Measurements of single diffraction using forward proton tagging at ATLAS

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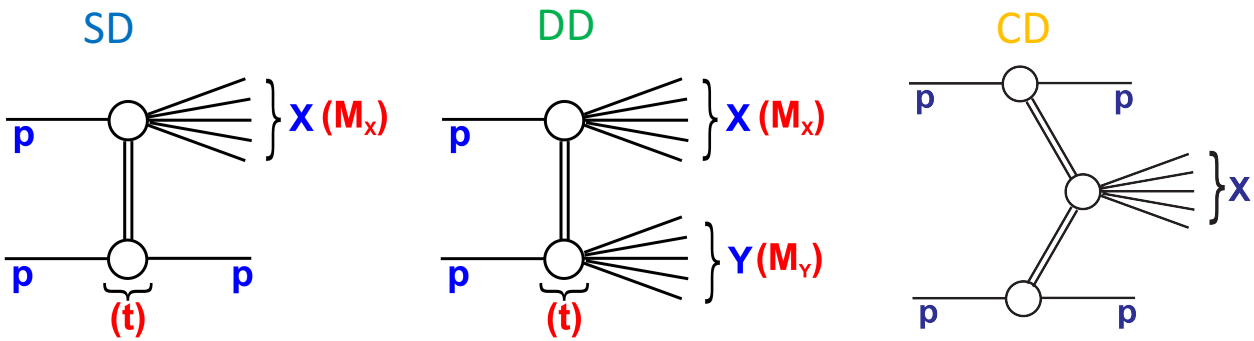
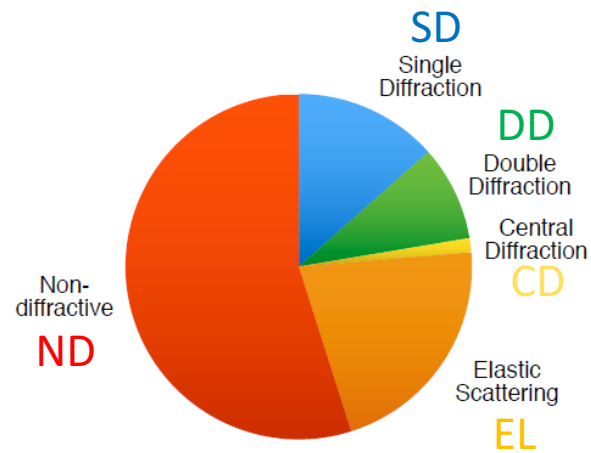
On behalf of the ATLAS collaboration

Conference note: ATLAS-CONF-2019-012

Diffractive pp interactions

Schematic illustrations of single-diffractive dissociation (SD), double-diffractive dissociation (DD) and central diffraction (CD)





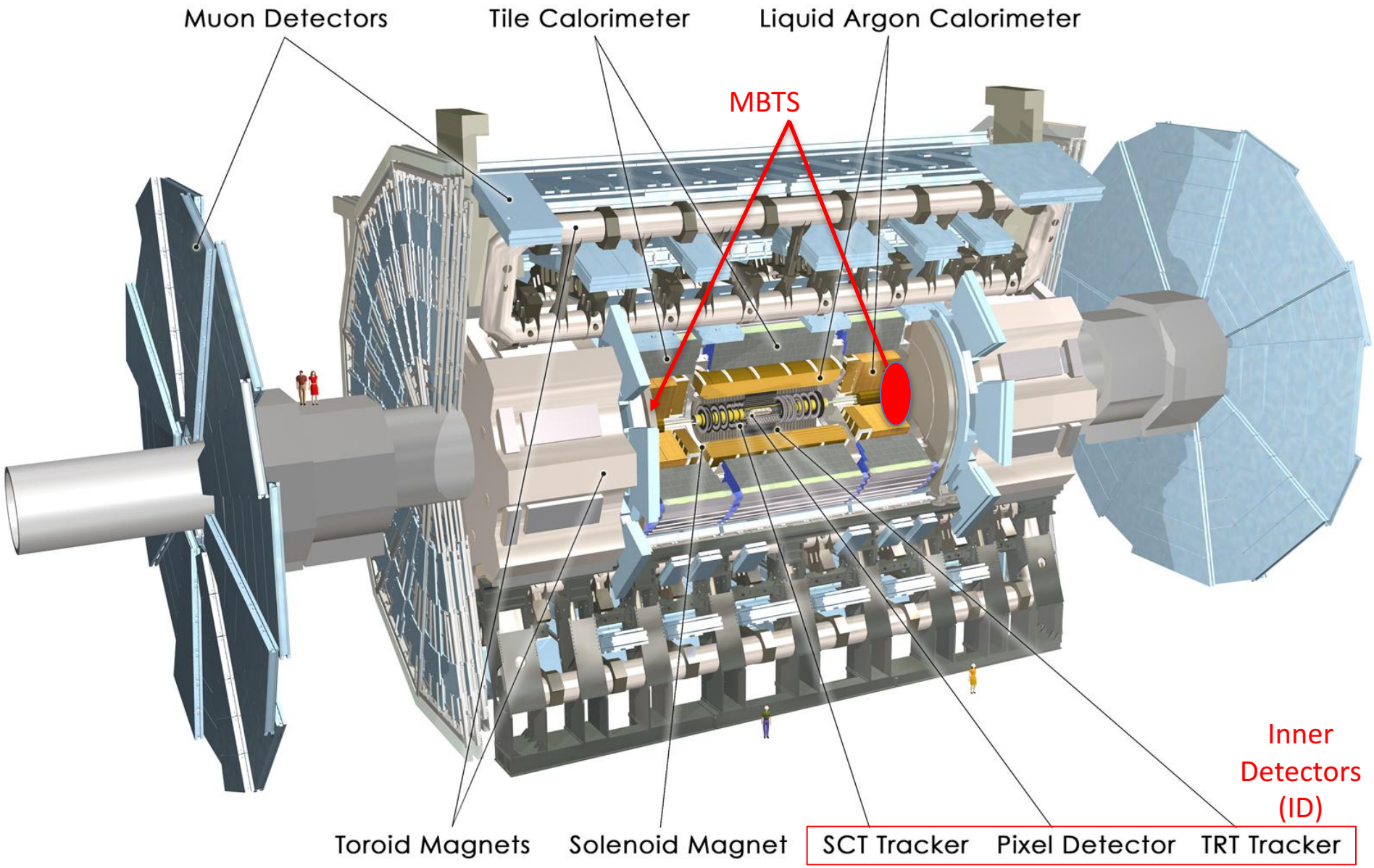
Large cross sections, not well constrained

- Is it always possible to disentangle diffractive and non-diffractive processes?
- Interactions mediated by Pomerons
  - t-channel exchange of vacuum quantum numbers
- Phenomenological approach (QCD + models)
- Previous studies based on rapidity gap.

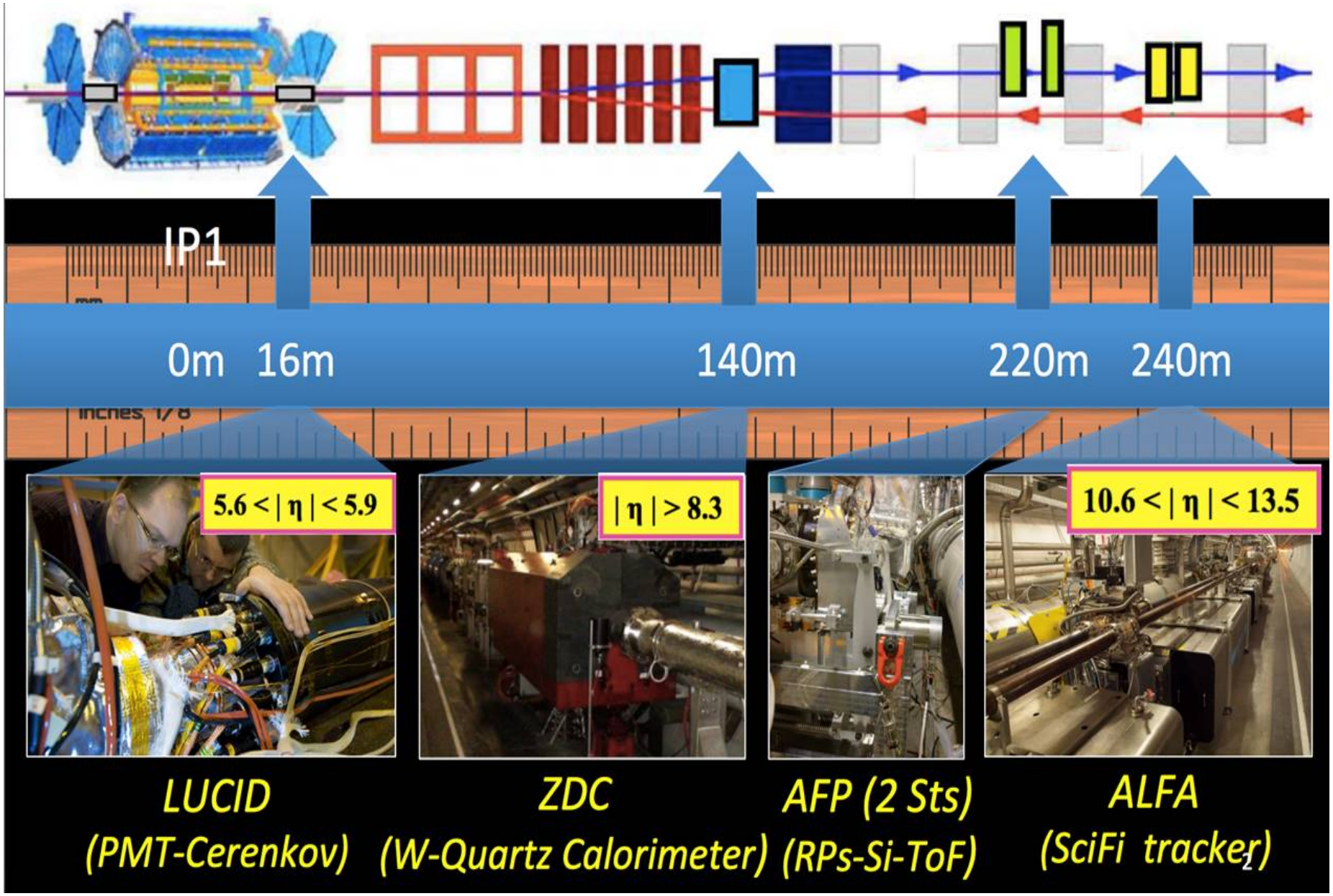
	Forward intact protons	Central detector visible mass
SD	1	M_X
DD	0	M_X, M_Y
CD	2	M_X

Exploit the potential of forward proton tag with the ATLAS detector for diffractive physics

ATLAS central detector



ATLAS forward detectors

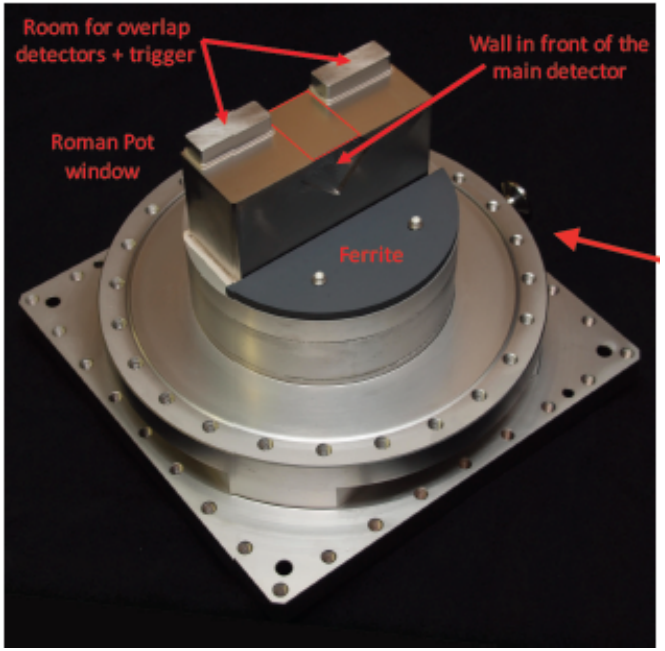


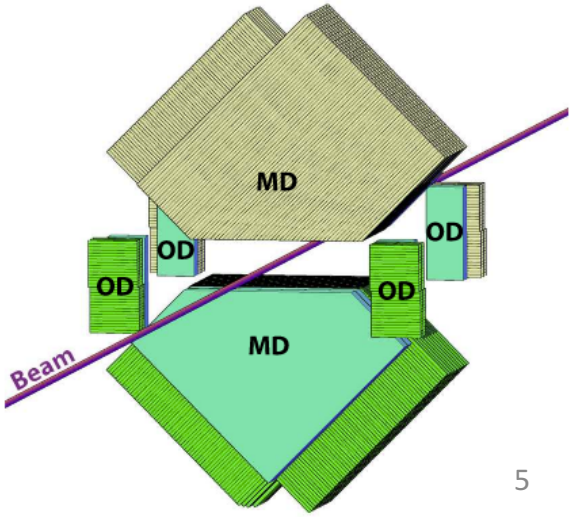
The ALFA detector

- The Roman Pots:
  - Made of stainless steel
  - Bellows allowing the movement of the pots
  - Secondary vacuum with respect to LHC UHV
  - Thickness of the wall in front: 500μm
  - Thin window thickness: 200μm

- Detectors:
  - Main Detector (MD): 20 staggered layers of 0.5 mm thick scintillating fibers (64 fibres/layer) inclined with respect to vertical direction ($\pm 45^\circ$) to provide a spatial resolution of about 30μm
  - Overlap Detector (OD): fibers placed horizontally are used to measure the vertical coordinate for the alignment of the upper and lower detectors
  - The trigger is provided by 3 mm thick plastic scintillators covering the area of the detectors

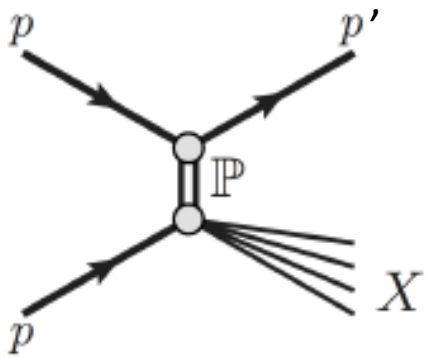
- Readout with MAPMT





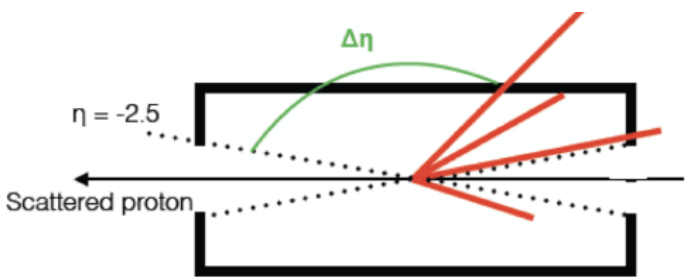
Kinematics of single diffraction

Rapidity gap ($\Delta\eta$), Fractional proton energy loss (ξ), Four-momentum transfer squared (t)



$$t = p - p' = -p_T^2$$

$$\xi = \frac{M_X^2}{s} = 1 - \frac{E_{p'}}{E_p}$$



$$M_X^2 = \sum_{i=1}^{n_{tracks}} m_i^2$$

Rapidity gap

$$\Delta\eta = (\eta_{edge} - \eta_{track}) \propto \log\left(\frac{1}{\xi}\right)$$

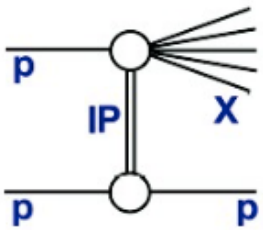
- $\sqrt{s} = 2E_p = 8$ TeV
- $|t| < 1$ GeV^2
- $\theta_{p'} = 10 - 100$ mrad
- M_X up to hundreds GeV

- ATLAS forward detector measurements: p_T and $E_{p'}$
- ATLAS central detector measurements: M_X and $\Delta\eta$

- η_{edge}: pseudo-rapidity of the ID edge on the side of the scattered proton ($\pm$ 2.5)
- η_{track}: pseudo-rapidity of the 1st ID reconstructed track

Diffraction model

- SD cross section is factorized into a Pomeron (IP) flux and a p+IP cross section
  - Triple Pomeron amplitudes as implemented in the Monte Carlo simulations



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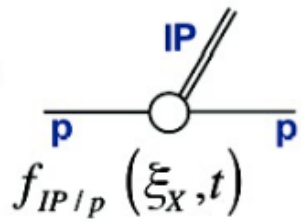

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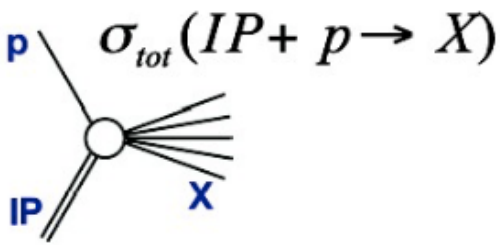

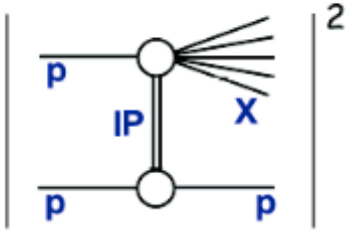

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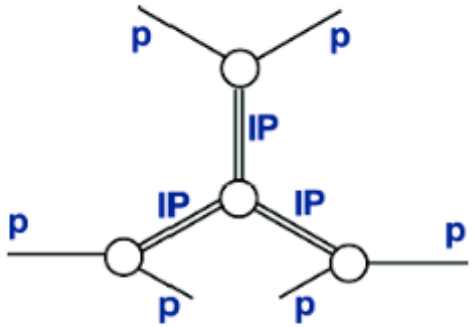


$$\frac{d\sigma}{d\xi\, dt} \propto \left(\frac{1}{\xi_X}\right)^{2\alpha(t)-\alpha(0)} e^{bt} \quad \text{(fixed s)}$$

$$[\alpha(t) = \alpha(0) + \alpha' t]$$

i.e approx: $\frac{d\sigma}{d\xi_X} \propto \frac{1}{\xi_X}$

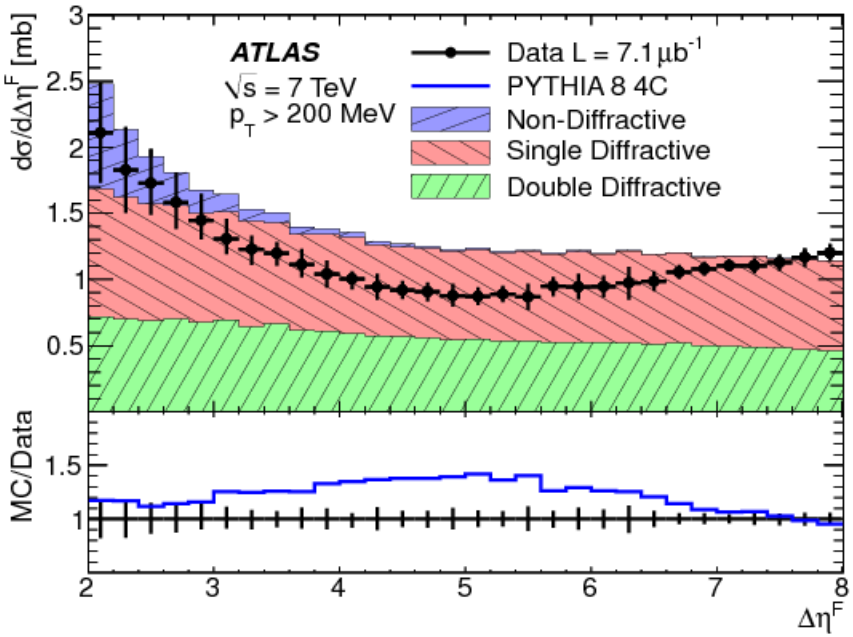
Diffractive plateau

$$\Delta\eta \propto \log\left(\frac{1}{\xi}\right) \rightarrow \frac{d\sigma}{d\Delta\eta} = const.$$

$\alpha(0) \sim 1$ (Pomeron intercept)
$\alpha' \sim 0.25\ \mathrm{GeV}^{-2}$

Previous results without proton tag

Eur. Phys. J. **C** (2012) 72

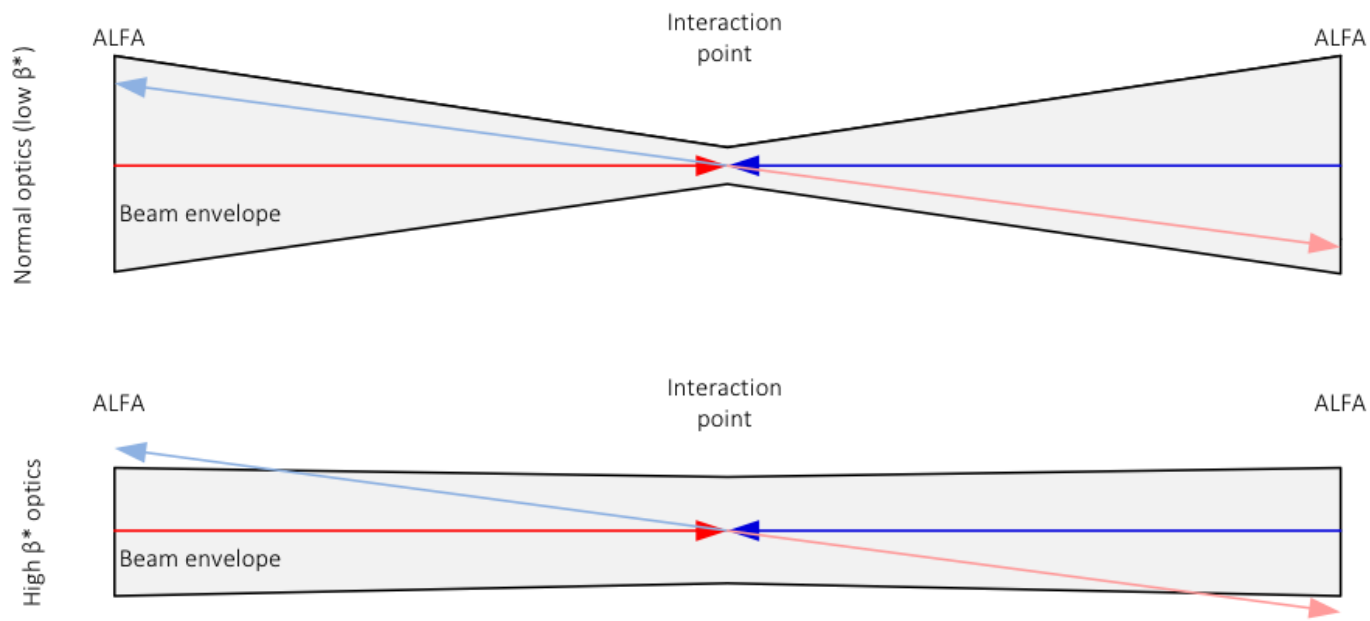


- Rapidity gap spectrum indicates large diffractive contribution.
  - Diffractive plateau is visible
- However:
  - Significant ND contributions due to random fluctuations in the hadronisation process.
  - No direct access to ξ and t dynamics
- The proton tag in the forward detector helps to improve SD event selection
  - ND and DD contributions are suppressed

- Motivations for better SD constraints
  - Improve the precision in direct measurements of the total inelastic *pp* cross section
  - Understanding the low Bjorken-*x* region of proton structure
  - Better understanding of cosmic ray air showers
  - Possible relations to the string theory of gravity

Data sample used for this analysis

- Dedicated data-taking period in July 2012, which has also been used to measure the elastic and total cross sections [*Phys. Lett.* **B** 761 (2016) 15].
- The mean number of inelastic interactions per bunch crossing (μ) is low to suppress random coincidences between protons in ALFA and unrelated activity in the central detector.
- Special high β^*optics to produces almost collinear protons at zero crossing angle.
  - The ALFA detector can approach the beam to detect protons at very small deflection angles.



$\sqrt{s} = 8$ TeV
$\beta^* = 90$ m
$\mathrm{L} = 1.67/\mathrm{nb}$
$\mu < 0.08$

Single Diffractive events in ALFA

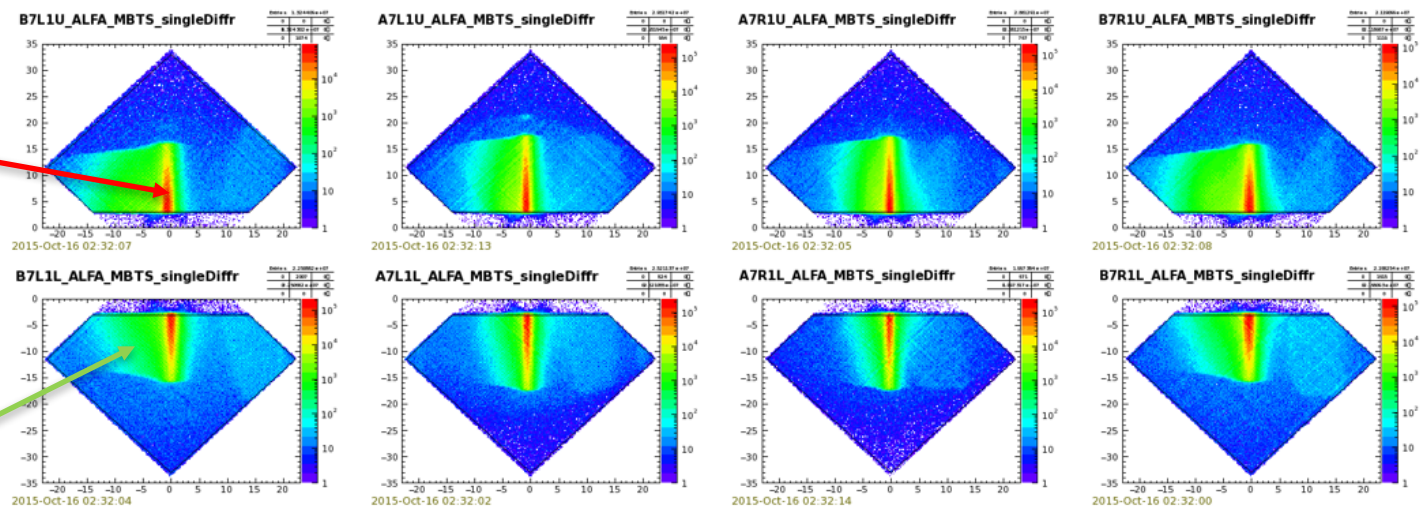
Position in ALFA planes

Elastic events

Y[mm]

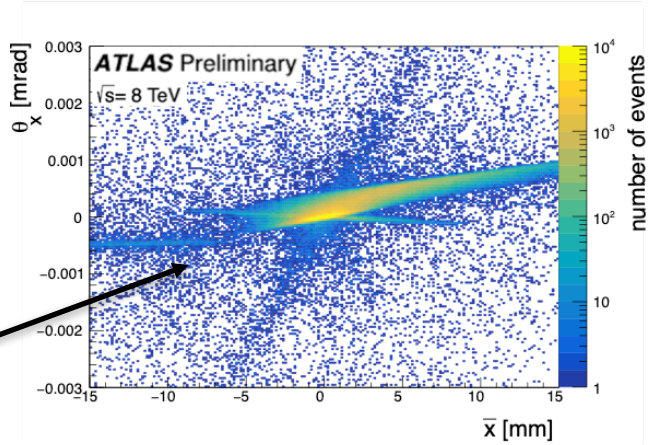
X[mm]

SD events



- Tracks reconstruction with a local precision of 30 μm in each coordinate
- Proton kinematics (ξ, t) relies on the alignment via elastic scattering and beam halo

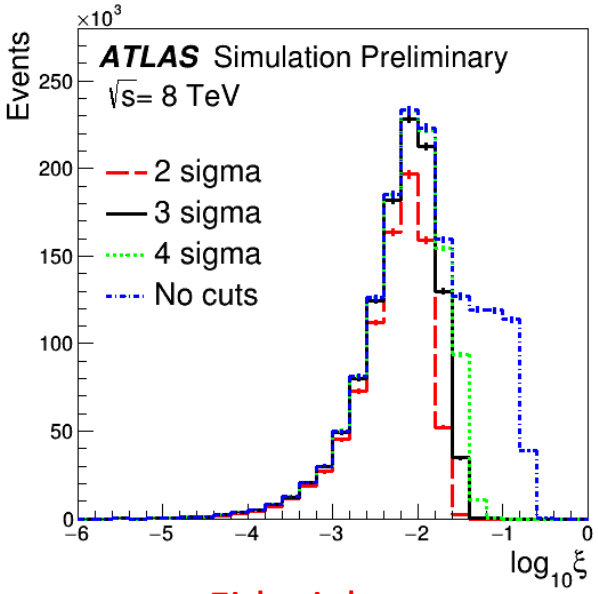
- Trigger:
  - Minimal activity in MBTS and opposite ALFA arms
- Event Selection:
  - A reconstructed vertex
  - At least 1 ID track with p_T > 200 MeV and $\eta < 2.5$
  - Exactly one reconstructed track in ALFA
  - Mean position and angle between stations within 3σ ellipse



Monte Carlo simulation

Background modeling (ND, DD, CD), unfolding detector effects (SD) and ALFA efficiency (EL)

- PYTHIA8 implements the "triple Regge" formalism
  - Proton PDF: NNPDF23 LO
  - Pomeron PDF: H1 2006 Fit B
- Two PYTHIA8 tunes with different Pomeron flux factor
  - A2: Donnachie-Landshoff (base model)
  - A3: Schuler-Sjöstrand
- HERWIG7 implements a different hadronisation model
  - Proton PDF: MMHT2014lo68cl
  - Pomeron PDF: H1 2006 Fit A
- Diffractive protons are transported to the ALFA location through the LHC matrix elements (thin lens approximation)



Fiducial cuts

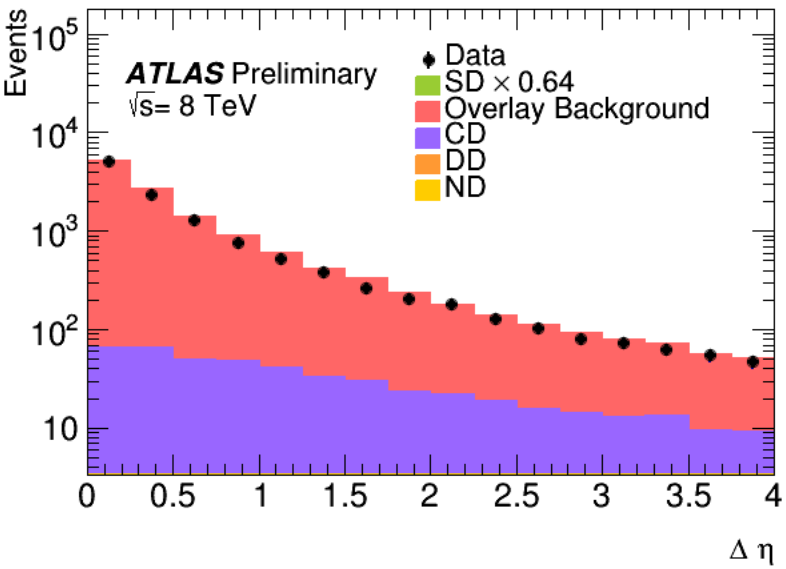
$0.016 < |t| \leq 0.43\ \mathrm{GeV}^2$
$-4.0 < \log_{10}(\xi) \leq -1.6$
$\rightarrow 80 < M_X < 1270\ \mathrm{GeV}$

PYTHIA8 is tuned to the previous ATLAS data without proton tag ($\Delta\eta$ and σ_{tot}).

Overlay Background

- Pile-up between a proton in ALFA and an uncorrelated activity in ID/MBTS
  - Dominant effect: elastic protons in ALFA overlapping to beam induced background (beam halo)
  - Estimated with data-driven technique using strongly enriched ND sample

Overlay background control region



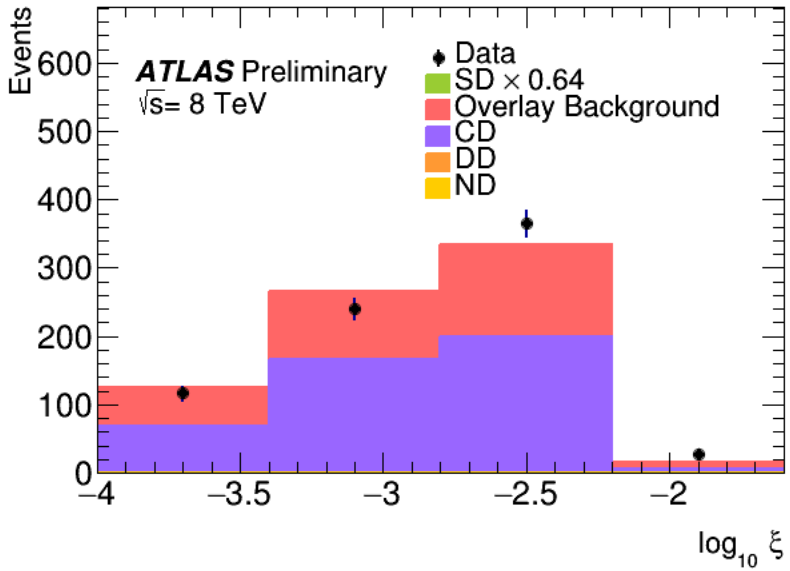
- Largest background (about 25 %)
- ND enrichment
  - All 32 MBTS segments fired
  - At least 1 track with p_T > 200 MeV
  - $|\Delta\eta| < 0.5$
- Overlay background normalization: 0.8 %
  - Fraction of the ND enriched events sample with a proton in ALFA
- Overlay background control region
  - In addition to the main event selection, a 2nd ALFA armlets with a reconstructed proton is required

Good description of shape and normalization

Physics Background

- Physics processes which ”look” like SD
  - Forward protons in ALFA with correlated activity in ID/MBTS
- Dominant physics background (CD) is estimated from simulations
  - ND and DD neglected

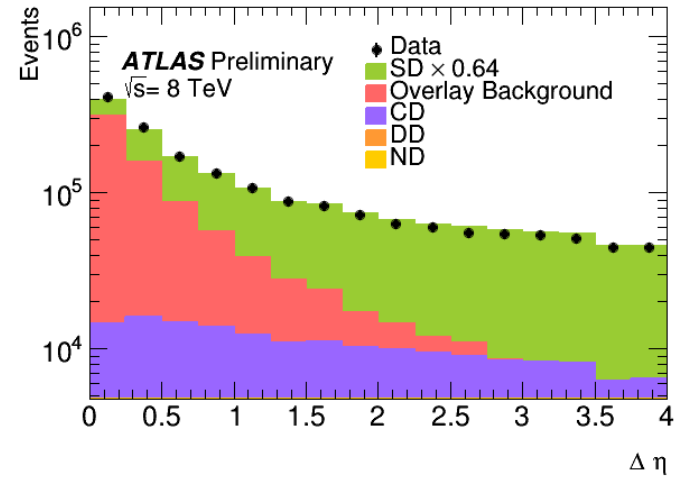
CD background control region

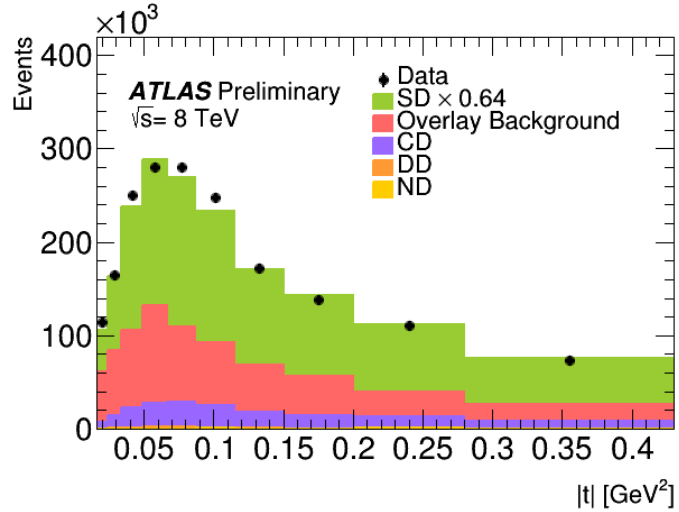


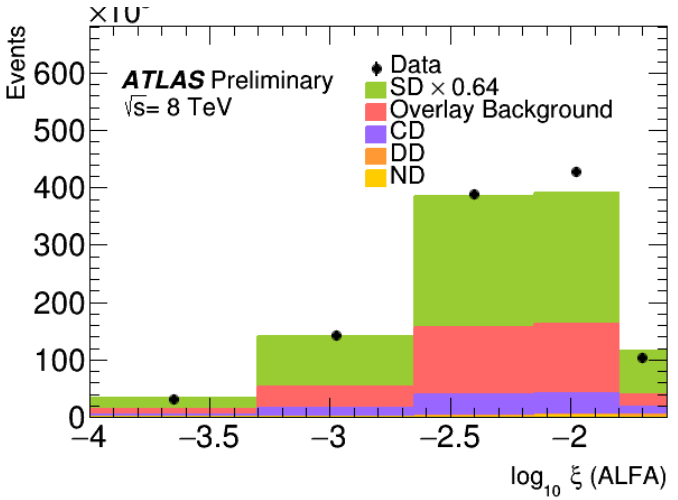
- Second largest background (about 10 %)
- CD enrichment in the control region
  - 2-10 MBTS segments fired
  - Two ALFA armlets with a reconstructed proton
- ξ distributions reweighted to match data

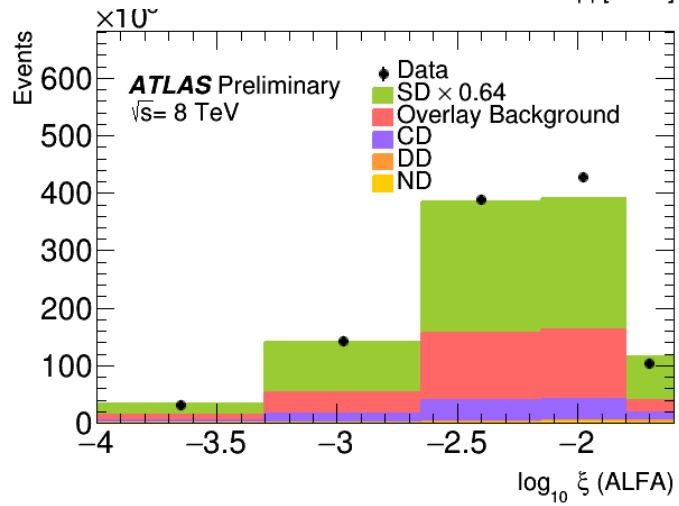
Good description of shape and normalization

Comparison data/simulations









PYTHIA8 cross sections before scaling

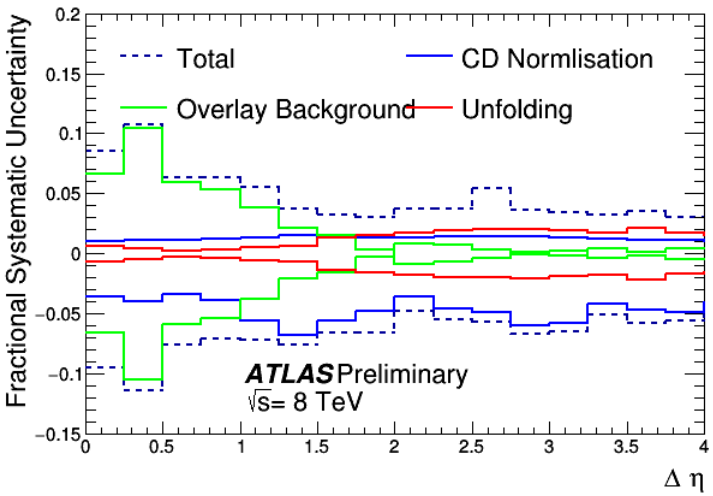
σ[mb] @ 8 TeV	
ND	51
SD	12.5
DD	8.3

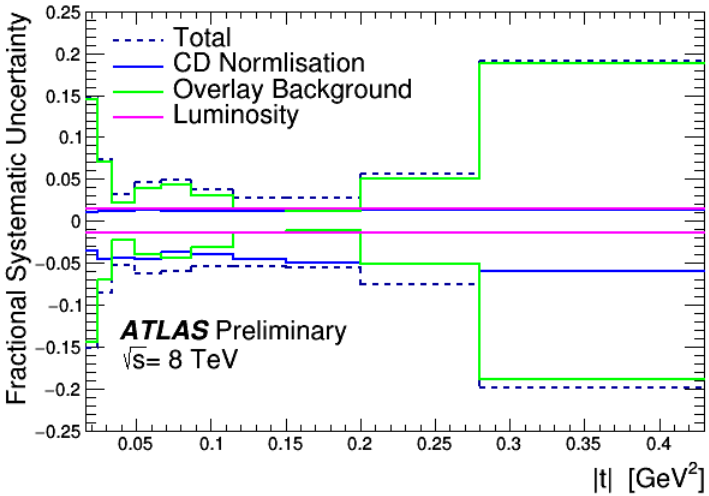
Good description of shape and normalization after SD rescaling by 0.64

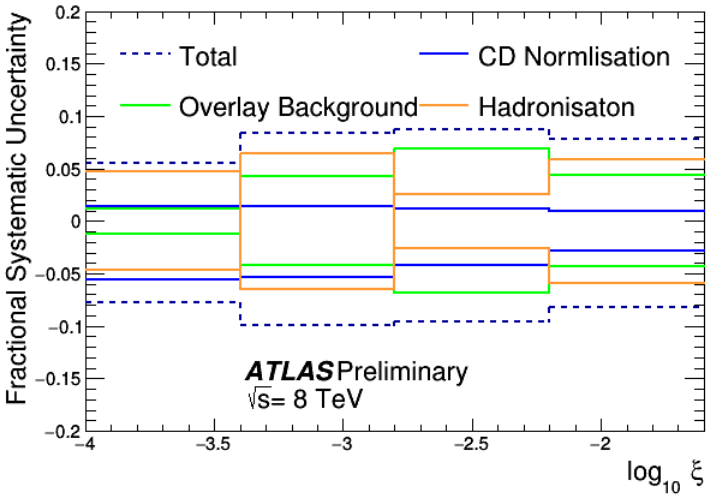
Systematic uncertainties

- The largest systematic uncertainty mostly arises from overlay background subtraction

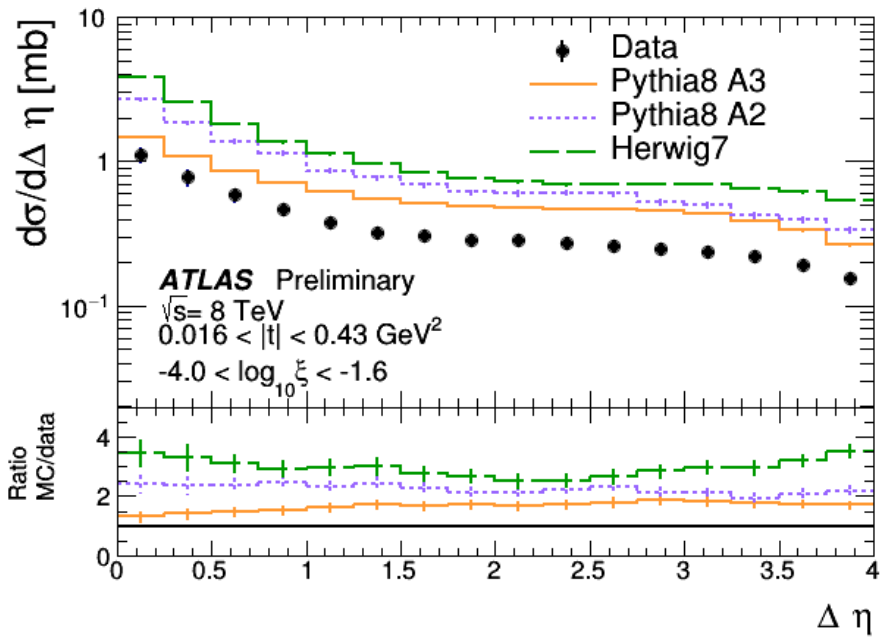
- Further relevant systematics
  - SD, DD and CD normalization to CDF data
  - Hadronisation model (PYTHIA vs HERWIG)
  - Unfolding of instrumental effects (closure test)
  - Luminosity precision from vdM scan







SD differential cross section ($\Delta\eta$)



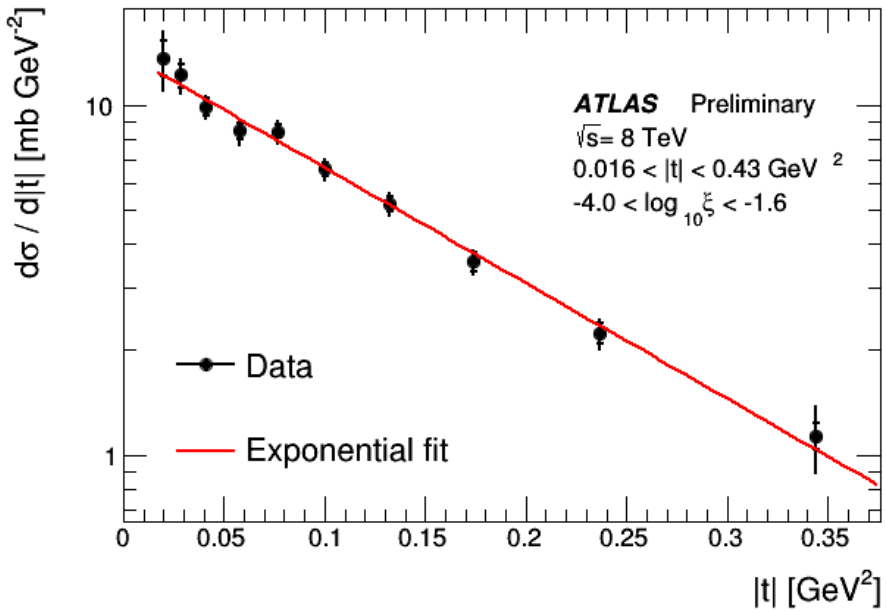
- Unfolded hadron level cross sections after background subtraction
- Error bars display statistical and systematic error added in quadrature

MC model	$\sigma_{MC}/\sigma_{Data}$
PYTHIA 8 A2	2.3
PYTHIA 8 A3	1.5
HERWIG 7.1	3.0

- Diffractive plateau is visible
- Cross section increase @ small rapidity gaps
  - Pile-up of all events with gap ending before the inner tracker acceptance
- Cross section decrease @ large rapidity gaps
  - Loss of small-ξ events close to the ξ-edge (10^{-4}).

σ_{SD} excess in PYTHIA8 is compatible with previous ATLAS data

SD differential cross section (t)



Measured exponential slope

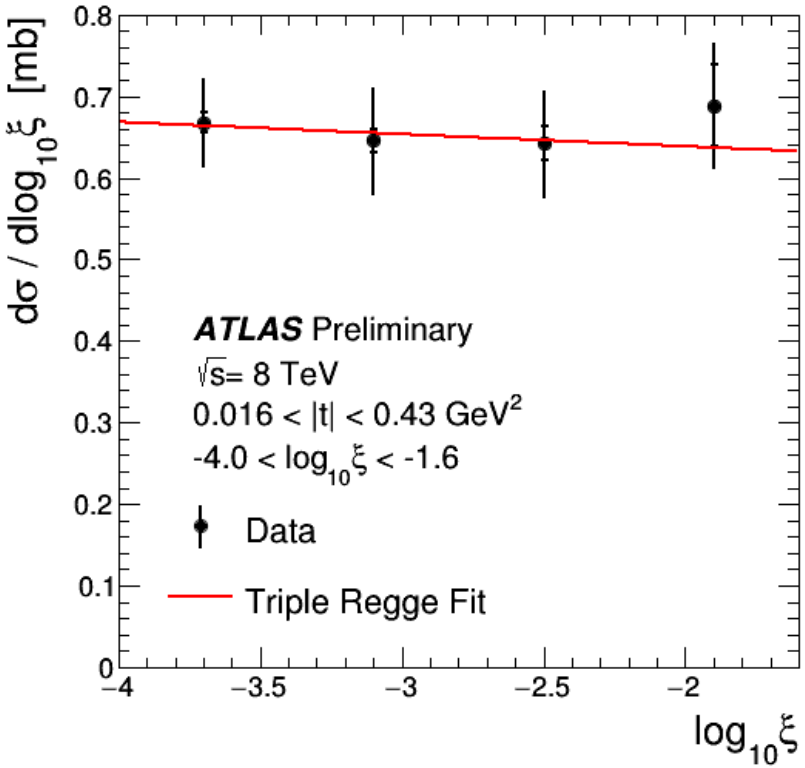
$$B = 7.60 \pm 0.23_{stat} \pm 0.22_{syst}\ \mathrm{GeV}^{-2}$$

MC prediction	B [GeV^{-2}]
PYTHIA8 A2	7.82
PYTHIA8 A3	7.10

- Main systematic uncertainty comes from overlay background subtraction
- The measured values lies between PYTHIA8 tune predictions A2 and A3.

First value published by an LHC experiment.

SD differential cross section (ξ)



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

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

Measured Pomeron intercept

$$\alpha(0) = 1.07 \pm 0.02_{stat} \pm 0.06_{syst} \pm 0.06_{\alpha'}$$

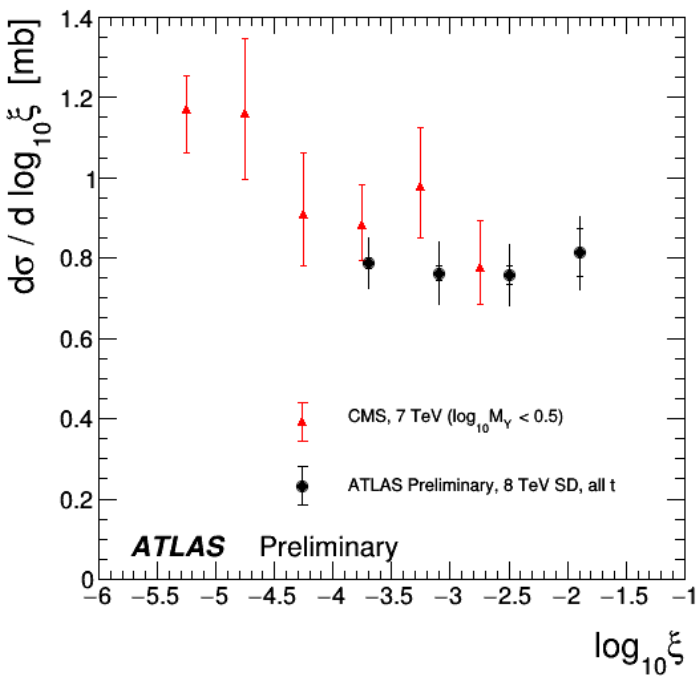
MC prediction	$\alpha(0)$
PYTHIA8 A2	1.00
PYTHIA8 A3	1.14

- Main systematic uncertainty comes from $\alpha' = 0.25 \pm 0.25\ \mathrm{GeV}^{-2}$
- Measured $\alpha(0)$ value lies between PYTHIA8 tune predictions A2 and A3.

Cross section extrapolation

Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t-\text{extrap}}$ [mb]	$\sigma_{SD}^{\xi,t-\text{extrap}}$ [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

Phys. Rev. D **92**, 012003 (2015)



- Extrapolation to $0 < |t| < \infty$ is done using the t-slope extracted from data.
- Extrapolation to the full ξ range not yet well constrained by LHC data
  - Since the measured $\alpha(0)$ lies between A2 and A3 predictions, total σ_{SD} in PYTHIA8 is scaled by the average ratio between A2 and A3 predictions.
- ATLAS and CMS data are in agreement
  - Small overlapping ξ range
  - CMS measurement is based on rapidity gap-based, therefore it contains a small DD admixture

Conclusions

- ATLAS provided the first measurement of single diffractive proton-proton cross section @ $\sqrt{s} = 8\ \mathrm{TeV}$ with tagged protons
  - Reduced background from non-diffractive and central-diffractive events
  - Access to kinematics of diffracted protons (ξ, t)

t-slope	$B = 7.60 \pm 0.23_{stat} \pm 0.22_{syst}\ \mathrm{GeV}^{-2}$
Pomeron intercept	$\alpha(0) = 1.07 \pm 0.02_{stat} \pm 0.06_{syst} \pm 0.06_{\alpha'}$

- The measured shape of ξ and t differential single diffractive cross sections is in agreement with Monte Carlo prediction
  - Integrated single diffractive cross section is significantly smaller than the predictions