Measurements of single diffraction using forward proton tagging at ATLAS

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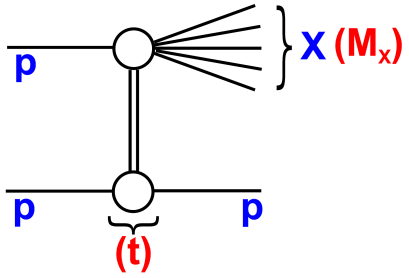
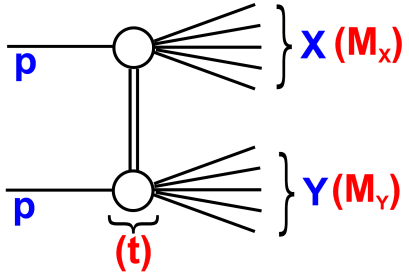
Single diffractive (SD) dissociation cross section

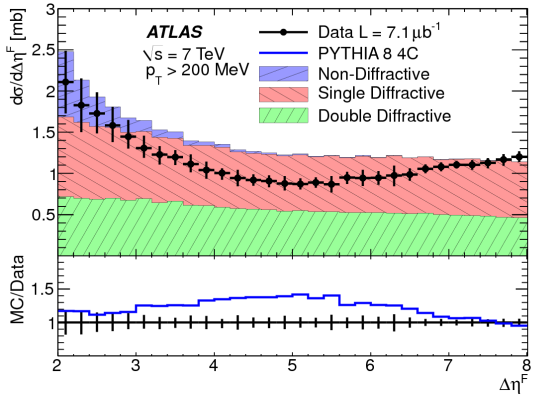
- The total $p + p \to p + X$ cross section is large and not well constrained at LHC energies.
- Previous analyses at LHC based on rapidity gaps:

  ATLAS: Eur. Phys. J. C72 (2012) 1926; CMS: Phys. Rev. D 92, 012003

  - Not able to distinguish fully between the SD process, its double dissociation (DD, $p + p \to X + Y$) analogue and the tail of non-diffractive (ND) contributions
  - No direct access to the underlying dynamics:
    - $-t$ - squared four momentum transfer
    - ξ - fractional energy loss of the intact proton ($\xi = M_X^2/s$)



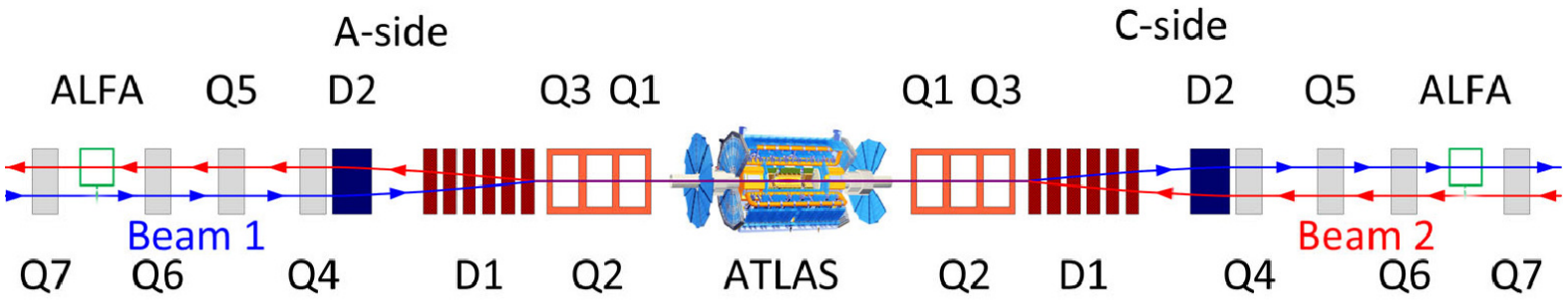




Motivations for better SD constraints:

- Better precision of the total inelastic pp cross section
- Understanding the low Bjorken-x region of proton structure
- Interpretation of cosmic ray air showers
- With proton tagging - removal of DD and ND; direct access to t and ξ

Experimental setup



- Intact final state proton is scattered through a very small angle of typically 10 - 100 μrad. Proton is measured in the ALFA detector at 240m from the IP, the detector was placed at 7.5 mm from the beam in a dedicated run of the LHC with special high $\beta^* = 90$ m optics
- Other proton dissociates to produce a multi-particle hadronic system X. Charged particles with $p_T > 0.2$ GeV and $|\eta| < 2.5$ are measured in Inner Detector (ID) allowing determination of the primary vertex position.
- Trigger: Opposite side coincidence of the signal in ALFA and Minimum Bias Trigger Scintilator (MBTS). MBTS covers pseudorapidity range of $2.1 < |\eta| < 3.8$

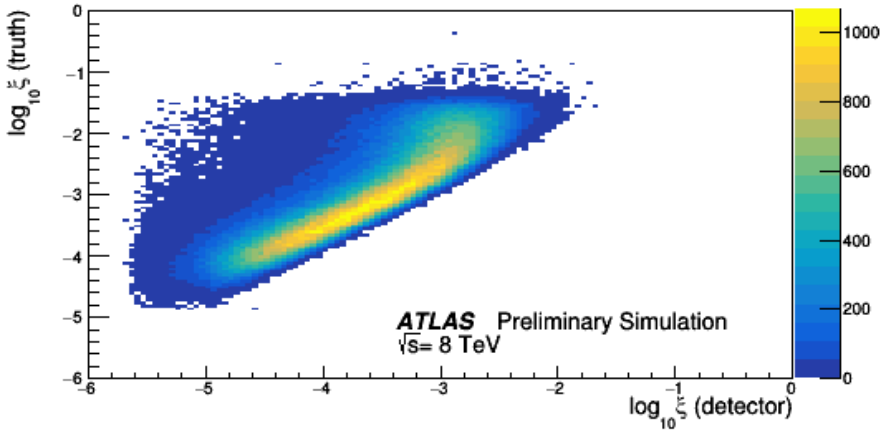
Principles of the measurement

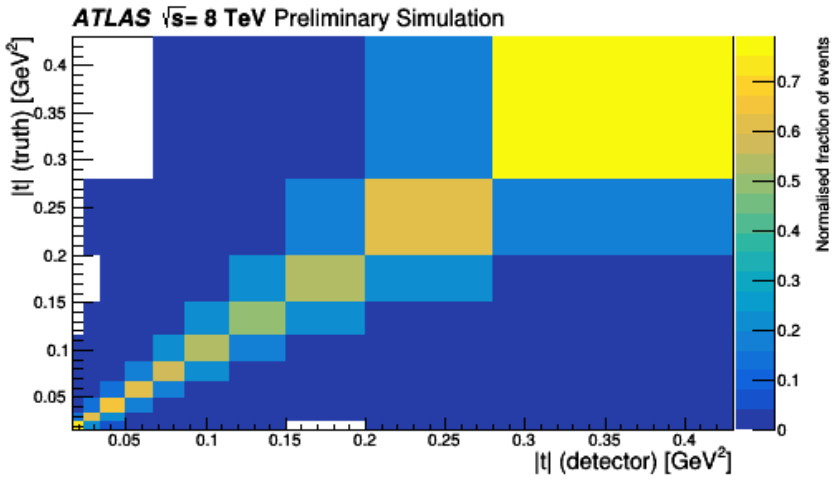
- Measure charged particles with $p_T > 0.2$ GeV and $|\eta| < 2.5$ in ID to get:
  - $\xi \approx \Sigma_i (E^i \pm p_Z^i)/\sqrt{s}$
  - 'visible size of rapidity gap' $\Delta\eta$
    - between tracker edge on side with proton ($\eta = +2.5$ or -2.5) and first ID track.
  - primary vertex position.
- Measure track position and local angle at ALFA to get the proton momentum and thereby:
  - $-t = p_T^2$
  - $\xi(ALFA) = 1 - E_p/E_{beam}$
- ALFA alignment done for ALFA elastic measurement
  - (Phys. Lett. B761 (2016) 158) performed with the same run.
- ALFA reconstruction efficiency obtained through a 'tag and probe' approach using a sample of elastic scattering events as described in published elastic measurement.

Monte Carlo Generators

- Main samples: PYTHIA8 A3 :
  - Proton PDF = NNPDF23 LO
  - Pomeron : PDF = H1 2006 Fit B; Flux: intercept: 1.06, slope: 0.25 (Donnachie-Landshoff)

  - SD for unfolding
  - CD, DD, ND for background subtraction
  - Elastics for ALFA Reconstruction efficiency

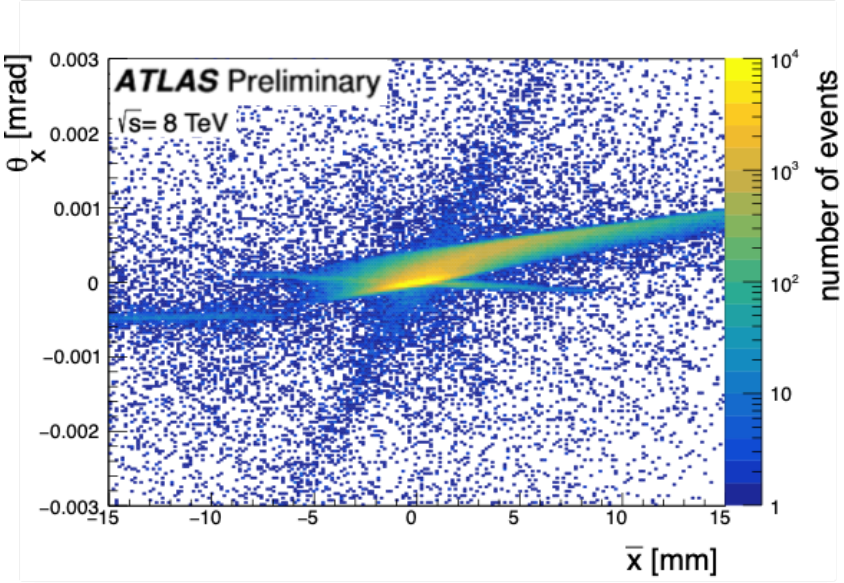


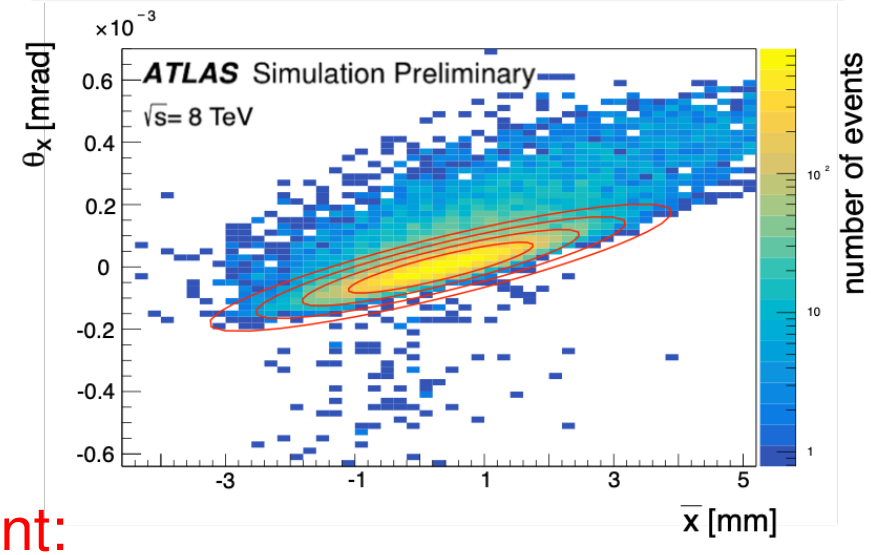


- For systematics:
  - PYTHIA 8 A2; same as A3 tune but with Schuler-Sjostrand flux
  - HERWIG 7.1: - Proton PDF = MMHT2014lo68cl - Pomeron : PDF = H1 2006 Fit A; Flux: intercept: 1.00, slope: 0.25

Event selection

- ALFA: exactly one reconstructed proton in two (far - near) stations geometrical cut: $(\bar{x}, \Theta_x)$ within 3σ ellipse around $(0, 0)$ ($\bar{x}$ = mean position, Θ_x = local angle between stations)
- ID: at least one track with $pT > 0.2$ GeV and $|\eta| < 2.5$ and reconstructed vertex
- MBTS: at least 5 (out of 16) counters above noise threshold





Fiducial region of the mesurement:

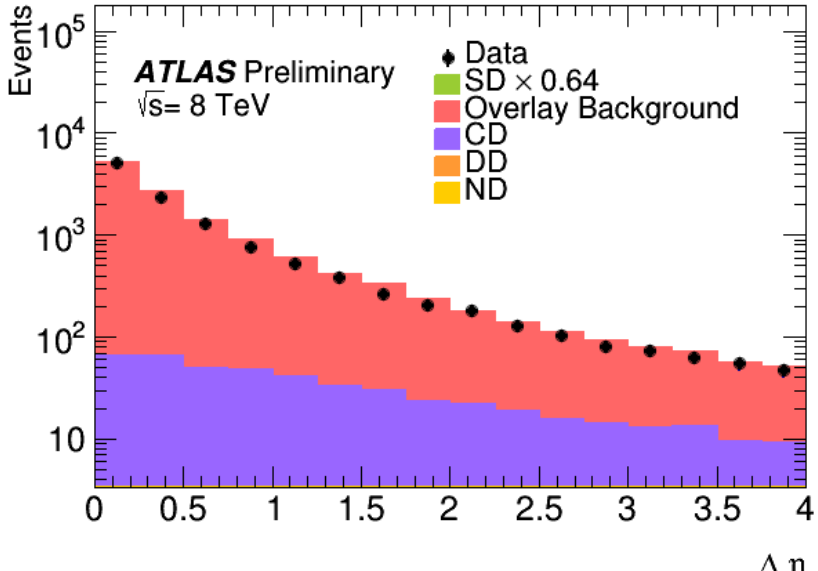
- $0.016 < |t| < 0.43$ GeV^2
- $-4.0 < log_{10}(\xi) < -1.6$ ($80 < M_X < 1270$ GeV)

Overlay Background

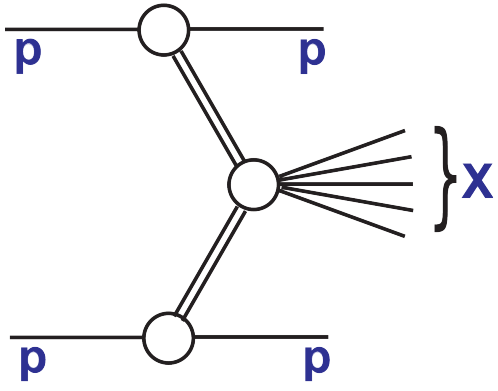
- Largest background (25% of selected events) from an overlay of two uncorrelated processes:
  ALFA (elastics / beam halo proton) + ID/MBTS (Minimum Bias)

- Data-driven estimate using strongly ND-enriched events with all 32 MBTS segments fired
  - ALFA: 1 proton (0.8% of such events) gives normalization
  - shape in *t* from ALFA in ND-enriched sample
  - shapes in ξ and $\Delta\eta$ from MC events that pass full analysis selection except for number of protons

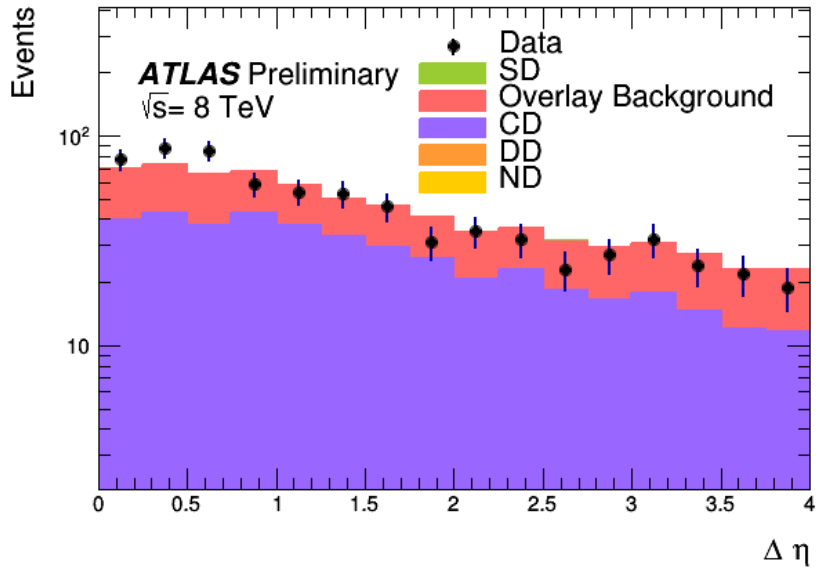
- Control region for overlay background: same as nominal selection, but with protons in exactly two ALFA armlets - dominated by elastics in ALFA + ND in ID

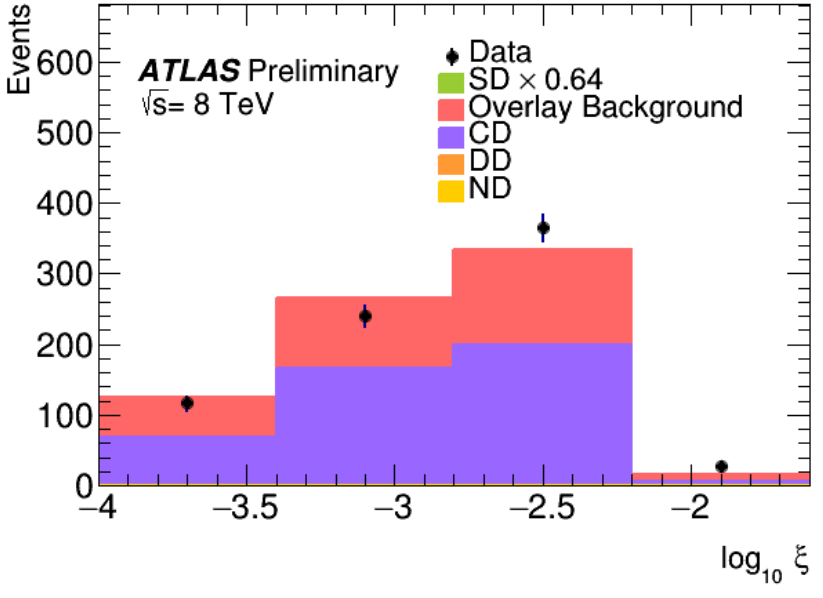


Central Diffraction Background

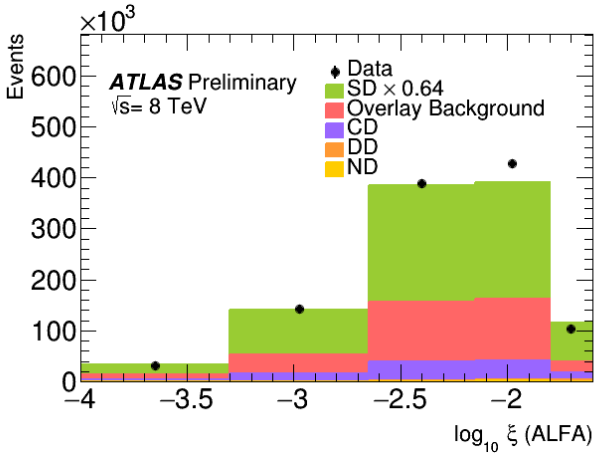


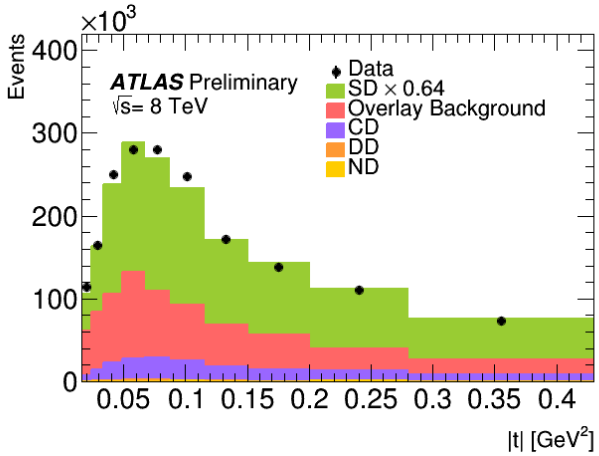
- Second largest background (9%)
- Obtained from MC
- Control region (CD-enriched sample):
  - protons in exactly two ALFA armlets
  - 2-10 MBTS segments fired
- Good description of normalizations and shapes
- Reweight ξ distributions to match the data, preserving normalization

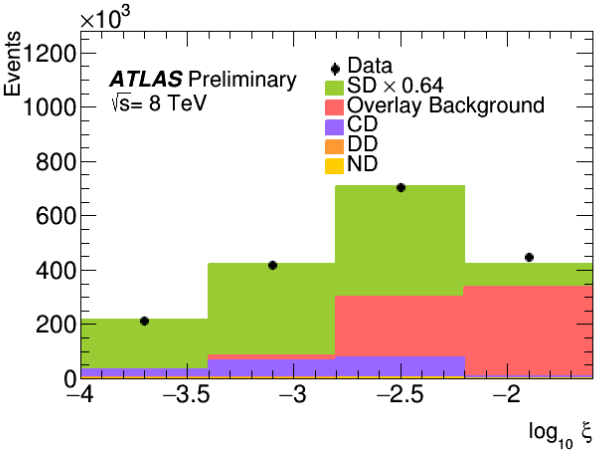


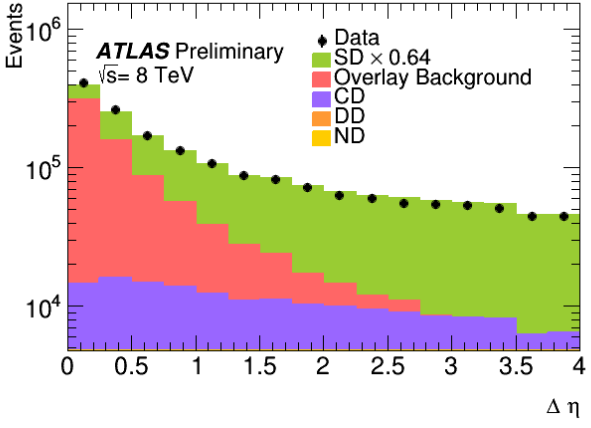


Uncorrected control plots







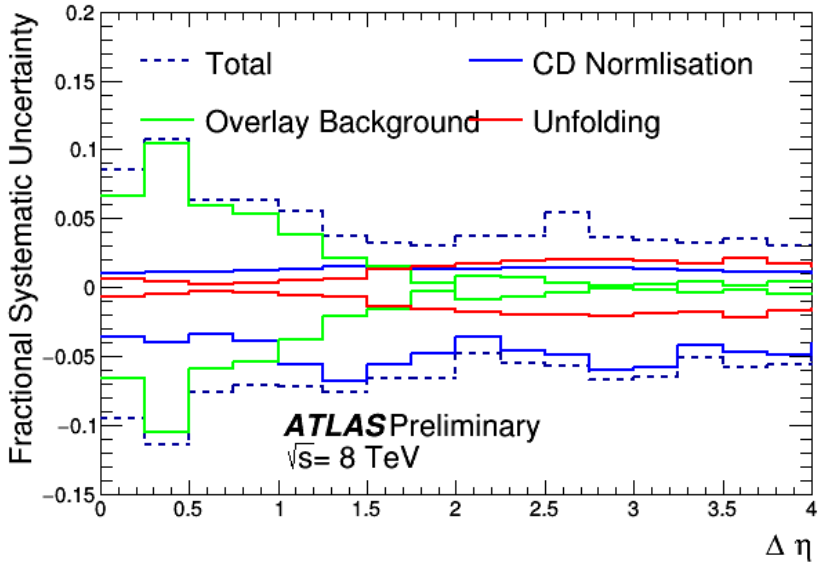


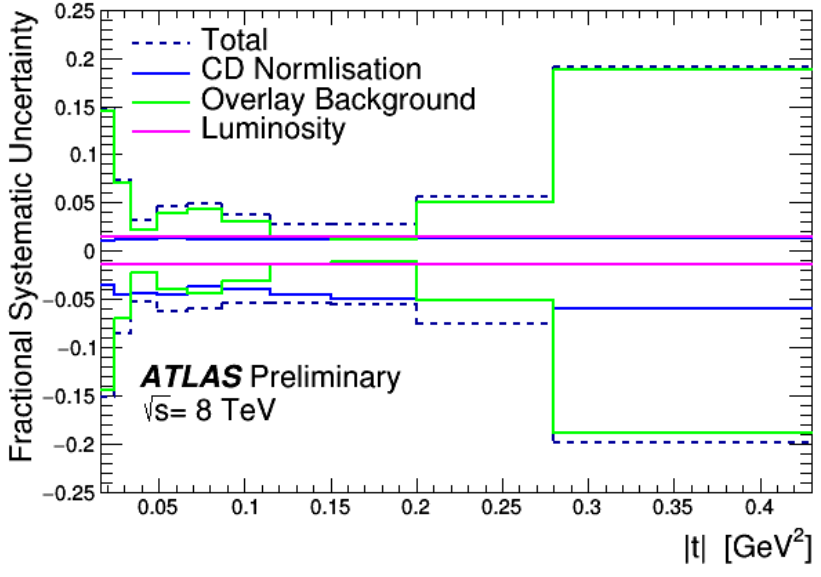
- Poor description with default PYTHIA8 normalization.
- Scale by 0.64 to adjust SD total cross section to the result of this measurement
- After scaling: good description of $\xi, \xi(ALFA), t$ and $\Delta\eta$

Systematic uncertainty

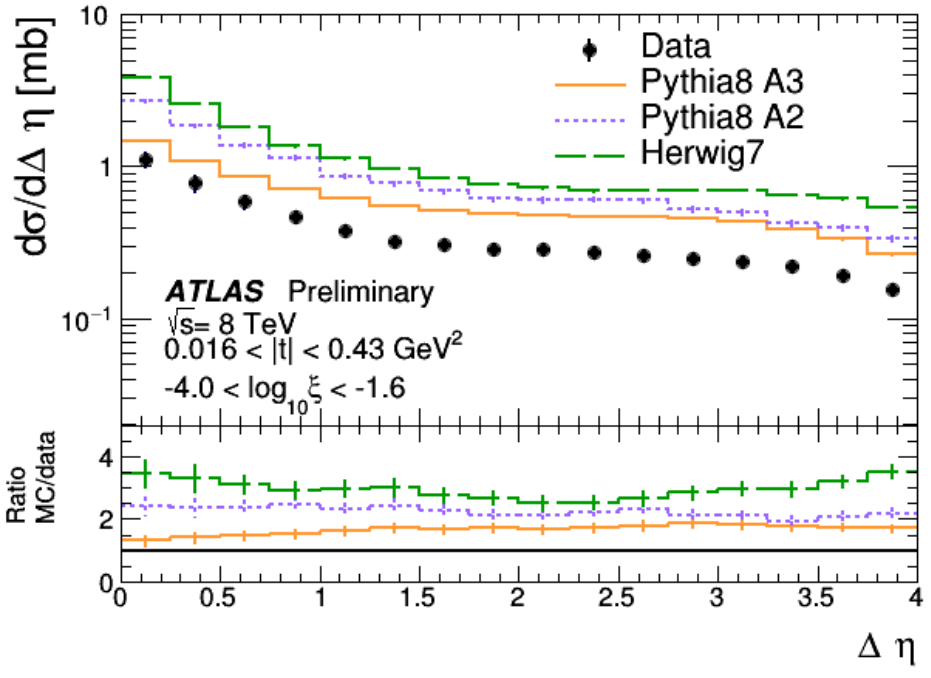
Main systematic uncertainties:

- Overlay background normalization (from control region)
- CD background shape (reweight or not) and normalization (CDF data)
- Hadronization uncertainty (PYTHIA vs HERWIG at particle level)
- ALFA alignment and reconstruction (followed ALFA elastics analysis from the same data)
- Luminosity (1.5%)





Results: $\Delta\eta$

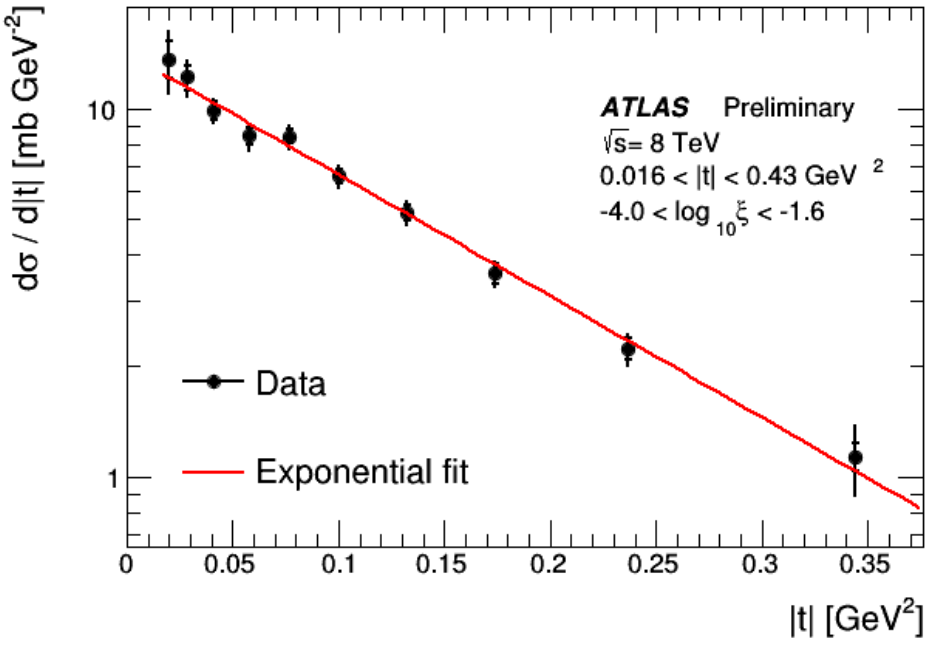


- Data corrected using Bayesian unfolding
- For gap sizes between 1.5 and 3.5, diffractive plateau is visible.
- Deviations at smaller gap sizes due to the restricted rapidity region of ID acceptance
- Deviations at larger gap sizes due to the fiducial range restriction $-4.0 < log_{10}(\xi)$

MC generators predict larger cross sections than data:

- PYTHIA 8 A3: 1.5
- PYTHIA 8 A2: 2.3
- HERWIG 7.1: 3.0

Results: $|t|$



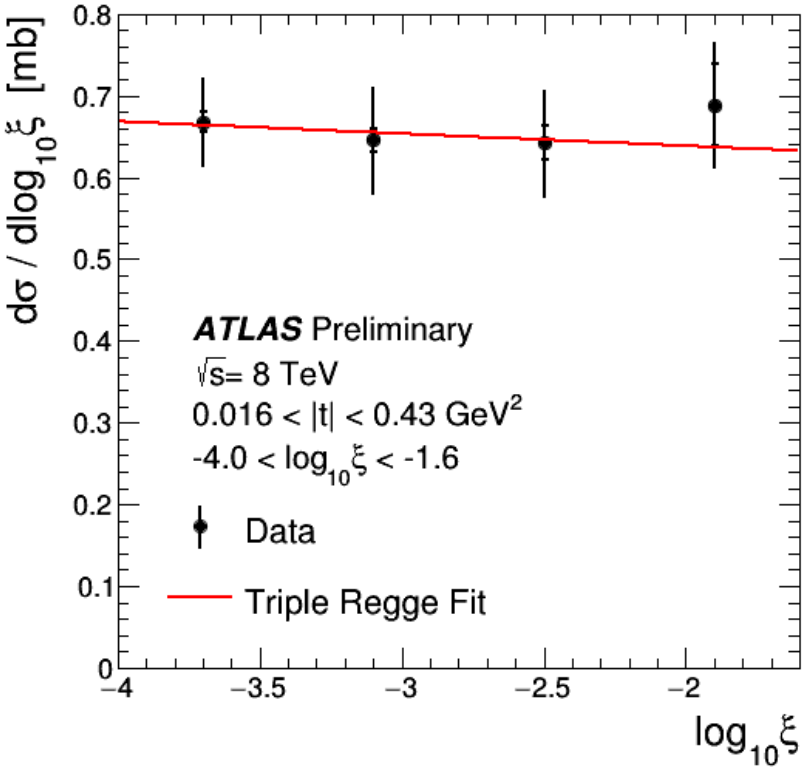
- Data corrected using Bayesian unfolding
- Acceptable fit with exponential form

$$\frac{d\sigma}{dt} \propto e^{Bt}$$

$B = 7.60 \pm 0.23(stat.) \pm 0.22(syst.)$ GeV^{-2}

- The largest contribution to the uncertainty on B arises from the proton overlay background subtraction
- MC generators predict similar values:
  - PYTHIA 8 A3: B = 7.10 GeV^{-2}
  - PYTHIA 8 A2: B = 7.82 GeV^{-2}

Results: ξ



- Data corrected using Bayesian unfolding
- Acceptable fit with expected from triple Pomeron model form

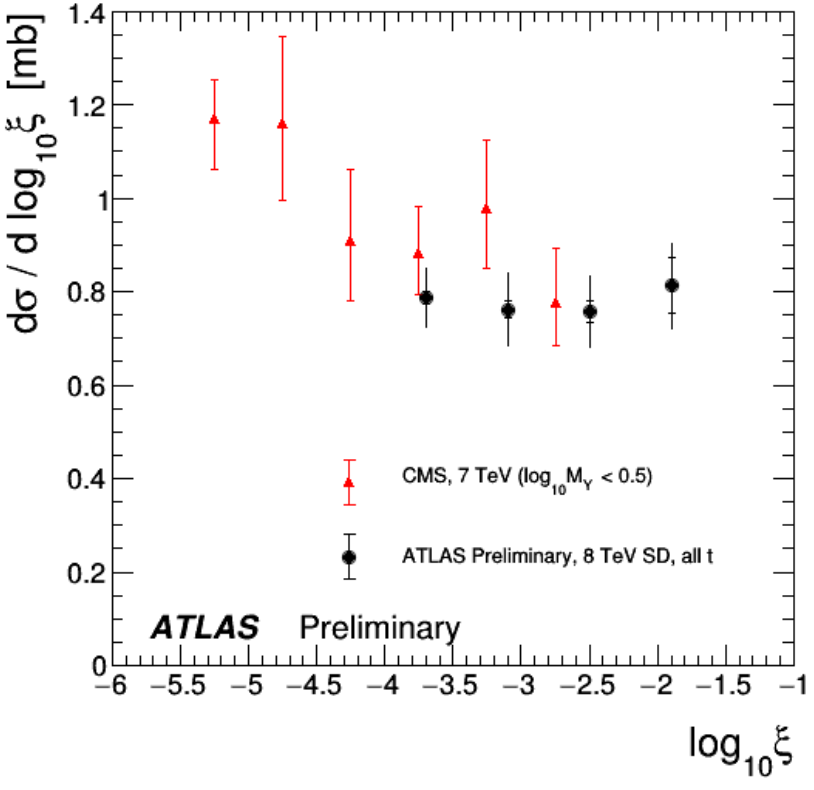
$$\frac{d\sigma}{d\log_{10}(\xi)} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)-1} \frac{1}{B}\left(e^{Bt_{high}} - e^{Bt_{low}}\right)$$

where $B(\xi) = B_0 - 2\alpha' ln\xi$

$\alpha(0) = 1.07 \pm 0.02(stat.) \pm 0.06(syst.) \pm 0.06(\alpha')$

- The largest contribution to the uncertainty on $\alpha(0)$ arises from using $\alpha' = 0.25 \pm 0.25$ GeV^{-2} in the fit
- MC generators predict:
  - PYTHIA 8 A3 (Donnachie-Landshoff): $\alpha(0) = 1.14$
  - PYTHIA 8 A2 (Schuler-Sjostrand): $\alpha(0) = 1.00$

Results: comparison with LHC data



- ATLAS data extrapolated to full t-range using the t-slope measured in this analysis (this gives a factor 1.18)
- Closest available data: CMS 7 TeV rapidity gap analysis using CASTOR as a veto (with some contamination from DD) (Phys. Rev. D92 (2015) 012003)

- A good agreement in the overlap region without subtracting any DD contribution from the CMS results

Results: integrated cross sections

- The cross section integrated over the full fiducial range of the analysis

$$1.59 \pm 0.03(\mathit{stat.}) \pm 0.13(\mathit{syst.})\ \mathrm{mb}$$

- Extrapolating to the full t range assuming the measured slope parameter B leads to a cross section of

$$1.88 \pm 0.15\ \mathrm{mb}$$

- Scaling the default total SD cross section in Pythia8 by the average of the ratios of the A3 and A2 tune normalisations to that of the data in the measured fiducial range gives an estimate of total SD cross section of

$$6.6\ \mathrm{mb}$$

Distribution	$\sigma_{SD}^{\mathrm{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t-\mathrm{extrap}}$ [mb]	$\sigma_{SD}^{\xi,t-\mathrm{extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15	6.6
Pythia8 A2 (Schüler-Sjostrand)	3.69	4.35	12.48
Pythia8 A3 (Donnachie-Landshoff)	2.52	2.98	12.48
Herwig7	4.96	6.11	24.0

Summary

- ATLAS performed a measurement of the inclusive single diffractive dissociation process $p + p \to X + p$ at $\sqrt{s} = 8$ TeV
- For the first time at LHC the final state protons are directly reconstructed greatly reducing backgrounds from Non-Diffraction and Double Diffraction compared to previous LHC analyses based on rapidity gaps
- Differential cross sections are measured as a function of ξ, t and the visible gap size $\Delta\eta$
- Normalization of PYTHIA 8 A2, A3, and HERWIG 7 significantly exceed the data
- Shapes more or less described by models
  - from a fit to t distribution the measured $B = 7.60 \pm 0.23(stat.) \pm 0.22(syst.)$ GeV^{-2}
  - from a fit to ξ distribution the measured $\alpha(0) = 1.07 \pm 0.02(stat.) \pm 0.06(syst.) \pm 0.06(\alpha')$
- A good agreement in the overlap ξ region with the CMS results