Overview of Higgs results from the ATLAS experiment

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J. Vossebeld,
University of Liverpool
on behalf of the ATLAS collaboration
ATLAS and the LHC: Run I performance

The LHC has performed very well

Peak luminosity: \(7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)

More than 25 fb\(^{-1}\) delivered to ATLAS and CMS.

ATLAS has collected data efficiently
Collecting good data 95% of the time

High quality data for physics analysis:
4.7 - 4.9 fb\(^{-1}\) at \(\sqrt{s} = 7 \text{ TeV}\) and 20.3 fb\(^{-1}\) at \(\sqrt{s} = 8 \text{ TeV}\)

Pile-up has been higher than foreseen
Well modelled
Not a major issue for analysis
What has happened since the discovery?

Combination of results \( H \rightarrow \gamma \gamma \), \( H \rightarrow ZZ^* \) & \( H \rightarrow WW^* \) with full data (25 fb\(^{-1}\)) to determine

⇒ mass and couplings (arXiv:1307.1427)
⇒ spin and parity (arXiv:1307.1432)

Preliminary results:
⇒ \( H \rightarrow \gamma \gamma \) differential cross-sections (25 fb\(^{-1}\)) (ATLAS-CONF-2013-072)
⇒ VH with \( H \rightarrow bb \) (25 fb\(^{-1}\)) (ATLAS-CONF-2013-079)
⇒ \( H \rightarrow \tau \tau \) (18 fb\(^{-1}\)) (ATLAS-CONF-2012-160)
⇒ ttH with \( H \rightarrow \gamma \gamma \) (20 fb\(^{-1}\)) (ATLAS-CONF-2013-080)
⇒ \( H \rightarrow \mu \mu \) (21 fb\(^{-1}\)) (ATLAS-CONF-2013-010)
⇒ \( H \rightarrow Z \gamma \) (25 fb\(^{-1}\)) (ATLAS-CONF-2013-009)
⇒ VH with \( H \rightarrow WW \) (25 fb\(^{-1}\)) (ATLAS-CONF-2013-075)
⇒ ZH with \( H \rightarrow \text{invisible} \) (18 fb\(^{-1}\)) (ATLAS-CONF-2013-011)
⇒ High mass Higgs (25 fb\(^{-1}\))
  ⇒ \( H \rightarrow ZZ \rightarrow 4 \) leptons (ATLAS-CONF-2013-013)
  ⇒ \( H \rightarrow WW \rightarrow e^+\nu\mu^- \nu \) (ATLAS-CONF-2013-067)

Cross section limits/significances presented are based on the signal confidence level \((CL_S)\) determined using the profile likelihood method (arXiv:1007.1727).
For more details see e.g. ATLAS-CONF-2013-034.
Production and decay modes at the LHC

Cross sections SM Higgs 125.5 GeV @ 8 TeV
- Gluon-gluon fusion (ggF): 19 pb
- Vector boson fusion (VBF): 1.6 pb
- Associated production:
  WH: 0.70 pb / ZH: 0.41 pb / ttH: 0.13 pb

Higgs decays to bosons

$H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\nu l\nu$
$H \rightarrow \gamma\gamma$

Small branching fraction, but excellent mass resolution.
Sensitivity to spin ($0^+/2^+$) / excludes spin 1 (Landau-Yang)

Excellent $\gamma$-jet separation in 1st layer of Liquid Argon calorimeter.
Only $\sim 25\%$ of background is from jet-jet or $\gamma$-jet events

Extract signal in simultaneous fit of signal and background.
H→γγ search categories

9 combinations of:
- converted/unconverted
- forward/central
- p_T range

2 VBF enhanced categories
- high mass jet pair and BDT cut

3 VH enhanced categories:
- low mass jet pair
- 1 lepton and/or missing E_T
**H → γγ results**

**Overall signal significance:**
7.4σ (4.3σ exp.)

**Best fit signal strength:**
$$\mu = 1.55^{+0.33}_{-0.28}$$

where:
$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$
NEW: $H\rightarrow\gamma\gamma$ differential cross sections

Repeat fit to extract signal in each bin
(Signal model: ggF + VBF + VH + ttH @ $m_H=126.8\text{GeV}$)

example: $\geq 3$ jets
NEW: $H \rightarrow \gamma\gamma$ differential cross sections

$\Rightarrow$ for other distributions see ATLAS-CONF-2013-072

$P_T$ spectrum in data appears harder but errors (stat & theory) are still large. No significant disagreements with expectation SM Higgs
H → ZZ* → 4 leptons

Small branching fraction, but very clean and good mass resolution.

Good sensitivity to spin and parity (0^+/0^-/1^+/1^-/2^+)

Analysis subcategories
- VBF enhanced: high mass jet pair (|Δη|>3)
- VH enhanced: additional lepton
- ggF dominated: inclusive

Overall signal significance

6.6σ (4.4σ exp.)
H → WW* → ℓνν

High branching fraction, but limited mass resolution and significant backgrounds.

Analysis categories
- ee, μμ or eμ pair
- 0, 1 or ≥2 jets

Evidence for a Higgs (over broad range of masses)
3.8σ excess observed (3.8σ expected) for m_H = 125.5 GeV

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H→γγ,ZZ*,WW* combined

Mass
Couplings
Spin and parity
Higgs mass

$(H \rightarrow \gamma\gamma / H \rightarrow ZZ^* \rightarrow 4l)$

arXiv:1307.1427

$H \rightarrow \gamma\gamma$ : $m_H$ determined from combined fit in all categories.

$m_H = 126.8 \pm 0.2 \text{(stat)} \pm 0.7 \text{(sys)} \text{GeV}$

$H \rightarrow 4$ leptons:

$m_H$ determined from unbinned likelihood fit

$m_H = 124.3_{-0.5}^{+0.6} \text{(stat)}_{-0.3}^{+0.5} \text{(sys)} \text{GeV}$

Mass difference $2.4\sigma$, which has a $\sim 1.5\%$ probability to occur. (increases to 8% if we assume a flat prior for the energy scale uncertainties)

Combined mass

$m_H = 125.5 \pm 0.2 \text{(stat)}_{-0.6}^{+0.5} \text{(sys)} \text{GeV}$
Couplings combination

Combined results $H \rightarrow \gamma \gamma$, $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow WW^* \rightarrow l\nu l\nu$ channels, including VBF or VH enhanced cases.

Overall signal strength:

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

Statistical, systematic and theory uncertainties are already comparable.
Evidence for Higgs production via vector-boson fusion

VBF enhanced analyses in $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW^* \rightarrow l\ell l\nu$ all find a VBF component consistent with the SM expectation.

Combined the VBF(+VH) to ggF(+ttH) ratio is

$$\frac{\mu_{\text{VBF}+\text{VH}}} {\mu_{\text{ggF}+\text{ttH}}} = 1.4^{+0.7}_{-0.5}$$

3.3 $\sigma$ evidence that a non-zero fraction of Higgs events is produced via vector boson fusion.
Coupling parameters

Assumption:
Single narrow resonance with $m=125.5\text{GeV}$

$\kappa_F, \kappa_V$: scale factors fermion/boson couplings

- $\kappa_F = 0$ (fermiophobic H) excluded at $>5\sigma$ CL
- Negative $\kappa_F$ still allowed at $\sim 2\sigma$ level

68% CL intervals:

- $\kappa_F \in [0.76, 1.18]$
- $\kappa_V \in [1.05, 1.22]$

Custodial symmetry

$\lambda_{WZ}$: ratio scale factors for W and Z couplings ($\lambda_{WZ} = 1$ in SM)

- $\lambda_{WZ} = 0.82 \pm 0.15$

$\kappa_g, \kappa_\gamma$: scale factors for gg→H and H→\gamma\gamma loops

- $\kappa_g = 1.04 \pm 0.14$
- $\kappa_\gamma = 1.20 \pm 0.15$
Spin and Parity of the candidate boson

Test various options ($J^p=0^-, 0^+, 1^-, 1^+, 2^+$) using angular and kinematic distributions in $H\rightarrow \gamma \gamma, H\rightarrow ZZ^*\rightarrow 4l$ and $H\rightarrow WW^*\rightarrow l\nu l\nu$.

For a detailed description of the used theoretical calculations and a complete set of references see:

CERN Yellow Report III (arXiv:1307.1347)
$J^p=0^+ \text{ vs } 0^- \ (H \rightarrow ZZ^* \rightarrow 4l)$

Measure the log likelihood ratio $q$

$$q = \log \frac{L(J^p = 0^+)}{L(J^p = 0^-)}$$

and compare to the expected distributions.

Data agree with $0^+$ hypothesis, $0^-$ hypothesis is excluded at 97.8% CL
$J^p=0^+ \text{ vs } 1^+/1^- (H \rightarrow ZZ^* \rightarrow 4\ell / H \rightarrow WW^* \rightarrow l\nu l\nu)$

Observation $H \rightarrow \gamma\gamma$ decay prohibits spin 1 option (Landau-Yang) for on-shell particle.

$H \rightarrow ZZ^* \rightarrow 4$ leptons

Combined $ZZ^*/WW^*$ data agree with $0^+$ hypothesis, $J^p = 1^+$ hypothesis is excluded at 99.97% CL, $J^p = 1^-$ hypothesis is excluded at 99.7% CL
$J^p=0^+ \text{ vs } 2^+ \ (H\to\gamma\gamma \ / \ H\to ZZ^*\to4l \ / \ H\to WW^*\to l\nu l\nu)$

We vary the production mode for a $2^+$ boson from fully gluon induced ($f_{qq}=0\%$) to fully quark induced ($f_{qq}=100\%$).

Data agree with $0^+$ hypothesis for all $f_{qq}$

$2^+$ hypothesis is excluded at >99.9% CL for all $f_{qq}$

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Higgs decays to fermions

$H \rightarrow bb, \ H \rightarrow \tau \tau$
VH with H to bb

Abundant channel with difficult backgrounds. Flavour composition of the main backgrounds is determined from data.

Analysis split in to many categories:
number of leptons = 0 / 1 / 2
number of jets (b-jets) = 2(2) / 3(2) / 2(1) / 3(1)
\(p_T^V = [< 90 \text{ GeV}] / [90..120 \text{ GeV}] / [120..160 \text{ GeV}] / [160..200 \text{ GeV}] / [> 200 \text{ GeV}]\)
Background subtracted $m_{bb}$ distribution, combining all regions with S/B based weighting

Combined 2011 + 2012 result: data are consistent with either SM backgrounds only, backgrounds + Higgs

Best fit signal strength: $\mu = 0.2^{+0.7}_{-0.6}$

ATLAS Prelim.

$\mu = 0.2^{+0.7}_{-0.6}$

$\sigma$(stat) $\sigma$(sys) $\sigma$(theo)
prediction

$\mu = 2.1^{+1.4}_{-1.4}$

$\mu = 2.7^{+1.9}_{-1.9}$

$\mu = 2.5^{+1.9}_{-1.9}$

$\mu = 0.6^{+1.3}_{-1.3}$

$\mu = 0.6^{+0.7}_{-0.7}$

$\mu = 0.9^{+0.9}_{-0.9}$

$\mu = 0.7^{+1.3}_{-1.3}$

$\mu = 0.3^{+1.3}_{-1.3}$

$\mu = 0.2^{+0.6}_{-0.6}$

$\mu = 0.5^{+0.9}_{-0.9}$

$\mu = 0.1^{+1.1}_{-1.1}$

$\mu = 0.4^{+1.5}_{-1.5}$

$\sigma = 1\sigma$ on $\mu$

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Search in lep-lep, lep-had and had-had channels
Analysis split in 0,1, 2 jet case (2 jet case optimized for VBF/VH)

Result 2011 and part of 2012 data:
1.1σ excess over SM background
Best fit: μ=0.7±0.7

Analysis with full 2012 data still to come.
Rare production and/or decay modes
Rare production/decay modes

\[ ttH \ (H \rightarrow \gamma\gamma) \]

\[ \mu < 5.3 \ (6.4 \ exp.) \ @ \ 95\% \ CL \]

\[ H \rightarrow Z\gamma \rightarrow ll\gamma \]

\[ \mu < 13.5 \ (18.2 \ exp.) \ @ \ 95\% \ CL \]

\[ VH \rightarrow VWV \]

\[ \mu < 7.2 \ (3.6 \ exp.) \ @ \ 95\% \ CL \]
BSM Higgs

A few recent results
Invisible decays of the Higgs: $ZH \rightarrow ll + \text{inv}$

Rate expected in SM ($H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$) negligible

Channel is sensitive to any new particle coupling to the Higgs, whilst invisible to our detectors (dark matter candidates).

Search for an excess of events with

2 leptons + high missing $E_T$

Extract limit from the missing $E_T$ distribution

Result 2011 and part 2012 data:

$\text{BR}(H(125 \text{ GeV}) \rightarrow \text{inv}) < 65\%$ (84% exp.) @ 95%CL
Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes.

Preliminary results $H \rightarrow ZZ \rightarrow 4l$ available in ATLAS-CONF-2013-013

New: $H \rightarrow WW \rightarrow e\nu\mu\nu$ search for a SM-like high mass Higgs.

Signal: SM like Higgs with full description of the width and of interference effects.

Vary width between a narrow width and that expected for a high mass SM Higgs.

Full combination to come. More WW/ZZ decay channels to be included:

$H \rightarrow ZZ \rightarrow ll\nu\nu$, $H \rightarrow ZZ \rightarrow llqq$, $H \rightarrow WW \rightarrow l\nuqq$

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More BSM Higgs

2HDM Higgs

H→WW→eνμν

(similar analysis to that on previous slide)

• 0 jets (ggF) and 2 jets (VBF)
• Assume 125 GeV Higgs candidate is h and look for H in mass range 135 – 300 GeV
• No indication of a signal, set limits in $m_H - \cos(\alpha)$ plane for varying values of $\tan(\beta)$

Search for $H^\pm \rightarrow \tau\nu + \text{jets}$ in mass range 180 – 600 GeV

Released today!

ATLAS-CONF-2013-090

Low mass

$(m_{H^\pm} < m_t)$

$t\bar{t} \rightarrow H^\pm bWb$

High mass

$(m_{H^\pm} > m_t)$

• Associated $tH^\pm$ production

More on these results in parallel talk Alessandro Manfredini
LHC Run I (2010-2013) a great success for ATLAS
Discovery of a new boson, and first measurement of its mass, ..
\[ m_H = 125.5 \pm 0.2 \text{(stat)}^{+0.5}_{-0.6} \text{(sys)} \text{GeV} \]
its coupling parameters (all consistent with a SM Higgs) and its spin and parity ..

**Strong evidence** \( J^P = 0^+ \)

No significant evidence yet for fermionic decays, but results are consistent with SM Higgs hypothesis

\[
\begin{align*}
H \rightarrow bb & : \mu = 0.2^{+0.7}_{-0.6} \\
H \rightarrow \tau\tau & : 1.1 \text{ sigma excess, best fit } \mu = 0.7 \pm 0.7
\end{align*}
\]

First results on various rare production decay modes (more data needed to observe these modes)

Direct limit on \( H \rightarrow \text{invisible particles} \)

**BR(H→inv) < 65%**

Search for high mass Higgs and SM and narrow width approach.

Many analyses of Run I data are ongoing, so more results to come ....
Outlook

ATLAS is preparing for LHC run II: $\sqrt{s}=$13/14 TeV and up to 80 interactions on average per bunch crossing.

Improvements on electronics, an extra b-tagging layer and improved forward muon tracking are ongoing.

Major upgrades are being planned for HL-LHC running to ultimately get to $\sim 3000\text{fb}^{-1}$ per experiment.

Very exciting times ahead ..