Combined measurements of the Mass and Couplings Properties of the Higgs boson

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Differential cross sections of the Higgs boson measured in the diphoton decay channel

using the ATLAS Detector

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on behalf of the ATLAS *Collaboration*

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Talk Overview

i. Higgs Boson Production and decay
ii. The ATLAS detector and the LHC
iii. Combining **Mass measurements** from $H \to \gamma\gamma$ & $H \to ZZ^*$
iv. Combining **Coupling measurements** for all search channels
v. **Differential Cross sections** from $H \to \gamma\gamma$
vi. Summary & Conclusions

[ATLAS-CONF-2013-014] [ATLAS-CONF-2013-034]
[Phys. Lett. B 726 (2013) 88] [ATLAS-CONF-2013-072]

Existence of Higgs field essential for mass generation of Weak vector bosons + quarks & leptons in Standard Model

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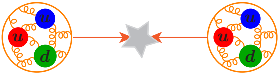
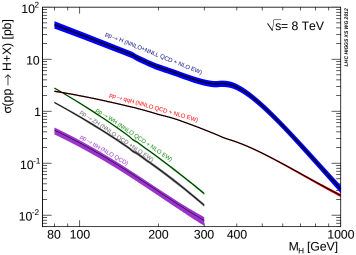
Spontaneous symmetry breaking in Higgs Mechanism produces new scalar particle: **the Higgs boson**

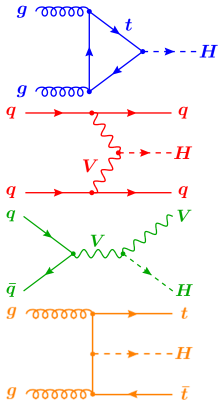


In *pp* **collisions** Higgs Boson produces via $gg \to H$, VBF, ZH, WH & ttH

Cross section for various m_H **at** $\sqrt{s} = 8$ **TeV**:

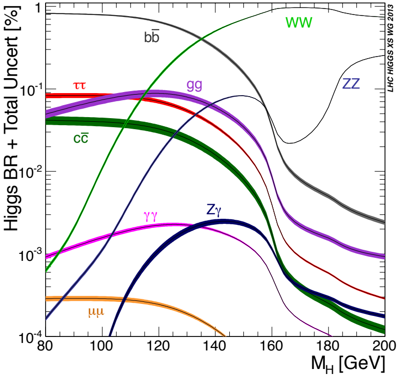


Higgs Production



Higgs Boson decays after $10^{-10} - 10^{-13}$ ps into other SM particles

Branching fractions for Higgs decay:



ATLAS Search Channels

- $H \to b\bar{b}$ for VH
- $H \to \tau^+\tau^-$
- $H \to \mu^+\mu^-$
- $H \to \gamma\gamma$
- $H \to Z\gamma$
- $H \to WW^{(*)}$
- $H \to ZZ^{(*)}$

Last year, 4th **of July** ATLAS and CMS announced discovery of new boson

↓

Couplings and spin **(see talk of Roberto Di Nardo)** seem compatible with SM Higgs boson

ii. ATLAS Detector & Large Hadron Collider

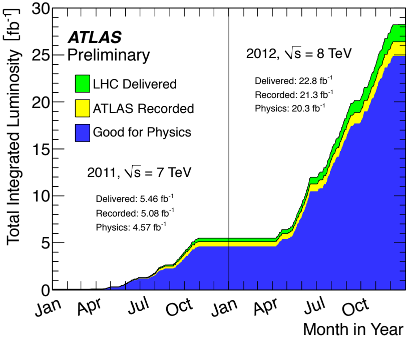
ATLAS is multipurpose detector

focus: Higgs, EW, BSM, *B* physics

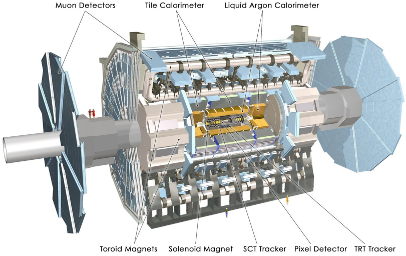
Multilayered EM & Hadronic calorimeter

excellent Tracking & Muon detection

Very successful 2011& 2012 run:



24.9/fb integrated luminosity good for physics



ATLAS detector & arial picture of the LHC

Two measurements w/ good mass resolution:
$H \to \gamma\gamma$ & $H \to ZZ^* \to 4\ell$

	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$
Higgs Mass [GeV]	$126.8 \pm 0.2 \pm 0.7$	$124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$

First error is statistical, second systematic.

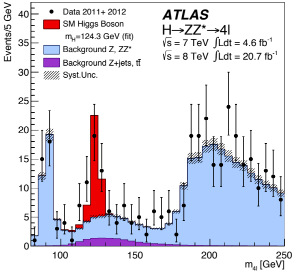
Can **combine both measurements** under the assumption of a single resonance:

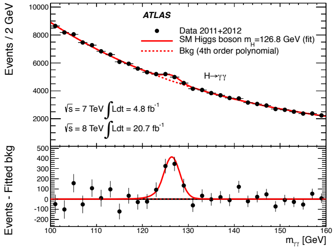
↓

Profile likelihood for combination

$$\Lambda(m_H) = \frac{\mathcal{L}(m_H)}{\mathcal{L}(\widehat{m}_H)}$$

with the full likelihood contours from the individual measurements in m_H & μ, taking into account correlated systematics.

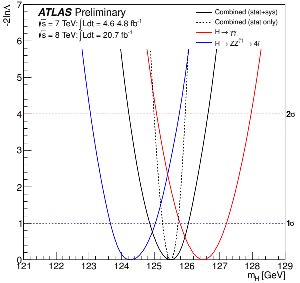




Diphoton and 4ℓ mass spectra

Combined mass maximizing test statstics:

$$m_H = 125.5 \pm 0.2^{+0.5}_{-0.6} \text{ GeV}$$

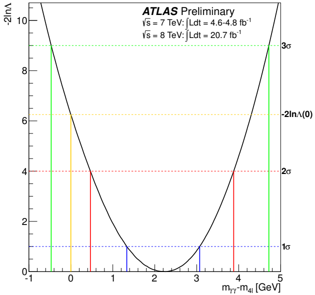


To test the consistency between both measurements a modified test statistic can be used.

↓

$$\Delta m_H = m_H^{\gamma\gamma} - m_H^{4\ell}$$

$$\Delta m_H = 2.3^{+0.6}_{-0.7} \pm 0.6 \text{ GeV}$$



Compatibility with Δm_H of the level of 1.5% (2.4σ), tension between both measurements

Assuming non-gaussian uncertainties for the 3 principal systematic uncertainties ($Z \rightarrow ee$ **calibration/extrapolation, material upstream & energy scale of presampler detector**) improves compatibility to **8%**.

Signal strength combination from

$H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW* \to \ell\nu\ell\nu$

↓

Can **combine both measurements** under the assumption of a single resonance:

↓

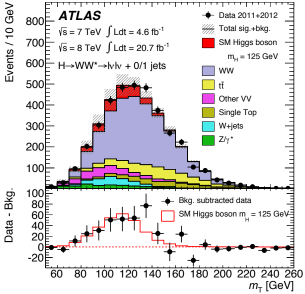
Profile likelihood for combination

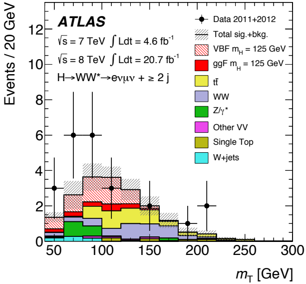
$$\Lambda(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

Coupling strength $\mu = \sigma^{\textbf{measured}} / \sigma^{\textbf{SM}}$

	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$	$H \to WW^* \to \ell\nu\ell\nu$
μ	1.6 ± 0.3	1.4 ± 0.4	1.0 ± 0.3

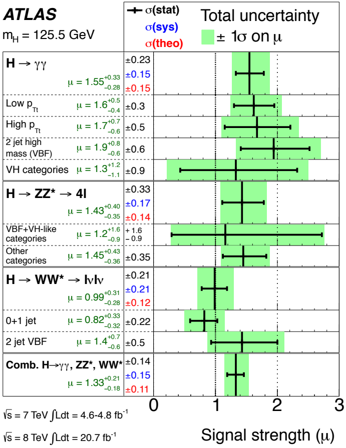
Evaluated at $m_H = 125.5$ GeV

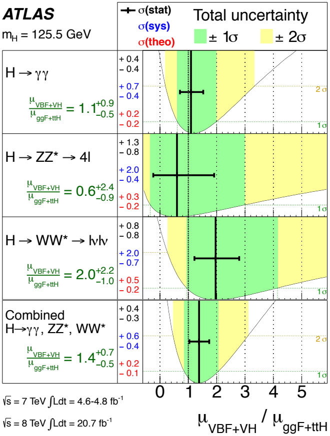




Transverse mass $m_T = \left(\left(E_T^{\ell\ell} + E_T^{\text{miss}} \right)^2 - \left| \mathbf{p}_\mathbf{T}^{\ell\ell} + \mathbf{E}_\mathbf{T}^{\text{miss}} \right| \right)^{1/2}$ distributions for $H \to WW* \to \ell\nu\ell\nu$

Combined signal strength results for μ and $\mu_{\mathbf{VBF+VH}}/\mu_{\mathbf{ggF+ttH}}$:

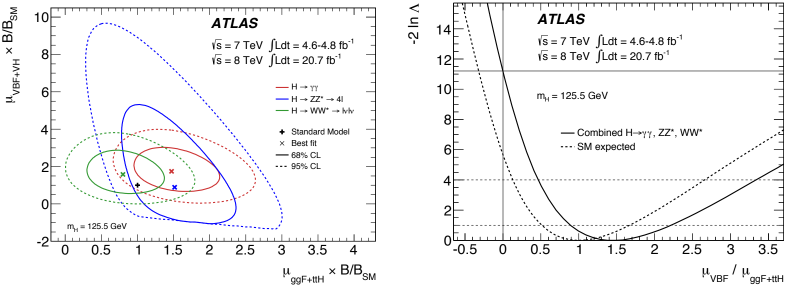




Overall signal production strength: $\mu = 1.33^{+0.21}_{-0.18}$

Evidence for VBF+VH: $\mu_{\mathbf{VBF+VH}}/\mu_{\mathbf{ggF+ttH}} = 1.4^{+0.7}_{-0.5}$

Projection in $\mu_{\mathbf{VBF+VH}}$-$\mu_{\mathbf{ggF+ttH}}$ plane:



Coupling ratio for VBF production only: $\mu_{\mathbf{VBF}}/\mu_{\mathbf{ggF+ttH}} = 1.4^{+0.4\,+0.6}_{-0.3\,-0.4}$

$\rightarrow$ Evidence at 3.3σ for VBF production!

More detailed study on the Higgs coupling can be done via *leading order tree-level motivated* framework.

Assumptions:

i. Single resonance at $m_H = 125.5$ GeV
ii. Narrow width approximation holds, i.e. rates of the process $i \to H \to f$ are given by

$$\sigma \cdot \mathcal{B} = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

with Γ_H the Higgs width, and Γ_f the partial width of the $H \to f$ transition, and σ_i the cross section for $i \to H$ production.

iii. No modifications in the tensor structure of the SM Lagrangian, i.e. Higgs is 0^+

Free parameters in the framework: coupling scale factors κ_j^2 ratio of measured over SM cross section times partial decay width , κ_H^2 the total Higgs width, or double ratios of the coupling scale factors $\lambda_{ij} = \kappa_i/\kappa_j$.

E.g. the effective couplings of $gg \to H \to \gamma\gamma$ can be written as

$$\frac{(\sigma \cdot \mathcal{B})^{\text{meas}}}{(\sigma \cdot \mathcal{B})^{\text{SM}}} = \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$

Variety of benchmark models with focus on different observables:

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$

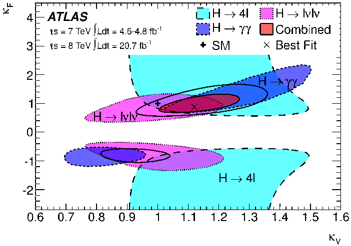
The ticks correspond to a certain fixed functional dependence – more details in backup

Model 1: One coupling factors for fermions and one coupling factor for bosons: κ_F, κ_V

Model 2: Removing the constraint on the Higgs boson width (i.e. that the measured partial widths have to saturate the total width) only the rato $\lambda_{FV} = \kappa_F/\kappa_V$ and $\kappa_{VV} = \kappa_V^2/\kappa_H$ can be measured.

Model 1	Model 2
$\kappa_F = 0.86^{+0.32}_{-0.10}$	$\lambda_{FV} \in [0.71, 1.01]$
$\kappa_V = 1.12^{+0.07}_{-0.10}$	$\kappa_{VV} \in [1.13, 1.45]$

Compatibility of SM with both model fits: 12%.



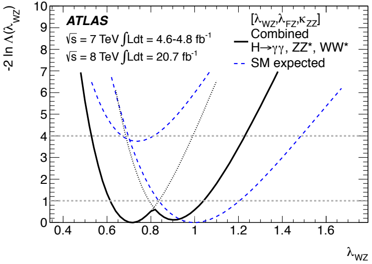
SM custodial symmetry: W & Z couple identically to Higgs , i.e. $\lambda_{WZ} = \kappa_W/\kappa_Z = 1$

Model 3 & 4: $H \rightarrow VV$ & $i \rightarrow H \rightarrow VV$ information; Model 4 also includes one degree of freedom for a potential BSM to $H \rightarrow \gamma\gamma$

Model 3	Model 4
$\lambda_{WZ} = 0.81^{+0.16}_{-0.15}$	$\lambda_{WZ} = 0.82 \pm 0.15$

Compatibility of SM with Model 4: 20%.

Calculated using full 4D covariance between determined values.

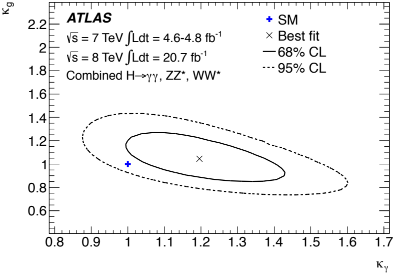


Model 5: Result for κ_g & κ_γ:

$$\kappa_g = 1.04 \pm 0.14$$
$$\kappa_\gamma = 1.20 \pm 0.15$$

Compatibility of SM with fit: 14%.

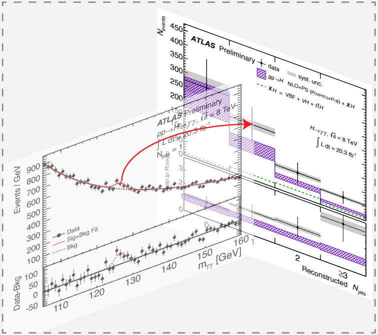
Calculated using full 2D covariance between determined values.



Differential cross section measurements from $H \to \gamma\gamma$

Analysis Idea Illustrated

Simultaneous unbinned Likelihood fit in $m_{\gamma\gamma}$

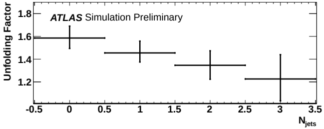


Unfolding

* Unfold yields into cross sections using **bin-by-bin** correction factors

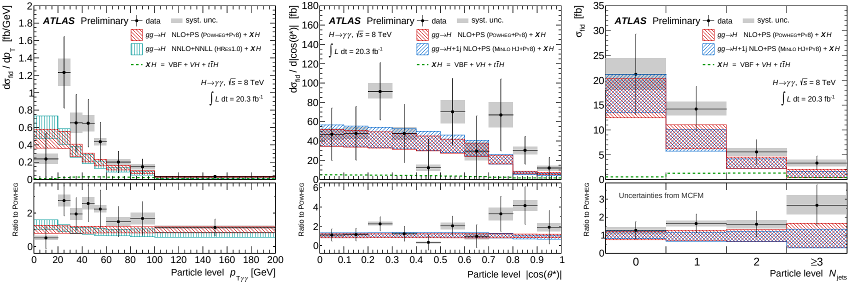
* Truth fiducial definition chosen to closely match experimental selection.

→ Minimizes model dependence.



Measured 7 variables: Higgs p_T and rapidity, $\cos\Theta^*$, N_{jets}, leading jet p_T, p_T^{H+jj}, $\Delta\phi_{jj}$

Higgs p_T, helicity angle, and N_{jets} compared with HRes, Powheg+Py8, HJ Minlo+Py8



Compatibility with SM predictions:

P-value based on χ^2 using full experimental + theory covariance

	N_{jets}	$p_{\mathrm{T}}^{\gamma\gamma}$	$\lvert y^{\gamma\gamma}\rvert$	$\lvert\cos\theta^*\rvert$	$p_{\mathrm{T}}^{j_1}$	$\Delta\phi_{jj}$	$p_{\mathrm{T}}^{\gamma\gamma jj}$
POWHEG	0.54	0.55	0.38	0.69	0.79	0.42	0.50
MINLO	0.44	–	–	0.67	0.73	0.45	0.49
HRes 1.0	–	0.39	0.44	–	–	–	–

∗ Statistical limited at this point

→ Good agreement with SM predictions.

* Combination of precision mass measurement from $H \to \gamma\gamma$ & $H \to ZZ^*$:

$$m_H = 125.5 \pm 0.2^{+0.5}_{-0.6}\ \text{GeV}$$

Seems to disfavor single Higgs-like boson; compatibility with a single resonance is 1.5% or a tension of 2.4σ between both masses is observed, maybe due to strong non-gaussian behavior of systematic uncertainties.

* Overall signal production strength combining $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$:

$$\mu = 1.33^{+0.21}_{-0.18}$$

Observed coupling compatible with SM Higgs

* VBF coupling strength from combination:

$$\mu_{\mathbf{VBF}}/\mu_{\mathbf{ggF+ttH}} = 1.4^{+0.4+0.6}_{-0.3-0.4}$$

$\to$ Evidence of 3.3σ for VBF production of Higgs

* Results with *leading order tree-level motivated* framework:

Assumptions — Single resonance, 0^+, narrow width approx.

* **5 models** with focus on different observables:

- **1/2** Couplings to Fermions & Bosons
- **3/4** Custodial Symmetry
- **5** Vertex loops

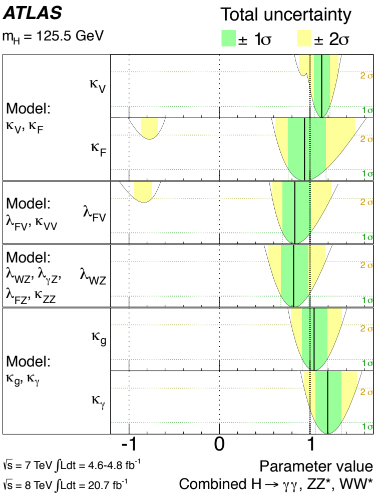
→ All determined couplings compatible with the SM

(p-values ranging from 12-20%)

* **Differential cross section measurements** from $H \to \gamma\gamma$

* 7 observables studied, e.g. Higgs p_T and helicity angle

→ All measured distributions compatible with the SM.



Backup