Higgs boson fiducial differential cross section measurements at ATLAS

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on behalf of the ATLAS Collaboration

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Fiducial differential cross section measurements

- The fiducial phase space is defined to minimize the extrapolation effects and mimic the detector & analysis acceptance.
- Most model independent way to study the properties of the Higgs boson.
- Downside: reduced sensitivity for BSM effects compared to dedicated analyses.
- Observable sensitive to: Higgs boson production kinematics, associated jet kinematics, decay kinematics e.g. to probe spin-CP of the Higgs boson.
Together with $H\rightarrow\gamma\gamma$ perfect channel to measure differential XS for several observables sensitive to the Higgs boson production and decay.

Final state can be fully reconstructed: SF-OC lepton (e,\(\mu\)) pairs.

~1-2% mass resolution, inclusive S/B ~2.

**Likelihood Unfolding** via inversion of detector response matrix.

Several observables measured — Measurements in agreement with SM predictions.

As an example, $m_{12}$ vs $m_{34}$ and its interpretation within the Pseudo Observable framework.

Constraints on flavour-universal contact terms interactions.
Fiducial and differential XS in $H \rightarrow ZZ^* \rightarrow 4l$

- Fiducial cross section measured in a VBF enriched region

![Plot 1](Image1)

| $\Delta \eta_{jj}$ vs $m_{jj}$ |
\begin{itemize}
  \item 59.3% VBF
  \item 37.5% ggF
  \item 1.7% VH
  \item 1.5% $ttH$
\end{itemize}

![Plot 2](Image2)

- Good agreement with SM predictions found
- In VBF enriched bin with $m_{jj} \geq 400\,\text{GeV}$ and $|\Delta \eta_{jj}| > 3$:
  \begin{align*}
  \text{(Obs)} & \quad 0.215^{+0.077}_{-0.064} \, \text{fb} \\
  \text{(exp)} & \quad 0.134^{+0.065}_{-0.053} \, \text{fb}
  \end{align*}

\begin{itemize}
  \item $\sim 36\%$ uncertainty dominated by the data statistics
\end{itemize}
• Very clean signature with two isolated photons
• Main background from the $\gamma\gamma$ continuum, signal extraction with a fit to $m_{\gamma\gamma}$
• Matrix unfolding implemented in the likelihood fit
• Inclusive fiducial cross section:

$\langle \text{obs} \rangle \sigma_{\text{fid}} = 67 \pm 5 \text{(stat)} \pm 4 \text{ (sys)} \text{ fb}$  \hspace{1cm} (SM) $\sigma_{\text{fid}} = 64 \pm 4 \text{ fb}$

• Differential cross sections measured in the inclusive fiducial phase space and in a VBF-enriched fiducial region

$\chi^2$ compatibility between the measured cross sections and SM predictions (default MC) ranges from 27% to 95%
**Fiducial and differential XS in $H \to \gamma \gamma$**

- Differential fiducial cross section measured for 5 observables used to constrain possible BSM effects in the Higgs boson interactions within the effective field theory framework
  
  - SM Lagrangian complemented with additional CP-even and CP-odd dim-6 operators in the SMEFT Warsaw basis
  
  - Variables: $p_T^{\gamma\gamma}$, $N_j$, $m_{jj}$, $\Delta \phi_{jj}$, $p_T^{j_1}$ with the correlation among the observables properly considered

- Limits set on SMEFT Wilson coefficients both using SM with dimension-6 operators interference-only terms and including the quadratic (dim-6) terms

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**ATLAS**

SM EFT (interference only), $\Lambda = 1$ TeV

- $c_{Kg}$ with $c_{Kg} = -0.0083$
- $c_{Hg}$ with $c_{Hg} = 0.013$
- $c_{Hh}$ with $c_{Hh} = -0.004$
- $c_{Hh}$ with $c_{Hh} = 0.0067$

**ATLAS**

$H \to \gamma \gamma$, $\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Observed 68% CL
- Observed 95% CL
- Expected 68% CL
- Expected 95% CL

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**H→ZZ*→4l and H→γγ combination**

- Fiducial cross section measurements at 13TeV extrapolated to the full phase-space and combined
  - Additional uncertainties + SM assumption on the BR, BUT significant reduction of stat unc.

- Total Higgs boson production cross section: 55.5 $^{+4.0}_{-3.8}$ pb (SM: 55.6±2.5 pb)

- Differential cross sections measured: $p_T^H$, $|y_H|$, $N_J$, $p_T^{\text{lead.}j}$, $p_T^H$ vs $|y_H|
  - Compatibility between the two channels between 20% ($p_T^H$) and 80% ($N_{\text{jets}}$)
  - Compatibility with SM predictions between 23% ($p_T^{\text{lead.}j}$) and 98% ($|y_H|$)

![Graphs showing ATLAS results for H→ZZ* and H→γγ measurements](arXiv:2207.08615)

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$H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma \gamma$ combination

- $p_T^H$ measured by $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma \gamma$ jointly interpreted in terms of anomalous couplings of the Higgs boson to bottom and charm quarks ($k_b$, $k_c$)
- Exploited shape and normalization effects on the distribution
- Combined also with the constraints from $VH$, $H \rightarrow bb$ and $VH$, $H \rightarrow cc$ analyses

$|k_c| < 2.5$ @ 95% CL assuming $B_{BSM}=0$ and $k_i=1$ excepting for $k_b$

arXiv:2207.08615
Run3 started in 2022 with p-p collisions at $\sqrt{s}=13.6$ TeV, collected about 30 fb$^{-1}$ of collision data

First fiducial and total cross section in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ and their combination

Same analysis strategy as in for the Run2, detector performances similar to Run2

Selection efficiency in the fiducial phase space $\sim$50%

$\text{(obs)}\sigma_{\text{fid}} = 2.8 \pm 0.7 \text{(stat)} \pm 0.2 \text{ (sys)}$ fb (SM) $\sigma_{\text{fid}} = 3.67 \pm 0.19$ fb

Main systematics: electron and muon syst.
Run3 started in 2022 with p-p collisions at $\sqrt{s}=13.6$ TeV – collected about 30/fb of collision data

⇒ First fiducial and total cross section in H→γγ and H→ZZ*→4l and their combination

• Same analysis strategy as in for the Run2, detector performances similar to Run2

Selection efficiency in the fiducial phase space ~72%

• $\langle \text{obs} \rangle \sigma_{\text{fid}} = 76\pm11\,(\text{stat})\pm8\,(\text{sys})$ fb \hspace{1cm} (SM) $\sigma_{\text{fid}} = 67.7\pm3.7$ fb

Main systematics: bkg modelling and photon efficiency syst.
New measurements at 13.6 TeV

- Fiducial cross sections extrapolated to the full phase space and combined

\[ \sigma(pp \rightarrow H) = 58.2 \pm 8.7 \text{ pb} \]
\[ \sigma(pp \rightarrow H)^{SM} = 59.9 \pm 2.6 \text{ pb} \]

- Compatibility with the SM prediction is 85%

- \( H \rightarrow ZZ^* \rightarrow 4l \) and \( H \rightarrow \gamma\gamma \) compatibility is 20%
Higher signal compared to $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ but lower S/B and final state not fully reconstructable.

Measurements performed in two distinct phase space regions targeting different prod. modes

- ggF: $=0, =1$ jet fiducial phase space
- VBF: $\geq 2$ jets fiducial phasespace

Observables used to extract the signal: $m_T$ or dedicated discriminant
Differential XS in $H \rightarrow WW \rightarrow \mu \nu$: ggF phase space

- $m_T$ used to extract the signal in each bin of a given observable
- Compared to $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ larger off-diagonal terms in the response matrix
  - Tikhonov-regularized in-likelihood unfolding used

In general, good agreement between th. predictions and measured cross sections

At high Higgs boson transverse momentum ($>120\text{GeV}$) $1\sigma$ sensitivity, competitive with other channels
Fiducial measurement in the VBF phase space
- 24% uncertainty, statistical still dominant
- TH predictions within 1σ excluding except for a pure LO prediction

Differential cross sections measured for several observables
- Uncertainties driven by data statistics
- In general in agreement with SM predictions
- Differential cross sections used to constrain anomalous interactions described by a dim-6 EFT

arXiv:2304.03053

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• **Run 2 data** have been already **heavily exploited** to feed the extended ATLAS Higgs boson physics program

  – A lot of measurements published using the full Run-2 available statistics

• **Fiducial differential cross sections measured in several decay modes**

  – Predictions tested against unfolded data in multiple observables sensitive to various BSM effects

    • In general, statistical uncertainty is still dominant

  – Results compatible with the SM predictions so far

• LHC Run3 has started in 2022 at 13.6 TeV

  – First fiducial and inclusive cross sections measured in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ and their combination

  – $\chi^2$ more data expected at the end of Run3 $\Rightarrow$ further improve the precision and sensitivity to possible BSM effects
Backup
• Fiducial cross section measured in VH, $H \rightarrow bb$ with 0 charged leptons associated to the V decay
  — No electron/muon required in the events
• Measured in two fiducial regions defined by the particle level $E_T^{\text{miss}}$

• High $p_T$ Higgs boson production explored in $H \rightarrow bb$ events with large Lorentz boost
  — Higgs boson reconstructed from a single large-radius jet
• Upper limits set on the Higgs boson production cross section as function of $p_T^H$
  95%CL on the fiducial cross section for $p_T^H>450\text{GeV}$ is 115 fb (SM 18.4fb)
### $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ fiducial phasespace

- **$4l$**

<table>
<thead>
<tr>
<th>Leptons and jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
</tr>
<tr>
<td>Jets</td>
</tr>
</tbody>
</table>

#### Lepton selection and pairing

| Lepton kinematics | $p_T > 20, 15, 10$ GeV |
|-------------------|
| Leading pair ($m_{12}$) | SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$ |
| Subleading pair ($m_{34}$) | remaining SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$ |

#### Event selection (at most one quadruplet per event)

| Mass requirements | $50$ GeV $< m_{12} < 106$ GeV and $12$ GeV $< m_{34} < 115$ GeV |
|--------------------|
| Lepton separation  | $\Delta R(\ell_i, \ell_j) > 0.1$ |
| Lepton/Jet separation | $\Delta R(\ell_i, \text{jet}) > 0.1$ |
| $J/\psi$ veto      | $m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs |
| Mass window        | $105$ GeV $< m_{4\ell} < 160$ GeV |

- **$\gamma\gamma$**

<table>
<thead>
<tr>
<th>Photons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading (sub-leading) $p_T^\gamma$</td>
</tr>
<tr>
<td>Pseudorapidity</td>
</tr>
<tr>
<td>Isolation</td>
</tr>
</tbody>
</table>

#### Di-photon system

| Mass window | $105$ GeV $< m_{\gamma\gamma} < 160$ GeV |

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![ATLAS Simulation](image-url)

- Diphoton fiducial
- VBF-enhanced
- $N_{\text{sys}} = 1$
- High $E_T^{\text{miss}}$
- ttH-enhanced

Fraction of signal process

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**H → WW → eνμν fiducial phase space**

- **ggF**

<table>
<thead>
<tr>
<th>Category</th>
<th>Selection Requirements</th>
<th>Signal Region</th>
<th>Fiducial Region</th>
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</thead>
<tbody>
<tr>
<td>Pre-Selection</td>
<td>Exactly two isolated leptons (ℓ = e, μ) with opposite charge</td>
<td>Lepton pair flavors</td>
<td>e-μ</td>
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<td></td>
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<td>Lepton pair charge</td>
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<td></td>
<td></td>
<td>Leading (subleading) lepton $p_T$</td>
<td>$p_T &gt; 22$ GeV (&gt; 15 GeV)</td>
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<td></td>
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<td>$N_{\text{Jet}, (p_T &gt; 30\text{ GeV})} = 0$</td>
<td>$N_{\text{Jet}, (p_T &gt; 30\text{ GeV})} = 1$</td>
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<tr>
<td>Background rejection</td>
<td>$\Delta\phi_{\ell\ell, E_T^{\text{miss}}/\ell} \geq \pi/2$</td>
<td>$\Delta R(\ell, \ell)$</td>
<td>overlap removal</td>
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<td></td>
<td>$p_T^{\ell} &gt; 30$ GeV</td>
<td>$m_{\ell\ell} &lt; m_T - 25$ GeV</td>
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<td>$m_T &gt; 80$ GeV</td>
<td>$m_{\ell\ell} &gt; 10$ GeV</td>
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<tr>
<td>$H → WW^* →\ell\nu\ell\nu$ topology</td>
<td>$m_{\ell\ell} &lt; 55$ GeV</td>
<td>Central jet veto ($p_T &gt; 20$ GeV)</td>
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<td>$\Delta\phi_{\ell\ell} &lt; 1.8$</td>
<td>Outside lepton veto</td>
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<tr>
<td>Source</td>
<td>Uncertainty [%]</td>
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<td>------------------------------------------</td>
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<td>Pile-up modelling</td>
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<td>Higgs boson mass</td>
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<tr>
<td>Theoretical (signal) modelling</td>
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<td><strong>Total</strong></td>
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<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
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<tbody>
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<td>Statistical uncertainty</td>
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<td>All electron uncertainties</td>
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<td>All muon uncertainties</td>
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<td>Other uncertainties</td>
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