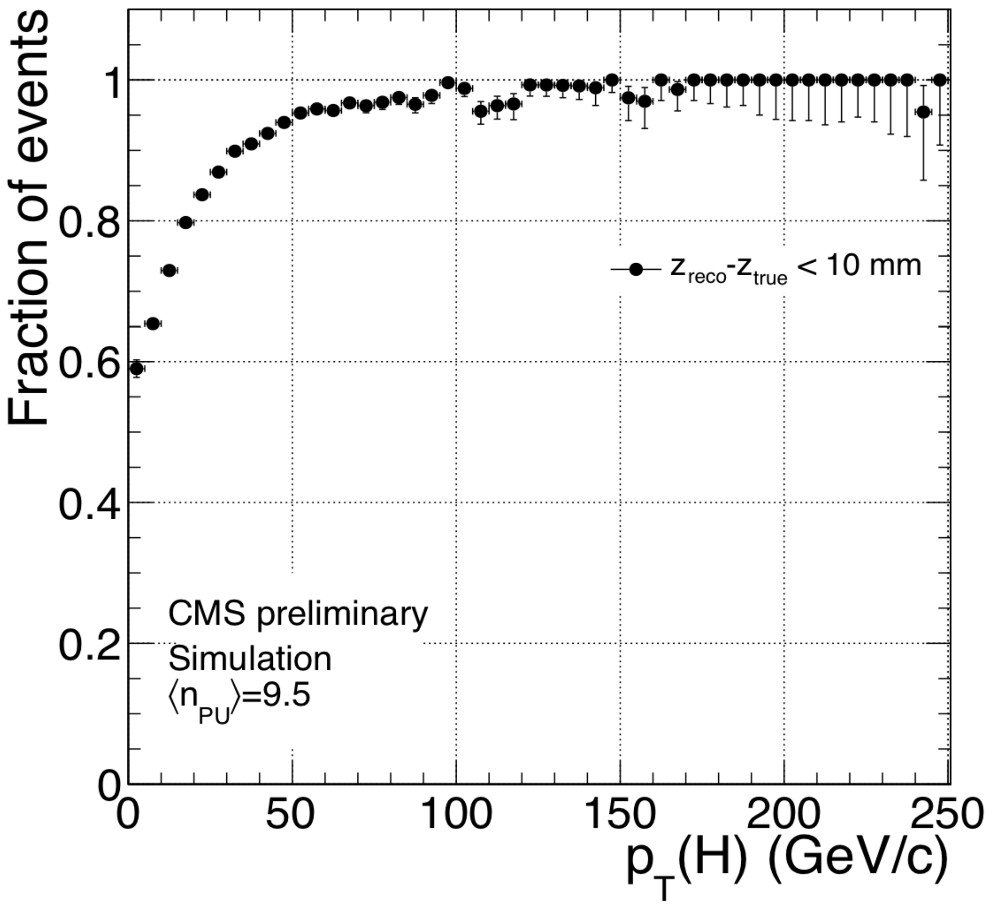


Converted photon vertexing

$$pull_{conv} = |z_{conversion} - z_{vertex}| / \sigma_{conversion}.$$

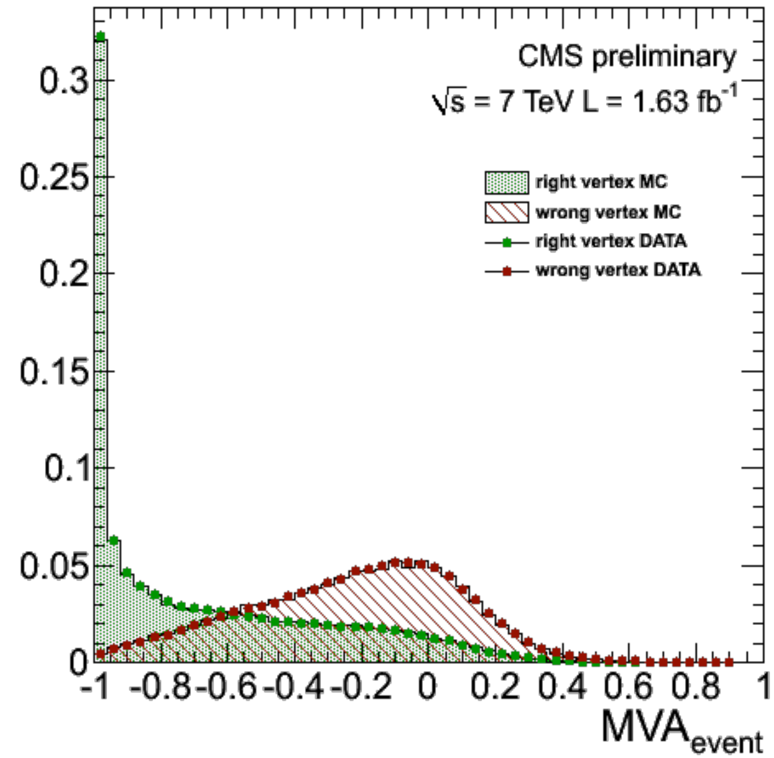


Vertex choice efficiency

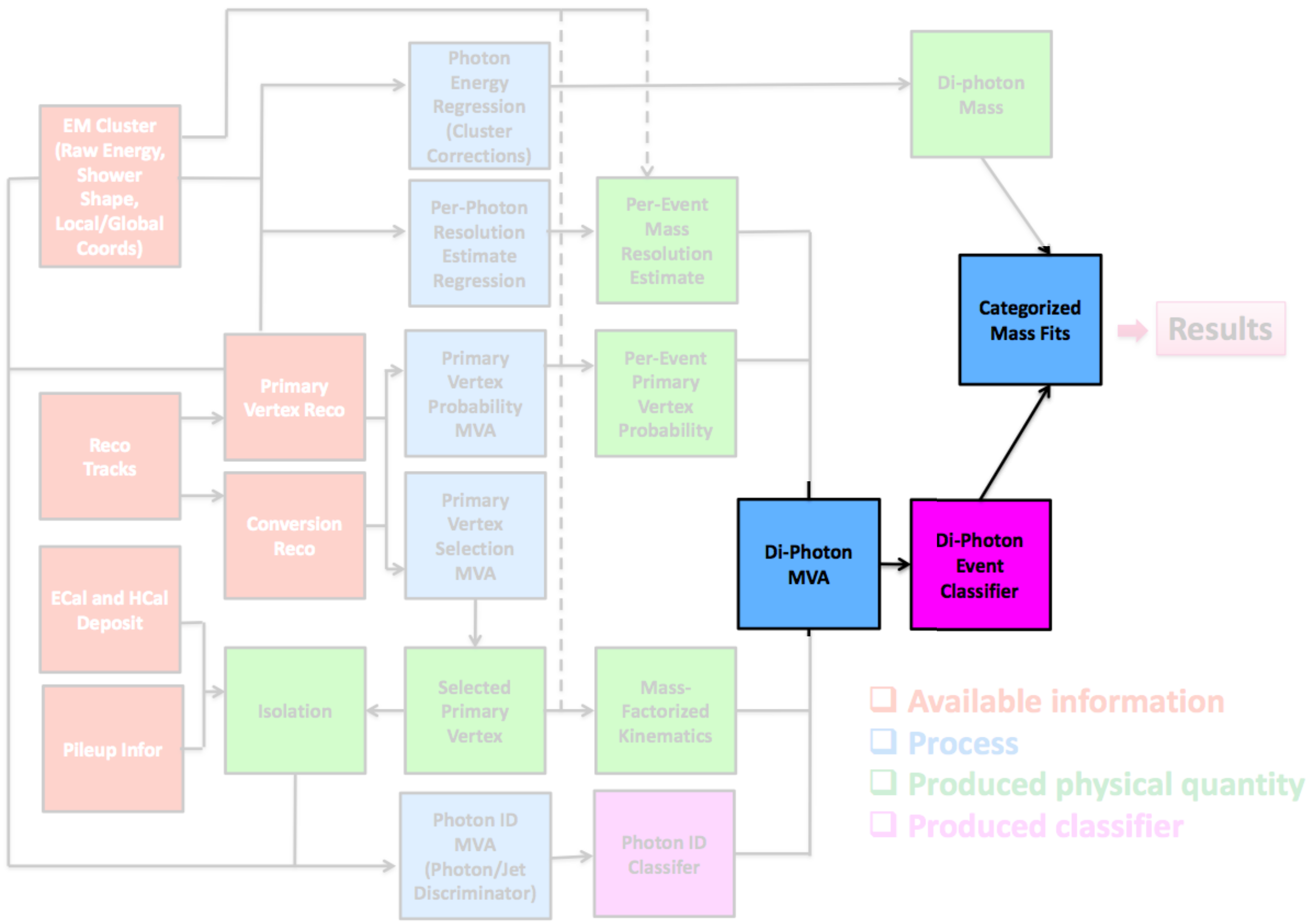


Is the best vertex the right one for this event?

- Make use of several event quantities:
  - Total number of vertices.
  - For each vertex:
    - MVA score.
    - Distance to best vertex.
  - Di-photon p_T.
  - Number of identified conversions.
- Validation in $Z \rightarrow \mu\ \mu$ events. ➔

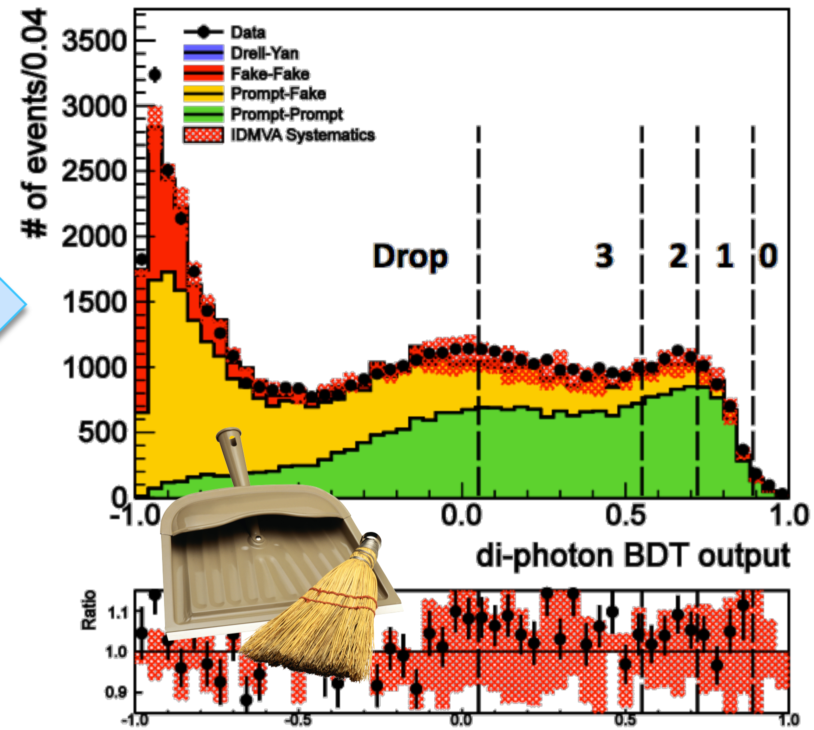


Anatomy of the analysis

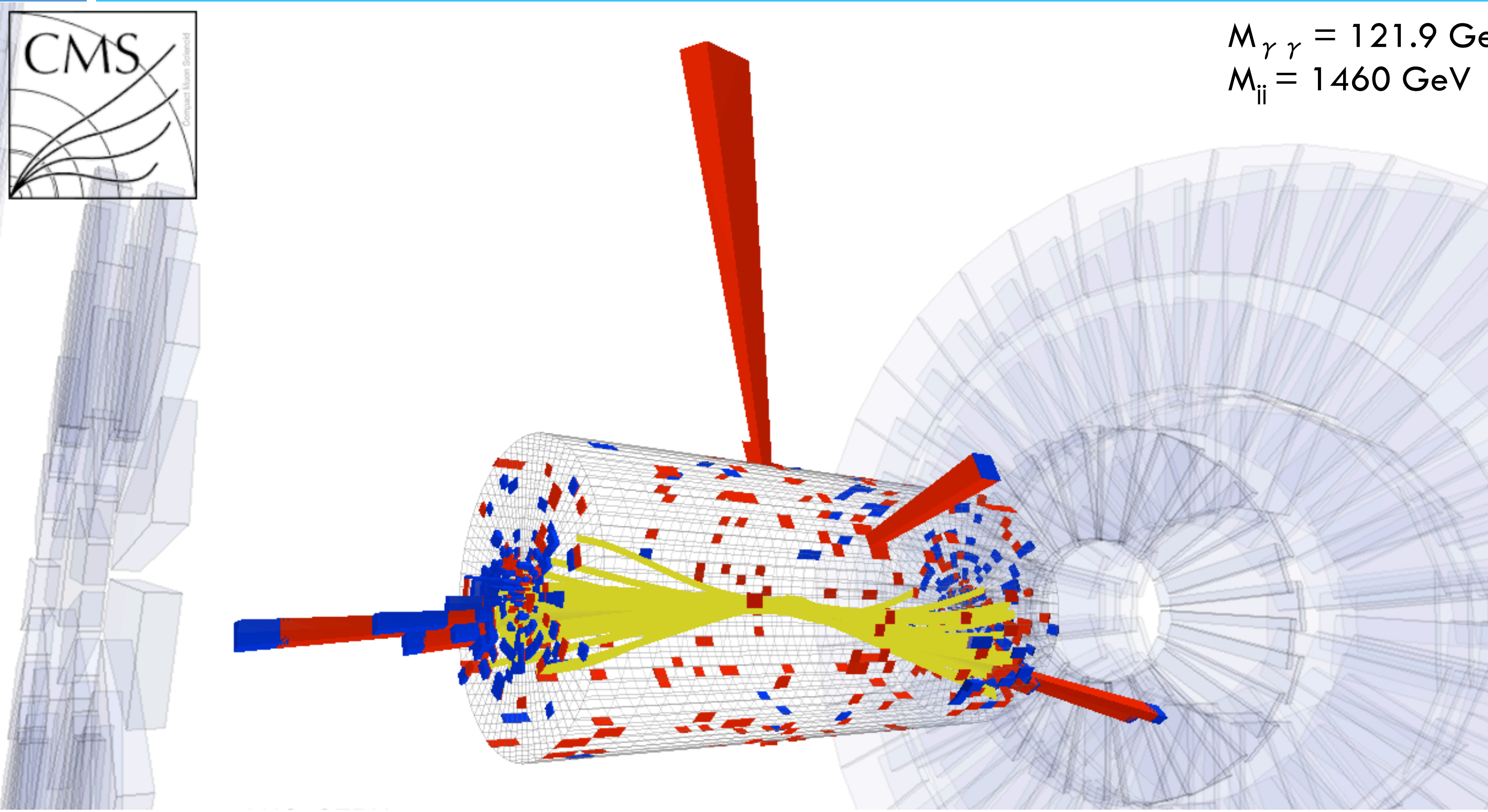


Di-photon classification

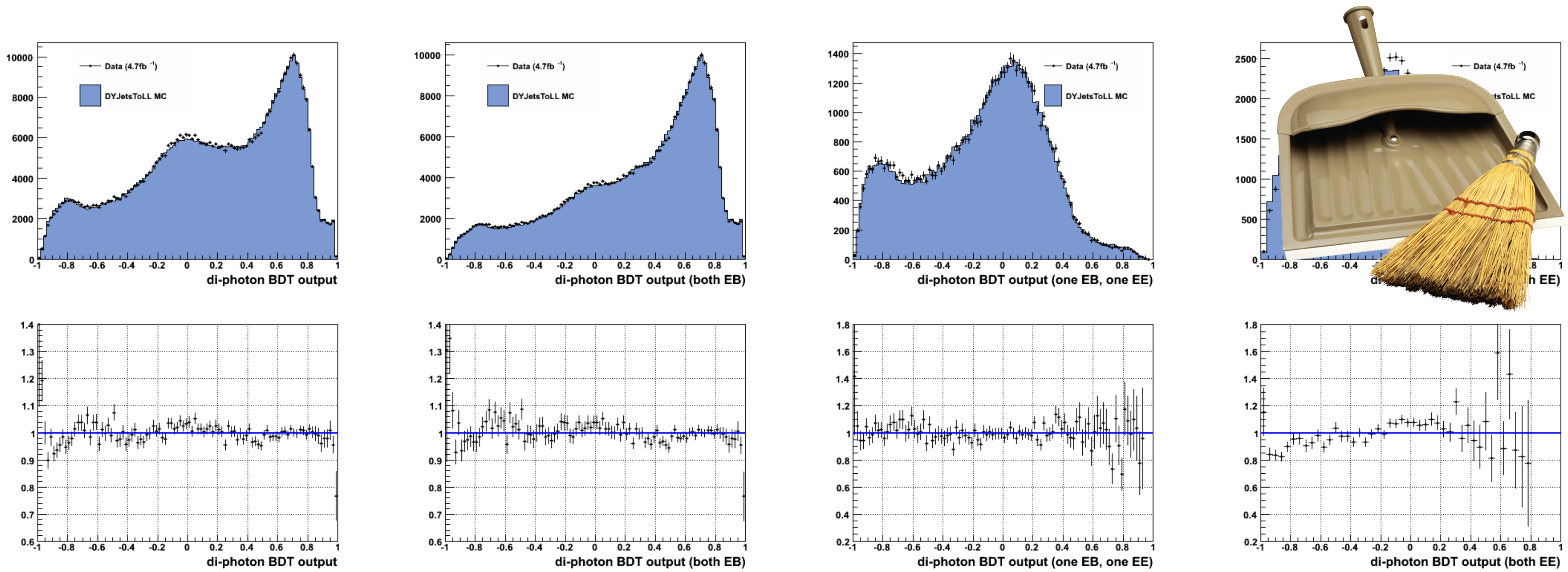
- Uses BDT method on MC background and Higgs boson signal events (m_H=123GeV)
- Training variables include photon ID, kinematics, right vertex probability and estimate mass resolution
- Keep Di-photon mass factorized
- Introduce good resolution as a desired feature by weighting signal events by 1/estimate mass resolution
- MVA output used to make 5 categories with different S/B
- Separate di-jet tagged category to select VBF Higgs production
- Signal event category migration systematics
  - Up to 11% due to photon ID
  - Up to 8% due to estimate mass resolution



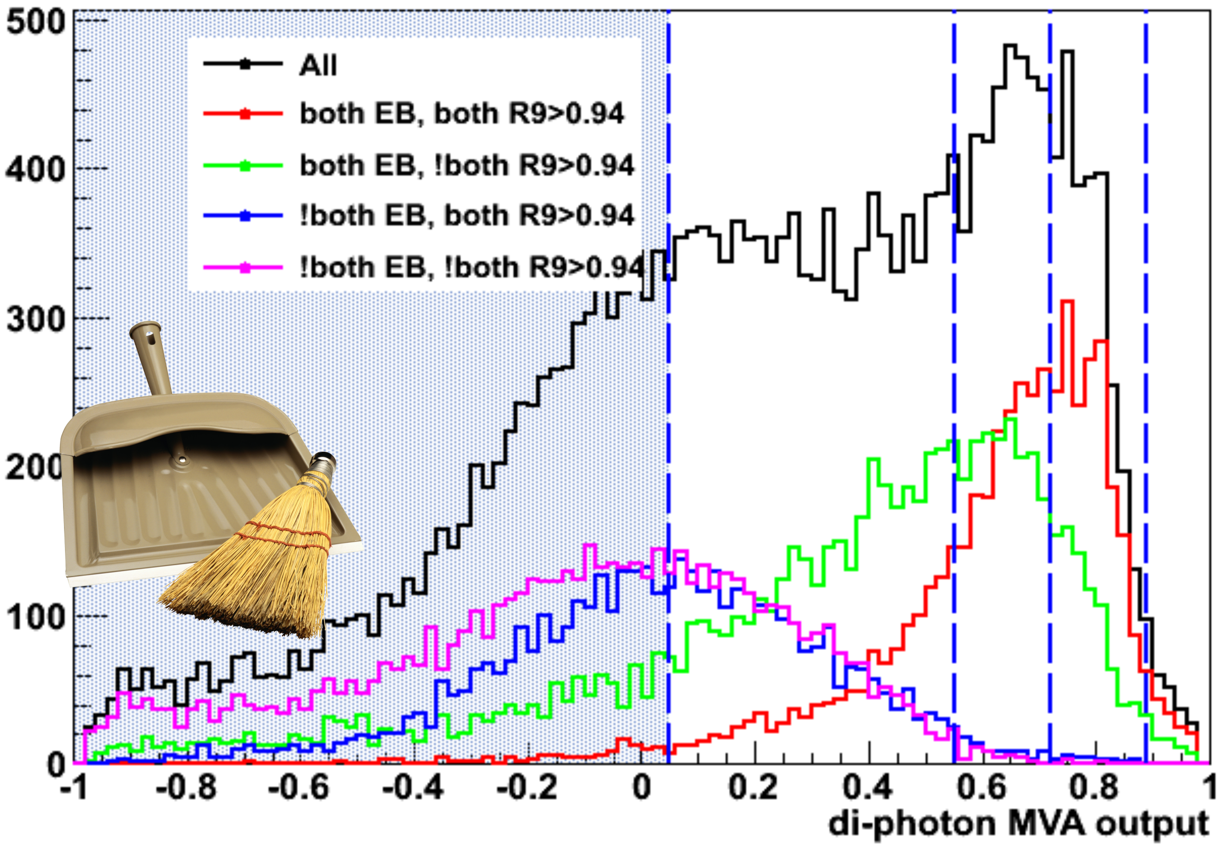
Di-jet tagged event



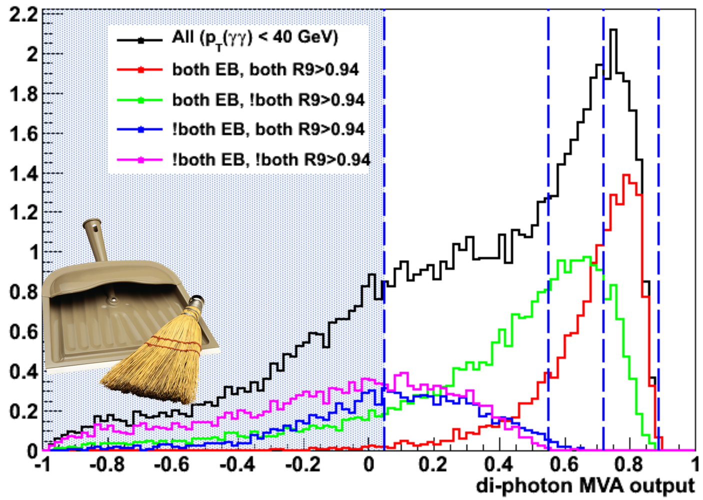
MVA validation on Z→ee

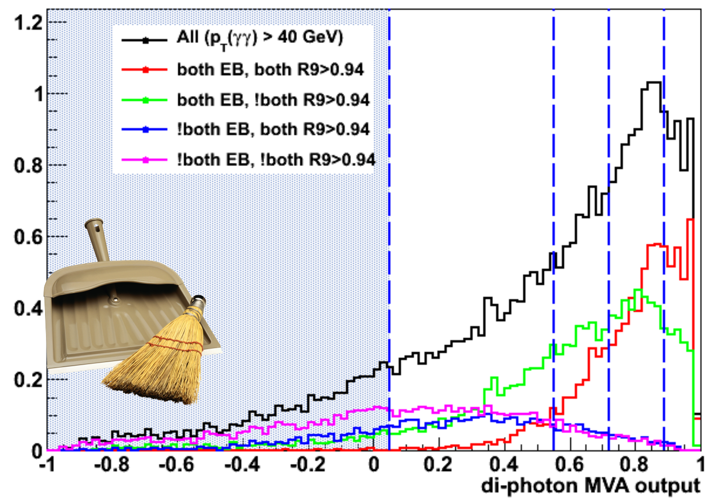


MVA in terms of simple classification



MVA in $p_T(\gamma\ \gamma)$ bins

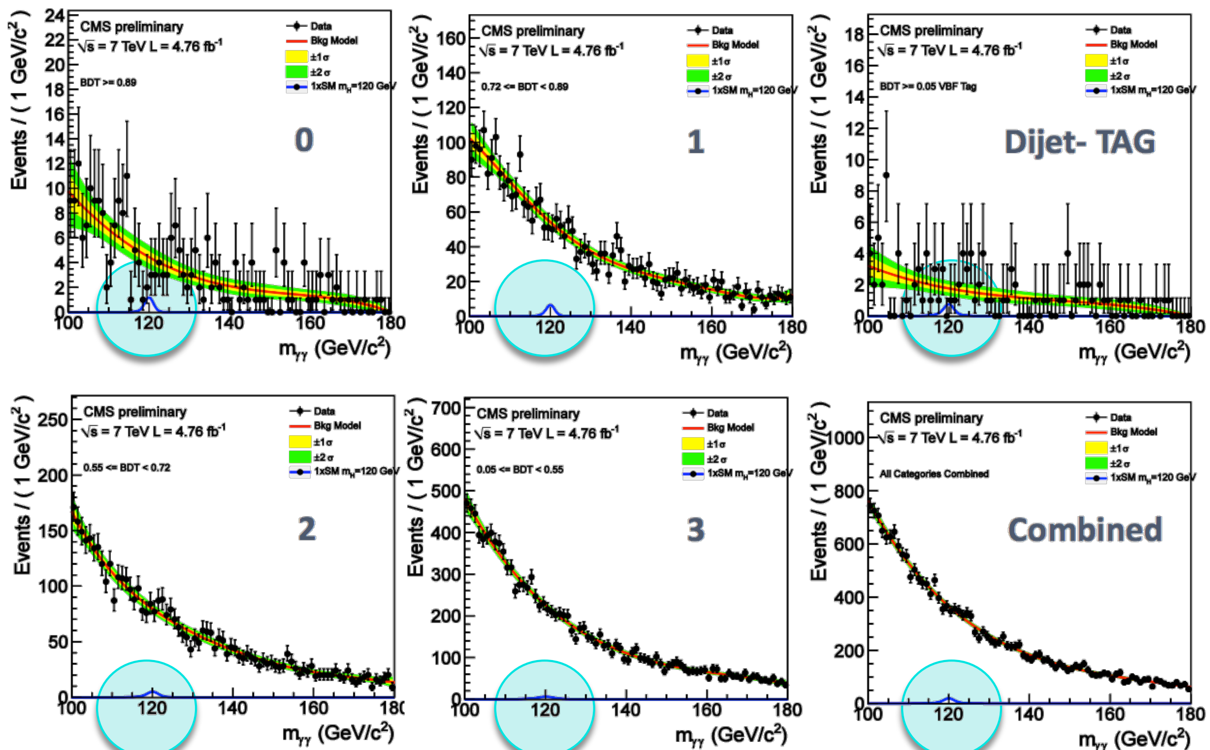




Signal and background modeling

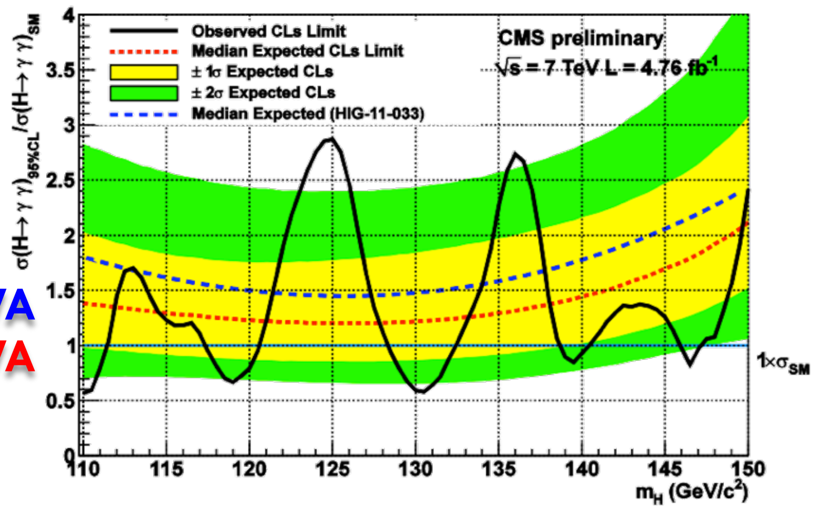
- Higgs mass modeled using MC with energy scale and resolution correction from $Z \rightarrow ee$
- Background mass spectrum modeled by polynomial fit
  - Polynomial order between 3 and 5 depending on event category statistics

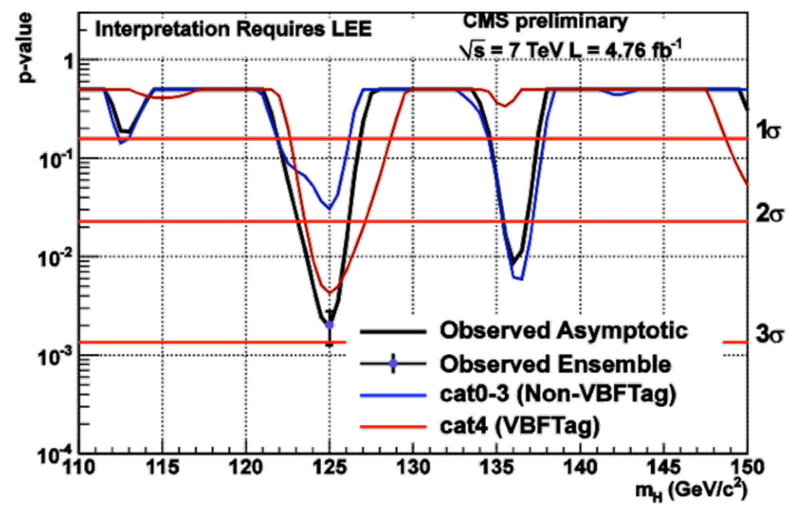
m_H = 120 GeV
1 × SM



Results

No MVA
MVA

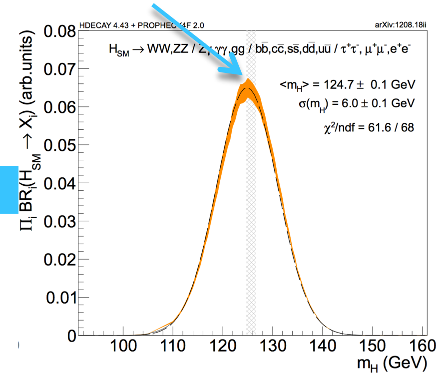




- Expected and observed exclusion limit at 95% CL
- Largest excess observed around 125 GeV with local significance 2.9 σ and global significance 1.6 σ

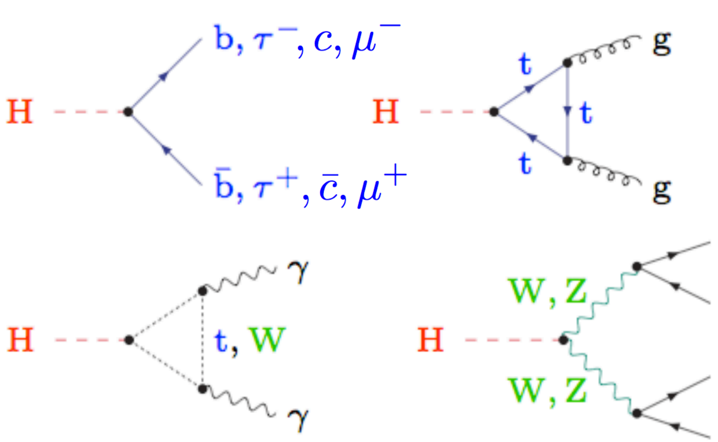
How SM Higgses die

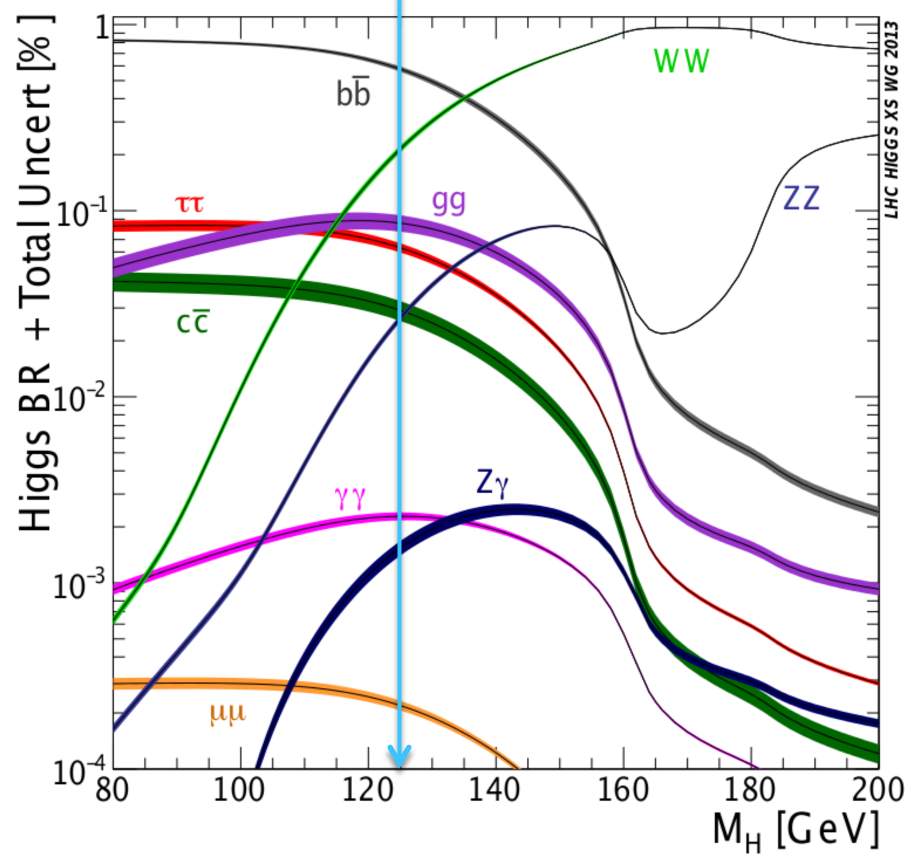
[http://cern.ch/go/qkh6][arXiv:1208.1993][arXiv:1408.0827]



Near to maximal ΠBR_i ⟶

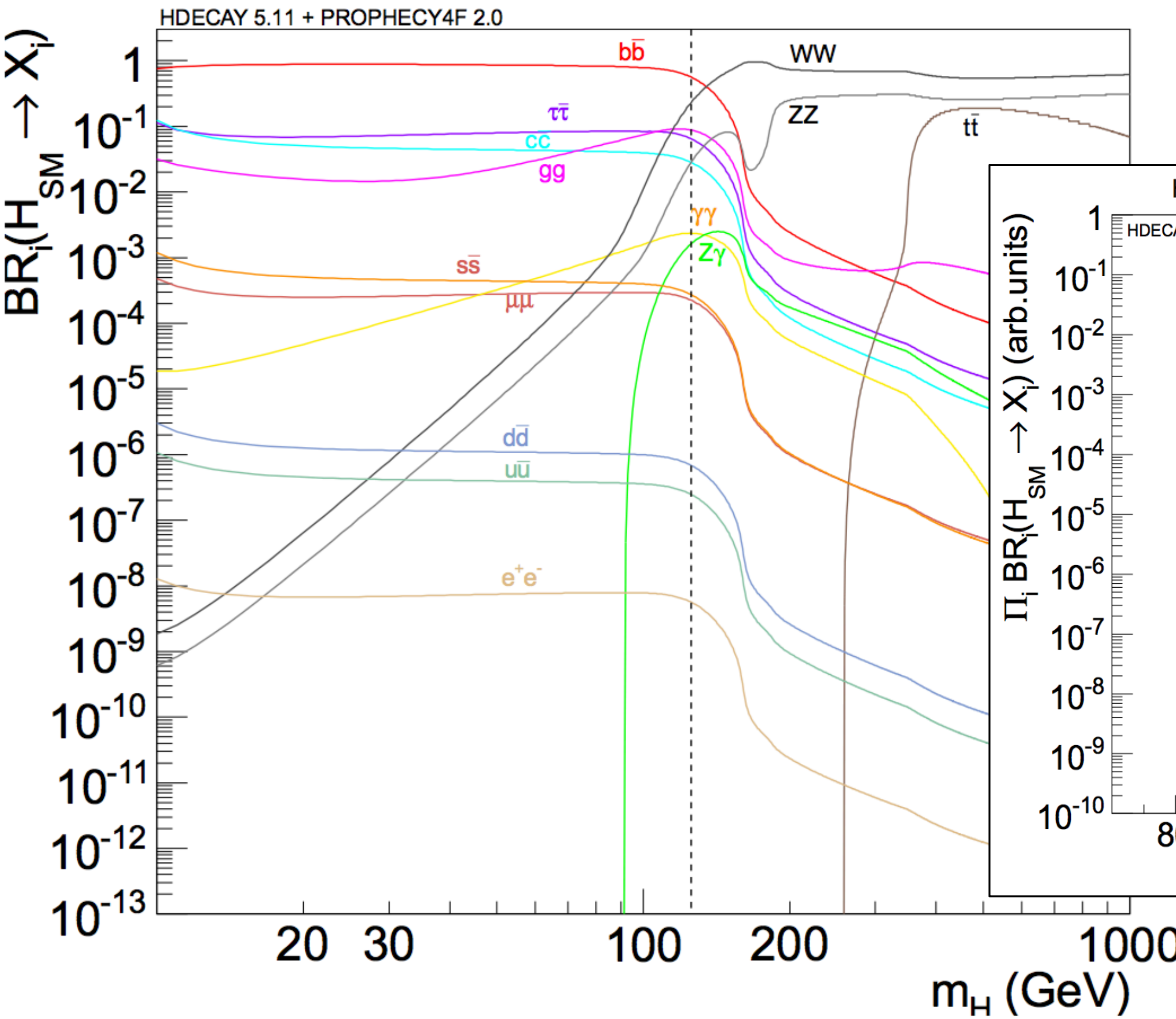
- Couplings and kinematics drive BR ($b\bar{b}$, WW, $\tau\tau$, ZZ).
  - Decays with photons ($\gamma\gamma$, $Z\gamma$) through loops.



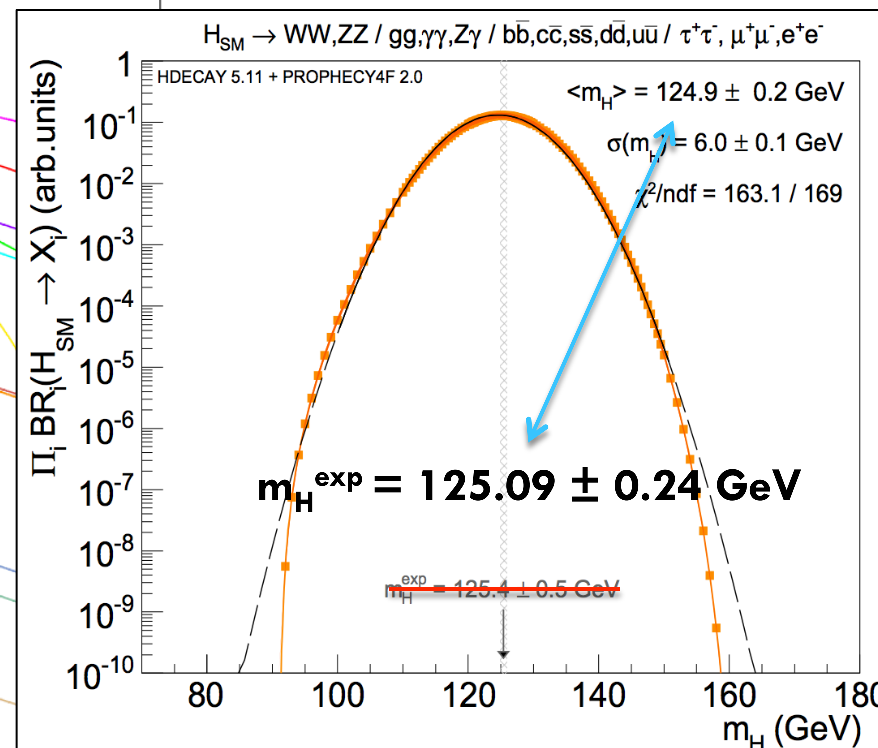


The product coincidence

[arXiv:1208.1993]



$$S_{Shannon} = - \Pi_i \, p_i$$



The information/entropy connection

[arXiv:1208.1993][arXiv:1408.0827]

Multinomial entropy: recent asymptotic formula.

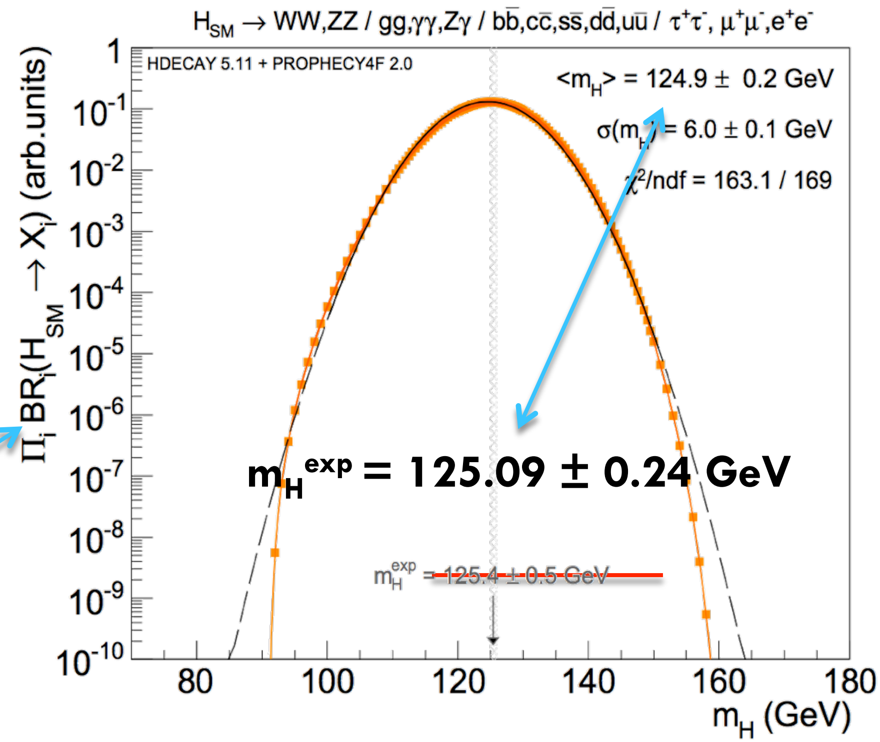
The total entropy is now given by the sum of the multinomial distribution of N Higgs bosons decaying to each possible partition of n_1 particles of type 1, n_2 of type 2, and so on until the m-th mode

$$\begin{aligned} S_N &= \sum_{\{n\}}^{N} -P(\{n_k\}_{k=1}^{m}) \ln\left[P(\{n_k\}_{k=1}^{m})\right] \\ &= \langle -\ln(P)\rangle \end{aligned} \tag{8}$$

where $\sum_{\{n\}}^{N}(\bullet) \equiv \sum_{n_1=0}^{N} \cdots \sum_{n_m=0}^{N}(\bullet) \times \delta\left(N - \sum_{i=1}^{m} n_i\right)$.

The number of possible configurations involved in the sum of Eq. (8) is huge for large N. Recently, an asymptotic formula up to order $1/N$ has been derived [10] and is given right below at Eq. (9)

$$\begin{aligned} S_N &= \frac{1}{2}\ln\left((2\pi N e)^{m-1}\prod_{k=1}^{m} p_k\right) \\ &\quad \cancel{+ \frac{1}{12N}\left(3m - 2 - \sum_{k=1}^{m}\frac{1}{p_k}\right) + O\left(\frac{1}{N^2}\right)} \end{aligned} \tag{9}$$



$m_H^{exp} = 125.09 \pm 0.24$ GeV

The information/entropy connection

[arXiv:1208.1993][arXiv:1408.0827]

m_H cannot be predicted. Or could it?

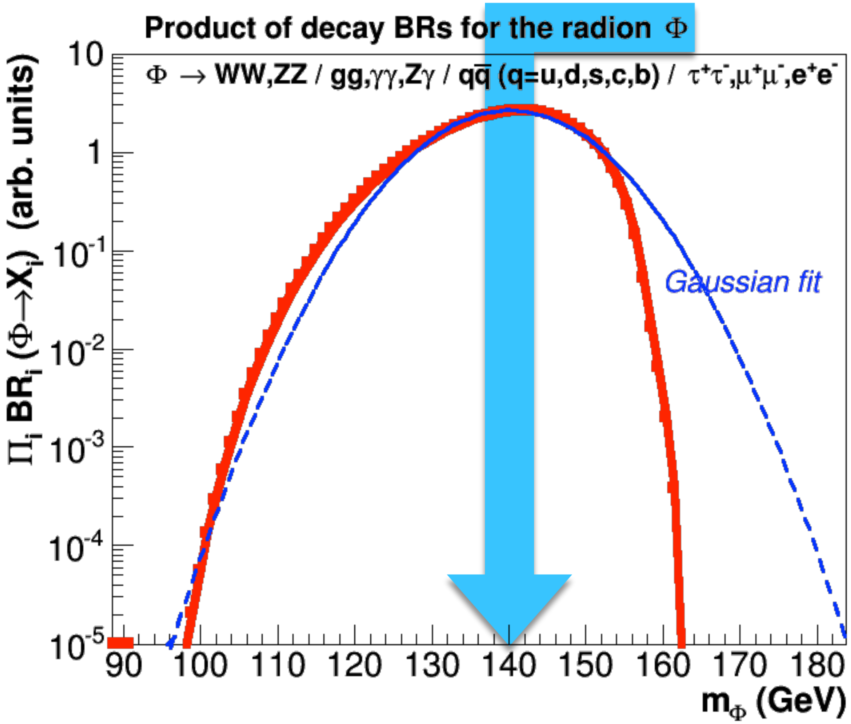
The total entropy is now given by the sum of the multinomial distribution of N Higgs bosons decaying to each possible partition of n_1 particles of type 1, n_2 of type 2, and so on until the m-th mode

$$S_N = \sum_{\{n\}}^{N} -P(\{n_k\}_{k=1}^{m}) \ln\left[P(\{n_k\}_{k=1}^{m})\right] = \langle -\ln(P)\rangle \quad (8)$$

where $\sum_{\{n\}}^{N}(\bullet) \equiv \sum_{n_1=0}^{N}\cdots\sum_{n_m=0}^{N}(\bullet)\times\delta\left(N-\sum_{i=1}^{m} n_i\right)$.

The number of possible configurations involved in the sum of Eq. (8) is huge for large N. Recently, an asymptotic formula up to order $1/N$ has been derived [10] and is given right below at Eq. (9)

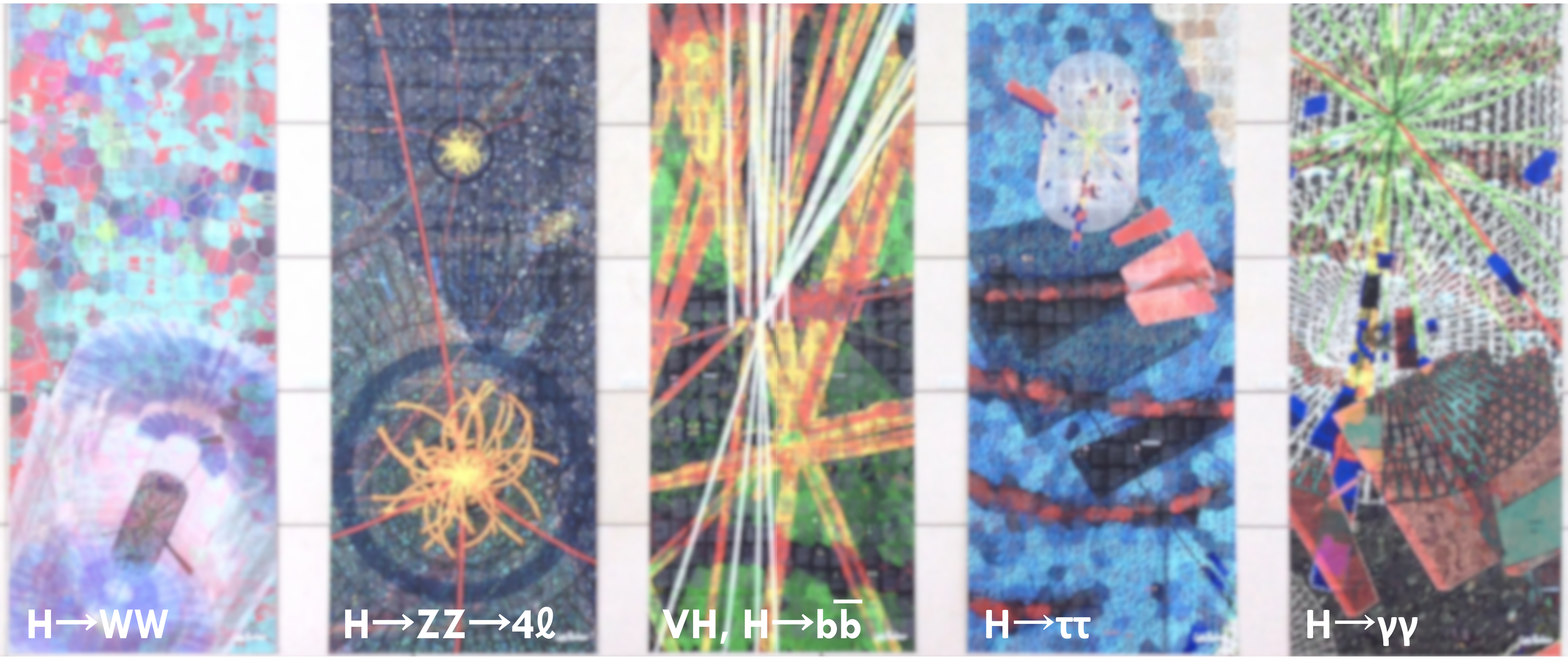
$$S_N = \frac{1}{2}\ln\left((2\pi N e)^{m-1}\prod_{k=1}^{m} p_k\right) + \cancel{\frac{1}{12N}\left(3m-2-\sum_{k=1}^{m}\frac{1}{p_k}\right)+O\left(\frac{1}{N^2}\right)} \quad (9)$$



More on the CMS combination

Bringing it all together in CMS

[arXiv:1412.8662]



JHEP 01(2014) 096 | **PRD 89 (2014) 092007** | **PRD 89 (2014) 012003** | **JHEP 05 (2014) 104** | **EPJC 74 (2014) 3076**

Also include further ttH searches:

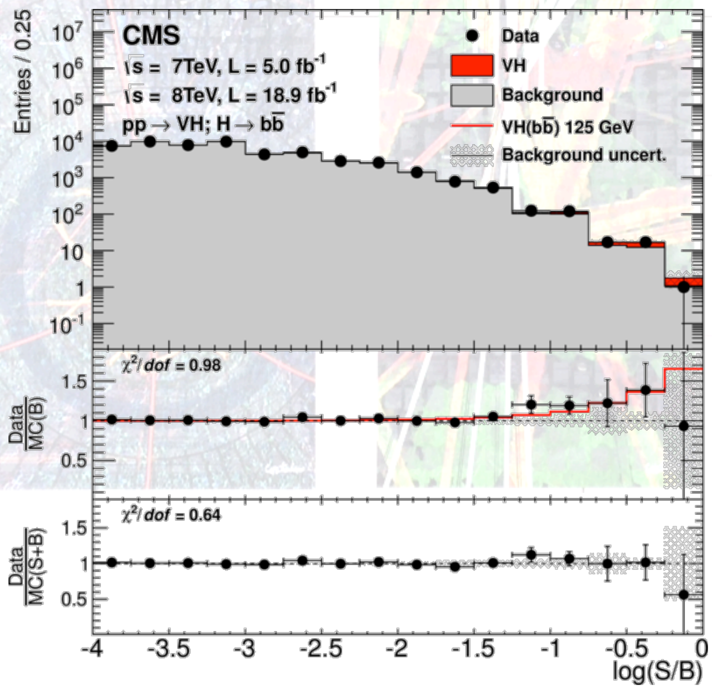
- JHEP 05(2013)145 – ttH, $H \to b\bar{b}$ (7 TeV).
- arXiv:1408.1682 (subm. to JHEP) – ttH, $H \to b\bar{b}$, $H \to \tau\tau$, and H decaying to multiple leptons (8 TeV).

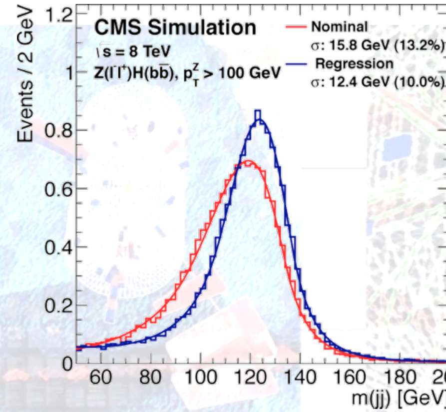
VH, H→b$\bar{b}$ vignettes

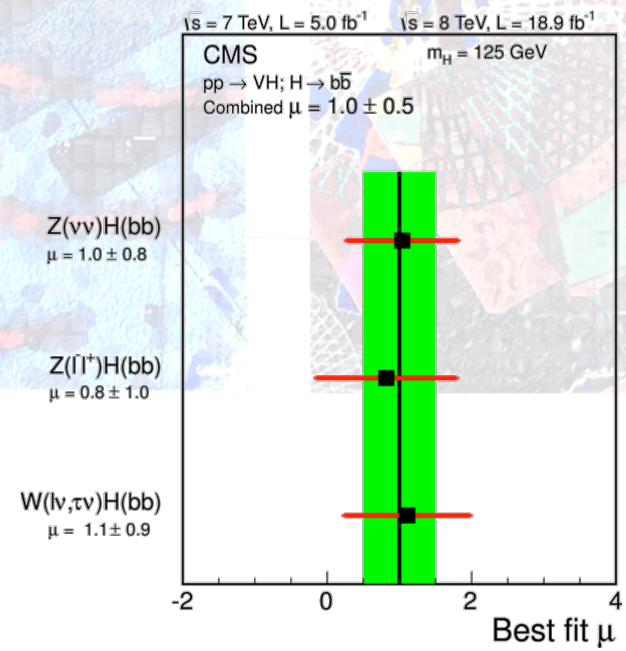
[PRD 89 (2014) 012003]

PRD 89 (2014) 012003

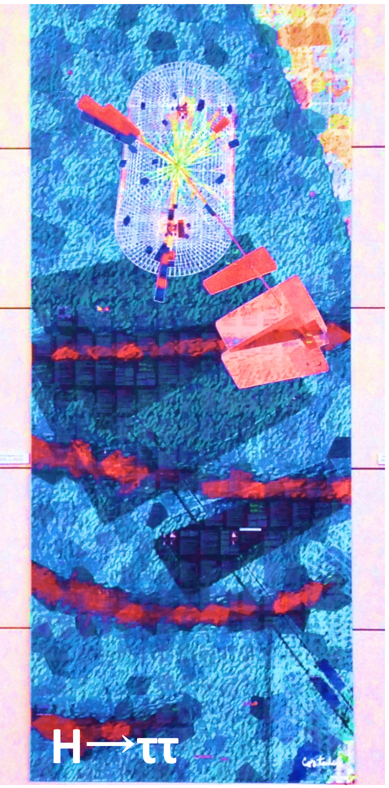
- 2.1σ (2.3σ exp.)
- σ/σ_{SM} = 1.0 ±0.5





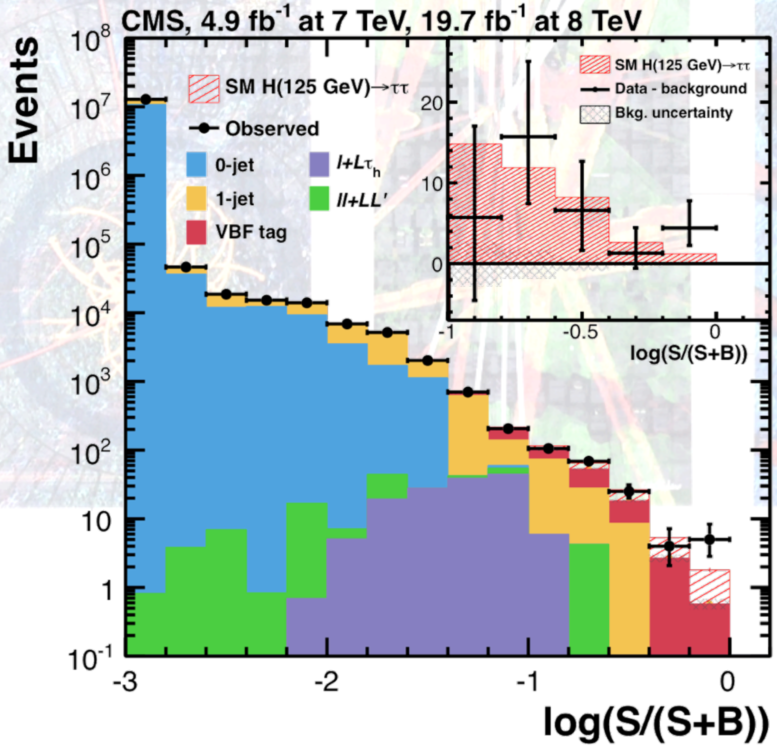


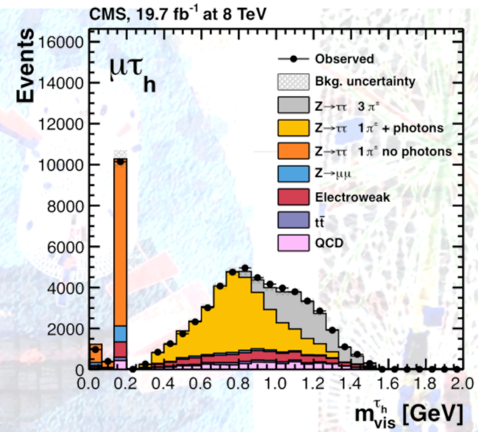
$H \to \tau\tau$ vignettes

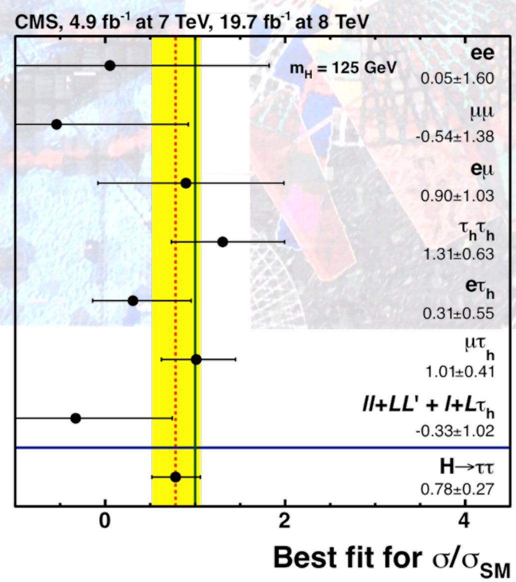


JHEP 05 (2014) 104

- 3.2σ (3.7σ exp.)
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$

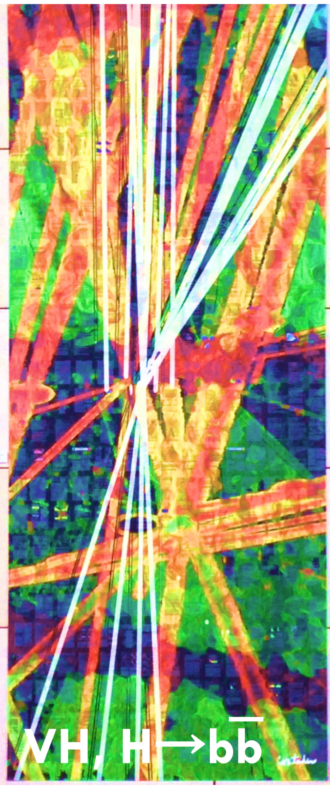




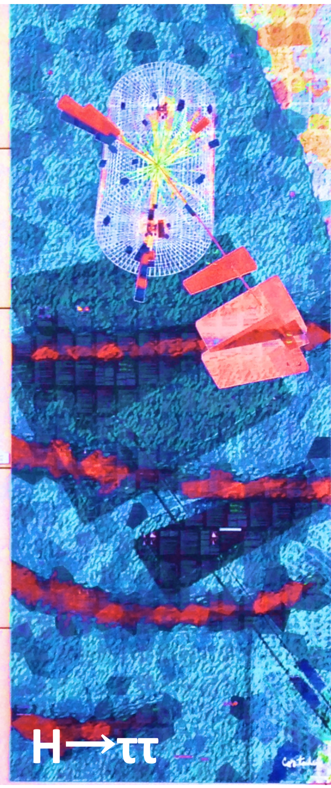


Fermion decay combination vignette

[Nature Physics 10 (2014) 557]

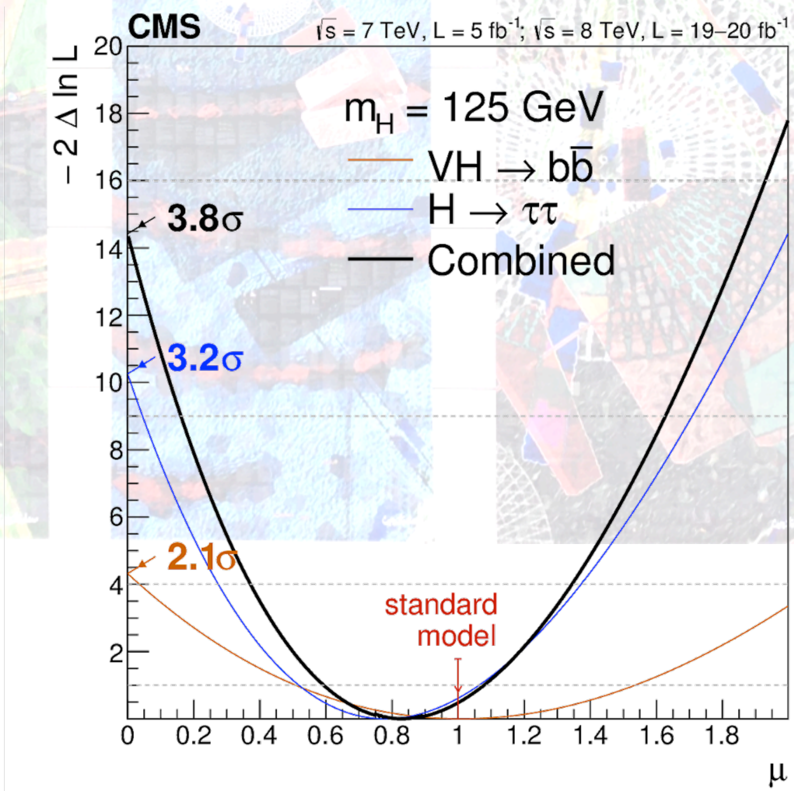


PRD 89 (2014) 012003



JHEP 05 (2014) 104

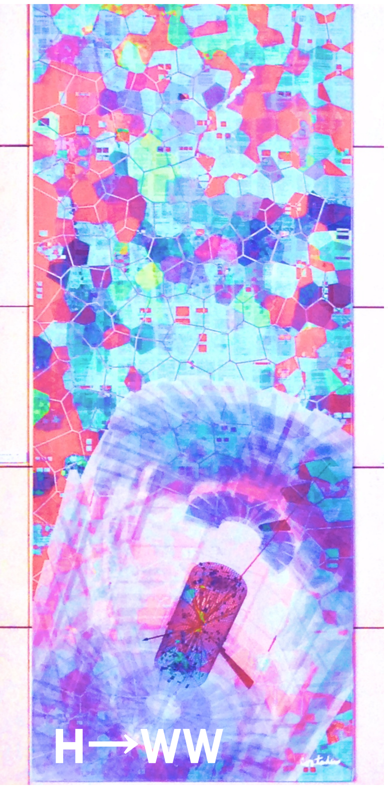
- 3.8σ (4.4σ exp.)
- $\sigma/\sigma_{SM} = 0.83 \pm 0.24$



Fermion decay combination
3.8σ obs. (4.4σ exp.)
Nature Physics 10 (2014) 557

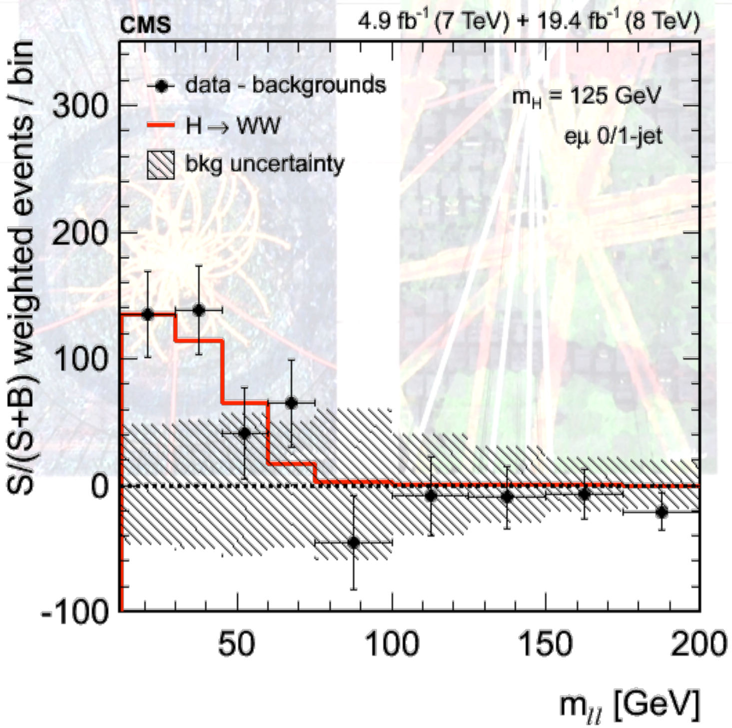
H→WW→2ℓ2ν vignettes

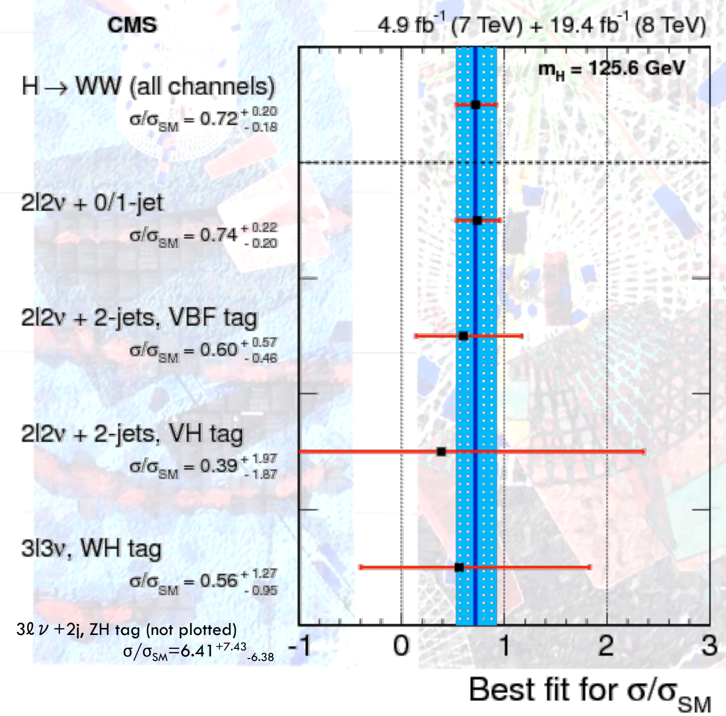
[JHEP 01 (2014) 096]



JHEP 01 (2014) 096

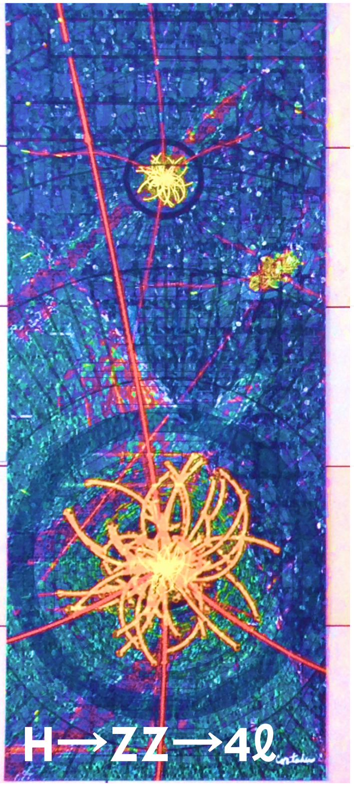
- 4.3σ (5.8σ exp.)
- $\sigma/\sigma_{SM} = 0.72 \pm 0.19$





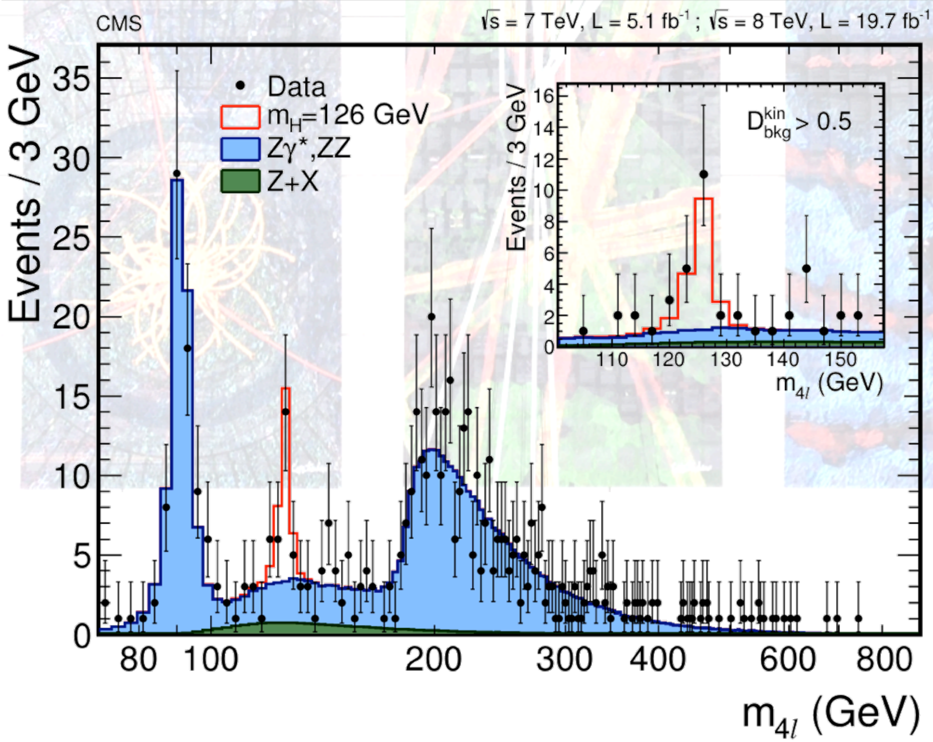
H→ZZ→4ℓ vignettes

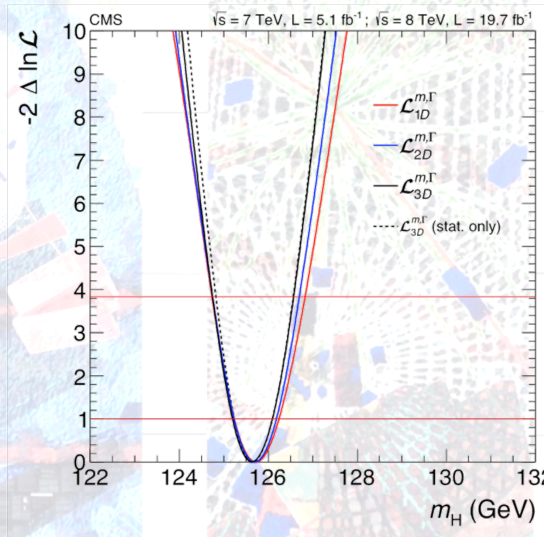
[PRD 89 (2014) 092007]

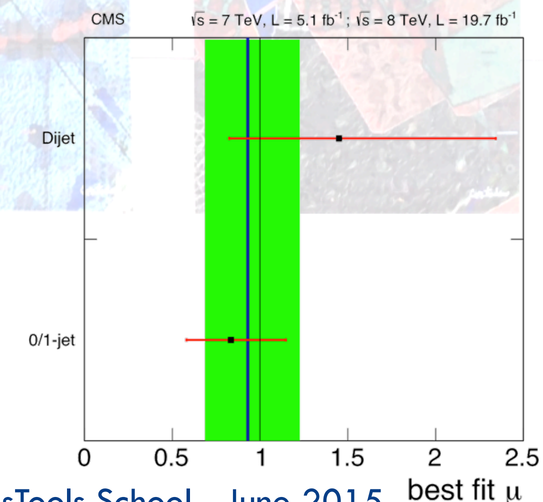


PRD 89 (2014) 092007

- 6.8σ (6.7σ exp.)
- m_H= 125.63 ±0.42 (stat.) ±0.16 (syst.) GeV
- σ/σ_{SM} = 0.93 ±0.25 (stat.) ±0.13 (syst.)





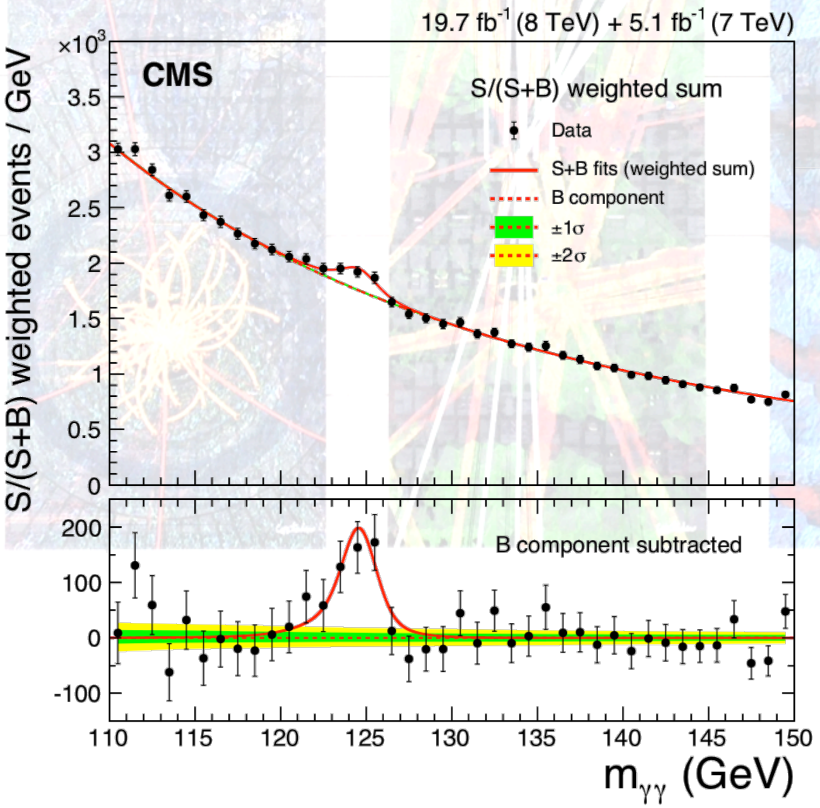


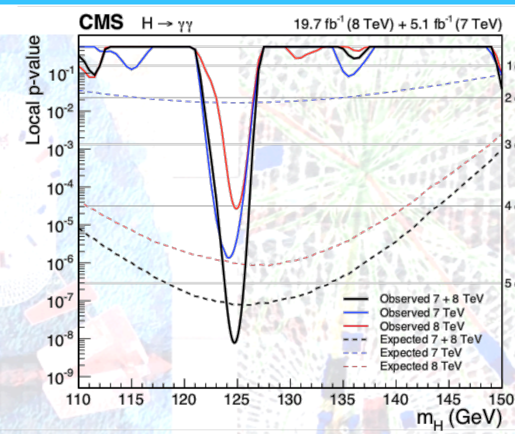
$H\to\gamma\gamma$ vignettes

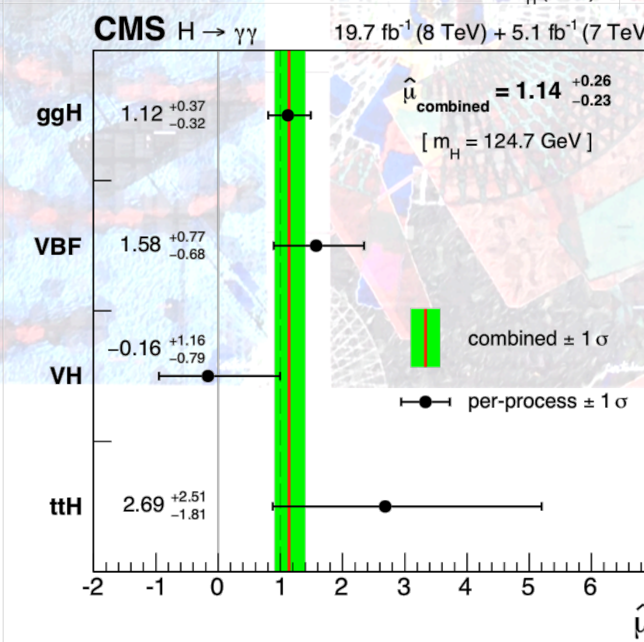
[EPJC 74 (2014) 3076]

EPJC 74 (2014) 3076

- 5.7σ (5.2σ exp.)
- m_H= 124.70 ±0.31 (stat.) ±0.15 (syst.) GeV
- σ/σ_{SM} = 1.14 ±0.21 (stat.) ±0.11 (theo.) ±0.07 (syst.)

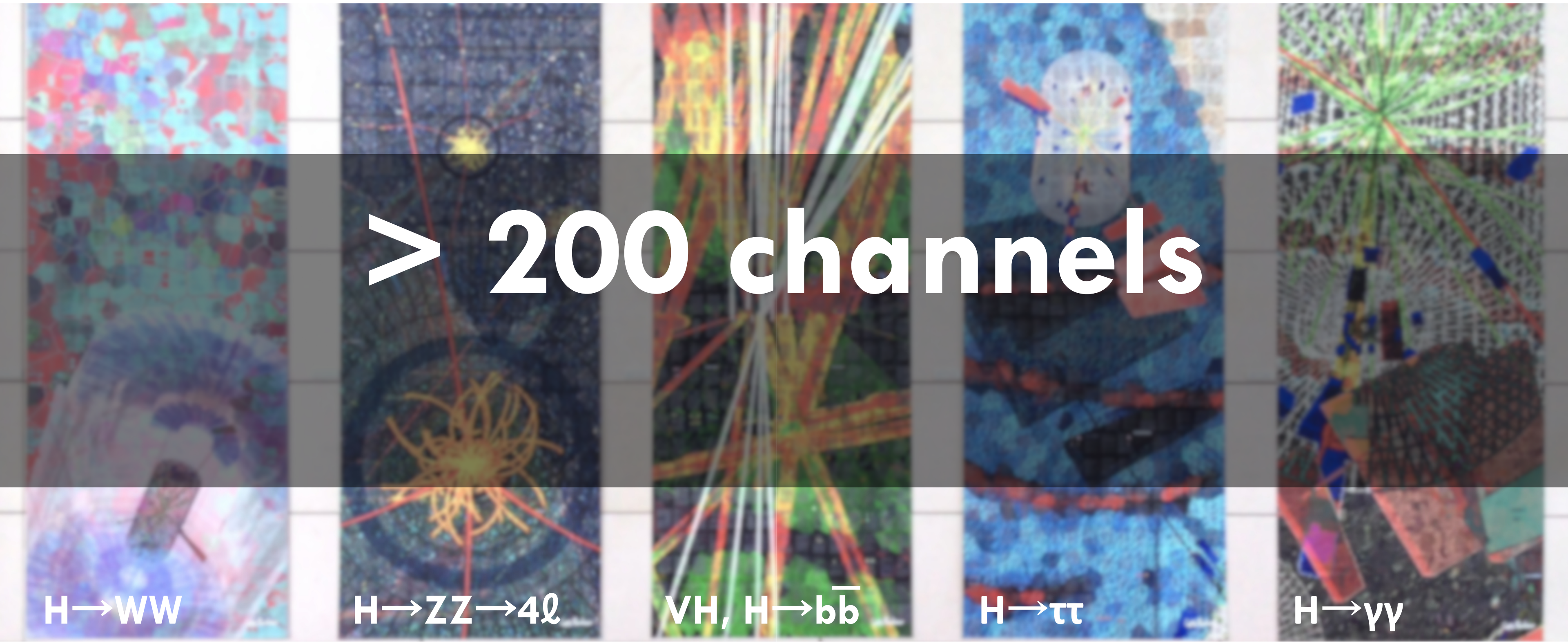






Bringing it all together in CMS

[arXiv:1412.8662]



JHEP 01(2014) 096 | **PRD 89 (2014) 092007** | **PRD 89 (2014) 012003** | **JHEP 05 (2014) 104** | **arXiv:1407.0558 (subm. to EPJC)**

Also include further ttH searches:

- JHEP 05(2013)145 – ttH, H→bb̄ (7 TeV).
- arXiv:1408.1682 (subm. to JHEP) – ttH, H→bb̄, H→ττ, and H decaying to multiple leptons (8 TeV).

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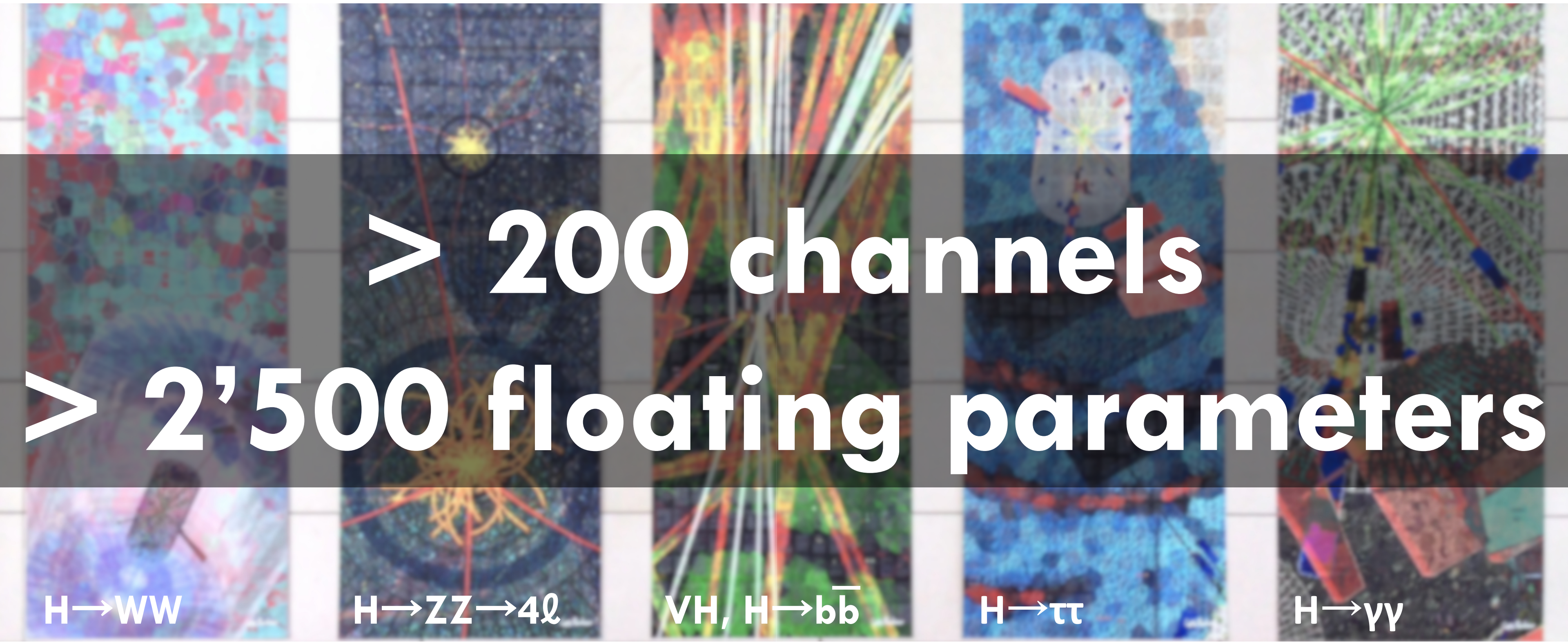

JHEP 01(2014) 096	PRD 89 (2014) 092007	PRD 89 (2014) 012003	JHEP 05 (2014) 104	arXiv:1407.0558 (subm. to EPJC)

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The challenge of combining

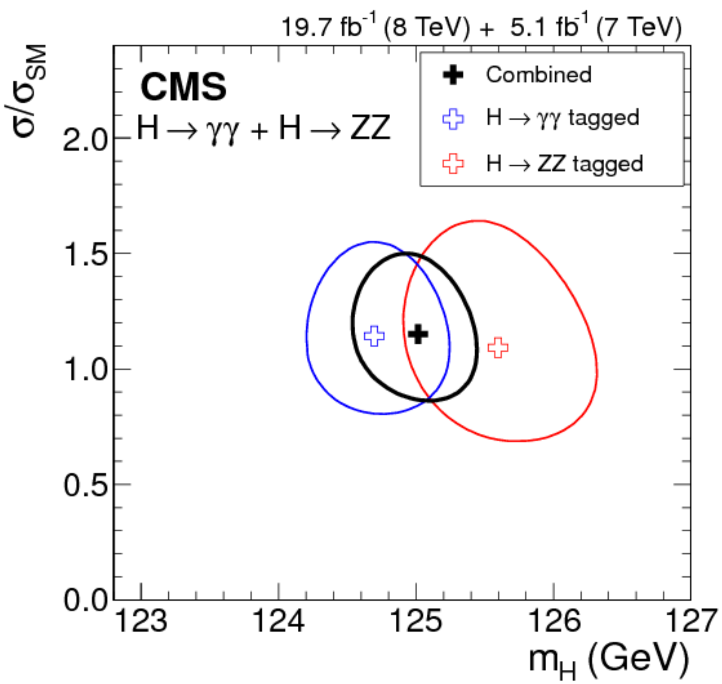
[arXiv:1412.8662]

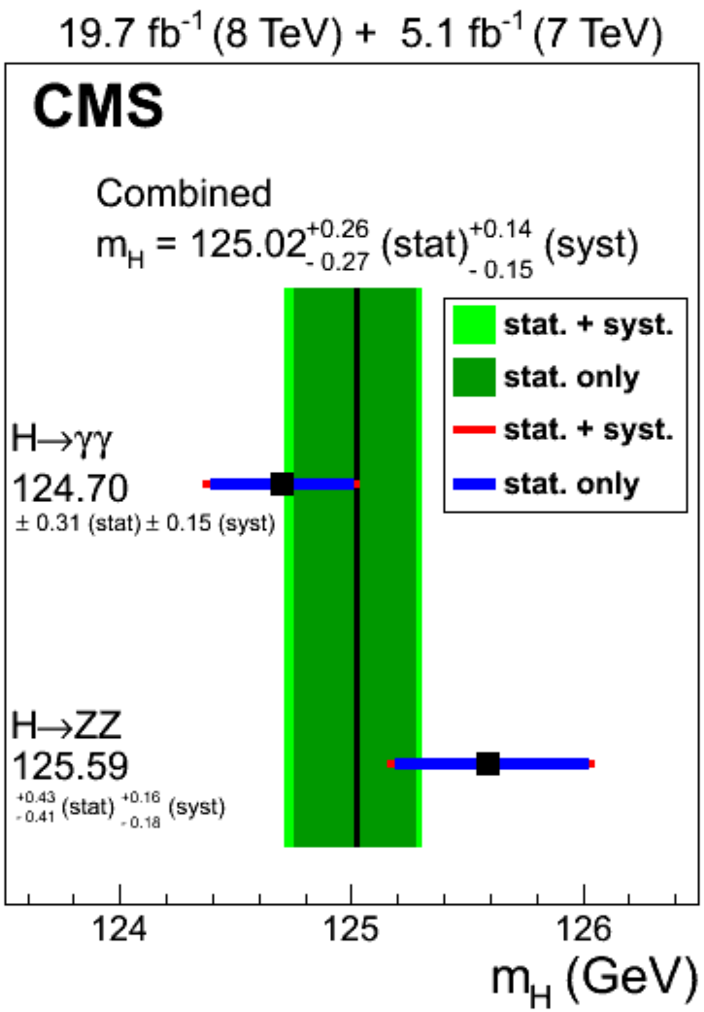
- Include **five main decays** and searches for **ttH production.**
- **207 channels.**
- **2519 parameters.**
  - 219 H→γγ background parameters.

Decay tag and production tag		Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) No. of categories 7 TeV	8 TeV
$H \to \gamma\gamma$ [20], Section 2.1				*5.1*	*19.7*
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic $t\bar{t}H$	≈95% $t\bar{t}H$	1.1%	$1^{\dagger}$	1
	Multijet $t\bar{t}H$	>90% $t\bar{t}H$	1.1%		1
$H \to ZZ^{(*)} \to 4\ell$ [18], Section 2.2				*5.1*	*19.7*
4μ, $2e2\mu$, $4e$	2-jet	42% VBF + VH	1.3, 1.8, 2.2%‡	3	3
	Other	≈90% ggH		3	3
$H \to WW^{(*)} \to \ell\nu\ell\nu$ [17], Section 2.3				*4.9*	*19.4*
$ee + \mu\mu$, $e\mu$	0-jet	96–98% ggH	$e\mu$: 16%‡	2	2
	1-jet	82–84% ggH	$e\mu$: 17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
$3\ell 3\nu$ WH	SF-SS, SF-OS	≈100% WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu jj$ ZH	eee, $ee\mu$, $\mu\mu\mu$, $\mu\mu e$	≈100% ZH		4	4
$H \to \tau\tau$ [19], Section 2.4				*4.9*	*19.7*
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	-	2
	2-jet VBF	80% VBF	11%	-	1
$e\mu$	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h, \ell\tau_h, e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ ($e\mu$)		8	8
$\ell + \tau_h\tau_h$ WH		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ WH		ZH/WH ≈ 5%, 9–11% WW		2	4
VH with $H \to bb$ [16], Section 2.5				*5.1*	*18.9*
$W(\ell\nu)bb$	$p_T(V)$ bins	≈100% VH, 96–98% WH	≈10%	4	6
$W(\tau_h\nu)bb$		93% WH		-	1
$Z(\ell\ell)bb$	$p_T(V)$ bins	≈100% ZH		4	4
$Z(\nu\nu)bb$	$p_T(V)$ bins	≈100% VH, 62–76% ZH		2	3
$t\bar{t}H$ with $H \to$ hadrons [14, 28], Section 2.6				*5.0*	*19.3*
$H \to bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% $\tau\tau$		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% $\tau\tau$, 13–22% WW, 5–13% bb		-	6
$t\bar{t}H$ with $H \to$ leptons [29], Section 2.6				-	*19.6*
2ℓ-SS		$WW/\tau\tau \approx 3$		-	6
3ℓ		$WW/\tau\tau \approx 3$		-	2
4ℓ		$WW : \tau\tau : ZZ \approx 3:2:1$		-	1

Combined m_H measurement

[arXiv:1412.8662]

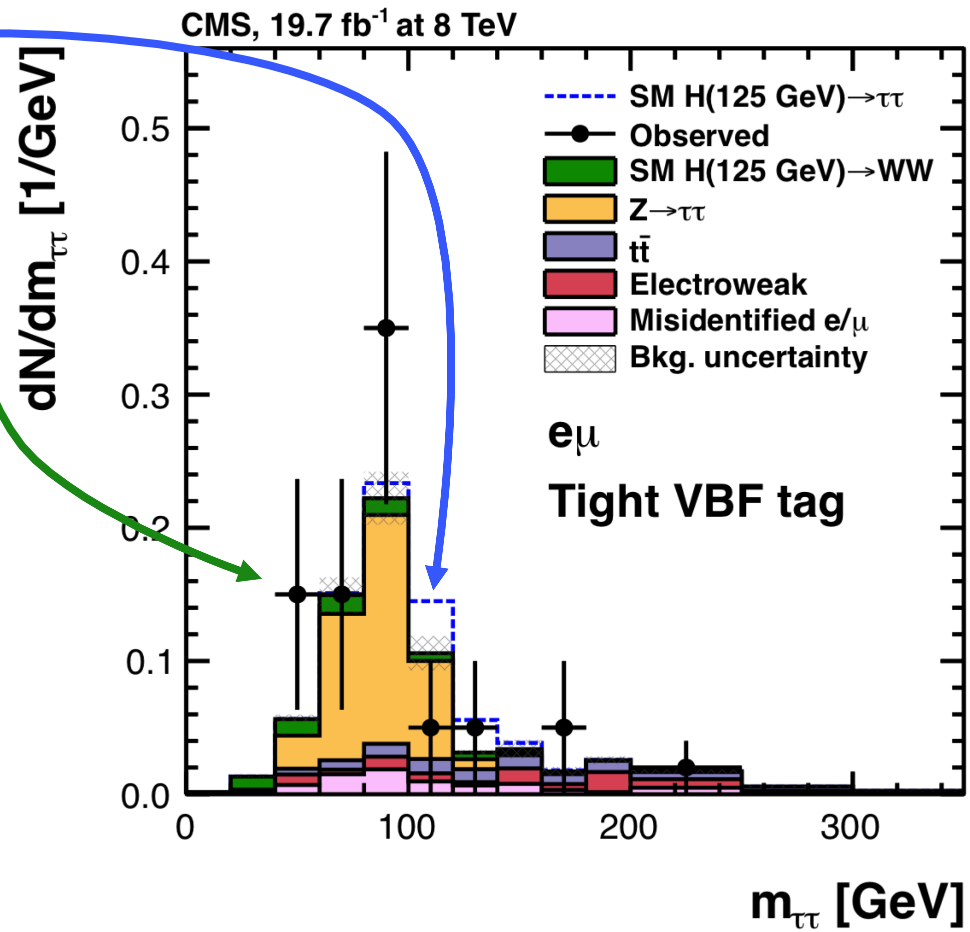




Extra Higgs sensitivity in H→ττ analysis

[JHEP 05 (2014) 104][arXiv:1412.8662]

- H→ττ analysis has **sensitivity** to:
  - **H→ττ decays**, and
  - **H→WW decays.**
- H→WW treatment:
  - **In combination: signal.**
    - 3.9σ obs. (3.9σ exp.)
  - **In H→ττ paper: SM background.**
    - 3.2σ obs. (3.7σ exp.)



$H \rightarrow VV$ results in combination

[JHEP 01 (2014) 096][PRD 89 (2014) 092007][arXiv:1412.8662]

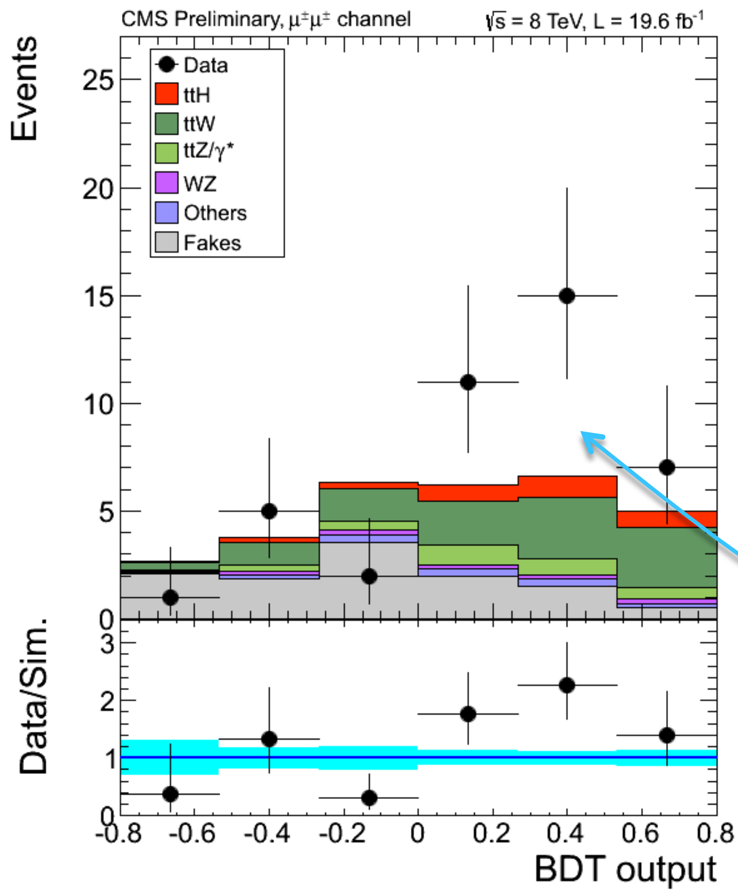
- What changed?
  - **BR($H \rightarrow VV$) changes by 4 – 5%.**
    - $H \rightarrow WW$ and $H \rightarrow ZZ$ paper results evaluated at $H \rightarrow ZZ$ m_H result: **m_H = 125.6 GeV**.
    - Combined mass slightly lower: **m_H = 125.0 GeV**.
  - In the combination **$H \rightarrow WW$ includes the ttH, H decaying to multi-lepton result:** $\sigma/\sigma_{SM} = 3.7 \pm 1.5$.

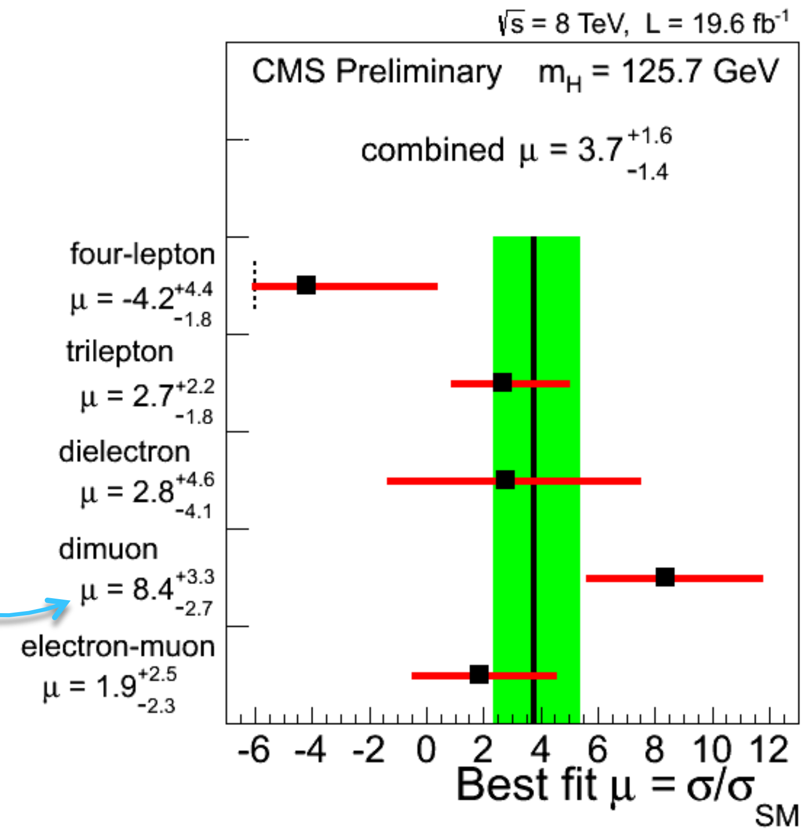
σ/σ_{SM}	Individual publication	Combination
$H \rightarrow ZZ$	0.93	1.00
$H \rightarrow WW$	0.72	0.83

ttH multi-leptons

[CMS-PAS-HIG-13-020][http://cern.ch/go/FKr9]

- Very extensive cross-checks performed: http://cern.ch/go/Xv8S





Significance of excesses

[arXiv:1412.8662]

Channel grouping	Significance (σ) Observed	Expected
$H \rightarrow ZZ$ tagged	6.5	6.3
$H \rightarrow \gamma\gamma$ tagged	5.6	5.3
$H \rightarrow WW$ tagged	4.7	5.4
Grouped as in Ref. [22]	*4.3*	*5.4*
$H \rightarrow \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [23]	*3.9*	*3.9*
$H \rightarrow bb$ tagged	2.0	2.6
Grouped as in Ref. [21]	*2.1*	*2.5*
$H \rightarrow \mu\mu$ tagged	< 0.1	0.4

Combined production measurement

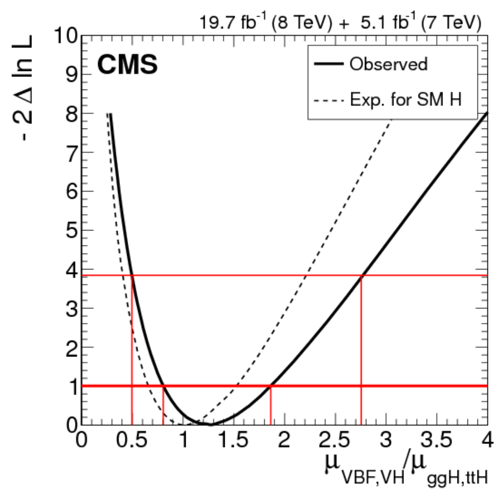
[arXiv:1412.8662]

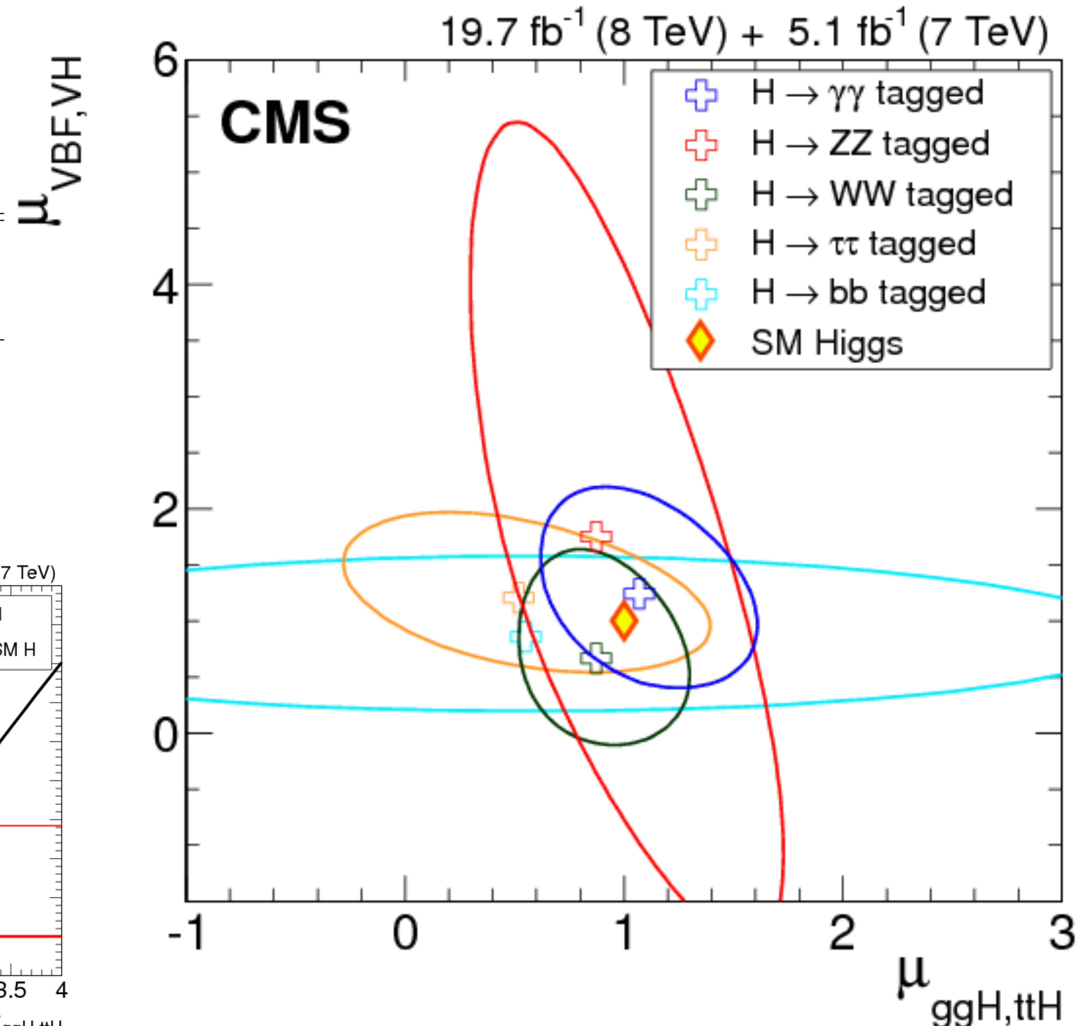
Channel grouping	Best fit $(\mu_{\mathrm{ggH,ttH}}, \mu_{\mathrm{VBF,VH}})$
$\mathrm{H} \to \gamma\gamma$ tagged	$(1.07, 1.24)$
$\mathrm{H} \to \mathrm{ZZ}$ tagged	$(0.88, 1.75)$
$\mathrm{H} \to \mathrm{WW}$ tagged	$(0.87, 0.66)$
$\mathrm{H} \to \tau\tau$ tagged	$(0.52, 1.21)$
$\mathrm{H} \to \mathrm{bb}$ tagged	$(0.55, 0.85)$

Combined best fit $\mu_{\mathrm{VBF,VH}}/\mu_{\mathrm{ggH,ttH}}$

Observed (expected)

$1.25^{+0.62}_{-0.44}$ $(1.00^{+0.49}_{-0.35})$



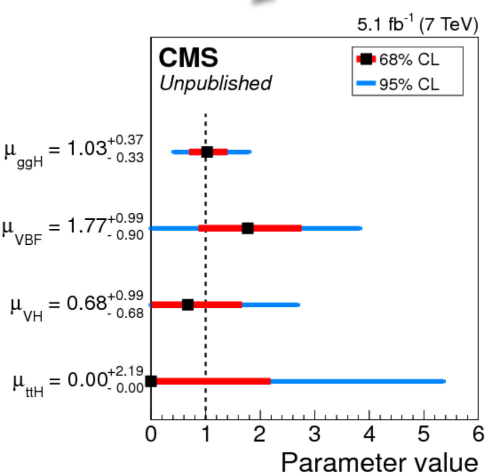


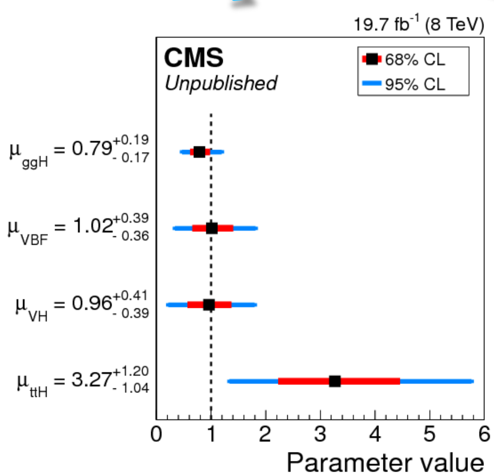
Production mode scaling assuming SM BR structure

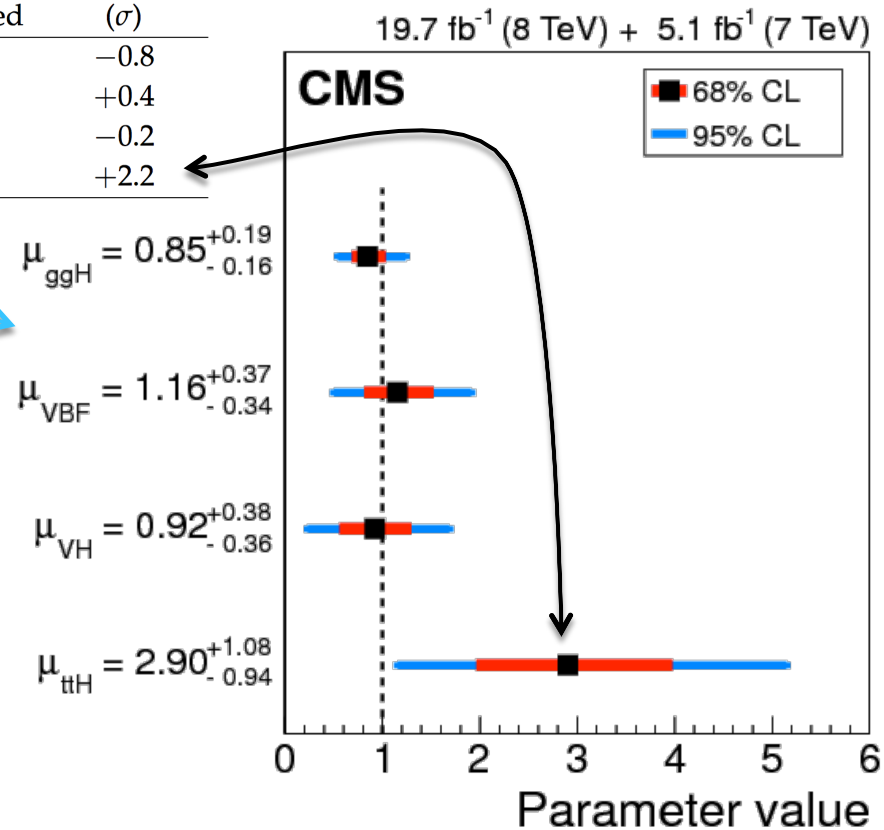
[arXiv:1412.8662]

- $\mu_{ggH} = 0.85\,^{+0.11}_{-0.09}\,(\mathrm{stat.})\,^{+0.11}_{-0.08}\,(\mathrm{theo.})\,^{+0.10}_{-0.09}\,(\mathrm{syst.})$

Parameter	Best-fit result (68% CL) 7 TeV	8 TeV	Combined	Significance (σ) Observed	Expected	Pull to SM (σ)
μ_{ggH}	$1.03^{+0.37}_{-0.33}$	$0.79^{+0.19}_{-0.17}$	$0.85^{+0.19}_{-0.16}$	6.6	7.4	-0.8
μ_{VBF}	$1.77^{+0.99}_{-0.90}$	$1.02^{+0.39}_{-0.36}$	$1.16^{+0.37}_{-0.34}$	3.7	3.3	$+0.4$
μ_{VH}	$0.68^{+0.99}_{-0.68}$	$0.96^{+0.41}_{-0.39}$	$0.92^{+0.38}_{-0.36}$	2.7	2.9	-0.2
μ_{ttH}	< 2.19	$3.27^{+1.20}_{-1.04}$	$2.90^{+1.08}_{-0.94}$	3.5	1.2	$+2.2$



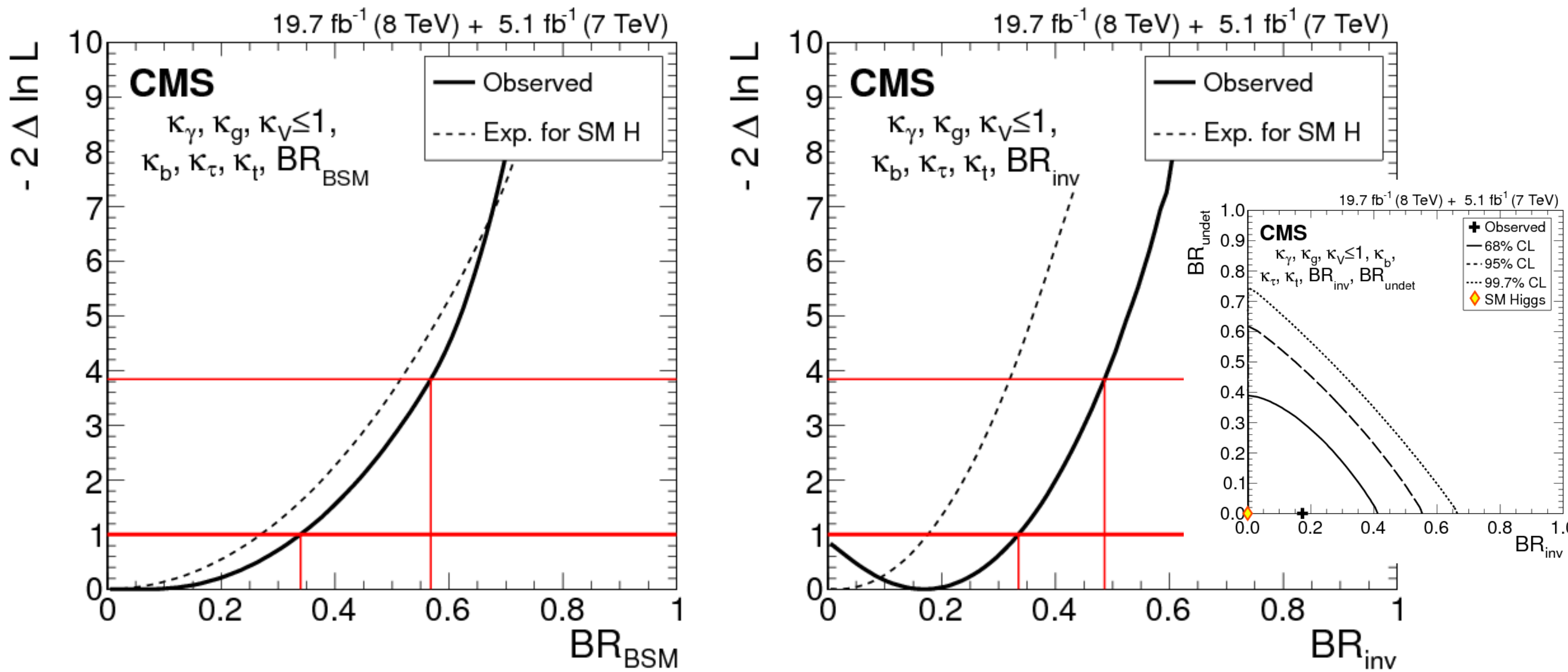




Coupling deviations summaries

[arXiv:1412.8662][arXiv:1307.1347]

- Visible searches can constrain $BR_{BSM}=BR_{inv}+Br_{undet}$.
- Combine with H(inv) searches, assuming $BR_{undet}=0$.
  - Can then scan BR_{inv} vs. BR_{undet}.



Coupling deviations

[arXiv:1412.8662][arXiv:1307.1347]

Model parameters	Table in Ref. [169]	Parameter	Best-fit result 68% CL	Best-fit result 95% CL	Comment
κ_Z, λ_{WZ} ($\kappa_f = 1$)	—	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	$[0.61, 1.45]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.92^{+0.14}_{-0.12}$	$[0.71, 1.24]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	$[0.87, 1.14]$	κ_V scales couplings to W and Z bosons.
		κ_f	$0.87^{+0.14}_{-0.13}$	$[0.63, 1.15]$	κ_f scales couplings to all fermions.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$0.99^{+0.19}_{-0.18}$	$[0.65, 1.39]$	$\lambda_{du} = \kappa_u/\kappa_d$, relates up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.03^{+0.23}_{-0.21}$	$[0.62, 1.50]$	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relates leptons and quarks.
$\kappa_W, \kappa_Z, \kappa_t,$ $\kappa_b, \kappa_\tau, \kappa_\mu$	Extends 51	κ_W	$0.95^{+0.14}_{-0.13}$	$[0.68, 1.23]$	
		κ_Z	$1.05^{+0.16}_{-0.16}$	$[0.72, 1.35]$	
		κ_t	$0.81^{+0.19}_{-0.15}$	$[0.53, 1.20]$	Up-type quarks (via t).
		κ_b	$0.74^{+0.33}_{-0.29}$	$[0.09, 1.44]$	Down-type quarks (via b).
		κ_τ	$0.84^{+0.19}_{-0.18}$	$[0.50, 1.24]$	Electron and tau lepton (via τ).
		κ_μ	$0.49^{+1.38}_{-0.49}$	$[0.00, 2.77]$	κ_μ scales the coupling to muons.
M, ϵ	Ref. [202]	M (GeV)	245 ± 15	$[217, 279]$	$\kappa_f = v\frac{m_f^\epsilon}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$
		ϵ	$0.014^{+0.041}_{-0.036}$	$[-0.054, 0.100]$	(Section 7.4)
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.11}_{-0.10}$	$[0.69, 1.11]$	Effective couplings to gluons (g) and photons (γ).
		κ_γ	$1.14^{+0.12}_{-0.13}$	$[0.89, 1.40]$	
$\kappa_g, \kappa_\gamma, \mathrm{BR_{BSM}}$	48 (middle)	$\mathrm{BR_{BSM}}$	≤ 0.14	$[0.00, 0.32]$	Allows for BSM decays.
with H(inv) searches	—	$\mathrm{BR_{inv}}$	$0.03^{+0.15}_{-0.03}$	$[0.00, 0.32]$	H(inv) use implies $\mathrm{BR_{undet}} = 0$.
with H(inv) and $\kappa_i = 1$	—	$\mathrm{BR_{inv}}$	$0.06^{+0.11}_{-0.06}$	$[0.00, 0.27]$	Assumes $\kappa_i = 1$ and uses H(inv).
$\kappa_{gZ},$ $\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$ $\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$	50 (bottom)	κ_{gZ}	$0.98^{+0.14}_{-0.13}$	$[0.73, 1.27]$	$\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating κ_H.
		λ_{WZ}	$0.87^{+0.15}_{-0.13}$	$[0.63, 1.19]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$.
		λ_{Zg}	$1.39^{+0.36}_{-0.28}$	$[0.87, 2.18]$	$\lambda_{Zg} = \kappa_Z/\kappa_g$.
		λ_{bZ}	$0.59^{+0.22}_{-0.23}$	≤ 1.07	$\lambda_{bZ} = \kappa_b/\kappa_Z$.
		$\lambda_{\gamma Z}$	$0.93^{+0.17}_{-0.14}$	$[0.67, 1.31]$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$.
		$\lambda_{\tau Z}$	$0.79^{+0.19}_{-0.17}$	$[0.47, 1.20]$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$.
		λ_{tg}	$2.18^{+0.54}_{-0.46}$	$[1.30, 3.35]$	$\lambda_{tg} = \kappa_t/\kappa_g$.
$\kappa_V, \kappa_b, \kappa_\tau,$ $\kappa_t, \kappa_g, \kappa_\gamma$	Similar to 50 (top)	κ_V	$0.96^{+0.14}_{-0.15}$	$[0.66, 1.23]$	
		κ_b	$0.64^{+0.28}_{-0.29}$	$[0.00, 1.23]$	Down-type quarks (via b).
		κ_τ	$0.82^{+0.18}_{-0.18}$	$[0.48, 1.20]$	Charged leptons (via τ).
		κ_t	$1.60^{+0.34}_{-0.32}$	$[0.97, 2.28]$	Up-type quarks (via t).
		κ_g	$0.75^{+0.15}_{-0.13}$	$[0.52, 1.07]$	
		κ_γ	$0.98^{+0.17}_{-0.16}$	$[0.67, 1.33]$	
with $\kappa_V \leq 1$ and $\mathrm{BR_{BSM}}$	—	$\mathrm{BR_{BSM}}$	≤ 0.34	$[0.00, 0.57]$	Allows for BSM decays.
with $\kappa_V \leq 1$ and H(inv)	—	$\mathrm{BR_{inv}}$	0.17 ± 0.17	$[0.00, 0.49]$	H(inv) use implies $\mathrm{BR_{undet}} = 0$.
with $\kappa_V \leq 1$, H(inv),	—	$\mathrm{BR_{inv}}$	0.17 ± 0.17	$[0.00, 0.49]$	Separates $\mathrm{BR_{inv}}$ from $\mathrm{BR_{undet}}$,
$\mathrm{BR_{inv}}$, and $\mathrm{BR_{undet}}$	—	$\mathrm{BR_{undet}}$	≤ 0.23	$[0.00, 0.52]$	$\mathrm{BR_{BSM}} = \mathrm{BR_{inv}} + \mathrm{BR_{undet}}$.

Direct searches

Other models?

[http://cern.ch/go/r8kv]

Fiat Turbina

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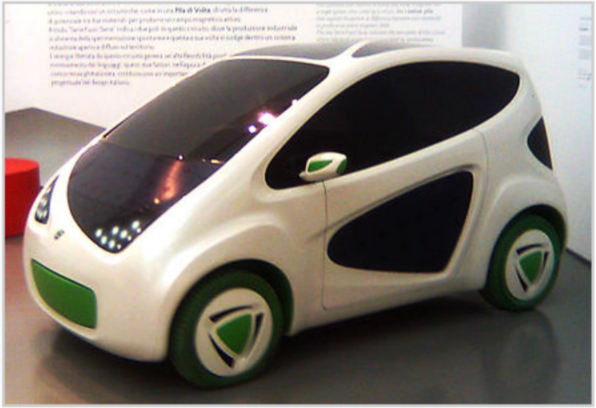
Fiat Turbina

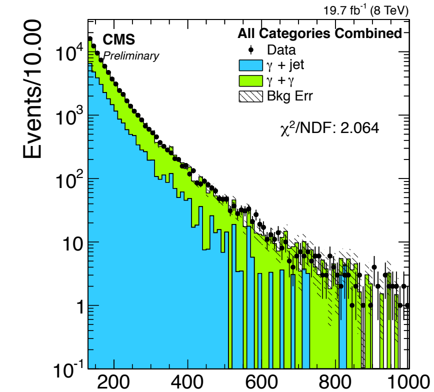


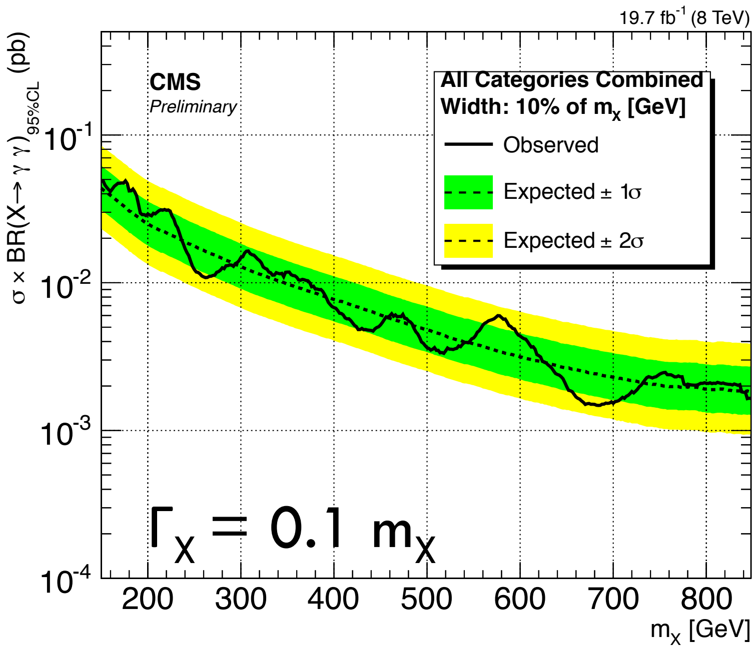
Fiat Phylla at Triennale Design Museum (Milan), 2009.

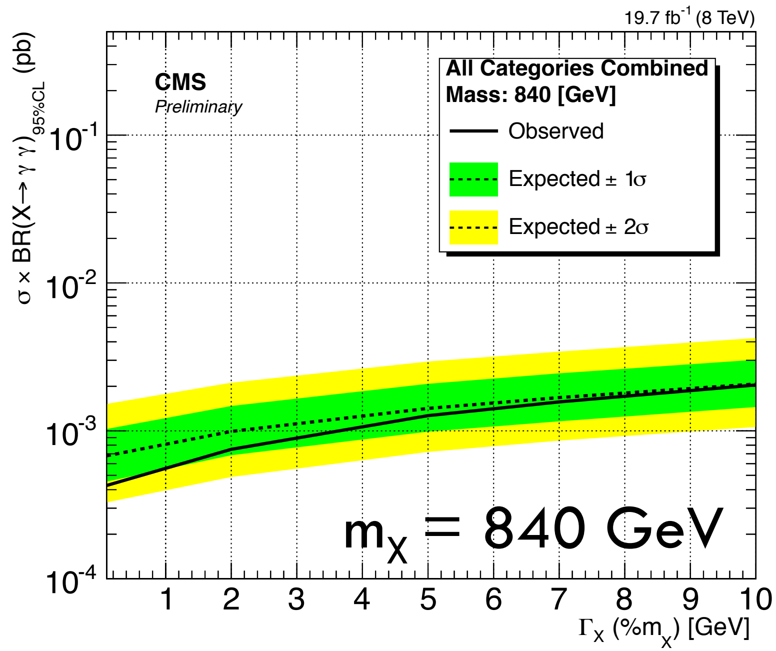
High-mass diphoton searches

[CMS-PAS-HIG-14-006]

- Simplified cut-based selection.
- Signal model: double Crystal-Ball ⊗ Breit-Wigner.
  - Signal width and mean scale appropriately with m_H.
- **Limits on σ×BR as a function of Γ_X and m_X.**

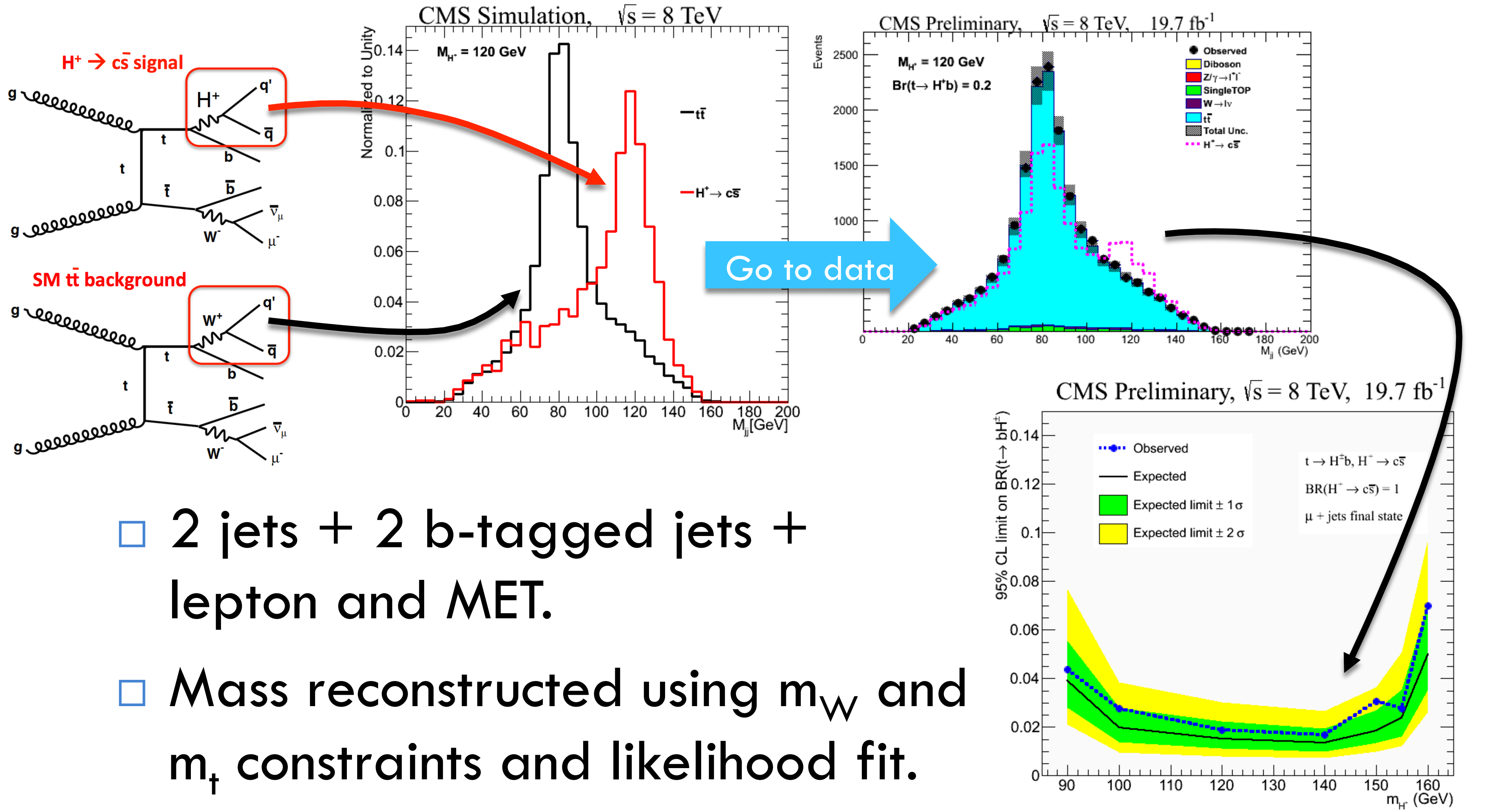






$H^+ \rightarrow cs$ in decays of $t \rightarrow H^+ + b$

[CMS-PAS-HIG-13-035]



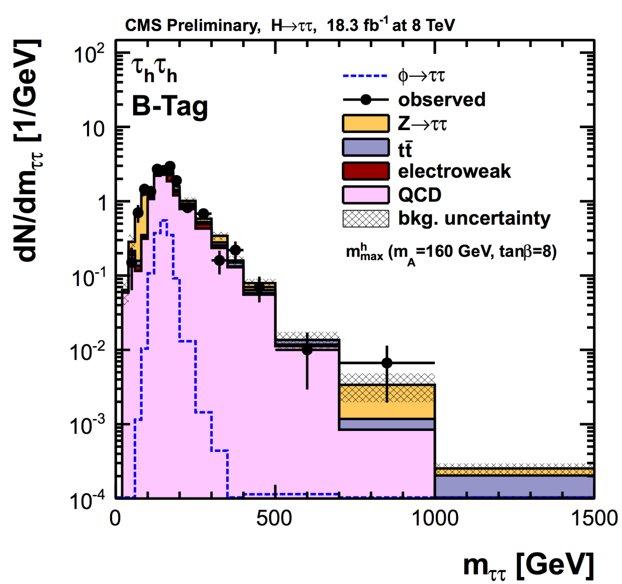
- 2 jets + 2 b-tagged jets + lepton and MET.
- Mass reconstructed using m_W and m_t constraints and likelihood fit.

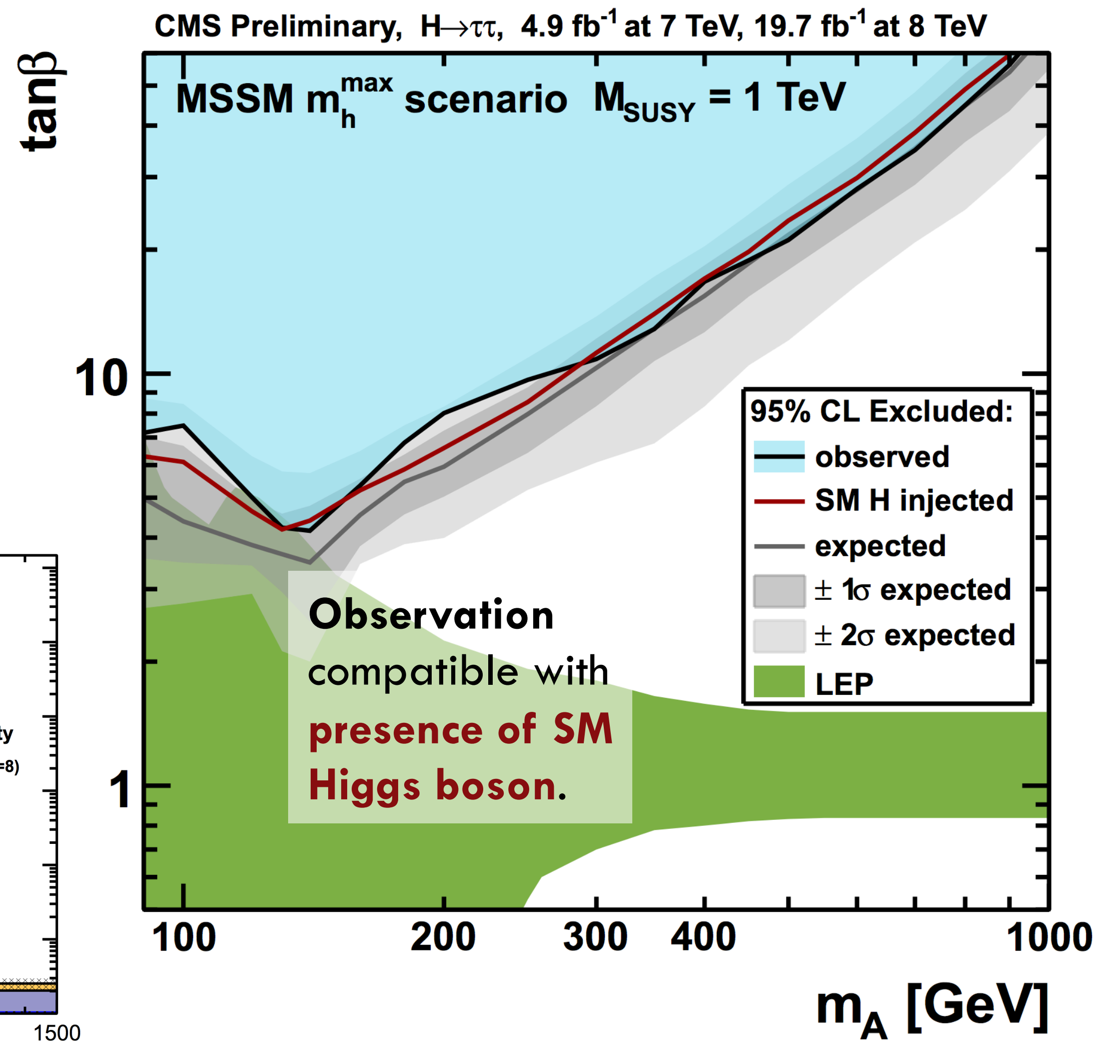
Search for MSSM $\Phi \to \tau\tau$

[CMS-PAS-HIG-13-021]

Not shown: model-independent limits on $gg \to \Phi$ and $gg \to \Phi b\bar{b}$.

- Minimal SuperSymmetric Model predicts:
  - **h^0, H^0, A^0: generically Φ.**
  - H^+ and H^-.
- Based on SM analysis but:
  - **Using extra b-tags (production).**
  - **Extended to up to $m_{\tau\tau}$ = 1.5 TeV:**





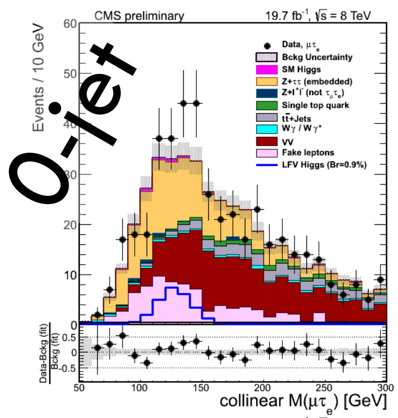
Observation compatible with **presence of SM Higgs boson.**

Search for H→μτ

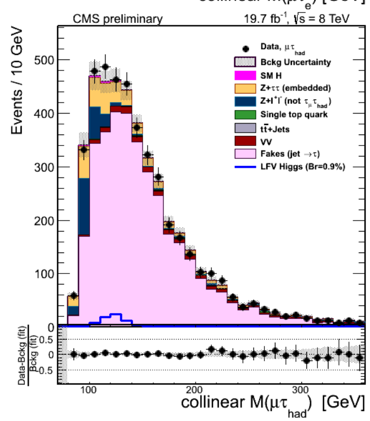
 [CMS-PAS-HIG-14-005]

- **τ lepton flavor violation not as well constrained as μe (MEG).**
- Based on SM H→ττ analysis. **Different kinematics allows good SM H rejection.**
  - **BR(H→μτ) < 1.57%** at 95%CL (expected limit of 0.75%)

$\mu\tau_e$



$\mu\tau_{had}$



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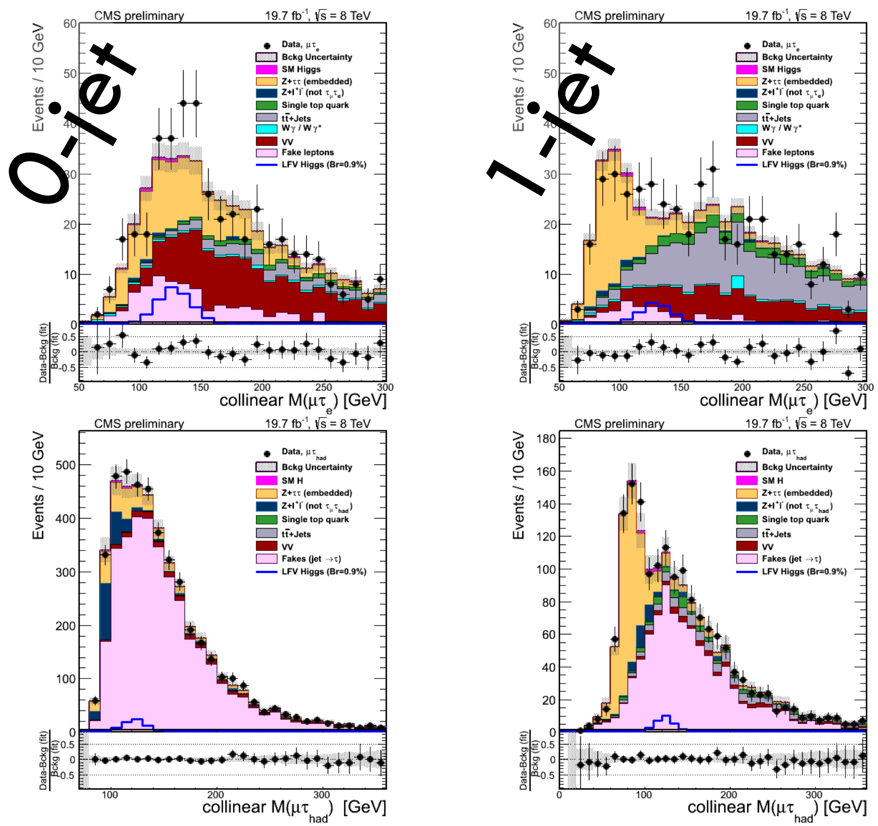

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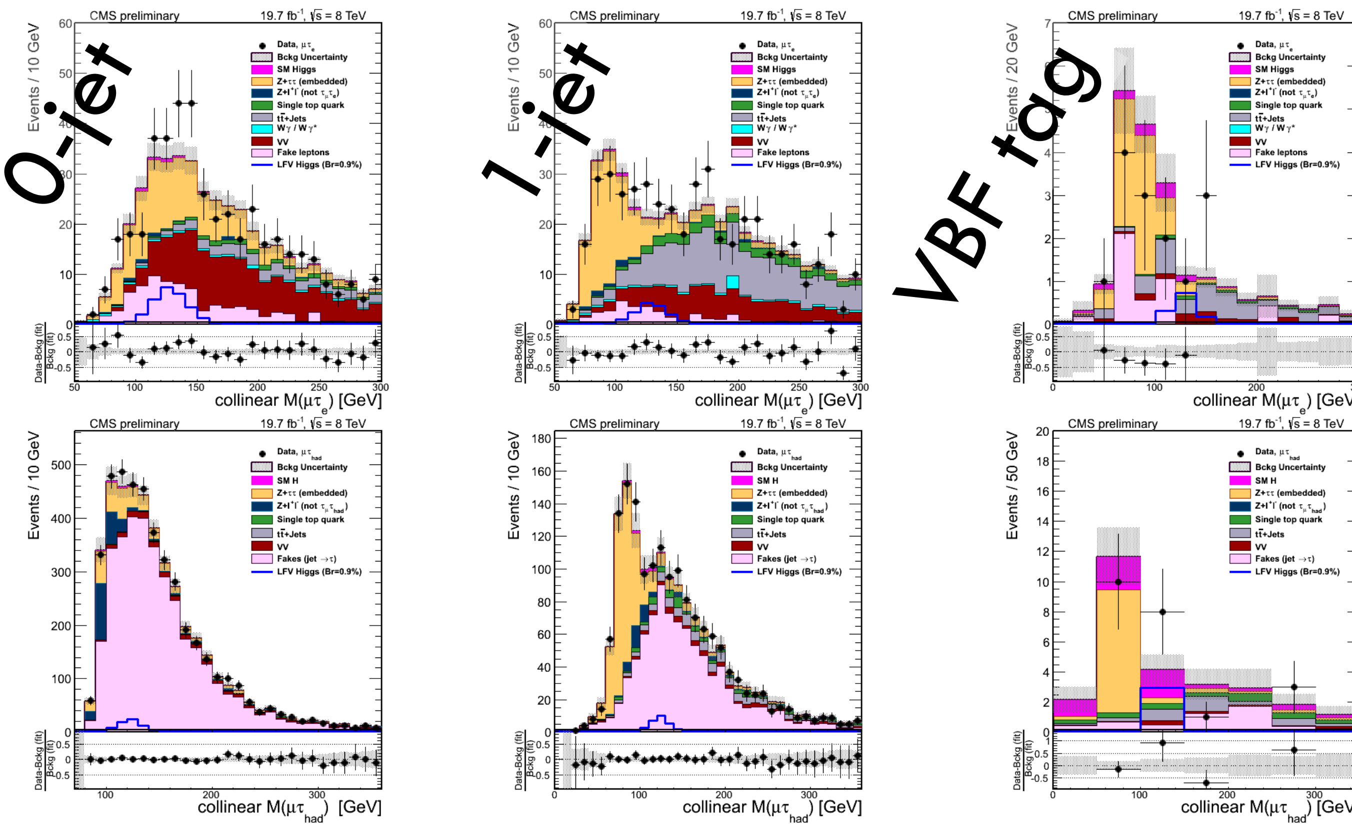
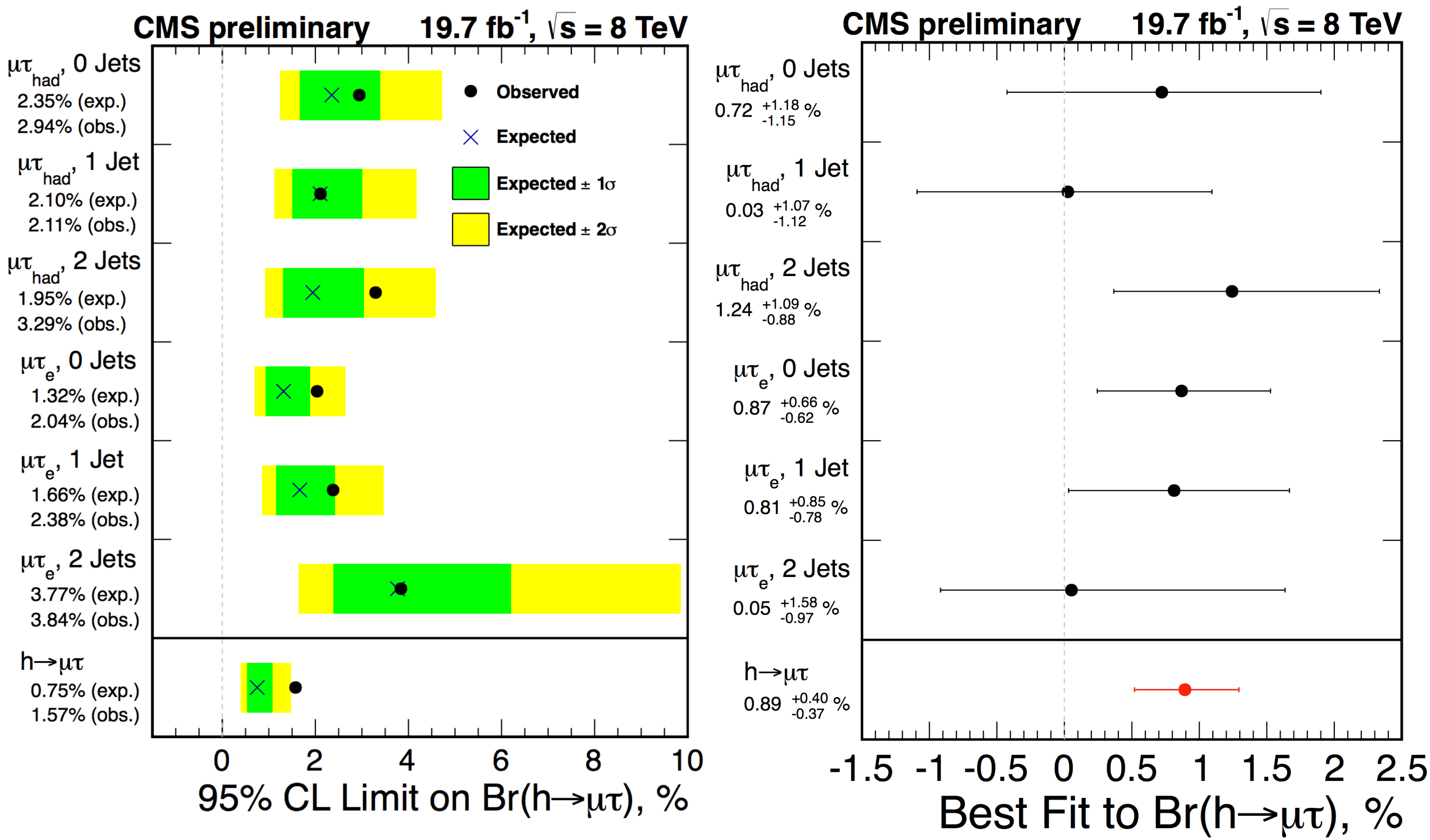


Search for H⟶μτ

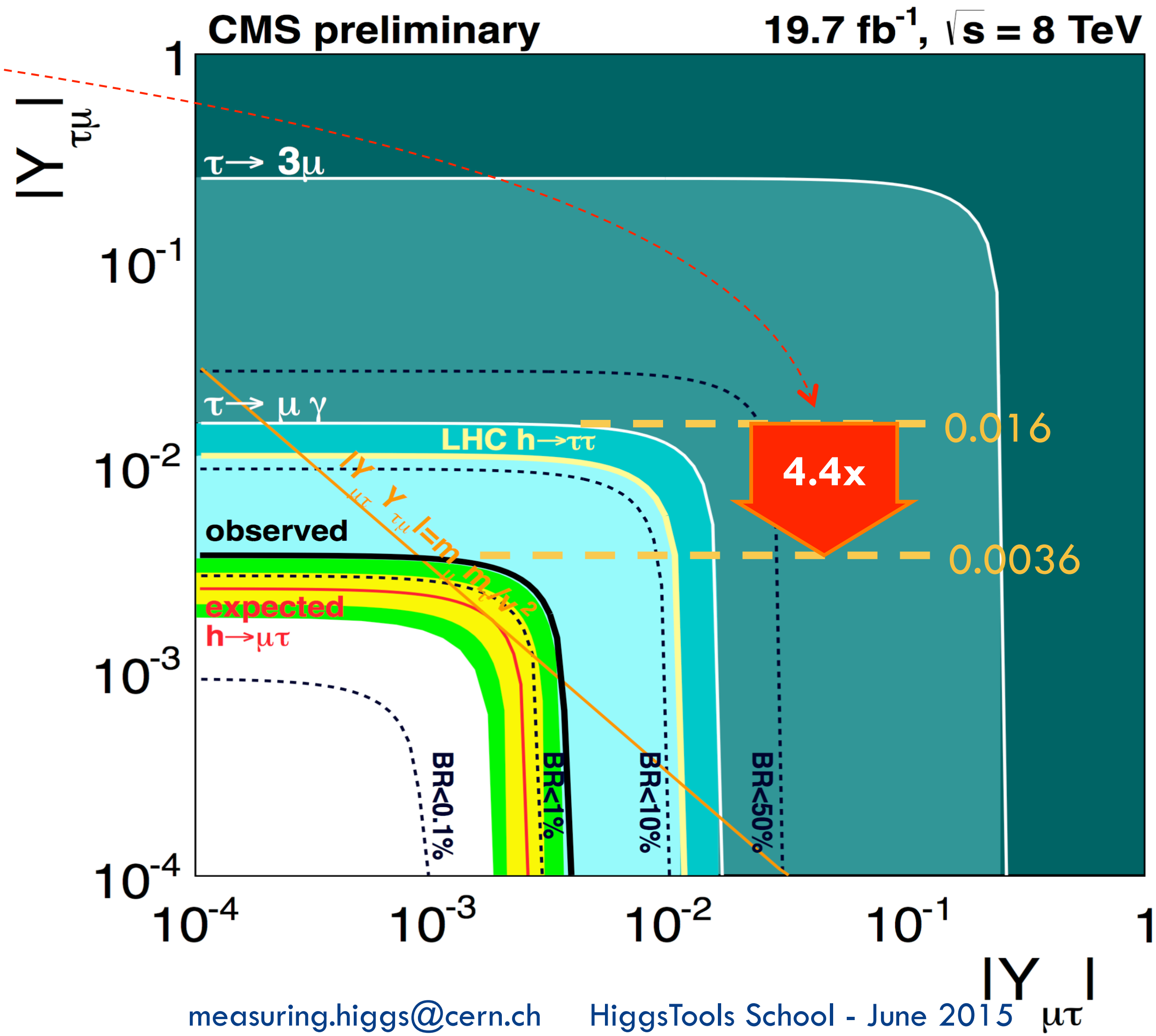
[CMS-PAS-HIG-14-005]



Search for H⟶μτ

 [CMS-PAS-HIG-14-005]

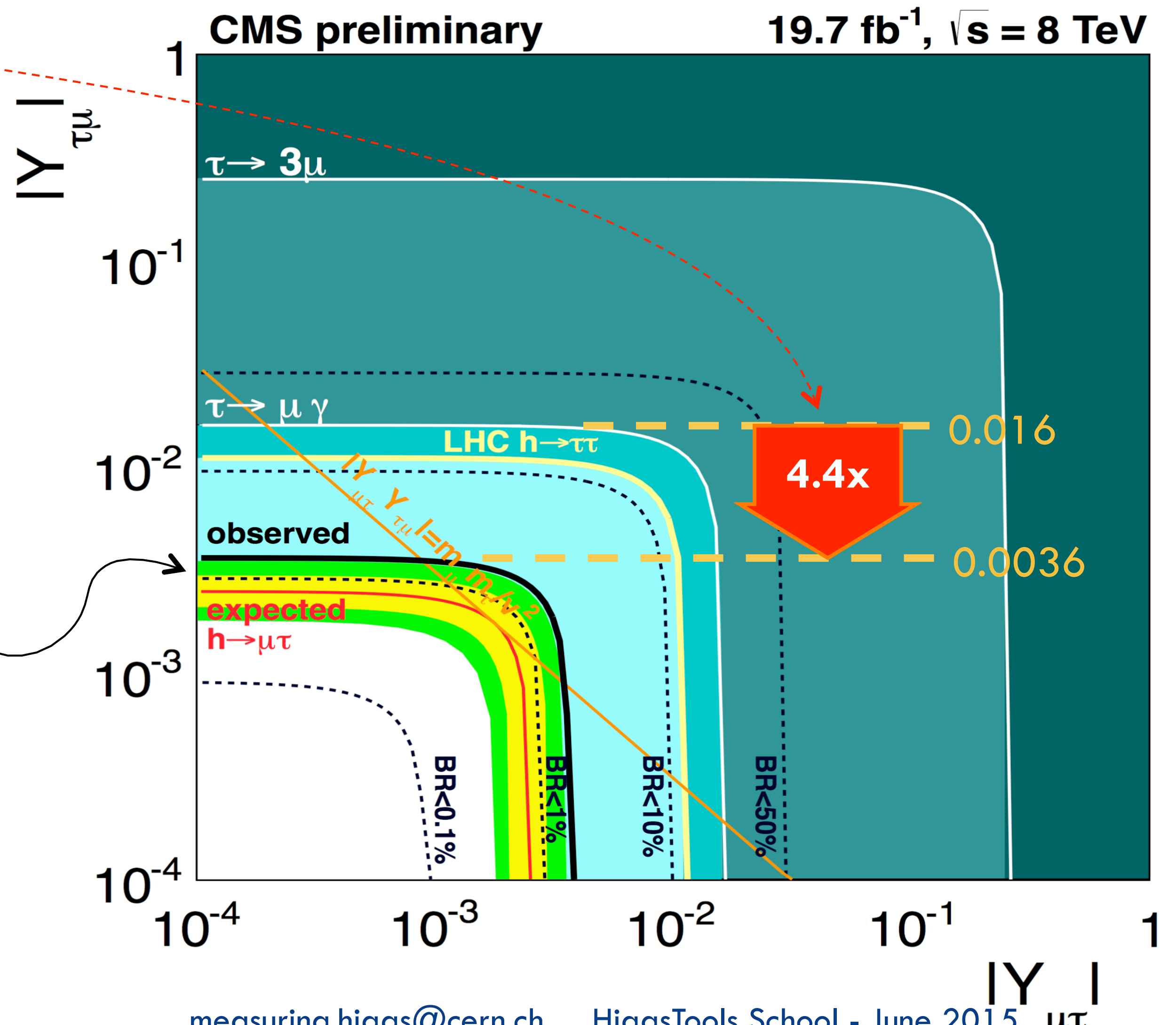
- **Best limits on τ anomalous Yukawa couplings.**



Search for H⟶μτ

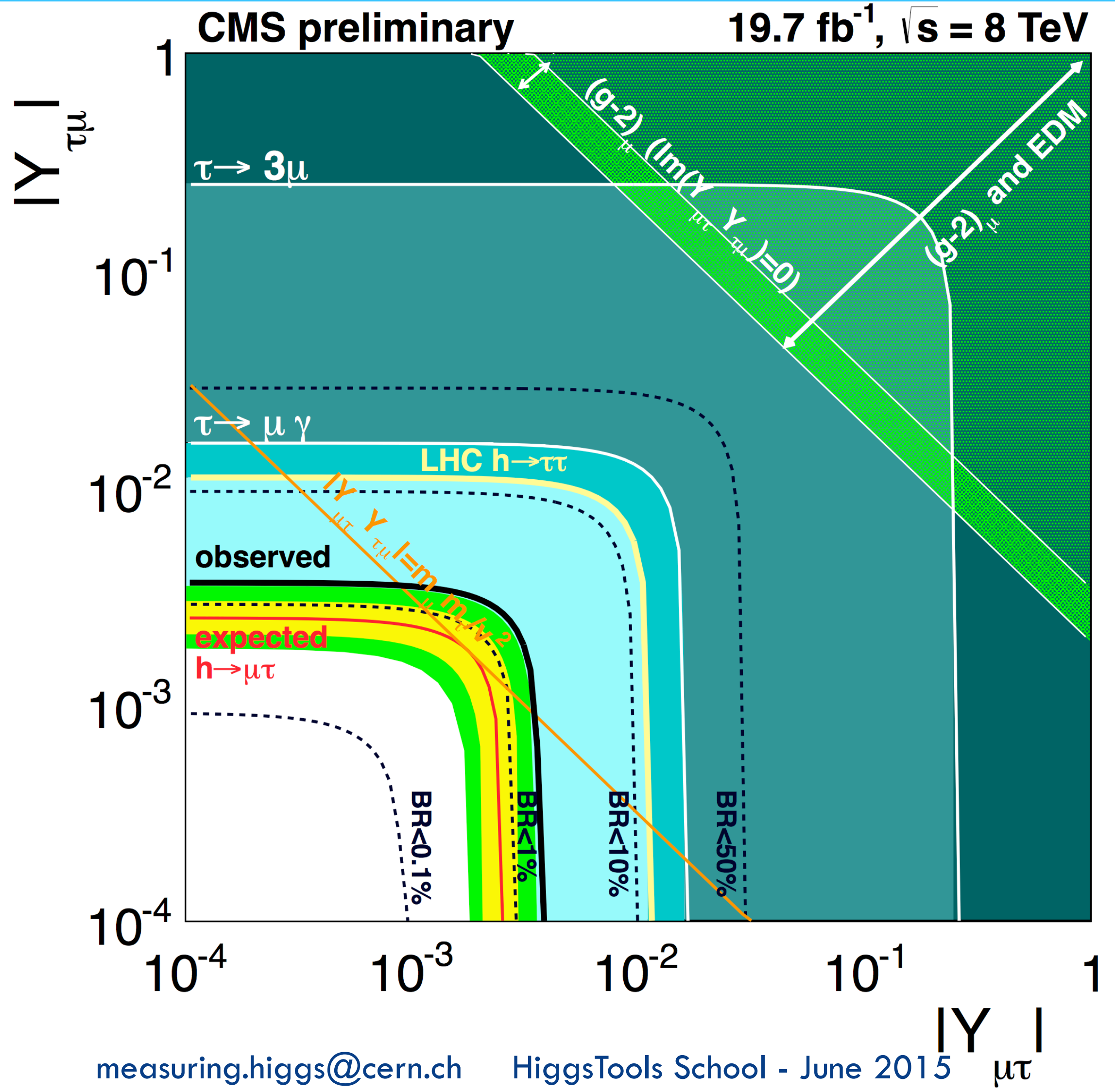
[CMS-PAS-HIG-14-005]

- **Best limits on τ anomalous Yukawa couplings.**
  - Higgs flavor sector could hold surprises.



Search for H→μτ

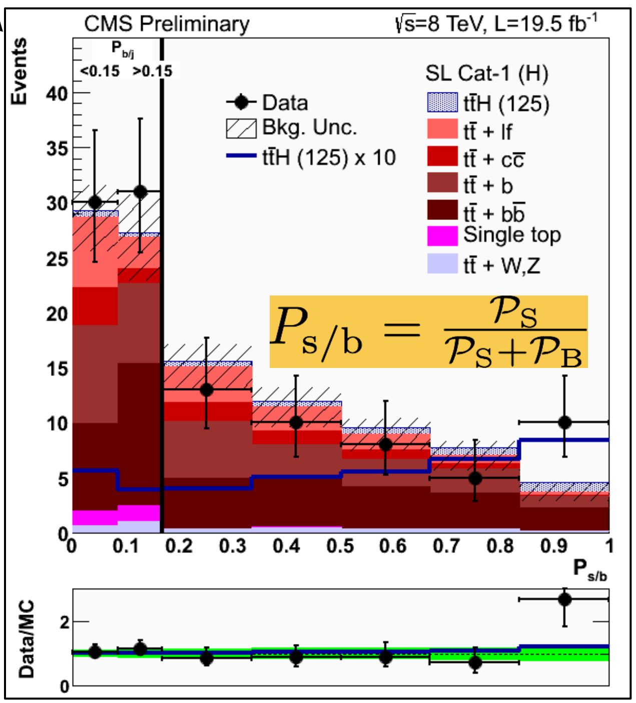
[CMS-PAS-HIG-14-005]



New search for ttH with H→$b\bar{b}$

[CMS-PAS-HIG-14-010]

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified W→jj (**SL Cat-1**).
  - Reduced dependency on tt+HF modeling.
- **Clearly a hot topic for Run 2.**



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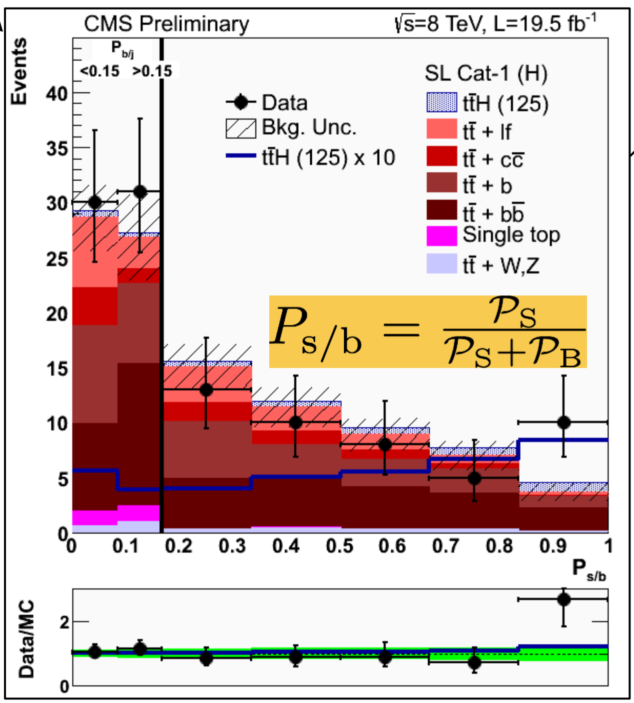

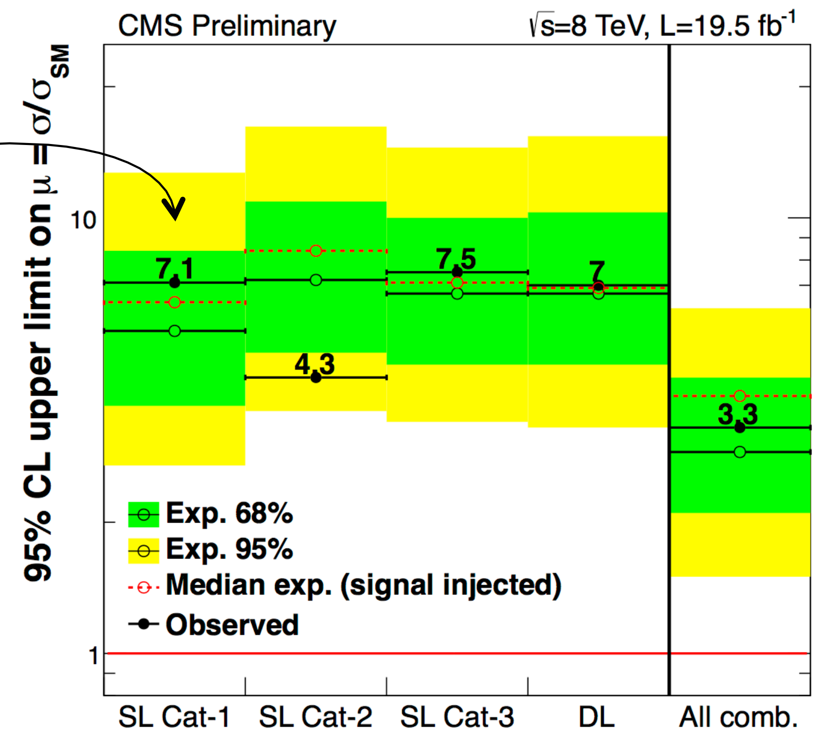

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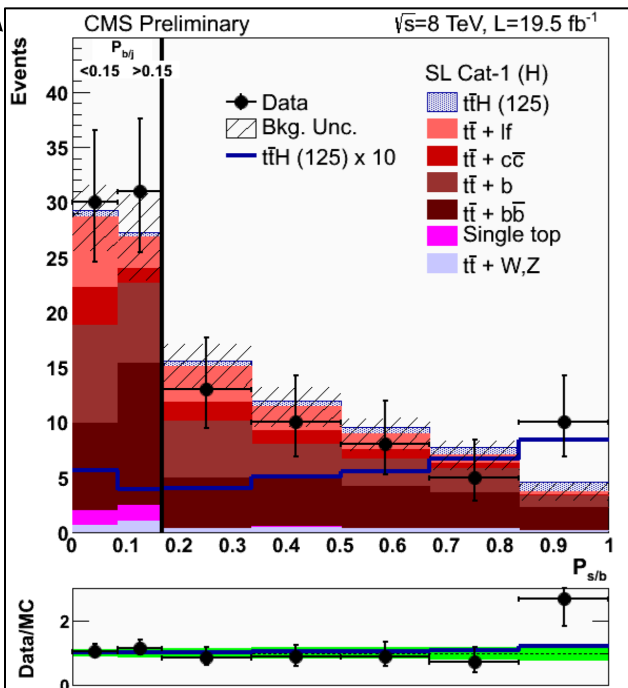
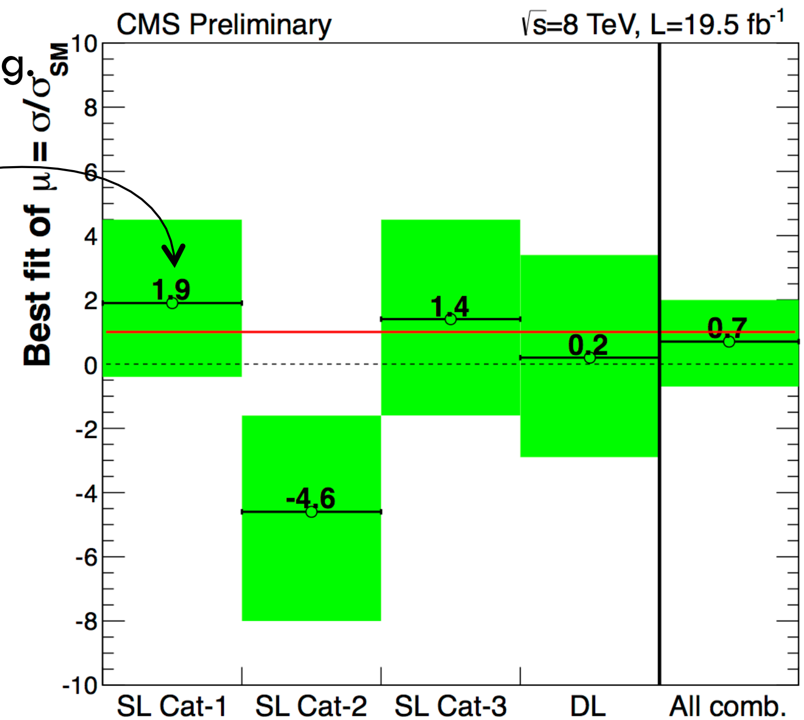




$$P_{s/b} = \frac{\mathcal{P}_{S(bbbb)}}{\mathcal{P}_{S(bbbb)} + \lambda \mathcal{P}_{B(bbbb)} + (1-\lambda)\mathcal{P}_{B(bbjj)}}$$

Tensor structure

Spin zero amplitude in H→VV

[arXiv:1411.3441]

- Parameterization in terms of cross-section fractions:

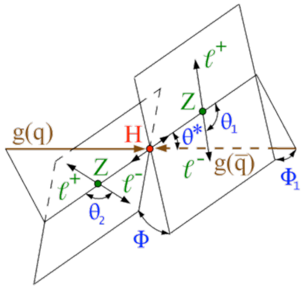
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / \left(\Lambda_1\right)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / \left(\Lambda_1\right)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

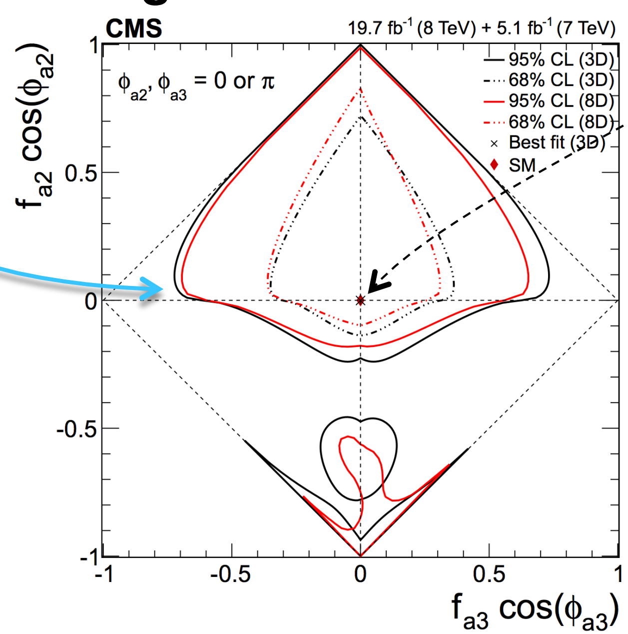
$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1} / \left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / \left(\Lambda_1\right)^4} \qquad \phi_{\Lambda 1},$$

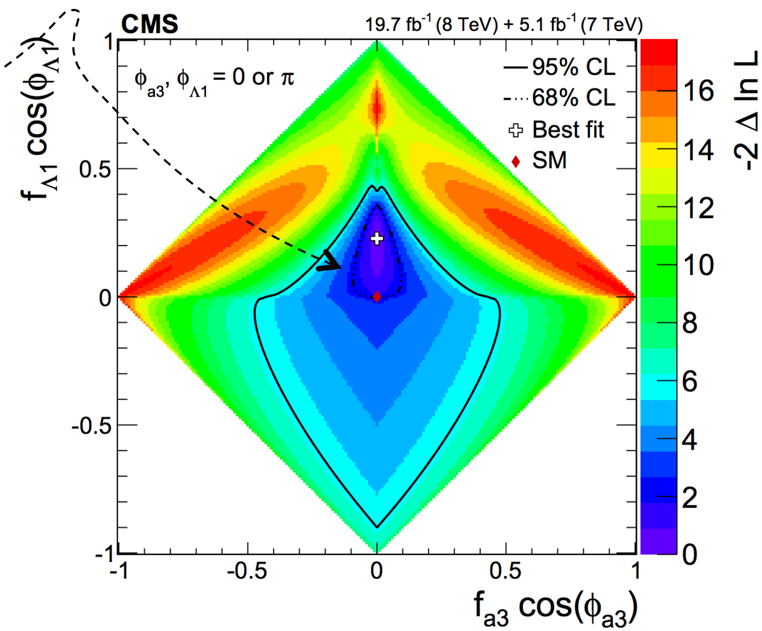
Spin zero amplitude in H→ZZ→4ℓ

[arXiv:1411.3441]



- Full final state available:
  - **Kinematic discriminants** reducing to 2D or 3D.
  - **8D likelihood** fit.
- 2D scans of anomalous coupling fractions (real phases).
  - But also done profiling over the phases.
- **No significant deviations from SM found.**





Spin zero amplitude in H→VV

[arXiv:1411.3441]

- Anomalous couplings formalism:
  - a_1 is the SM amplitude.
  - Λ_1 is a higher-term of an expansion in momentum.
  - a_2 and a_3 control the CP-even and CP-odd amplitudes.
- Parameterized using fractions of cross-sections: f_{a1}, f_{a2}, f_{a3}, $f_{\Lambda 1}$.

$$
\begin{aligned}
A(X_{J=0} \to V_1 V_2) \sim\ & v^{-1}\Bigg(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2}\right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \\
& + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\
& + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
& + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu}\Bigg)
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& + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
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Spin zero amplitude in H→VV

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\end{aligned}
$$

a_2 terms
CP-even (scalar)

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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a_2 terms
CP-even (scalar)

a_3 terms
CP-odd
(pseudoscalar)

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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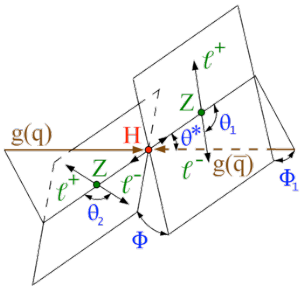
ZZ, WW	$+$	$a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu}$	$+ a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu}$
Zγ*	$+$	$a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu}$	$+ a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu}$
γ*γ*	$+$	$a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu}$	$+ a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \Bigg)$
		a_2 terms CP-even (scalar)	**a_3 terms** CP-odd (pseudoscalar)

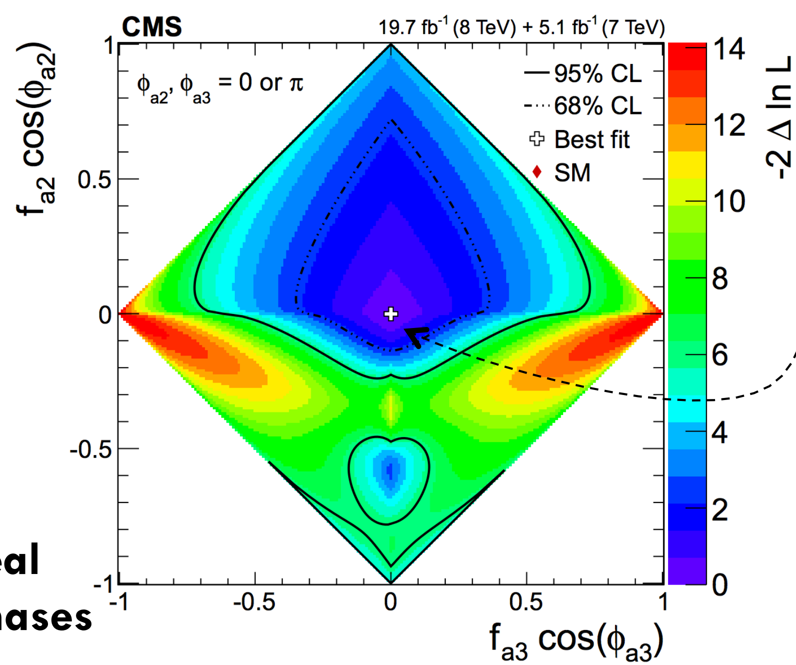
Spin zero amplitude in $H\to ZZ\to 4\ell$

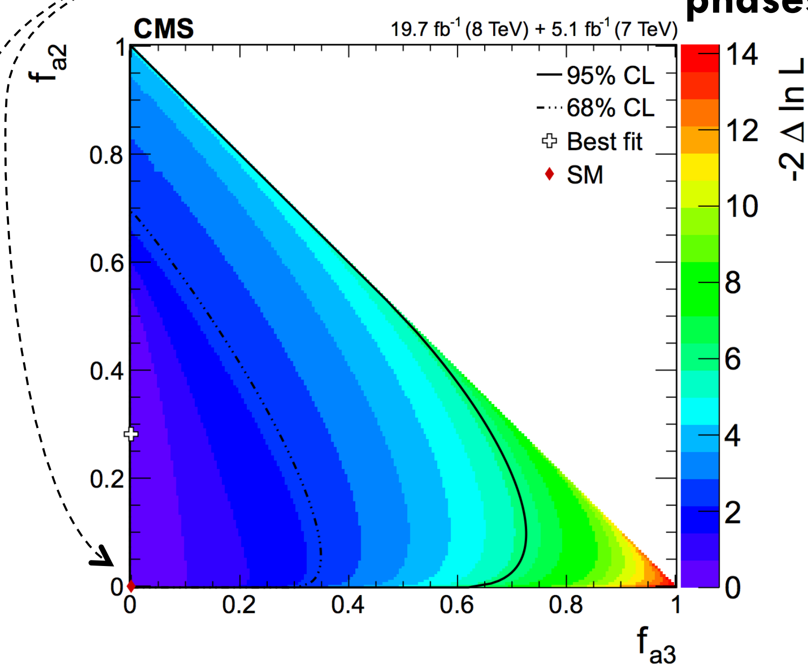
[arXiv:1411.3441]



- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
- 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.
- **No significant deviations from SM found.**

Floating phases



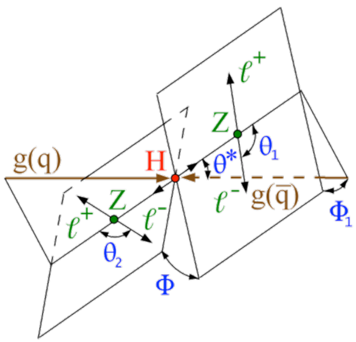


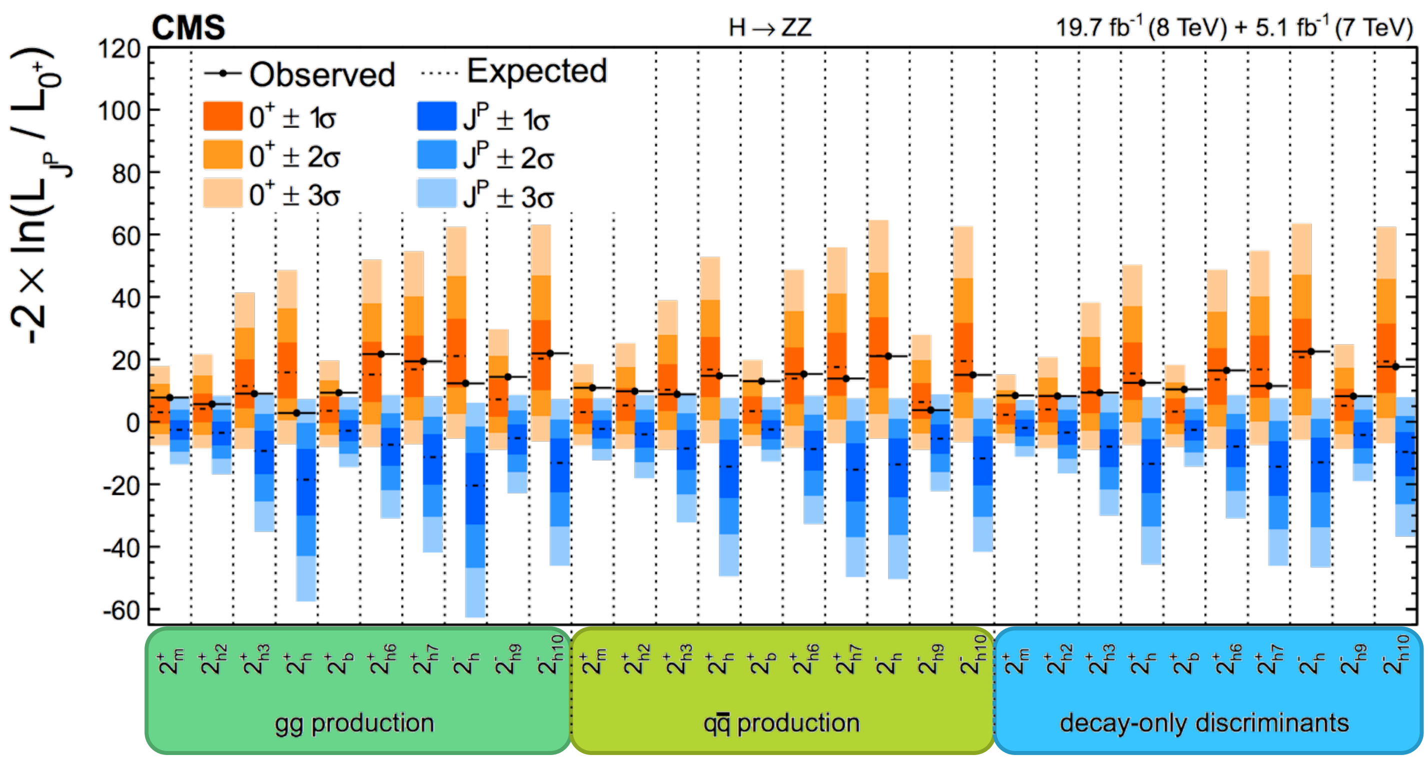
Real phases

H→ZZ→4ℓ – J=2 states

[arXiv:1411.3441]

- Broad range of hypothesis tests based on the observables optimized for each case.

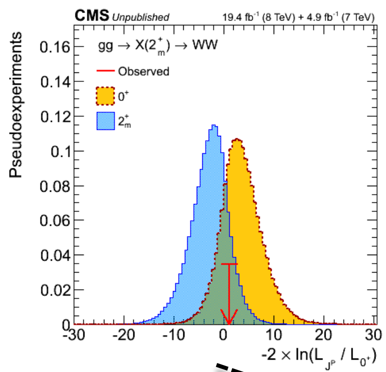


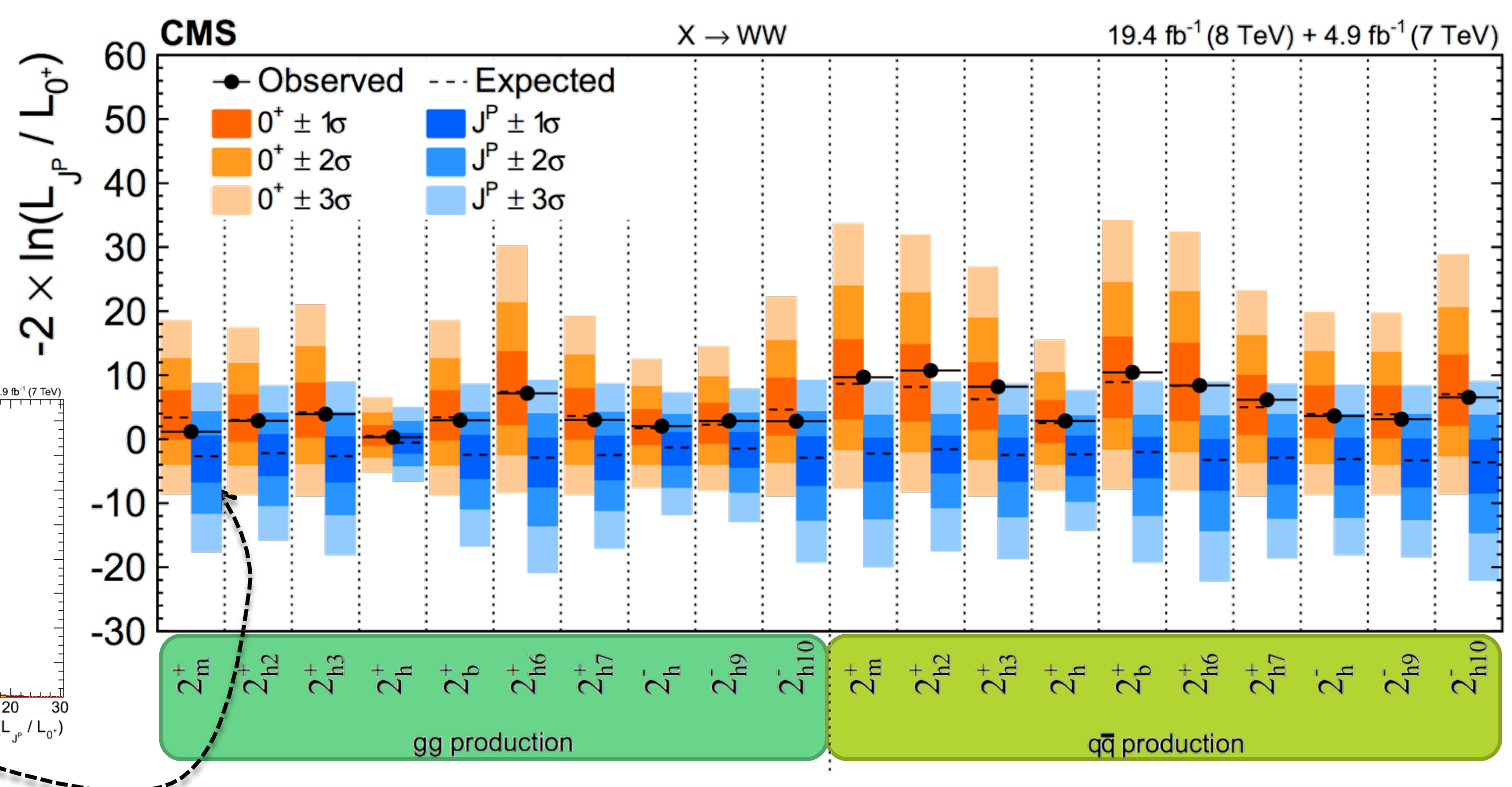


H→WW→2ℓ2ν – J>0 states

[CMS-PAS-HIG-14-012]

- Broad range of hypothesis tests based on the observables used for the SM measurements.

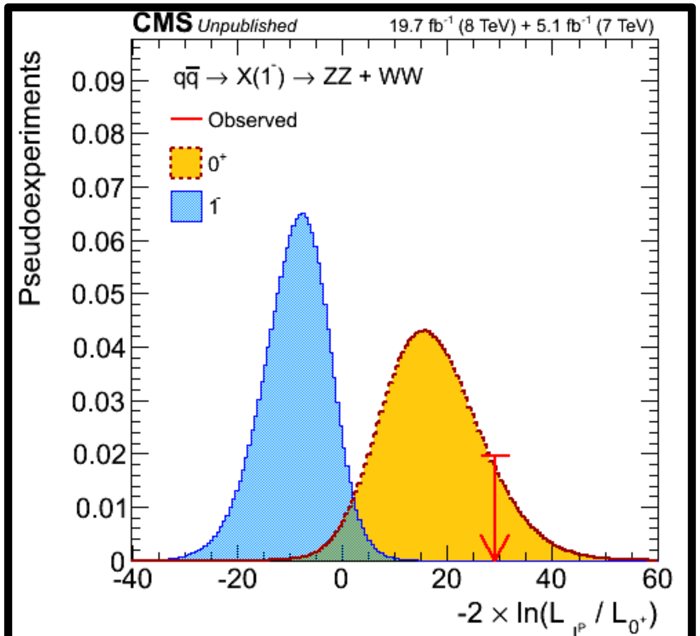




H→VV combination on J>0 states

[CMS-PAS-HIG-14-012][arXiv:1411.3441]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
-

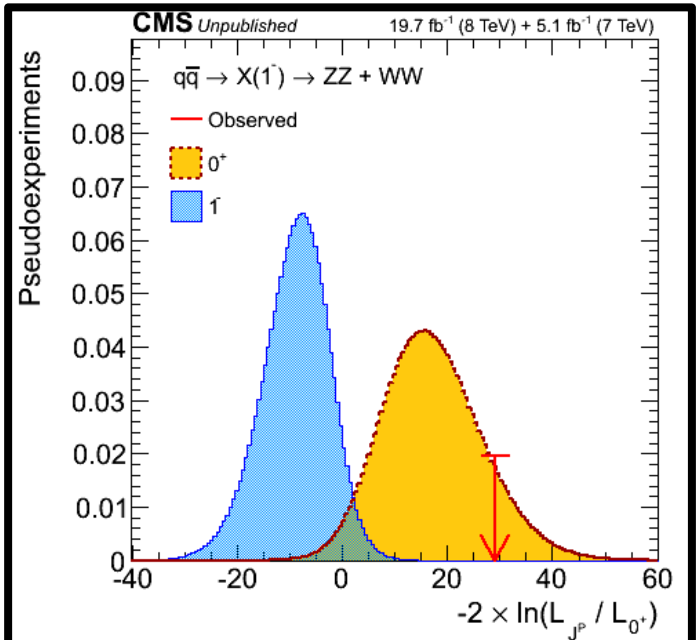


Hypothesis test for 0^+ vs. 1^-

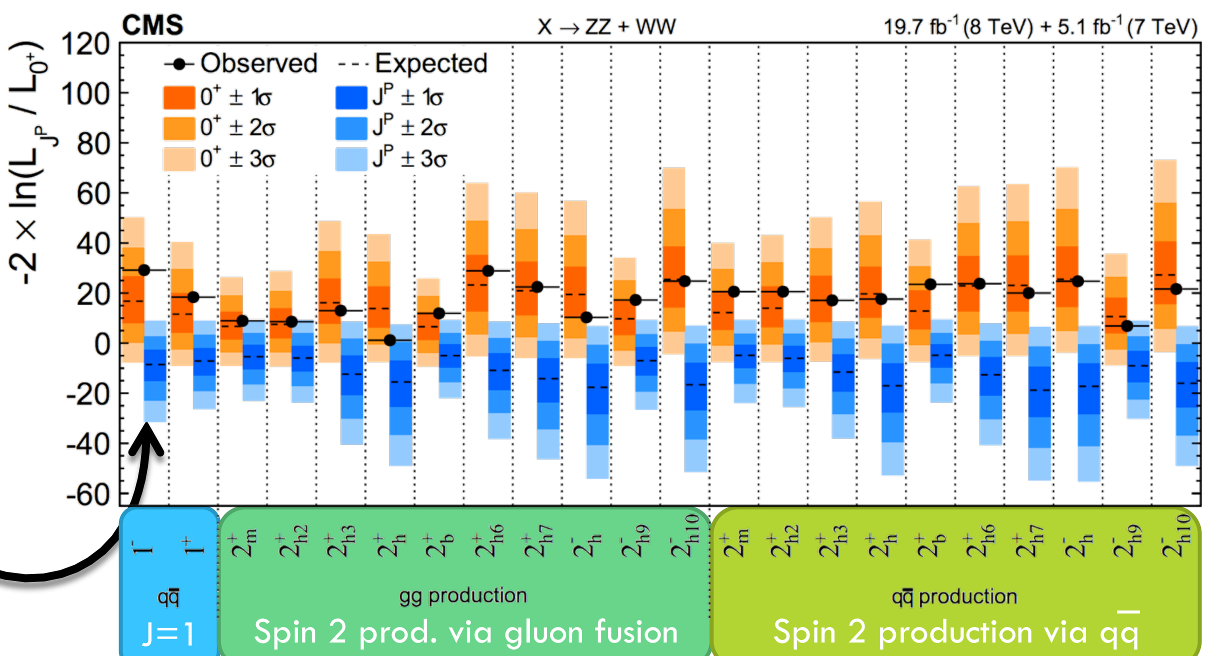
H→VV combination on J>0 states

[CMS-PAS-HIG-14-012][arXiv:1411.3441]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.



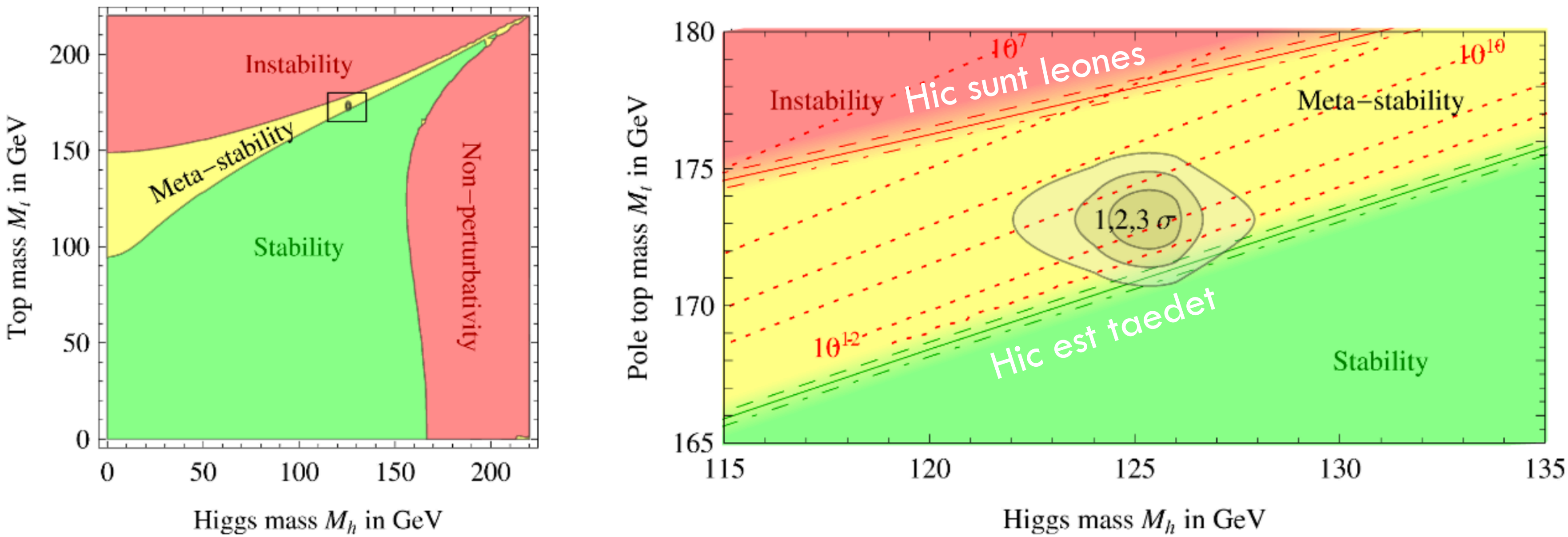
Hypothesis test for 0^+ vs. 1^-



Combined m_H measurement

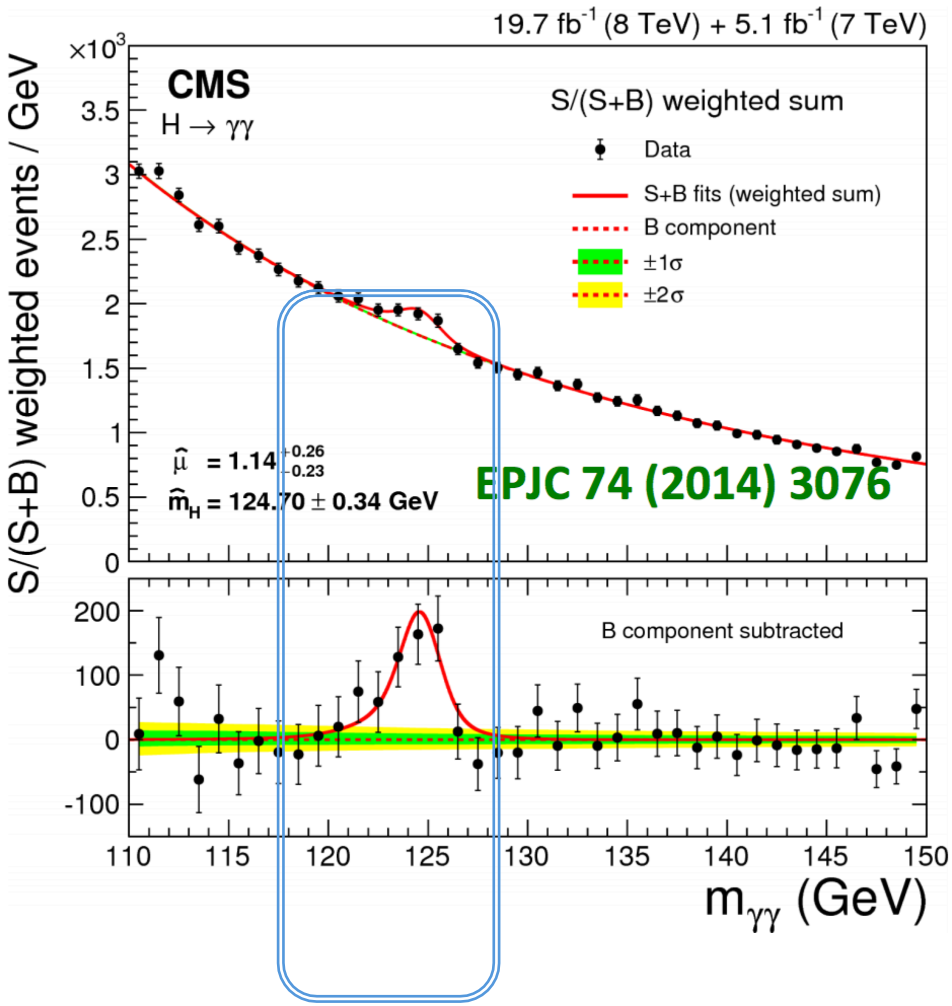
The fate/character of the Universe

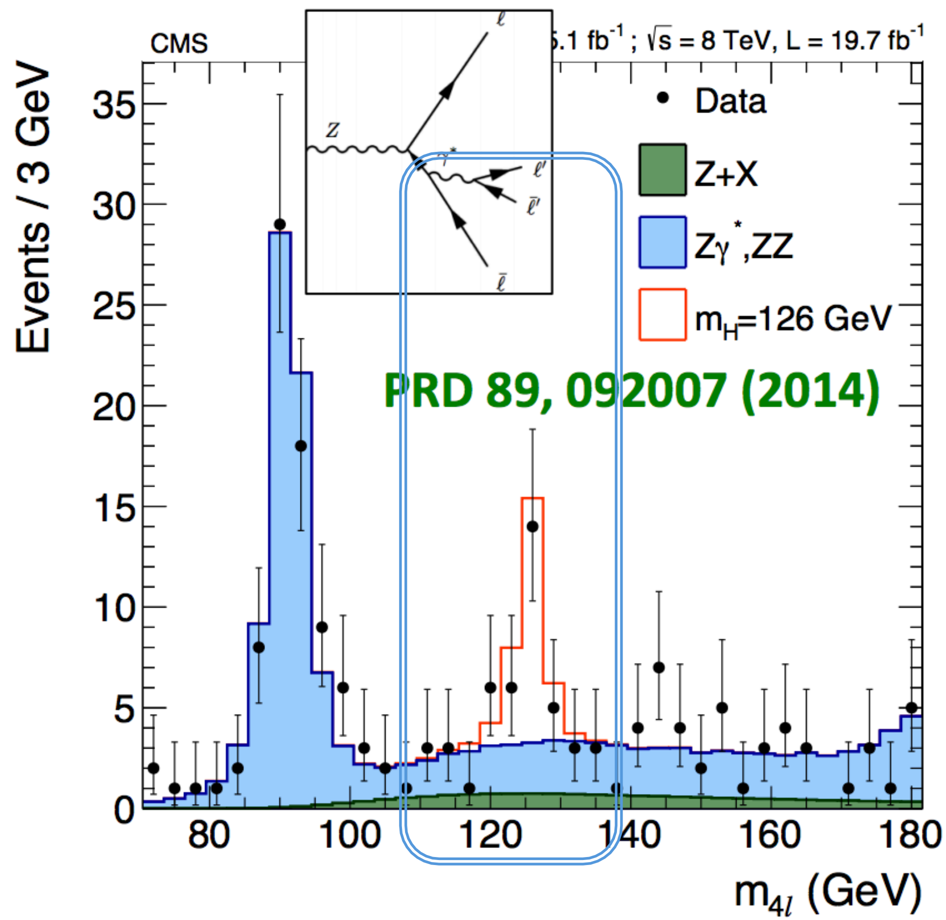
[JHEP 08 (2012) 098]



- The SM vacuum stability depends crucially on the masses of the top quark and Higgs boson.

Mass peaks: mass measurements





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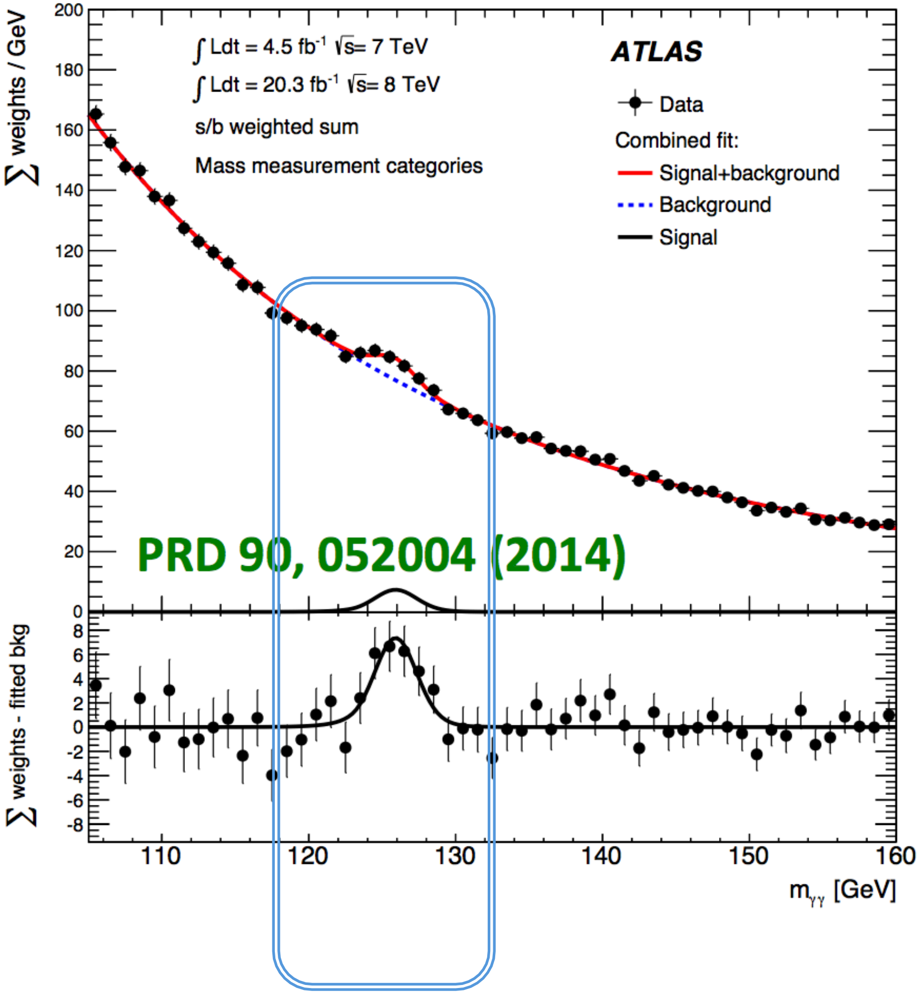
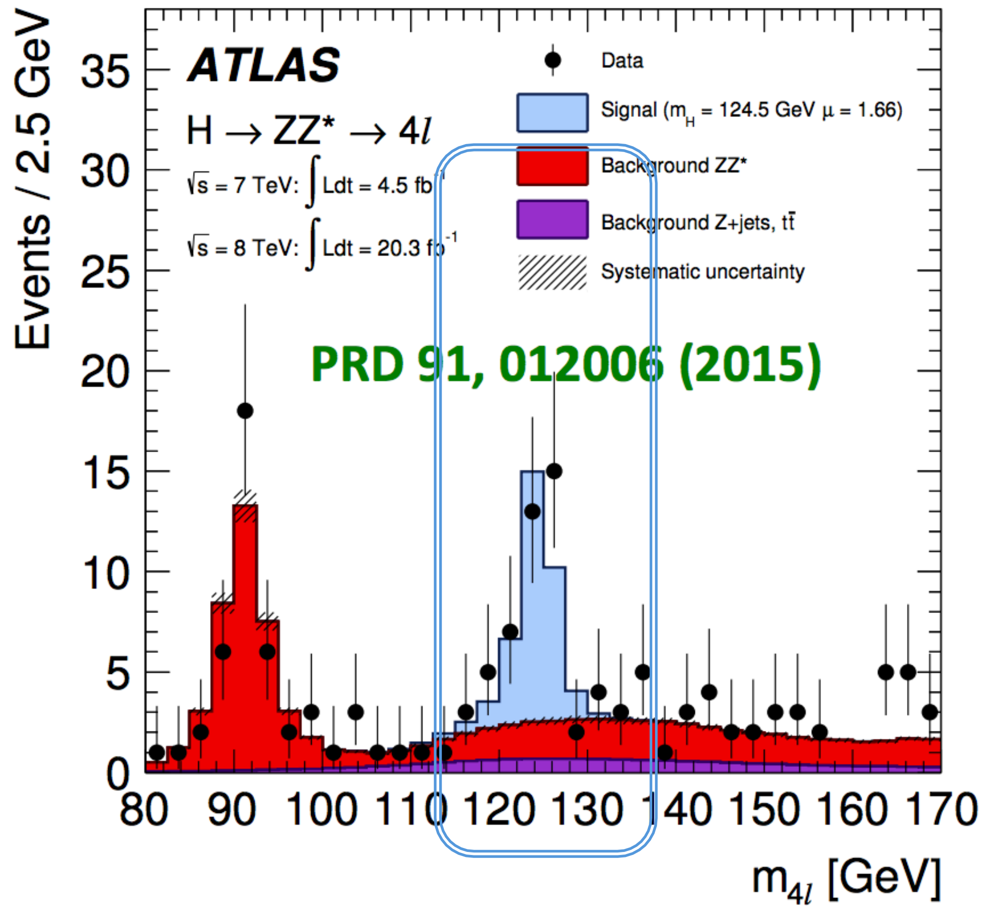
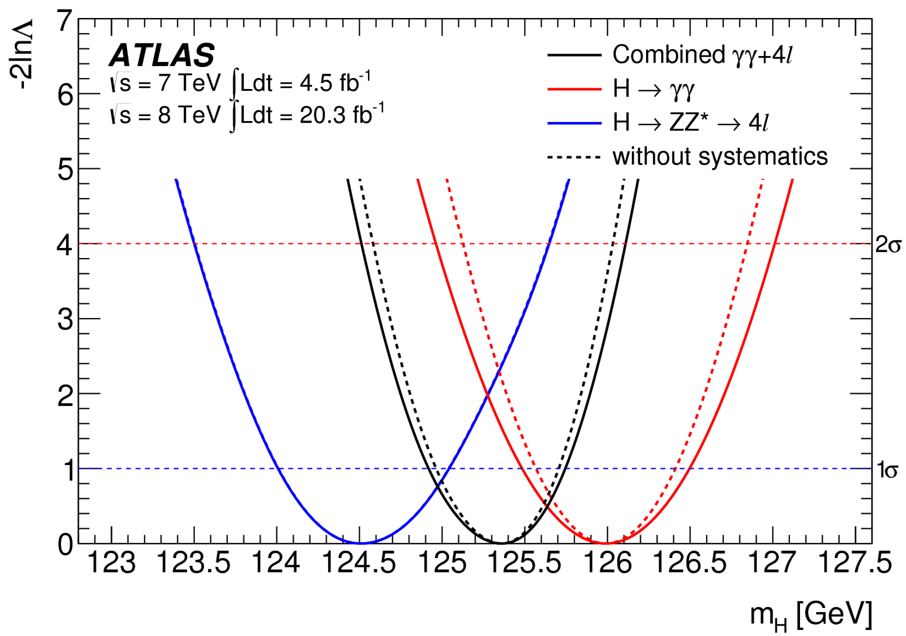
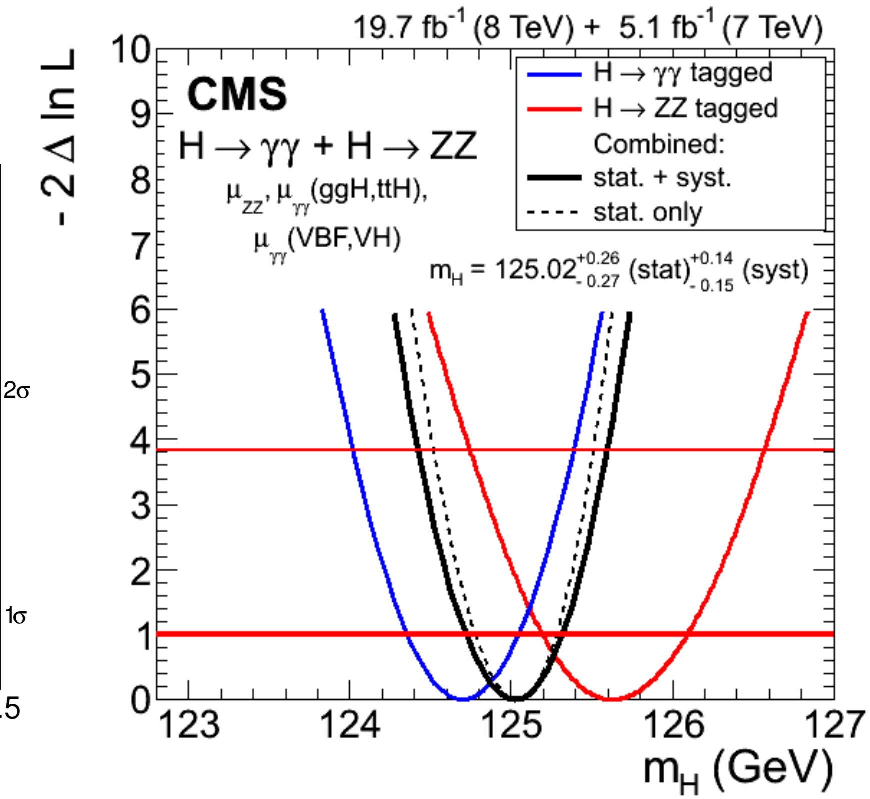




Mass measurement

[arXiv:1406.3827][arXiv:1412.8662]

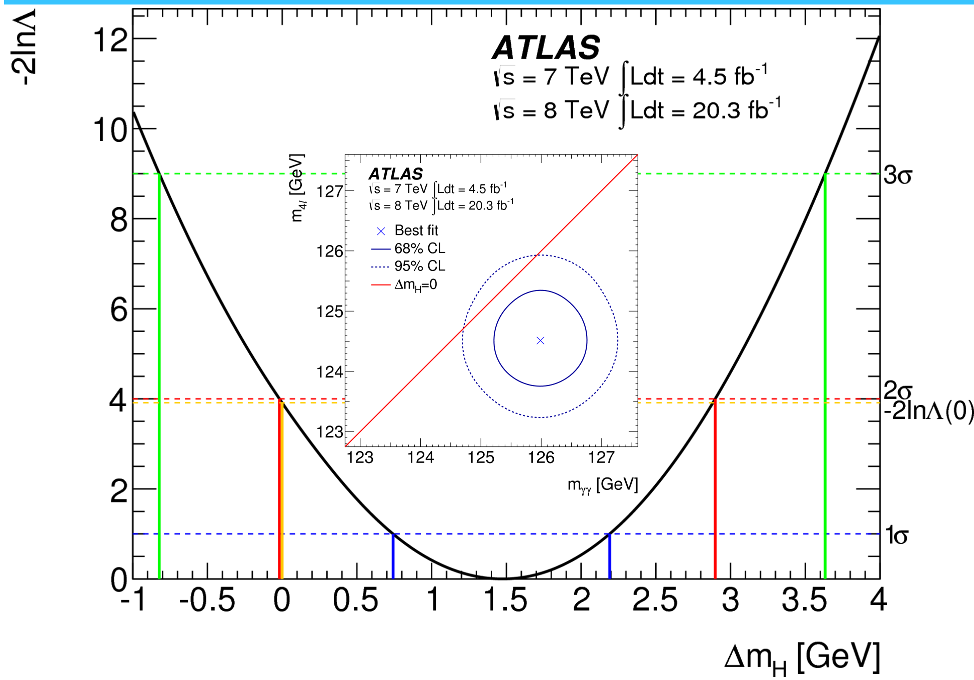


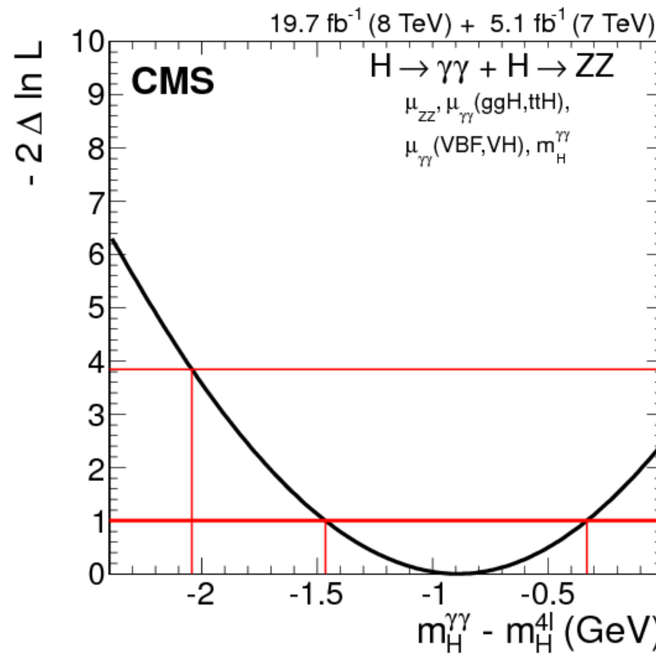


	ATLAS	CMS
m_X	125.36 ±0.37 (stat.) ±0.18 (syst.) GeV	125.02 ±0.27 (stat.) ±0.15 (syst.) GeV
Naïve average: 125.15 ±0.25 GeV		

More on mass

[arXiv:1406.3827][arXiv:1412.8662]



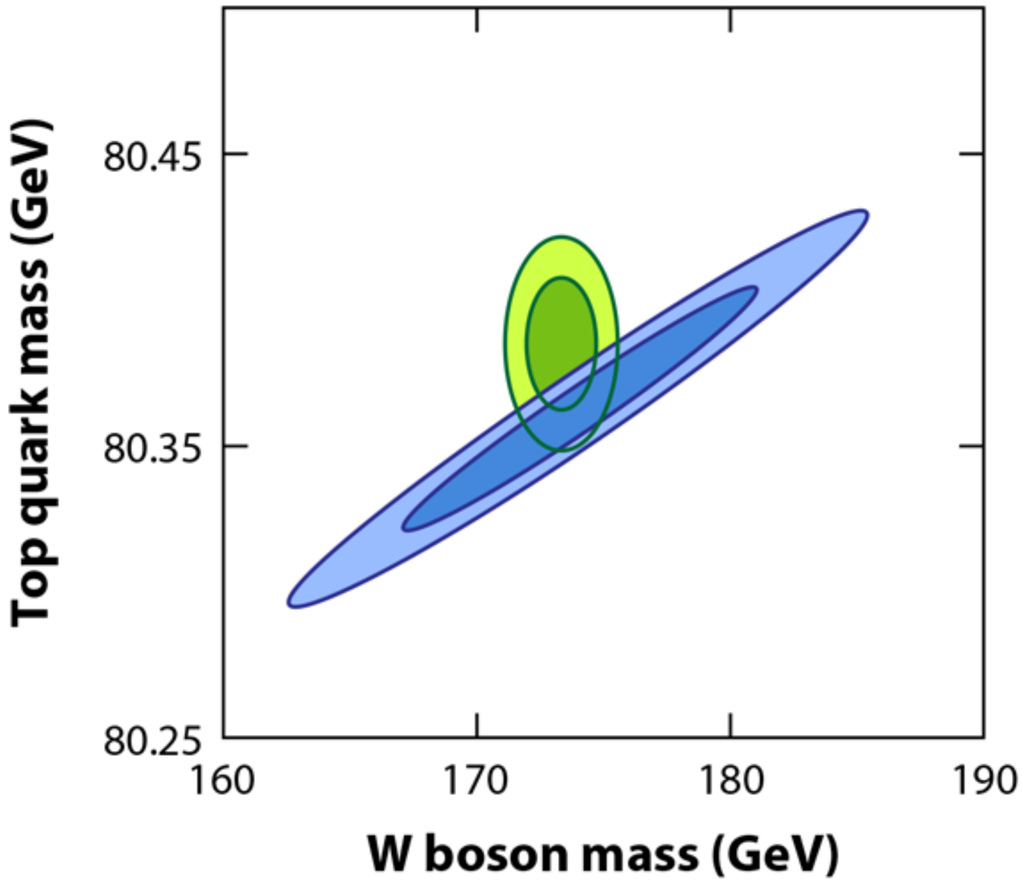


- Slight difference in ATLAS results:
  - $m_H^{\gamma\gamma}$-m_H^{ZZ} = 1.47 ±0.67(stat.) ±0.28(syst.) GeV
  - **1.97σ (p=4.9%).**
  - Using more conservative energy scale uncertainties: 1.8σ (p=7.5%).
- In CMS, less significant and with **opposite sign**:
  - $m_H^{\gamma\gamma}$-m_H^{ZZ} = -0.9 ±0.6 GeV
  - 1.6σ.

ATLAS+CMS m_H in PRL

[PRL 114 (2015) 191803][http://physics.aps.org/articles/v8/45]

- First ATLAS+CMS publication.
  - 0.2% precision.
- PRL Viewpoint by Chris Quigg: "*With LHC Run 2 [we] can look forward to a new round of exploration, searches for new phenomena, and refined measurements. Combined analyses […], such as the measurement of the Higgs boson mass discussed here, will help make the most of the data.* ***We still have much to learn about the Higgs boson, the electroweak theory, and beyond.***"



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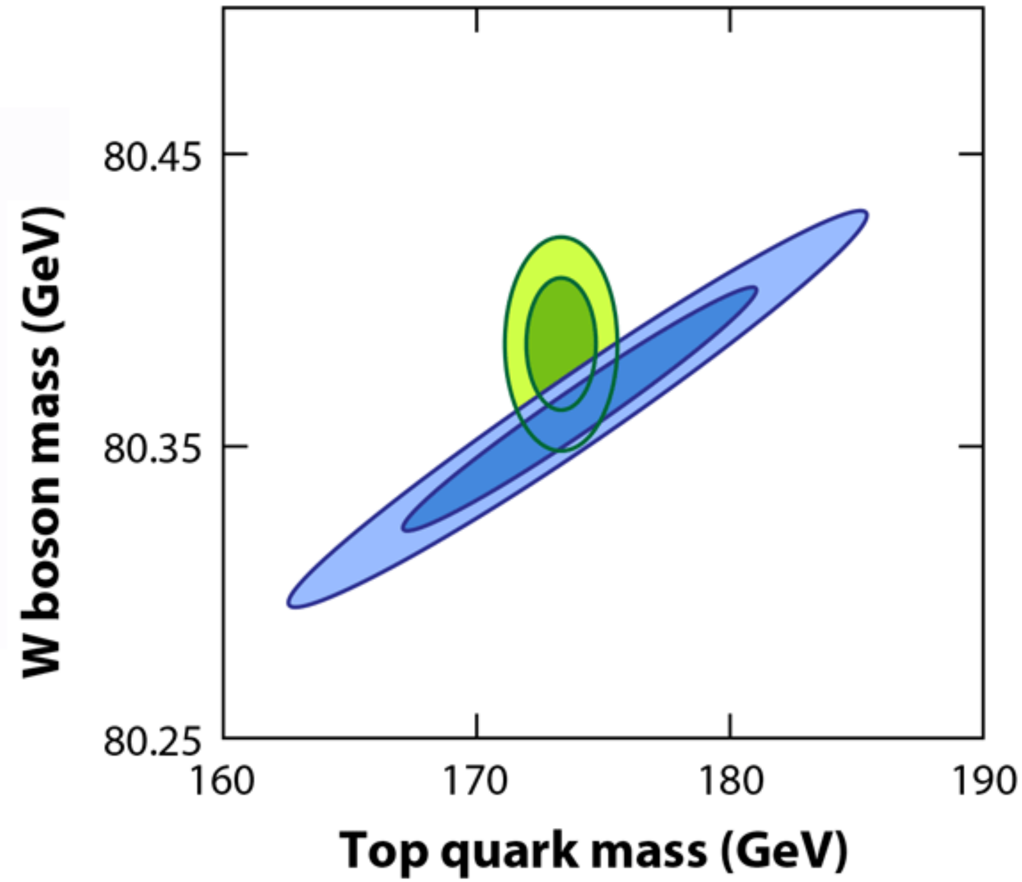

For the record

- ~5150 authors.
- Found that there are two:
  - Archana Sharma (both CMS)
  - Andrea Bocci
  - Muhammad Ahmad
  - F. M. Giorgi (one CMS, one ATLAS)

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Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

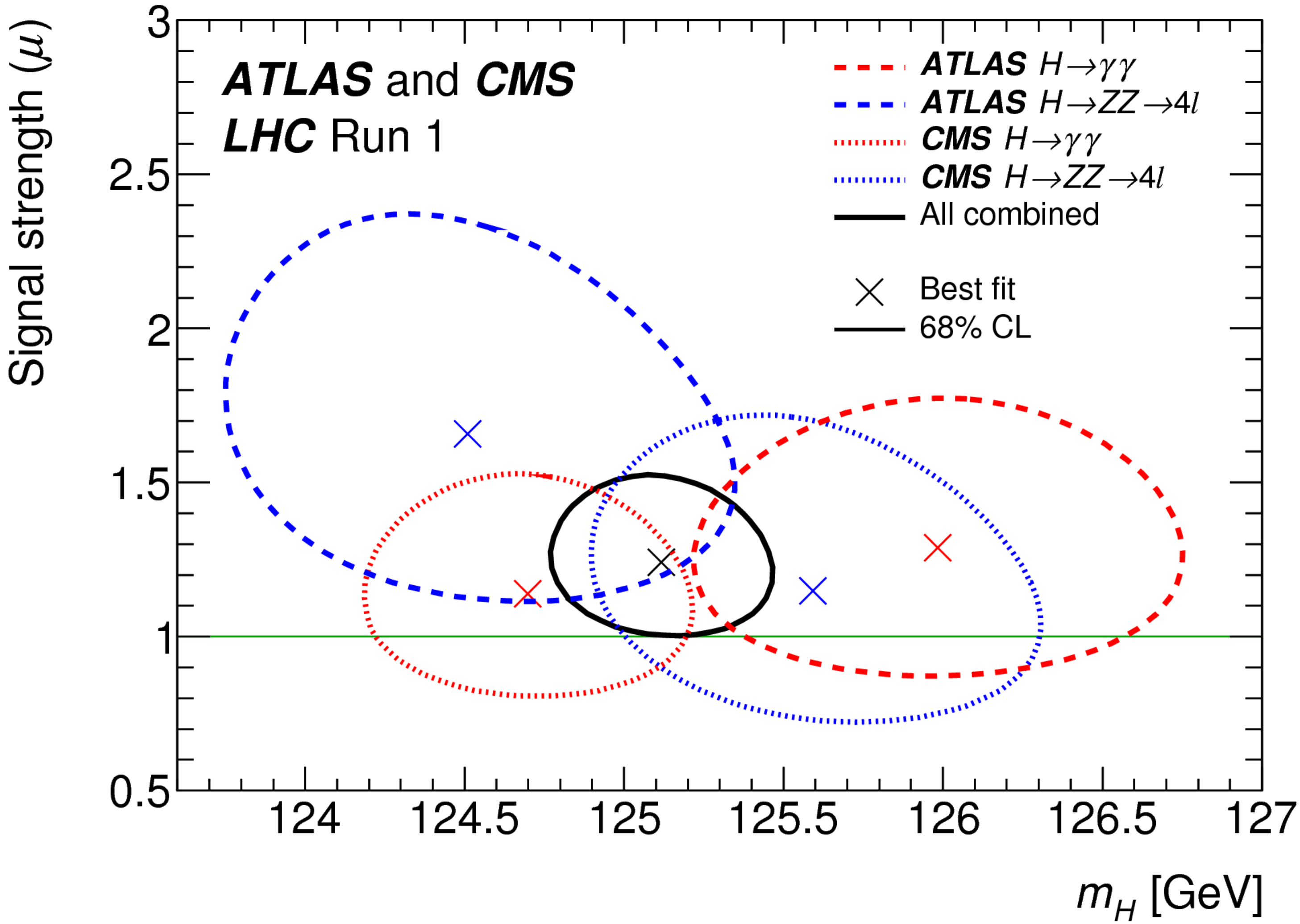
CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of contributors to a single research article.

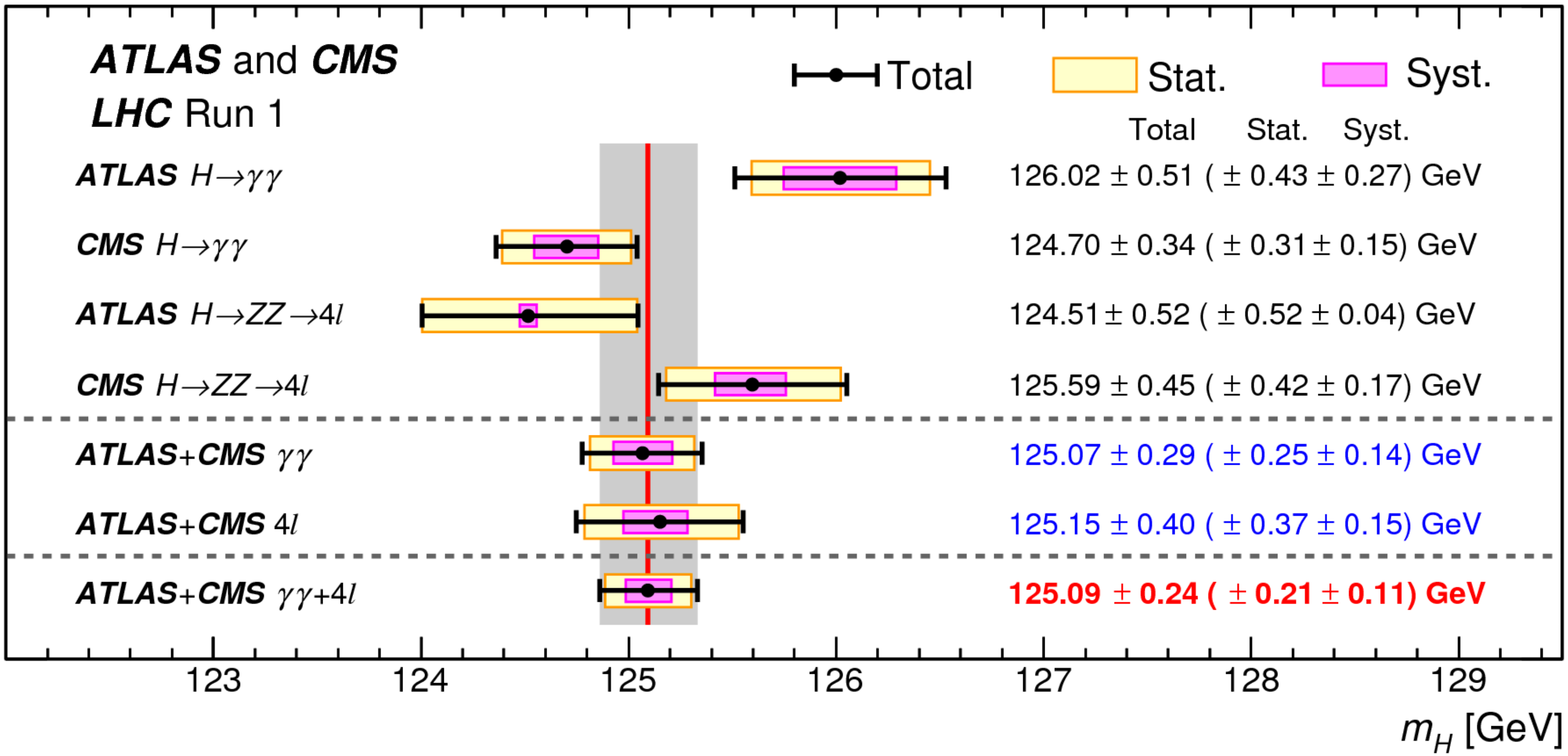
Combined LHC mass measurement

[arXiv:1503.07589]



Combined LHC mass measurement

[arXiv:1503.07589]



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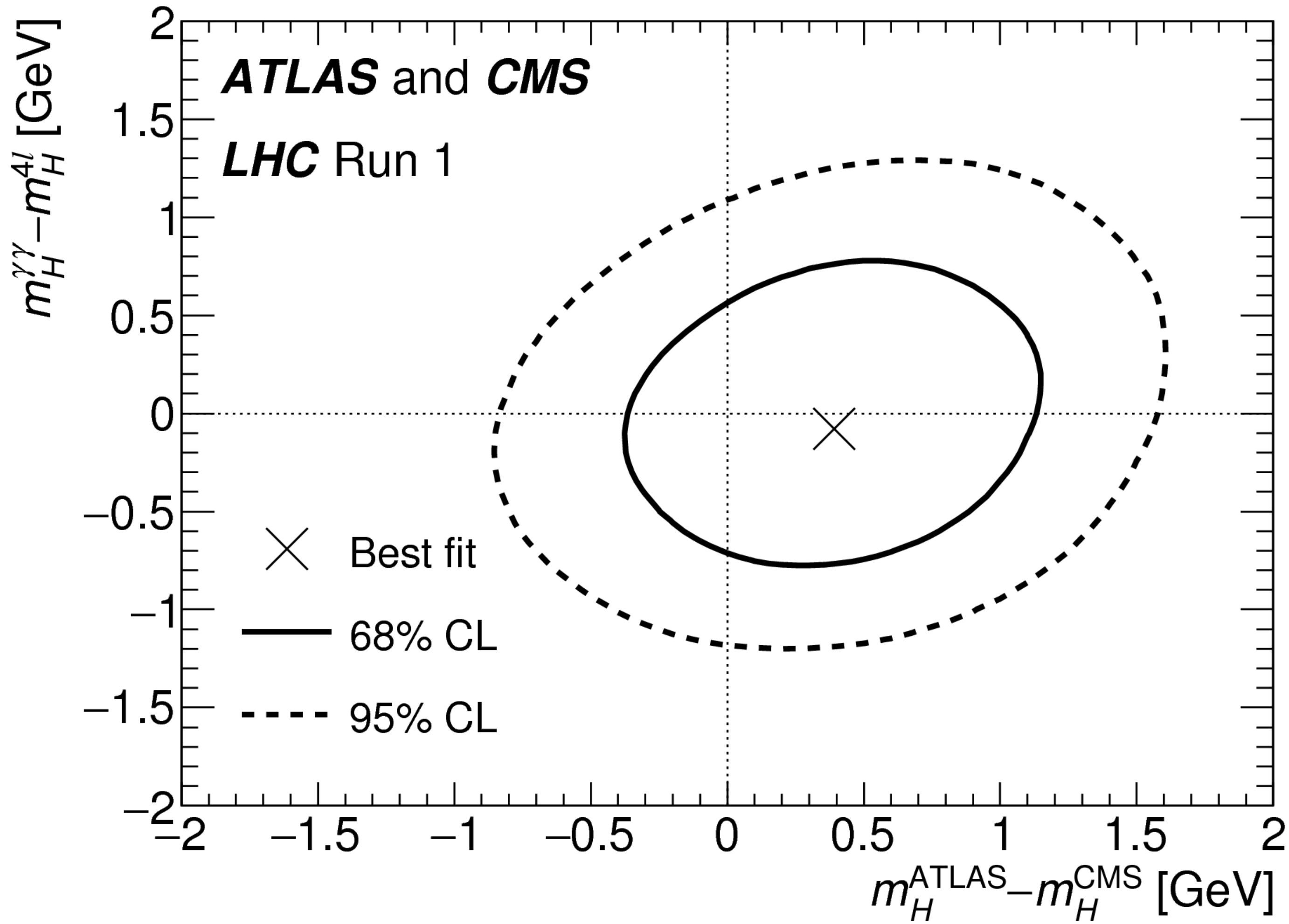
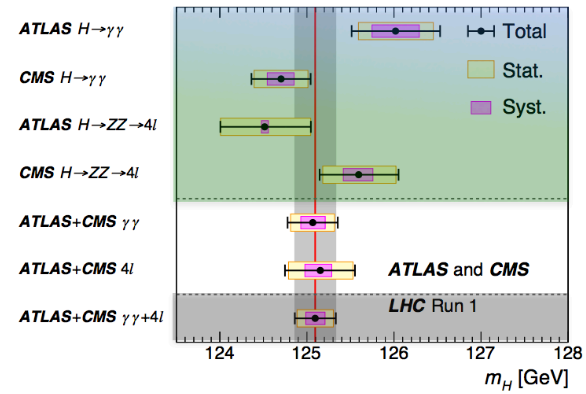


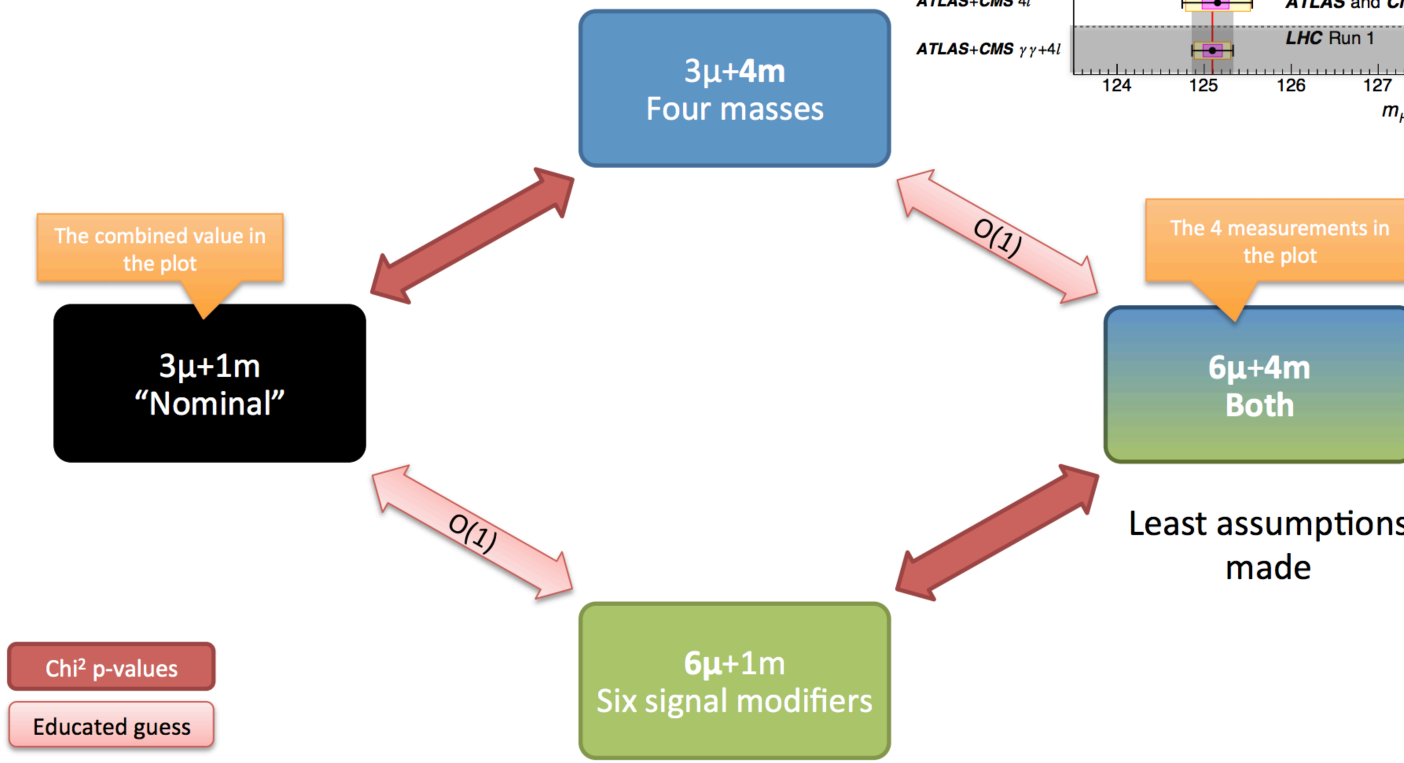
Combined LHC mass measurement

[arXiv:1503.07589]

Compatibility

A number of different models to check compatibility of the result …

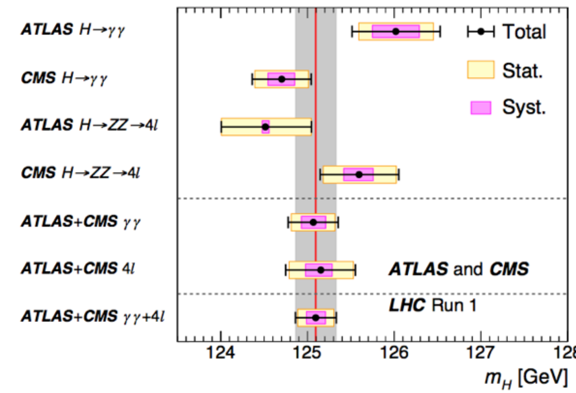




Combined LHC mass measurement

[arXiv:1503.07589]

Compatibility



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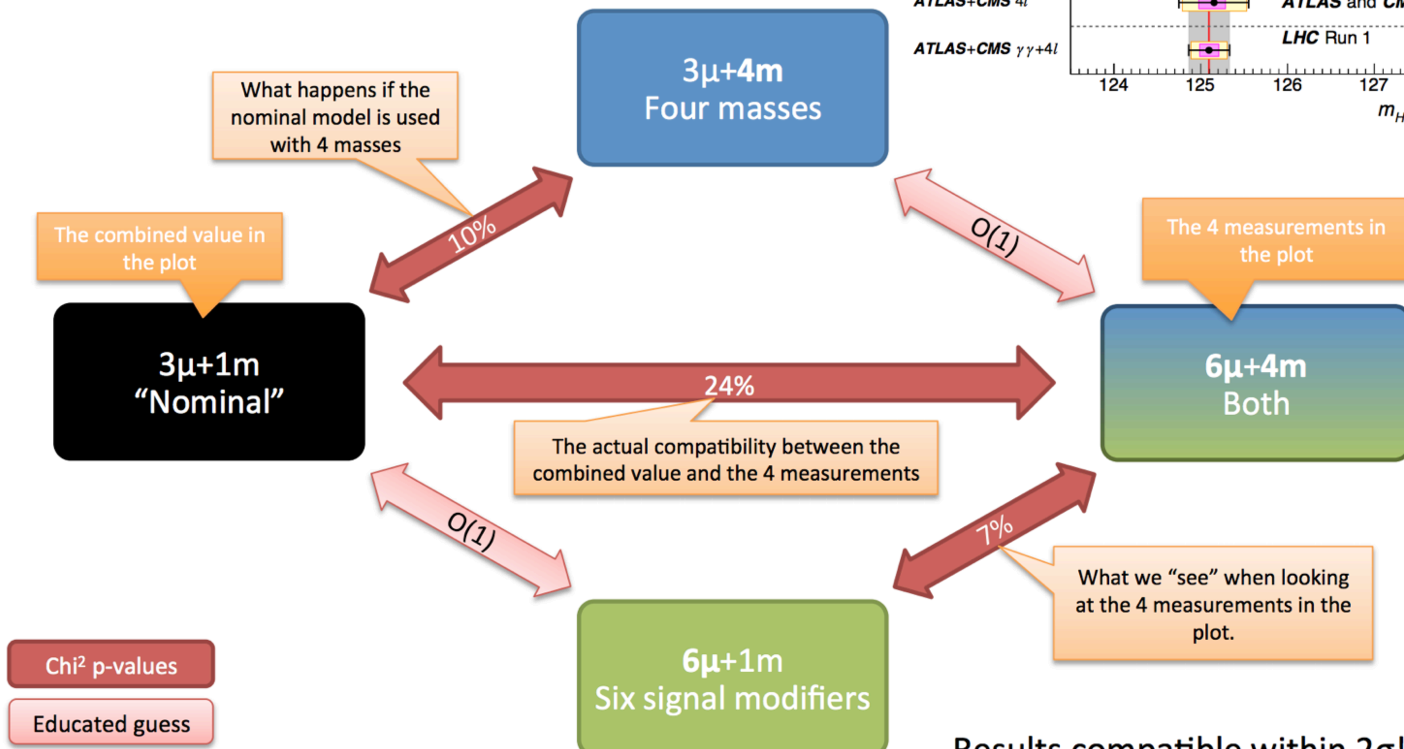


Results compatible within 2σ!

Combined LHC mass measurement

[arXiv:1503.07589]

$$\mathbf{m_H = 125.09 \pm 0.21\ (stat)}$$

$$\mathbf{\pm 0.11\ (scale)}$$

$$\mathbf{\pm 0.02\ (other)}$$

$$\mathbf{\pm 0.01\ (theory^{*})}$$

$$\mathbf{GeV}$$

Uncertainty is mostly statistical

Scale uncertainties dominate systematic

→ But we can expect that to improve with more data!

One model

One model

Fiat 124

Fiat 126

One model


Fiat 125
a very
high-performance saloon
$2898
Willys Motors
STAND No. 8
(AUSTRALIA) PTY. LTD. 79 YARRABANK ROAD, SOUTH MELBOURNE. 69-7411
594 ELIZABETH STREET, MELBOURNE. Phone 34-1519


Fiat 124


CB 29070
Fiat 126

One model

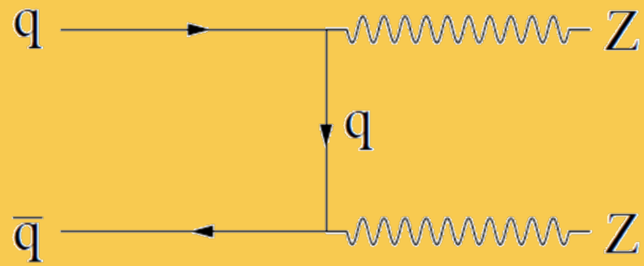
Fiat 124

Fiat 126

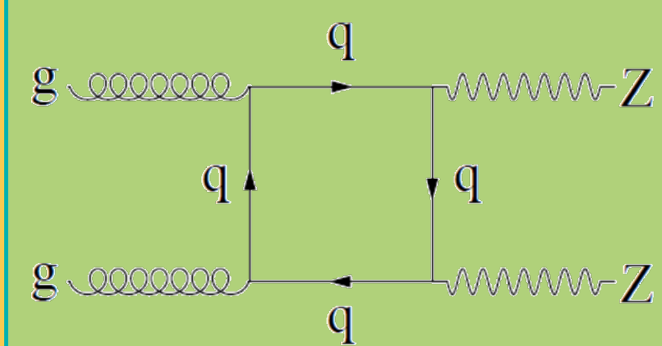
Going off-shell

Off-shell – involved processes

Backgrounds

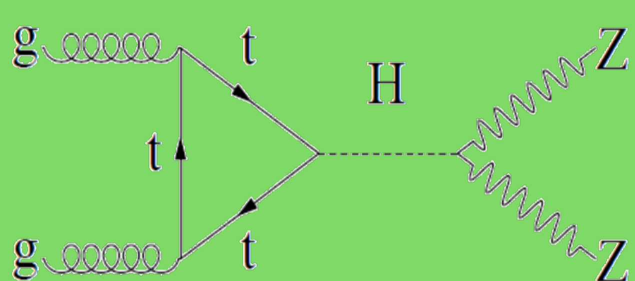


Strong interference



NNLO/LO k-factors depend on m_{ZZ}
[G. Passarino, arXiv:1312.2397]
Use the same k-factors for signal and gg continuum
[M. Bonvini et al., PRD 88 2013]

Signal



H* – off-shell

[PLB 736 (2014) 64][JHEP 08 (2012) 116][PRD 88 (2013) 054024][arXiv:1311.3589]

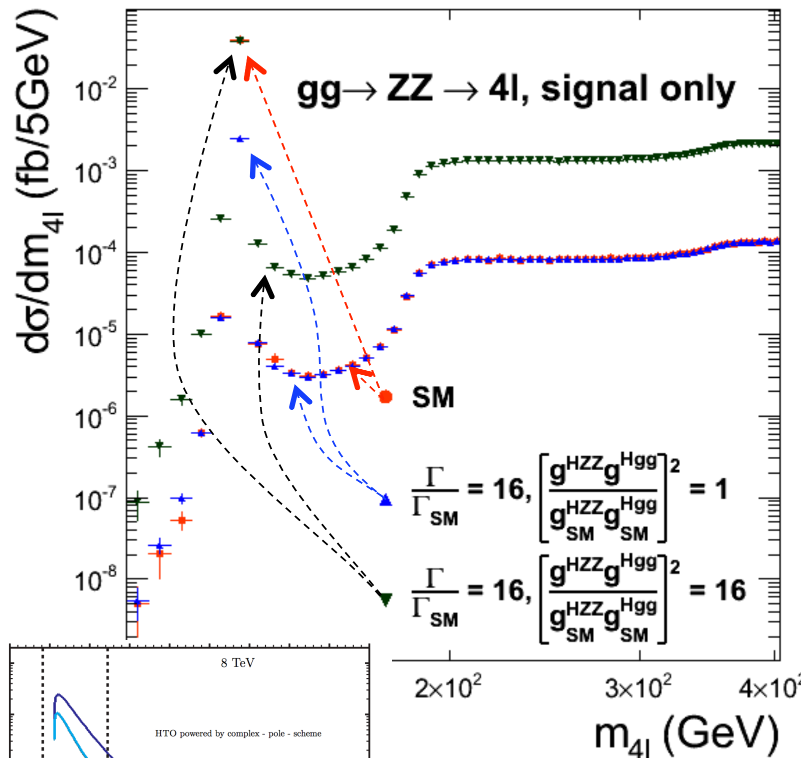
- Define $r = \Gamma_H / \Gamma_H^{SM}$
- On-mass-shell we have

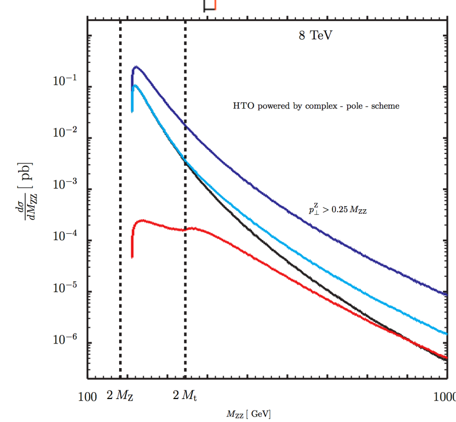
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{SM}$$

- Off-mass-shell there is no ***r***:

$$\frac{d\sigma^{\text{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma^{\text{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

- Can make inference on ***r*** from on- **and** off-shell **assuming:**
  - $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$
  - Only SM processes → ZZ:
    - gg→H*
    - **gg** = |gg→H* + gg→non-H|²
    - |gg→H*|² + |gg→non-H|²
    - **Total** = **gg** + $q\bar{q}$

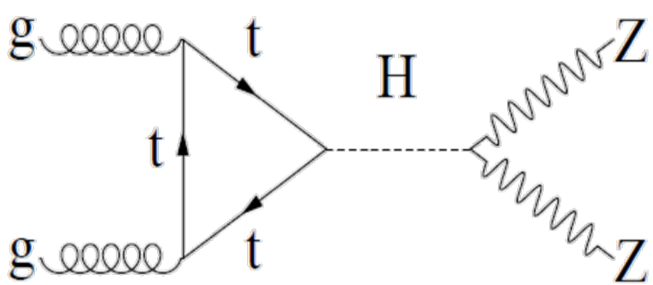


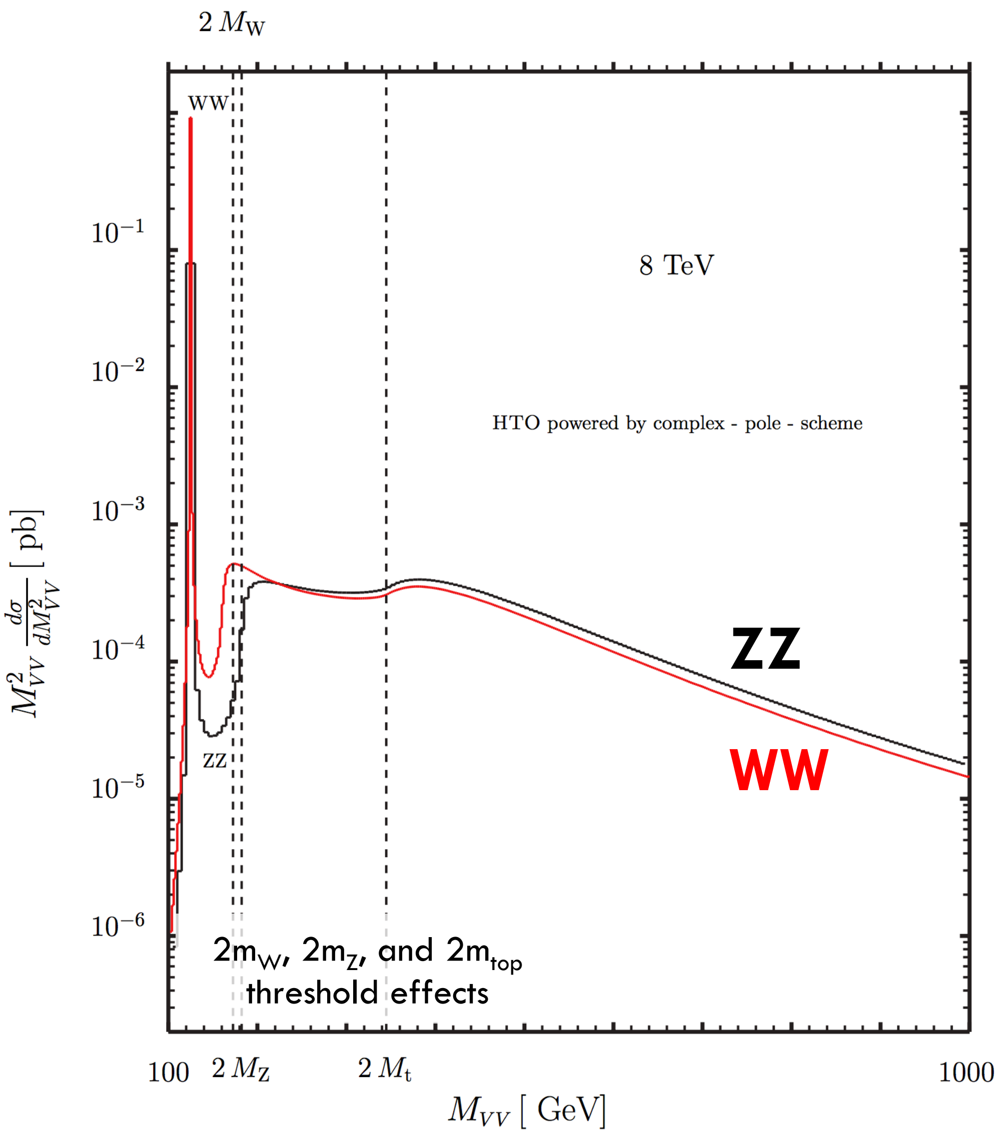


H* – going off-shell

[PLB 736 (2014) 64][arXiv:1206.4803]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$





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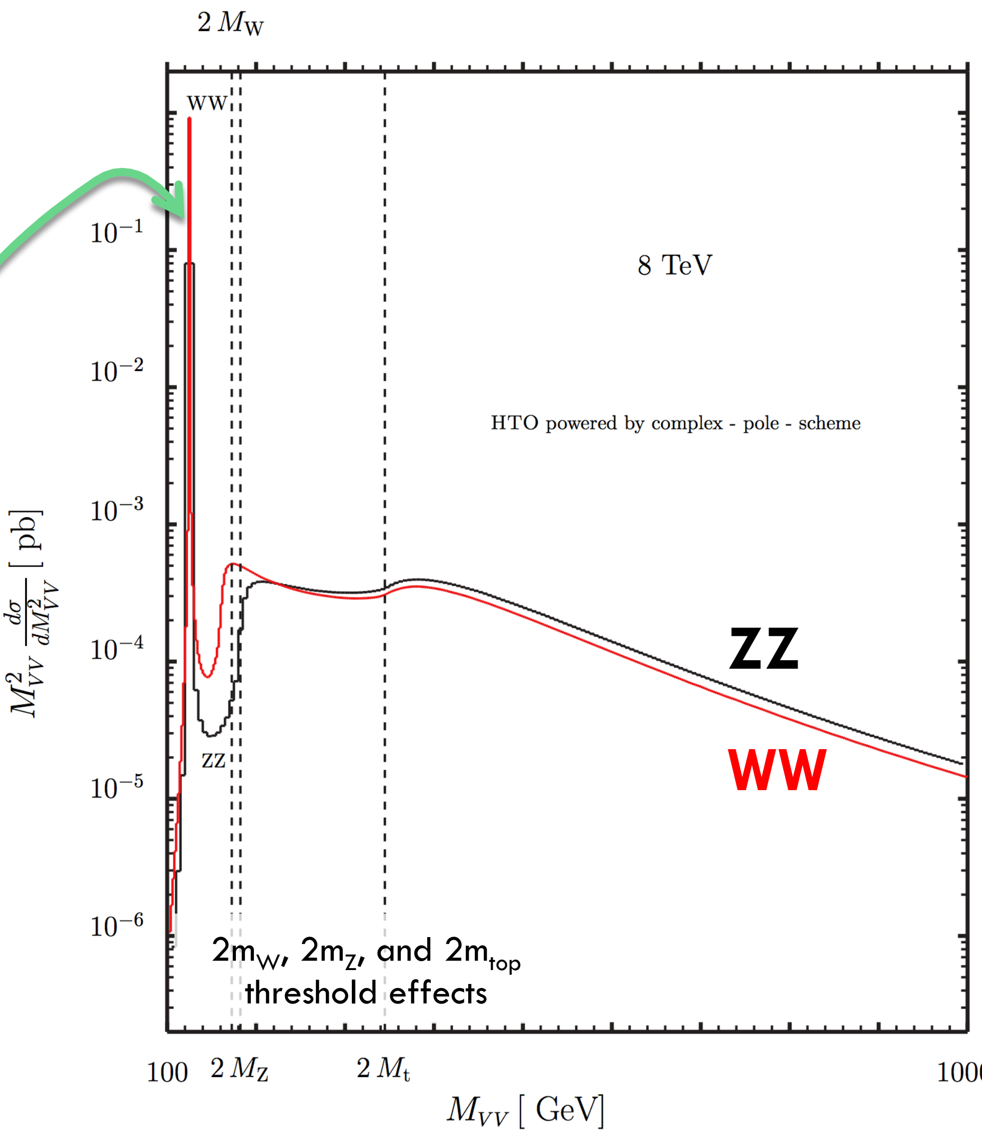
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

$m_{ZZ} \sim m_H$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$



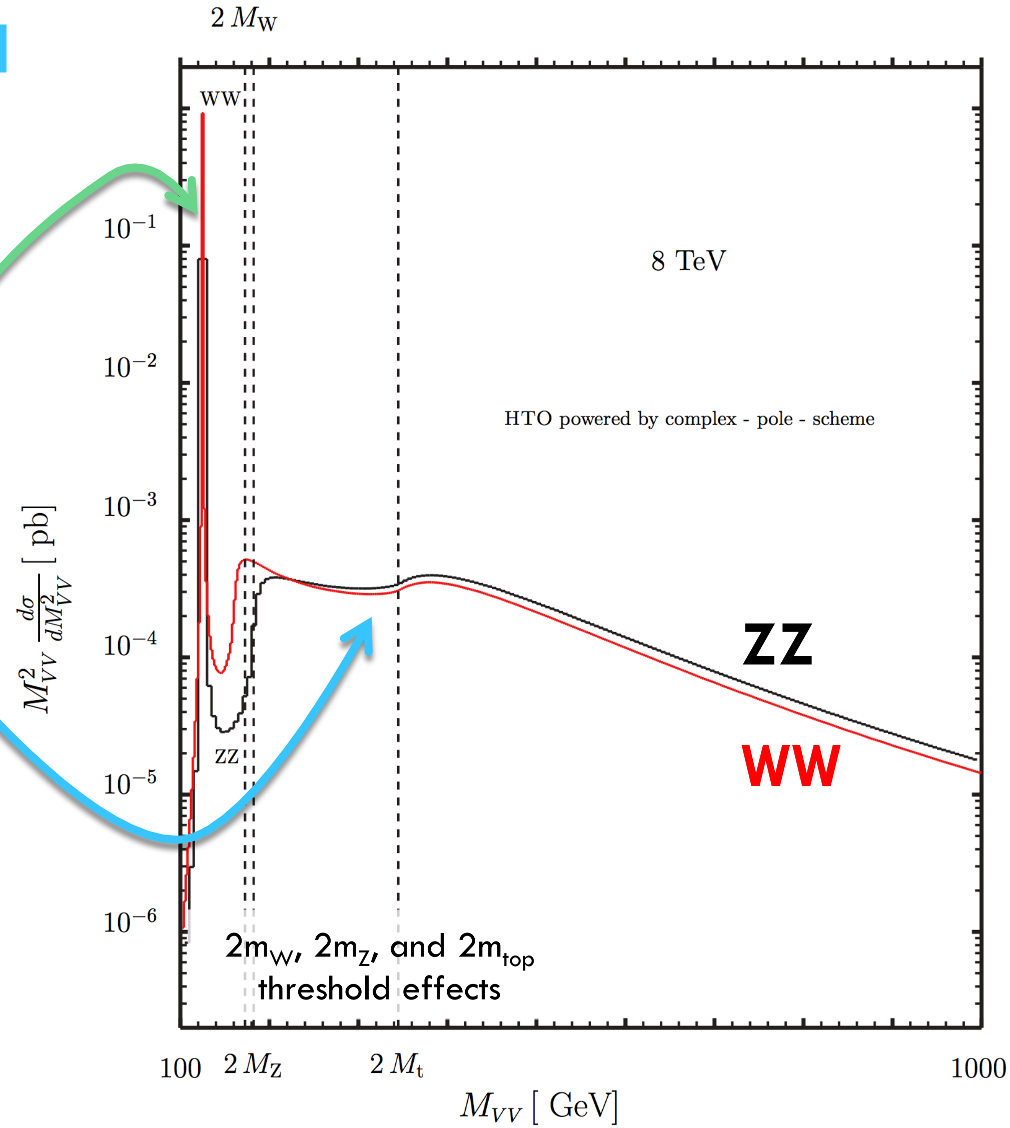
H* – going off-shell

[PLB 736 (2014) 64][arXiv:1206.4803]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

$m_{ZZ} \sim m_H$ $$\sigma_{gg\to H\to ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H\Gamma_H}$$

$m_{ZZ} \gg m_H$ $$\sigma_{gg\to H\to ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$



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[PLB 736 (2014) 64][arXiv:1206.4803]

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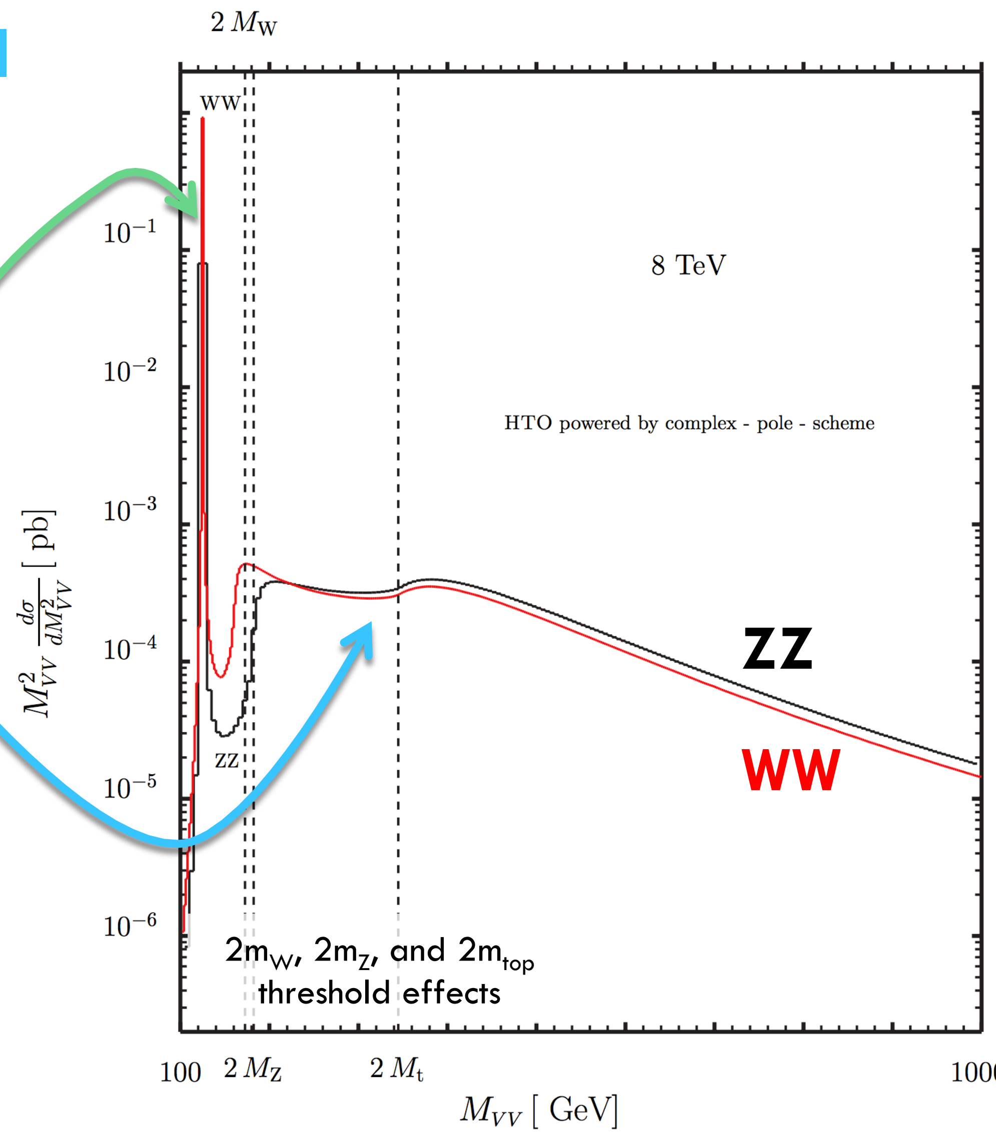
$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

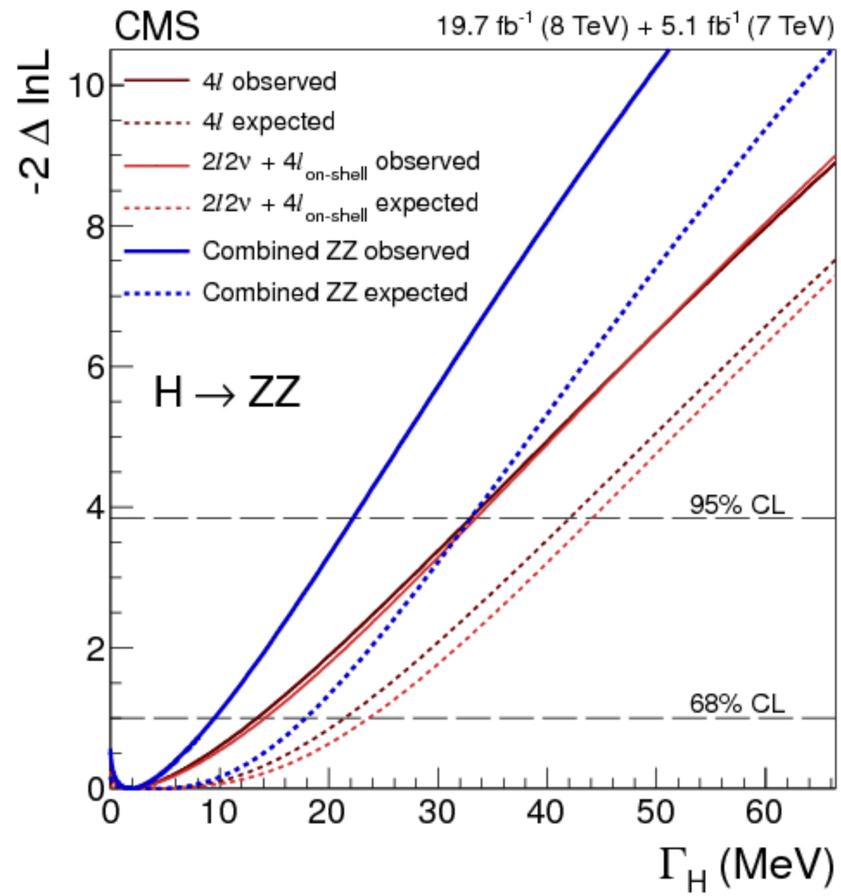
$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$



H* – off-shell decay to ZZ

[PLB 736 (2014) 64]

- Two channels exploited:
  - ZZ→4ℓ
    - 2D: $m_{4\ell}$ and gg vs. $q\bar{q}$ discriminant.
  - ZZ→2ℓ2ν
    - Jet-inclusive m_T shape.
- Observed limit lower than expected.



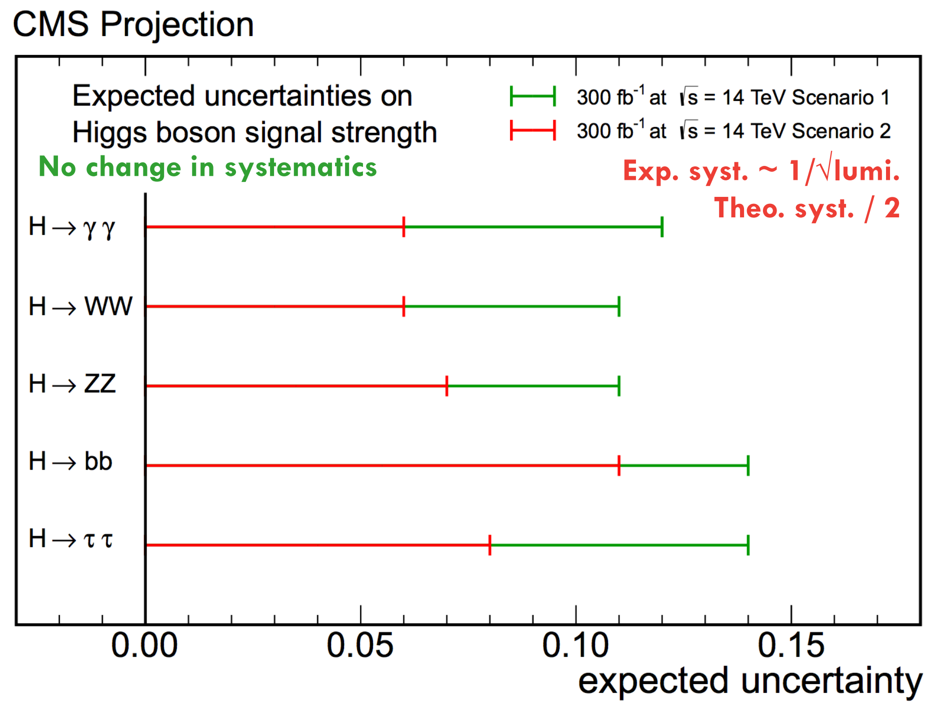
Obs. (exp.)	4ℓ	2ℓ2ν	Combined
Γ_H/Γ_H^{SM} (95% CL)	< 8.0 (10.1)	< 8.1 (10.6)	< 5.4 (8.0)

The Future

Looking ahead

[arXiv:1307.7135][CMS-PAS-HIG-13-007]

- 300 fb^{-1} at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**



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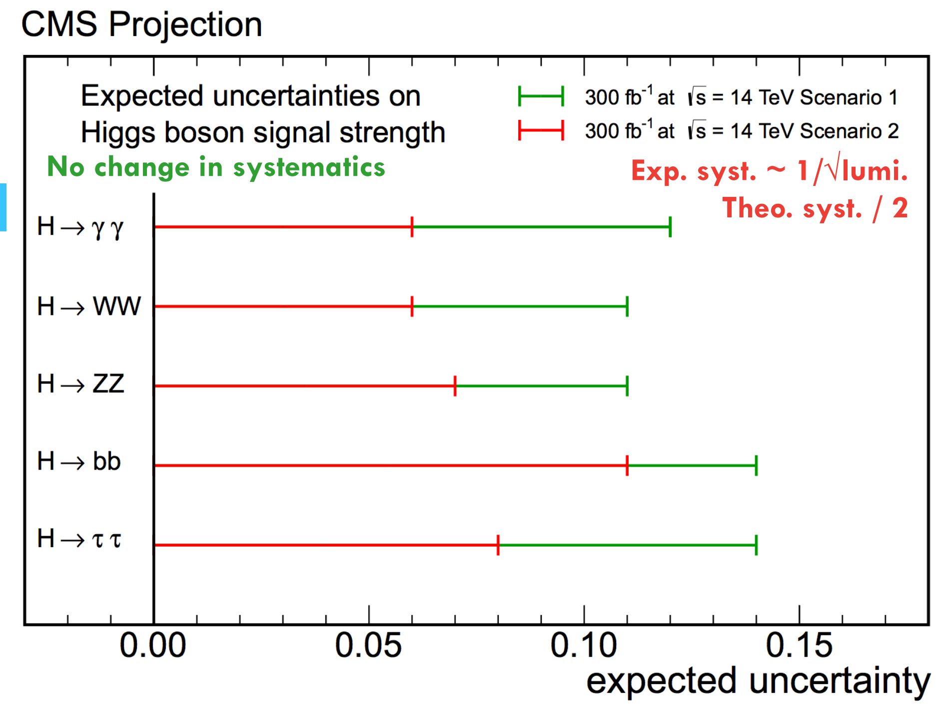
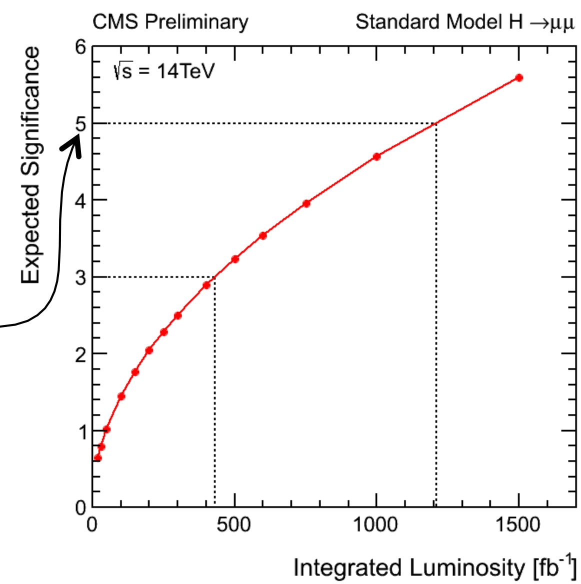


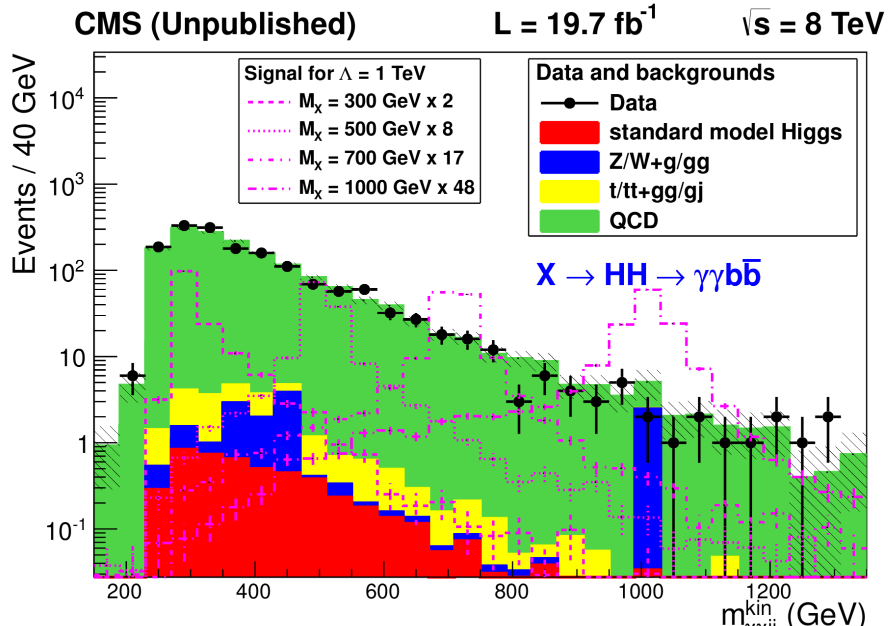
- For (HL-LHC) 3000 fb^{-1}:
  - **$H \to \mu\mu$ at > 5σ.**
  - Can we get to the Higgs self-coupling?



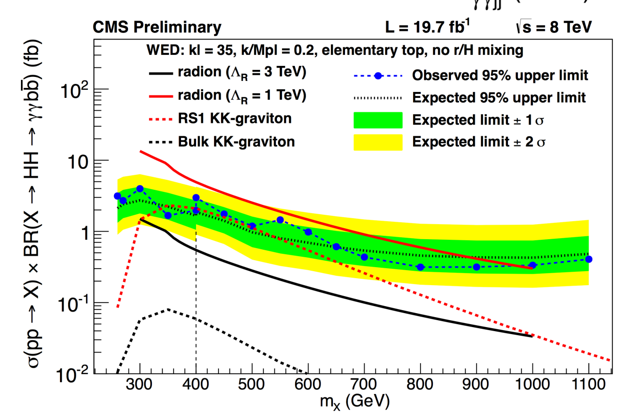
X→HH→b$\bar{b}$γγ and the future

[CMS-PAS-HIG-13-032]

- First step towards two-Higgs measurements at the HL-LHC.



- For now setting limits on radion production from warped extra dimensions.



More on theory

Decompose all the kappas

Production	Loops	Interference	Expression in terms of fundamental coupling strengths	
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06\cdot\kappa_t^2 + 0.01\cdot\kappa_b^2 - 0.07\cdot\kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	-	-	$\sim$	$0.74\cdot\kappa_W^2 + 0.26\cdot\kappa_Z^2$
$\sigma(WH)$	-	-	$\sim$	κ_W^2
$\sigma(q\bar{q}\to ZH)$	-	-	$\sim$	κ_Z^2
$\sigma(gg\to ZH)$	✓	$Z-t$	$\kappa_{ggZH}^2 \sim$	$2.27\cdot\kappa_Z^2 + 0.37\cdot\kappa_t^2 - 1.64\cdot\kappa_Z\kappa_t$
$\sigma(bbH)$	-	-	$\sim$	κ_b^2
$\sigma(ttH)$	-	-	$\sim$	κ_t^2
$\sigma(gb\to WtH)$	-	$W-t$	$\sim$	$1.84\cdot\kappa_t^2 + 1.57\cdot\kappa_W^2 - 2.41\cdot\kappa_t\kappa_W$
$\sigma(qb\to tHq')$	-	$W-t$	$\sim$	$3.4\cdot\kappa_t^2 + 3.56\cdot\kappa_W^2 - 5.96\cdot\kappa_t\kappa_W$
Partial decay width				
$\Gamma_{b\bar{b}}$	-	-	$\sim$	κ_b^2
Γ_{WW}	-	-	$\sim$	κ_W^2
Γ_{ZZ}	-	-	$\sim$	κ_Z^2
$\Gamma_{\tau\tau}$	-	-	$\sim$	κ_τ^2
$\Gamma_{\mu\mu}$	-	-	$\sim$	κ_μ^2
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59\cdot\kappa_W^2 + 0.07\cdot\kappa_t^2 - 0.66\cdot\kappa_W\kappa_t$
$\Gamma_{Z\gamma}$	✓	$W-t$	$\kappa_{Z\gamma}^2 \sim$	$1.12\cdot\kappa_W^2 + 0.00035\cdot\kappa_t^2 - 0.12\cdot\kappa_W\kappa_t$
Total decay width				
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim$	$0.57\cdot\kappa_b^2 + 0.22\cdot\kappa_W^2 + 0.09\cdot\kappa_g^2 +$ $0.06\cdot\kappa_\tau^2 + 0.03\cdot\kappa_Z^2 + 0.03\cdot\kappa_c^2 +$ $0.0023\cdot\kappa_\gamma^2 + 0.0016\cdot\kappa_{Z\gamma}^2 + 0.00022\cdot\kappa_\mu^2$

MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Shifts to tree-level couplings due to mixing with heavier Higgs

$$c_V = \sin(\beta - \alpha) \qquad c_t = \frac{\cos\alpha}{\sin\beta} \qquad c_b = -\frac{\sin\alpha}{\cos\beta}$$

c_V always reduced

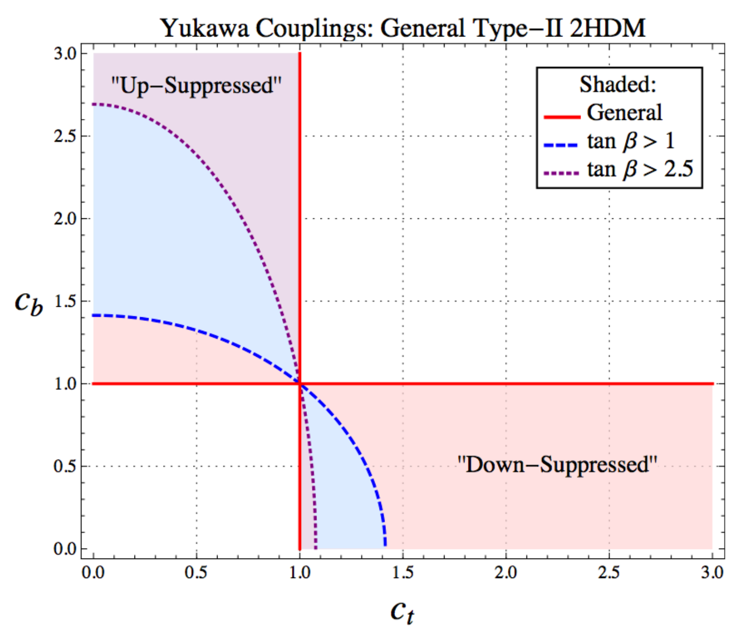
if $c_t > 1$ then $c_b < 1$ and viceversa

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}\, H_u^0 \\ \mathrm{Re}\, H_d^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_u}{v_d}$$

Only two regions in the (c_t, c_b) plane accessible in a *generic* Type-II 2HDM

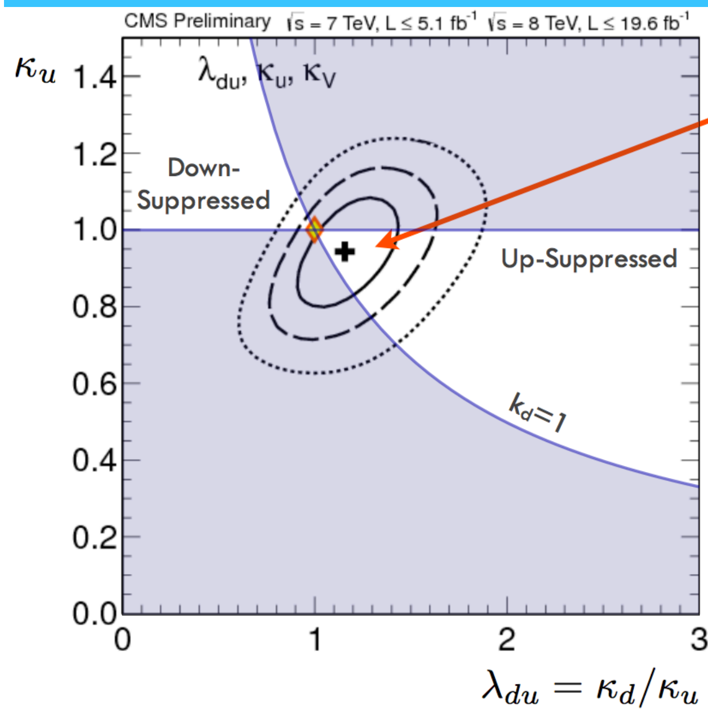
Down-Suppressed region almost *not accessible* in the MSSM for $\tan\beta > 1$



see: Azatov, Chang, Craig, Galloway PRD 86 (2012) 075033

MSSM (R.Contino)

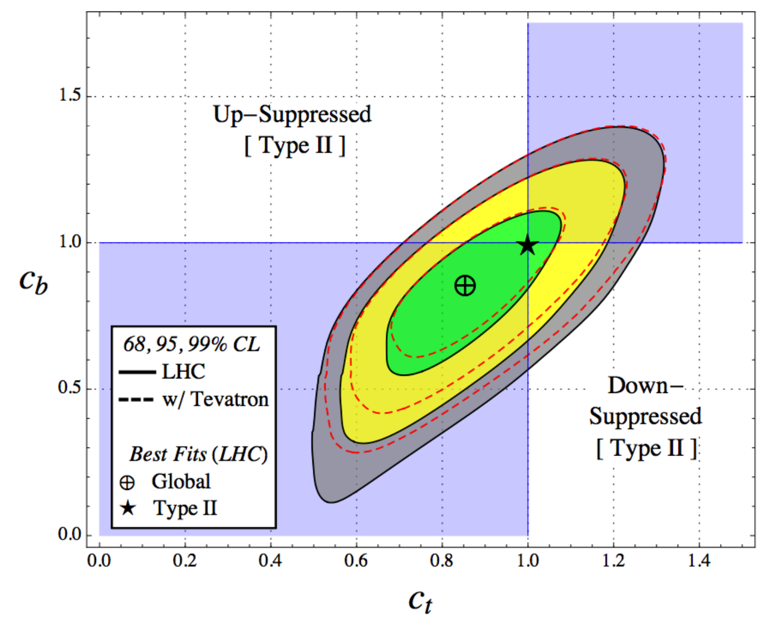
[http://cern.ch/go/W96V]



the current fit by CMS seems to favor the MSSM region, though errors are large

It would be nice to see the same plot by ATLAS and even nicer to see plot in the plane (κ_u, κ_d)

For the impatient ones here is a theorist's combination of ATLAS+CMS+Tevatron:

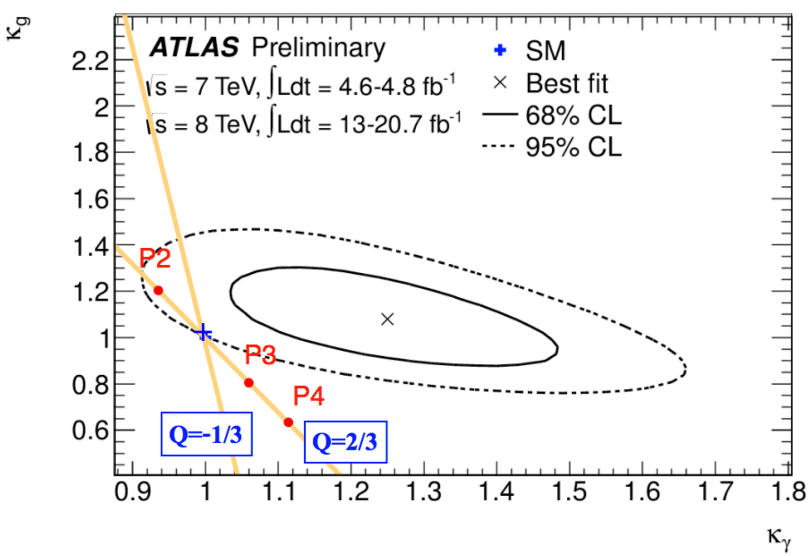


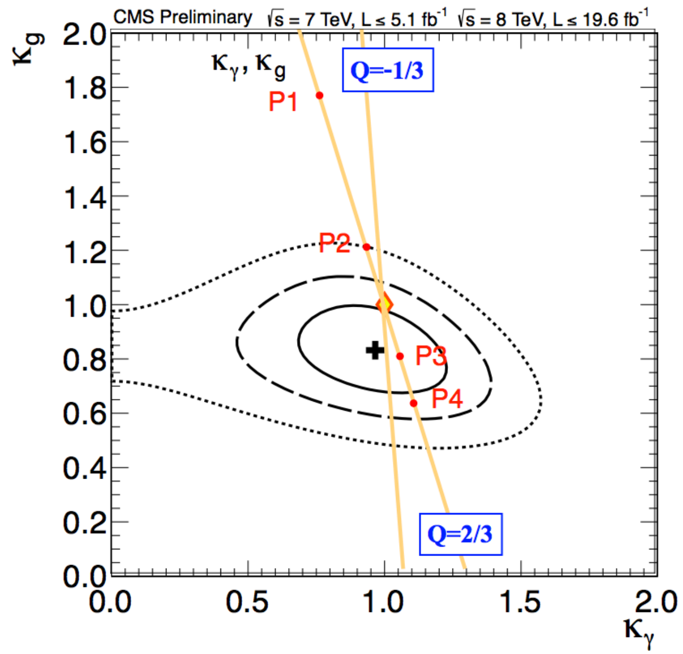
from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Shifts to loop-induced couplings due to squarks





Small mixing: ➡ $\Gamma(gg \to h)$ enhanced, $\Gamma(h \to \gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg \to h)$ suppressed, $\Gamma(h \to \gamma\gamma)$ enhanced

P1: $m_{\tilde{t}_1} = 100\,\mathrm{GeV},\ m_{\tilde{t}_2} = 300\,\mathrm{GeV},\ \theta_t = 0$

P2: $m_{\tilde{t}_1} = 200\,\mathrm{GeV},\ m_{\tilde{t}_2} = 500\,\mathrm{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1000\,\mathrm{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\mathrm{GeV},\ m_{\tilde{t}_2} = 1500\,\mathrm{GeV},\ \theta_t = \pi/4$

MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Implications on the masses of the heavier Higgses

In the decoupling limit: $\boxed{\alpha \to \beta - \pi/2}$

$$c_V = 1 - \Delta^2 \frac{1}{\tan^2\beta} + O(\Delta^3) \qquad c_t = 1 - \Delta\,\frac{1}{\tan^2\beta} + O(\Delta^2) \qquad \Delta = O\left(\frac{m_Z^2}{m_H^2}\right)$$

starts at $O(m_H^{-4})$

$$c_b = 1 + \Delta + O(\Delta^2)$$

c_b most sensitive probe of spectrum of Heavy Higgses

$$\boxed{\frac{\delta c_b}{c_b} > 0.1 \quad \Rightarrow \quad m_H > 300-400\,\mathrm{GeV}}$$

Notice:

masses of Heavy Higgses are *not* linked to naturalness of m_h anyway

Lighter masses (up to m_H ~200 GeV) however simple to obtain in explicit models (ex: NMSSM) with mild tuning of Δ

see for example: Barbieri et al. arXiv:1304.3670

The case for the SMH (R.Contino)

[http://cern.ch/go/W96V]

If one assumes that

1. The new boson is part of an $SU(2)_L$ doublet

2. There is a gap between the NP scale and m_H

then it must follow:

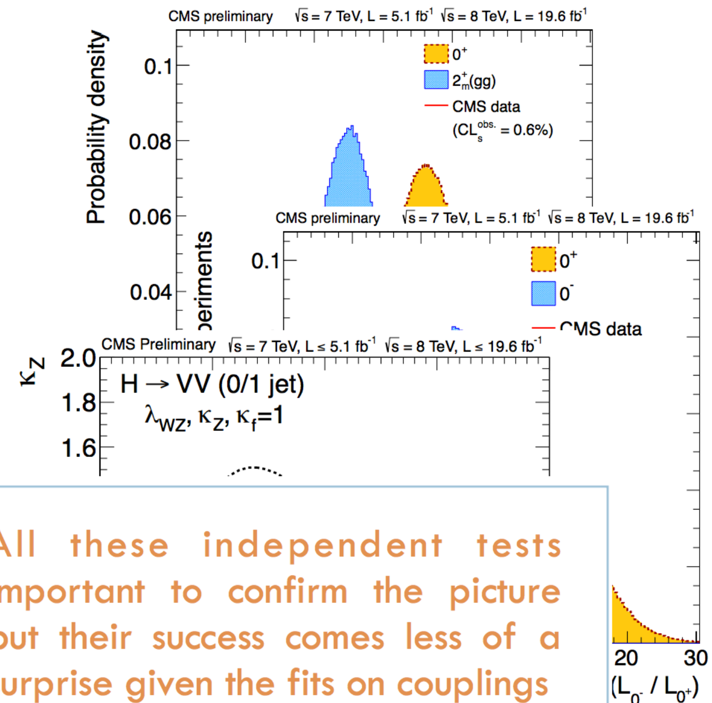
- h has spin 0 ✓
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons

  Ex: custodial symmetry ✓

  $$\frac{m_W}{m_Z \cos\theta_W} = 1 \quad \Rightarrow \quad \lambda_{WZ} = \frac{c_W}{c_Z} = 1$$

- There are no new light states to which the Higgs boson can decay

  Ex: Invisible width=0 ✓



All these independent tests important to confirm the picture but their success comes less of a surprise given the fits on couplings

Ex: there's no reason why a $J^P=0^-$ boson should have SM coupling strength

$$|D_\mu H|^2 \quad \text{vs} \quad \frac{\tilde{c}_{WW}}{M^2} W_{\mu\nu}\tilde{W}^{\mu\nu} H^\dagger H$$

To loop or not to loop

To loop or not to loop

Generic coupling fit

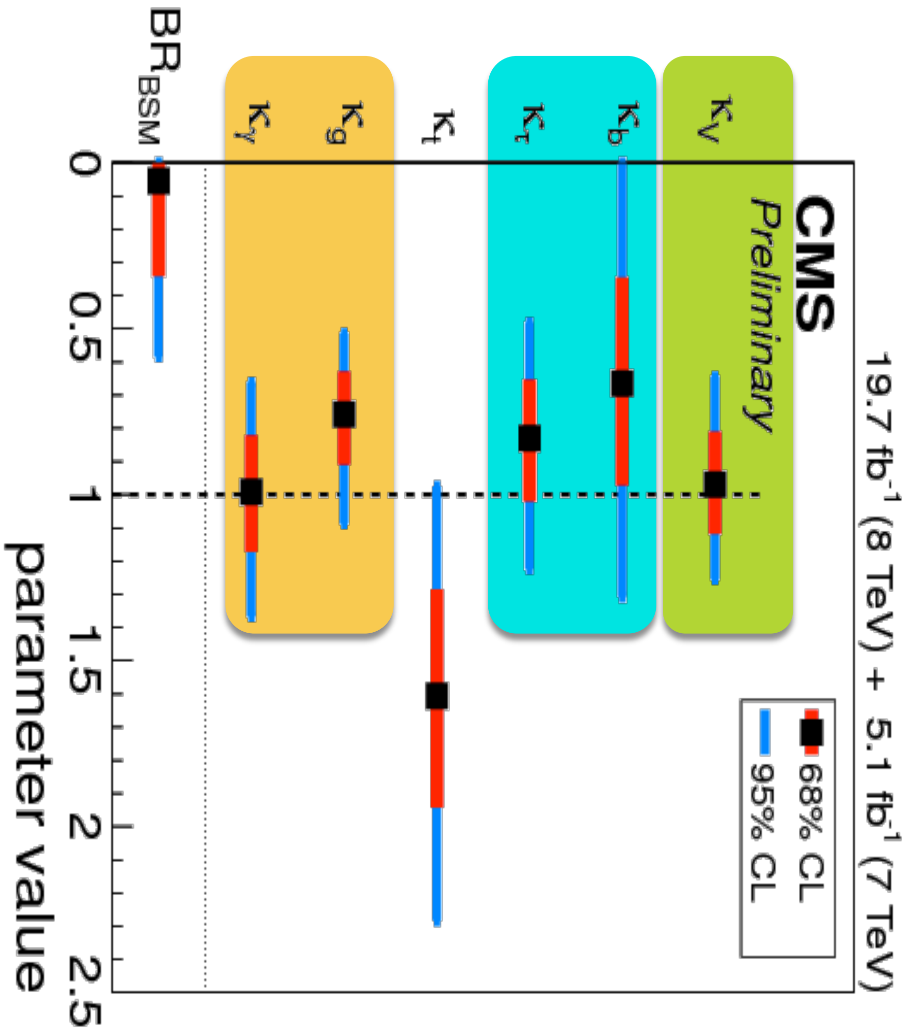
- Assume custodial symmetry ($\kappa_V = \kappa_W = \kappa_Z$).
- Loops treated effectively (κ_γ, κ_g).
- Option to allow BSM decays, forcing $\kappa_V \leq 1$.

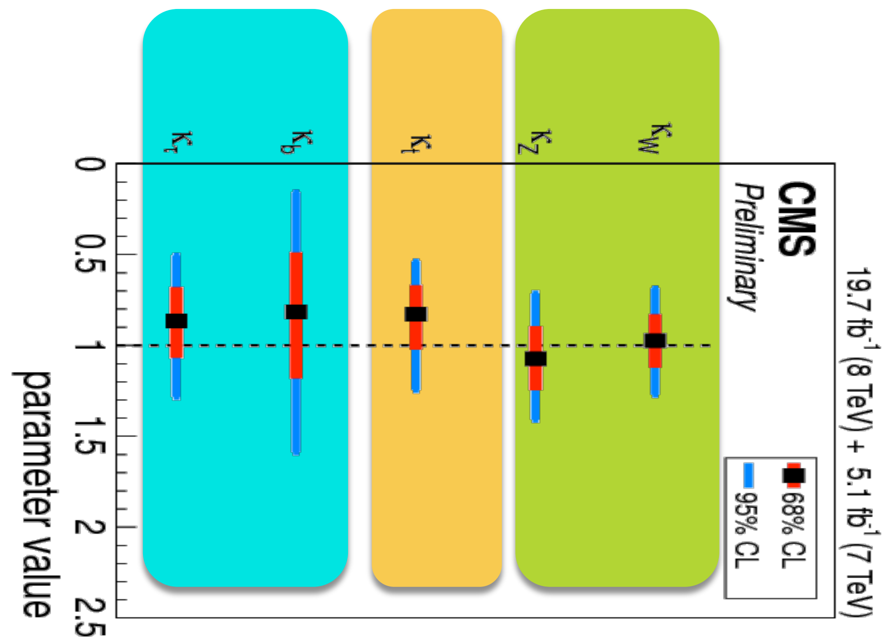
Resolved coupling fit

- Keep W and Z separate.
- Loops assuming SM structure:
  - κ_g (κ_b, κ_t).
  - κ_γ (κ_W, κ_b, κ_t, κ_τ).
- Only SM-like decays.

To loop or not to loop

[arXiv:1412.8662]





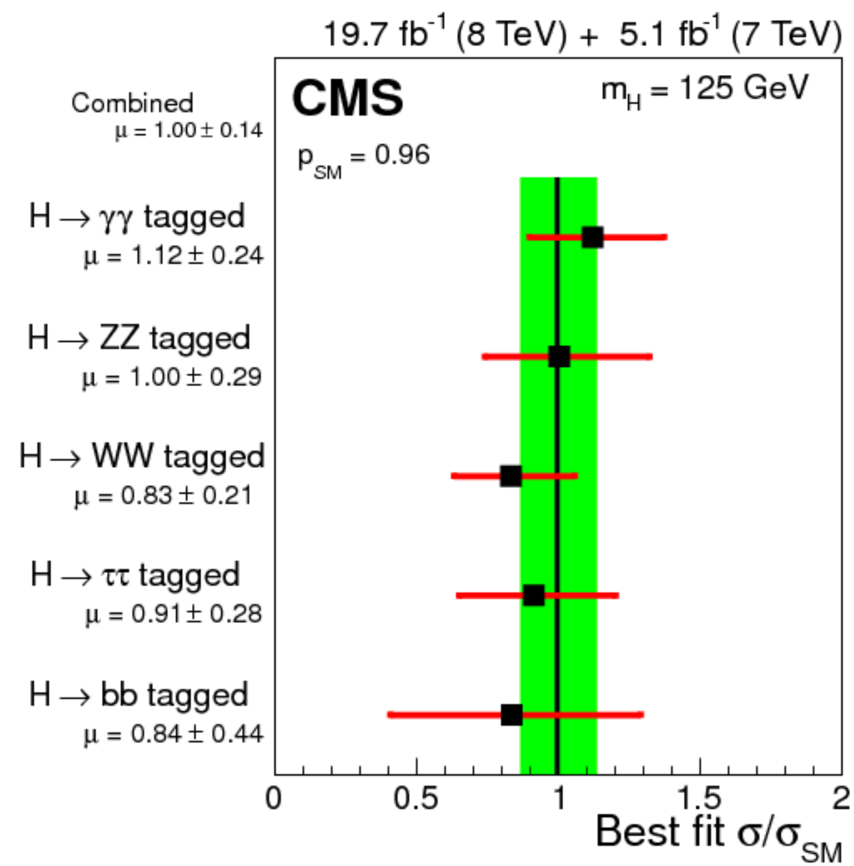
More on scalar couplings

Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by dominant decay:
  - $\chi^2/\text{dof} = 1.0/5$
  - p-value = 0.96 (asymptotic)

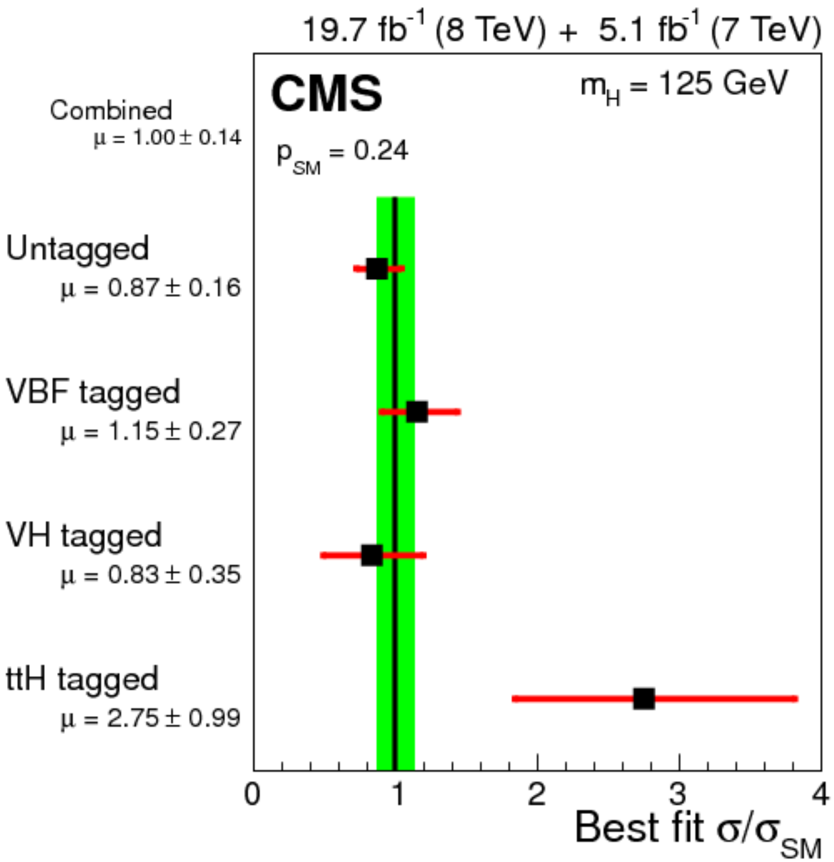


Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by production tag:
  - $\chi^2/\text{dof} = 5.5/4$
  - p-value = 0.24 (asymptotic)
- **ttH-tagged 2.0σ above SM.**

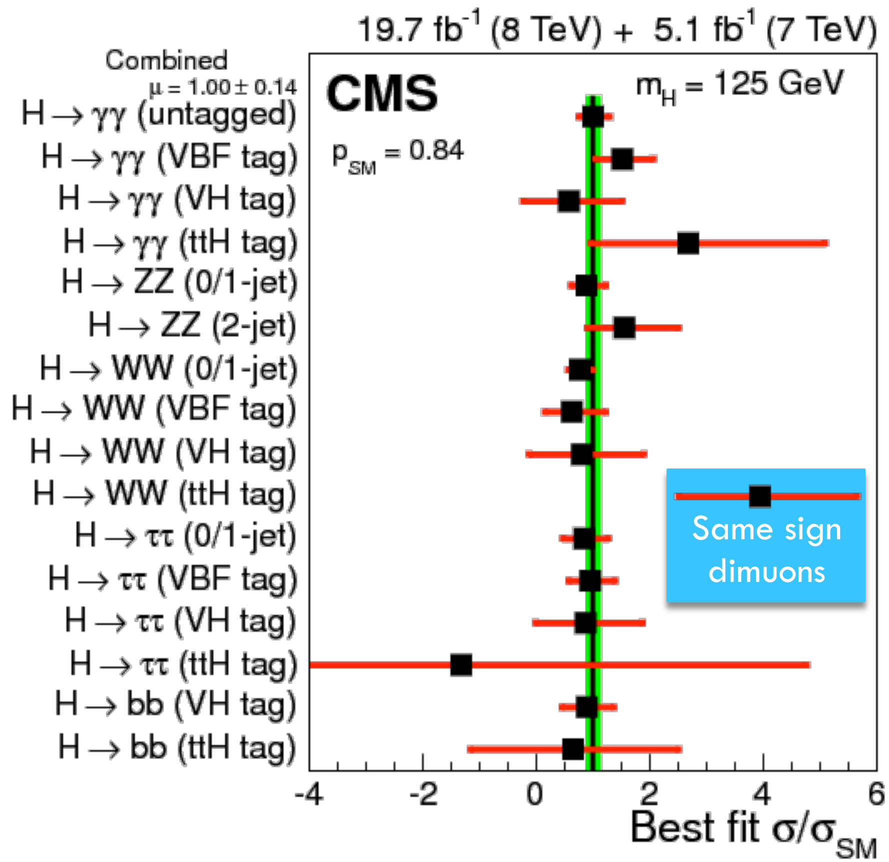


Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,{}^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by production tag and dominant decay:
  - $\chi^2/\text{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**



Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

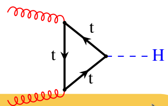
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes



$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa^2_{\mathrm{g}}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{g}} \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa^2_{\mathrm{VBF}}(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa^2_{\mathrm{t}}$$

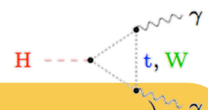
Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa^2_{\mathrm{W}}$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa^2_{\mathrm{Z}}$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa^2_{\tau}$$



$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa^2_{\gamma}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{\gamma} \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa^2_{(\mathrm{Z}\gamma)}(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa^2_{(\mathrm{Z}\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{t\bar{t}}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma^{\mathrm{SM}}_{\mathrm{gg}}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{c\bar{c}}}} = \kappa^2_{\mathrm{t}}$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}} = \kappa^2_{\mathrm{b}}$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa^2_{\tau}$$

Total width

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma^{\mathrm{SM}}_{\mathrm{H}}} = \begin{cases} \kappa^2_{\mathrm{H}}(\kappa_i, m_{\mathrm{H}}) \\ \kappa^2_{\mathrm{H}} \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \quad : \quad \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_{H}}{\Gamma^{SM}_{H}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H. (invisible decays)

Weak bosons and fermions

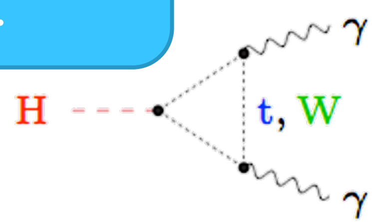
[arXiv:1307.1347]

Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

$H \to \gamma\gamma$ resolved into top-loop, b-loop, τ-loop, and W-loop.



Probing custodial symmetry

[arXiv:1307.1347]

Probing custodial symmetry assuming no invisible or undetectable widths

Free parameters: κ_Z, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$, $H\to\tau^-\tau^+$
ggH, $t\bar{t}H$	$\frac{\kappa_f^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ})\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$
WH	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$
ZH	$\frac{\kappa_Z^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2\cdot\kappa_f^2}{\kappa_H^2(\kappa_i)}$

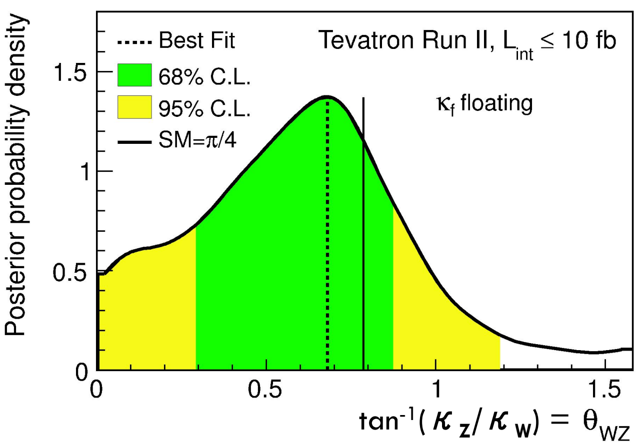
Probing custodial symmetry without assumptions on the total width

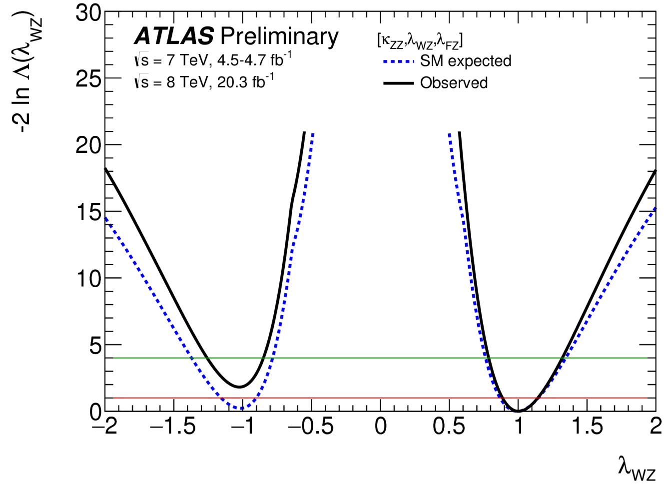
Free parameters: $\kappa_{ZZ}(=\kappa_Z\cdot\kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

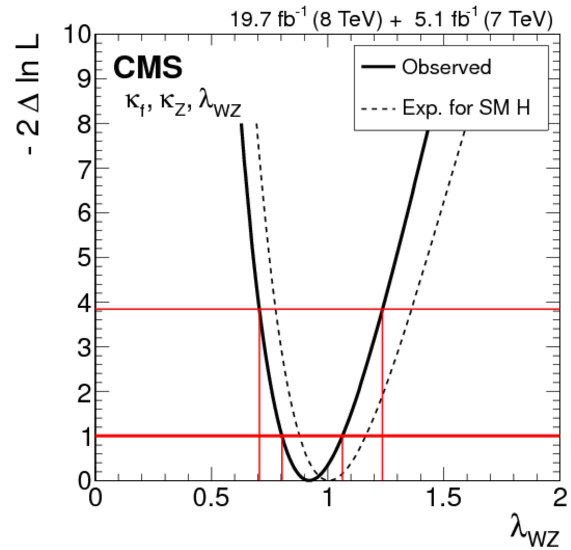
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$, $H\to\tau^-\tau^+$
ggH, $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2\cdot\lambda_{FZ}^2$
VBF	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)\cdot\lambda_{FZ}^2$
WH	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2\cdot\lambda_{FZ}^2$
ZH	$\kappa_{ZZ}^2\cdot\kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2\cdot\lambda_{WZ}^2$	$\kappa_{ZZ}^2\cdot\lambda_{FZ}^2$

Probing custodial symmetry

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







	Tevatron [$\kappa_W, \kappa_Z, \kappa_f$]	ATLAS [$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$]	CMS [$\lambda_{WZ}, \kappa_Z, \kappa_f$]
λ_{WZ}	$1.24^{+2.34}_{-0.42}$	$1.00^{+0.15}_{-0.11}$	$0.92^{+0.14}_{-0.12}$

Looking for new particles

[arXiv:1307.1347]

Probing loop structure assuming no invisible or undetectable widths

Free parameters: κ_g, κ_γ.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			

Probing loop structure allowing for invisible or undetectable widths

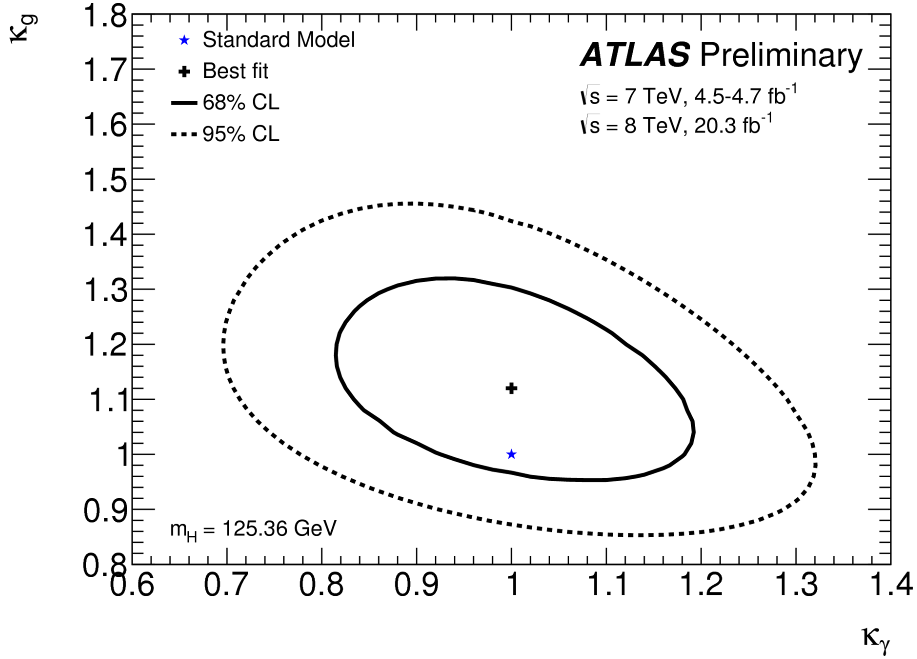
Free parameters: $\kappa_g, \kappa_\gamma, \mathrm{BR}_{\mathrm{inv.,undet.}}$.

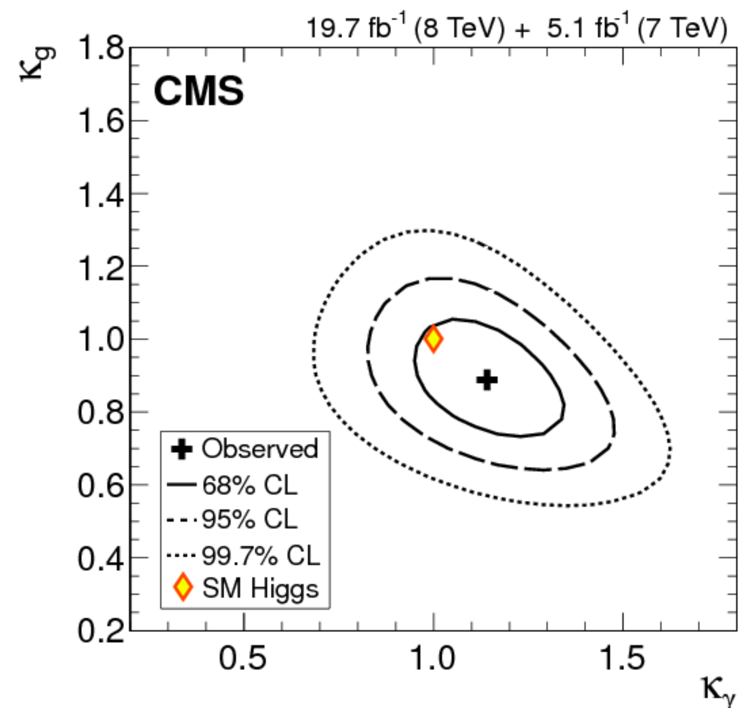
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$	$\frac{1}{\kappa_H^2(\kappa_i)/(1-\mathrm{BR}_{\mathrm{inv.,undet.}})}$			

$$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{\mathrm{SM}}$$

Looking for new particles in loops

[ATLAS-CONF-2015-007][arXiv:1412.8662]

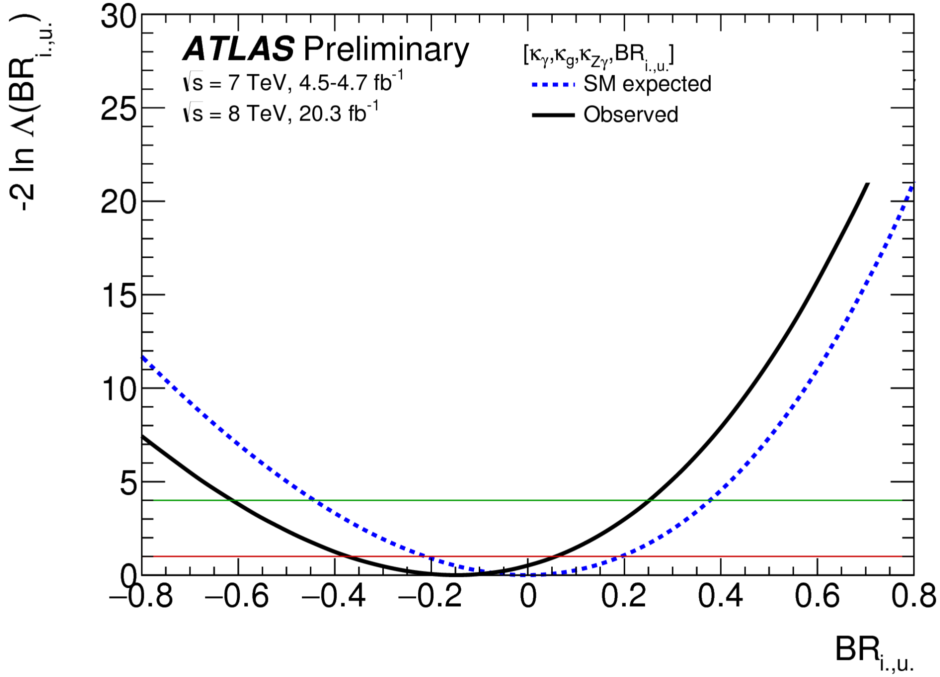


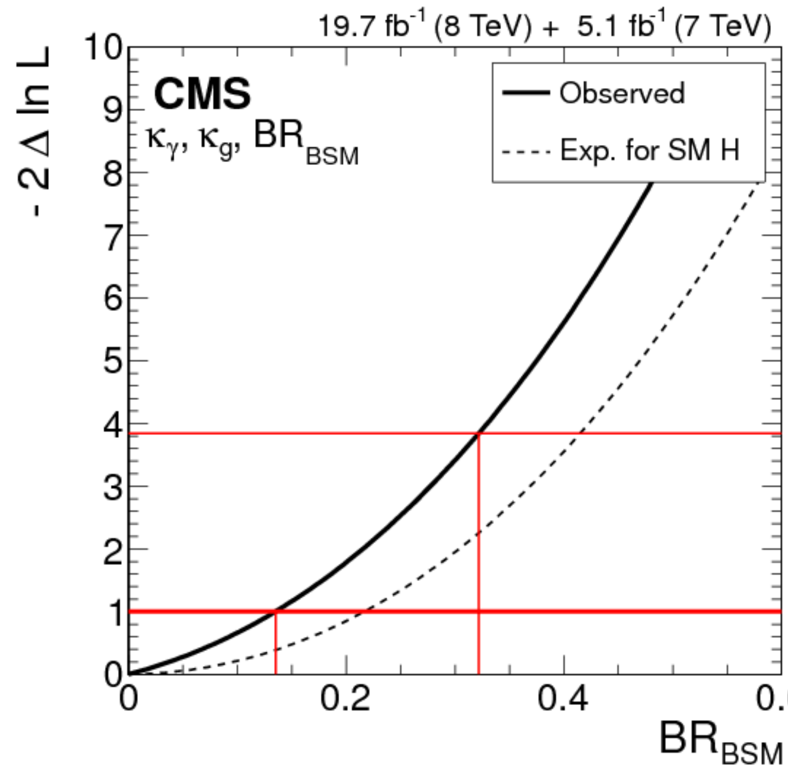


	ATLAS	CMS
κ_γ	**1.00 ±0.12**	**$1.14^{+0.12}_{-0.13}$**
κ_g	**1.12 ±0.12**	**$0.89^{+0.11}_{-0.10}$**

Looking for new particles

[ATLAS-CONF-2015-007][arXiv:1412.8662]





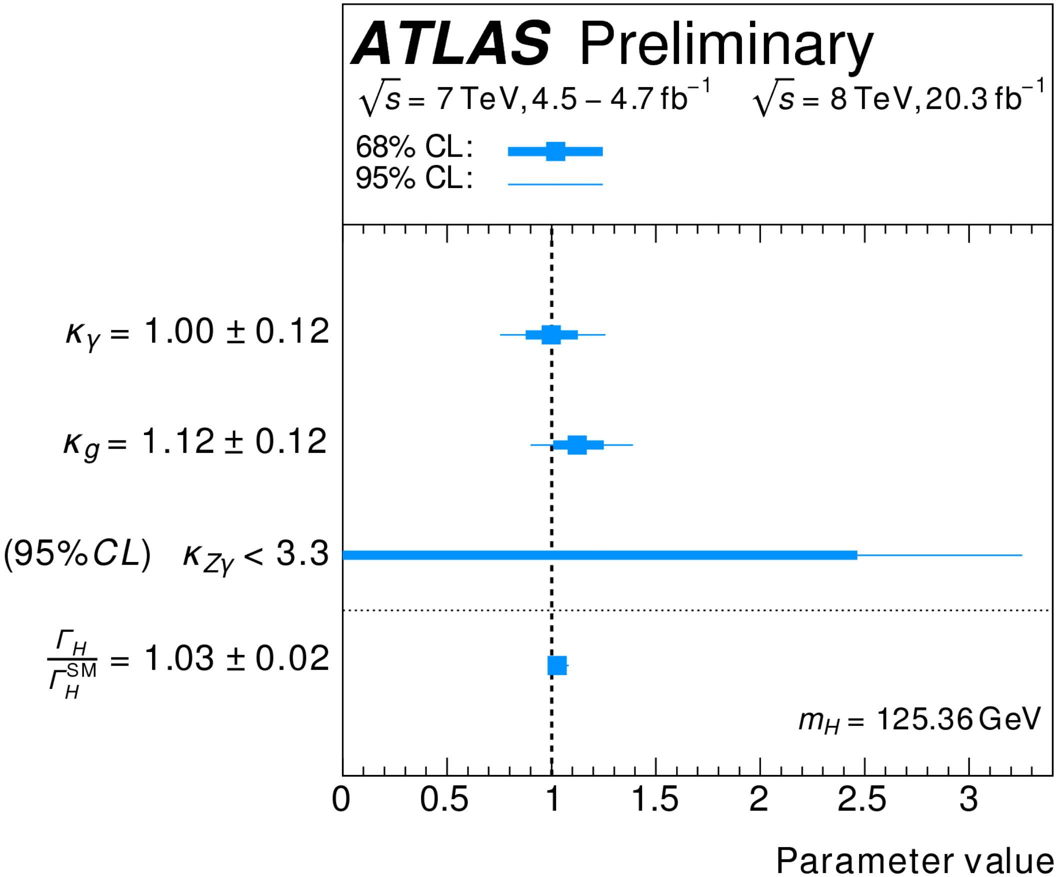
	ATLAS	CMS
BR_{BSM}	**< 0.27 (95% CL, BR_{BSM}>0)**	**< 0.32 (95% CL)**

A further take on loops

[ATLAS-CONF-2015-007]

Effective $H \longrightarrow \gamma\gamma$, $H \longrightarrow Z\gamma$, and ggH loops.

- Waiting for more data.



Probing the fermion sector

[arXiv:1307.1347]

2HDM

	u-type	d-type	lepton	
I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	SM-like
I'	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
II	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
II'	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_Z=\kappa_W), \lambda_{du}(=\kappa_d/\kappa_u), \kappa_u(=\kappa_t)$.

Probing up-type and down-type fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{uu}(=\kappa_u\cdot\kappa_u/\kappa_H), \lambda_{du}(=\kappa_d/\kappa_u), \lambda_{Vu}(=\kappa_V/\kappa_u)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$	
ttH	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\cdot\lambda_{du}^2$	
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$		$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$	

Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V(=\kappa_Z=\kappa_W), \lambda_{lq}(=\kappa_l/\kappa_q), \kappa_q(=\kappa_t=\kappa_b)$.

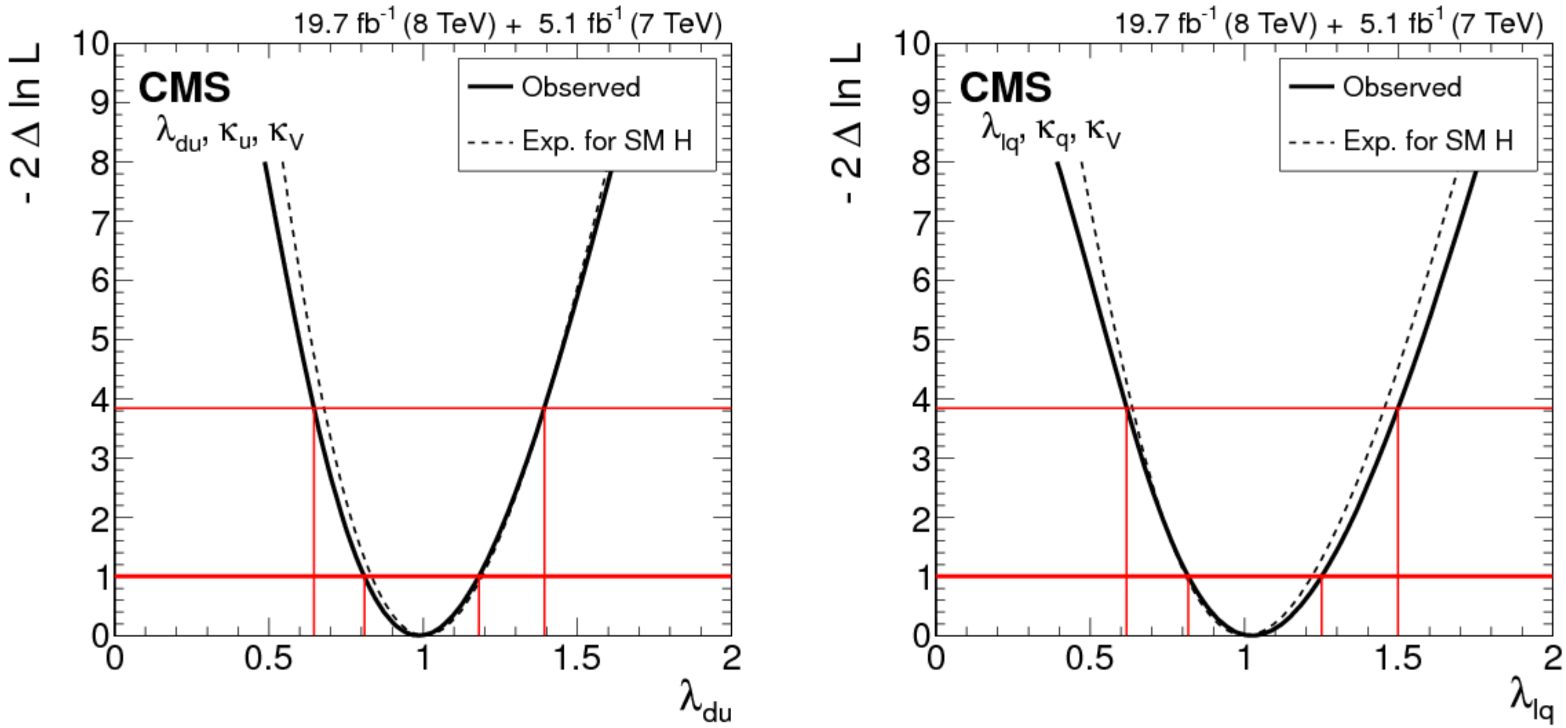
Probing quark and lepton fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{qq}(=\kappa_q\cdot\kappa_q/\kappa_H), \lambda_{lq}(=\kappa_l/\kappa_q), \lambda_{Vq}(=\kappa_V/\kappa_q)$.

	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH ttH	$\kappa_{qq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$		κ_{qq}^2	$\kappa_{qq}^2\cdot\lambda_{lq}^2$
VBF WH ZH	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$		$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{lq}^2$

Probing the fermion sector

[arXiv:1412.8662]

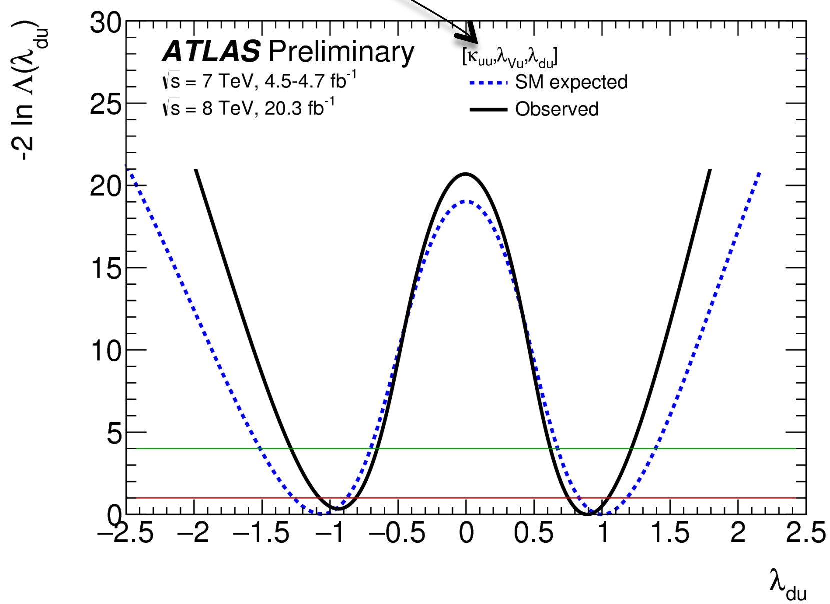


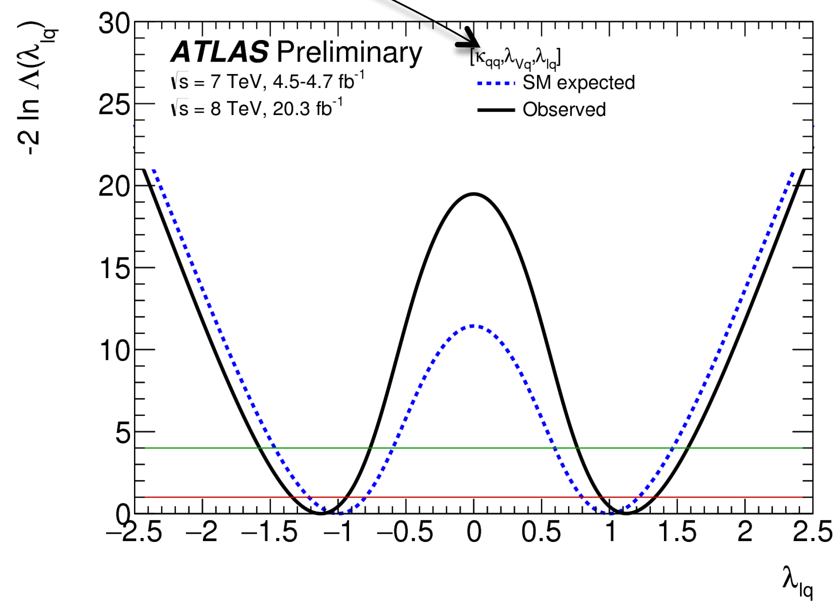
	λ_{du}	λ_{lq}
CMS	**$0.99^{+0.19}_{-0.18}$**	**$1.03^{+0.23}_{-0.21}$**

Probing the fermion sector

[ATLAS-CONF-NOTE-2015-007]

Floating total width





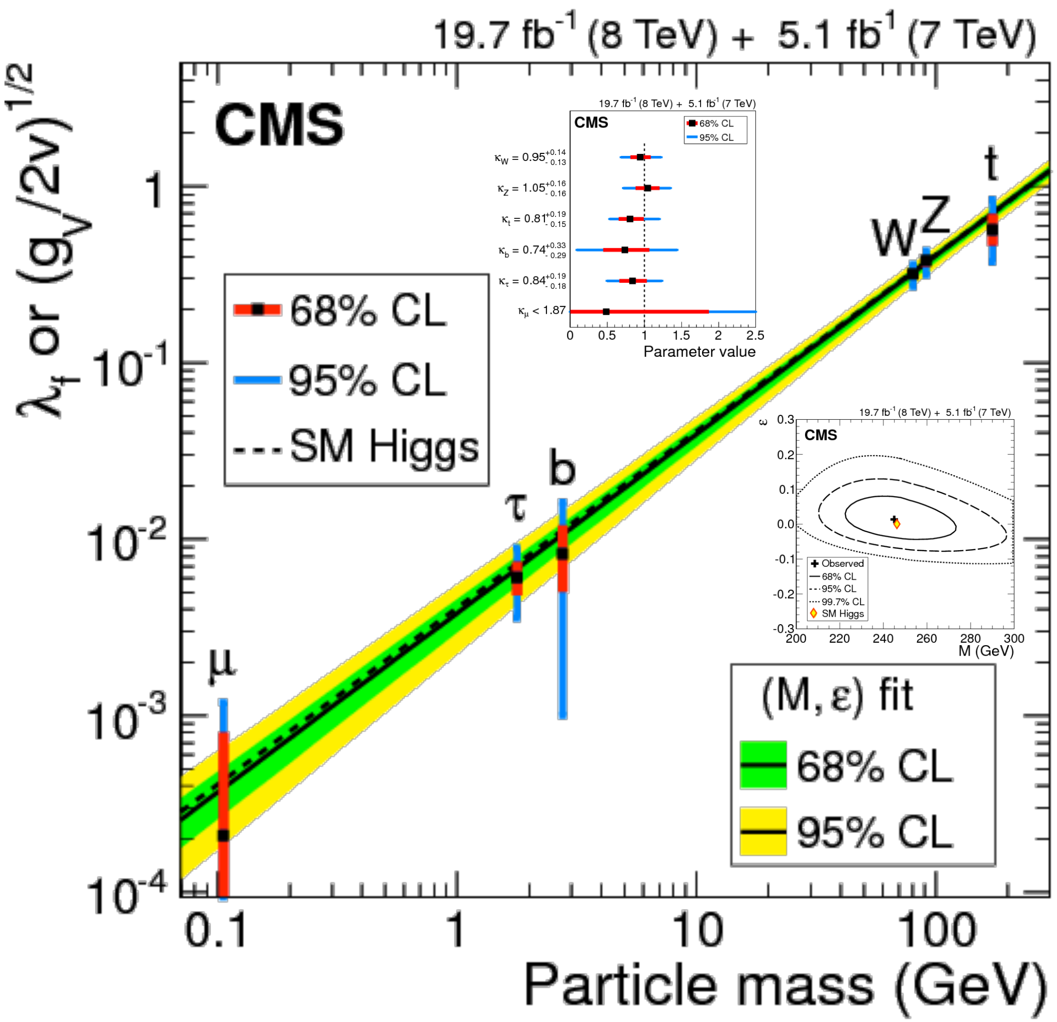
	λ_{du}	λ_{lq}
ATLAS	**[-1.08, -0.81] ∪ [0.75, 1.04] (68% CL)**	**[-1.34, -0.94] ∪ [0.94, 1.34] (68% CL)**

Resolving SM contributions

[arXiv:1412.8662][arxiv:1303.3570]

- Individual coupling scaling factors:
  - κ_W, κ_Z, κ_b, κ_t, κ_τ.
  - All loops resolved:
    - $\kappa_\gamma(\kappa_W, \kappa_t)$
    - $\kappa_g(\kappa_t, \kappa_b)$
  - SMH width scaled.

- “Reduced” couplings as function of “mass”:
  - $\lambda_f = \kappa_f\ (m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{\color{red}{1/2}}\ (m_V/vev)$

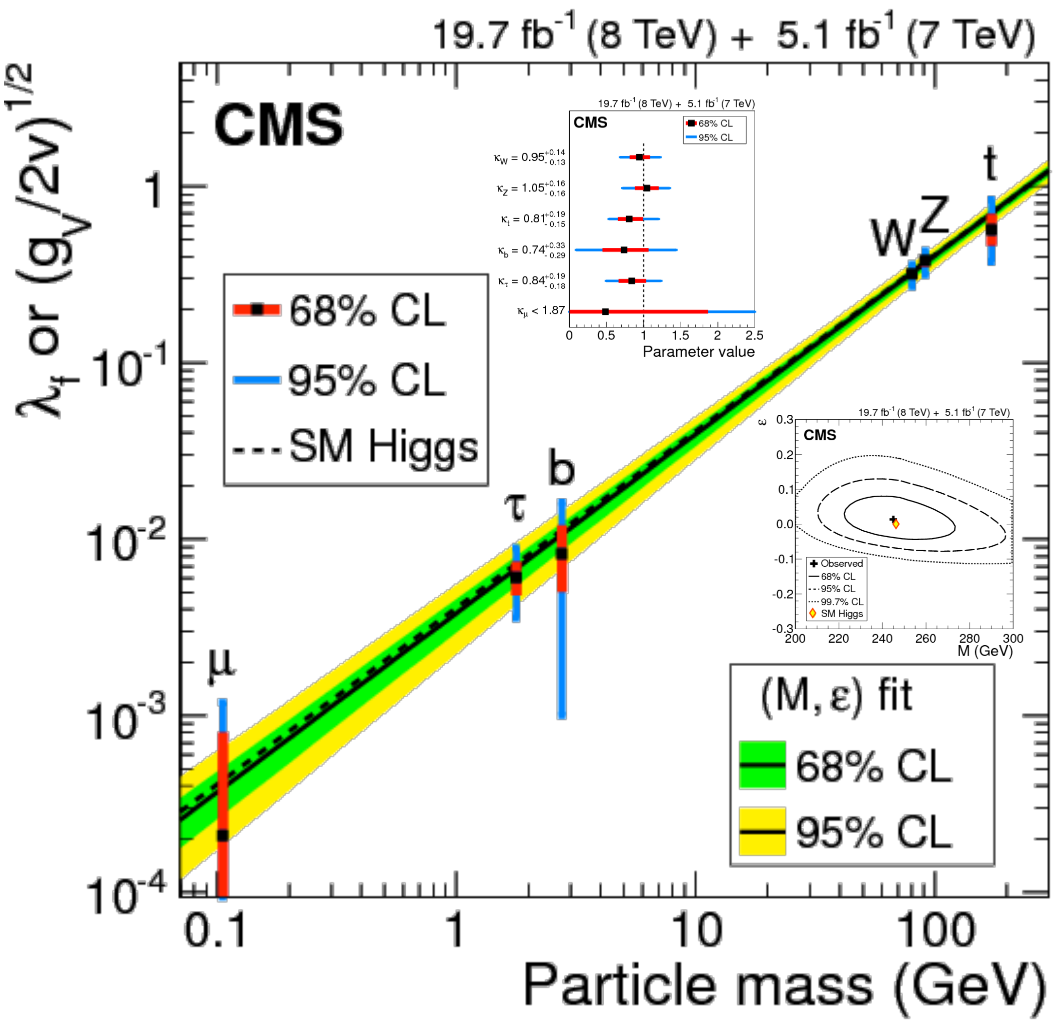


Mass power parametrization

[arXiv:1412.8662][arxiv:1207.1693]

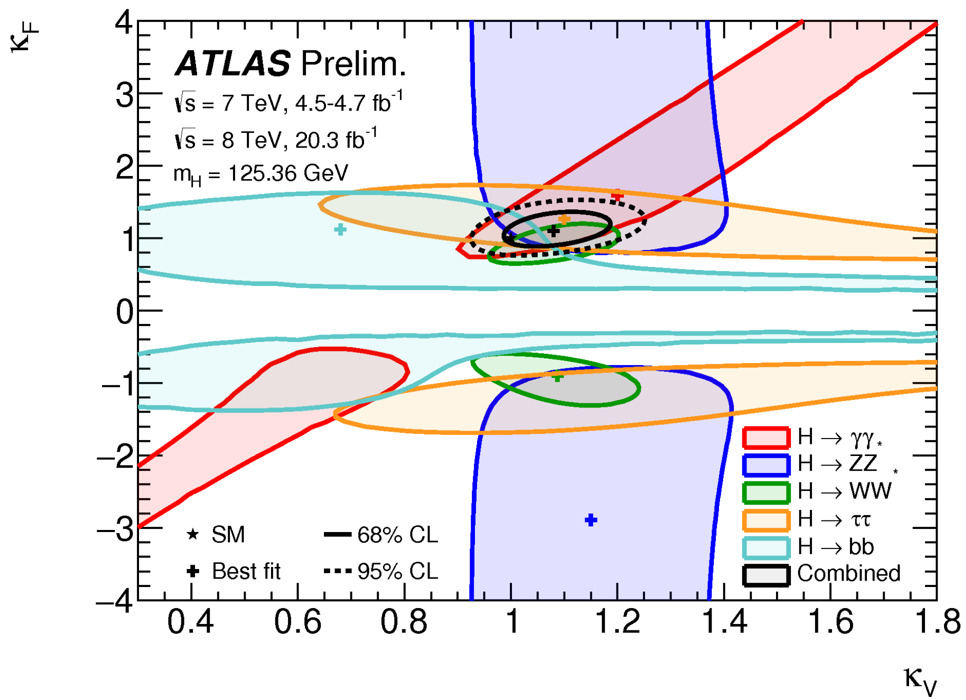
- *Vev* modifier and power of coupling to mass:
  - Gauge bosons: $\kappa_V = vev \times m_V^{2\varepsilon} / M^{1+2\varepsilon}$
  - Fermions: $\kappa_f = vev \times m_f^{\varepsilon} / M^{1+\varepsilon}$

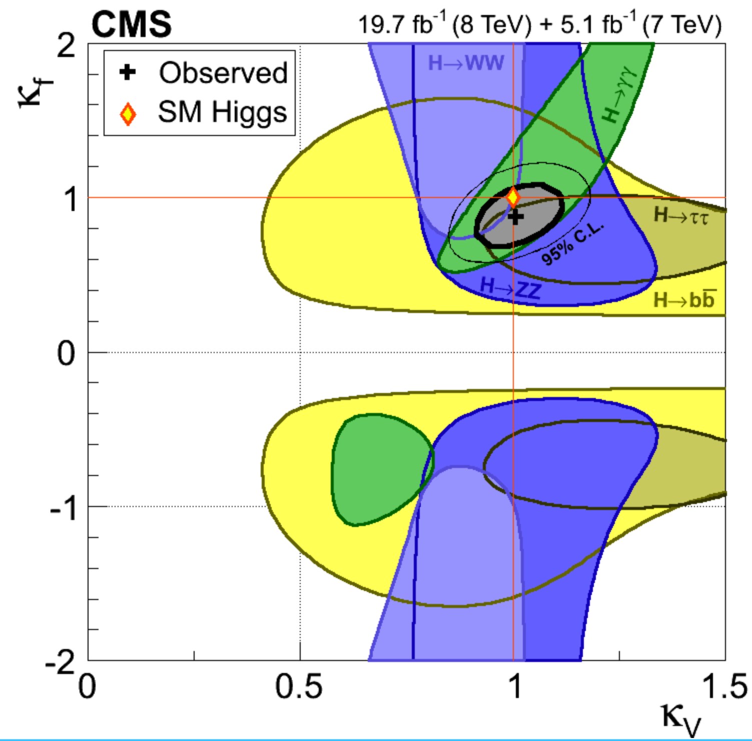
- For SMH, $M = vev = 246.22$ GeV and $\varepsilon = 0$.



Weak bosons and fermions

[ATLAS-CONF-2015-007][arXiv:1412.8662]

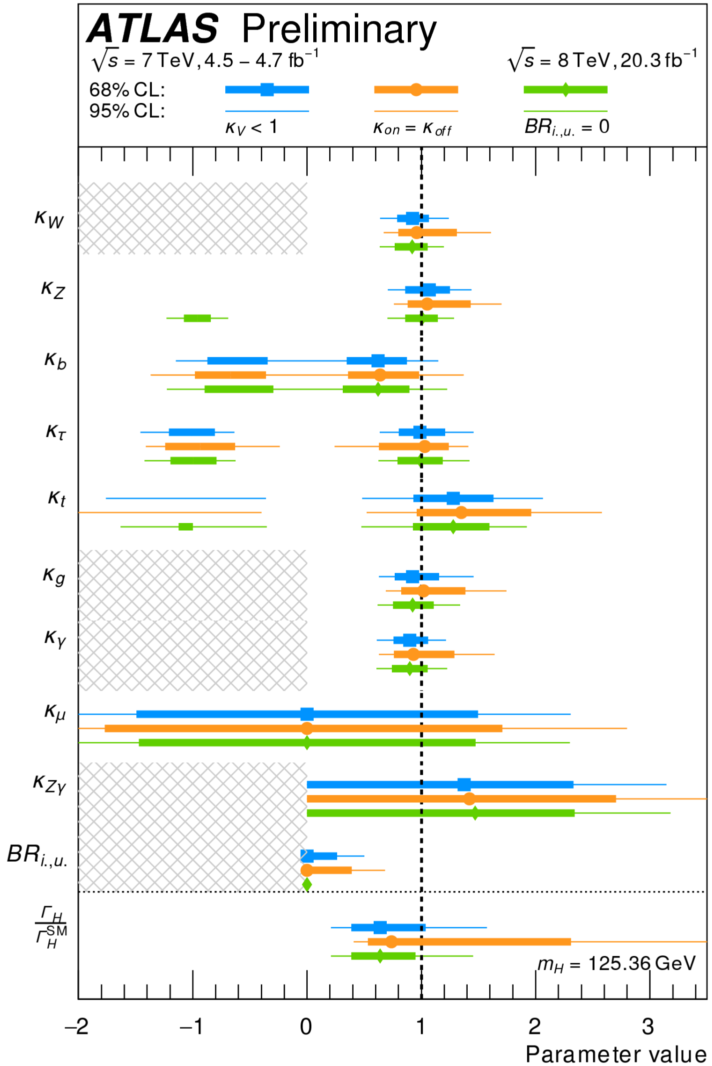


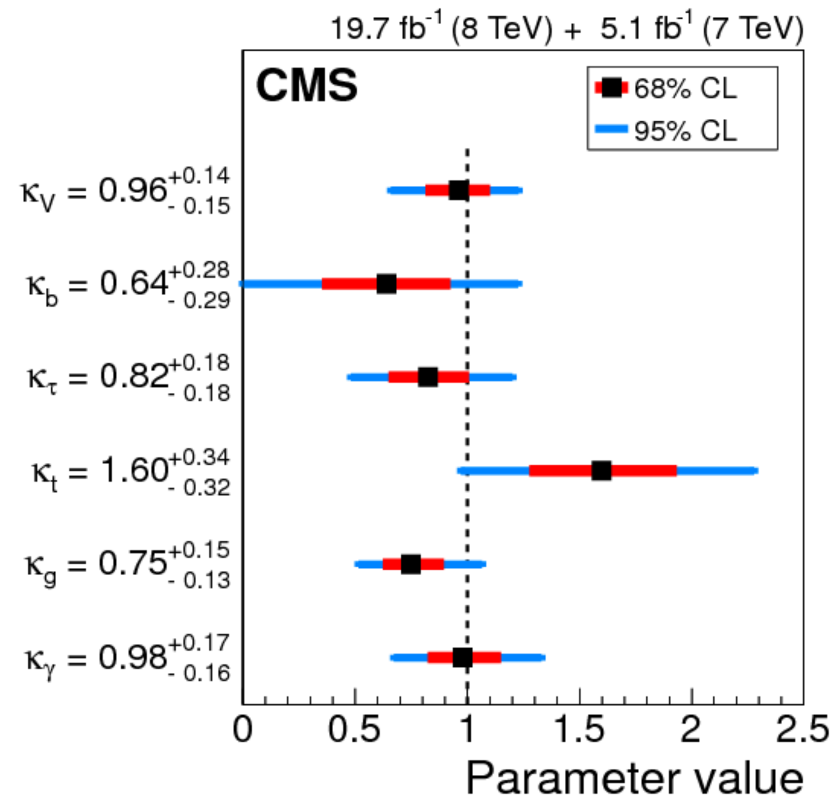


	ATLAS	CMS
P(SM)	**10%**	**< 1 σ**

The deviations that we do not (yet) see

[ATLAS-CONF-2015-007][arXiv:1412.8662]

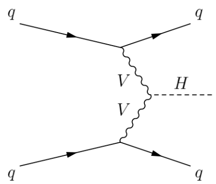


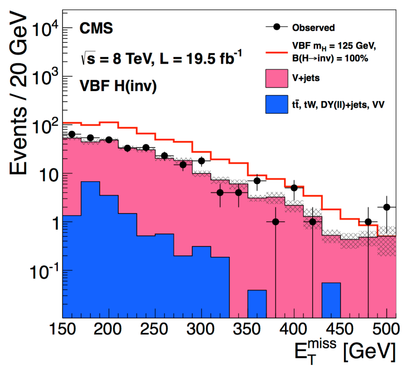


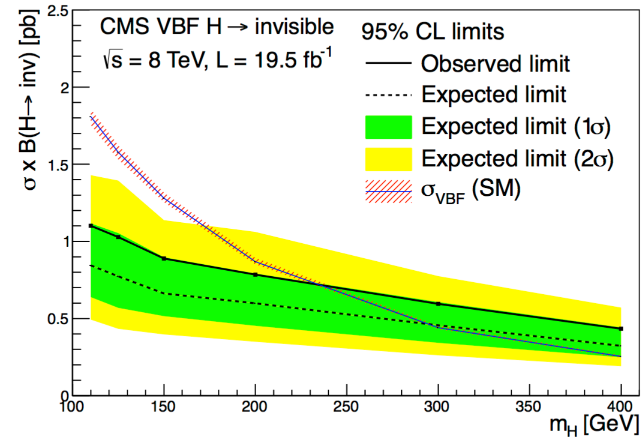
Dark matter: invisible Higgs decay search

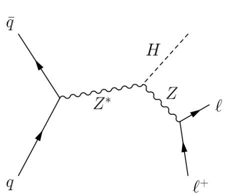
[EPJC 74 (2014) 2980]

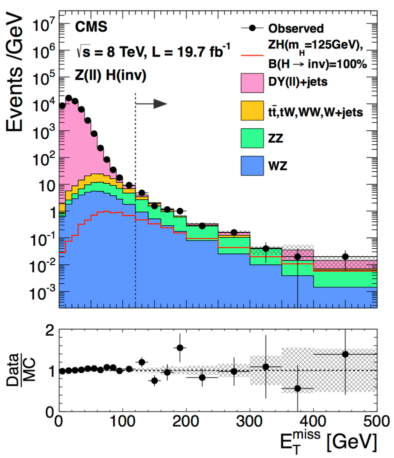
- VBF and ZH topologies combined; $Z \to \ell\ell$ and $Z \to b\bar{b}$.
- **BR(H→inv.) < 0.58 (0.44 exp.) at 95% CL**

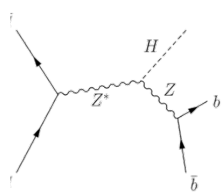


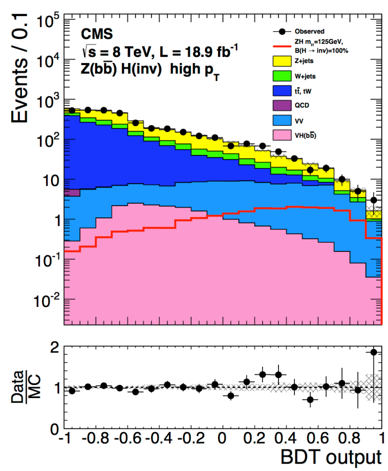


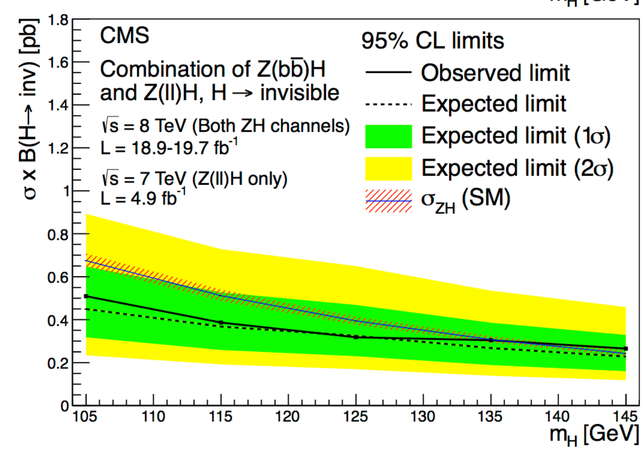








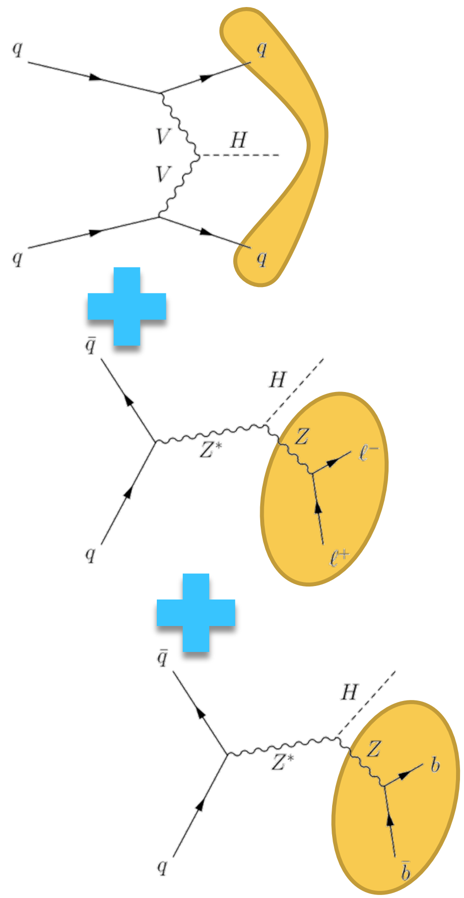




Invisible Higgs search combination

[EPJC 74 (2014) 2980]

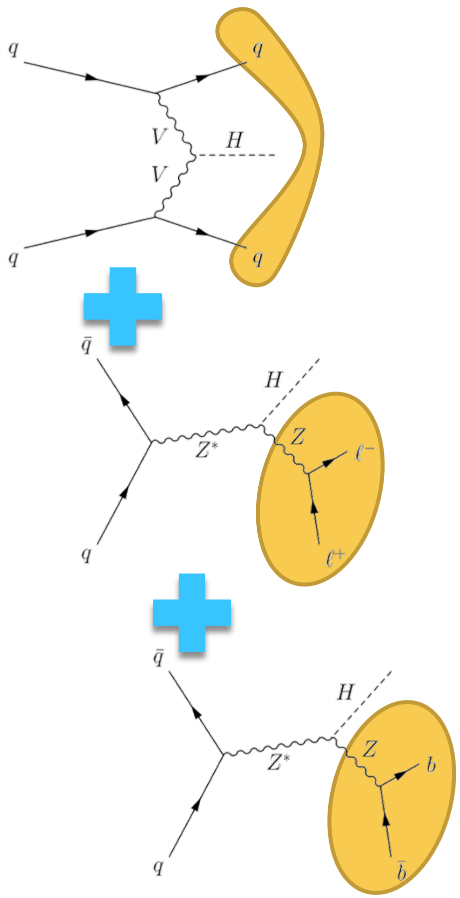
- Combination of **VBF, Z(ℓℓ)H, and Z($b\bar{b}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.
-

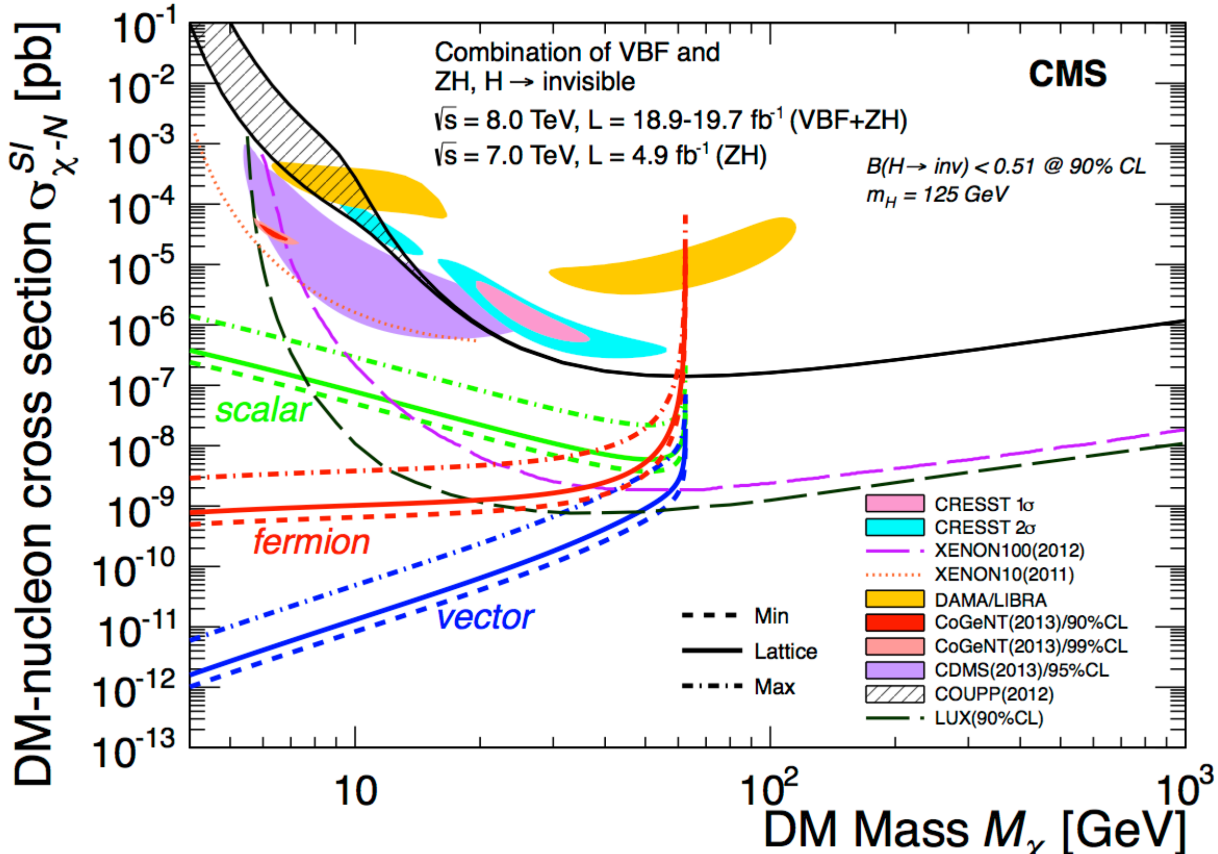


Invisible Higgs search combination

[EPJC 74 (2014) 2980]

- Combination of **VBF, Z(ℓℓ)H, and Z($b\bar{b}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.
- **Competitive limits for low mass DM in "Higgs portal" models.**



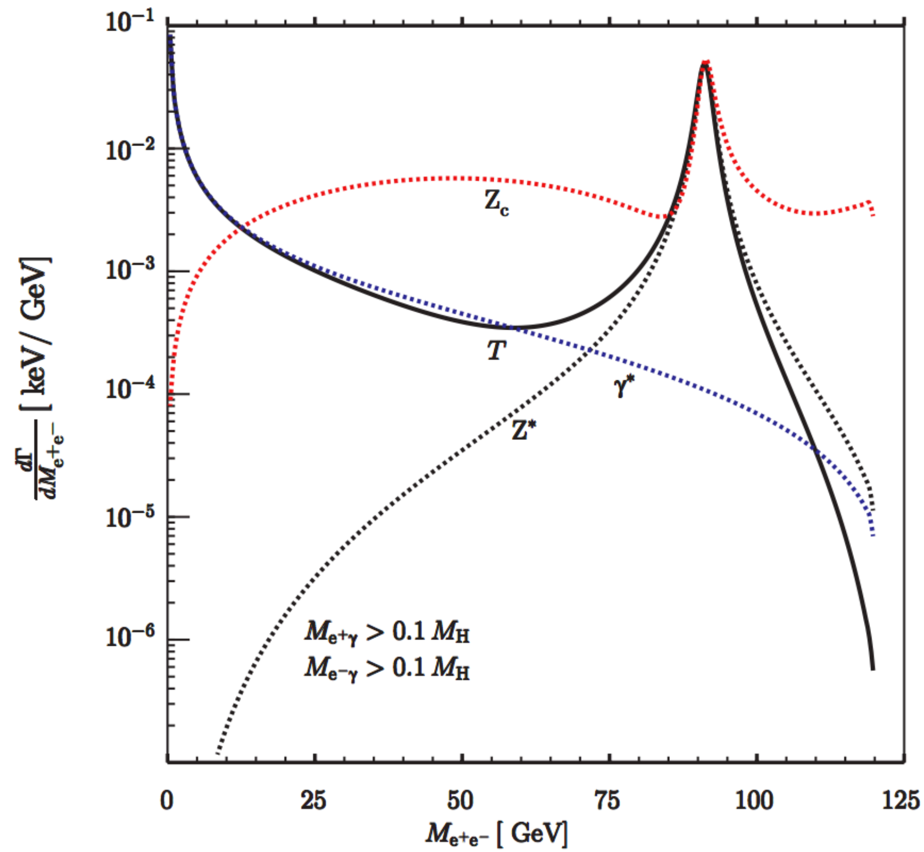


Rare decays: full Dalitz analysis

[arXiv:1308.0422]

- $\gamma\gamma$ and $Z\gamma$ loops sensitive to different physics because of V-A structure for Z.

- More information from full $m_{\ell\ell}$ spectrum.
  - Need to clearly define the phase-space used in analysis.

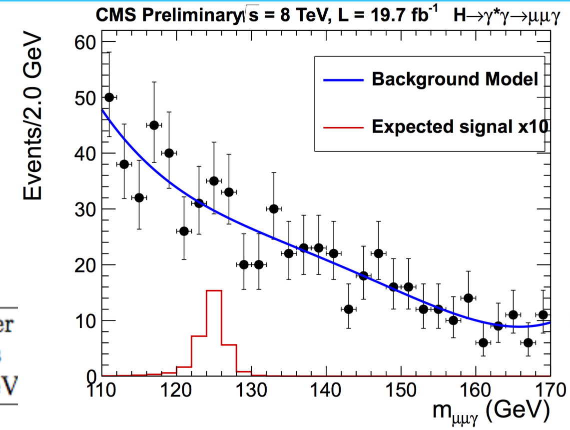


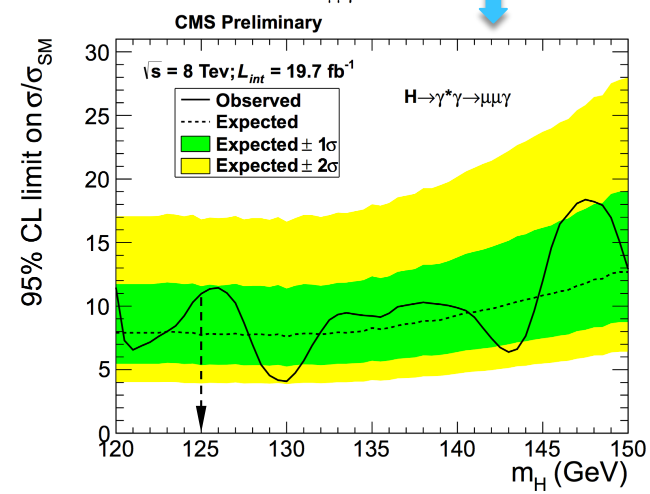
$H \rightarrow \gamma^* \gamma \rightarrow \ell\ell\gamma$

[CMS-PAS-HIG-14-003]

- $m_{\mu\mu} < 20$ GeV.
- Veto out J/ψ and Υ.

Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^{\gamma} > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta R(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^{\gamma}/m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu}/m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9





Obs. (exp.)	CMS
μ at 125 GeV (95% CL)	< 11 (8)

Statistics

Statistics interlude

[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2\ln\frac{\mathcal{L}(data\vert\mu,\tilde{\theta})}{\mathcal{L}(data\vert 0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2\ln\frac{\mathcal{L}(data\vert\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\vert 0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(data\vert\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\vert\hat{\mu},\hat{\theta})}$	yes $(0 \le \hat{\mu} \le \mu)$	frequentist

- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ=0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating signal strength**.
  - **Nice asymptotic properties, savings in computational power.**

On the shoulders of giants

[arXiv:1412.8662]

The overall statistical methodology used in this combination was developed by the ATLAS and CMS Collaborations in the context of the LHC Higgs Combination Group and is described in Refs. [15, 180, 181]. The chosen test statistic, q, is based on the profile likelihood ratio and is used to determine how signal-like or background-like the data are. Systematic uncertainties are incorporated in the analysis via nuisance parameters that are treated according to the frequentist paradigm. Below we give concise definitions of statistical quantities that we use for characterizing the outcome of the measurements. Results presented herein are obtained using asymptotic formulae [182], including routines available in the RooStats package [183].

Signal model parameters a, such as the signal strength modifier μ, are evaluated from scans of the profile likelihood ratio $q(a)$:

$$q(a) = -2\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data} \,|\, s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{data} \,|\, s(\hat{a}) + b, \hat{\theta})}. \tag{4}$$

The parameter values $\hat{a}$ and $\hat{\theta}$ correspond to the global maximum likelihood and are called the best-fit set. The post-fit model, obtained using the best-fit set, is used when deriving expected quantities. The post-fit model corresponds to the parametric bootstrap described in the statistics literature and includes information gained in the fit regarding the values of all parameters [184, 185].

The 68% and 95% confidence level (CL) confidence intervals for a given parameter of interest, a_i, are evaluated from $q(a_i) = 1.00$ and $q(a_i) = 3.84$, respectively, with all other unconstrained model parameters treated in the same way as the nuisance parameters. The two-dimensional (2D) 68% and 95% CL confidence regions for pairs of parameters are derived from $q(a_i, a_j) = 2.30$ and $q(a_i, a_j) = 5.99$, respectively. This implies that boundaries of 2D confidence regions projected on either parameter axis are not identical to the one-dimensional (1D) confidence interval for that parameter. All results are given using the chosen test statistic, leading to approximate CL confidence intervals when there are no large non-Gaussian uncertainties [186–188], as is the case here. If the best-fit value is on a physical boundary, the theoretical basis for computing intervals in this manner is lacking. However, we have found that for the results in this paper, the intervals in those conditions are numerically similar to those obtained by the method of Ref. [189].

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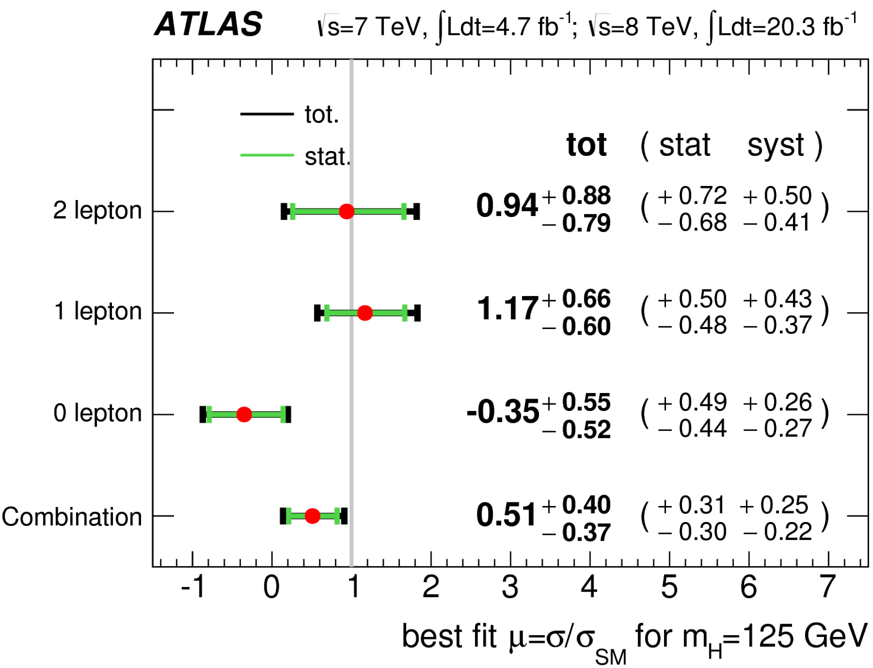
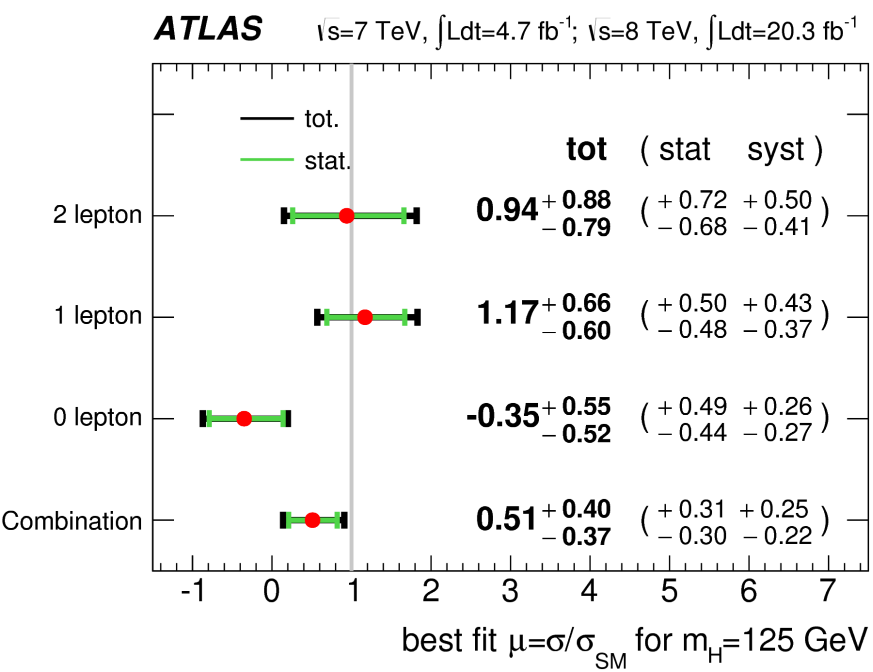
Post-fit

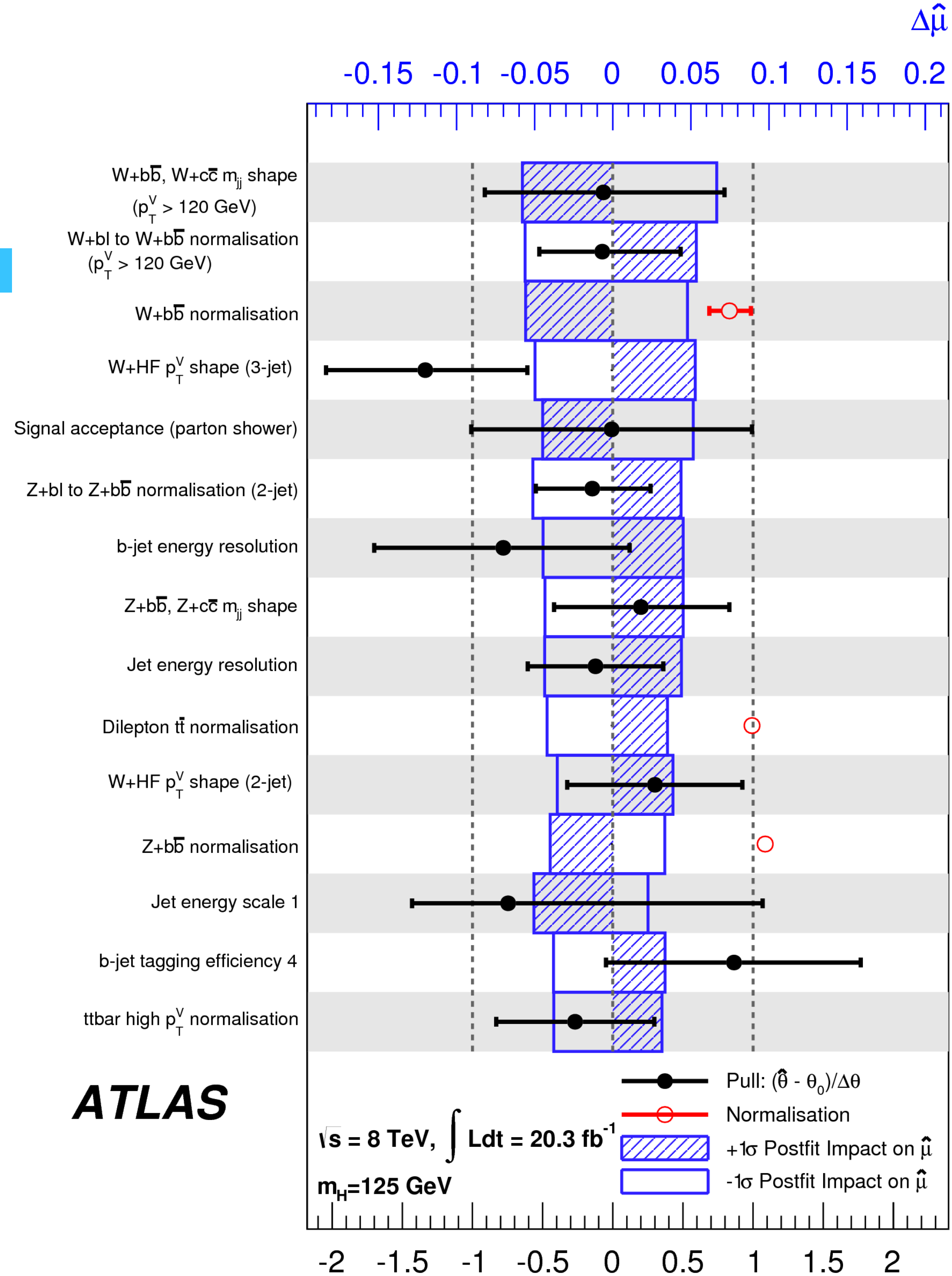
[arXiv:1409.6212]



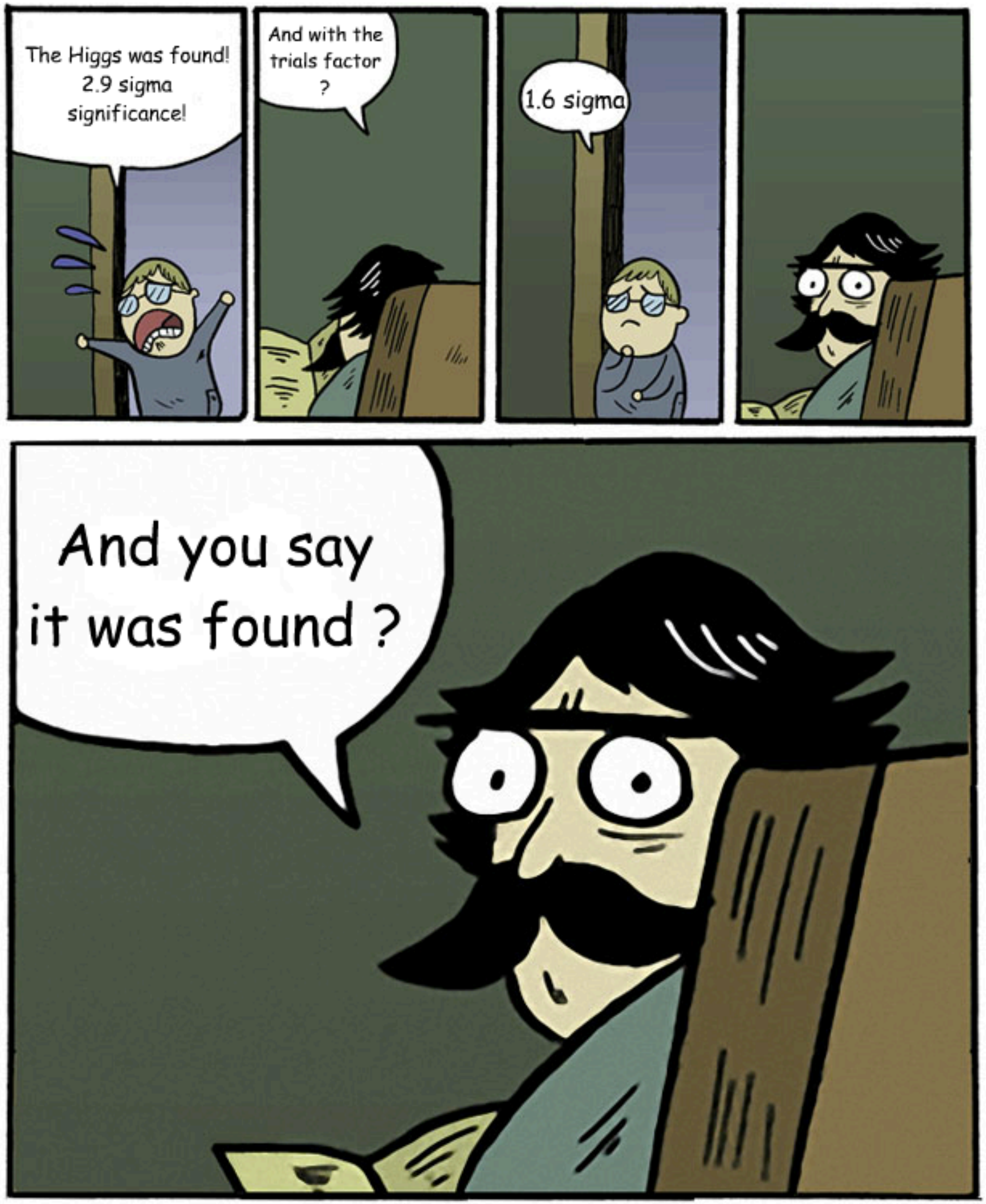
Post-fit

[arXiv:1409.6212]



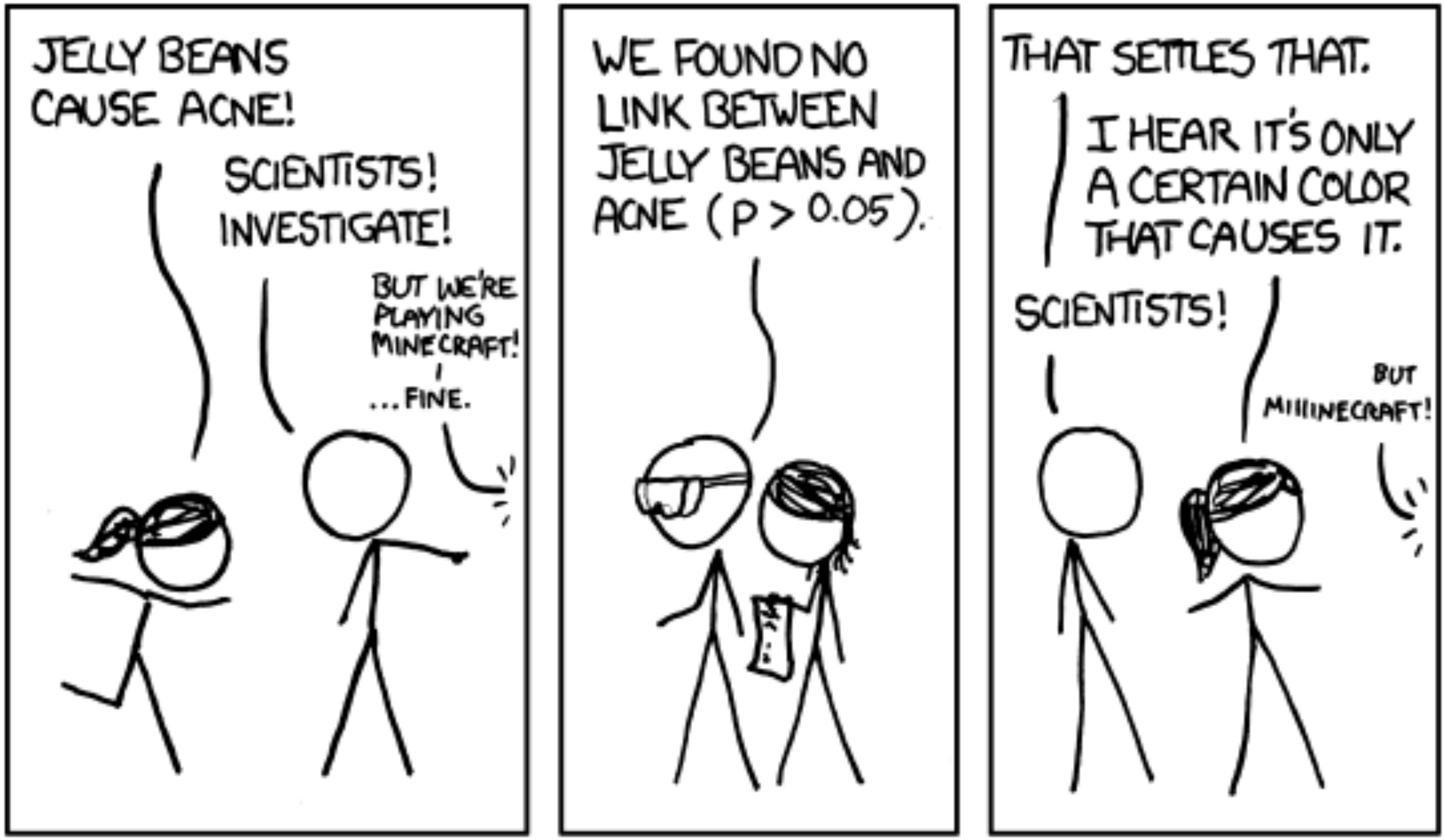


Some theorists…

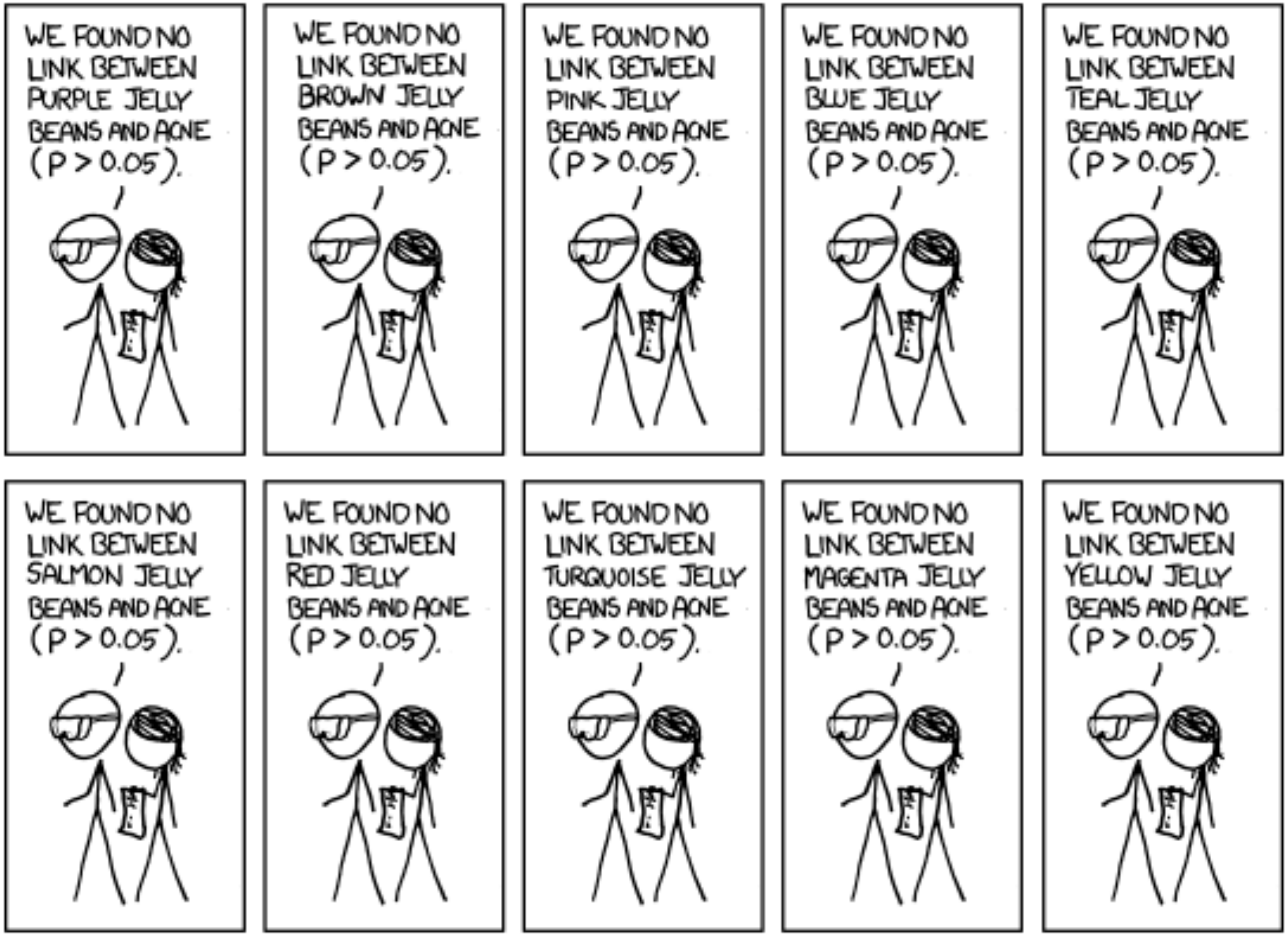


About significance…

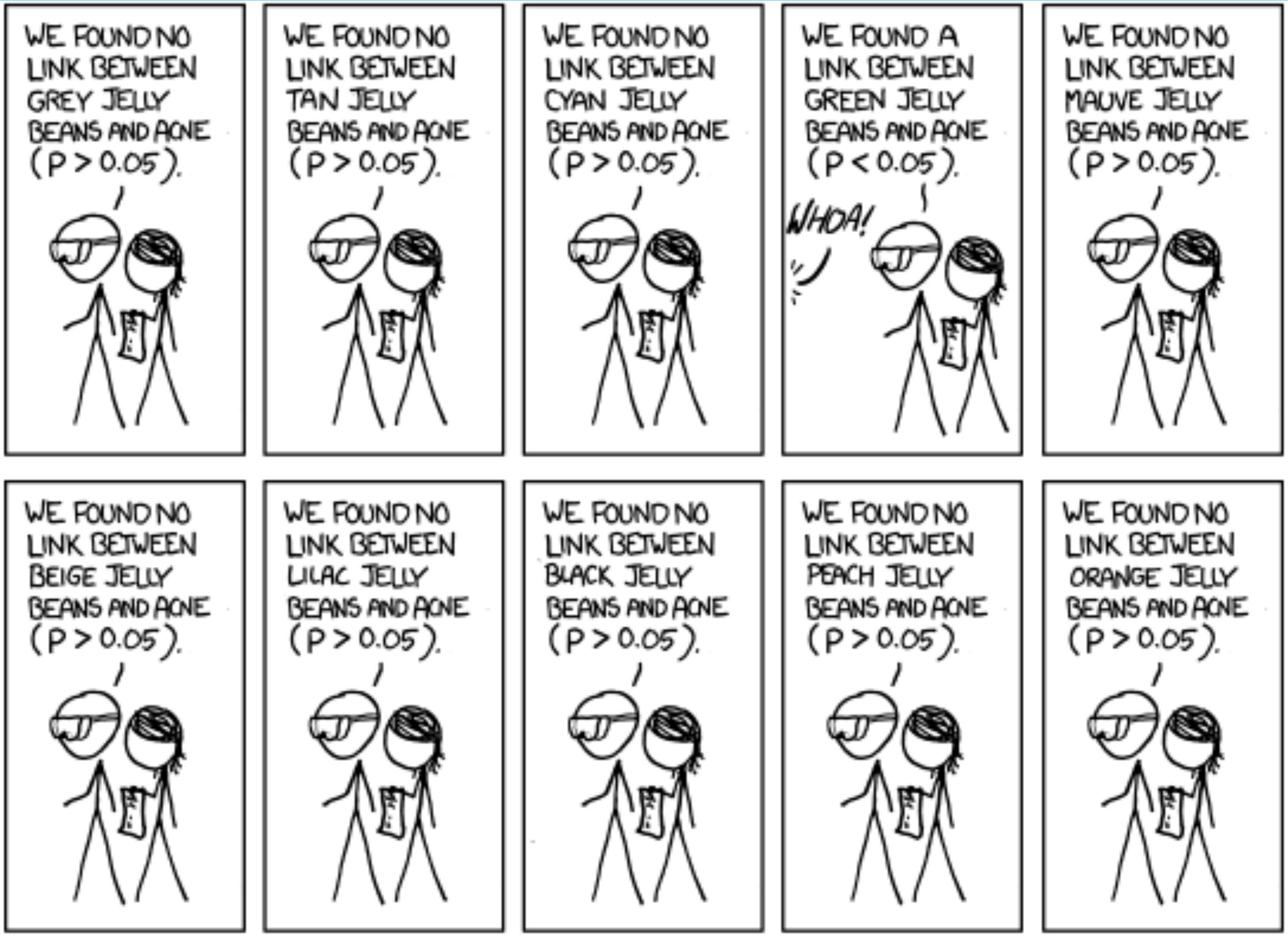
Significant – xkcd.com/882



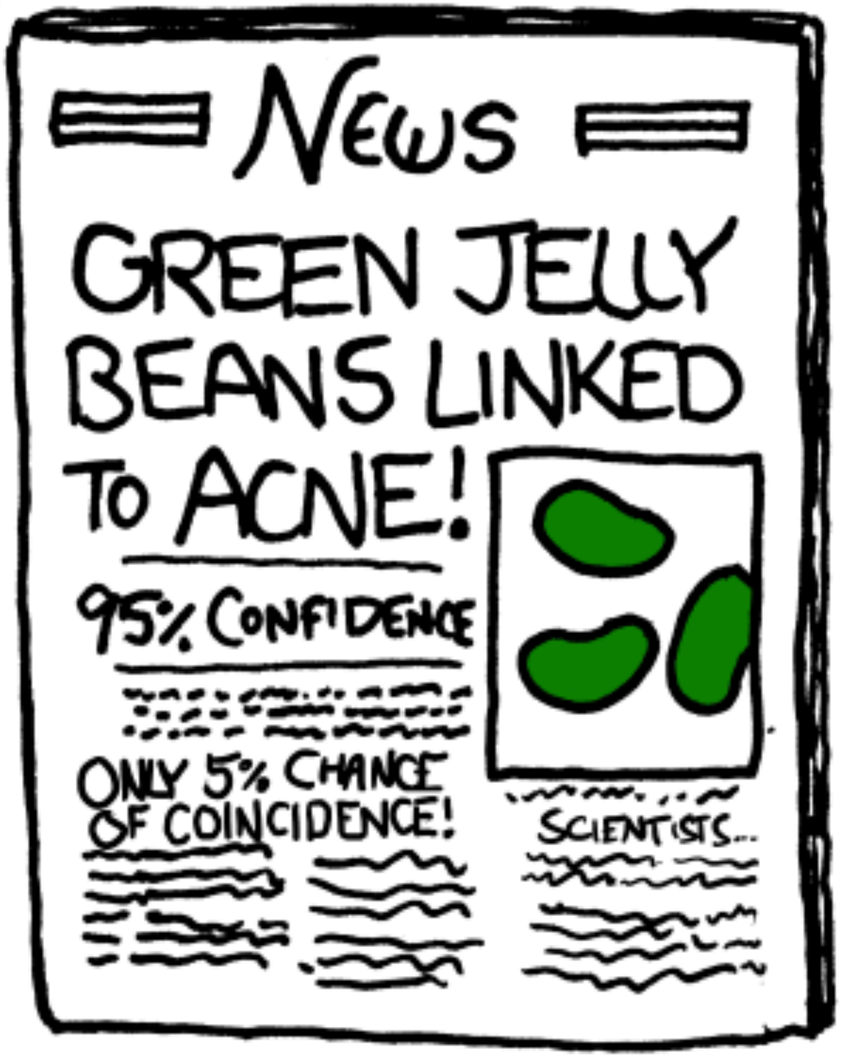
Significant – xkcd.com/882



Significant – xkcd.com/882



Significant – xkcd.com/882



Breaking down uncertainties

- Nuisances grouped into **stat, theo, other.**
  - **stat** includes $H \to \gamma\gamma$ background parameters.
  - **theo** includes QCD scales, PDF+α_s, UEPS, and BR.
  - **syst** = **theo** $\cup$ **other.**
- Procedures:
  - For (**stat**)+(**syst**):
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}$.
  - For (**stat**)+(**theo**)+(**other**)
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{stat+other}$ from scan floating **stat** and **other.**
    - $\sigma_{theo} = \sigma_{all} \ominus \sigma_{stat+other}$.
    - $\sigma_{other} = \sigma_{all} \ominus \sigma_{stat} \ominus \sigma_{theo}$.

Odds and ends

A 2012 hit

403 [http://goo.gl/ShJJG]

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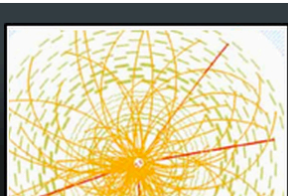
Home > Collections > Online Extras > Special Issues 2012 > Breakthrough of the Year, 2012

Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



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The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up

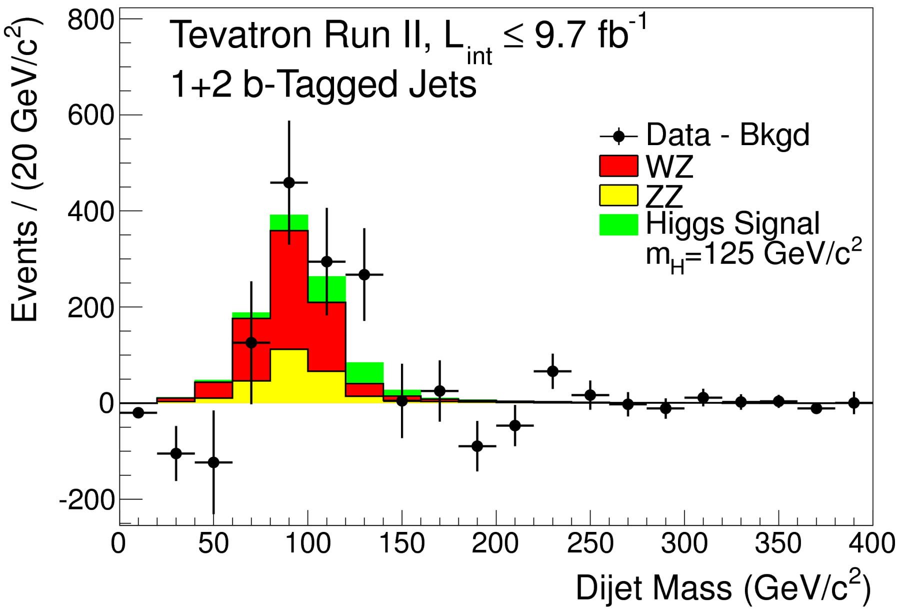
FREE WITH REGISTRATION

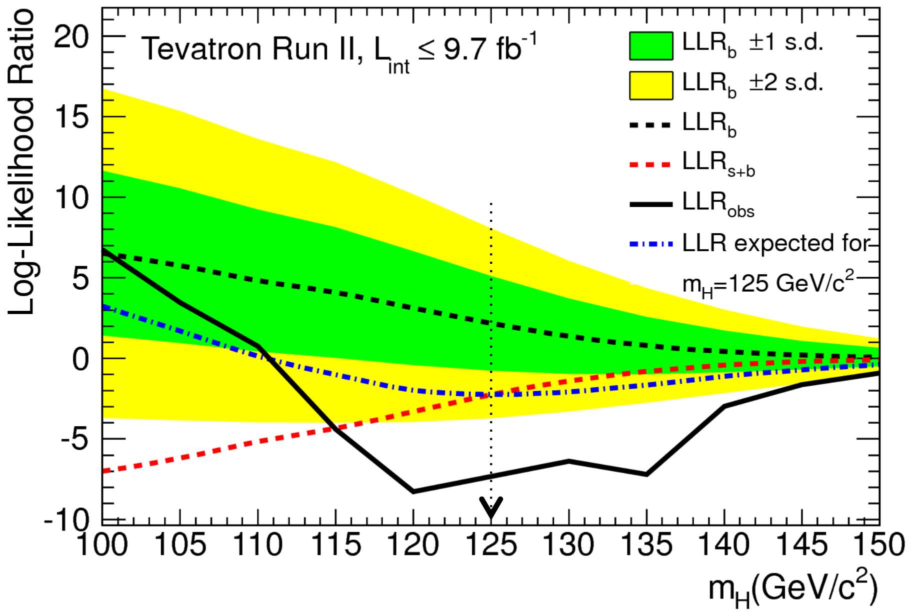
This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Oct 2013: boson becomes Nobel

From the other side of the pond

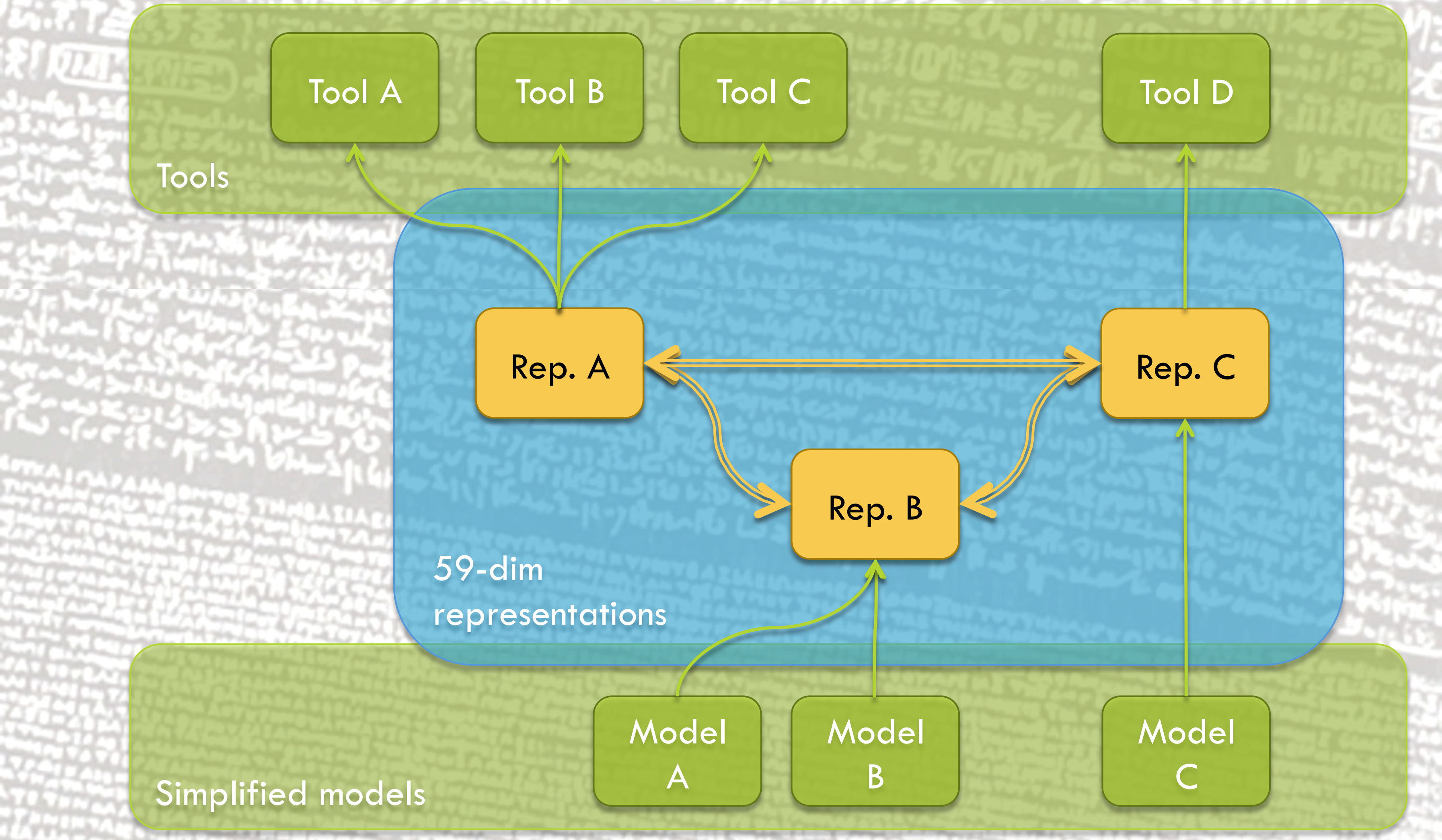
[arXiv:1207.6436]





- Combination of Tevatron VH⟶$b\bar{b}$ searches, in July 2012:
  - **2.8 σ local significance at m_H=125 GeV.**

A Rosetta stone for Higgs EFT



First steps in YR3

[arXiv:1307.1347]

Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2 \mathrm{X}\Phi$ operators and for $\mathcal{O}_{\Phi\mathrm{ud}}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_{\Phi} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}_{G} = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{d}}\mathrm{d}\Phi)$	$\mathcal{O}_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK} \widetilde{\mathrm{W}}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
$\mathrm{X}^2\Phi^2$	$\psi^2\mathrm{X}\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\mathrm{l}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu \mathrm{l})$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) G_{\mu\nu}^A$	$\mathcal{O}_{\Phi\mathrm{l}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{l}}\gamma^\mu \tau^I \mathrm{l})$
$\mathcal{O}_{\Phi\mathrm{W}} = (\Phi^\dagger\Phi) \mathrm{W}_{\mu\nu}^I \mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu \mathrm{e})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{W}}_{\mu\nu}^I \mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi}) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{q}}^{(1)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu \mathrm{q})$
$\mathcal{O}_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi) \mathrm{B}_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}_{\Phi\mathrm{q}}^{(3)} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{q}}\gamma^\mu \tau^I \mathrm{q})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{B}}_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{eB}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu \mathrm{u})$
$\mathcal{O}_{\Phi\mathrm{WB}} = (\Phi^\dagger\tau^I\Phi) \mathrm{W}_{\mu\nu}^I \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu \mathrm{d})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}\mathrm{B}} = (\Phi^\dagger\tau^I\Phi) \widetilde{\mathrm{W}}_{\mu\nu}^I \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$

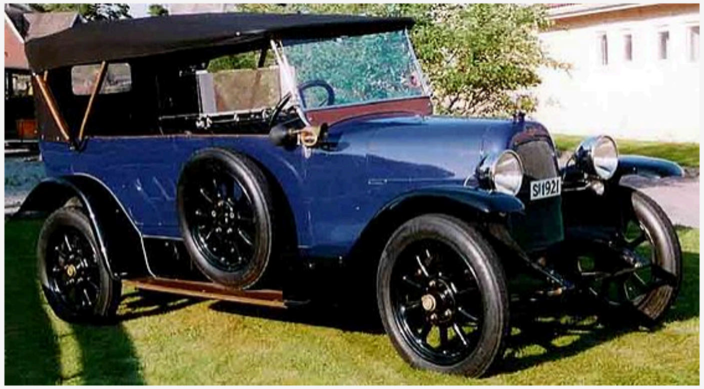
Table 53: Alternative basis of dimension-6 operators involving Higgs doublet fields or gauge-boson fields.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_{6} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}'_{G} = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}'_{\Phi} = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}'_{\mathrm{T}} = (\Phi^\dagger \overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{d}d\Phi)$	$\mathcal{O}'_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}'_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK} \widetilde{\mathrm{W}}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
$\mathrm{X}^2\Phi^2$	$\psi^2\mathrm{X}\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{DW} = \left(\Phi^\dagger\tau^I \mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(D^\nu \mathrm{W}_{\mu\nu})^I$	$\mathcal{O}'_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) G_{\mu\nu}^A$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu \mathrm{l})$
$\mathcal{O}'_{DB} = \left(\Phi^\dagger \mathrm{i}\overleftrightarrow{D^\mu}\Phi\right)(\partial^\nu \mathrm{B}_{\mu\nu})$	$\mathcal{O}'_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) G_{\mu\nu}^A$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{l}}\gamma^\mu \tau^I \mathrm{l})$
$\mathcal{O}'_{D\Phi\mathrm{W}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu \mathrm{e})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{W}}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{\mathrm{W}}_{\mu\nu}^I$	$\mathcal{O}'_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi}) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu \mathrm{q})$
$\mathcal{O}'_{D\Phi\mathrm{B}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi) \mathrm{W}_{\mu\nu}^I$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu^I\Phi)(\bar{\mathrm{q}}\gamma^\mu \tau^I \mathrm{q})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{B}}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{\mathrm{B}}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eB}} = (\bar{l}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi) B_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu \mathrm{u})$
$\mathcal{O}'_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi) B_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) \mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu \mathrm{d})$
$\mathcal{O}'_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi) \mathrm{B}_{\mu\nu} \widetilde{\mathrm{B}}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G_{\mu\nu}^A G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G_{\mu\nu}^A \widetilde{G}^{A\mu\nu}$		

Other models?

[http://cern.ch/go/X6rC]

Fiat 505

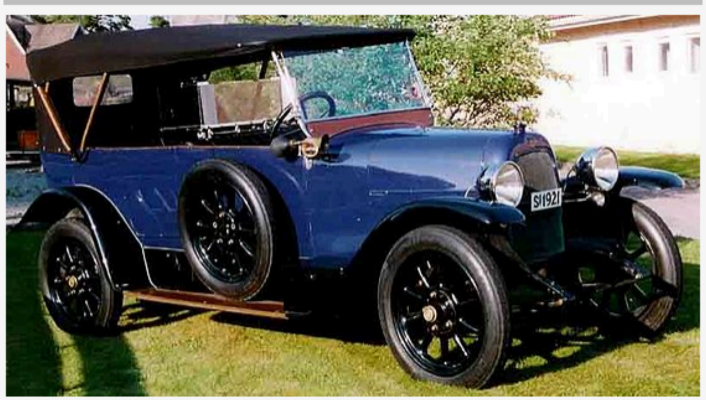


Other models?

[http://cern.ch/go/X6rC]

Fiat 1400/1900

Fiat 505



Other models?

[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 505

Other models?

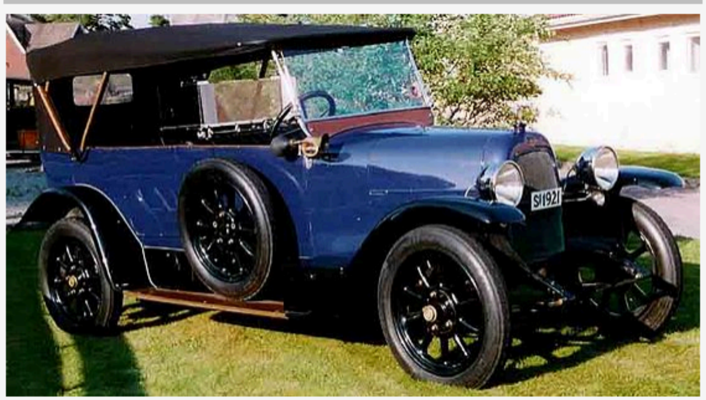
[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 2300

Fiat 505



Other models?

[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 2300

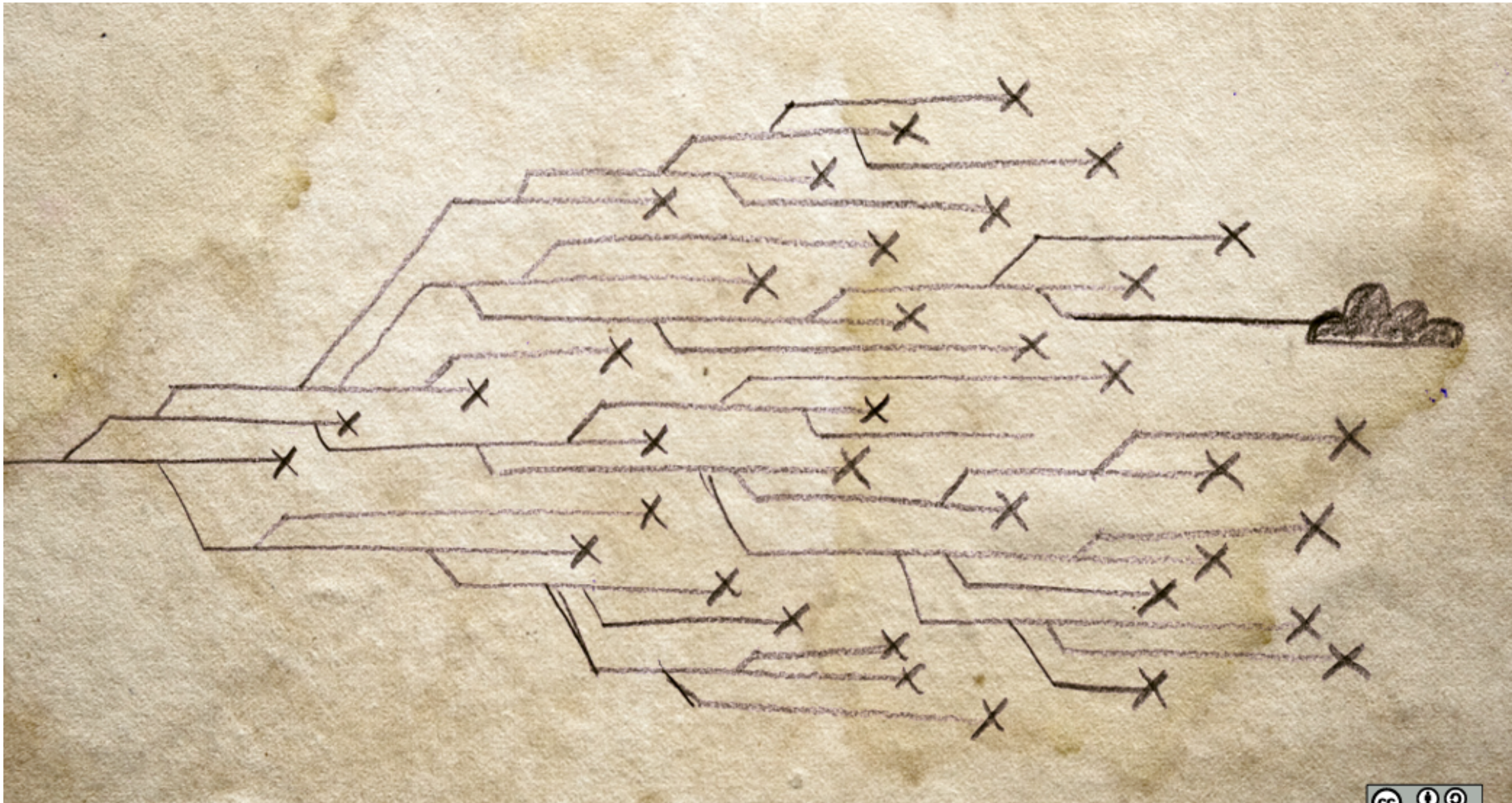
Fiat Seicento

Fiat 505

The experimental method

falsifying theories since the dawn of reason

[opensource.com]

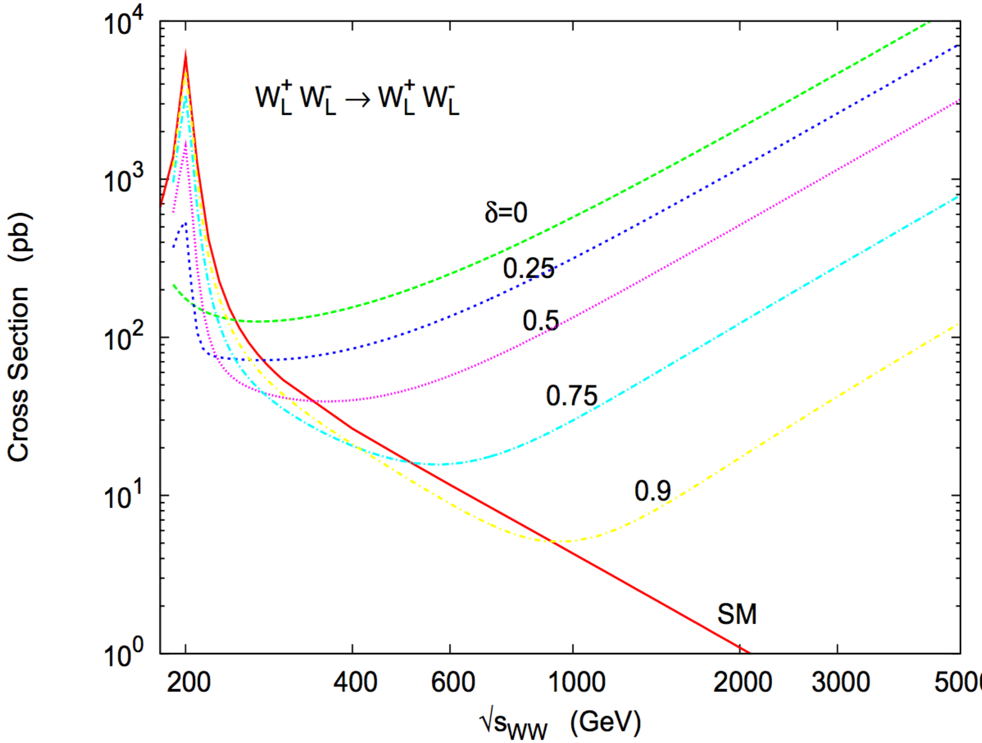


Crosses: experimental results pushing humans to track back and rethink their models.

Delayed unitarization: until when?

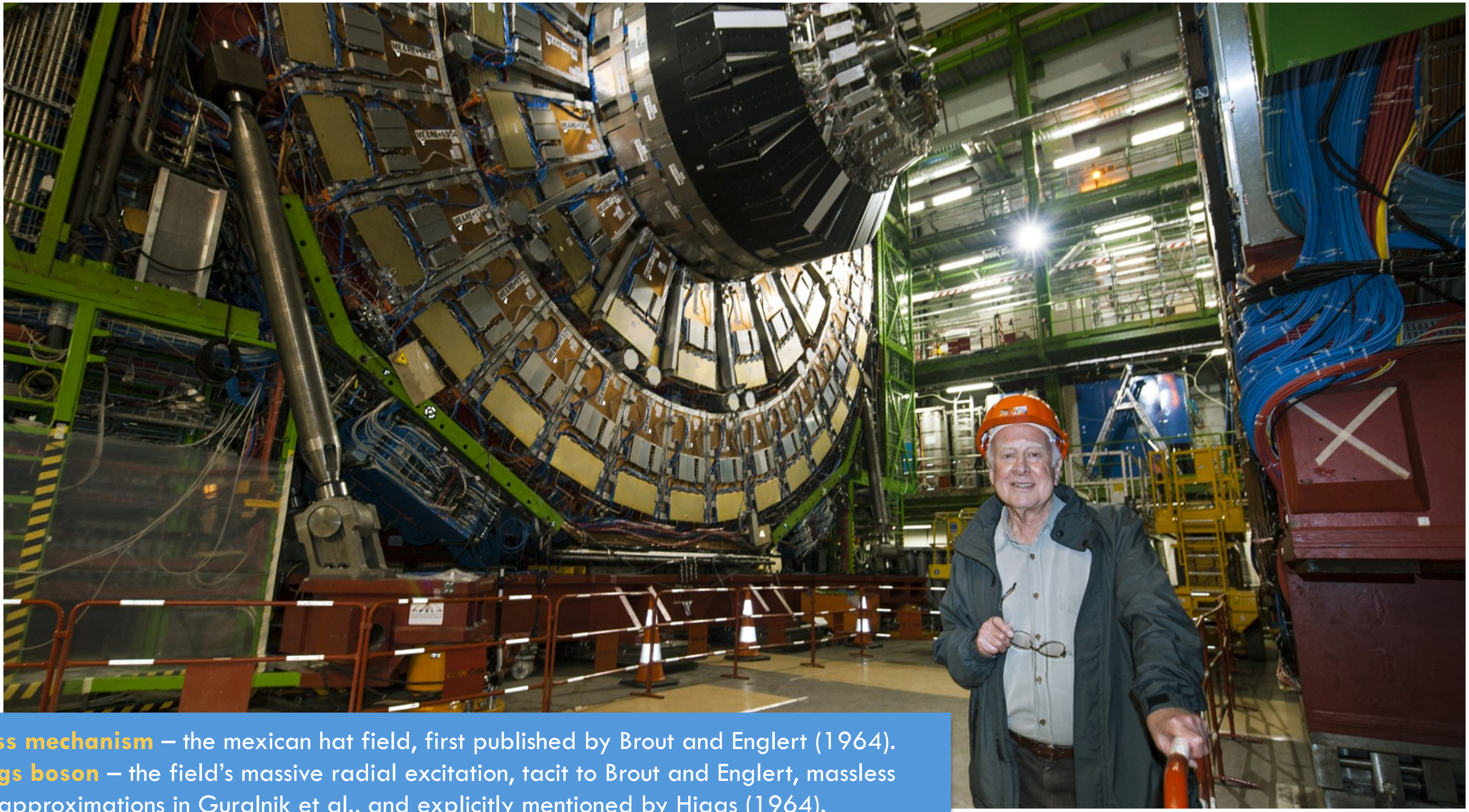
[http://cern.ch/go/q8Gq]

- Assume that WW scattering is $\delta^{-1/2}$ that of SM.
- Things can look like the SM for a long time.
  - **Time ~ Energy.**



Higgs in CMS – ca. 2008

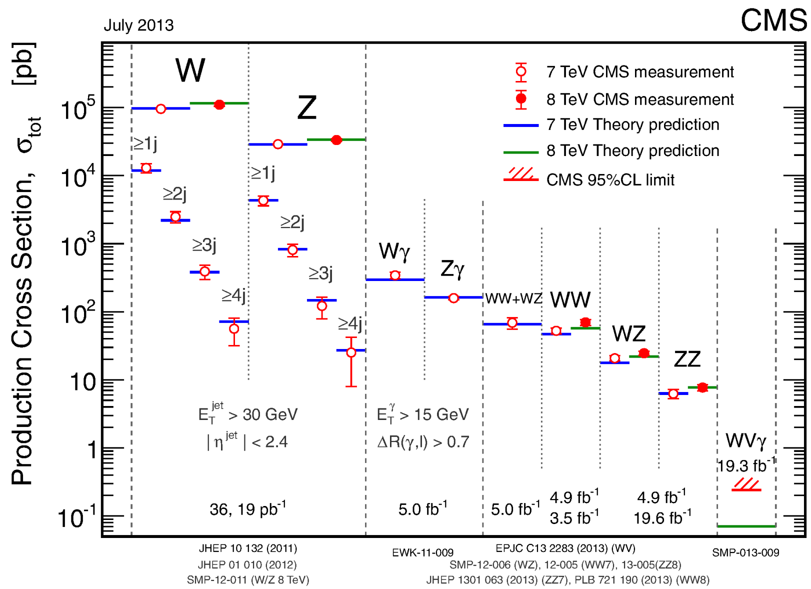
[http://cern.ch/go/dJf7] [http://cern.ch/go/Sx8m]

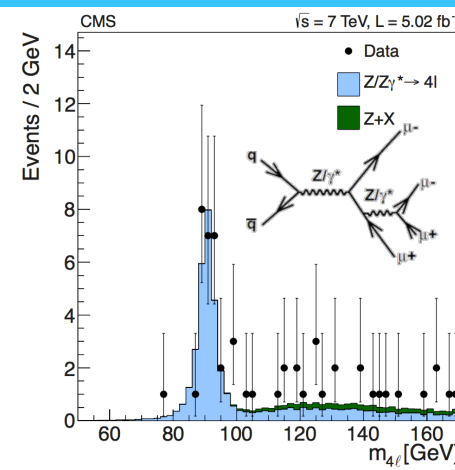


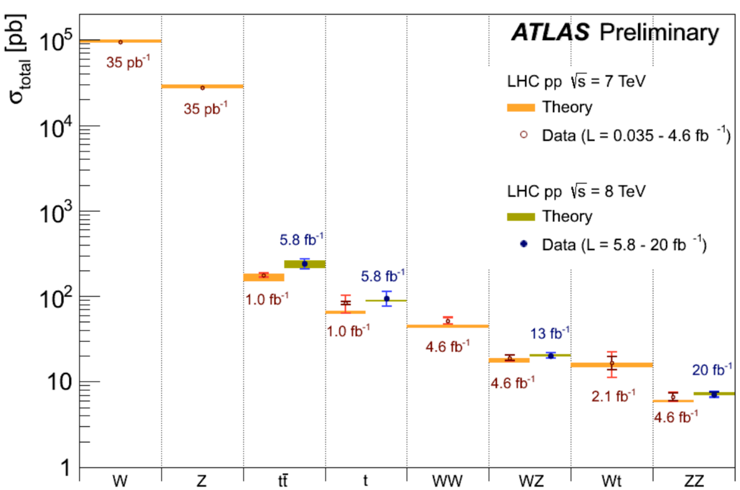
- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive weak bosons can coexist was shown by Kibble (1967).

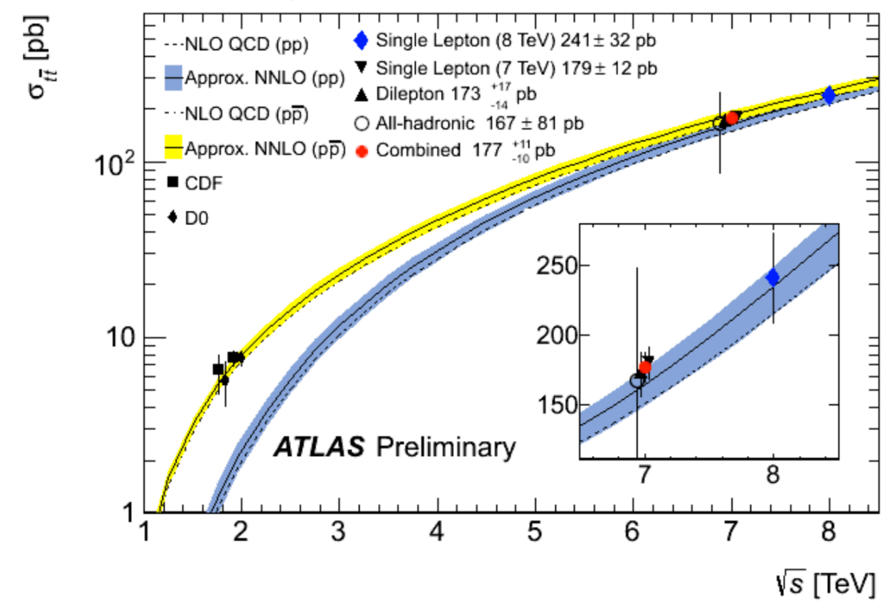
A tribute to those doing SM calculations

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi





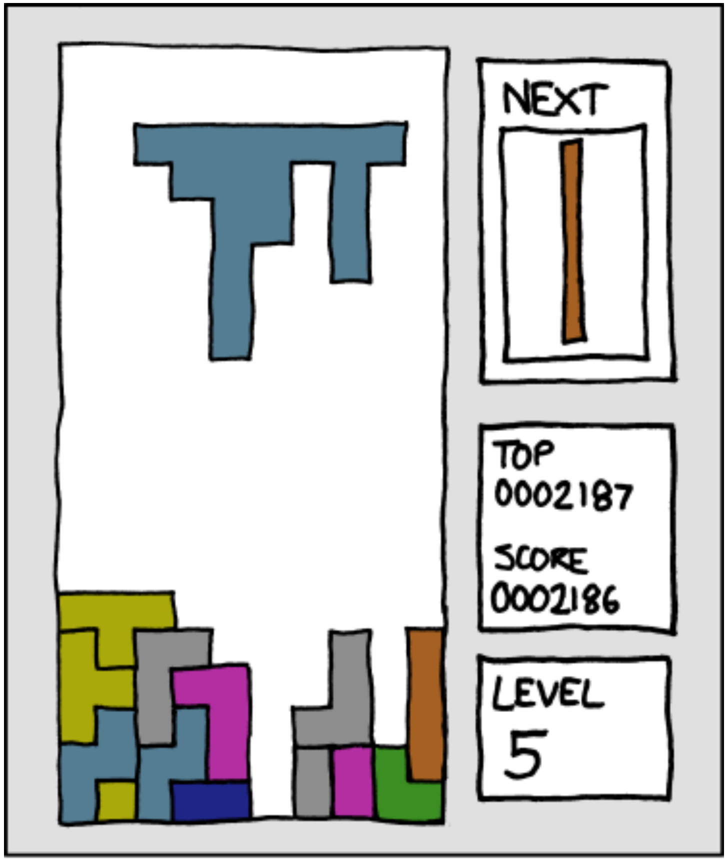




LHC Higgs Cross Section WG

[http://xkcd.com/888/]

- **Experimentalists and theorists.**
  - Together since 2010.
  - Produce the best pieces for a common Higgs puzzle. ➘



HEAVEN

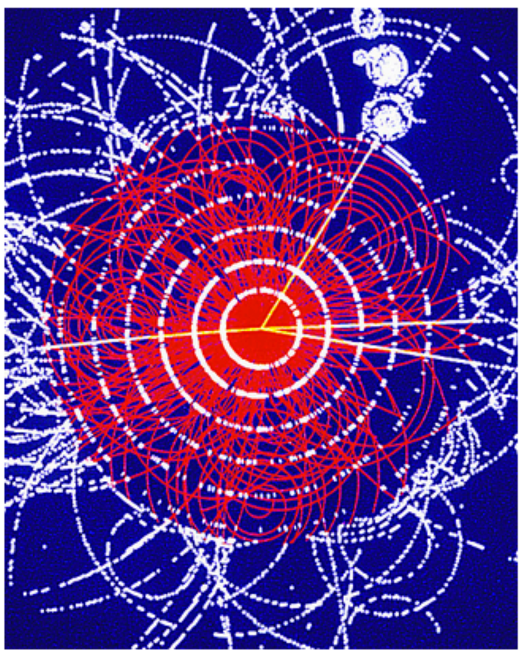
Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?
The Candidates
Video
Poll Results

PAST PERSONS OF THE YEAR

2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

2008: Barack Obama

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1 Who Should Be TIME's Person of the Year 2012?
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Person of the Year

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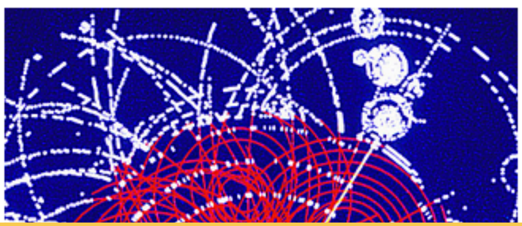

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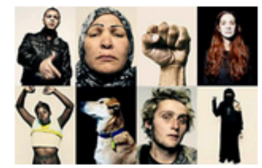
WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

PAST PERSONS OF THE YEAR



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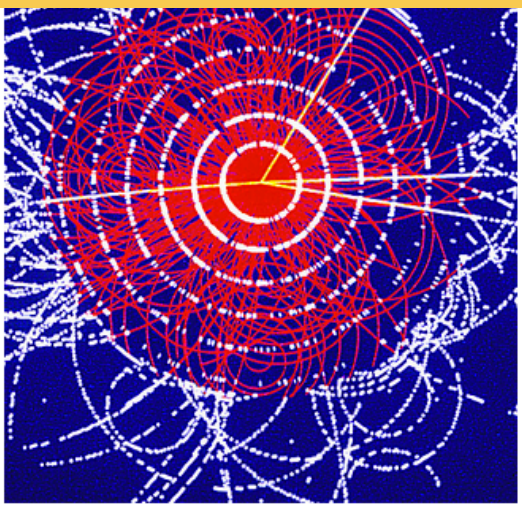
Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.



SSPL/GETTY IMAGES

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Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in

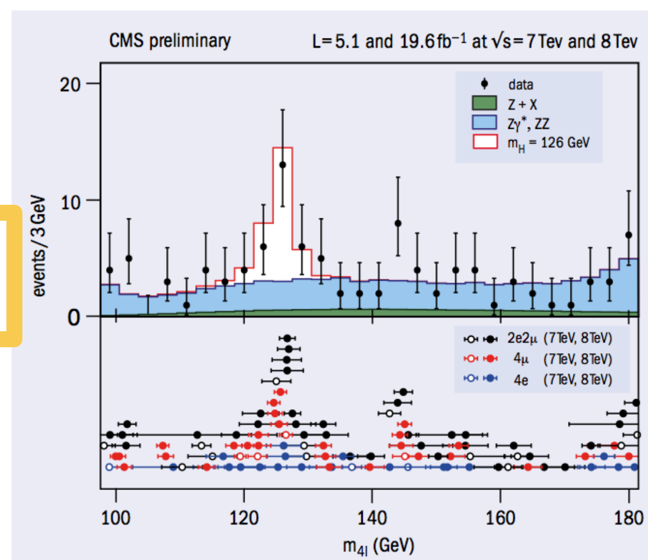
March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.



Entry in the PDG

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

H^0 MASS

INSPIRE search

Value (GeV)	Document ID		TECN	Comment
125.9 ± 0.4	OUR AVERAGE			
$125.8 \pm 0.4 \pm 0.4$	CHATRCHYAN [1]	2013J	CMS	pp , 7 and 8 TeV
$126.0 \pm 0.4 \pm 0.4$	AAD [2]	2012AI	ATLS	pp , 7 and 8 TeV
*** We do not use the following data for averages, fits, limits, etc ***				
$126.2 \pm 0.6 \pm 0.2$	CHATRCHYAN [3]	2013J	CMS	pp , 7 and 8 TeV
$125.3 \pm 0.4 \pm 0.5$	CHATRCHYAN [4]	2012N	CMS	pp , 7 and 8 TeV

[1] Combined value from ZZ and $\gamma\gamma$ final states.

[2] AAD 2012AI obtain results based on $4.6 - 4.8$ fb^{-1} of pp collisions at E_{cm} = 7 TeV and $5.8 - 5.9$ fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 2012DA.

[3] Result based on final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV.

[4] CHATRCHYAN 2012N obtain results based on $4.9 - 5.1$ fb^{-1} of pp collisions at E_{cm} = 7 TeV and $5.1 - 5.3$ fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 2012BY.

References

Document Id		Journal Name
CHATRCHYAN	2013J	PRL 110 081803
AAD	2012AI	PL B716 1
CHATRCHYAN	2012N	PL B716 30

NB: the mass measurement alone "cleared up" a huge chunk of BSM space.

2013: “killer” news

[“Lawrence of Arabia” idea from C. Grojean]

- SM-like: the Swedish academy shot the prize at Englert and Higgs.

Nobel prizes…

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
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Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

…and knighthoods.

Eminent physicists receive royal honours

by Deborah Evanson, Colin Smith, Gail Wilson
16 June 2014

Two of Imperial's physicists, best known for predicting and finding the Higgs boson, have been knighted in this year's Queen's Birthday honours list.

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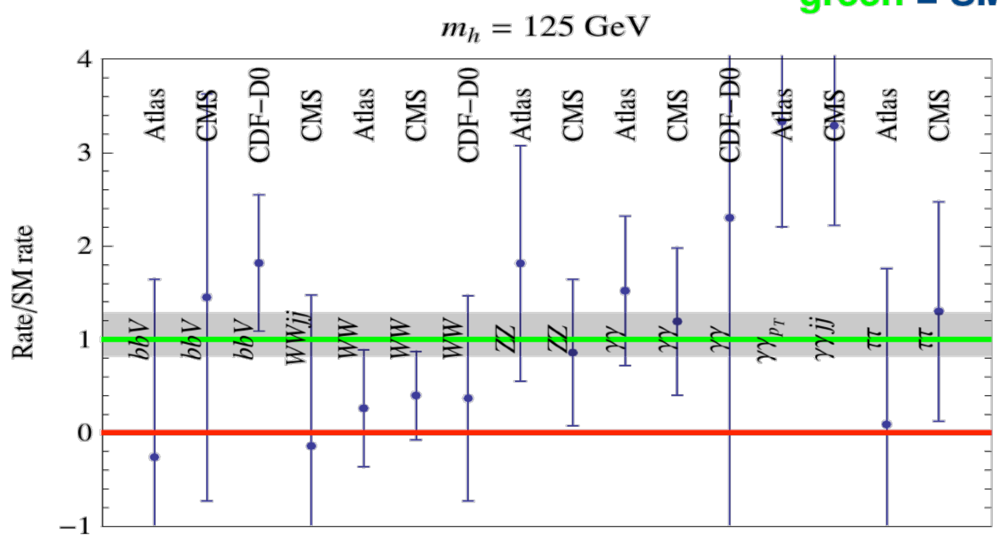
In 2012 some theorists speculated…

[http://goo.gl/CVm6s]

- **After Moriond 2012, new fits disfavor the SM and motivate for New Physics**

red = no Higgs boson
green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

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[http://goo.gl/CVm6s]

- After Moriond 2012 new fits disfavor the SM and motivate for New

new fits disfavor the SM

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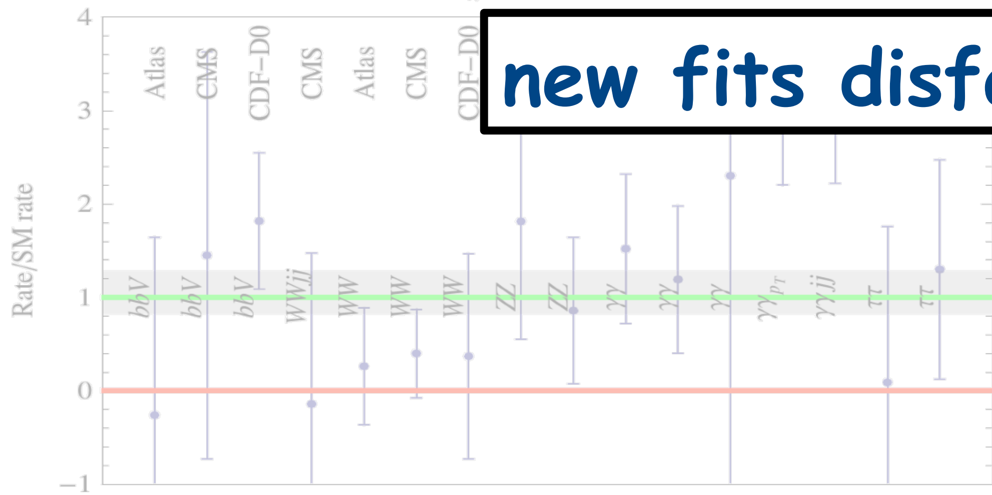

P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

In 2012 some theorists speculated…

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After Moriond 2012, new fits disfavor the SM and motivate for New

new fits disfavor the SM

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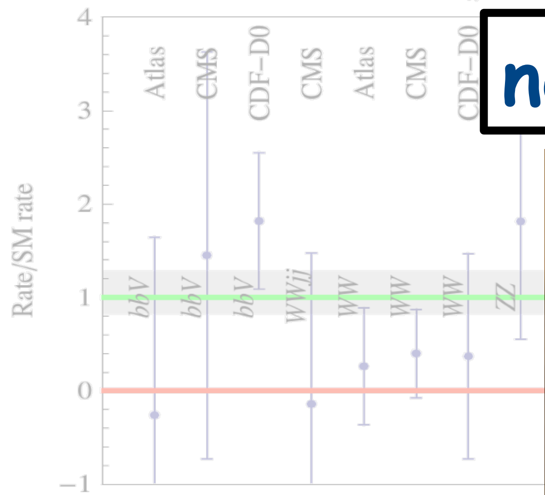
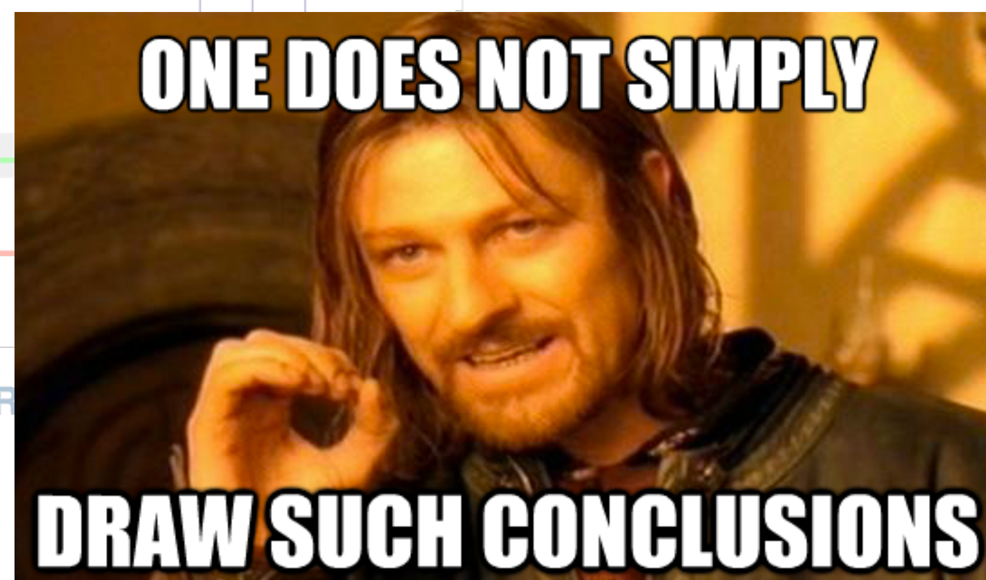
new fits disfavor the SM





P. Giardino, K. Kannike, M. R

Things you can't "unsee"

[http://cern.ch/go/Dxh7]

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Things you can't "unsee"

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