Higgs physics at Run II: a theory perspective

YETI
IPPP Durham - 13.01.2016

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Outline

- Framework for BSM Higgs studies

➡ Kappa-formalism vs EFT vs Simplified Model vs Full theory

- Probing the Higgs couplings at different energy scales

➡ Boosted Higgs

➡ Off-shell Higgs: couplings and width measurements

- Loop-induced processes

Motivation

- The main motivation to build the LHC was to explore the Higgs sector

➡ We knew that something "new" was there:

$$\sigma(W_L W_L \to W_L W_L) \propto E^2_{CM}$$

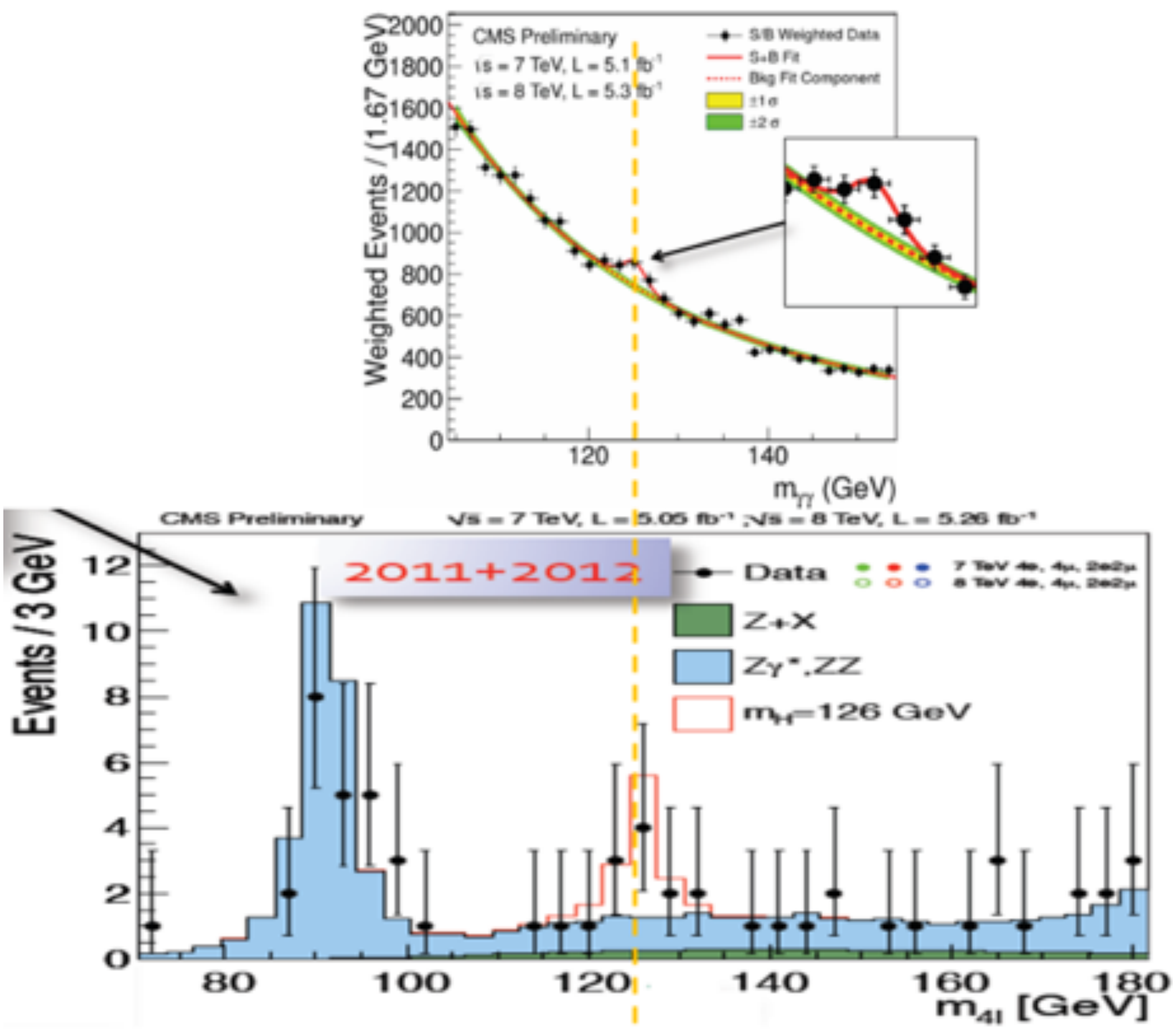
➡ We even knew that the "new physics" was at the TeV scale:

$W_L W_L$ scattering probability becomes larger than unity for $E_{cm} > 1.2 TeV$

To restore unitary it needs something like the SM Higgs boson

Motivation

A discovery has been made



The nobel prize has been awarded

But is it really the SM Higgs boson?

Strategy of Higgs analysis

- Is it really the SM Higgs boson? Strategy of Higgs analysis for Run-I:

Unique resonance?

↓

Spin/CP?

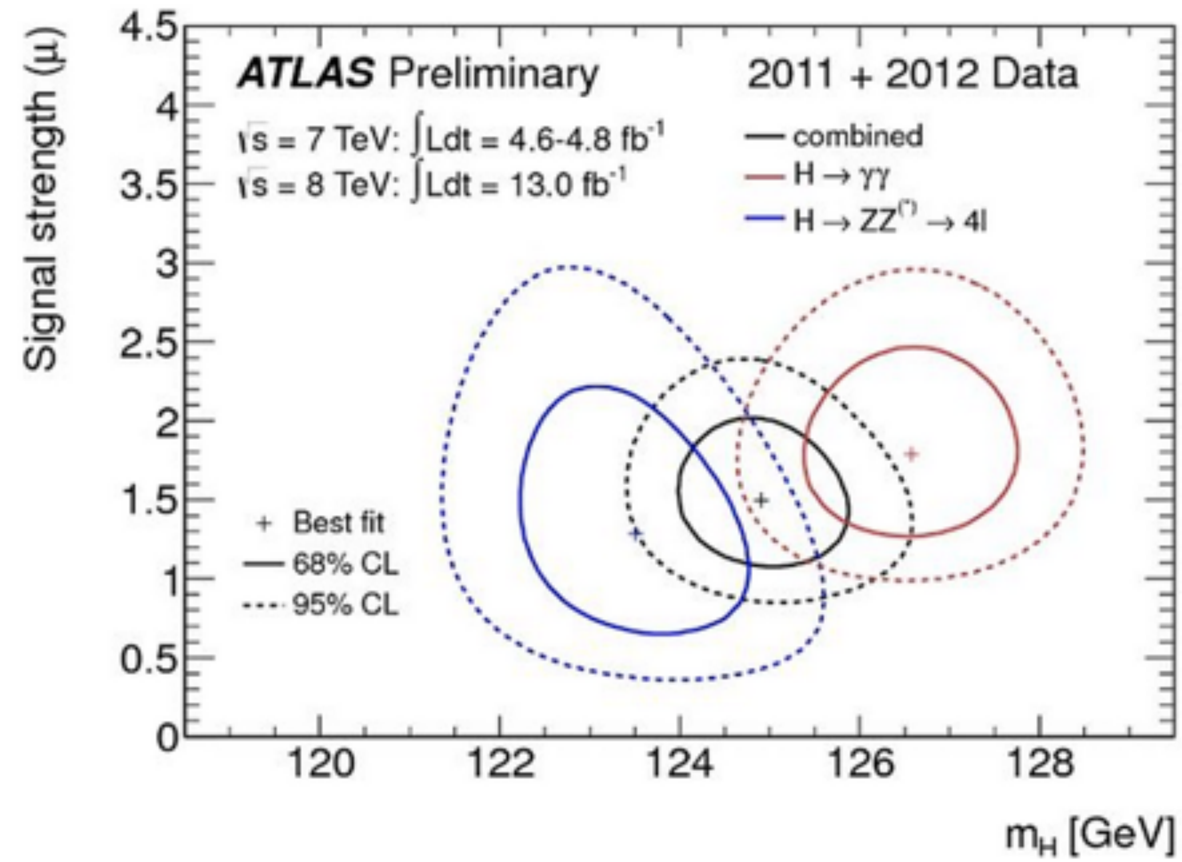
↓

Lagrangian?

↓

Coupling strength?

- Twin peaks?



→ Unique resonance

→ m_H=125.09±0.21 (stat.)±0.11 (syst.) [ATLAS+CMS]

Strategy of Higgs analysis

- Is it really the SM Higgs boson? Strategy of Higgs analysis for Run-I:

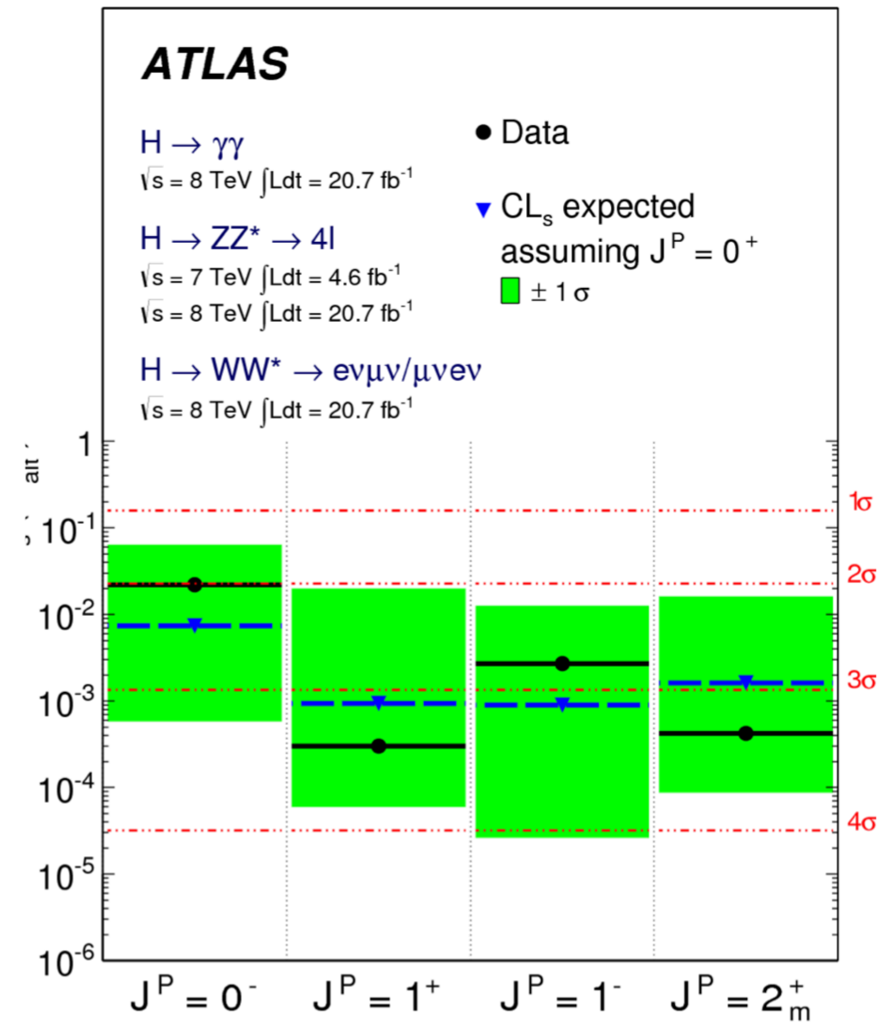
Unique resonance?

Spin/CP?

Lagrangian?

Coupling strength?

- $H \to \gamma\gamma, ZZ, WW$



→ Hypotheses $J^P \neq 0^+$ rejected at 95% CL

Strategy of Higgs analysis

- Is it really the SM Higgs boson? Strategy of Higgs analysis for Run-I:

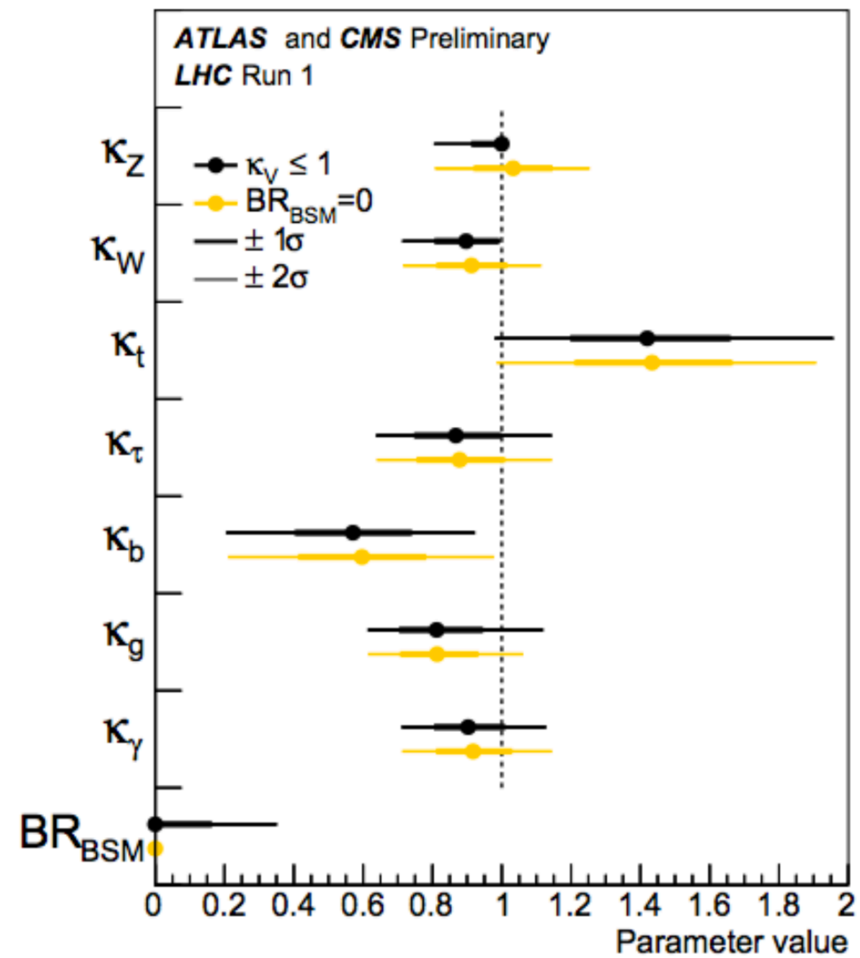
Unique resonance?

Spin/CP?

Lagrangian?

Coupling strength?

- All couplings in agreement with the SM

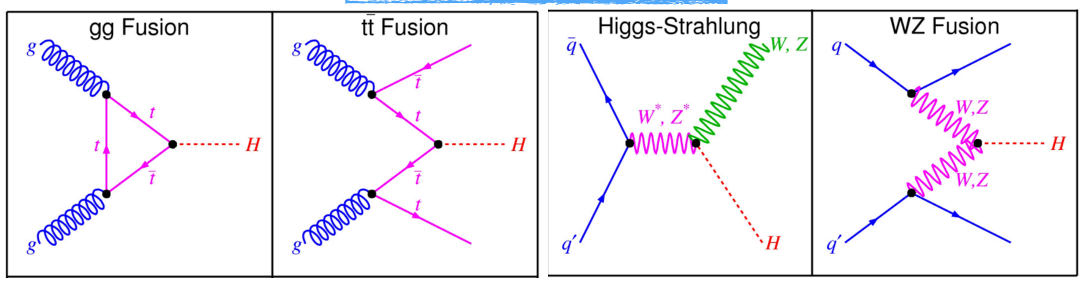


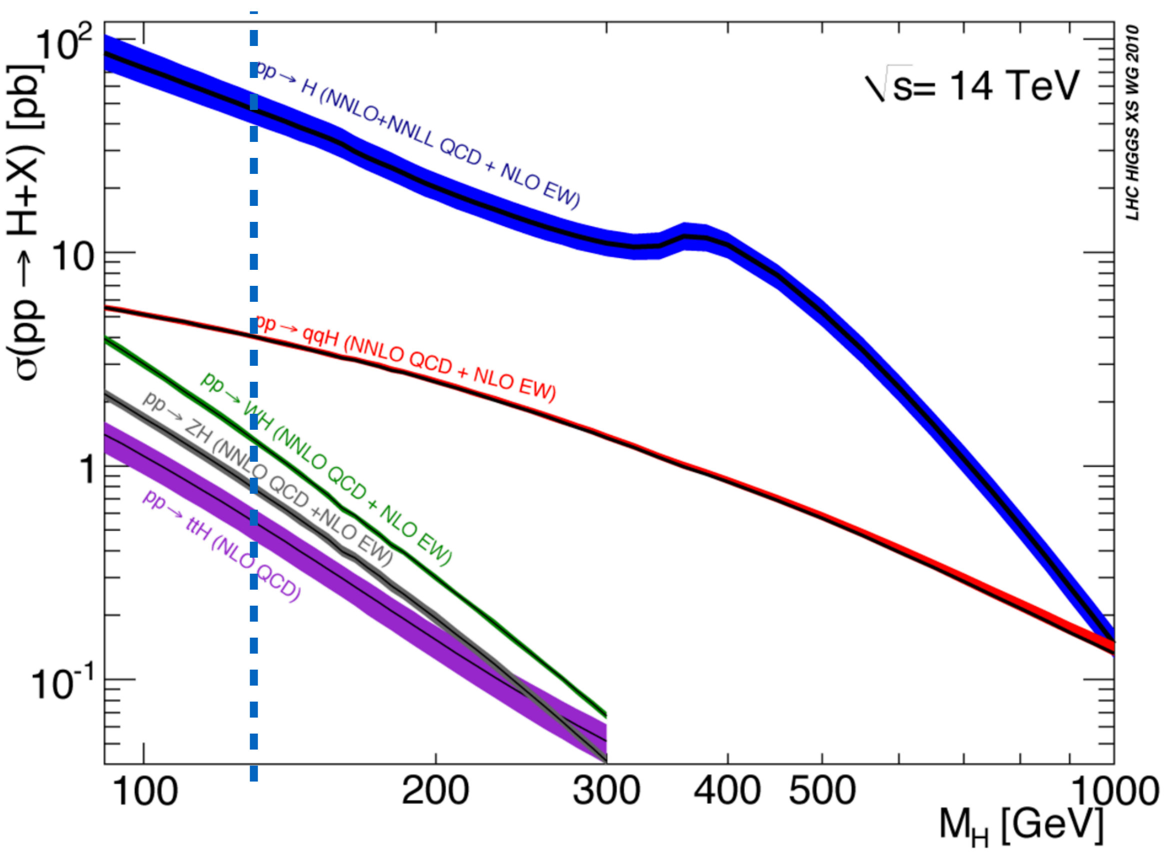
Run I tells that we are seeing the SM Higgs
(with large error bars and several degeneracies in the fits)

We expect a big improvement in the current Run:
More data, energy and more distributions!

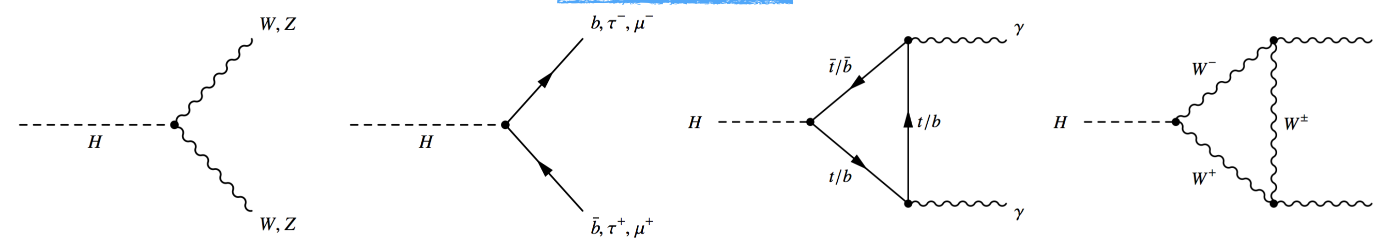
Higgs production and decay at the LHC

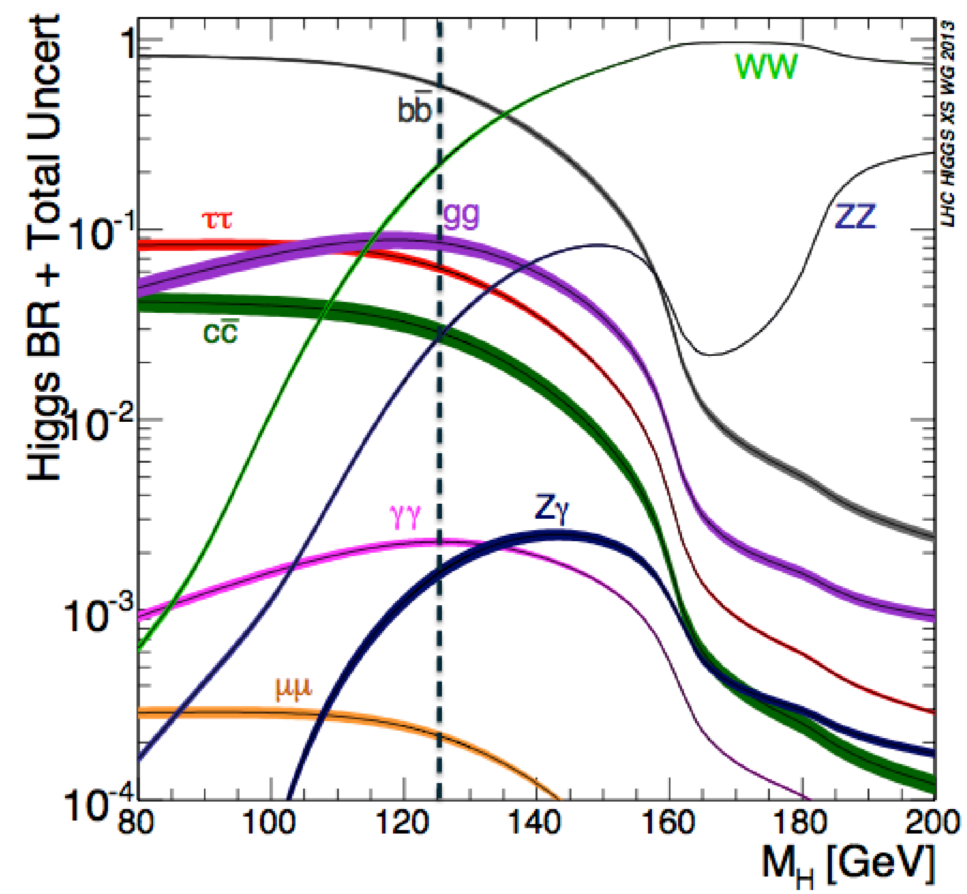
Production





Decay





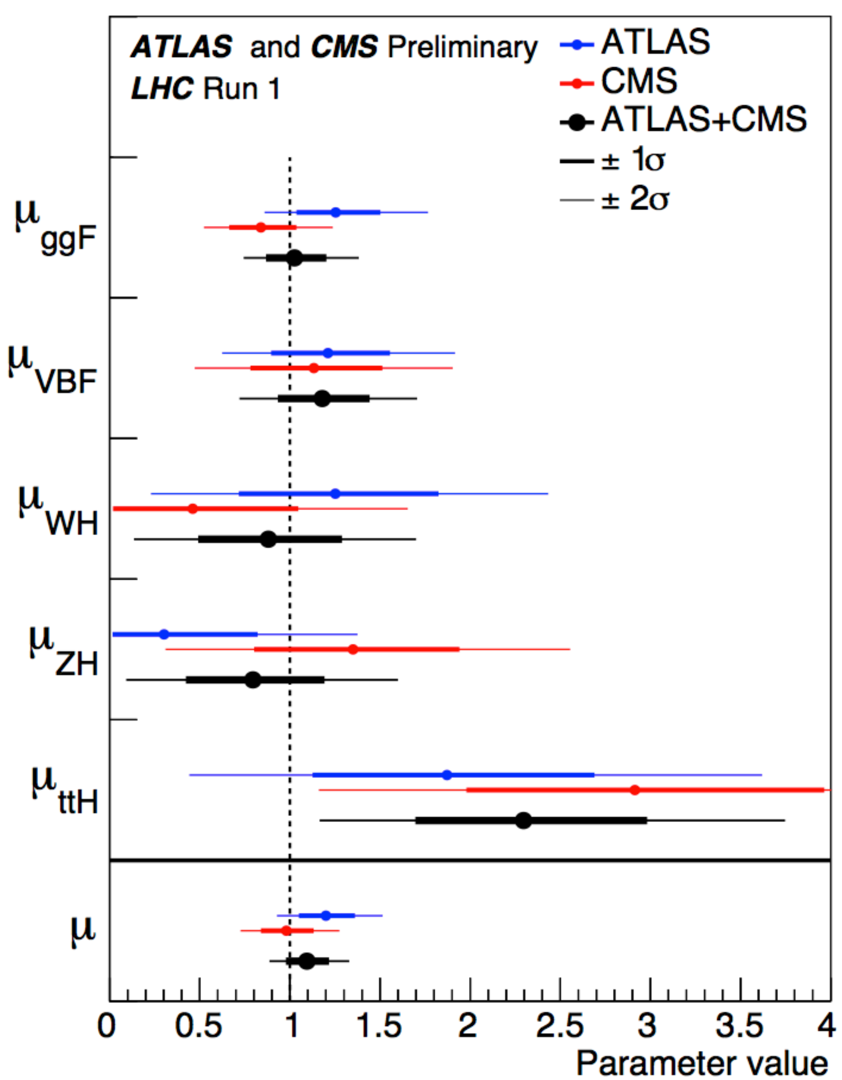
- m_H=125 GeV is in a lucky spot. Many decay channels → Rich phenomenology
- How to look for new physics in the LHC?

1st attempt - signal strength

- Run I - ATLAS and CMS started to report results via the signal strengths μ:

$$i \rightarrow H \rightarrow f$$

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \qquad \mu^f = \frac{{\rm BR}^f}{({\rm BR}^f)_{\rm SM}}$$



- Pros:
  1) Very simple to implement and interpret the results:
  μ=0 - Background hypothesis
  μ=1 - SM Higgs hypothesis
  2) Deviations are scale factors to the SM cross-section

- Cons:
  1) Mixes production and decays couplings
  2) Does not directly access the kinematics (distributions)
  BSM can be at "the tail" of some distributions

BSM approaches

Energy/Complexity

Full theory

New Lorentz structures
New degrees of freedom
Very complex/many parameters
But if correct gives predictability!

Simplified models

New Lorentz structures (interesting subset)
New degrees of freedom (interesting subset)

EFT

Same symmetries of the SM
New Lorentz structures
No new degrees of freedom

kappa formalism
(Run I paradigm)

Simple coupling rescaling
No new Lorentz structures
No new degrees of freedom

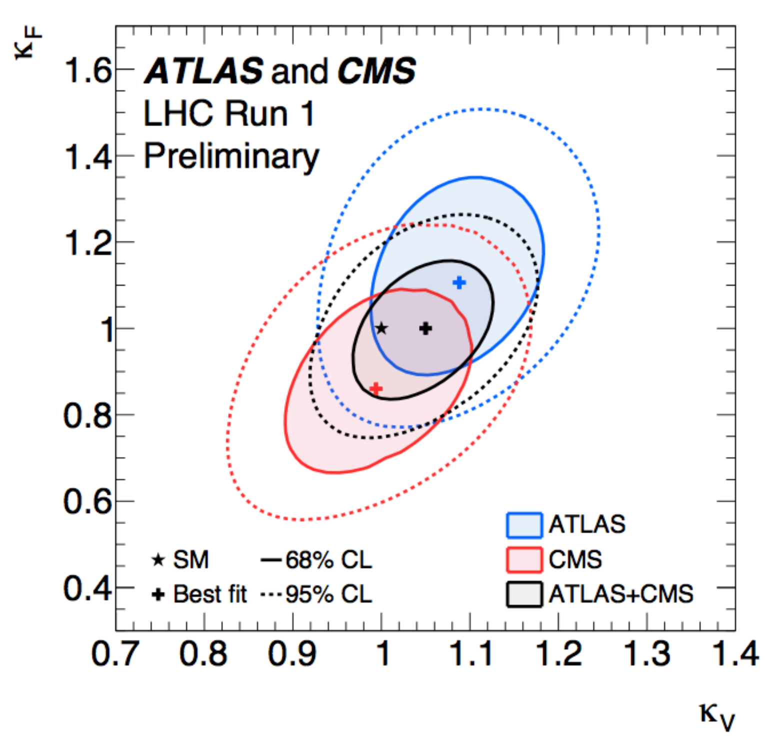
Kappa formalism

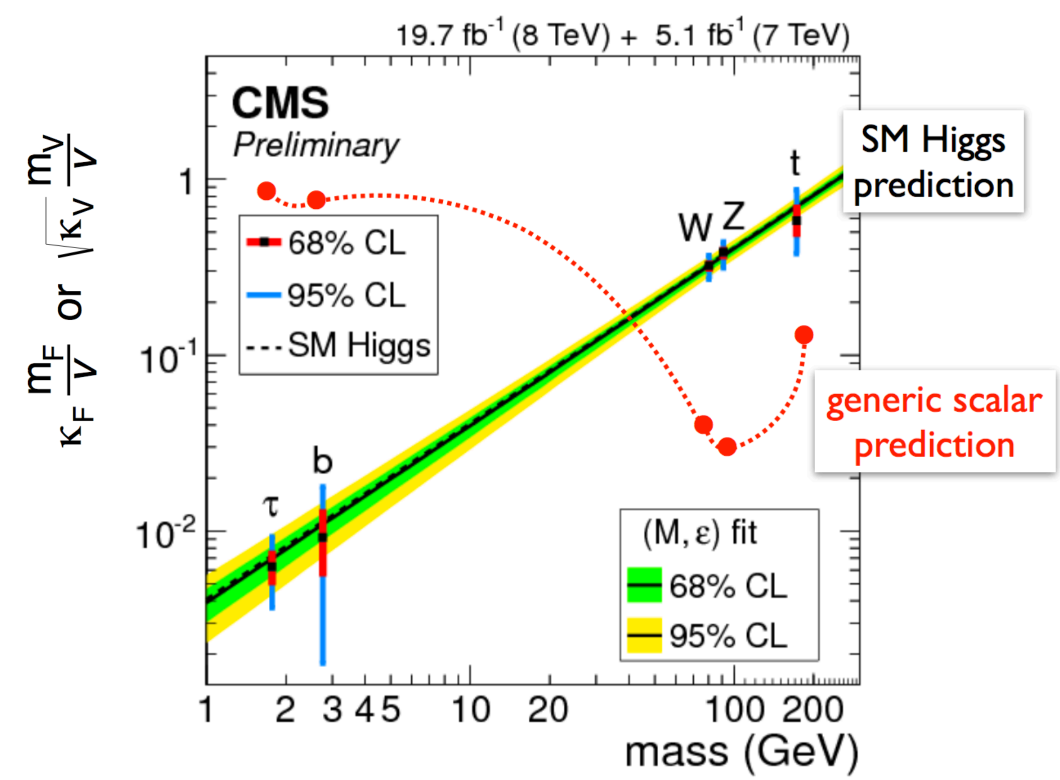
- Deviations from SM are encoded via a coupling rescaling factor κ_i (Run I paradigm)

$$\kappa_i = \frac{g_i}{g_{SM}} \qquad\qquad \kappa_H^2 = \sum_j BR^j_{SM}\kappa_j^2 = \frac{\Gamma_H}{\Gamma_H^{SM}}$$

- Coupling strength is the most characteristic footprint of the SM Higgs
  It scales with the mass:

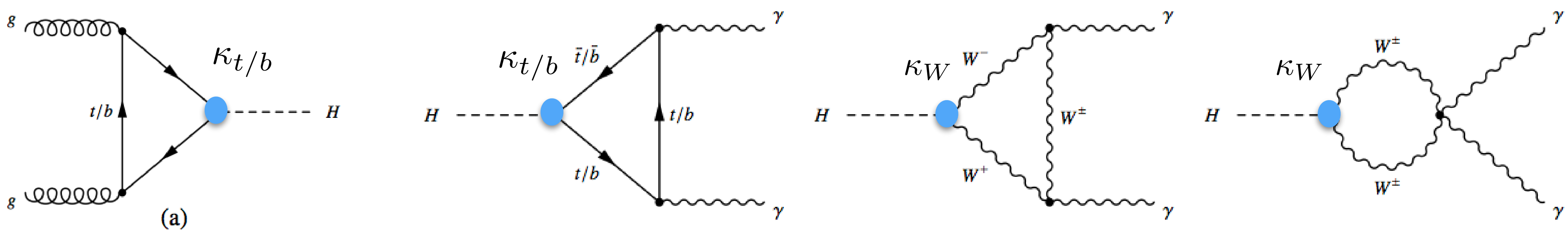
Fermions: $g_f = \kappa_f \dfrac{\sqrt{2}m_f}{v}$ Gauge bosons: $g_V = \kappa_V \dfrac{2m_V^2}{v}$





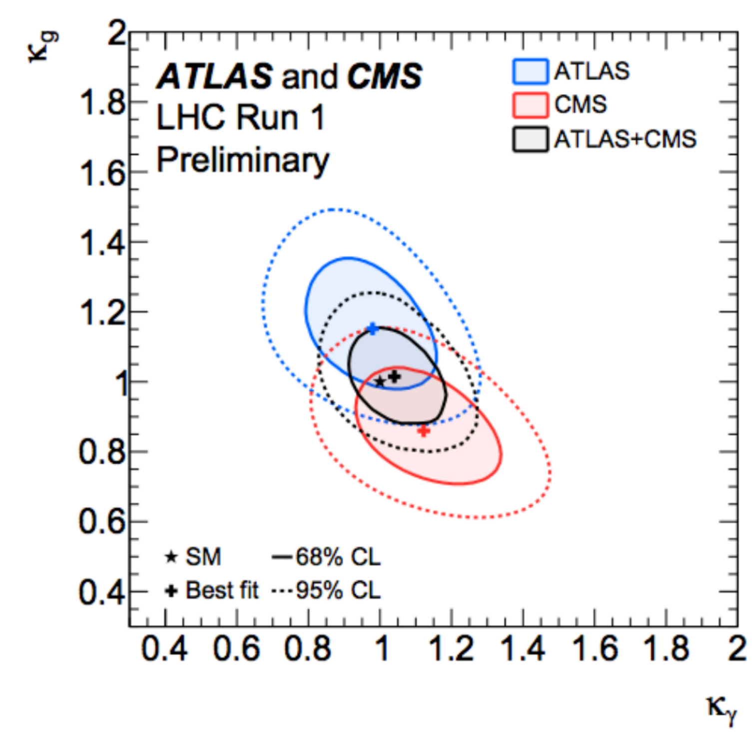
Kappa formalism

- Example $$\frac{\sigma.BR}{\sigma_{SM}.BR_{SM}}(gg \to H \to \gamma\gamma) = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$



	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim \quad 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim \quad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$

- Pros:
  1) Intuitive coupling rescaling
  2) Allows for more complex cases: loop contributions and interferences



- Cons:
  1) Assumes SM production and decays
  2) No new Lorentz structures
  3) No new degrees of freedom

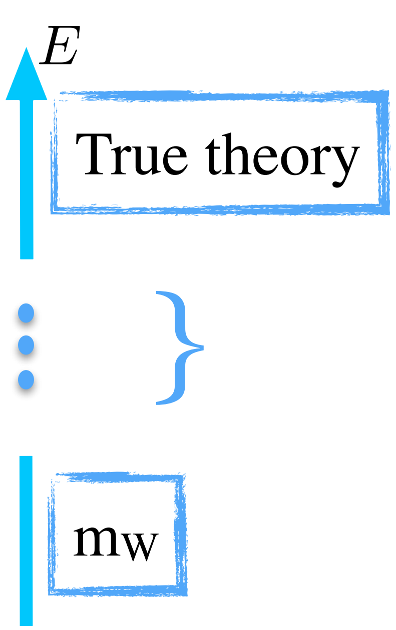
EFT formalism

- Going beyond the kappa-formalism for the LHC Run-2
- Bottom-up approach: Model independent searches for New Physics

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i^{Dim6} + \ldots$$

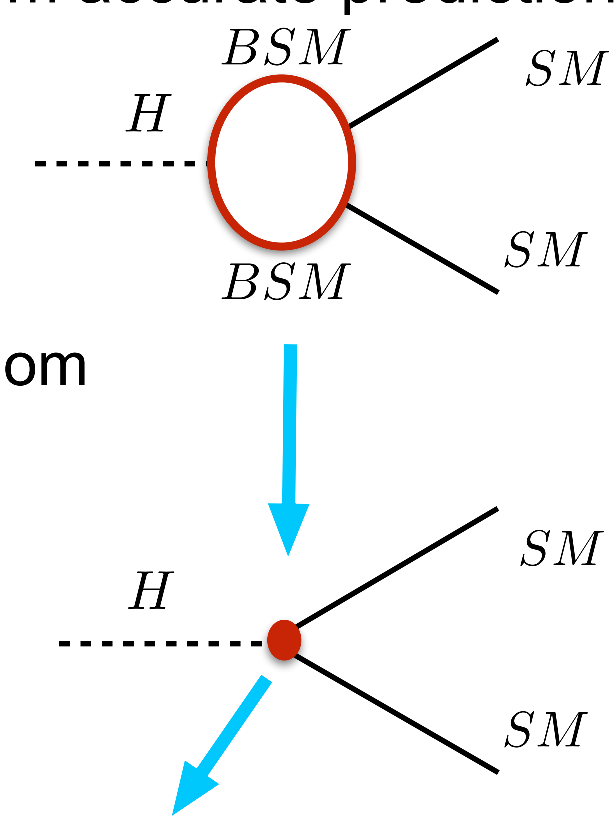
EFT - Consistent gauge invariant method to look for the effects of high mass BSM physics

Renormalizable order by order in $1/\Lambda$. Consistent framework to perform accurate predictions



Energy gap between SM and new BSM degrees of freedom

Low energy approximation of high scale BSM physics



EFT interaction $\mathcal{O}_i$ with strength $\frac{c_i}{\Lambda^2}$

EFT formalism

- Field with big progress in the recent years

Reduced by EOM

80 EFT operators for one fermion family → 59 EFT operators for one fermion family

Buchmuller, Wyler 1986 — Grzadkowski et al. 2010

"It is really amazing that no author of almost 600 papers that quoted Ref. [Buchmuller,Wyler] over 24 years has ever decided to rederive the operator basis from the outset to check its correctness. As the current work shows, the exercise has been straightforward enough for an M. Sc. thesis." Grzadkowski et al. 2010

- Many discussions on EFT basis

Bottom line: All EFT basis are equivalent as long as a complete basis is implemented

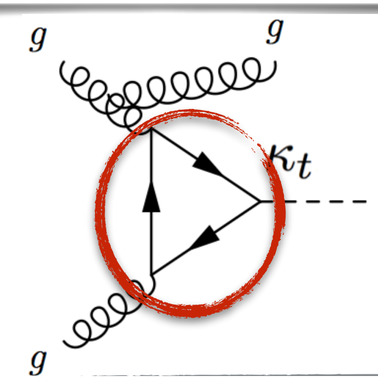
Rosetta package can translate bases in FeynRules Falkowski, Fuks, Mawatari, Mimasu, Riva, Sanz 2015

- Are there tools for EFT calculations?

→ EFT Lagrangian implementation in FeynRules -> get UFO output - talk by Celine & Olivier

→ MC generation: MadGraph5, Sherpa, Herwig, MCFM, VBFNLO,…

EFT example 1: Boosted Higgs



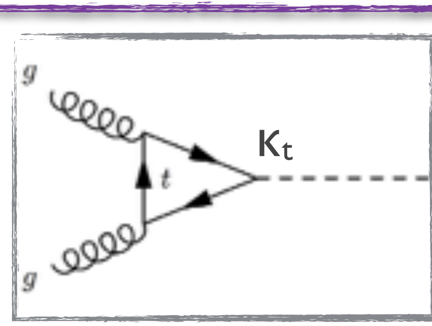
- Higgs production: Is the y_t responsible for the ggH coupling or are there BSM contributions?

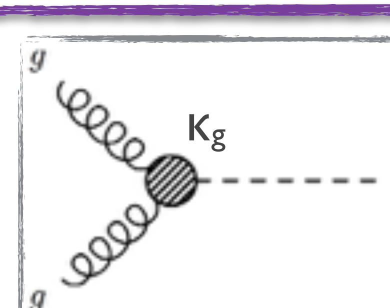
Relevant CP-even dim6 operators to GF:

$$\mathcal{O}_g = \frac{\alpha_s}{12\pi v^2}|H|^2 G^a_{\mu\nu}G^{a\,\mu\nu} \qquad \mathcal{O}_y = \frac{y_t}{v^2}|H|^2 \bar{Q}_L \tilde{H} t_R \qquad \mathcal{O}_H = \frac{1}{2v^2}\partial_\mu |H|^2 \partial^\mu |H|^2$$

$$k_t = 1 - \frac{c_H}{2} - \mathrm{Re}(c_y) \qquad k_g = c_g$$

$$\boxed{\mathcal{L}_{ggH} \supset -\kappa_t \frac{m_t}{v}\bar{t}th + \kappa_g \frac{\alpha_s}{12\pi}\frac{h}{v}G^a_{\mu\nu}G^{\mu\nu\,a}}$$



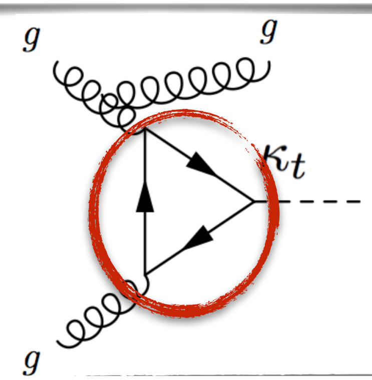


$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g$$

Hj:
Azatov, Paul (2014)
Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant (2014)
Banfi, Martin, Sanz (2013)
Grojean, Salvioni, Schlaffer Weiler (2013)
Hjj:
Buschmann, Englert, DG, Plehn, Spannowsky (2014)
H+jets with NLO Merging+...:
Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn

- κ_t and κ_g need to satisfy Higgs total rate $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g = 1$

EFT example 1: Boosted Higgs



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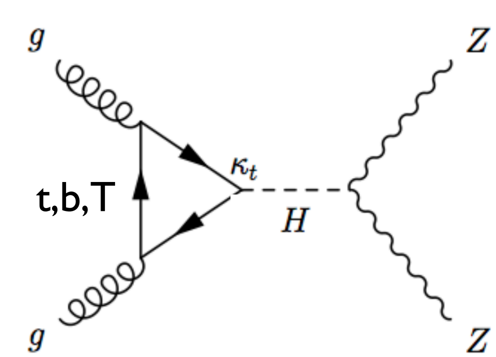
- Top partners - Prototype model inducing this degeneracy

$$\mathcal{L} = -y\bar{Q}_L t_R H - M\bar{T}T - Y_T\bar{Q}_L T_R H$$



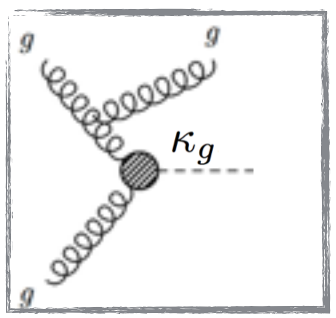
→ Heavy fermion loops generate k_g and mixing modifies y_t (k_t)

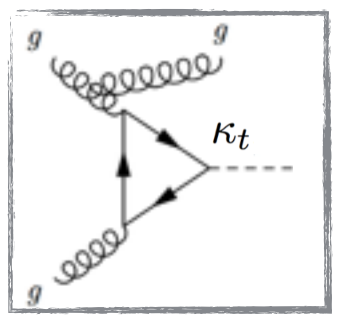
Dawson, Furlan (2014); Chen, Dawson, Lewis (2014)

EFT example 1: Boosted Higgs

- Distributions are fundamental to break the degeneracy: $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g = 1$
  This information is missed in the rate analysis, i.e., we would miss the BSM effects!

$$\mathcal{L}_{ggH} \supset -\kappa_t \frac{m_t}{v} \bar{t}th + \kappa_g \frac{\alpha_s}{12\pi} \frac{h}{v} G^a_{\mu\nu} G^{\mu\nu\, a}$$





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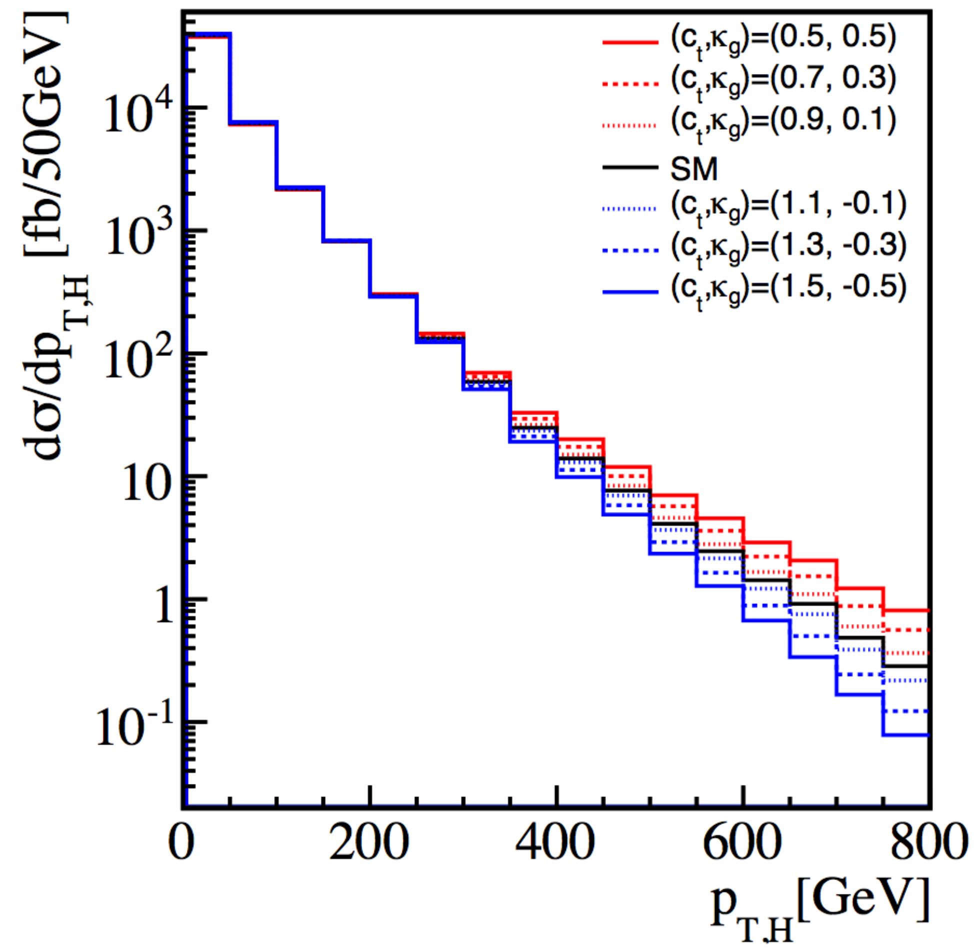

Grojean, Salvioni, Schlaffer Weiler 2013

Schlaffer, Spannowsky, Takeuchi, Weiler, Wymant 2014

Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn 2015

→ Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV

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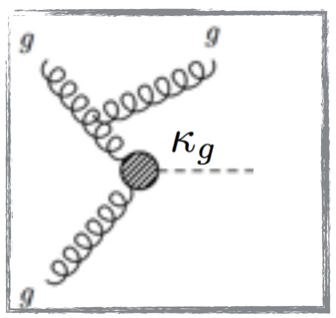

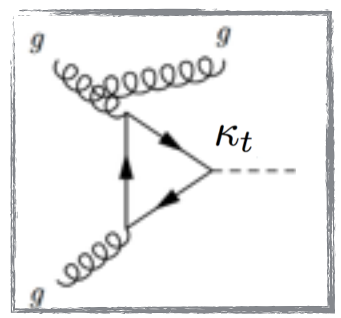

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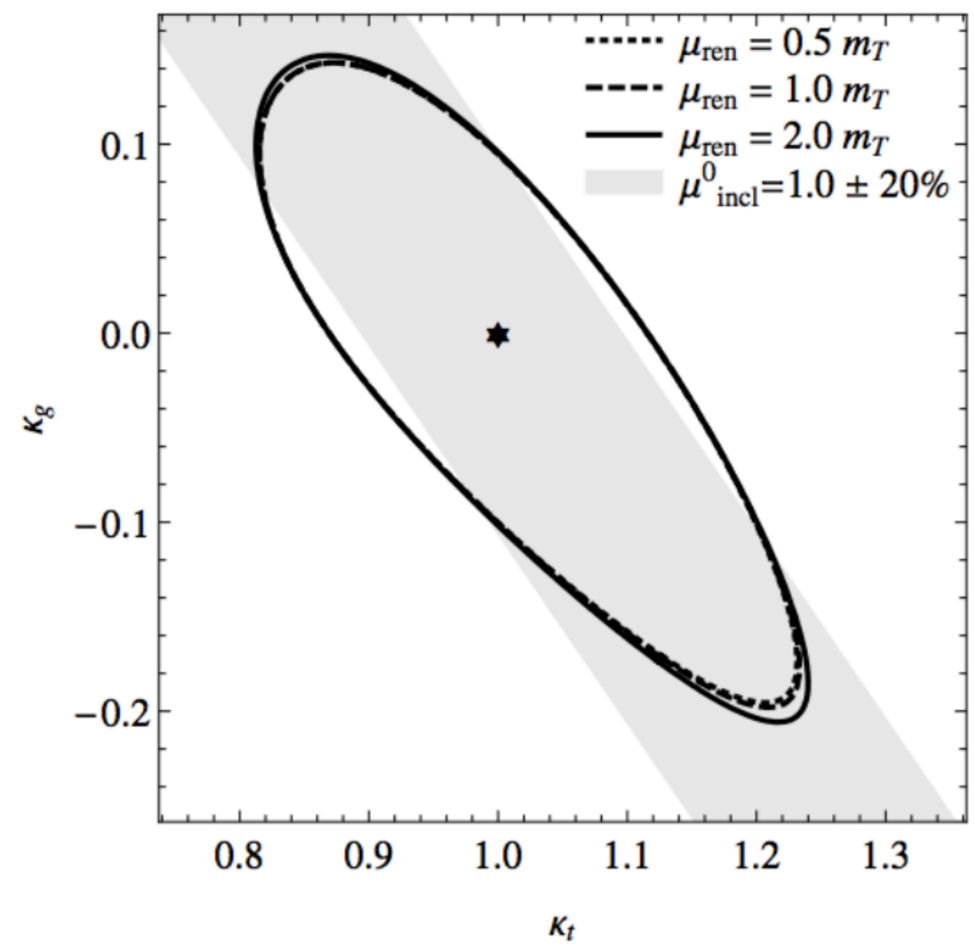

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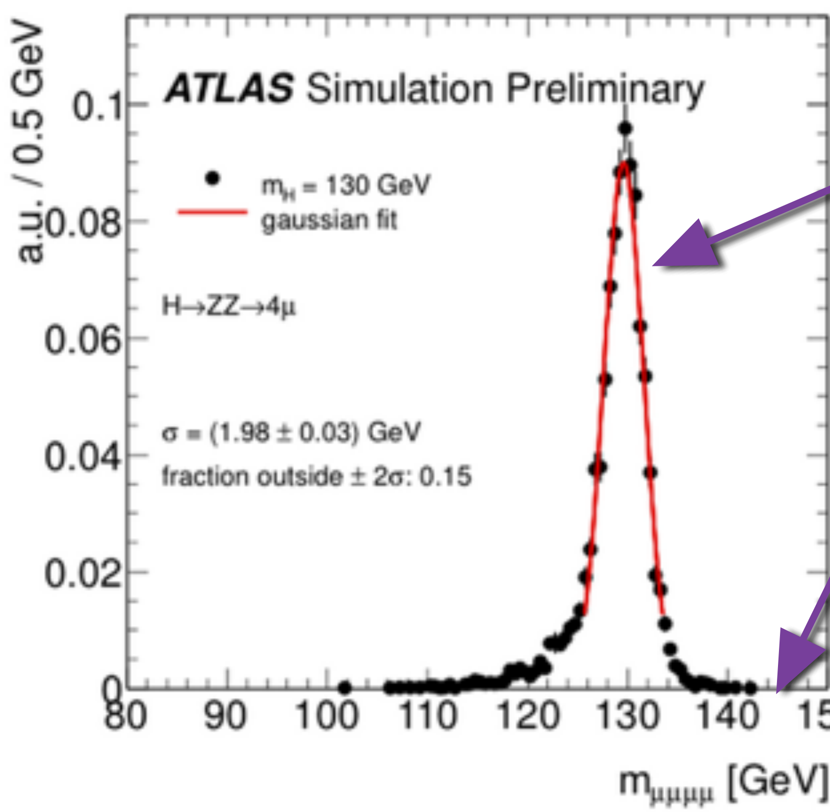
EFT example 2: Off-Shell Higgs Production

- Just recently, we started to recognize the importance of the Off-Shell Higgs

→ since $\Gamma_H/m_H \sim 3\times 10^{-5}$ one naively expects very small off-shell rates



$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{\Gamma_H}$$

$$\frac{d\sigma}{dm_{4l}} \sim \frac{(g_i g_f)^2}{(m_{4l}^2 - m_H^2)^2}$$

- However, at least 15% of the cross-section comes from m_{4l}>300 GeV

Narrow Width Approximation fails spectacularly - unitarizing property of Higgs

→ Interference with background: $gg\to H^*\to ZZ$ with $gg\to ZZ$;

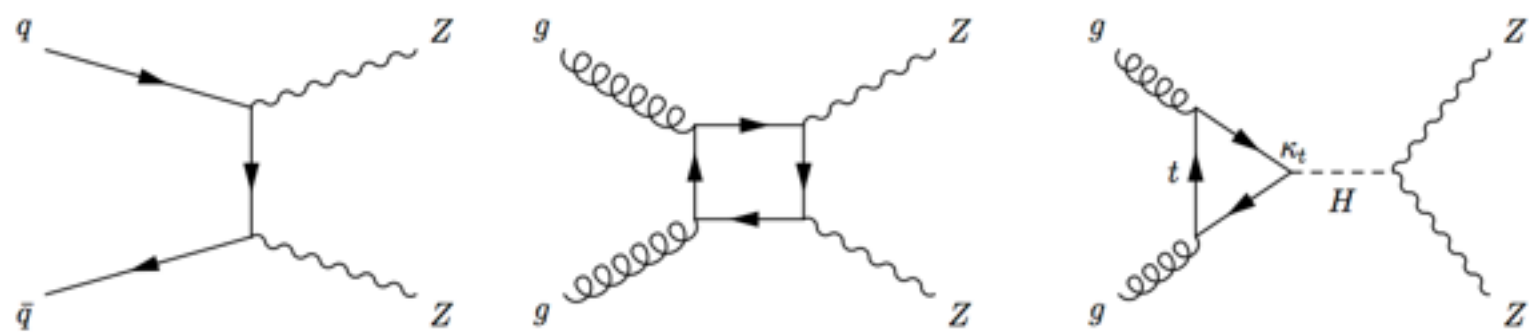
→ ZZ Threshold;

→ and top mass effects change our naive expectations

Kauer, Passarino 2012
Caola, Melnikov 2013
Campbell, Ellis, Williams 2013

Theoretical ingredients

- Signal and background components:



(a) (b) (c)

→ $|a|^2$ - Background component: generated already at tree level (large) known at NNLO (Cascioli *et. al*. 2014)

→ $|b|^2$ - Continuum background known at LO only. Internal masses make it a non-trivial multi-scale problem; Big uncertainties; Very important calculation for Run II

→ $|c|^2$ - signal (loop-induced) known at NNLO

→ b*c - Signal/background interference. Large and destructive at large invariant mass. $|c|^2$ and b*c present similar perturbative QCD enhancement: $K^{NLO}_{b*c} \sim K^{NLO}_{|c|^2}$

Bonvini, Caola, Forte, Melnikov, Ridolfi (2013)

Theoretical ingredients

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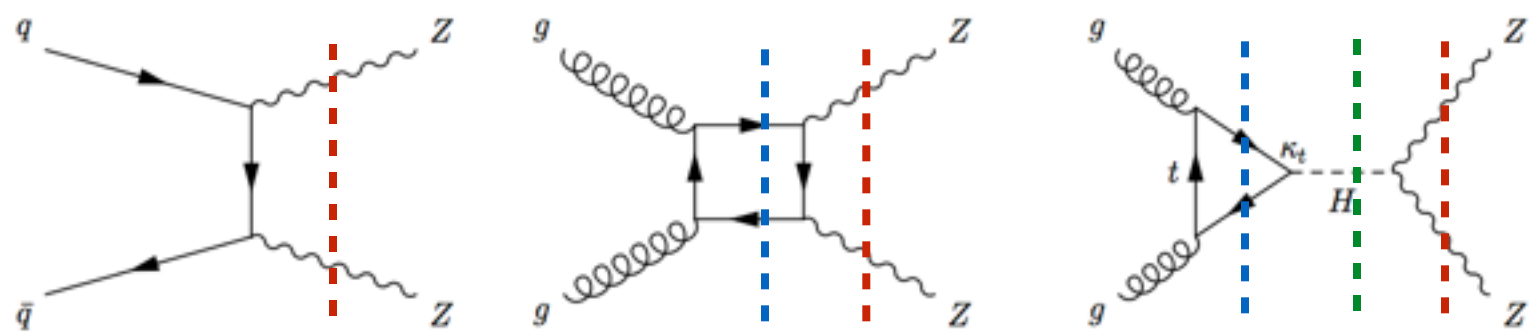

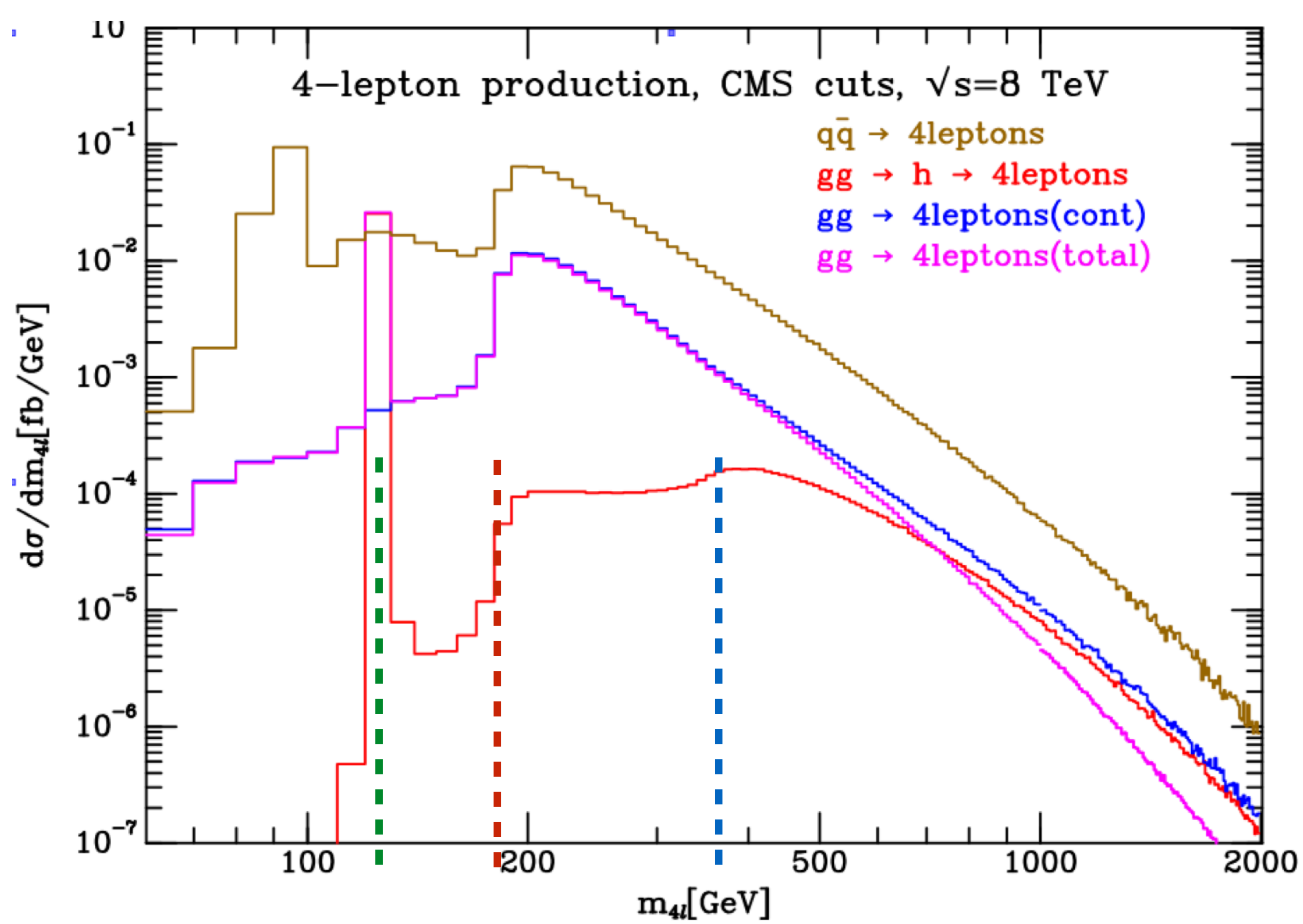

Campbell, Ellis, Williams 2013

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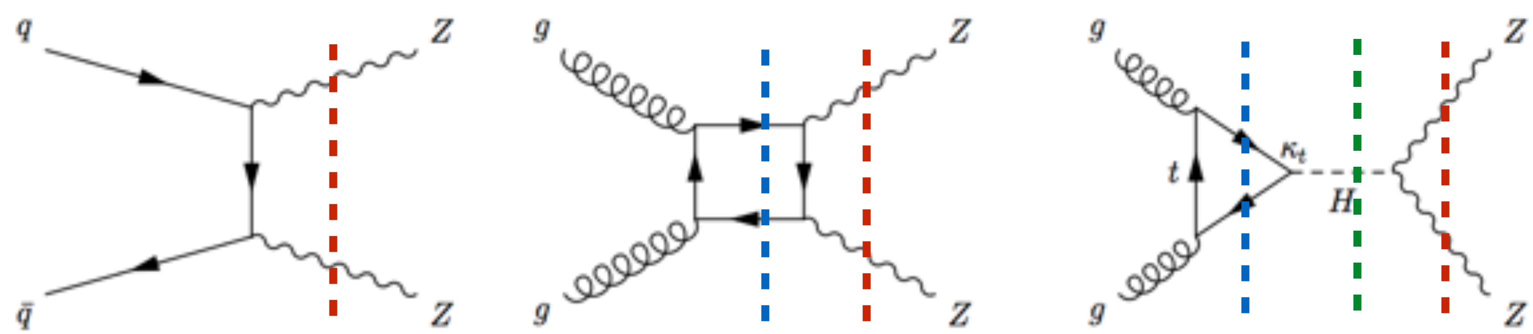


$$\mathcal{M}_t^{++00} = -2\frac{m_{4\ell}^2 - 2m_Z^2}{m_Z^2}\frac{m_t^2}{m_{4\ell}^2 - m_H^2 + i\Gamma_H m_H}\left[1 + \left(1 - \frac{4m_t^2}{m_{4\ell}^2}\right) f\left(\frac{4m_t^2}{m_{4\ell}^2}\right)\right]$$

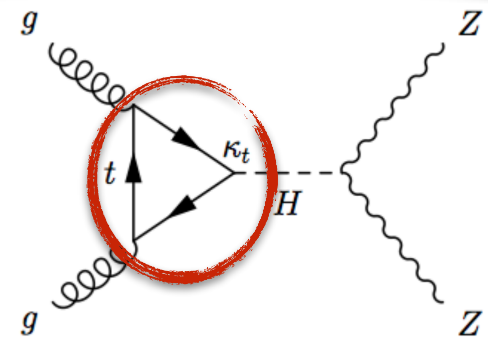
→ Top mass effects in Higgs production

- $\mathcal{M}_t^{++00} \approx +\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_H, m_Z$
- $\mathcal{M}_c^{++00} \approx -\frac{m_t^2}{2m_Z^2}\log^2\frac{m_{4\ell}^2}{m_t^2}$ with $m_{4\ell} \gg m_t \gtrsim m_Z$.

→ Full top mass: destructive interference

→ The Higgs does what he is expected to do! (Quigg, Lee, Thacker 1977)

Framework



- Higgs production - Relevant CP-even dim6 operators to GF:

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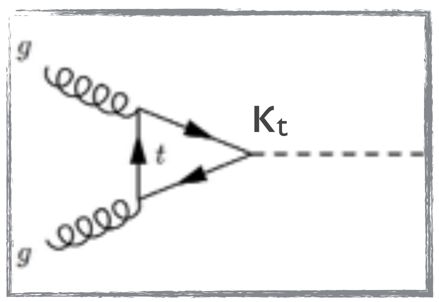

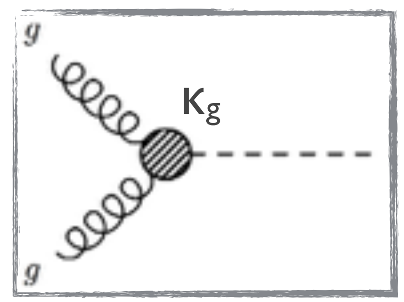

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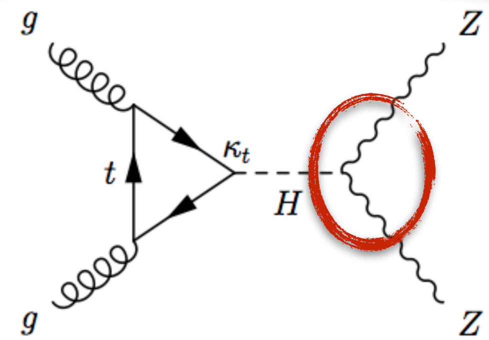
- κ_t and κ_g need to satisfy Higgs total rate $\sigma \sim |\kappa_t + \kappa_g|^2 \rightarrow \kappa_t + \kappa_g = 1$

Framework



- Higgs decays - the dim6 operators give rise to the following Higgs interactions:

$$\mathcal{L}^{HVV} = g^{(1)}_{HZZ} Z_{\mu\nu} Z^{\mu} \partial^{\nu} + g^{(2)}_{HZZ} H Z_{\mu\nu} Z^{\mu\nu} + g^{(3)}_{HZZ} H Z_{\mu} Z^{\mu}$$

➡ The additional operators $Z_{\mu\nu} Z^{\nu} \partial^{\nu}$ and $H Z_{\mu\nu} Z^{\mu\nu}$ do not affect the longitudinal Z polarisation

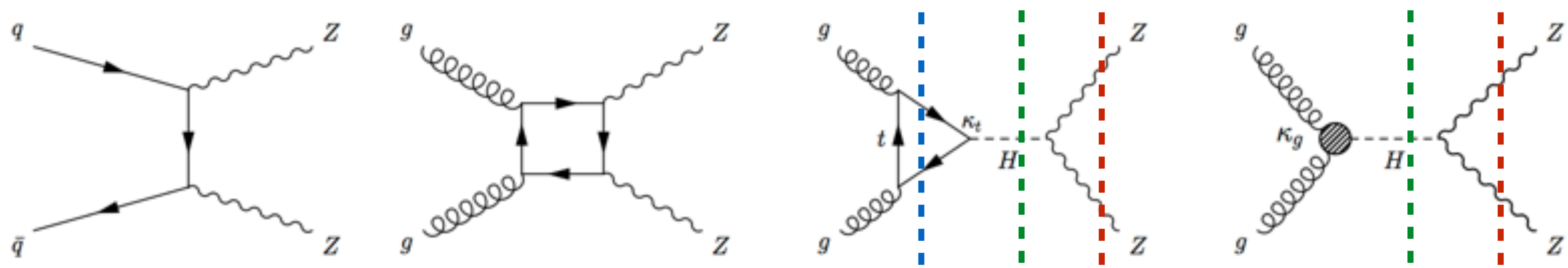
➡ So they lead to similar m_{4l} kinematics as the SM $H Z_{\mu} Z^{\mu}$
We consider only $g^{(3)}_{HZZ}$ in our analysis

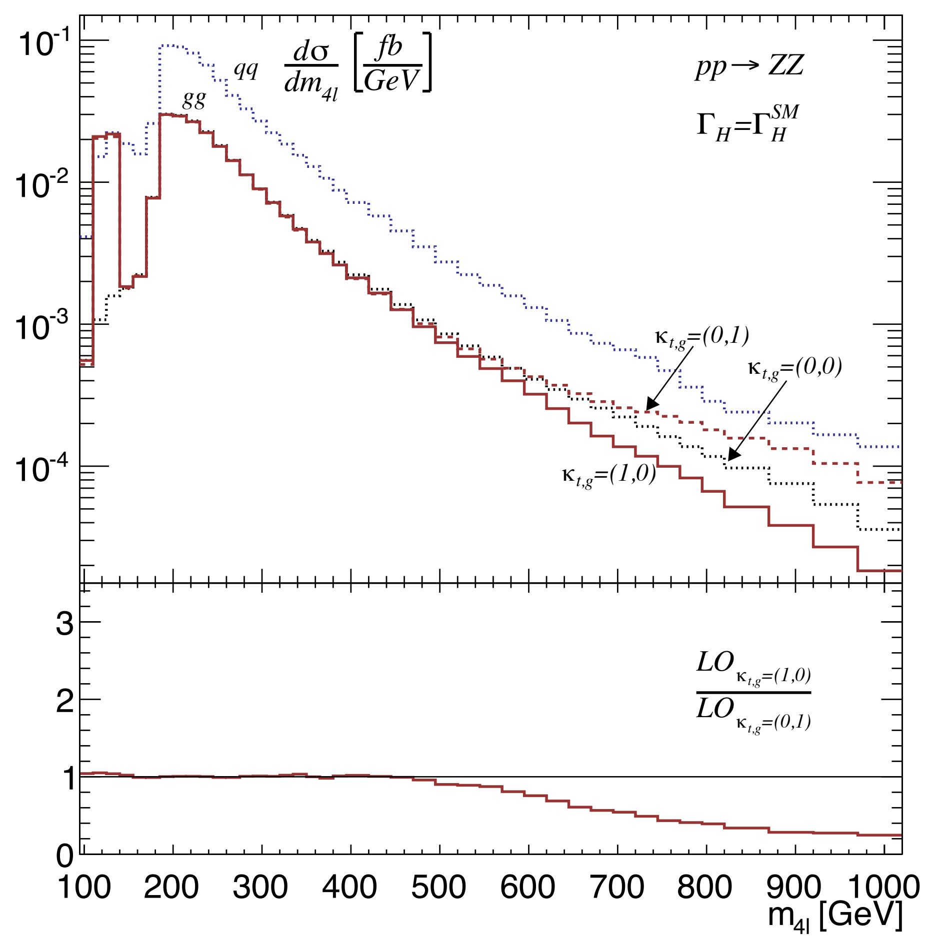
Gainer, Matchev, Mrenna, Park (2014)
Azatov, Grojean, Paul, Salvioni (2014)

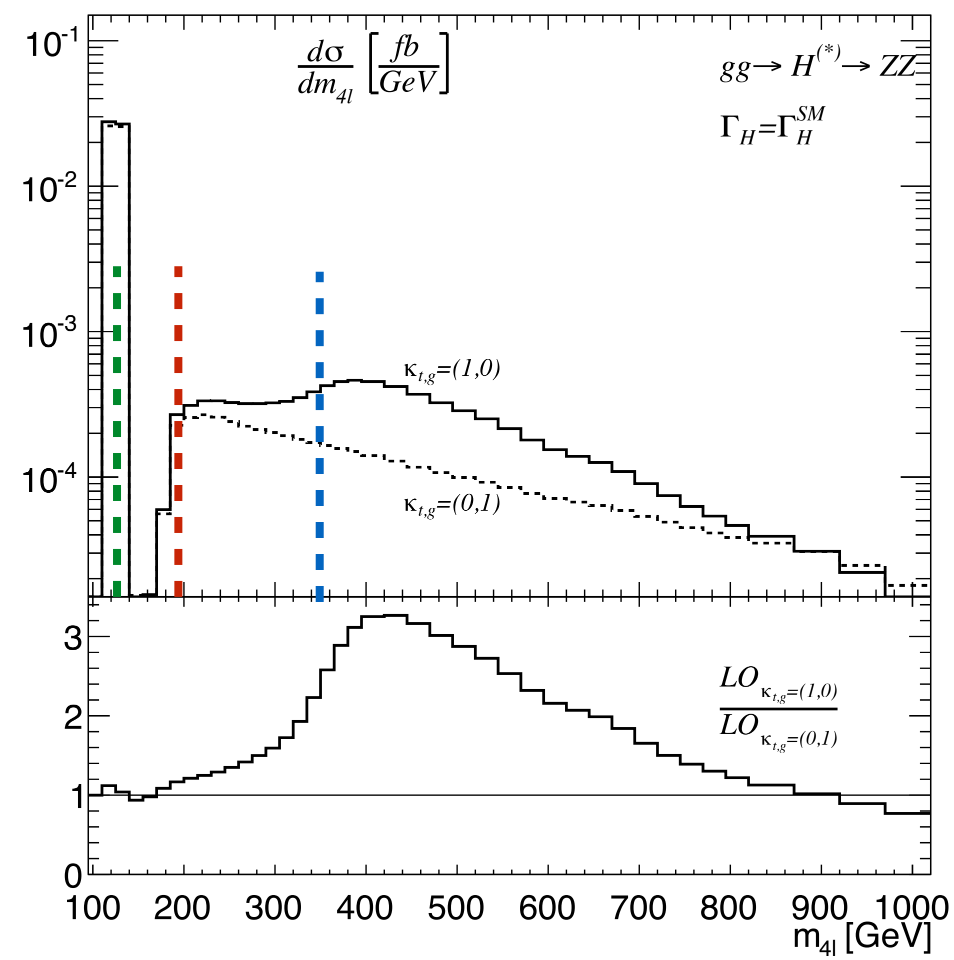
➡ On-Shell H → ZZ angles provide a better probe to the different decay couplings than off-shell measurement. More data and better kinematic sensitivity. Off-shell mostly probes energy growth

Off-Shell Higgs Production

- Carries information on the Higgs couplings at different energy scales





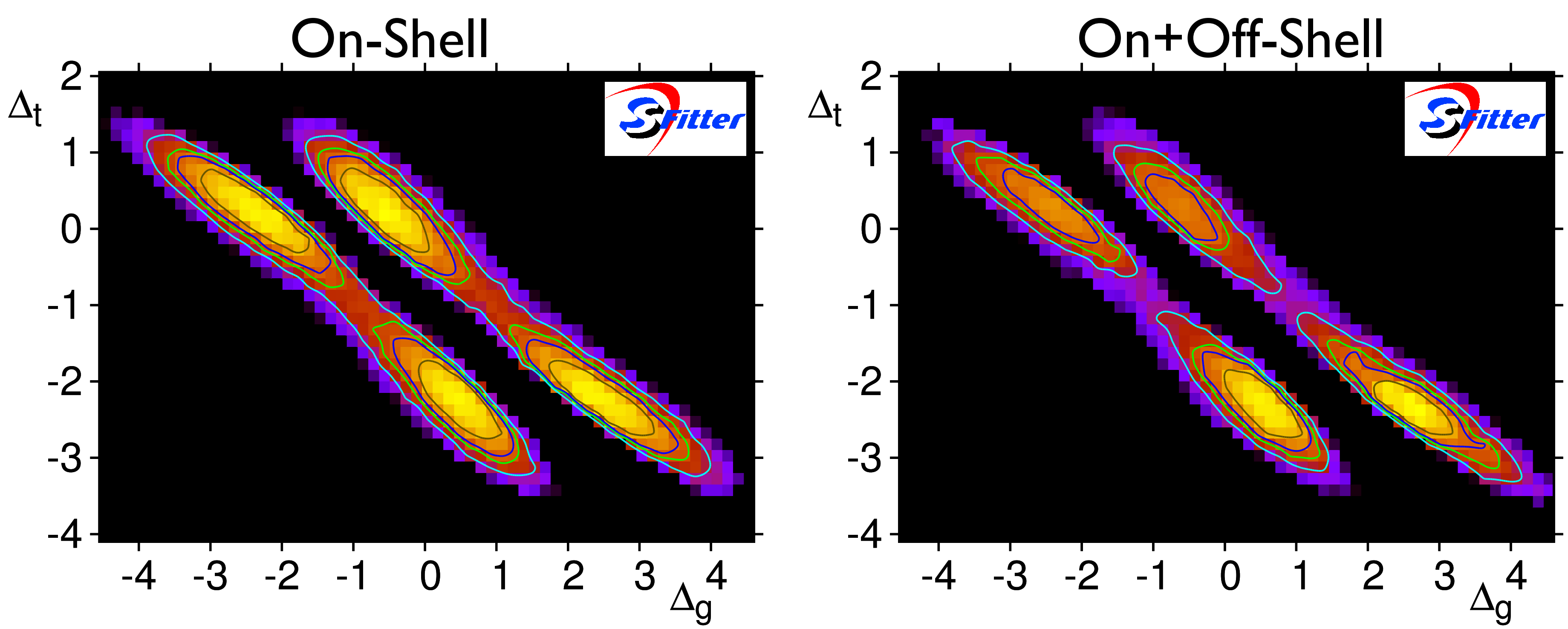


Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

Off-Shell Measurements: Sfitter results

- Full coupling fit to the ATLAS+CMS Run I data:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \, g m_W H \, W^\mu W_\mu + \Delta_Z \, \frac{g}{2c_w} m_Z H \, Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \, \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \, \frac{H}{v} \, G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \, \frac{H}{v} \, A_{\mu\nu} A^{\mu\nu}$$



→ The Run I CMS results present an excess of events in the off-shell tail

→ Atlas sees the opposite, however it has much less statistics for this measurement

→ This gives a slight preference to the negative solutions in the fit

Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

Higgs width measurement

- SM prediction $\Gamma_H \sim 4$MeV

→ Best limit from direct measurement $H \to ZZ$ $\Gamma_H < 3.4$ GeV

- New idea: combine on-shell & off-shell rates to break the ξ-degeneracy

$$\sigma^{\text{On-Shell}}_{i\to H\to f} \propto \frac{g_i^2(m_H) g_f^2(m_H)}{\Gamma_H}\,, \qquad g_{i,f}(m_H) = \xi g^{SM}_{i,f}(m_H)\,, \qquad \Gamma_H = \xi^4 \Gamma_H$$

→ Sub-leading dependence on Γ_H in the off-shell regime

$$\sigma^{\text{Off-Shell}}_{i\to H^*\to f} \propto g_i^2(\sqrt{\hat{s}}) g_f^2(\sqrt{\hat{s}})$$

Caola, Melnikov (2013)
Kauer, Passarino (2012)
Campbell, Ellis, Williams (2014)

- While interesting idea, it is not a model independent width measurement

Englert, Spannowsky (2014)
Englert, Soreq, Spannowsky (2014)

Higgs width measurement

- Model dependency ultimately reflect the non-trivial ggH momentum running

  This EFT is a prime example of it:

$$\sigma^{\text{On-Shell}}_{gg\to H\to ZZ} \propto (\kappa_t+\kappa_g)^2 \frac{g^2_{ggH}(m_H)\, g^2_{HZZ}(m_H)}{\Gamma_H}$$

→ k_t & k_g factorize

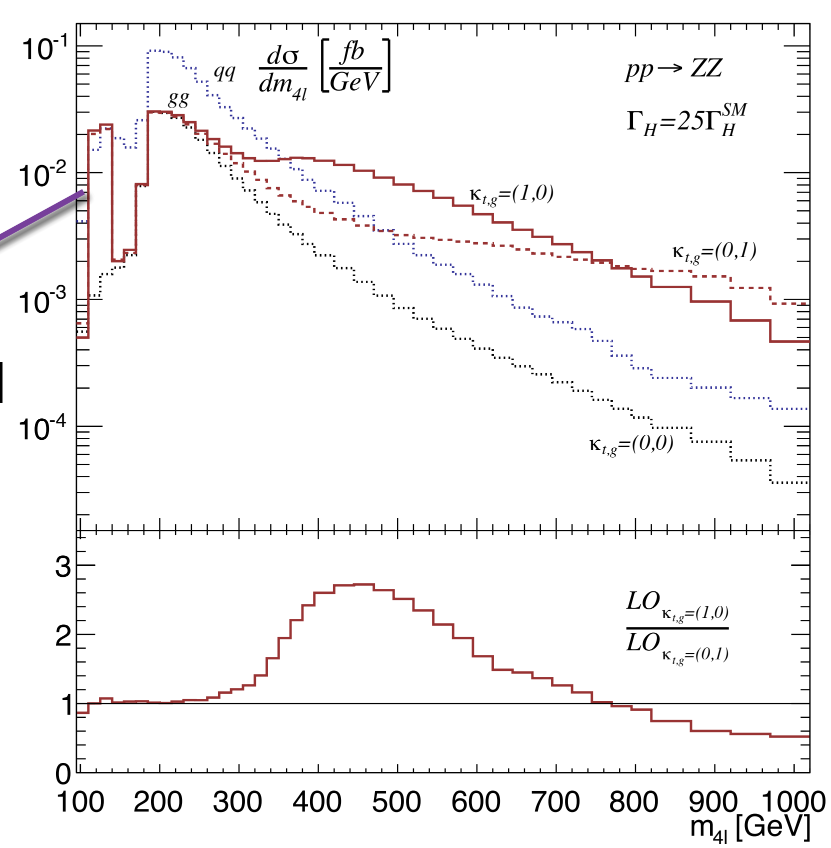
$$\sigma^{\text{Off-Shell}}_{gg\to H^*\to ZZ} \propto \left(k_t g_{ggH}(m_{4\ell}) + k_g g_{ggH}(m_H)\right)^2 g^2_{HZZ}(m_{4\ell})$$

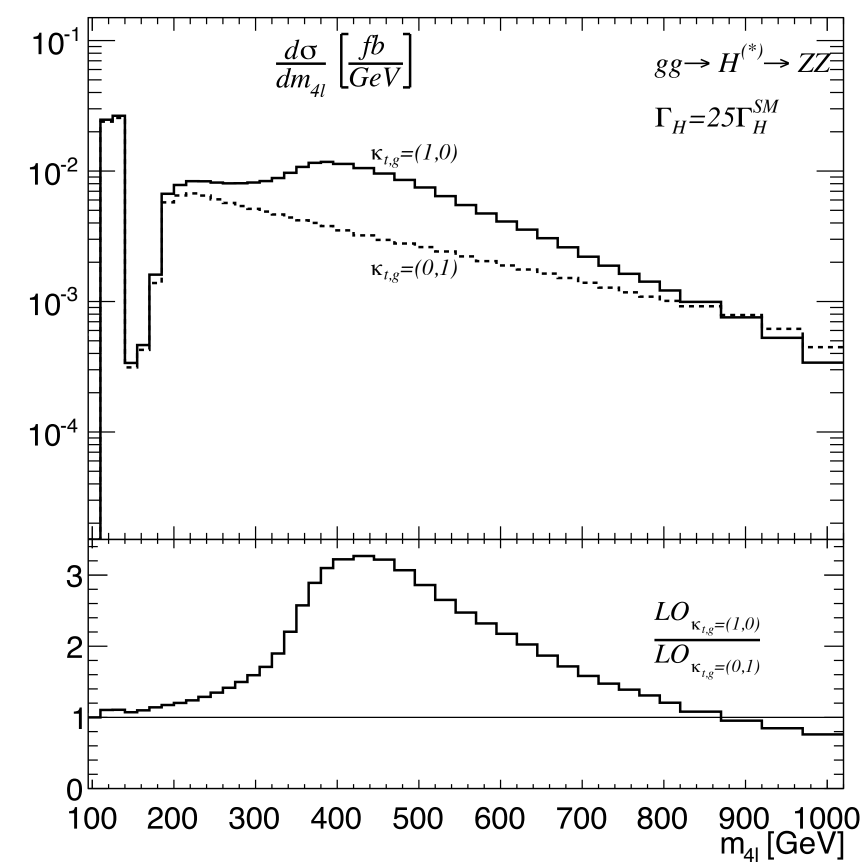
→ non-trivial k_t & k_g dependence

- Example: $\xi^4 = 25 \quad \to \quad \Gamma_H = 25\Gamma_H^{SM}$

Signal strength still

μon-shell = 1



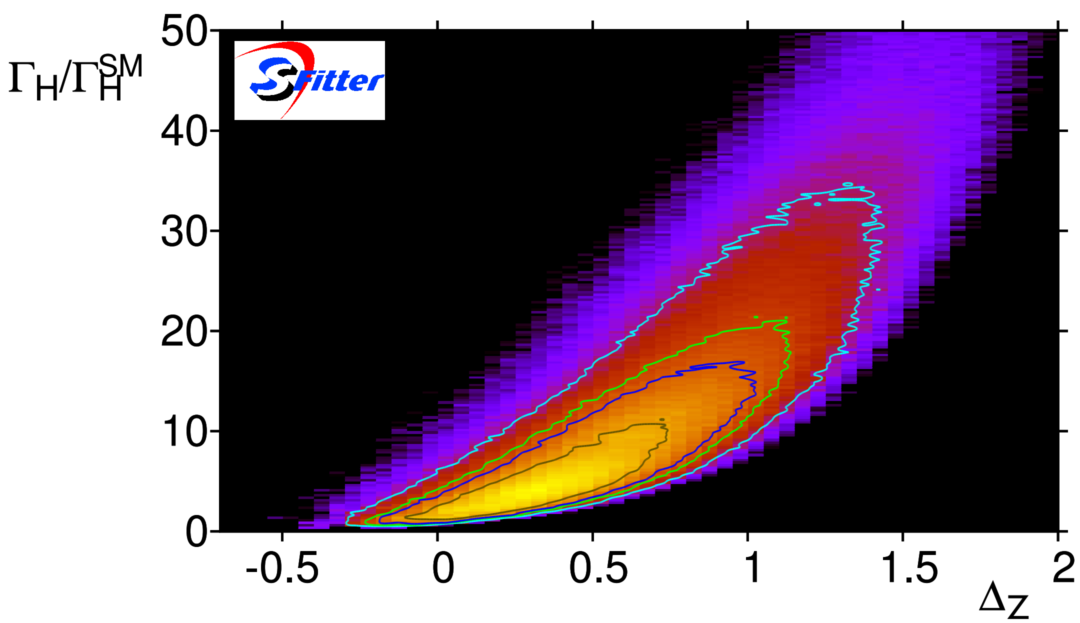


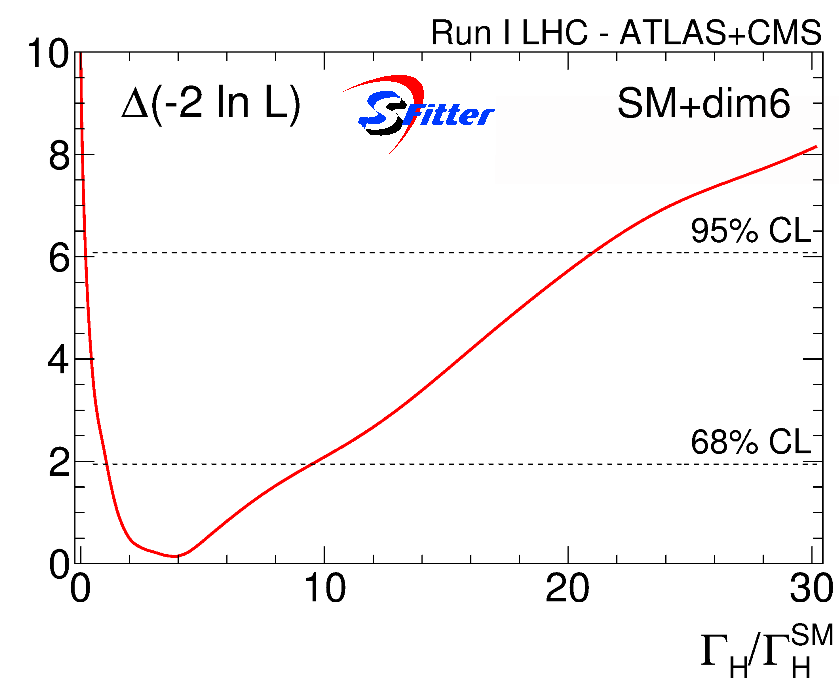
Higgs width measurement

- Leaving the Higgs width as a free parameter in the SFitter setup:

➡ Total width measurement - combination of Off+On-Shell measurements. But now accounting for the full m_{4l} profile

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + {\rm h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible decays} + \text{unobservable decays}$$





Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

➡ For $\Gamma_H/\Gamma^{SM} \gg 1$ Higgs production and decay rates scale like $g_X{}^4/\Gamma_H$

As expected, for $\Gamma_H/\Gamma^{SM} \sim 30 \sim 2.3^4$ we have $\Delta Z \sim 1.3$

Higgs width measurement

- Leaving the Higgs width as a free parameter in the SFitter setup:

→ Total width measurement - combination of Off+On-Shell measurements. But now accounting for the full m_{4l} profile

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
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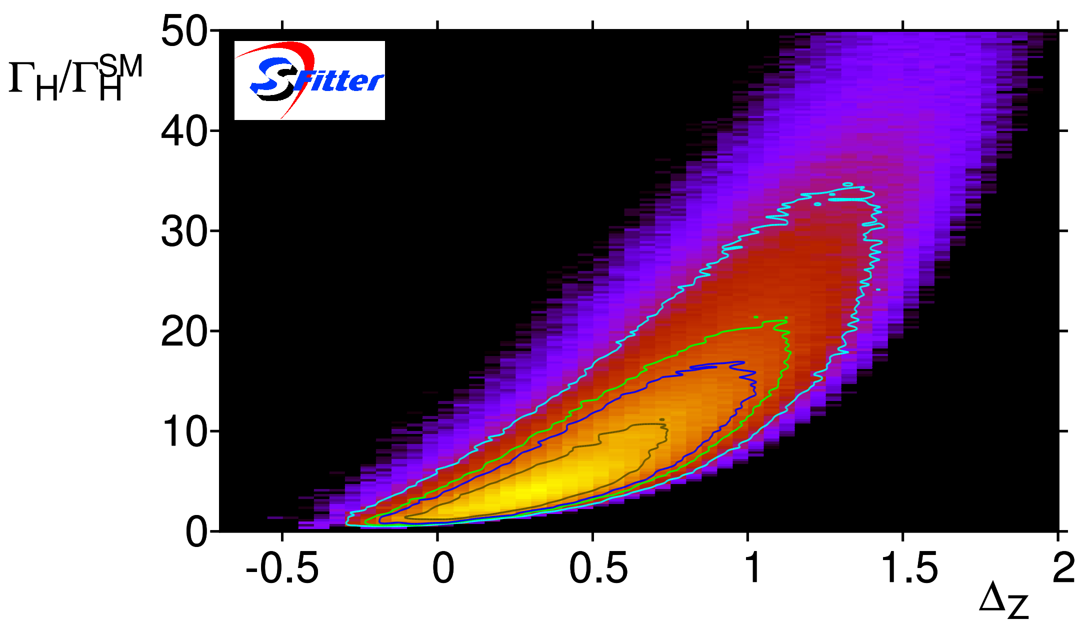
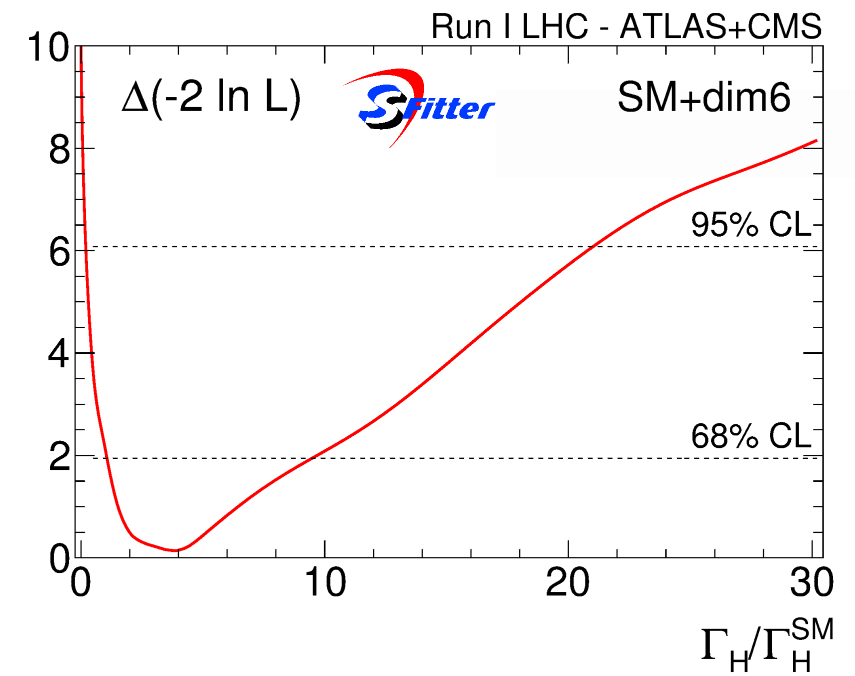




→ $\Gamma_H < 9.3\Gamma^{SM}$ at 68% CL. While this width constraint was obtained considering possible BSM operators, the bound is still competitive to other analysis that account only to SM-like interactions

→ Key ingredient: full m_{4l} profile

Corbett, Eboli, DG, Gonzalez-Fraile, Plehn, Rauch (2015)

Loop induced Processes

- Until very recently, loop induced processes have been overlooked in the literature
- Many interesting processes are loop-induced:

  $pp \rightarrow H$+jets (HEFT fails for $p_T > m_t$)

  $pp \rightarrow HH$+jets (HEFT fails spectacularly)

  $pp \rightarrow VV$+jets (Off-shell Higgs production and background)

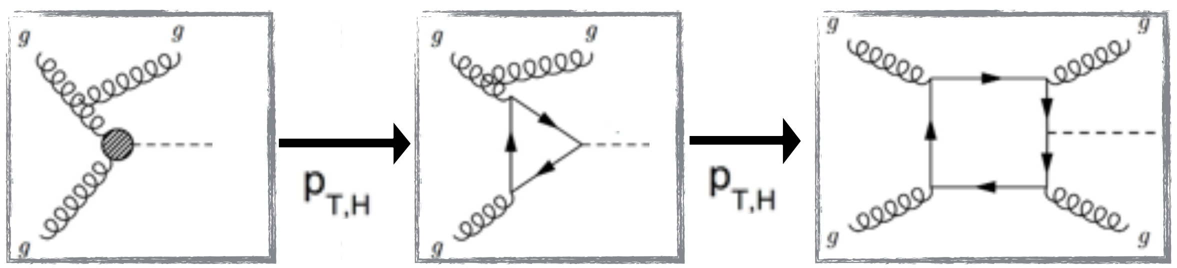
  $pp \rightarrow HZ$+jets for $p_T > m_t$

  …

- Now, all the above processes can be obtained via, for instance, MCFM, SHERPA+OpenLoops, MadGraph5…
- However, most of these are only known at LO
  We urge their higher order corrections to reduce theoretical uncertainties!

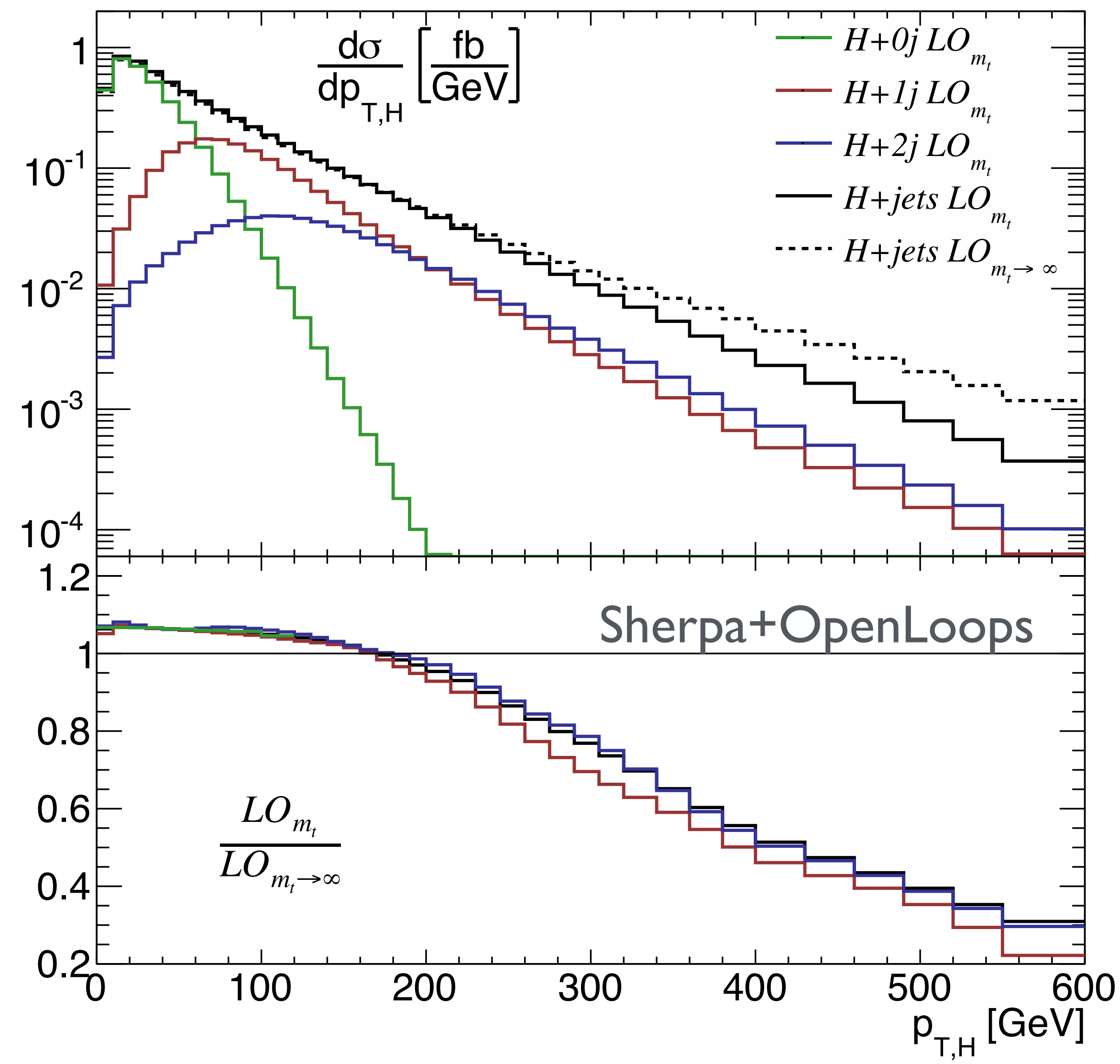
Loop induced: H+jets

- H+jets CKKW merging



➡ How many jets do we need to account for?

As many as we can add!



Buschmann, DG, Krauss, Kuttimalai, Schonherr, Plehn (2014)

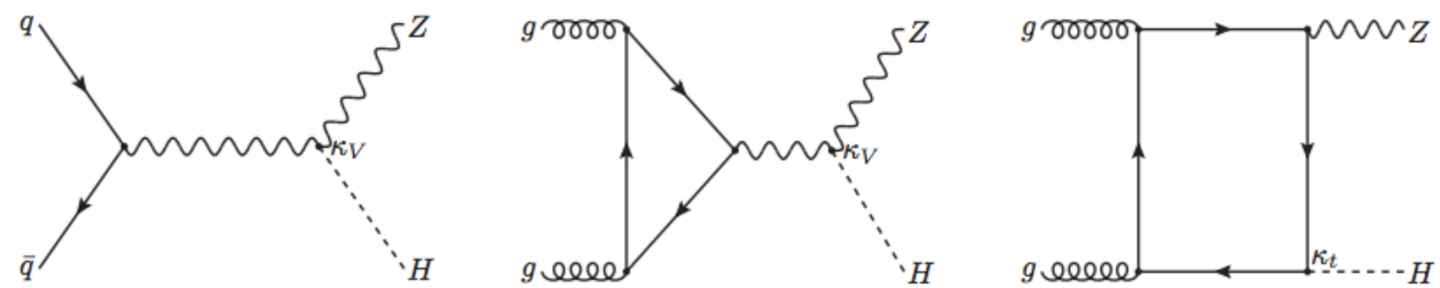
➡ Top mass effects fundamental for boosted H: correction of O(4) at p_{TH}~600 GeV

➡ Each jet multiplicity has approximately same top mass correction

➡ Consequently the same happens for the merged results

Loop induced: ZH

- Higgs-Strahlung: Z(ll)H(inv) & Z(ll)H(bb)



@LO~O(α_{EW}^2)　　　　@LO~O($\alpha_s^2\alpha_{EW}^2$)

- There are four major factors that guarantee GF larger than the anticipated naive $\alpha_s^2 \approx 1\%$

➡ Larger gluon PDF

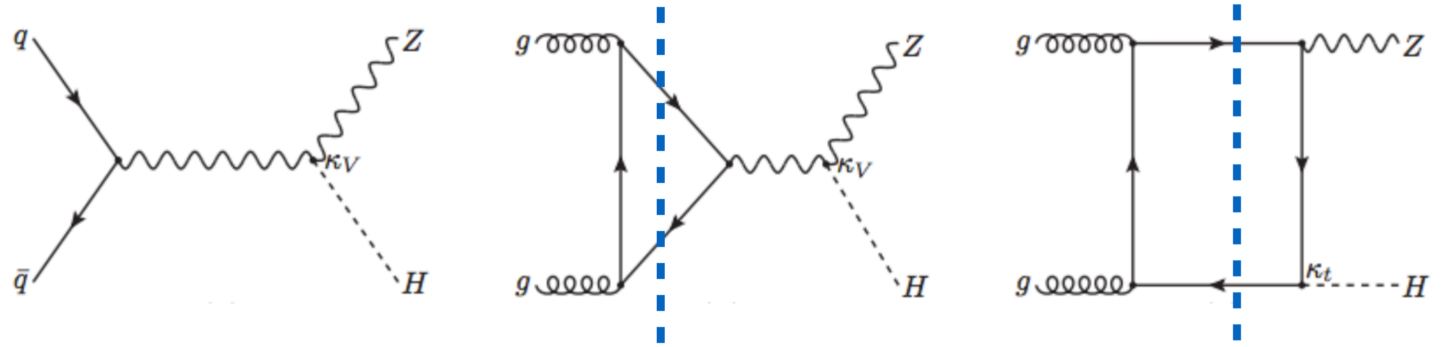
➡ Larger initial state colour factor

➡ Top Yukawa coupling appears in the place α_{EW} factors: $y_t \sim O(1)$

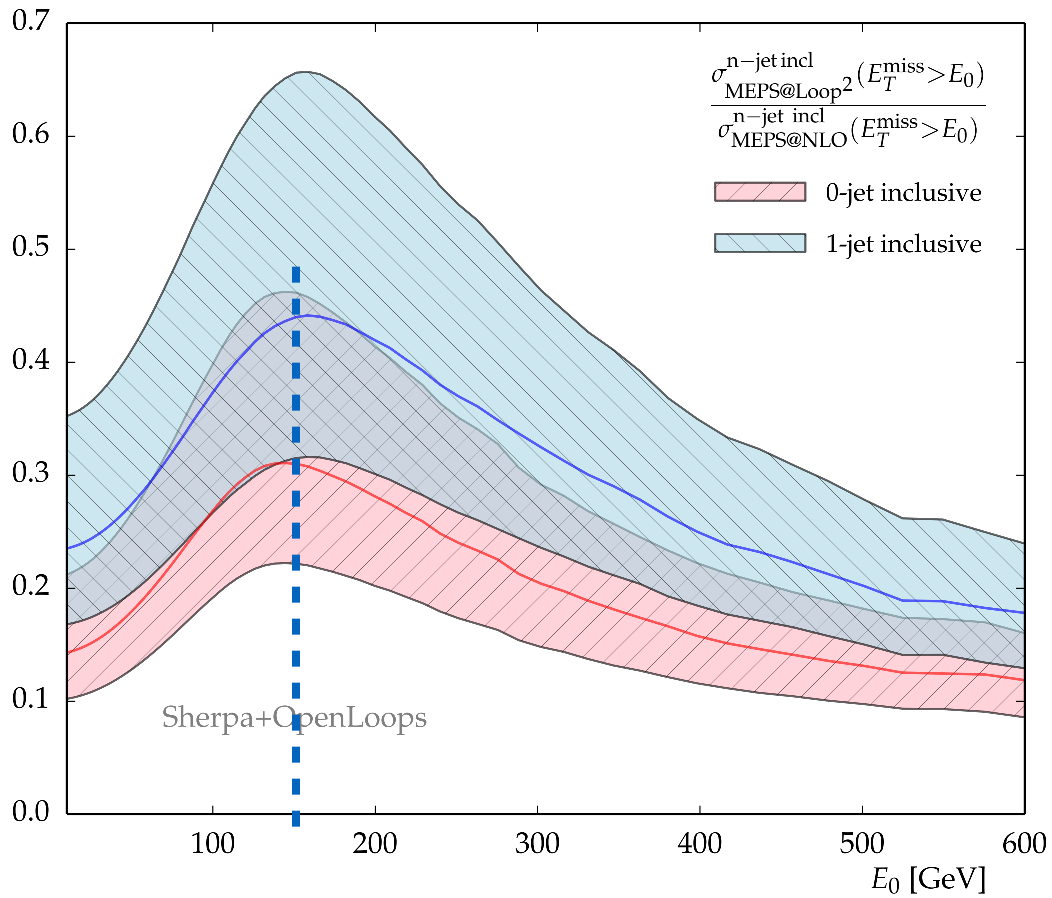
➡ Threshold enhancement at $m_{ZH} \sim 2m_t$, which gives rise to relevant rates at the boosted regime $p_{TH} \sim m_t$

Loop induced: ZH

- Higgs-Strahlung: Z(ll)H(inv) & Z(ll)H(bb)



- Boosted kinematics enhances loop-induced component



DG, Krauss, Kuttimalai, Maierhoefer (2015)

Most of Run I LHC analysis neglect this component

Note that this might change:

→ The invisible bounds from Z(ll)H(inv)

→ And y_b from Z(ll)H(bb)

Altenkamp, Dittmaier, Harlander, Rzehak, Zirke (2013)

Brein, Harlander, Wiesemann, Zirke (2011)

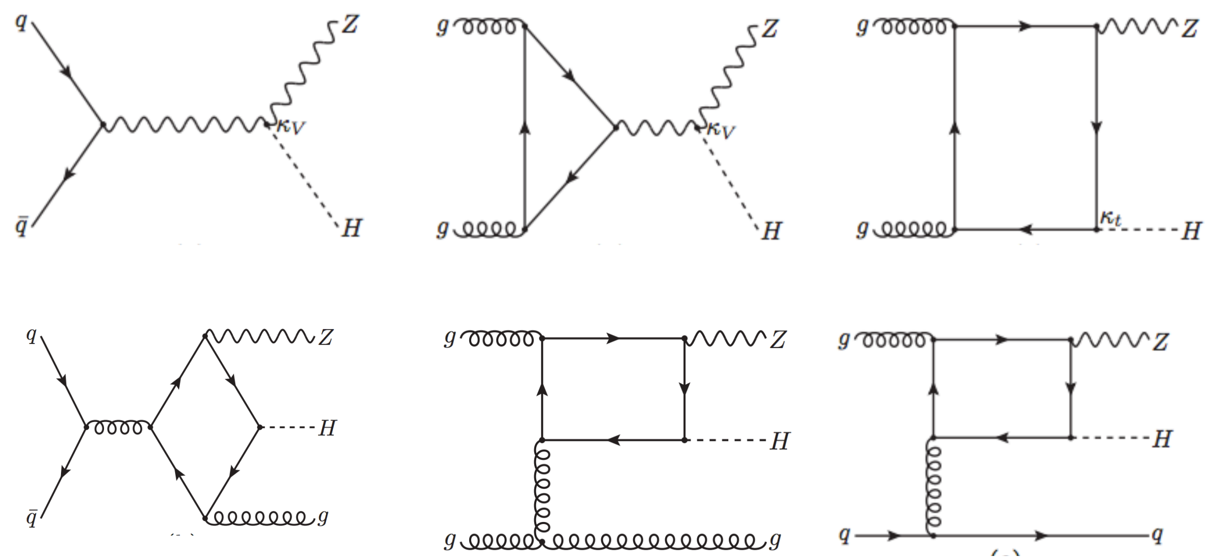
Englert, McCullough, Spannowsky (2014)

Hespel, Maltoni, Vryonidou (2015)

Ferrera, Grazzini, Tramontano (2014)

ZH Boosting Coupling Constraints

- DY+Loop-induced contributions access the size and sign of y_t:

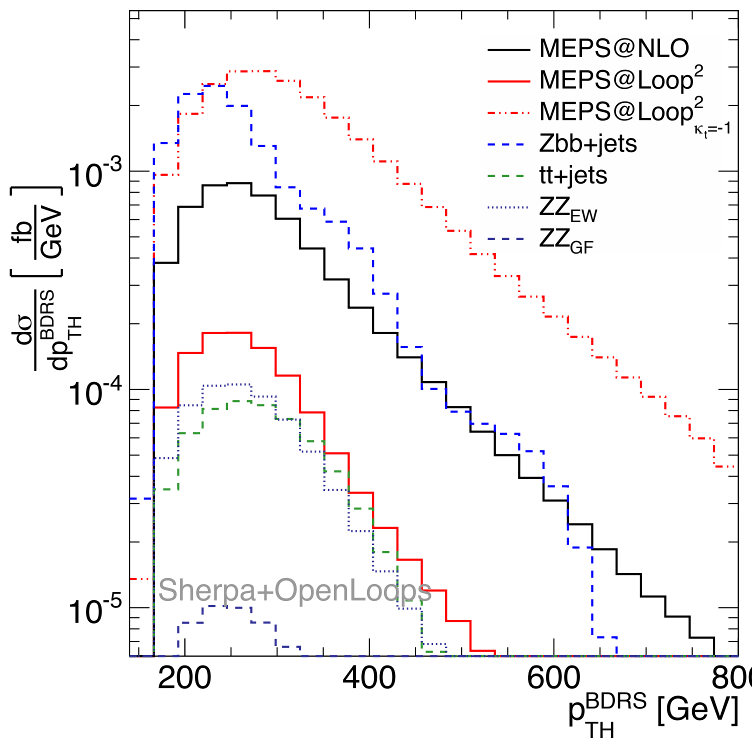


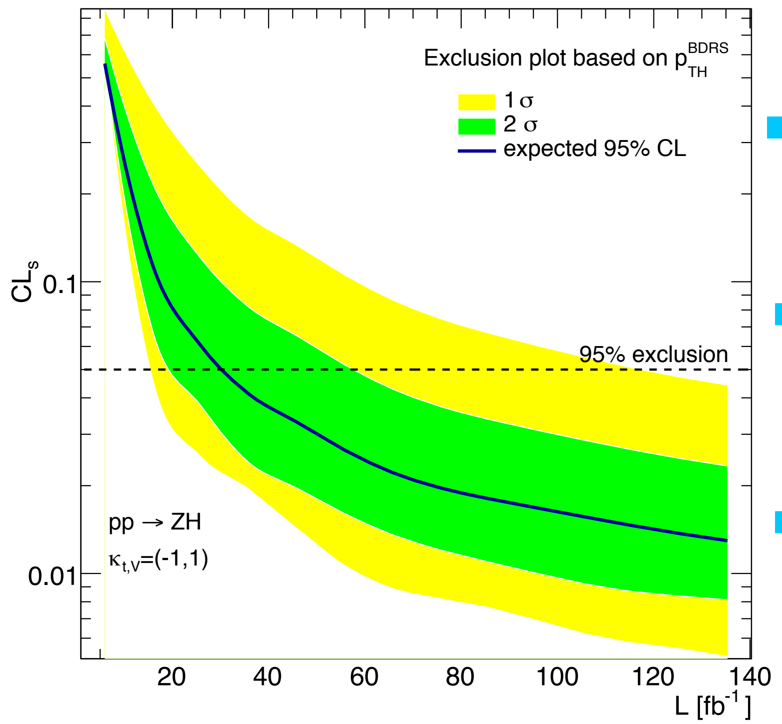
$$\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_V \mathcal{M}_V$$

$$\frac{d\sigma}{dp_{TH}} = \kappa_t^2 \frac{d\sigma_{tt}}{dp_{TH}} + \kappa_t \kappa_V \frac{d\sigma_{tV}}{dp_{TH}} + \kappa_V^2 \frac{d\sigma_{VV}}{dp_{TH}}$$

sign

Good to break the degeneracies in the coupling fits

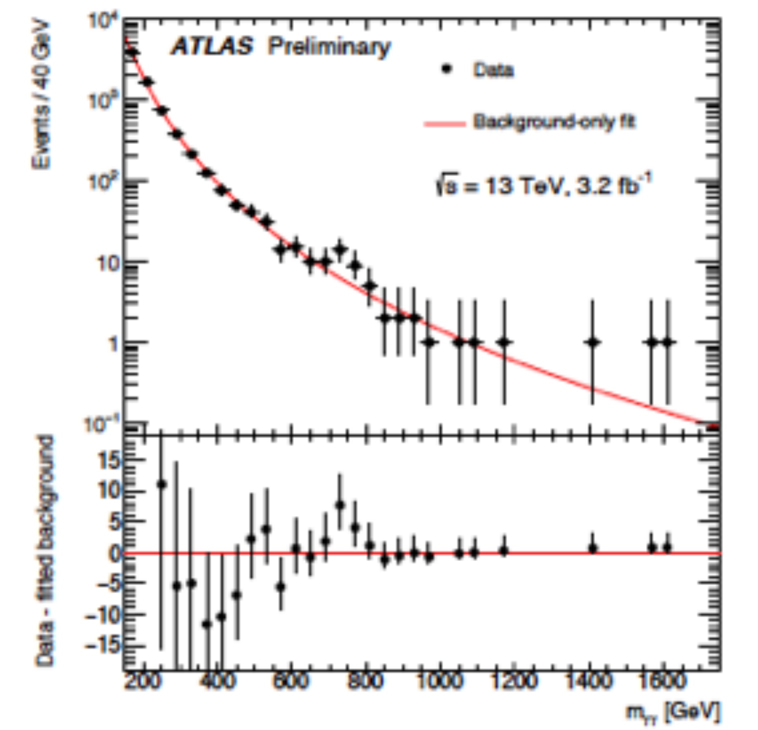




- Benefits from σ_{tV} that presents destructive interference in the full p_T distribution
- Conservative systematic uncertainty of 50% to GF (unknown higher order corrections)
- BSM hypothesis excluded with ~30 fb^{-1} of data

Englert, McCullough, Spannowsky (2014)
DG, Krauss, Kuttimalai, Maierhoefer (2015)

New physics might be around the corner!

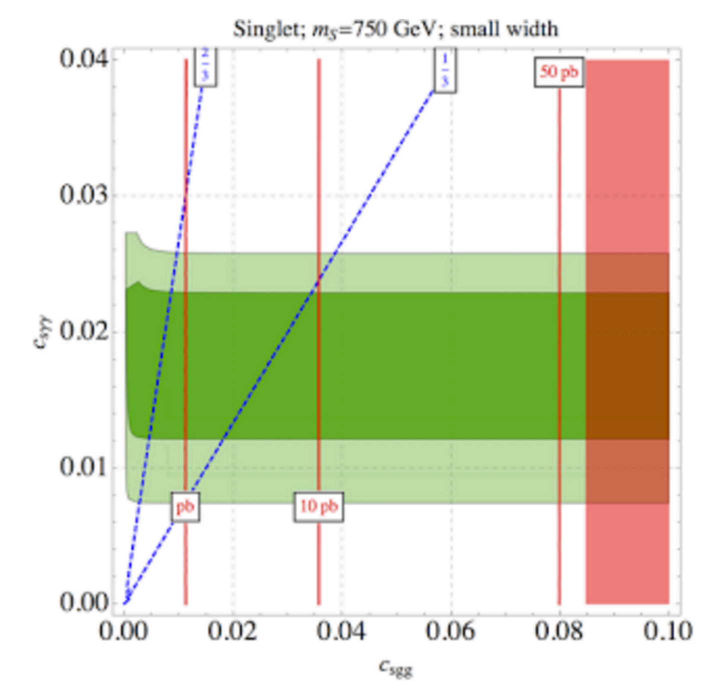


- Local significance: 3.6 sigma ATLAS; 2.6 sigma CMS
  One cannot claim discovery but it is significant

  If the resonance that we see at 750 GeV
  is confirmed we need another approach

- The simplest toy model needs couplings to gluons and photons. This we know very well how to do:

$$\mathcal{L}_{S,\text{eff}} = \frac{e^2}{4v} c_{s\gamma\gamma} S A_{\mu\nu} A_{\mu\nu} + \frac{g_s^2}{4v} c_{sgg} S G^a_{\mu\nu} G^a_{\mu\nu}$$



Important to check other decay channels:
ATLAS claims that the best fit is obtained for a wider width extra decays to SM particles and/or new hidden sector.
For more details see Ben's slides from yesterday

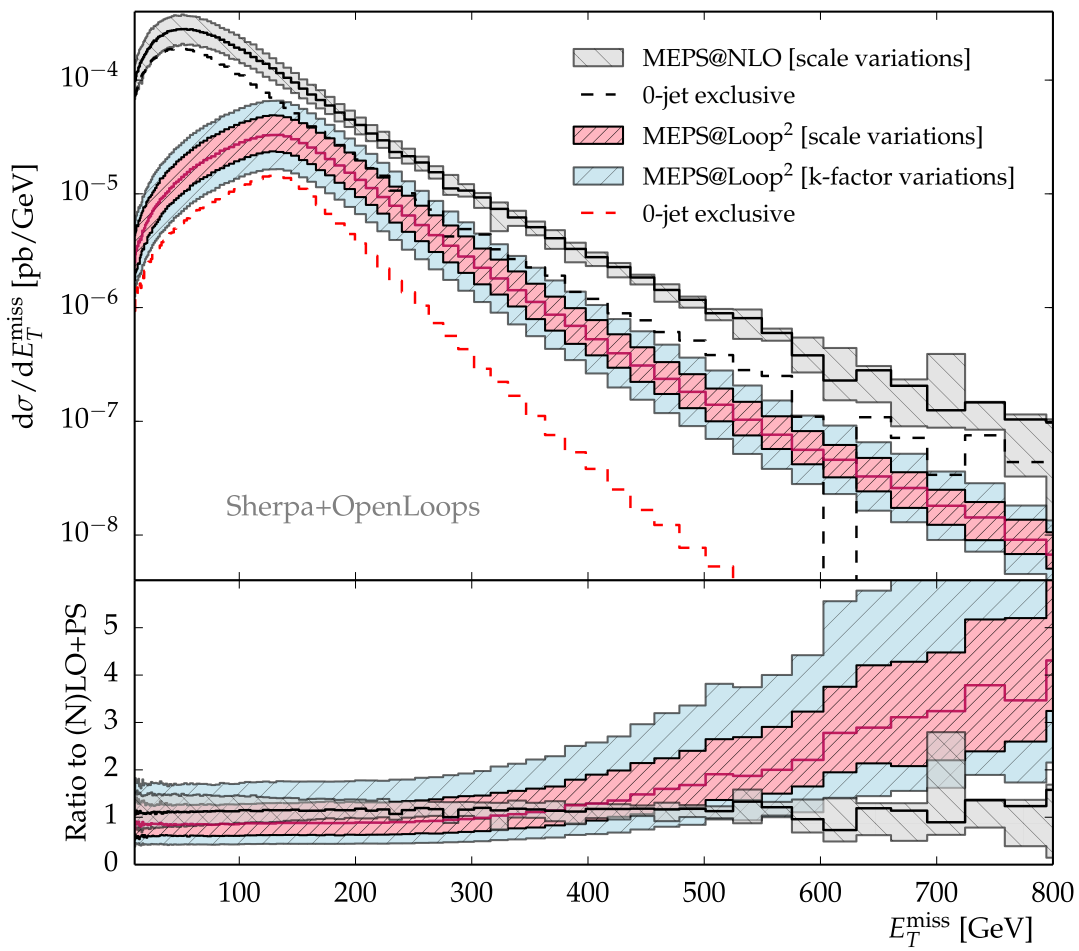
- We might have to start all over again: spin, CP, coupling…

Summary

- LHC Run II will give very energetic Higgses with significant statistics
- Off-shell, boosted (H+jets, HZ+jets…) will be very important to further explore TeV scale
- We should go beyond the total rate information. Distribution profiles significantly improve our constraints and should be added to the coupling fits via EFT framework
- Watch out the loop induced process. They might be not as small as you think

Backup slides

- DY does not feature threshold enhancement but rather show the typical s-channel suppression for large energies



➡ DY presents the typical 10-20% uncertainty

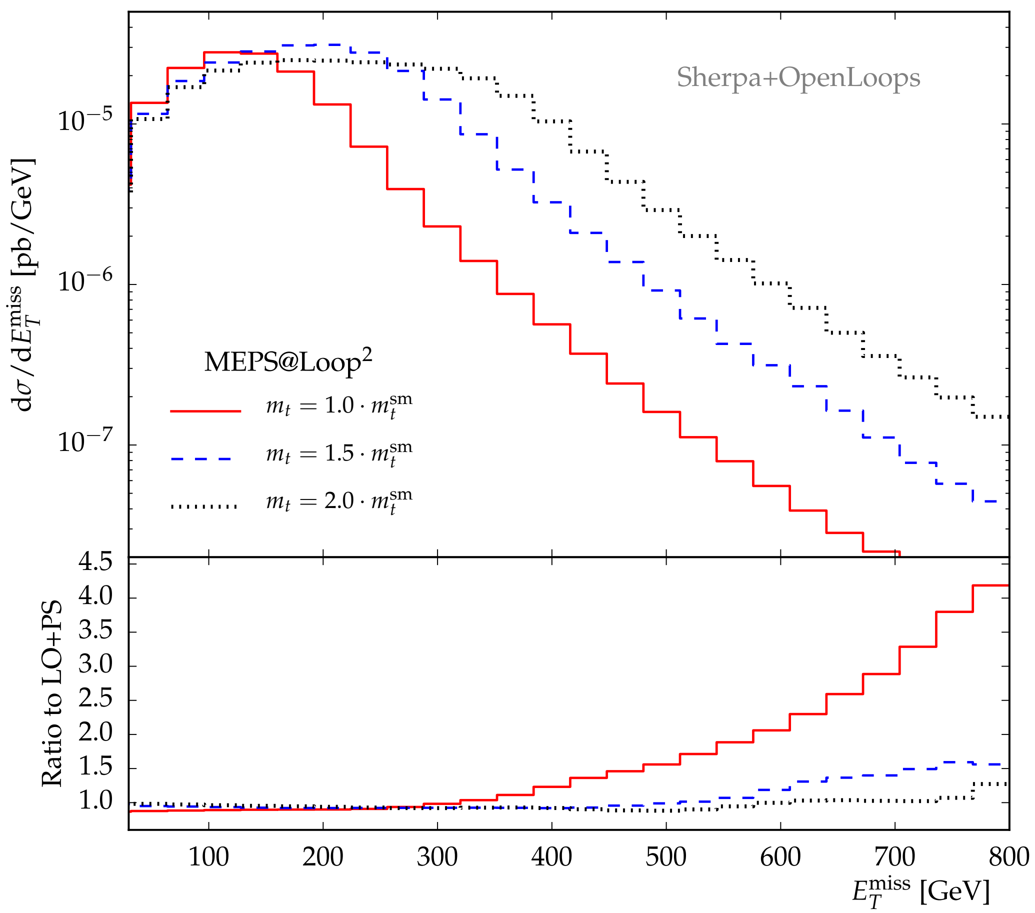
➡ GF presents O(30%) - Typical for merging at LO

➡ K-factor variation - translates into uncertainty, twice as large as the effect of the standard scale variation in the GF mode

➡ MEPS@NLO/MC@NLO~1 for MET distrib.

➡ Loop^2+PS significantly undershoots the merged result at the boosted regime

Backup slides



- Loop^2+PS significantly undershoots the merged result at the boosted regime
- Larger m_t pushes effect to higher energies
  Similar to the H+jets case (HEFT vs Full)
- Effects induced by higher jet multiplicity ME beyond the scope of conventional PS alone
- Multijet merging correctly fill these phase space regions

- As the GF becomes a significant player in the boosted regimes a proper modelling is of vital importance