Elastic and inelastic cross section measurements with the ATLAS detector

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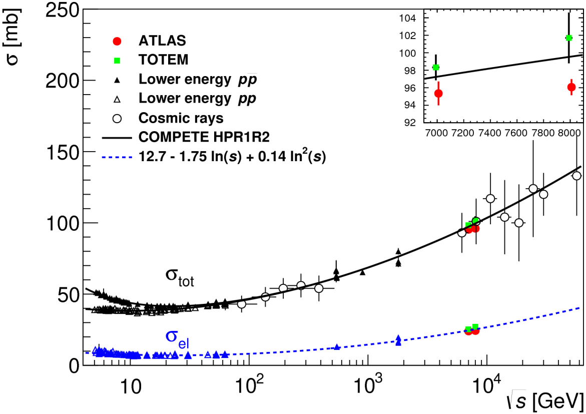
Outline:

- Physics motivation.
- Inelastic cross section at $\sqrt{s} = 13$ TeV.
- Elastic, inelastic and total cross sections at $\sqrt{s} = 8$ TeV.
- Future elastic measurements.

Physics motivation

- The elastic (σ_{el}), inelastic (σ_{inel}) and total (σ_{tot}) *pp* cross sections are fundamental quantities which cannot be calculated with perturbative QCD.
- Regge theory provides general description but data is needed to constrain models.
- σ_{tot} gives the upper bound on any *pp* process and is observed to rise with $\sqrt{s}$.
- A substantial fraction of σ_{inel} is diffractive processes and a measurement of σ_{inel} gives better background determination for high p_T processes.



Inelastic cross section measurement at $\sqrt{s} = 13$ TeV

Phys. Rev. Lett. 117 (2016) 182002

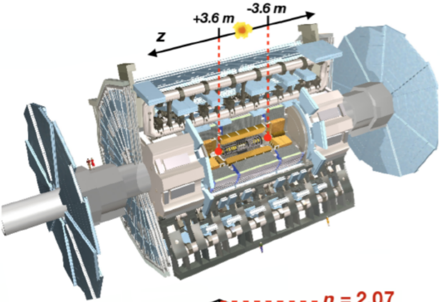
Inelastic cross section at 13 TeV - Strategy

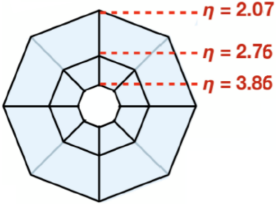
- Measure the σ_{inel} in a fiducial region and extrapolate to full phase-space using simulations.
  - The better detector coverage, the smaller extrapolation uncertainty.

- ATLAS uses the MBTS plastic scintillator discs at $z = \pm 3.6$ m covering $2.07 < |\eta| < 3.86$
  - Corresponds to

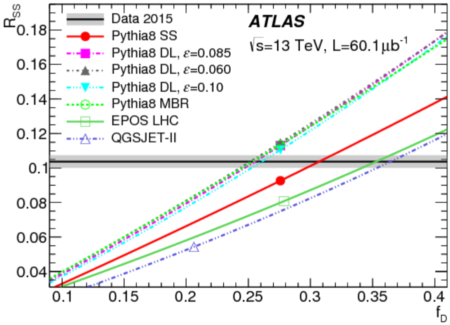
$$\xi \equiv M_X^2/s > 10^{-6} .$$

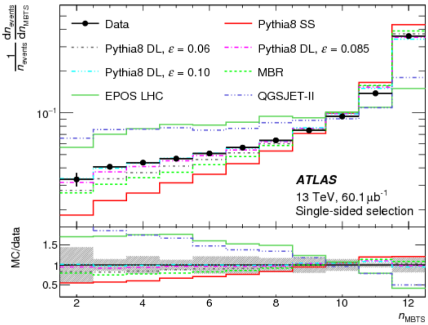
  - 8 inner and 4 outer counters in each disc.
  - ~ 99 % efficiency for charged particles.
- The fiducial σ_{inel} is the number of observed events with ≥ 2 hits corrected for background, pile-up, efficiencies and luminosity.
- Use 60 μb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with $\mu \sim 0.002$





- The inelastic cross section is the sum of the non-diffractive and the diffractive cross section.
- The ratio $f_D = (\sigma_{SD} + \sigma_{DD})/\sigma_{\text{inel}}$ is poorly known and differs between models.
- The fraction of single-sided events, R_{SS}, is related to f_D and used to tune f_D in the models.
- Using the f_D-tuned models, the hit multiplicity in the MBTS for the models are compared to data:
  - The DL (Donnachie-Landshoff) pomeron flux model is best.
    - ε is a free parameter in the pomeron Regge trajectory.
  - The EPOS LHC and QGSJET-II models (developed mostly for cosmic-ray showering) are worst.



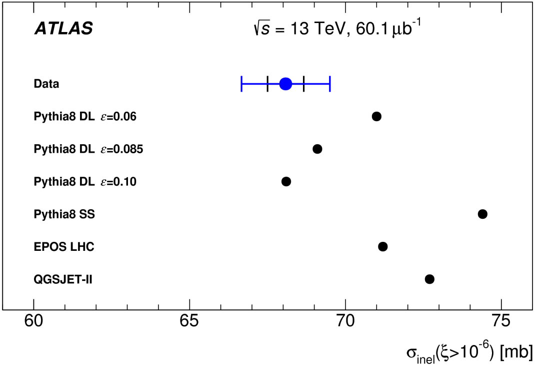


Inelastic cross section at 13 TeV - Results

- The fiducial inelastic cross section in $\xi > 10^{-6}$ is measured to be

$$\sigma_{\text{inel}}^{\text{fid}} = 68.1 \pm 0.6_{(\text{exp.})} \pm 1.3_{(\text{lum.})} \text{ mb}$$

- This is in good agreement with the Pythia8 DL model.



(inner error bars are without luminosity uncertainty)

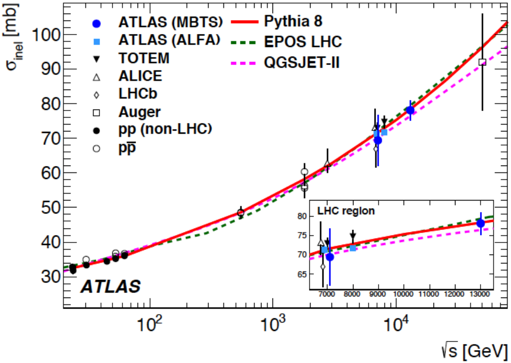
- The fiducial cross section is extrapolated to the full phase space using the Pythia8 DL and MBR models:

$$\sigma_{\text{inel}} = 78.1 \pm 0.6_{(\text{exp.})} \pm 1.3_{(\text{lum.})} \pm 2.6_{(\text{extr.})} \text{ mb}$$

- The inelastic cross section is still increasing with $\sqrt{s}$.
- This is in agreement with model predictions.
- The CMS result is:

$$\sigma_{\text{inel}} = 71.3 \pm 3.5 \text{ mb}$$

which is a 1.5 σ difference.



Elastic, inelastic and total cross sections measurement at $\sqrt{s} = 8$ TeV

Phys. Lett. B 761 (2016) 158-178

Elastic analysis at 8 TeV - Strategy

- From the optical theorem we get:

$$\sigma^2_{\text{tot}} = \frac{16\pi(\hbar c)^2}{1+\rho^2}\frac{1}{L}\frac{\mathrm{d}N_{\text{el}}}{\mathrm{d}t}\bigg|_{t=0} \quad \text{with} \quad \rho \equiv \frac{\mathrm{Re}\left[F_{\text{el}}(t=0)\right]}{\mathrm{Im}\left[F_{\text{el}}(t=0)\right]}$$

- The four-momentum transfer t is calculated as

$$-t = (p \times \theta^*)^2.$$

  where the scattering angle θ^* is calculated from the proton trajectories and p is the beam momentum.

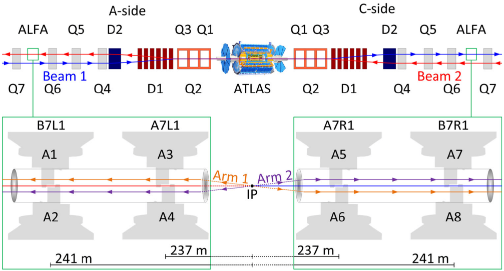
- Minimum accessible t-value is given by

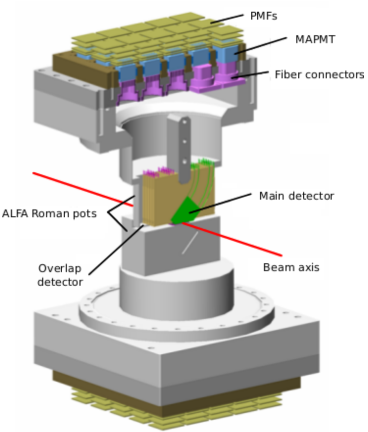
$$-t_{\text{min}} \propto \frac{d^2}{\beta^*}$$

- Use 500 μb^{-1} with a $\beta^* = 90$ m collision optics and low pile-up ($\mu \approx 0.1$).
  - Standard LHC running uses $\beta^* \sim 0.5$ m.

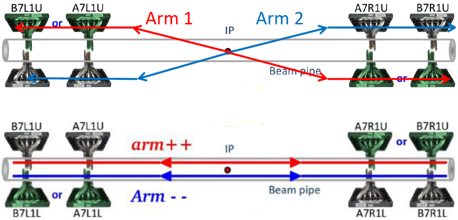
Elastic analysis at 8 TeV - The ALFA detector

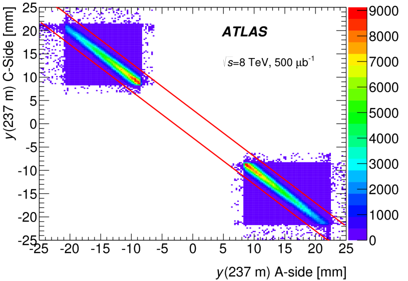
- Built to measure elastically scattered protons at μrad angles.
- Located 240 m from the ATLAS interaction point inside Roman Pots.
- The main detector is built of scintillating fibers.
  - The fiber width of 500 μm and layer staggering gives $\approx$ 30 μm tracking resolution.
- The scattering angle is reconstructed from the tracks using knowledge about the LHC magnet strengths.

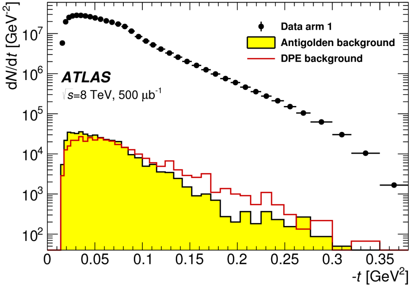




- Events are selected when all four detectors in an arm have a track.
- Momentum conservation provides strong selection cuts.
- Total number of elastic candidates is 3.8 M.
- Background level is 0.12 % estimated from the antigolden topology.
  - Primarily Double Pomeron Exchange (DPE).
- Observed t-spectrum is corrected for acceptance, detector resolution, luminosity, and efficiencies.







Elastic analysis at 8 TeV - Theoretical prediction

- The differential elastic cross section is a superposition of the strong interaction amplitude F_N and the Coulomb amplitude F_C added in quadrature giving

$$\frac{d\sigma_{el}}{dt} \propto \frac{G^4(t)}{|t|^2} + \boldsymbol{\sigma}_{\mathbf{tot}}^2(1+\rho^2)\cdot\exp(-\mathbf{B}|t|) - \frac{\boldsymbol{\sigma}_{\mathbf{tot}} G^2(t)}{|t|}\left[\sin(\phi(t)) + \rho\cos(\phi(t))\right]\cdot\exp\left(\frac{-\mathbf{B}|t|}{2}\right)$$

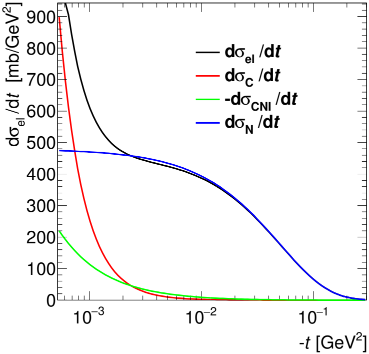
- The fit range is $0.014 \leq |t| \leq 0.1$ GeV^2.
- The unfolded differential cross section is fitted with σ_{tot} and B as free parameters.

- **No sensitivity to:**
  - The ρ-parameter fixed to 0.1362 from COMPETE predictions.
  - The interference phase taken as:

$$\phi(t) = -\ln\left(\frac{B|t|}{2}\right) - \gamma_E$$

  - The proton form factor taken as:

$$G(t) = \left(\frac{\Lambda}{\Lambda + |t|}\right)^2, \quad \Lambda = 0.71 \text{ GeV}^2$$

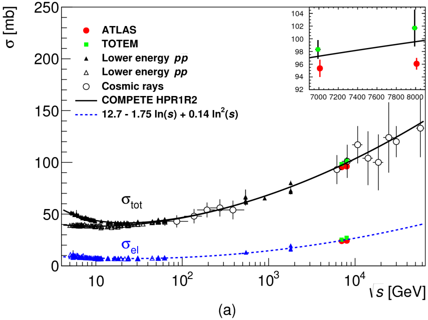


Elastic analysis at 8 TeV - Results (1/2)

- The result for the total cross section is:

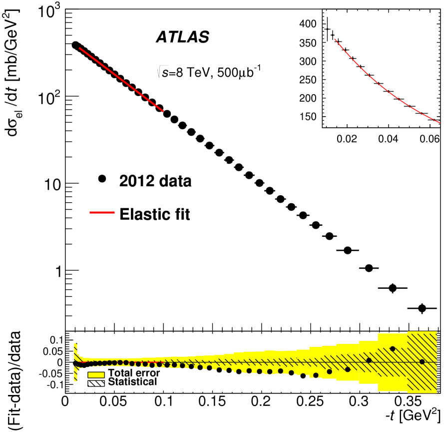
$$\sigma_{\text{tot}} = 96.07 \pm 0.18_{(\text{stat})} \pm 0.85_{(\text{exp.})} \pm 0.31_{(\text{extr.})} \text{ mb} .$$

σ_{tot} is still rising with energy.



(fit not updated with latest ATLAS result)

Unfolded t-spectrum:



Elastic analysis at 8 TeV - Results (2/2)

- The elastic cross section σ_{el} is the integral of the nuclear part:

$$\sigma_{\text{el}} = 24.33 \pm 0.04_{(\text{stat.})} \pm 0.39_{(\text{syst.})} \text{ mb} .$$

- The inelastic cross section is the difference between the total and the elastic:

$$\sigma_{\text{inel}} = 71.73 \pm 0.15_{(\text{stat.})} \pm 0.69_{(\text{syst.})} \text{ mb} .$$

- This is about 4 times more precise than the direct measurement at 13 TeV (page 7):

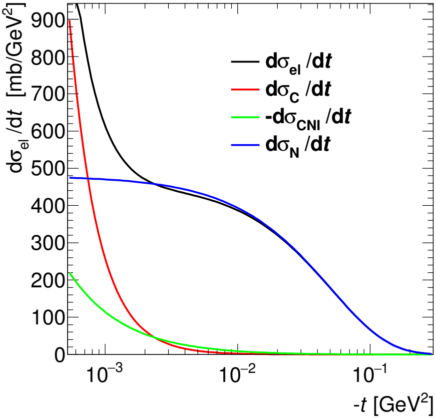
$$\sigma_{\text{inel}}^{13\text{ TeV}} = 78.1 \pm 0.6_{(\text{exp.})} \pm 1.3_{(\text{lum.})} \pm 2.6_{(\text{extr.})} \text{ mb}$$

- The extrapolation uncertainty on σ_{inel} from elastic scattering comes from a simple fit range variation.

Future elastic analyses

- Data in the Coulomb-Nuclear-Interference region at $-t \approx 10^{-3}$ GeV^2 allows a measurement of the ρ-parameter.
  - Provides insight to the understanding of elastic scattering.
  - Dispersion relations derived from analyticity relates energy evolution of the σ_{tot} and ρ.
  - The simultaneous measurement of σ_{tot} and ρ therefore tests a very basic assumption.
  - High energy predictions of σ_{tot} will be possible.

- Data has been collected at $\sqrt{s} = 8$ TeV with $\beta^* = 1$ km optics.
  - **The analysis is in review.**
- Data has been collected at $\sqrt{s} = 13$ TeV with $\beta^* = 2.5$ km optics.
  - The analysis is ongoing.



Summary

Inelastic cross section at $\sqrt{s} = 13$ TeV:

- The diffractive fraction in several models are tuned to match an observable in data.
- The fiducial cross section agrees well with Pythia8 DL model.
- The full inelastic cross section is in agreement with models and is still observed to rise with $\sqrt{s}$.

Total cross section at $\sqrt{s} = 8$ TeV:

- The differential elastic cross section is measured with tracking detectors in Roman pots.
- The total cross section is inferred using the optical theorem and is still observed to rise with $\sqrt{s}$.
- Future measurements of the ρ-parameter will provide further insight to the non-perturbative regime of QCD.

Backup slides

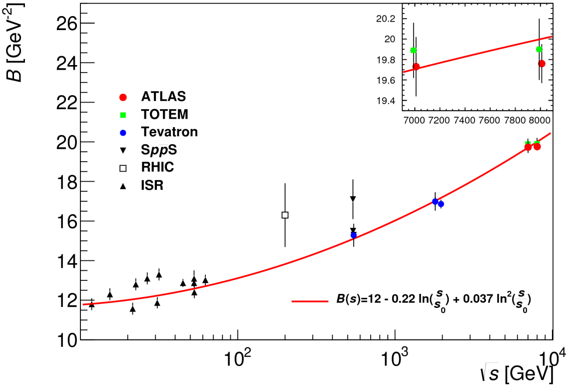
Backup - Investigations of nuclear slope parametrization

- Different parametrizations for the nuclear slope have been investigated.
- The upper limit of the fit range was increased to $|t| = 0.3$ GeV^2 in order to increase the sensitivity of additional parameters.
- The quality of the fit is increased due to the higher number of free parameters.

	σ_{tot}[mb]	Model
Nominal	96.07 ± 0.86	$f_{\text{N}}(t) = (\rho + i)\,\frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2}$
Ct^2	96.16 ± 0.80	$f_{\text{N}}(t) = (\rho + i)\,\frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2-Ct^2/2}$
$c\sqrt{-t}$	96.40 ± 0.80	$f_{\text{N}}(t) = (\rho + i)\,\frac{\sigma_{\text{tot}}}{\hbar c} e^{-Bt/2-c/2(\sqrt{4\mu^2-t}-2\mu)}$, $\mu = m_\pi$
SVM	96.16 ± 0.80	$f_{\text{N}}(t) = \rho\frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_R t/2} + i\frac{\sigma_{\text{tot}}}{\hbar c} e^{-B_I t/2}$
BP	96.81 ± 0.95	$f_{\text{el}}(t) = i\left[G^2(t)\sqrt{A}e^{-Bt/2} + e^{i\phi}\sqrt{C}e^{-Dt/2}\right]$
BSW	96.67 ± 0.99	$\text{Re} f_{\text{el}}(t) = c_1(t_1 + t)e^{-b_1 t/2}$, $\text{Im} f_{\text{el}}(t) = c_2(t_2 + t)e^{-b_1 t/2}$

Backup - Results for the nuclear B-slope

- ATLAS measurement: $B = 19.73 \pm 0.24$ GeV^{-2}
- TOTEM measurement: $B = 19.9 \pm 0.3$ GeV^{-2}
- Pre-LHC expectations was a linear evolution of the B-slope with $\ln(s)$
- LHC measurements of the B-slope favours a second $\ln^2(s)$ term.

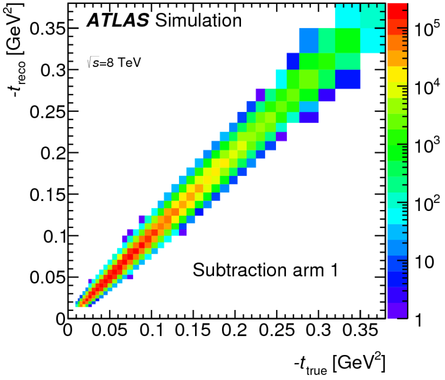


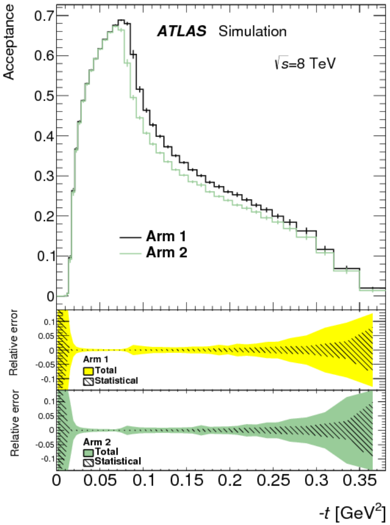
(b)

(fit not updated with latest ATLAS result)

Backup - Acceptance and resolution

- **Detector acceptance** is highly dependent on detector distance to the beam and beam divergence.
  - Found from simulation tuned to data.
- ***t*-resolution** is influenced by detector resolution and beam divergence.
  - Relative *t*-resolution is better than 10 % and corrected for by unfolding.





Backup - Beam optics corrections

- The beam optics has direct influence on the t-reconstruction.
- Different t-reconstructions gives different results
  $\Rightarrow$ the initial **design** optics needs modifications.
- Elastic data is used to constrain an optics fit including magnet strengths whereby an **effective** optics in obtained.