Measurement of the total cross section in pp collisions at $\sqrt{s} = 7$ TeV with the ALFA sub-detector of ATLAS

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Total cross section

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

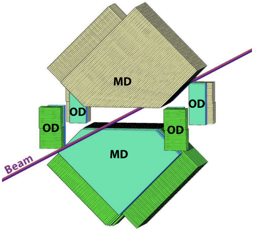
$$\sigma_{\text{tot}} = 4\pi \ \mathrm{Im}(f_{\text{el}})|_{t\to 0} \qquad \sigma^2_{\text{tot}} = \frac{1}{L}\frac{16\pi}{1+\rho^2}\frac{\mathrm{d}N_{\text{el}}}{\mathrm{d}t}|_{t\to 0}$$

- Luminosity-dependent method where $\rho = \frac{\mathrm{Re}(f_{\text{el}})}{\mathrm{Im}(f_{\text{el}})}|_{t\to 0}$ 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

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

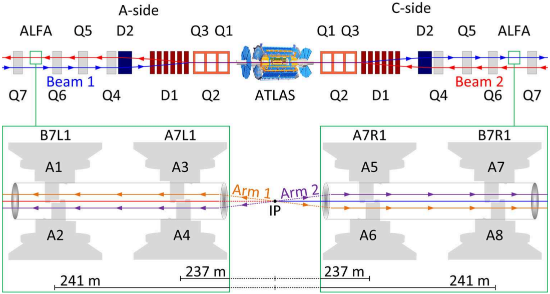
  - Elastic scattering is measured in a dedicated run of the LHC with special high $\beta^* = 90$ m optics with the ALFA Roman Pot sub-detector.

Experimental setup



- Type of tracking detector with scintillating fibers.
- Main Detector: 10 double-sided modules with 64 fibers.
- Spatial resolution $\approx 30\ \mu$m
- Overlapping Detector for relative alignment
- 8 detectors housed in Roman Pot.

The ALFA detector is at 240m from the IP, the detector was placed at 5mm from the beam, 800k elastic events were recorded.



Principles of the measurement

- Measure track positions at ALFA to get the scattering angle and thereby the t-spectrum $\mathrm{d}\sigma/\mathrm{d}t$

$$-t = (p\theta^*)^2, \quad p - \text{beam momentum}, \quad \theta^* - \text{scattering angle}$$

- Calculate scattering angle from position using beam optics transport matrix elements

$$\begin{bmatrix} y^* \\ \theta_y^* \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}^{-1} \cdot \begin{bmatrix} y \\ \theta_y \end{bmatrix}$$

parallel-to-point focusing

$$\theta_y^* = y/M_{12}$$

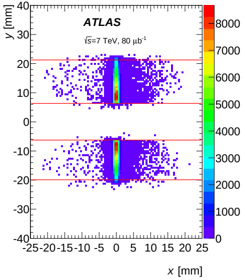
- Different reconstruction methods:
  - Subtraction method

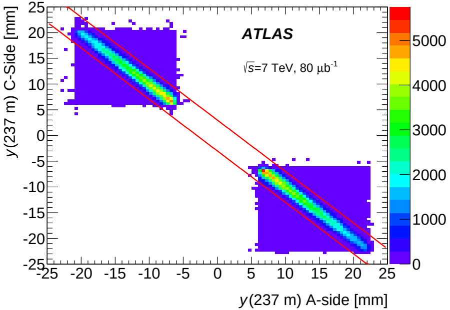
$$\theta_y^* = \frac{y_A - y_C}{M_{12,A} + M_{12,C}}$$

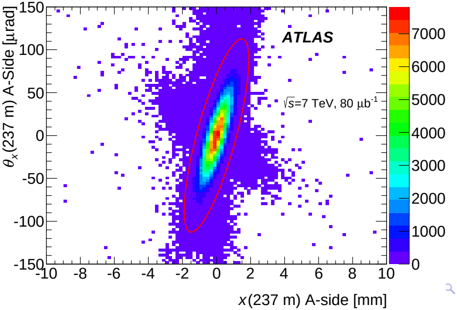
  - Three other methods for horizontal plane: local angle method, local subtraction method and lattice method
- Subtraction method has best resolution and is therefore used for analysis

Event selection

- Elastic trigger
- Data quality requirements
- Geometrical acceptance requirements
- Elastic selection based on back-to-back topology
- Background rejection



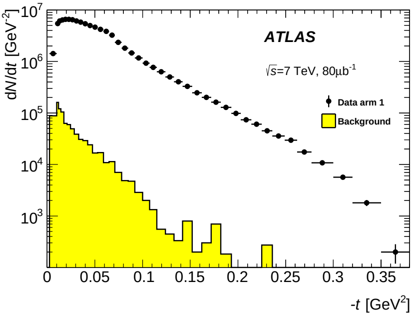


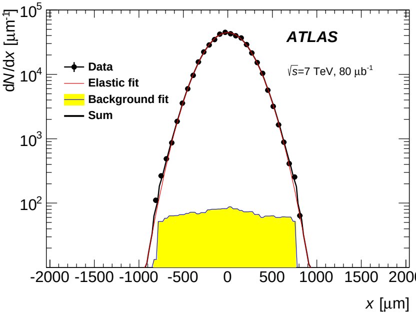


Background

Two ways to estimate the irreducible background under the elastic peak:

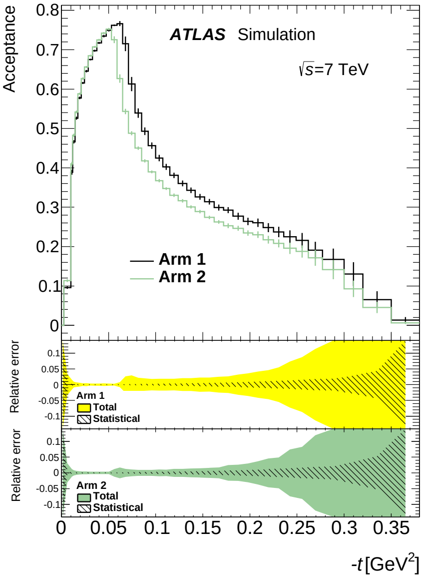
- Back-to-back topology requires golden (up-down) configuration. Counting events in the anti-golden configuration, can also be used to get a t-spectrum for background events for subtraction (nominal method)
- Reconstructing the vertex distribution in x through the lattice, where background appears in non Gaussian tails, fraction estimated with background templates obtained from data (for systematics)





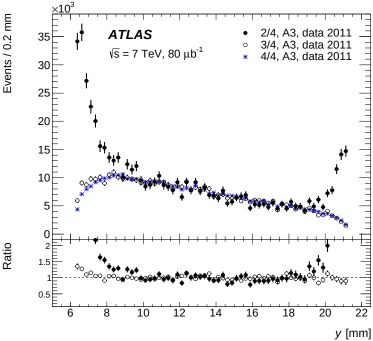
Acceptance

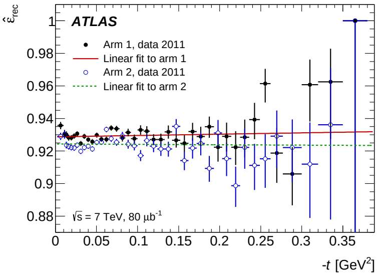
- MC Simulation:
  - Pythia8 as elastic scattering generator
  - Proton transport through beam-line (transport matrix / MadX)
  - Fast detector response parameterization tuned to data
- Acceptance given by geometry and mostly by vertical cuts
- Slightly different vertical cuts in the two arms: different acceptance
- Systematics from parameters in simulation and beam optics



Reconstruction efficiency

Fully data-driven method, using a tag-and-probe approach exploiting elastic back-to-back topology and high trigger efficiency





- The 3/4 case contributes with $\approx$ 66 % to the losses, compatible with flat t-distribution $\hat{\varepsilon} = N_{44}/(N_{44} + N_{34})$
- Different material budget: slightly different overall efficiency in the two arms

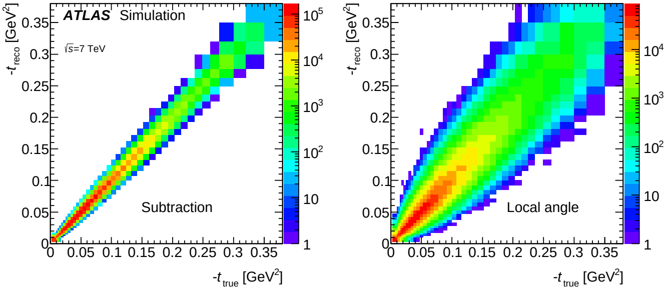
  $\varepsilon_{\mathrm{rec},1} = 0.8974 \pm 0.0004(\mathrm{stat.}) \pm 0.0061(\mathrm{syst.})$

  $\varepsilon_{\mathrm{rec},2} = 0.8800 \pm 0.0005(\mathrm{stat.}) \pm 0.0092(\mathrm{syst.})$

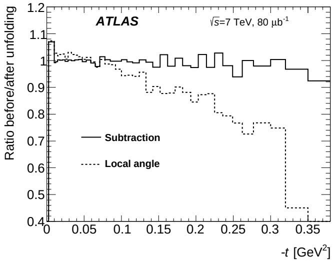
  $\varepsilon = N_{44}/(N_{44} + N_{34} + \text{other losses})$

Unfolding resolution effects

Respond matrix from true *t*-value vs. reconstructed *t*-value



- Used as input for IDS unfolding (B. Malaescu, arXiv:1106.3107)
- Systematic uncertainties evaluated with a data driven closure test
- Test is based on small data/MC differences at reconstruction level

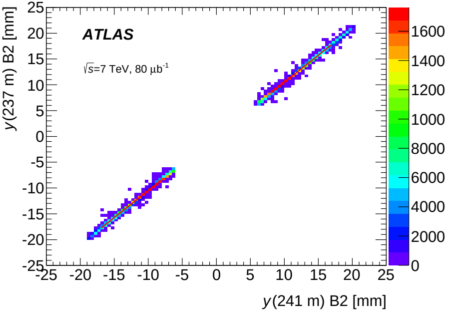


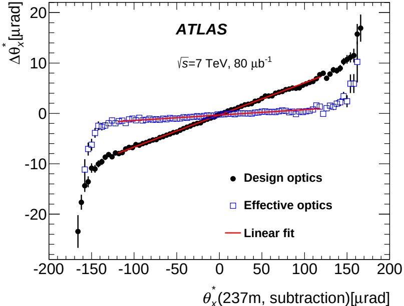
Beam optics

- Fine tuning of the transport matrix elements
- Several constraints obtained from position correlations in elastic scattering data:

$$\frac{y_{\text{inner}}}{y_{\text{outer}}} = \frac{M_{12,\text{inner}}}{M_{12,\text{outer}}}$$

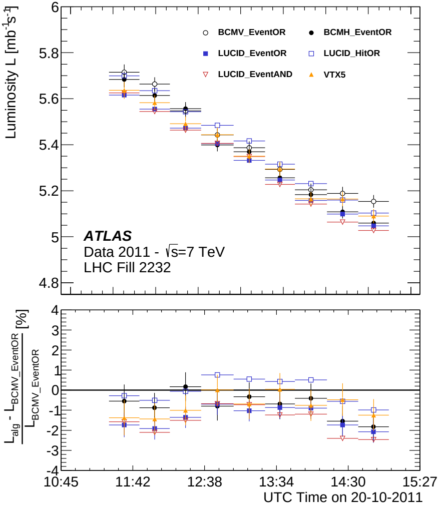
- Other constraints from reconstructed scattering angles correlations
- Indicate amount of scaling needed to equalize measurements from different methods





Luminosity

- Dedicated analysis for the $\beta^* = 90$ m, low-luminosity fill
- Beam condition monitors used as luminosity detectors
- Cross-checks and systematics with LUCID and vertex counting method
- Systematics
  - vdM calibration: 1.5 %
  - BCM instrumental: 0.25 %
  - Background: 0.2 %
  - Time stability: 0.7 %
  - Consistency: 1.6 %
- Total uncertainty: 2.3 %
- Int. luminosity = 78.7 $\pm$ 1.9 μb^{-1}

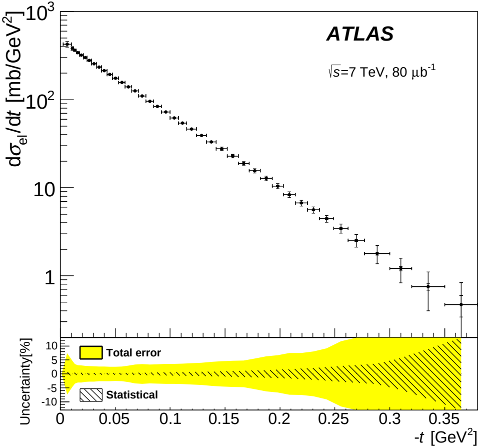


The differential elastic cross section

Fully corrected t-spectra in the two arms are combined and divided by the luminosity to yield the differential elastic cross section.

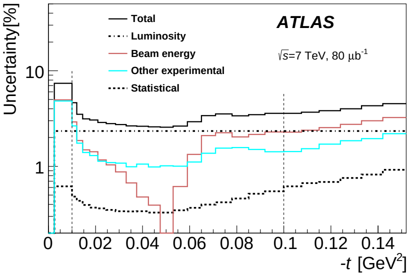
$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{\Delta t_i} \frac{U^{-1}(N_i - B_i)}{A_i \varepsilon_{\mathrm{rec}} \varepsilon_{\mathrm{trig}} \varepsilon_{\mathrm{DAQ}} L_{\mathrm{int}}}$$

- i: Bin number
- Δt: Bin width
- U^{-1}: represents unfolding procedure
- N: selected events
- B: estimated background
- $\varepsilon_{\mathrm{rec}}$: reconstruction efficiency
- $\varepsilon_{\mathrm{trig}}$: trigger efficiency
- $\varepsilon_{\mathrm{DAQ}}$: dead-time correction
- L_{int}: Luminosity



Systematic uncertainty

- Several contributions are varied:
  - Luminosity: $\pm$ 2.3 %
  - Beam energy: $\pm$ 0.65 %
  - Background: $\pm$ 0.25 %
  - Optics fit
  - Residual crossing angle: $\pm$ 10 μ rad
  - Reconstruction efficiency: $\pm$ 0.8 %
  - Detector resolution: $\pm$ 15 %
  - Physics model in MC
  - Emittance: $\pm$ 10 %
  - Unfolding: closure test
  - Alignment
  - Track reconstruction
- Systematic shifts for each source from offset method



- Most important experimental systematic uncertainties are luminosity and beam energy.
- Systematic shifts are included in the fit of σ_{tot} and slope of t-distribution.

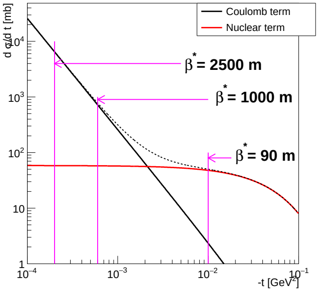
Theoretical prediction

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

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

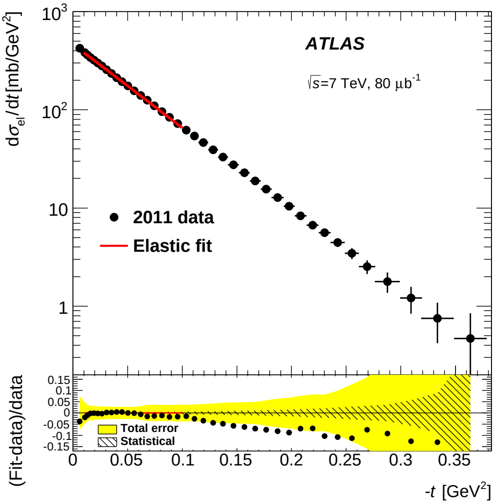
$$\begin{aligned}\frac{d\sigma}{dt} &= \frac{4\pi\alpha^2(\hbar c)^2G^4}{t^2} \\ &+ \sigma_{tot}\frac{\alpha G^2}{t}[\sin(\alpha\phi) + \rho\cos(\alpha\phi)]\exp(B\,t/2) \\ &+ \sigma_{tot}^2\frac{1+\rho^2}{16\pi(\hbar c)^2}\exp(B\,t)\end{aligned}$$

- $\rho = \frac{\mathrm{Re}(f_{el})}{\mathrm{Im}(f_{el})}|_{t\to 0} = 0.14$
- $G(t) = \left(\frac{\Lambda}{\Lambda - t}\right)^2, \quad \Lambda = 0.71\ \mathrm{GeV}^2$
- $\phi(t) = -ln(-Bt/2) - \phi_C, \quad \phi_C = 0.577$



The total cross section fit result

- 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 $-t = [0.01, 0.1]$ GeV^2
  possible deviations from exponential form of nuclear amplitude expected to be small
- Fit quality: χ^2/Ndof = 7.4/16



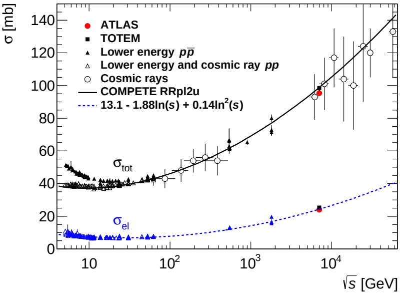
$$\sigma_{tot} = 95.4 \pm 1.3 \text{ mb}$$

$$B = 19.73 \pm 0.24 \text{ GeV}^{-2}$$

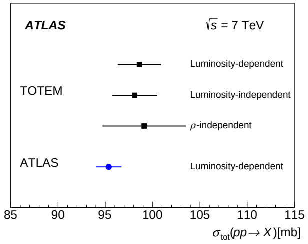
Further uncertainty arise from the extrapolation $t \to 0$, probed by a variation of the upper fit range from 0.1 to 0.15 and $\rho \pm 0.008$

Extrapolation error $\Delta\sigma_{tot} = \pm 0.37$ mb, $\Delta B = \pm 0.17$ GeV^2

The total cross section



- Energy evolution of $\sigma_{\rm tot}$ and $\sigma_{\rm el}$
- Elastic cross section from the nuclear part of the integrated fit function

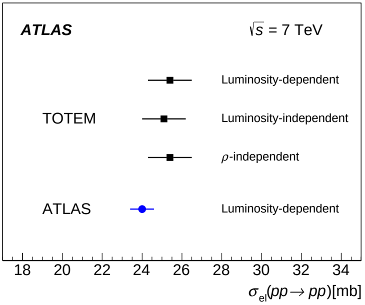


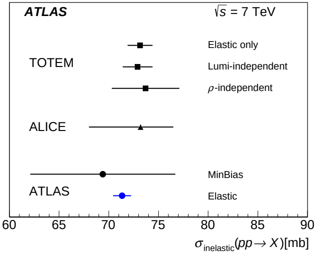
- Comparison with results from TOTEM using the luminosity dependent method
- Our measurement is 3.2 mb smaller than TOTEM's
- Corresponds to 1.3 σ, assuming uncorrelated uncertainties/

ATLAS: $\sigma_{\rm tot} = 95.4 \pm 1.4\ \rm mb$ $\quad B = 19.7 \pm 0.3$ GeV^{-2}

TOTEM: $\sigma_{\rm tot} = 98.6 \pm 2.2\ \rm mb$ $\quad B = 19.9 \pm 0.3$ GeV^{-2}

The elastic and inelastic cross sections





- Elastic cross section from the nuclear part of the integrated fit function
  $\sigma_{\text{el}} = 24.0 \pm 0.6$(total error) mb

- Total inelastic cross section from subtracting the elastic from the total cross section
  $\sigma_{\text{inel}} = 71.3 \pm 0.9$(total error) mb

Conclusions and summary

- ATLAS performed a measurement of the proton-proton σ_{tot} at the LHC at $\sqrt{s} = 7$ TeV from elastic scattering with the ALFA detector
- The results are in good agreement with previous measurements from TOTEM
- We have collected more data in 2012 at $\sqrt{s} = 8$ TeV, $\beta^* = 90$ m and $\beta^* = 1$ km . Enabling access to even smaller t values in the CNI region
- Substantial consolidation of the ALFA detector during shutdown: RF protection, optimized placement of Roman Pot stations
- Looking forward to collect more data with forward proton tagging in Run 2
  - elastic data at $\sqrt{s} = 13$ TeV with $\beta^* = 90$ m
  - elastic data at $\sqrt{s} = 14$ TeV with $\beta^* = 2$ km for absolute luminosity measurement
  - diffractive data (ALFA+ATLAS) : inclusive SD and CD measurements, exclusive central production
  - diffractive data (ALFA+LHCf) : study of $p + \pi^0 + X$ diffractive states
  - approved ATLAS Forward Physics (AFP) project for extended diffractive program