ATLAS results on Higgs boson couplings and properties

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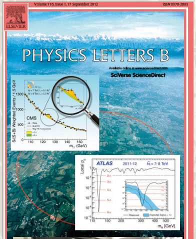
Outline

- In the following slides, results on ATLAS measurements of some of the properties of the Higgs boson discovered in 2012
- Mass measurement will be shown first. In the SM other properties can be computed for a given value of the Higgs mass.



Outline:

Introduction

- ATLAS have chosen a model-independent approach to measure the Higgs boson mass.
- Fitting the mass spectra of the two decay modes $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$.
- In these two channels the Higgs boson produces a narrow mass peak with a typical experimental resolution of 1.6 GeV to 2 GeV over a smooth background.
- Effects are expected between the Higgs boson signal and SM background processes.

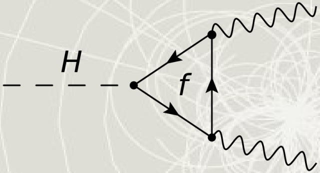
$H \to ZZ^* \to 4\ell$ interference is negligible if Higgs width is close to the SM value

$H \to \gamma\gamma$ interference is expected to have a small impact in the mass measurement (about 50 MeV) with respect to current experimental uncertainties

$H\to\gamma\gamma$ channel

Event selection

- Events selected by di-photon trigger
- Two offline identified photons passing a *tight* identification
- Within the pseudorapidity acceptance: $0< |\eta| <1.37$, $1.56< |\eta| <2.37$
- The calorimeter pointing information are combined with the track information to determine the z position of the H decay
- $\gamma^1_{p_T} > 0.35 \times m_{\gamma\gamma}$, $\gamma^2_{p_T} > 0.25 \times m_{\gamma\gamma}$, 105 GeV $< m_{\gamma\gamma} <$160 GeV
- Photons are required to be isolated:



Calorimeter Energy deposit in a cone of $\Delta R = 0.4$ around the photon candidate excluding an area of $\Delta\eta \times \Delta\phi$=0.125×0.175

Track Scalar sum of track p_T in a cone ΔR=0.2, except tracks associated to converted photons

Data-taking	Trigger	Calorimeter isolation	track isolation
7 TeV	$\gamma^{1,2}_{p_T} > 20$ GeV	< 5.5 GeV	none
8 TeV	$\gamma^1_{p_T} > 35$ GeV, $\gamma^2_{p_T} > 25$ GeV	< 6 GeV	< 2.6 GeV

10 Categories defined by the $|\eta|$ of each photon and the p_{Tt}[1] with different s/b ratios

[1] Component of the diphoton thrust axis in the transverse plain

Signal/Background modeling

Signal modeling

- The signal mass spectrum is modeled by the sum of a Crystal Ball function for the bulk of the events and a wide Gaussian distribution to model the far outliers in the mass resolution
- All parameters as a function of the mass are obtained by fitting MC simulated signal

Background modeling

- Background modeling is taken from 12 function candidates including exponentials of first-, second-, or third-order polynomials, and third-, fourth-, or fifth-order Bernstein polynomials.
- For each category, background only MC simulation is fitted by signal+background hypothesis using all background models.
- The fitting function is chosen to be the one that better fit the background with the smallest bias on the signal.

Mass Measurement

- The mass spectra for the ten data categories and the two center-of-mass energies are fitted simultaneously
- Using an unbinned maximum likelihood fit with background and signal parameterization
- Mass and signal strength (yield normalized to the SM prediction) and background parameters obtained from the fit.
- Systematic uncertainties are dominated by the photon Energy scale.

Result

$$m_H = 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})\ \text{GeV}$$

$$\mu = 1.29 \pm 0.30$$

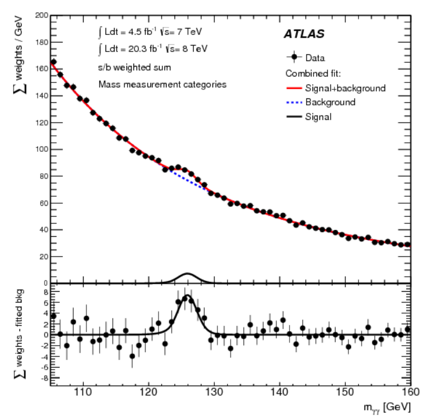
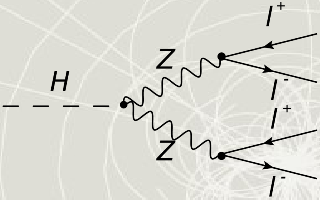


Figure: Invariant mass distribution in the $H\to\gamma\gamma$ analysis for data (7 TeV and 8 TeV samples combined), showing weighted data points with errors, and the result of the simultaneous fit to all categories.

H→ ZZ^* → 4ℓ channel

Event selection



- Events selected by a trigger requiring either a single muon, single electron, two muons or two electrons (see table below)
- Four leptos required ($4e$, $2e2\mu$, $2\mu2e$, 4μ)
  - first pair matches the Z mass: 50 GeV $< m_{12} <$ 106 GeV.
  - second pair matches: $m_{thr}(m_{4\ell}) < m_{34} <$ 115 GeV.

Electron ID Cut based for 7 TeV and likelihood for 8 TeV data, 0< $|\eta|$ <2.47, $p_T >$ 7 GeV

Muon ID Uses tracks from ID, MS and information from the calorimeters, 0< $|\eta|$ <2.7, $E_T >$ 6 GeV

- Two same flavor opposite sign leptons required, $\Delta R >$ 0.1(0.2) for same (different) flavor

Multivariative Discriminant to separate signal and ZZ^* background

- Multivariative discriminant was implemented to better discriminate signal over ZZ^* background based on Boosted Decision Tree
- Variables for the training: $p_T^{4\ell}$, $\eta^{4\ell}$ and $D_{ZZ^*} = ln\left(\frac{|M_{sig}|^2}{|M_{ZZ}|^2}\right)$; M_{sig}, M_{ZZ} taken from LO MadGraph

Data-taking	single Trigger	double Trigger
7 TeV	$e_{E_T} >$ 20 GeV, $\mu_{p_T} >$ 18 GeV	$e_{E_T}^{1,2} >$ 10 GeV, $\mu_{p_T}^{1,2} >$ 6 GeV
8 TeV	$e_{E_T} >$ 25 GeV, $\mu_{p_T} >$ 18 GeV	$e_{E_T}^{1,2} >$ 13 GeV, $\mu_{p_T}^{1,2} >$ 13 GeV or $\mu_{p_T}^{1}$ >18 GeV $\mu_{p_T}^{2}$ >8 GeV

Mass measurement

2D fit

- The mass measurement is performed on a 2D fit on $m_{4\ell}$ and the output of the BDT $O_{BDT_{ZZ*}}$
- The PDF in the 2D model is:

$$\mathcal{P}(m_{4\ell}, O_{BDT_{ZZ*}}|m_H) = \mathcal{P}(m_{4\ell}|O_{BDT_{ZZ*}}, m_H)\mathcal{P}(O_{BDT_{ZZ*}}|m_H) \simeq \left(\sum_{n=1}^{4} \mathcal{P}_n(m_{4\ell}|m_H)\theta_n(O_{BDT_{ZZ*}})\right)\mathcal{P}(O_{BDT_{ZZ*}}|m_H)$$

- θ_n defines four equal-sized bins for the value of the BDT_{ZZ*}
- $\mathcal{P}_n$ is the 1D PDF for $m_{4\ell}$

Result

$m_H =$ 124.51 $\pm$ 0.52 (stat) $\pm$ 0.06 (syst) GeV

$\mu =$ 1.66 $^{+0.45}_{-0.38}$

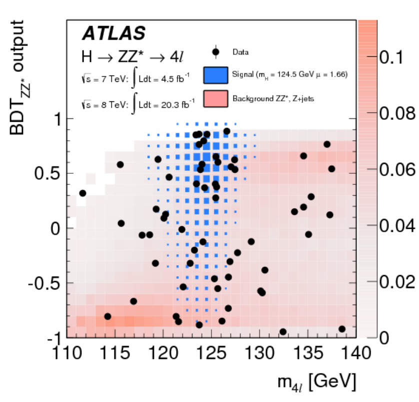


Figure: Distribution of the BDT ZZ^* output, versus $m_{4\ell}$ for the selected candidates in the 110-140 GeV $m_{4\ell}$ range for the combined 7 TeV and 8 TeV data samples.

Mass combination

- For the combination, hypothesized values of m_H are tested using the profile likelihood ratio:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_{\gamma\gamma}(m_H), \hat{\hat{\mu}}_{4\ell}(m_H), \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell})}$$

- $\mu_{\gamma\gamma}(m_H)$ and $\mu_{4\ell}(m_H)$ are treated as nuisance parameters to avoid making assumptions on the SM Higgs couplings

Result

m_H = 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV

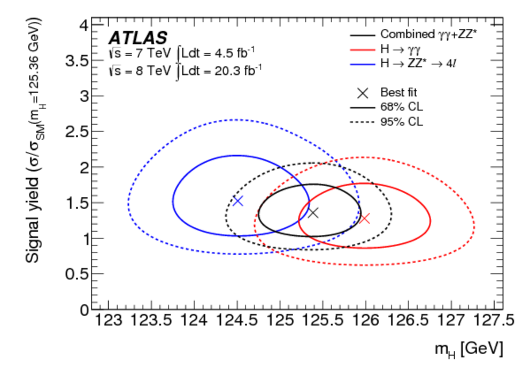


Figure: Likelihood contours $-2\ln\Lambda(S, m_H)$ as a function of strength μ and m_H for the H→ $\gamma\gamma$ and H→ ZZ^* → 4ℓ channels and their combination, including all systematic uncertainties.

Production, decay and coupling strengths

- Signal strengths and coupling combinations are done using the $\gamma\gamma$, ZZ^*, WW, $\tau\tau$, $b\bar{b}$, $\mu\mu$ and $Z\gamma$
- Table below (and following) describe each decay channel, with categorization aiming to identify production process
- Signal strength from individual analyses (before combination)
- Significances observed for 7 TeV (8TeV) and check marks if category used for each data taking
- Both, H$\rightarrow \gamma\gamma$ and H$\rightarrow ZZ^* \rightarrow 4\ell$ target ggF, VBF and VH production. ttH production only addressed by H$\rightarrow \gamma\gamma$

Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \rightarrow \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, $E_{\mathrm{T}}^{\mathrm{miss}}$, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \rightarrow ZZ^* \rightarrow 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓

H→ WW^*

- H→ WW^* analysis targets the ggF, VBF, and VH production modes.
- Candidates are categorised according to the number of jets, number of leptons and lepton flavours.

ggF 0, 1 or ≤ 2 Jets (latter only different flavour leptons, only), combined fit to the transverse mass of dilepton plus E_T^{miss}

VBF ≤ 2 Jets, same and different lepton flavour. BDT combining rapidity separation and mass of leading jets

VH Different lepton multiplicities and/or E_T^{miss}, depending on the targeted decay of the vector bosons. Events with b-jet vetoed.

Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \to WW^*$ [14,15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ ($ee + \mu\mu$, $e\mu$)			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓

- Although all production channels studied on both 7 TeV and 8 TeV data, not all categories defined in 7 TeV analysis.

H$\to\tau\tau$ and VH, H$\to b\bar{b}$

- The H$\to\tau\tau$ considers both the leptonic and hadronic τ decay.
  - ggF Boosted production, defined as $H_{p_T} >$100 GeV.
  - VBF Requires two separated additional jets. BDT implemented to discriminate signal from background
- The H$\to b\bar{b}$ is analyzed only in the VH production, as inclusive search not possible due overwhelming background from multijet production
- VH search is performed for events containing 0, 1 or 2 ℓ, b-tagging, and different Jet multiplicity categories
- An maximum-likelihood fit is performed an all categories simultaneously to extract the signal

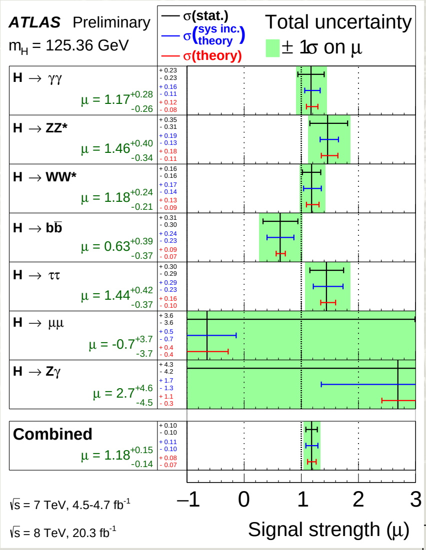
Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H\to\tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH\to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH\to\nu\nu bb$): $N_{jet}=2,3$, $N_{btag}=1,2$, $p_T^V >$ and $<$ 120 GeV			✓	✓
1ℓ ($WH\to\ell\nu bb$): $N_{jet}=2,3$, $N_{btag}=1,2$, $p_T^V >$ and $<$ 120 GeV			✓	✓
2ℓ ($ZH\to\ell\ell bb$): $N_{jet}=2,3$, $N_{btag}=1,2$, $p_T^V >$ and $<$ 120 GeV			✓	✓

Measurement of signal strength

- Hypothesis testing and confidence intervals are based on the $\Lambda(\alpha)$ profile likelihood ratio test statistic.

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})}$$

- Figure shows measurements of μ from a simultaneous fit to all decay channels analysed, for m_H=125.36 GeV.
- Signals corresponding to the same decay channel are combined together.
- The best-fit values $\rightarrow$ vertical lines. The total $\pm 1\sigma$ in GREEN, stat (top), total (middle), and theory (bottom) uncertainties.



Combining all measurements using $\Lambda(\mu)$ Results

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10\,\text{(stat.)} \pm 0.07\,\text{(syst.)}\,^{+0.08}_{-0.07}\,\text{(theo.)}$$

Production cross section

- Assuming SM BRs, the production can be probed with signal-strength parameters μ_{gg}, μ_{VBF}, μ_{VH} and μ_{ttH}
- Then SM predictions scaled to these strengths
- The theoretical uncertainties on the SM prod. cross sections are removed
- Remaining theoretical uncertainties related to the modelling of the Higgs production and acceptance of the event selection

Production process	Cross section [pb] at $\sqrt{s} = 8$ TeV	
ggF	23.9 ± 3.6	$\begin{bmatrix} +3.1 & +1.9 & +1.0 \\ -3.1 & -1.6 & -1.0 \end{bmatrix}$
VBF	2.43 ± 0.58	$\begin{bmatrix} +0.50 & +0.27 & +0.19 \\ -0.49 & -0.20 & -0.16 \end{bmatrix}$
VH	1.03 ± 0.53	$\begin{bmatrix} +0.37 & +0.22 & +0.13 \\ -0.36 & -0.20 & -0.06 \end{bmatrix}$
ttH	0.24 ± 0.11	$\begin{bmatrix} +0.07 & +0.08 & +0.01 \\ -0.07 & -0.08 & -0.01 \end{bmatrix}$

Table: Measured cross sections of different Higgs boson production processes at $\sqrt{S} = 8$ TeV for m_H = 125.36 GeV obtained from the signal-strength values

- The resulting total Higgs boson production cross sections at the two energies are

$$\sigma_H(7\,\text{TeV}) = 22.1\,^{+7.4}_{-6.0}\,\text{pb} = 22.1\,^{+6.7}_{-5.3}\,(\text{stat.})\,^{+2.7}_{-2.3}\,(\text{syst.})\,^{+1.9}_{-1.4}\,(\text{theo.})\,\text{pb}, \text{ and}$$

$$\sigma_H(8\,\text{TeV}) = 27.7 \pm 3.7\,\text{pb} = 27.7 \pm 3.0\,(\text{stat.})\,^{+2.0}_{-1.7}\,(\text{syst.})\,^{+1.2}_{-0.9}\,(\text{theo.})\,\text{pb},$$

- To be compared to calculated XS: 17.4 ± 1.6 at $\sqrt{s} = 7$ TeV and 22.3 ± 2.0 at $\sqrt{s} = 8$ TeV (1).

Boson and fermion-mediated production

- The relative production cross sections of the vector boson and fermion-mediated processes can be tested
- The Higgs boson production processes can be categorised into:

Coupling to Fermions ggF and ttH productions

Coupling to Vector bosons VBF and VH productions

- Deviations from SM can be tested with two signal-strength parameters, $\mu^f_{ggF+ttH} \equiv (\mu^f_{ggF} = \mu^f_{ttH})$ and $\mu^f_{VBF+VH} \equiv (\mu^f_{VBF} = \mu^f_{VH})$, for each decay channel f
- SM values for the ratio of ggF and ttH cross sections and the ratio of VBF and VH cross sections are assumed
- The relative production cross sections of the processes mediated by vector bosons and by fermions can be tested using the ratio

$$R = \frac{\mu^f_{VBF+VH}}{\mu^f_{ggF+ttH}}$$

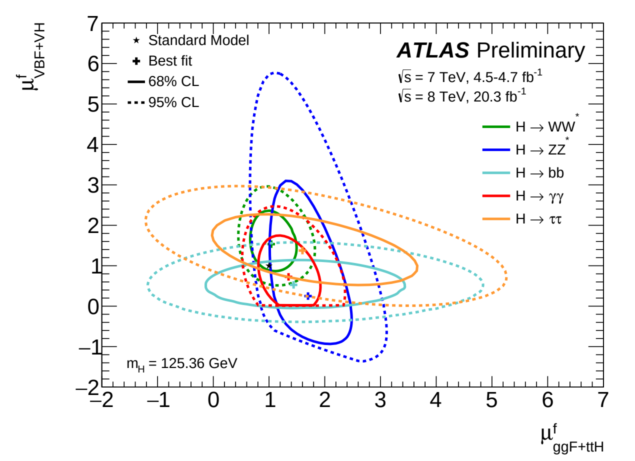
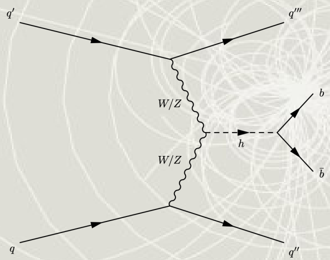


Figure: Likelihood contours in the $(\mu^f_{ggF+ttH}, \mu^f_{VBF+VH})$ plane for a Higgs boson mass m_H= 125.36 GeV measured separately for H→ WW^*, H→ $ZZ^* \to 4\ell$, H→$b\bar{b}$, H→ $\gamma\gamma$ and H→ $\tau\tau$.

Combination of ratio: $R_{combined} = 0.96^{+0.43}_{-0.31} = 0.96^{+0.33}_{-0.26}(stat.)^{+0.20}_{-0.13}(syst.)^{0.18}_{-0.10}(theo.)$.

Coupling strength fits

- Production and decay modes cannot be treated independently $\rightarrow$ at least two coupling strengths
- Measurements scale factors k_j are implemented for the combination of all analyses (2)
- Using the zero width approximation, cross section $\sigma(i \rightarrow H \rightarrow f)$ becomes
  $$\sigma(i \rightarrow H \rightarrow f) = \frac{\sigma_i(k_j) \cdot \Gamma_f(k_j)}{\Gamma_H(k_j)}$$
- for SM, $k_j = 1$, otherwise, $\sigma_j = k_j^2 \sigma^{SM}$
- Deviations from 1 of k_j would change the Higgs width by a factor of:
  $$\Gamma_H(k_j) = k_H^2(k_j) \cdot \Gamma_H^{SM}$$
  - Only modifications of coupling strengths are taken into account
  - The channels H$\rightarrow WW^*$, H$\rightarrow ZZ^*$, H$\rightarrow b\bar{b}$, H$\rightarrow \tau\tau$ probe a single coupling-strength scale factor to either a gauge boson or a fermion
  - The channels H$\rightarrow \gamma\gamma$, H$\rightarrow Z\gamma$ probe W and t couplings



2D fit to k_V and k_F

- Assuming only SM contributions to the width (two-parameter benchmark model):

$$k_V = k_Z = k_W$$
$$k_F = k_t = k_b = k_g = k_\mu$$

- As a result of the fit the scale factors obtained:

$$k_V = 1.09 \pm 0.7 \left[^{+0.05}_{-0.05}(stat.)^{+0.03}_{-0.03}(syst.)^{+0.04}_{-0.03}(theo.) \right]$$
$$k_F = 1.11 \pm 0.16 \left[^{+0.12}_{-0.11}(stat.)^{+0.10}_{-0.09}(syst.)^{+0.06}_{-0.05}(theo.) \right]$$

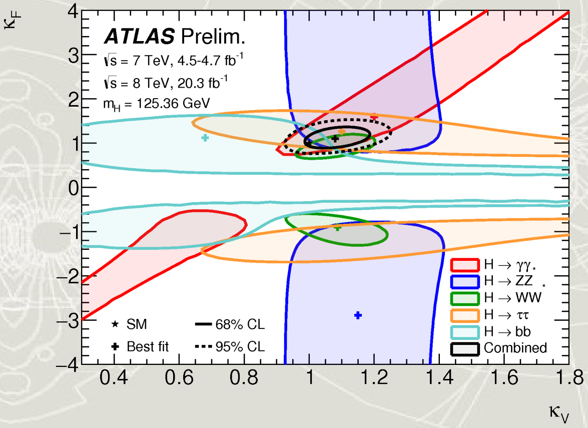


Figure: Results of fits for the two-parameter benchmark model, probing coupling-strength scale factors for fermions and vector bosons, assuming only SM contributions to the total width.

No assumption on the width

- As the total width is dominated by b, τ and gluon-decay widths $\rightarrow$ strong constrain on fermion coupling strength
- Another test was using no assumption on the total width of the Higgs Boson.
- Only ratios of coupling-strengths can be measured, chosen as free parameters of the fit:

$$\lambda_{FV} = k_F / k_V$$
$$k_{VV} = k_V \cdot k_V / k_H$$

- As a result of the fit:

$$\lambda_{FV} = 1.02^{+0.15}_{-0.13} \left[{}^{+0.11}_{-0.11}(stat.){}^{+0.08}_{-0.07}(syst.){}^{+0.04}_{-0.03}(theo.)\right]$$
$$k_{VV} = 1.07^{+0.14}_{-0.13} \left[{}^{+0.11}_{-0.11}(stat.){}^{+0.06}_{-0.06}(syst.){}^{+0.04}_{-0.04}(theo.)\right]$$

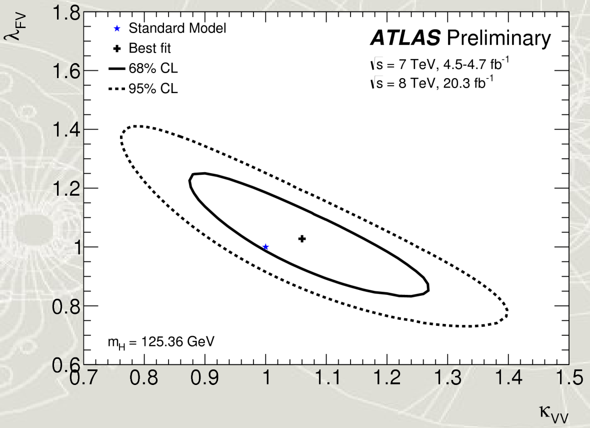
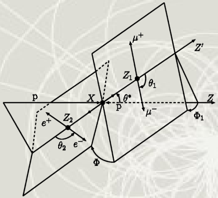
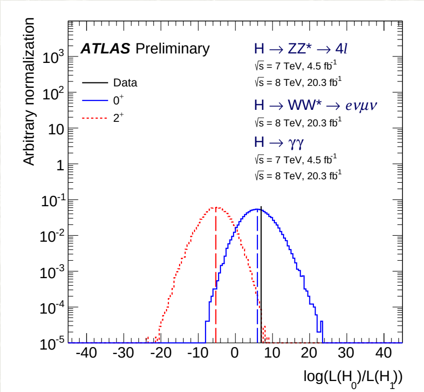


Figure: Results of the two-dimensional fit to k_{VV} and λ_{FV}, including 68% and 95% CL contours.

Spin measurement

- The study of the spin and parity properties of the Higgs boson is based on the $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to e\nu\mu\nu$
- $H \to \gamma\gamma$ spin hypothesis is tested via production angle of the two photons, measured in the Collins-Soper frame.





- $H \to ZZ^* \to 4\ell$ has full kinematic information to determine spin and CP
- $H \to WW^*$ makes use of $m_{\ell\ell}$, $p_T^{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and m_T to test spin hypothesis
- All three channels $H \to \gamma\gamma$, $H \to ZZ^*$ and $H \to WW^*$ are combined for the spin hypothesis test
- A test statistic q used to distinguish between spin-parity hypotheses is a ratio of profiled likelihoods
- Figure shows the distribution of q after combination of results from $H \to ZZ^* \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^*$
- Solid vertical line is the observed value

Summary

- Full analysis of Run1 data taken by ATLAS has been performed
- Detailed study of the properties of the discovered Higgs boson done with Run1 data
- No significant deviation from SM predictions observed
- Data favours Spin0 Higgs hypothesis
- Coupling tests consistent with SM
- Looking forward Run2 data to improve these measurements

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