Higgs at Hadron Collider

Higgs Properties and Precision Test

Lecture 12

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Fisica delle Particelle Elementari, Anno Accademico 2015-16

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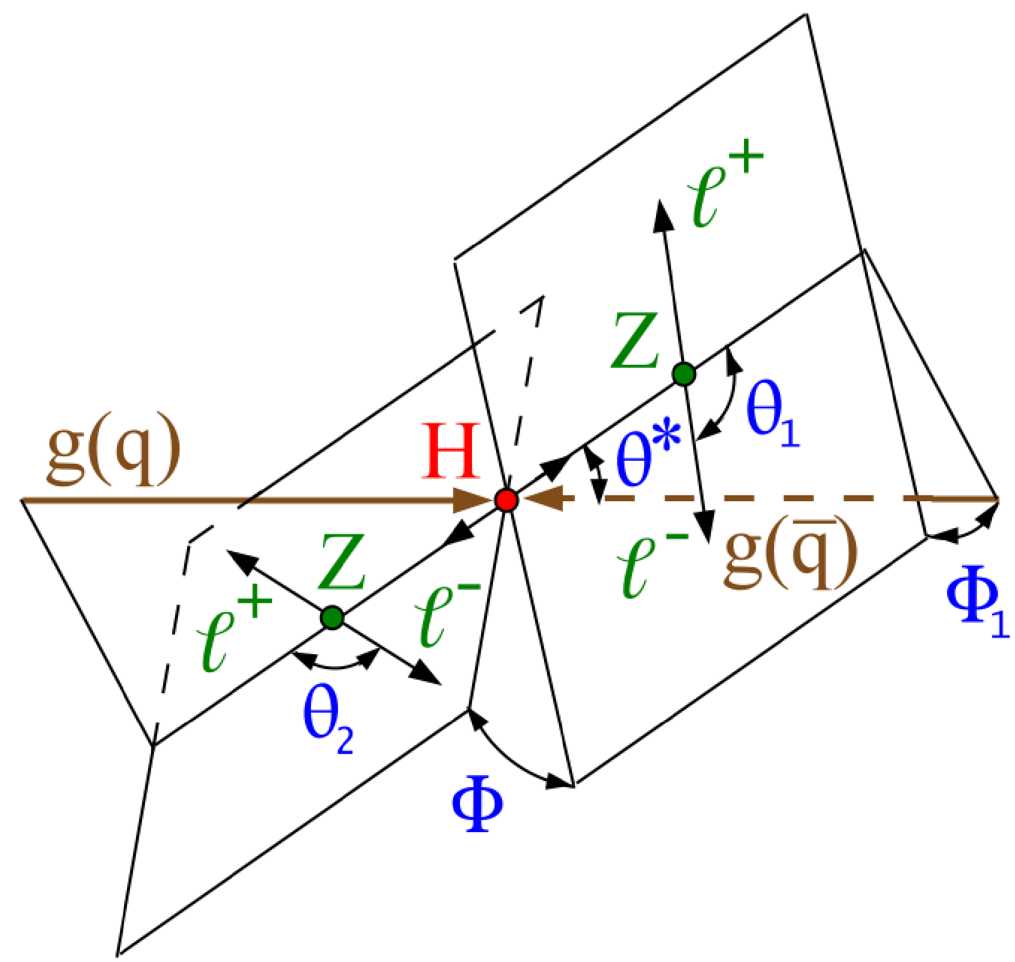
Why and Which Boson?

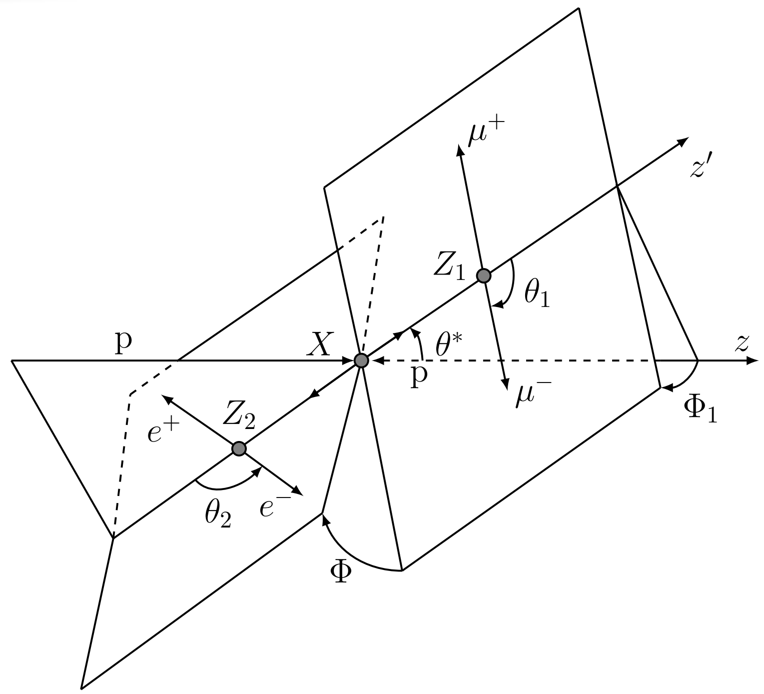
- Is it statistically significant?
  - use of p-value. Put threshold at 5σ
- Is it a boson?
  - determined by decay products
- Which is the mass?
  - to be studied with modes with good resolution, i.e. ZZ and $\gamma\gamma$
- Is it "the" SM Higgs boson?
  - study compatibility of $BR^*\sigma$ in different decay modes
- Is it "a" Higgs boson?
  - study the Higgs couplings to different particles
  - search for new bosons

SPIN AND PARITY

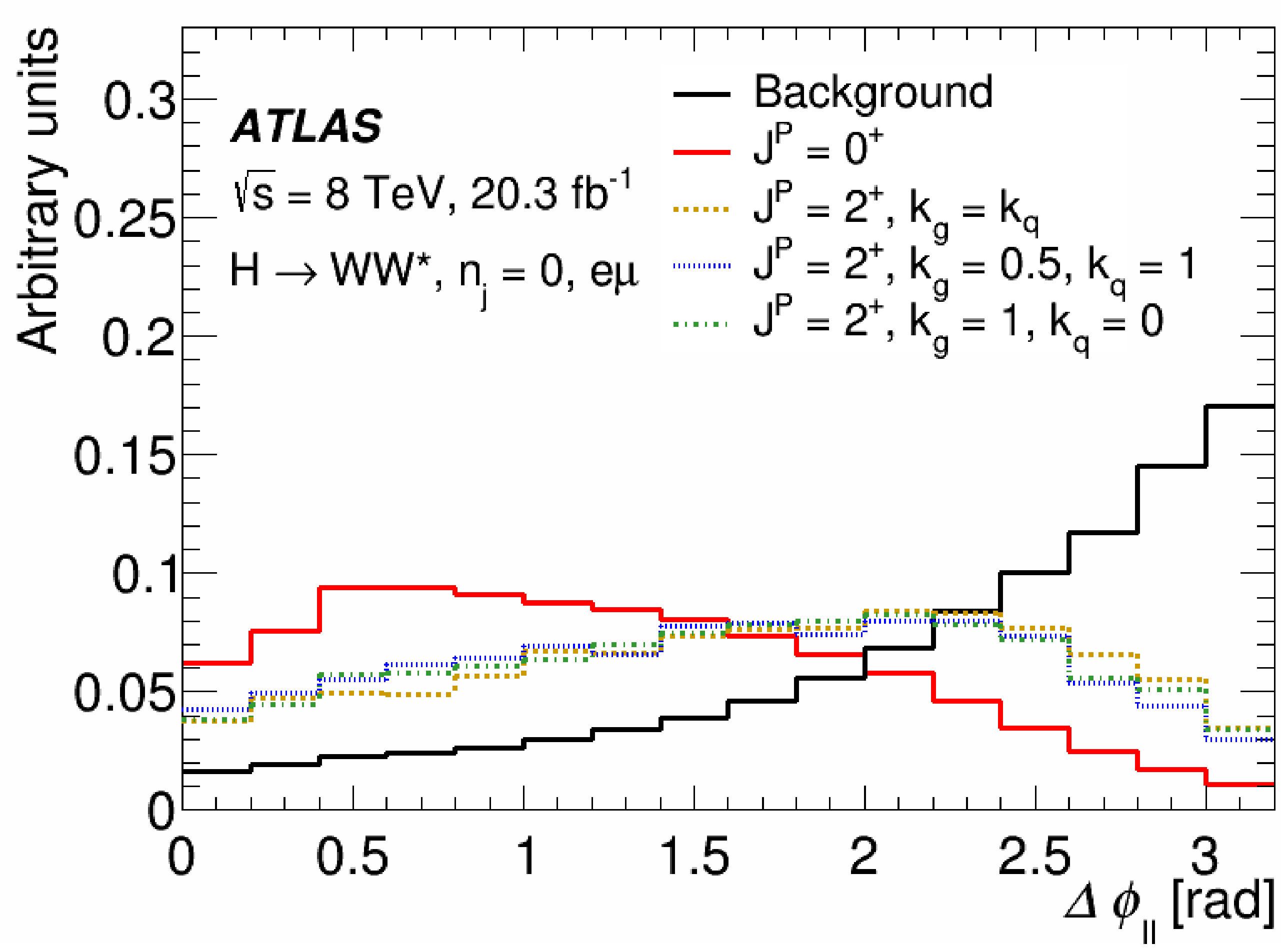
- SM Higgs is a scalar boson with $J^P = 0^+$
- Observation of $H \rightarrow \gamma\gamma$ decays implies $J \neq 1$
  - Landau-Yang theorem
- Observation of WW and ZZ decays disfavors CP-odd hypothesis
- Use angular kinematic variables from final states to distinguish different spin and parity hypotheses
  - m_{ll}, $\Delta\Phi_{ll}$, m_T, $\cos\theta^*$
- No variable alone powerful enough
- Combine all information with multivariate method e.g. neural network or boosted decision tree

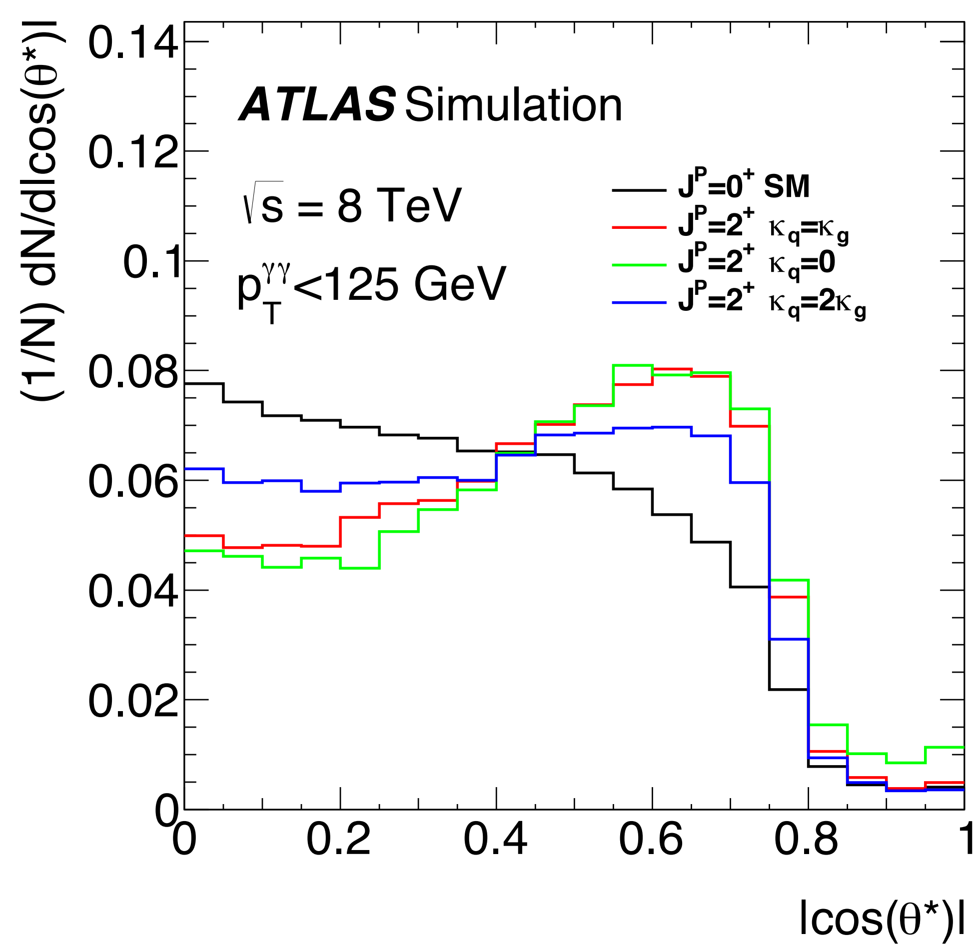


Angular Variables



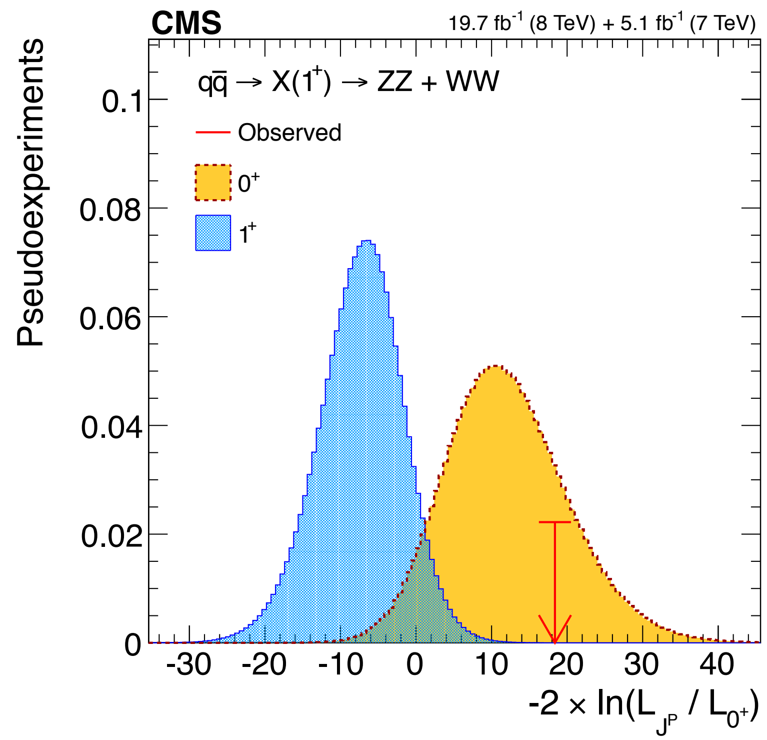
$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+\left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

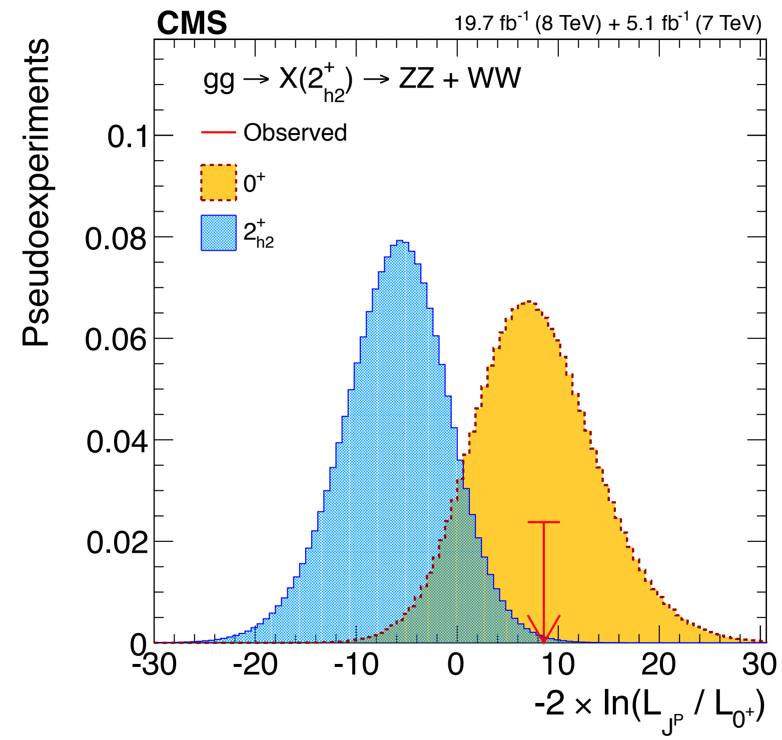


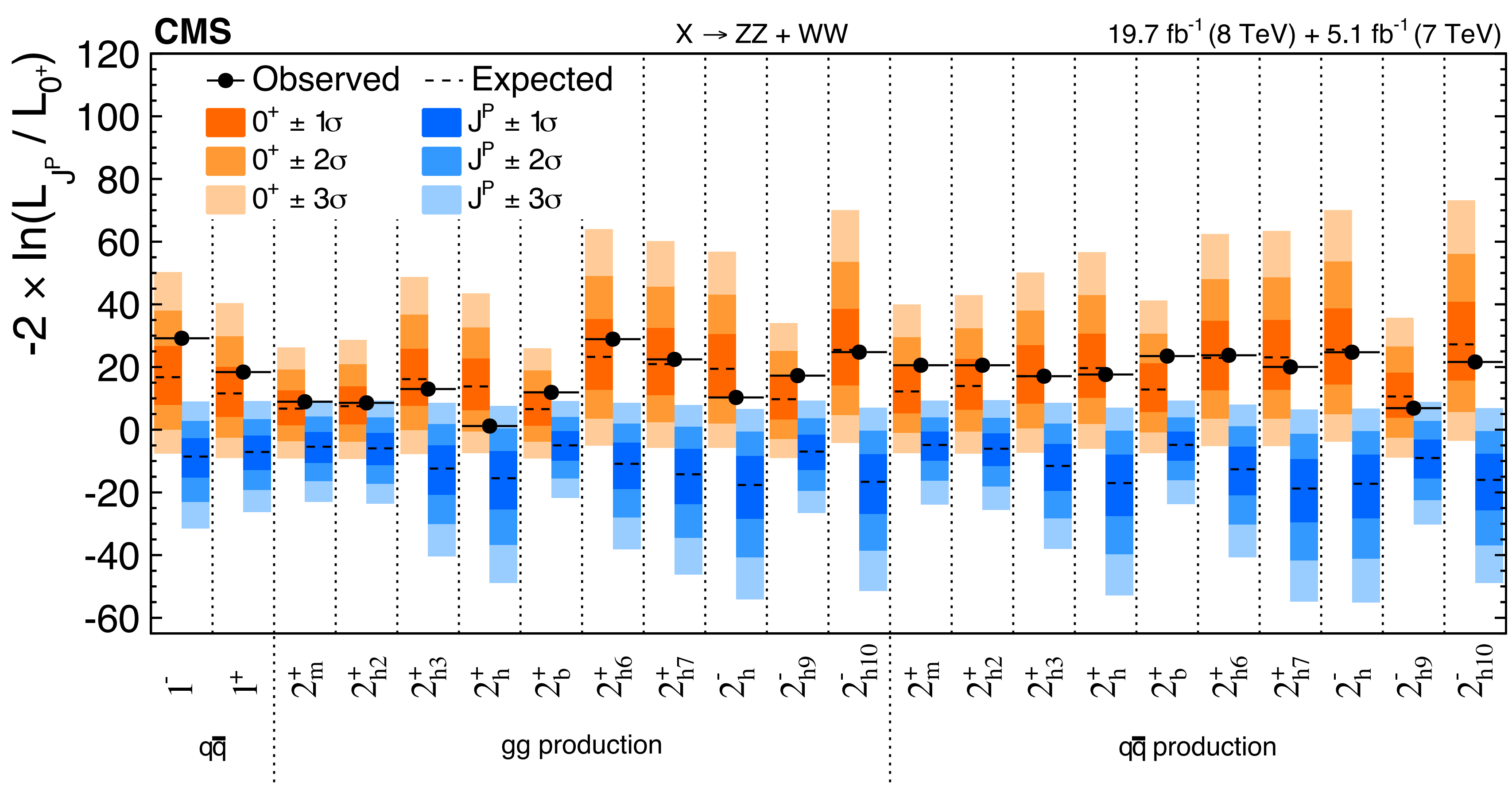


ATLAS: arXiv:1506.05669

CMS: arXiv:1411.3441

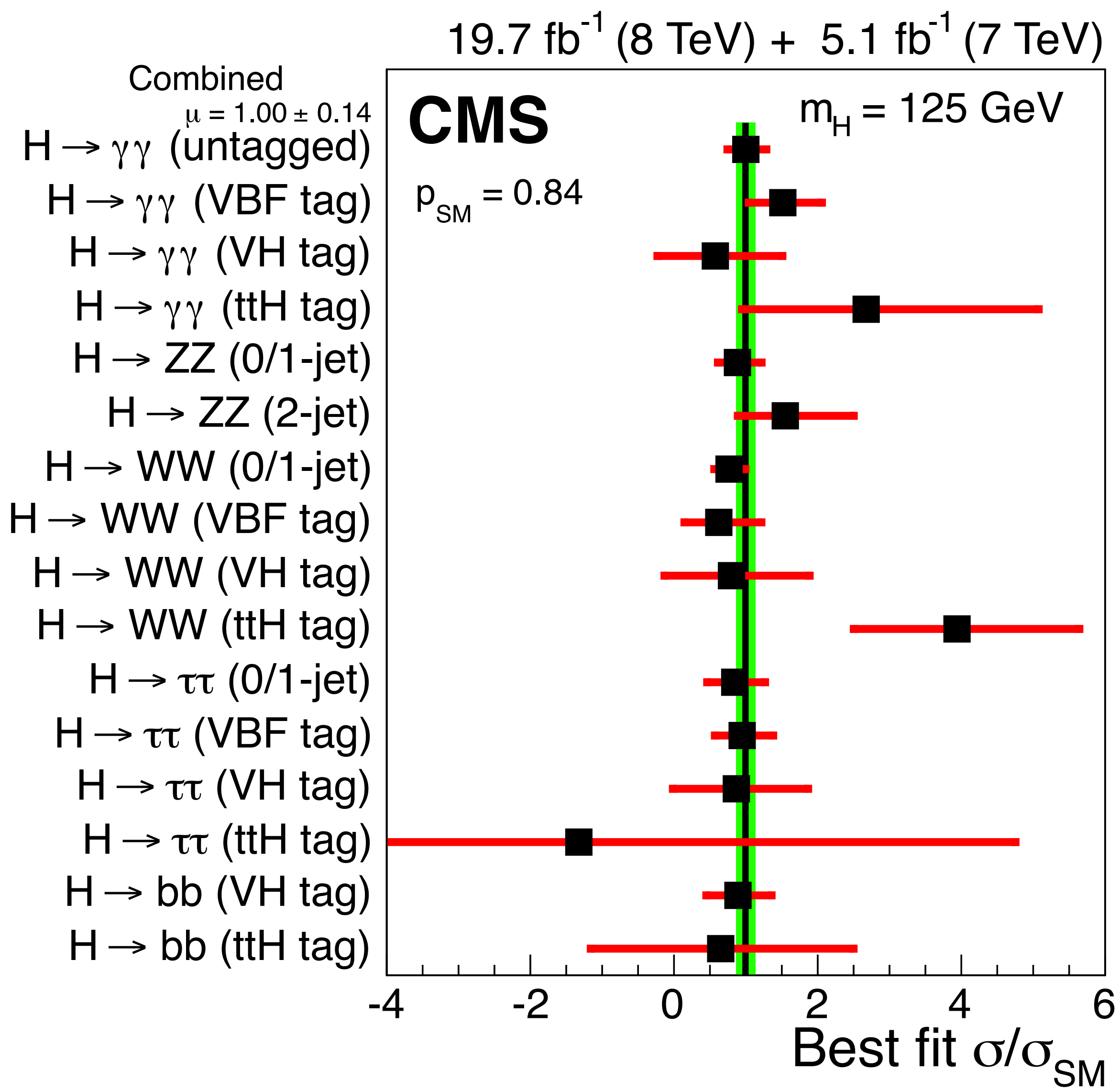




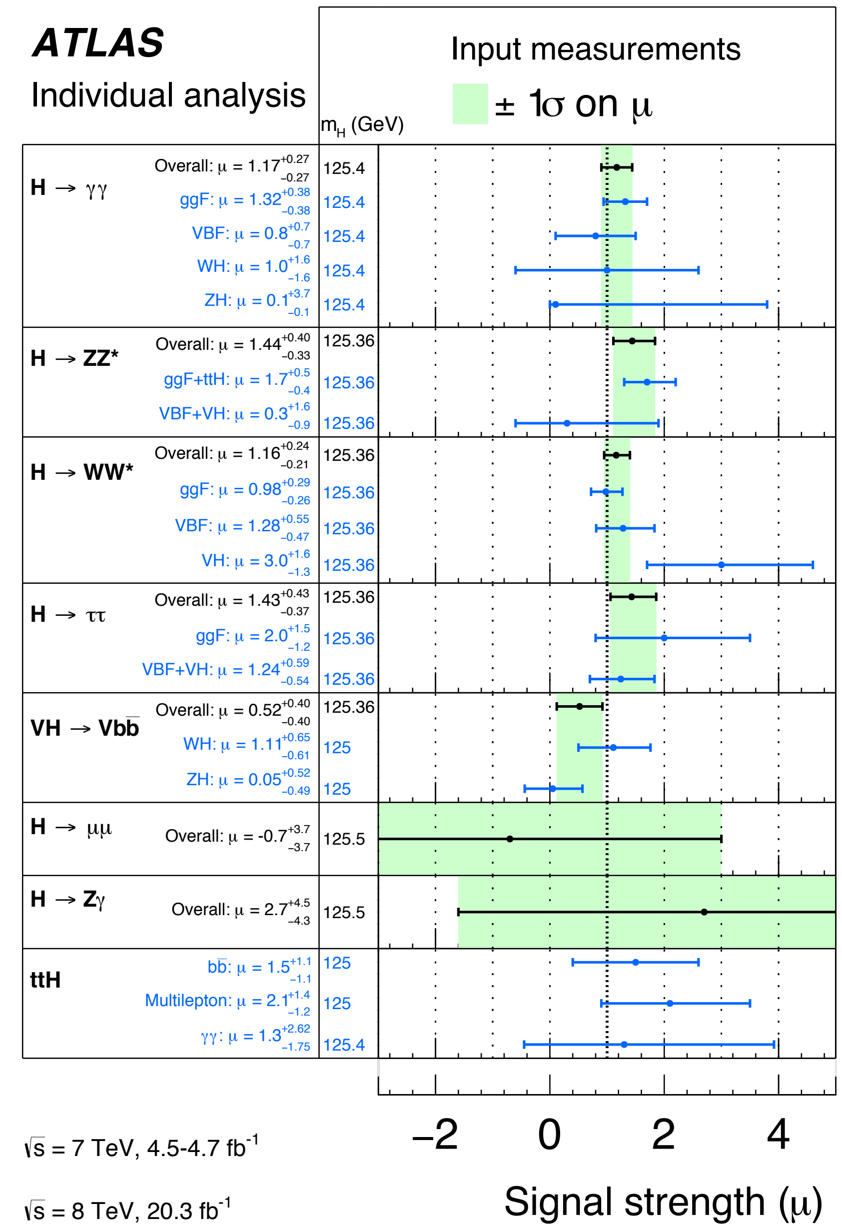


Compatibility with Standard Model

CMS: Eur. Phys. J. C 75 (2015) 212



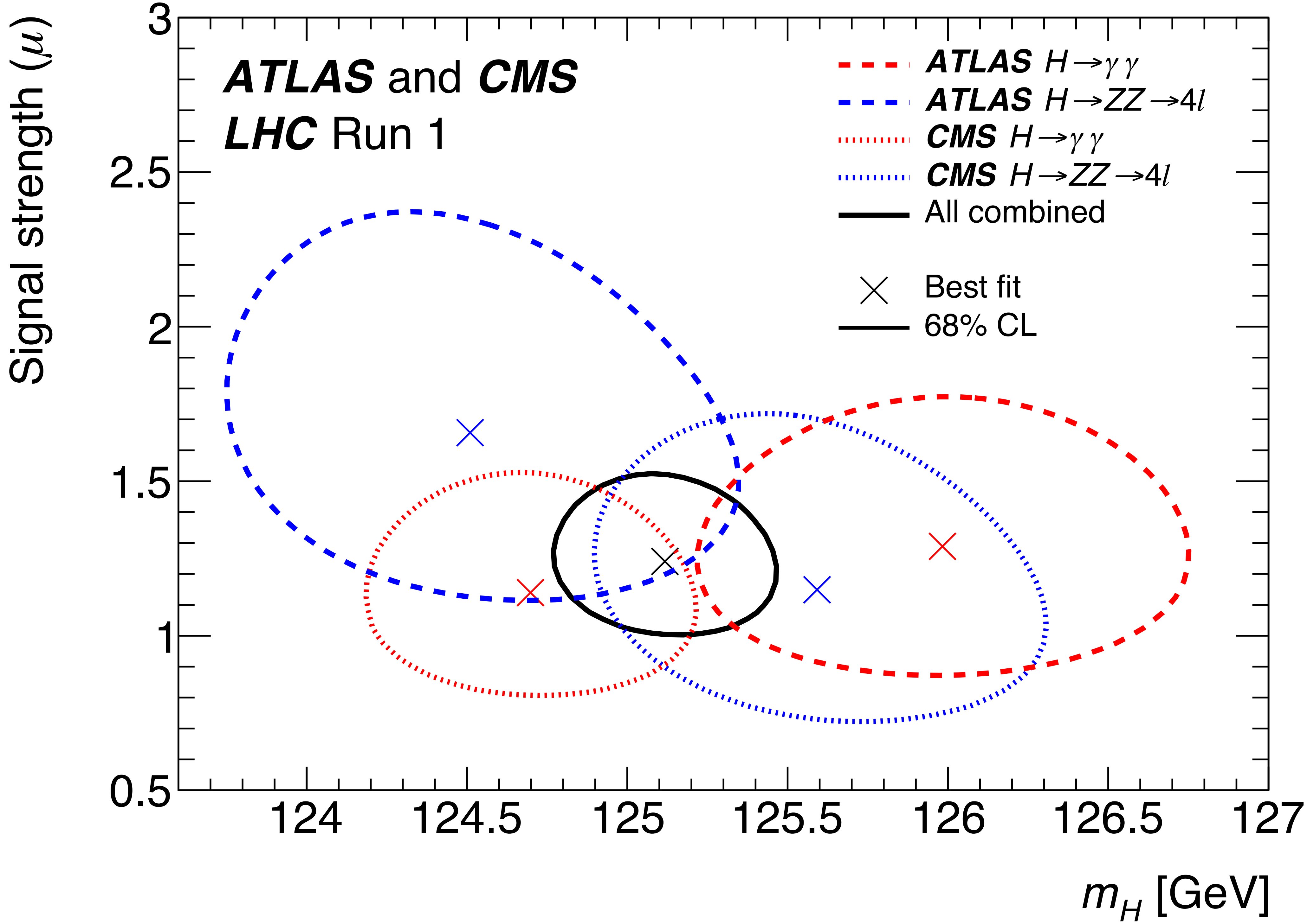
ATLAS: arxiv:1507.04548



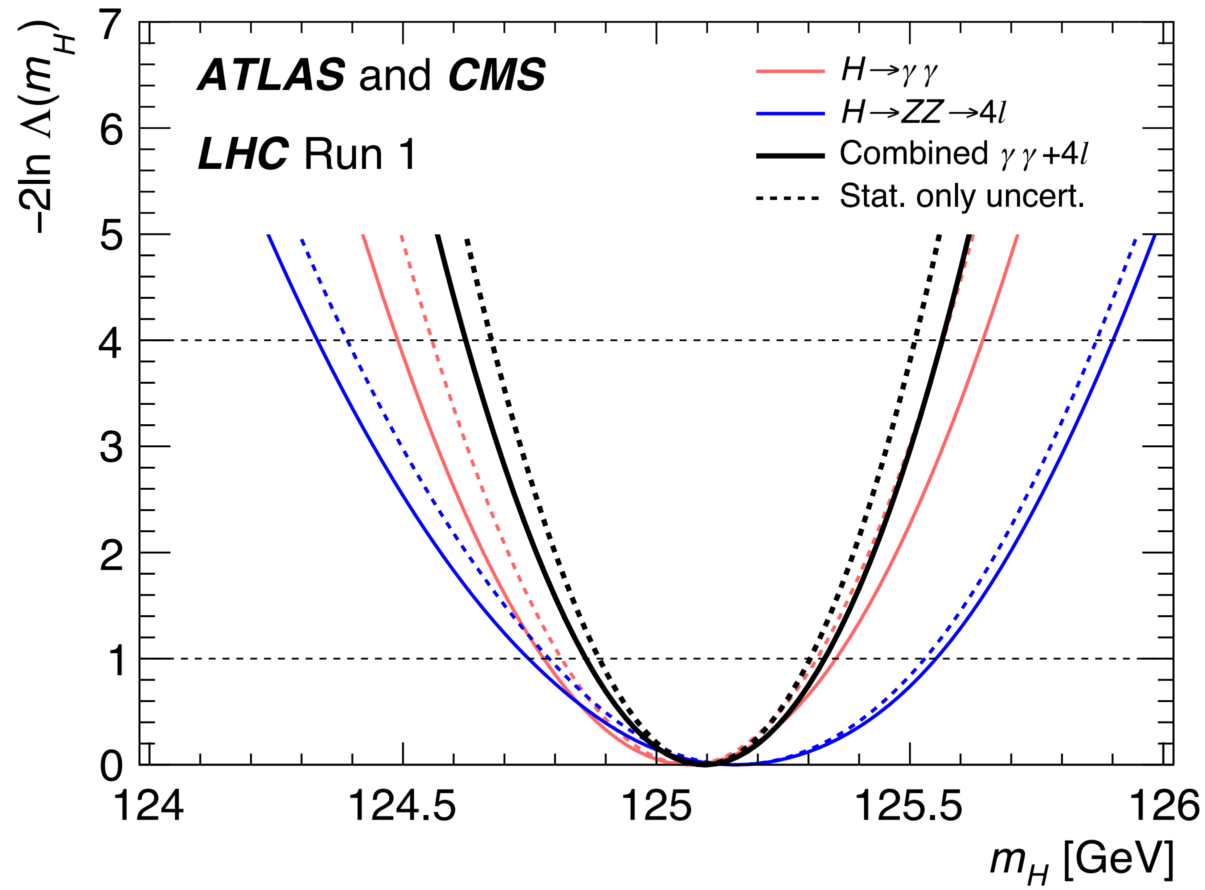
- Best fit SM strength
  - CMS $\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$
  - ATLAS $\mu = \sigma/\sigma_{SM} = 1.17 \pm 0.27$
- Good agreement among modes

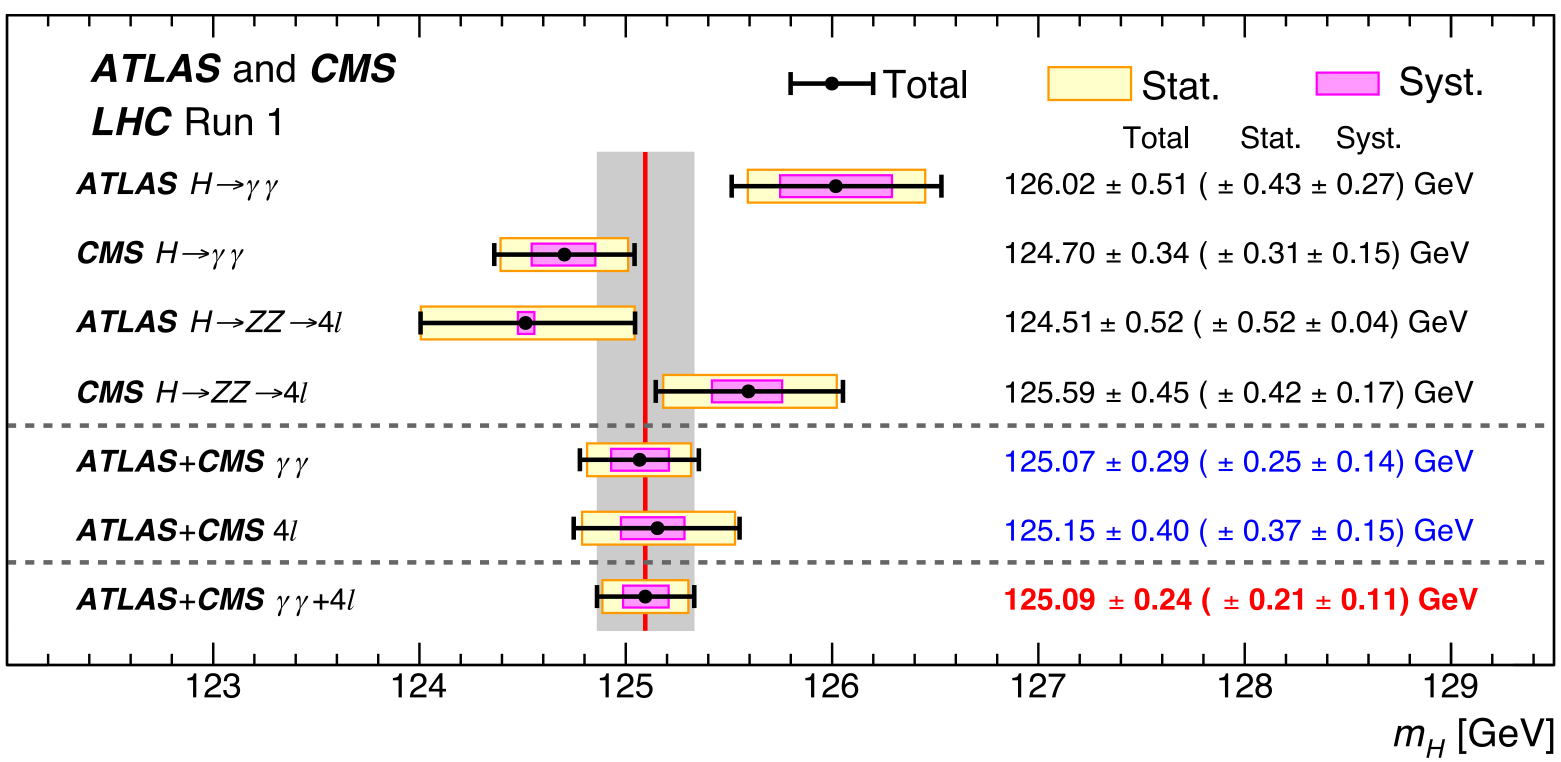
ATLAS and CMS Combination

MASS VS SIGNAL STRENGTH



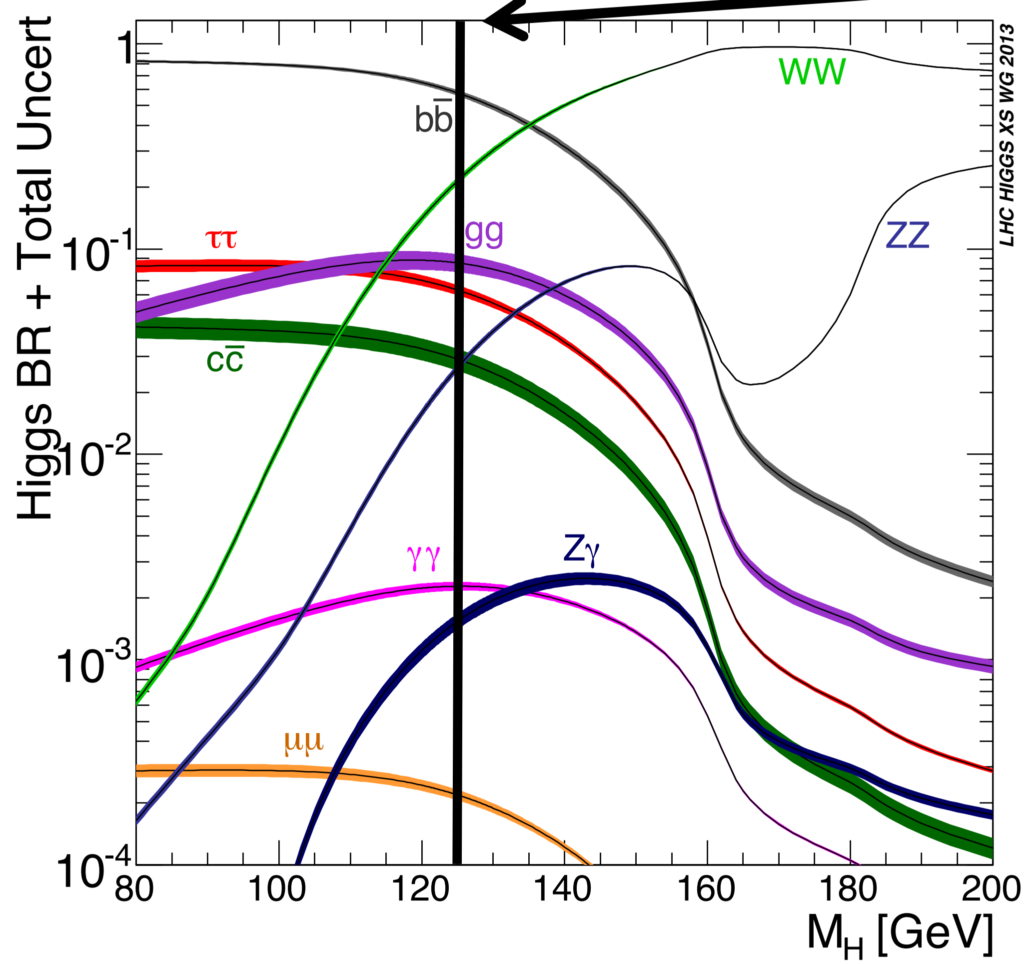
Higgs Mass Run 1





HIGGS WIDTH

m_H=125.09 GeV



Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Theory uncertainty ~ 2-5%
for most important modes

- Natural width of Higgs boson expected to be very small ~ 4.1 MeV
  - Mass resolution larger by x10-100 !
- Measurement of Higgs width very challenging

COMPATIBILITY WITH STANDARD MODEL

- Measure spin and parity of new boson and compare to Standard Model predicted scalar boson
  - angular distribution of decay products depends on these quantum numbers
- Assume a SM-like Higgs with $J^P = 0+$ with narrow width
  - decouple production and decay process

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

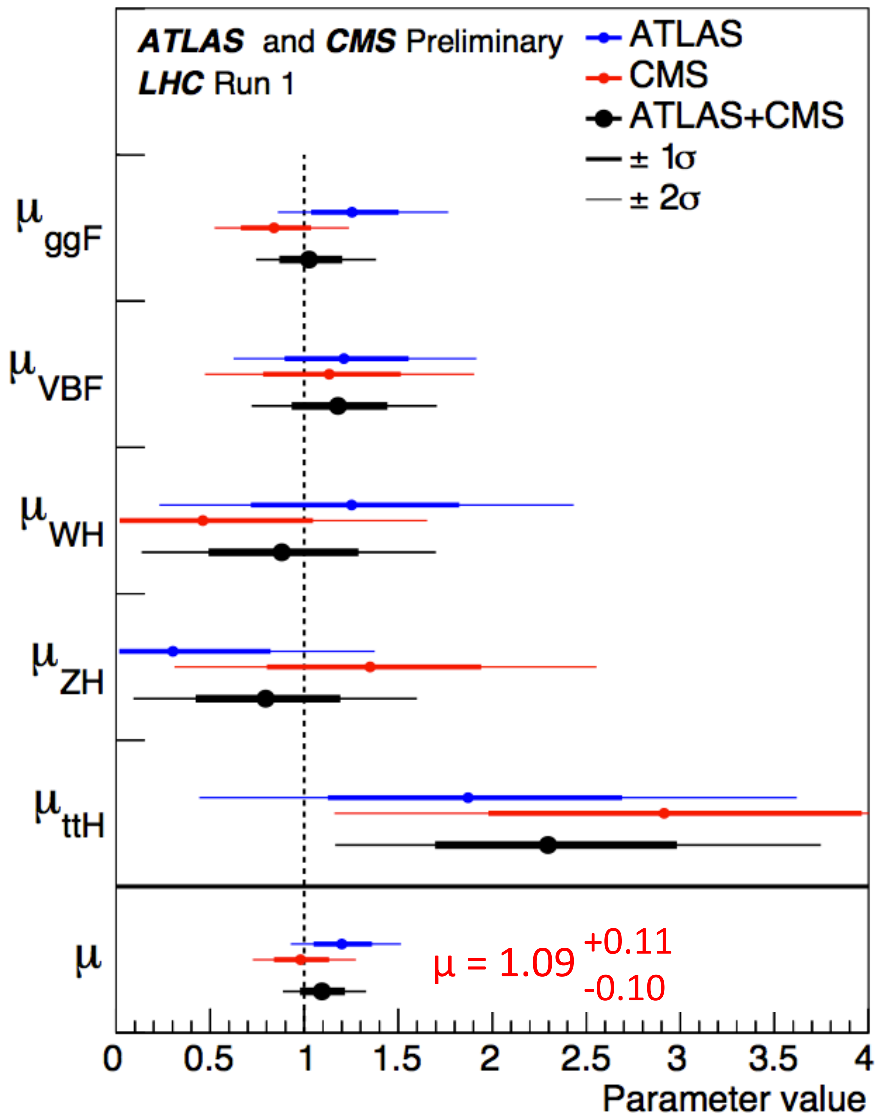
- Measure cross section and branching fractions and compare to SM
  - expect small deviations from SM predictions
  - at LHC only measure the product σ x BR not each separately
    - unless you make further assumptions
- Three general approaches to test compatibility
  - Measure of signal strengths μ for σ and BR relative to SM
  - Introduce modifier κ for each coupling constant relative to SM κ-framework)
  - Generic parameterization of σ and BR, measuring a mixture of σ and μ

SIGNAL STRENGTH TEST

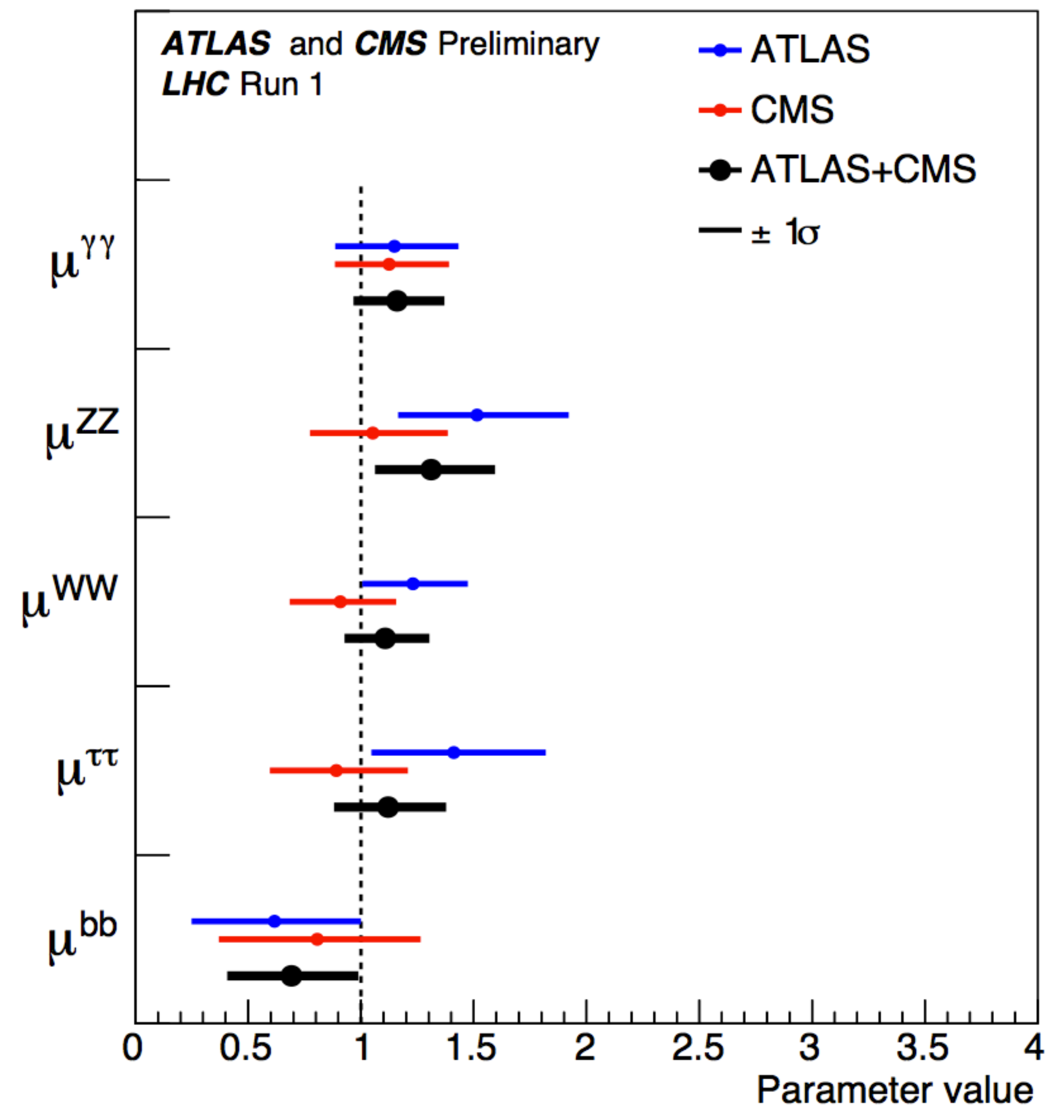
$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \quad \text{and} \quad \mu^f = \frac{BR^f}{BR^f_{SM}}. \qquad \mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$$

- Most constrained parameterization
  - one single signal strength μ
  - assuming also same value at 7 and 8 TeV

Assume SM BR



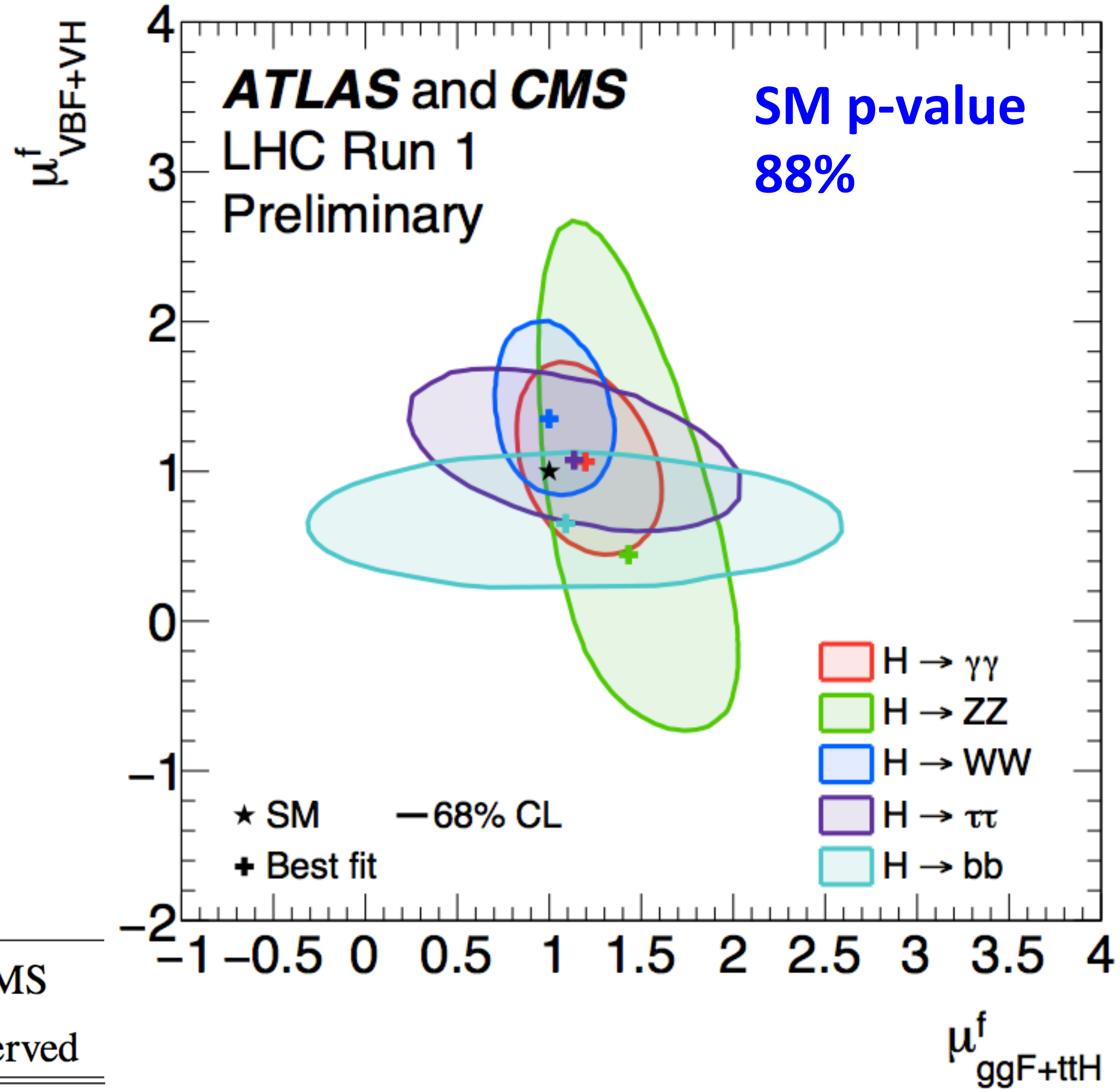
Assume SM production σ



Bosons (μ_V)vs Fermions(μ_f)

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

$$\mu_{V/}\mu_f = 1.06 \begin{smallmatrix}+0.35 \\ -0.27\end{smallmatrix}$$



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%

κ-Framework Test

- Scale Higgs boson couplings by coupling modifiers κ

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

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

- Allow for possibile new invisibile or undetected Higgs decays
  - Invisibile final states possibly due to new non-SM particles
  - undetected decays could be not yet measured and small decays like ccbar
- New decays and particles have two possible effects
  - $m_X < m_H/2$: BR_{BSM} will be affected
  - $m_X > m_H/2$: κ_i will be affected

Higgs Couplings

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{\mathrm{SM}}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{\mathrm{SM}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{\mathrm{SM}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{\mathrm{SM}}} : \text{ see Section 3.1.2}$$

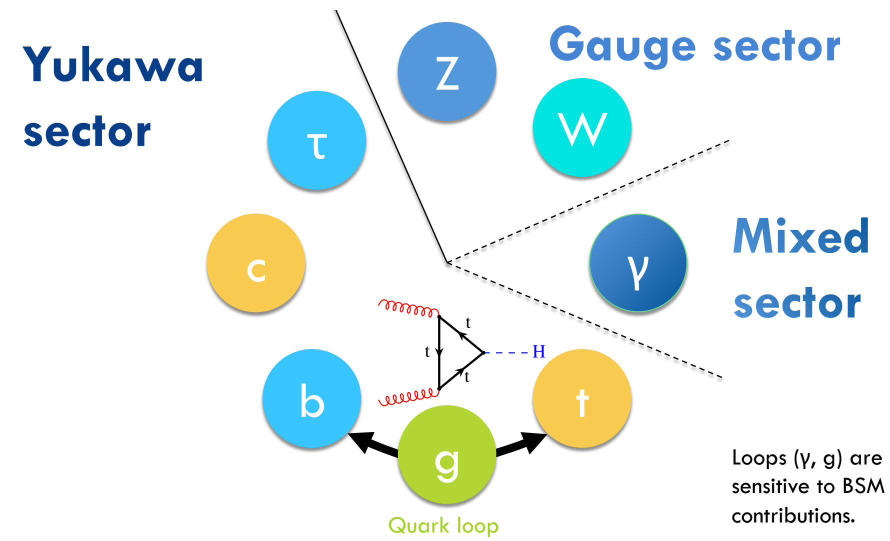
$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{\mathrm{SM}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{\mathrm{SM}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_\tau^2$$

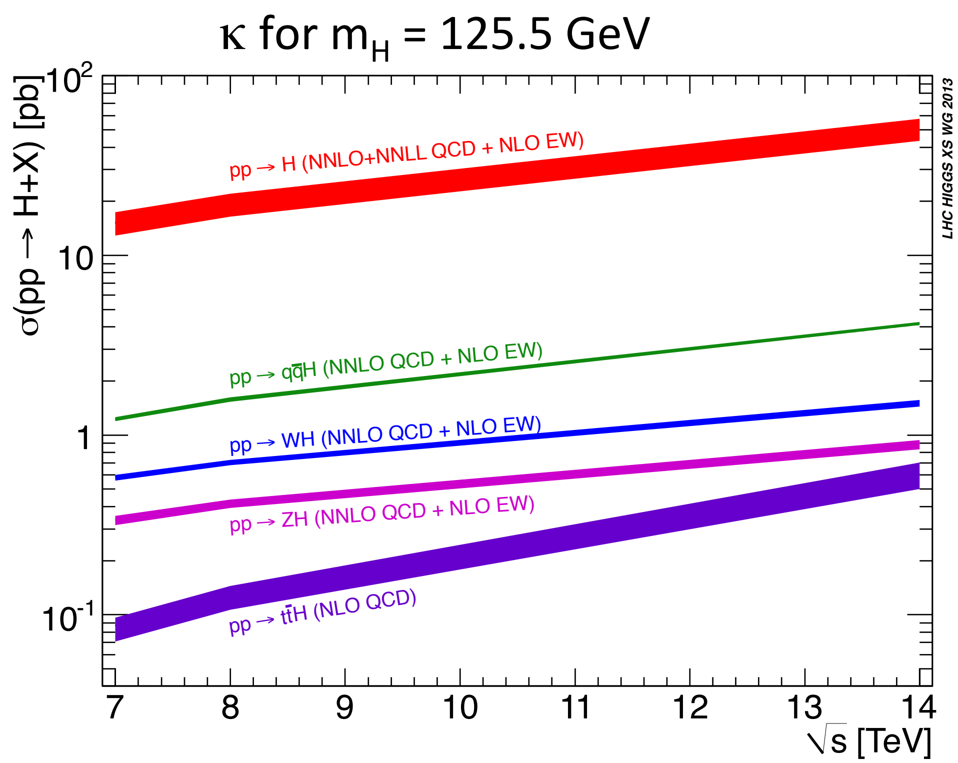
Total width

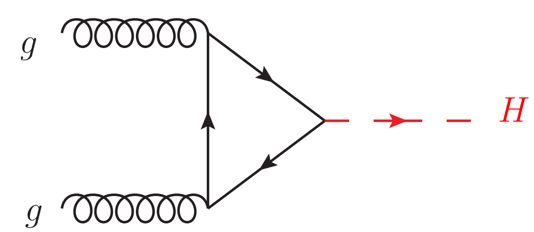
$$\frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$



Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(ggF)$	✓	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			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
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	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

Higgs Production Modes



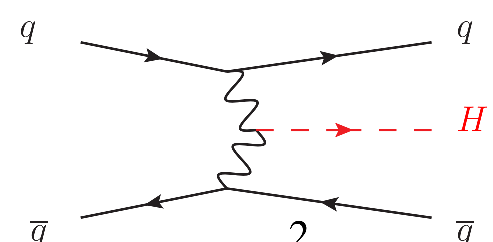


Gluon fusion process

NNnLO ~O(10%)

~0.5 M events produced

$$\kappa_g \propto 1.\times 06\kappa_t^2 - 0.07\times\kappa_t\kappa_b + 0.01\times\kappa_b^2$$



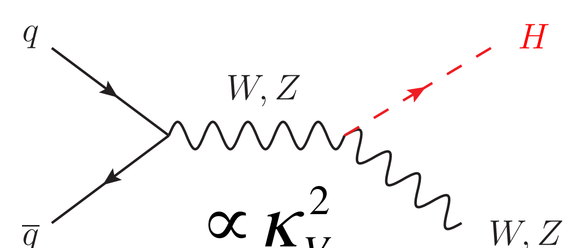
$\propto \kappa_V^2$

Vector Boson Fusion

NLO TH uncertainty ~O(5%)

Two forward jets and a large rapidity gap

~40 k events produced

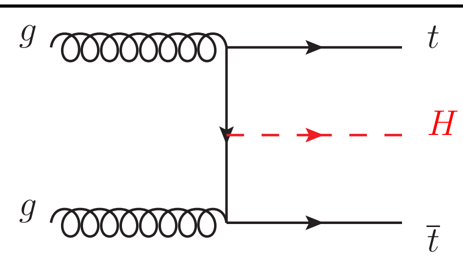


$\propto \kappa_V^2$

W and Z Associated Production

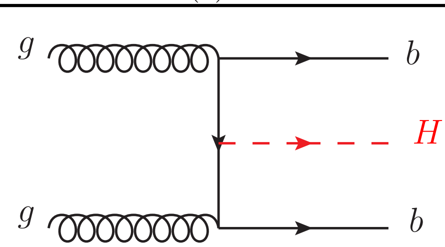
NNLO TH uncertainty ~O(5%)

~20 k events produced



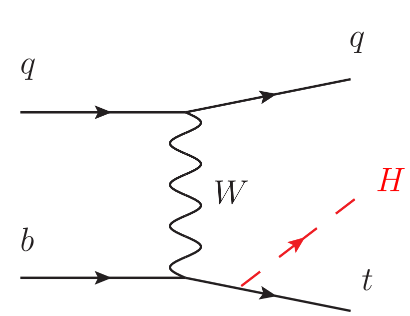
$\propto \kappa_t^2$

Top Assoc. Prod. ~3 k evts produced

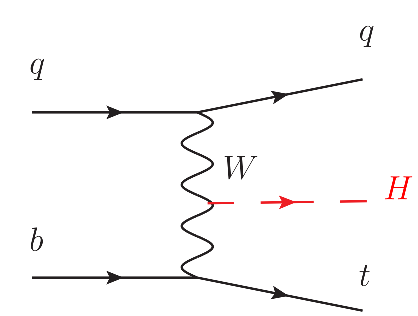


$\propto \kappa_b^2$

B-quark Assoc. Prod. ~5 k evts produced



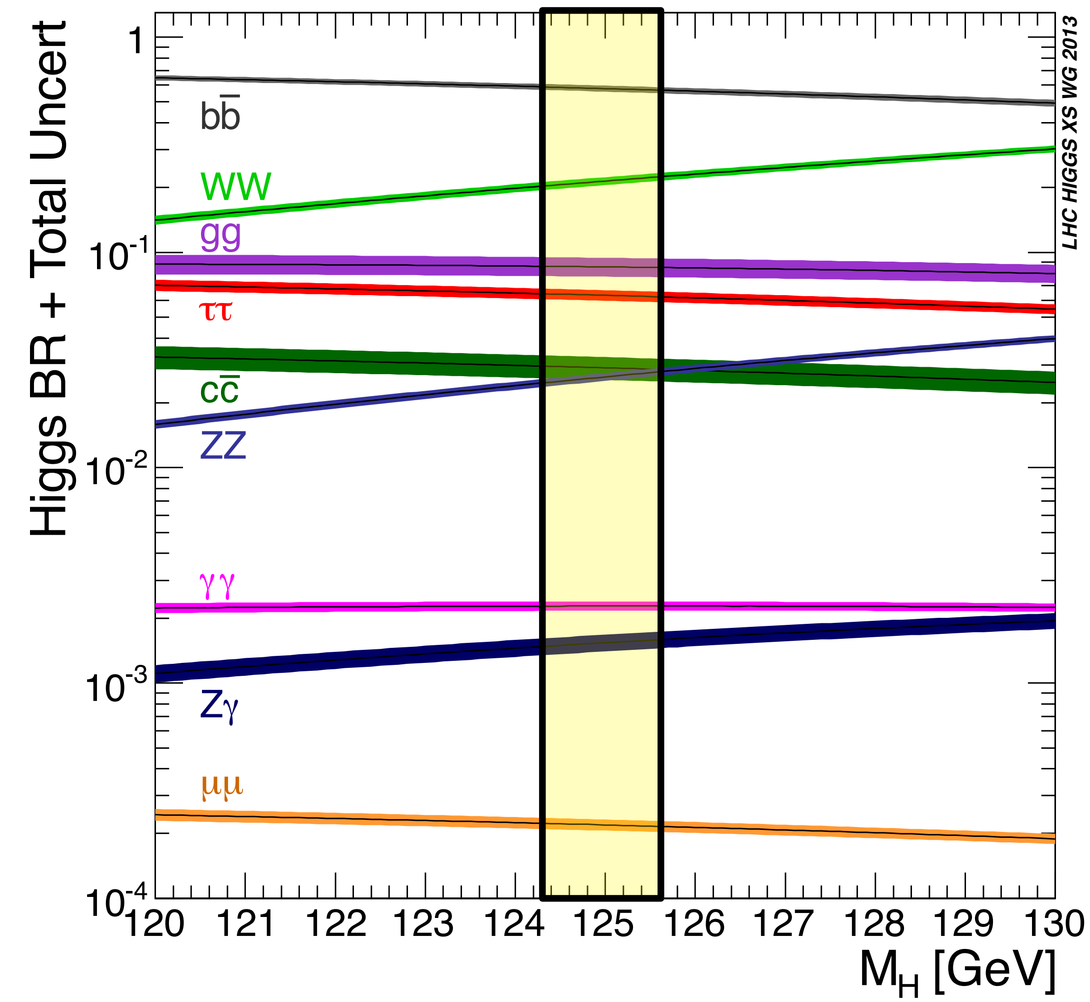
tH

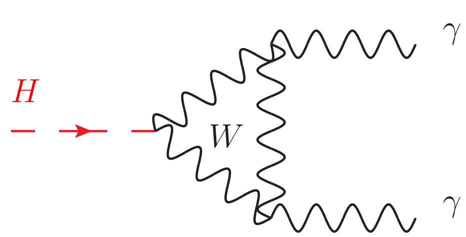


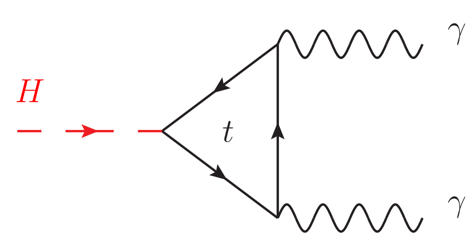
$$\propto 3.3\times\kappa_W^2 - 5.1\times\kappa_t\kappa_W + 2.8\times\kappa_t^2$$

Higgs Decay Channels

- Dominant: bb (57%) $\propto \kappa_b^2 / \kappa_H^2$
- WW channel (22%) $\propto \kappa_W^2 / \kappa_H^2$
- ττ channel (6.3%) $\propto \kappa_\tau^2 / \kappa_H^2$
- ZZ channel (3%) $\propto \kappa_Z^2 / \kappa_H^2$
- cc channel (3%) $\propto \kappa_c^2 / \kappa_H^2$
  Extremely difficult
- The γγ channel (0.2%) $\propto \kappa_\gamma^2 / \kappa_H^2$





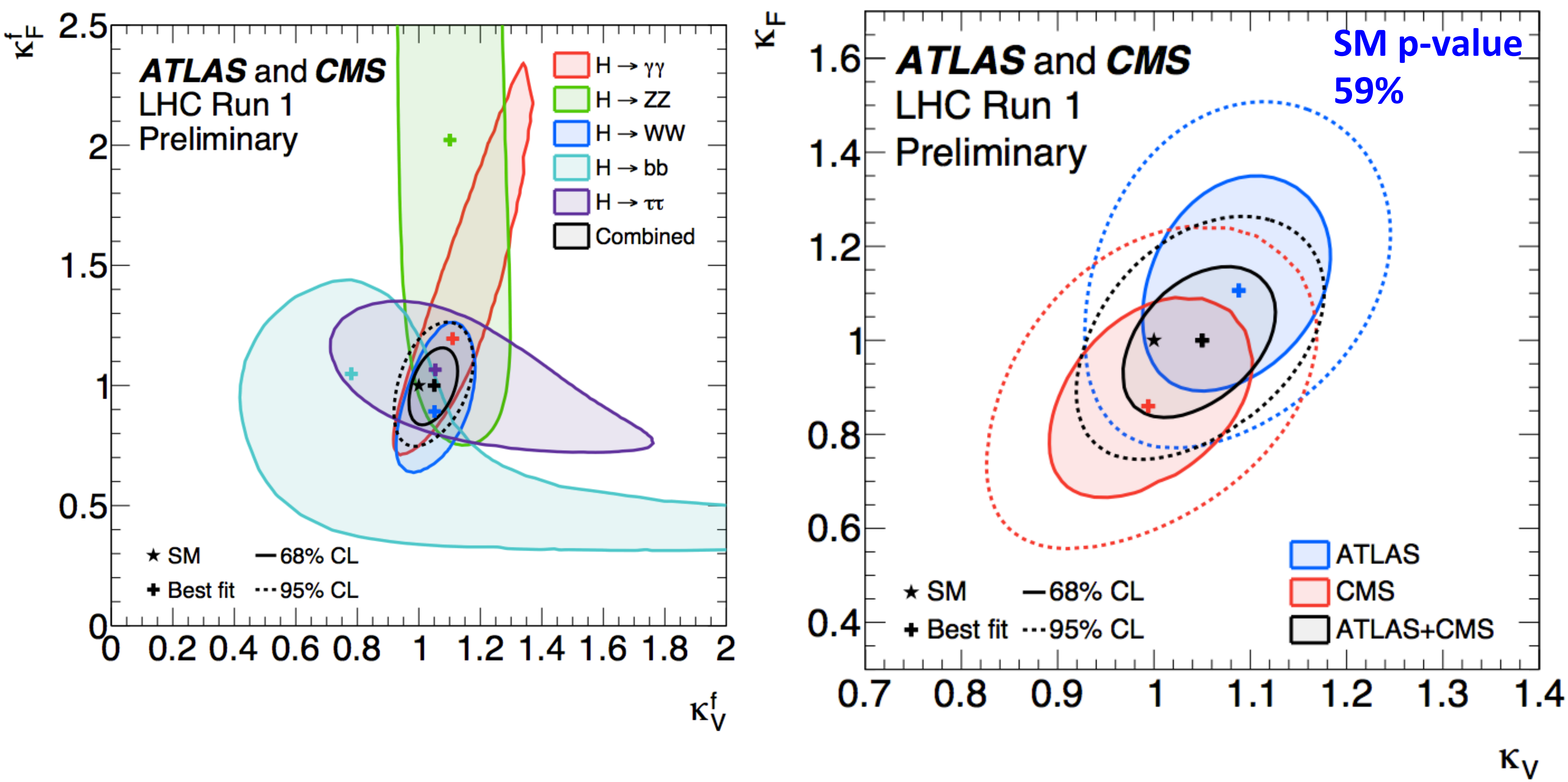


$$\kappa_\gamma \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

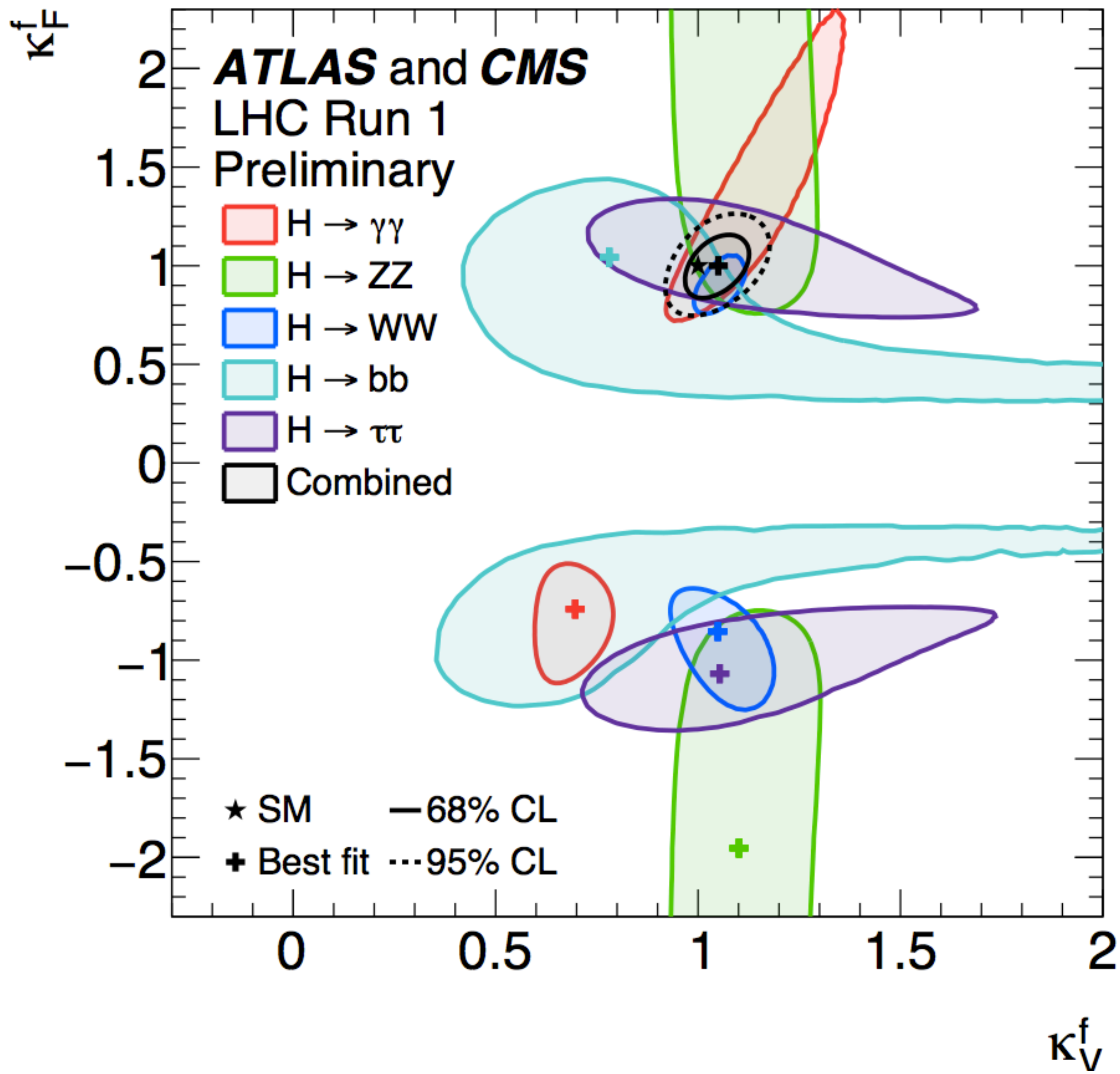
(when assuming no BSM charged in the loop)

- The Zγ (0.2%) $\kappa_{Z\gamma} \propto 1.12 \times \kappa_W^2 - 0.15 \times \kappa_t \kappa_W + 0.03 \times \kappa_t^2$
- The μμ channel (0.02%) $\propto \kappa_\mu^2 / \kappa_H^2$

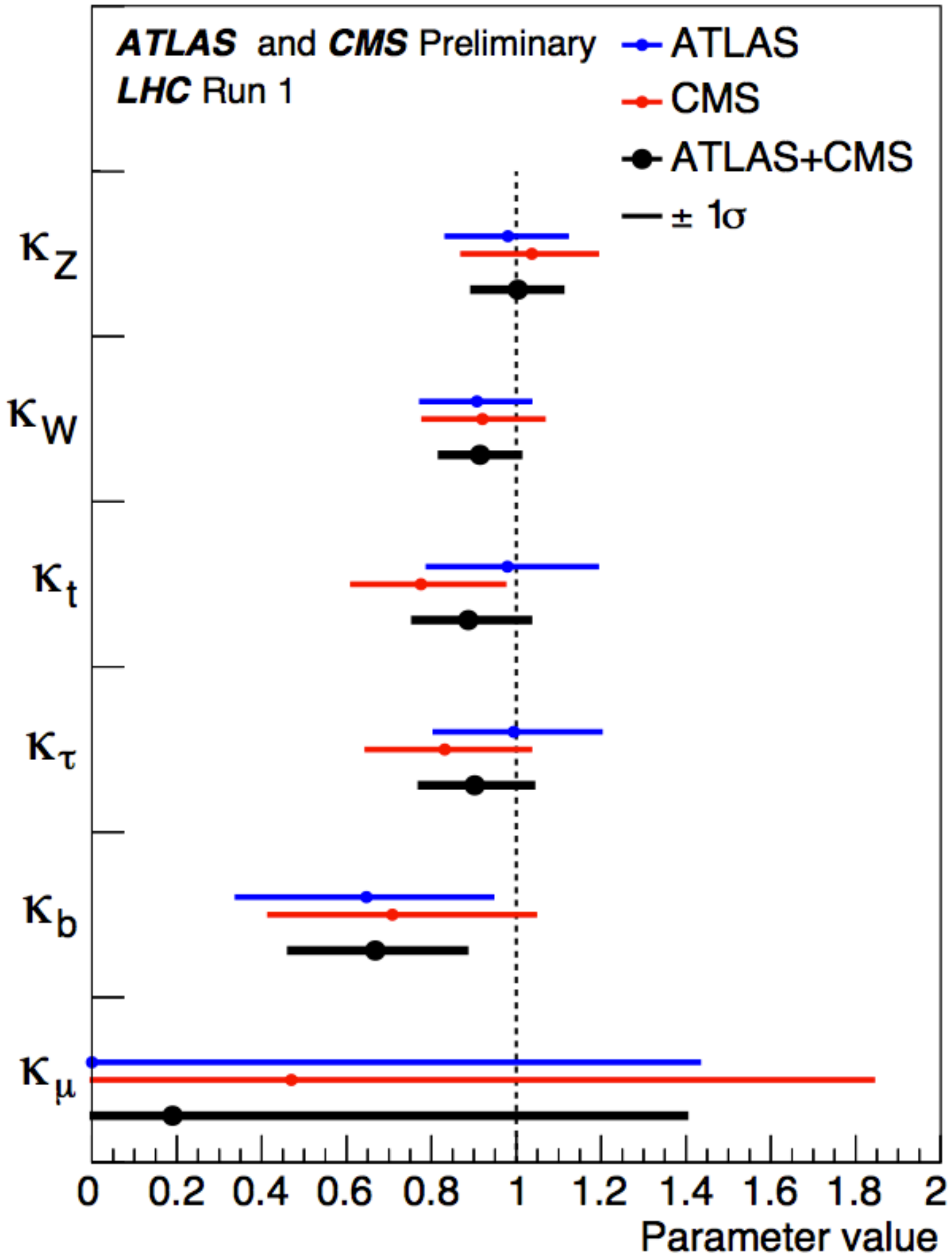
κ_F and κ_V Contours

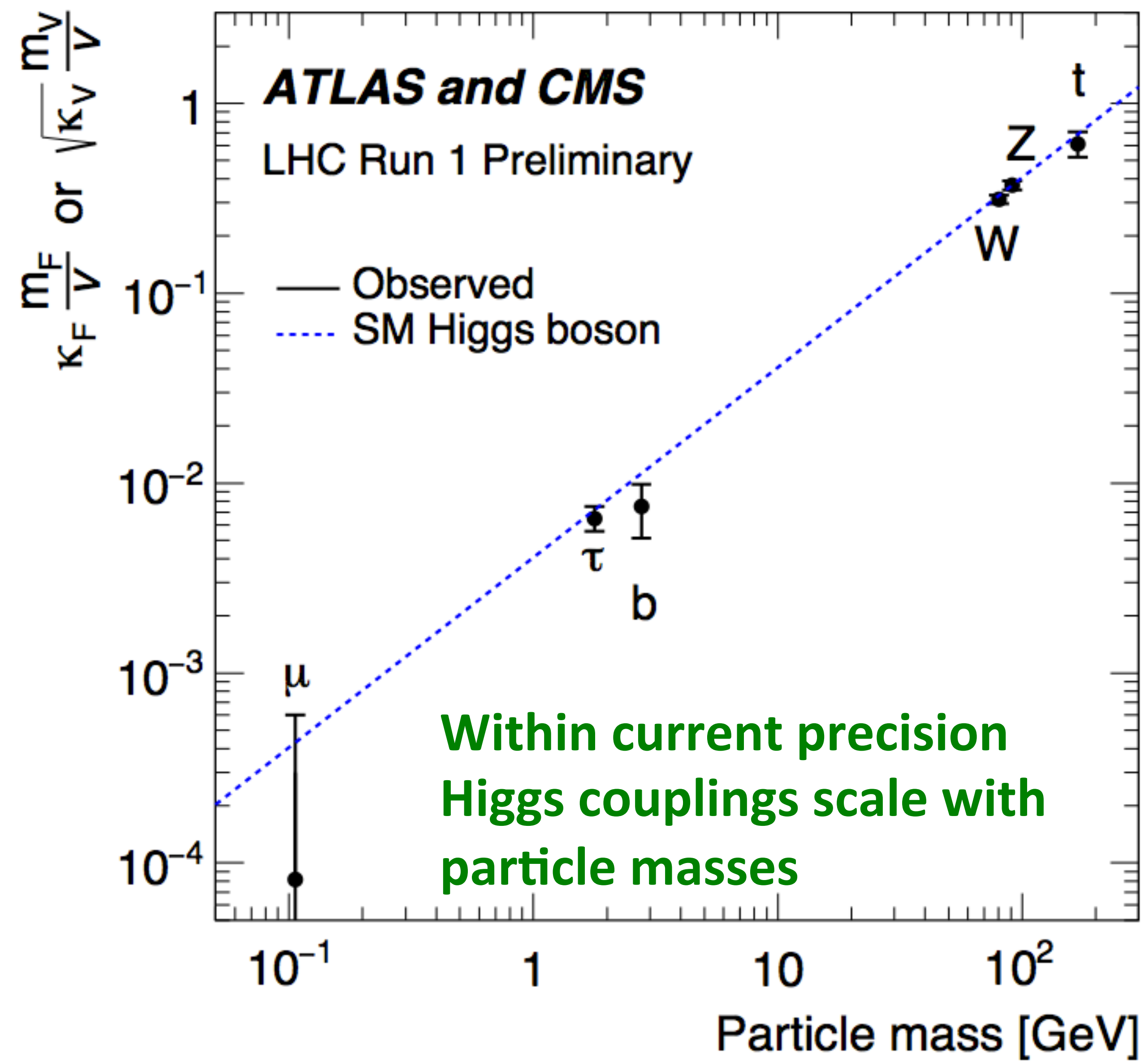


κ_F and κ_V Contours



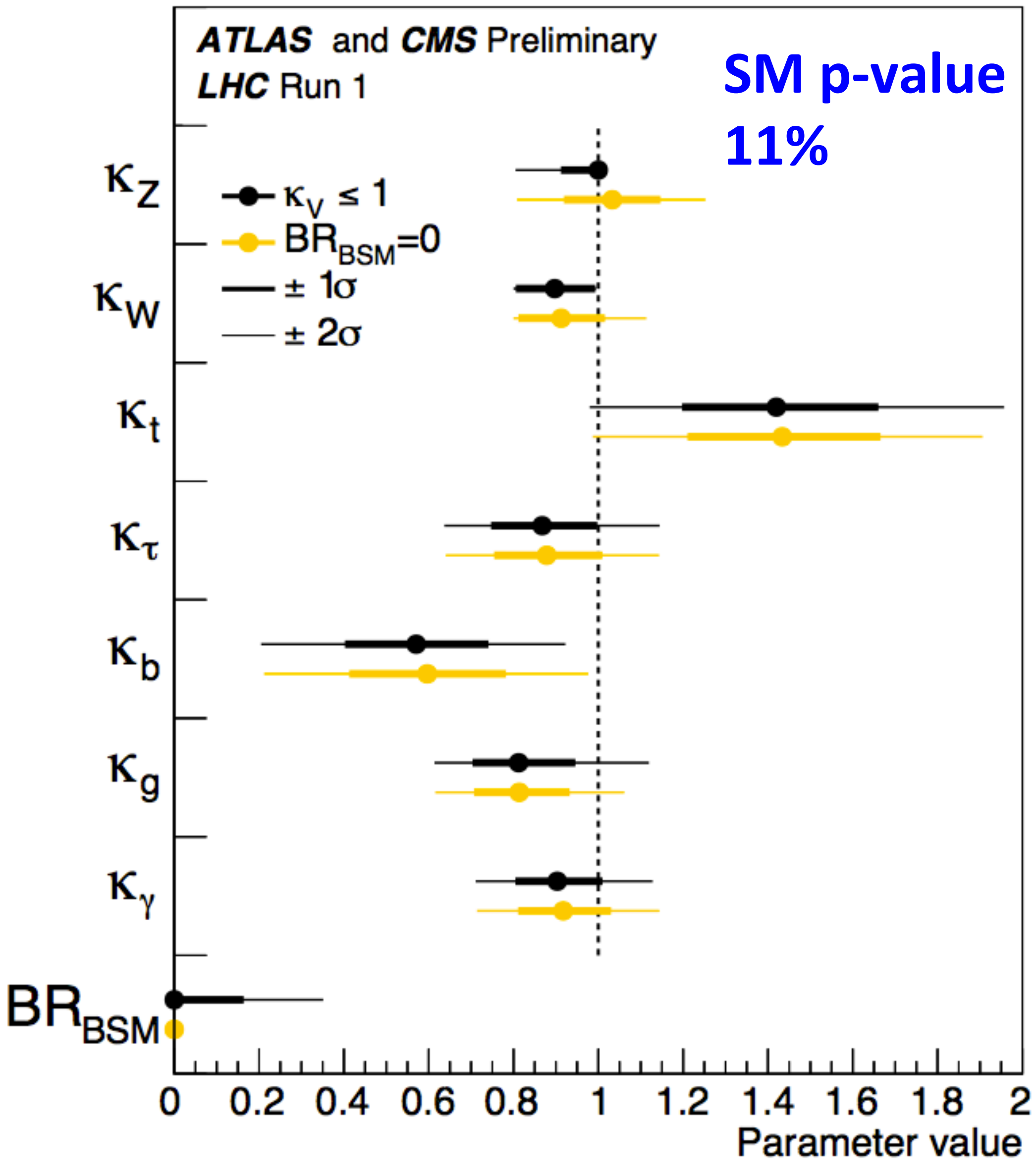
Coupling vs Mass

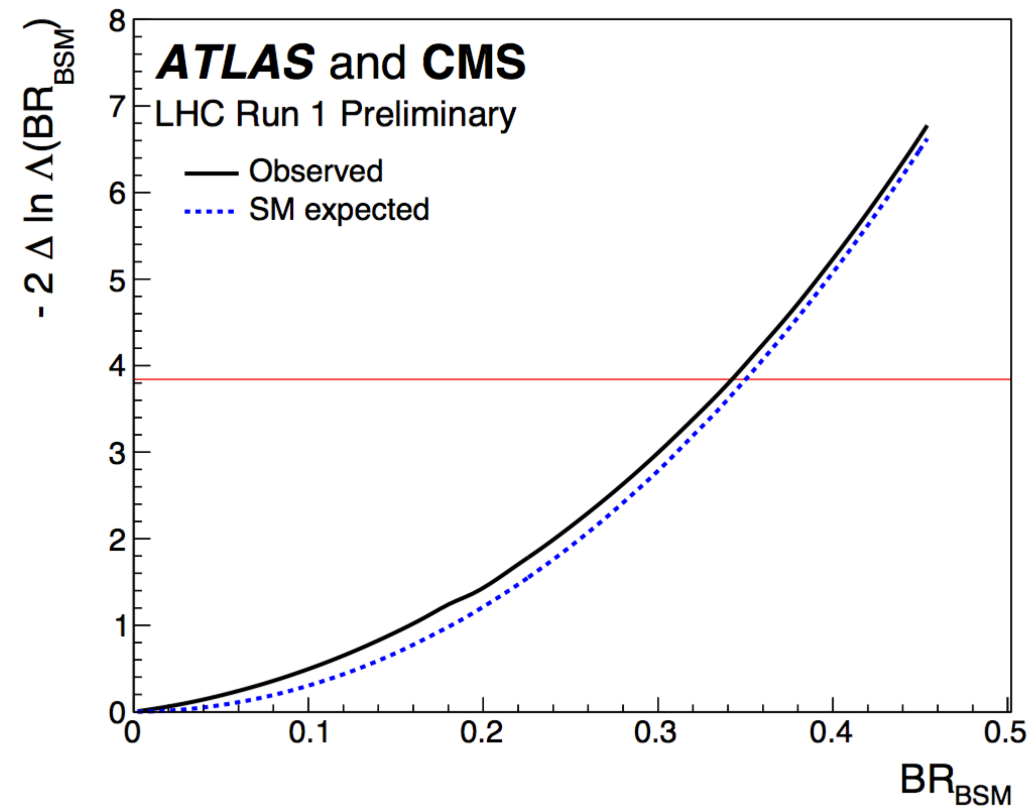




Within current precision Higgs couplings scale with particle masses

INVISIBLE HIGGS DECAYS

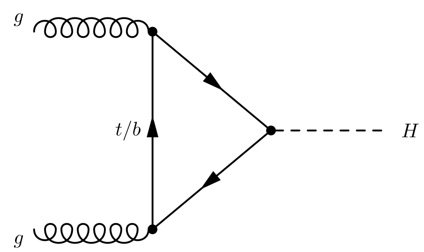




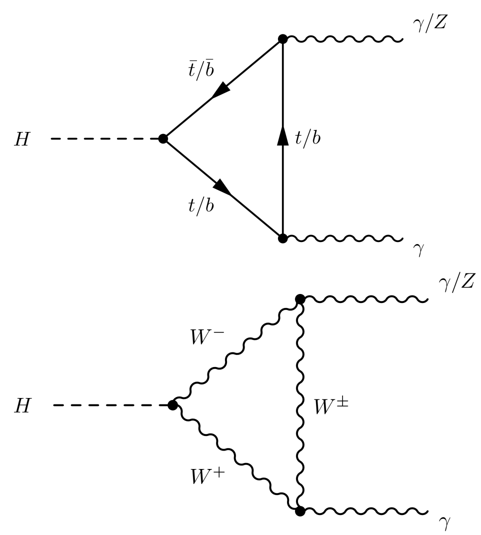
$BR_{BSM} < 0.34$ at 95% C.L. (assuming $\kappa_V \leq 1$)
BR_{BSM} includes all possible non standard decays, visible or invisible

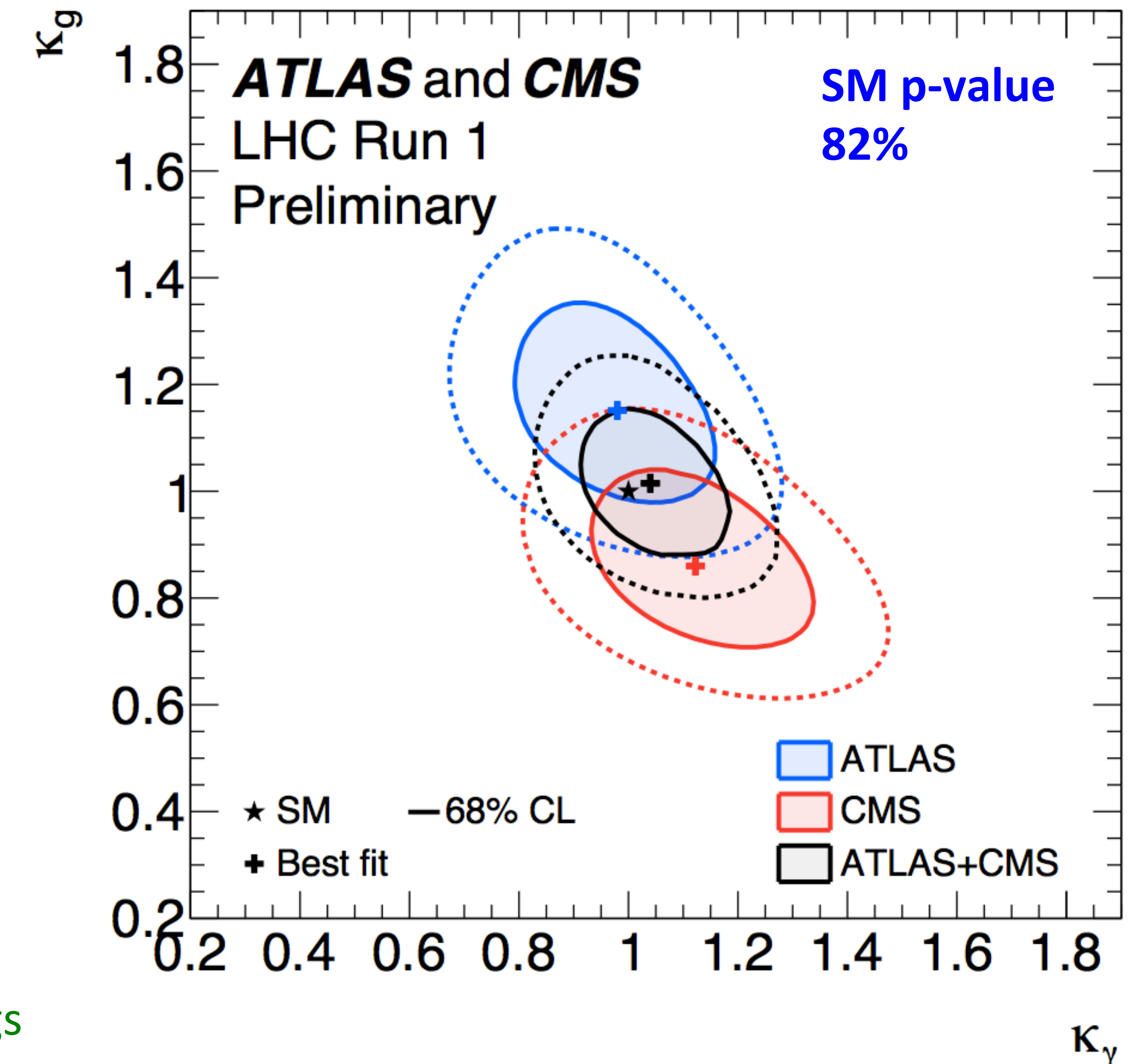
κ_g and κ_γ

ggF loop



H→γγ loop



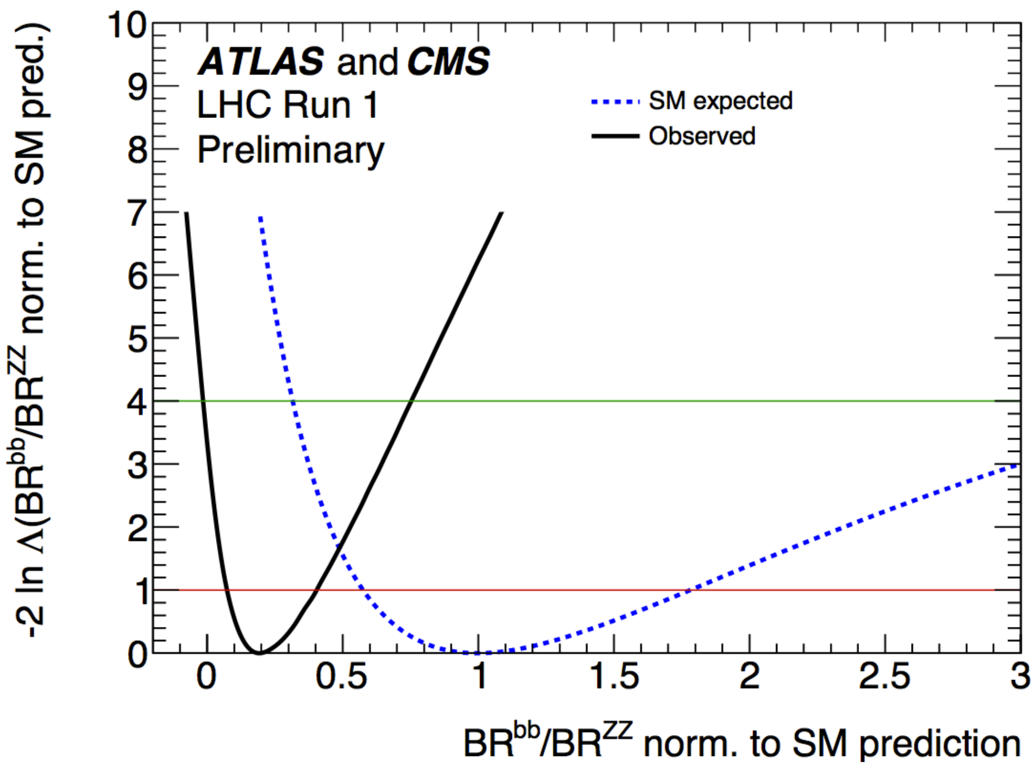


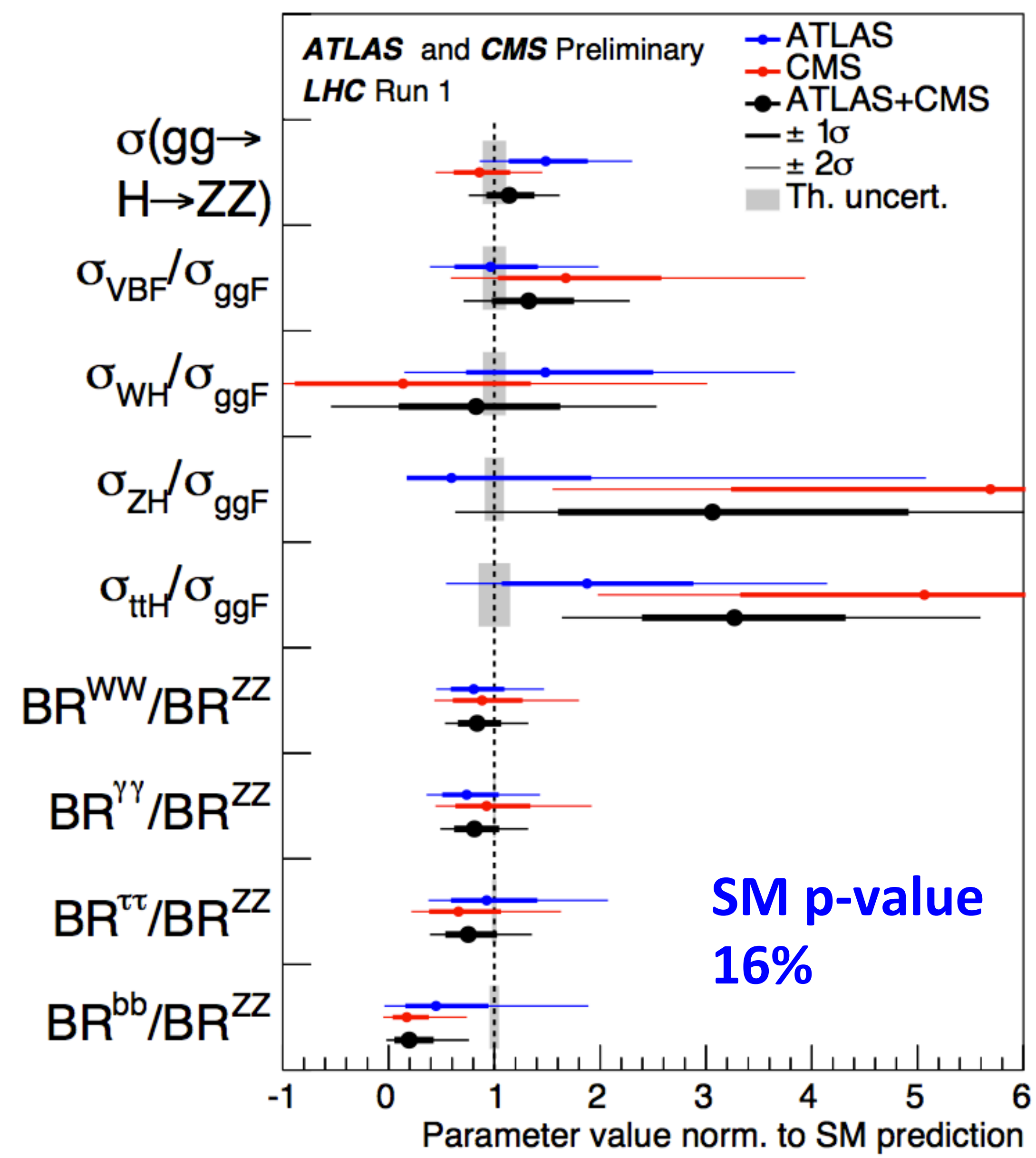
Additional heavy fermions or charged Higgs boson would modify the effective couplings

- Assume SM to be valid at tree level (no change to SM couplings)
- Consider modification only to main two loops
  - gluon-gluon fusion loop for production
  - top and W loop for Higgs decay to photons

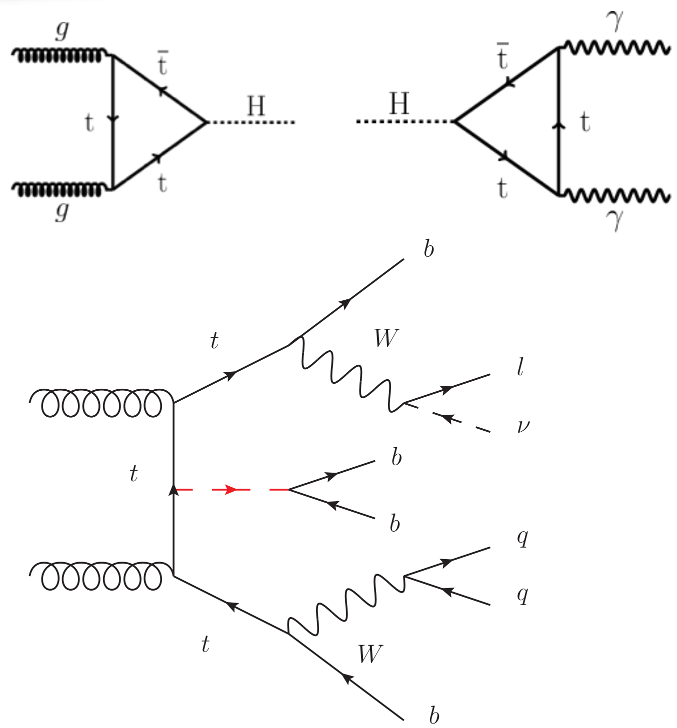
Generic Parameterization

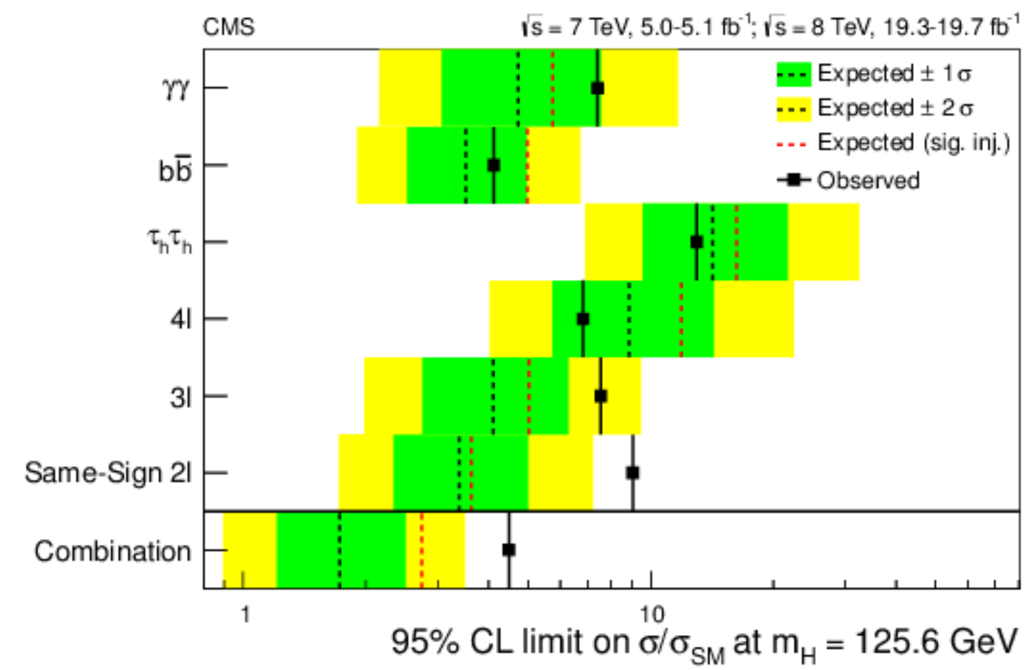
- No attempt to disentangle production cross section from decay BR
- Measure everything relative to
  - gluon-gluon fusion: production mode with smallest systematic uncertainty
  - H→ZZ decay: cleanest experimental decay mode

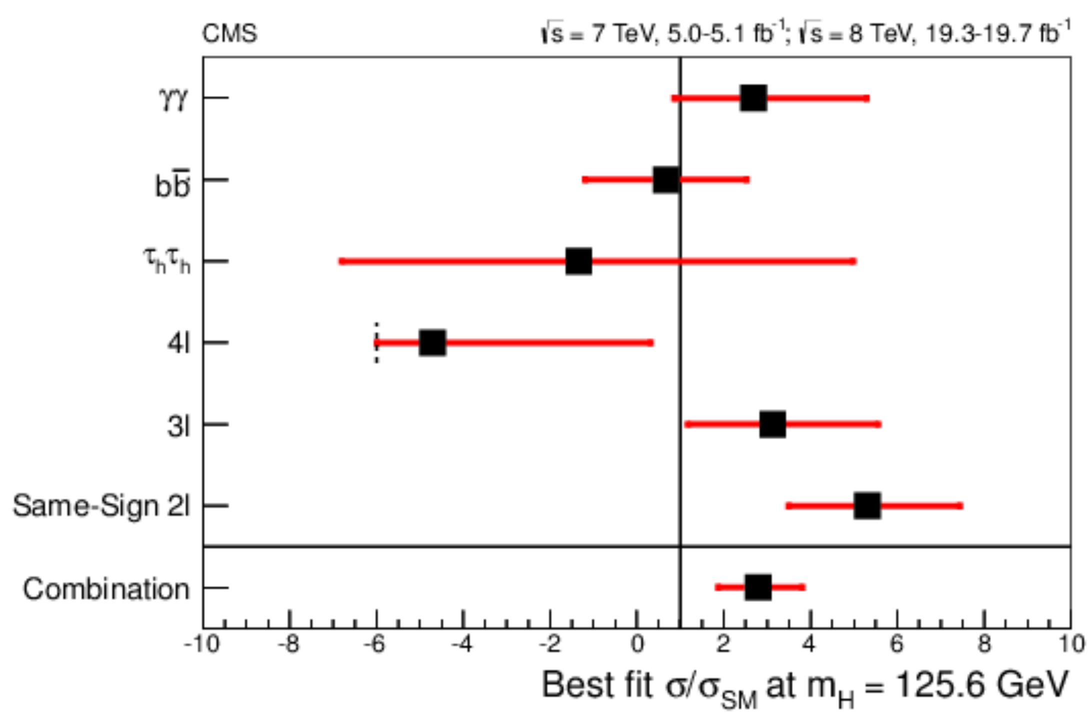


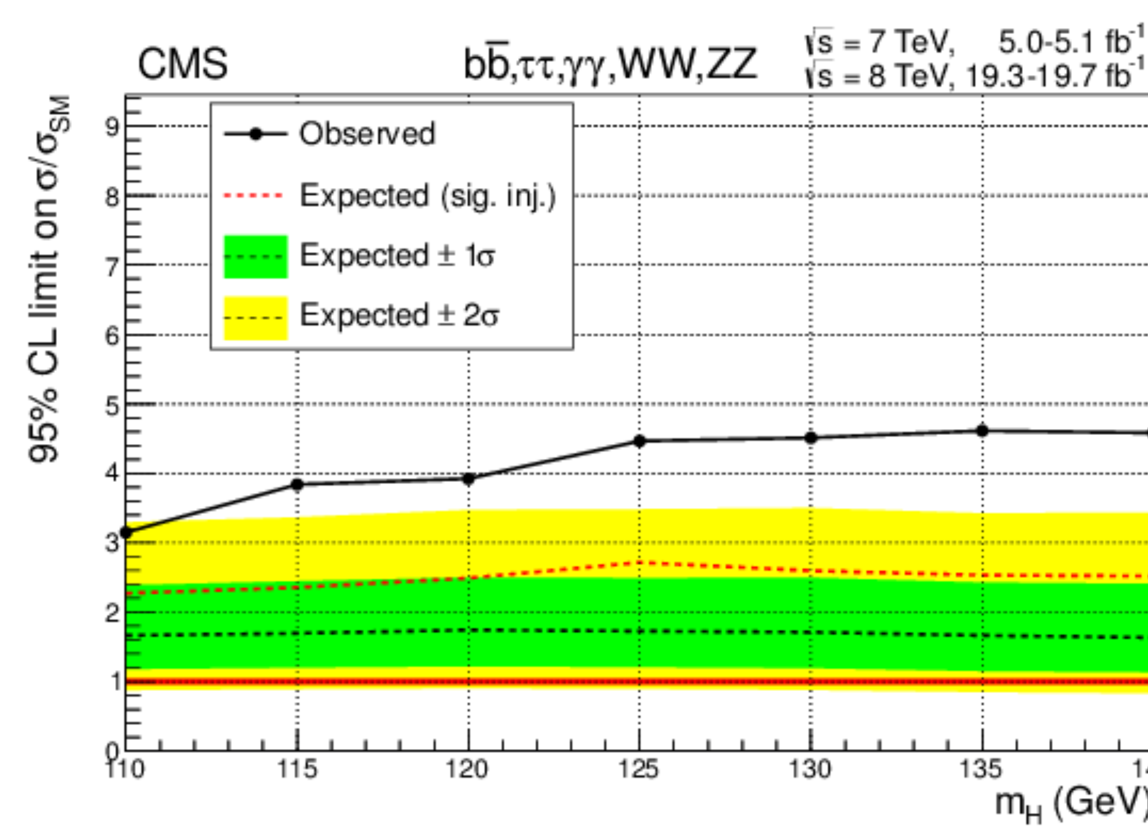


ttH




CMS
√s = 7 TeV, 5.0-5.1 fb⁻¹; √s = 8 TeV, 19.3-19.7 fb⁻¹
Expected ± 1σ
Expected ± 2σ
Expected (sig. inj.)
Observed
γγ
bb̄
τhτh
4l
3l
Same-Sign 2l
Combination
95% CL limit on σ/σSM at mH = 125.6 GeV


CMS
√s = 7 TeV, 5.0-5.1 fb⁻¹; √s = 8 TeV, 19.3-19.7 fb⁻¹
γγ
bb̄
τhτh
4l
3l
Same-Sign 2l
Combination
Best fit σ/σSM at mH = 125.6 GeV


CMS
bb̄,ττ,γγ,WW,ZZ
√s = 7 TeV, 5.0-5.1 fb⁻¹
√s = 8 TeV, 19.3-19.7 fb⁻¹
Observed
Expected (sig. inj.)
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σSM
mH (GeV)

How Many Higgs Are Out There?

- Higgs doublet was introduced to cure missing mass term for vector bosons
- Yukawa coupling to fermions, again added intentionally, cured origin of fermion mass
- However no constraint on how many Higgs doublet must/can/should exist!

TWO HIGGS DOUBLETS

- Two doublets with opposite hypercharge

$$H_d = \begin{pmatrix} H_d^1 \\ H_d^2 \end{pmatrix} = \begin{pmatrix} \Phi_1^{0\,*} \\ -\Phi_1^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^1 \\ H_u^2 \end{pmatrix} = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

$$Y = -1 \qquad\qquad Y = +1$$

  – 8 total degrees of freedom

- Different coupling to quarks for each doublet
  – H_u to up quarks
  – H_d to down quarks

$$\mathcal{L}_{\text{Yukawa}} = -h_u^{ij}(\bar{u}_R^i u_L^j H_u^2 - \bar{u}_R^i d_L^j H_u^1) - h_d^{ij}(\bar{d}_R^i d_L^j H_d^1 - \bar{d}_R^i u_L^j H_d^2) + \text{h.c.}$$

- Slightly more complicated Higgs potential

$$V = \left(m_d^2 + |\mu|^2\right) H_d^{i*} H_d^i + \left(m_u^2 + |\mu|^2\right) H_u^{i*} H_u^i - m_{ud}^2 \left(\epsilon^{ij} H_d^i H_u^j + \text{h.c.}\right)$$

$$+\tfrac{1}{8}\left(g^2 + g'^2\right)\left[H_d^{i*} H_d^i - H_u^{j*} H_u^j\right]^2 + \tfrac{1}{2} g^2 |H_d^{i*} H_u^i|^2 ,$$

$$\epsilon^{12} = -\epsilon^{21} = 1 \text{ and } \epsilon^{11} = \epsilon^{22} = 0$$

Five Higgs Bosons!

- After EW symmetry breaking, 3 scalars are absorbed by W and Z
- 5 remaining scalar degrees of freedom and two vacuum expectation value

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}$$

$$v^2 \equiv v_d^2 + v_u^2 = 4m_W^2/g^2 = (246 \;\; \mathrm{GeV})^2$$

$$\tan\beta \equiv \frac{v_u}{v_d}$$

- Combination of remaining fields results in 5 physical scalars

$$H^\pm = H_d^\pm \sin\beta + H_u^\pm \cos\beta$$

CP-odd

$$A^0 = \sqrt{2}\left(\mathrm{Im}\, H_d^0 \sin\beta + \mathrm{Im}\, H_u^0 \cos\beta\right)$$

CP-even

$$h^0 = -(\sqrt{2}\,\mathrm{Re}\, H_d^0 - v_d)\sin\alpha + (\sqrt{2}\,\mathrm{Re}\, H_u^0 - v_u)\cos\alpha\,,$$

$$H^0 = (\sqrt{2}\,\mathrm{Re}\, H_d^0 - v_d)\cos\alpha + (\sqrt{2}\,\mathrm{Re}\, H_u^0 - v_u)\sin\alpha\,,$$

- Mixing angle α due to diagonalization of original H_u and H_d fields to obtain physical mass

Higgs Mass Hierarchy

- 5 mass terms + 2 angles + coupling terms for each new Higgs but only two independent variables
  - constraints provided by supersymmetry (will be discussed in next lecture)

- Typically use m_A and $\tan\beta$ to parameterize other parameters

$$m^2_{H^\pm} = m^2_A + m^2_W$$

$$m^2_{H,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_Z m^2_A \cos^2 2\beta}\right)$$

$$m_h \leq m_Z |\cos 2\beta| \leq m_Z$$

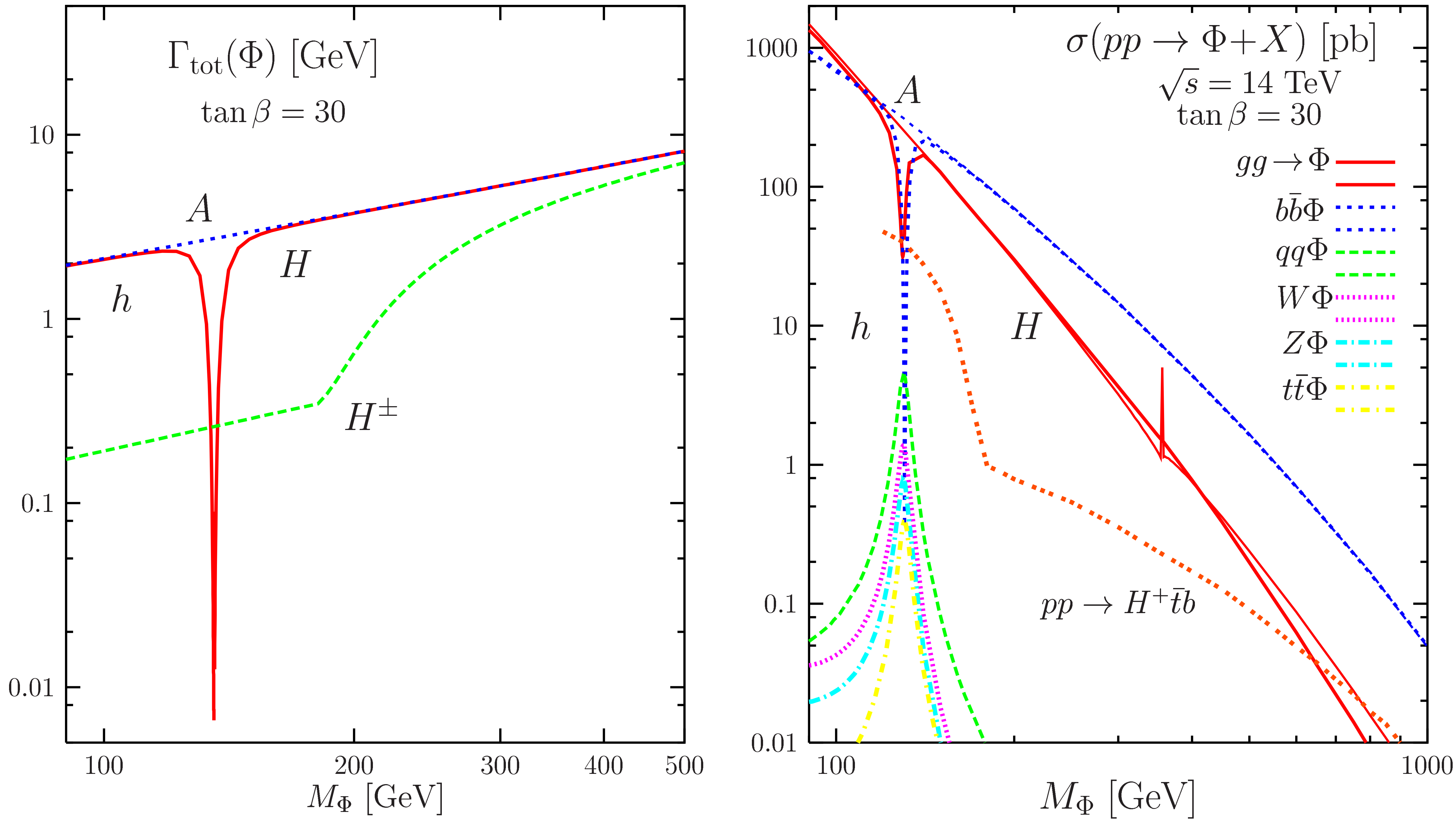
- For $m_A >> m_Z$ h decouples from remaining for Higgs bosons!

$$m_A \simeq m_H \simeq m_{H^\pm}$$

$$\begin{aligned} m^2_h &\simeq m^2_Z \cos^2 2\beta\,, \\ m^2_H &\simeq m^2_A + m^2_Z \sin^2 2\beta \\ m^2_{H^\pm} &= m^2_A + m^2_W\,, \\ \cos^2(\beta-\alpha) &\simeq \frac{m^4_Z \sin^2 4\beta}{4m^4_A} \sim 0 \end{aligned}$$

- Lowest Higgs h will behave like SM Higgs
  - similar coupling to fermions and vector bosons

HIGGS PROPERTIES



- Enhanced cross section for large tanβ compared to Standard Model