MEASUREMENTS OF ELASTIC PP INTERACTIONS AND EXCLUSIVE PRODUCTION WITH THE ATLAS DETECTOR

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This talk presents ATLAS results on

Elastic measurements
- elastic cross section $pp \rightarrow pp$ at 7 TeV; Nucl. Phys. B (2014) 486-548

Central exclusive production (CEP)
- exclusive $\gamma\gamma \rightarrow l^+l^-$ production at 13 TeV, Phys. Lett. B 777 (2018) 303
- exclusive $\gamma\gamma \rightarrow l^+l^-$ production at 7 TeV, Phys. Lett. B 749 (2015) 242
- exclusive $\gamma\gamma \rightarrow W^+W^-$ production at 8 TeV, Phys. Rev. D 94 (2016) 32011

More results on standard model physics at:
- [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults)
**ATLAS detector**

25 meters high, 44 meters long, weight 7000 tons

Coverage:
- Inner Detector $|\eta| < 2.5$
- Calorimeters $|\eta| < 4.9$
- Muons $|\eta| < 2.7$
- Minimum bias trigger scintillators $2.1 < |\eta| < 3.9$

Forward proton detectors:
- **ALFA** vertical Roman Pots at 237+241m from IP
  - optimized for elastic scattering
  - suitable for processes with relatively high cross. sect. and low mass CEP
- **AFP** one/two arms in 2016/2017, horizontal RPs at 205+217m from IP
  - optimized for hard diffraction
  - suitable for high mass CEP
Total cross section from elastic scattering in pp-collisions

Total pp cross section is fundamental observable in particle physics, giving the upper bound of any process in pp collisions.

\[
\sigma_{\text{tot}} \text{ is estimated from } \sigma_{\text{el}} \text{ via the optical theorem}
\]

where \( \rho = \frac{\text{Re}(f_{el})}{\text{Im}(f_{el})} \bigg|_{t \to 0} \) is taken from model extrapolations

\[
\sigma_{\text{tot}} = 4\pi \text{ Im} (f_{el}) \bigg|_{t \to 0}, \quad \sigma_{\text{tot}}^2 = \frac{16\pi (hc)^2}{1+\rho^2} \frac{d\sigma_{\text{el}}}{dt} \bigg|_{t = 0}
\]

Measurement based on small angle elastic scattering \((t \to 0)\),
Elastic data fitted as sum of a Coulomb term and a Nuclear term

\[
\frac{d\sigma}{dt} = \frac{1}{16\pi} \left| f_N(t) + f_C(t)e^{i\rho \phi(t)} \right|^2
\]

\[
\rho = \frac{\text{Re}(f_{el})}{\text{Im}(f_{el})} \bigg|_{t \to 0} = 0.1362
\]

\[
G(t) = \left( \frac{\Lambda}{\Lambda - t} \right)^2, \quad \Lambda = 0.71 \text{ GeV}^2
\]

\[
\phi(t) = -\ln \left( -\frac{Bt}{2} \right) - \phi_c, \quad \phi_c = 0.577
\]

Beam angular divergence should be smaller than scattering angle to be measured \( \sigma_{\text{beam}} = \sqrt{\frac{\varepsilon}{\beta^*}} \Rightarrow \text{high } \beta^* \)

In ATLAS, elastic scattering is measured with the ALFA Roman Pot sub-detector, in dedicated runs of LHC with special optics at high \( \beta^* = 90 \text{ m} \).

dσ_{el}/dt measured to extract σ_{tot} and nuclear slope B

ATLAS: Elastic scattering measured in a dedicated run of LHC in 2012 with high β* = 90 m optics with the ALFA Roman Pot sub-detector, int. luminosity 500 ub^{-1}

Exponential fit in the region 0.014 GeV^2 < -t < 0.1 GeV^2, where deviations from exponential form of nuclear amplitude expected to be small, with free parameters σ_{tot} and B gave:

B = 19.74 ± 0.05 (stat) ± 0.16 (exp) ± 0.15 (extr) GeV^{-2}

σ_{tot} = 96.07 ± 0.18 (stat) ± 0.85 (exp) ± 0.31 (extr) mb

exp. error dominated by beam energy (for B) and luminosity error (σ_{tot}); extr. error dominated by fit range variation
Escattering in pp-collisions at @ 8 TeV


Energy evolution of nuclear slope $B$

ATLAS @ 8 TeV: $B = 19.74 \pm 0.17$ GeV$^{-2}$

Very good agreement with TOTEM measurement (same LHC fill)

TOTEM: $B = 19.9 \pm 0.3$ GeV$^{-2}$

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Total cross section from elastic scattering in pp-collisions at @ 8 TeV

Energy evolution of $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$.

ATLAS $\sigma_{\text{tot}} = 96.07 \pm 0.92$ mb

TOTEM (same LHC fill): $\sigma_{\text{tot}} = 101.7 \pm 2.9$ mb

ATLAS measurement is 5.63 mb smaller than TOTEM’s
Corresponds to 1.9 $\sigma$, assuming uncorrelated
uncertainties
Exclusive $\gamma\gamma$ production of lepton pairs in $pp$ @ 7, 13 TeV

$\gamma\gamma$ induced interactions provide unique opportunity to study electroweak high energy processes

Equivalent Photon Approximation (EPA): beam of quasi-real photons with a small virtuality of $Q^2 < 0.1$ GeV$^2$

Small corrections due to the finite size of protons reduce the EPA cross section

- Photon induced production of lepton pairs is up to a few percent of the inclusive dilepton production at LHC energies
- Exclusive $\gamma\gamma \to \ell^+\ell^-$ production process competes with the two-photon interactions involving single- or double-proton dissociation
- Proton-dissociative processes have different kinematic distributions (i.e. $\ell^+\ell^-$-acoplanarity) and can be separated from exclusive reactions
Exclusive $\gamma\gamma$ production of lepton pairs in pp @ 7, 13 TeV

- 7 TeV: Data: 4.6 fb$^{-1}$ in 2011 @ 7 TeV, $e^+e^-$ and $\mu^+\mu^-$ channel
- 13 TeV: Data: 3.2 fb$^{-1}$ in 2015 @ 13 TeV, $\mu^+\mu^-$ channel

Exclusive selection: exactly one pair of $l^+l^-$ associated to a vertex and 1(3) mm vertex isolation

Binned maximum-likelihood fit of the exclusive and single-dissociative contributions to the measured dilepton acoplanarity distribution; Double-dissociative and Drell-Yan background are fixed to the MC predictions
Exclusive $\gamma \gamma$ production of lepton pairs in pp @ 7, 13 TeV


Cross sections measured in the fiducial region:

7 TeV: $\gamma\gamma \rightarrow e^+e^-, \mu^+\mu^-$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^\ell$</td>
<td>$&gt; 12$ GeV</td>
<td>$&gt; 10$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta^\ell</td>
<td>$</td>
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<tr>
<td>$m_{\ell^+\ell^-}$</td>
<td>$&gt; 24$ GeV</td>
<td>$&gt; 20$ GeV</td>
</tr>
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13 TeV: $\gamma\gamma \rightarrow \mu^+\mu^- = 3.12 \pm 0.07$ (stat.) $\pm 0.14$ (syst.) pb

| Invariant mass range | $p_T^{\mu}$ requirement | $|\eta^{\mu}|$ requirement |
|----------------------|--------------------------|---------------------------|
| 12 GeV $< m_{\mu^+\mu^-} < 30$ GeV | $> 6$ GeV | $< 2.4$ |
| 30 GeV $< m_{\mu^+\mu^-} < 70$ GeV | $> 10$ GeV | $< 2.4$ |

Dominant uncertainty from template fit to acoplanarity shape (reducible with proton tagging)

Measured cross-sections consistent with the CMS measurement JHEP 1201 (2012) 052

and in agreement with the predicted values corrected for proton absorptive effects (corrections $\sim$20%)
Exclusive $\gamma\gamma$ production of lepton pairs in pp @ 13 TeV

- $d\sigma/dm_{\mu^+\mu^-}$ compared to models
- correction to the EPA cross sections measured vs the average $\langle m_{\mu^+\mu^-} \rangle$ scaled by a given $pp$ centre-of-mass energy

\[ \frac{d^2\sigma}{dm_{\mu^+\mu^-}} \]

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The size of absorptive corrections tends to increase with $\langle m_{\mu^+\mu^-} \rangle/\sqrt{s}$. 

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Data: 20.2 fb$^{-1}$ of pp collisions collected by the ATLAS @ 8 TeV. selection requires $l^{+}l^{-}$ associated with W,H, no additional charged track, lepton vertex isolated

Exclusive production of $W^+W^-$ consistent with the Standard Model prediction is found with 3.0σ significance. 

$\sigma(\gamma\gamma \rightarrow W^+W^- \rightarrow e^\pm \mu^\pm X) = 6.9 \pm 2.2\text{(stat.)} \pm 1.4\text{(sys.)} \text{ fb}$, in agreement with the Standard Model

Limits on anomalous quartic gauge couplings are set at 95% confidence-level as

$-1.7 \times 10^{-6} < a^W_0 / \Lambda^2 < 1.7 \times 10^{-6} \text{ GeV}^{-2}$ and $-6.4 \times 10^{-6} < a^W_C / \Lambda^2 < 6.3 \times 10^{-6} \text{ GeV}^{-2}$

A 95% confidence-level upper limit on the total production cross-section for exclusive Higgs boson is set to 1.2 pb
Exclusive production with forward proton detectors: ongoing measurements

Data collected in special high $\beta^* = 90$ m optics runs with ALFA detector:

- Analysis of exclusive dipion production $p + p \rightarrow p + \pi^+\pi^- + p$ @ $\sqrt{s} = 7, 8, 13$ TeV. Due to the ALFA geometrical acceptance range process dominated by Double Pomeron Exchange (DPE): $\text{IPIP} \rightarrow \pi^+\pi^-$
- @ 13 TeV also candidates for exclusive production of KK, pp, $\pi\pi\pi\pi$ final states as well as $\gamma\text{IP} \rightarrow \pi^+\pi^-$ are observed

Data collected during normal running with AFP detector (fully installed in 2017):

- $\sim 32$ fb$^{-1}$ collected in 2017 with $\mu \sim 50$
- TOF still in commissioning - plan for this year
- Central exclusive QCD production (dijets)
- Central exclusive production from $\gamma\gamma$
  - Dilepton; diboson (aQGC)
  - AFP can provide large reduction of background and systematic uncertainty of previous measurements
- Searches for heavy new particles

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Summary and plans

- The differential elastic cross section is measured with tracking detectors in Roman pot @ \( \sqrt{s} = 7.8 \) TeV
- The total cross section is inferred using the optical theorem and is still observed to rise with energy
  - Future elastic measurements:
    - Data in the Coulomb-Nuclear-Interference region at \( -t \approx 10^{-3} \text{GeV}^2 \) allows a measurement of the \( \rho \)-parameter
    - Dispersion relations relates energy evolution of the \( \sigma_{\text{tot}} \) and \( \rho \) Allows high energy predictions of \( \sigma_{\text{tot}} \)
    - Data has been collected at 8 TeV with \( \beta^* = 1 \) km, the analysis is in review.
    - Data has been collected at 13 TeV with \( \beta^* = 2.5 \) km and 90m optics; the analysis is ongoing.
- Cross sections of the exclusive \( \gamma\gamma \rightarrow l^+l^- \) production have been measured @ \( \sqrt{s} = 7, 13 \) TeV, corrections \( \sim 20\% \) due to proton absorption have been measured
- Ongoing measurements of low mass exclusive processes using data collected in special high \( \beta^* = 90 \) m optics runs with protons measured in ALFA
- Lots of prospects for improvement on current measurements and brand new analysis with AFP during LHC Run-II and beyond.