Determination of Higgs boson properties in decays to bosons at the ATLAS experiment
Outline

• Introduction

• $H \rightarrow \gamma \gamma$

• $H \rightarrow ZZ^*$

• $H \rightarrow WW^*$

• $H \rightarrow ll \gamma$

• $H \rightarrow Z \gamma$

• EFT Interpretations
Introduction

- Experimental characterization of the Higgs boson:
  - Critical for elucidating the mechanism of the electroweak symmetry breaking.
  - Provide constraints on physics beyond the Standard Model (SM).

- Phenomenology
  - Higgs couples directly to all massive particles
  - Variety of production/decay modes within reach at the LHC

- Different paths taken to further scrutinise the Higgs
  - Mass measurement (latest measurement $m_H = 124.97 \pm 0.24$ GeV) doi.org/10.1016/j.physletb.2018.07.050
  - Couplings measurement
  - Simplified template cross sections
  - Differential cross sections
  - CP measurement
  - EFT interpretations
Experimental characterization of the Higgs boson:
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Phenomenology:
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- Simplified template cross sections
- Differential cross sections
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- EFT interpretations

🌟 STXS have been adopted by the LHC experiments as a common framework for Higgs measurements.
🌟 Allow for combination of the measurements between different decay channels as well as between experiments.
🌟 Reduce the theoretical uncertainties as much as possible.
Signature: a narrow resonance with a width consistent with detector resolution rising above a smooth background in the diphoton invariant mass ($m_{\gamma\gamma}$) distribution.

Despite a small branching ratio of about 0.227%, precise measurements of Higgs boson properties yielded.

Excellent performance of photon reconstruction and identification with the ATLAS detector.

**Higgs boson production cross section times $H \rightarrow \gamma\gamma$ branching ratio**

$$(\sigma \times B_{\gamma\gamma})_{\text{obs}} = 127 \pm 10 \text{ fb} = 127 \pm 7 \text{ (stat.)} \pm 7 \text{ (syst.) fb}$$

$$(\sigma \times B_{\gamma\gamma})_{\text{exp}} = 116 \pm 5 \text{ fb}$$
STXS:

- Cross-sections are presented in 27 regions of Higgs boson production phase.
- Level of compatibility between the measured STXS cross-sections and their Standard Model predictions is 60%.

Differential:

- Njets sensitive to production modes and higher order QCD effects.
- Di-jet kinematics sensitive to anomalous operators including CP-odd.
H→ZZ*→4l

139 fb⁻¹

**Improvements brought to the final Run-2 measurement:**

✿ Improved **lepton isolation** to mitigate the impact of pile-up
✿ Improved **jet reconstruction** using a particle flow algorithm
✿ **Additional event categories** for the classification of Higgs boson candidates
✿ **New discriminants** to enhance the sensitivity to distinguish the various production modes of the SM Higgs boson
✿ Use of data sidebands to constrain the dominant ZZ* background process

**STXS**

◆ **High S/B** and clean signature with fully reconstructed final state.
◆ Several bins measured for ggH and qqH, despite few statistics (low BR).
◆ On top of kinematic categories matching the STXS categorisation, analysis utilises NN-based categorisation to define the observable for fit.
  ✓ Kinematic categories **minimise the model extrapolation**.
  ✓ **NN discriminants** maximise the sensitivity.
◆ **Good agreement** with SM predictions (within large stat. uncertainty).

Many distributions measured, including:

- Higgs kinematics, including angular variables.
- Jet activities.
- $m_{12}$ vs. $m_{34}$ - specific to $ZZ^* \rightarrow 4l$ decays and offers good sensitivity to BSM physics.
- $p_T^{4l}$ constrains the Yukawa couplings of the Higgs boson with the $b$- and $c$-quarks.
- Double differential distributions

Limited by statistical uncertainties.

Matrix-based likelihood unfolding.

Probing transition region effects in $pTH$ (vs jets)

- compared to state of the art calculations (RADISH, NNLOJET)


Anamika Aggarwal
The analysis is performed separately with respect to jet multiplicity:

- For ggF, the $m_T$ distribution is used as the final discriminant.
- For the VBF-enriched $N_{\text{jet}} \geq 2$ category, the DNN output is used as the discriminating variable to enhance the low s/b.
Measurements are dominated by systematic uncertainties.

- $\mu_{ggF}$ uncertainties from both experimental and theoretical sources are comparable.
- $\mu_{VBF}$ signal theory uncertainties make up the largest contribution.

Higgs boson production is further characterised through measurements of STXSs in a total of 11 categories.

Results are compatible with the Standard Model predictions with a $p$-value of 52%.
This decay mode probes several scenarios beyond the SM, for example, if the Higgs boson were a neutral scalar of different origin or a composite state.

Improvements w.r.t. previous iterations:
- Increase in the size of the data set
- An improved event categorisation
- Optimised lepton and photon identification criteria.

Dominant background: Irreducible non-resonant production of Z bosons together with photons.

Six Categories in the fit:
(a) VBF-enriched
(b) High relative $p_T^{\gamma}$
(c) High $p_T^{ee}$
(d) Low $p_T^{ee}$
(e) High $p_T^{\mu\mu}$
(f) Low $p_T^{\mu\mu}$.

Signal and background yields are extracted from a fit to the $m_{Z\gamma}$ distribution observed in data.

Observed data are consistent with the expected background.

Expected and Observed p-value are 12.3% and 1.3% respectively.

Expected and Observed significance of 1.2 and 2.2 standard deviations, respectively.

Observed 95% CL upper limit on the $\sigma(pp \to H) \cdot B(H \to Z\gamma)$ is 3.6 times the SM prediction for a Higgs boson mass of 125.09 GeV.

Best-fit value for the signal yield normalised to the SM prediction is $2.0 \pm 1.0 - 0.9$ where the statistical component of the uncertainty is dominant.

The results represents an improvement of about a factor of 2.4 in expected sensitivity compared with the previous ATLAS publication.
Search for the Higgs boson decaying into a photon and a pair of electrons or muons with an invariant mass $m_{ll} < 30$ GeV.

- Probe coupling modifications introduced by possible extensions to the SM.
- Three-body Higgs boson decays can be used to probe $CP$-violation.

Multiple processes contribute:

- Dalitz decays involving a $Z$ boson or a virtual photon.
- Decay of the Higgs boson to two leptons and a photon from final-state radiation (FSR)

To enhance sensitivity, selected events are divided into mutually exclusive categories, according to the event topology and lepton flavour.

Dominant background: irreducible non-resonant production of $ll\gamma$.

<table>
<thead>
<tr>
<th>Category</th>
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<tbody>
<tr>
<td>$ee$ resolved VBF-enriched</td>
</tr>
<tr>
<td>$ee$ merged VBF-enriched</td>
</tr>
<tr>
<td>$\mu\mu$ VBF-enriched</td>
</tr>
<tr>
<td>$ee$ resolved high-$p_Tt$</td>
</tr>
<tr>
<td>$ee$ merged high-$p_Tt$</td>
</tr>
<tr>
<td>$\mu\mu$ high-$p_Tt$</td>
</tr>
<tr>
<td>$ee$ resolved low-$p_Tt$</td>
</tr>
<tr>
<td>$ee$ merged low-$p_Tt$</td>
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<td>$\mu\mu$ low-$p_Tt$</td>
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</table>
Evidence for the $H \rightarrow ll\gamma$ process is found with a significance of 3.2 over the background-only hypothesis.

The Higgs boson production cross-section times the $H \rightarrow ll\gamma$ branching ratio for $m_{ll} < 30$ GeV is determined to be $8.7^{+2.8}_{-2.7}$ fb.
EFT Interpretations

- Novel interpretations of the combined Higgs boson measurements have been performed.
- Decay channels, targeted production modes and integrated luminosities of the datasets used in this combination.
- Combination takes advantage of the eigen vector decomposition of the Wilson coefficients, to enhance sensitivity.
- Constraints on linear combinations of Wilson coefficients corresponding to SMEFT operators.
- Constraints set on parameters $m_A$, $\tan \beta$ of the MSSM, in context of six benchmark scenarios proposed by the BSM subgroup of the LHC Higgs Cross-Section WG.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Integrated lumi (fb$^{-1}$)</th>
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<tbody>
<tr>
<td>$H \to \gamma\gamma$ (all production modes)</td>
<td>139</td>
</tr>
<tr>
<td>$H \to ZZ^* \to 4\ell$ (all production modes)</td>
<td>139</td>
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<tr>
<td>$H \to b\bar{b}$ (VH)</td>
<td>139</td>
</tr>
<tr>
<td>$H \to WW^*$ (ggH, VBF)</td>
<td>36.1</td>
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<tr>
<td>$H \to \tau\tau$ (ggH, VBF)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \to b\bar{b}$ (VBF)</td>
<td>24.5 – 30.6</td>
</tr>
<tr>
<td>$H \to b\bar{b}$ (t\bar{t}H)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \to$ multilepton (t\bar{t}H)</td>
<td>36.1</td>
</tr>
<tr>
<td>$H \to \mu\mu$ (all production modes)</td>
<td>139</td>
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</table>
Comparison of results interpreted with a linearized SMEFT model and a model that also includes quadratic terms shows sizeable sensitivity to operators suppressed by $\Lambda^4$ in all of the measured parameters.

In this model-independent parametrization of new physics effects, no significant deviations from the SM have been observed.

Results are complementary to limits from direct searches for additional Higgs bosons.
Conclusion

- Many new results across multiple Higgs production and decay modes for Run-2 ATLAS.
- With more stats and improvements in the analysis strategies, more granularity in results.
- Advanced the knowledge of the Higgs properties measuring cross sections (total, STXS and differential), CP, mass and width.
- Measurements continue to be consistent with the Standard Model, placing further constraints on new physics.
- More results to come from Run-2, stay tuned!