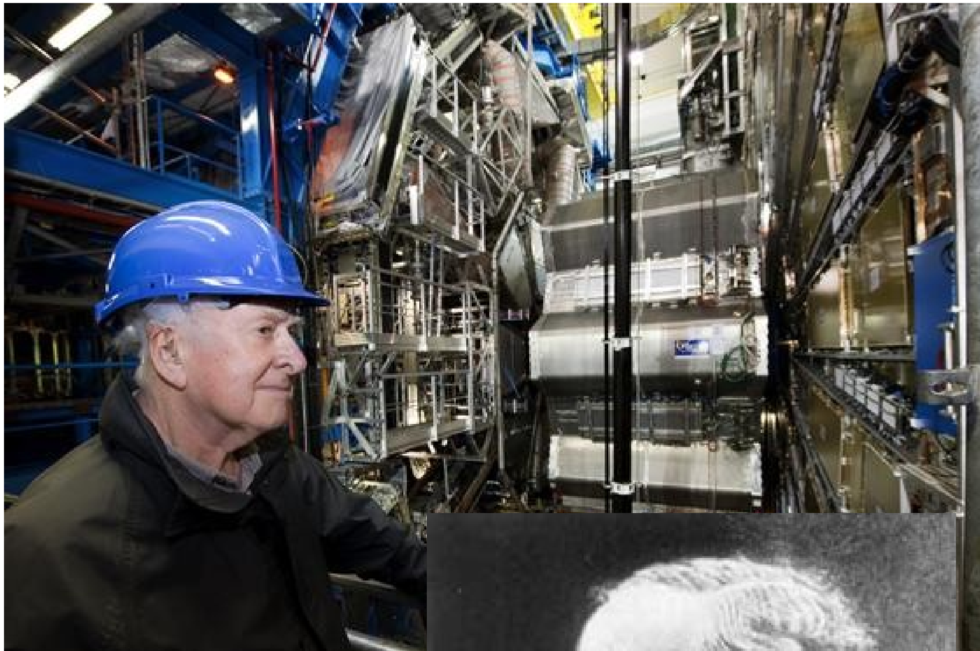
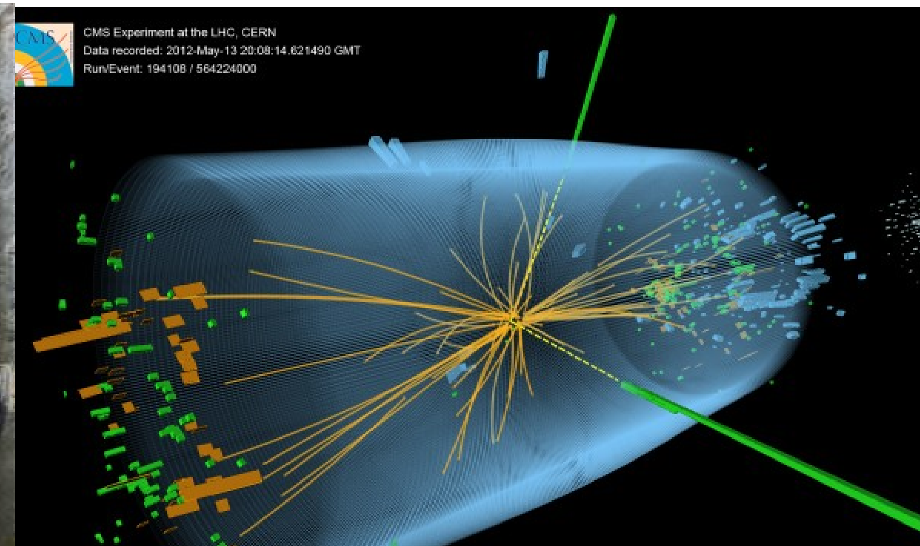
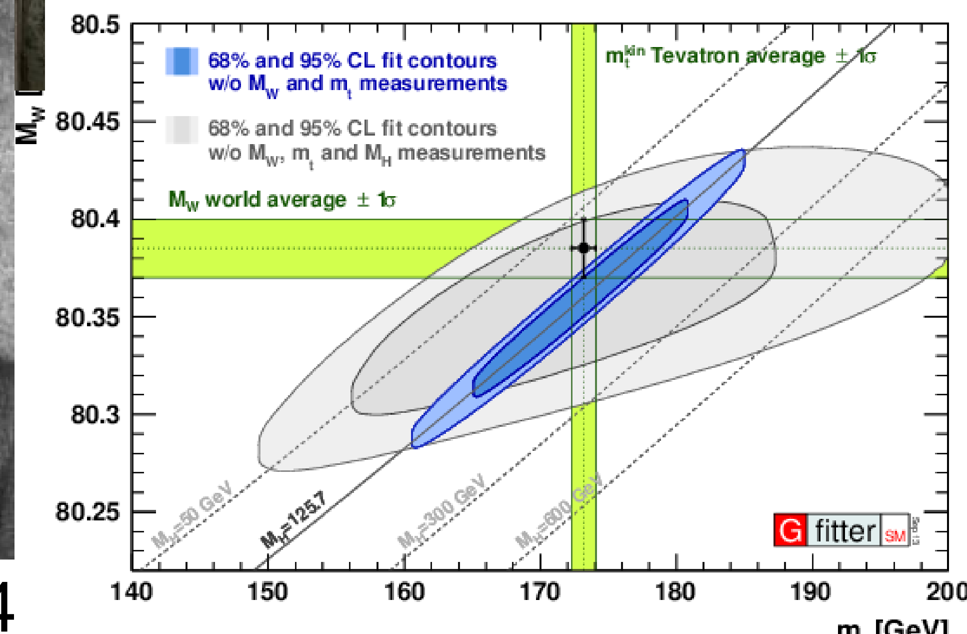
News from the Higgs-Boson and Electroweak Fits







Klaus Mönig

DESY

Maxwell Higgs workshop 2014

Introduction

- The Standard Model of Electroweak Interactions is a closed theory that is valid on loop level
- It is therefore important to verify the consistency of the theory on this level
- In the theory masses are generated by the Brout-Englert-Higgs mechanism which requires in its simplest version one neutral scalar particle
- However we still need to find out
  - Is the mechanism realised in its simplest form?
  - Is the Higgs mechanism a low energy limit of a more complicated theory?
- Since the Higgs influences the precision electroweak data this question is answered by direct Higgs measurements but also by the electroweak fits

Electroweak fits

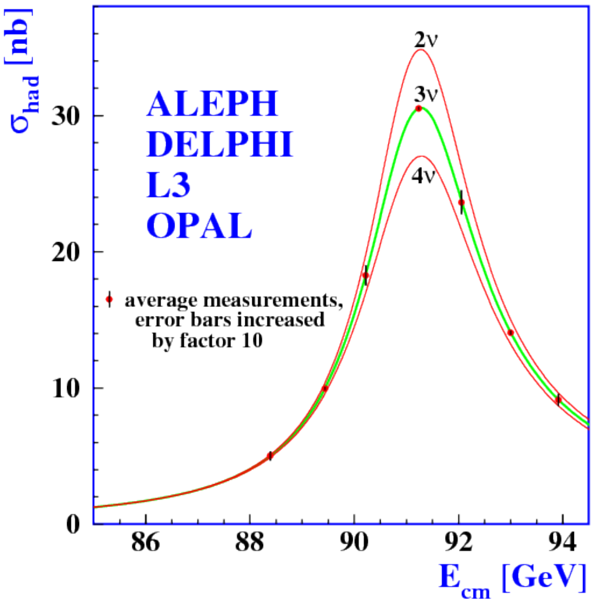
- Idea of electroweak fits:
  - Observables receive loop corrections from unseen effects
  - If the system is overconstrained one can fit for unknown parameters or test the model for consistency
  - If precision is better than typical loop factor ($\alpha \approx 1/137$) one can test the model or try to obtain information on new physics in loops (like old m_H fit)

The Data

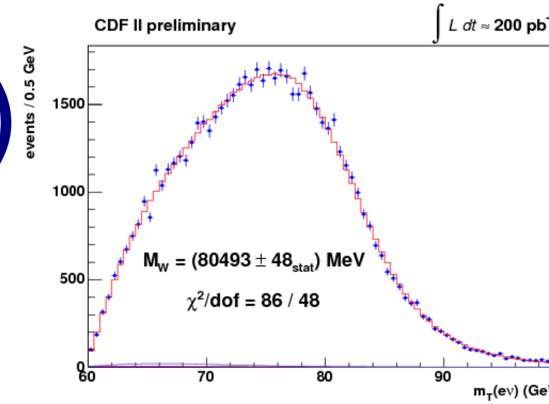
- On tree level need three parameters to define electroweak coupling sector

  ⇨ use the most precise: $\alpha(\Delta\alpha/\alpha=3\cdot10^{-9})$, $G_F(\Delta G_F/G_F=5\cdot10^{-7})$, $m_Z(\Delta m_Z/m_Z=2\cdot10^{-5})$
- Electroweak precision data to overconstrain the system: Z (partial) widths from LEP, $\sin^2\theta$ from LEP& SLD, m_W from LEP& Tevatron
- Fixing the loops: m_t from Tevatron, m_H from LHC
- Running of α from low energy e^+e^- and theory
- Other low energy data play only a minor role

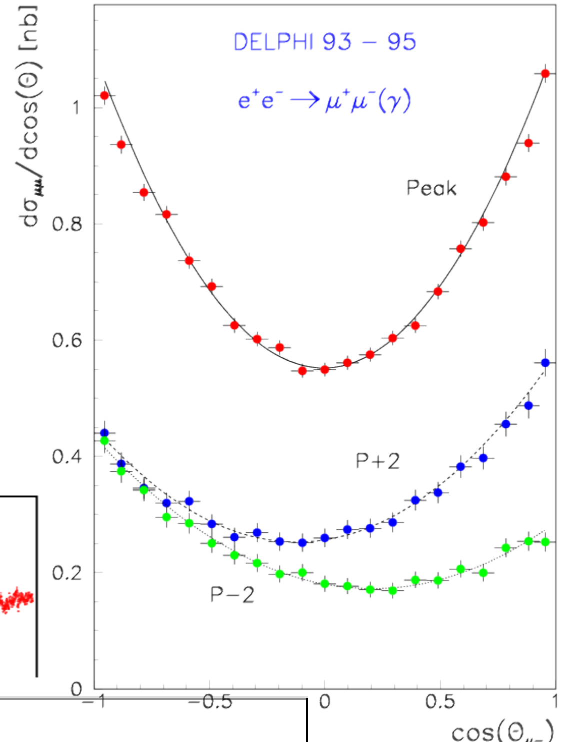
The Data (II)



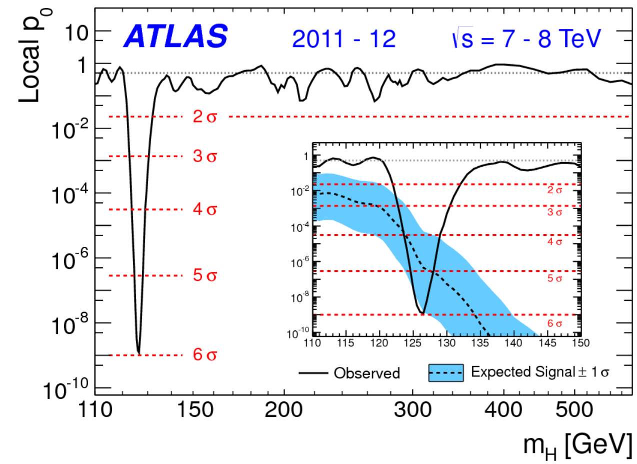
σ_{had} [nb]
ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements, error bars increased by factor 10
E_{cm} [GeV]



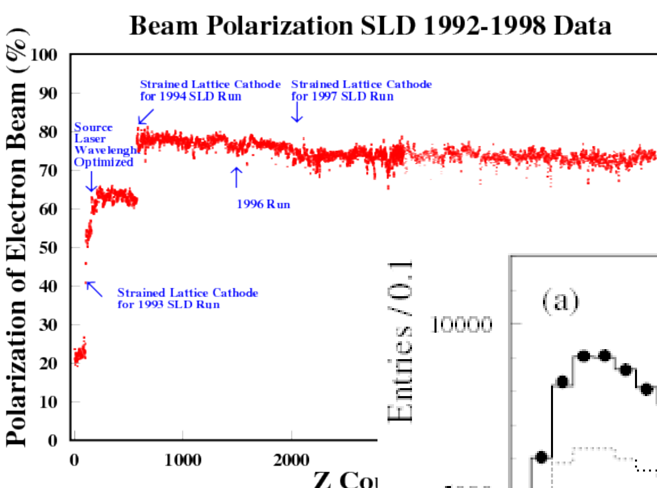
CDF II preliminary
$\int L\,dt \approx 200\ pb^{-1}$
events / 0.5 GeV
$M_W = (80493 \pm 48_{stat})$ MeV
χ^2/dof = 86 / 48
$m_T(e\nu)$ (GeV)



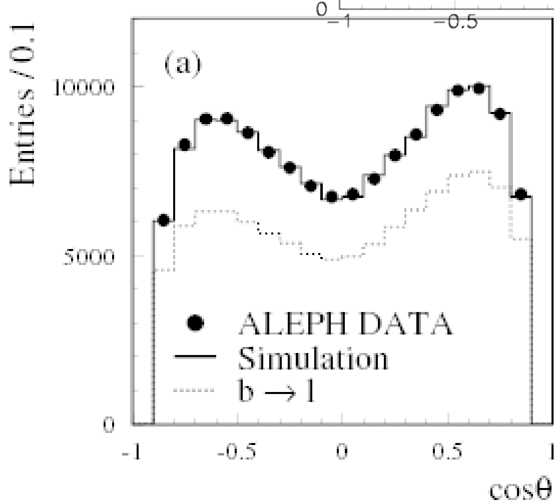
DELPHI 93 – 95
$e^+e^- \to \mu^+\mu^-(\gamma)$
$d\sigma_{\mu\mu}/d\cos(\Theta)$ [nb]
Peak
P+2
P−2
$\cos(\Theta_{\mu^-})$



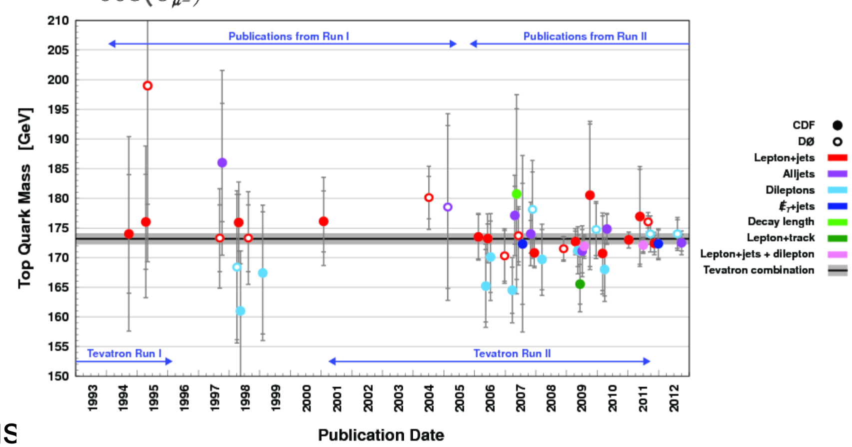
ATLAS
2011 - 12
$\sqrt{s}$ = 7 - 8 TeV
Local p_0
2 σ
3 σ
4 σ
5 σ
6 σ
Observed
Expected Signal ± 1 σ
m_H [GeV]



Beam Polarization SLD 1992-1998 Data
Polarization of Electron Beam (%)
Strained Lattice Cathode for 1994 SLD Run
Strained Lattice Cathode for 1997 SLD Run
Source Laser Wavelength Optimized
1996 Run
Strained Lattice Cathode for 1993 SLD Run

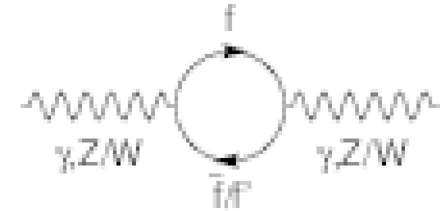


(a)
Entries / 0.1
ALEPH DATA
Simulation
b → l
cosθ



Publications from Run I
Publications from Run II
Top Quark Mass [GeV]
Tevatron Run I
Tevatron Run II
Publication Date
CDF
DØ
Lepton+jets
Alljets
Dileptons
$\not{E}_T$+jets
Decay length
Lepton+track
Lepton+jets + dilepton
Tevatron combination

The Theory



- m_W and $\sin^2\theta_{eff}$ are calculated at 2-loop
- Z partial widths leading 2-loop terms are available
- Z-pole observables and m_W can be parametrised with three form factors:
  - $g_A = \sqrt{1+\Delta\rho} I_3$ (normalisation of Z-widths)
  - $\sin^2\theta_{\text{eff}} = (1+\Delta\kappa)\sin^2\theta$ (g_v/g_a from Z-asymmetries)
  - $m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$
- All form factors factors depend on m_t^2 from weak isospin breaking and on $\log(m_H)$

Fit codes

- LEPEWWG and others used theory predictions from ZFITTER (D. Bardin et al.) in their fits
- TopaZ (G. Passarino) discontinued now but very important to validate ZFITTER
- GAP (J. Erler) used for PDG review
- Gfitter (M. Baak et al.) several publications in the last years
- Several codes extending the fits to BSM, especially SUSY
- The fits of the different groups agree very well and it's mostly personal preference which one is shown
- Some differences in treatment of theory errors which just start to matter

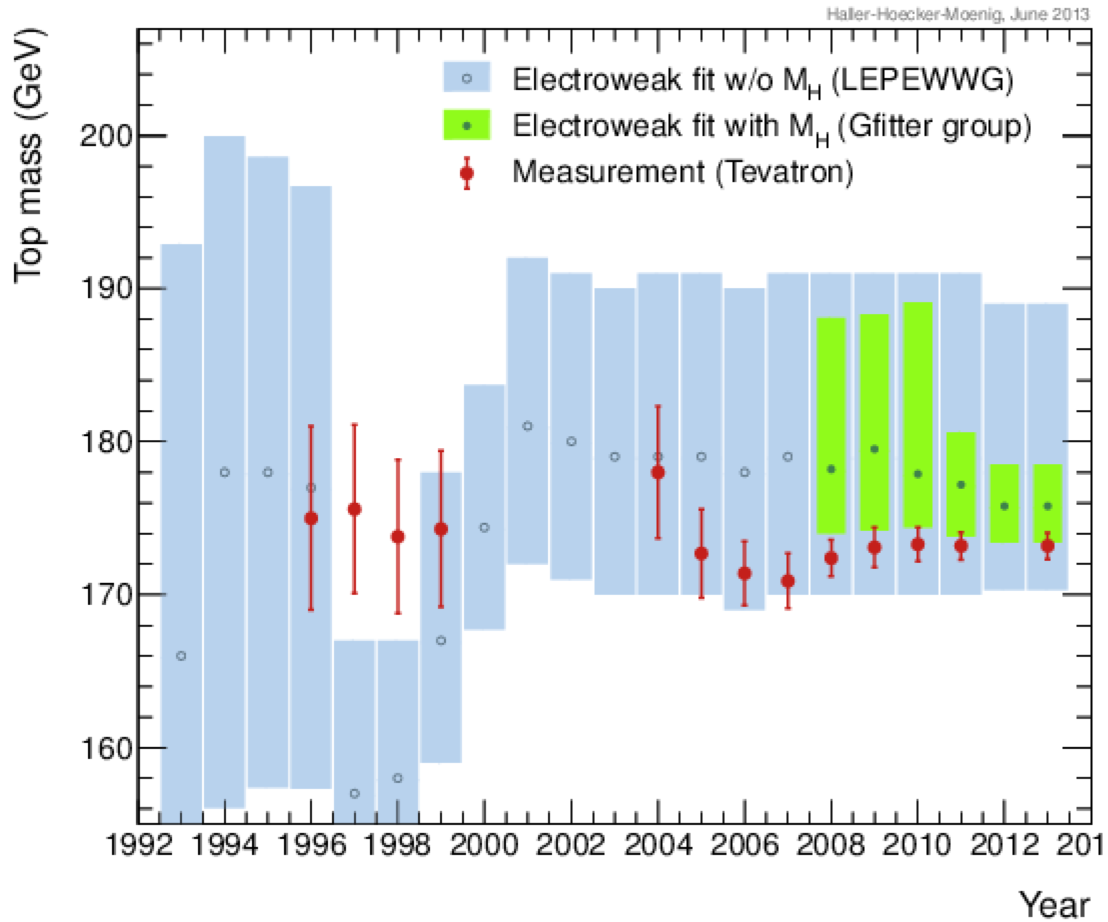
Recent News

- The Higgs was discovered ⇨ for the first time electroweak observables can be unambiguously predicted at loop level
- Final publication of LEP2 results (arXiv:1302.3415) (Small change to “preliminary” W-mass)
- Small update on m_t (Tevatron)
- Fermionic electroweak 2-loop calculation on Γ_f (A. Freitas, arXiv:1401.2447)
  - Very small effect, can be safely ignored in the fits
  - However there was an intermediate wrong R_b result which claimed a shift much larger than the estimated theory error
  - This triggered the statement by some groups that e.g. the error on the STU parameters are much larger than assumed, which can be ignored now!

History of Electroweak Fits

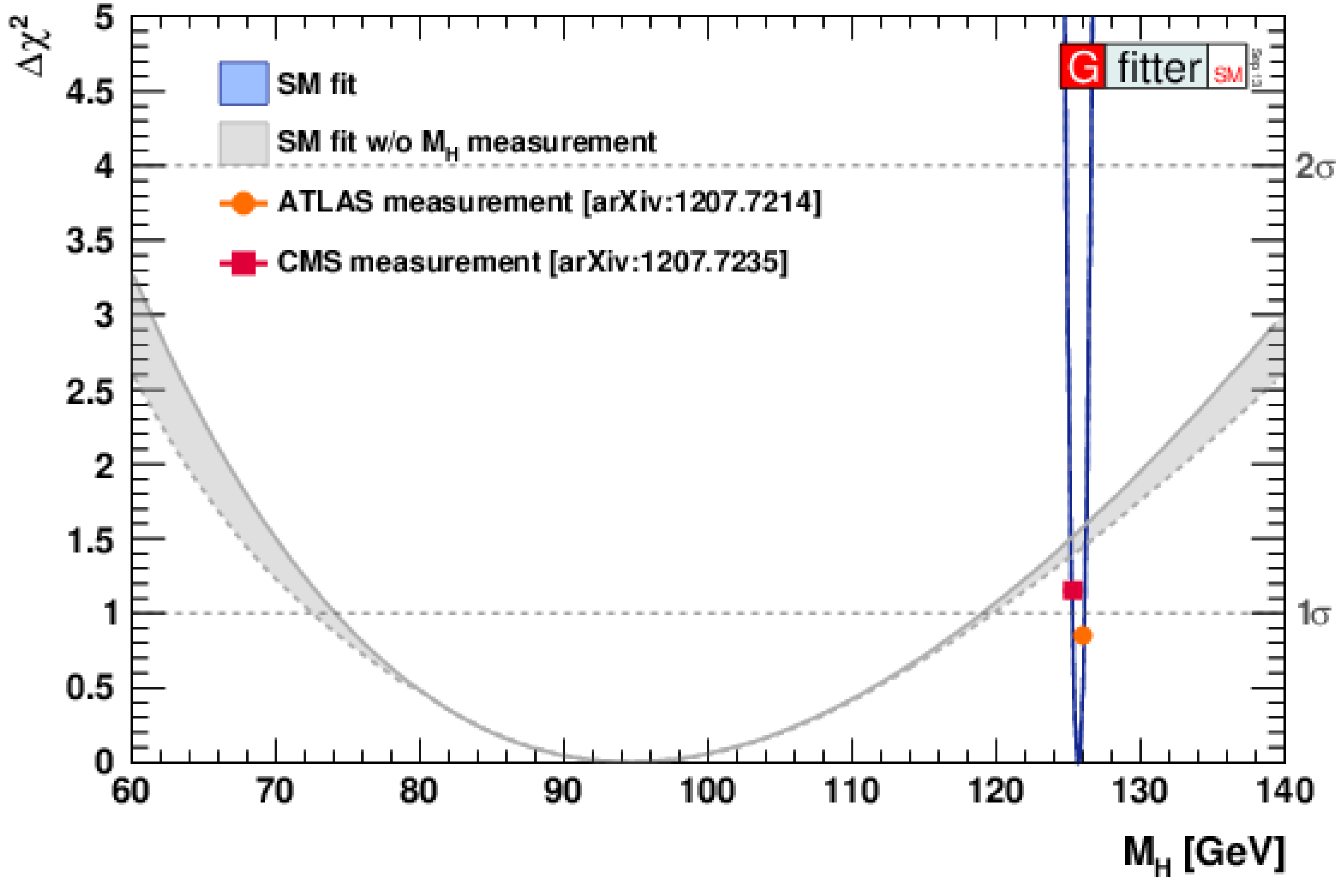
- m_t predictions from loop effects since 1990
- Official LEPEW fit since 1993
- The fits have always been able to predict m_t and m_H correctly!

History of top-mass predictions



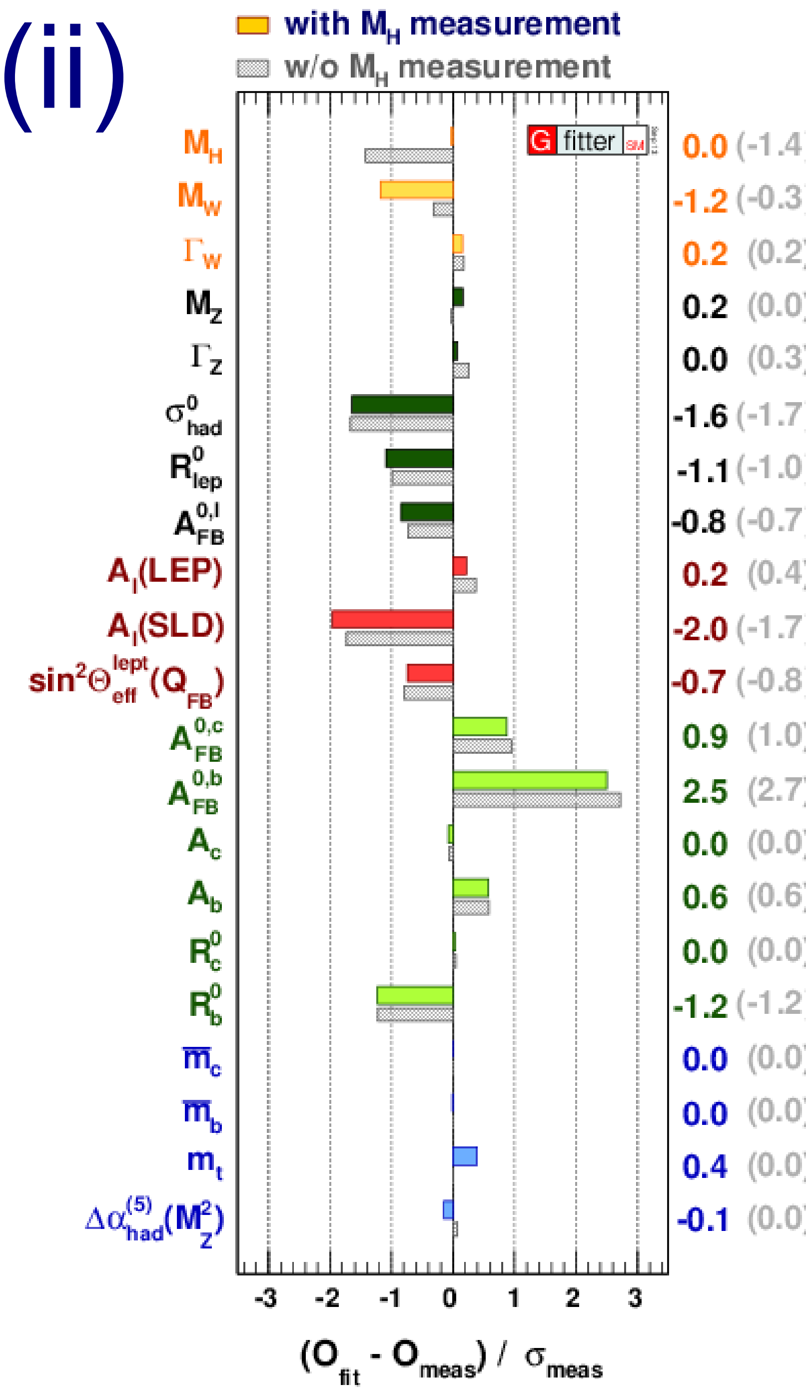
The electroweak fit

- The data have been fitted with and without the Higgs mass from LHC
- The fitted Higgs mass agrees well with the one measured
- If the Higgs mass is included in the fit it completely dominated the result



The electroweak fit (ii)

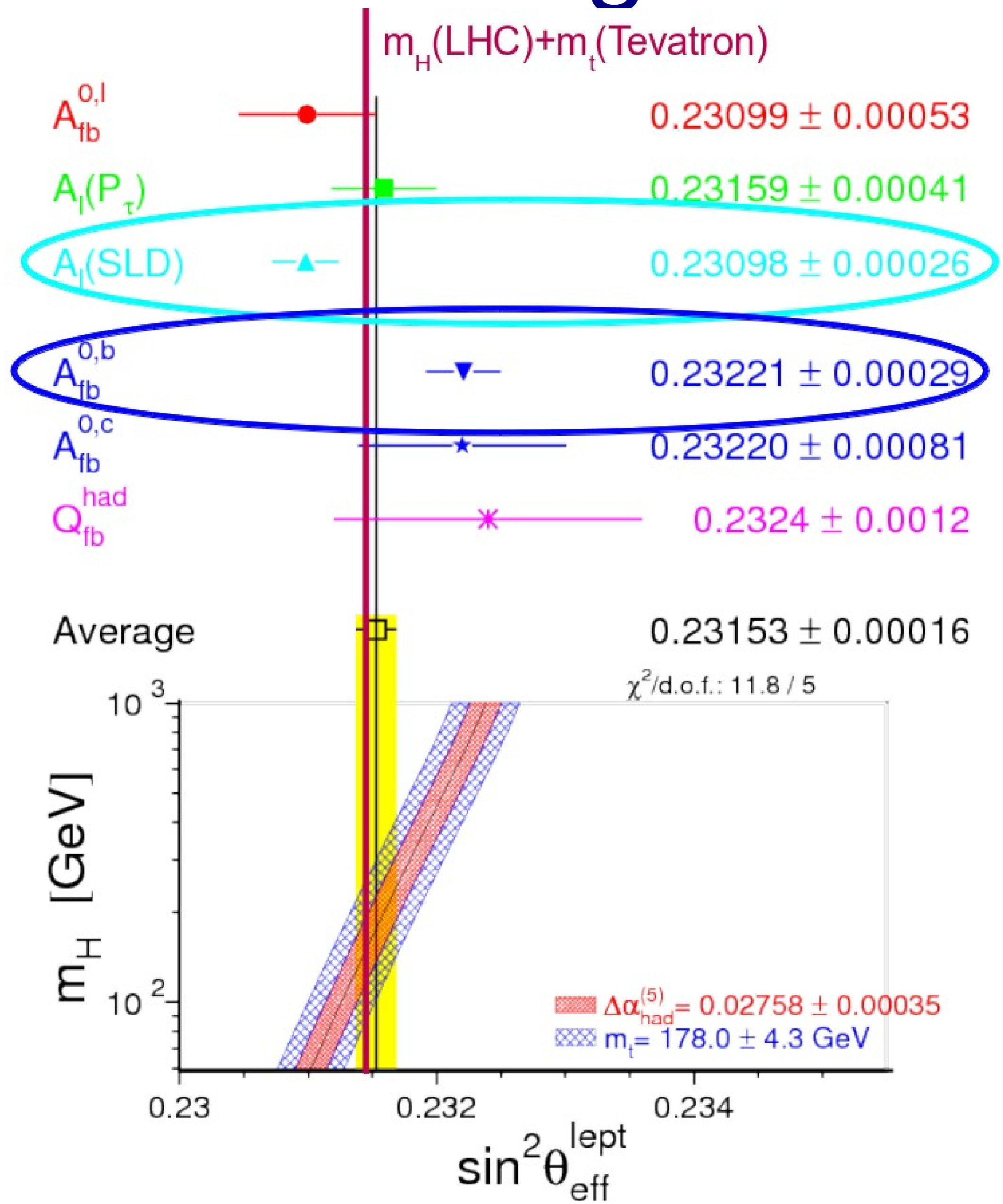
- For the first time all observables can be predicted uniquely
- All data agree well with the fit prediction
- Modifications due to m_H inclusion modest
- X^2/ndf=18.1/14, p-value from a toy MC study: 18%
- α_s=0.1190±0.0027 (4th order) in good agreement with world average (α_s=0.1184±0.0007)



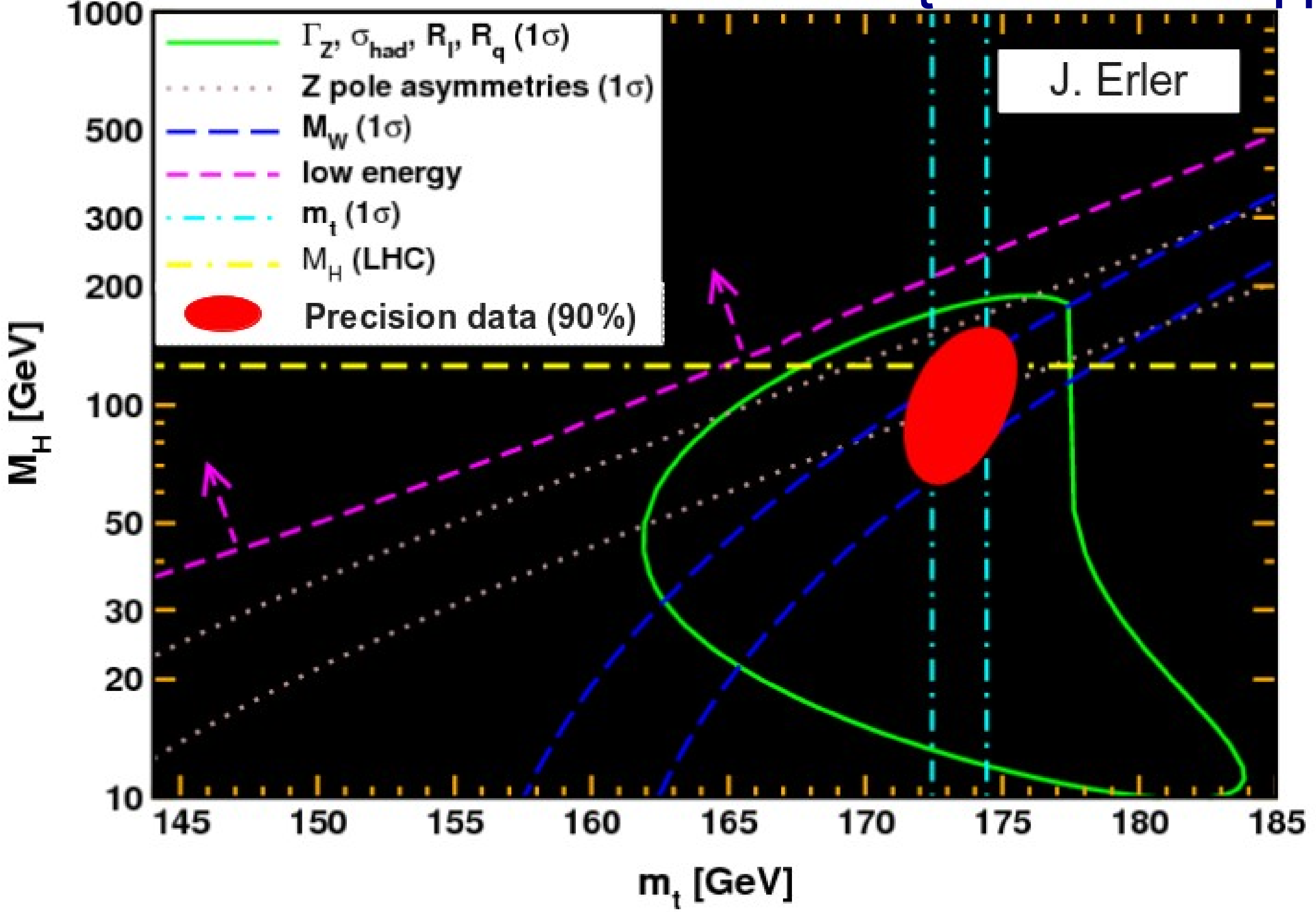
Plot inspired by Eberhardt et al. [arXiv:1209.1101]

m_H and the $\sin^2\theta$ saga

- The two most precise $\sin^2\theta_{eff}$ measurements (A_{LR}(SLD), A_{FB}^{b}(LEP)) don't agree very well
- The prediction including m_H agrees well with the average
- The agreement with the two single measurements is similar



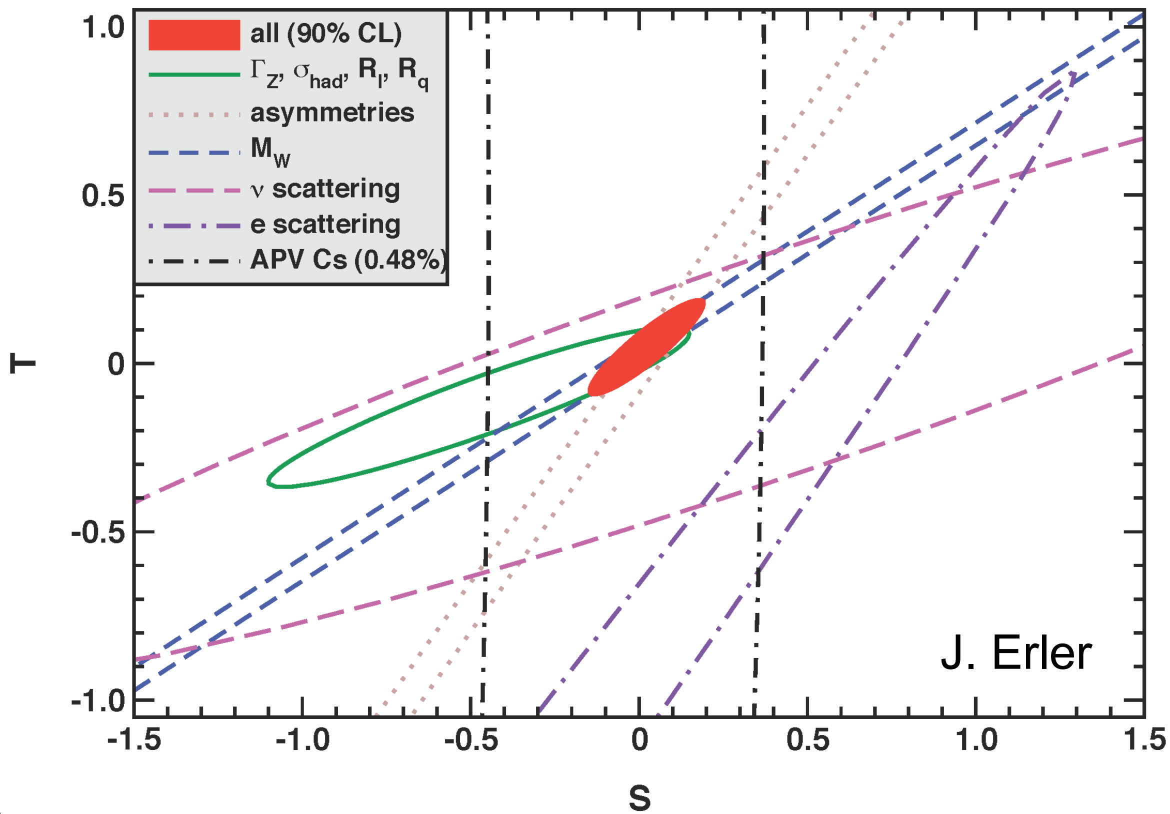
Prediction of m_t and m_H



- Loop-predictions agree well with direct measurements
- Precision mainly from m_W, $\sin^2\theta_{eff}$
- Partial widths play only minor role

STU parameters

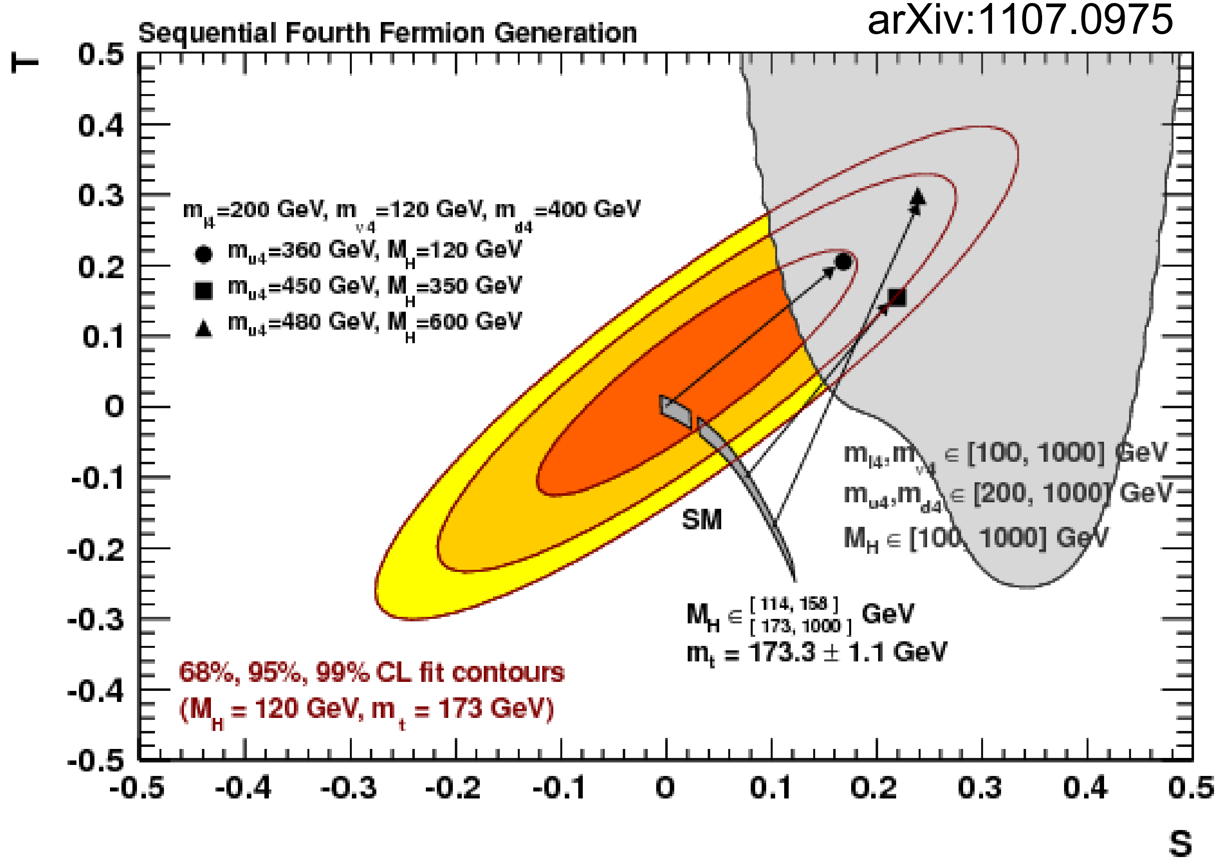
- The STU parameters were designed to ease BSM analyses:
  - T absorbs the isospin breaking contributions ($\Delta\rho$)
  - S takes the remainder in $\Delta\kappa$
  - U takes what is still left in Δr (U=0 in many models)



STU without m_H

- Without m_H new physics effects could often be compensated by a change in the Higgs mass
- This resulted often in weak limits

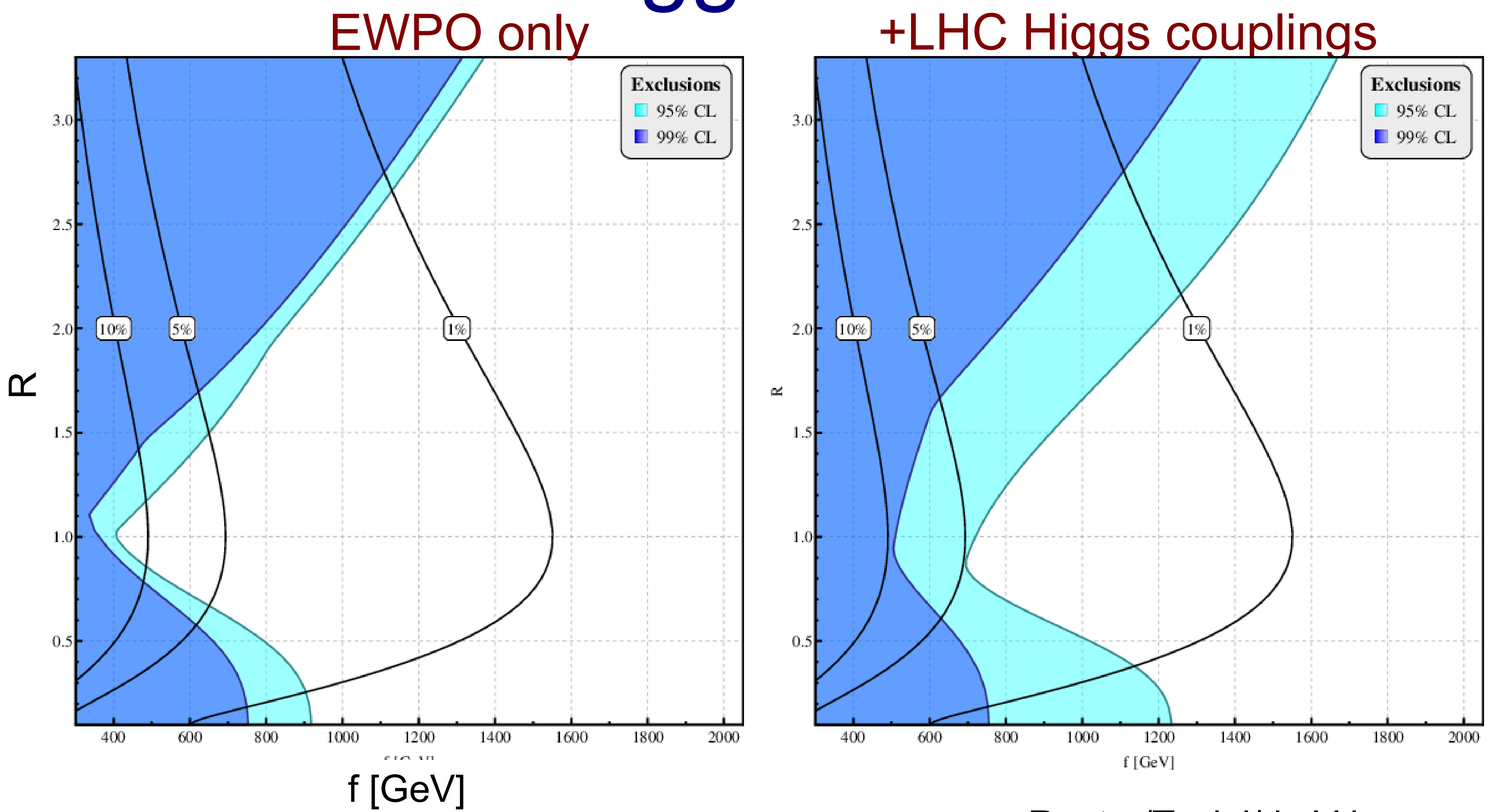
arXiv:1107.0975



Little Higgs

- Little Higgs models solve hierarchy problem making it a pseudo-Goldstone boson of a new gauge group
- This introduces new gauge bosons and a top-partner of same spin
- A new T-parity prevents large disagreement with electroweak precision observables and provides a dark matter candidate.
- Nevertheless precision data can severely constrain these models

Littlest Higgs exclusion



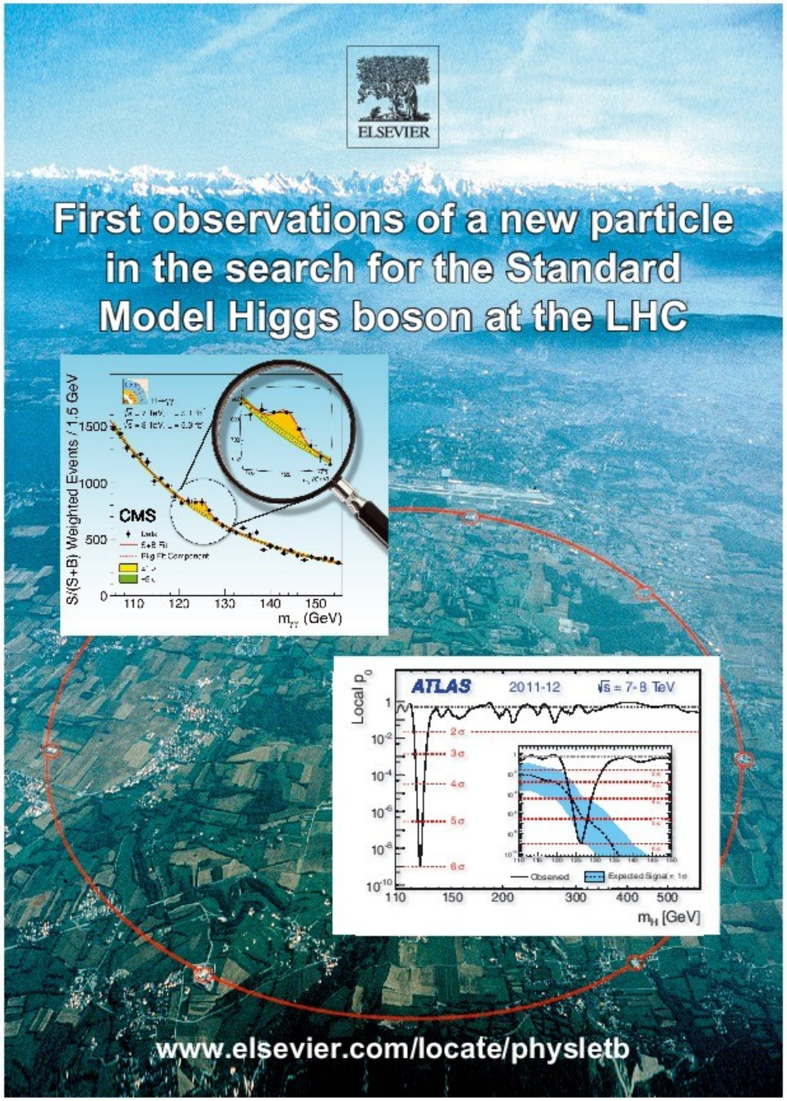
Reuter/Tonini/de Vries
arXiv:1310.2918

f: breaking scale of new symmetry

$R=\lambda_1/\lambda_2$=ratio of Yukawa couplings in top-sector

Higgs news from the LHC

- On July 2012 ATLAS and CMS announced a new particle with mass around 125 GeV found in the Standard Model Higgs searches
- Since then a vast amount of analyses has been performed
- By now
  - The particle is established in several single analyses
  - There are very strong indications that its spin/CP is 0^+
  - Also all other properties measured are consistent with what is predicted for a Standard Model Higgs boson

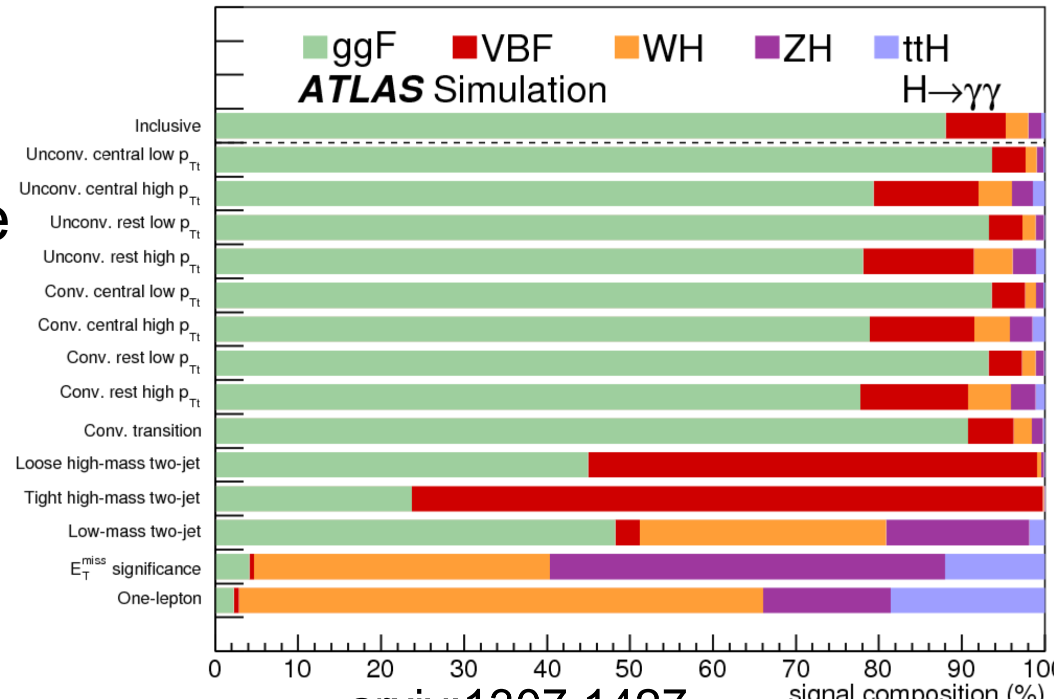


Analysis strategy

- Analyses are performed according to the final state of the Higgs decay
- In most analyses the events are separated into categories
- This increases the sensitivity because of different s/b ratios
- However the categories also depend on the production mechanisms (gg-fusion, VV-fusion, VH production)

  (ttH is mostly treated in separate analyses)
- This allows to separate the production mechanisms in the coupling fits
- Results are published as

$$\mu = \frac{\sigma_{\rm meas}}{\sigma_{\rm SM}}$$

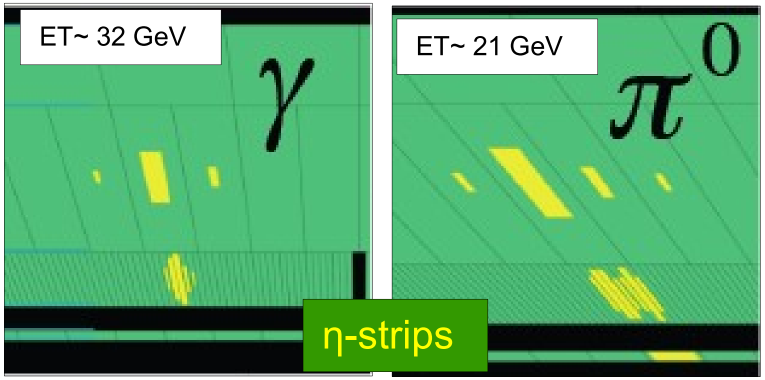


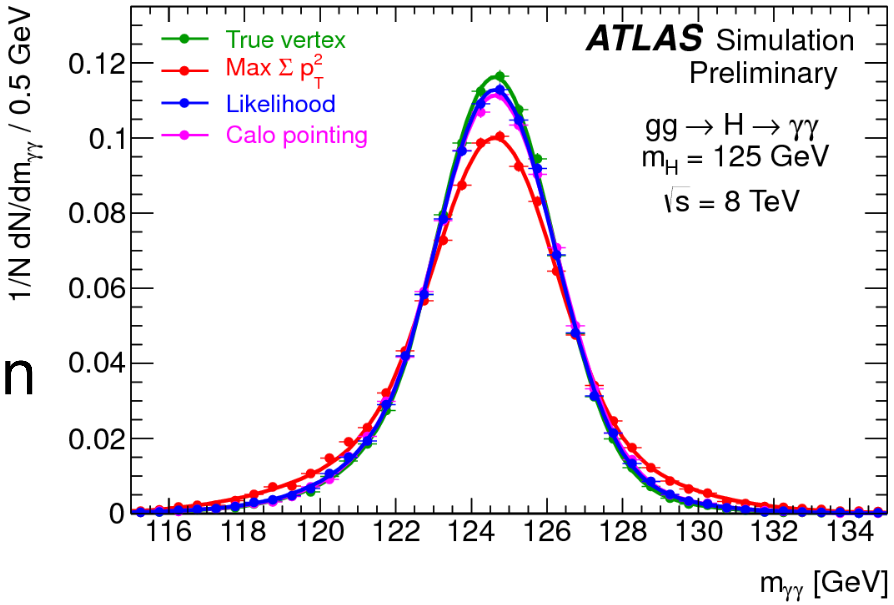
arxiv:1307.1427

$H \rightarrow \gamma\gamma$

- Large background from QCD $q\bar{q} \rightarrow \gamma\gamma$
- Huge bg. from $q\bar{q} \rightarrow \gamma j$ and $q\bar{q} \rightarrow jj$
  ⇨ need excellent γ-j separation
- Signal fitted on top of smooth bg.
- Need good mass resolution to get good signal/bg
- ATLAS: very good spacial resolution for γ-j separation and photon direction
- CMS: excellent energy resolution in crystal calorimeter, however need vertex for direction

ATLAS lAr-calorimeter

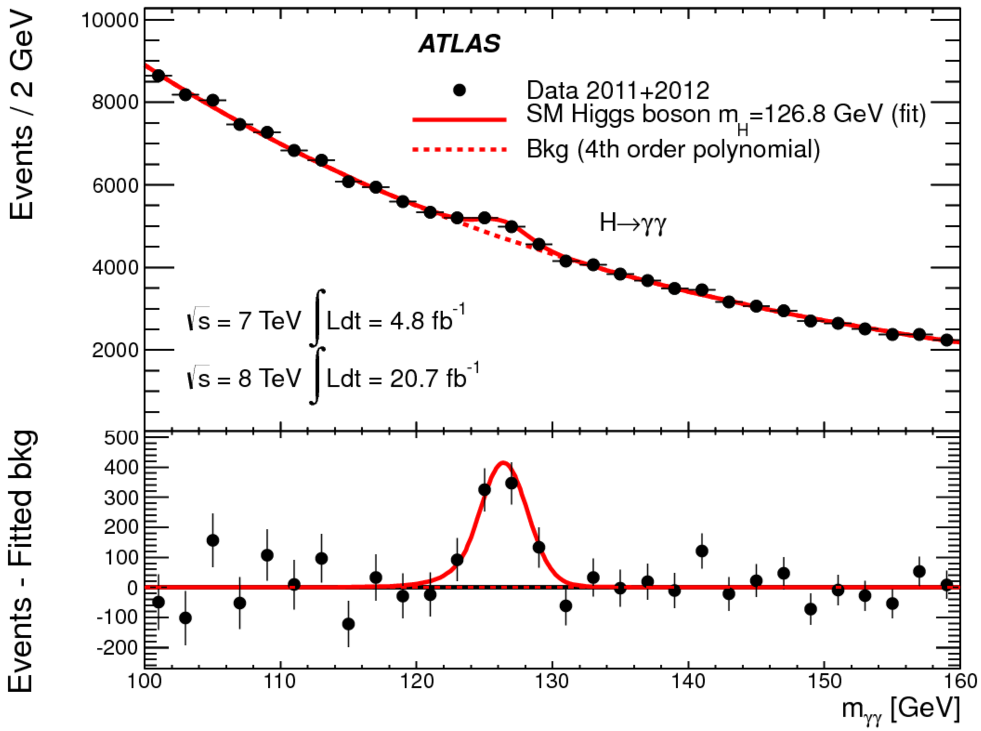




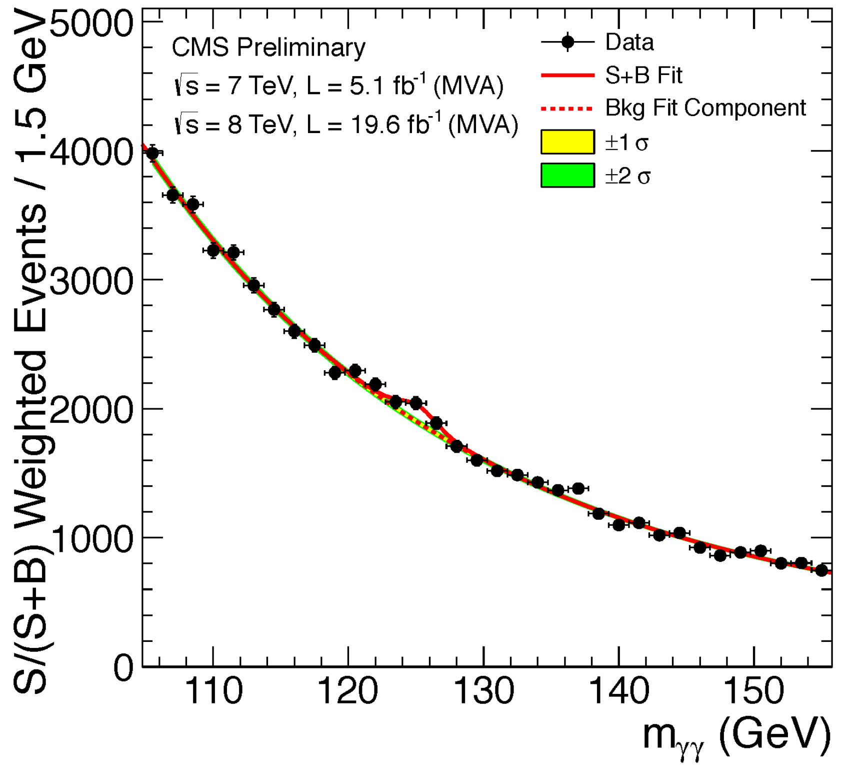
$H \rightarrow \gamma\gamma$ (ii)

- Both experiments see a clear signal, ATLAS with a slight upward and CMS with a slight downward fluctuation

arxiv:1307.1427



CMS-PAS-HIG-13-001

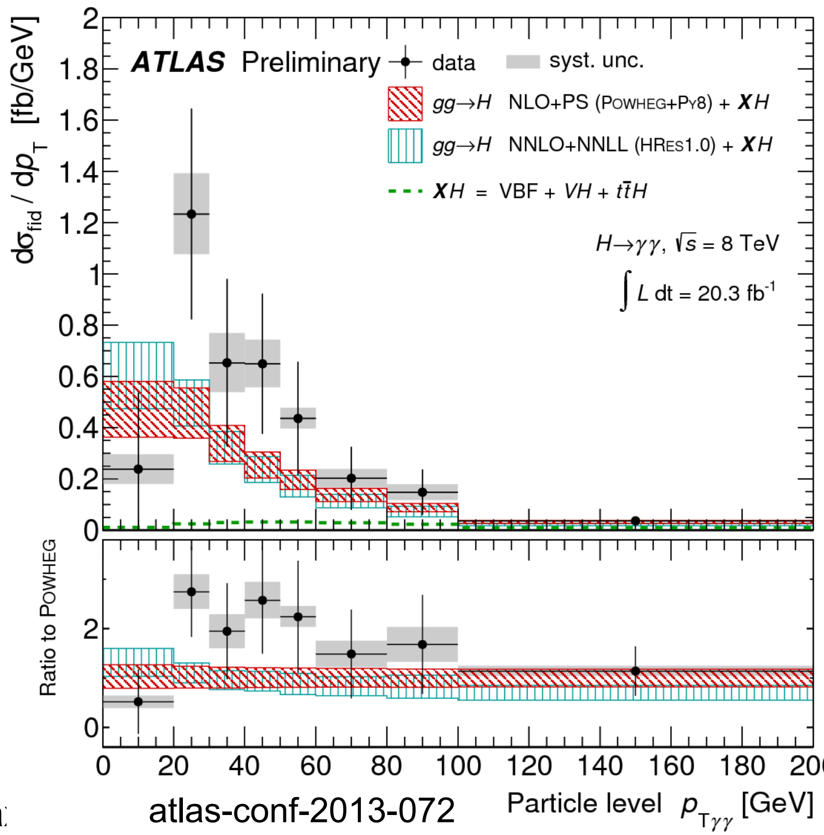


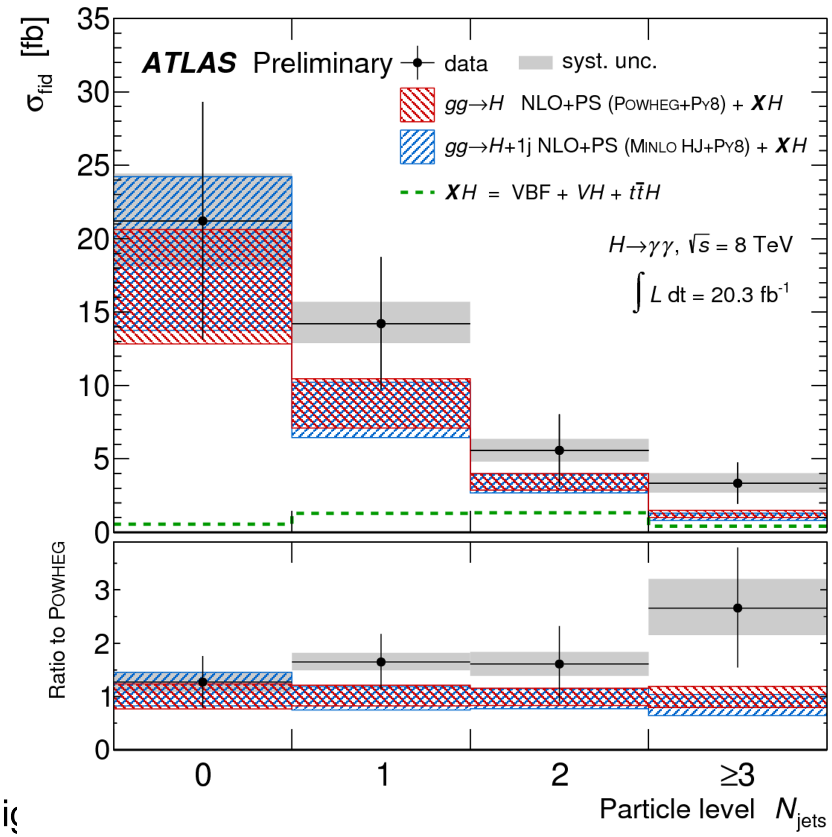
$$\mu = 1.55^{+0.33}_{-0.28} \quad (7.4\sigma)$$

$$\mu = 0.78^{+0.28}_{-0.26} \quad (3.2\sigma)$$

H→γγ (iii)

- ATLAS uses the H→γγ data sample to measure fully unfolded differential cross sections
- These are needed to calibrate the QCD calculations and reduce the theoretical uncertainties
- Up to now all distributions agree with the prediction (P(χ^2)>0.3)

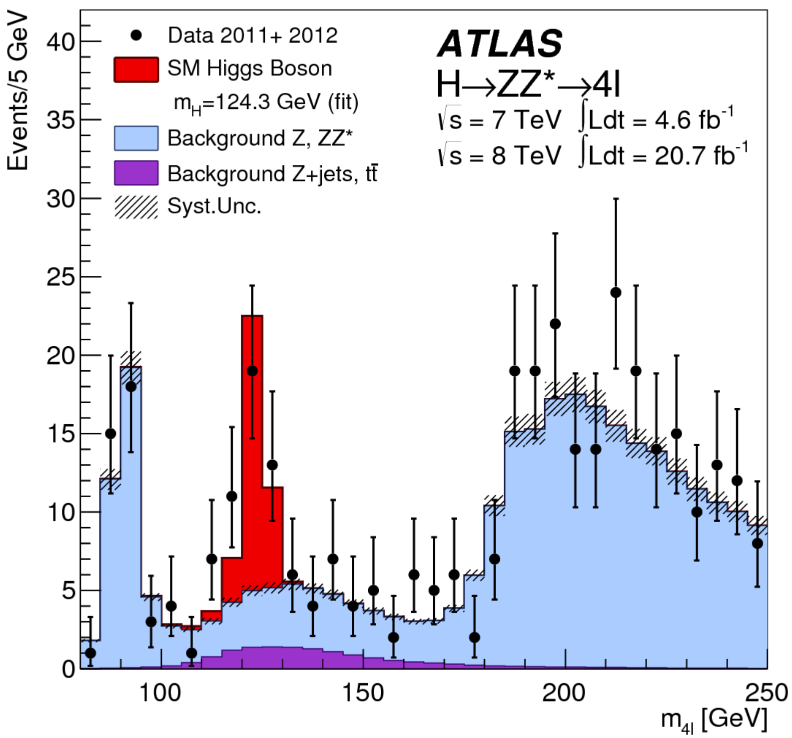




H→ZZ→4l

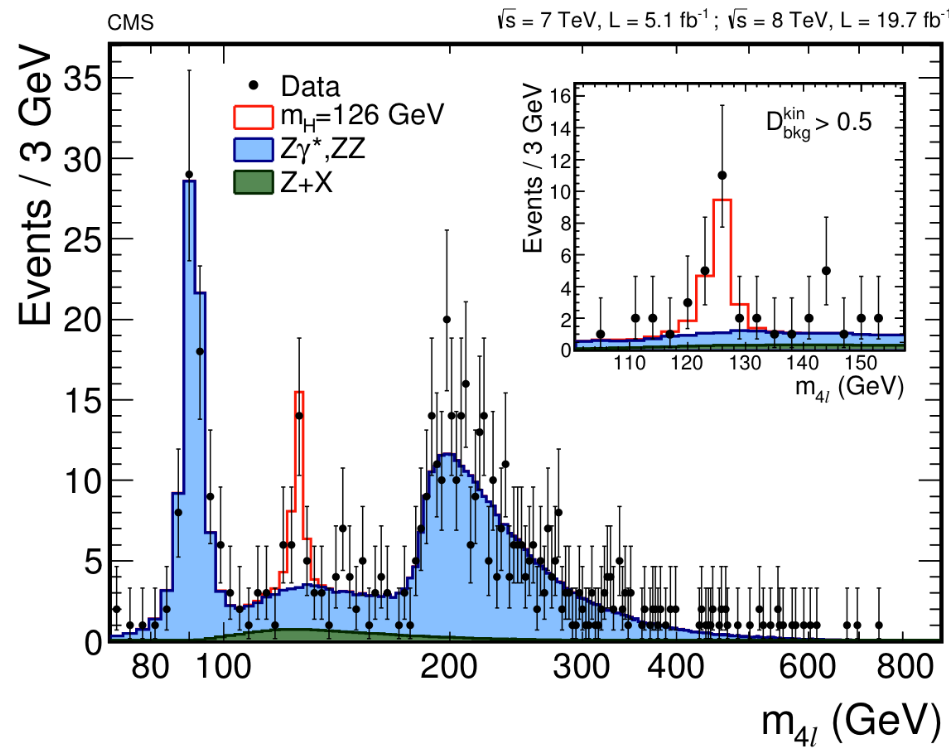
- Very clean channel, however low branching ratio
- Almost only irreducible background ZZ→4l
- CMS uses an additional classifier to reject SM ZZ→4l

arxiv:1307.1427



$$\mu = 1.5 \pm 0.4 \quad (6.6\sigma)$$

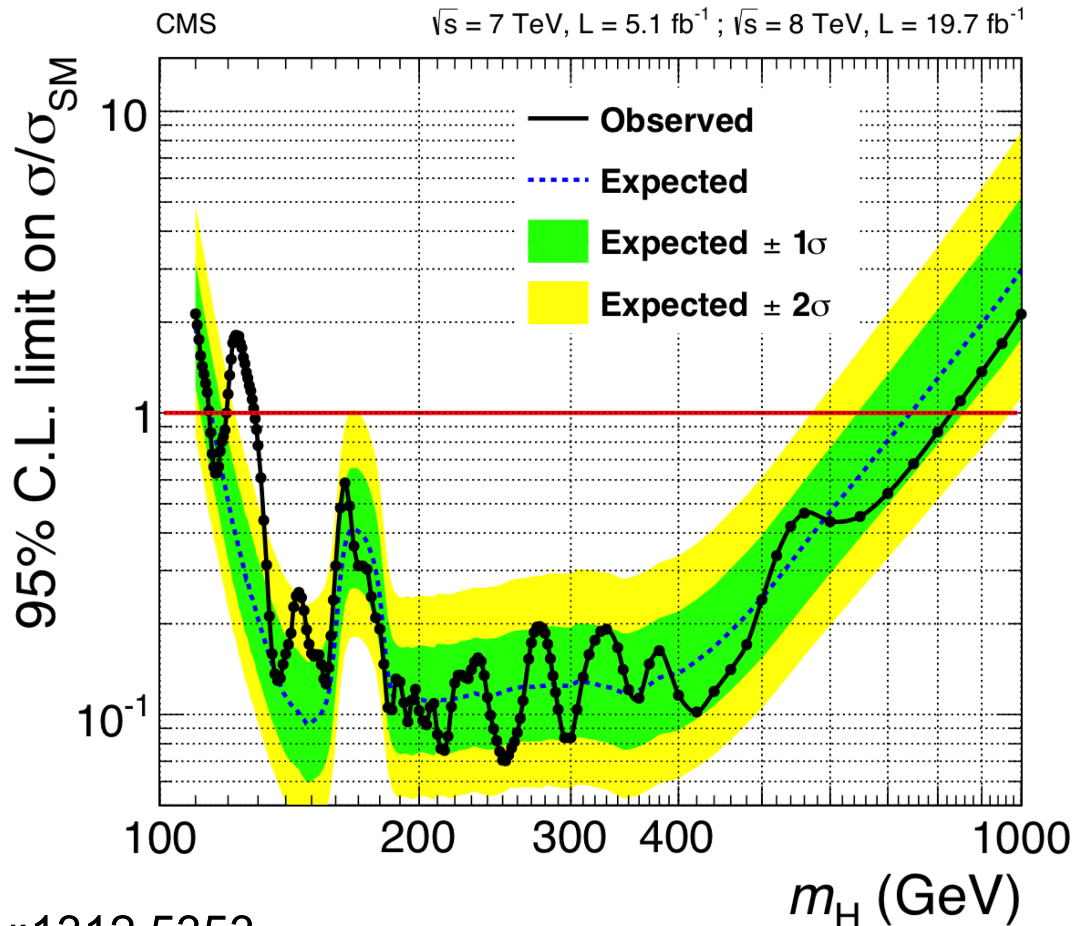
arxiv:1312.5353



$$\mu = 0.93^{+0.29}_{-0.25} \quad (6.8\sigma)$$

H→ZZ→4l (ii)

- This channel alone is also able to exclude another SM-like Higgs up to 800 GeV

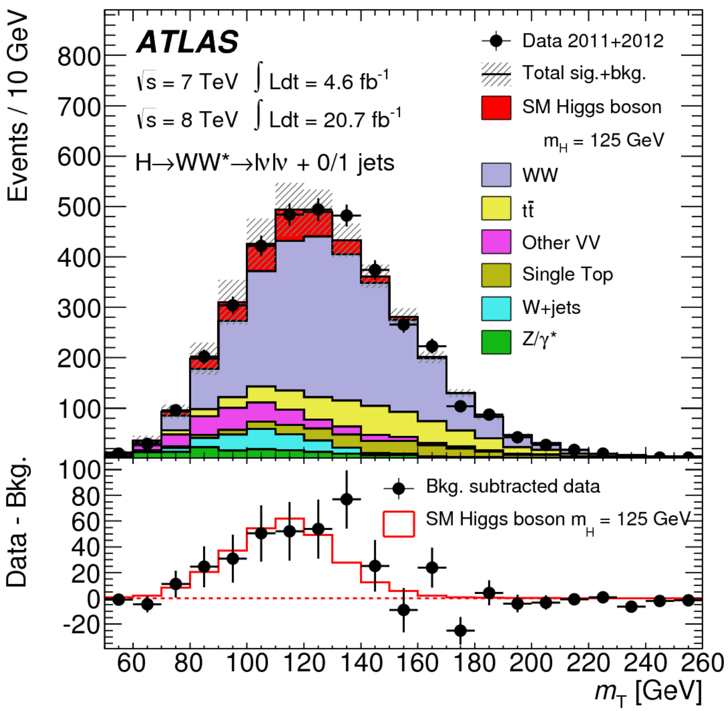


arxiv:1312.5353

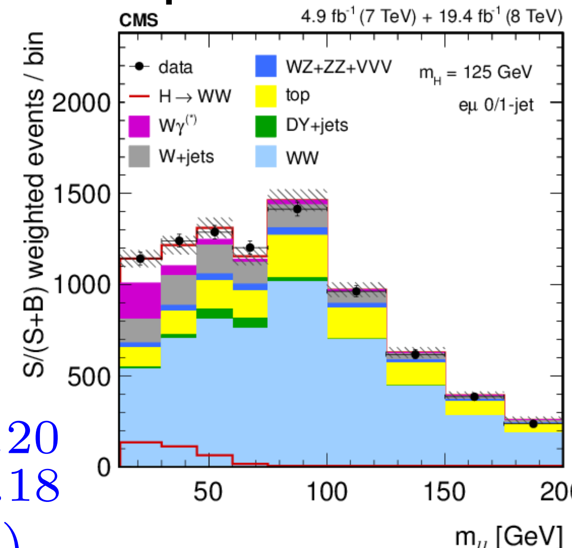
H→WW→2l2ν

- No mass peak, need to understand background very well
- Categorisation in number of jets to separate production modes

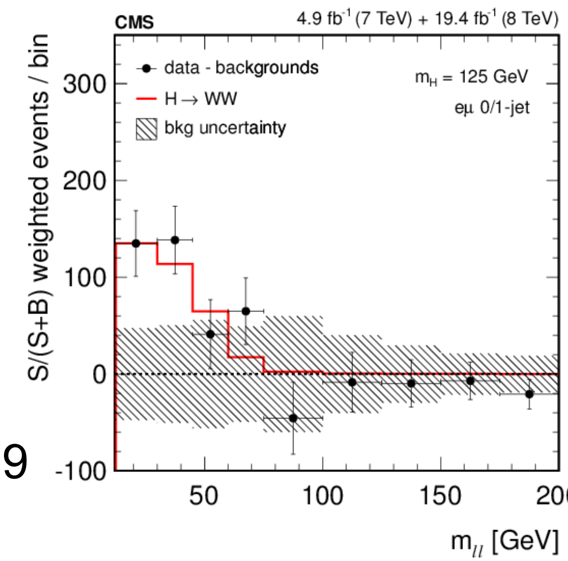
arxiv:1307.1427



$$\mu = 1.01 \pm 0.31\ (3.8\sigma)$$



$$\mu = 0.72^{+0.20}_{-0.18}$$
$$(4.3\sigma)$$



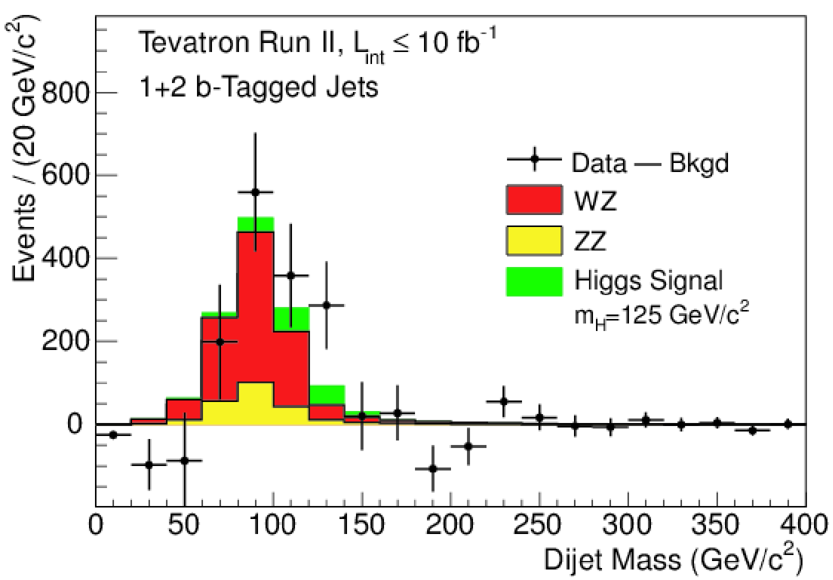
arxiv:1312.1129

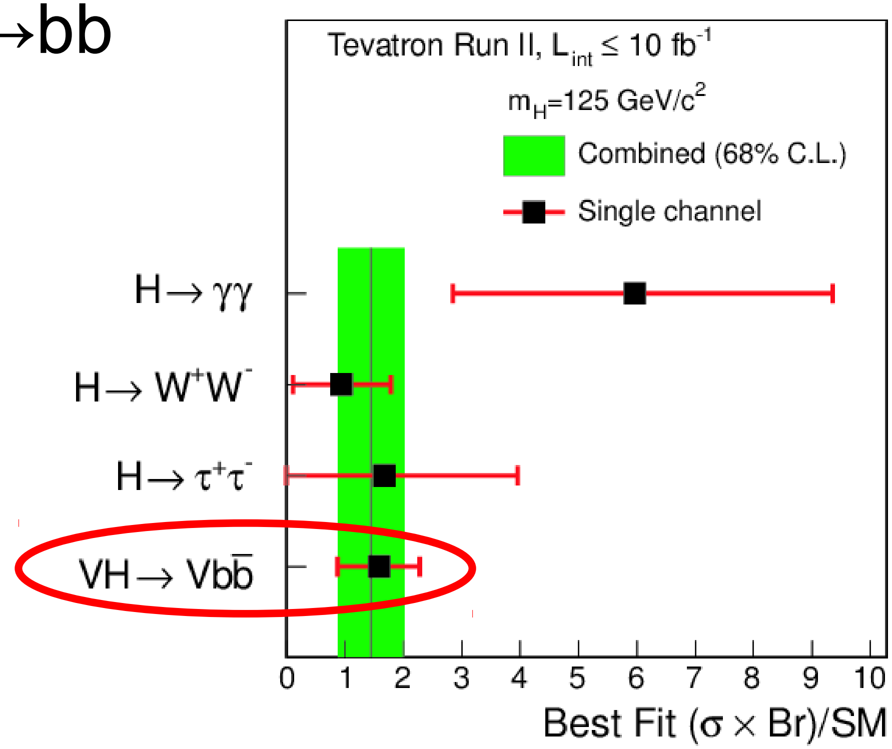
$H \to b\bar{b}$

- $H \to b\bar{b}$ is the largest decay mode (57%)
- $gg \to H \to b\bar{b}$ is completely hopeless due to QCD background
- $VH \to Vb\bar{b}$ has some chance due to the additional vector boson
- Signal/background is better at lower energy so that the Tevatron is competitive in this channel
- At the LHC one can improve signal/bg by going to boosted topologies (large $V, b\bar{b}$ energies $\to$ merging jets)

$H \to b\bar{b}$ at the Tevatron

- The Tevatron has searched for the Higgs with their full luminosity of ~10 fb^{-1}
- In the 115-140 GeV region $VH \to Vb\bar{b}$ is the most sensitive channel
- With some upward fluctuation the Tevatron sees about 3σ evidence for $H \to b\bar{b}$



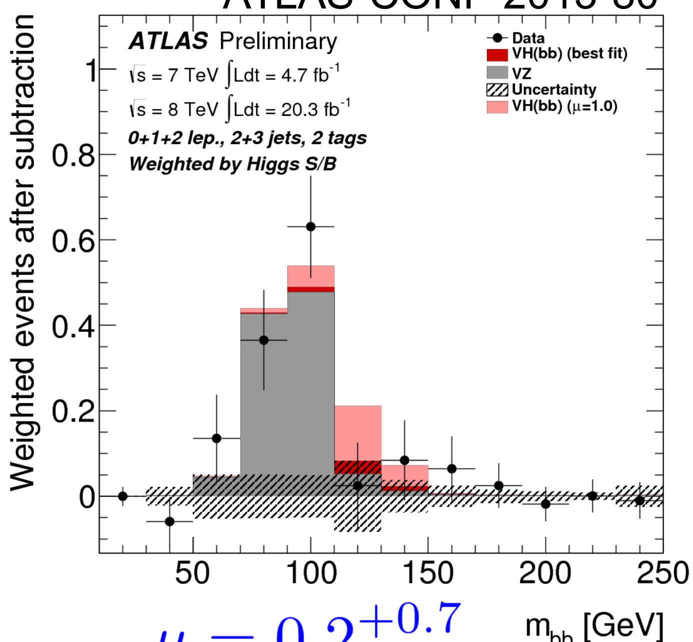


arXiv:1207.0449

$H \to b\bar{b}$ at the LHC

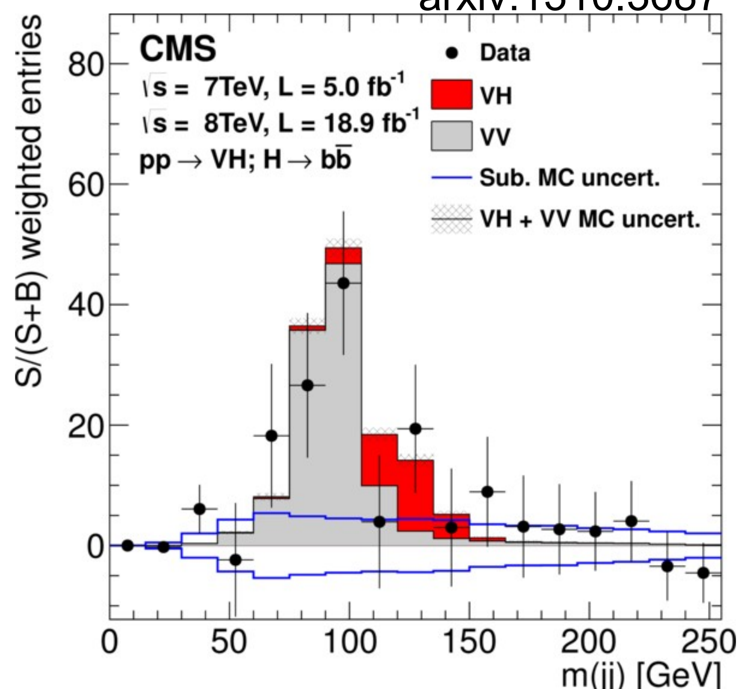
- Both experiments search for $VH \to Vb\bar{b}$ in the 0/1/2-jet mode and in bins of $p_{T,H}$
- Both experiments see clear signal of VZ production
- CMS has some evidence for $H \to b\bar{b}$ while ATLAS has a downward fluctuation with similar sensitivity

ATLAS-CONF-2013-80



$$\mu = 0.2^{+0.7}_{-0.6}$$

arxiv:1310.3687

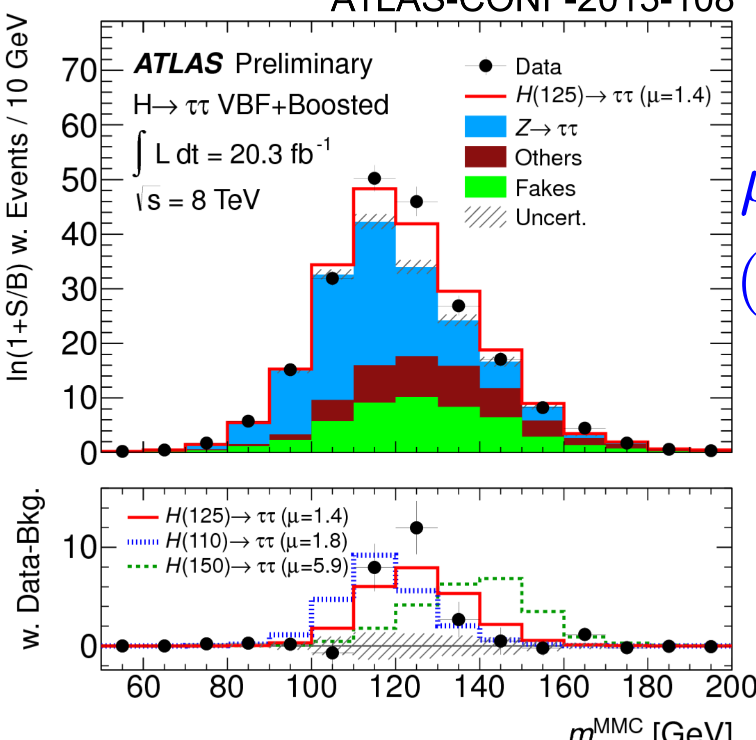


$$\mu = 1.0 \pm 0.5 \; (2.1\sigma)$$

H→ττ

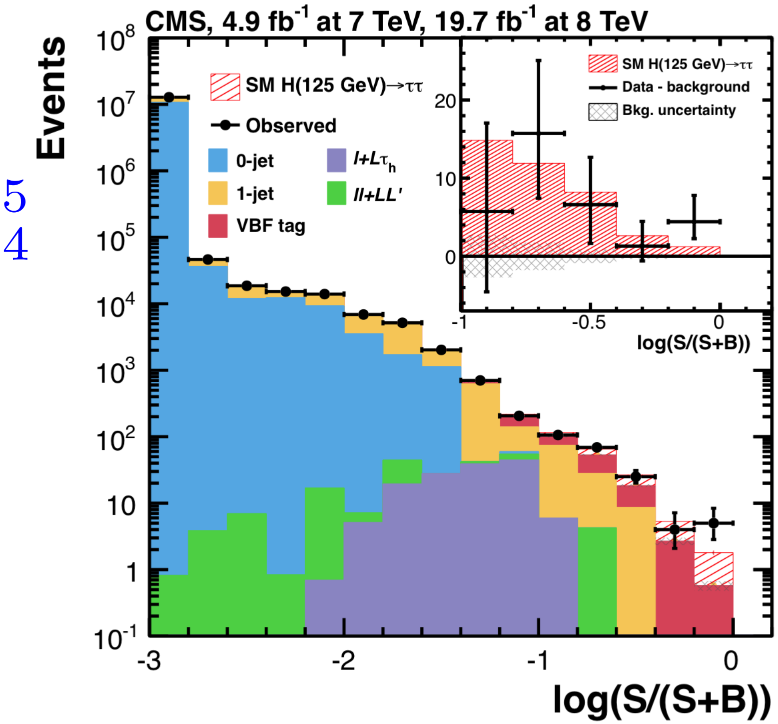
- Both experiments have a multivariate analysis for H→ττ
- Since a boost is needed to reconstruct the Higgs (≥2 missing νs) the analyses are especially sensitive to VBF
- Both results on their own show clear evidence for Higgs decays to down-type fermions

ATLAS-CONF-2013-108



$$\mu = 1.4^{+0.5}_{-0.4}$$
$$(4.1\sigma)$$

arxiv:1401.5041



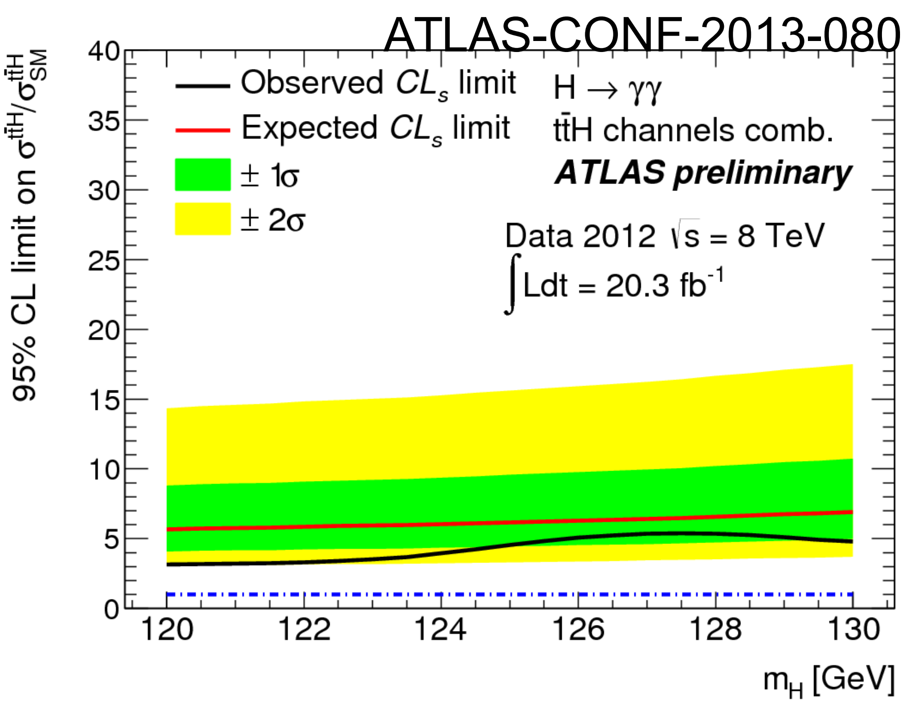
$$\mu = 0.78 \pm 0.27 \ (3.2\sigma)$$

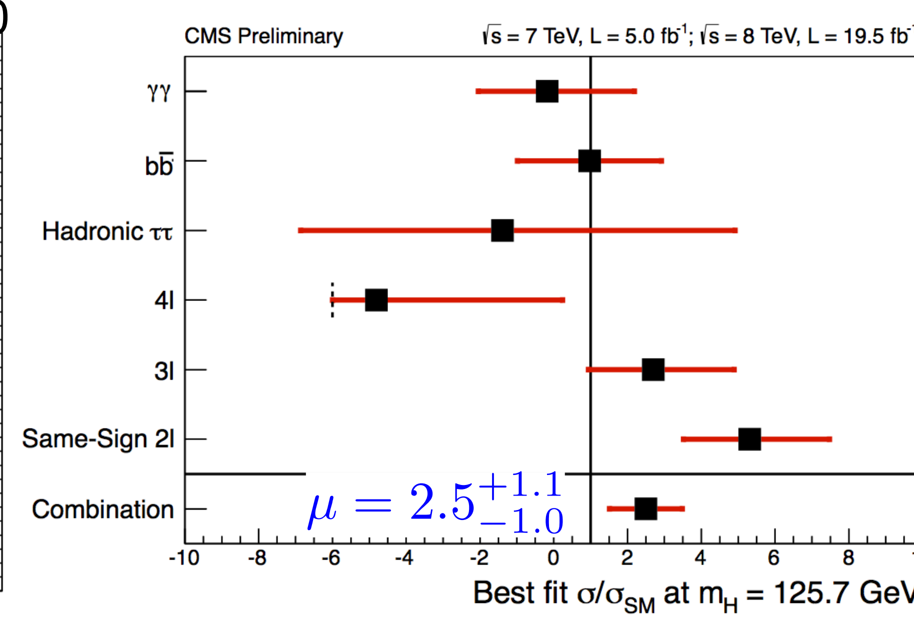
Search for other modes

- The experiments also searched for other production and decay modes
  - Higgs production via $t\bar{t}$ fusion: very interesting because of large top Yukawa coupling
  - Loop induced processes ($H \to Z\gamma$, $t \to cH$): can be strongly enhanced in BSM models
  - $H \to \mu\mu$: 1st place, where lepton universality is violated
  - $H \to$ invisible: Possible in SUSY and other places where the Higgs can couple to dark matter

Search for $t\bar{t}H$

- ATLAS has searched in $H\rightarrow\gamma\gamma$ only
- CMS has searched in several channels the most sensitive being 2 ss-leptons from $t\rightarrow lX$ and $H\rightarrow ZZ,WW,\tau\tau \rightarrow lX$
- ATLAS shows only a limit, CMS has a weak signal due to an upward fluctuation



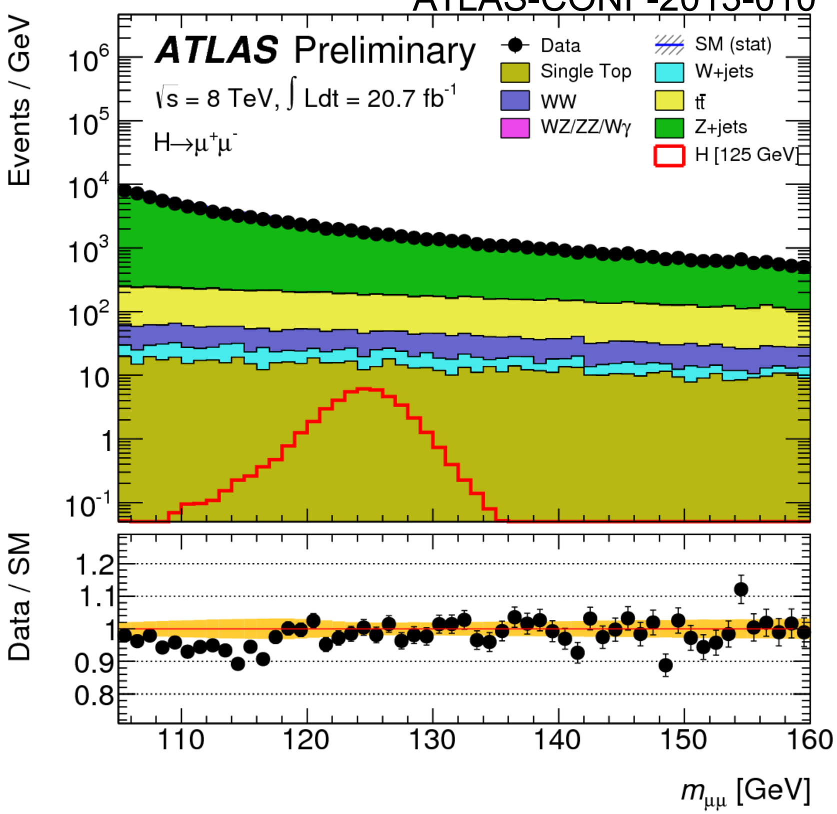


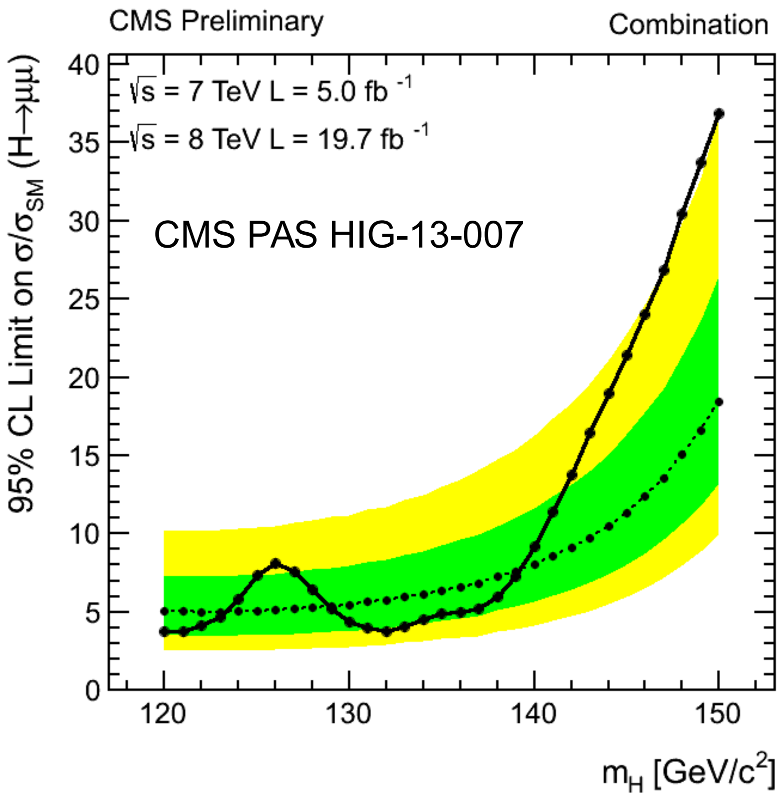
https://twiki.cern.ch/twiki/bin/view/CMSPublic/ttHCombinationTWiki

$H \to \mu\mu$

- $H \to \mu\mu$ is suppressed wrt. $H \to \tau\tau$ by $m(\mu)^2/m(\tau)^2$
- In principle clean signal, however huge Drell-Yan background
- Both experiments show limits around μ<8-10
- This is the first place where lepton universality is violated

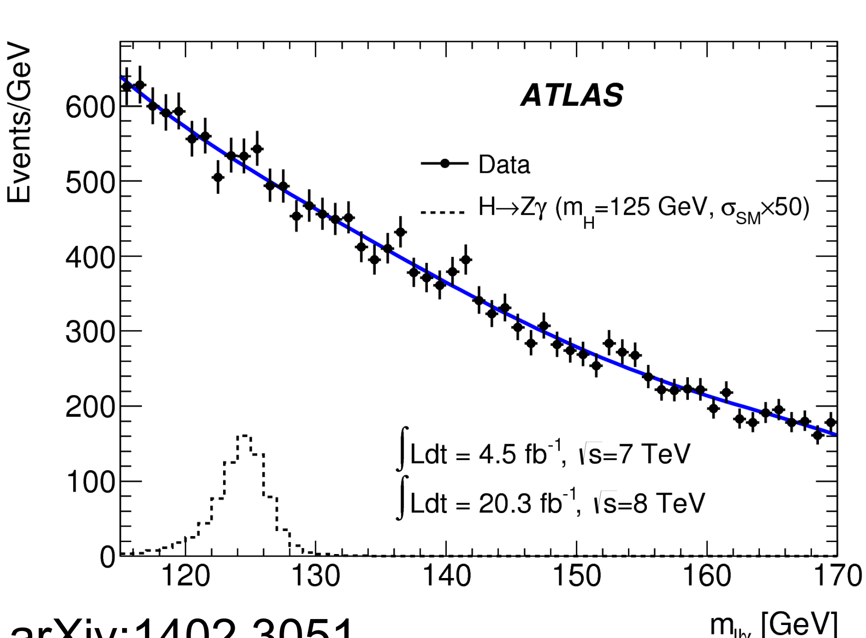
ATLAS-CONF-2013-010



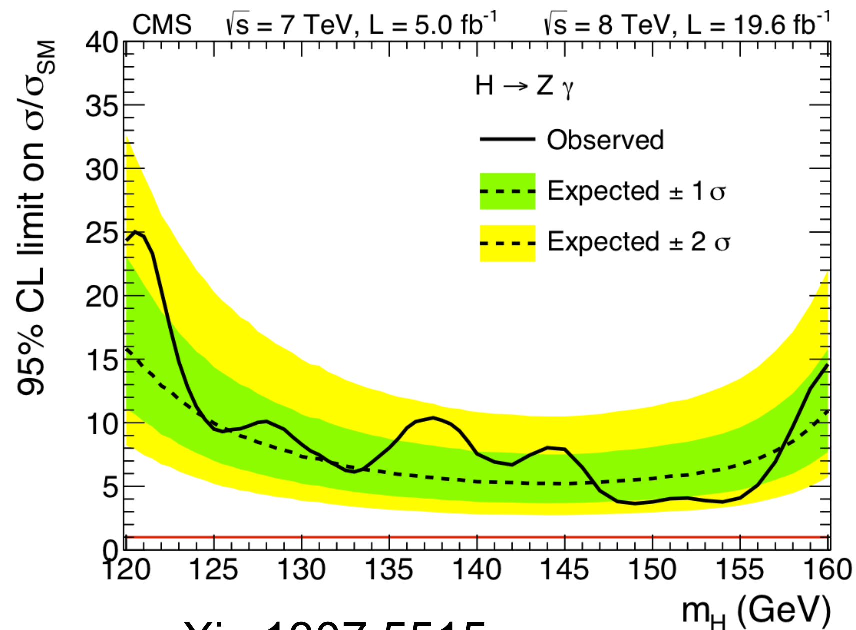


H→Zγ

- In the SM BR(H→Zγ)≈BR(H→γγ)
- However in BSM it maybe largely different
- Due to the low BR(Z→ll) the experimental limits are much worse
- Again both experiments put limits around μ<10



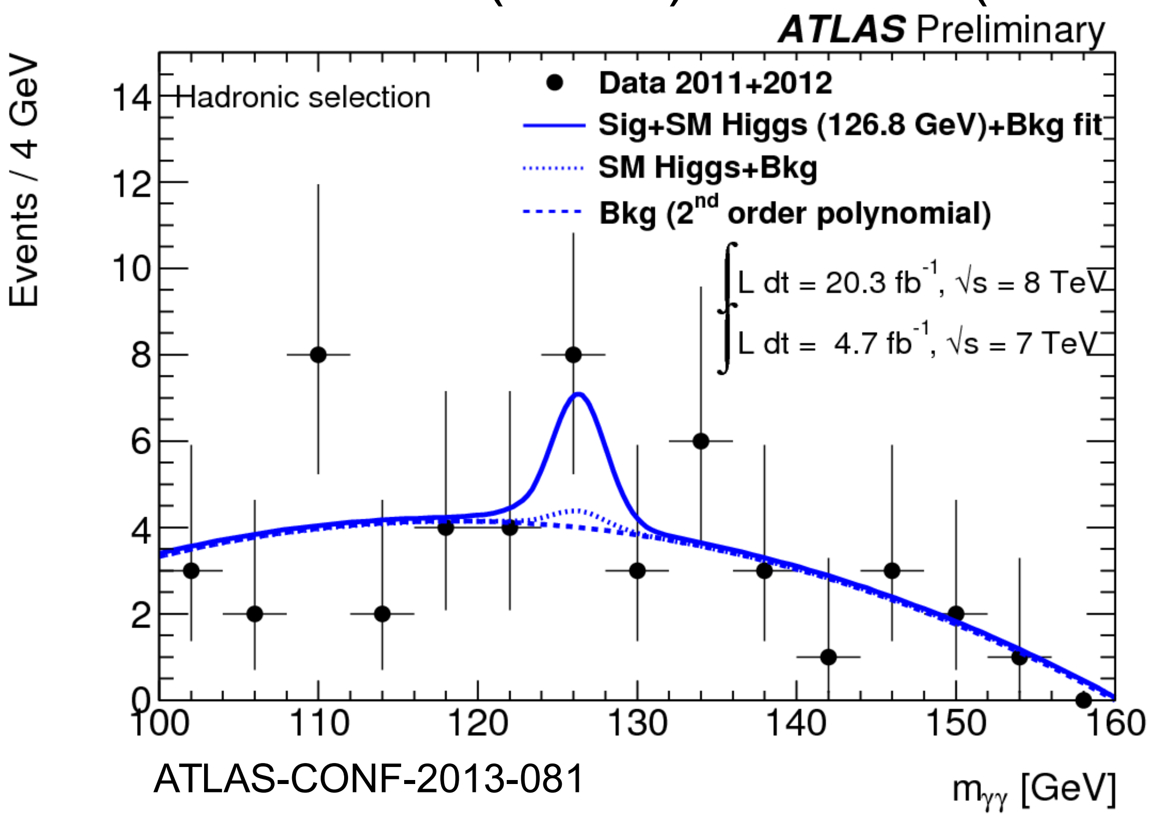
arXiv:1402.3051



arXiv:1307.5515

Search for t→cH

- In the SM FCNC decays like t→cH are forbidden (BR≈10^{-15})
- In BSM models it can be dramatically enhances (up few x10^{-3} in some 2HDM models)
- ATLAS searched for this decay in $t\bar{t}$ events with H→$\gamma\gamma$
- No signal is found with BR(t→cH)<8.3x10^{-3} (95% CL)

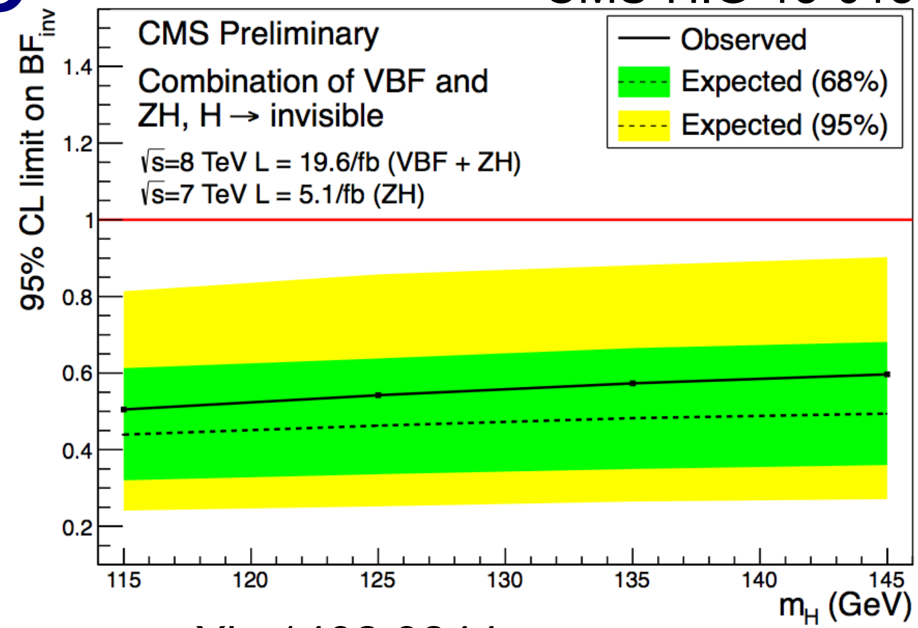


ATLAS-CONF-2013-081

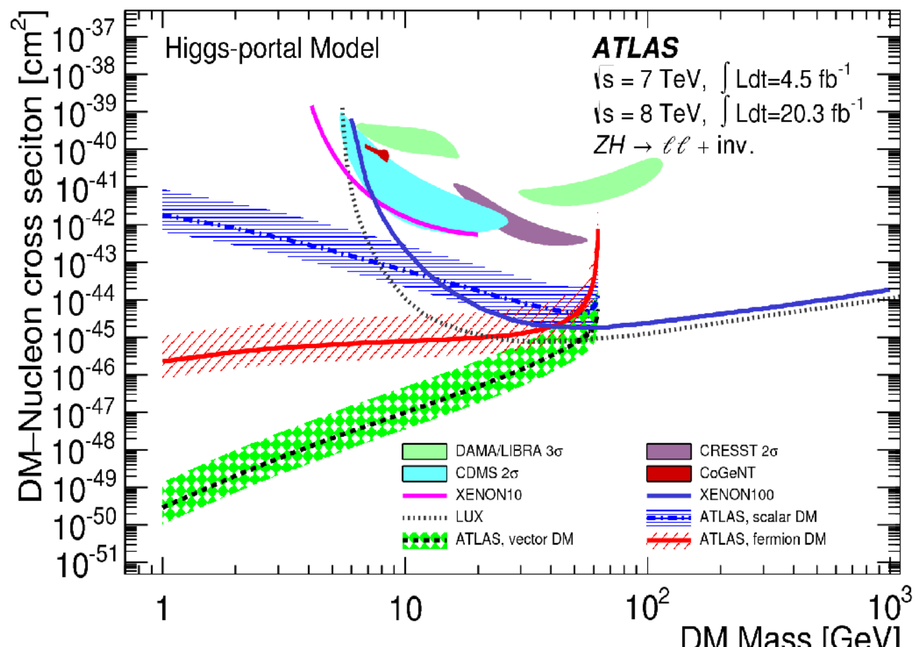
Search for invisible Higgs decays

- Invisible Higgs decays arise naturally in models like SUSY with Higgs → LSP
- The experiments have searched for invisible Higgs decays in VH and VBF
- Both set limits around BR(H→inv)<50-75%
- In Higgs portal models, where the dark matter interaction is mediated by the Higgs these searches complement the direct DM searches at low masses

CMS-HIG-13-018



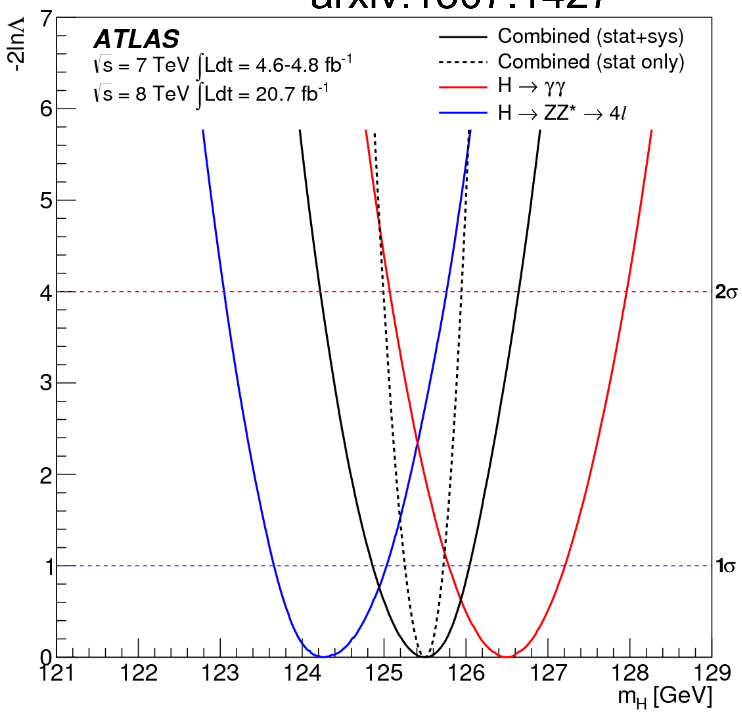
arXiv:1402.3244

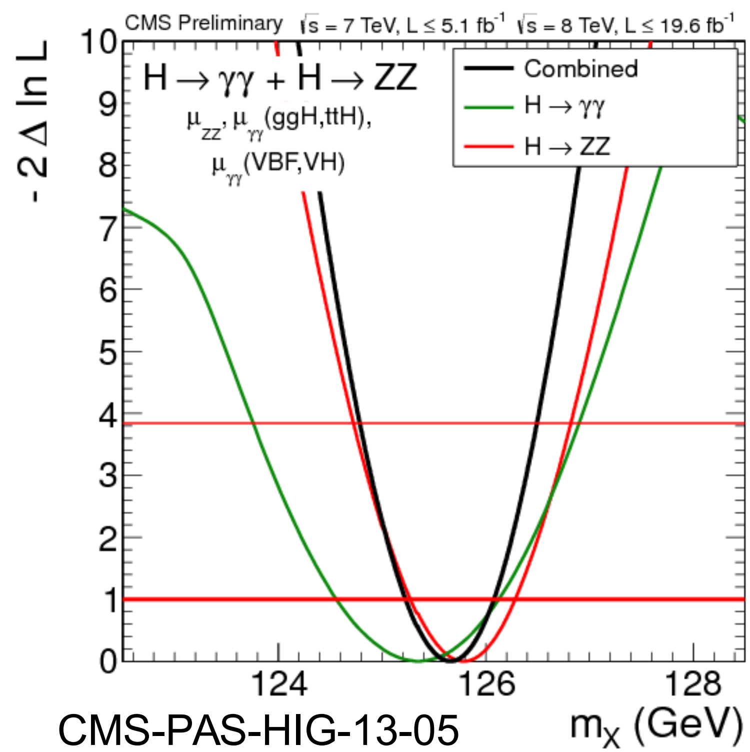


Mass of the Higgs Boson

- The mass can be obtained in an (almost) model independent way from the two high resolution channels $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ$
  - ATLAS: $m_H = 125.5 \pm 0.2 \pm 0.6 \mathrm{GeV}$
  - CMS: $m_H = 125.7 \pm 0.3 \pm 0.3 \mathrm{GeV}$
- This is already better than needed for any application

arxiv:1307.1427

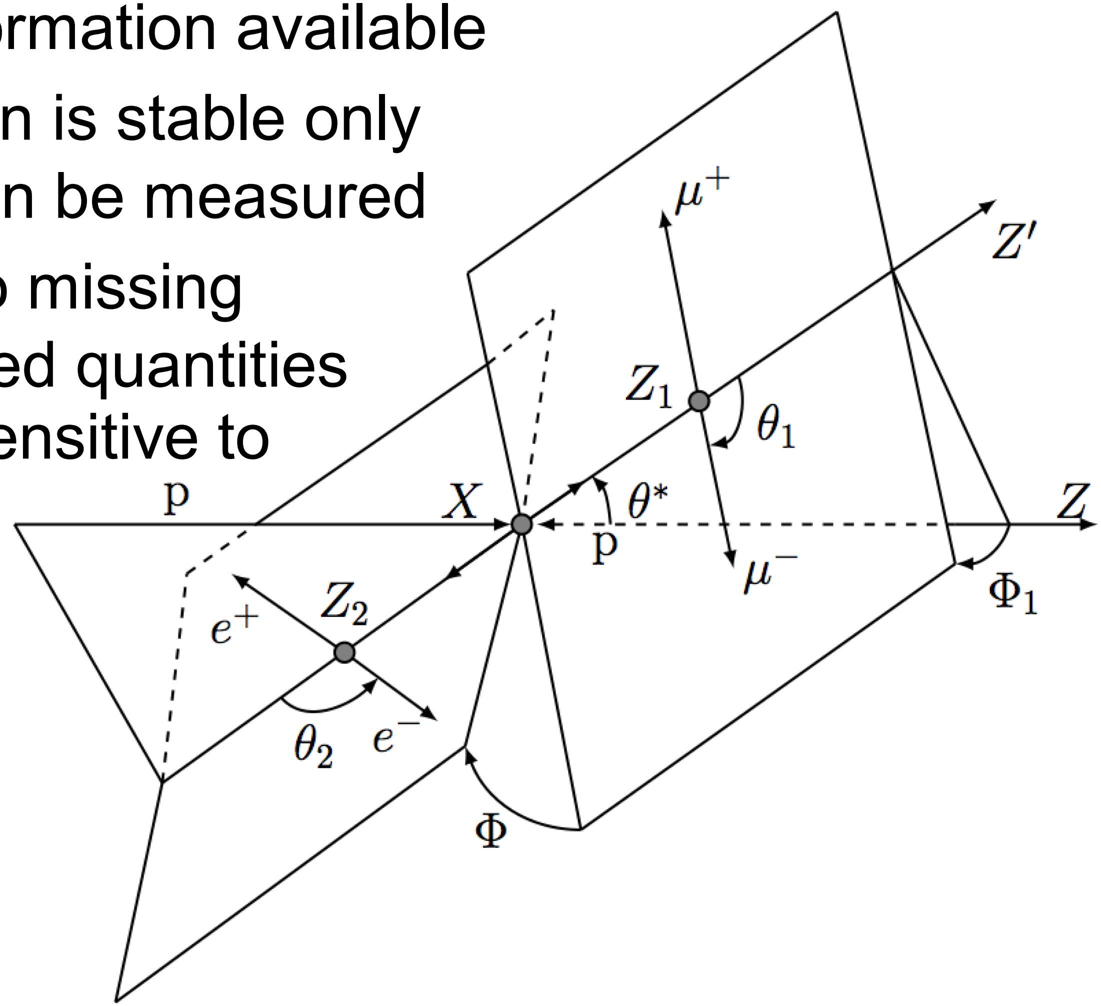




CMS-PAS-HIG-13-05

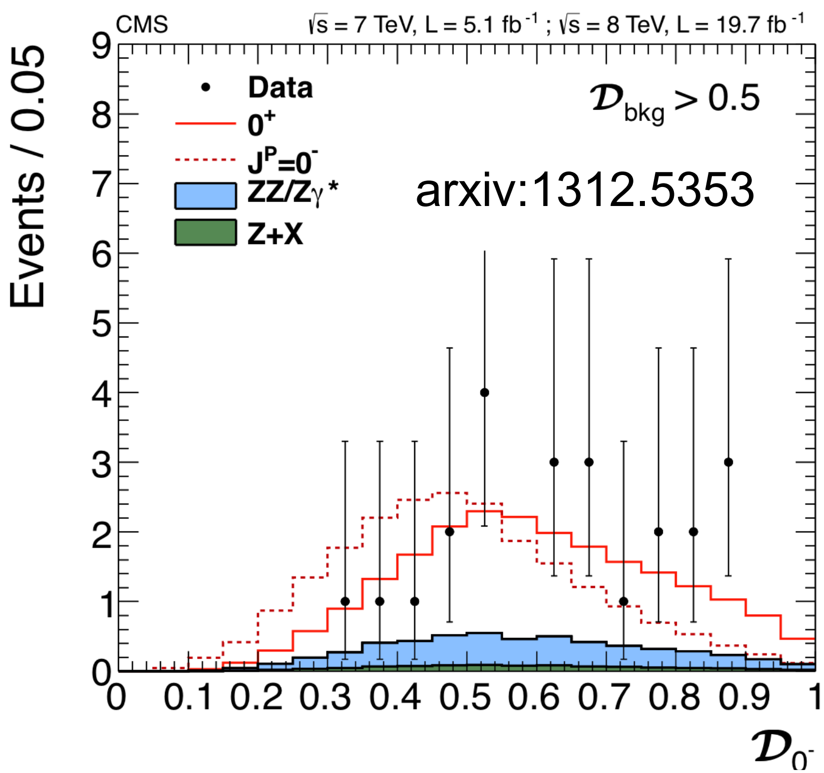
Spin and parity of the new boson

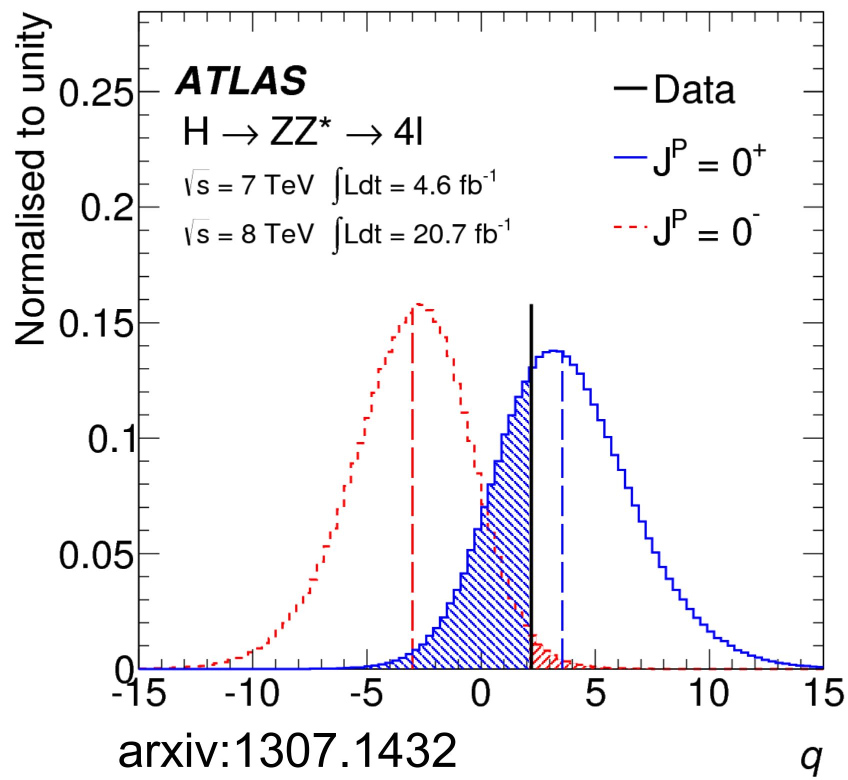
- Spin and CP can be reconstructed from the production and decay angles
  - $H \to ZZ \to 4l$: Full information available
  - $H \to \gamma\gamma$: Since photon is stable only production angle can be measured
  - $H \to WW \to 2l2\nu$: Two missing neutrinos, but derived quantities like m(ll) or $\Delta\Phi$(ll) sensitive to spin CP



Analysis of spin/CP

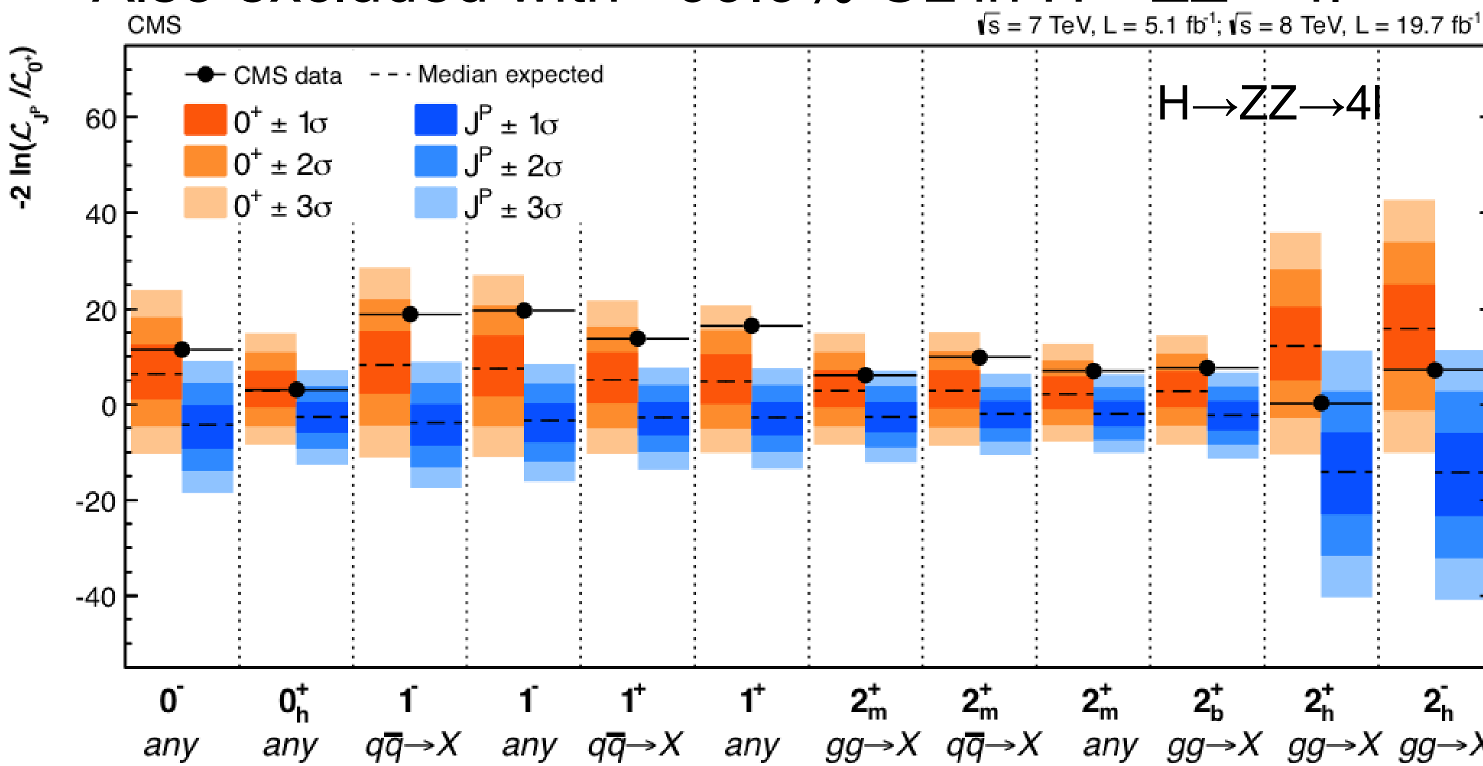
- Analyses test pairwise SM against alternative
- A discriminating variable is constructed from the available information eg. with a BDT or a matrix element method
- From this a likelihood ratio is calculated for the two hypotheses
- This is compared with toy experiments to derive a limit





Spin/CP results

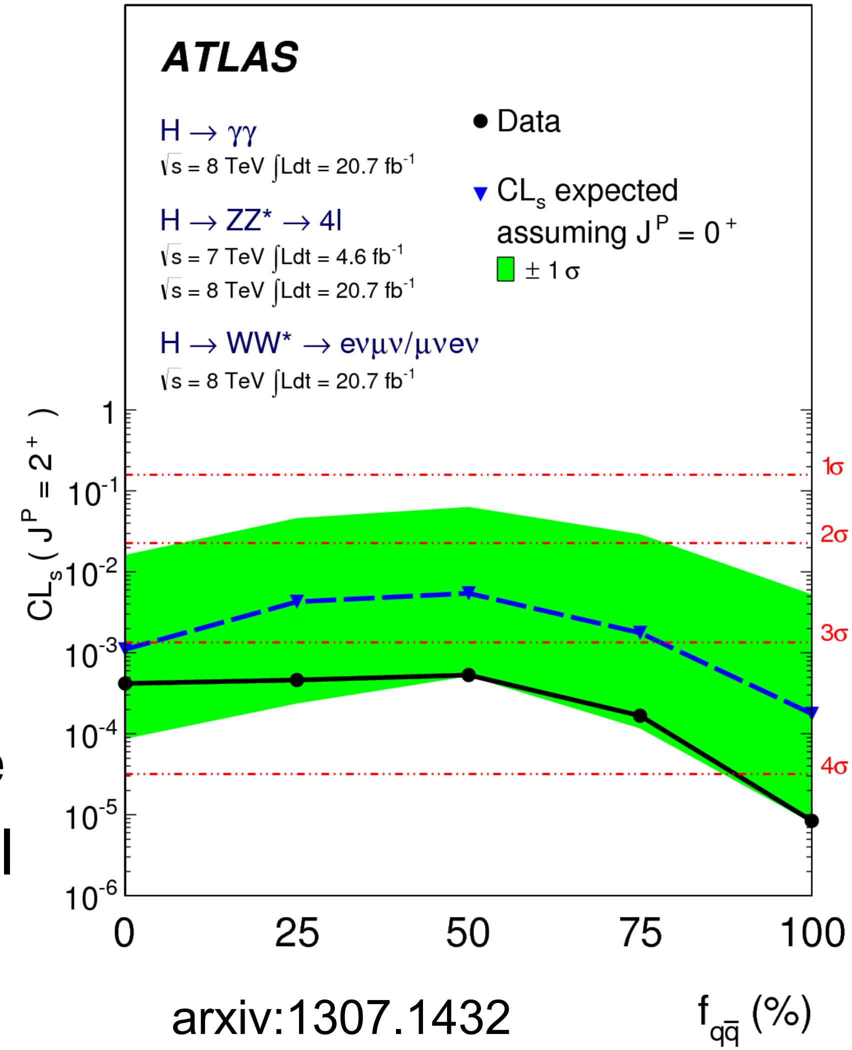
- 0^-:
  - Only decay angles sensitive ⇨ $H \to ZZ \to 4l$ used
  - Excluded with 97.8%/99.9% CL by ATLAS/CMS
- S=1:
  - Forbidden by Landau-Yang theorem for $H \to \gamma\gamma$
  - Also excluded with >99.9% CL in $H \to ZZ \to 4l$



arxiv:1312.5353

Spin/CP results (ii)

- S=2:
  - Complete coupling structure not yet studied
  - Most studies assume minimal couplings a la gravitons
  - First results for additional couplings exist
  - Analyses assume free mixture of gg and $q\bar{q}$ initial state
  - Different modes are complementary wrt initial state
  - S=2 in minimal coupling model is excluded with >99.9% CL independent of $q\bar{q}$ fraction



arxiv:1307.1432

Higgs couplings

- A single Higgs cross section is proportional to $\Gamma_i \Gamma_f / \Gamma_H$
- There is no model independent way to measure the Higgs width and consequently the partial widths
- Model independent measurements:
  - measure cross sections and express results as $\mu = \sigma_{meas}/\sigma_{SM}$
  - from fits to different categories can get ratio of partial widths of initial state
  - from ratio of different analyses can get ratio of partial widths of final state
- Any further interpretation needs model assumptions!
- In coupling fits experiments fit scale factors $\kappa_i = g_{i,meas}/g_{i,SM}$ $(\Gamma_i \propto \kappa_i^2)$

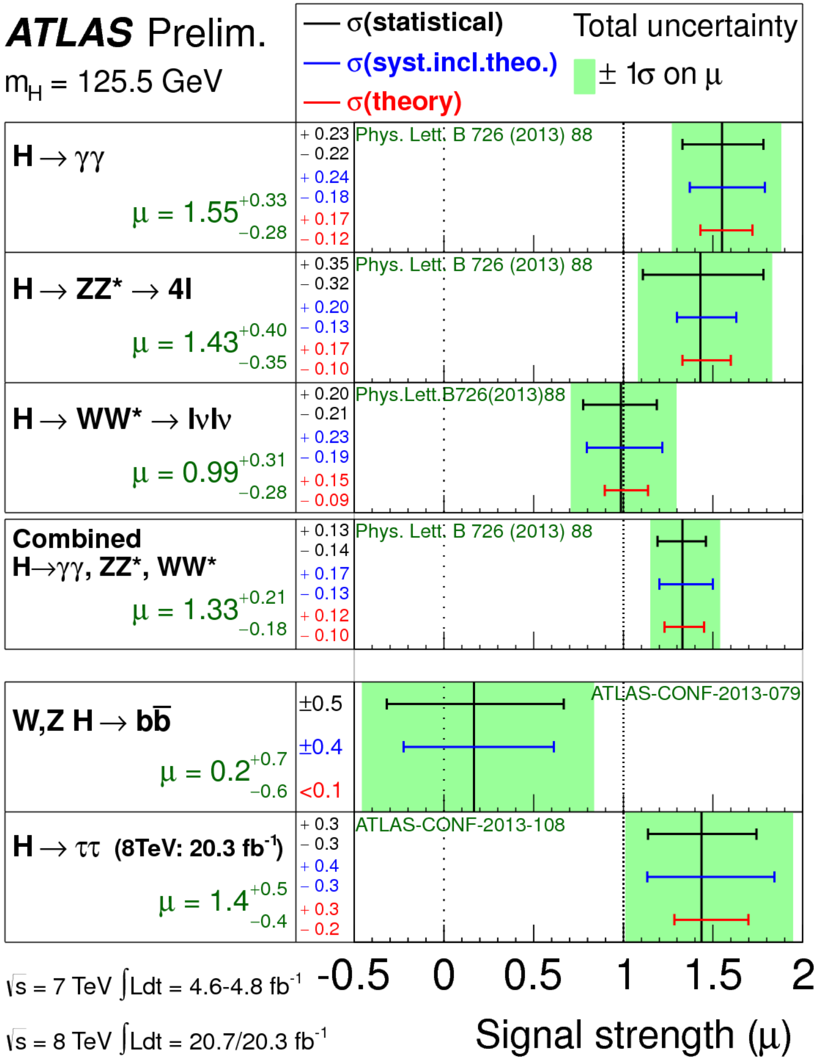
Higgs couplings

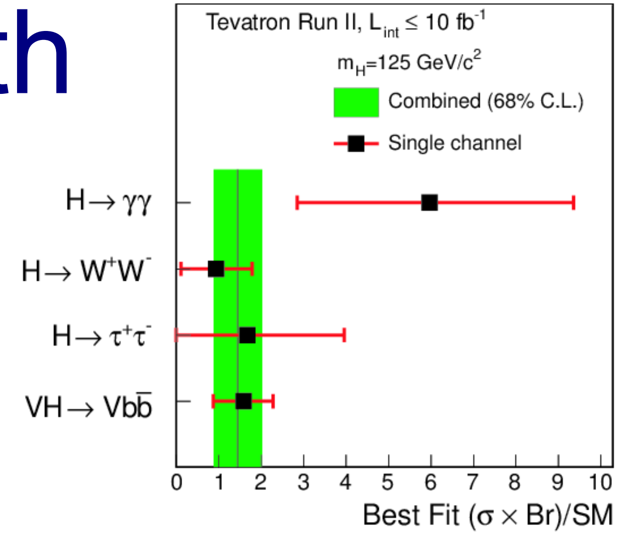
- A single Higgs cross section is proportional to ...
- There is no model independent way to ... width and consequently the parti...
- Model independent measu...
  - measure cross se... $\sigma_{meas}/\sigma_{SM}$
  - from fits to ... of partial widths ...
  - ... can get ratio of partial
- Any ... needs model assumptions!
- In co... periments fit scale factors $\kappa_i = g_{i,meas}/g_{i,SM}$ ($\Gamma_i \propto \kappa_i^2$ ...

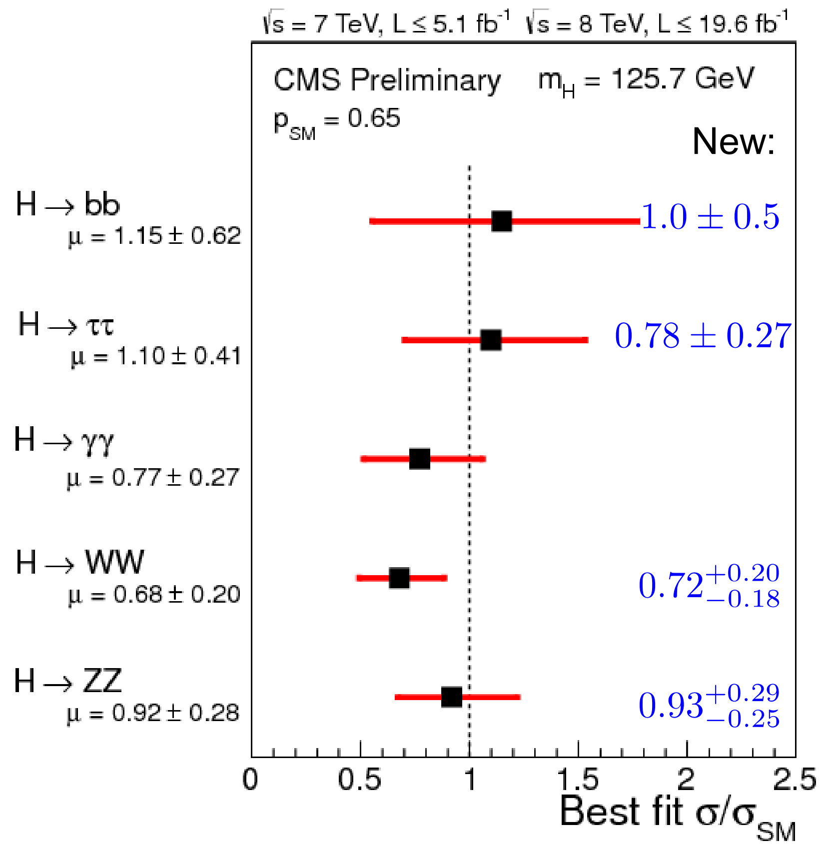
Disclaimer:
Some coupling fits have been done on now partially obsolete datasets
However since the old and new results agree with the SM prediction it is expected that the conclusions stay the same with smaller errors

Signal strength

- All results consistent with SM prediction

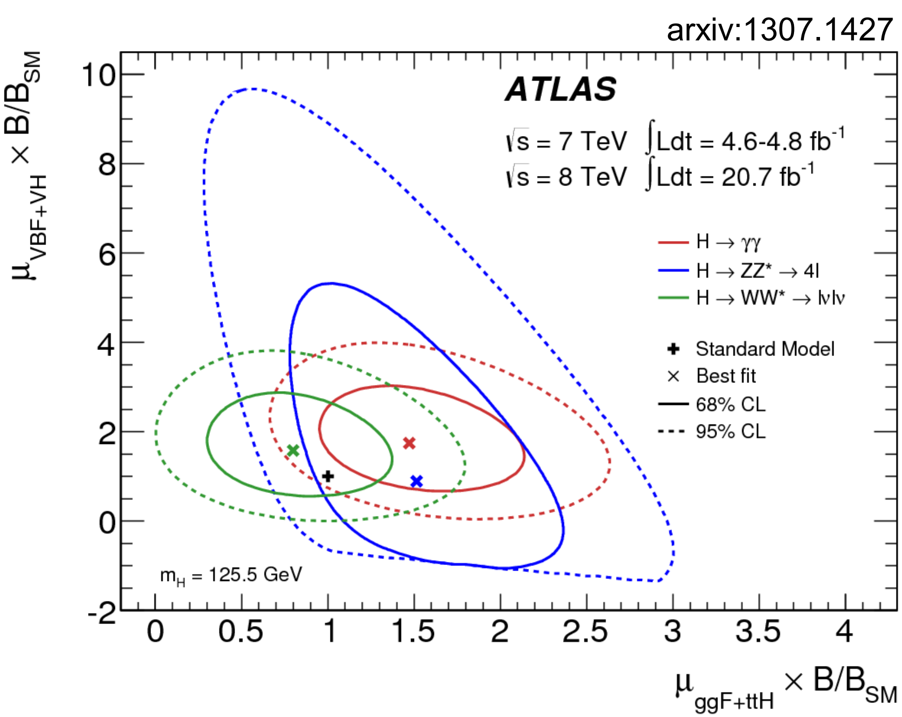


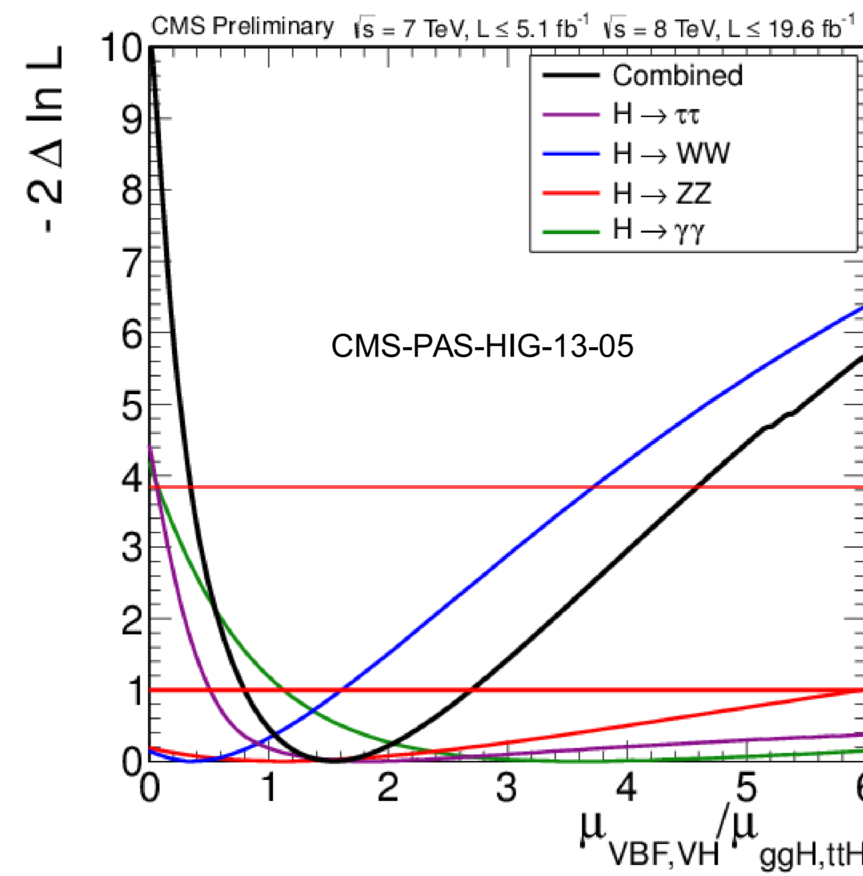




Higgs production modes

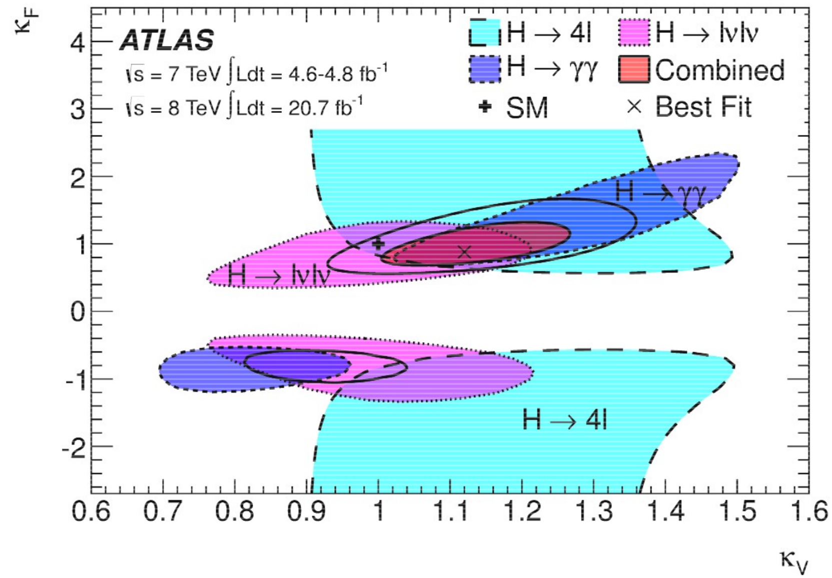
- 2D fits are only possible in μ_{prod}•BR
- The ratio can be obtained in a model independent way
- gg production is established without any doubt and vector boson production with >3σ

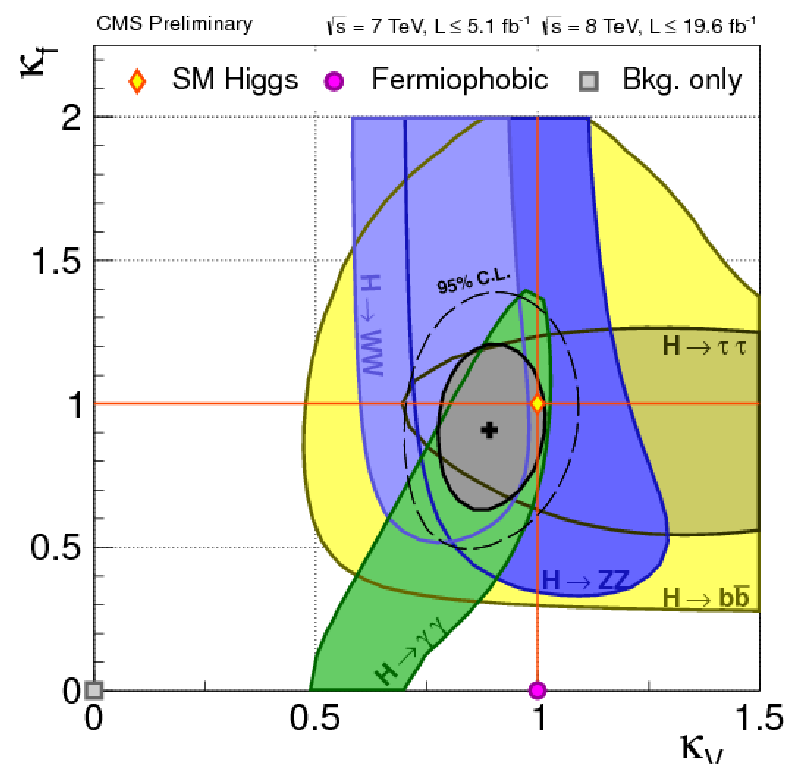




Fermion vs boson couplings

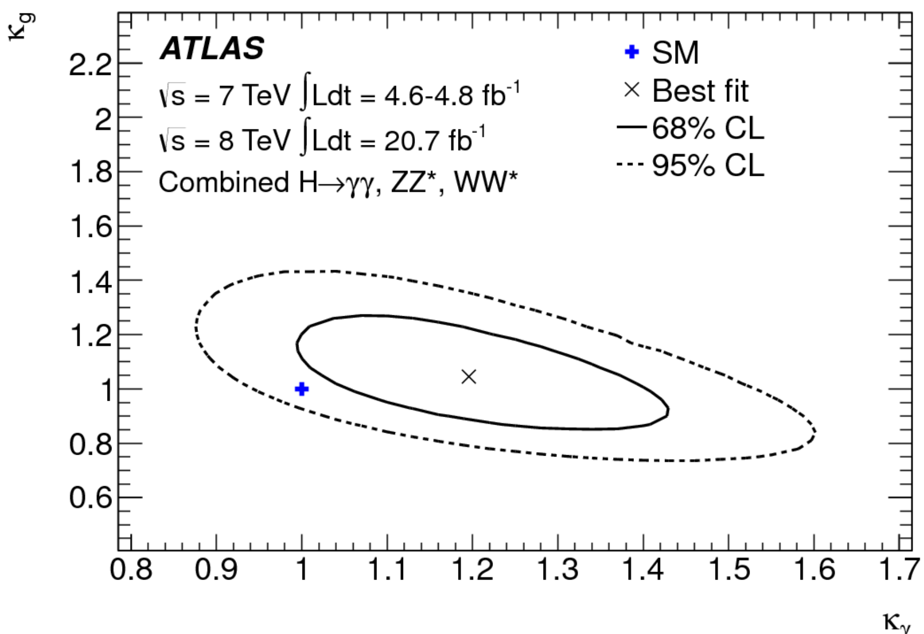
- Assume:
  - all fermion couplings scale with $\kappa_F(=\kappa_b=\kappa_t=\kappa_\tau...)$
  - all boson couplings scale with $\kappa_V(=\kappa_W=\kappa_Z)$
  - no BSM contributions to Γ_H and γ,g loops
- $\kappa_F,\kappa_V\neq0$ established at $>5\sigma$
- (κ_F mainly from gg-loop, direct evidence from both exp. around 4σ)

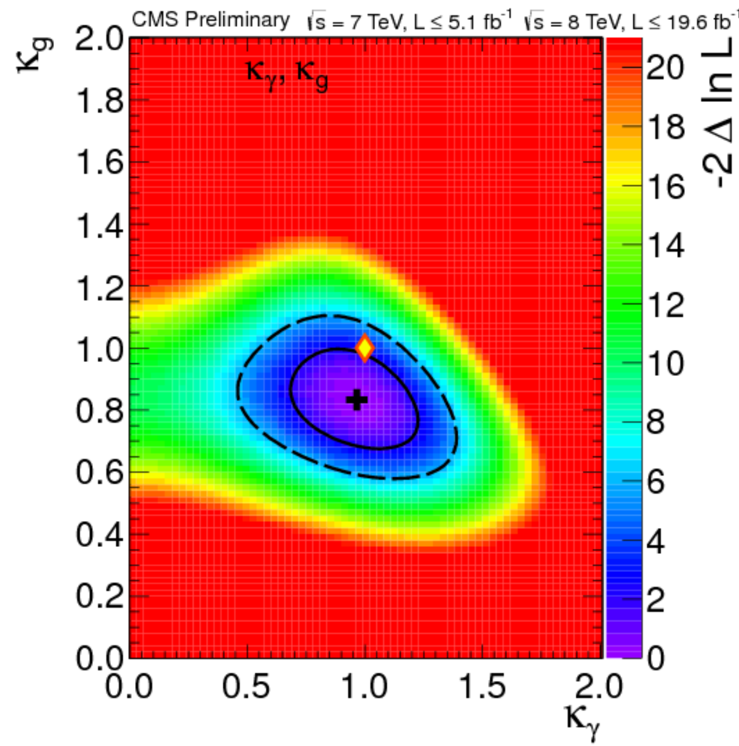




Loop induced couplings

- Assume:
  - all tree-level couplings to SM particles as in SM
  - no direct BSM contributions to Γ_H

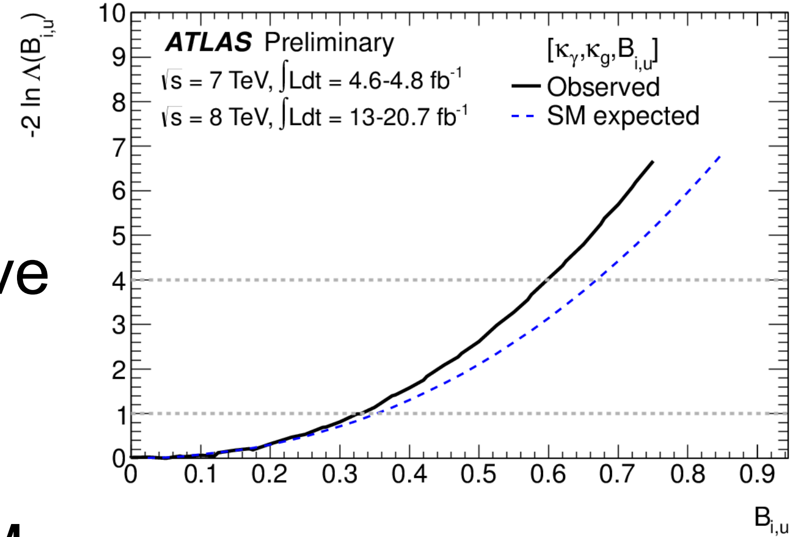


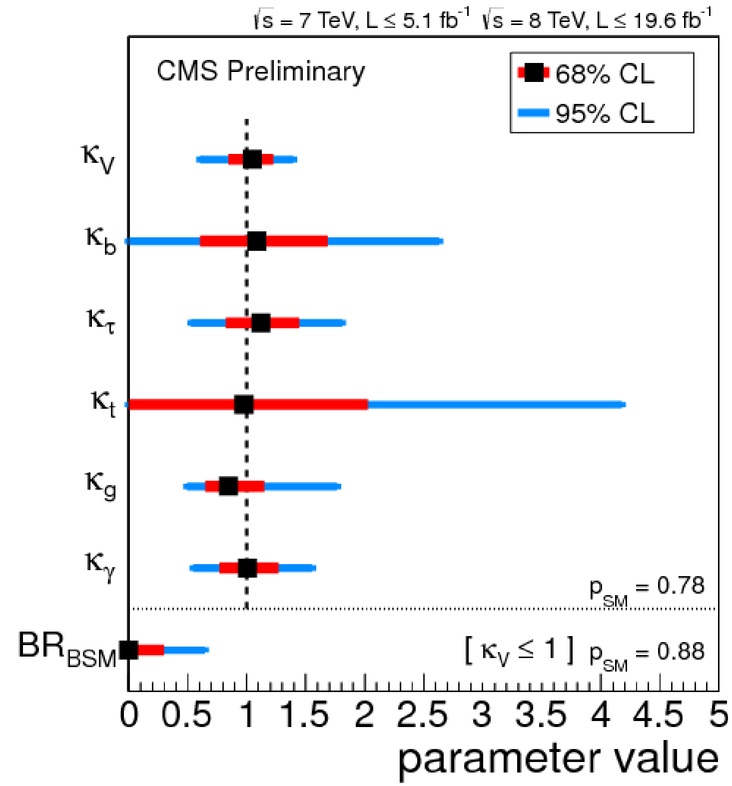


- κ_γ and κ_g compatible with 1 with ~15% uncertainty
- Puts limits on heavy (colour-)charged particles coupling to the Higgs

BSM couplings

- Direct searches ZH→ll+inv. gives BR(H→inv)<0.6 (95%C.L.)
- Parametrise $\Gamma_H=\Gamma_{SM}+\Gamma_{BSM}$ (sensitive to undetectable modes)
- ATLAS:
  - assume κ=1 for all tree level SM modes
  - fit for κ_γ, κ_g, BR_{BSM}
  - BR_{BSM}<0.60 (95%C.L.)
- CMS:
  - assume $\kappa_V \leq 1$
  - fit for κ_V, κ_b, κ_τ, κ_t, κ_γ, κ_g, BR_{BSM}
  - BR_{BSM}<0.64 (95%C.L.)





Conclusions and Outlook

- The Standard Model seems stronger than ever
  - All precision observables are described by the data at 2-loop level without ambiguities
  - A scalar particle has been found by the LHC
  - This particle has been measured by now in several bosonic and fermionic decay mode
  - This particle is compatible with the Higgs boson required by the minimal Brout-Englert-Higgs mechanism with a typical precision of 10-20%
- The LHC will continue with $\sqrt{s}$=13-14 TeV and higher luminosity in 2015
  - Higher precision Higgs measurement might show, if the BEH mechanism, realised in the SM, is indeed minimal
  - The higher mass reach may also show deviations from the SM in direct discoveries of new particles