Measurements of elastic pp interactions and exclusive production with the ATLAS detector

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Elastic and Exclusive Production with ATLAS

- **Elastic measurements**
  - \( pp \to pp \) at 7(8) TeV, 80(500) \( \mu b^{-1} \)
    - fundamental process for any accelerator at each energy
    - allows to give the upper bound on total \( pp \) cross sections

- **Central Exclusive Production (CEP)**
  - \( pp(\gamma\gamma) \to p + l^+l^- + p \) at 7(13) TeV, 4.6(3.2) \( fb^{-1} \)
    - provides direct access to the elastic photon distributions in proton
    - non-negligible background to Drell-Yan like reactions
  - \( pp(\gamma\gamma) \to p + W^+W^- + p \) at 8 TeV, 20.2 \( fb^{-1} \)
    - tests of SM \( \gamma\gamma WW \) quartic gauge coupling
    - can probe physics beyond the electroweak scale and set limits on anomalous quartic gauge couplings (aQGCs)
  - \( pp(gg) \to p + Higgs + p \to p + W^+W^- + p \) at 8 TeV, 20.2 \( fb^{-1} \)
    - can be used for Higgs properties studies
  - \( p + p \to p + M + p \) with forward proton detectors (analysis in progress)
ATLAS detector

- Inner Detector ($|\eta| < 2.5$)
- Calorimeters ($|\eta| < 4.9$)

- Muon spectrometer ($|\eta| < 2.7$)
- Minimum Bias Trigger Scintillator ($2.1 < |\eta| < 3.9$)

Forward proton detectors:

- **ALFA**: vertical RPs
  - located $\approx 240$ m from IP1
  - optimized for elastic scattering
  - suitable for processes with relatively high cross. sect. (low mass CEP)

- **AFP**: horizontal RPs
  - located $\approx 210$ m from IP1
  - optimized for hard diffraction
  - suitable for high mass CEP
Elastic and Total Cross Sections

- The total $p + p \rightarrow X$ cross section is a fundamental quantity that cannot be calculated in perturbative QCD but still can be measured for example using the Optical Theorem:

$$\sigma_{\text{tot}} = 4\pi \left| \text{Im}(f_{\text{el}}) \right|_{t \rightarrow 0}$$

$$\sigma_{\text{tot}}^2 = \frac{1}{L} \frac{16\pi}{1 + \rho^2} \frac{dN_{\text{el}}}{dt} \bigg|_{t \rightarrow 0}$$

- Luminosity-dependent method where $\rho = \frac{\text{Re}(f_{\text{el}})}{\text{Im}(f_{\text{el}})} \bigg|_{t \rightarrow 0}$ is taken from model extrapolation

- Measurement based on small angle elastic scattering ($t \rightarrow 0$)
  - Beam angular divergence should be smaller than scattering angle to be measured
  - Small $\sigma_{\text{beam}} = \sqrt{\epsilon/\beta^*}$ ⇒ large $\beta^*$

- Elastic scattering is measured in a dedicated run of the LHC with special high $\beta^* = 90\,\text{m}$ optics with the ALFA Roman Pot sub-detector.
The theoretical prediction used to fit the elastic data consists of the Coulomb term, the Coulomb-Nuclear-Interference term and the dominant Nuclear term.

\[
\frac{d\sigma}{dt} = \frac{1}{16\pi} |f_N(t) + f_C(t) \exp(i\alpha(t))|^2
\]

\[
\frac{d\sigma}{dt} = \frac{4\pi\alpha^2(\hbar c)^2 G^4}{t^2}
\]

\[
+ \sigma_{\text{tot}} \frac{\alpha G^2}{t} \left[ \sin(\alpha\phi) + \rho \cos(\alpha\phi) \right] \exp(\frac{B t}{2})
\]

\[
+ \sigma_{\text{tot}}^2 \frac{\frac{1+\rho^2}{16\pi(\hbar c)^2}} \exp(\frac{B t}{t})
\]


- \( \rho = \frac{\text{Re}(f_{el})}{\text{Im}(f_{el})} \bigg|_{t \to 0} = 0.1362 \)
- \( G(t) = \left( \frac{\Lambda}{\Lambda - t} \right)^2, \quad \Lambda = 0.71 \text{ GeV}^2 \)
- \( \phi(t) = -\ln(-Bt/2) - \phi_C, \quad \phi_C = 0.577 \)
Fit of $\frac{d\sigma_{el}}{dt}$ with two free parameters: $\sigma_{tot}$ and $B$

- All statistical and experimental systematic uncertainties included
- Fit range of $-t = [0.014, 0.1]$ GeV$^2$
  - possible deviations from exponential form of nuclear amplitude expected to be small
- Fit quality: $\chi^2$/Ndof = 17.8/14

$$B = 19.74 \pm 0.17 \text{ GeV}^{-2}$$

$$\sigma_{tot} = 96.07 \pm 0.86 \text{ mb}$$

Further uncertainty arise from the extrapolation $t \to 0$, probed by a variation of the upper fit range to 0.152 and 0.065, lower end to 0.009 and 0.0245 and $\rho \pm 0.0034$

Extrapolation error $\Delta\sigma_{tot} = \pm 0.31$ mb, $\Delta B = \pm 0.15$ GeV$^2$
Elastic $pp \rightarrow pp$ at 8 TeV

- Energy evolution of $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$
- Elastic cross section from the nuclear part of the integrated fit function
- Very good agreement with TOTEM measurement

ATLAS: $\sigma_{\text{tot}} = 96.07 \pm 0.92$ mb
TOTEM: $\sigma_{\text{tot}} = 101.7 \pm 2.9$ mb

Our measurement is 5.63 mb smaller than TOTEM's
Corresponds to $1.9 \sigma$, assuming uncorrelated uncertainties

$B = 19.74 \pm 0.19$ GeV$^{-2}$
$B = 19.9 \pm 0.3$ GeV$^{-2}$
Selection of exclusive production of state $X$:

- no additional activity in Inner Detector associated with the production vertex of state $X$

- without forward proton detectors:
  - search for kinematic variable with power to suppress non-exclusive (proton dissociation) production of state $X$

- with forward proton detectors (ALFA/AFP) at low pile-up select events with single primary vertex:
  - direct proof of exclusive production
  - event kinematics fully reconstructed (make use of correlation between central and forward regions)
  - no additional activity in MBTS.

- with AFP forward proton detectors (high pile-up):
  - Time Of Flight measurement required to associate forward protons with production vertex (still commissioning)
- Signal modeling using the Equivalent Photon Approximation (EPA) + QED with non-negligible absorptive corrections

- Cross-section dominated by so-called single- and double-proton dissociative reactions

- Elastic process is characterized by the production of back-to-back leptons, $p_T^{ll} \approx 0$, providing a way to separate the elastic from the dissociative production
Cross section measurement:
- 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

Fiducial region:
- 7 TeV $\gamma\gamma \rightarrow ee$: $m_{e^+e^-} > 24$ GeV, $p_T^e > 12$ GeV
- 7 TeV $\gamma\gamma \rightarrow \mu\mu$: $m_{\mu^+\mu^-} > 20$ GeV, $p_T^\mu > 10$ GeV
- 13 TeV $\gamma\gamma \rightarrow \mu\mu$: $12 < m_{\mu^+\mu^-} < 70$ GeV, $p_T^\mu > 6$ GeV
Theory predictions (QED-EPA) with absorptive corrections (20% effect) from PLB 741 (2015) 66-70

- Dominant uncertainty from template fit to acoplanarity shape (reducible with proton tagging)
- Measured cross-sections are in agreement with the predicted values corrected for proton absorptive effects
- They are also consistent with the CMS measurement JHEP 1201 (2012) 052
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): $IPIP \rightarrow \pi^+ \pi^-$
  - @ $\sqrt{s} = 13$ TeV also candidates for exclusive production of $KK, pp, \pi\pi\pi\pi$ final states as well as $\gamma IPI \rightarrow \pi^+ + \pi^-$ 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
- CEP QCD production (dijets)
- CEP from $\gamma\gamma$
  - Dilepton; diboson (aQGC)
  - AFP can provide large background and systematic uncertainty reduction on previous measurements
- Searches for heavy new particles
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 $-t \approx 10^{-3}$ 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
    - The analysis is ongoing.

- Cross sections of the exclusive $\gamma\gamma \rightarrow l^+l^-$ production have been measured @ $\sqrt{s} = 7, 13$ TeV
  - Observation is consistent with the suppression (20%) expected due to proton absorption contributions

- Ongoing measurements of low mass (DPE) 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.