Experimental Overview
Higgs Couplings and Spin/CP

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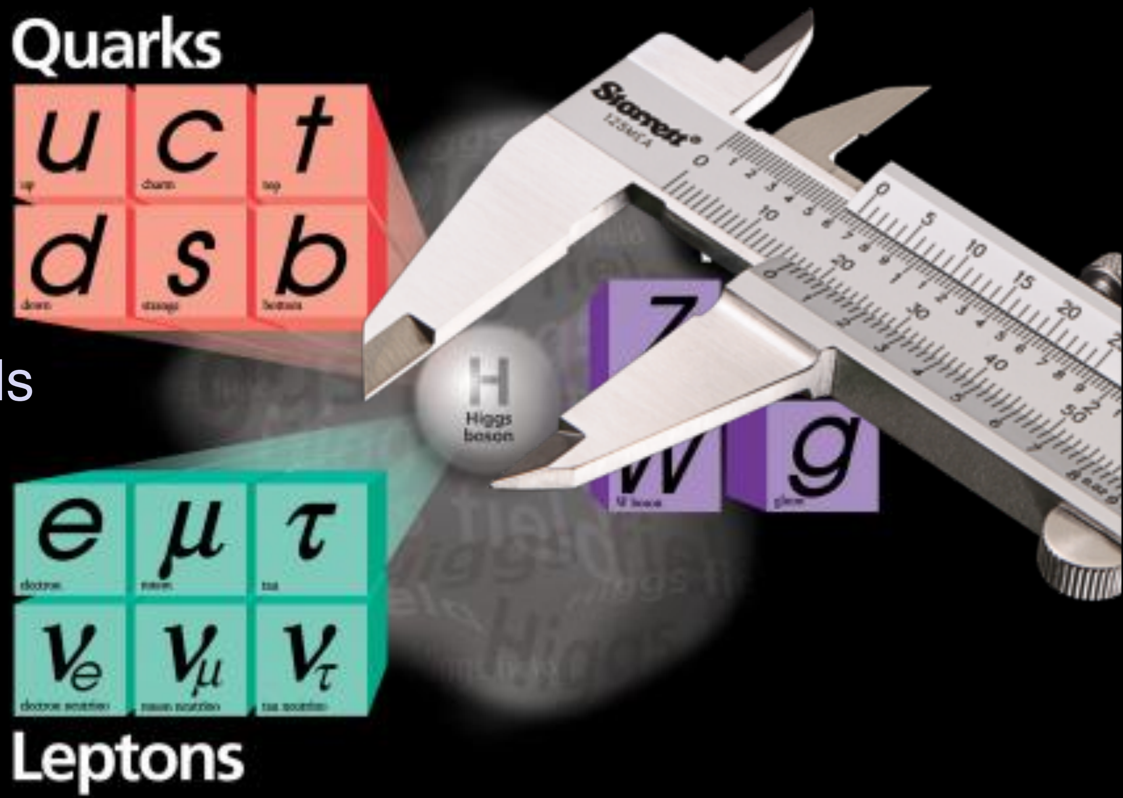
Higgs and Beyond
(Pittsburgh Dec. 2015)

Outline

- Introduction

- 125 GeV Higgs Properties
  - Mass
  - Production and decay channels
  - Spin/CP
  - Width
  - Higgs couplings
  - Invisible width
  - Differential cross sections

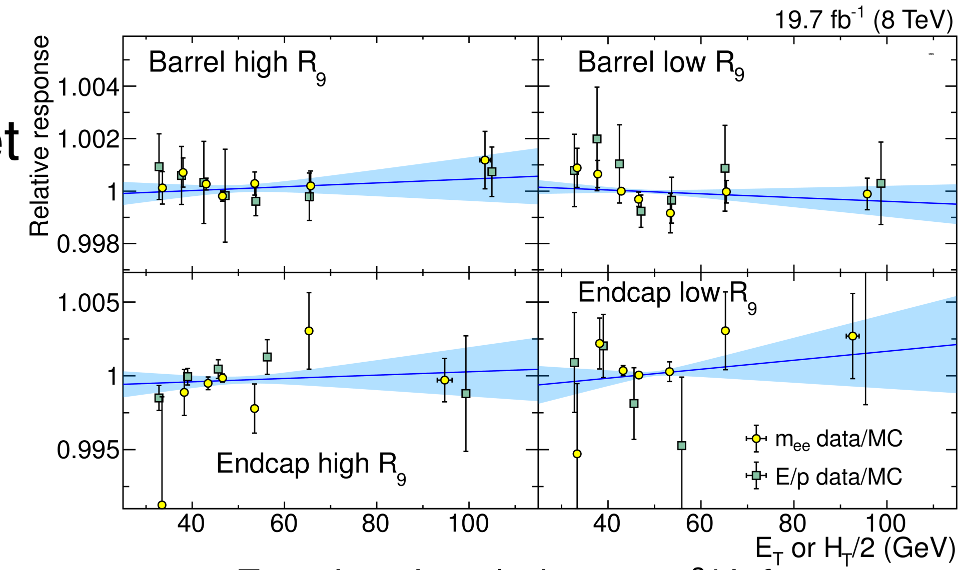


- Conclusions and Outlook

Introduction

•First Run 1 Higgs results with full dataset were first presented in March of 2013

•In the last two years, detectors were re-calibrated, reconstruction and analysis techniques were improved, and the data were re-analyzed



Error band scaled to get χ^2/dof =1

CMS Photon Performance: CERN-PH-EP-2015-006

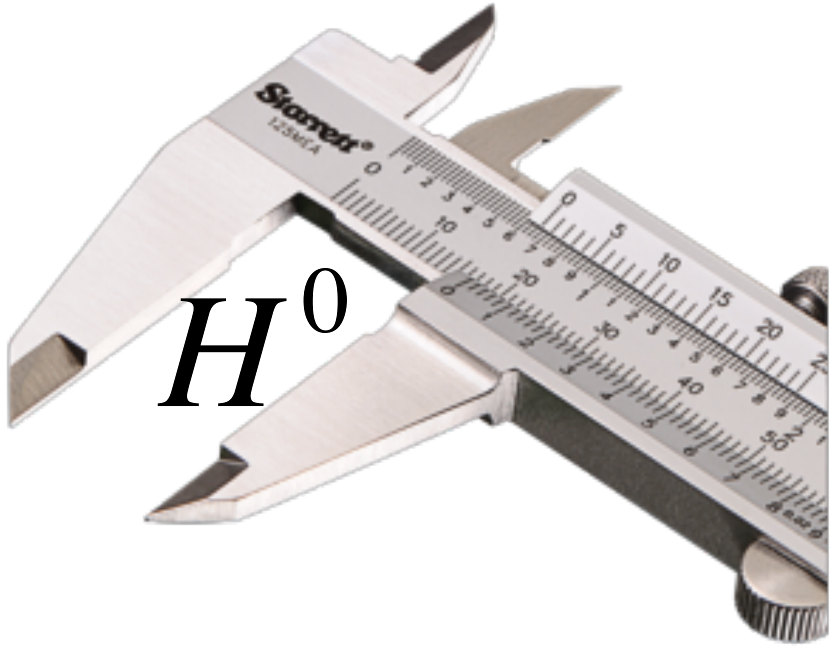
•The final Run 1 results are in general significantly better than those presented in early 2013

- •Legacy papers on couplings and spin CP by CMS were submitted a few months ago: Phys. Rev. D. 92.012004., Eur. Phys. J. C (2015) 75-212
- •Final results on Higgs spin CP and couplings from ATLAS recently submitted: arxiv:1507.04548 (accepted), Eur. Phys. J. C75 (2015) 476
- •Preliminary combination of ATLAS/CMS Higgs couplings: ATLAS-CONF-2015-044; CMS-PAS-HIG-15-002

SM Higgs Physics Program

Testing the SM Higgs hypothesis:

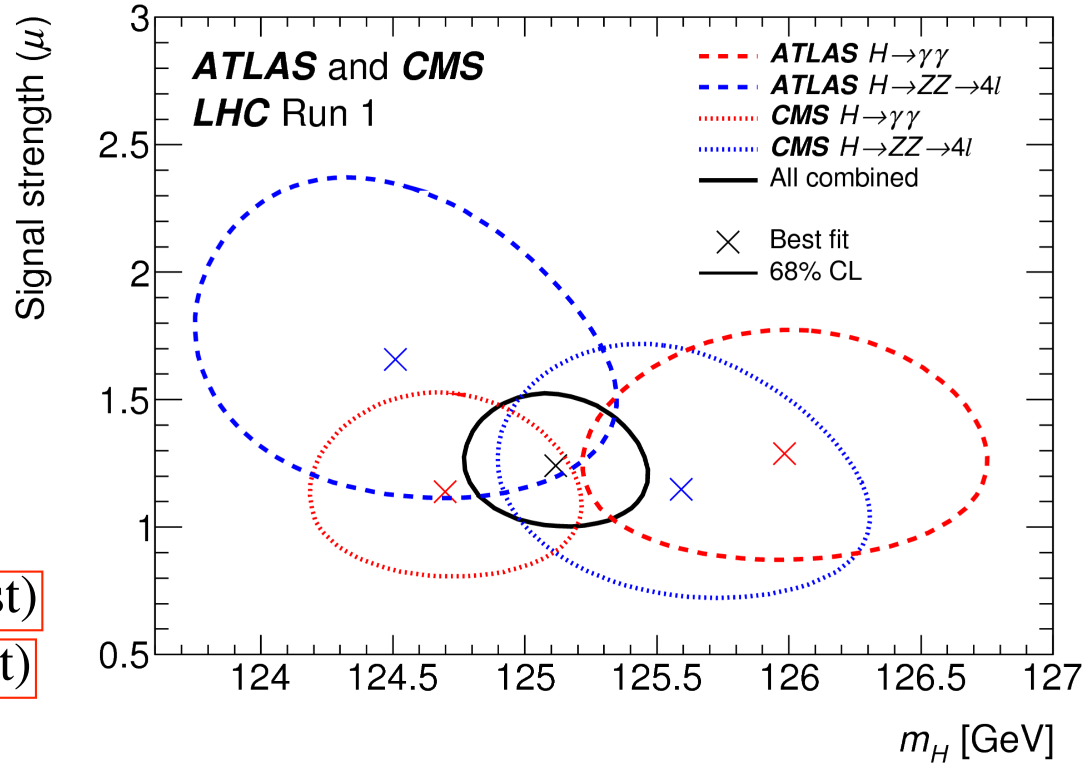
- Input: precision mass measurement
- Measurements of couplings
  - Main production modes
    - ggH, WH, ZH, VBF, ttH
  - Main decay modes:
    - γγ, WW, ZZ, tt, bb
- Rare Decay modes:
  - μμ, Zγ, J/ψ γ
- Rare production modes:
  - tH, hh, bbH
- Spin and CP-mixing properties
- Width
- Fiducial and differential measurements



Higgs Mass

The SM does not predict the Higgs boson mass: we need to measure it *(the last missing SM parameter!)*

Given a mass, we can make predictions* for the production cross section and decay rates



Higgs mass measurements (GeV):

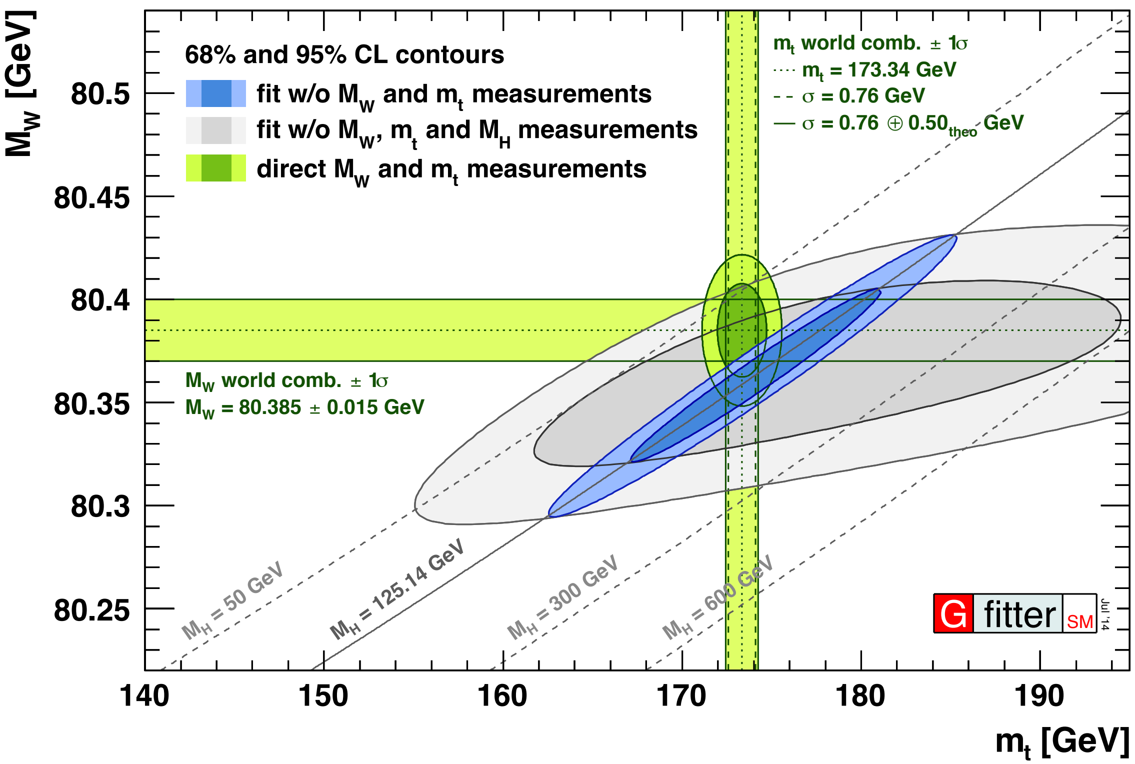
ATLAS: 125.36 ± 0.37 (stat) ± 0.18 (syst)
CMS: 125.02 ± 0.27 (stat) ± 0.15 (syst)

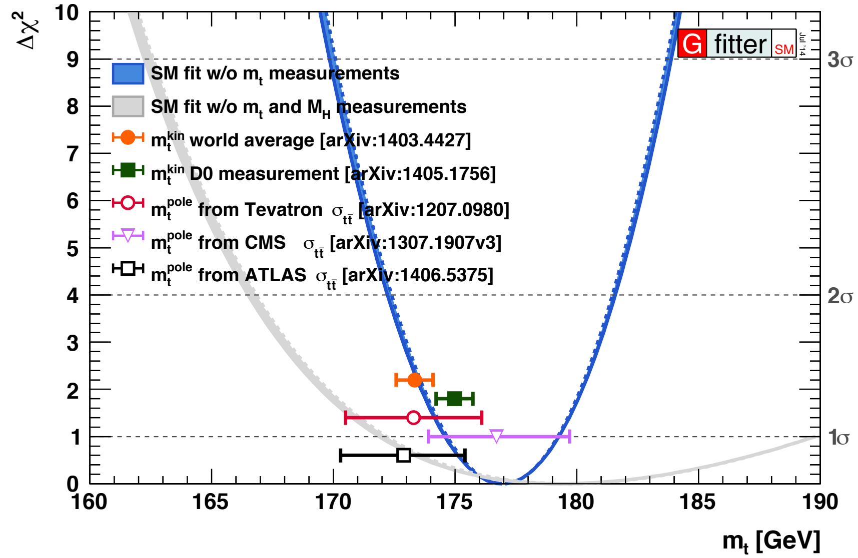
Precision measurement: <0.2%

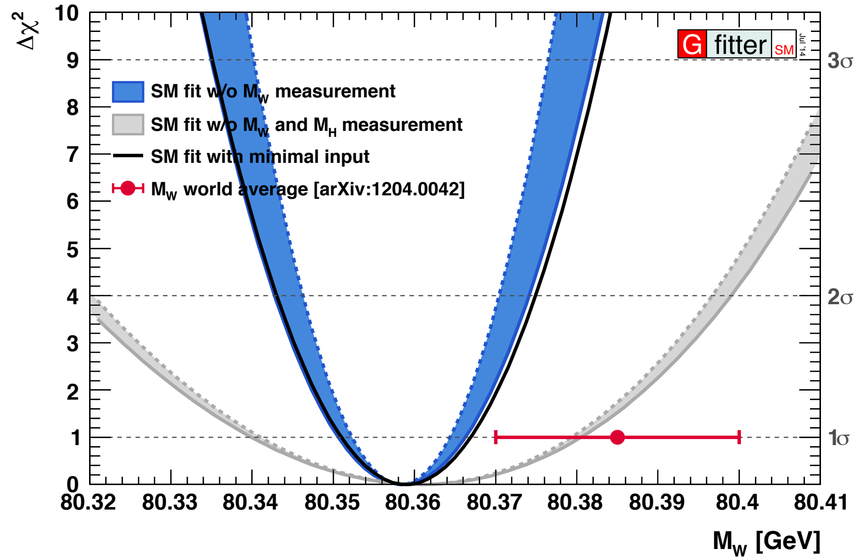
LHC combination:
125.09 ± 0.21 (stat) ± 0.11 (syst)

*a lot of progress by theory/MC community, LHCXSWG. Improvements continue…

Impact of Higgs Mass Measurement on Electroweak Fits

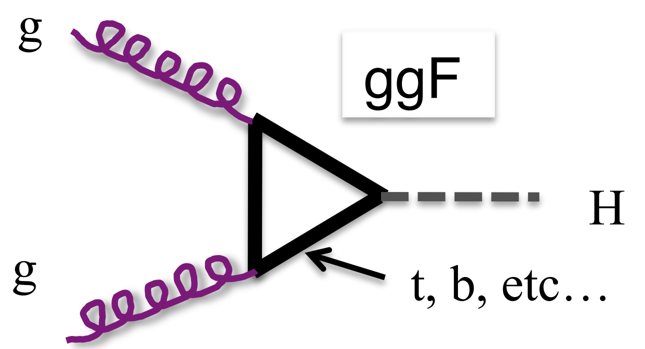


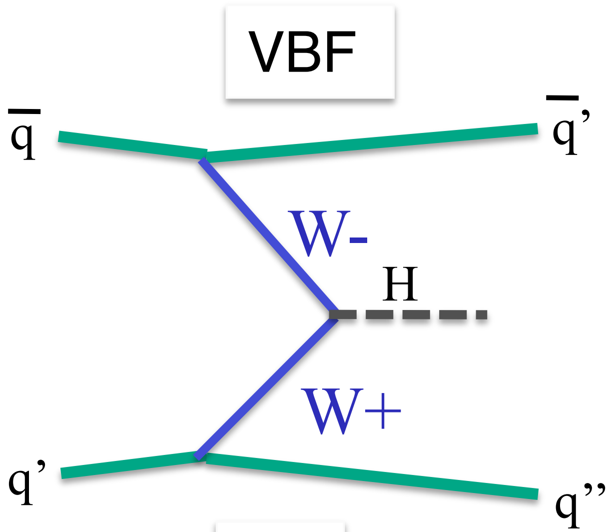


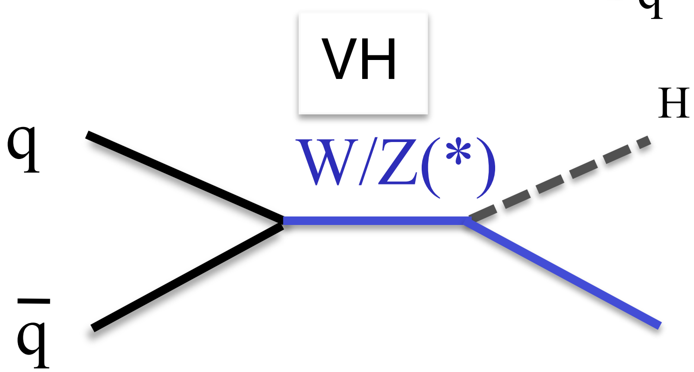


Eur. Phys. J. C **74**, 3046 (2014)

Higgs Production at the LHC

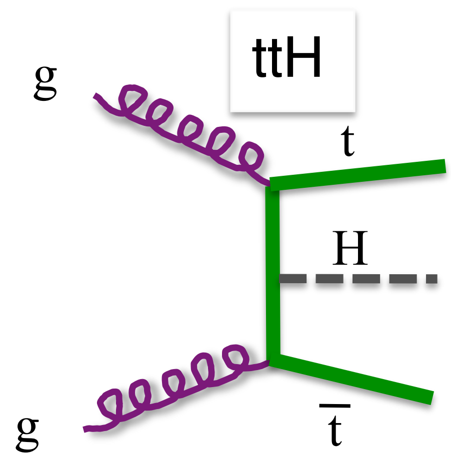


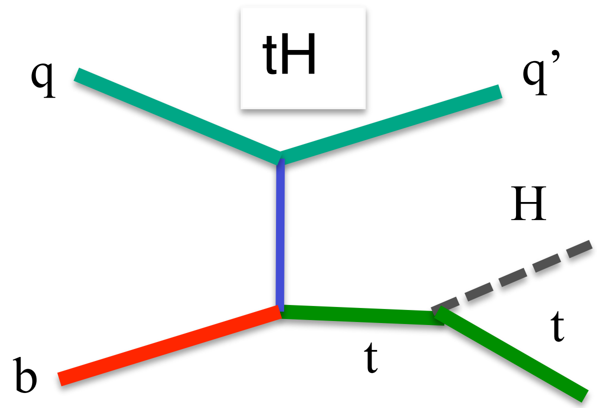




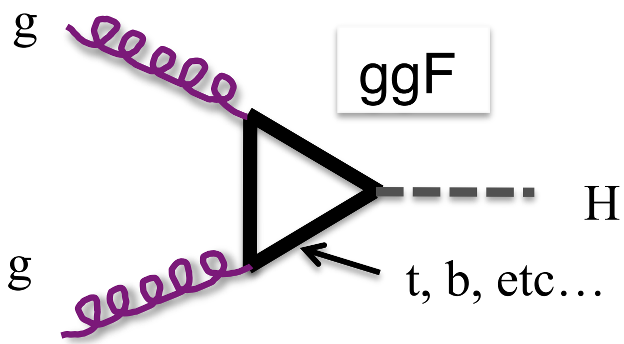
	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

SM Production Modes
(M_H = 125 GeV)

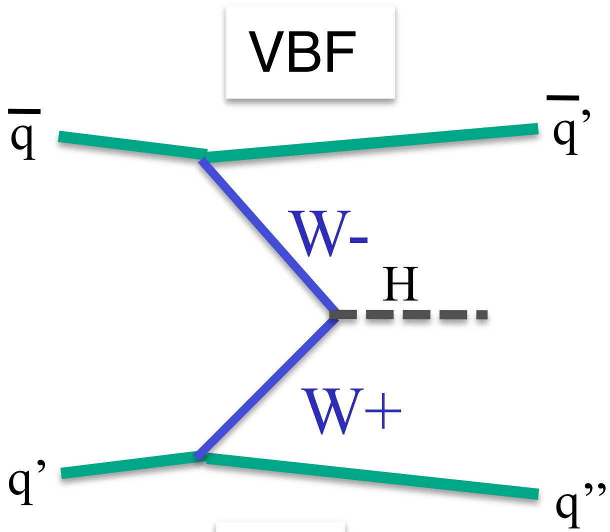




Higgs Production Modes

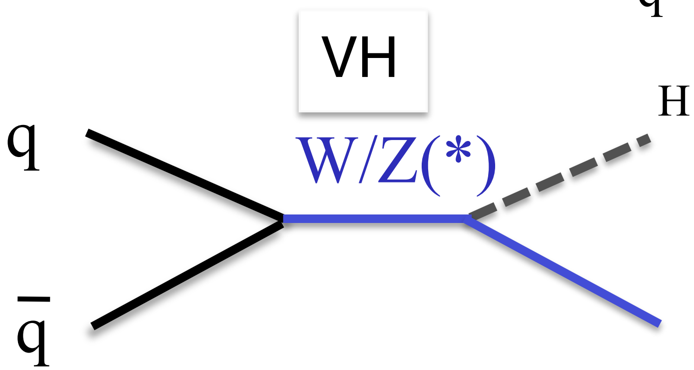


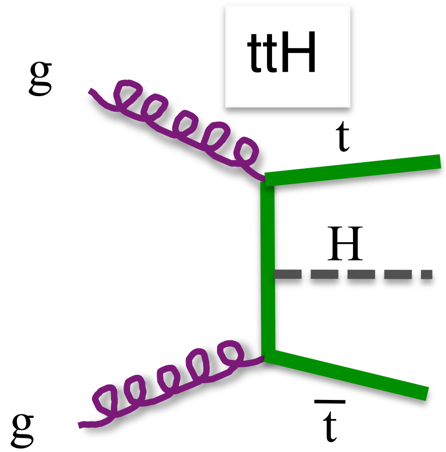
ggH and VBF well established (see ATLAS/CMS combination)

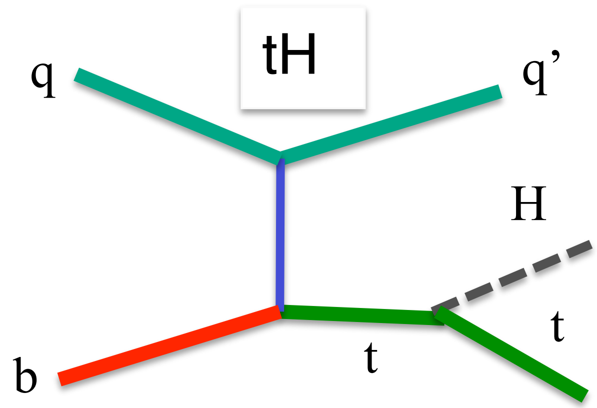


VH will have to wait for run 2 (but a close relative of VBF…)

ttH: strong evidence (see combination)





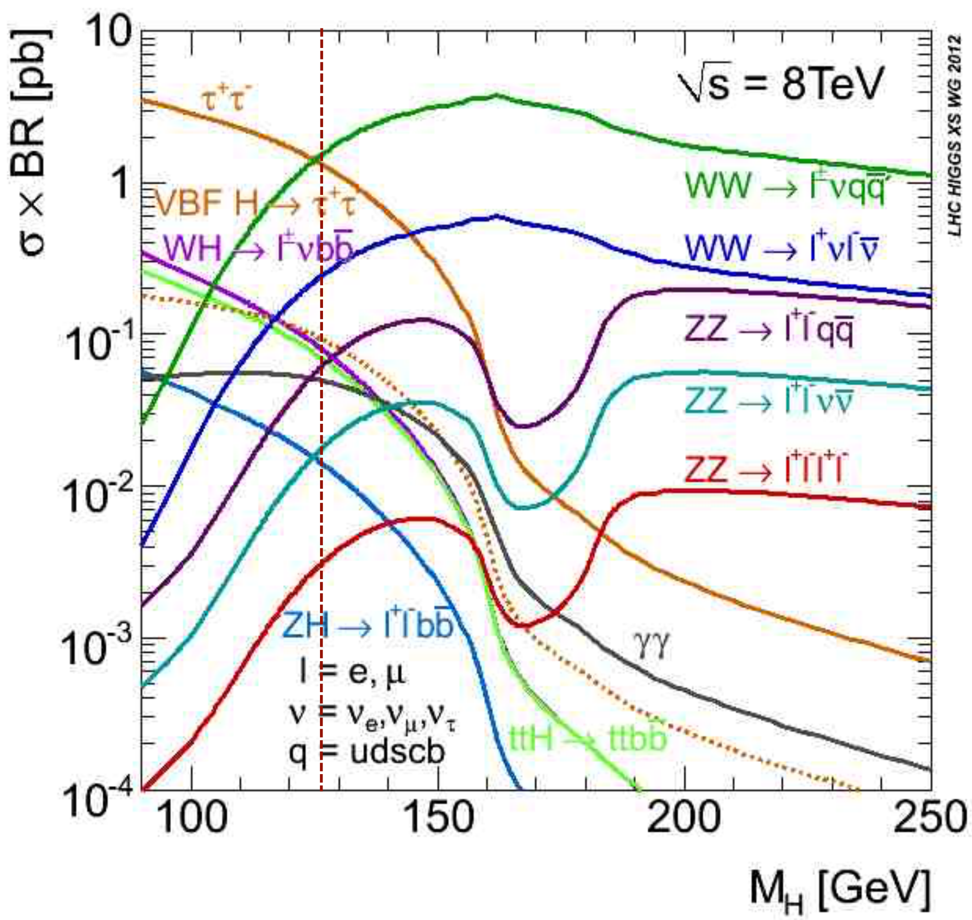


Higgs Decays

SM Decay Modes
(M_H = 125.1 GeV)

Process	Br
bb	0.58
WW	0.22
ττ	0.06
ZZ	0.027
γγ	0.0023
Zγ	0.0016
μμ	0.0002

- At m_H = 125 GeV, many decay channels can be studied



Main Production and Decays

Specific production and decay modes targeted by either ATLAS or CMS

	WW	ZZ	$\gamma\gamma$	bb	$\tau\tau$
ggH	X	X	X		X
VBF	X	X	X	X	X
WH	X	X	X	X	X
ZH	X	X	X	X	X
ttH	X	X	X	X	X

Represents an enormous amount of work

Main Production and Decays

Specific production and decay modes targeted by either ATLAS or CMS

	WW	ZZ	$\gamma\gamma$	bb	$\tau\tau$
ggH	σ_{ggH}*BR^{WW}	σ_{ggH}*BR^{ZZ}	σ_{ggH}*$BR^{\gamma\gamma}$	σ_{ggH}*BR^{bb}	σ_{ggH}*$BR^{\tau\tau}$
VBF	σ_{VBF}*BR^{WW}	σ_{VBF}*BR^{ZZ}	σ_{VBF}*$BR^{\gamma\gamma}$	σ_{VBF}*BR^{bb}	σ_{VBF}*$BR^{\tau\tau}$
WH	σ_{WH}*BR^{WW}	σ_{WH}*BR^{ZZ}	σ_{WH}*$BR^{\gamma\gamma}$	σ_{WH}*BR^{bb}	σ_{WH}*$BR^{\tau\tau}$
ZH	σ_{ZH}*BR^{WW}	σ_{ZH}*BR^{ZZ}	σ_{ZH}*$BR^{\gamma\gamma}$	σ_{ZH}*BR^{bb}	σ_{ZH}*$BR^{\tau\tau}$
ttH	σ_{ttH}*BR^{WW}	σ_{ttH}*BR^{ZZ}	σ_{ttH}*$BR^{\gamma\gamma}$	σ_{ttH}*BR^{bb}	σ_{ttH}*$BR^{\tau\tau}$

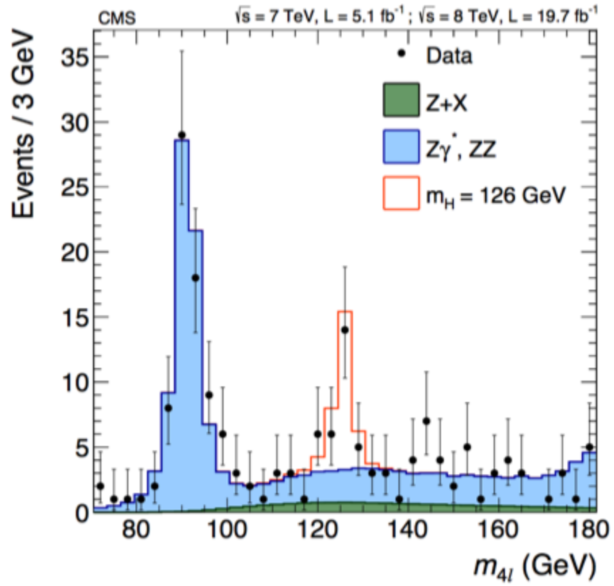
Signal yields proportional to $\sigma_{Prod.}$*BR^{Decay}

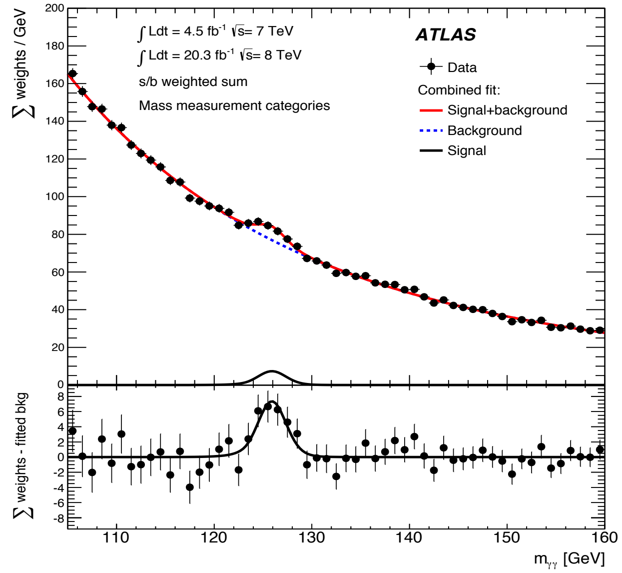
Main Production and Decays

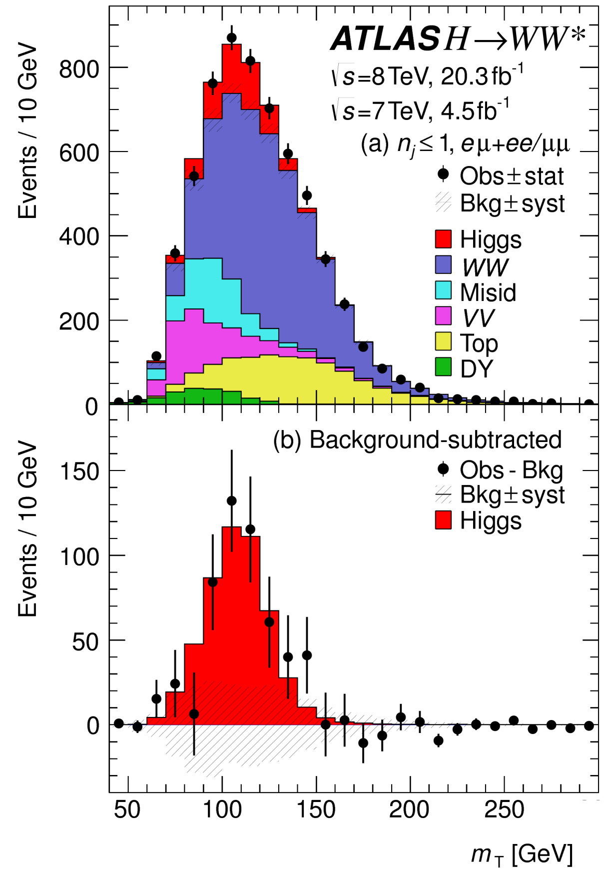
Using ratios, we can isolate production vs decay

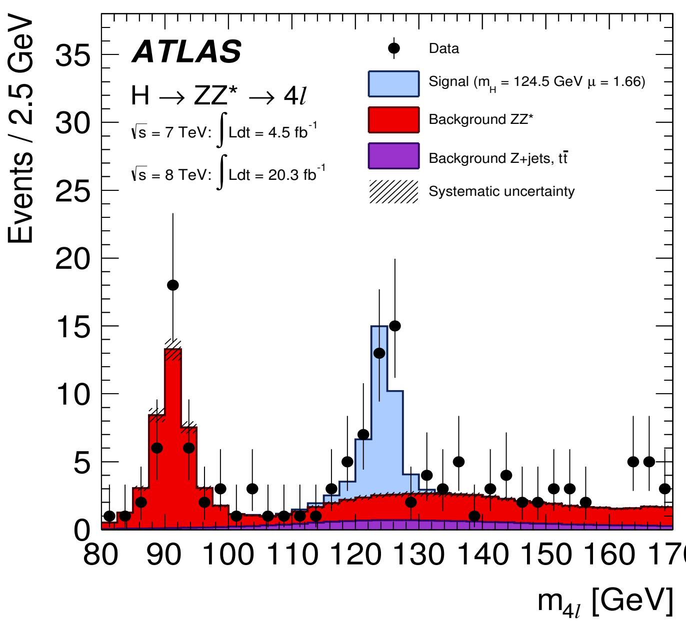
	WW	ZZ/WW	$\gamma\gamma$/WW	bb/WW	$\tau\tau$/WW
ggH	σ_{ggH}*BR^{WW}	→	→	→	→
VBF/ ggH	↓				
WH/ ggH	↓				
ZH/ ggH	↓				
ttH/ ggH	↓				

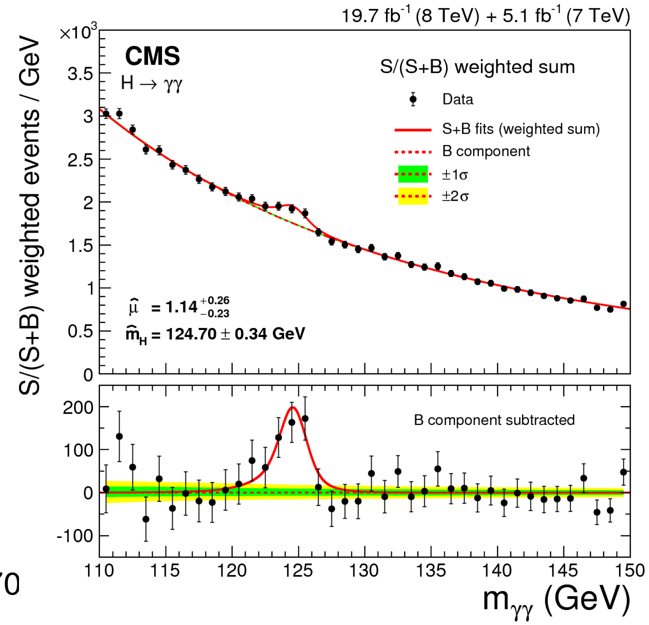
5σ Observation in γγ, ZZ and WW Decays

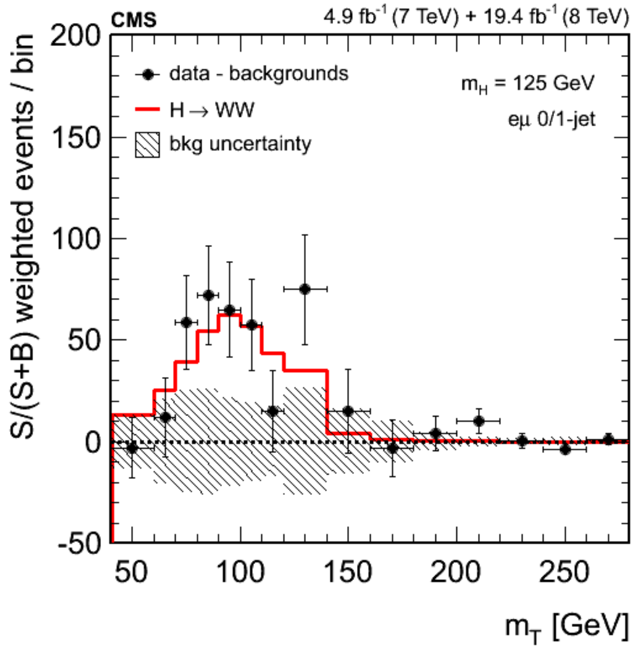










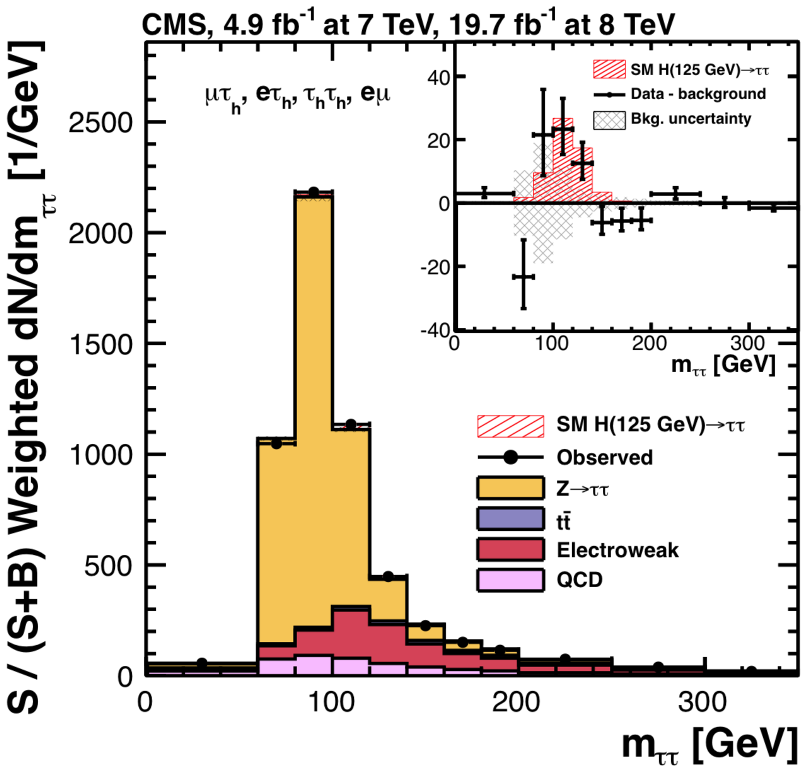


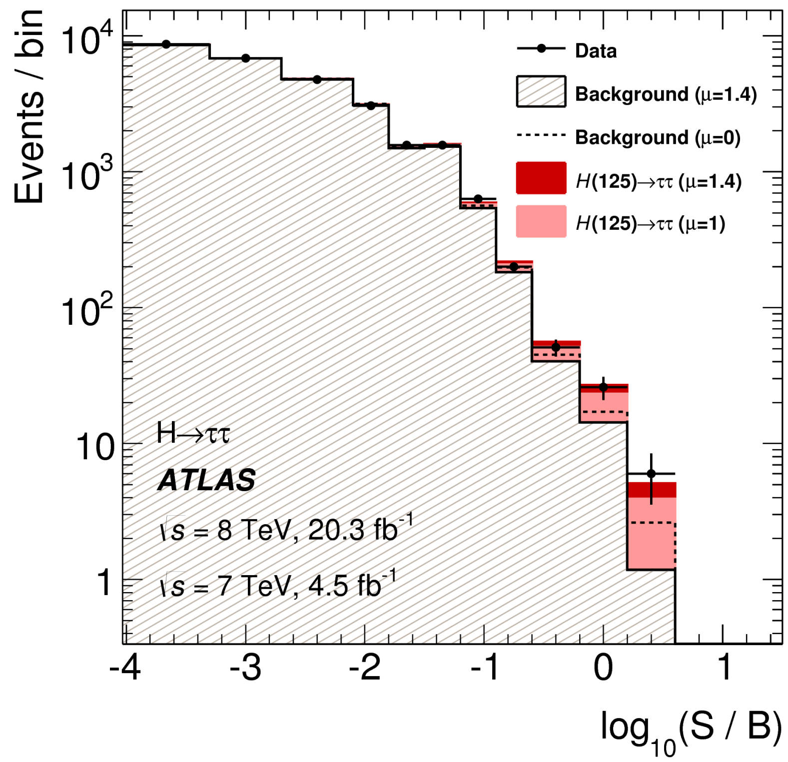
Decays to Fermions ($\tau\tau$)

Significance obs. (exp.) in ATLAS/CMS combination: 5.5 (5.0)

CMS:
- **3.2 (3.7) σ**

ATLAS:
- **4.5 (3.4) σ**





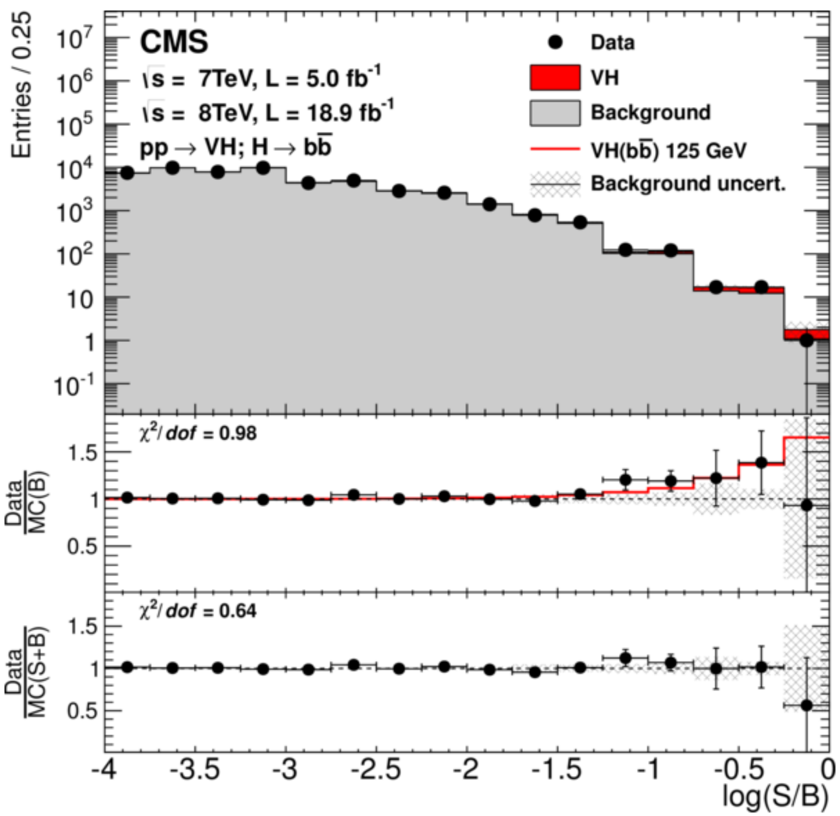
DECAYS TO FERMIONS (bb)

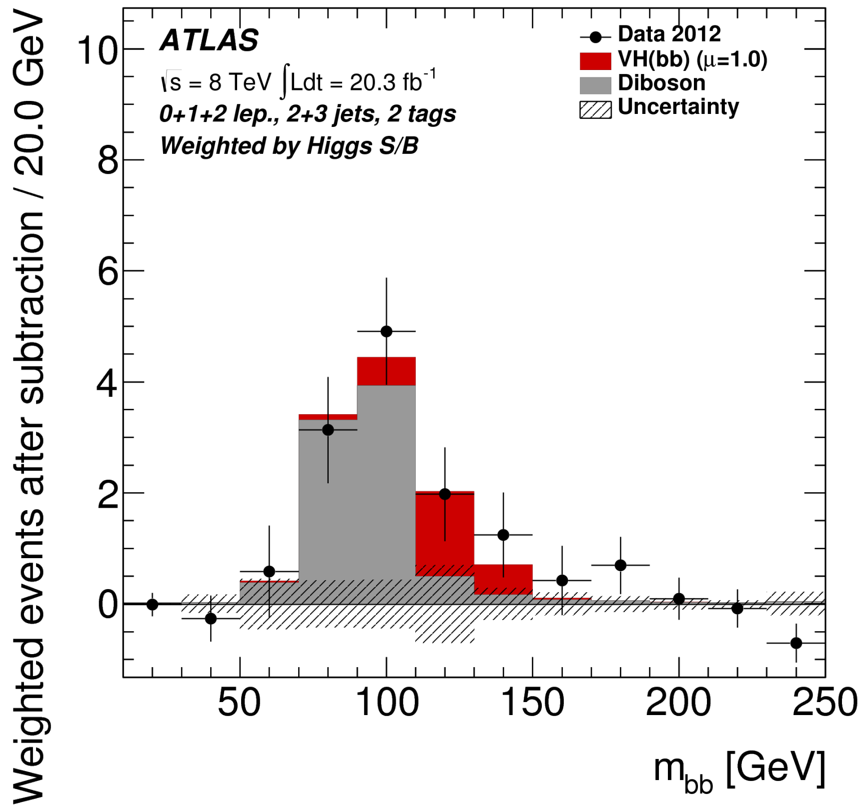
Significance obs. (exp.) in ATLAS/CMS combination: 2.6 (3.7)

CMS(VH+VBF+ttH):
- **2.6 (2.7) σ**

Tevatron(VH):**
- **2.2 (1.4) σ**

ATLAS(VH+ttH):
- **1.8 (2.8) σ**





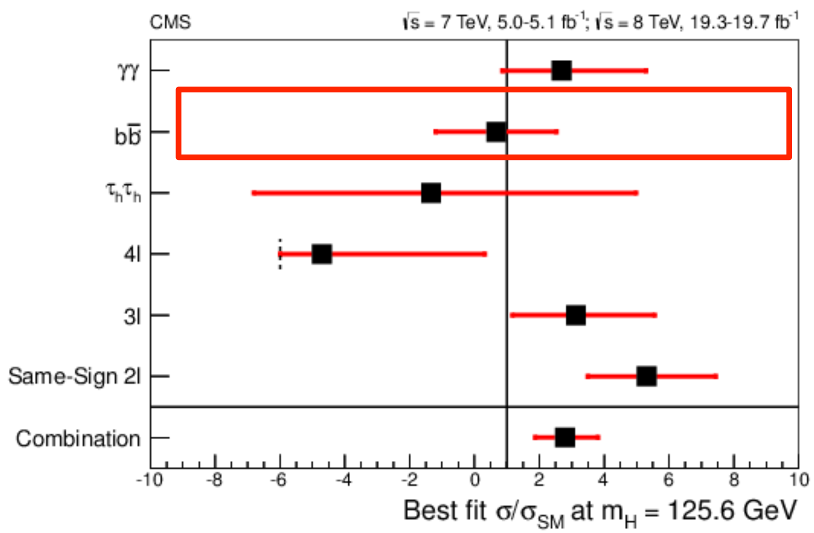
**my estimate from: Phys. Rev. D 88, 052014 (2013)

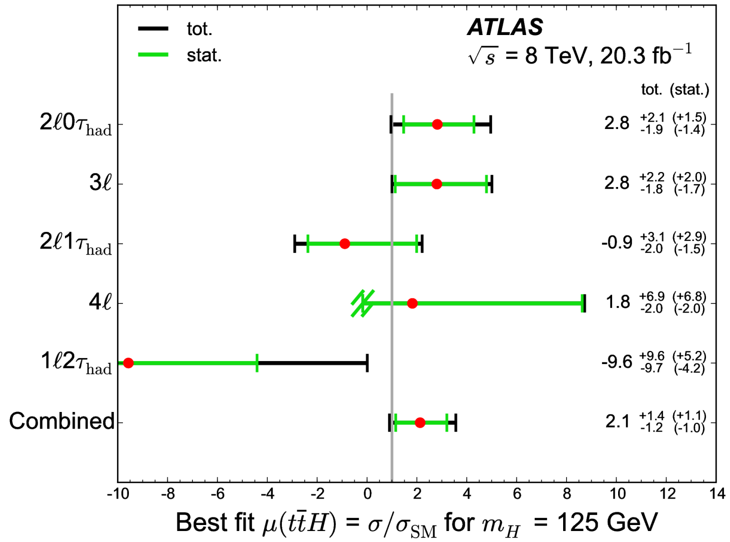
ttH Associated Production

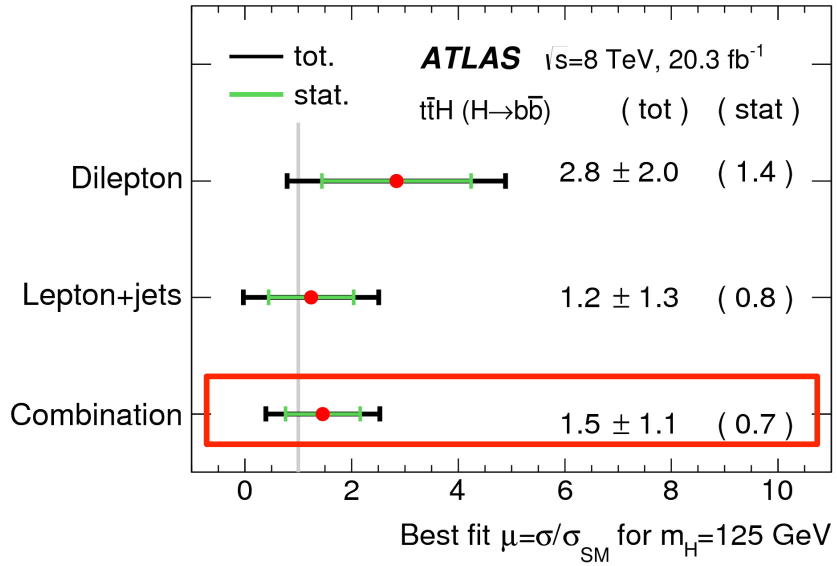
Test Yukawa coupling of the top quark (large! ~1.0 in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…







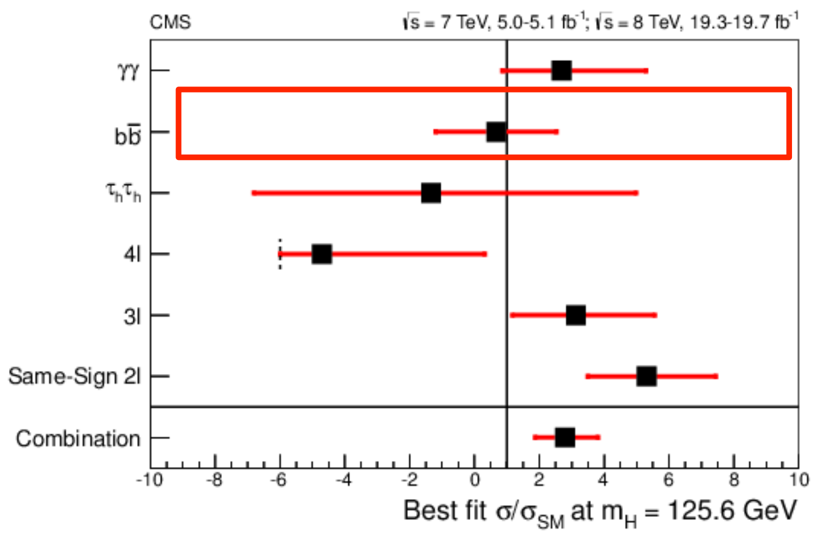
Combination of signal strengths:
CMS: μ = 2.8 +/- 1.0
ATLAS: μ = 1.8 +/- 0.8

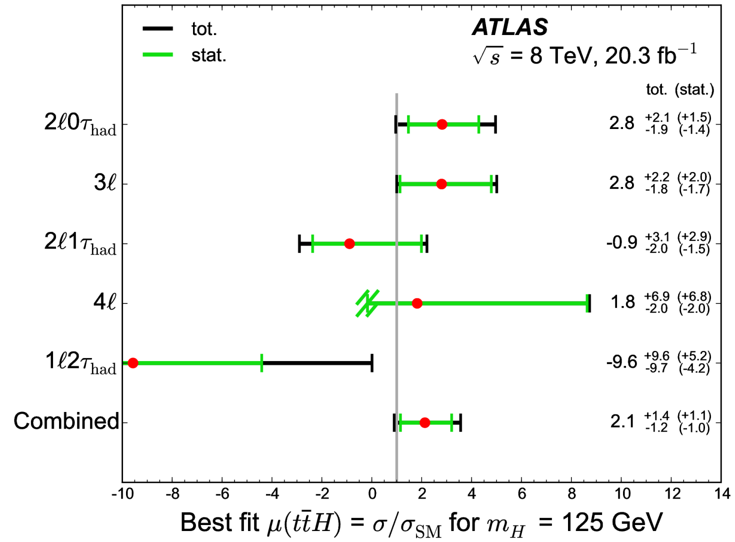
ttH Associated Production

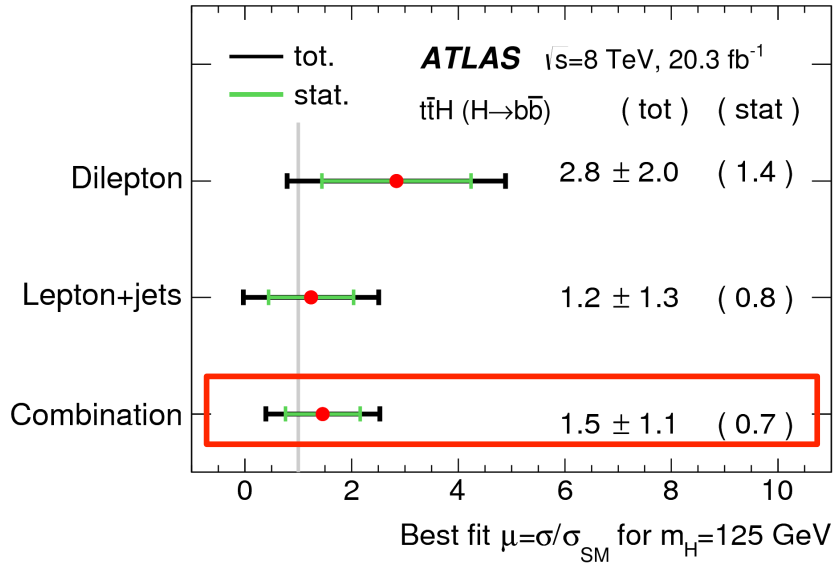
Test Yukawa coupling of the top quark (large! ~1.0 in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…







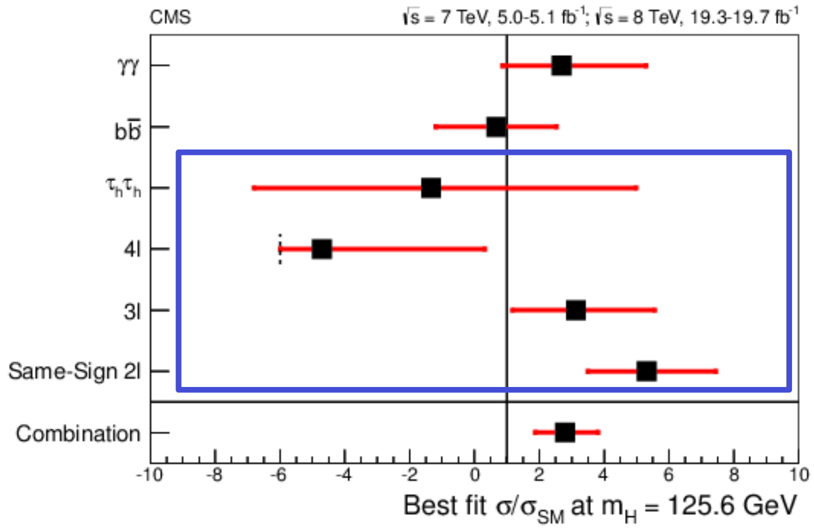
ATLAS/CMS combination:
significance obs (exp): 4.4 (2.0)

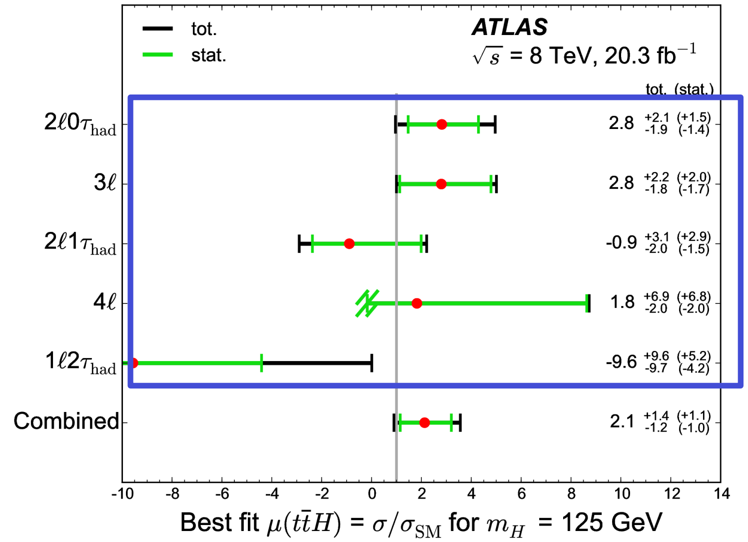
ttH Associated Production

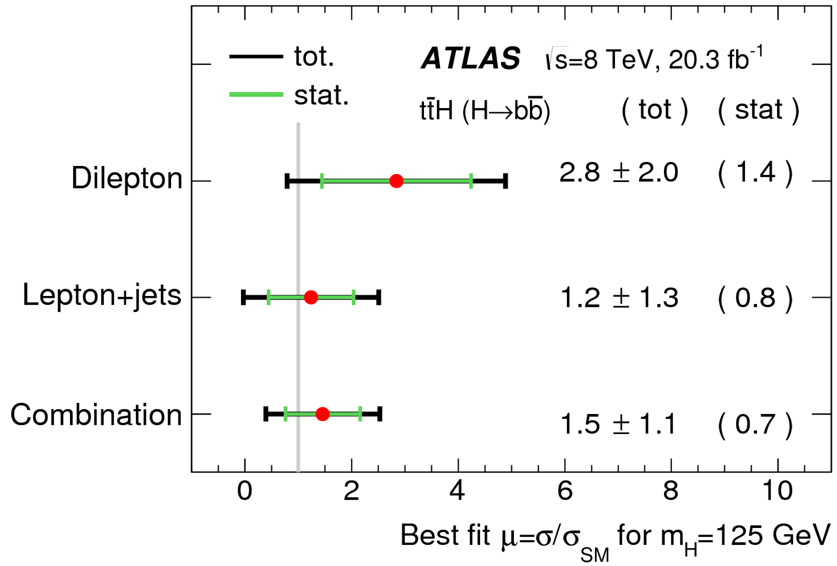
Test Yukawa coupling of the top quark (~1.0 in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…







Combination of signal strengths:

$\mu = 2.3^{+0.7}_{-0.6}$

Status of SM Rare Decays

Searches for rare decays performed in various channels

Observation of these decays in Run 1 would signal BSM physics

Non-universal coupling of Higgs to leptons:

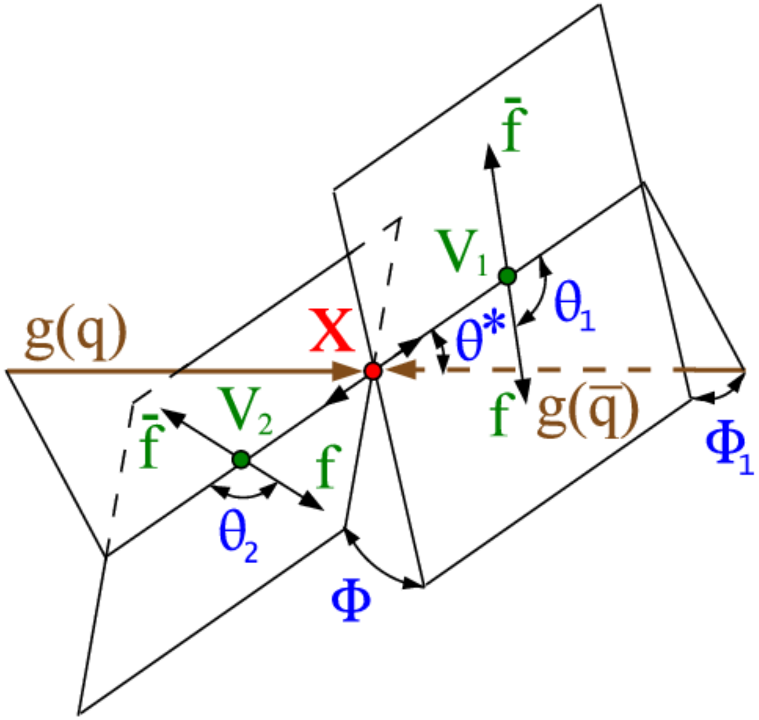
- $\mu\mu$ signal would be 280 times larger than SM if μ coupling was equal to that of τ

Process	limit (times SM)
$\mu\mu$ (ATLAS)	7.0
$\mu\mu$ (CMS)	7.4
$Z\gamma$ (ATLAS)	11
$Z\gamma$ (CMS)	9
$\gamma\gamma^*$ (CMS)	7.7
$J/\psi\gamma$ (ATLAS)	540
$J/\psi\gamma$ (CMS)	540
ee(CMS)	10^5

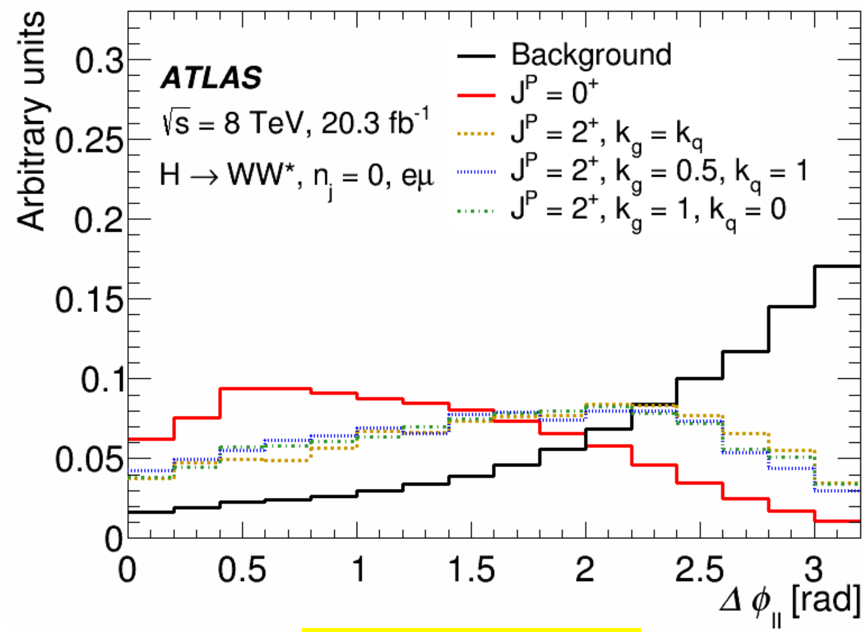
Spin/CP Hypotheses Tests

Tests of spin/CP properties performed in ZZ, γγ, WW channels

ZZ: full kinematic information available for spin/CP determination

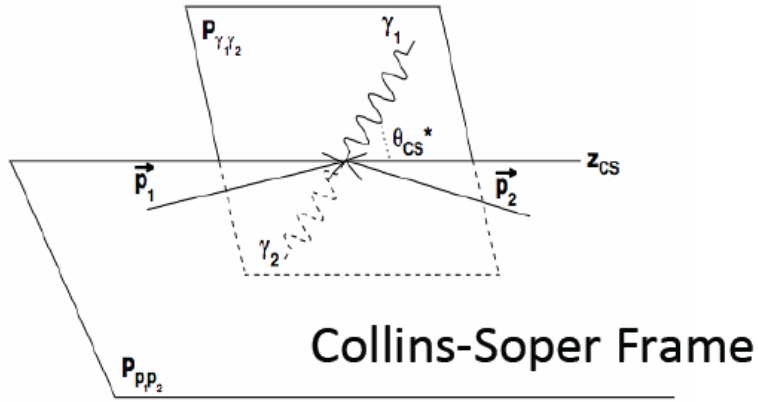


WW spin information from kinematic variables



γγ: use cos(θ*)

γγ



Fixed Spin and Parity Tests

Test alternative fixed spin and parity hypotheses relative to the SM 0^+ hypothesis

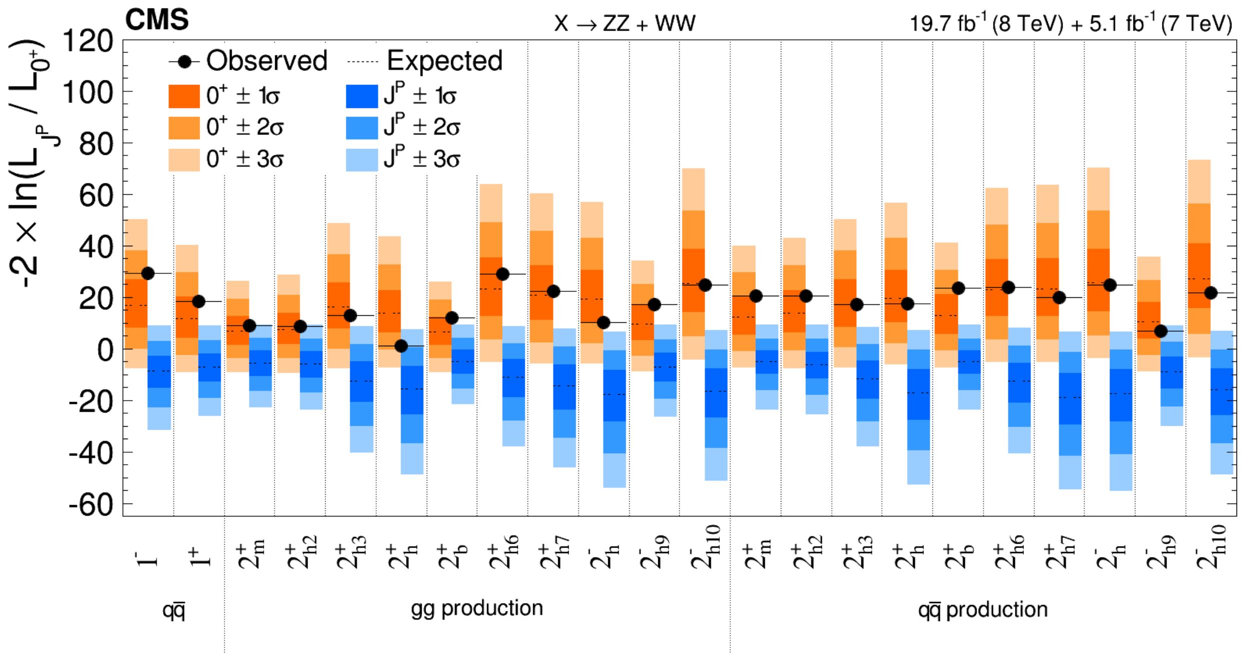
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\hat{\mu}}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\hat{\mu}}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

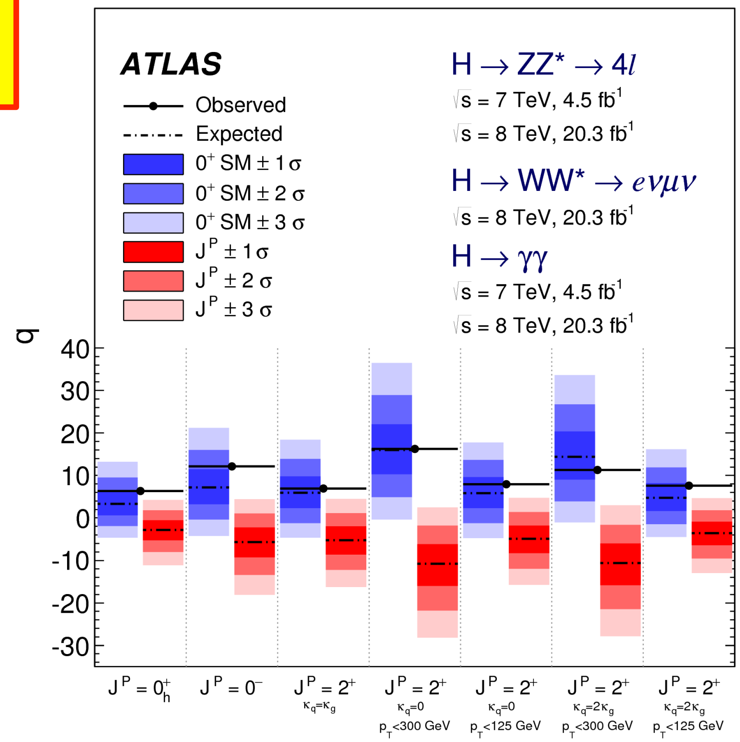
Results favour the spin 0^+ hypothesis

Alternatives: 0-, 1-, 1+, various spin 2 models are typically excluded at > 99.9% CL

Also Tevatron results: **PRL 114, 151802 (2015)**

Large anomalous couplings are excluded. Next step: look for presence of smaller contributions





CP Mixing Results

Probe potential CP-mixing and tensor structure of Higgs interactions

•Amplitude describing interaction between a spin 0 and two spin 1 particles used by CMS:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

SM (a_1^{VV}), BSM CP-even (a_2^{VV} term), BSM CP-odd (a_3^{VV} term)

ATLAS: different formulation (see next slide), but results can be compared

No significant contributions from BSM terms are observed (see next slides)

BSM CP-even (95% CL)

CMS	$f_{a2}\cos(\phi_{a2}) \in [-0.11, 0.17]$
ATLAS	$f_{a2} < 0.12$ for $\phi_{a2} = 0$
	$f_{a2} < 0.16$ for $\phi_{a2} = \pi$

BSM CP-odd (95% CL)

CMS	$f_{a3}\cos(\phi_{a3}) \in [-0.27, 0.28]$
ATLAS	$f_{a3} < 0.090$ for $\phi_{a3} = 0$
	$f_{a3} < 0.41$ for $\phi_{a3} = \pi$

CMS CP Mixing Results

Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{(\Lambda_1^{\mathrm{VV}})^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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

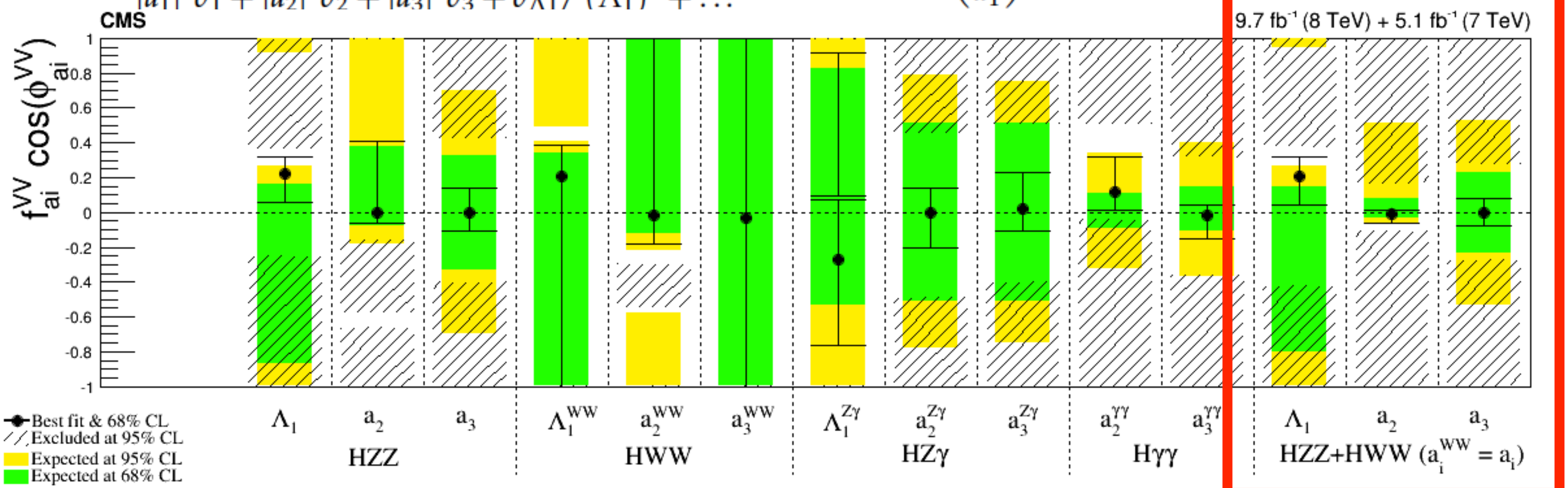
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i : xs for $a_i = 1$

$\Lambda_1 = 1$ TeV

Phys Rev D. 89.035007



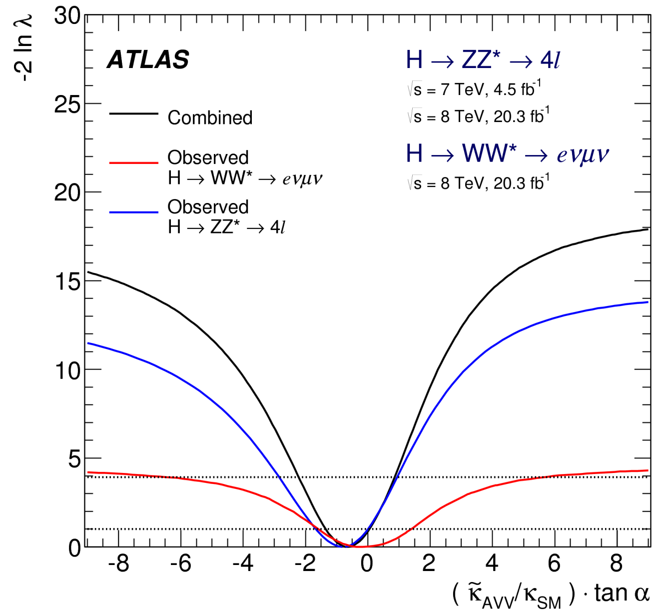
ATLAS CP Mixing Results

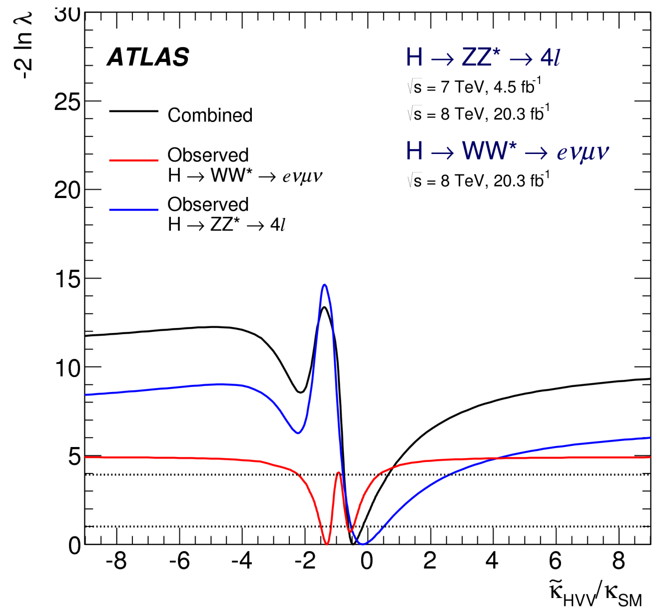
Lagrangian describing interaction between a spin 0 and a pair of W or Z bosons (from JHEP 1311 (2013) 043):

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \frac{1}{4}\frac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \frac{1}{2}\frac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \Big\} X_0.$$

J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

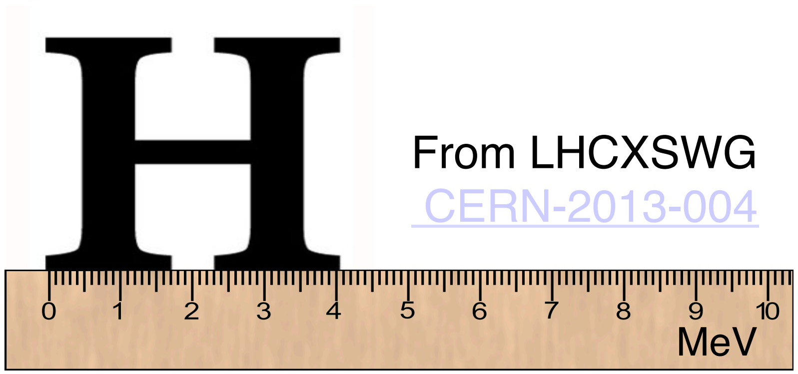
No significant contributions from BSM terms are observed





Width and Lifetime

SM width (m_H=125.1 GeV): 4.1 MeV



From LHCXSWG
CERN-2013-004

Higgs width measurements at LHC:

- Direct (limit at 95% CL obs. (exp.))
  - ~2 GeV from ATLAS and CMS ($\gamma\gamma$,ZZ):
- Interference in $\gamma\gamma$ (signal – continuum)
  - Expected mass shift ~40 MeV for SM
  - No assumptions but small effect
- Lifetime: Γ(H) > 3.9 x10^{-9} MeV (CMS)

- Via off-shell couplings:

Direct measurement of Off Shell couplings (independent of width)

- Measure width assuming SM running (or measure running assuming width)

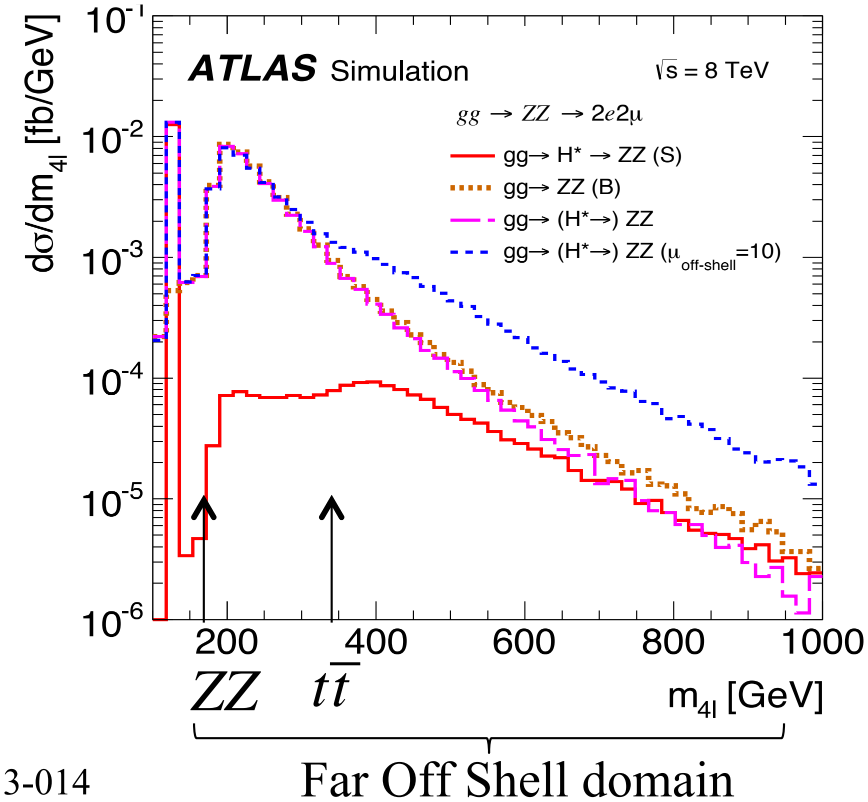
Assuming* $\mu_{OffShell} = \mu_{OnShell}$

- CMS: 22 (33) MeV (95%CL)
- ATLAS: 23 (33) MeV (95%CL)

at HL-LHC*:

$\Gamma = 4.1^{+1.5}_{-2.1}\, MeV$

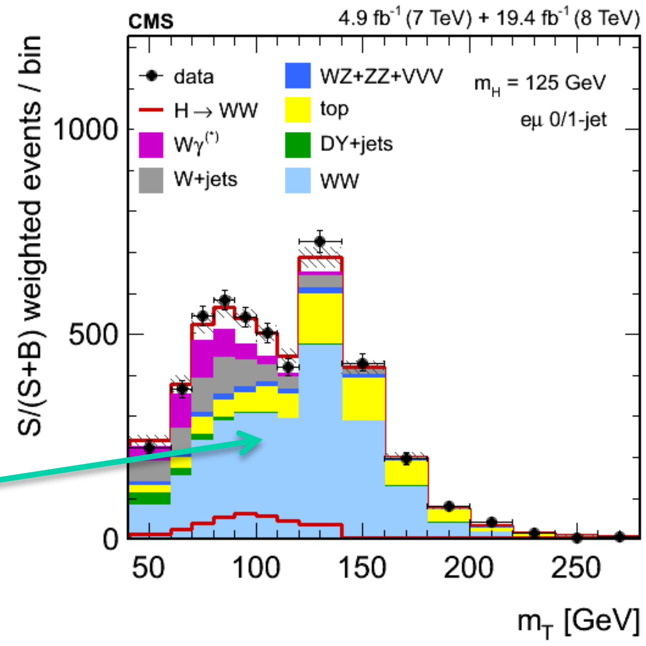
*ATL-PHYS-PUB-2013-014



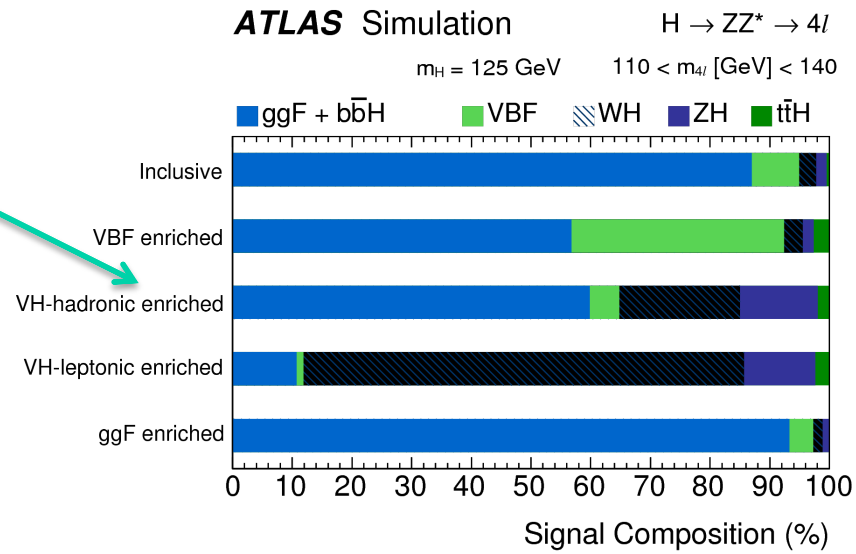
Combination of Signal Strengths

- We measure event yields n_{evt} and we need to extract signal yields n_s
  - Estimate and subtract backgrounds

$n_s = n_{evt} - n_{bkg}$



- Production mode categories c are contaminated by other signal processes
- Global fit to all categories can take into account all contributions and correlations



We extract the signal strength μ : ratio of the observed yield to the SM prediction

$$n_s^{c,i} = \sum_p \left[\mu^p \mu^i_{BR}\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

ATLAS/CMS Combination

Signal strength: $$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Use parametrization that constrains production and decay signal strengths to be the same:

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

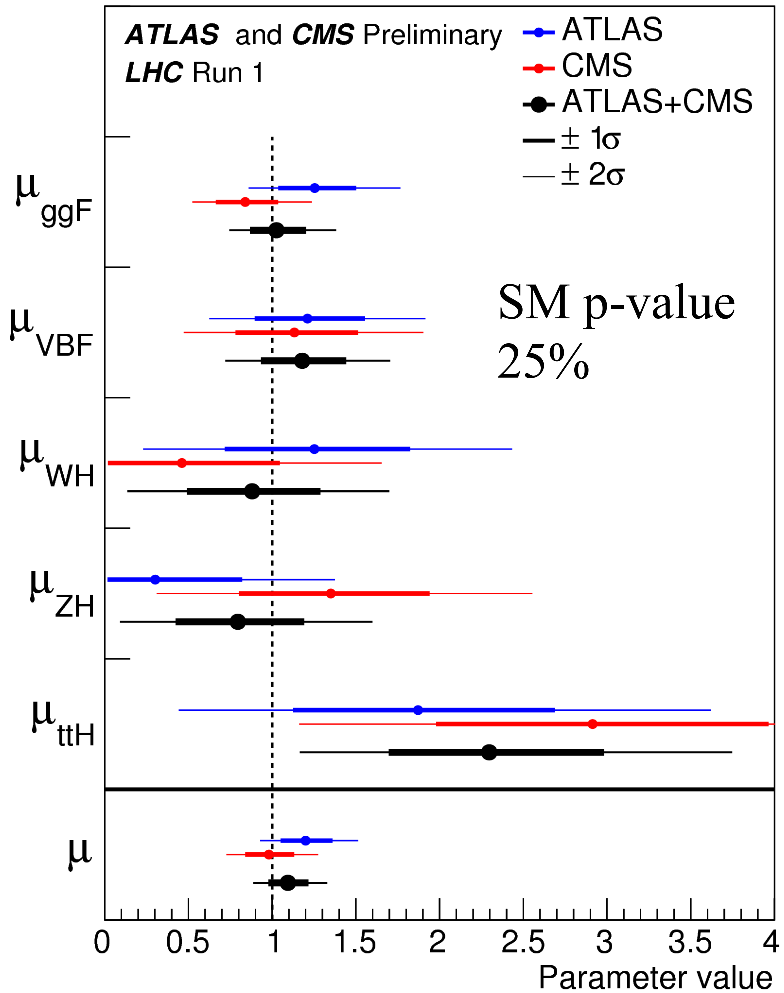
Theory uncertainties equal to statistical uncertainties

- **Recent improvements will help (but we can be more clever too)**

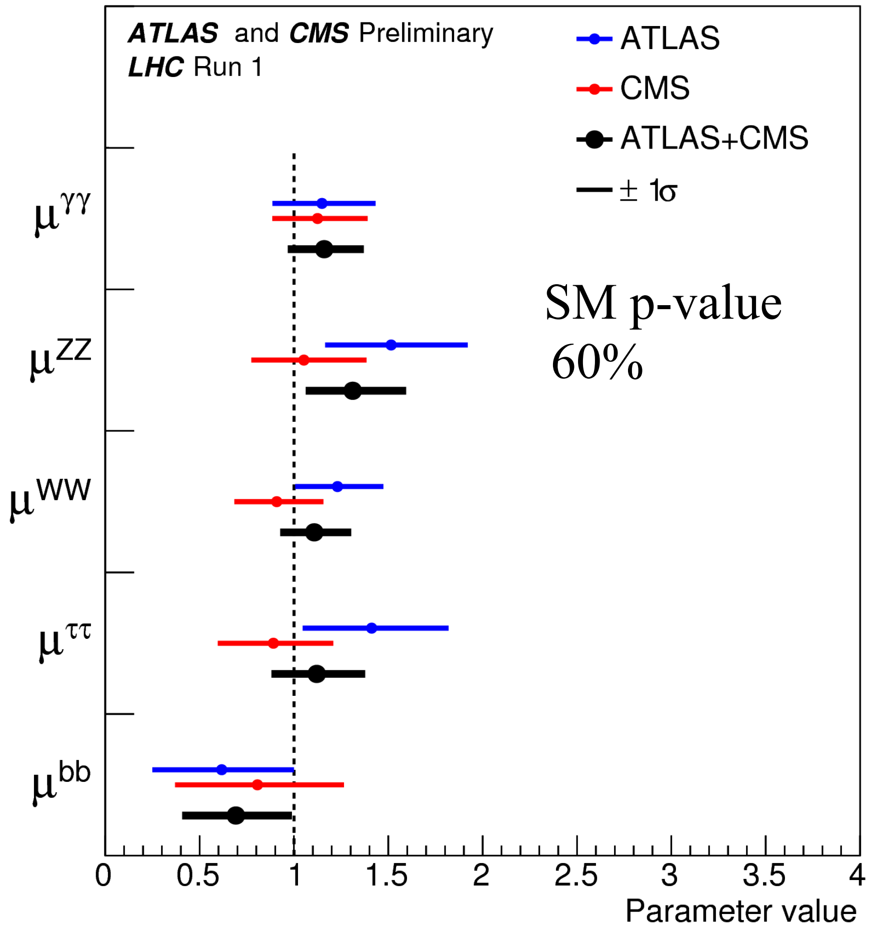
Overall systematic uncertainty larger than statistical uncertainty

ATLAS/CMS Combination

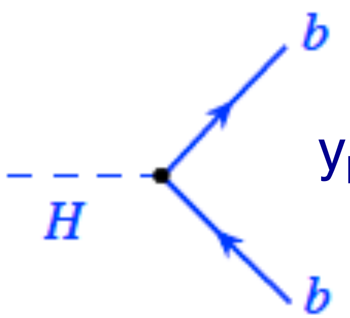
Production Signal Strengths



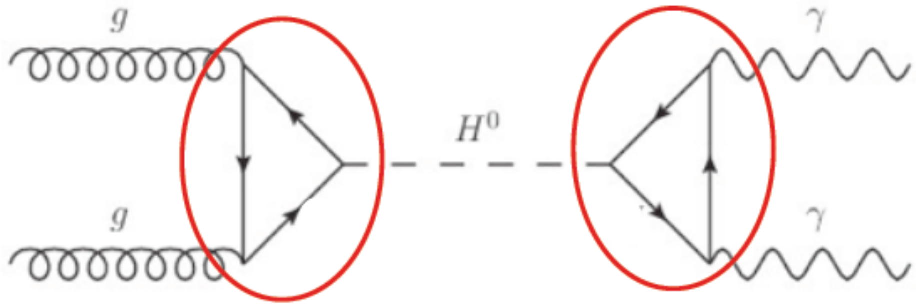
Decay Signal Strengths



Couplings Framework



y_b : b yukawa



assuming no BSM particles in the loops

$$\kappa_g^2 \propto 1.06 \times \kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$$

$$\kappa_\gamma^2 \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

- $y_b := \kappa_b \, y_b^{SM}$

- "κ framework": interpret signal strength parameters (μ_p, μ^i_{BR}) in terms of modifiers to the SM couplings:

- Decay: $\Gamma_i = \kappa_i^2 \; \Gamma_i^{SM}$
- Production: $\sigma_i = \kappa_i^2 \; \sigma_i^{SM}$
- Width: $\Gamma_H = \Sigma_i \, \kappa_i^2 \; \Gamma_i^{SM}$

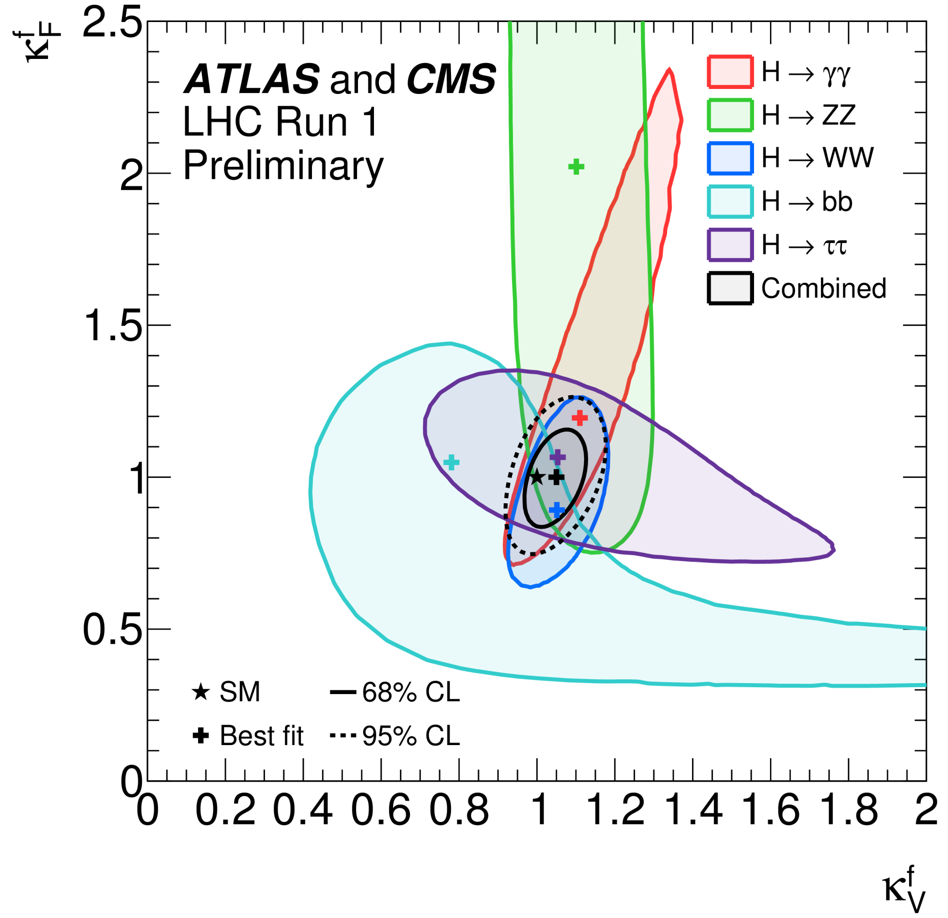
Assumptions (see LHCXSWG YR3):

- Only one Higgs
- SM production and decay kinematics
  - Tensor structure is that of SM
  - 0+ scalar
- Narrow resonance

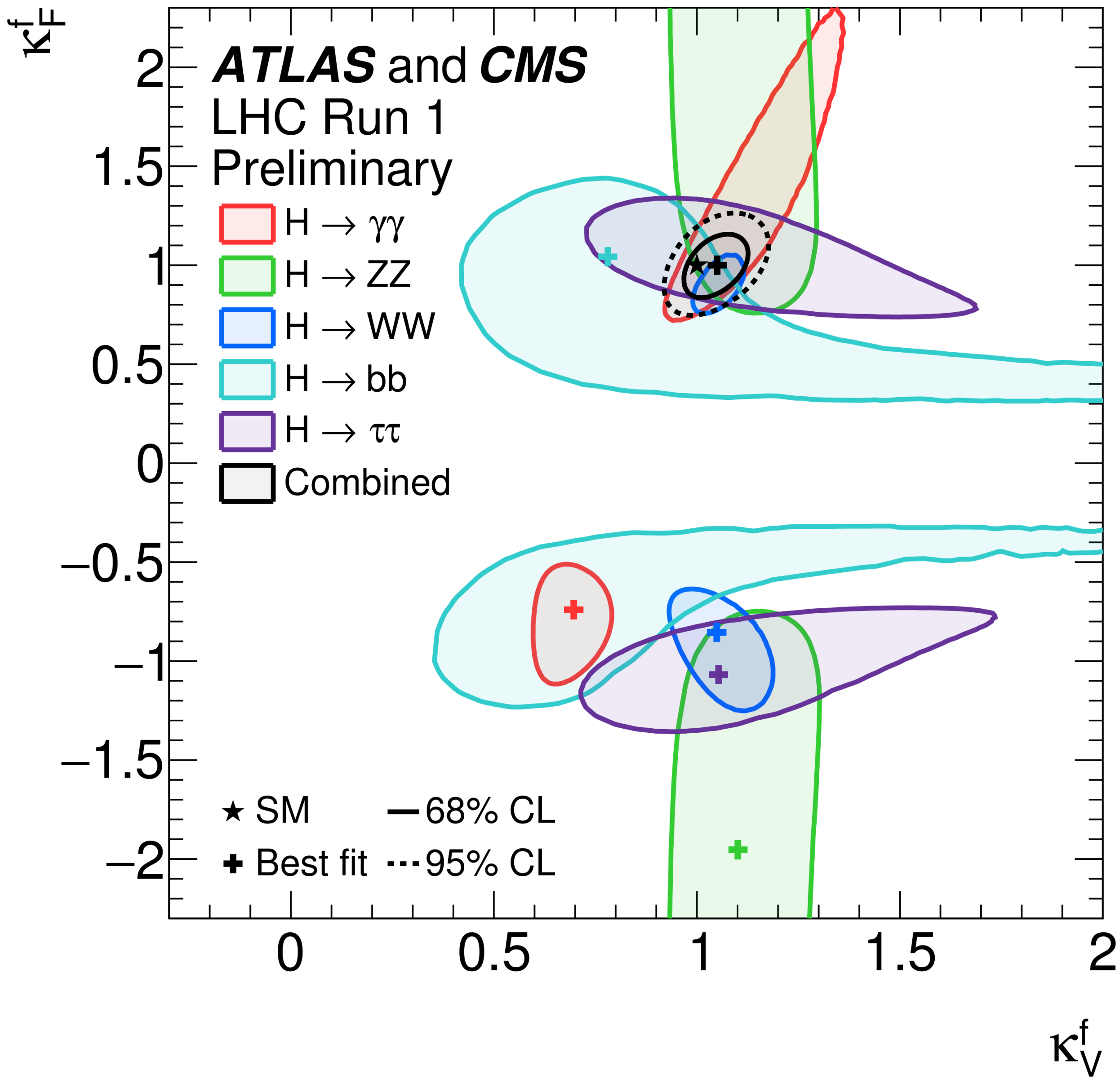
ATLAS/CMS Combination

Test gauge vs Yukawa couplings

- Assumptions:
  - Common scaling factor for fermions and gauge bosons:
    - κ_F and κ_V
  - No BSM contributions to width
  - No BSM contributions to loops
- Interference in $\gamma\gamma$, tH, gg->ZH can resolve relative sign between κ_F and κ_V
- Results compatible with SM



ATLAS/CMS Combination



Sensitivity to sign of k_F due to H->γγ decay, gg->ZH and tH production (in WW and bb)

Couplings with SM Particle content

"Absolute couplings". Assumptions:

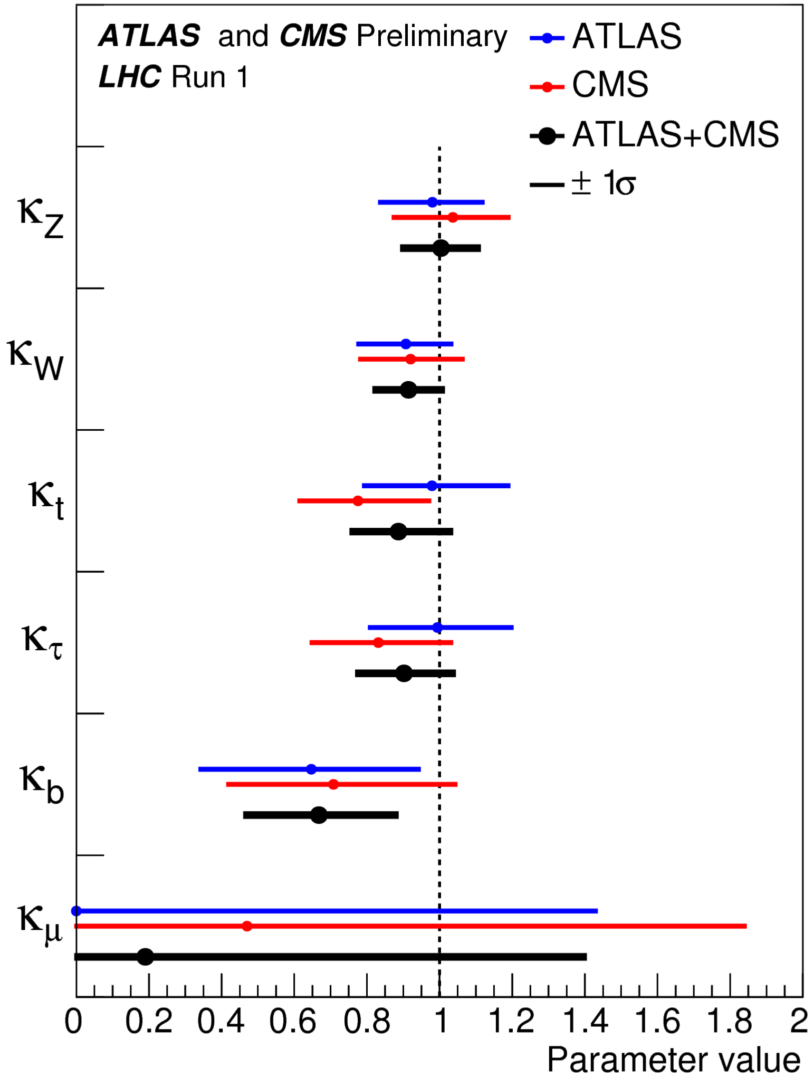
- No contributions to width from BSM particles
- No contributions to loops from BSM particles

- Why are the κ values low when the global μ is 1.09?

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

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

$$\kappa_\mathrm{H}^2 \sim \begin{array}{l} 0.57 \cdot \kappa_\mathrm{b}^2 + 0.22 \cdot \kappa_\mathrm{W}^2 + 0.09 \cdot \kappa_\mathrm{g}^2 + \\ + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_\mathrm{Z}^2 + 0.03 \cdot \kappa_\mathrm{c}^2 + \\ + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{\mathrm{Z}\gamma}^2 + \\ + 0.0001 \cdot \kappa_\mathrm{s}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

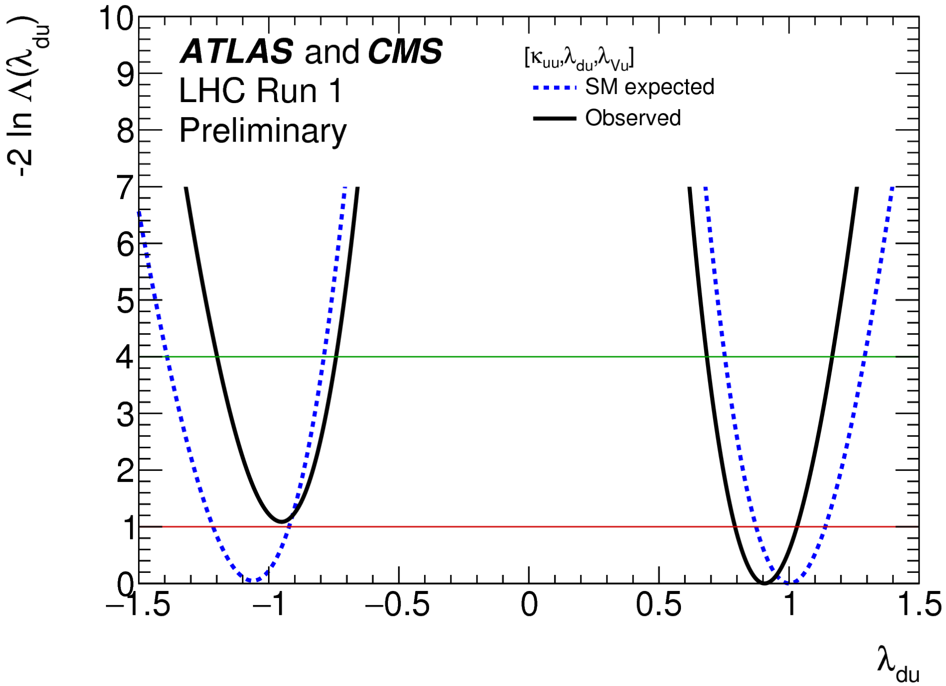


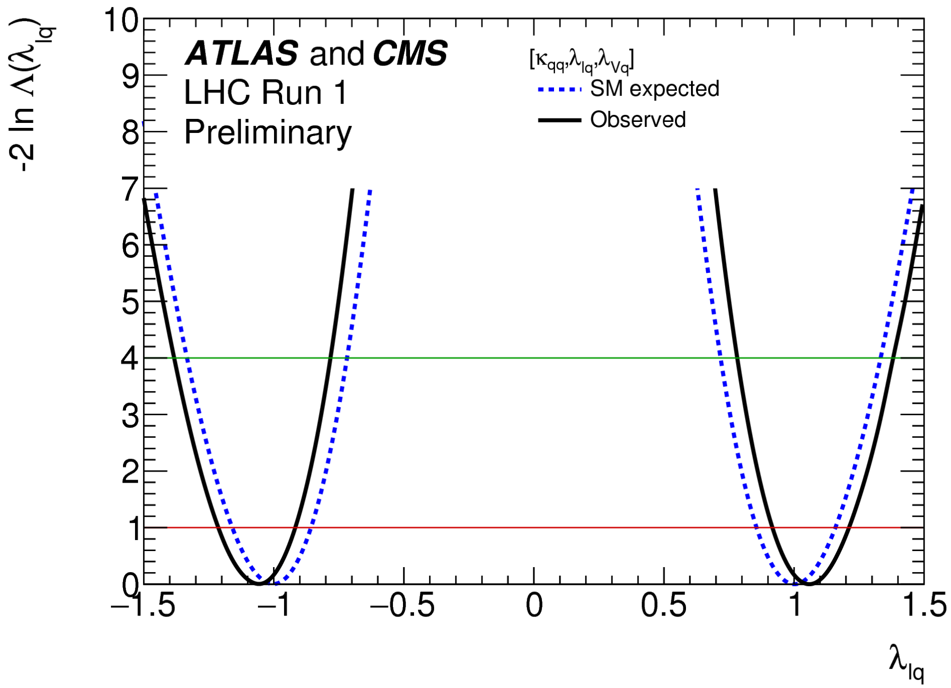
Low value of k_b reduces total width

Up/down and lepton/quark Couplings

Check coupling ratios between up-type and down-type fermions (left) and quarks and leptons (right)

- motivated by e.g. two Higgs doublet scenarios

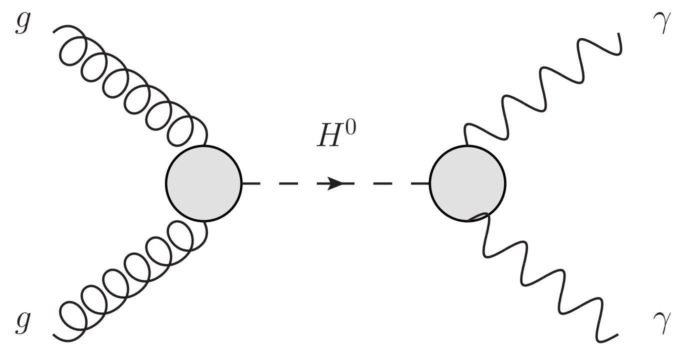




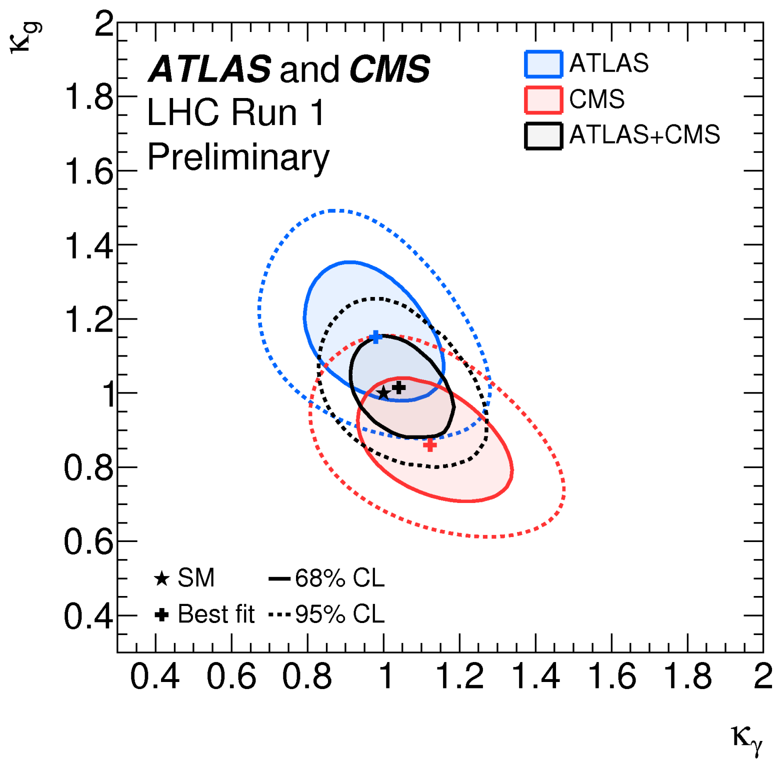
New Physics in Loops?

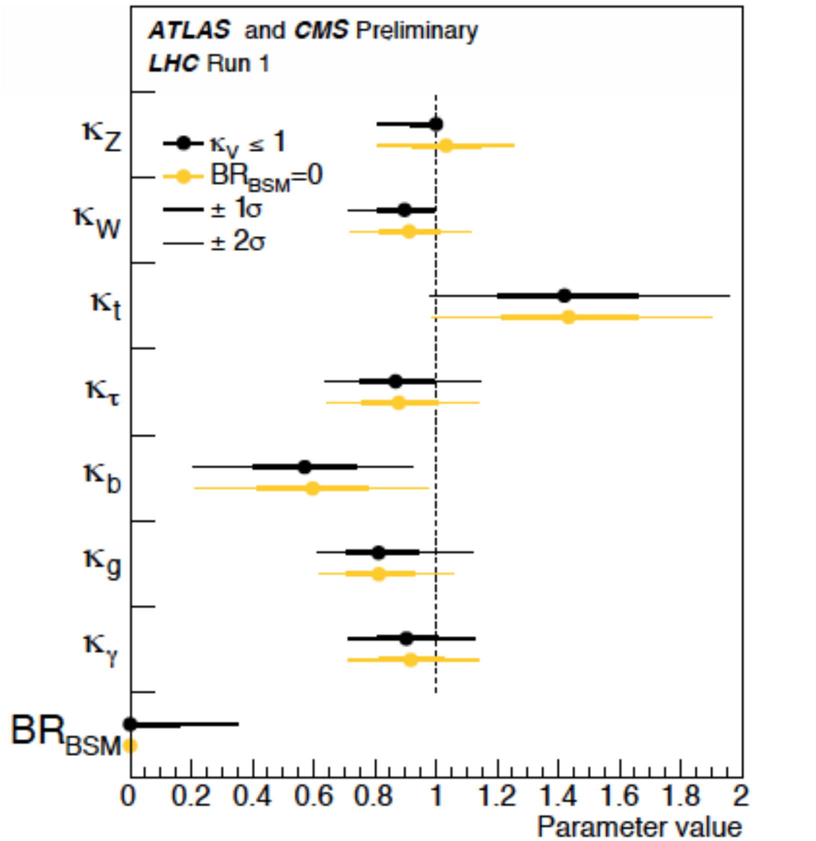
Test for "heavy" BSM physics (BSM particles > $m_H/2$) with possible contributions to ggH, $H\gamma\gamma$ (and $HZ\gamma$) loops, or "light" physics in the decay loop

- Assume SM couplings for known particles



$$\frac{(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

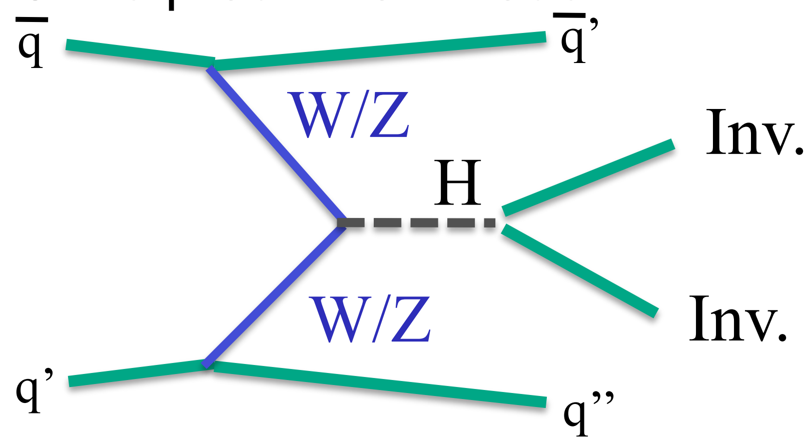




Invisible Decays: Direct Searches

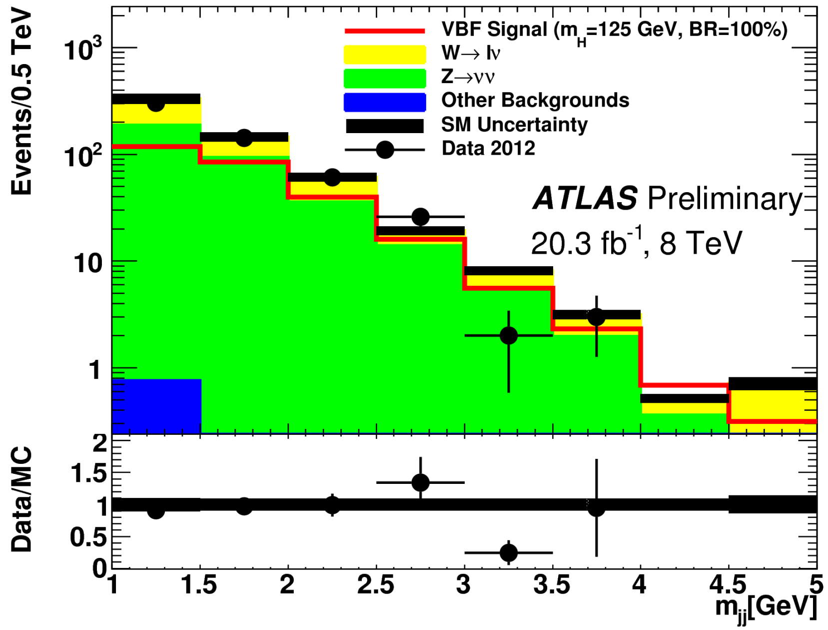
SM BR to invisible: 0.1% (ZZ->4ν)

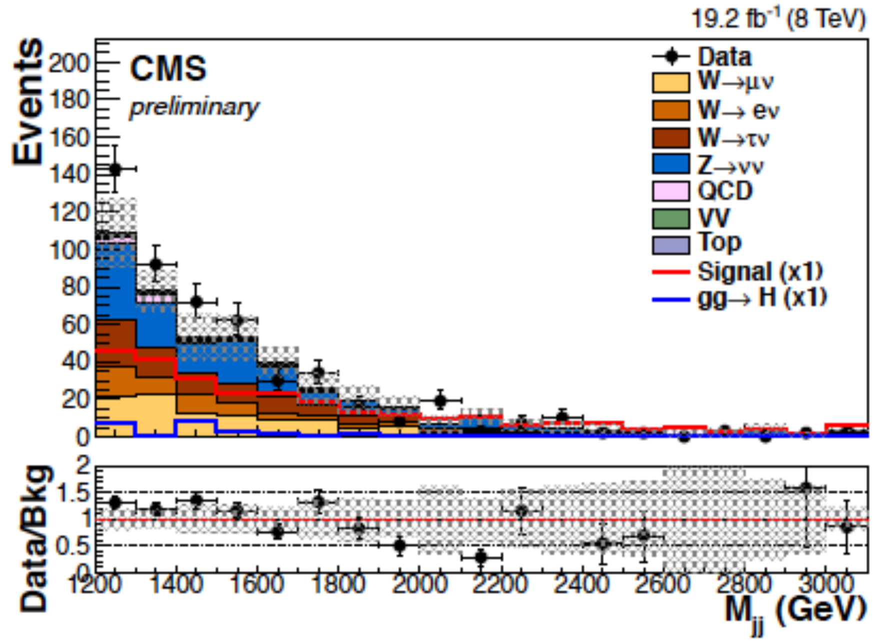
Weak vector boson fusion is the most sensitive production mode



- Require E_TMiss and VBF signature:
  - Large separation between jets in η
  - Large mjj
- Results (95% CL) on BR:
  - ATLAS: 28% (31% exp.)
  - CMS: 58 % (40% exp.)
- Combination of all channels:

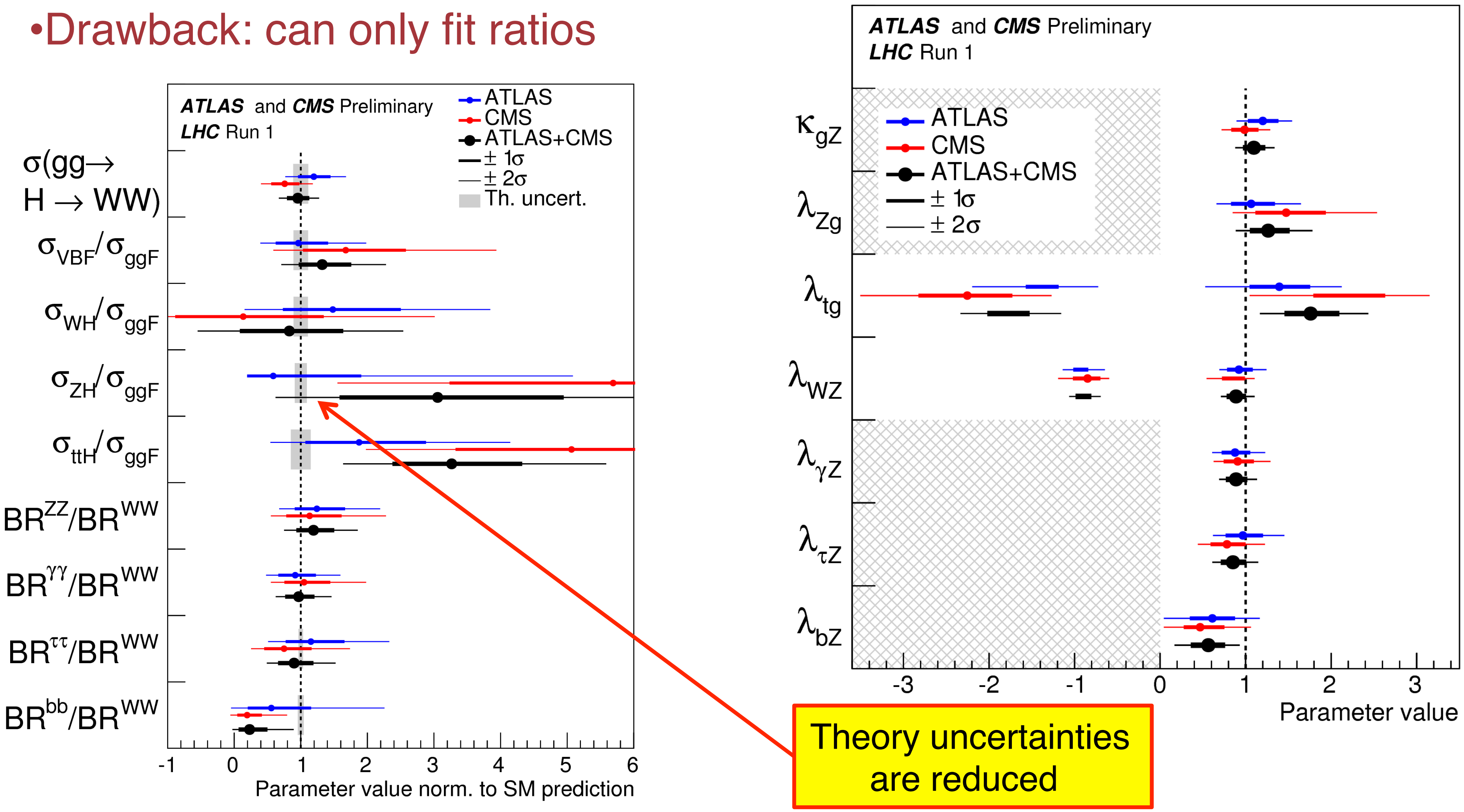
- ATLAS: BR(inv) < 25% (27% exp.) at 95% CL
- CMS: BR(inv) < 36% (30% exp.) at 95% CL





Most General Fit

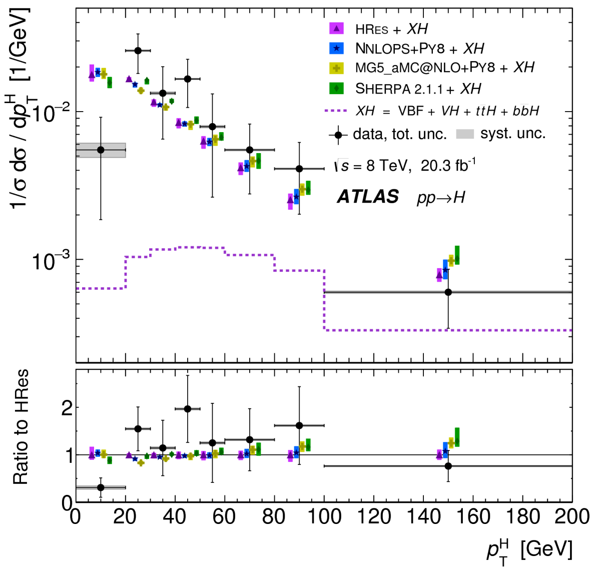
- No assumptions on particle content in loops
- No assumptions on BSM decay or Higgs width
  - Drawback: can only fit ratios



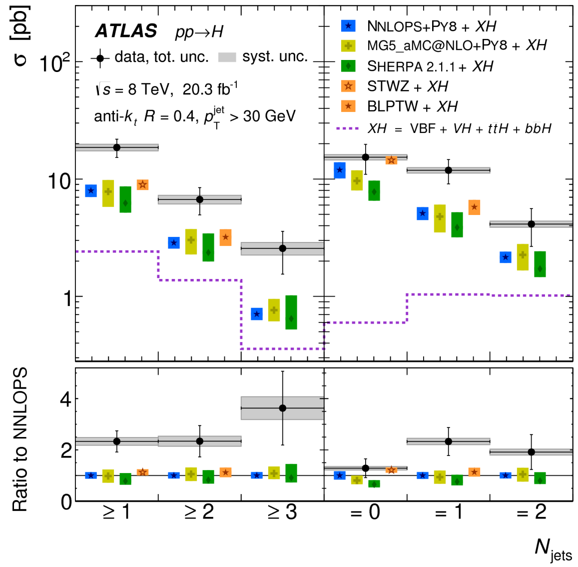
Differential Cross Sections (ATLAS)

SM Higgs theory predictions for kinematics: combination of γγ and ZZ

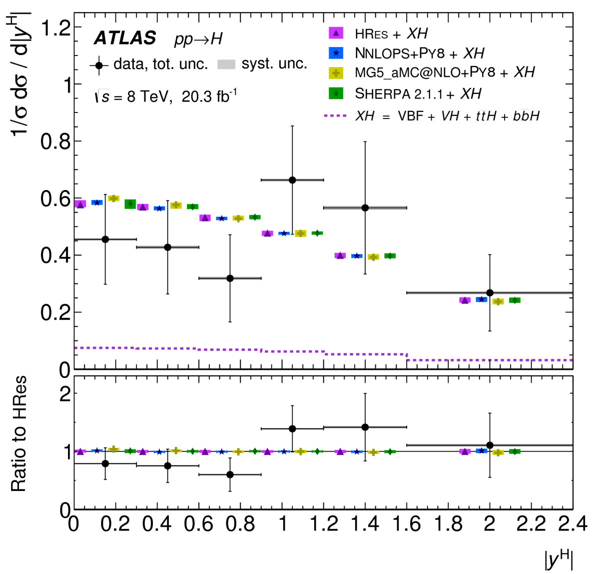
$p_T(H)$



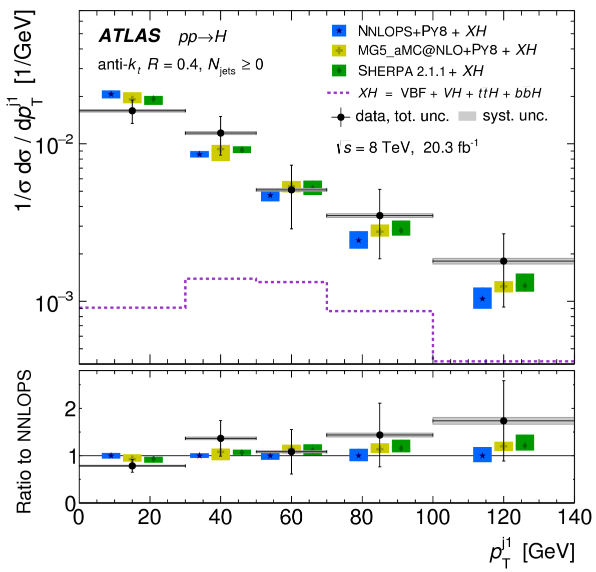
N_{jets}



|y|(H)



$p_T(j_1)$

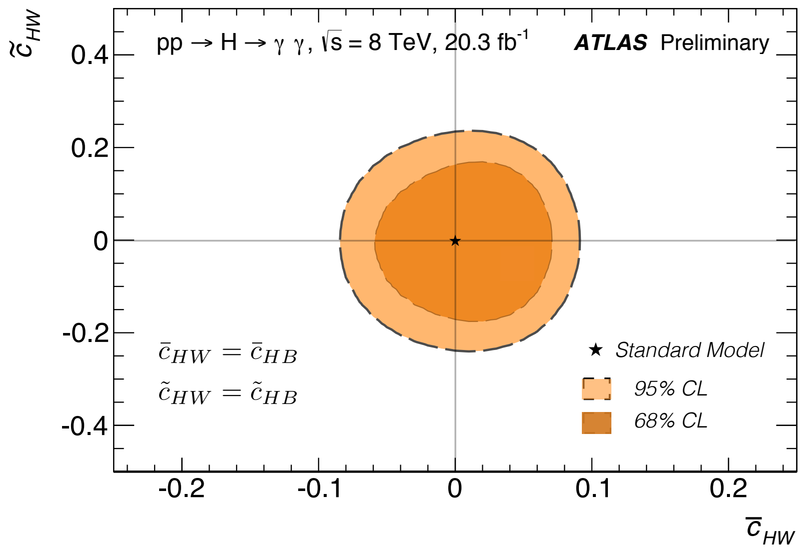


Differential Cross Sections and EFT

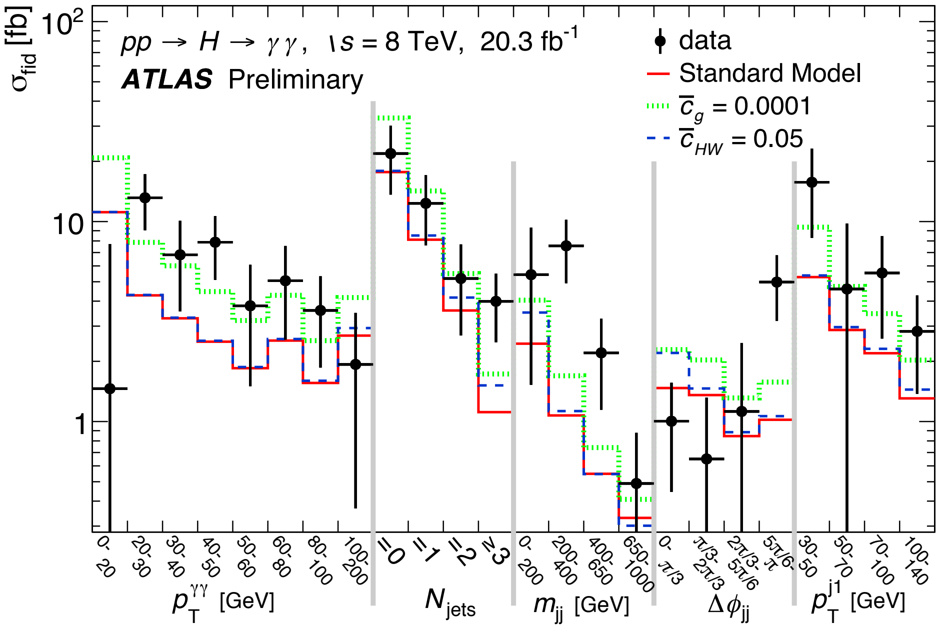
EFT papers:
JHEP 07(2015) 035
JHEP 06(2007) 045

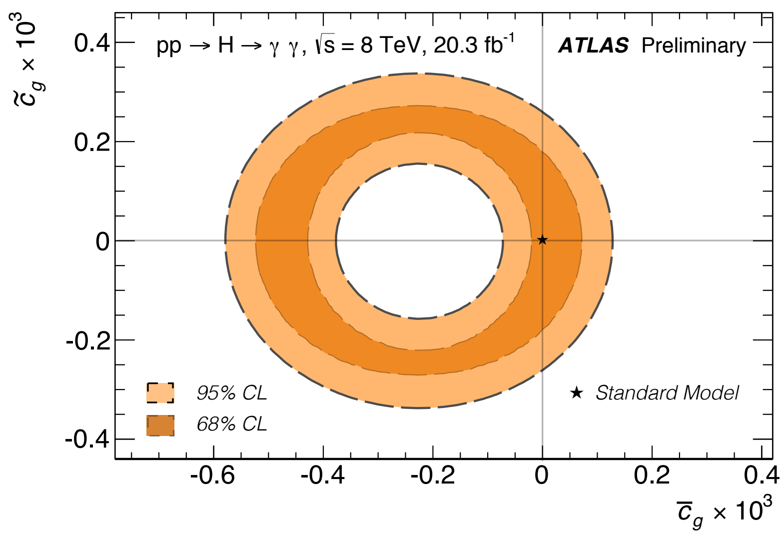
- Study tensor structure and strength of Higgs interactions in the context of an effective Lagrangian framework
- Use Strongly Interacting Light Higgs (SILH) formulation:

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$



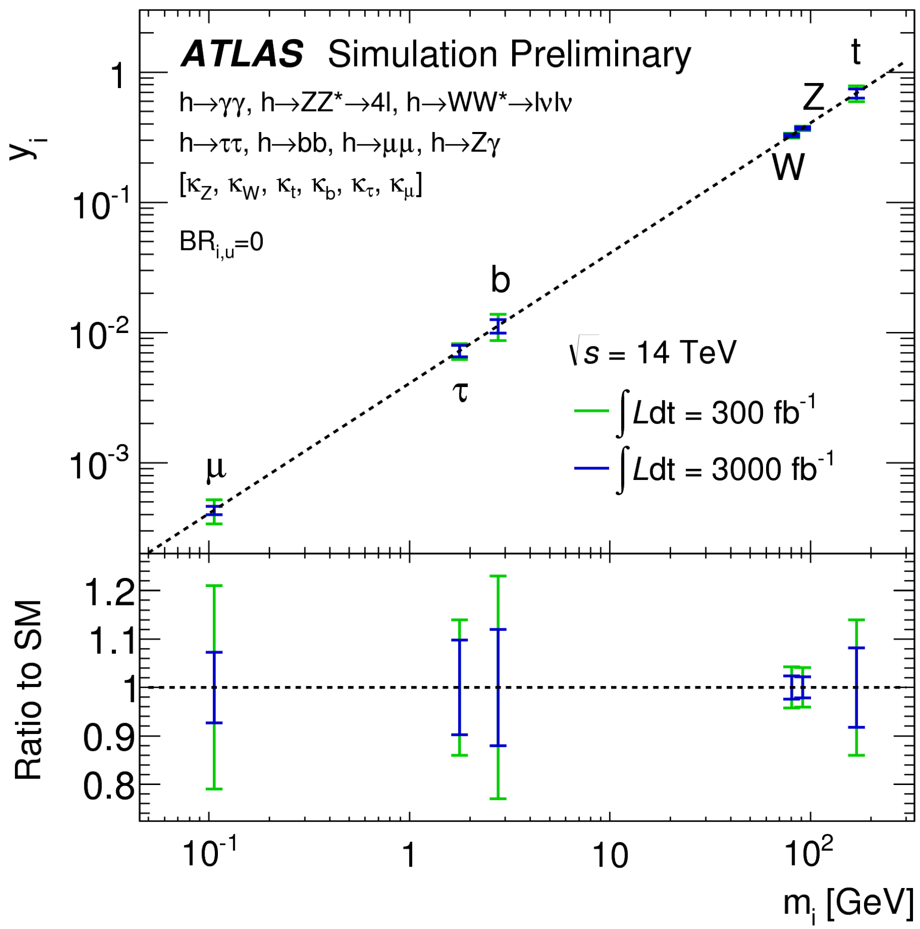
Statistical combination of 5 γγ input variables:

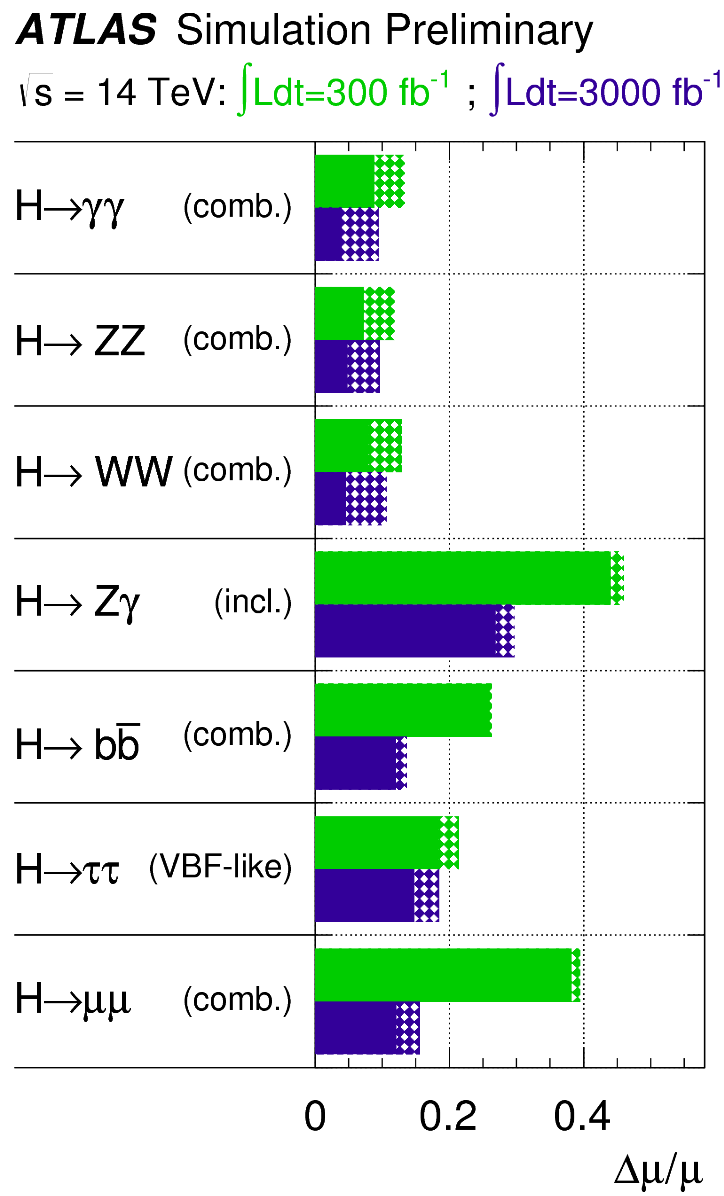




Run 3 and Beyond

Ongoing studies of Higgs physics potential at high luminosity



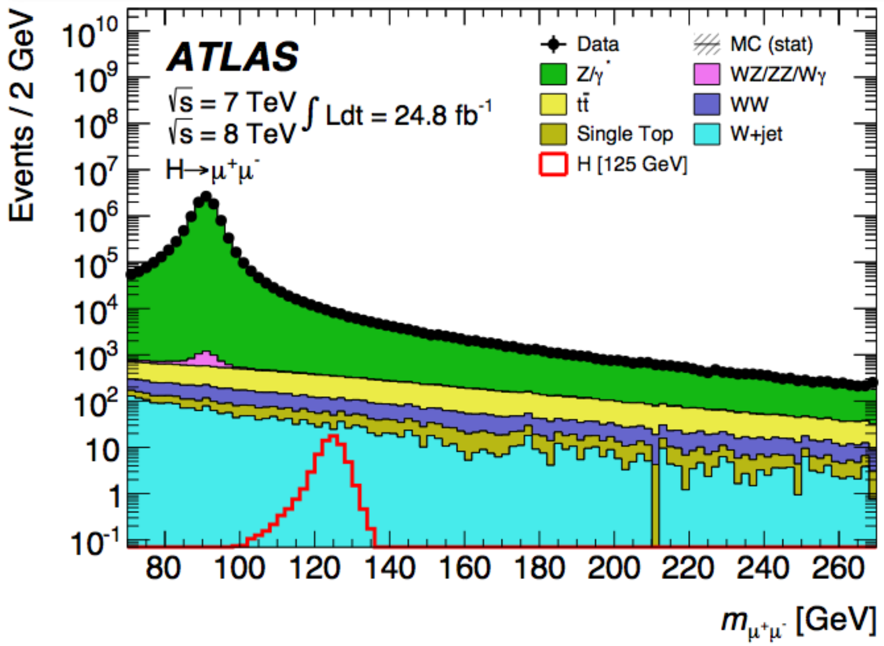


Conclusions

- A lot of progress made since the discovery 3 years ago
  - The measurements of the production and decay properties of the Higgs boson are consistent with SM predictions
    - The SM 0^+ hypothesis is preferred over all other tested spin/parity alternatives (almost all excluded at > 95% CL)
    - Coupling strengths consistent with SM
  - No evidence of BSM physics in the scalar sector (yet…)
- Improving the Run 1 results significantly will require a substantial dataset and a lot of work on both the experimental and theory/MC modeling side
- We have a very exciting and challenging Higgs physics program for Run II

Backup Slides

Status of Rare SM Decays: μμ



$\mu^+\mu^-$ analysis:

- 2 analysis channels (ggF and VBF)
- Analytic background model (similar to γγ)

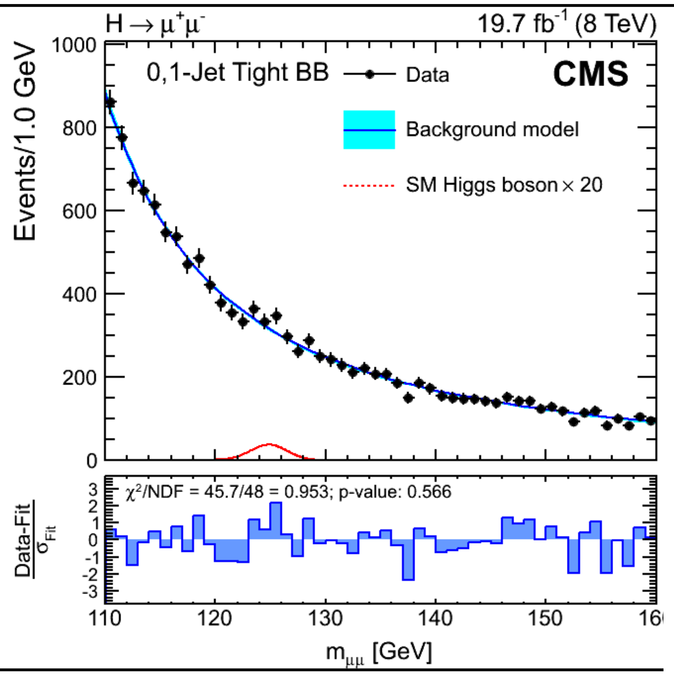
Results at 95% CL:

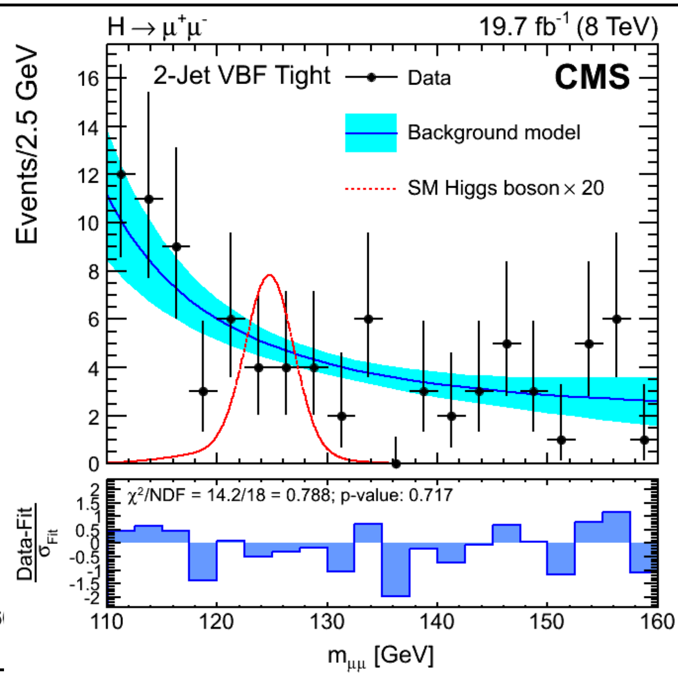
σ.Br < 7.0 (7.2)(σ.Br)$_{SM}$

Universal couplings (same as τ lepton) would imply signal ~280 times SM

PLB

PLB 732 (2014)

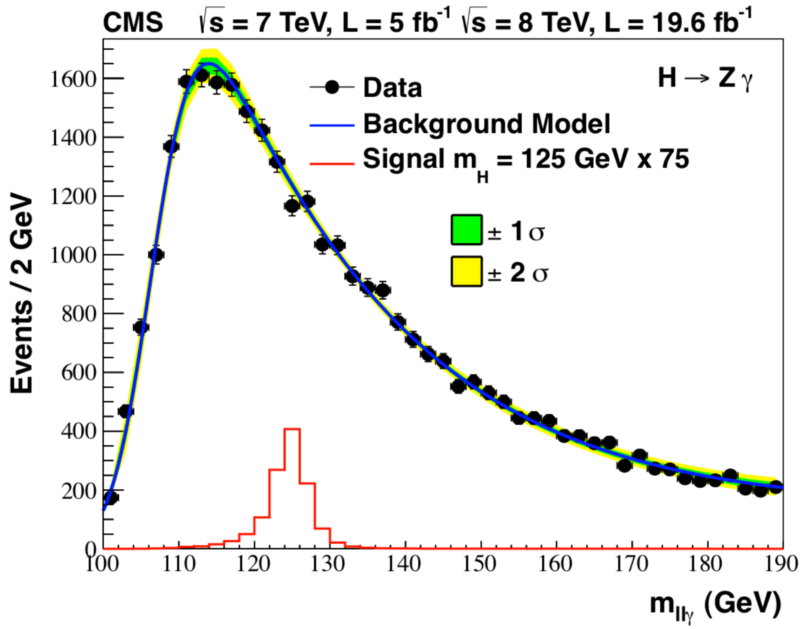




Results at 95% CL :

σ.Br < 7.4 (6.5)(σ.Br)$_{SM}$

Status of Rare SM Decays: $Z\gamma$



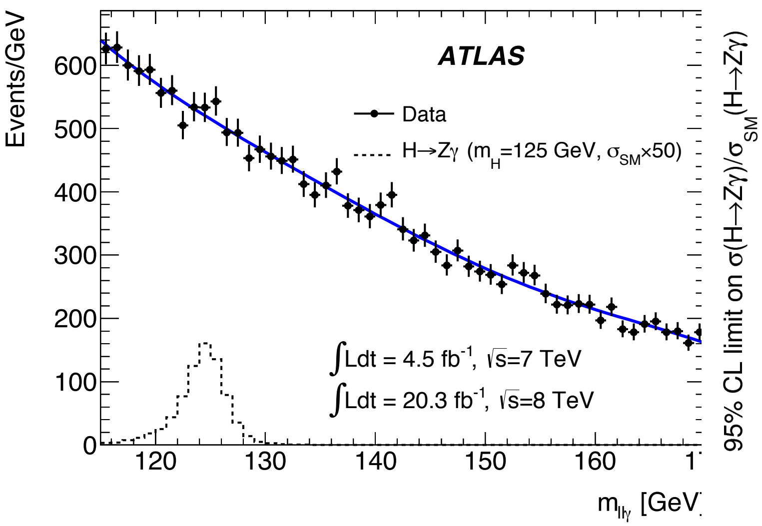
$Z\gamma$ analysis strategy

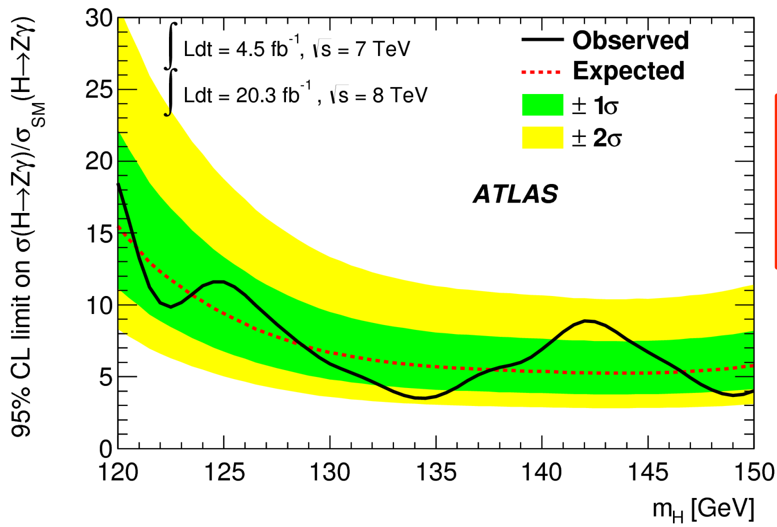
- Detector and p_T categories
- Analytic background model (similarly to $\gamma\gamma$)

Results at 95% CL:

$\sigma.Br < 9\ (9)(\sigma.Br)_{SM}$

PLB 732 (2014)





Results, 95% CL:

$\sigma.Br < 11\ (9)(\sigma.Br)_{SM}$

CMS CP Mixing Results

Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

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

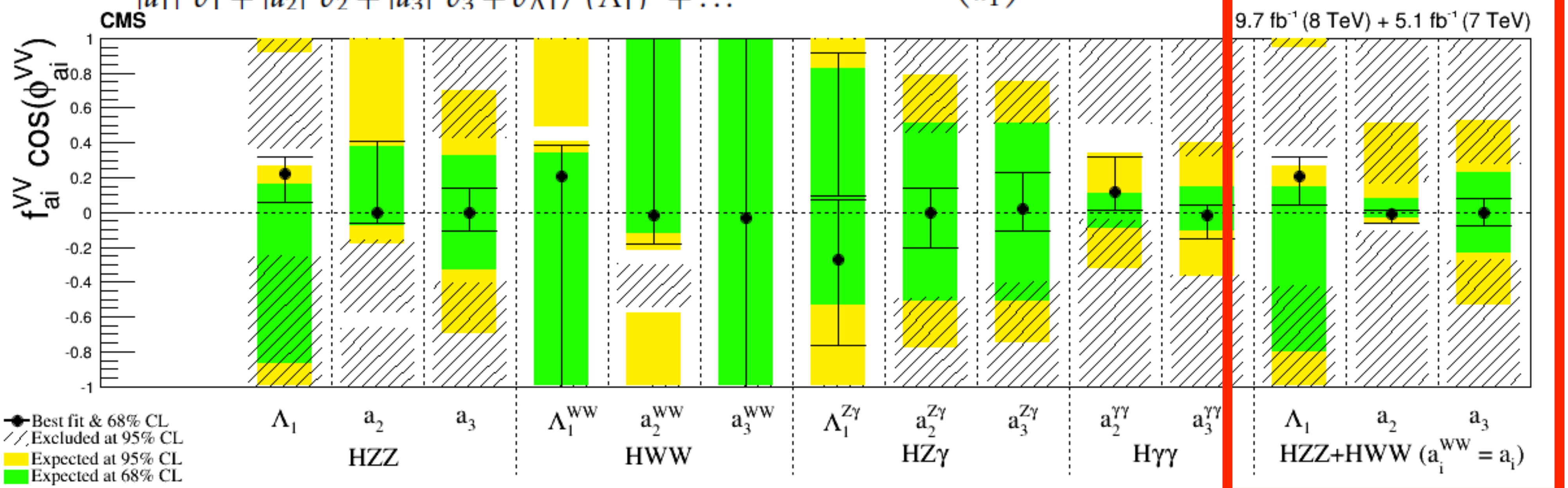
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/(\Lambda_1)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i : xs for $a_i = 1$

$\Lambda_1 = 1$ TeV

Phys Rev D. 89.035007



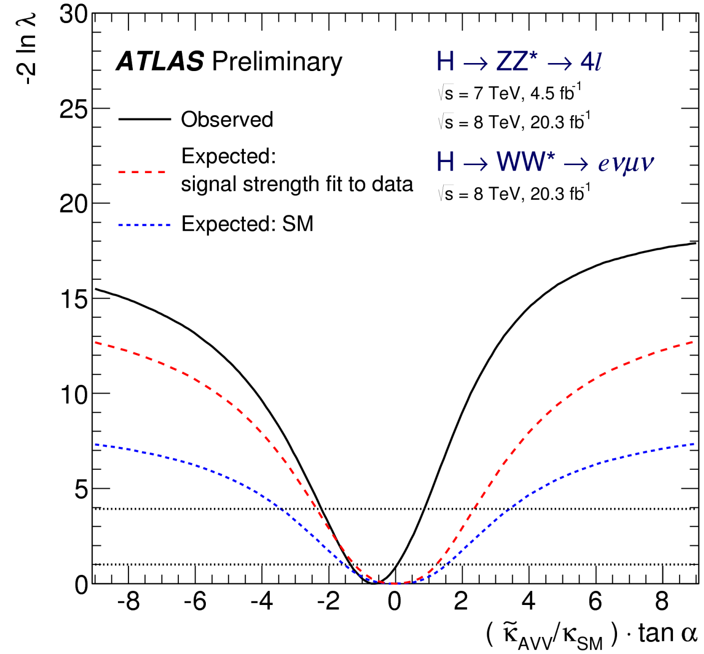
ATLAS CP Mixing Results

Lagrangian describing interaction between a spin 0 and a pair of W or Z bosons (from JHEP 1311 (2013) 043):

$$= \mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

ATLAS paper: JHEP 1311 (2013) 043



CMS/ATLAS comparison

BSM CP-even (95% CL)

CMS $f_{a2}\cos(\phi_{a2}) \in [-0.11, 0.17]$

ATLAS $f_{a2} < 0.12$ for $\phi_{a2} = 0$

$f_{a2} < 0.16$ for $\phi_{a2} = \pi$

BSM CP-odd (95% CL)

CMS $f_{a3}\cos(\phi_{a3}) \in [-0.27, 0.28]$

ATLAS $f_{a3} < 0.090$ for $\phi_{a3} = 0$

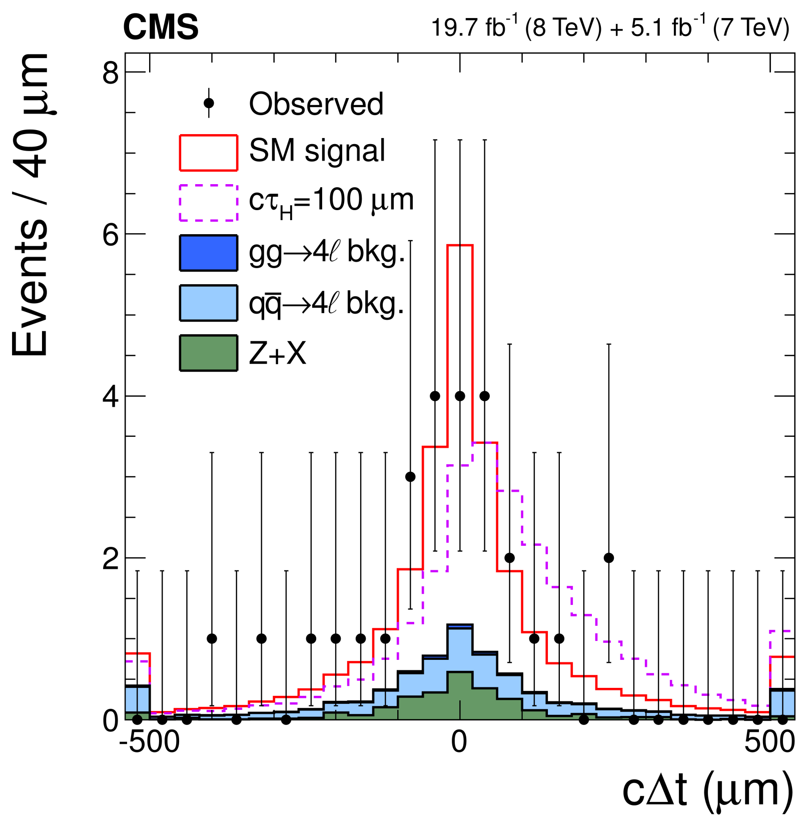
$f_{a3} < 0.41$ for $\phi_{a3} = \pi$

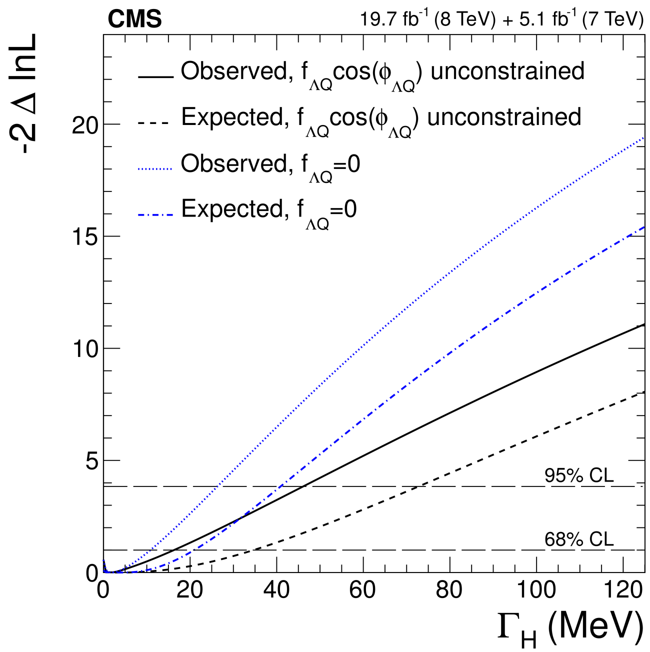
No significant contributions from BSM terms are observed

Width: Lifetime and Off-shell couplings (CMS)

SM lifetime (m_H= 125 GeV): 1.6x10^{-7} fs

Measure flight distance in the detector using H->ZZ->4l channel
τ(H) < 190 fs at 95% CL
Γ(H) > 3.9 x10^{-9} MeV





Enhancement of off-shell production possible through anomalous HVV couplings:

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Width derived with/without profiling of cross section fraction:

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$