Combined Measurements of the Higgs Boson using the ATLAS detector

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on behalf of the ATLAS collaboration

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Standard Model Lagrangian

NIKHEF

ttH $\quad h \to b\bar{b}$ $\quad h \to \tau\tau$

$V(\Phi)$

$$
\begin{aligned}
\mathcal{L} = &- \frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\
&+ \bar{Q}_i i \not{D} Q_i + \bar{u} i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{\ell}_i i \not{D} \ell_i \\
&+ \left(Y_u^{ij} \boxed{\bar{Q}_i u_j \tilde{H}} + Y_d^{ij} \boxed{\bar{Q}_i d_j H} + Y_\ell^{ij} \boxed{\bar{L}_i \ell_j H} + c.c. \right) \\
&- \lambda (H^\dagger H)^2 + \boxed{\lambda v^2} H^\dagger H - (\partial^\mu H)^\dagger \partial_\mu H \\
&- 2 \frac{M_W^2}{v} \boxed{W^{+\mu} W^-_\mu H} - \frac{M_Z^2}{v} \boxed{Z^\mu Z_\mu H} + \ldots
\end{aligned}
$$

$\Re\mathrm{e}(\Phi)$

m_H $\quad h \to ZZ^*$

$\Im\mathrm{m}(\Phi)$ $\quad h \to WW^*$

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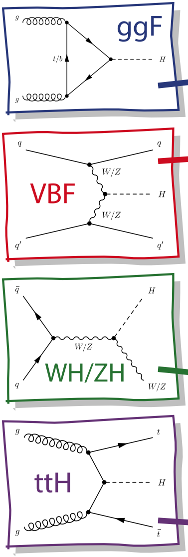
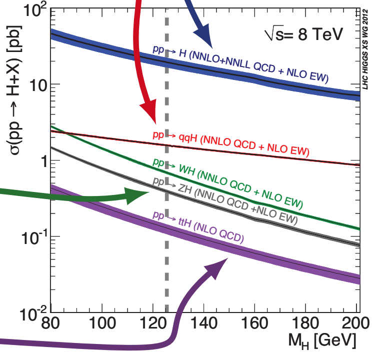
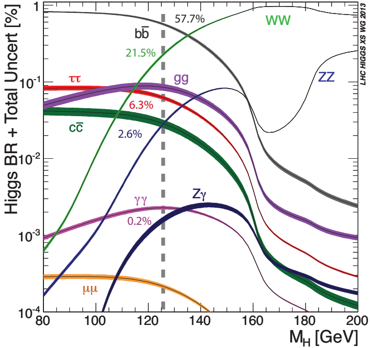
Higgs at the LHC

- *WW*: broad sensitivity, different backgrounds
- $b\bar{b}$, $\tau\tau$: fermion couplings, challenging backgrounds
- *ZZ*: very clean, low statistics
- $\gamma\gamma$: simple final state, low BR

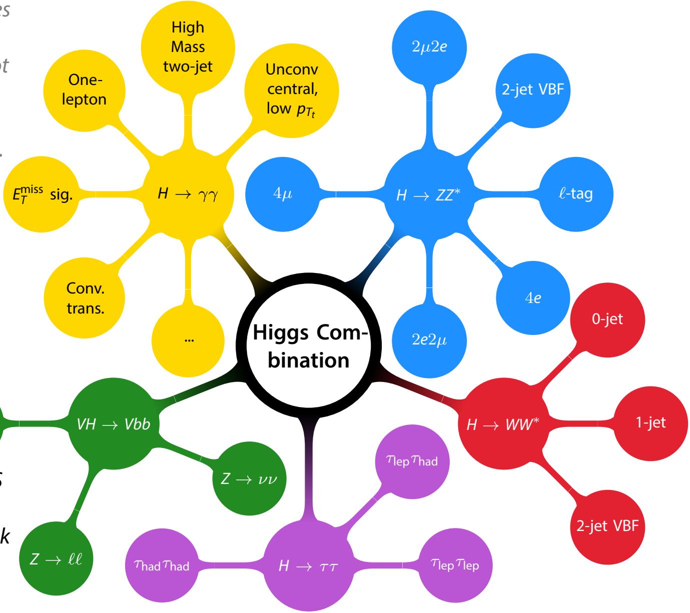






Overview of measurements

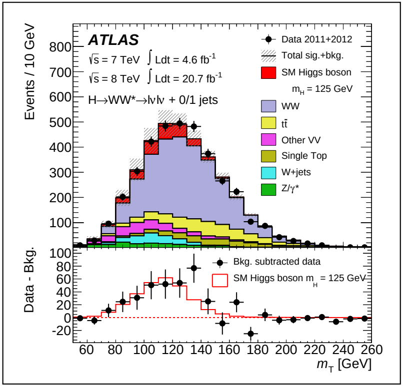
Map of categories in the SM Higgs combination. Not included are the recent results for $H \to \mu\mu$ and ttH.

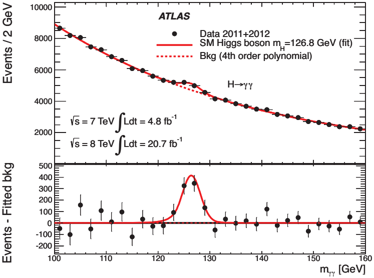


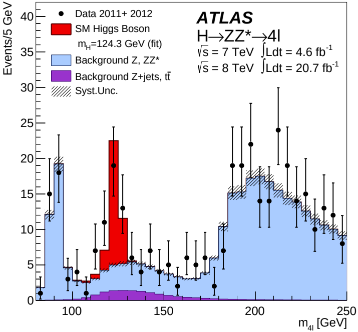
References ATLAS results can be found in the back up material

Higgs signal spectra

- The $\gamma\gamma$, *ZZ*, *WW* and $\tau\tau$ channels all exhibit a prominent excess corresponding to $m_H \approx 125.5$ GeV







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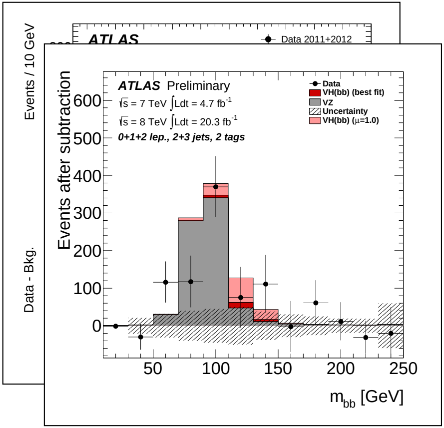

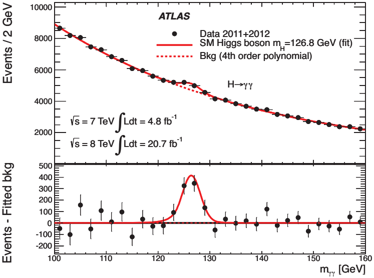

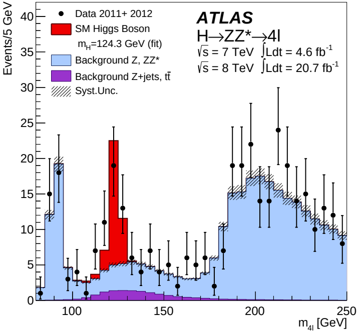

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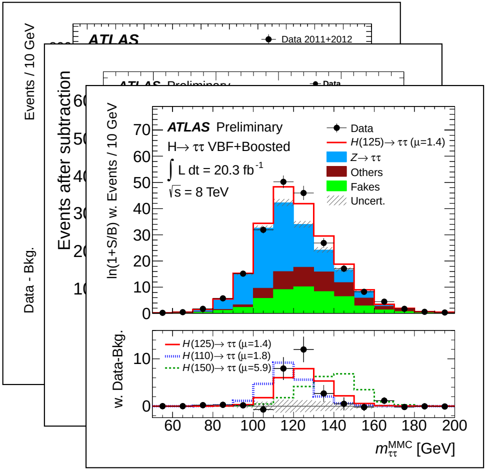
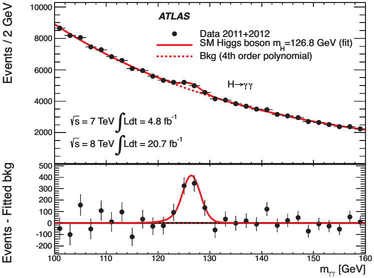
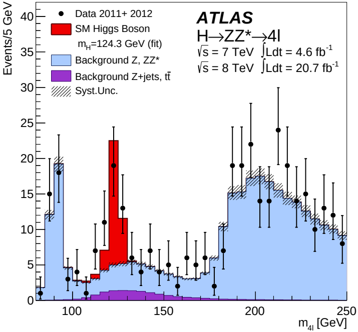
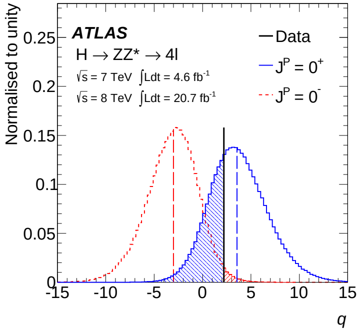






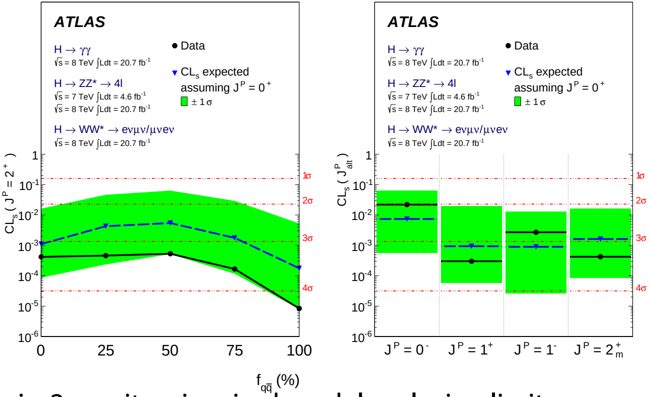
The following properties can be measured:

- Mass (not discussed here)
- Spin and $\mathcal{CP}$
- Couplings (see later)



- Standard Model Higgs has Spin $\mathcal{CP}$ $J^P = 0^+$
- Alternative models can be tested $J^P = 0^-, 1^+, 1^-$ and 2^+
- Use angular and kinematical distributions in $\gamma\gamma$, *ZZ* and *WW* channels to test models

Spin and CP measurements



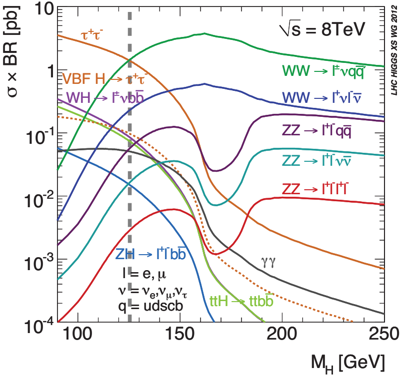
- The spin-2 graviton-inspired model exclusion limits vary as a function of the qq to gg fraction
- Results are consistent with the $J^P = 0^+$ hypothesis
- Alternative models are excluded at 97.8% CL

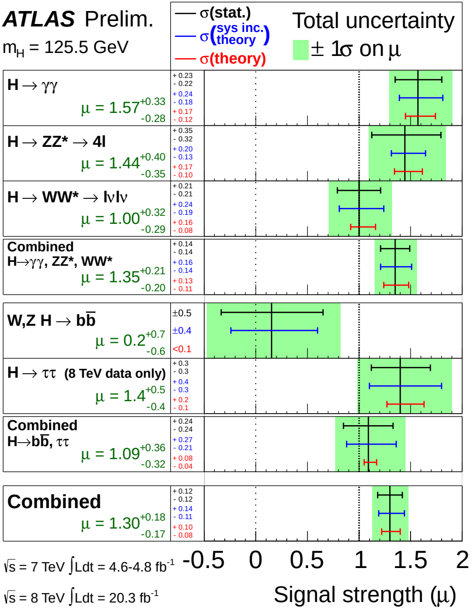
Inclusive signal strength

- Measure the ratio between observed rate and SM Higgs expectation for $\sigma \times \mathcal{BR}$:

$$\mu = \frac{\sigma \cdot \mathcal{BR}}{(\sigma \cdot \mathcal{BR})_{SM}}$$

- Consistent with the SM





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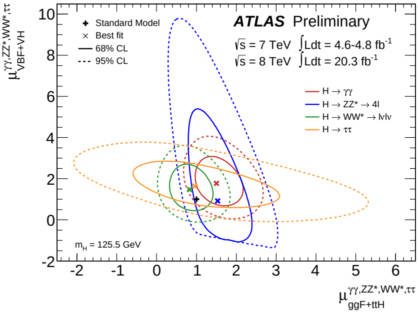
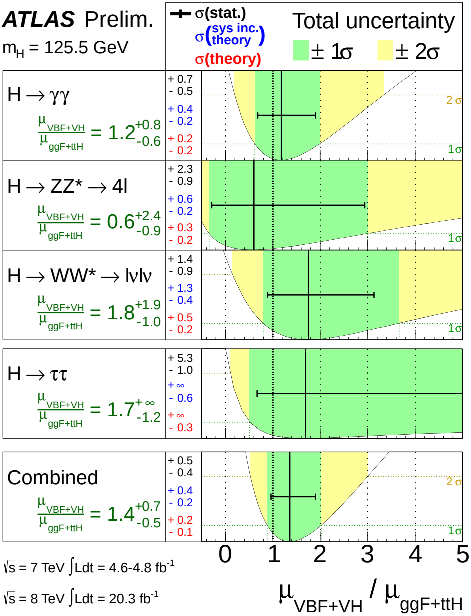
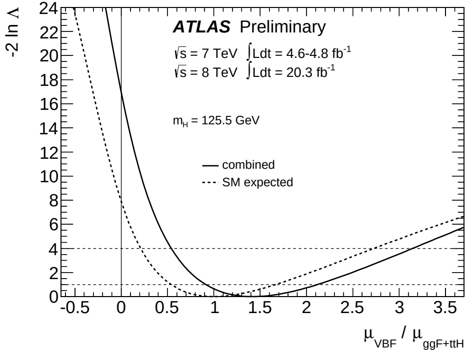
Higgs production modes

- 2D scan of $\mu_{\mathrm{ggF}+ttH}$ and $\mu_{\mathrm{VBF}+VH}$ modified by $\mathcal{BR}/\mathcal{BR}_{\mathrm{SM}}$
- Interesting observable is the ratio $\dfrac{\mu_{\mathrm{VBF}+VH}}{\mu_{\mathrm{ggF}+ttH}}$ that is independent of the $\mathcal{BR}$ and thus channels can be combined





Evidence for VBF production



- Test sensitivity to VBF production by profiling μ_{VH}:
- $\mu_{\text{VBF}}/\mu_{\text{ggF}+ttH} = 1.4^{+0.5}_{-0.4}(\text{stat})^{+0.4}_{-0.3}(\text{sys})$
- 4.1σ evidence for VBF production

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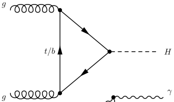
Framework to probe couplings

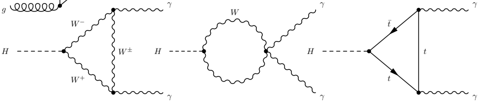
- Coupling strengths g of the Higgs to other SM particles scale with the particle mass
  - Fermions: $g_F = \sqrt{2}m_F/v$, Gauge bosons: $g_V = 2m_V^2/v$
- Measure strength in units of SM expectation, $\kappa_i = g_i/g_{i,\mathrm{SM}}$, in a leading-order tree-level motivated framework

Assumptions: only one CP-even scalar Higgs ($m_H = 125.5$ GeV), narrow-width approx.: $\sigma \cdot BR(ii \to H \to ff) = \sigma_{ii} \cdot \Gamma_{ff}/\Gamma_H$

Example: $gg \to H \to \gamma\gamma$



$$\sigma(gg \to H) \propto \kappa_g^2 \simeq 1.058\kappa_t^2 + 0.007\kappa_b^2 - 0.065\kappa_t\kappa_b$$



$$\Gamma(H \to \gamma\gamma) \propto \kappa_\gamma^2$$
$$\simeq |1.26\kappa_W - 0.27\kappa_t|^2$$

Total decay width scales with $\kappa_H^2 = \sum_{jj} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}}$

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

arXiv:1307.1427 [hep-ex]

Simplified benchmark models

- Study simple parametric extensions of the SM, without proper physics motivation
- Reduce degrees of freedom in the different scenarios to increase statistical precision and sensitivity

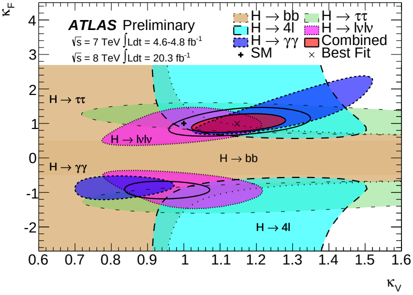
N.B. *Other approaches are BSM-specific models and effective field theory*

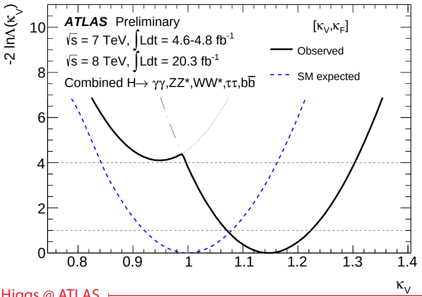
Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
Couplings to fermions and bosons	κ_V, κ_F	✓	✓	✓	✓	✓	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F,\kappa_V)/\kappa_H^2(\kappa_F,\kappa_V)$
	$\lambda_{FV}, \kappa_{VV}$	✓	✓	✓	✓	–	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV},\lambda_{FV},\lambda_{FV},1)$
Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	–	✓	✓	✓	–	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FY},\lambda_{WZ})$
Up/down fermions	$\lambda_{du}, \lambda_{Vu}, \kappa_{uu}$	✓	κ_u, κ_d	✓	✓	–	$\kappa_{uu}^2 \cdot \kappa_g^2(\lambda_{du},1) \cdot \kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$
Leptons/quarks	$\lambda_{\ell q}, \lambda_{Vq}, \kappa_{qq}$	✓	κ_ℓ, κ_q	✓	✓	–	$\kappa_{qq}^2 \cdot \kappa_\gamma^2(1,1\lambda_{\ell q},\lambda_{Vq})$
Vertex loops	κ_g, κ_γ	$=1$	$=1$	–	–	✓	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g,\kappa_\gamma)$
+ H →i./u. decays	κ_g, κ_γ, $BR_{i.,u.}$	$=1$	$=1$	–	–	–	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g,\kappa_\gamma) \cdot (1 - BR_{i.,u.})$
Generic models w/ & w/o ass. on vertex loops & Γ_H	κ_W, κ_Z, κ_t, κ_b, κ_τ	–	–	✓	✓	✓	$\frac{\kappa_g^2(\kappa_b,\kappa_t)\cdot\kappa_\gamma^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W)}{\kappa_H^2(\kappa_b,\kappa_t,\kappa_\tau,\kappa_W,\kappa_Z)}$
	λ_{WZ}, λ_{tg}, λ_{bZ}, $\lambda_{\tau Z}$, λ_{gZ}, $\lambda_{\gamma Z}$, κ_{gZ}	–	–	–	–	–	$\kappa_{gZ}^2 \cdot \lambda_{\gamma Z}^2$

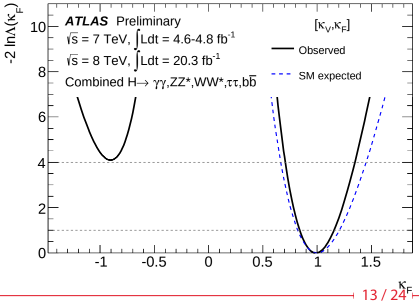
- Nomenclature: $\lambda_{ij} = \kappa_i/\kappa_j$ and $\kappa_{ii} = \kappa_i\kappa_i/\kappa_H$
- Results for the Generic models can be found in the backup slides

Gauge bosons vs fermions (I)

- Test fundamental difference between couplings to fermions κ_f and vector-bosons κ_V
  - $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$ and $\kappa_V = \kappa_W = \kappa_Z$
  - no new Physics in loops or decay
- $\kappa_F = 1.15 \pm 0.08$ $\kappa_V = 0.99^{+0.17}_{-0.15}$

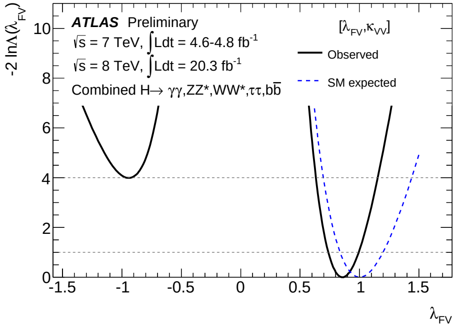






Gauge bosons vs fermions (II)

- Loop diagrams with interference (e.g. in $\gamma\gamma$) have sensitivity to relative sign of κ
- Fermiophobic Higgs ($\kappa_F = 0$) excluded by more than 5σ
- In fits of λ_{FV} no assumption is needed for the total width
- $\lambda_{FV} = 0.86^{+0.14}_{-0.12}$



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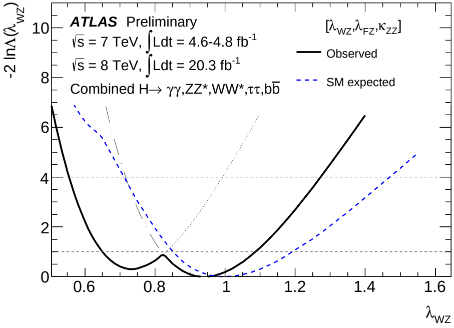
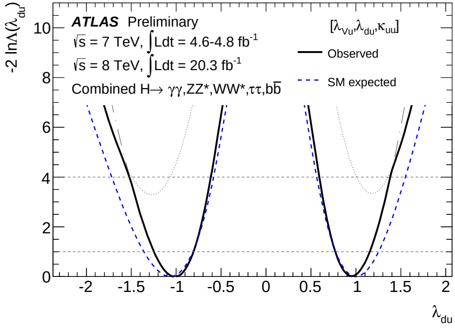
Custodial symmetry

- Standard Model predicts the same coupling strength of the Higgs to *W* and *Z* bosons from Custodial symmetry
- At the LHC one can probe the ratio of the couplings $\lambda_{WZ} = \kappa_W / \kappa_Z$ directly in the Higgs sector
- $\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$



Up- and down-type fermions

- Many extensions of the SM predict $\lambda_{du} = \kappa_d/\kappa_u \neq 1$
- Up-type quark coupling indirectly constrained by top-quark loop in $gg \to h$ production; Down-type fermion coupling directly constrained through $h \to b\bar{b}$ and $h \to \tau\tau$
- $\lambda_{du} = 0.78 - 1.15$ @ 68% CL
- 3.6σ evidence of the coupling of the Higgs boson to down-type fermions



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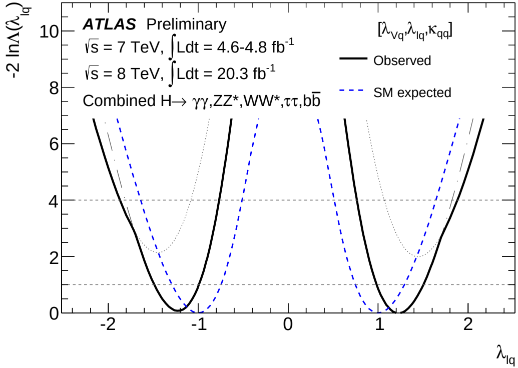
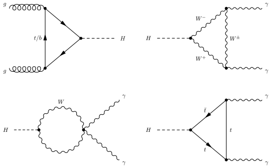
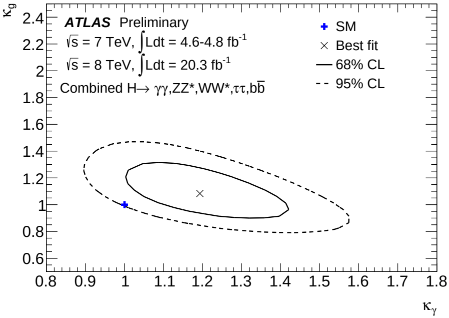
Quark and lepton symmetry

- Lepton coupling strength currently only constrained through $h \to \tau\tau$
- $\lambda_{lq} = 0.99 - 1.50$ @ 68% CL
- Vanishing coupling to leptons excluded at 4σ level





- SM processes at 1-loop particularly sensitive to anomalous new physics effects
  - $gg \to H$ production
  - $H \to \gamma\gamma$ decay
- Introduce effective coupling scale factors κ_g and κ_γ for those loop induced couplings
  - All other tree-level couplings have SM strength, $\kappa_i = 1$
  - Assume no BSM contributions to the total decay width
- $\kappa_g = 1.08^{+0.15}_{-0.13}$ $\kappa_\gamma = 1.19^{+0.15}_{-0.12}$



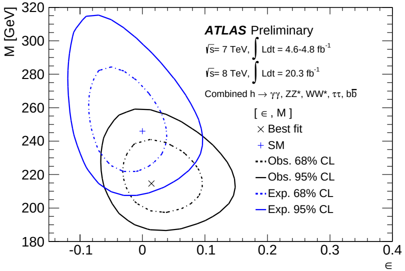
Mass scaling of couplings

- Introduce a mass scaling parameters ϵ and M:

$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}} \quad \text{and} \quad \kappa_{V,j} = v\frac{m_{V,j}^{2\epsilon}}{M^{1+2\epsilon}}$$

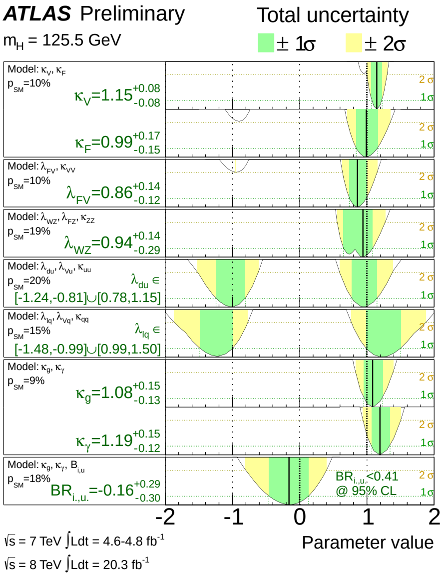
with $v \approx 246$ GeV and fermion (boson) masses $m_{f,i}$ ($m_{V,j}$)
In the SM $\epsilon = 0$ and $M = v$

- The dependence of the Higgs boson couplings fermions (bosons) is linear (quadratic) in their masses to better than 10 percent
- Inclusive signal strength μ_h drives M to be smaller than 246 GeV



Summary

- The Spin and Parity of the observed boson is consistent with $J^P = 0^+$
- The boson is produced in ggF and VBF with cross sections and branching ratios that are consistent with one SM Higgs boson.
- The coupling fits are consistent with one SM Higgs boson and symmetries and mass scaling have been measured.
- Expect improved final Run-1 analysis and >2014 higher statistics Run-2 results



Backup slides

Generic models (I)

Previous models minimized number of coupling scale factors to the ones sensitive to the probed scenario

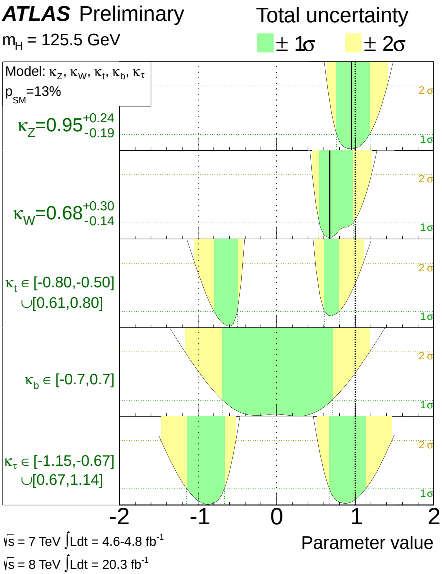
Only SM particles in loops and total width fixed to the SM value

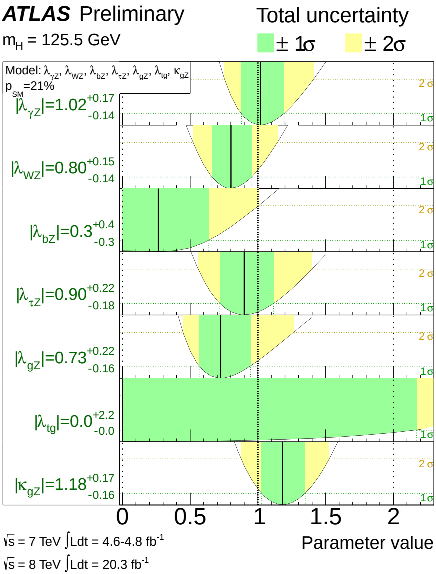
- Vertex loop factors and the total width resolved
- Sensitivity to relative sign between the *W*- and top-coupling ($h \to \gamma\gamma$)
- Small sensitivity to relative sign between the top- and bottom-coupling ($gg \to h$)

Allowing deviations in vertex loop couplings and the total width

- Drop assumptions about which particles contribute to the loops and the total width
- Effective coupling scale factors for the $gg \to h$ and $h \to \gamma\gamma$ vertices
- No sensitivity to the relative sign between coupling scale factors

Generic models (II)





References

The results are based upon:

- Phys. Lett. B 716 (2012) 1-29, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector*
- Phys. Lett. B 726 (2013), 120-144, *Evidence for the spin-0 nature of the Higgs boson using ATLAS data*
- ATLAS-CONF-2013-108, *Evidence for Higgs Boson Decays to the* $\tau^+\tau^-$ *Final State with the ATLAS Detector*
- ATLAS-CONF-2013-079, *Search for the bb decay of the Standard Model Higgs boson in associated (W/Z)H production with the ATLAS detector*
- ATLAS-CONF-2014-009, *Updated coupling measurements of the Higgs boson with the ATLAS detector using up to 25 fb*$^{-1}$
- ATLAS-CONF-2014-010, *Constraints on New Phenomena via Higgs Boson Coupling Measurements with the ATLAS Detector*
- ATL-PHYS-PUB-2013-014, *Projections for measurements of Higgs boson cross sections, branching ratios and coupling parameters...*