Measurements of the Total Proton-Proton Cross Section with the ATLAS Detector



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Central Exclusive



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→ Elastic & total cross sections with ALFA Roman pots

→ Total inelastic cross section from minimum bias data





1) Directly tag outgoing protons in ALFA Roman pot spectrometer [4 stations at ~240m from interaction point]. ... obtain σ_{el} directly and apply optical theorem for σ_{tot} .



 $[z = \pm 3.6m, 2.1 < |\eta| < 3.9$, rebuilt in long shutdown]

1) Proton Tagging Method

- Earlier result at √s=7 TeV: Nucl Phys B889 (2014) 486
- Presented here, √s=8 TeV result: Phys Lett B761 (2016) 158



2012 $\beta^* = 90m$ run low lumi run ($\mu=0.1$) with pots at 7.5mm (9.5 σ) from beam, allowing access to small t \rightarrow 3.8M events after selection, background ~0.1% ³



Measurement Principle

Main detectors (MD) are 2x10 layers of 0.5mm² square scintillating fibres per pot.

Elastically scattered protons characterised by back-to-back topology (anti-correlation in x and y between A and C sides of ATLAS)

At high β^* , parallel-topoint focusing in vertical plane...

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



- θ^* from y coordinate and knowledge of beam optics

Correcting for Instrumental Effects

- Reconstruction (~90%), trigger (>99.9%) efficiencies from data.
- Beam optics model tuned with ALFA constraints and applied via PYTHIA8:



- Unfolding corrections usually < 2%
- Acceptance limitations due to fiducial volume cuts well controlled



- Dedicated lumi determination: Beam Condition Monitors (& vertices, LUCID, van der Meer) \rightarrow 1.5% uncertainty ⁵

Unfolded Data



- 0.65% uncertainty on beam energy generates largest systematic at high |t|

- Data cover the region 0.01
 |t| < 0.36 GeV², systemtaics
 limited throughout
- Dominant systematic at small |t| is luminosity (1.5% normalisation)



Fitting the Data

$$\begin{aligned} \frac{\mathrm{d}\sigma}{\mathrm{d}t} &= \frac{1}{16\pi} \left| f_{\mathrm{N}}(t) + f_{\mathrm{C}}(t) \mathrm{e}^{\mathrm{i}\alpha\phi(t)} \right|^2 \\ f_{\mathrm{C}}(t) &= -8\pi\alpha\hbar c \frac{G^2(t)}{|t|} , \\ f_{\mathrm{N}}(t) &= (\rho + \mathrm{i}) \frac{\sigma_{\mathrm{tot}}}{\hbar c} \mathrm{e}^{-B|t|/2} , \end{aligned}$$



Fixed parameters: $-\rho$ (~0.14) = ratio of Re/Im amplitudes at t=0

- G = proton electric form factor
- φ = phase of Coulomb-nuclear interference at t=0
- Fit 0.014 < |t| < 0.1 GeV², where acceptance is large and theory uncertainty is small
- Influence of interference small.
- Hadronic region compatible with pure exponential: ~ e^{Bt}
- Total hadronic cross section emerges via fit normalisation

Results and Energy Dependence: σ_{tot}



Data remain compatible with slow growth with $\int s$ (logarithmic or power law?...)

Results and Energy Dependence: B $B(8 \text{ TeV}) = 19.74 \pm 0.05(\text{stat.}) \pm 0.16(\text{exp.}) \pm 0.15(\text{extr.}) \text{ GeV}^{-2}$



- Dominant uncertainties are beam energy (exp), fit range (extr)
- ALFA and TOTEM in good agreement
- Data remain compatible with shrinkage of forward elastic peak with ${\it J}$ s [Schegelsky & Ryskin model shown, α '~0.11 GeV^2] 9

2) Minimum Bias Method

- Earlier result at *J*s=7 TeV: Nature Commun 2 (2011) 463
- Presented here, 13TeV result: PRL 117 (2016) 182002 (from short low pile-up (μ <0.1) run taken in June 2015)





 $\begin{array}{ll} \text{MBTS} = \text{plastic scintillator,} \\ \text{2.1 < } |\eta| < 3.9 \text{ with 8-fold} \\ \text{segmentation nearest beampipe and 4-fold further out.} \\ \text{... obtain almost all of } \sigma_{\text{inel}} \\ \text{directly.} \end{array}$

Total Inelastic Cross Section

- MBTS sees 90-95% of all inelastic events \rightarrow "simple" counting experiment.

- Complication: controlling $\xi = \frac{M_X^2}{s}$ low mass diffractive dissociation that leaves no signal in MBTS (M_X <~ 13 GeV)







Why low mass diffraction is a problem



Benchmarking Diffractive MC models

"Single Sided" sample: ... activity on one side of MBTS, empty on other: enriched in SD events





→ MBTS multiplicity in single sided sample distinguishes between MC diffraction models

... Baseline MC is PYTHIA8 with DL pomeron flux and $\alpha_{\text{IP}}(0) = 1.085$

Cross Section in Fiducial Range $\sigma_{\text{inel}}^{\text{fid}}(13 \text{ TeV}) = 68.1 \pm 0.6 \text{ (exp.)} \pm 1.3 \text{ (lumi) mb}$



- Correction factor to reach fiducial region ξ<10-6 is 0.7%

- 1.9% luminosity
uncertainty (from
Van der Meer scans)

- Donnachie-Landshoff implmentation in PYTHIA8 consistent with data within ~2 σ for $\alpha_{\text{IP}}(0)$ = 1.06 ... 1.14

- EPOS, QGSJET, PYTHIA8 S&S ($\alpha_{IP}(0) = 1$) exceed result by >2 σ

Extrapolation to Full Inelastic Cross Sec

Data-driven extrapolation into region with $\xi < 10^{-6}$, with minimal dependence on MC models:

$$\sigma_{\text{inel}} = \sigma_{\text{inel}}^{\text{fid}} + \sigma^{7 \text{ TeV}}(\xi < 5 \times 10^{-6}) \times \frac{\sigma^{\text{MC}}(\xi < 10^{-6})}{\sigma^{7 \text{ TeV}, \text{ MC}}(\xi < 5 \times 10^{-6})}$$

$$\sigma^{7 \text{ TeV}}(\xi < 5 \times 10^{-6}) = \sigma_{\text{inel}}^{7 \text{ TeV}} - \sigma^{7 \text{ TeV}}(\xi > 5 \times 10^{-6})$$

= 9.9 ± 2.4 mb
previous fiducial MBTS result

$$\frac{\sigma^{\text{MC}}(\xi < 10^{-6})}{\sigma^{7 \text{ TeV}, \text{ MC}}(\xi < 5 \times 10^{-6})} = 1.015 \pm 0.081$$

... extrapolation uncertainty is 2.5 mb, dominates in total inelastic cross section measurement

Extrapolation to Full Inelastic Cross Sec

 σ_{inel} =78.1 ± 0.6(exp.) ± 1.3(lumi) ± 2.6(extrap) mb



- Within current uncertainties, result consistent with indicative selection of models based on Regge phenomenology, eikonal approaches and other models of non-perturbative strong interactions

Future at ATLAS

- 13 TeV σ_{tot} ALFA measurement still ongoing
- Diffactive studies still ongoing
- ALFA being preserved for 14 TeV running
- Meanwhile, focus of Roman pots in ATLAS switches towards AFP & high lumi \rightarrow rare exclusive









Proton-tagged elastic and total cross sections at $\int s = 8$ TeV

- Highly precise measurements of σ_{tot} (\rightarrow <1%), σ_{el} , σ_{inel} , B_{el}
- Continued cross sec growth and elastic peak shrinkage with $\ensuremath{{\sc s}}$ s
- Compatibility with TOTEM at 2σ level

Direct Inelastic Cross Section Measurement at $\int s = 13$ TeV

- Improvement in precision (\rightarrow 2%) over previous data.
- Some discrimination between models
- Consistent with ATLAS-ALFA extractions using optical theorem