Measurements of the Higgs boson properties at the ATLAS experiment

with 80 fb$^{-1}$ 13 TeV dataset

Paul Glaysher (DESY), on behalf of the ATLAS collaboration

28 Aug 2018
QCD@LHC Dresden 2018
Higgs boson in the Standard Model

- The Higgs discovery in 2012 allows for the exploration of a new sector of the SM Lagrangian

- Two types of tree-level coupling to other SM particles determine Higgs boson production and decay modes

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} D\psi + |D_\mu \phi|^2 - V(\phi) + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
The LHC Run 1 dataset (2011-2012), with 7/8 TeV proton-proton collisions already established the presence of a SM-like Higgs boson with mass of 125 GeV.

Higgs boson mass: fixed free parameter in SM predictions

- Higgs boson couplings were measured to 10-25% precision.
- Experimental precision of vector boson coupling higher than to fermions.
- Decays with bosonic coupling allow for precision measurements of other properties.
- Fermionic couplings pose larger experimental challenge and not yet fully established.

Run 1 signal significance by decay mode [JHEP08(2016)045]:

<table>
<thead>
<tr>
<th>Decay</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \to \gamma\gamma$</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>(4.6)</td>
<td>(5.1)</td>
</tr>
<tr>
<td>$H \to ZZ$</td>
<td>7.6</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>(5.6)</td>
<td>(6.8)</td>
</tr>
<tr>
<td>$H \to WW$</td>
<td>6.8</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>(5.8)</td>
<td>(5.6)</td>
</tr>
<tr>
<td>$H \to \tau\tau$</td>
<td>4.4</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>(3.3)</td>
<td>(3.7)</td>
</tr>
<tr>
<td>$H \to bb$</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>(2.7)</td>
<td>(2.5)</td>
</tr>
</tbody>
</table>

High mass resolution in $\gamma\gamma$, ZZ decay channels

Width measurement is limited by detector resolution.
Higgs boson production at the LHC

Number of Higgs boson events in Run 2 dataset (2015-2017)

- Increase in production cross section due to higher centre of mass energy in Run 2
- Enhances feasibility of measuring $ttH$, e.g.

- $\sim 4M$
- $\sim 300K$
- $\sim 200k$
- $\sim 40k$
Higgs boson decay modes

- ZZ, γγ: high mass resolution and precise differential measurements
  - Low Branching Ratio (BR)
  - Measurements greatly improved with larger dataset
- WW: High BR, but low mass resolution
- μμ: very small BR, but access to coupling of 2nd generation fermions
- ττ, bb: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions
Overview

Current results of Higgs boson properties with up to 80 fb$^{-1}$ 13 TeV data

- mass, width and differential cross sections in the H->ZZ and H->γγ decay modes

Higgs to fermion coupling:

- Bottom quark: VH, H->bb associated production mode (V=W/Z)
- Top quark: in ttH associated production mode

- Combined coupling measurements
Determining the mass is vital to determining other properties of the Higgs boson. The mass is determined as the best fit value of signal distribution given by parametric function vs data, with free parameter $m_H$ and width=4.1 MeV. Detector response systematics on signal estimated from MC as a function of $m_H$.

$m_H = 124.86 \pm 0.27 \pm (0.18 \text{ stat. only}) \text{ GeV}$
Higgs boson width

The SM prediction of the Higgs boson width is 4 MeV and too small to be measured directly. Instead, cross section ratio of on- to off-shell H->VV is sensitive to width.

assume effective coupling modifiers $\kappa$ to SM couplings of ggF production and H->ZZ decay process ($\kappa_g$, $\kappa_Z$) and that $\kappa_{\text{off-shell}} = \kappa_{\text{on-shell}}$

$\Gamma_H < 14.4$ MeV (15.2 MeV exp.)

Ratio of data and $\mu_{\text{off-shell}}=5$ example to SM with $\mu_{\text{on-shell}}=1$.

- Sizeable negative interference between off-shell signal and gg->ZZ bkg. taken into account.
- Use m(ZZ) depended NLO k factors.
- Improvement of ~2 over Run 1 results.
Precise differential measurement could test the SM and show signs of new physics

Here Higgs transverse momentum ($p_T$) in $H\rightarrow\gamma\gamma$ channel

Higgs $p_T$ is a probe of the QCD radiative processes in the initial state

New particles could contribute to loop production and alter the $p_T$ spectrum

High Higgs $p_T$ tail shows no hint of new physics (yet?)

In good agreement with predictions

Subtract background and correct for detector effects via unfolding. Compare data to ggF signal from Powheg NNLOPS or NNLOJET+SCET calculation.
Higgs boson couplings to fermions

- **Indirect probes through loops in ggF and $H \rightarrow \gamma \gamma$ set limits on fermion coupling**

- **Direct probes to bottom and top quarks possible in VH, $H \rightarrow bb$ and $ttH$ measurements**

**VH** production allows to suppress QCD Background by selecting a charged lepton. Largest BR, $H \rightarrow bb$, only recently observed.

$H \rightarrow bb$ uncertainty driving factor in Higgs width determination and sensitivity to $H \rightarrow$invisible decays

Yukawa coupling $\lambda_t$ is proportional to the mass of the fermion, Top quark is the heaviest particle in the SM

$$\lambda_t = \sqrt{2} \frac{m_t}{v} \approx \sqrt{2} \frac{173 \text{ GeV}}{246 \text{ GeV}} \approx 0.99 \approx 1.$$  

**$ttH$** production gives a direct way to probe the top quark Yukawa coupling

**Tree-level process, cross-section proportional to $\lambda_t^2$**

only:

$$\sigma_{ttH} = 508 \text{ fb}$$
VH production, H→bb

- Make use of 0, 1 or 2 charged lepton channels
- VH is most sensitive mode to measure H→bb at the LHC
- Select 2 b-tagged jets and pT(V) > 75 or 150 GeV
- Main discriminant variables m(bb), pT(V) and ΔR(bb) (combined into a Boosted Decision Tree)

Non-resonant backgrounds:
- \texttt{ttbar}, single top
  (NLO, PowHeg)
- W+jets
- Z+jets
  (NLO for up to 2 extra jets, Sherpa 2.2.1)

Run 2 best fit result $\mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}}$:

\[
\mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}} = 1.16^{+0.27}_{-0.25}
\]

Significance: $4.9\sigma$ (4.3$\sigma$ expected)

Combined with Run 1:

\[
\mu = 0.98 \pm 0.14(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})
\]

Significance: $4.9\sigma$ (5.1$\sigma$ expected)

MC predictions normalised to data in fit.
The recent VH, H→bb measurement when combined with other channels leads to observation of H→bb decay and VH production mode

**Observation of H→bb**
Significance: 5.4σ observed (5.5σ expected)
Run 1+ Run 2 measurements:
- VH, H → bb
- VBF(+ggF), H → bb
- ttH, H → bb

**Observation of VH production**
Significance: 5.3σ observed (4.8σ expected)
Run 2 measurements:
- VH, H → bb
- VH, H → γγ
- VH, H → ZZ*

Assumes SM BR.
ttH production

- ttH cross section only 508 fb, ~1% of total Higgs boson cross-section at 13 TeV
- Need to target all Higgs and top decay modes

Channels

- \( tt(1-2 \ e/\mu) + H(bb) \)
- \( tt(1-2 \ e/\mu/\tau{\text{-had}}) + H(WW, ZZ^*, \tau\tau) \)
- \( tt(0-2 \ e/\mu) + H(ZZ^*) \)
- \( tt(0-2 \ e/\mu) + H(\gamma\gamma) \)

- Complex final states: \( \gamma, \ e, \ \mu, \ \tau{\text{-hadronic}}, \ \text{high jet and b-jet multiplicities} \)
- Sensitivity enhanced by dedicated channels
ttH channels

Higher cross section x branching ratio

Higher signal purity
ttH, H→ZZ and H→γγ

- Consider ttH enriched regions from inclusive studies of H→ZZ→4l and H→γγ searches.
- Employs BDT to isolate ttH from other Higgs production modes.

H→ZZ:
- Select events as:
  - 115 < m_{4l} < 130 GeV + b-jets
- Orthogonal to 4l ML (ZZ veto)
- Very rare but clean channel
- Zero ttH events observed, 0.6 ttH (0.4 Bkg) expected
- Upper limit on μ_{ttH} of 1.77 at 68% C.L.
- Will become more important as more data is gathered

H→γγ:
- Select events based on m_{γγ} + b-jets
- Significance: 4.1σ (3.7σ exp.)

Signal model: double-sided Crystal Ball
Background model: data driven by inverting γ ID or isolation, or removing b-tagging; shape+normalisation from fit to m_{γγ}
Many possible final states, Focus on those with clean signature and low background

- Select electron/muon from Higgs and top decay
- Requiring same-sign leptons or 3 leptons with charge sum ±1 reduces large QCD background from tt background
- Remaining background from tt̅ + misidentified leptons, Signal/Background ratio up to 1.8
- H→WW most sensitive channel, H→ττ next sensitive
  - Hadronic τ reconstruction has larger uncertainties

Overview of analysis categories:

Extract signal from BDT discriminant

**ATLAS**

<table>
<thead>
<tr>
<th>Events/bin</th>
<th>Data</th>
<th>ttH</th>
<th>ttW</th>
<th>ttZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>12</td>
<td>20</td>
<td>5</td>
<td>3</td>
</tr>
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<td>30</td>
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</tr>
<tr>
<td>5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**3ℓ SR**

Post-Fit

**Data/Pred.**

**BDT output**

**Pre-Fit Bkgd.**

**Uncertainty**
ttH, H→bb

- Largest H→bb branching ratio of 58.1%
- Suffers from large irreducible QCD background from tt+ b-jets
- Ambiguous event reconstruction due to final state with high combinatorics of b-jets

- Define signal rich and background rich regions based on b-tagging discriminants
- Signal/Background ratio up to ~5%
- Rely on Boosted Decision trees to further separate Signal from Bkg.

- Dominant modelling uncertainty of tt+ b-jets:
  - Determined from comparison of PowHegPythia8 to Sherpa ttbar generators

- Uncertainties and background normalisation controlled in simultaneous fit over signal-rich and background-rich regions
Combination of ttH results

Observation of ttH production!

Compute signal strength $\sigma_{\text{ttH}}/\sigma_{\text{SM}}$ from profile likelihood fit over all channels. Correlate systematic uncertainties were appropriate.

Sensitivity limited by theory uncertainties on signal and background modelling.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta \sigma_{\text{ttH}}/\sigma_{\text{ttH}}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory uncertainties (modelling)</td>
<td>11.9</td>
</tr>
<tr>
<td>$t\bar{t}$ + heavy flavour</td>
<td>9.9</td>
</tr>
<tr>
<td>ttH</td>
<td>6.0</td>
</tr>
<tr>
<td>Non-(t\bar{t}H) Higgs boson production</td>
<td>1.5</td>
</tr>
<tr>
<td>Other background processes</td>
<td>2.2</td>
</tr>
<tr>
<td>Experimental uncertainties</td>
<td>9.3</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>5.2</td>
</tr>
<tr>
<td>Jets, $E_{\text{T}}^{\text{miss}}$</td>
<td>4.9</td>
</tr>
<tr>
<td>Electrons, photons</td>
<td>3.2</td>
</tr>
<tr>
<td>Luminosity</td>
<td>3.0</td>
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<tr>
<td>$\tau$-leptons</td>
<td>2.5</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>1.8</td>
</tr>
<tr>
<td>MC statistical uncertainties</td>
<td>4.4</td>
</tr>
</tbody>
</table>

ATLAS (up to 80 fb^{-1})
Run-2: 5.8\(\sigma\) (4.9\(\sigma\) exp.)
Run-1+Run-2: 6.3\(\sigma\) (5.1\(\sigma\) exp.)
Measurements of all Higgs production modes

- combined production cross-section times branching fraction results for ggF, VBF, VH and ttH+tH production in each relevant decay mode, normalised to their SM predictions.

- obtained from a simultaneous fit to all decay channels, for each production mode.

- 9% precision on ggF

- VH: assume SM WH/ZH cross section ratio & SM expectation for H→ττ

- Statistically limited in ZZ & γγ

- Overall combined signal strength, i.e. if the SM signal yield in all channels were scaled by a single factor

\[ \mu = \frac{(\sigma \times B)_{if}}{(\sigma \times B)_{if}^{SM}} = 1.13^{+0.09}_{-0.08} \]
Coupling from combining all channels

- Use all production and decay modes to measure couplings expressed in $\kappa$-scales. Scale SM production process $(i)$, decay width to final state $f$ and the Higgs total width.

- $\kappa_i, \kappa_f$ can be parameterised as combinations of Higgs to SM particles tree-level coupling.

- Effective gluon, photon coupling, assumes no BSM contributions.

- Assuming uniform $\kappa$ modifier for vector boson and fermion couplings:

$$ (\sigma \times B)_{if} = \kappa_i^2 \sigma^\text{SM}_i \frac{\kappa_f^2 \Gamma^\text{SM}_f}{\kappa_H^2 \Gamma^\text{SM}_H}, $$

Best fit value in good agreement with SM:

$$ \kappa_V = 1.06^{+0.04}_{-0.04}, $$

$$ \kappa_F = 1.05^{+0.09}_{-0.09}. $$
Coupling results

- For vacuum expectation value of the Higgs field $\nu = 246$ GeV, reduced coupling $\kappa_V^F m_F$ and $\sqrt{\kappa_V m_V}$ are proportional to the fermion or boson particle mass.

- Results show high agreement to SM over full mass range.

- For direct and indirect coupling measurements:

  \[
  \frac{m_F}{\kappa_V^F} \quad \text{or} \quad \frac{m_V}{\kappa_V^V}
  \]

  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_Z$</td>
<td>$1.07^{+0.11}_{-0.10}$</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>$1.04 \pm 0.10$</td>
</tr>
<tr>
<td>$\kappa_b$</td>
<td>$1.00^{+0.24}_{-0.22}$</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>$1.03^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>$\kappa_\tau$</td>
<td>$1.04^{+0.17}_{-0.16}$</td>
</tr>
<tr>
<td>$\kappa_\mu$</td>
<td>$&lt; 1.63$ at 95% CL.</td>
</tr>
</tbody>
</table>

- Assumes expected coupling for other SM process and zero BSM contribution.

- The compatibility of the measurements corresponds to a p-value = 79%.
Conclusion

- With the large Run 2 dataset of 36-80 fb\(^{-1}\) the properties of the Higgs boson can be determined with unprecedented precision at the ATLAS experiment
- \(~3x~\) improvement in precision for bosonic channels over Run 1 results
- Direct observation achieved for the main production and decay modes
  - Recent **observation of VH production** shown
- Confirmation of coupling to 3rd generation fermions
  - Recent **observation bottom and top quark Higgs coupling** were presented
- All measurements of the Higgs boson are compatible with the Standard Model
- Precise knowledge of the Higgs boson properties will enhance searches for new phenomena, use the Higgs boson as a probe for beyond the SM effects
- Only a fraction of the total expected LHC luminosity analysed to date
  - Rich Higgs boson properties program still lies ahead
Backup
## Inputs to combination

### Production

<table>
<thead>
<tr>
<th>Process</th>
<th>Diagram</th>
<th>Cross Section (80 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluon fusion (gg)</td>
<td><img src="gg" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>Vector boson fusion (VBF)</td>
<td><img src="VBF" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>Associated prod. with W/Z</td>
<td><img src="W/Z" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>Associated prod. with tt</td>
<td><img src="tt" alt="Diagram" /></td>
<td>✔️</td>
</tr>
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</table>

### Decay

<table>
<thead>
<tr>
<th>Decays</th>
<th>Diagram</th>
<th>Cross Section (80 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → τl, WW and ZZ pairs</td>
<td><img src="tauWZ" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → Z+ Z−</td>
<td><img src="Z+Z%E2%88%92" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → W+ W−</td>
<td><img src="W+W%E2%88%92" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → τ− τ+</td>
<td><img src="tau++" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → b bar b</td>
<td><img src="bbarb" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → μ+ μ−</td>
<td><img src="mumu" alt="Diagram" /></td>
<td>✔️</td>
</tr>
<tr>
<td>H → Invisible</td>
<td><img src="invisible" alt="Diagram" /></td>
<td>✔️</td>
</tr>
</tbody>
</table>

**CMS ATLAS**

Giacinto Piacquadio - ICHEP 2018