Measurement of the four-lepton invariant mass spectrum in 13 TeV proton-proton collisions with the ATLAS detector*

from particlezoo.net

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Group B
The ATLAS Experiment
Theoretical Prediction

\[ \text{ATLAS Simulation} \quad \sqrt{s} = 13 \text{ TeV} \]

- \( q\bar{q} \rightarrow 4l \)
- \( gg \rightarrow 4l \) (inclusive)
- \( gg \rightarrow H \rightarrow 4l \)
- \( gg \rightarrow ZZ \rightarrow 4l \)
- \( VH/t\bar{t}H/VBF \ H \rightarrow 4l \)

\( m_{4l} \) [GeV]
Theoretical Prediction

\[ \text{ATLAS Simulation} \]
\[ \sqrt{s} = 13 \text{ TeV} \]

\[ \text{d} \sigma / \text{d} m_{4l} \text{ [fb/GeV]} \]

\[ m_{4l} [\text{GeV}] \]
Theoretical Prediction

\begin{align*}
\text{ATLAS Simulation} & \quad \sqrt{s} = 13 \text{ TeV} \\
\text{d}\sigma/dm_{4l} [\text{fb/GeV}] & \quad 10^{-3} \\
80 & \quad 100 \quad 200 \quad 300 \quad 400 \quad 500 \quad 600 \quad 700 \quad 800 \quad 900 \quad 1000 \\
\text{m}_{4l} [\text{GeV}] & \\
\text{q\bar{q} \rightarrow 4l} & \quad \text{gg \rightarrow 4l (inclusive)} \\
\text{gg \rightarrow H \rightarrow 4l} & \quad \text{gg \rightarrow ZZ \rightarrow 4l} \\
\text{VH/ttH/VBF H} & \\
\end{align*}
Simulation

Parton Distributions: NNPDF3.0 NNLO
Simulation

LO+ Parton Shower (SHERPA)+K-factor

Parton Distributions:
NNPDF3.0 NNLO

+ Irreducible Background (ZWW, ZZW, ZZZ, ttbarZ, ttbarWW) Simulated with SHERPA
Fiducial cross-section

Physics Object Preselection

| Muon selection | $p_T > 5 \text{ GeV}, |\eta| < 2.7$ |
|----------------|----------------------------------|
| Electron selection | $p_T > 7 \text{ GeV}, |\eta| < 2.47$ |

Quadruplet Selection

| Lepton pairing | Assign SFOS lepton pairs with smallest and second-smallest $|m_{\ell\ell} - m_Z|$ as primary and secondary lepton pair, defining exactly one quadruplet |
|----------------|----------------------------------------------------------------------------------|
| Lepton kinematics | $p_T > 20/15/10 \text{ GeV}$ for leading three leptons |
| Mass window, primary pair | $50 \text{ GeV} < m_{12} < 106 \text{ GeV}$ |
| Mass window, secondary pair | $f(m_{4\ell}) < m_{34} < 115 \text{ GeV}$ |
| Lepton separation | $\Delta R_{ij} > 0.1(0.2)$ for same (opposite) flavour leptons |
| $J/\psi$ veto | $m_{ij} > 5 \text{ GeV}$ for all SFOS pairs |
| Mass interval of measurement | $70 \text{ GeV} < m_{4\ell} < 1200 \text{ GeV}$ |

Isolate off shell H (LO):

\[
D_{ME} = \log_{10} \frac{\tilde{M}^2_{gg\rightarrow H(\rightarrow ZZ)\rightarrow 4\ell} \left( p_{1,2,3,4}^\mu \right)}{\tilde{M}^2_{gg(\rightarrow H(\rightarrow ZZ)\rightarrow 4\ell)} \left( p_{1,2,3,4}^\mu \right) + 0.1 \cdot \tilde{M}^2_{q\bar{q}\rightarrow ZZ \rightarrow 4\ell} \left( p_{1,2,3,4}^\mu \right)}
\]
# Data Sample and Event Selection

<table>
<thead>
<tr>
<th>Physics Object preselection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrons</strong></td>
</tr>
<tr>
<td>Identification</td>
</tr>
<tr>
<td>Kinematics</td>
</tr>
<tr>
<td>Interaction point constraint</td>
</tr>
<tr>
<td>Cosmic-ray muon veto</td>
</tr>
</tbody>
</table>

## Quadruplet Selection

<table>
<thead>
<tr>
<th>Quadruplet formation</th>
<th>Procedure and kinematic selection criteria as in Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton isolation</strong></td>
<td></td>
</tr>
<tr>
<td>Track isolation</td>
<td>$\sum_{\Delta R \leq 0.2} p_T &lt; 0.15E_T^e$</td>
</tr>
<tr>
<td>Calorimeter isolation</td>
<td>$\sum_{\Delta R = 0.2} E_T &lt; 0.2E_T^e$</td>
</tr>
<tr>
<td><strong>Lepton transverse impact parameter</strong></td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>$d_0/\sigma_{d_0} &lt; 5$</td>
</tr>
<tr>
<td>Muons</td>
<td></td>
</tr>
<tr>
<td>$4\ell$ vertex fit</td>
<td>$\chi^2/\text{ndof} &lt; 6$ (4\mu) or &lt; 9 (4e, 2e2\mu)$</td>
</tr>
</tbody>
</table>
FREE TIME

EXCURSIONS

2019 CERN Latin-American School
Unfolding procedure

Corrects for experimental effects, allows direct comparison with particle-level predictions within fiducial phase space.

The response matrix $K_{sy}$ consists of three contributions:

- **Reconstruction efficiency:**
  60-80% but lower (~30%) for lower $m_{4l}$

- **Fiducial fraction:**
  Close to unity, ~90% for $m_{4l} < 200$ GeV

- **Bin migration effects:**
  Fiducial purity (i=j) ~ 80%

Measurement

$$g(s) = \int \Omega K(s, y)f(y)dy$$

(Mis-reconstruction, non uniform efficiency, resolution...)

Observed $g(s)$

Detector-level

“True” $f(y)$

Particle-level

$N_{fiducial & detector}$

$N_{fiducial}$

$N_{fiducial & detector}$

$N_{detector}$

$N_{fid,i} \rightarrow N_{det,j}$
Uncertainties

- Stats limited analysis (2000 Poisson pseudo-datasets).
- Lepton
  - electron and muon reco, ID and isolation efficiency.
  - resolution and scale uncertainties.
- Unfolding
  - Reco MC vs particle level distribution
  - Generator choice for qq->4l.
- Theoretical
  - Particle-level predictions.
  - Renormalisation and factorisation scales, PDF and parton showering.
- Luminosity
  - 2015+2016 luminosity uncertainty ~ 2.1%
μ_{gg} = \frac{\sigma_{gg\rightarrow 4\ell}^{\text{measured}}}{\sigma_{gg\rightarrow 4\ell}^{\text{SM}}} \\
μ_{gg} = 1.3 \pm 0.5 \\
Expected value: 1.0 \pm 0.4
Results and Interpretation

$$\mu^O_S \ = \ \frac{\sigma_{gg\to H^*\to 4\ell}}{\sigma_{gg\to H^*\to 4\ell}^{SM}}$$

Upper limit off-shell Higgs production (95% CL):

$$\mu^O_S \ < \ 6.5$$
Results and Interpretation

Higgs boson to top quark (C_t) and gluons (C_g, zero in the SM) constrained.

Parameter space which lies outside contour excluded @ 95% CL.
Back up: Experiment
**Back up: Data Sample**

**Medium muons** The *Medium* identification criteria provide the default selection for muons in ATLAS. This selection minimises the systematic uncertainties associated with muon reconstruction and calibration. Only CB and ME tracks are used. The former are required to have $\geq 3$ hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. The latter are required to have at least three MDT/CSC layers, and

**Loose muons** The *Loose* identification criteria are designed to maximise the reconstruction efficiency while providing good-quality muon tracks. They are specifically optimised for reconstructing Higgs boson candidates in the four-lepton final state [5]. All muon types are used. All CB and ME muons satisfying the *Medium* requirements are included in the *Loose* selection. CT and ST muons are restricted to the $|\eta| < 0.1$ region. In the region $|\eta| < 2.5$, about 97.5% of the *Loose* muons are combined muons, approximately 1.5% are CT and the remaining 1% are reconstructed as ST muons.
Fig. 4. Distribution of events passing the selection as a function of the four-lepton invariant mass.
Back up: Results and Interpretation
Back up: Results and Interpretation
Conclusions

m4l distribution using 36.1 fb-1 p-p collision @ 13 TeV in ATLAS

Results consistent with SM predictions