Review of the current status of Higgs Properties

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November, 2013

CAP 2014
Sudbury

Talk Overview

Introduction

i. Higgs Boson Production and decay
ii. The ATLAS detector and the LHC
iii. Combined **Mass measurements** from $H \to \gamma\gamma$ & $H \to ZZ^*$

Properties

iv. Combining **Coupling measurements** for all search channels
v. **Combined** Spin analysis from $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$
vi. **Differential Cross sections** from $H \to \gamma\gamma$

Summary

vii. Conclusions & Outlook

[ATLAS-CONF-2014-009] [Phys. Lett. B 726 (2013) 88]
[ATLAS-CONF-2013-072] [ATLAS-CONF-2013-040]

New: [Mass paper – to be submitted]

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

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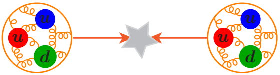
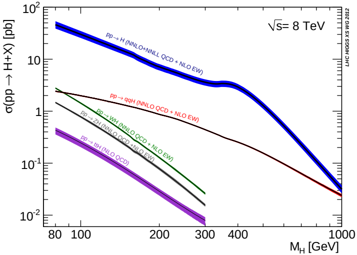
Spontaneous symmetry breaking in Higgs Mechanism produces new scalar particle: **the Higgs boson**

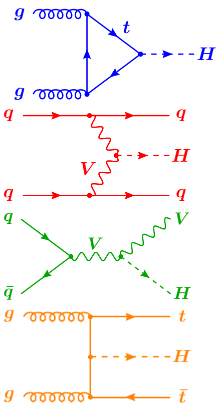


In *pp* **collisions** Higgs Boson produces via $gg \to H$, VBF, ZH, WH & ttH

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

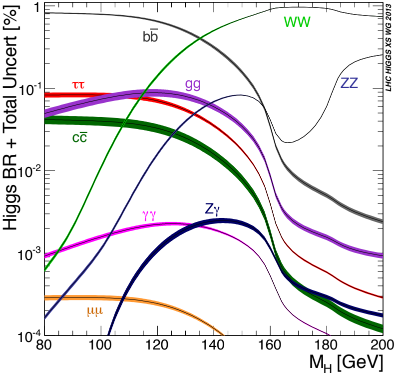


Higgs Production



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

July 4th 2012: ATLAS and CMS announced discovery of new boson

↓

Searches overview: **(see talk of Doug Schouten)**; Coupling & Spin compatible with SM Higgs boson

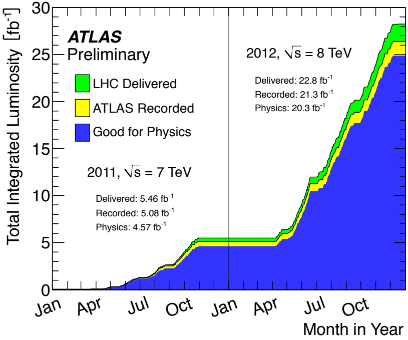
ATLAS is multipurpose detector

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

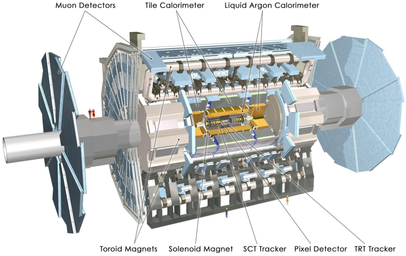
Multilayered EM & Hadronic calorimeter

excellent Tracking & Muon detection

Very successful 2011& 2012 run period:



24.9/fb integrated luminosity good for physics



ATLAS detector & arial picture of the LHC

iii.a New! Combined mass measurements for $H \to \gamma\gamma$ & $H \to ZZ^*$

Much improved EM cluster energy correction via MVA regression & more accurate geometry

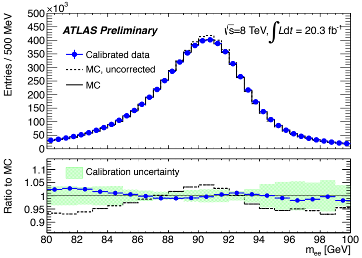
→ Largely improved resolution for $H \to \gamma\gamma$.

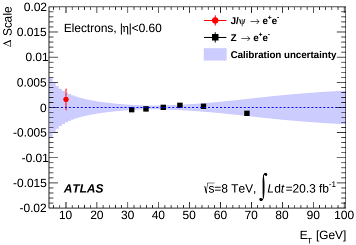
Energy scale & resolution extracted from reference process: $Z \to ee$

Good data & sim. agreement after corrections

linearity and extrapolation to photons checked with other leptonic reference processes and $Z \to \ell\ell\gamma$ events.

Large effort reduced systematic uncertainties in $H \to \gamma\gamma$ by more than a factor of two





iii.b New! Combined mass measurements for $H \to \gamma\gamma$ & $H \to ZZ^*$

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]	$125.98 \pm 0.42 \pm 0.28$	$124.51 \pm 0.52 \pm 0.06$
Old calibration	$126.8 \pm 0.2 \pm 0.7$	$124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$

First error is statistical, second systematic.

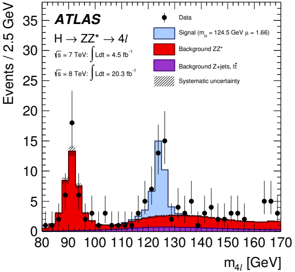
Combine both measurements under the assumption of a single resonance:

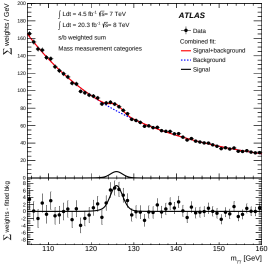
↓

Profile likelihood for combination

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

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

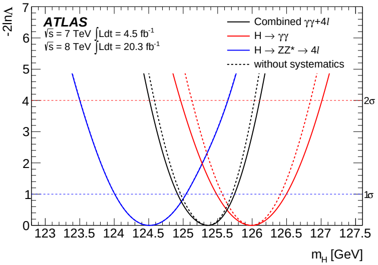




Combined mass maximizing test statstics:

$$m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$$

Old calibration $125.5 \pm 0.2^{+0.5}_{-0.6}$ GeV



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

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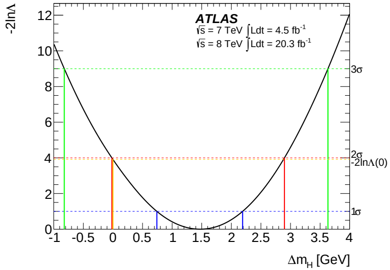
$$\Delta m_H = m_H^{\gamma\gamma} - m_H^{4\ell}$$

$$\Delta m_H = 1.47 \pm 0.67 \pm 0.28 \text{ GeV}$$

Old calibration $2.3^{+0.6}_{-0.7} \pm 0.6$ GeV



Compatibility with Δm_H of the level of 4.9% (2.0σ)

Assuming non-gaussian uncertainties for the 3 principal systematic uncertainties ($Z \to ee$ **calibration/extrapolation, material upstream & energy scale of presampler detector**) improves compat. to **11%**.

Signal strength combination from

$H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, $H \to WW^* \to \ell\nu\ell\nu$
$VH \to Vb\bar{b}$, $H \to \tau\tau$

$\downarrow$

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

$\downarrow$

Profile likelihood for combination

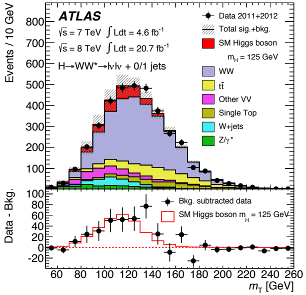
$$\Lambda(\mu) = \frac{\mathcal{L}(\mu)}{\mathcal{L}(\hat{\mu})}$$

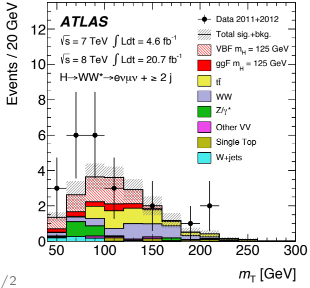
Coupling strength $\mu = \sigma^{\textbf{measured}} / \sigma^{\textbf{SM}}$

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

$VH \to Vb\bar{b}$	$H \to \tau\tau$
0.2 ± 0.7	1.4 ± 0.5

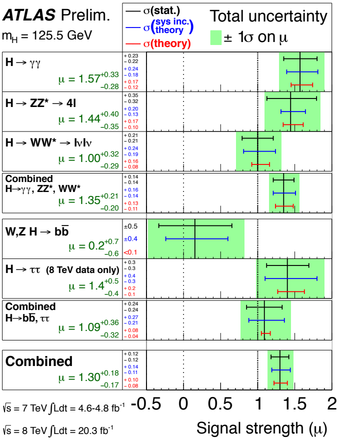
Evaluated at $m_H = 125.5$ GeV

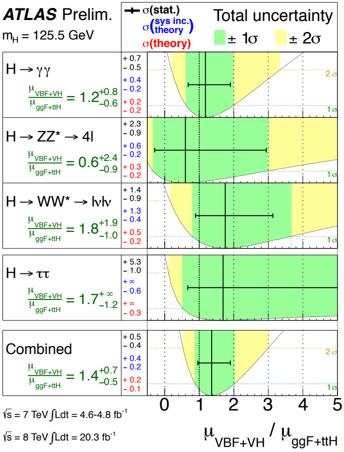




Plots: Transverse mass $m_T = \left(\left(E_T^{\ell\ell} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_\mathbf{T}^{\ell\ell} + \mathbf{E}_\mathbf{T}^{\text{miss}}\right|\right)^{1/2}$ distributions for $H \to WW* \to \ell\nu\ell\nu$

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

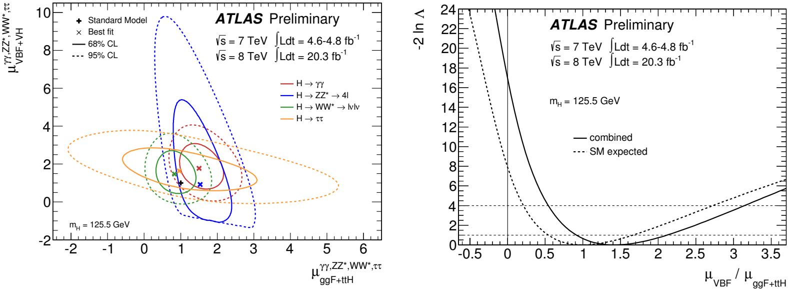




Overall signal production strength: $\mu = 1.30^{+0.18}_{-0.17}$

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: $\mu_{\mathbf{VBF}}/\mu_{\mathbf{ggF+ttH}} = 1.4^{+0.5}_{-0.4}{}^{+0.4}_{-0.3}$

$\rightarrow$ Evidence at 4.1σ 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

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

Selection of benchmark models with focus on different observables:

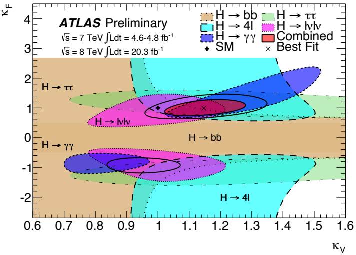
Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
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
$\kappa_F = 0.99^{+0.17}_{-0.15}$	$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$
$\kappa_V = 1.15^{+0.08}_{-0.08}$	$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$



Compatibility of SM with both model fits: 10%.

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

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

Model 3	**Model 4**
$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$	$\lambda_{WZ} = 0.80 \pm 0.15$

Compatibility of SM with Model 4: 21%.

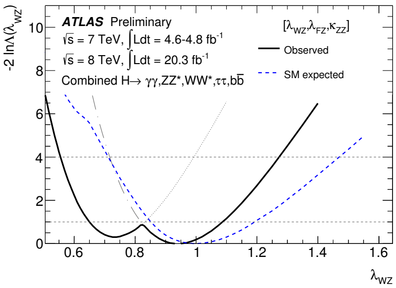
Calculated using full 7D covariance between determined values.

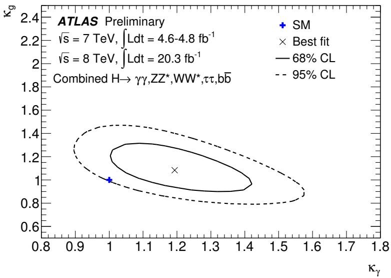
Model 5: Result for κ_g & κ_γ:

$$\kappa_g = 1.08^{+0.15}_{-0.13}$$
$$\kappa_\gamma = 1.19^{+0.15}_{-0.12}$$

Compatibility of SM with fit: 9%.

Calculated using full 2D covariance between determined values.





Spin & CP can be inferred by angular correlation of Higgs decay products:

Channels used for combination: $H \to \gamma\gamma$
$H \to ZZ^*$, $H \to WW^*$.

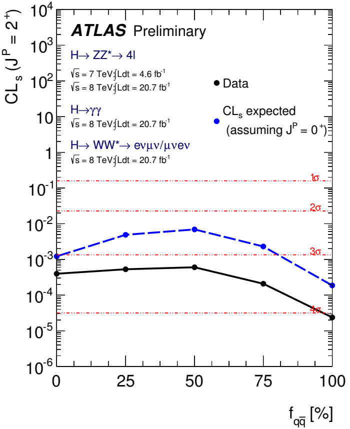
↓

Hypothesis test: Spin 0^- **(SM)** versus Spin 2^+

Test spin 2 admixture of leading order $q\bar{q} \to X$ & $gg \to X$ production: $f_{q\bar{q}}$

↓

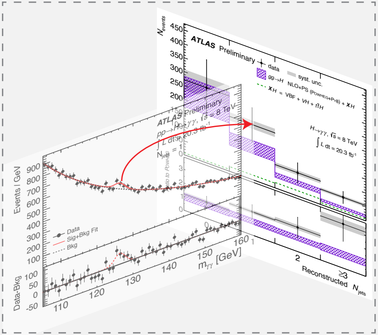
Entire Spin 2^+ configuration space excluded at **99.9%** CL_s.



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

Analysis Idea Illustrated

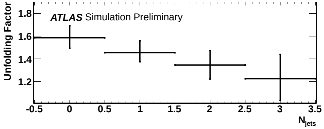
Simultaneous unbinned Likelihood fit in $m_{\gamma\gamma}$



Unfolding

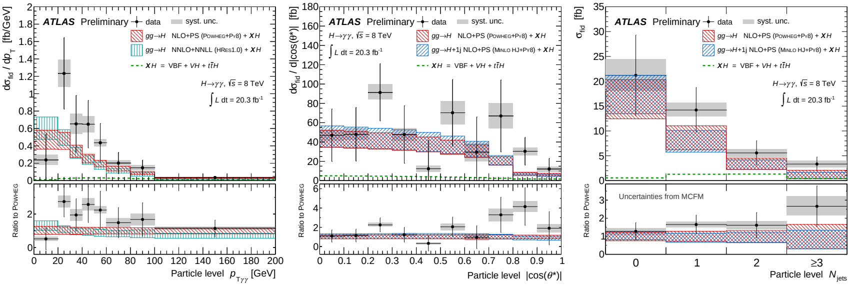
- * Unfold yields into cross sections using **bin-by-bin** correction factors
- * Truth fiducial definition chosen to closely match experimental selection.

→ 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}	$p_T^{\gamma\gamma}$	$\lvert y^{\gamma\gamma}\rvert$	$\lvert\cos\theta^*\rvert$	$p_T^{j_1}$	$\Delta\phi_{jj}$	$p_T^{\gamma\gamma jj}$
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.

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

$$m_H = 125.36 \pm 0.37 \pm 0.18 \text{ GeV}$$

New calibration reduces tension between both channels.

* Overall signal production strength combining $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$, $VH \to Hb\bar{b}$, $H \to \tau\tau$: (with old calibration and mass)

$$\mu = 1.30^{+0.18}_{-0.17}$$

Observed coupling compatible with SM Higgs

* VBF coupling strength from combination:

$$\mu_{\mathbf{VBF}} / \mu_{\mathbf{ggF+ttH}} = 1.4^{+0.5+0.4}_{-0.4-0.3}$$

$\to$ Evidence of 4.1σ for VBF production of Higgs

vi.b Conclusion

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

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

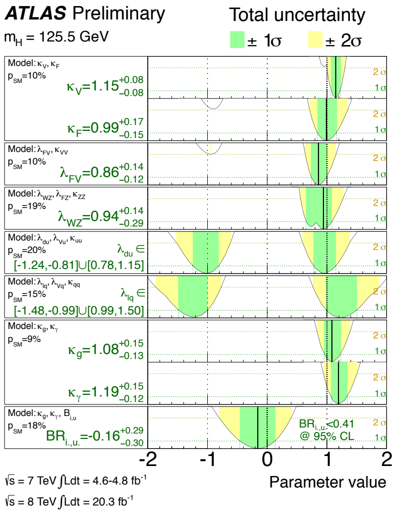
- * **5 models** with focus on different observables:
  - **1/2** Couplings to Fermions & Bosons
  - **3/4** Custodial Symmetry
  - **5** Vertex loops

→ 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.



Updated coupling analysis paper in preparation

Updated differential & fiducial cross section paper in preparation

Other interesting results out, like low- & high-mass search for additional narrow resonances [ATLAS-CONF-2014-031]

We are in the transition period from discovery to more precise measurements. Very exciting conditions for LHC Run period 2.

Slight **Paradigm shift ongoing:** unfolded differential distributions will make it possible for outsiders to test our understanding of the Higgs boson

Thank you

Backup