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

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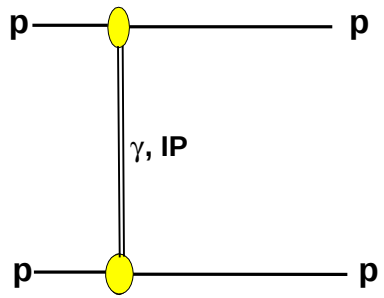
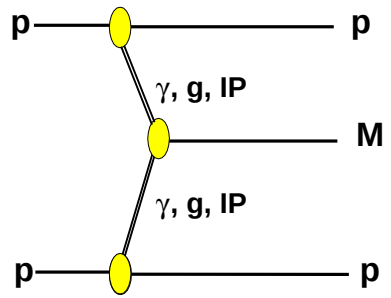
Elastic and Exclusive Production with ATLAS

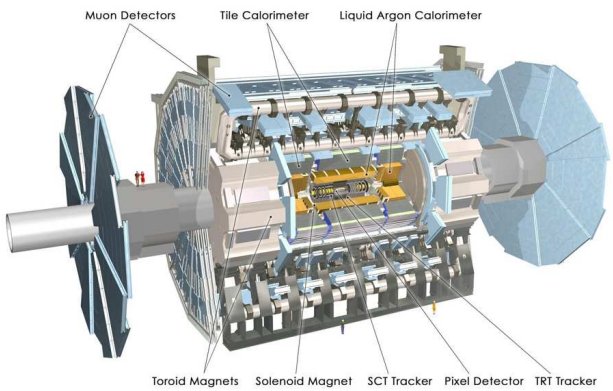




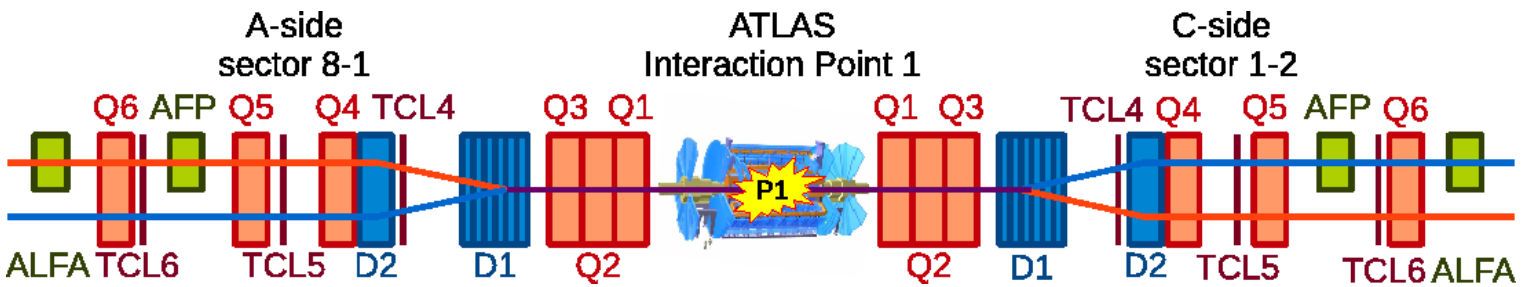
- Elastic measurements
  - $pp \to pp$ at 7(8) TeV, 80(500) μb^{-1}
    - fundamental process for any accelerator at each energy
    - allows to give the upper bound on total pp cross sections
- Central Exclusive Production (CEP)
  - $pp(\gamma\gamma) \to p + l^+l^- + p$ at 7(13) TeV, 4.6(3.2) fb^{-1}
    - 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 $p + p \to X$ cross section is a fundamental quantity that can not be calculated in perturbative QCD but still can be measured for example using the Optical Theorem:

$$\sigma_{\text{tot}} = 4\pi \ \ \text{Im}(f_{\text{el}})|_{t\to 0} \qquad \sigma_{\text{tot}}^2 = \frac{1}{L}\frac{16\pi}{1+\rho^2}\frac{\text{d}N_{\text{el}}}{\text{d}t}|_{t\to 0}$$

- Luminosity-dependent method where $\rho = \frac{\text{Re}(f_{\text{el}})}{\text{Im}(f_{\text{el}})}|_{t\to 0}$ is taken from model extrapolation
- Measurement based on small angle elastic scattering ($t \to 0$)
  - Beam angular divergence should be smaller than scattering angle to be measured

$$\text{small} \ \ \sigma_{\theta_{\text{beam}}} = \sqrt{\varepsilon}/\beta^* \Rightarrow \text{large} \quad \beta^*$$

  - Elastic scattering is measured in a dedicated run of the LHC with special high $\beta^* = 90$ m optics with the ALFA Roman Pot sub-detector.

Theoretical prediction

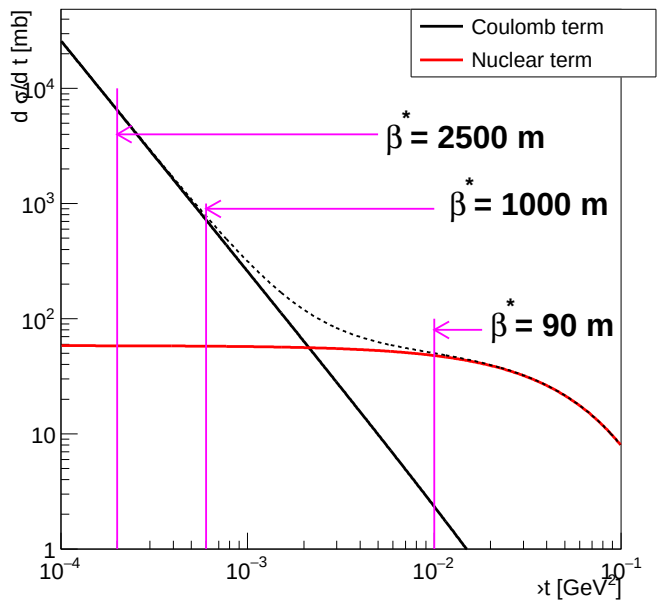
The theoretical prediction used to fit the elastic data consists of the Coulomb term, the Coulomb-Nuclear-Interference term and the dominant Nuclear term.

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

$$\begin{aligned}\frac{d\sigma}{dt} &= \frac{4\pi\alpha^2(\hbar c)^2 G^4}{t^2} \\ &+ \sigma_{tot}\frac{\alpha G^2}{t}[\sin(\alpha\phi) + \rho\cos(\alpha\phi)]\exp(B\,t/2) \\ &+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\exp(B\,t)\end{aligned}$$

Phys. Lett. B 761 (2016) 158-178: Elastic $pp \to pp$ at 8 TeV

- $\rho = \frac{\mathrm{Re}(f_{el})}{\mathrm{Im}(f_{el})}|_{t\to 0} = 0.1362$
- $G(t) = \left(\frac{\Lambda}{\Lambda - t}\right)^2, \quad \Lambda = 0.71\ \mathrm{GeV}^2$
- $\phi(t) = -ln(-Bt/2) - \phi_C, \quad \phi_C = 0.577$



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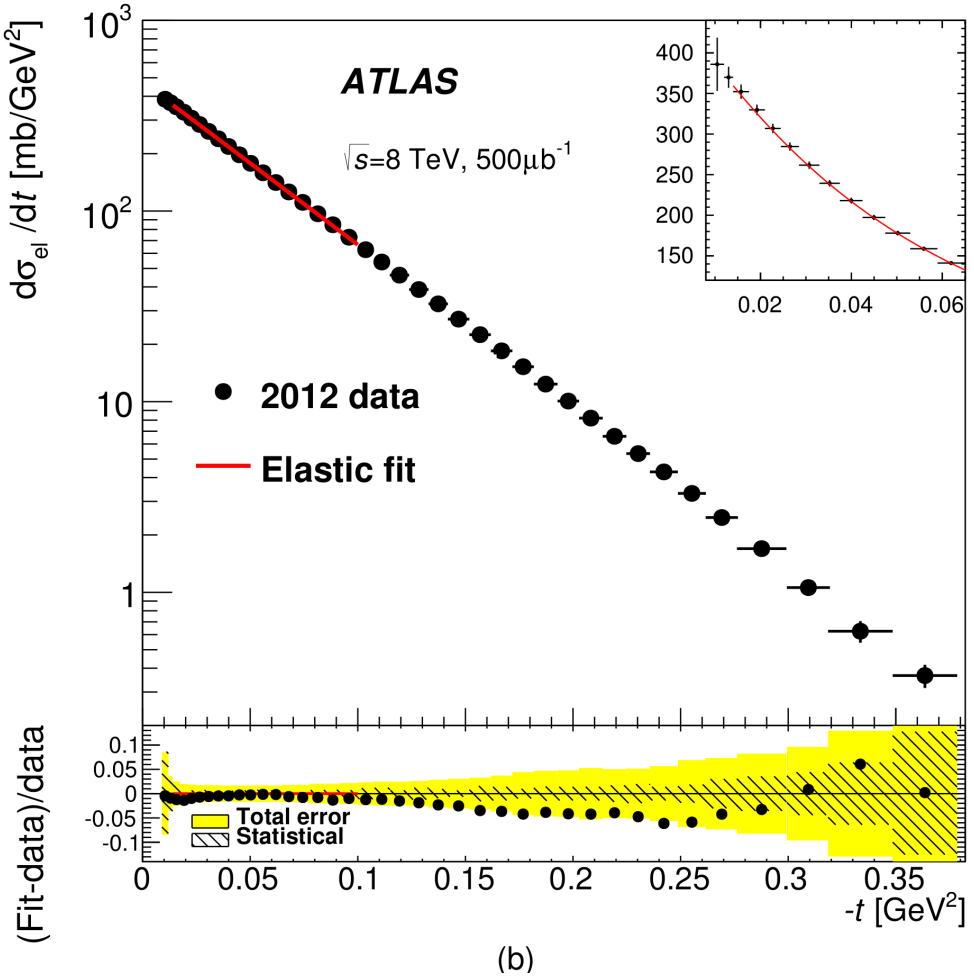
- Fit of $\frac{d\sigma_{el}}{dt}$ with two free parameters: σ_{tot} and B
- All statistical and experimental systematic uncertainties included
- Fit range of $-t = [0.014, 0.1]$ GeV^2
  possible deviations from exponential form of nuclear amplitude expected to be small
- Fit quality: χ^2/Ndof = 17.8/14

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

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



(b)

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 t0 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

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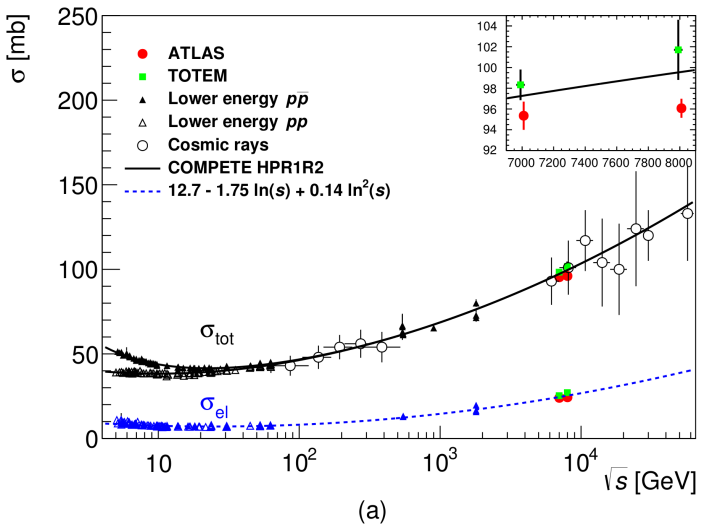
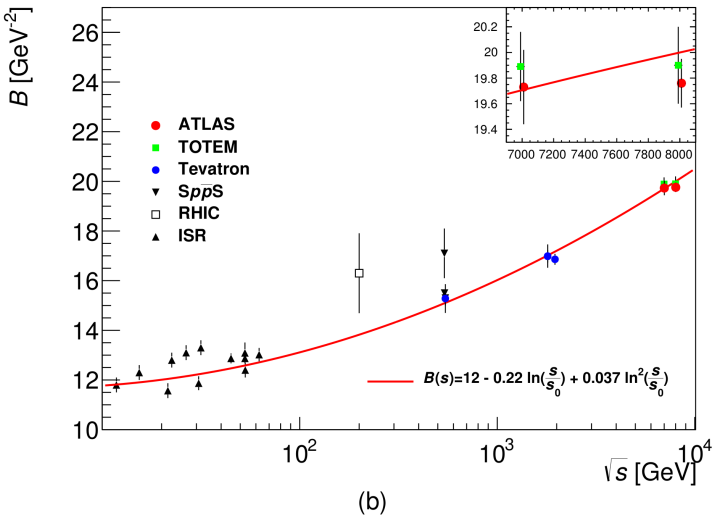




- Energy evolution of σ_{tot} and σ_{el}
- Elastic cross section from the nuclear part of the integrated fit function

- Energy evolution ofnuclear slope B
- 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

$B = 19.74 \pm 0.19$ GeV^{-2}
$B = 19.9 \pm 0.3$ GeV^{-2}

- Our measurement is 5.63 mb smaller than TOTEM's
- Corresponds to 1.9 σ, assuming uncorrelated uncertainties

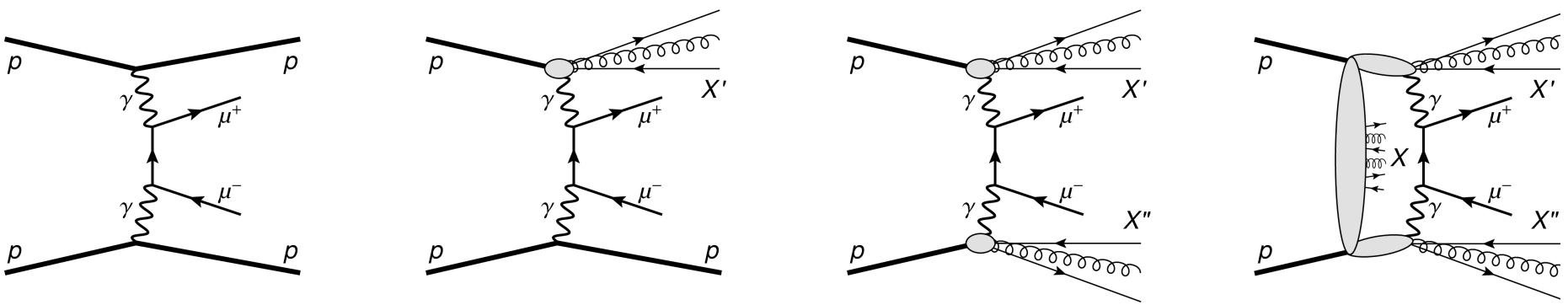
CEP with ATLAS detector

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)

Phys. Lett. B 749 (2015) 242: Exclusive $\gamma\gamma \to l^+l^-$ at 7 TeV
Phys. Lett. B 777 (2018) 303: Exclusive $\gamma\gamma \to \mu^+\mu^-$ at 13 TeV

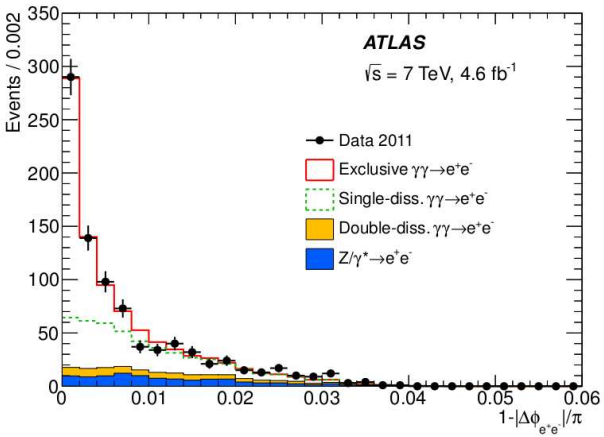
- Signal modeling using the Equivalent Photon Approximation (EPA) + QED with non-negligible absorptive corrections
- Cross-section dominated by so-called single- and double-proton dissociative reactions
- Elastic process is characterized by the production of back-to-back leptons, $p_T^{ll} \approx 0$, providing a way to separate the elastic from the dissociative production

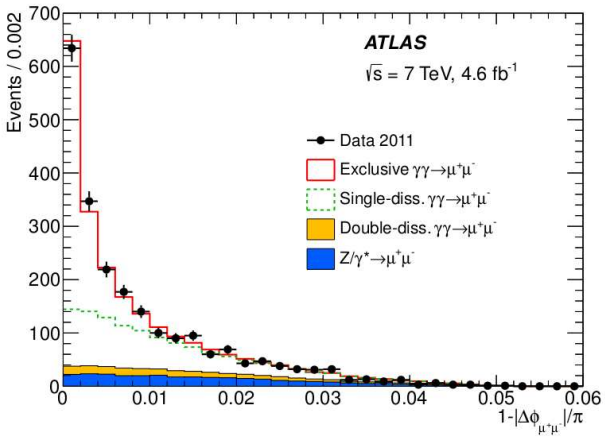


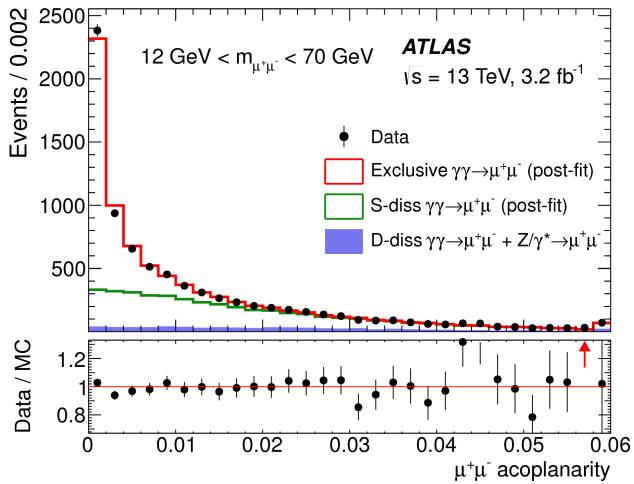
Phys. Lett. B 749 (2015) 242-261: Exclusive $\gamma\gamma \to l^+l^-$ at 7 TeV
Phys. Lett. B 777 (2018) 303: Exclusive $\gamma\gamma \to \mu^+\mu^-$ at 13 TeV

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 $\gamma\gamma \to ee$: $m_{e^+e^-} > 24$ GeV, $p_T^e > 12$ GeV
- 7 TeV $\gamma\gamma \to \mu\mu$: $m_{\mu^+\mu^-} > 20$ GeV, $p_T^\mu > 10$ GeV
- 13 TeV $\gamma\gamma \to \mu\mu$: $12 < m_{\mu^+\mu^-} < 70$ GeV, $p_T^\mu > 6$ GeV

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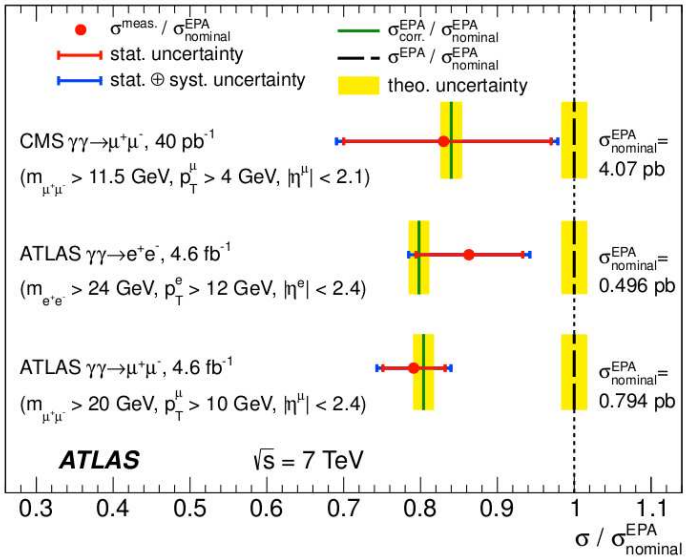
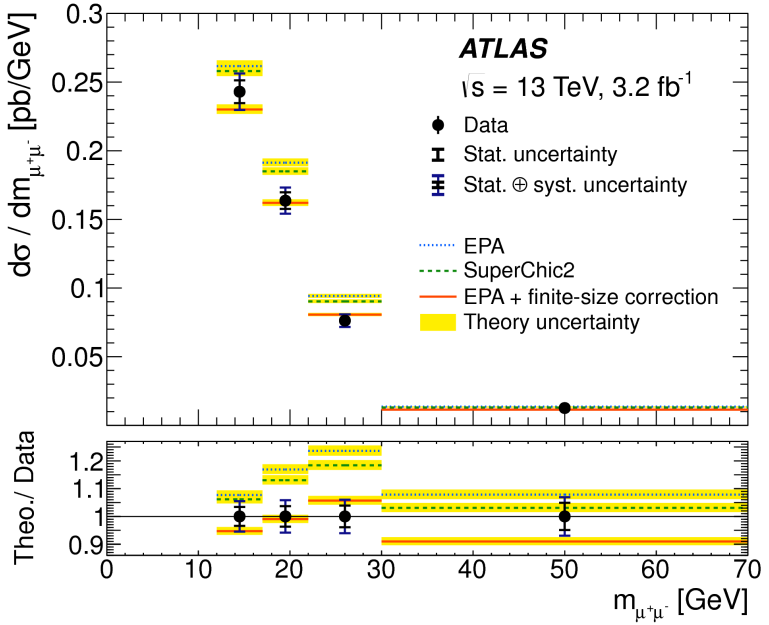
Theory predictions (QED-EPA)
with absorptive corrections(20 % effect) from PLB 741 (2015) 66-70





- 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 $\beta^\star = 90$ m optics runs with ALFA detector:

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

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

- ~ 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 ρ-parameter
  - Dispersion relations relates energy evolution of the σ_{tot} and ρ
  - Allows high energy predictions of σ_{tot}
  - Data has been collected at 8 TeV with $\beta^\star = 1$ km
    - The analysis is in review.
  - Data has been collected at 13 TeV with $\beta^\star = 2.5$ km
    - The analysis is ongoing.
- Cross sections of the exclusive $\gamma\gamma \to l^+l^-$ 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 $\beta^\star = 90$ 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.