Higgs Property Measurement with ATLAS

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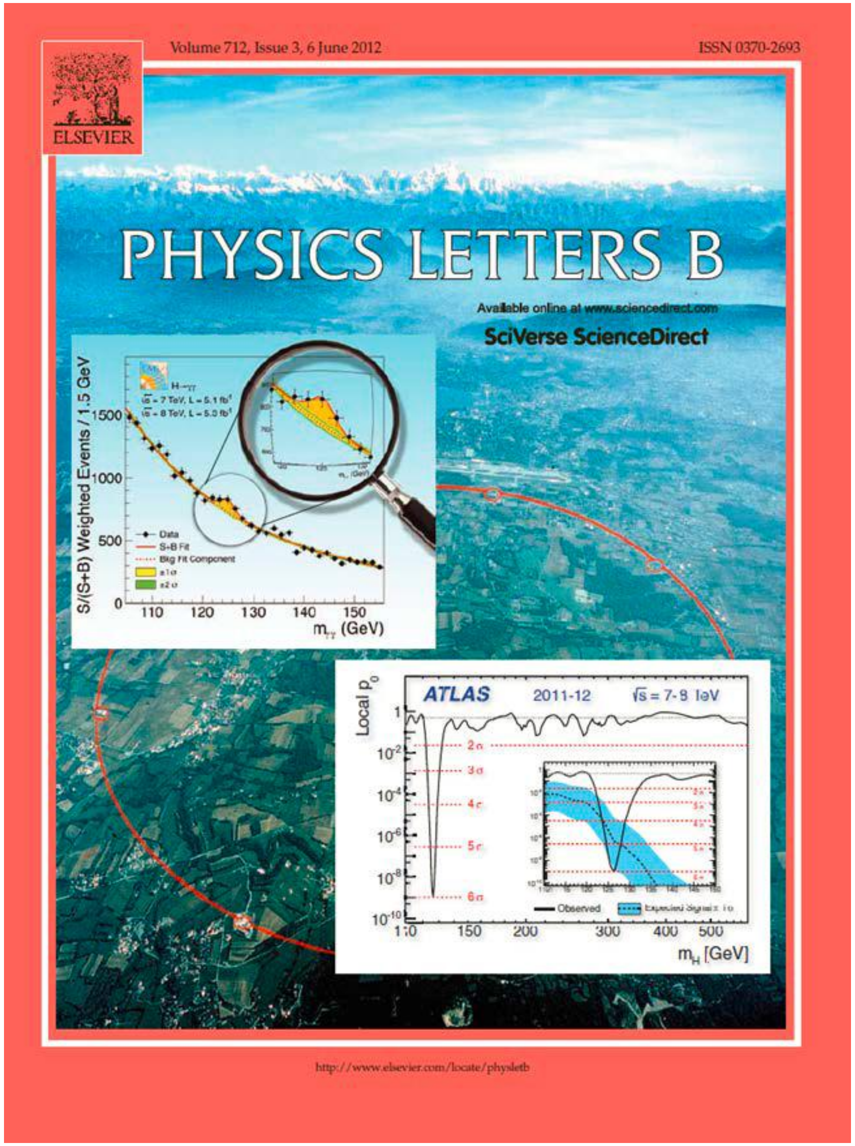
Observation of a new Particle (2012.7.4) !



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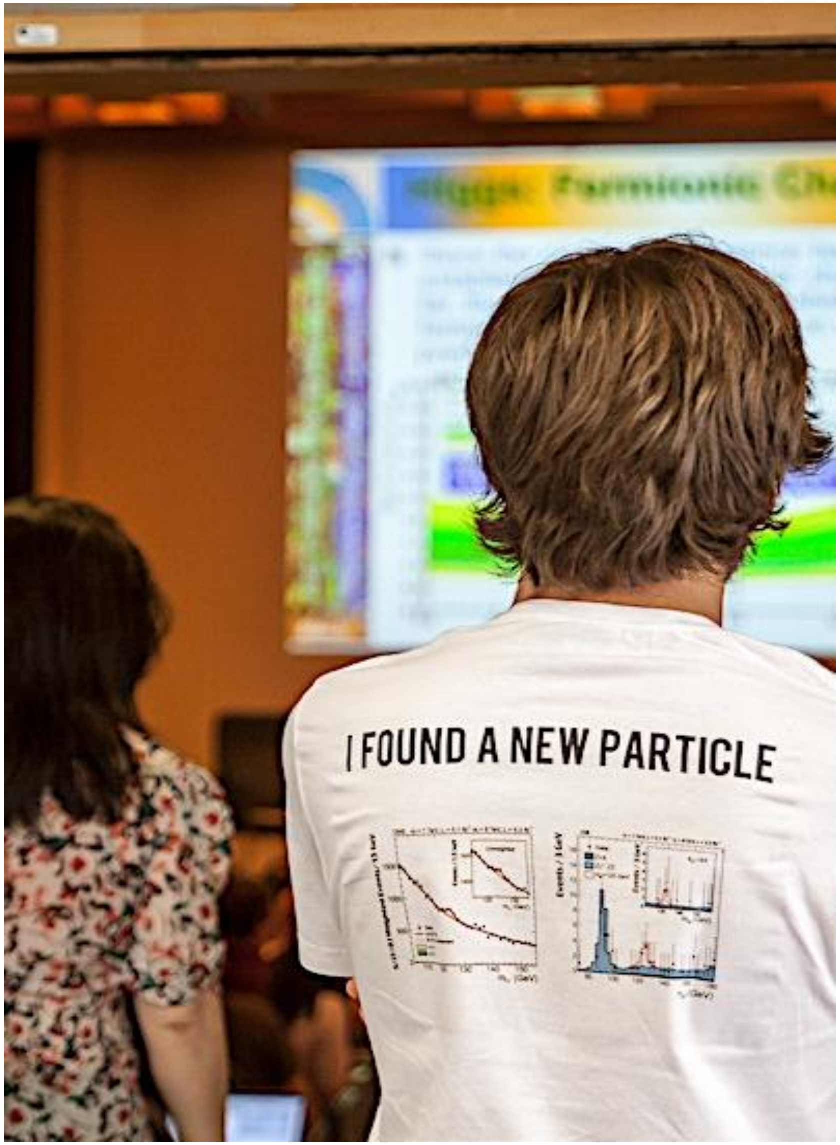
Phys. Lett. B 716 (2012) 1-29 (ATLAS)



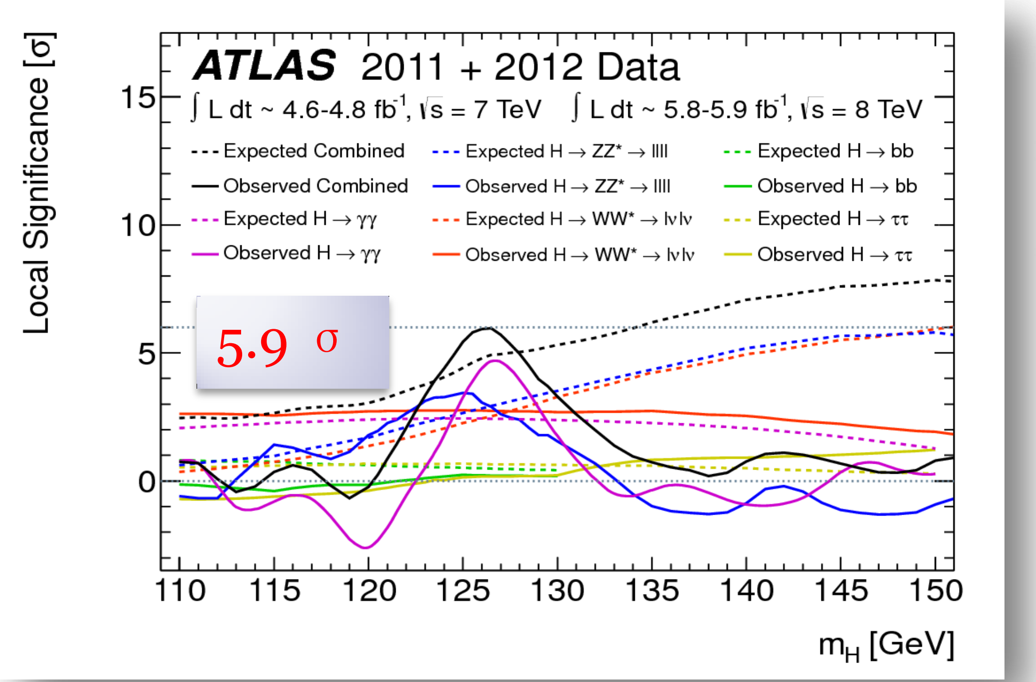
Phys. Lett. B 716 (2012) 30-61 (CMS)

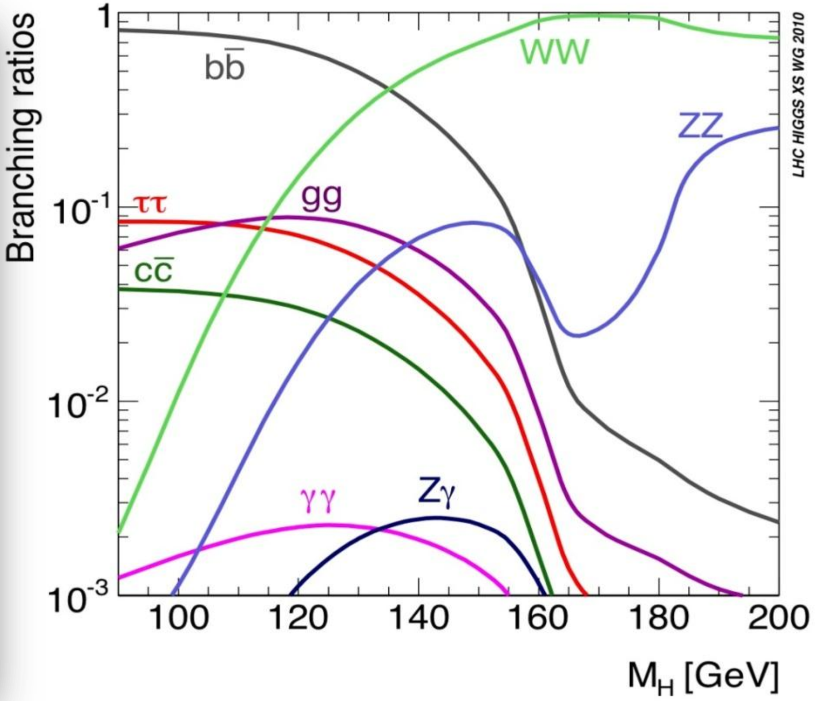
Is it the SM Higgs ?

- ☐ Verify the new observed particle
  - ✓ Spin-0 particle
    - Spin-1: excluded by H→γγ
    - Spin-2: look at angular correlations
  - ✓ CP-nature
    - SM Higgs CP-even, extended Higgs sectors has CP-odd or mixed states
    - Look at angular correlations
  - ✓ Couplings
    - Gauge / Yukawa couplings → g_{vvH}, $g_{ffH} \propto m$
    - Unitarity in $W_L W_L$ scattering → $g_{WWH} \propto m_W$
    - Higgs self-couplings, determine shape of Higgs potential via trilinear and quartic couplings, $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4$ + constant

ATLAS Combined Results

➔ **Discovery of a particle with a local significance of 5.9σ.**





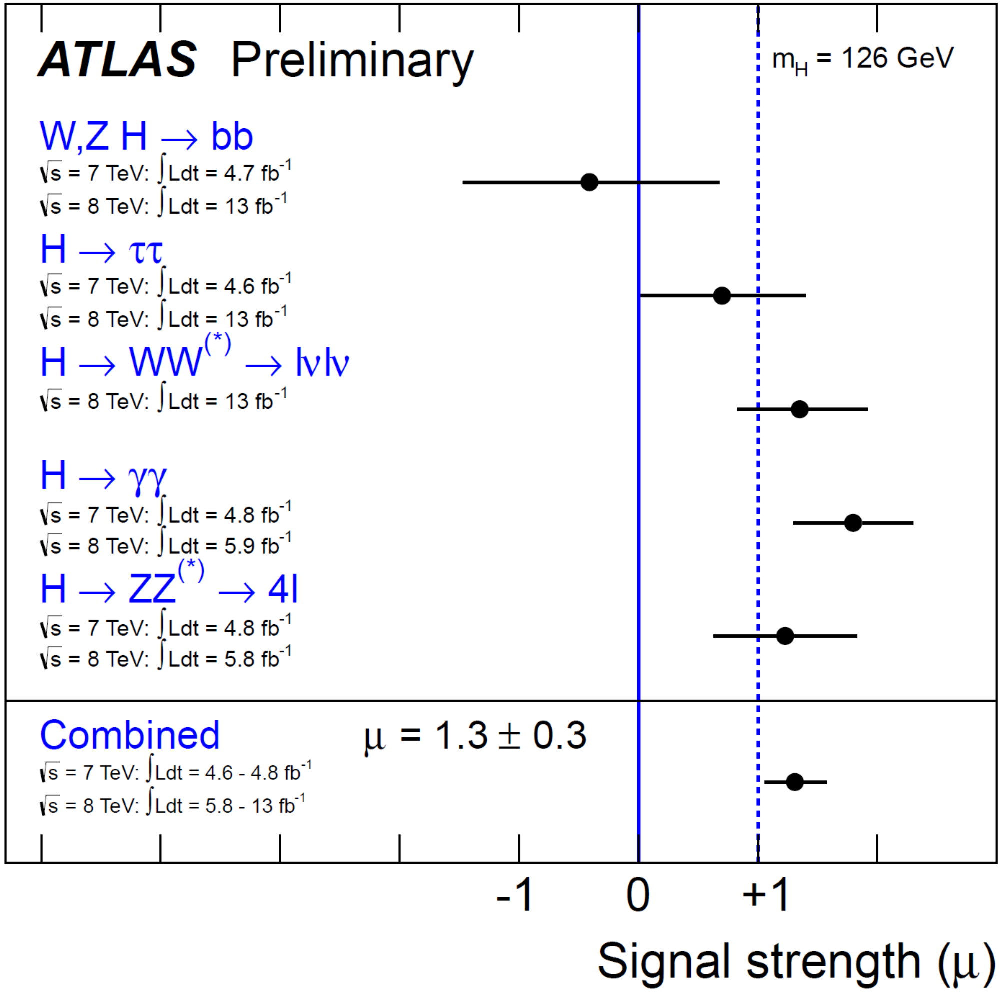
Channel	Fitted m_H	Observed	Expected
H→γγ	126.5 GeV	4.5σ	2.5σ
H→ZZ*→4l	125.0 GeV	3.6σ	2.7σ
H→WW*→lνlν	125.0 GeV	2.8σ	2.3σ
Combined	**126.0 GeV**	**5.9σ**	**4.9σ**

ATLAS Combined Results

- H→bb, ττ and WW* analyses have been updated using 13fb^{-1} data collected at 8 TeV in 2012.
- Higgs decays to γγ, ZZ* and WW* are established, but H → bb, ττ still lack of statistics to draw definitive conclusion.

Best–fit Higgs mass m_H :

126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

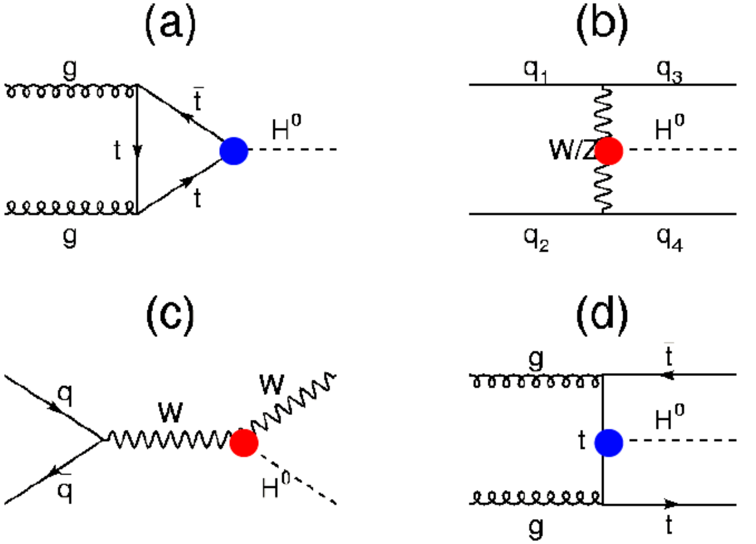


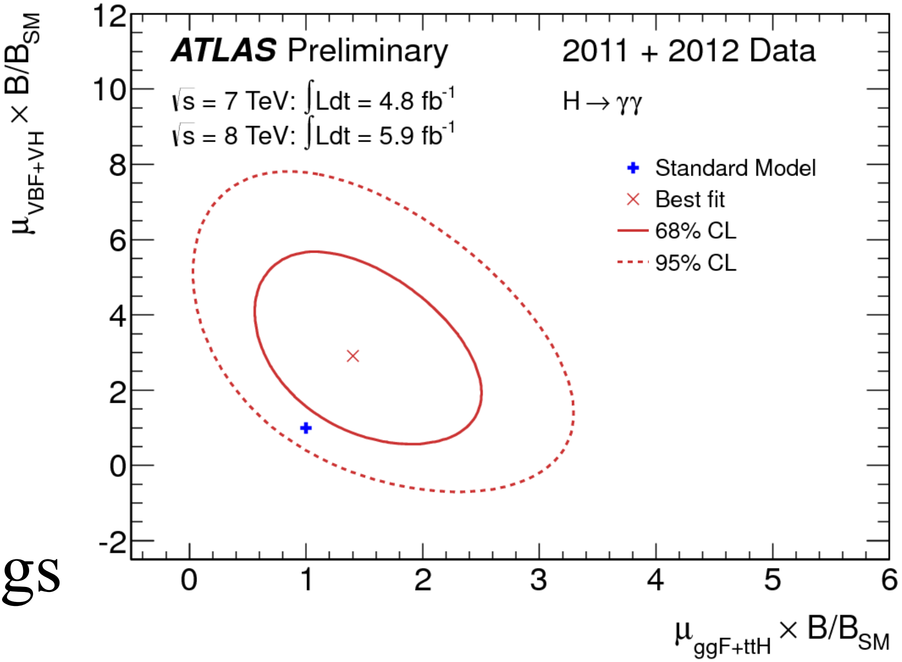
Best-fit signal strength:

$\mu = 1.3 \pm 0.3$

Higgs → γγ

❑ Observation of H → γγ excludes spin-1





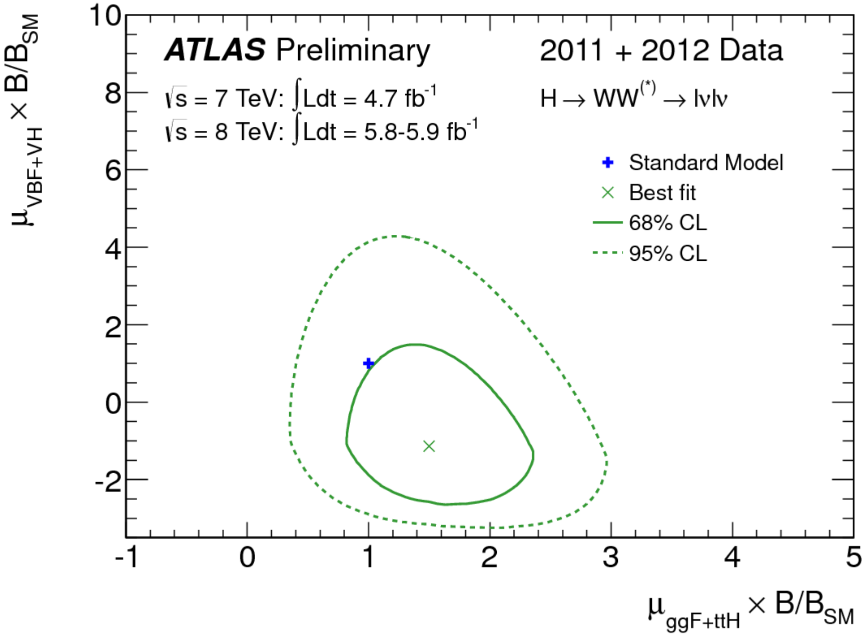
❑ Higgs has two types of couplings

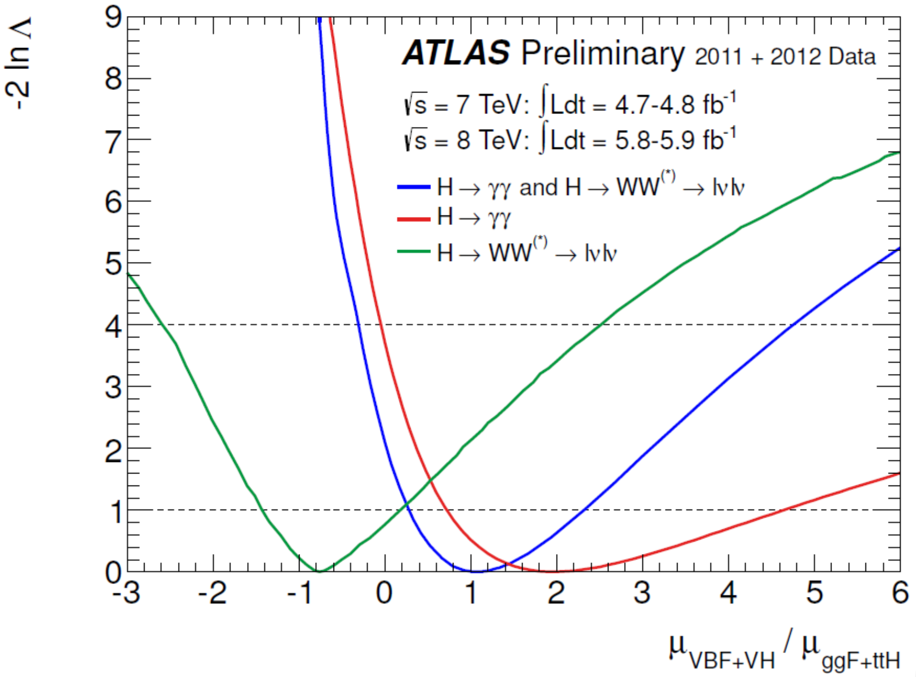
- "Gauge" couplings (to bosons)
- Yukawa couplings (to fermions)

❑ Explore tension between SM value and observation from different Higgs production modes: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$

Higgs → WW* → lνlν

- ☐ Model independent coupling studies which are directly related to experimental observables. 2D contour: μ_{VBF+VH} vs. $\mu_{ggF+ttH}$
- ☐ H→ZZ*→4l has low statistics and uses inclusive analysis





➔The signal strength ratios cancel the branching ratios of different channels so that the results can be compared directly.

Measurement of Higgs Couplings

☐ **Assumptions (LHC HXSWG, arXiv:1209.0040):**

- The signal observed in different channels originate from a single narrow resonance with mass near 125 GeV.
- The width of the assumed Higgs boson near 125 GeV is neglected, hence the signal cross section can be decomposed in the following for all channels:

$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff\,) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

- Only modifications of couplings strengths are taken into account, while the tensor structure of the couplings is assumed to be same as in the SM prediction (CP-even scalar). **[ATLAS-CONF-2012-127]**

Higgs Coupling Structure

- Depending on the benchmark model, κ_g, κ_γ and κ_H are either functions of other couplings or independent parameters.
- Notation for gg→H→γγ

Zero Width Approximation

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{ggF}} \cdot \frac{\Gamma_{\gamma\gamma}}{\Gamma_H}$$

$$\frac{\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}^{\mathrm{SM}}} = \kappa_g^2 \qquad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \kappa_\gamma^2 \qquad \frac{\Gamma_H}{\Gamma_H^{\mathrm{SM}}} = \kappa_H^2$$

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

fixed

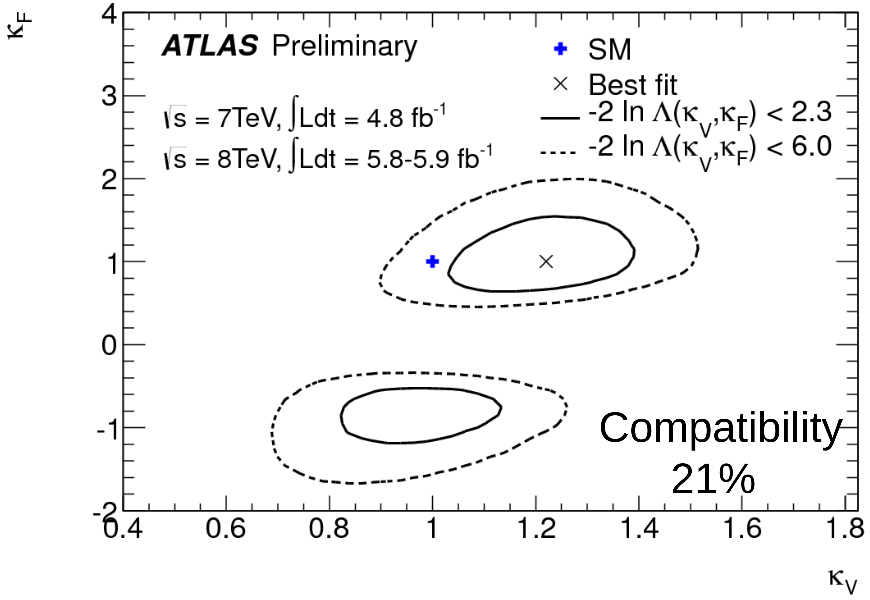
Higgs Couplings

- No BSM particle contributions to gg→H, H→γγ and the total width. Two coupling scale factors κ_F for fermions and κ_V for bosons,

$$\begin{aligned} \kappa_F &= \kappa_t = \kappa_b = \kappa_\tau \\ \kappa_V &= \kappa_W = \kappa_Z \end{aligned}$$

68% CL intervals

$$\boxed{\begin{array}{lll} \kappa_F & \in & [-1.0, -0.7] \cup [0.7, 1.3] \\ \kappa_V & \in & [0.9, 1.0] \cup [1.1, 1.3] \end{array}}$$

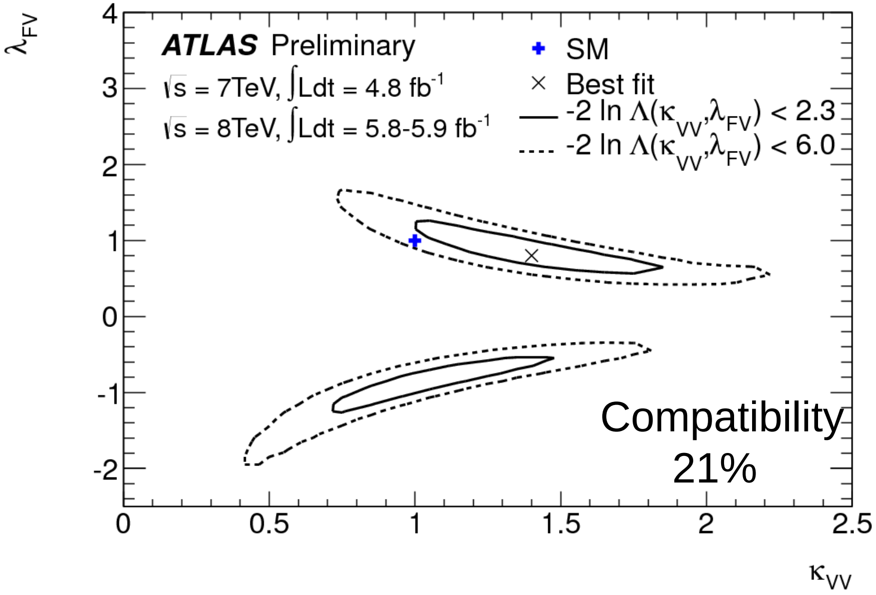


- Same as above, but without the assumption on the total width

$\lambda_{FV}=\kappa_F/\kappa_V$, $\kappa_{VV}=\kappa_V\cdot\kappa_V/\kappa_H$

68% CL intervals

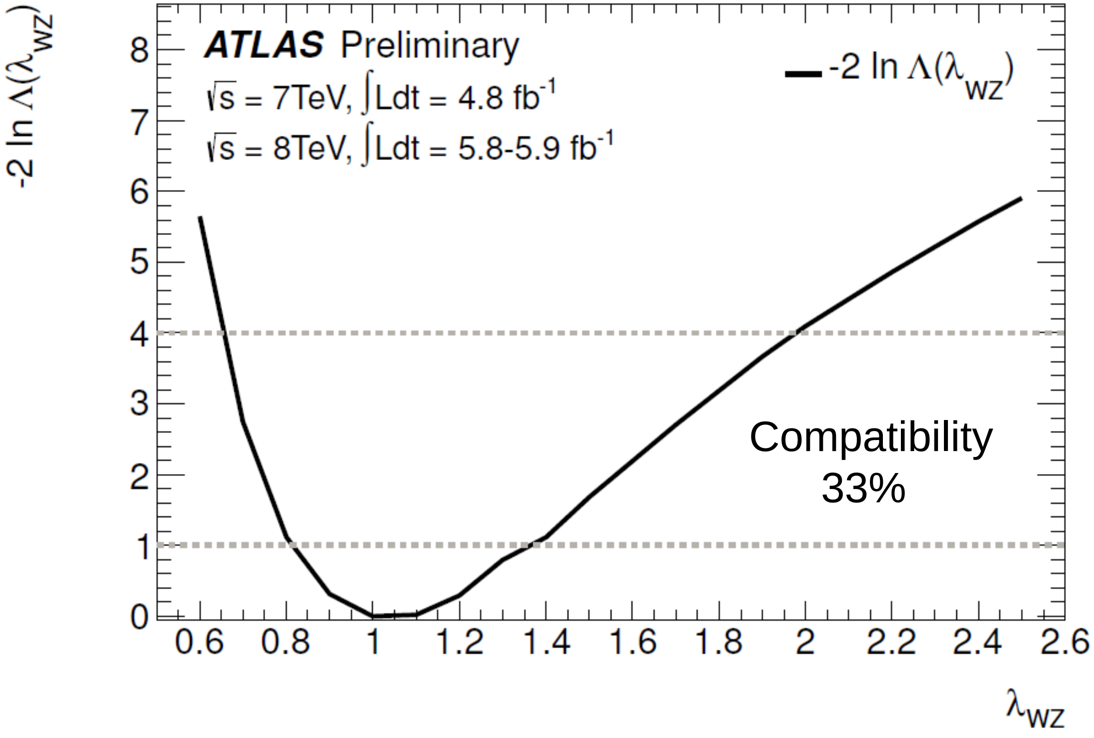
$$\begin{aligned} \lambda_{FV} &\in [-1.1, -0.7] \cup [0.6, 1.1] \\ \kappa_{VV} &= 1.2^{+0.3}_{-0.6} \end{aligned}$$



Probing custodial symmetry of the W/Z Coupling

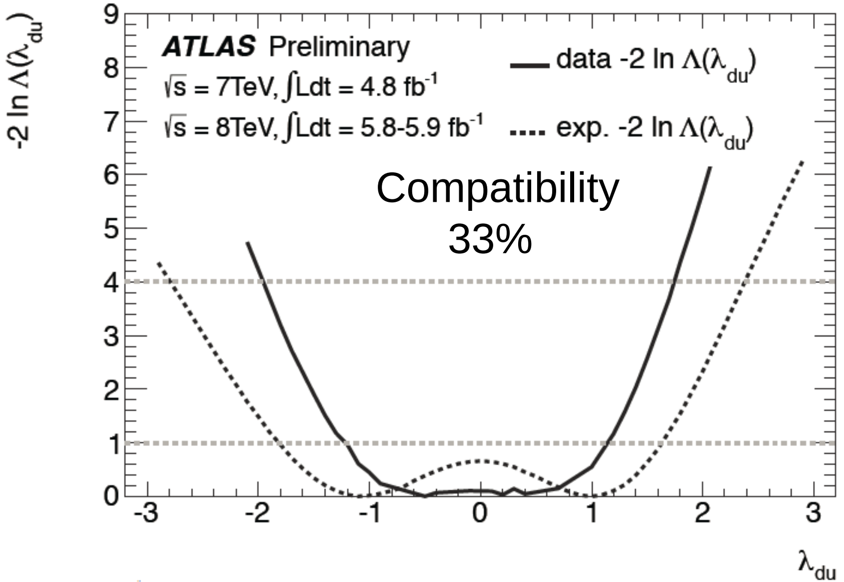
- ☐ Similar to previous benchmark model, but $\kappa_V \rightarrow \kappa_W$ and κ_Z, so there are three free parameters κ_W , κ_Z and κ_F. Identical couplings scale factors for the W and Z are required within tight bounds by SU(2) custodial symmetry and ρ parameter.
- ☐ The VBF process is parametrized with κ_W and κ_Z according to the Standard Model.

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z} = 1.07^{+0.35}_{-0.27}$$



Probing the up-type and down-type fermion and quark-lepton symmetry

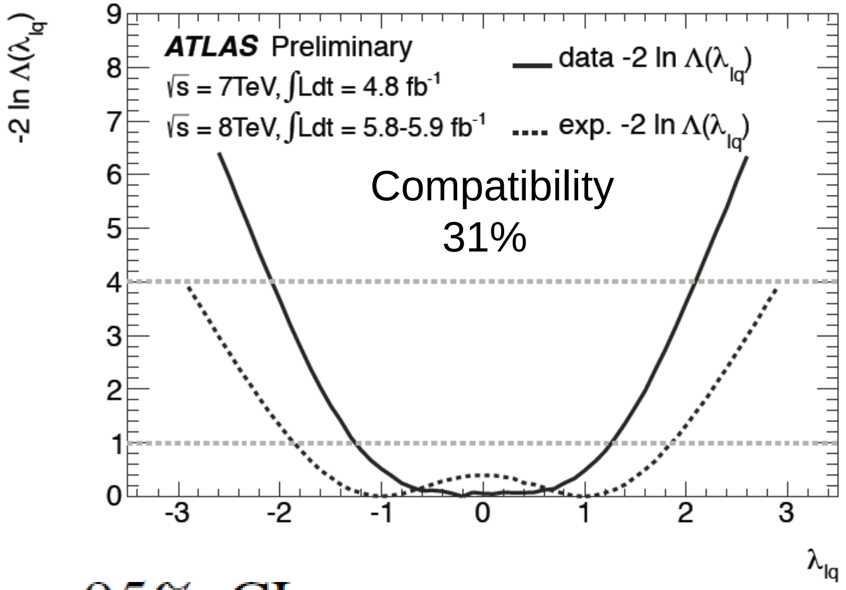
- In many extensions of the SM, the couplings of the light Higgs boson to up-type and down-type fermions differ ($|\lambda_{du}|$).
- The measurement is dominated by channels where we don't observe an excess, H→bb ($\mu=-0.4\pm1.1$) and H→ττ ($\mu=0.7\pm0.6$).



95% CL

$$\lambda_{du} \in [-2.0, 1.8]$$

$$\lambda_{du} = \frac{\kappa_d}{\kappa_u}$$



95% CL

$$\lambda_{lq} \in [-2.1, 2.1]$$

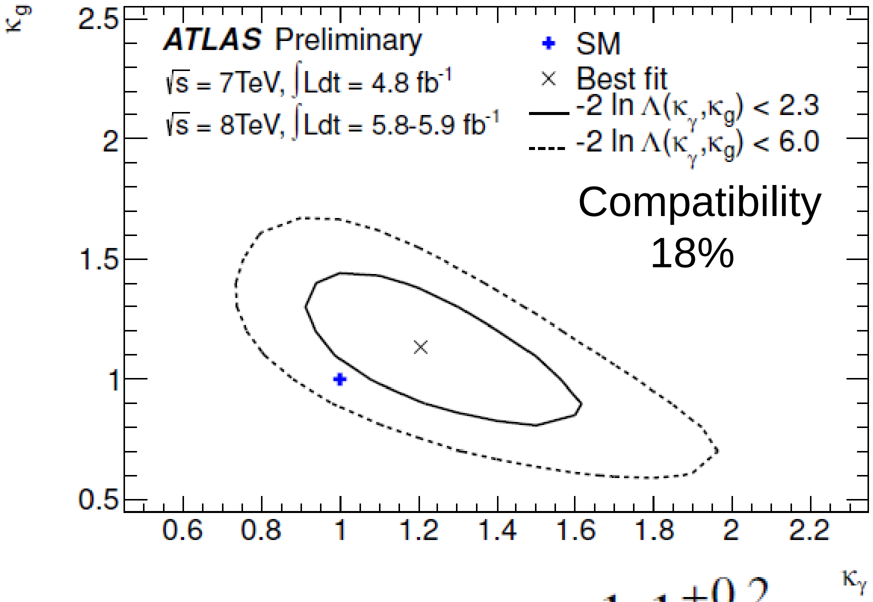
$$\lambda_{lq} = \frac{\kappa_l}{\kappa_q}$$

Probing Potential Non-SM Particle Contributions

- ☐ For H→γγ and gg→H vertices, effective scale factors κ_γ and κ_g are introduced (two free parameters). Non-SM particles can contribute to H→γγ and gg→H loops or in new final states.

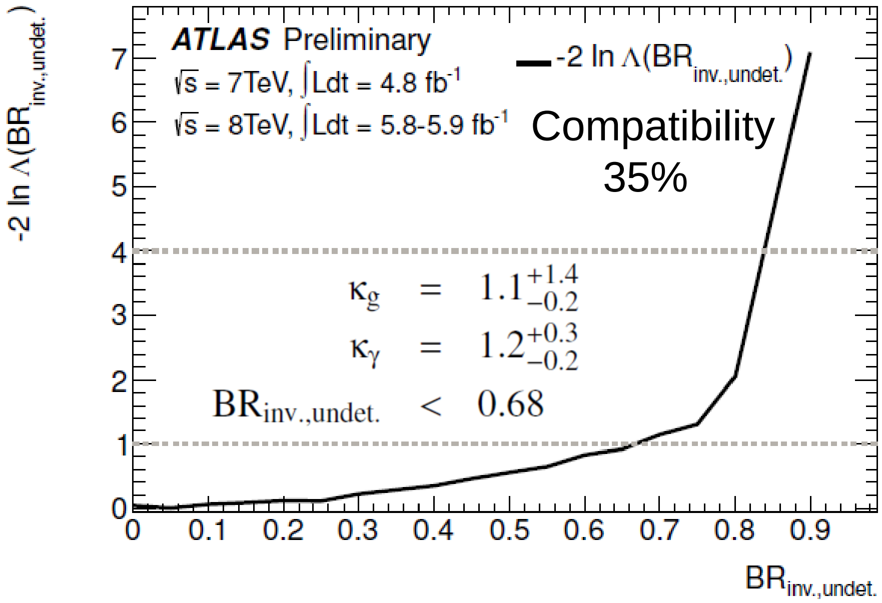
assuming only SM contributions to total width and $\kappa_i = 1$ for all SM particles

no assumption on total width, but $\kappa_i = 1$ for all SM particles



68% CL

$$\kappa_g = 1.1^{+0.2}_{-0.3}$$
$$\kappa_\gamma = 1.2^{+0.3}_{-0.2}$$



$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})}\Gamma_H^{SM}$$

Summary and Conclusions

- A new Higgs-like particle was observed on July 4, 2012

Mass: m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV
Signal strength: μ = 1.3 ± 0.3

- Higgs decays to $\gamma\gamma$, ZZ^* and WW^* (gauge coupling) are established, but $H \rightarrow bb$, $\tau\tau$ (Yukawa coupling) still lack of statistics to draw definitive conclusion.
- The spin-1 is excluded due to observation of $H \rightarrow \gamma\gamma$.
- Uncertainties of couplings parameters ~20-30% , no significant deviations from the SM couplings are observed.

Please stay tuned !

Backup Slides

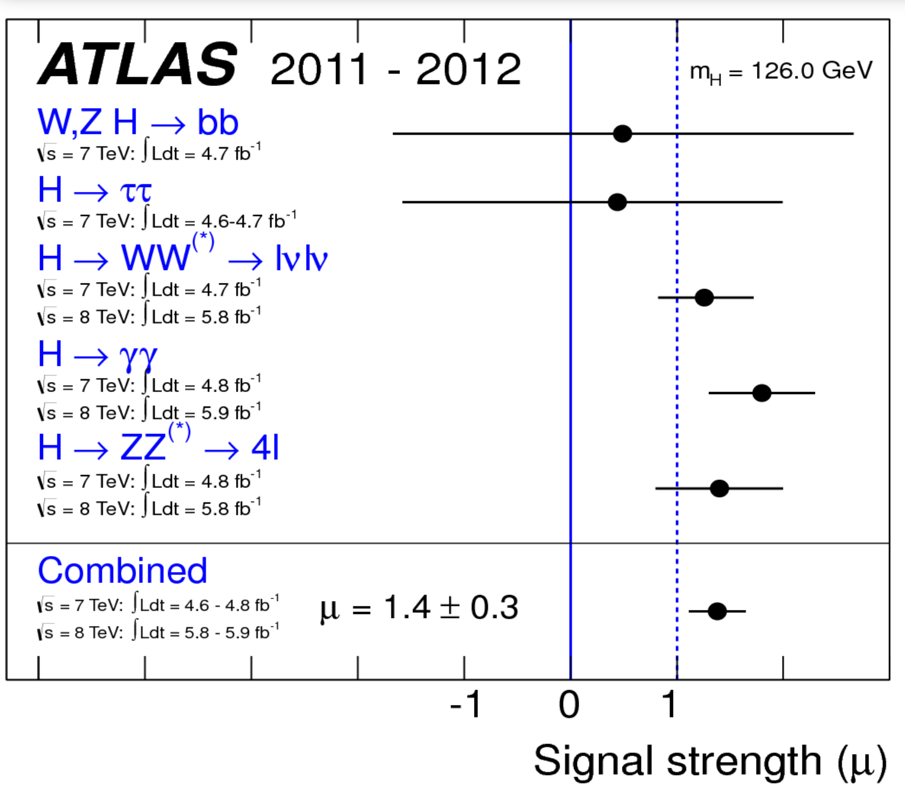
Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int$ L dt [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.8
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	4.8
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{\text{0-jet}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jet, boosted, } VH\}$	4.7
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, boosted, 2-jet}\}$	4.7
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{boosted, 2-jet}\}$	4.7
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	4.6
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	4.7
		2012 $\sqrt{s}$ =8 TeV	
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	5.8
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jet}\}$	5.9
$H \to WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{\text{0-jet, 1-jet}\}$	13
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{\text{1-jet, 2-jet, boosted, } VH\}$	13
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{\text{0-jet, 1-jet, boosted, 2-jet}\}$	13
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{\text{boosted, 2-jet}\}$	13
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200 \text{ GeV}\} \otimes \{\text{2-jet, 3-jet}\}$	13
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200 \text{ GeV}\}$	13

ATLAS Combined Results

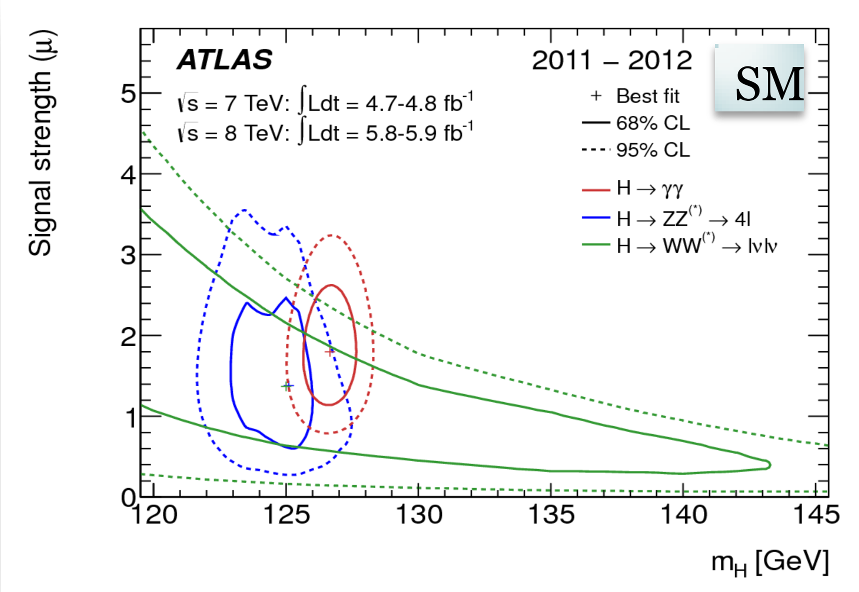
❑ Higgs decays to γγ, ZZ* and WW* are well established, but H → bb, ττ still lack statistics to draw definitive conclusion.

Best–fit Higgs mass:

$m_H = 126 \pm 0.4$ (stat) ± 0.4 (syst) GeV



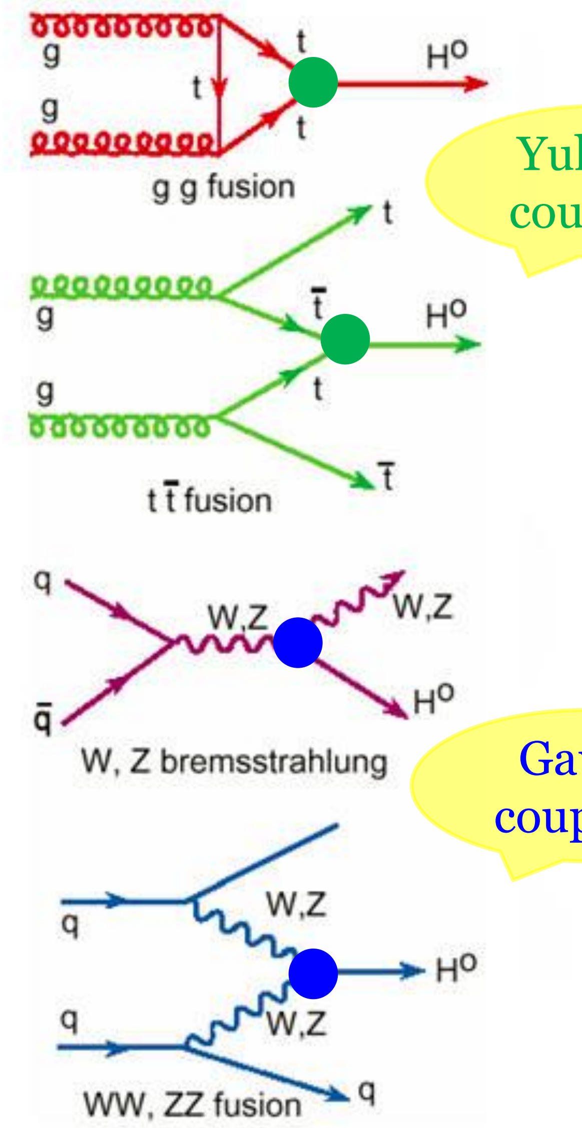
2D likelihood fit: mass vs strength



Best-fit signal strength:

μ = 1.4 ± 0.3

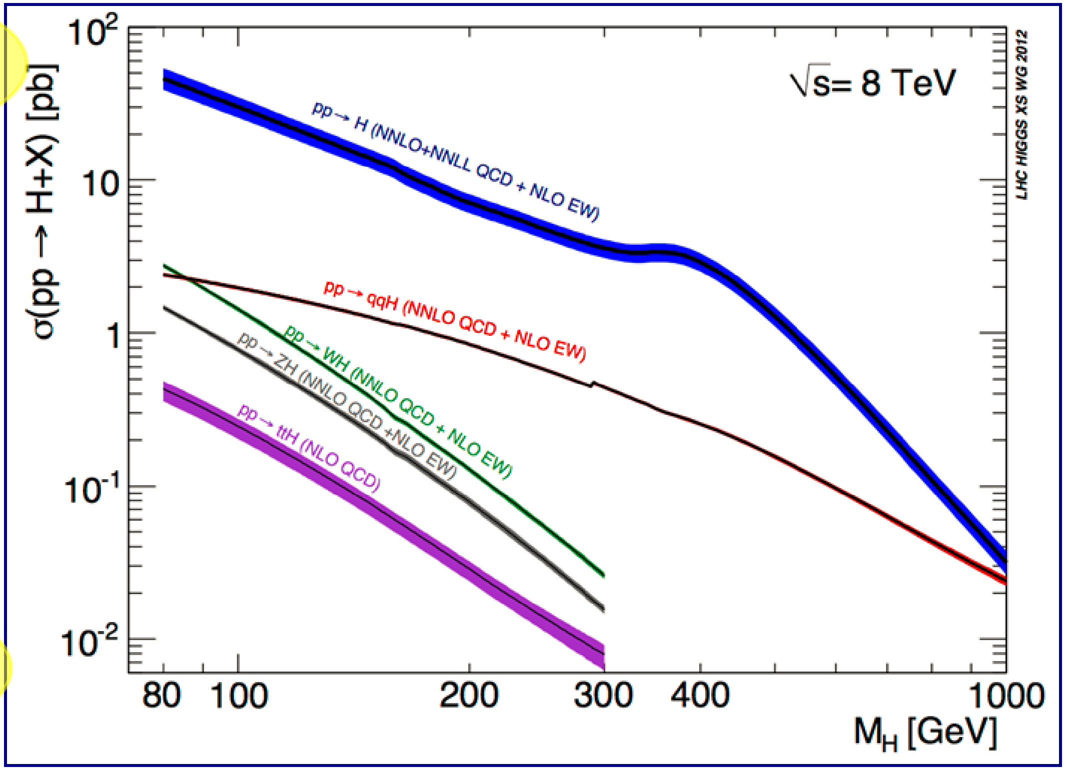
Higgs Boson Production at LHC



Yukawa coupling

Gauge coupling

Gluon-gluon fusion gg→H and vector-boson fusion qq→qqH are dominant processes



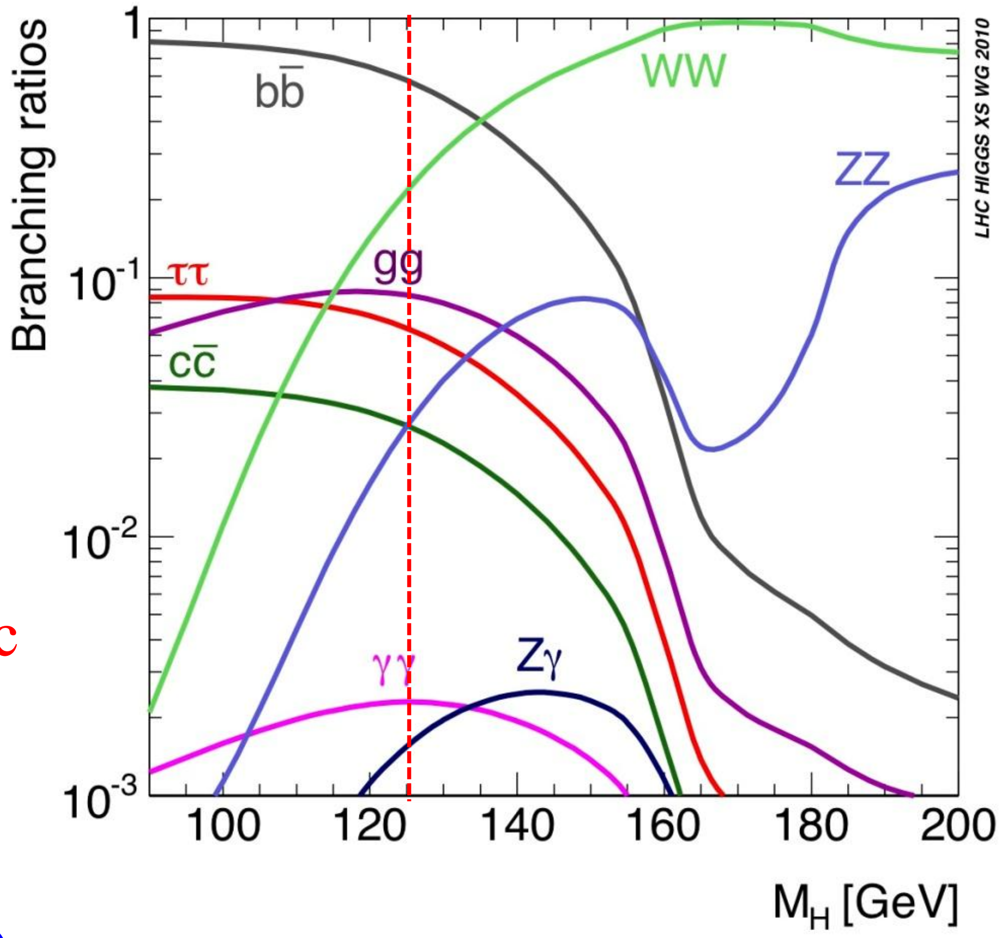
$$@125\text{ GeV: } \sigma_{ggH}=19.5\text{ pb}, \sigma_{VBF}=1.6\text{ pb},$$
$$\sigma_{WH}=0.70\text{ pb}, \sigma_{ZH}=0.39\text{ pb}, \sigma_{ttH}=0.13\text{ pb}$$

➔ ~230k events in 2011+2012 samples

Higgs Boson Decay

Higgs decay branching ratio at m_H=125 GeV

- bb: 57.7% (huge QCD background)
- WW*: 21.5% (easy identification in di-lepton mode, complex background)
- ττ: 6.3% (complex final states with τ leptonic and/or hadronic decays)
- ZZ*: 2.6% ("gold-plated", clean signature of 4-lepton, high S/B, excellent mass peak)
- γγ: 0.23% (excellent mass resolution, high sensitivity)



Higgs boson production rate: 1 out of 10^{12} collision events

Higgs Boson Width

- **Strong mass dependent**

Γ_H = 3.5 MeV @ 120 GeV

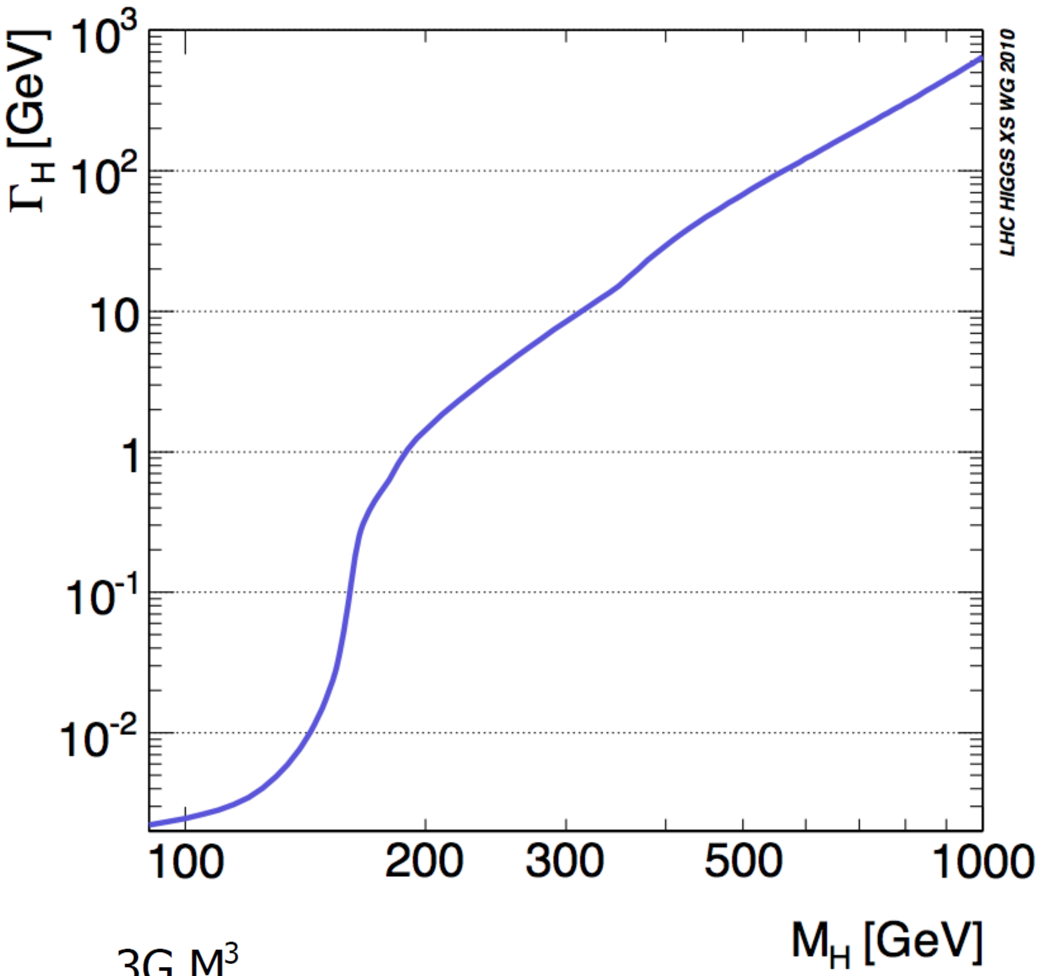
1.4 GeV @ 200 GeV

8.4 GeV @ 300 GeV

68.0 GeV @ 500 GeV

- At low mass region (<200 GeV), detector resolution dominates mass resolution

- At high mass, intrinsic width becomes dominant

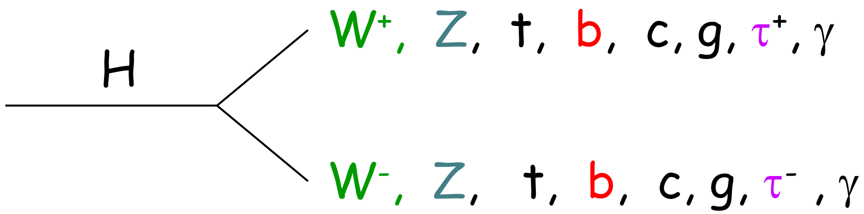


$$\Gamma_H \approx \frac{3G_F M_H^3}{16\pi\sqrt{2}}$$

$$\approx 500\ \text{GeV} \cdot \left(\frac{M_H}{1\ \text{TeV}}\right)^3$$

Higgs Boson Decays

The decay properties of the Higgs boson are fixed, if the mass is known:



$$\Gamma(H \to f\bar{f}) \;=\; N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2)\; M_H$$

$$\Gamma(H \to VV) \;= \delta_V \frac{G_F}{16\sqrt{2}\pi}\; M_H^3\; (1 - 4x + 12x^2)\; \beta_V$$

where: $\delta_Z = 1, \delta_W = 2, \quad x = M_V^2/M_V^2, \quad \beta = \text{velocity}$

$$\Gamma(H \to gg) \;= \frac{G_F\; \alpha_s^2(M_H^2)}{36\sqrt{2}\pi^3}\; M_H^3\; \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_s}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) \;= \frac{G_F\; \alpha^2}{128\sqrt{2}\pi^3}\; M_H^3\; \left[\tfrac{4}{3}N_C e_t^2 - 7\right]^2$$

Higgs Boson:

- it couples to particles proportional to their masses
- decays preferentially in the heaviest particles kinematically allowed