ATLAS

Higgs Properties at the LHC

(focusing on results from CMS and combinations of CMS+ATLAS)

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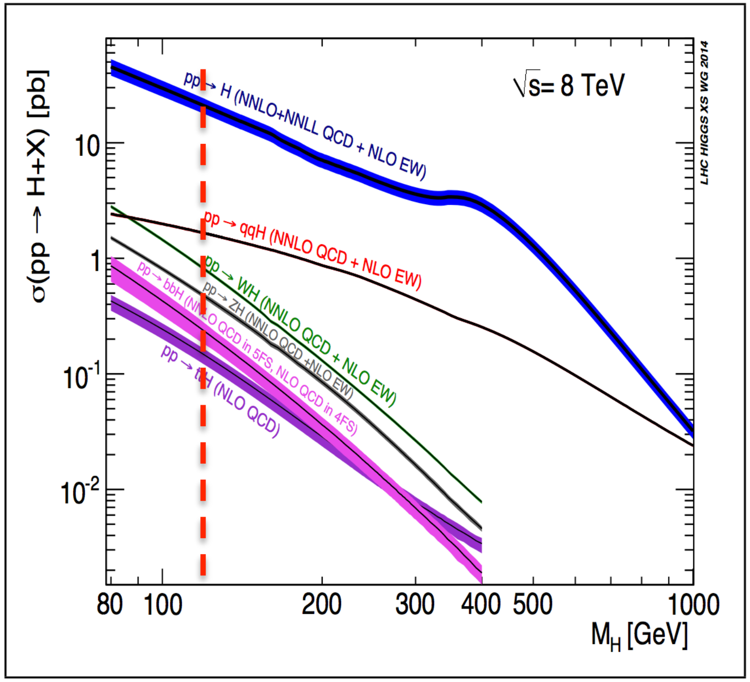
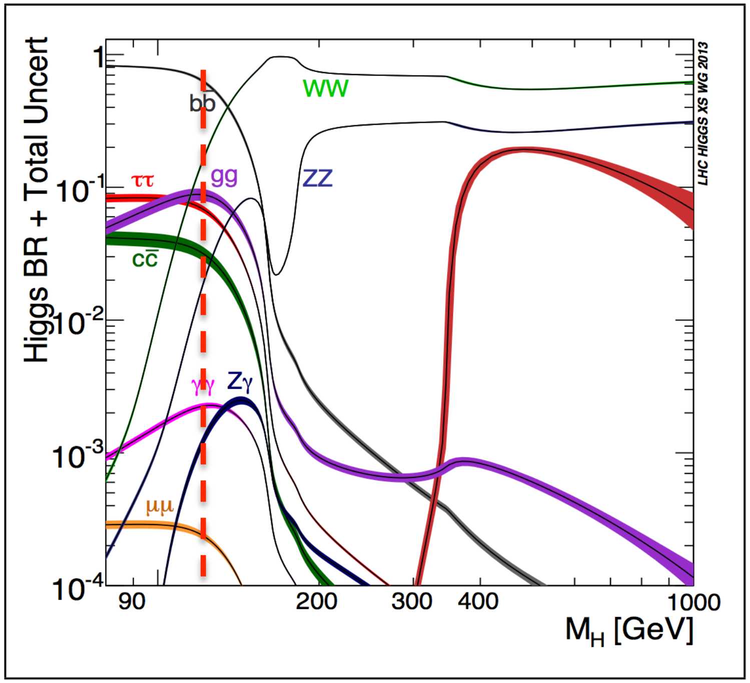
CMS

Introduction

- Discovery of the 125 GeV Higgs boson → a milestone
- Opportunity to investigate the Higgs sector of nature in detail
  - Studies of the properties of the new Higgs boson to test SM
  - Searches for new physics hints through the Higgs sector

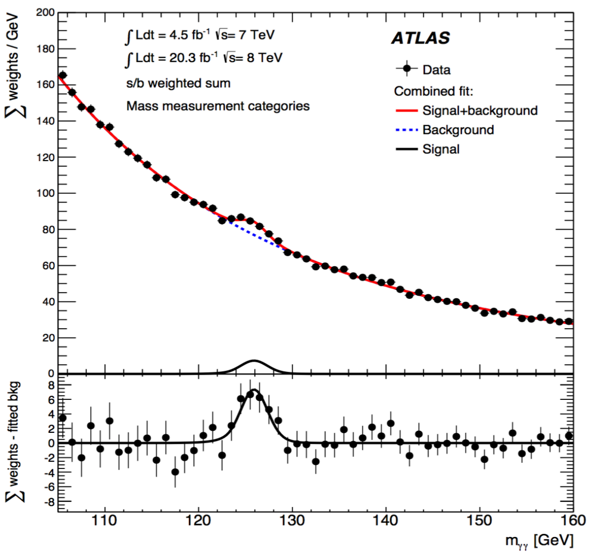


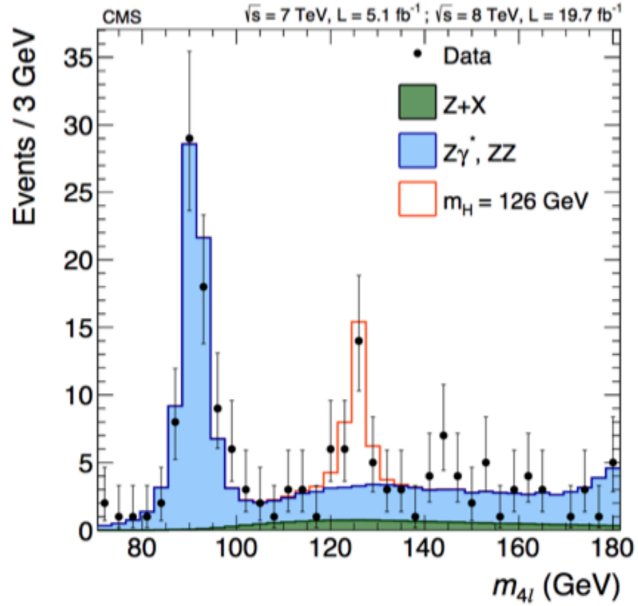
~1M Higgs produced in RUN 1

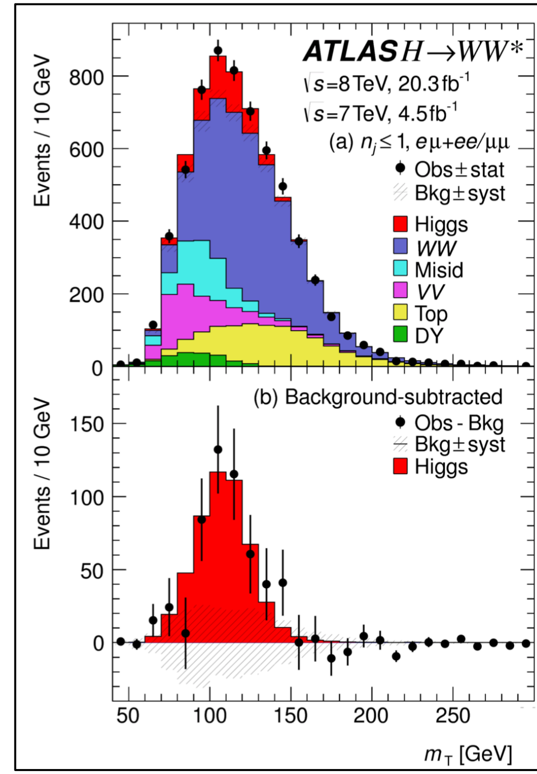


many decay channels

Current status: bosonic channels

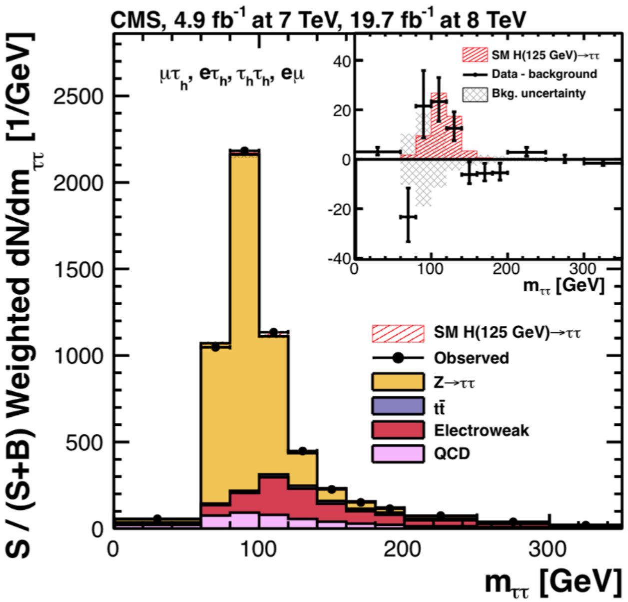


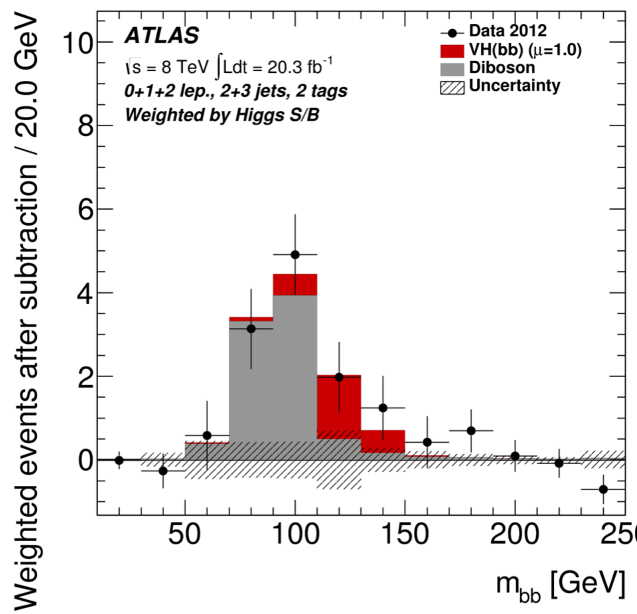


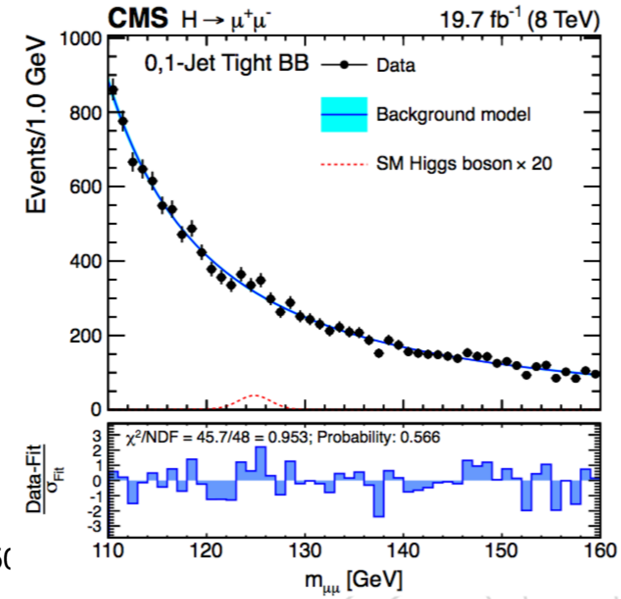


Significances obs (exp)	$H \rightarrow \gamma\gamma$	$H \rightarrow ZZ \rightarrow 4l$	$H \rightarrow WW \rightarrow 2l2\nu$
ATLAS 125.36 GeV	5.2 (4.6) σ	8.1 (6.2) σ	6.1 (5.8) σ
CMS 125.02 GeV	5.6 (5.3) σ	6.5 (6.3) σ	4.7 (5.4) σ

Current status: fermionic channels







Significances obs (exp)	H → ττ	H→bb	H→μμ
ATLAS 125.36 GeV	4.5 (3.4) σ	1.4 (2.6) σ	μ<7.0(7.2)@95%CL
CMS 125.02 GeV	3.2 (3.7) σ	2.6 (2.7) σ	μ<7.4(6.5)@95%CL

Next: measurements of its properties

Mass & width

Spin/Parity & CP mixing

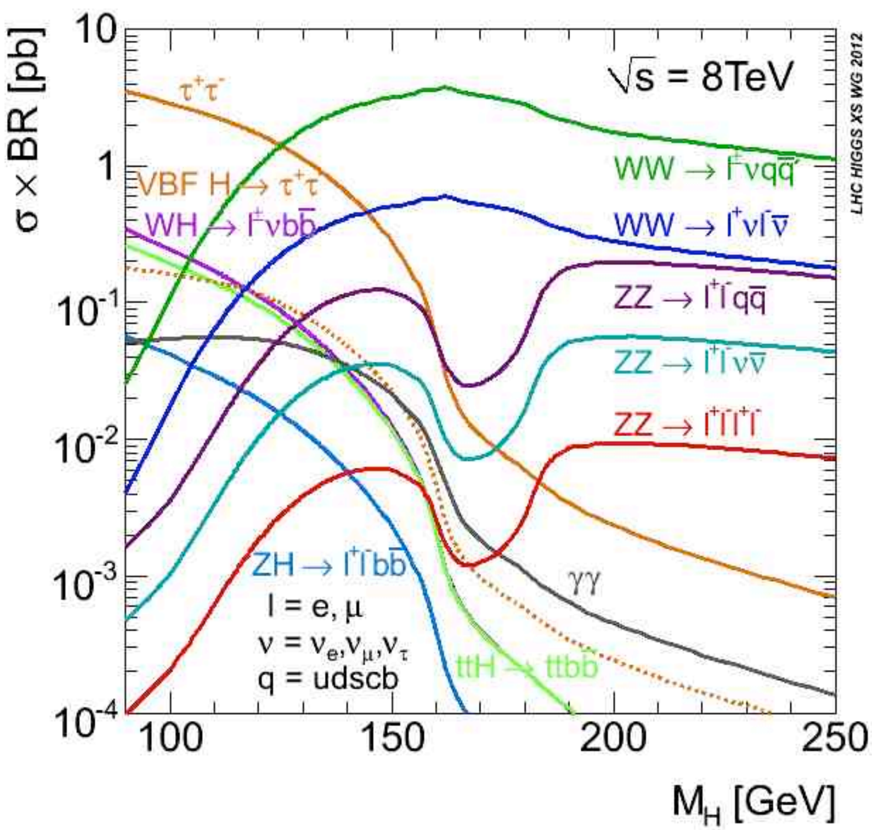
Signal strengths and couplings

Differential cross sections

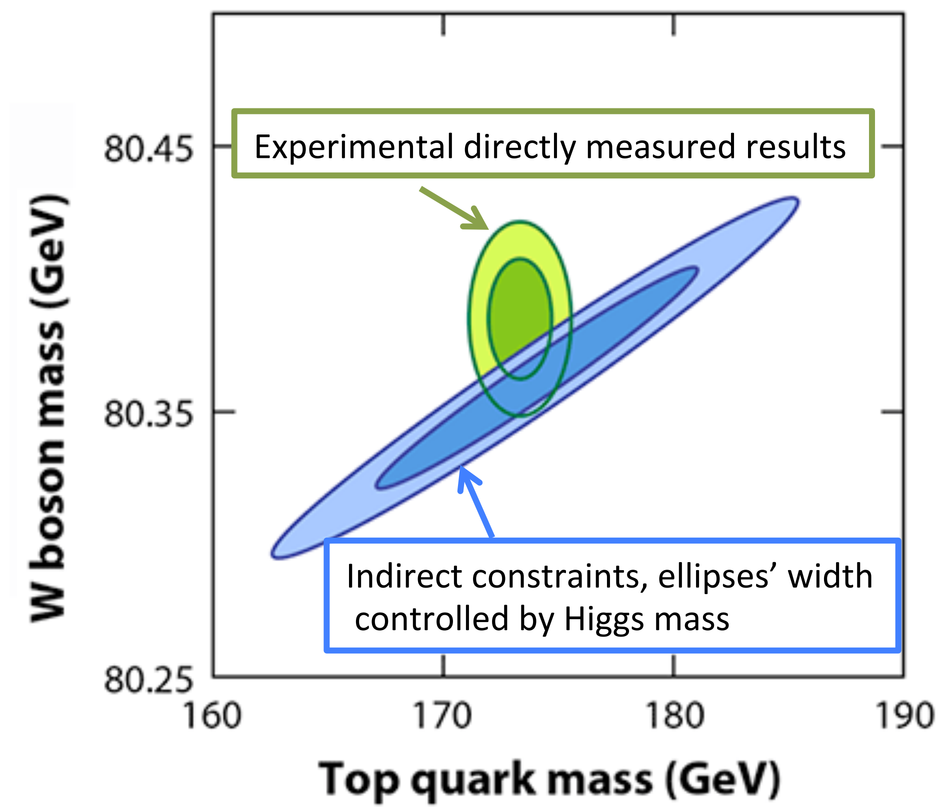
Higgs mass

- A fundamental parameter not predicted by theory
- More precise value enables physicists to make more stringent tests of the electroweak theory and of the Higgs boson's properties.

Higgs production cross section times branching ratio

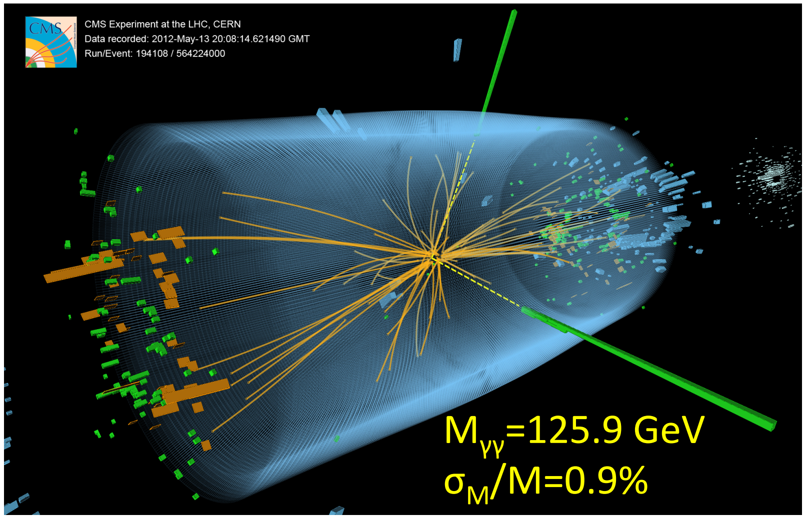


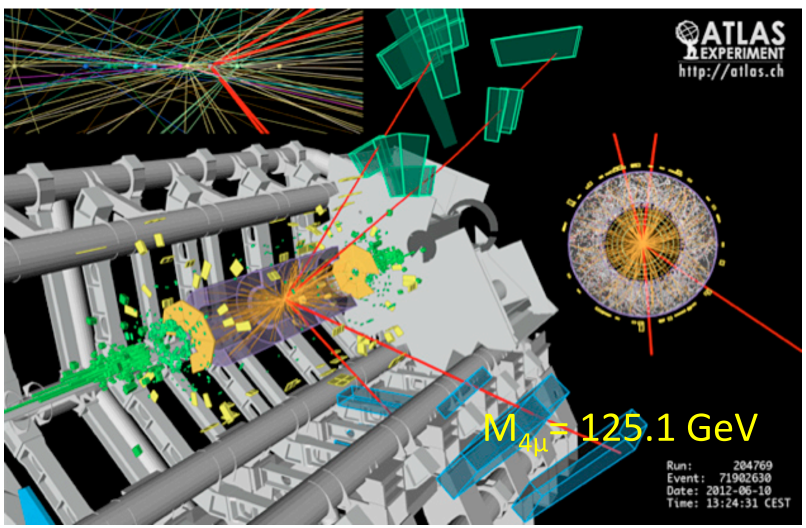
http://physics.aps.org/articles/v8/45

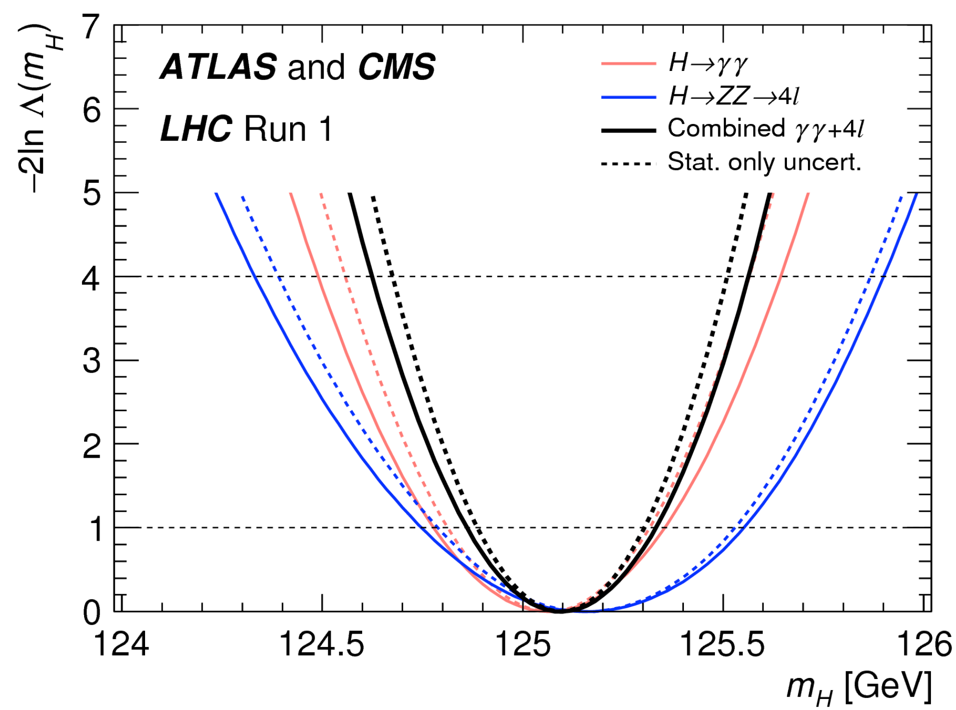


Higgs mass

- Measured in high resolution channels H→γγ and H→ZZ→4l





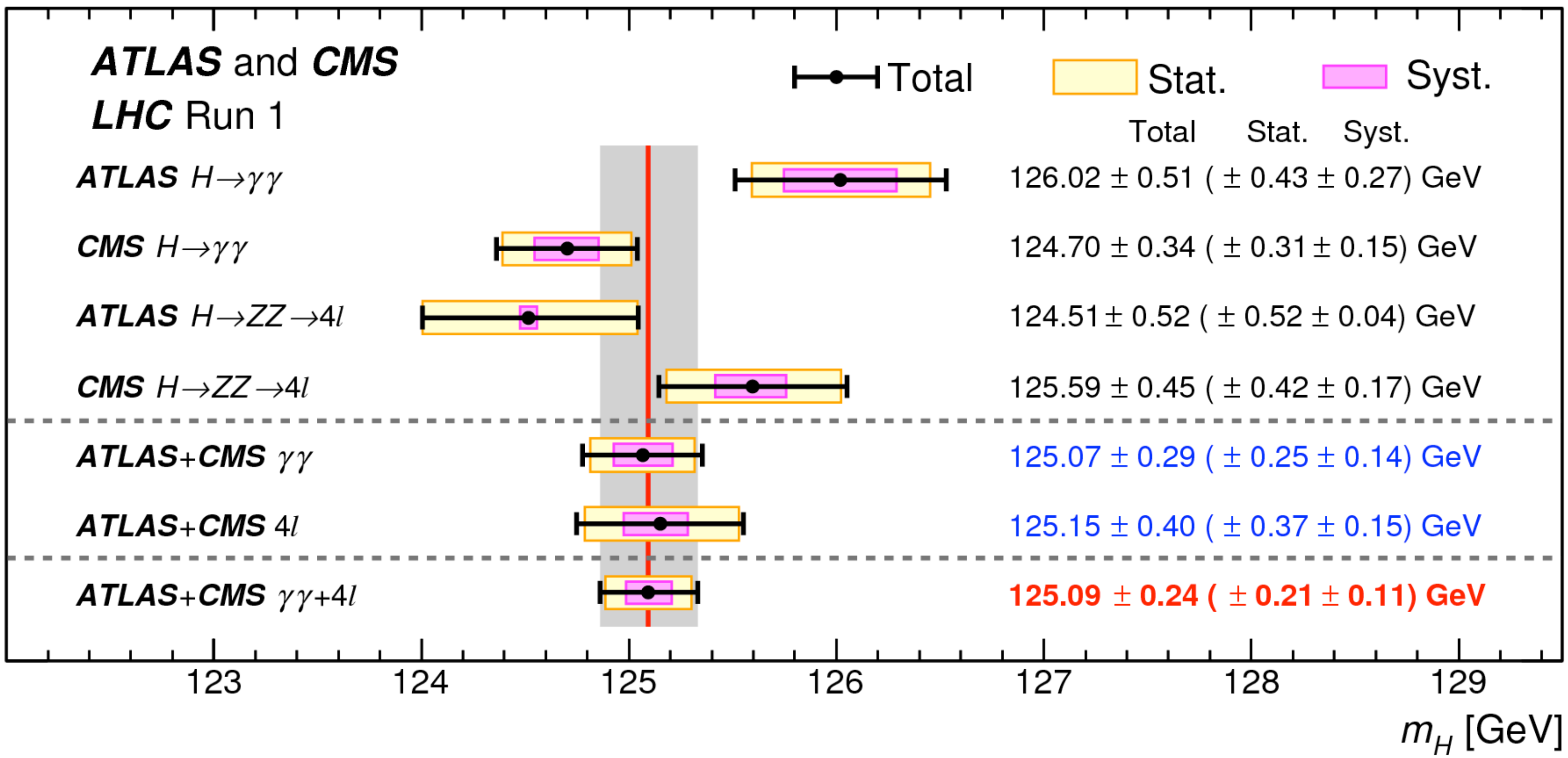


$M_H = 125.09 \pm 0.24$ GeV

$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

ATLAS+CMS PRL 114 (2015) 191803

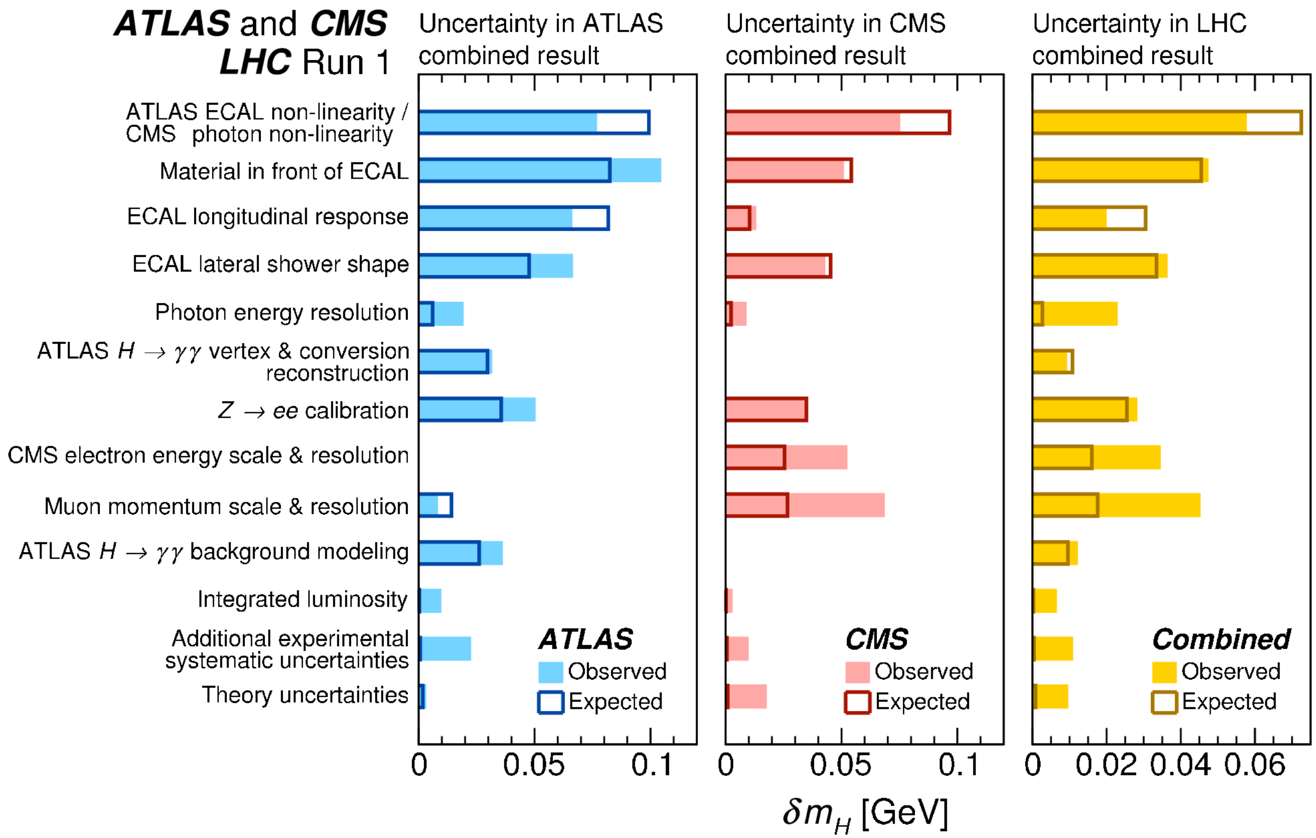
Higgs mass



Some tension between the four measurements (p-value ~10%) and opposite in ATLAS and CMS - very good agreement in the central values

Systematic uncertainties

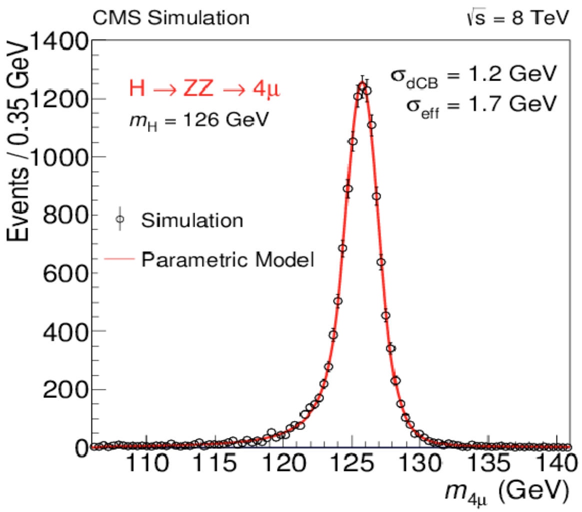
- Systematic uncertainties were studied carefully in preparation for couplings even if currently much smaller than statistical uncertainties for mass

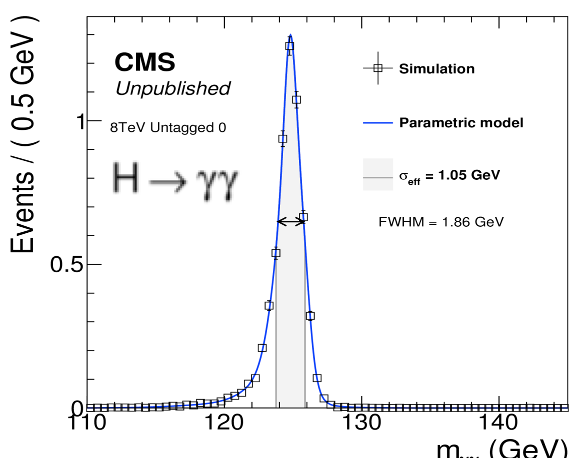


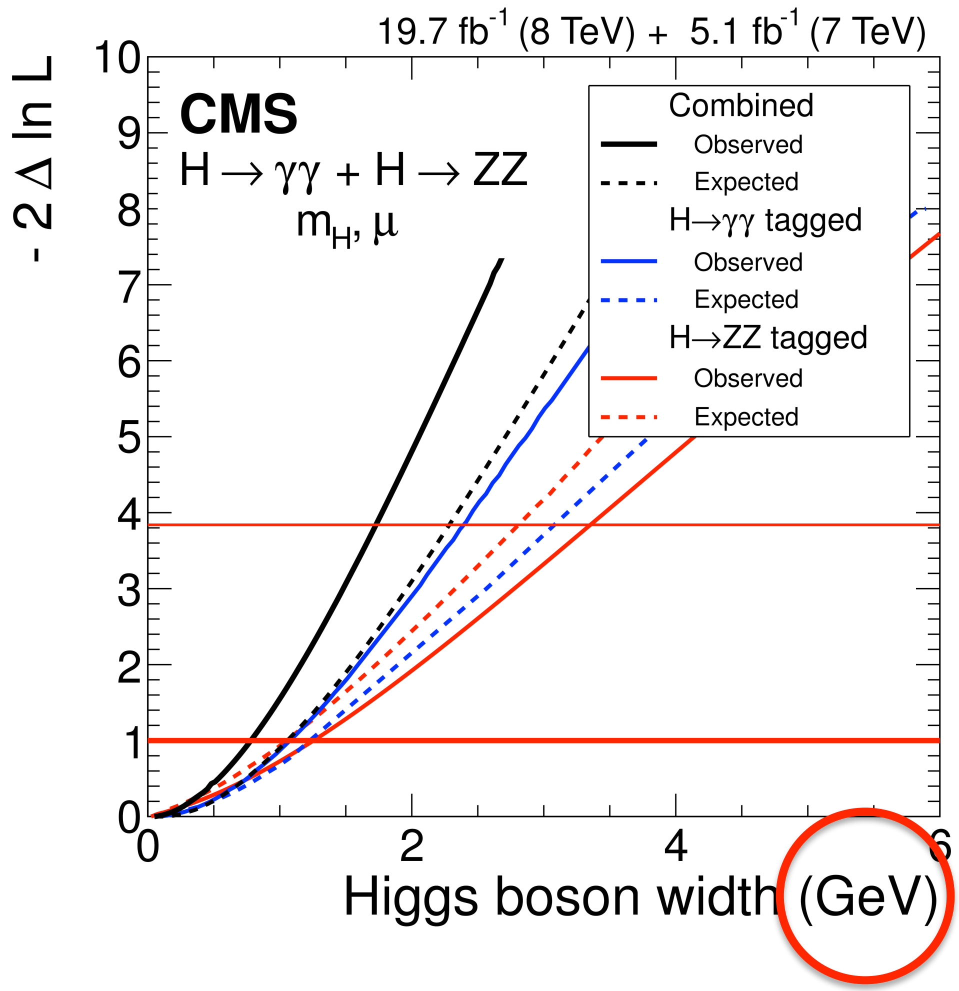
Energy scale uncertainties are the most important in the combination

Higgs total width : direct limit

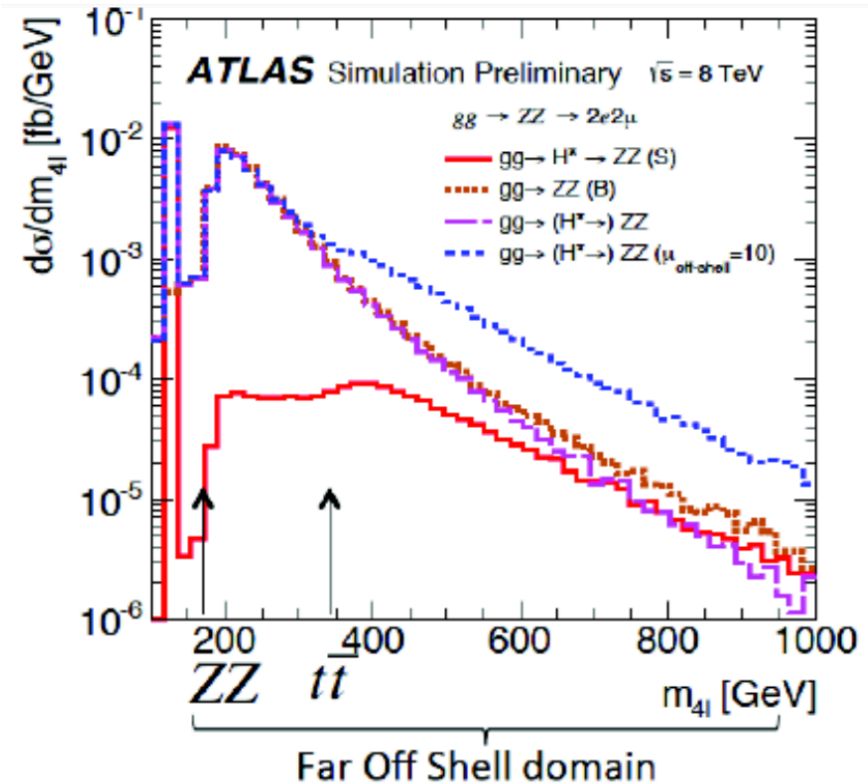
- 4 MeV predicted in SM, direct measurement from peak width limited by detector resolution (~1 GeV)







Higgs total width : on/off shell



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma^{gg\to H^*\to VV}_{\text{off-shell}}(\hat{s})}{\sigma^{gg\to H^*\to VV}_{\text{off-shell, SM}}(\hat{s})} = \kappa^2_{g,\text{off-shell}}(\hat{s}) \cdot \kappa^2_{V,\text{off-shell}}(\hat{s})$$

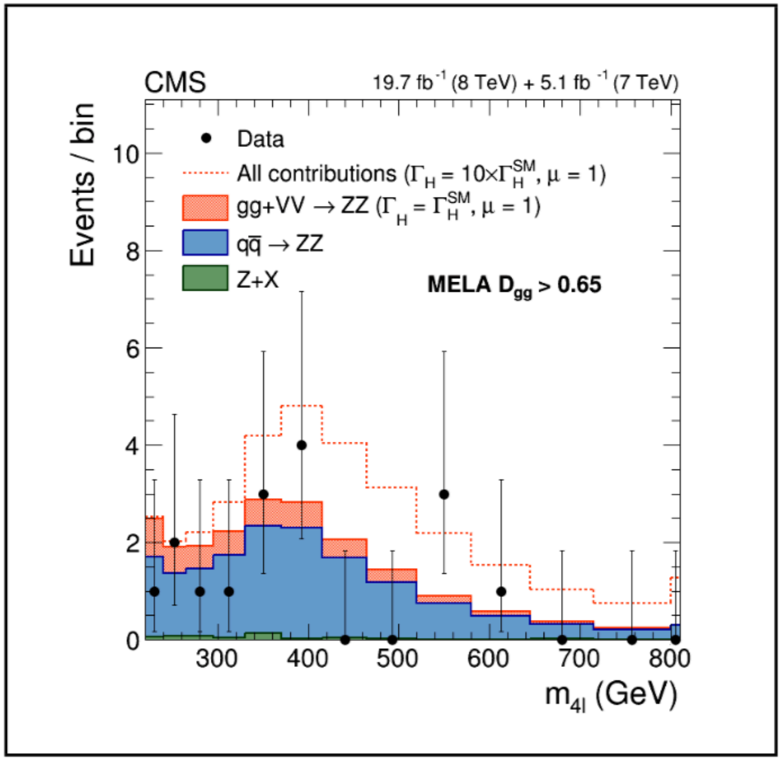
$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$

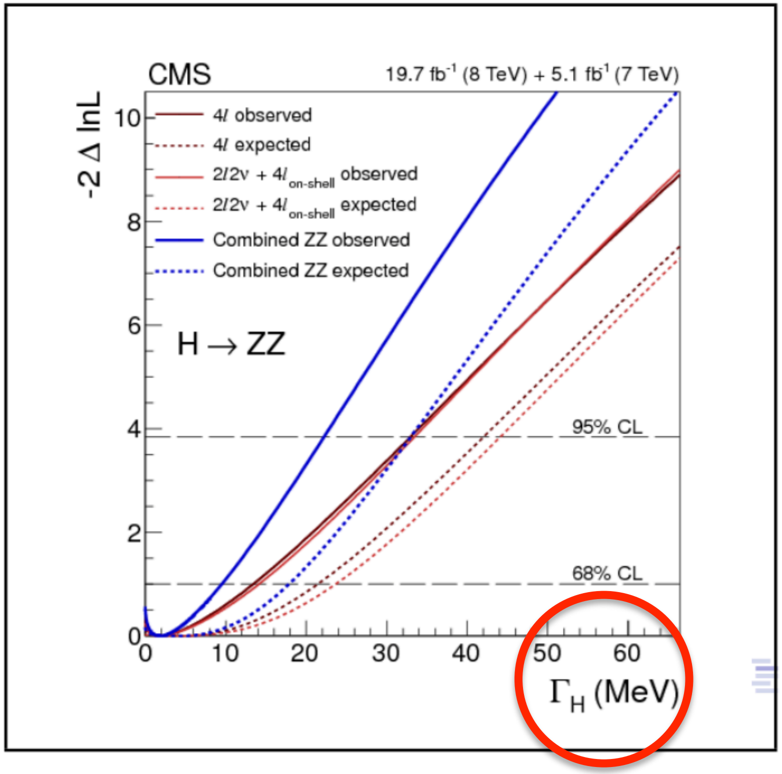
$$\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_{\text{H}}$$

The ratio of $\mu_{\text{off-shell}}$ to $\mu_{\text{on-shell}}$ provides a measurement of the total width of the Higgs boson, under several assumptions

Higgs total width : on/off shell

- Expect an excess of events at high m_{VV} for large Γ_H
- Use a multivariate discriminant to enhance sensitivity
- For $H \rightarrow ZZ$, may include both 4l and 2l2ν final states





Next: measurements of its properties

Mass & width

Spin/Parity & CP mixing

Signal strengths and couplings

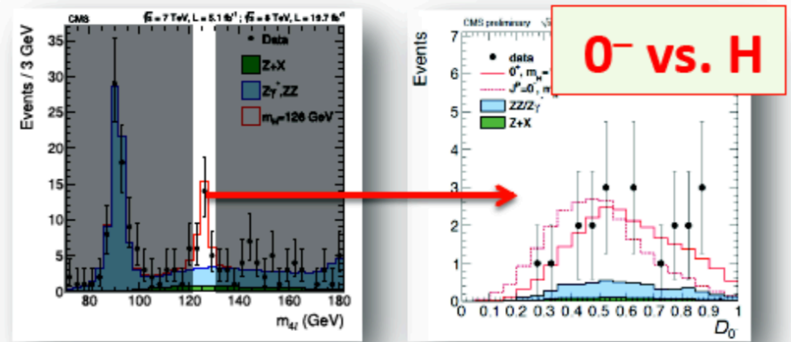
Differential cross sections

Spin-Parity test: $X(J^P)$ vs. $H(0^+)$

H→ZZ→4l

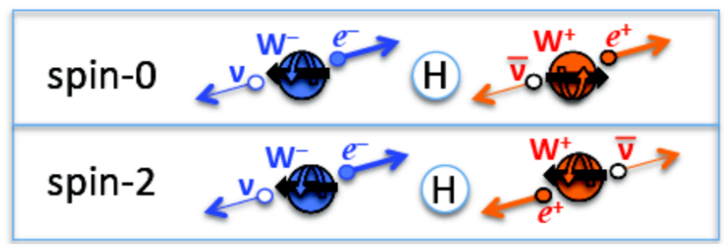
- 4l system is fully reconstructed
- use ME-based discriminator

$$d = \frac{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4 \middle| \mathrm{H}\right)\right|^2}{\left|ME\left(\vec{p}_1,\vec{p}_2,\vec{p}_3,\vec{p}_4 \middle| J^P\right)\right|^2}$$



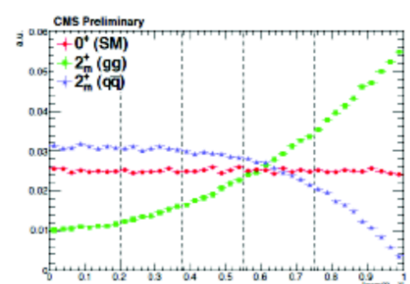
H→WW→lνlν

- di-lepton angle and mass are sensitive to the spin of the decaying $X(J^P)$



H→γγ

- J=1 forbidden (Landau-Yang theorem)
- cosθ* is the only variable sensitive to J^P information at leading order



- shown: before acceptance and reconstruction
- after acc x reco, discrim. power lessens
- poor S:B makes measurements difficult

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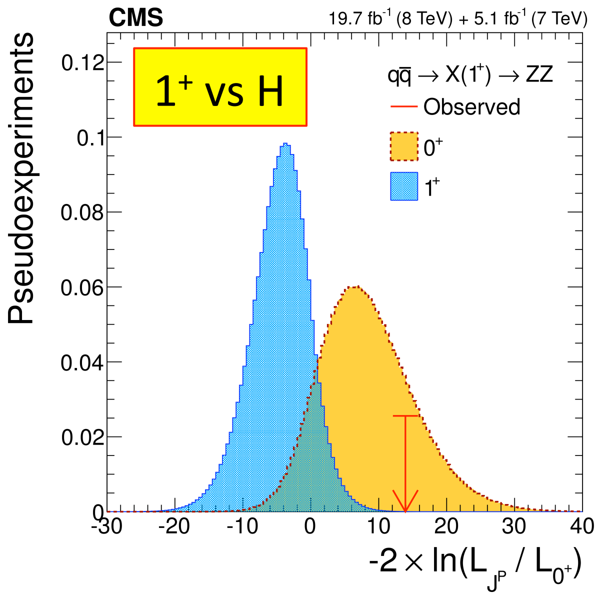
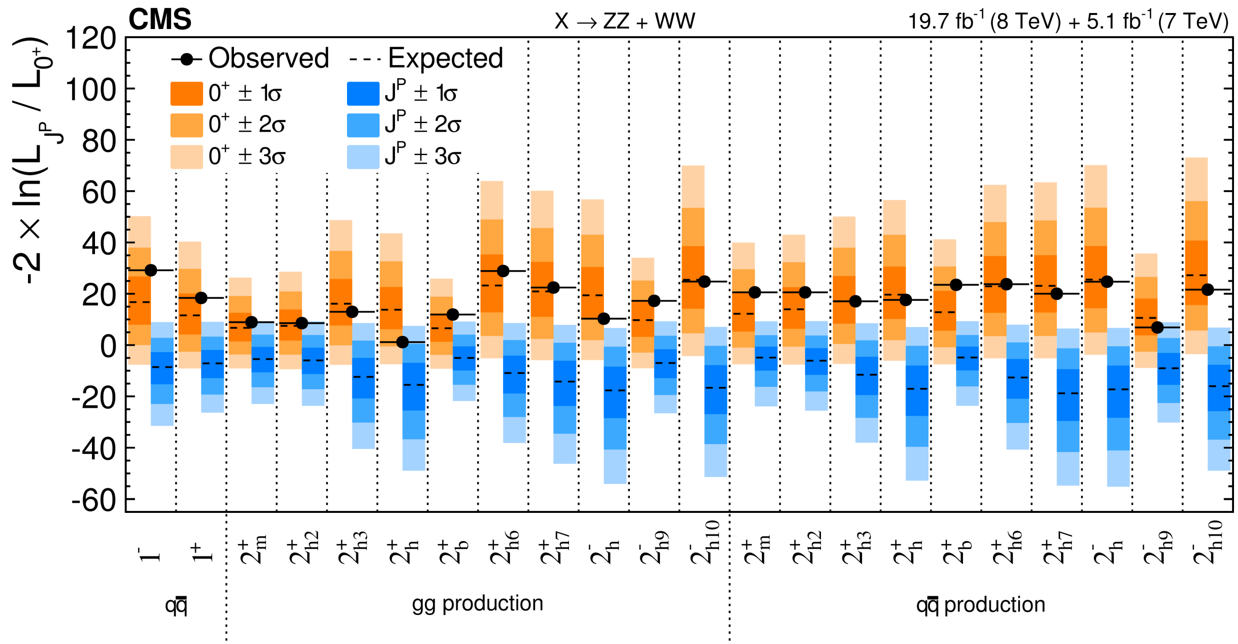
Spin-Parity results: $X(J^P)$ vs $H(0^+)$





In general data favors SM 0^+ hypothesis

Alternative tested pure states typically excluded at >99% CL

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CP mixing

Anomalous couplings (compatible with Lorentz and gauge invariance)

$$A(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{V_1V_2}} + \frac{\kappa_1^{\mathrm{V_1V_2}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{V_1V_2}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{V_1V_2}}\right)^2} \right] m_{\mathrm{V}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} f^{*(\mathrm{V_2}),\mu\nu} + a_3^{\mathrm{V_1V_2}} f_{\mu\nu}^{*(\mathrm{V_1})} \tilde{f}^{*(\mathrm{V_2}),\mu\nu}$$

Λ_1 term
leading momentum expansion

a_2 term
CP even state

a_3 term
CP odd state

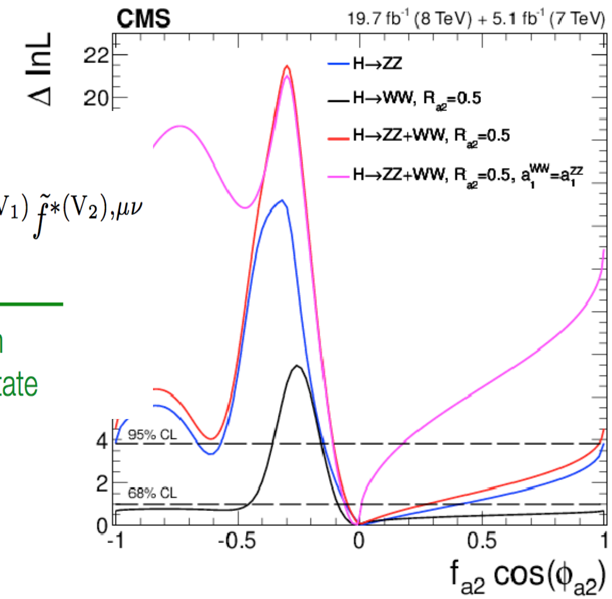
Tested parameters

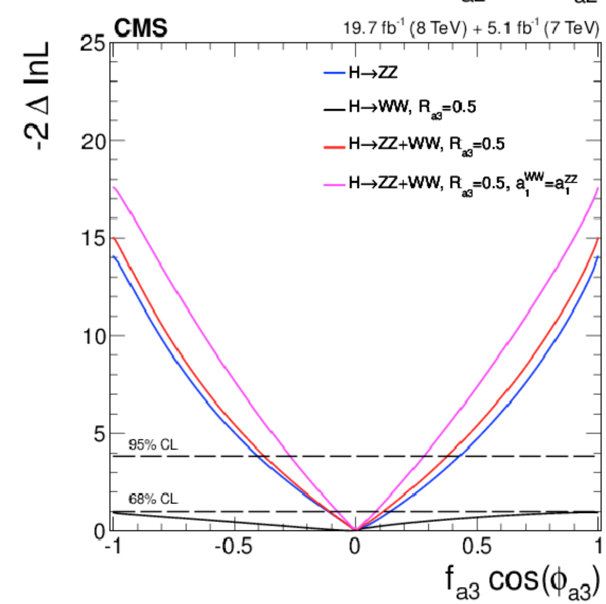
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}$$

$$\phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

Combination of $H \to ZZ^*$ and $H \to WW^*$

$$r_{ai} = \frac{a_i^{\mathrm{WW}}/a_1^{\mathrm{WW}}}{a_i/a_1}, \text{ or } R_{ai} = \frac{r_{ai}|r_{ai}|}{1 + r_{ai}^2}$$





No significant admixture of non-SM CP states

Next: measurements of its properties

Mass & width

Spin/Parity & CP mixing

Signal strengths and couplings

Differential cross sections

LHC Higgs coupling combination

Higgs production and decay – Run 1 input measurements

Channel	References for individual publications	
	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]
$H \to ZZ \to 4\ell$	[53]	[54]
$H \to WW$	[55, 56]	[57]
$H \to \tau\tau$	[58]	[59]
$H \to bb$	[38]	[39]
$H \to \mu\mu$	[60]	[61]
ttH production	[28, 62, 63]	[65]

ATLAS,CMS Higgs signal strength measurements, and signal searches used in this combination are documented in 17 journal publications

[28] ATLAS Collaboration, *Search for $H \to \gamma\gamma$ produced in association with top quarks and constraints on the Yukawa coupling between the top quark and the Higgs boson using data taken at 7 TeV and 8 TeV with the ATLAS detector*, Phys. Lett. **B740** (2015) 222, arXiv:1409.3122 [hep-ex].

[38] ATLAS Collaboration, *Search for the $b\bar{b}$ decay of the Standard Model Higgs boson in associated $(W/Z)H$ production with the ATLAS detector*, JHEP **1501** (2015) 069, arXiv:1409.6212 [hep-ex].

[39] CMS Collaboration, *Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks*, Phys. Rev. D **89** (2014) 012003, arXiv:1310.3687 [hep-ex].

[51] ATLAS Collaboration, *Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D90** (2014) 112015, arXiv:1408.7084 [hep-ex].

[52] CMS Collaboration, *Observation of the diphoton decay of the 125 GeV Higgs boson and measurement of its properties*, Eur. Phys. J. C 74 (2014) 3076, arXiv:1407.0558 [hep-ex].

[53] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. **D91** (2015) 012006, arXiv:1408.5191 [hep-ex].

[54] CMS Collaboration, *Measurement of the properties of a Higgs boson in the four-lepton final state*, Phys. Rev. D 89 (2014) 092007, arXiv:1312.5353 [hep-ex].

[55] ATLAS Collaboration, *Observation and measurement of Higgs boson decays to WW^* with the ATLAS detector*, Phys. Rev. D92 (2015) 012006, arXiv:1412.2641 [hep-ex].

[56] ATLAS Collaboration, *Study of the Higgs boson decaying to WW^* produced in association with a weak boson with the ATLAS detector at the LHC*, JHEP **1508** (2015) 137, arXiv:1506.06641 [hep-ph].

[57] CMS Collaboration, *Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states*, JHEP **01** (2014) 096, arXiv:1312.1129 [hep-ex].

[58] ATLAS Collaboration, *Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*, arXiv:1501.04943 [hep-ex].

[59] CMS Collaboration, *Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons*, JHEP **05** (2014) 104, arXiv:1401.5041 [hep-ex].

[60] ATLAS Collaboration, *Search for the Standard Model Higgs boson decay to $\mu^+\mu^-$ with the ATLAS detector*, Phys. Lett. **B738** (2014) 68, arXiv:1406.7663 [hep-ex].

[61] CMS Collaboration, *Search for a standard model-like Higgs boson in the $\mu^+\mu^-$ and e^+e^- decay channels at the LHC*, Phys. Lett. B (2015), arXiv:1410.6679 [hep-ex].

[62] ATLAS Collaboration, *Search for the Standard Model Higgs boson produced in association with top quarks and decaying into $b\bar{b}$ in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Eur. Phys. J. C **75** (2015) 349, arXiv:1503.05066 [hep-ex].

[63] ATLAS Collaboration, *Search for the associated production of the Higgs boson with a top quark pair in multi-lepton final states with the ATLAS detector*, ATLAS-CONF-2015-007 (2015).

[65] CMS Collaboration, *Search for the associated production of the Higgs boson with a top-quark pair*, JHEP **09** (2014) 087, arXiv:1408.1682 [hep-ex].

+ CMS and ATLAS individual combinations:
Eur. Phys. J. C 75 (2015) 212, arXiv:1507.04548

Input channels

Deacay/Production	Untagged	VBF	VH	ttH
H→γγ				
H→ZZ→4l				
H→ZZ→4l				
H→ττ				
H→bb				
H→μμ				

- Other production modes included in the fit and selected by other channels but not specifically tagged, e.g. tH is selected by the ttH analyses
- Directly sensitive to the couplings of H to W, Z and γ bosons and to τ, b and t fermions + indirectly to gluons and t-quarks
- Full combination ~580 signal/control regions, and ~4200 nuisances
- Gain a factor √2 in precision (still statistics limited, including many syst.)

Signal strength μ

- μ is the so called signal strength (μ=1 in the SM):

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{\mathrm{BR}^f_{\mathrm{SM}}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

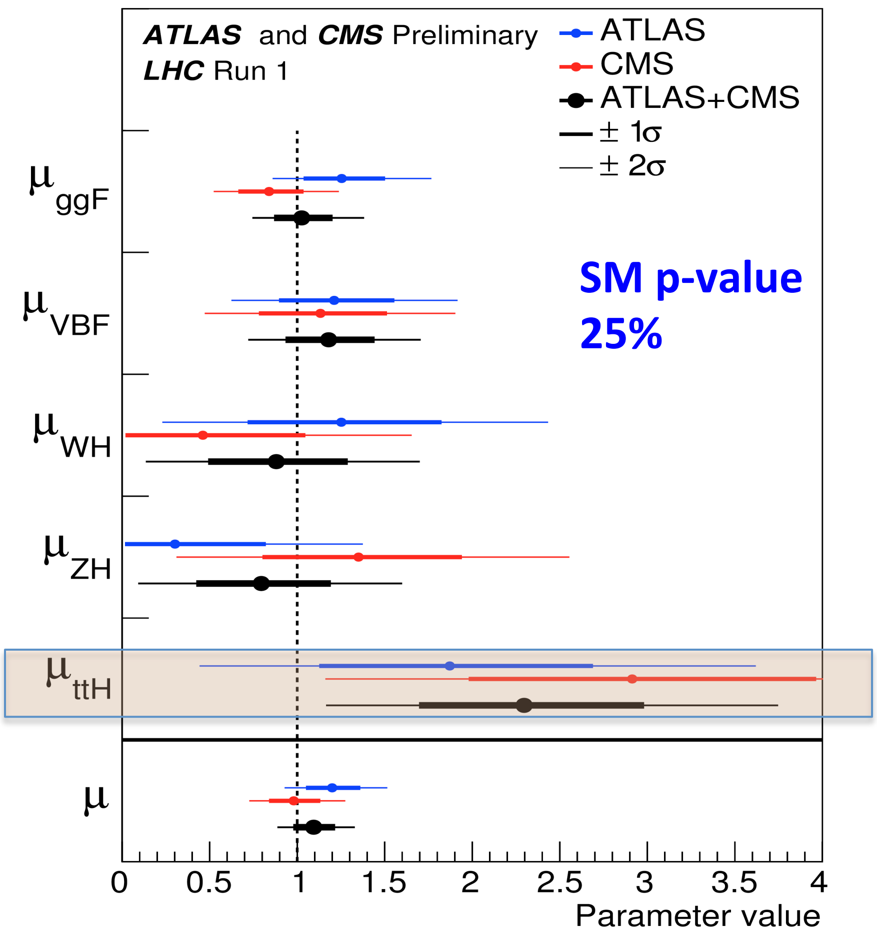
- Most constrained parameterization: one single signal strength μ (and assuming the same at 7 and 8 TeV)

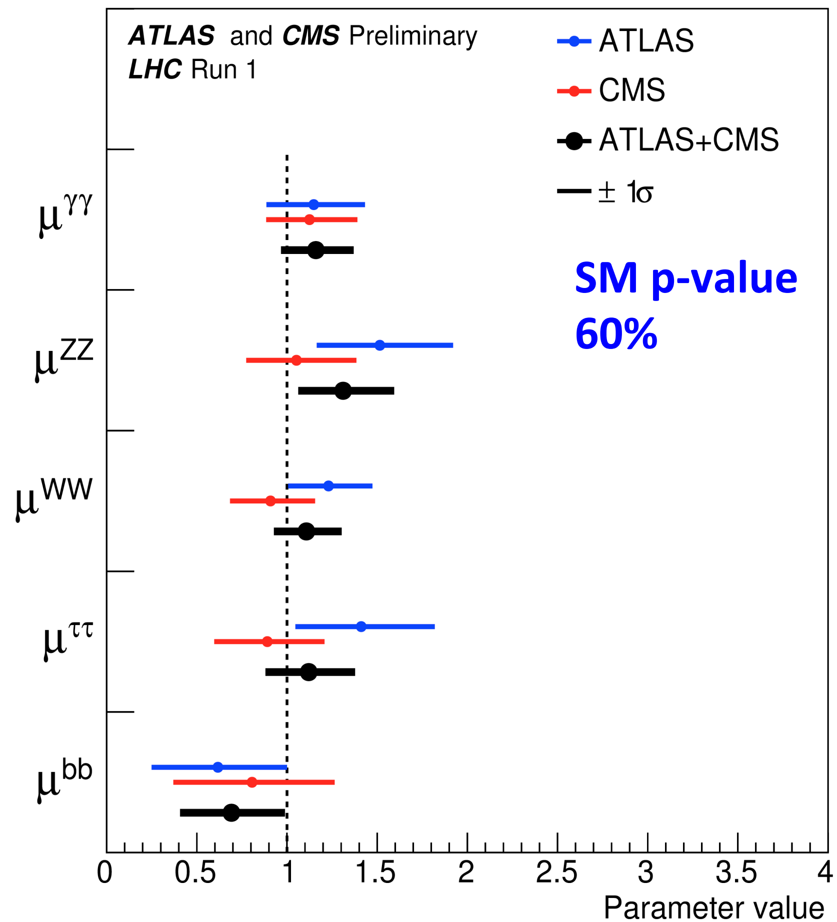
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\mathrm{stat})\,^{+0.04}_{-0.04}\,(\mathrm{expt})\,^{+0.03}_{-0.03}\,(\mathrm{thbgd})^{+0.07}_{-0.06}\,(\mathrm{thsig})$$

- Signal theory uncertainty due to QCD scale and PDF as large as statistical uncertainty

Productions and decays

- Best-fit signal-strength values of different production/ decay modes determined from the combined fits





Significances in different channels

- First observations of VBF and H→ττ achieved through the LHC combination

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to b\bar{b}$	2.6	3.7

Coupling fits: κ-framework

- The k-framework has been developed within the LHC Higgs Cross Section WG

$$\sigma(i \to H \to f) = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

- Higgs boson couplings are scaled by coupling modifiers κ, defined as

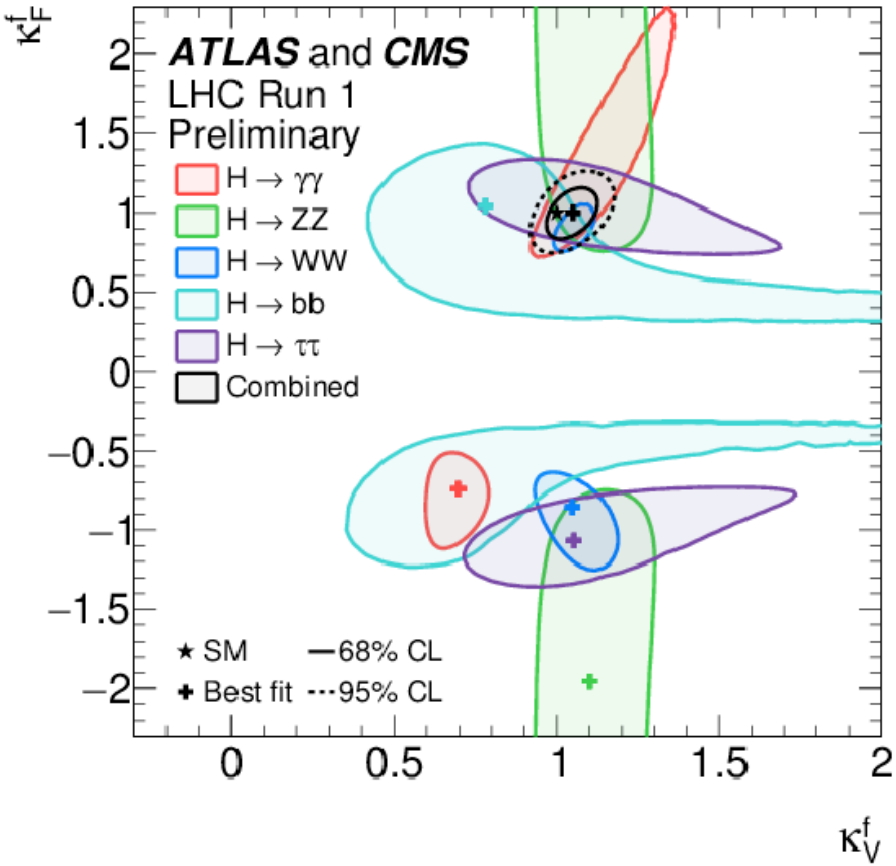
$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \quad \text{or} \quad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

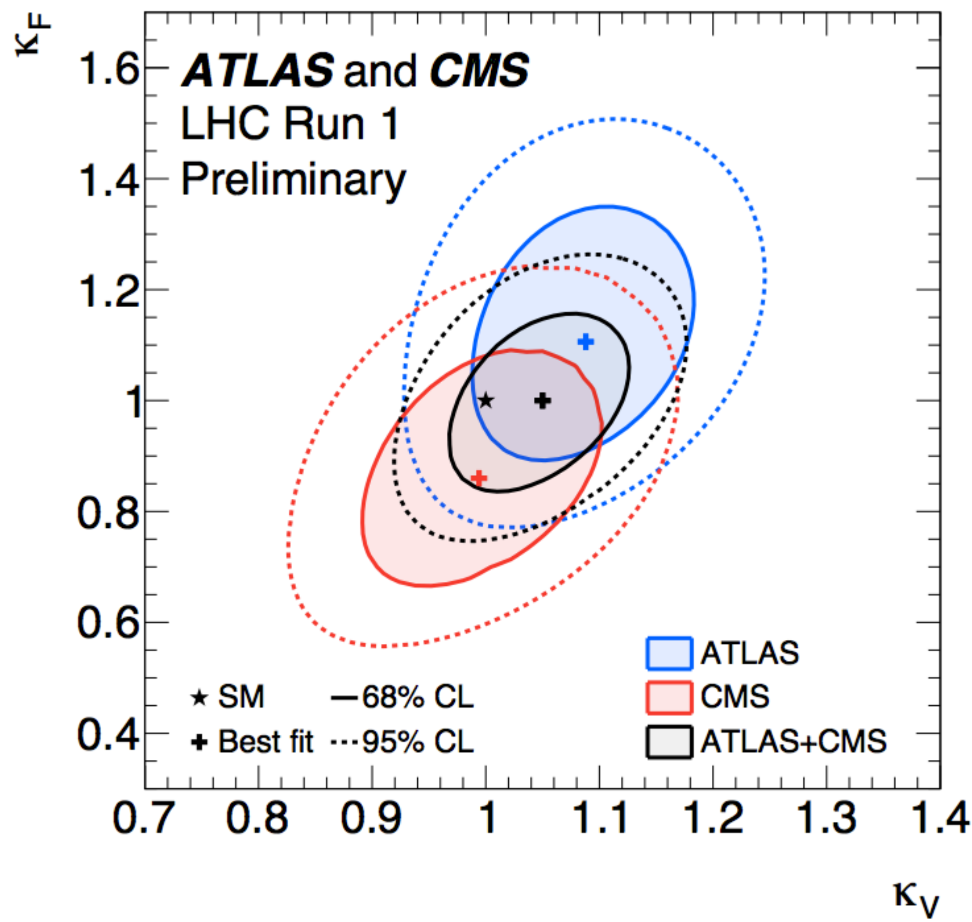
$$\kappa_H^2 = \sum_j \mathrm{BR}^j_{\mathrm{SM}} \kappa_j^2 \qquad \Gamma_\mathrm{H} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$

- With $\mathrm{BR}_{\mathrm{BSM}}$ the BR of invisible + undetected decays
    - Undetected decays can be either non SM decays or come from different BRs of known but not measured decays: cc, gg, …

κ_V, κ_F contours

- All vector and fermion couplings are scaled by κ_V and κ_F

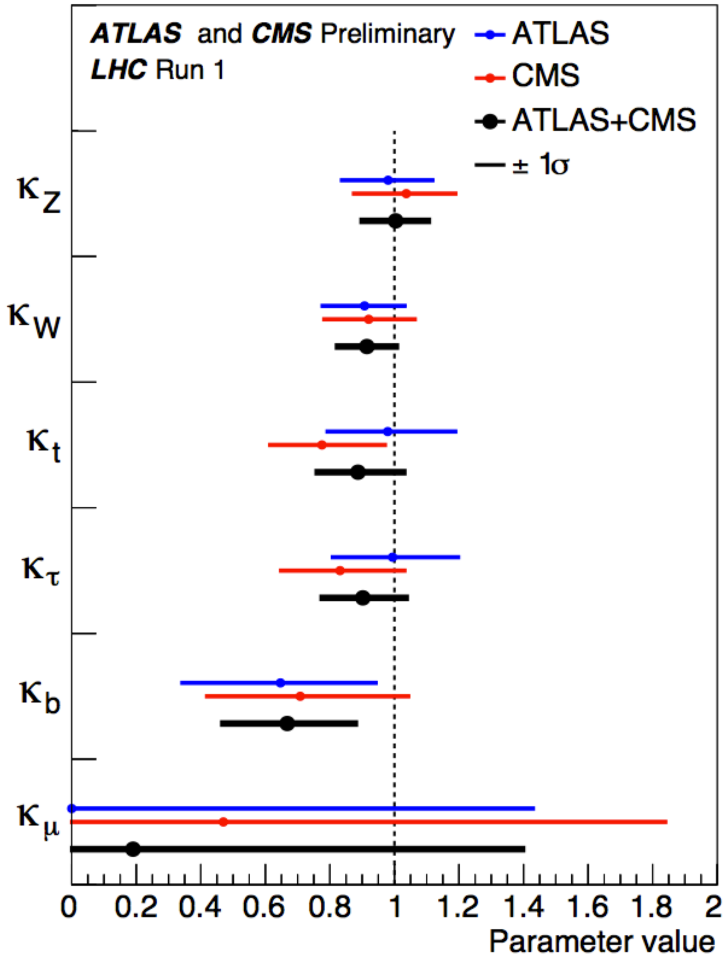


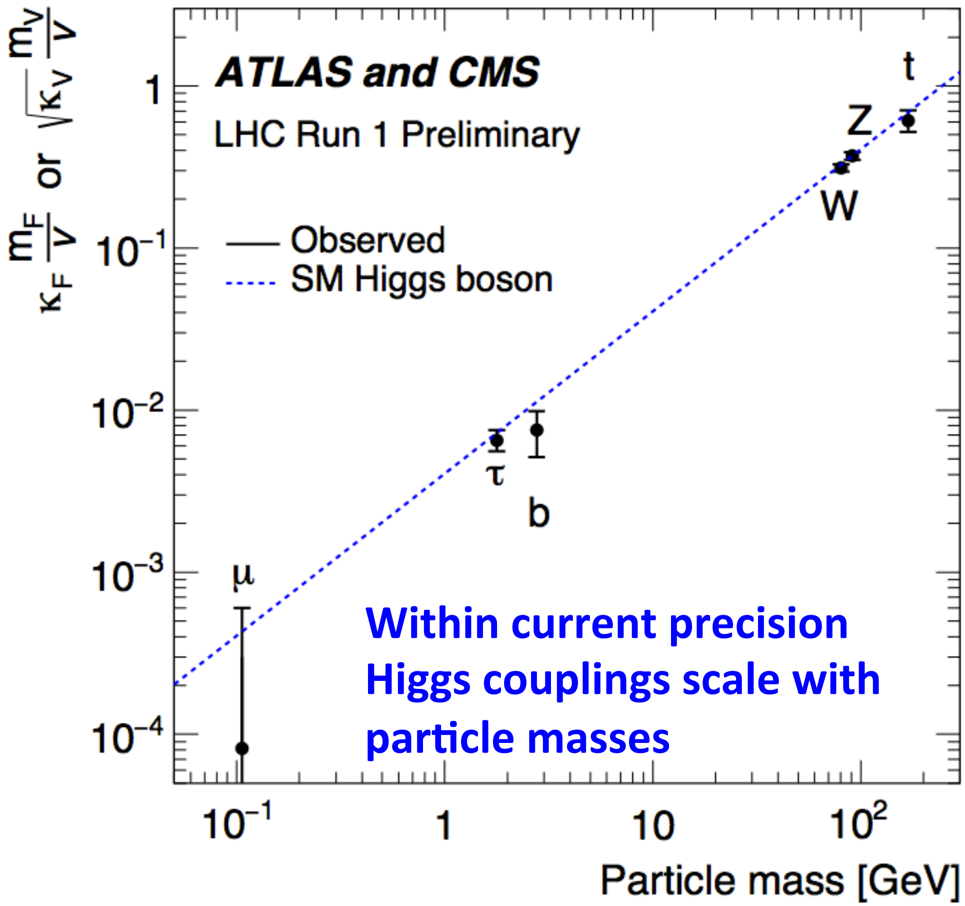


All results in agreement with SM ($\kappa_V = \kappa_f = 1$) within 1 σ

No effective couplings – loops resolved

- Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops



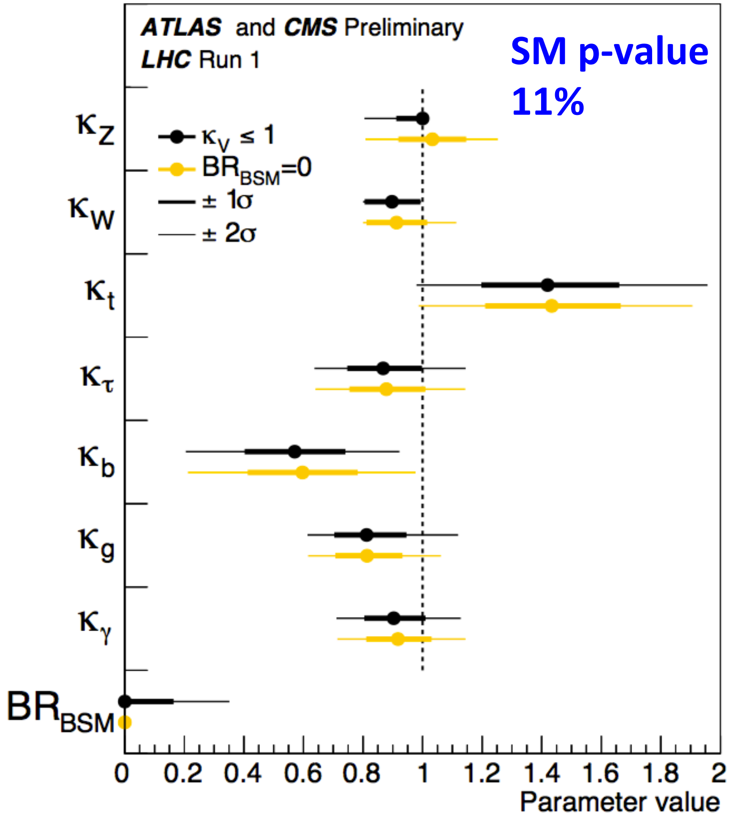


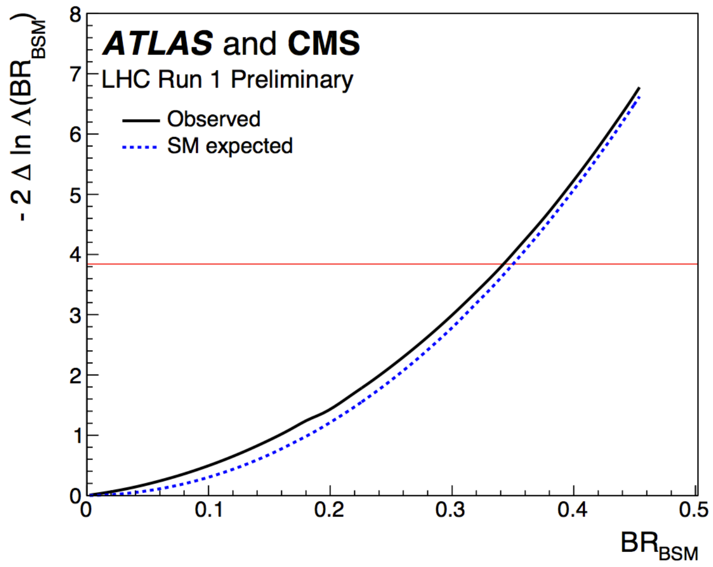
Within current precision Higgs couplings scale with particle masses

BSM physics in the loops

- We can also allow effective couplings κ_g and κ_γ
- Only σ x BRs can be measured, without further assumptions the width of the Higgs boson cannot be measured. Options are:
  - $BR_{BSM}=0$
  - $kV \leq 1$ (as in 2HDM) - BR_{BSM} can be measured

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H}$$





$BR_{BSM} < 0.34$ at 95% C.L. (with $\kappa_V \leq 1$)

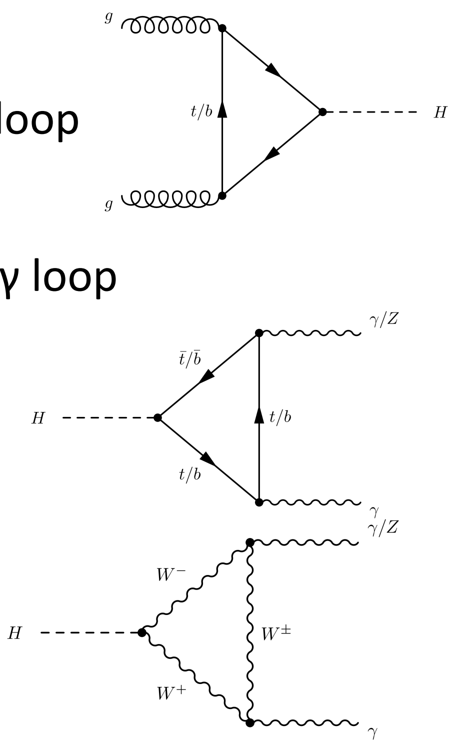
BR_{BSM} includes all possible non standard decays, visible or invisible

κ_g and κ_γ

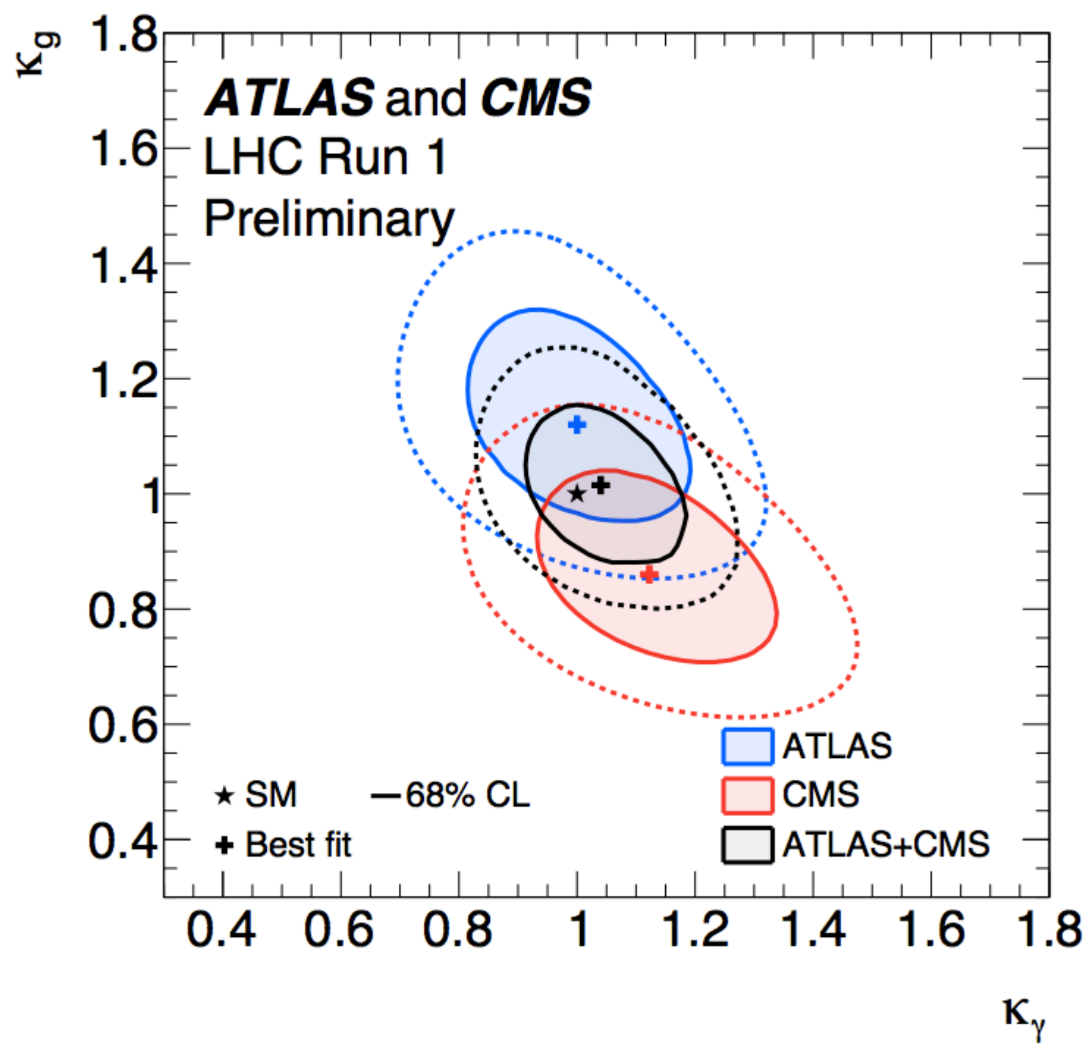
- Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and H→γγ

ggF loop

H→γγ loop



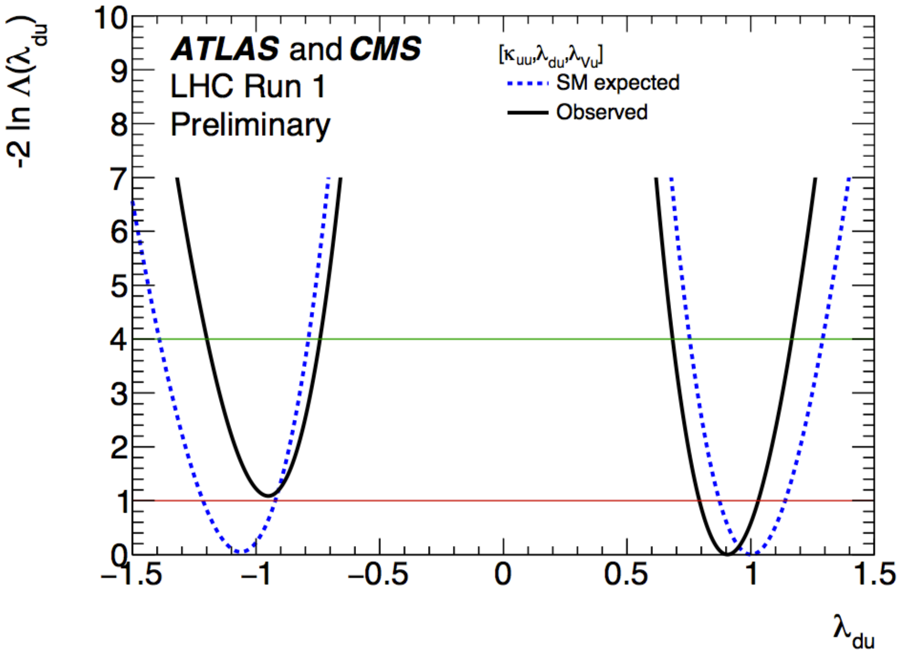
Additional heavy fermions or Charged Higgs boson would Modify the effective couplings



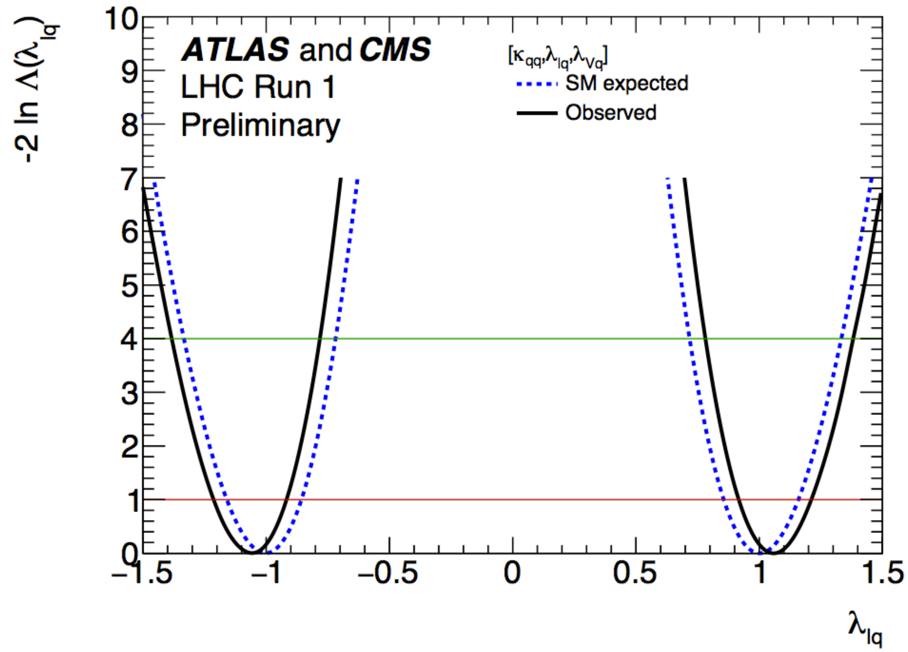
Up-down fermions and lepton-quark symmetries

- In 2HDM ratios of up/down fermions or leptons/quarks maybe different from 1 , for example in MSSM up/down fermions couplings are modified
  - The ratio of coupling modifiers is checked also allowing negative values

$K_{\text{down-type quarks}}/K_{\text{up-type quarks}}$



$K_{\text{leptons}}/K_{\text{quarks}}$



The results are all consistent with the SM

Most generic parameterizations used

- At LHC, not possible to disentangle production cross section from decay BR in a model-independent way
- But possible to measure ratios of cross sections and BR or ratios of μ's
- Most generic parameterizations used considered are:

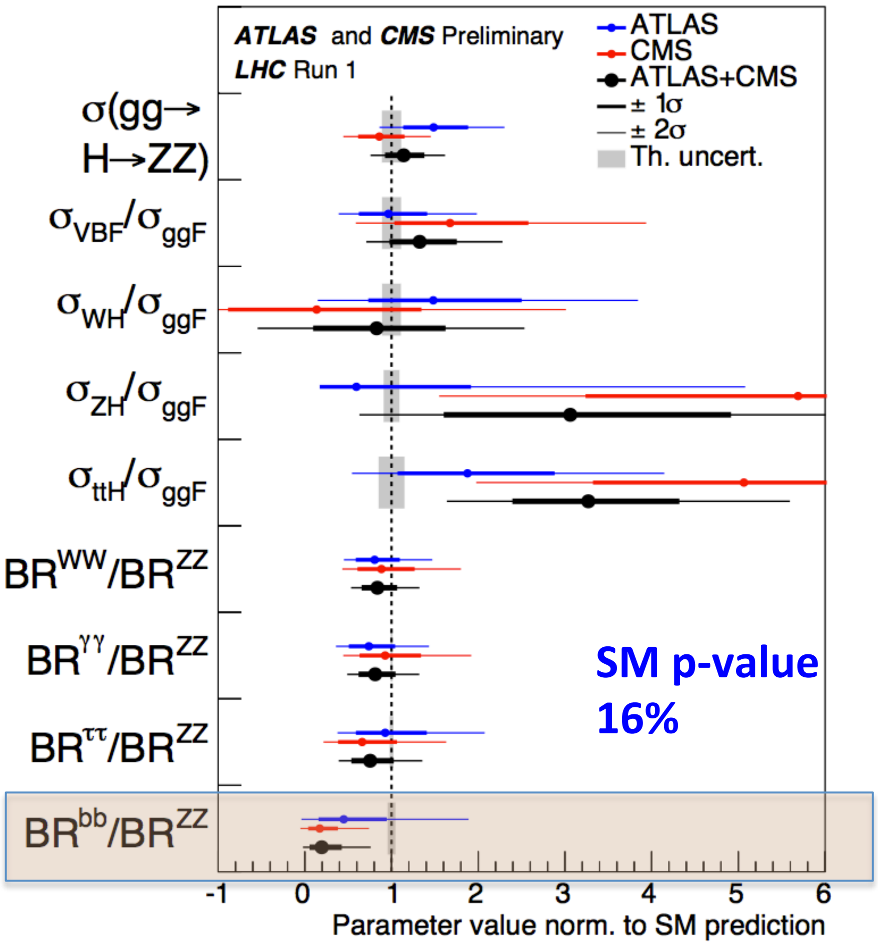
σ and BRs ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$

In this parameterization BR^{ZZ}, BR^{WW}, σ_{WH} , σ_{WH} and σ_{VBF} are function of κ_Z and κ_W

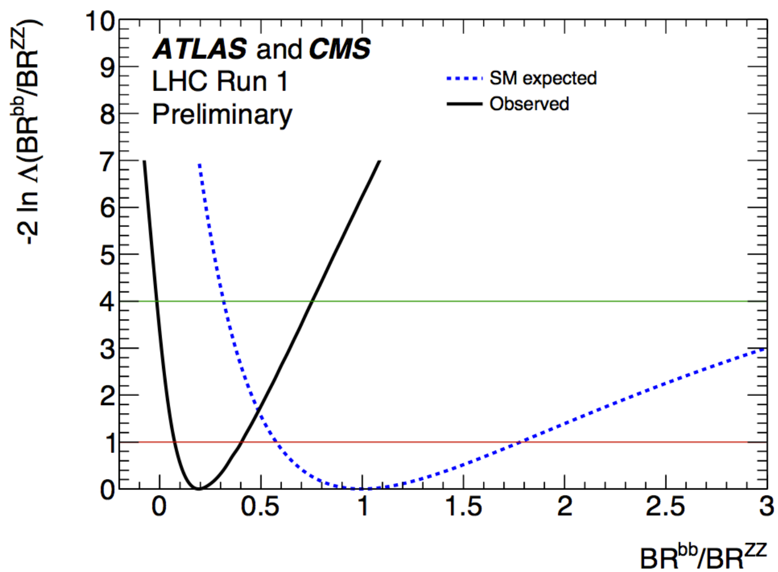
- Both refer to ggF, H→ZZ→4l that is the cleanest channel and less affected by systematic uncertainties

σ and BR ratio parametrization

- Parameterization of ratio of observables with minimal dependence on theory predictions
- Results remain valid when theory predictions are updated

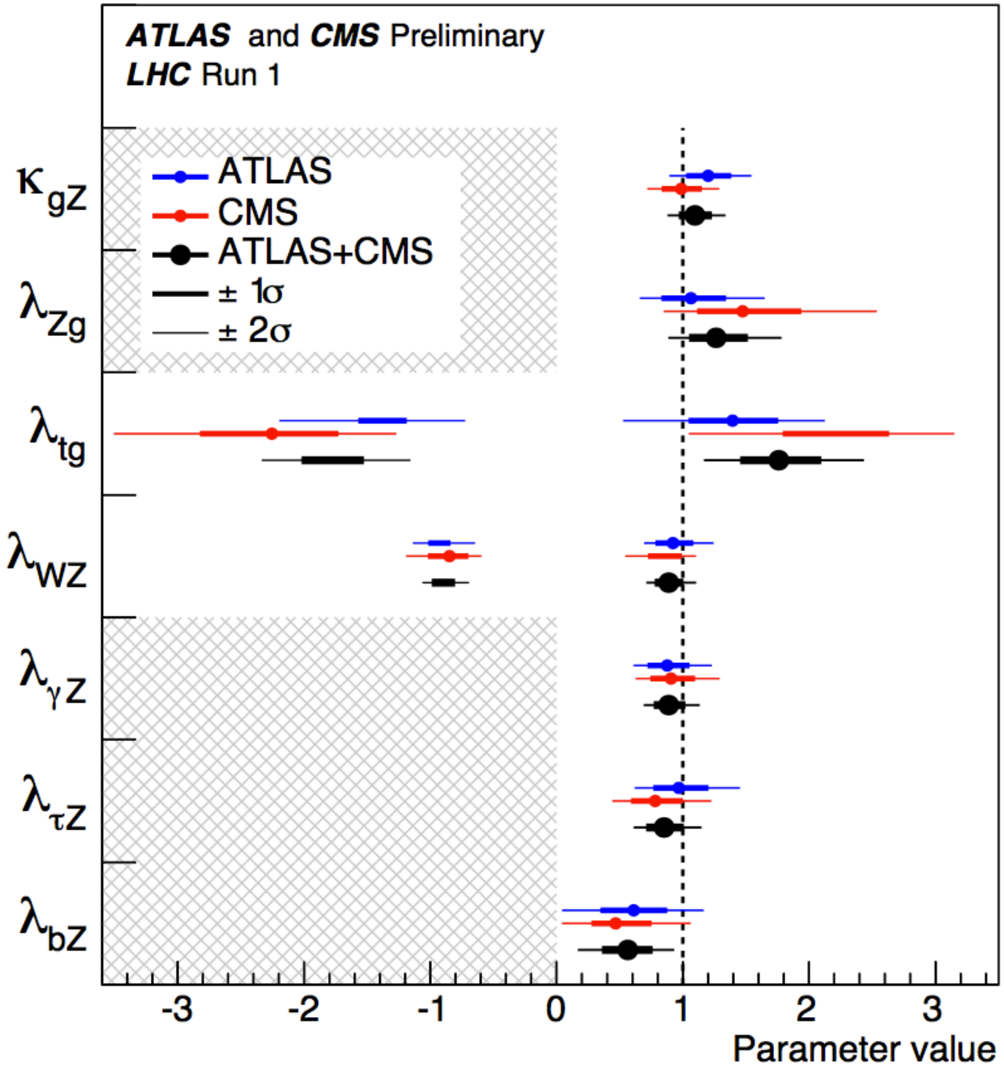


- Results are in general agreement with the SM
- Largest discrepancy is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ
  - Effect mainly coming from large ZH and ttH (both ratios $\sigma_{ttH}/\sigma_{ggF}$ ~ 3)



Ratios of κ's

- Again, results in agreement with SM



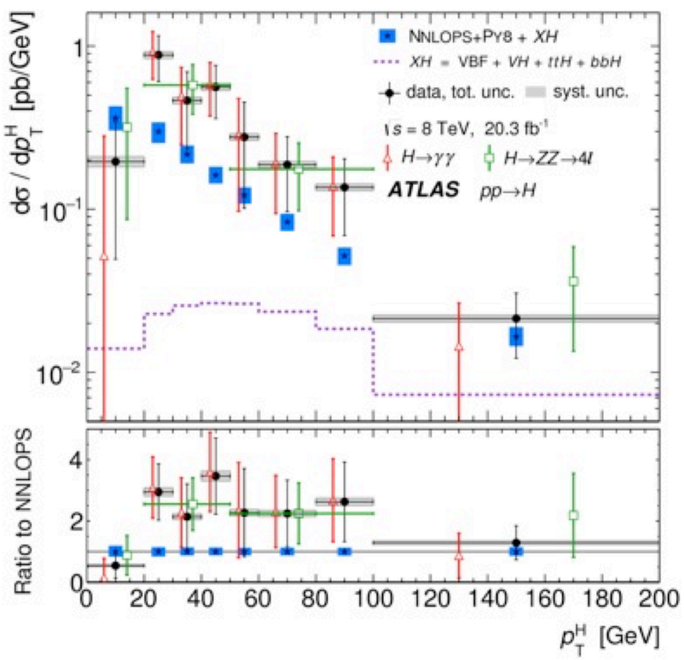
Next: measurements of its properties

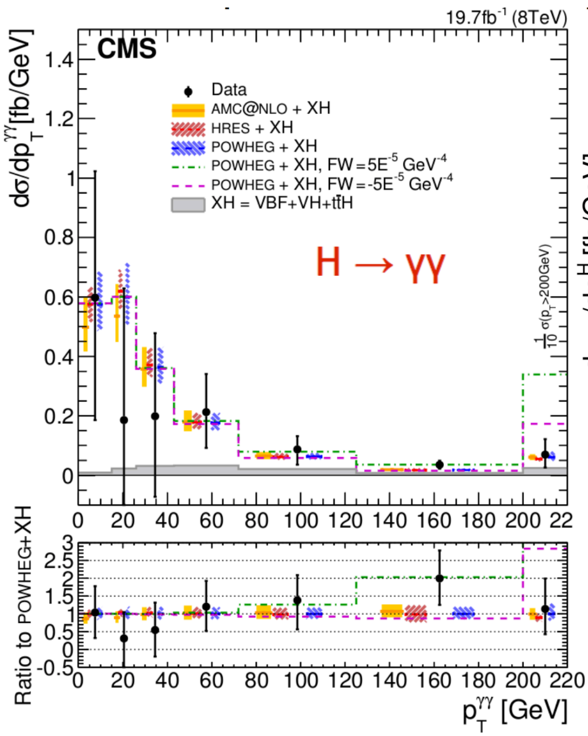
Mass & width
Spin/Parity & CP mixing
Signal strengths and couplings
Differential cross sections

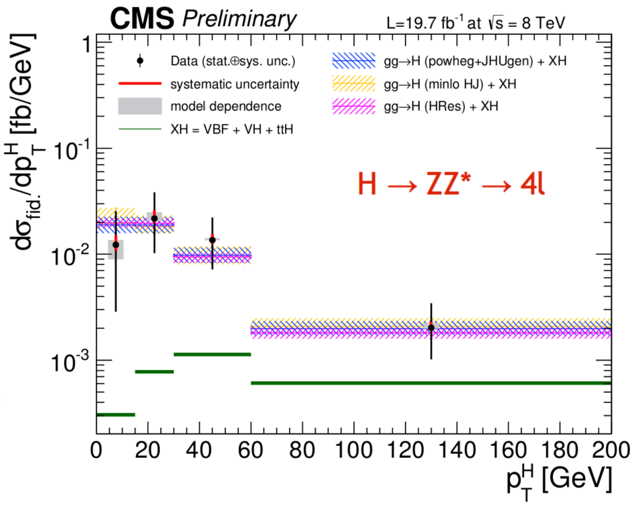
Differential cross sections: p_T^H

Measurements designed as model independent as possible

Higgs p_T distributions are sensitive to new physics in loops





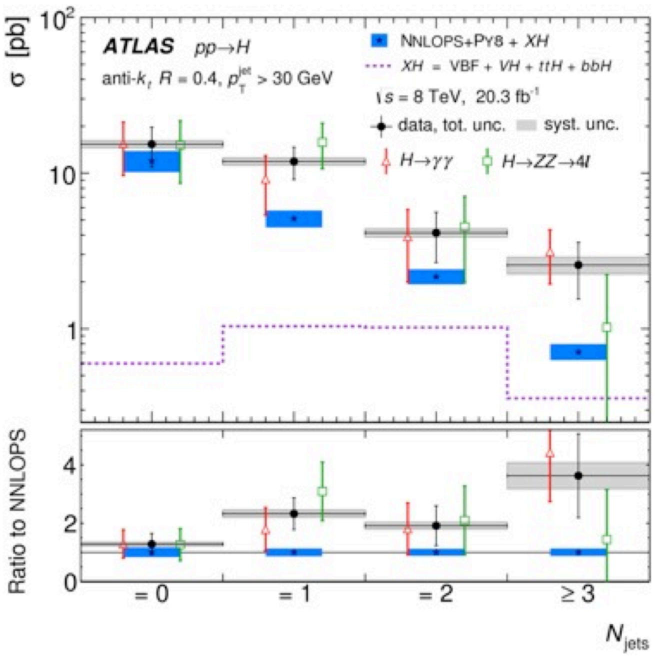


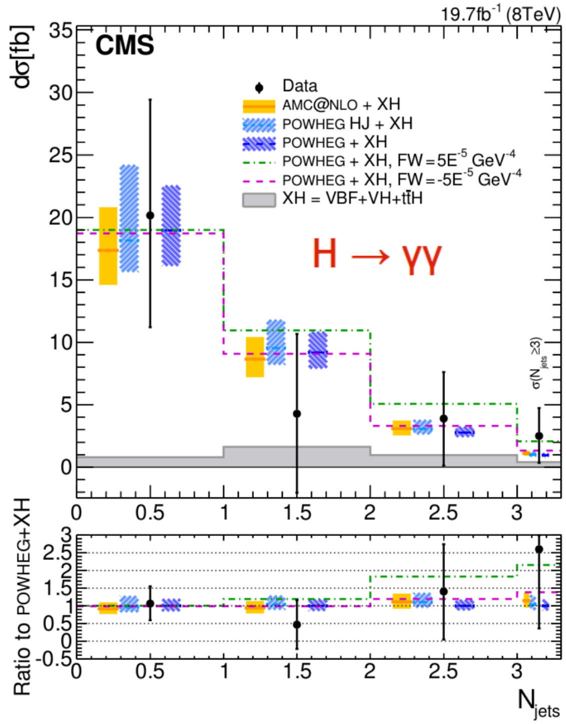
ATLAS see ~2 σ trend of more boosted Higgs boson, not seen by CMS

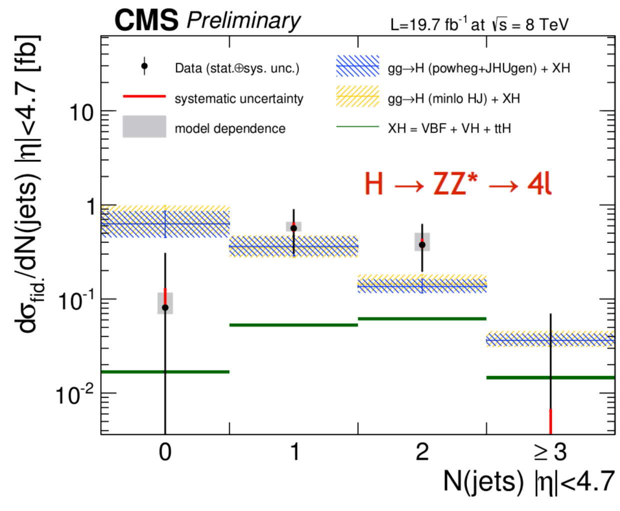
Differential cross sections: N(jets)

Measurements designed as model independent as possible

Higgs exclusive N-jet cross sections are of a particular challenge in theory





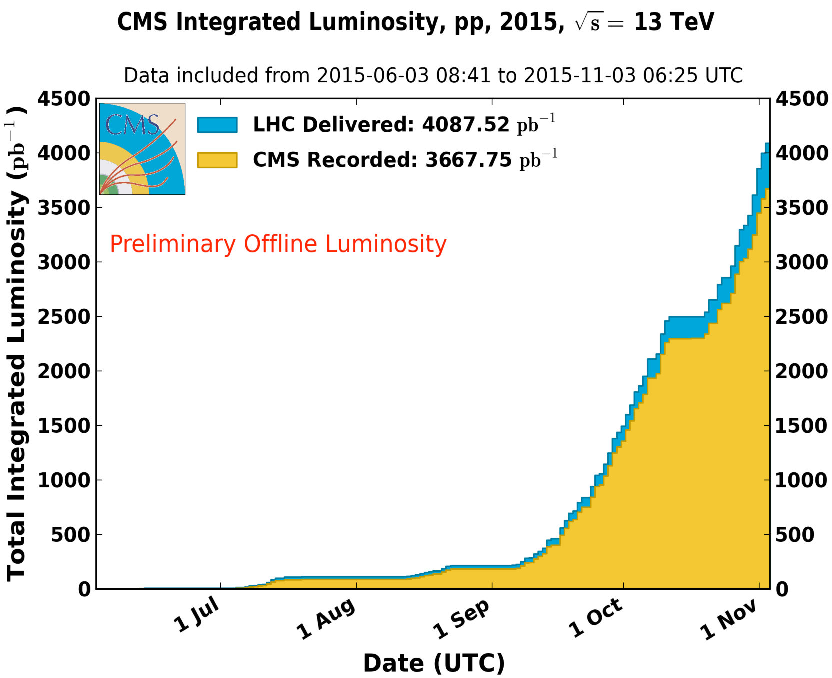


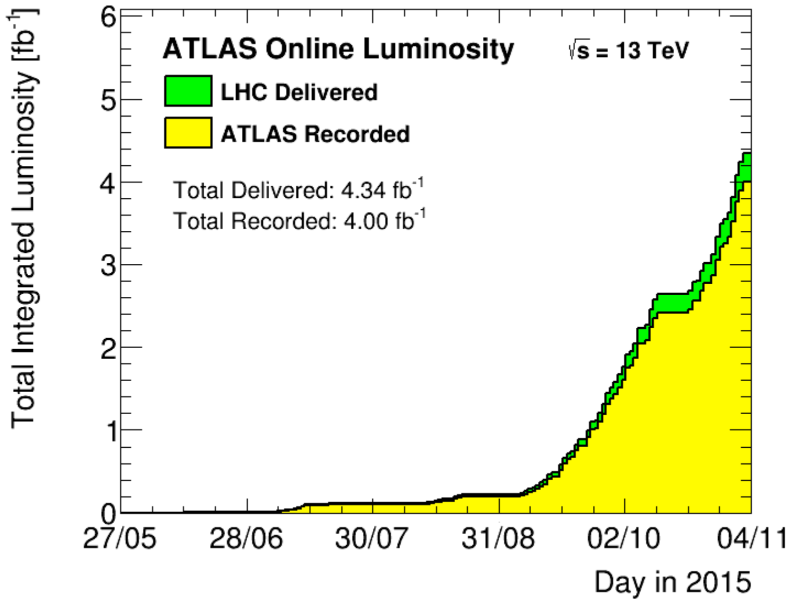
Both experiments see slightly more associated jets

Summary of the Higgs properties

- Spin 0, CP even, SM-like Higgs boson
- 0.2% precision on M_H = 125.09 ± 0.24 GeV
- Obtained most precise results on Higgs production and decay and couplings
  - in general at O(10%) precision
  - global $\mu = 1.09^{+0.11}_{-0.10}$
- Now also $H \rightarrow \tau\tau$ and VBF established
- More results available at ATLAS and CMS websites
  - rare/exotic decays, additional Higgs boson searches, etc
- Some small excesses here and there
  - need more data to see if any of them is real

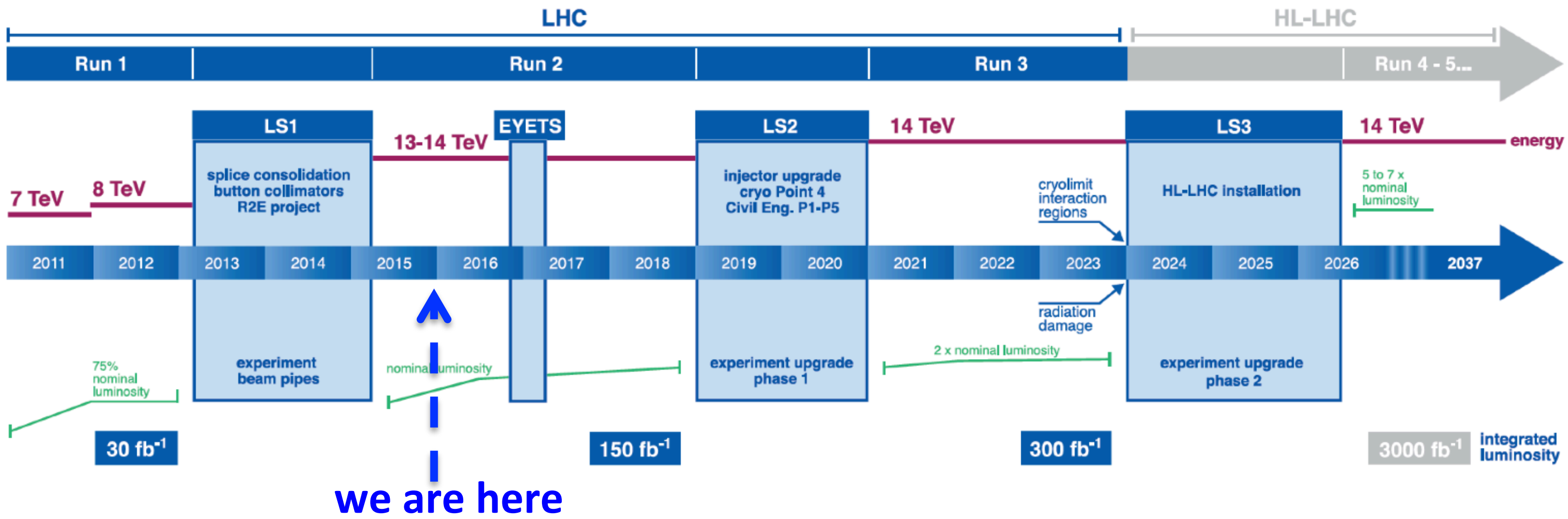
Status of RUN 2



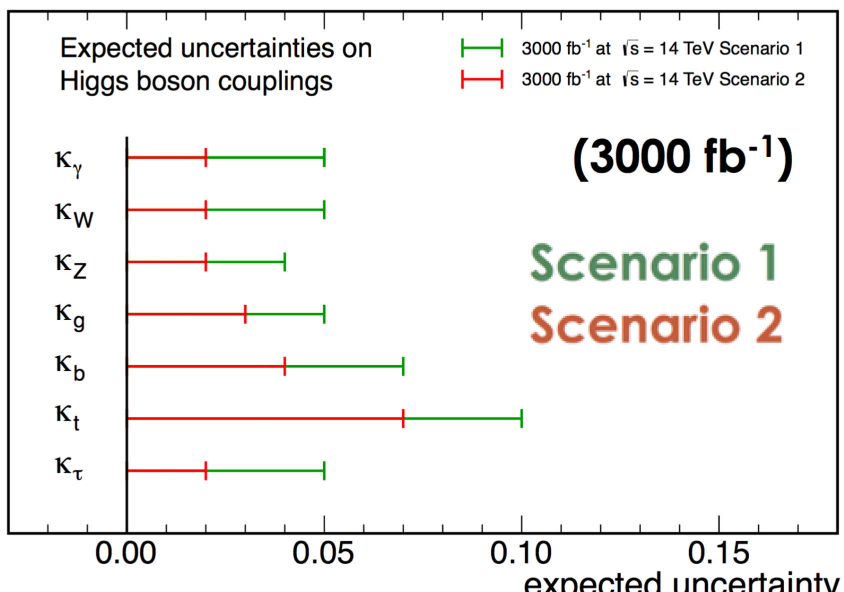


LHC Run-2 at 13 TeV, precision will be improved during the coming years thanks to higher energy, larger integrated luminosity and progress in the theory predictions

Prospects of HL-LHC



CMS Projection



Ultimate precision 2-10%, varies by coupling

(similar sensitivity from ATLAS)

Coupling deviations in BSM

- But HL-LHC is not the end of the story
- Typical effect on coupling from heavy particle M or new physics at scale M:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 5\% \ @\ \mathrm{M} \sim 1\ \mathrm{TeV}$$

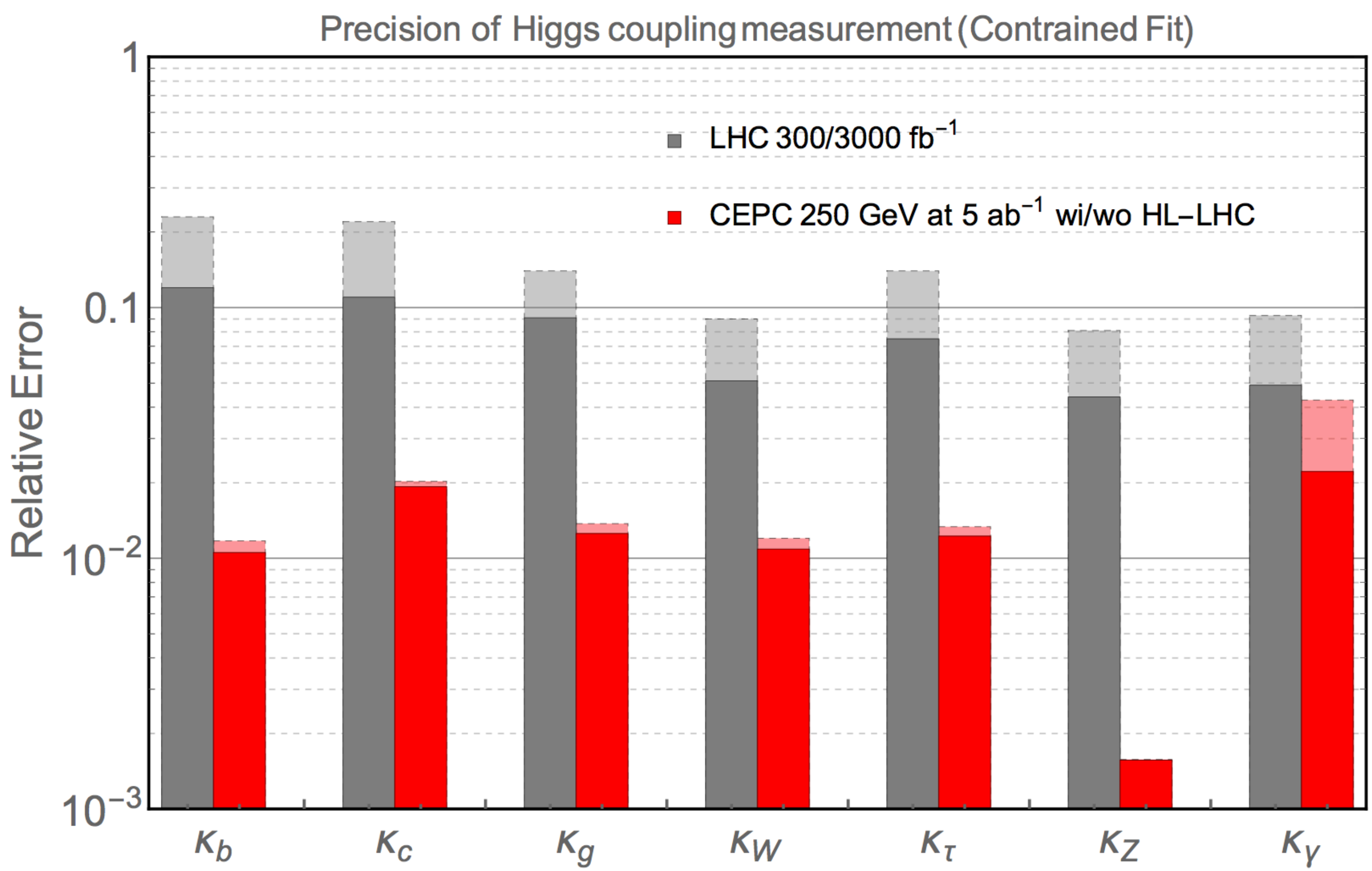
*Han et al., hep-ph/*0302188
*Gupta et al., arXiv:*1206.3560
……

Typical sizes of coupling modifications: arXiv:1310.8361

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Need sub-percent experimental precision to discriminate them (and SM)

We need



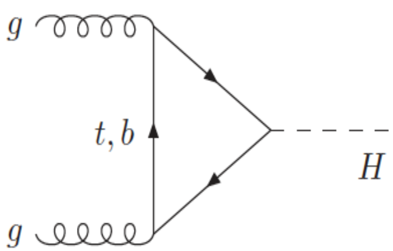
A large factor of improvement on the sensitivity for probing BSM

Thanks to CEPC folks for their hard work over the past few years

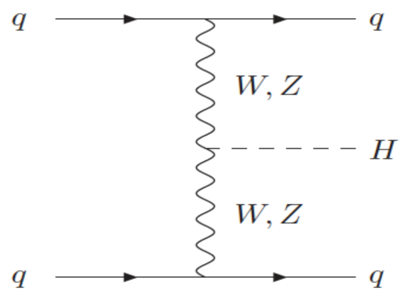
Back up

Main production processes

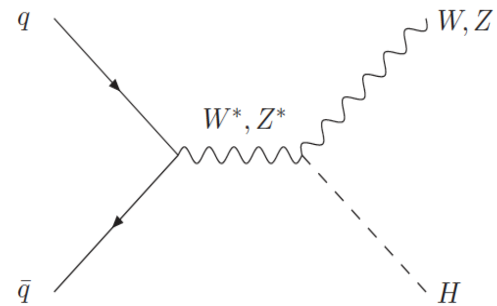
ggH



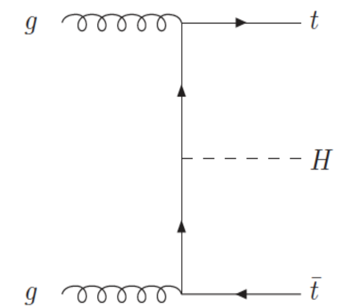
VBF

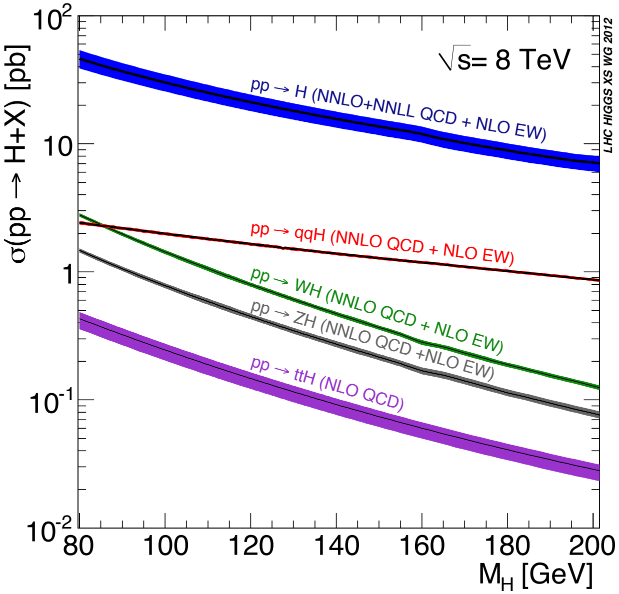


VH



ttH



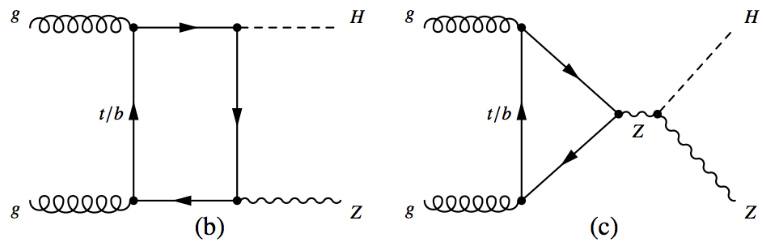


Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

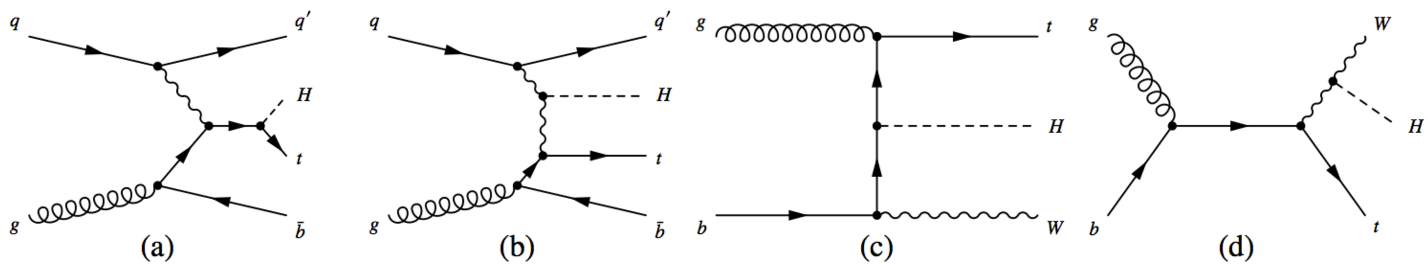
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Other production processes

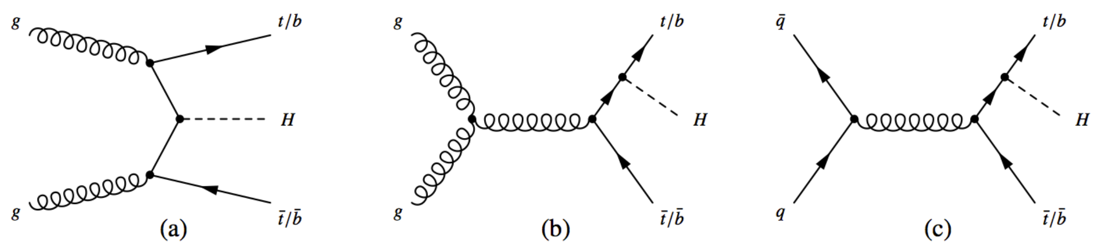
- ggZH:
  - O(10%) effect on VHbb in SM, higher p_T than qqZH



- tHq + tHW
  - Not really sensitive but has larger effects for negative couplings



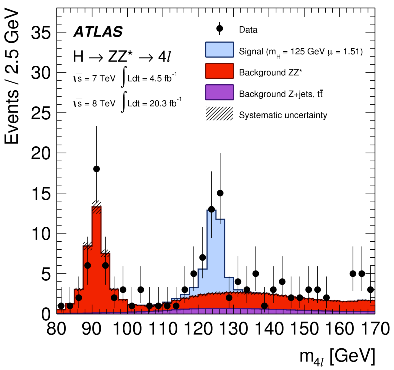
- bbH
  - Similar to ttH but not really distinguishable from ggF



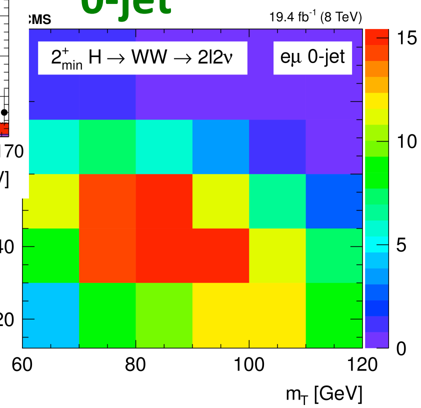
Categories addressing production and decays

- Many different final discriminant distributions combined

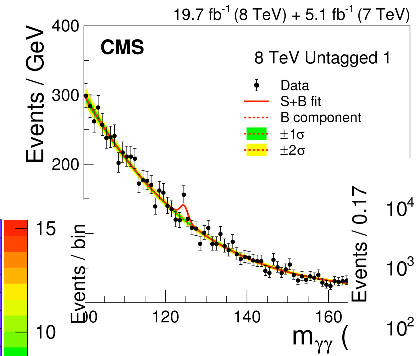
ATLAS ZZ



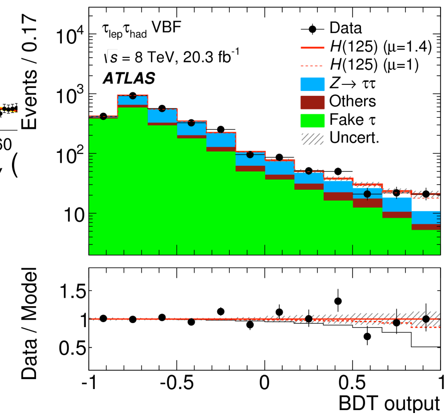
CMS WW 0-jet



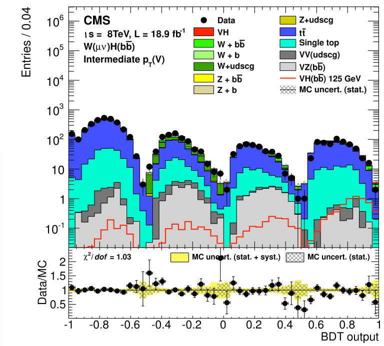
CMS γγ untagged



ATLAS ττ VBF μ-τ$_{had}$



CMS bb



- Purity varies between categories (especially for production modes)
- A … re combined

Signal yield

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{\sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f\right\},$$

$$= \mathcal{L}(k) \times \sum_i \sum_f \mu_i \mu^f \left\{\sigma_i^{\text{SM}} \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}_{\text{SM}}^f\right\}$$

L: integrated luminosity,
A: acceptance,
E: efficiency

Statistical treatment

- Profile likelihood ratio test statistics:

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

  - for each likelihood evaluation, all systematic uncertainties (**nuisances**) are varied to maximize the profile likelihood (**profiled**)
- ~4200 nuisances in the combined fits
  - A large part related to the finite MC statistics
  - Signal theory normalization uncertainties
  - BG theory uncertainties (for BGs not using the data)
  - Other experimental uncertainties
- Most experimental uncertainties are assumed uncorrelated between the two experiments and many tests have been carried out to check the possible impact that was found negligible

- Main correlated systematic uncertainties are the cross sections and BRs between ATLAS and CMS: QCD scale uncertainties and PDF
  - Theory cross sections and BR, Higgs p_T, … state-of-the art calculations in common between the two experiments for this analysis

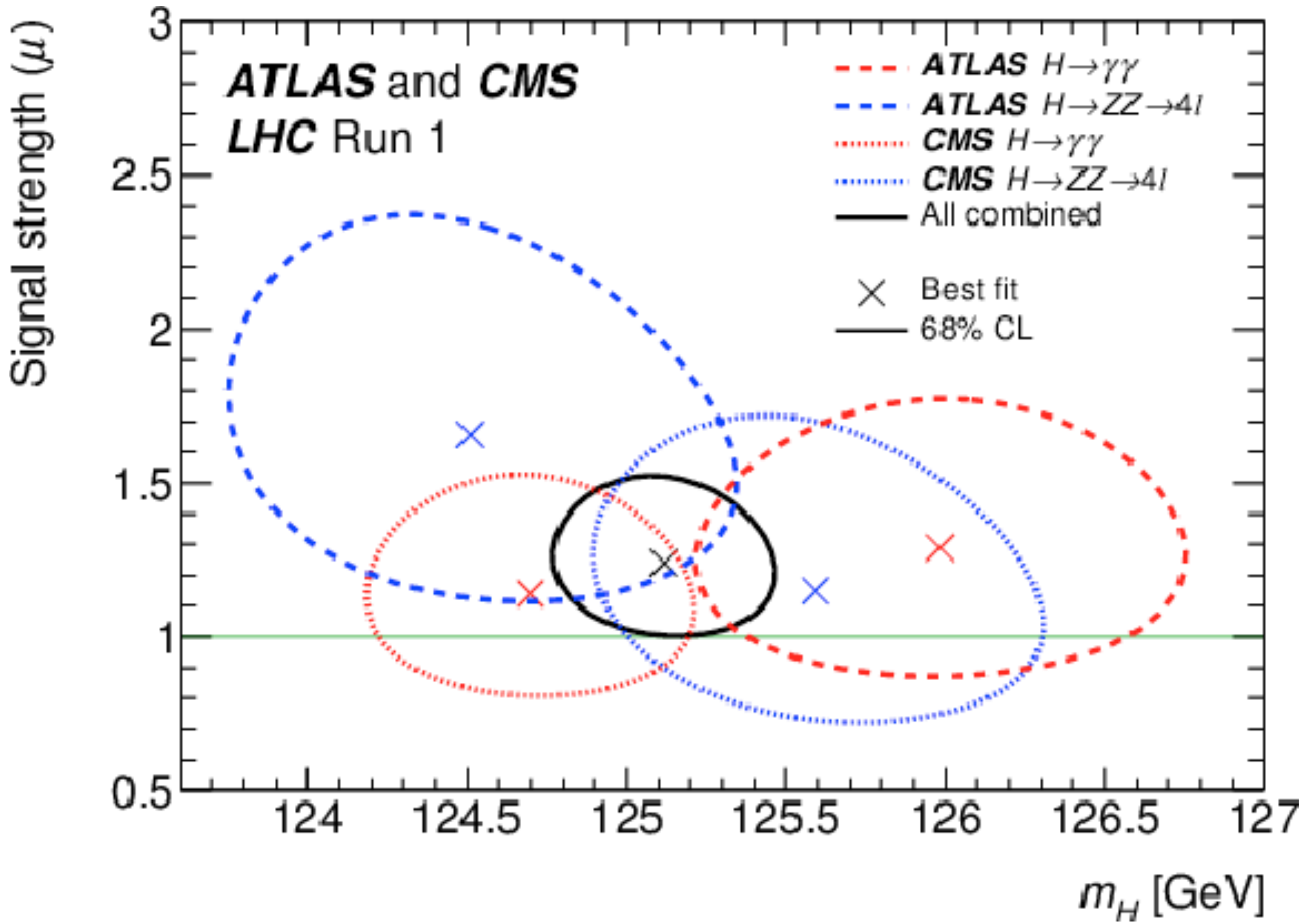
Measurements, compatibility tests

- Different measurement and compatibility tests are carried out (described here):
  - Fits of signal strengths μ – σ, BR relative to SM
  - Fits in the κ-framework – coupling modifiers
  - Generic fits (based on XS and BR, and on coupling modifier ratios)
- All of them assume a SM-like Higgs boson Spin Parity 0^+ and with a narrow width such that production and decay are decoupled

$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}}$$

- Results are rigorously valid on for small deviations from this hypothesis but larger differences would be detected
- At the LHC we can only measure σxBR need further assumptions to extract σ or BR independently

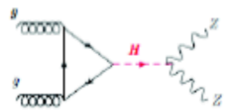
Higgs mass vs. μ

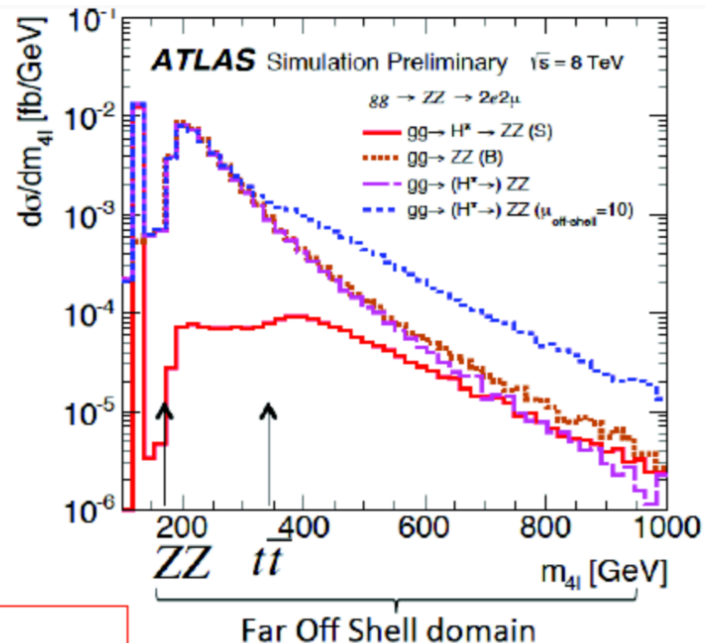


Higgs total width : on/off shell

Breit-Wigner production gg→H→ZZ:

$$\frac{d\sigma}{dm^2} \sim g_g^2 g_Z^2 \frac{F(m)}{(m^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$





On-peak and off-peak cross sections:

$$\sigma^{\text{on-shell}} = \int_{|m-m_H| \leq n\Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim \frac{g_g^2 g_Z^2}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}} = \int_{m-m_H \gg \Gamma_H} \frac{d\sigma}{dm} \cdot dm \sim g_g^2 g_Z^2$$

Off-peak to on-peak ratio is proportional to Γ_H

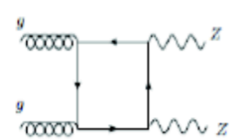
$$\frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \sim \Gamma_H$$

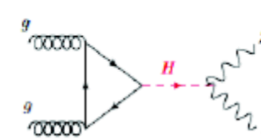
CAVEATS (model-dependent assumptions):

- assume that gg → H is the dominant production mechanisms (e.g., not qq → H)
- evolution of $g_{ggH}(m_{H*})$ depends on what is in the loop: assume top-loop dominance
- off-peak production depends strongly on tensor structure of H→ZZ: assume SM-like 0^+

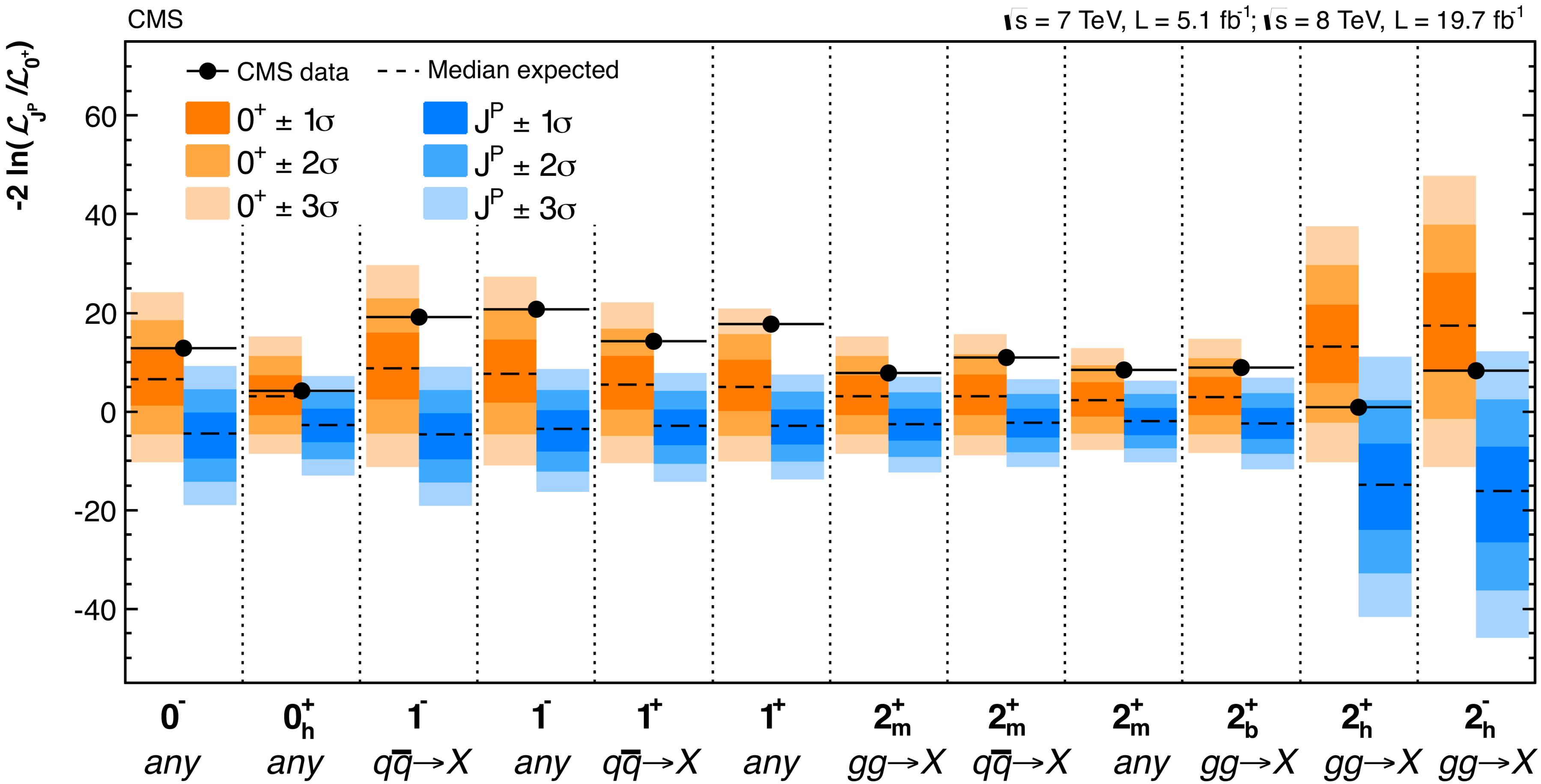
Technical, but very important, detail:

- must include negative interference between gg→H*→ZZ and gg→(box)→ZZ
- off-shell production: $\sigma_{gg\to H^*\to ZZ} + \sigma_{gg\to(box)\to ZZ} + \sigma_{interference}$
- K-factor on gg→(box)→ZZ is large and not well known





Spin-parity



下标 m 的含义: the spin-two model with minimal couplings (2+_m) represents a massive Graviton-like boson as suggested in models with warped extra dimensions (ED) . (arXiv:hep-th/9906064,arXiv:hep-ph/9905221)

下标 b 的含义是: modified minimal coupling model (2+_b) is also considered, where the SM fields are allowed to propagate in the bulk of the ED (arXiv:hep-ph/0701186).

Anomalous HVV coupling definition

Decay amplitude of spin-0 particle → WW:

$$A(X_{J=0} \to WW) \sim v^{-1}\left(\left[a_1^{WW} - e^{i\phi_{\Lambda_1}} \frac{q_1^2 + q_2^2}{(\Lambda_1^{WW})^2}\right] m_W^2 \epsilon_1^* \epsilon_2^* + a_2^{WW} f_{\mu\nu}^{*(W)} f^{*(W),\mu\nu} + a_3^{WW} f_{\mu\nu}^{*(W)} \tilde{f}^{*(W),\mu\nu}\right.$$

SM tree level + leading momentum expansion. Λ_1: scale of new physics

If particles in the loop are heavy, couplings will be real (in general complex).

Equivalent to an effective field theory Langrangian.

a_2 terms: CP-even scalar (not participating in EWSB)

a_3 terms: CP-odd scalar

Analysis fits for the terms of the expansion: a_2, a_3, Λ_1

Couplings are converted into effective cross section fractions (anomalous coupling parameters):

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

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

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

σ_i is cross section of process corresponding to a_i=1and $a_{i\neq j}$≠0

$\sigma_{\Lambda 1}$ is effective cross section of process corresponding to Λ_1>0, $a_{j\neq\Lambda 1}$=0

CP mixing: ATLAS

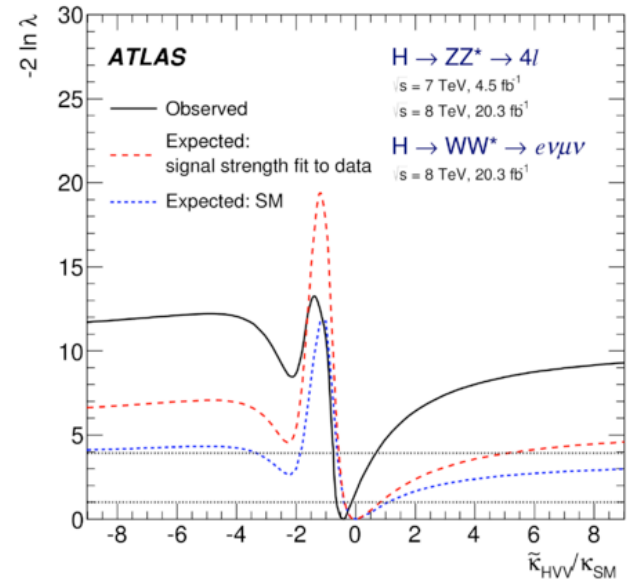
SM 0^+ and BSM $0^\pm$ Lagrangrian:

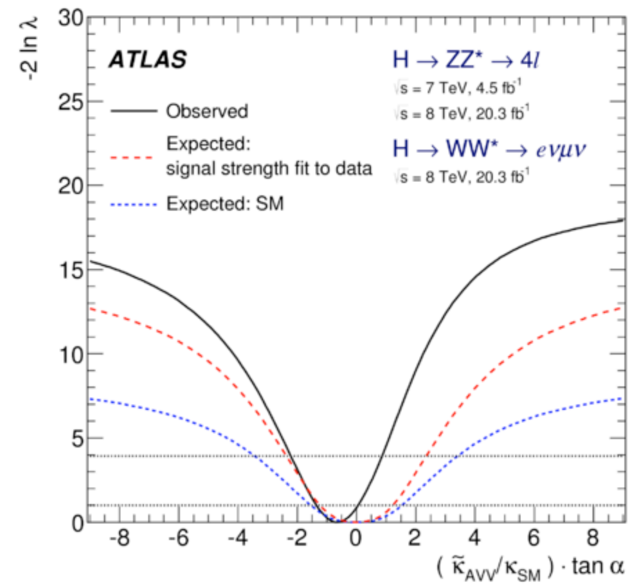
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0$$

- Admixture of BSM 0^+ and BSM 0^- tested separately
- Combination under the assumption of same admixture in $H \to ZZ^*$ and $H \to WW^*$

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\rm SM}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\rm SM}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

No significant admixture of non-SM CP states

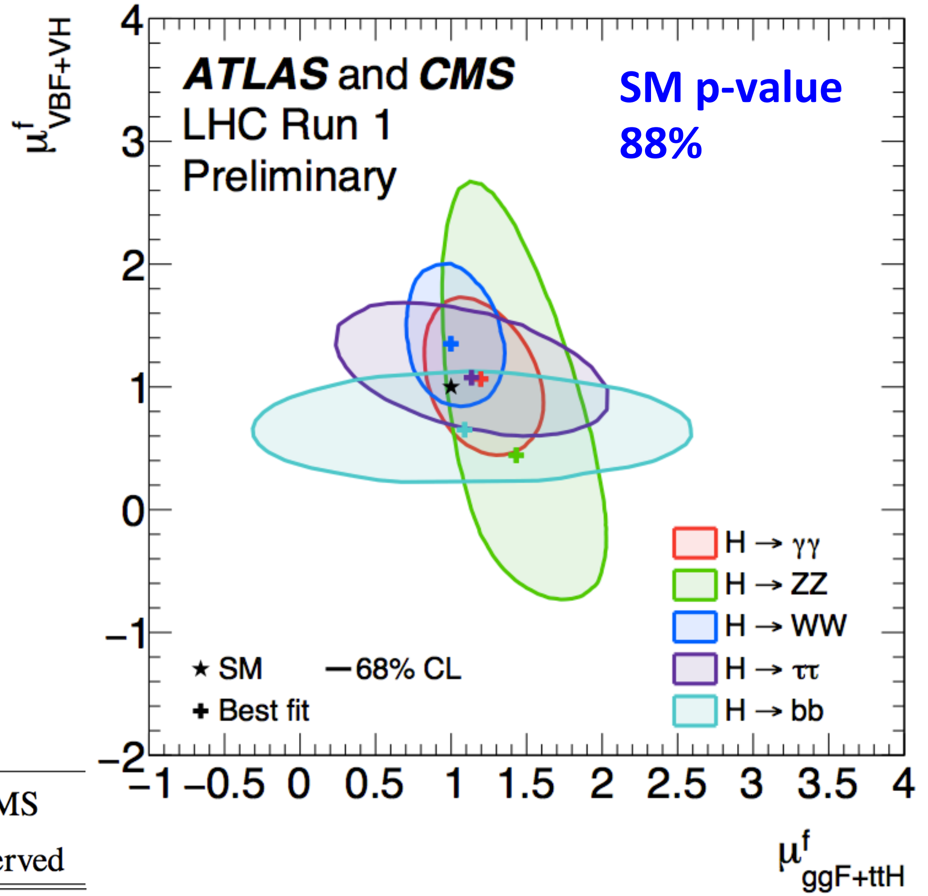




μ_V vs μ_F

- Can also fit μ_V^f vs μ_F^f per decay:
  - $\mu_V^f = \mu^f_{VBF+VH}$
  - $\mu_F^f = \mu^f_{ggF+ttH}$
- μ_{V}/μ_{f} can be measured in the different decay channels and combined:

$$\mu_{V}/\mu_{f} = 1.06^{+0.35}_{-0.27}$$



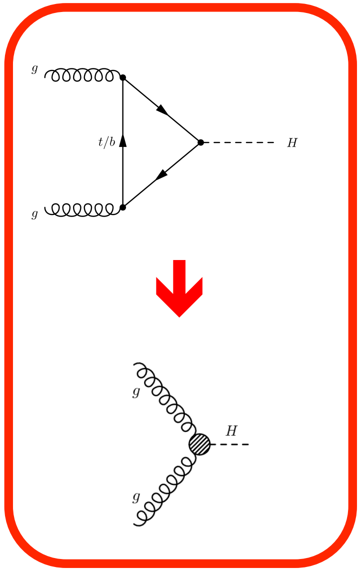
Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.	ATLAS observed	CMS observed
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

SM p-value 62%

Scaling of σ's and BR's with κ's

- Loops can be resolved or parameterized with **an effective κ**
  - No effective couplings for ggZH and tH because of the limited sensitivity

Production	Loops	Interference	Multiplicative factor
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_{\mathrm{g}}^2 \sim 1.06\cdot\kappa_{\mathrm{t}}^2 + 0.01\cdot\kappa_{\mathrm{b}}^2 - 0.07\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{b}}$
$\sigma(\mathrm{VBF})$	–	–	$\sim 0.74\cdot\kappa_{\mathrm{W}}^2 + 0.26\cdot\kappa_{\mathrm{Z}}^2$
$\sigma(WH)$	–	–	$\sim \kappa_{\mathrm{W}}^2$
$\sigma(q\bar{q}\to ZH)$	–	–	$\sim \kappa_{\mathrm{Z}}^2$
$\sigma(gg\to ZH)$	✓	$Z-t$	$\sim 2.27\cdot\kappa_{\mathrm{Z}}^2 + 0.37\cdot\kappa_{\mathrm{t}}^2 - 1.64\cdot\kappa_{\mathrm{Z}}\kappa_{\mathrm{t}}$
$\sigma(bbH)$	–	–	$\sim \kappa_{\mathrm{b}}^2$
$\sigma(ttH)$	–	–	$\sim \kappa_{\mathrm{t}}^2$
$\sigma(gb\to WtH)$	–	$W-t$	$\sim 1.84\cdot\kappa_{\mathrm{t}}^2 + 1.57\cdot\kappa_{\mathrm{W}}^2 - 2.41\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
$\sigma(qb\to tHq')$	–	$W-t$	$\sim 3.4\cdot\kappa_{\mathrm{t}}^2 + 3.56\cdot\kappa_{\mathrm{W}}^2 - 5.96\cdot\kappa_{\mathrm{t}}\kappa_{\mathrm{W}}$
Partial decay width			
$\Gamma_{b\bar{b}}$	–	–	$\sim \kappa_{\mathrm{b}}^2$
Γ_{WW}	–	–	$\sim \kappa_{\mathrm{W}}^2$
Γ_{ZZ}	–	–	$\sim \kappa_{\mathrm{Z}}^2$
$\Gamma_{\tau\tau}$	–	–	$\sim \kappa_{\tau}^2$
$\Gamma_{\mu\mu}$	–	–	$\sim \kappa_{\mu}^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_{\gamma}^2 \sim 1.59\cdot\kappa_{\mathrm{W}}^2 + 0.07\cdot\kappa_{\mathrm{t}}^2 - 0.66\cdot\kappa_{\mathrm{W}}\kappa_{\mathrm{t}}$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_{H}	✓	–	$\kappa_{\mathrm{H}}^2 \sim 0.57\cdot\kappa_{\mathrm{b}}^2 + 0.22\cdot\kappa_{\mathrm{W}}^2 + 0.09\cdot\kappa_{\mathrm{g}}^2 + 0.06\cdot\kappa_{\tau}^2 + 0.03\cdot\kappa_{\mathrm{Z}}^2 + 0.03\cdot\kappa_{\mathrm{c}}^2 + 0.0023\cdot\kappa_{\gamma}^2 + 0.0016\cdot\kappa_{\mathrm{Z}\gamma}^2 + 0.0001\cdot\kappa_{\mathrm{s}}^2 + 0.00022\cdot\kappa_{\mu}^2$



- not measured κ's are scaled as similar ones: $\kappa_c=\kappa_t$, $\kappa_\mu=\kappa_\tau$, $\kappa_s=\kappa_b$