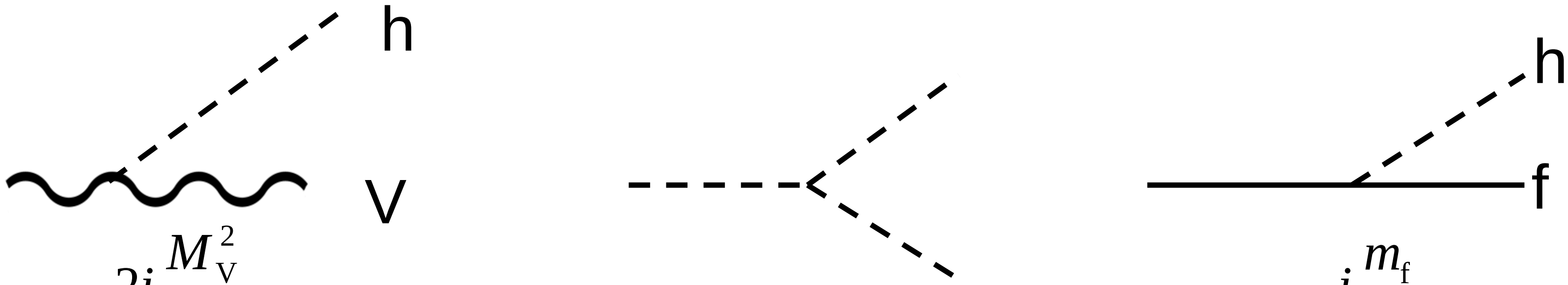
Standard Model Higgs Boson(?)

Sinéad Farrington (University of Warwick)

SM Higgs Boson Couplings

- **Standard Model Higgs: h: $J^{PC}=0^{++}$**

$$D_m F^* D^m F \quad + \quad V(F^* F) \quad + \quad \overline{D}_L Y_D D_R F$$



$$2i\frac{M_V^2}{v} \qquad\qquad -i\frac{m_f}{v}$$

SM Higgs Boson Couplings

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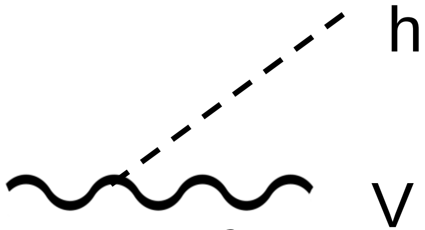

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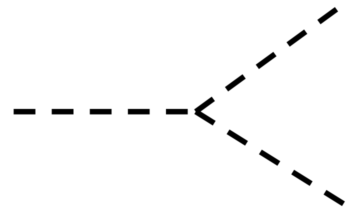
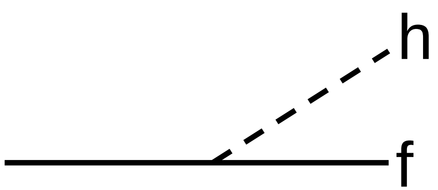
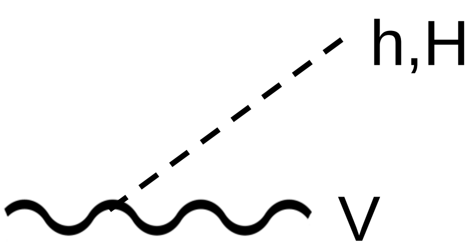




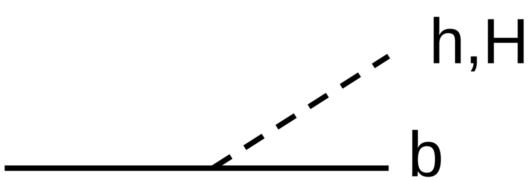
$$-i\frac{m_f}{v}$$

- **2HDM (SUSY) Higgs: h^0, H^0: 0^{++}; A^0: 0^{-+}; $H^\pm$**

$$D_\mu\Phi^*_{1,2} D^\mu\Phi_{1,2} \quad + \quad V(\Phi_1,\Phi_2) \; + \quad \overline{D}_L Y_D D_R \Phi_1 \quad + \quad \overline{U}_L Y_D U_R \Phi_2$$



$$2i\frac{M_V^2}{v}\left[\sin(\beta-\alpha)h^0+\cos(\beta-\alpha)H^0\right]$$



$$-i\frac{m_f}{v}\left[-\frac{\sin\alpha}{\cos\beta}h^0+\frac{\cos\alpha}{\cos\beta}H^0\right]$$

SM Higgs Boson Couplings

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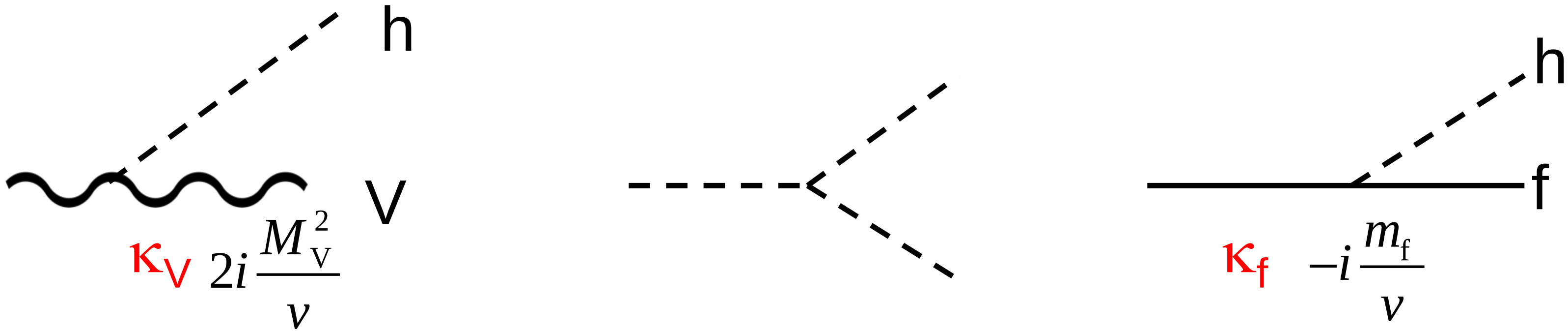
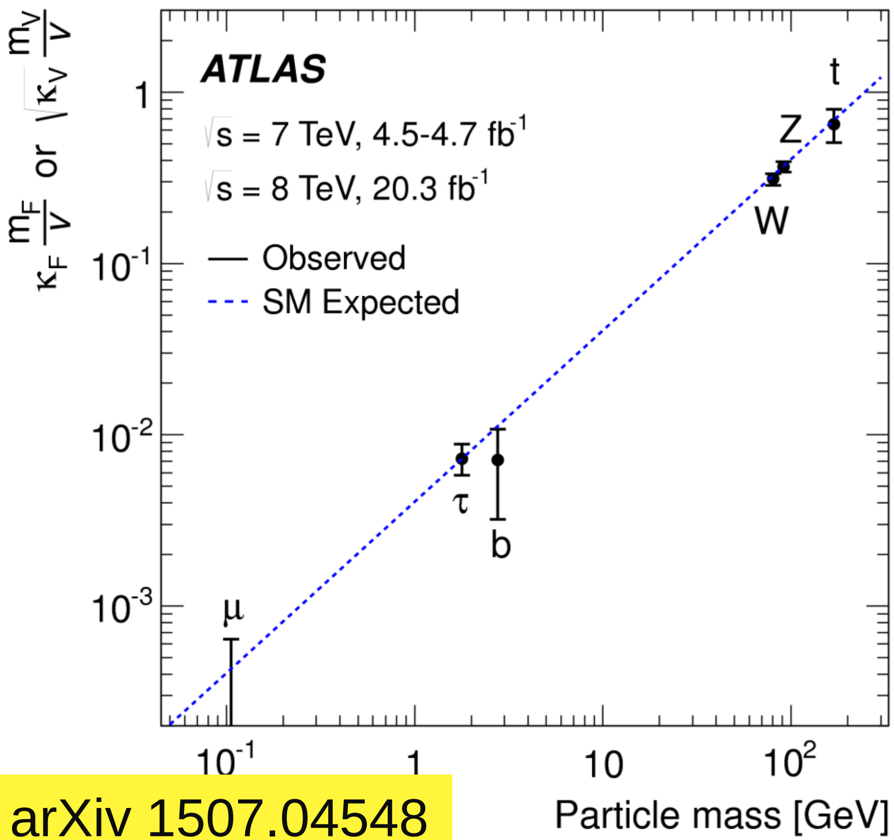


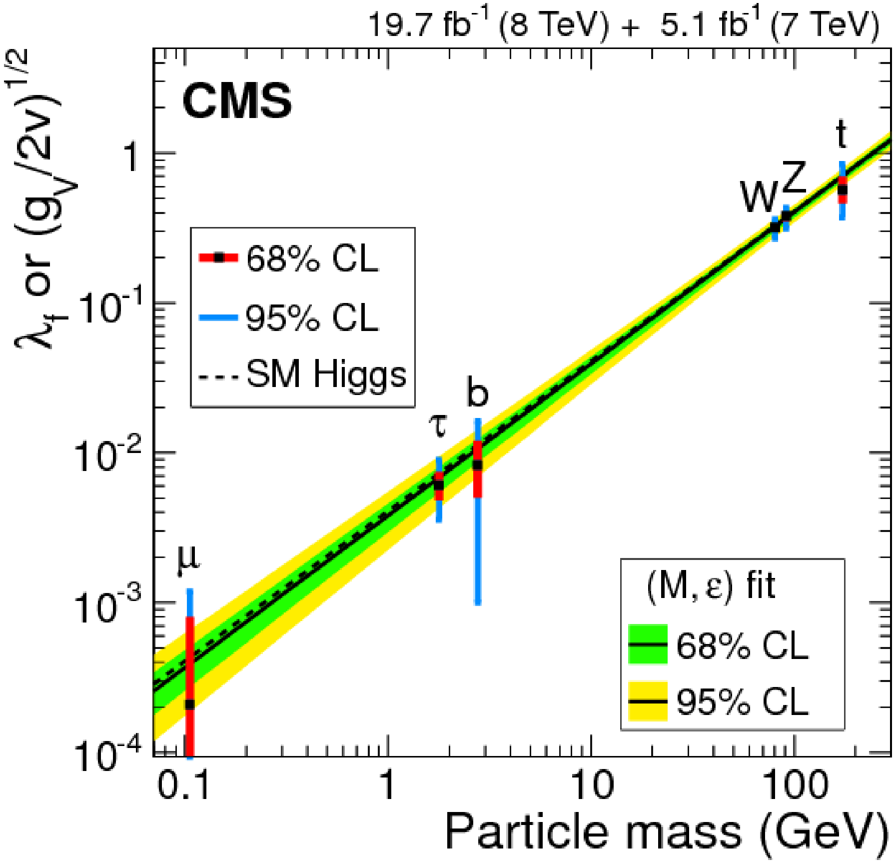
Standard Model Agreement with Data

- **Within uncertainties the data agree with the Standard Model**

$$g_V \sim \frac{\kappa_V \cdot m_V^2}{v}$$

$$\lambda_f \sim \frac{\kappa_f \cdot m_f}{v}$$





arXiv 1507.04548

EPJC 75 (2015) 212

What precision is necessary?

- **SM couplings can be modified by new physics**

$$\Gamma_i = \kappa_i^2\ \Gamma_i^{SM}$$

- **Modifications can be small depending on the BSM scenario (Snowmass report)**
  - For new physics at the 1TeV mass scale:

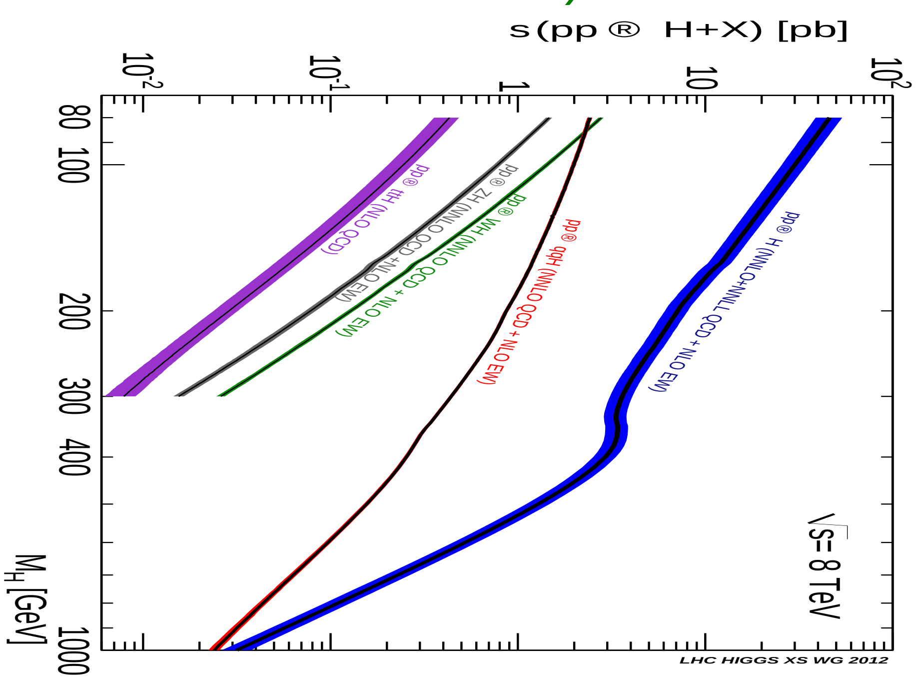
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

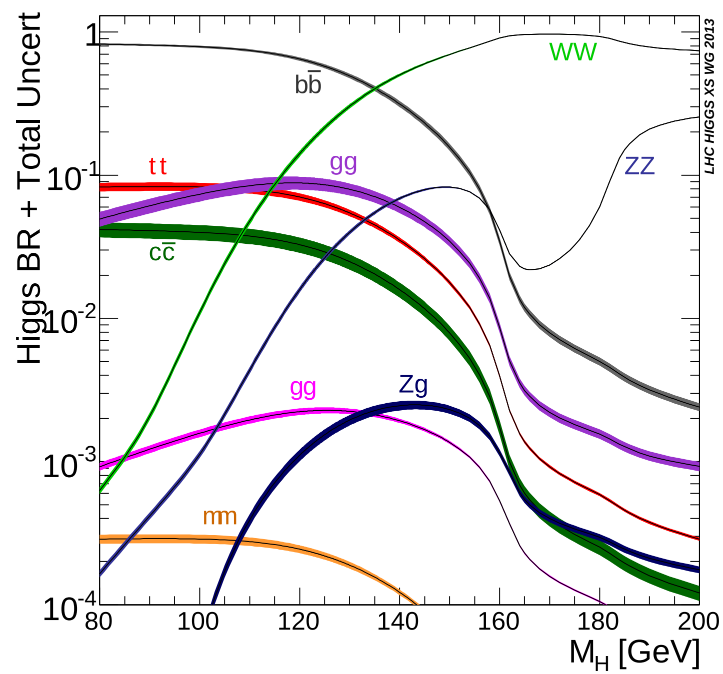
arXiv:1310.8361

  - Higher scales imply smaller effects

H(125): Is it the Standard Model Higgs?

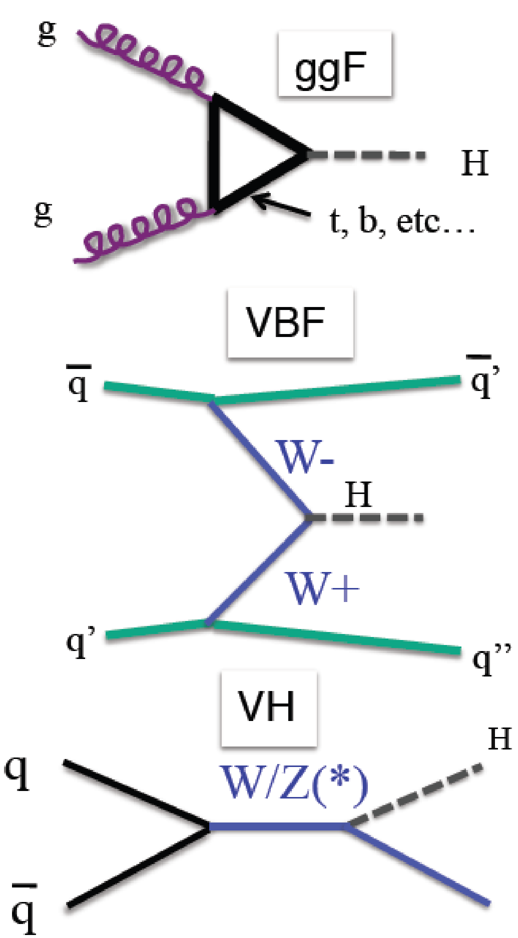
- **Standard Model predicts production and decay rates for a given mass**
- **We measure:**
  - Mass (Done to 0.2% precision), Width (Measured indirectly)
  - Couplings at a given mass (Done to 10-30% precision depending on the channel)





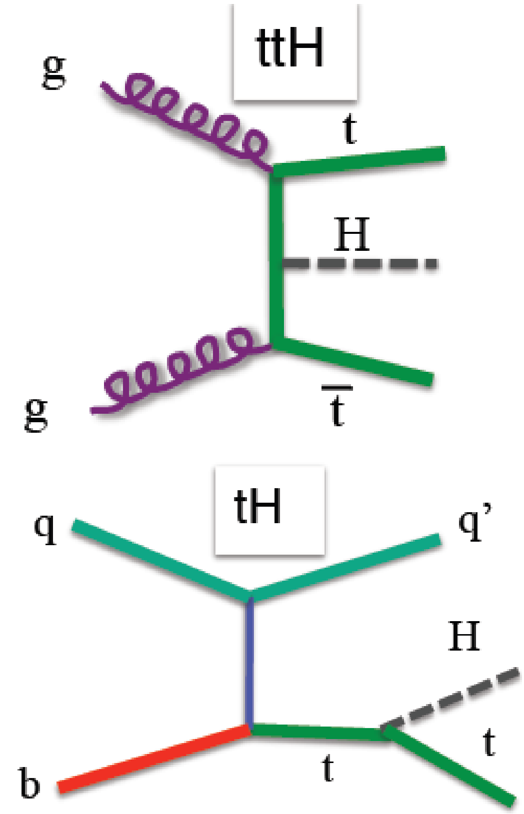
arXiv:1201.3084

Dominant Production Modes



	8 TeV	13 TeV
ggF	19 pb	44 pb
VBF	1.6 pb	3.7 pb
VH	1.1 pb	2.2 pb
ttH	0.13 pb	0.51 pb
tH	~20 fb	~90 fb

Cross-sections at 125 GeV

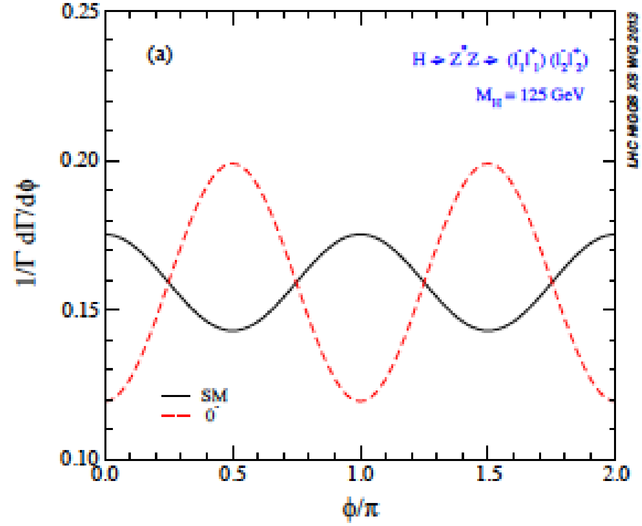


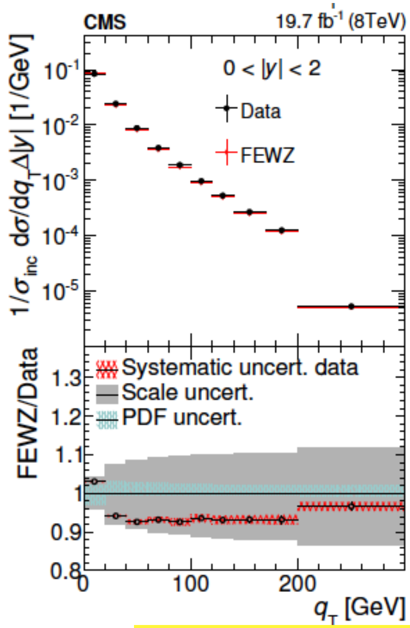
H(125): Is it the Standard Model Higgs?

arXiv:1307.1347

- **We measure**
  - Spin/CP: 0^{++} predicted by SM
  - Analyse decay topologies

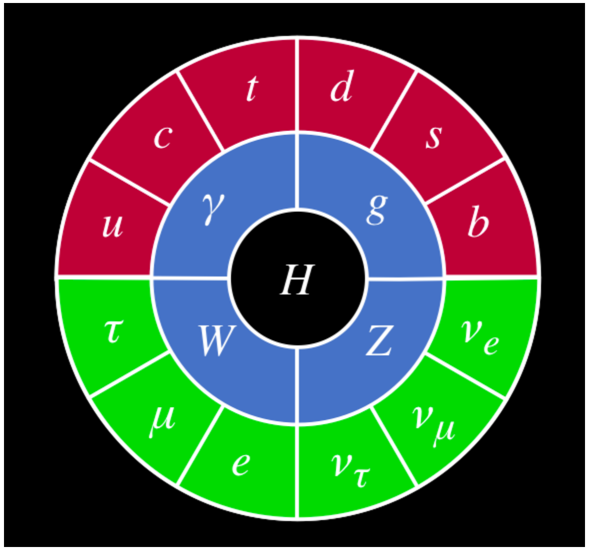
    (Done in boson channels, what about fermion channels?)
- **Differential distributions are predicted by SM (currently in the form of NLO/NNLO calculations)**
  - Precision physics has been reached for W/Z bosons probing QCD and the EW sector over many years
  - To be done!: Higgs production mechanisms will be examined to precision





arXiv:1504.03511

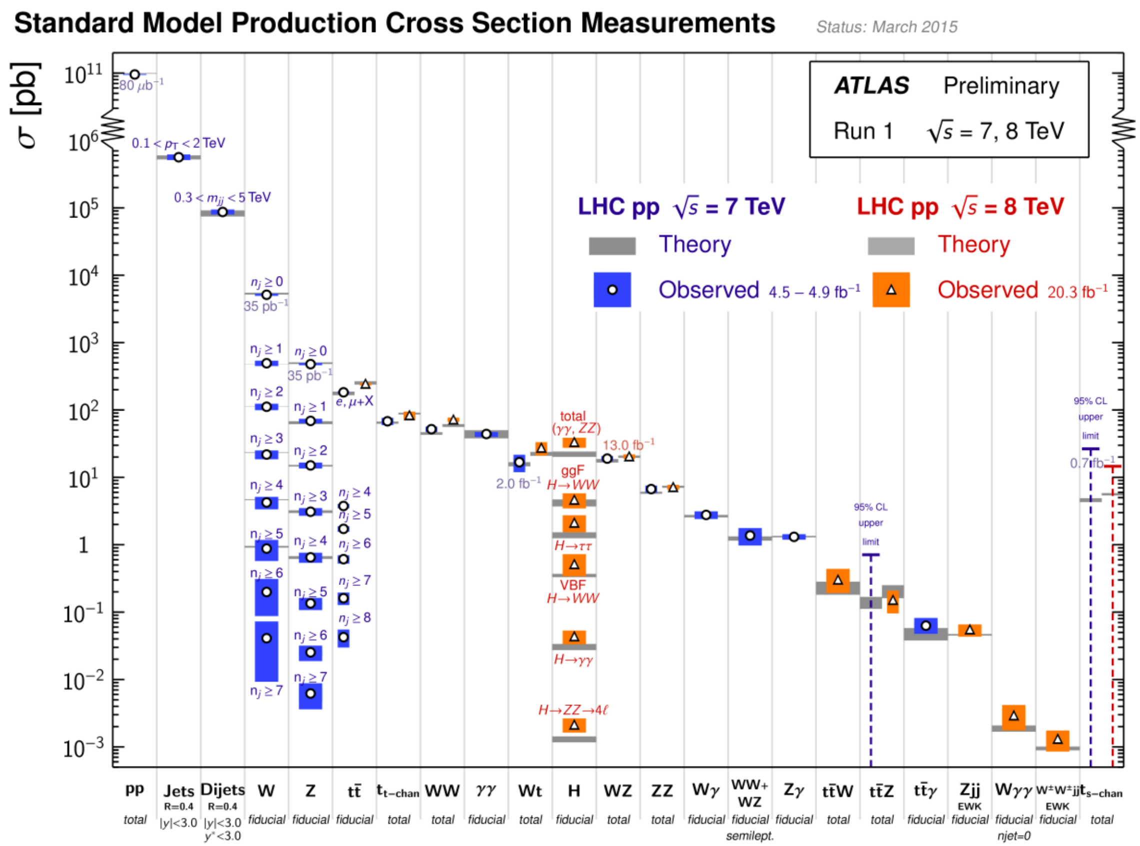
Outline



- **Datasets**
- **Higgs Couplings**
- **Higgs Properties**
  - Mass
  - Spin/CP
  - Width
- **Next talk: Higgs combination, differential measurements, BSM**

Datasets

- Copious production of SM particles and the Higgs



- Run 2: ~4fb^{-1} so far.
    - Expect ~100fb^{-1} by 2018 and ~300fb^{-1} by 2023.
- After ~2026, HL-LHC: 3000fb^{-1}

EPJC 74(2014) 3076, PRD 92 012006(2015),PRD 91 012006(2015), PRD 90 112015(2014), JHEP 01 (2014) 096, PRD 89 (2014) 092007

Run 1: Higgs Decaying to Bosons

- **Observation in γγ**

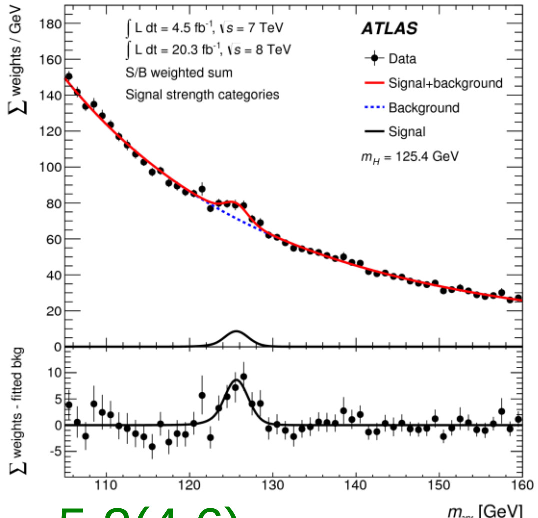
ZZ*

WW*

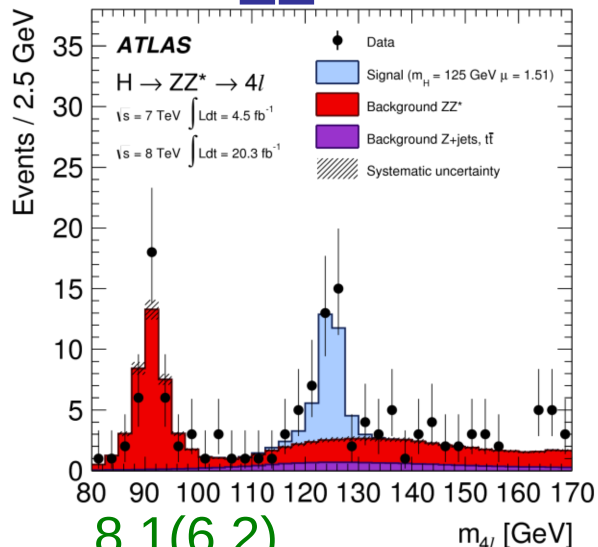
ATLAS

obs(expected) significance

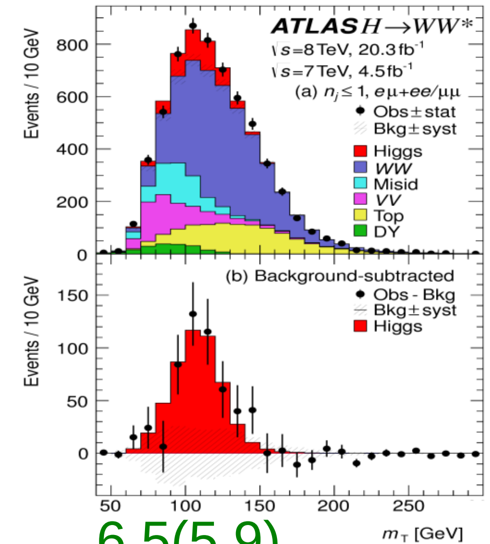
CMS



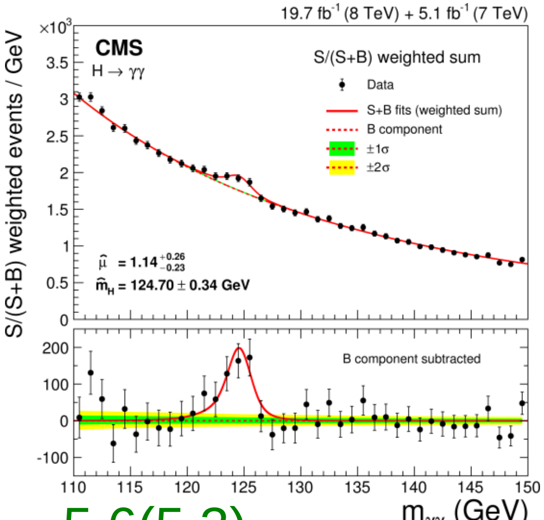
5.2(4.6)



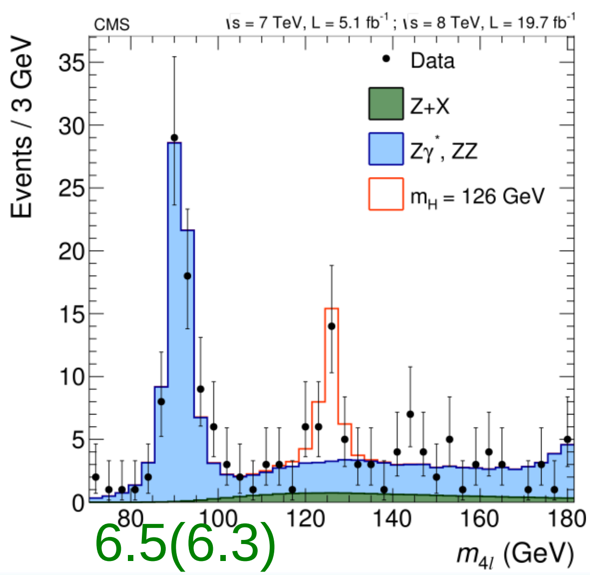
8.1(6.2)



6.5(5.9)



5.6(5.3)



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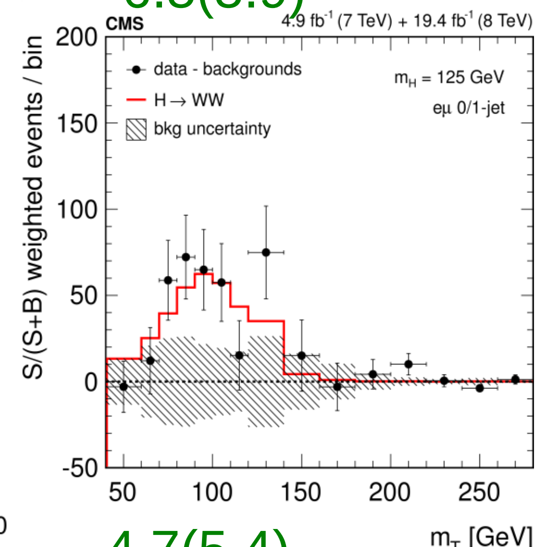


4.7(5.4)

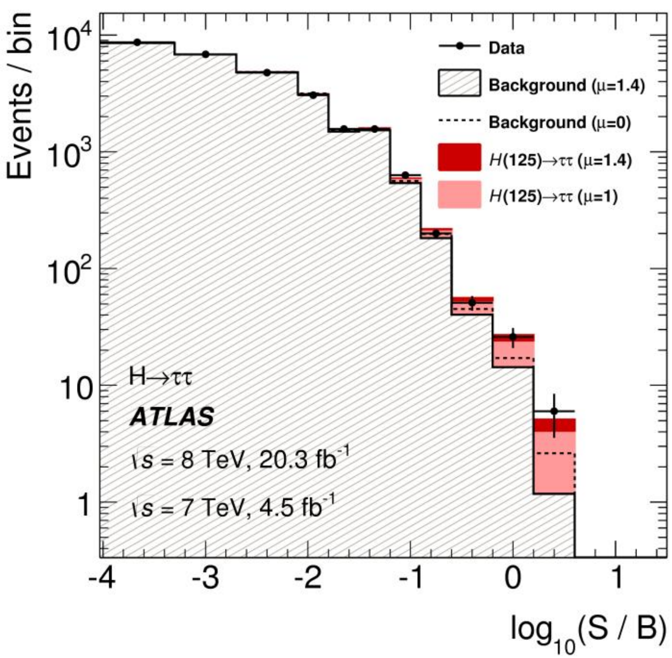
Decays to Bosons

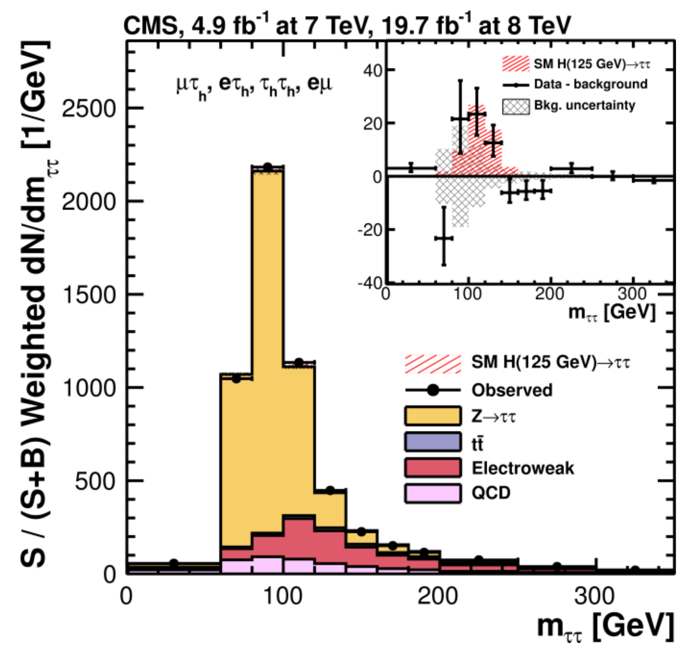
- **Production mechanisms: gg fusion, VBF, VH, a little ttH**
- **ZZ: 4 lepton**
  - Backgrounds: SM ZZ, Z+jets, ttbar
    - Determined with theory cross-sections, control regions
- **WW: $l^+\nu l^-\nu$ final state**
  - Backgrounds: SM WW, W+jets with jet faking lepton
    - Also determined with theory cross-sections, control regions
- **$\gamma\gamma$: direct reconstruction**
  - Backgrounds: Continuum $\gamma\gamma$ production
    - Determined by shape fit

- **Dominant systematics: photon/electron ID, Jet Energy Scale, theory uncertainties**

Run 1: Higgs Decaying to Fermions

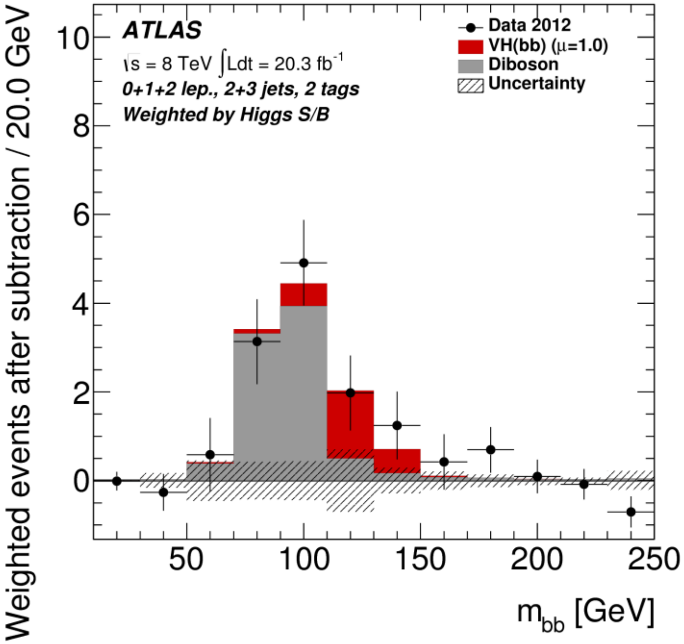
- **Tau leptons: Reconstruct $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$**
  - Good sensitivity for Vector Boson Fusion, gg fusion from boosted Higgs selection
  - Background depends on channel
    - Z+jets: determined from “embedding” using $Z\mu\mu$ data
    - multijet(QCD): determined using “fake factors”
    - Dominant systematics: Jet Energy Scale, background modelling

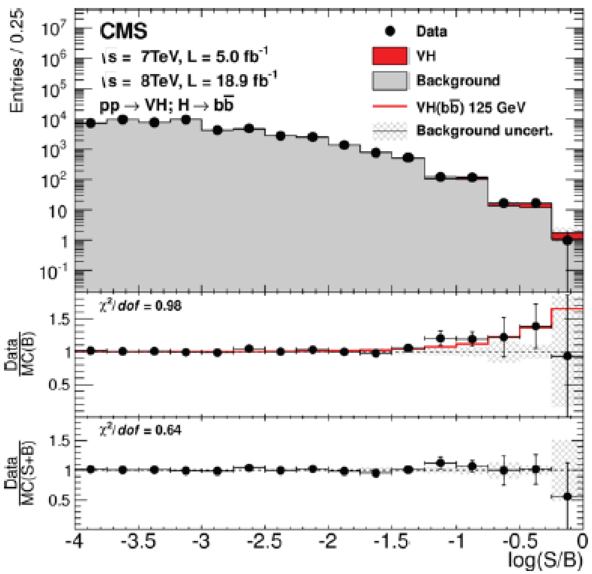


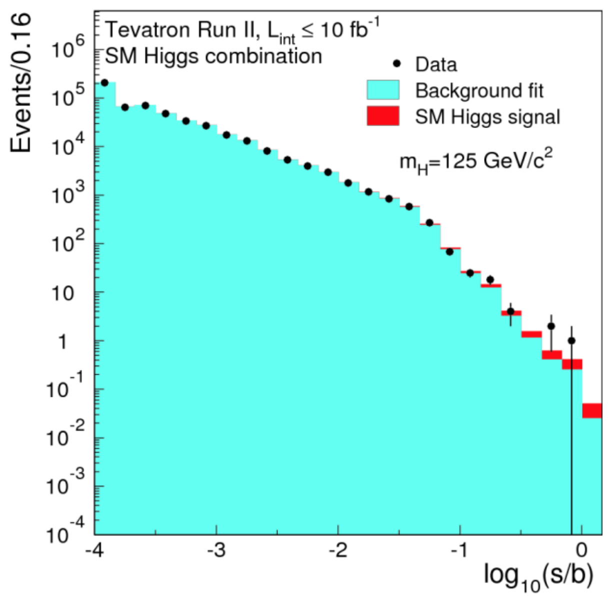


Run 1: Higgs Decaying to Fermions

- **b quarks: reconstruct using b-tagged jets**
  - Sensitivity driven by VH, some VBF more recently.
  - Dominated by multijet(QCD) background. Makes gg fusion ~impossible in this channel. ttH gives additional tags.
    - Background determined from fit to data using control regions





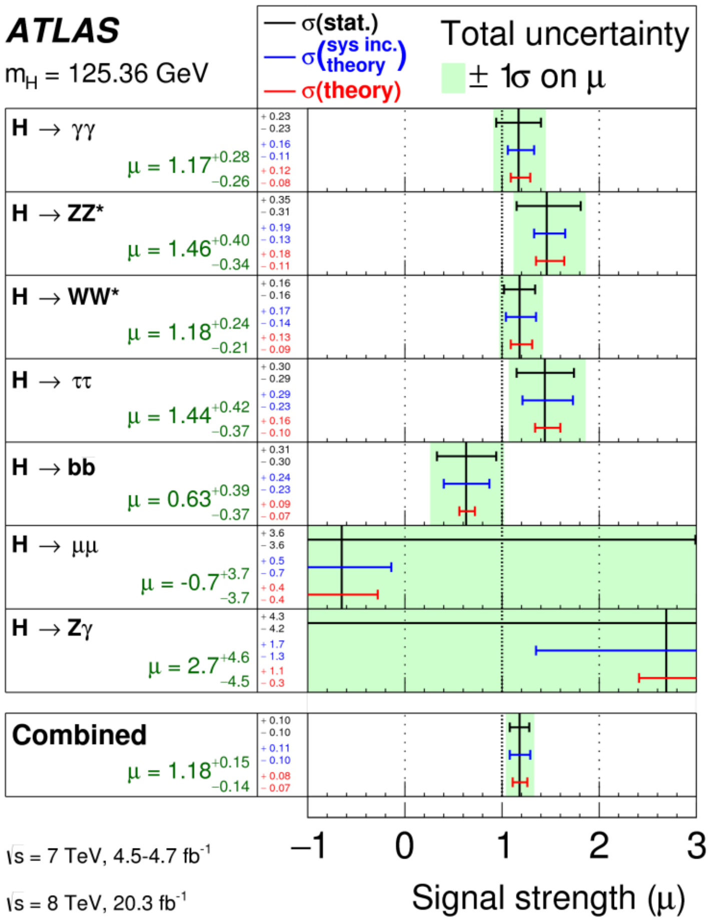


σ Observed (Expected)

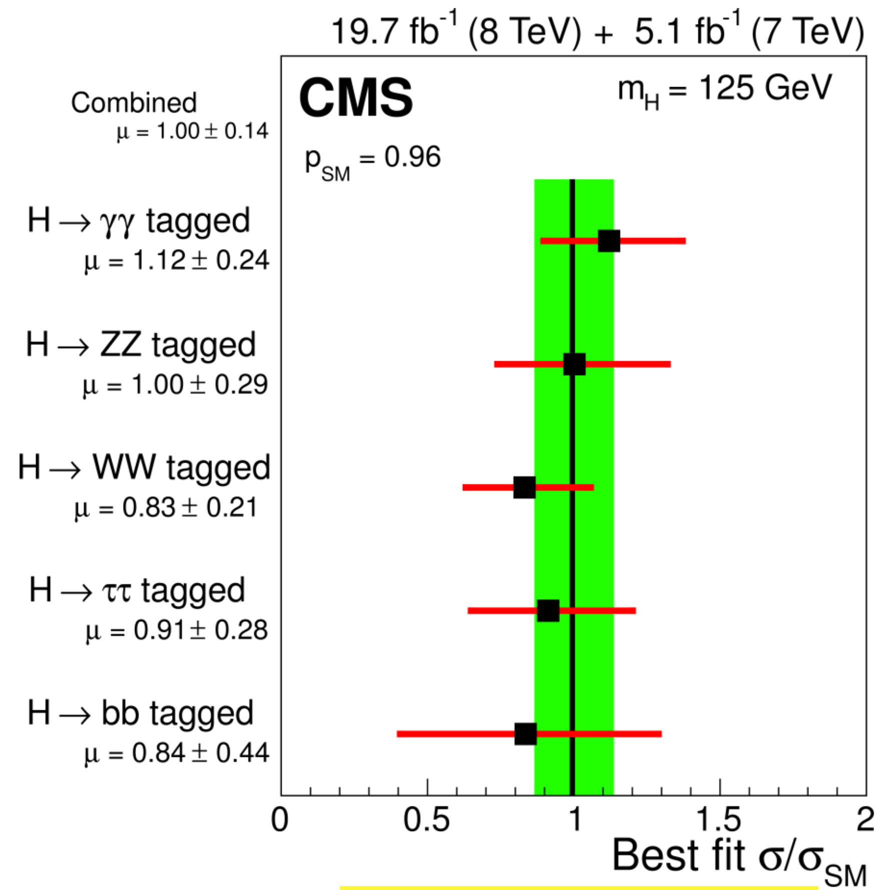
1.8 (2.8)	2.6 (2.7)	2.2(1.4)
JHEP01(2015)069	arXiv:1506.01010	PRD 88, 052014 (2013)

Decay Mode Signal Strength

- μ = ratio of measured to predicted cross-section
  - Agreement with 1 is good but uncertainties large (10-30%) compared to the "Snowmass challenge" predicted BSM deviations



arXiv:1507.04548



EPJC 75 (2015) 212

Couplings – thoughts for the future

- **Statistics!**

Couplings – thoughts for the future

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- **Triggers**
  - Both experiments rely mainly on lowest threshold single-lepton triggers (~24/30 GeV currently for μ/e)
    - Most challenging triggers in SM Higgs are for $\tau_{had}\tau_{had}$, bb

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- **Hard work**
  - Beat down systematic uncertainties on object ID

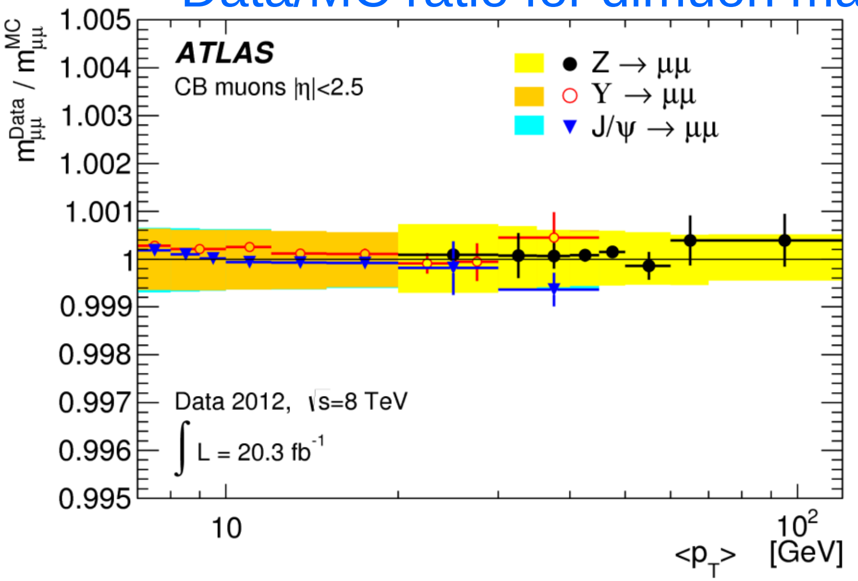
Higgs Properties

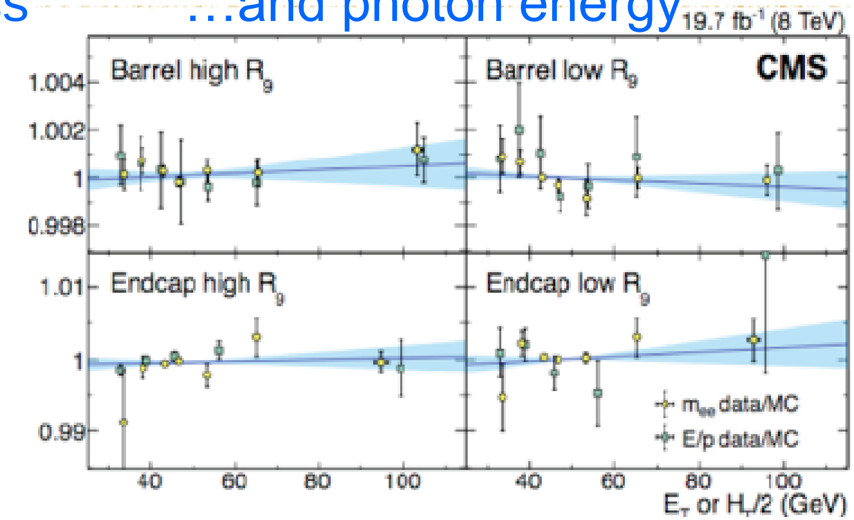
- Couplings
- **Mass**
- Spin/CP
- Width

Higgs Mass

- **Measure mass in H ➔ γγ and H ➔ ZZ**
  - Fully reconstructed channels, relatively clean objects
  - Scale measurements/Calibrations are crucial
    - Uncertainties reduced by 25-30% on same data with better calibrations in analyses during the shutdown
  - Data/MC ratio for dimuon mass …and photon energy

Phys. Rev. D. 90, 052004 (2014)





CERN-PH-EP-2015-006

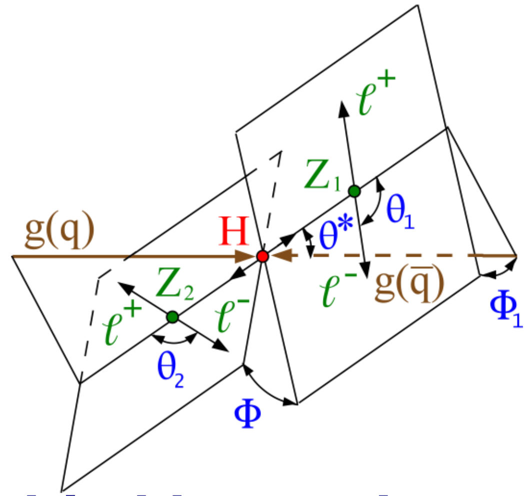
  - ATLAS+CMS combined mass: $125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$
    - 0.2% uncertainty! Precision era.
  - What about fermions? Hμμ? HL-LHC gives 7σ gg fusion

Higgs Properties

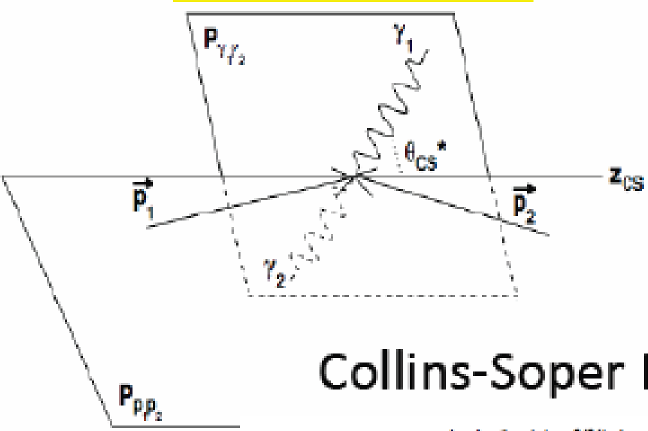
- Couplings
- Mass
- Spin/CP
- Width

Spin/CP

- **Hypothesis tests are made in the boson channels**
- **ZZ decay products give Z polarisation**
  - Matrix element



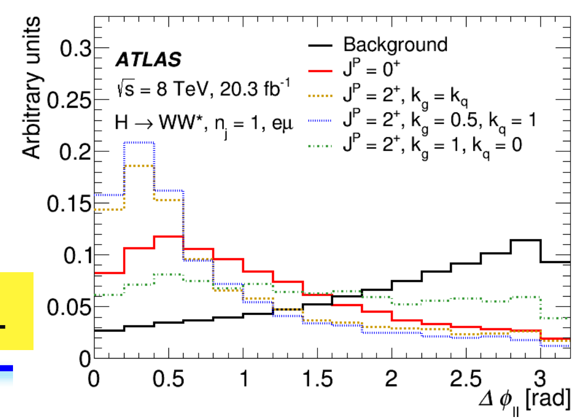
- **γγ fully reconstructed**
  - less information because two-body final-state
  - Use cos θ* and $p_t(\gamma\gamma)$



Collins-Soper Frame

$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2p_T^{\gamma_1}p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

- **WW: use available kinematics**
  - ATLAS: BDT with $\Delta\phi(ll)$, $p_t(ll)$, $m(ll)$
  - CMS: 2D fit to $m(ll)$ and m_T



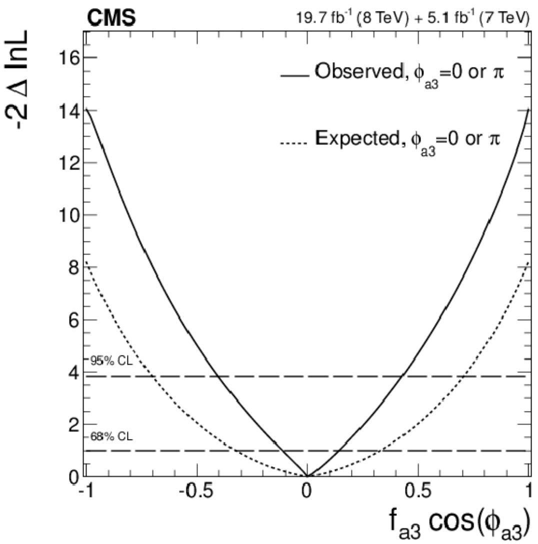
Eur. Phys. J. C75 (2015) 231

Spin/CP

Phys. Rev. D 92 (2015) 012004

arXiv:1506.05669

- **Data favours 0^{++} and excludes alternatives at 99.9% C.L. in boson channels**
  - What about fermions? ($\tau\tau$ polarisation)
- **What about tensor structure?**
  - Probe this in two equivalent formulations:
    - ATLAS: Effective field theory; fit a general Lagrangian compatible with Lorentz invariance
    - CMS: Anomalous couplings; fit a generic amplitude compatible with Lorentz and gauge invariance
- **Data shows no evidence of CP violation**
  - Use of EFT/anomalous couplings framework developing – opportunity to define this now



Higgs Properties

- Couplings
- Mass
- Spin/CP
- **Width**

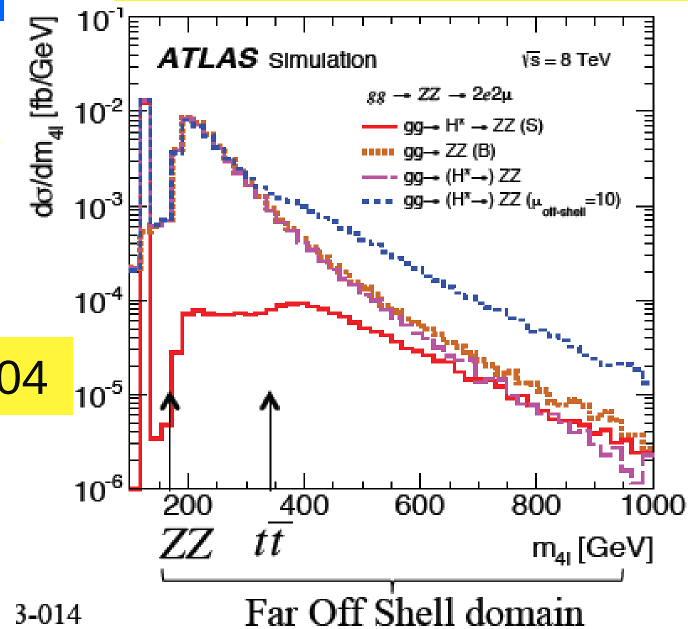
Width

- **Expected SM width 4.1 MeV**
- **Direct 95% C.L. limits (expected):**
  - ATLAS: 2.6 (6.2) GeV (ZZ)
    5.0 (6.2) GeV ($\gamma\gamma$)
  - CMS: 1.7 (2.3) GeV ($\gamma\gamma$ and ZZ combined)

JHEP 08, 116 (2012),
PRD 88, 054024 (2013),
JHEP 04, 060 (2014)

- **Also probe via off-shell couplings**
  - Assume off-shell μ is the same as on-shell

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



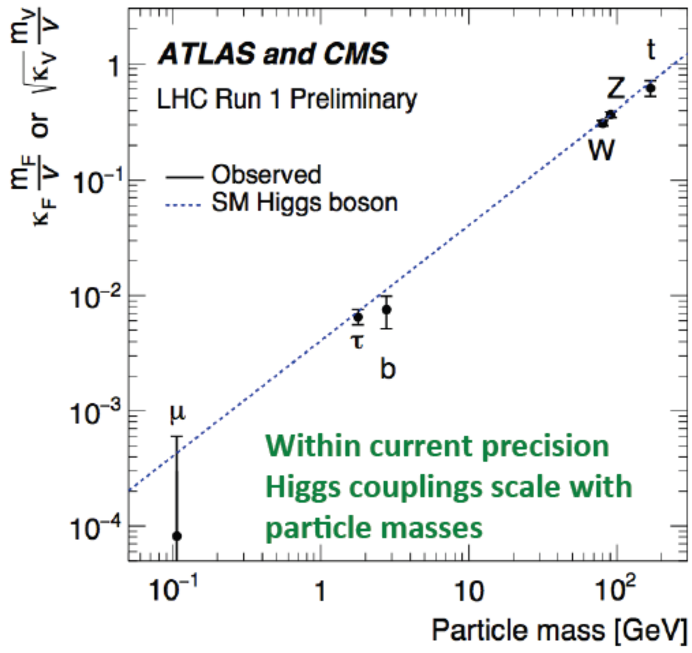
  - 95% C.L. limits (expected)
    - ATLAS: 23 (33) MeV
    - CMS: 22 (33) MeV

PRD 92 (2015) 012004
PLB 736 (2014) 64

  - HL-LHC will bring sensitivity at SM-level:
    - $\Gamma = 4.2^{+1.5}_{-2.1}$ MeV

Status Summary

- **Couplings**
  - Determined to 10-20% precision for observed modes
  - The Higgs-fermion sector is relatively unknown but Run 2 will close in on it
- **Mass**
  - Determined to ~0.2%
- **Spin/CP**
  - Measured in decays of Higgs to bosons
  - Exclude non-SM scenarios at 99.9% C.L.
- **Width**
  - Limit set at ~4 x SM Higgs boson width
- **There is ample room for new physics to enter**



Next Steps in Higgs Physics

- **LHC Run 2 has begun**
  - Higher energy, higher collision rates
  - Gains will arise from statistics

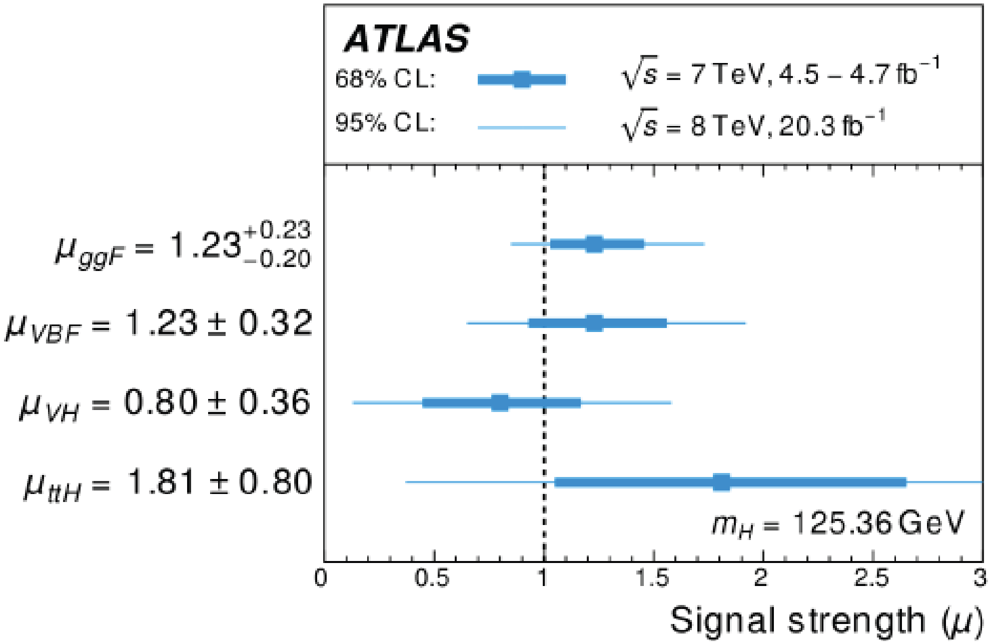
- **Future studies:**
  - Trigger choices – low thresholds and/or target specific final states
  - Ingenuity in covering production/decay mechanisms
  - Hard work to pin down object ID systematics

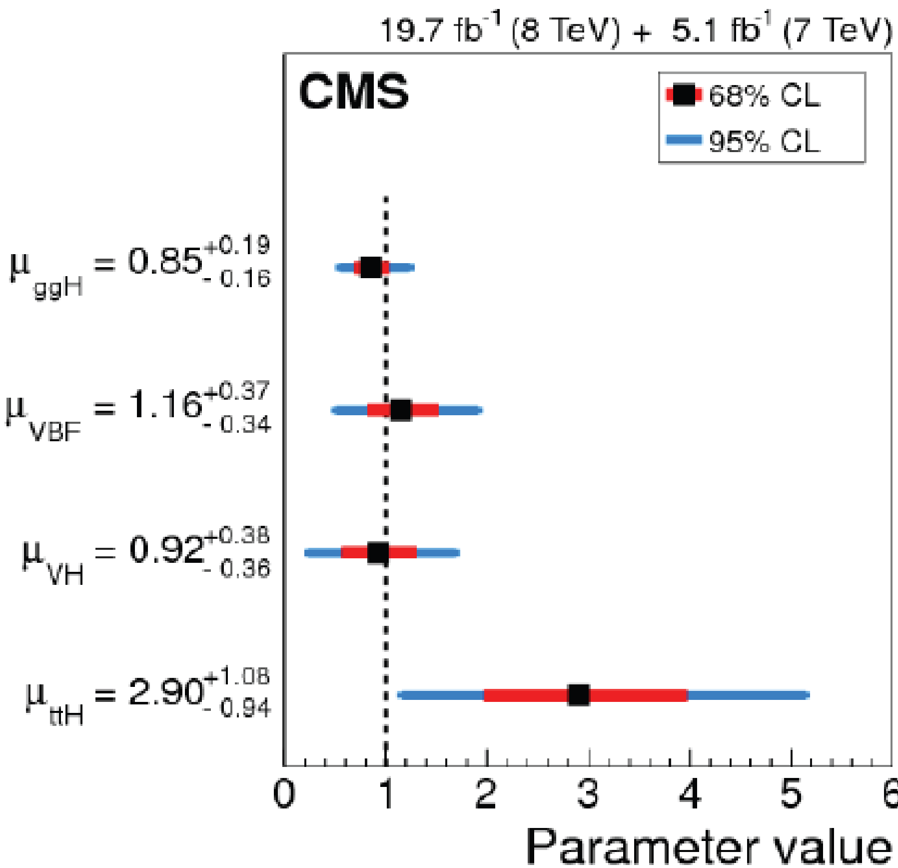
- **Switch from search mode to precision physics**
  - Emphasis on publishing what we measure in pure form

Back-up

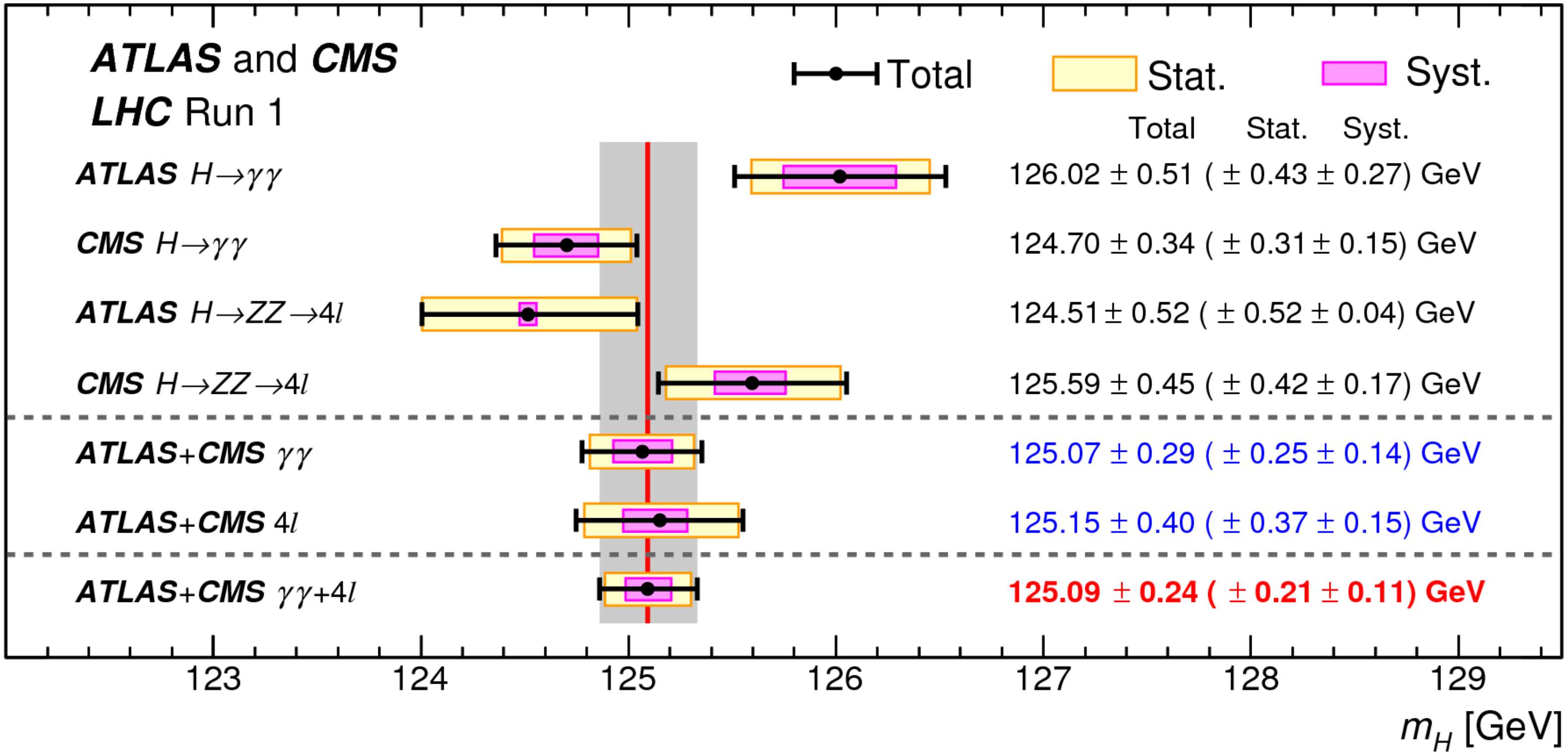
Production Mode Signal Strength

- **Fix decays to SM ratios and extract strength per production mode**





Channel Compatibility



- **ATLAS(CMS) has 2σ(1.6σ) difference between its two channels**
- **ATLAS-CMS difference of 2.1σ(1.6σ) in γγ (ZZ) masses**
- **p-value of 10% for the four mass measurements**

Production Mechanisms

- **gg fusion clearly observed; evidence for VBF**

ATLAS

Process	VBF	ttH	WH	ZH	VH
Observed	4.3	2.5	2.1	0.9	2.6
Expected	3.8	1.5	2.0	2.1	3.1

CMS

Parameter	Significance (σ)	
	Observed	Expected
μ_{ggH}	6.6	7.4
μ_{VBF}	3.7	3.3
μ_{VH}	2.7	2.9
μ_{ttH}	3.5	1.2

Higgs Coupling Combination

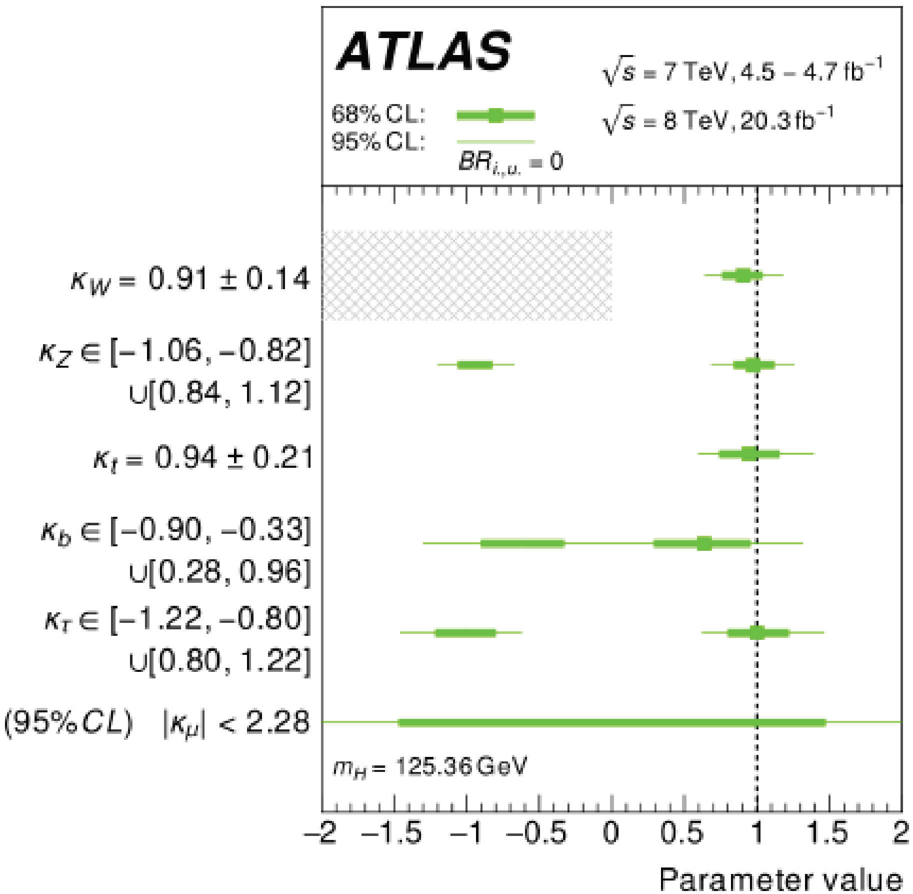
- **Signal strengths can be interpreted as coupling strengths, related to the particles participating in production mechanisms**
  - Allow non-SM modifiers (κ) to SM couplings

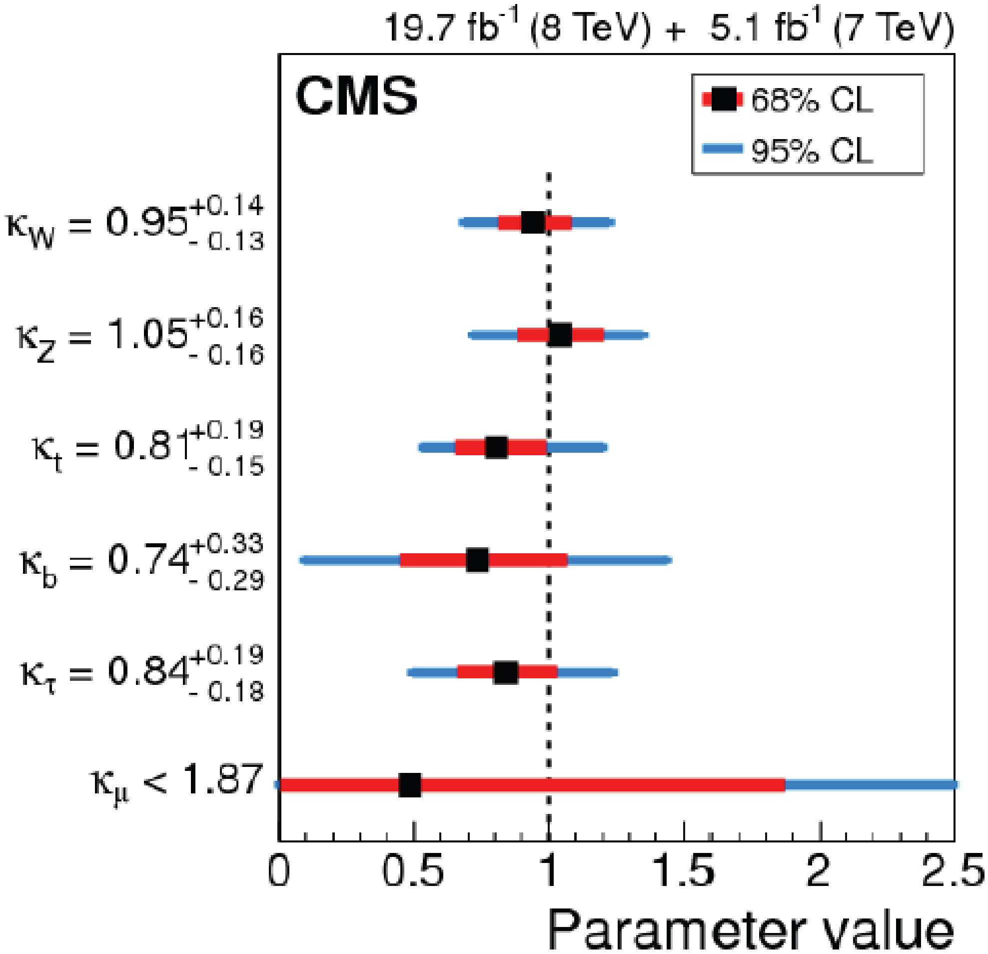
$$\Gamma_i = \kappa_i^2 \; \Gamma_i^{SM}$$

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

Couplings Results (Per SM Particle)

- **Assume no contributions from BSM to width or loops**





Production/Decay Modes Covered

- **Most combinations probed by at least one experiment**

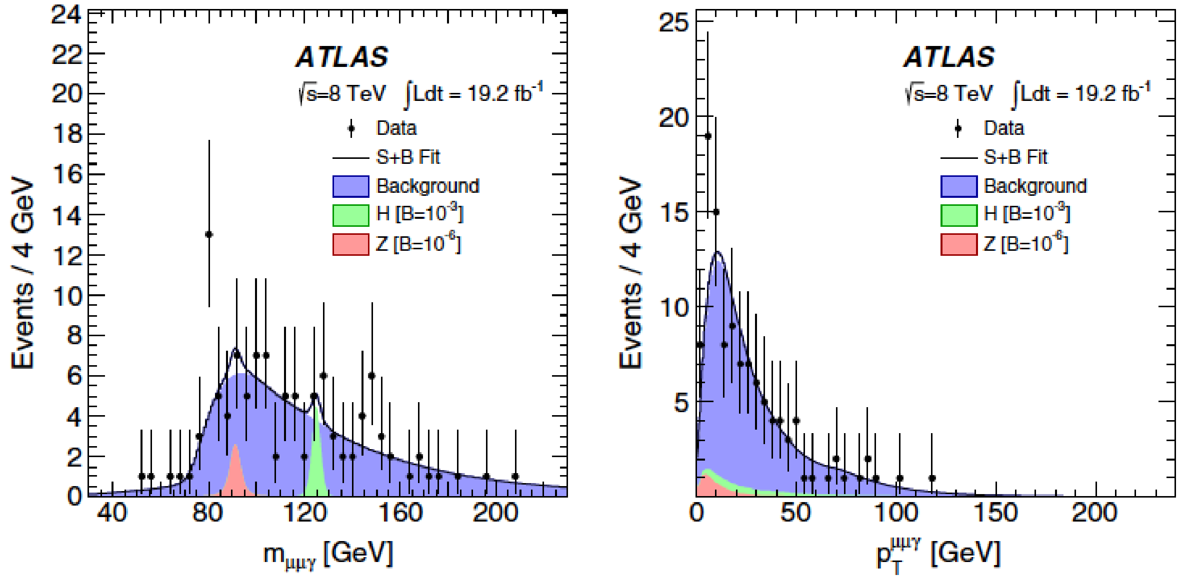
	WW	ZZ	$\gamma\gamma$	bb	$\tau\tau$
ggH	X	X	X		X
VBF	X	X	X	X	X
WH	X	X	X	X	X
ZH	X	X	X	X	X
ttH	X	X	X	X	X

Search for J/ψ γ

- **Predicted BR**

$$\mathcal{B}(H \to J/\psi\gamma) = (2.8 \pm 0.2) \times 10^{-6}$$

- **Probe Higgs charm coupling**

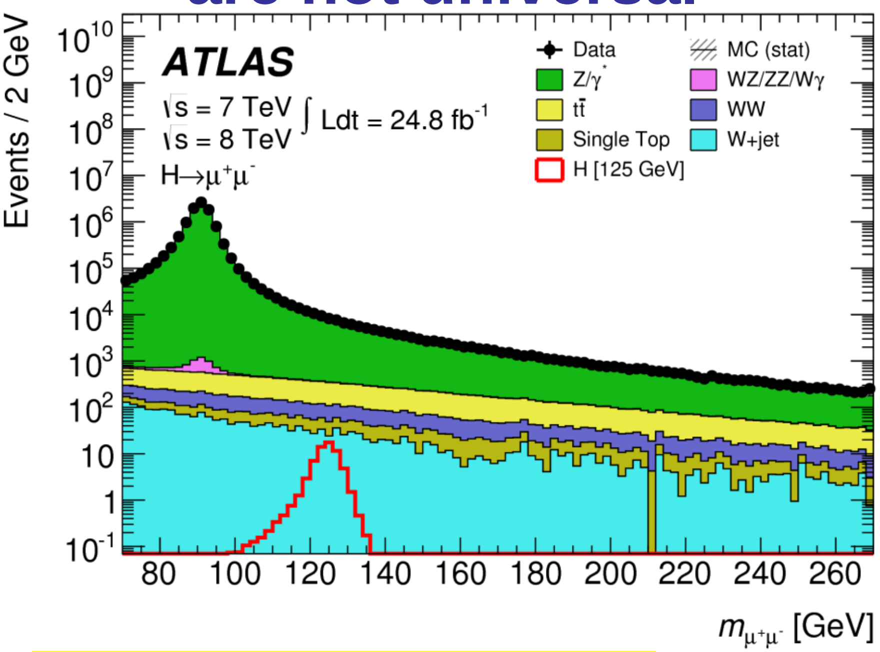


	95% C.L. upper limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
	$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ $[10^{-6}]$				
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
	$\mathcal{B}(H \to \mathcal{Q}\gamma)$ $[10^{-3}]$				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

Rare Higgs Decays

- **Several search channels, summary:**

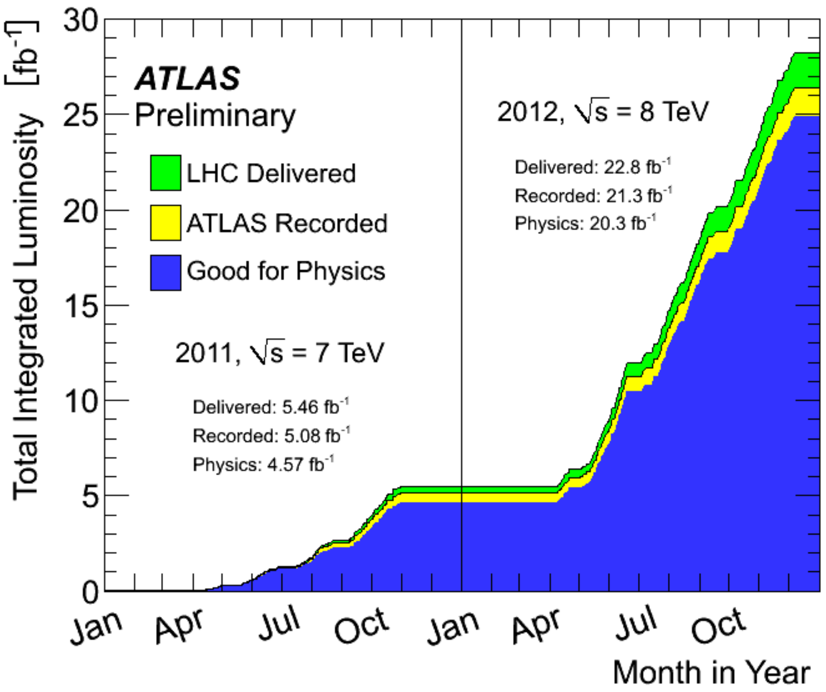
- **Run 1 data demonstrates that couplings to fermions are not universal**



PLB 738 (2014) 68-86

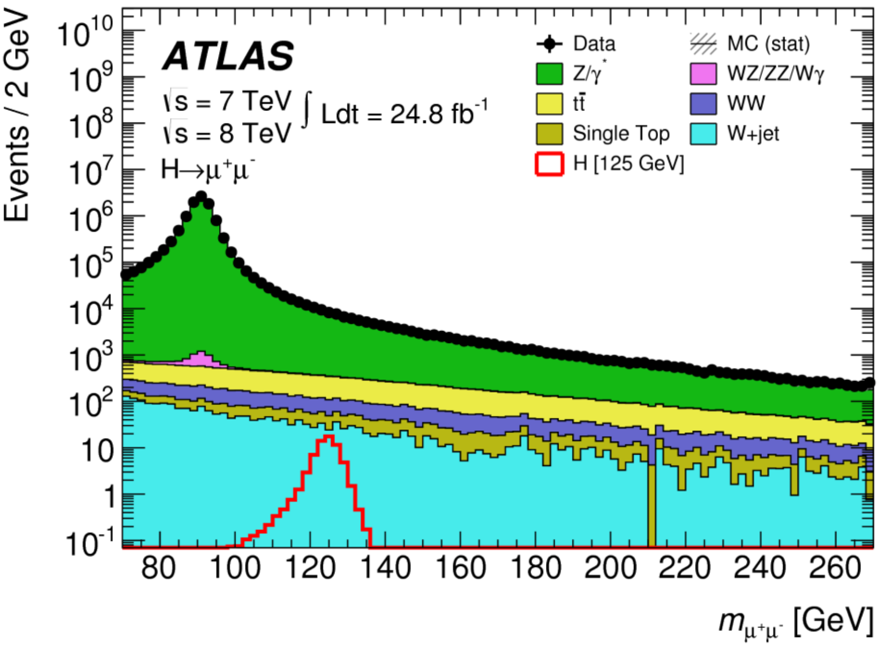
Process	limit (times SM)
μμ (ATLAS)	7.0
μμ (CMS)	7.4
Zγ (ATLAS)	11
Zγ (CMS)	9
γγ* (CMS)	7.7
J/ψγ (ATLAS)	540
J/ψγ (CMS)	540
ee(CMS)	10^5

The Datasets



Rare Higgs Decays

- **Many BSM searches**
- **Run 1 data demonstrates that couplings to fermions are not universal**

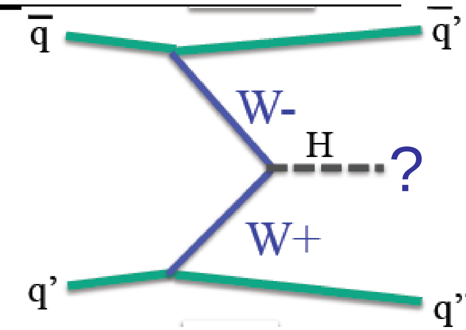


Process	limit (times SM)
μμ (ATLAS)	7.0
μμ (CMS)	7.4

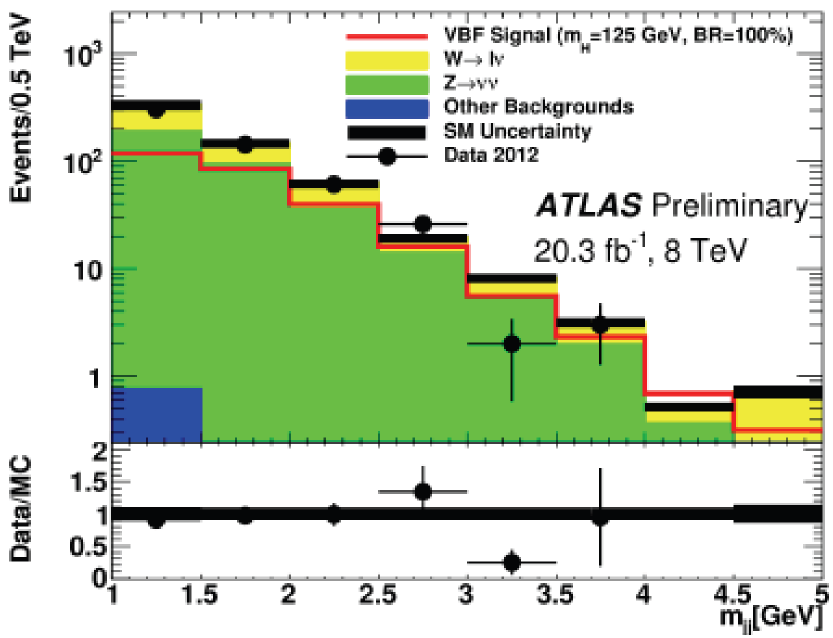
PLB 738 (2014) 68-86

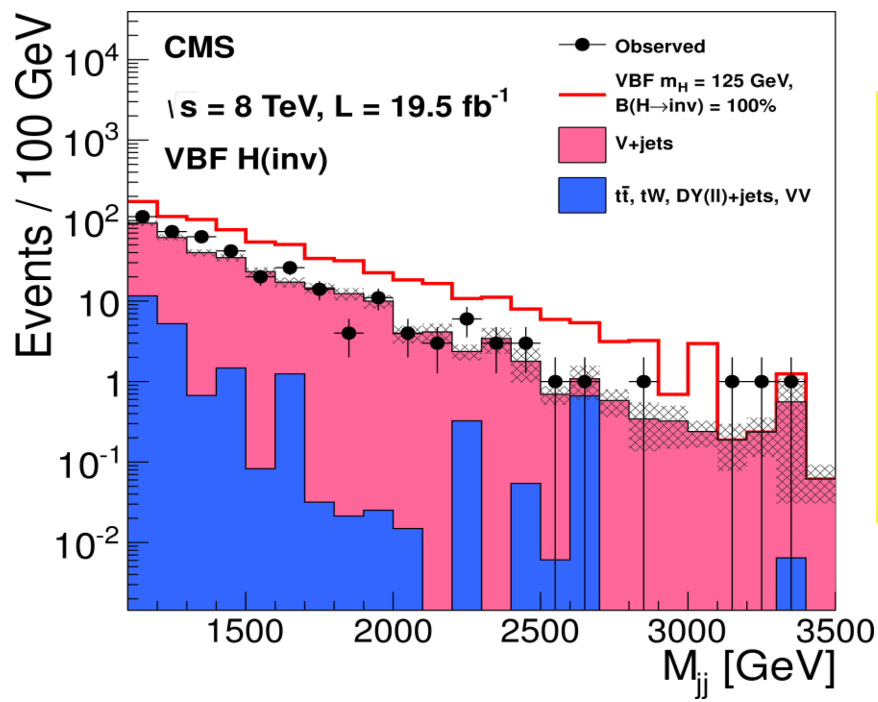
Higgs Decaying to Invisible Particles

- **SM expectation only 0.1% (ZZ to 4ν)**
- **Sensitivity from VBF-tagged events**
  - Large Δη(jj) and m(jj) with large missing energy



ATLAS-CONF-2015-004





arXiv:1507.00359

- **95% C.L. limits (expected)**
  - ATLAS <25% (27%), combined with ZH and VH results; CMS <58% (44%)

arXiv:1509.00672

ATLAS/CMS Combined μ

- **ATLAS/CMS combined in August this year**
  - 4200 nuisance parameters in the fit, most experimental systematics assumed to be uncorrelated
  - Still statistically dominated (as expected)

Mainly ggF

Decay / Production	Untagged	VBF	VH	ttH
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb			✓	✓
H→μμ	✓	✓		

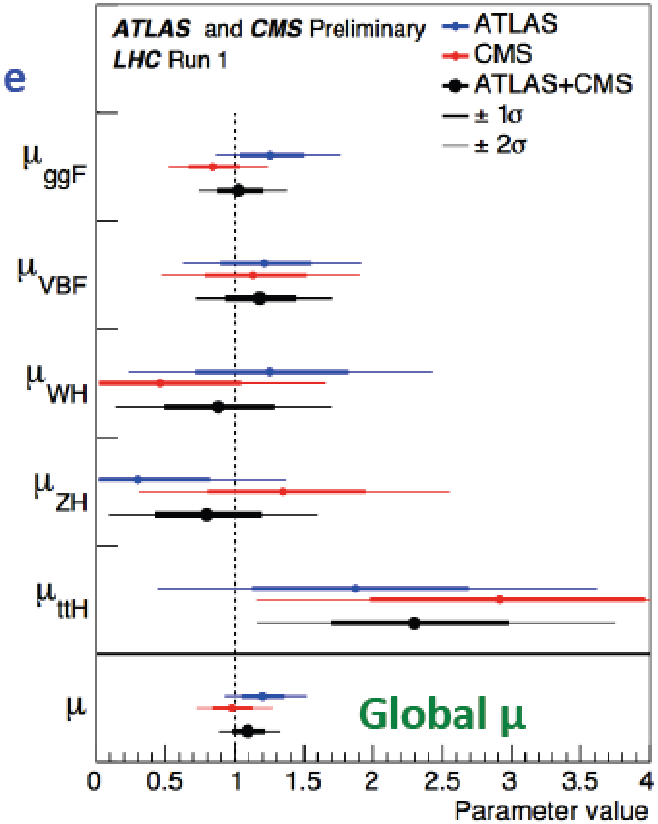
✓ = Combined (green)

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

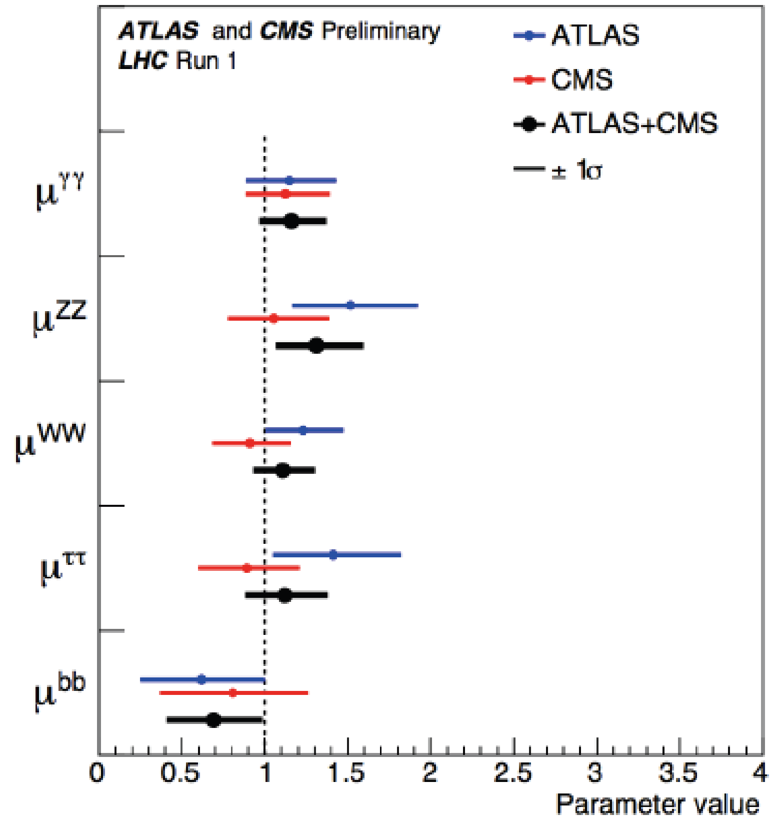
Combined μ per production/decay type

SM p-value 25%

SM BRs assumed



SM production σ assumed



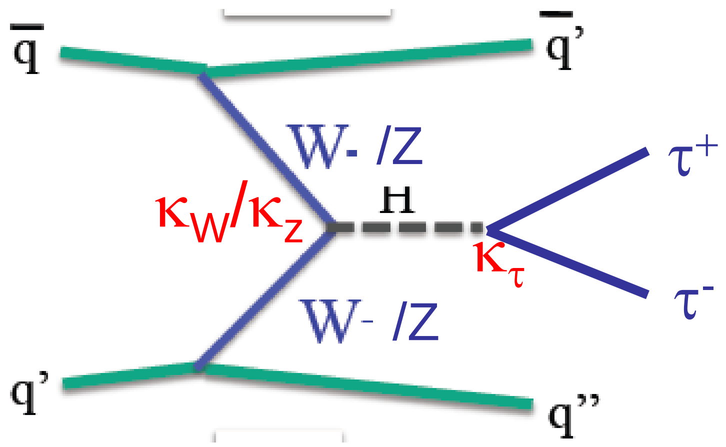
SM p-value 60%

- In good agreement with the Standard Model
  - Largest deviation is ttH production at 2.3σ

Extraction of Couplings

- **Signal strengths can be interpreted as coupling strengths, related to the particles participating in production mechanisms**
  - Allow non-SM modifiers (κ) to SM couplings

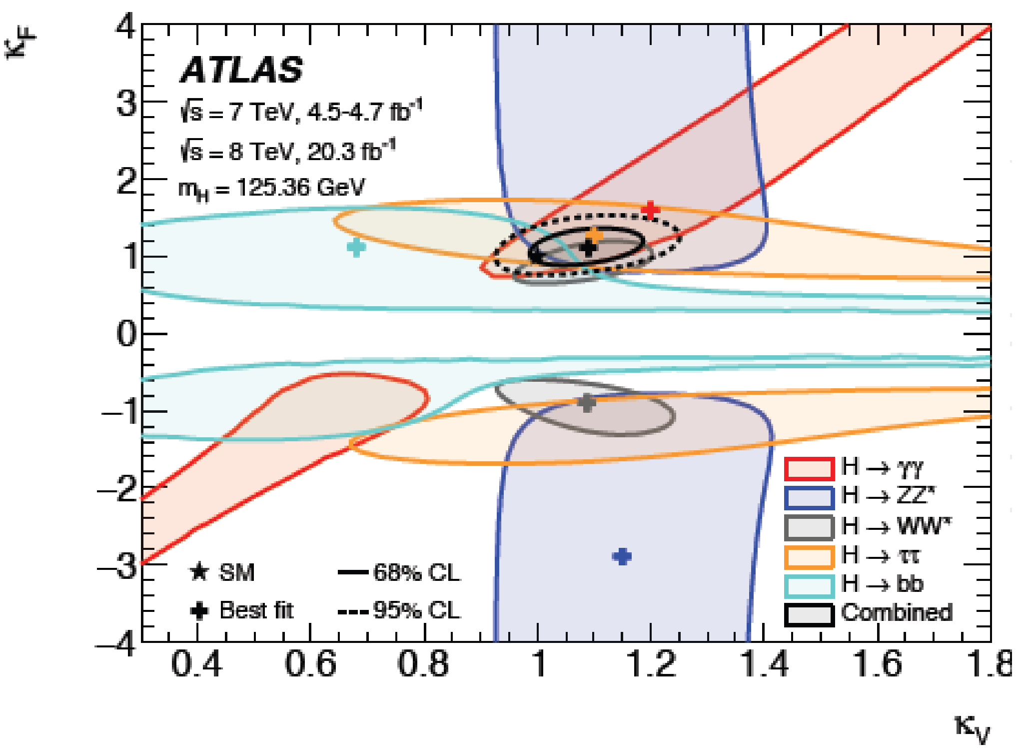
$$\Gamma_i = \kappa_i^2 \, \Gamma_i^{SM}$$

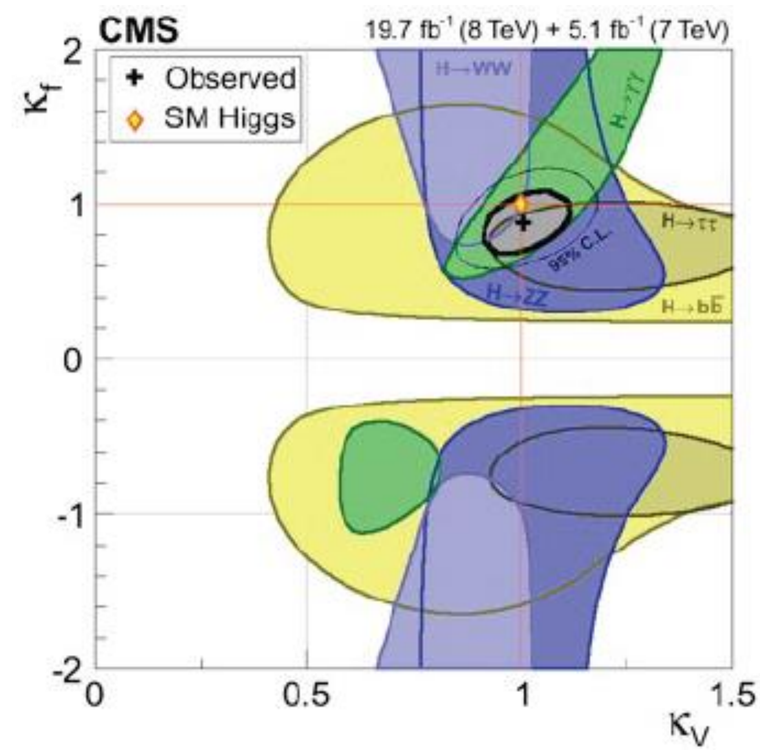


$$\approx 0.74 k_W^2 + 0.26 k_Z^2$$

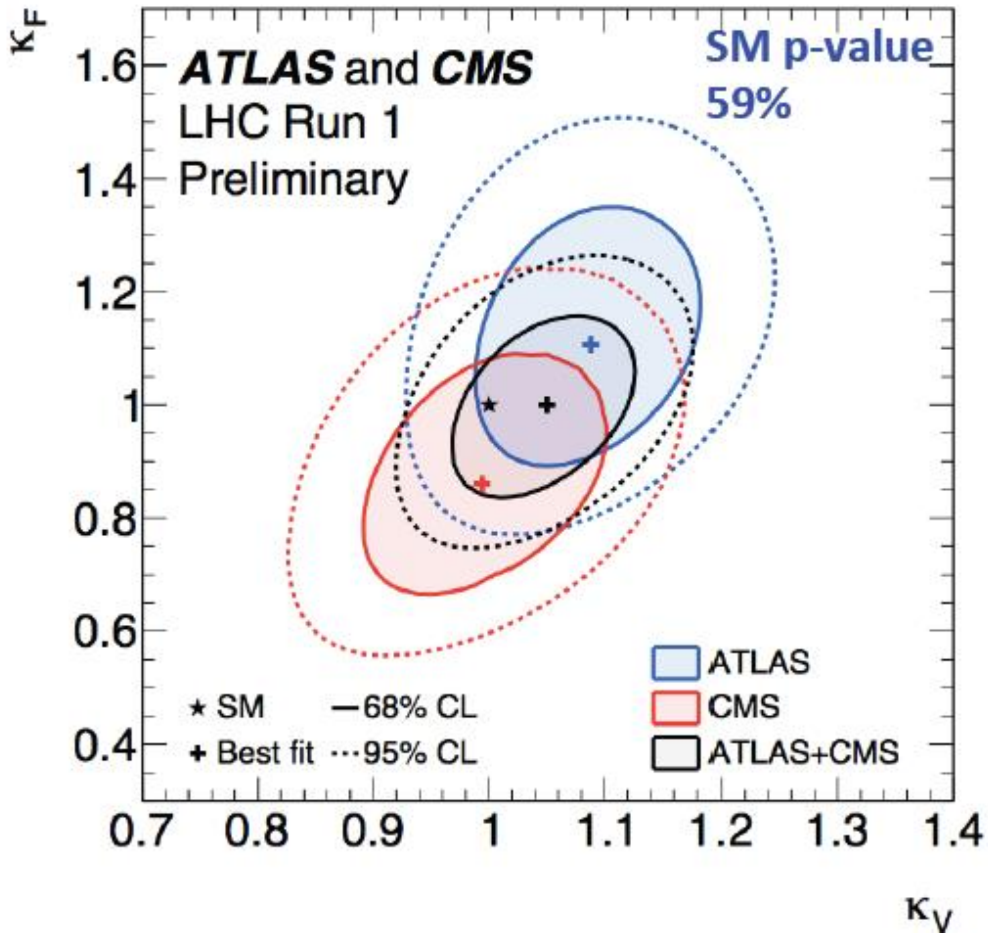
Couplings Results (Fermion vs Boson)

- **Assume**
  - One Higgs boson
  - All fermions scale the same (κ_F) and all bosons scale the same (κ_V)
  - No BSM interactions in width or loops





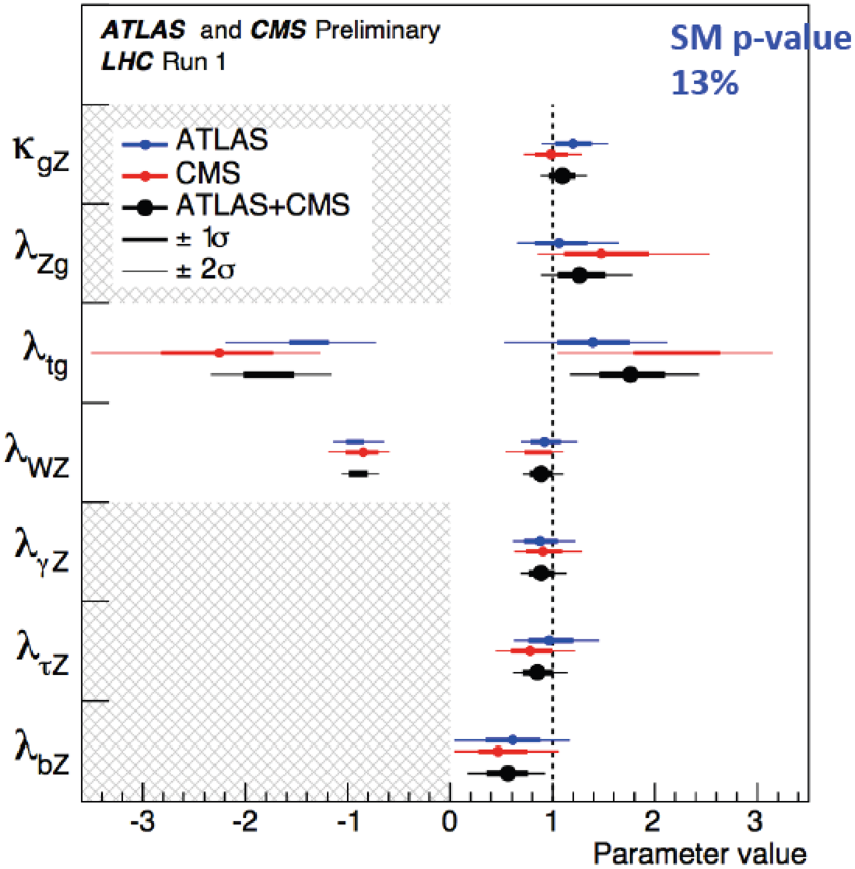
ATLAS/CMS Combined Couplings



- Agree with Standard Model within 1σ

Fit Without Assumptions

- **Making no assumptions about particles participating in loops or Higgs width, or BSM decays**
  - Nomenclature e.g. $\lambda_{WZ} = \kappa_W / \kappa_Z$ $\kappa_{gZ} = \kappa_g \cdot \kappa_Z / \kappa_H$



LHC Higgs Mass Combination

- **Profile likelihood ratio**

$$\Lambda(m_H) = \frac{L\left(m_H\,,\, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+t\bar{t}H}(m_H)\,,\hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H)\,,\,\hat{\hat{\mu}}^{4\ell}(m_H)\,,\,\hat{\hat{\theta}}(m_H)\right)}{L(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}^{4\ell}, \hat{\theta})}$$

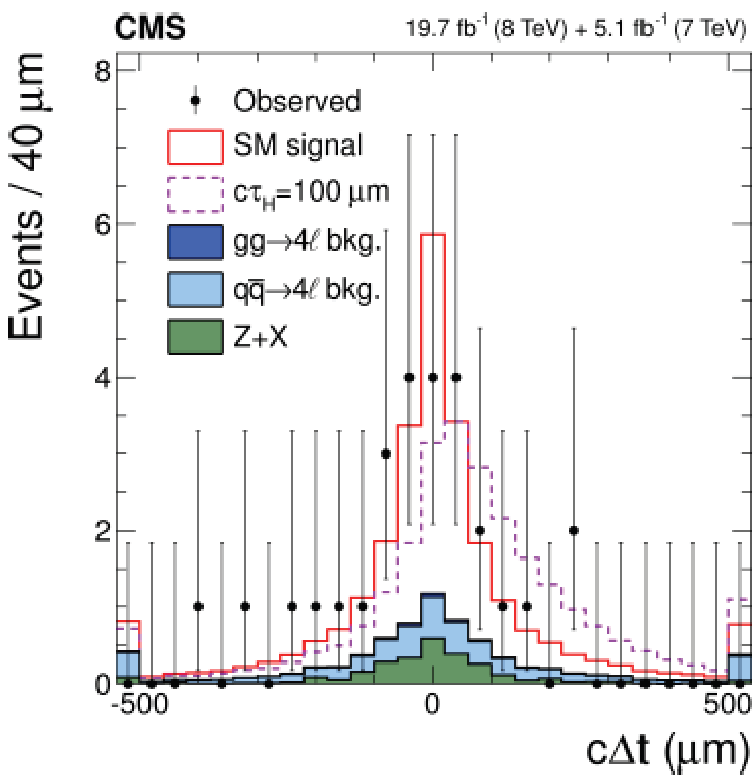
- **Float m_H, μ values for each production mechanism**

$$\mu = \frac{\text{measured cross section}}{\text{SM cross section}}$$

$\mu^{\gamma\gamma}_{ggF+ttH}$	ggF (+ttH) production, H→γγ decay
$\mu^{\gamma\gamma}_{VBF+VH}$	VBF (+VH) production, H→γγ decay
μ^{4l}	ZZ→4*l* decay

Lifetime

- **Expected SM lifetime 1.6x10^{-7} fs**
- **Measured at CMS using ZZ. Vertexing yields:**
  - τ(Higgs)<190 fs at 95% C.L.
  - Γ(Higgs)>3.9x10^{-9} MeV

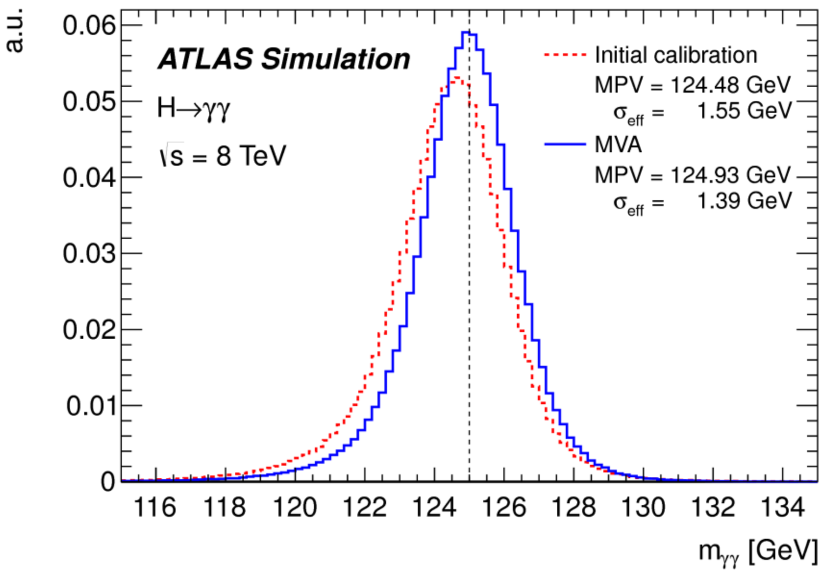


arXiv:1507.06656

Status

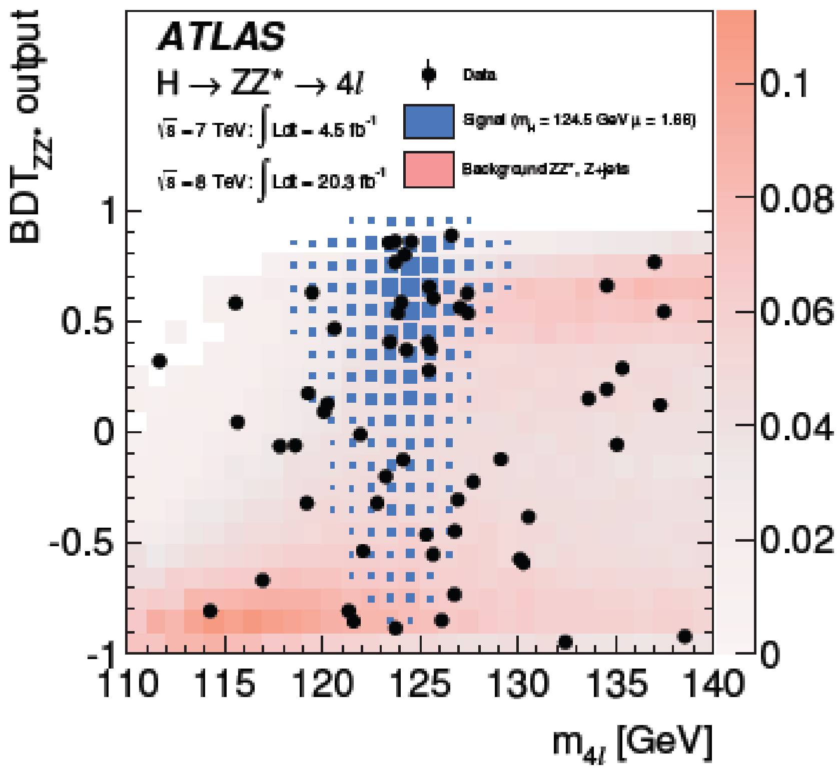
- **Nearly all of the SM Higgs results are based on Run 1 data**
  - First analyses of complete Run 1 dataset shown at Moriond 2013
  - Higgs observation and some properties measurements

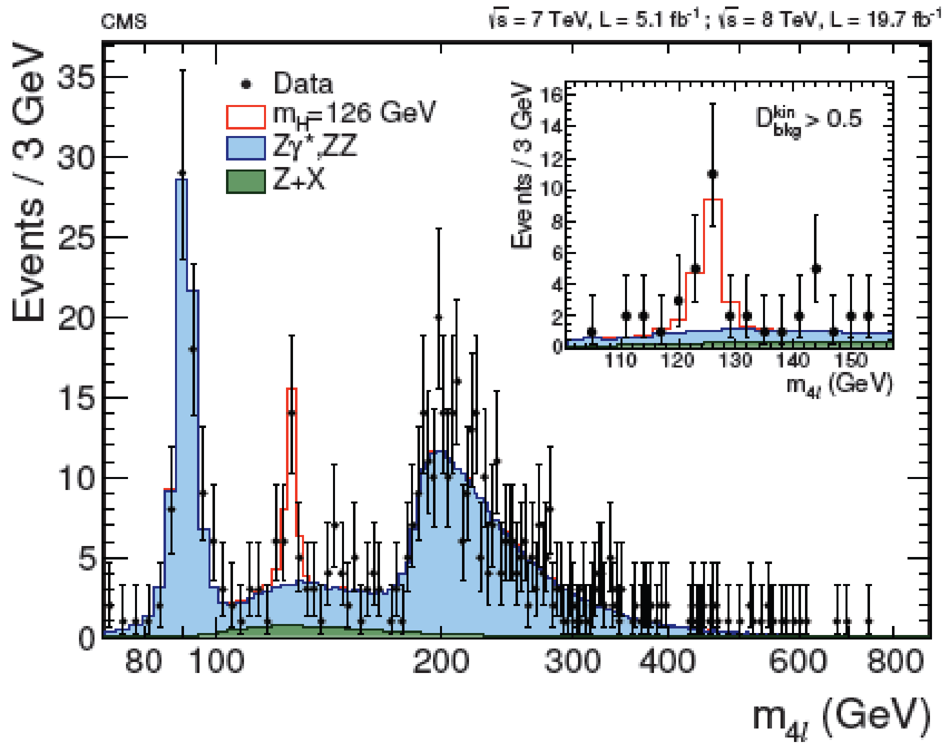
- **Since then, a lot of work and ingenuity**
  - Detector calibrations redone
  - Resolutions re-measured
  - Data re-analysed



ATLAS/CMS Measurements

- **Experiment measurements differ in detail**
  - e.g. ATLAS ZZ measurement uses 2-d fit to mass(4leptons) and Boosted Decision Tree score





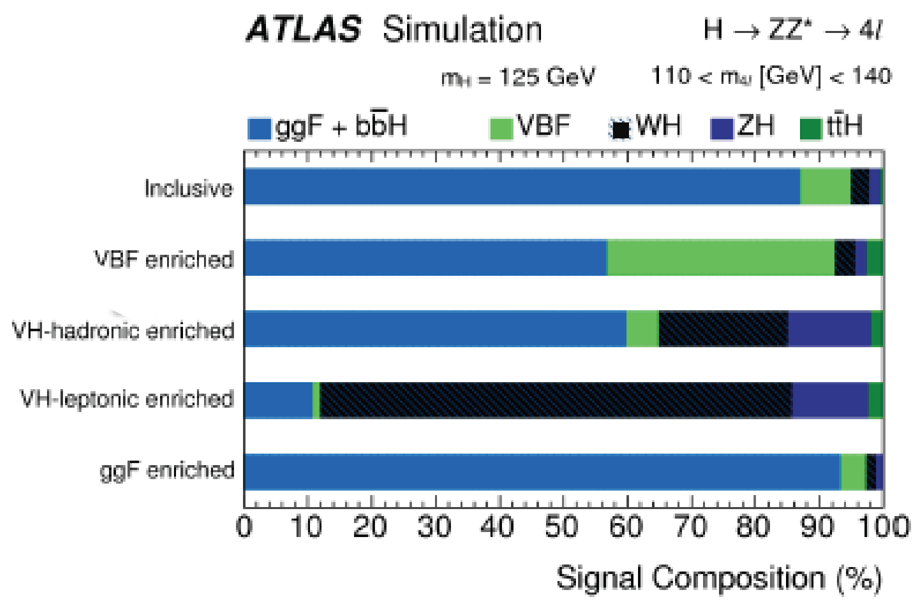
  - CMS include third parameter: event-by-event mass uncertainty

Phys. Rev. D. 90, 052004 (2014)

Phys. Rev. D 89 (2014) 092007

Signal Strength Combination

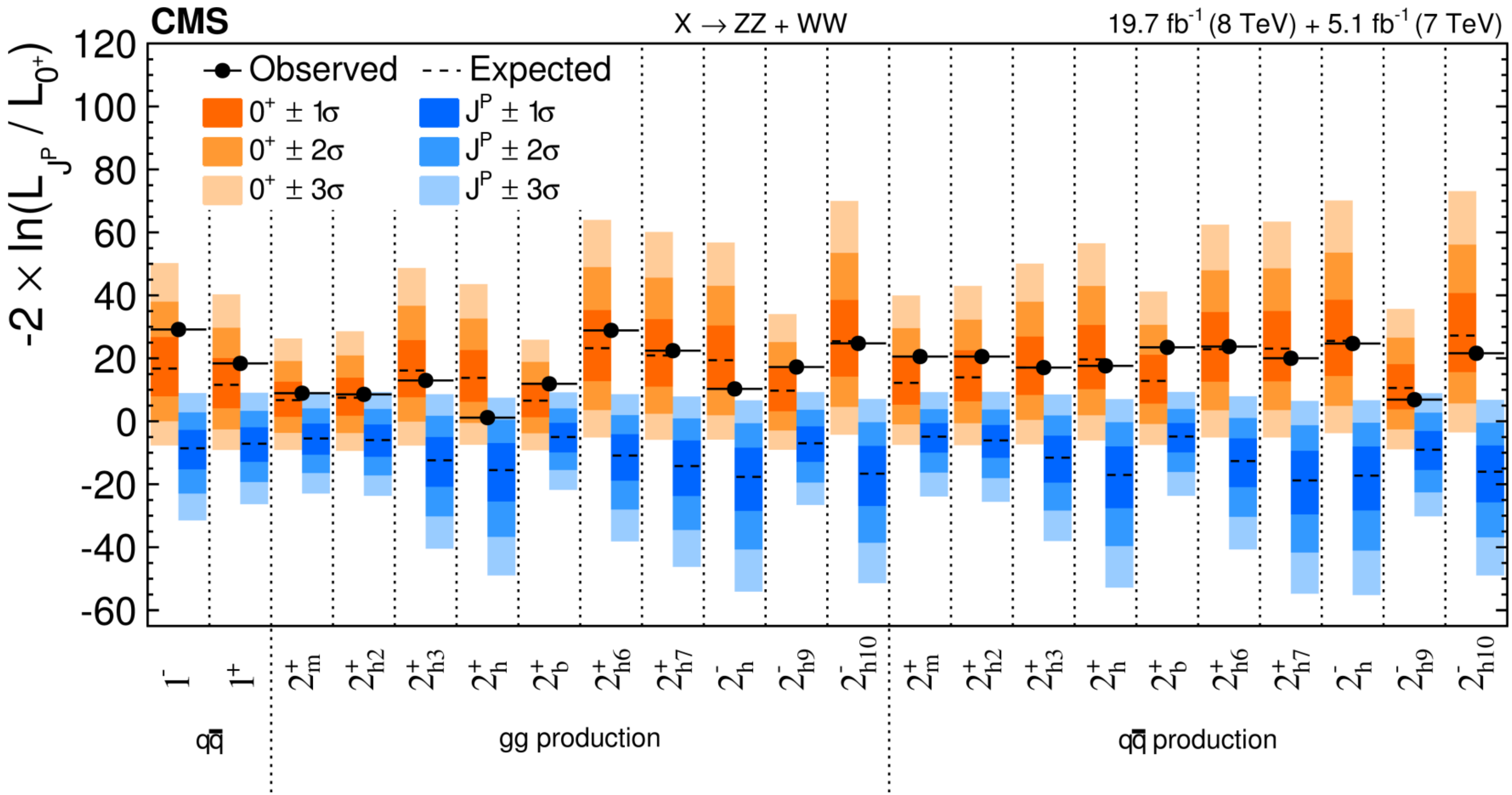
- **Cover as many production and decay channels as possible and combine the information**
  - Extract yields in each production/decay
  - Correlate systematic uncertainties across channels



  - Evaluate μ, the ratio of the measured cross-section to the SM expectation
  - Can extract more information from combination, see next talk

Spin/CP Results (Channels Combined)

Phys. Rev. D 92 (2015) 012004



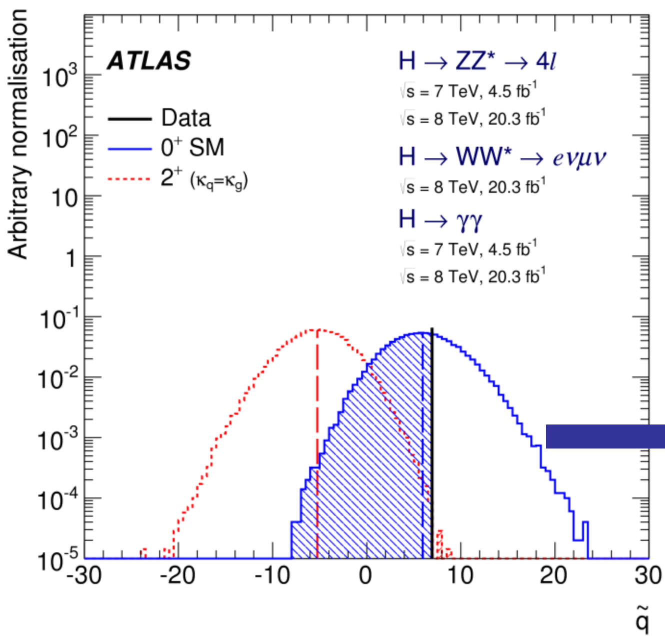
Spin/CP (Boson Channels Combined)

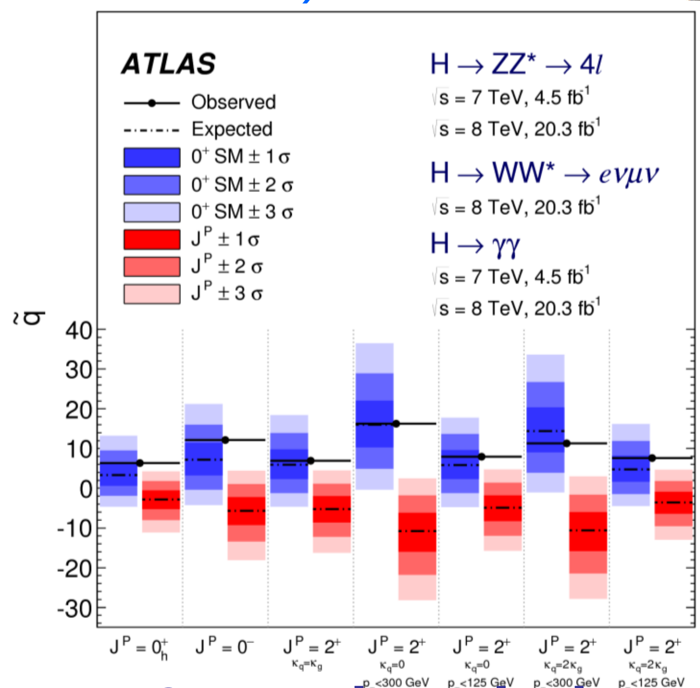
- **Test ratio of SM and alternative hypotheses**
  - Test for spin 0, 1, 2 with various BSM CP hypotheses (mixed CP even/odd etc)

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

Phys. Rev. D 92 (2015) 012004

arXiv:1506.05669





- **Both experiments favour 0^{++} and exclude alternatives at 99.9% C.L.**
  - ***conclusion already reached – but what about fermions?

CP Mixing and Tensor Structure

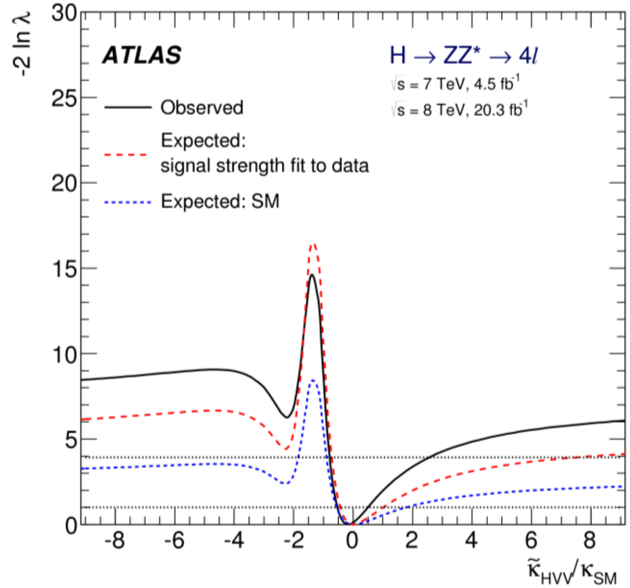
- **Higgs coupling could have CP-mixing and alternative tensor structure**

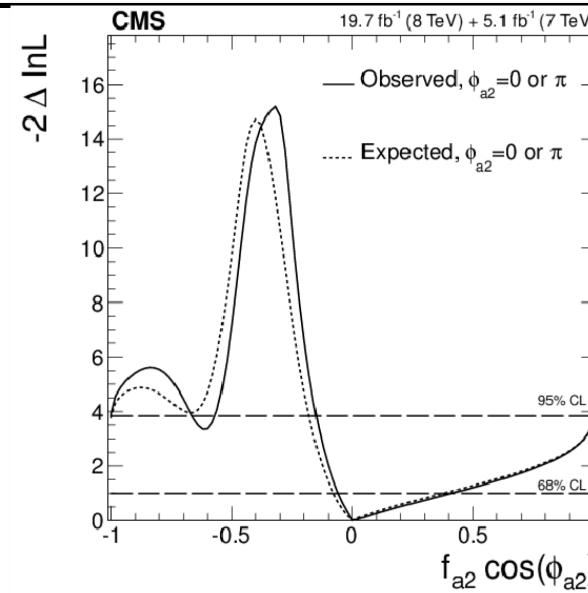
$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}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

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

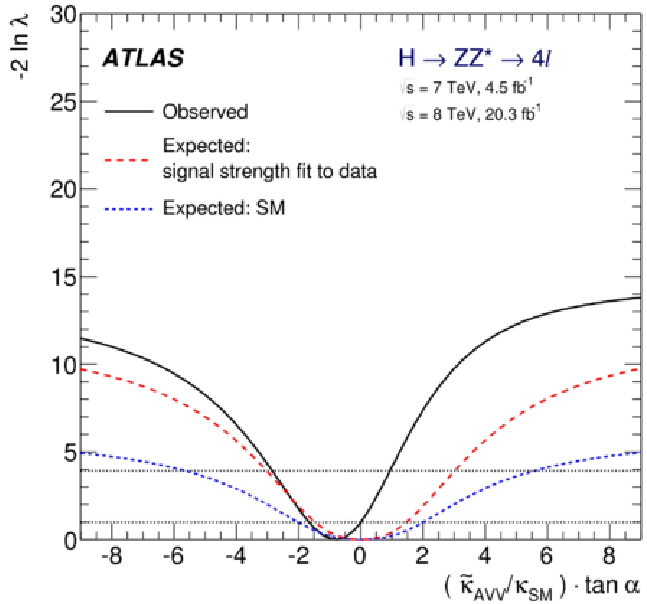
CP Mixing Results

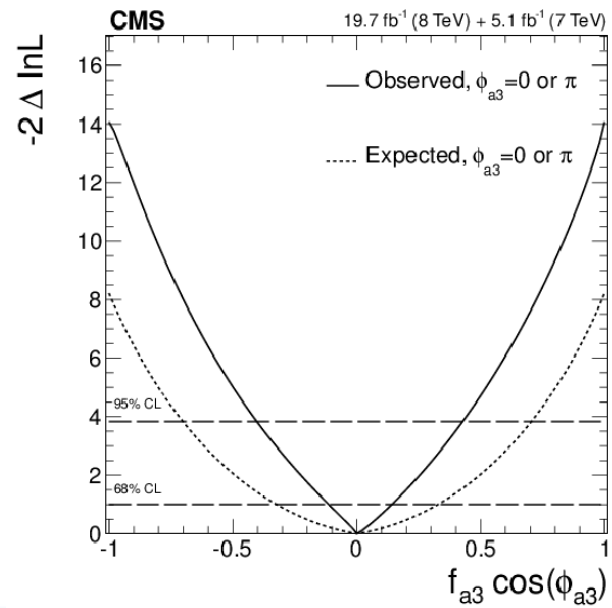
- Test coupling and mixing angle in CP even and odd hypotheses





- No evidence of CP violation observed***what significance?



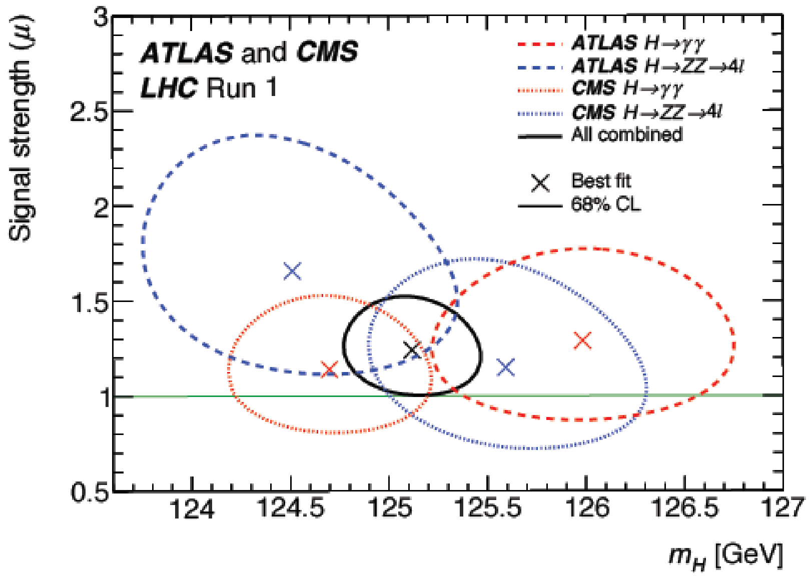


Results

- **Likelihood fits performed**
- **Higgs mass in GeV:**
  - ATLAS, CMS combined:

$$125.09 \pm 0.21\ (\text{stat}) \pm 0.11\ (\text{syst})$$

  - -0.2% uncertainty
    - Higgs precision era!



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Phys. Rev. Lett. 114, 191803