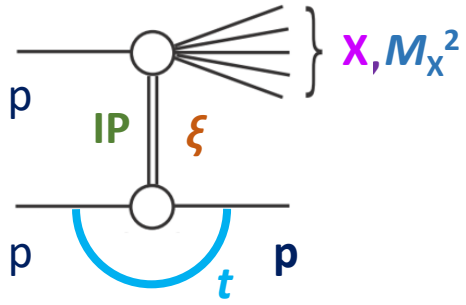
measurements of single diffraction using the ALFA forward spectrometer at ATLAS

Tomáš Sýkora
Institute of Particle and Nuclear Physics, Charles University

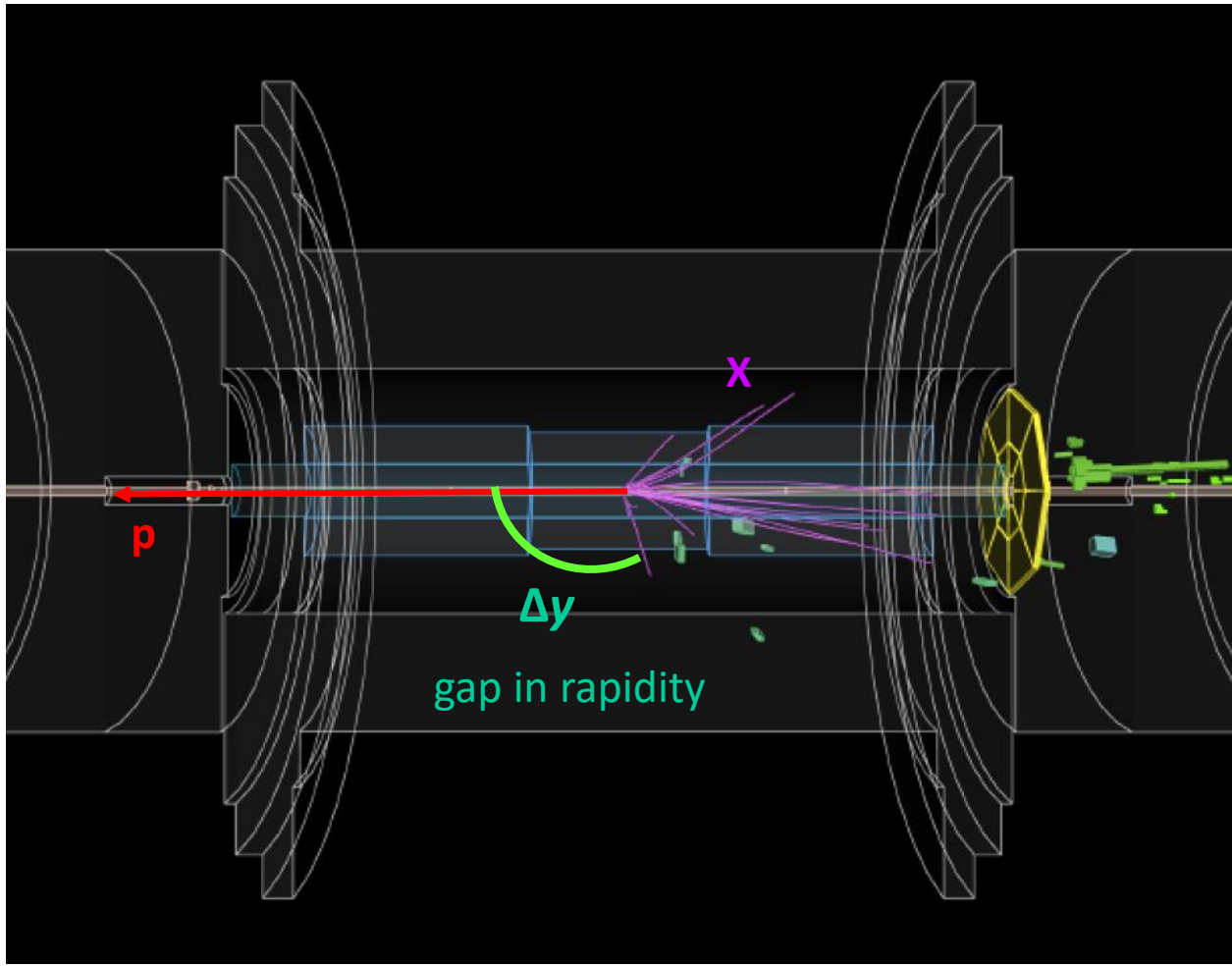
on behalf of the ATLAS collaboration

single diffraction



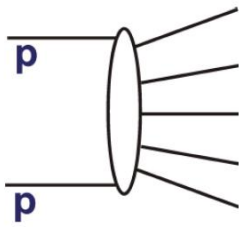
Inclusive single diffractive dissociation, p + p → **p** + **X**, where **X** stands for a dissociative system, with a mass M_X^2, is studied using data **collected by the ATLAS** experiment **at the LHC**. The **intact proton p** is reconstructed and measured in the **ALFA forward spectrometer**, while charged particles from the **dissociative system** are **reconstructed and measured using the ATLAS Inner tracking Detector (ID) and calorimeters**.

Differential cross sections are presented as functions of the proton **p** fractional momentum loss ξ, the four-momentum transfer squared t, and the size of a pseudorapidity gap measured from the edge of the ATLAS calorimeters $\Delta\eta$. The **results** are **interpreted in the framework of Regge phenomenology**, with pomeron **IP** as exchanged "particle".

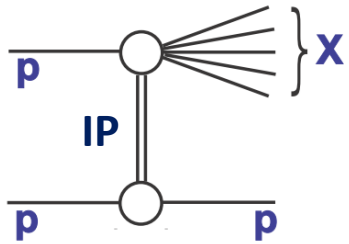


talk is based on the conference note:
Measurement of Differential Cross Sections for Single Diffractive Dissociation in √s = 8 TeV pp collisions using the ATLAS ALFA Spectrometer
ATLAS-CONF-2019-012

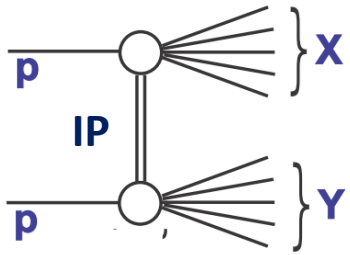
p-p collisions: diffractive and non-diffractive components



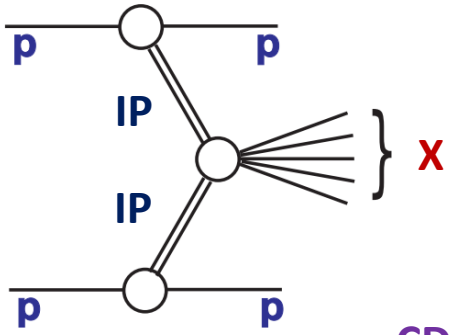
ND



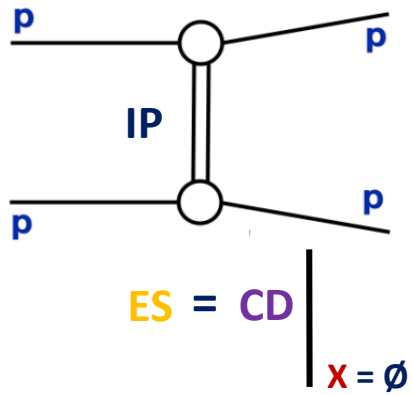
SD



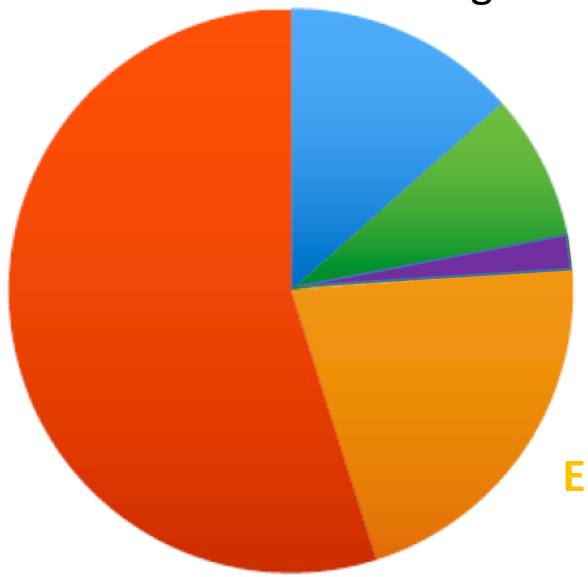
DD



CD



for illustration



Single Diffraction

Double Diffraction

Central Diffraction

Non Diffractive

Elastic Scattering

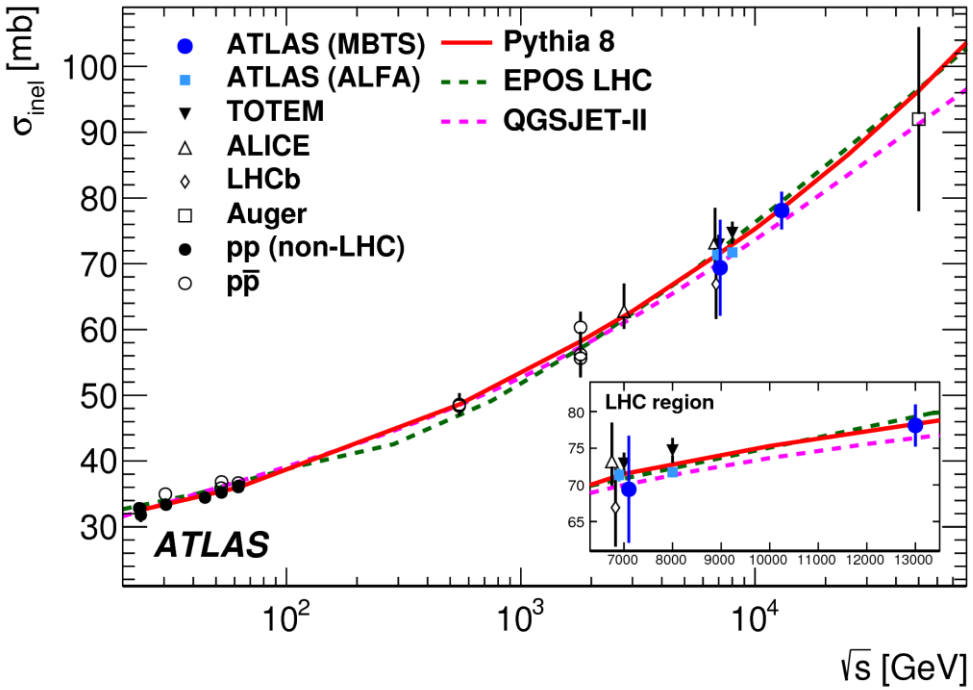
- SD has large cross section but was not precisely measured in **previous analyses** based on **rapidity gaps**

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

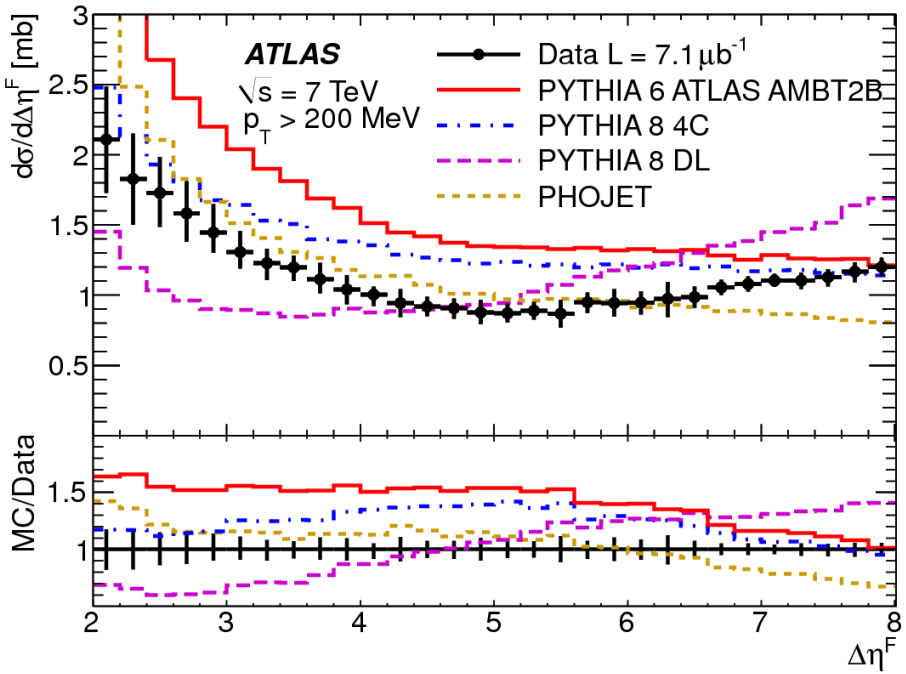
  due to **no possibility** to well distinguish SD, DD and the tail of ND contributions and no direct access to the underlying dynamics

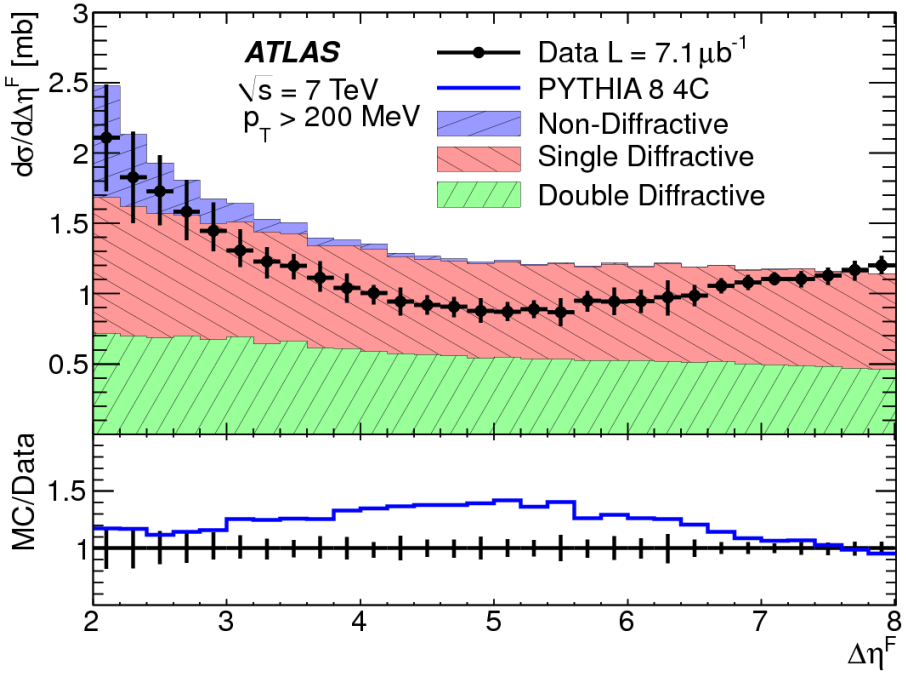
- **present analysis based on proton tagging**

measurement based on rapidity gap – motivation for proton tagged measurement(s)



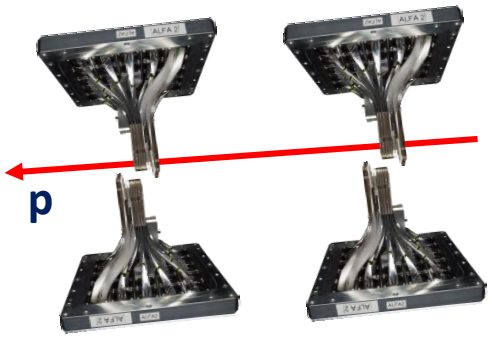
- better precision of the total inelastic p-p cross section
- understanding the low Bjorken-*x* region of proton structure
- interpretation of cosmic ray air showers
- with proton tagging - removal of **DD** and **ND**
- direct access to ***t*** and ***ξ***





experimental setup

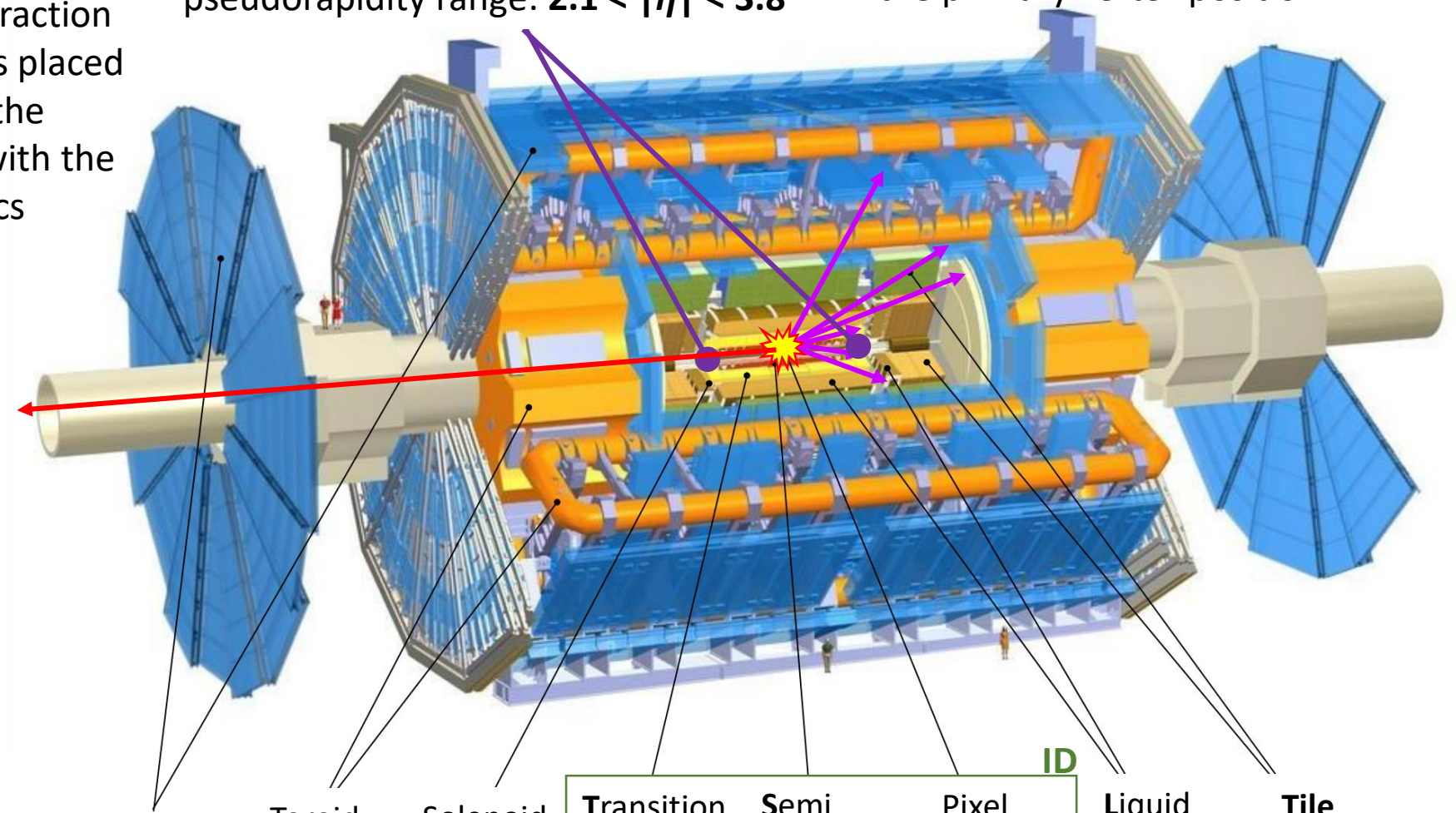
proton p is scattered through a very small angle of typically 10 - 100 μrad and is measured by **ALFA detector** 240 m from the ATLAS Interaction Point (IP); the detector was placed 7.5 mm from the beam in the dedicated run of the LHC with the special high $\beta^* = 90$ m optics



ALFA detector (one side)

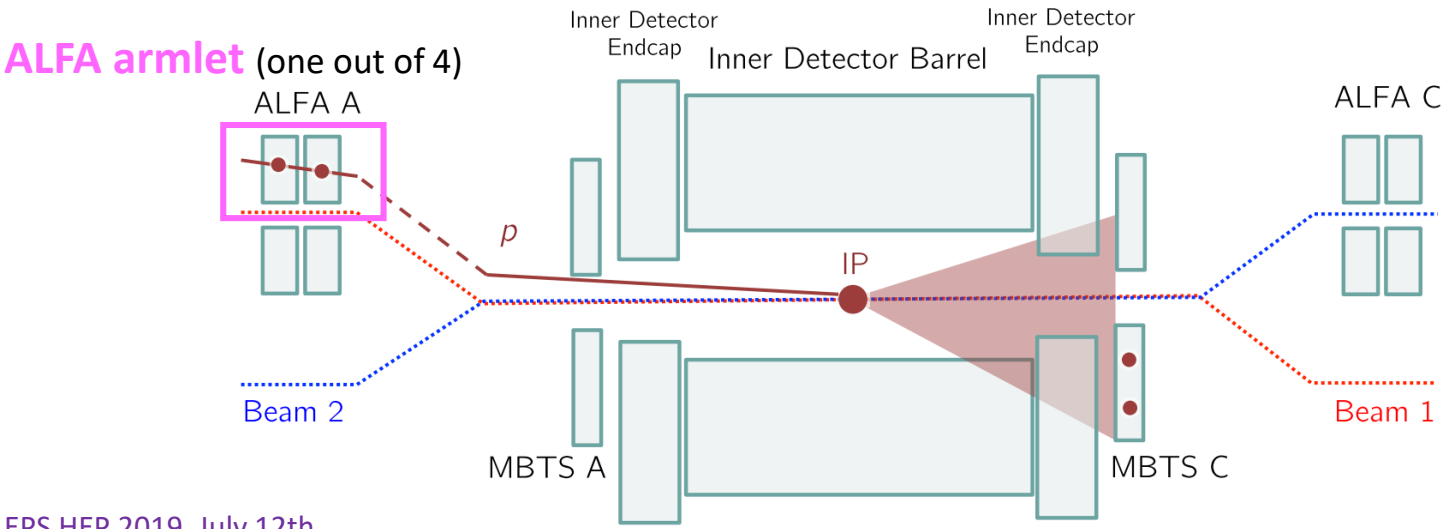
Minimum **B**ias **T**rigger **S**cintillator (**MBTS**) pseudorapidity range: **$2.1 < |\eta| < 3.8$**

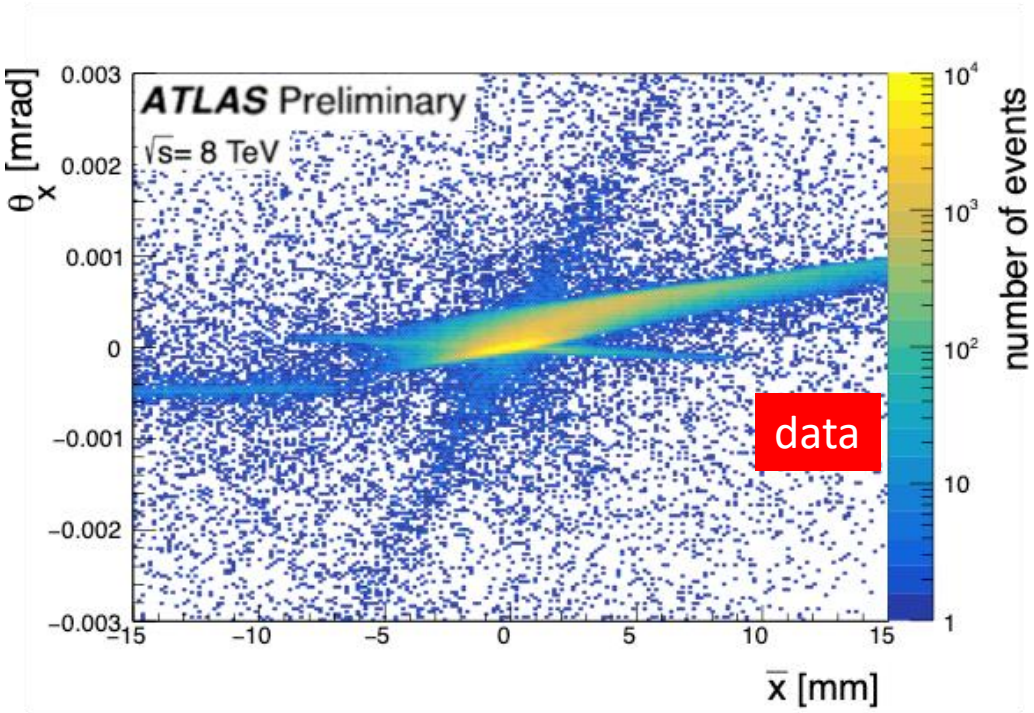
second proton dissociates, producing a multi-particle hadronic system **X**; charged particles with **$p_T \geq 0.2$ GeV** and **$|\eta| \leq 2.5$** are measured in the **ID** allowing determination of the primary vertex position.

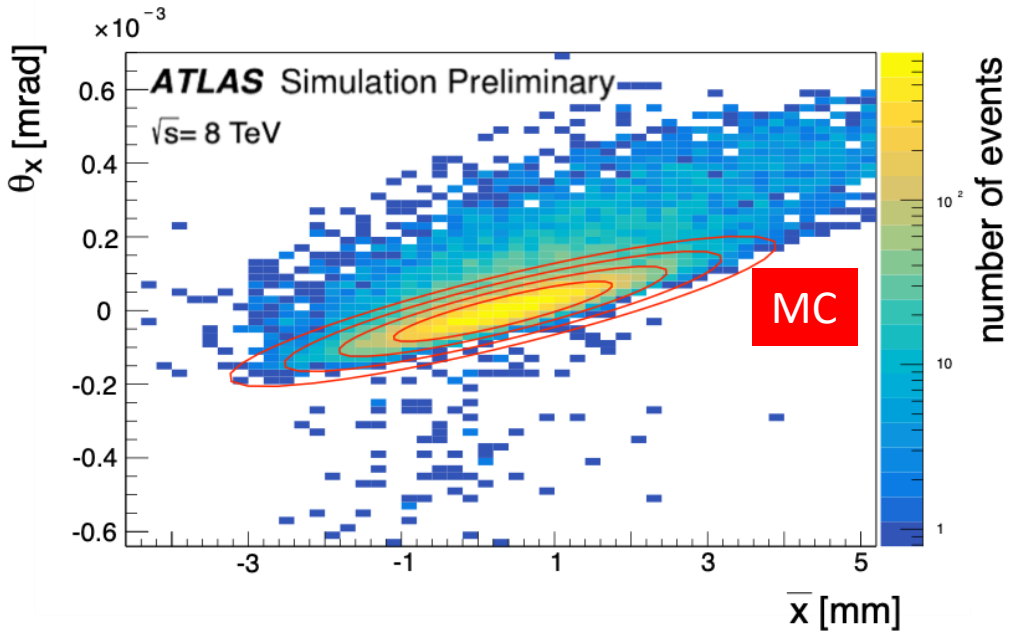


measurement conditions and event selection

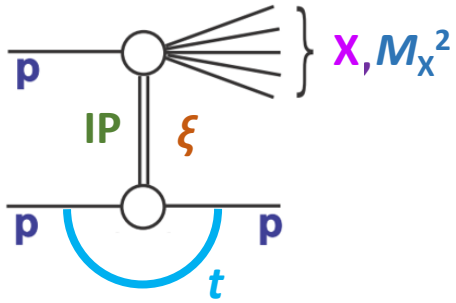
- **8 TeV** data from low lumi and pile-up run 206881, LHC fill 2836, July 12–13, 2012; μ **= 0.08**, β^* **= 90 m**
  (the same run was used for 8 TeV ALFA elastic / total cross-section analysis Phys. Lett. B761 (2016) 158)
- **trigger**: **ALFA** and **MBTS** signals on opposite sides of the IP
- **ALFA** selection: exactly one reconstructed proton in an **ALFA armlet** with additional off-line selection for SD events using the geometrical cut: $(\bar{x}, \theta_x)$ within 3σ ellipse around [0, 0], where $\bar{x}$ is a proton track mean position, θ_x is a proton track local angle between stations
- **MBTS** selection: at least 5 (out of 16) counters above noise threshold
- **ID** selection: ≥ 1 track with $p_T \geq 200$ MeV, reconstructed vertex







variables and fiducial region of the measurement



t = - p_T^2 : four-momentum transfer squared; p_T reconstructed from proton track in ALFA detector

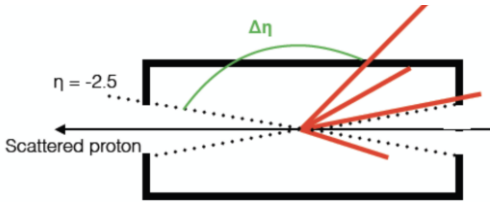
$\xi = M_X^2/s$: fractional proton energy loss; reconstructed from

- tracks in the **ID**

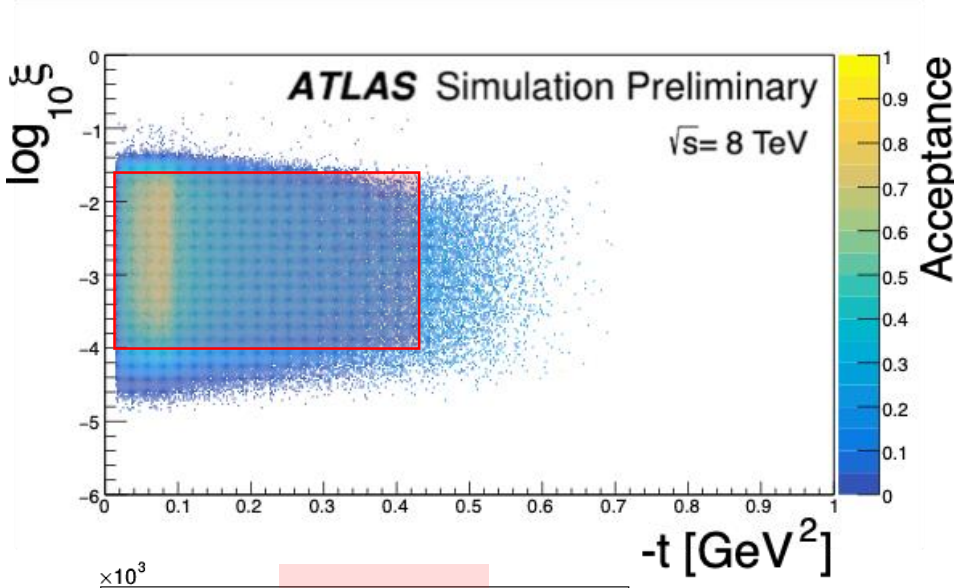
$$\xi^{\pm}_{EPz} = \sum_i (E_i \mp p_{z,i})/\sqrt{s}$$

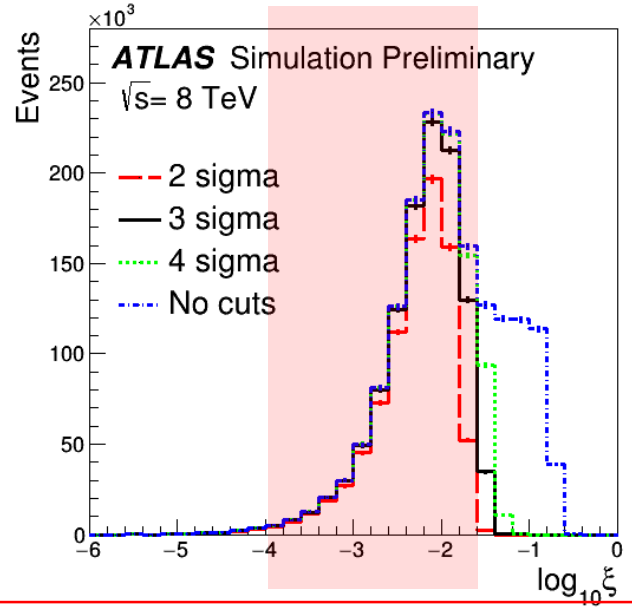
- track in ALFA

$$\xi_{ALFA} = 1 - E_p/E_{beam}$$



- 'visible size of pseudorapidity gap' **Δη** - between tracker edge on side with proton (η = +2.5 or −2.5) and the first **ID** track with $p_T \geq 0.2$ GeV





fiducial region of the measurement:

- 0.016 < |t| < 0.43 GeV^2
- −4.0 < $\log_{10}\xi$ < −1.6 (↔ 80 < M_X < 1270 GeV)
- lower limit in ξ determined by MBTS requirement
- upper limit in ξ and range in t determined by ALFA acceptance

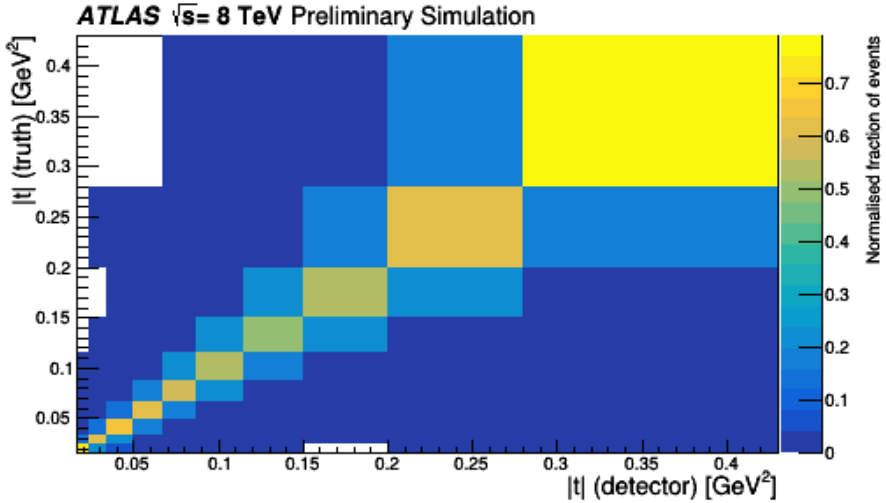
MC generators

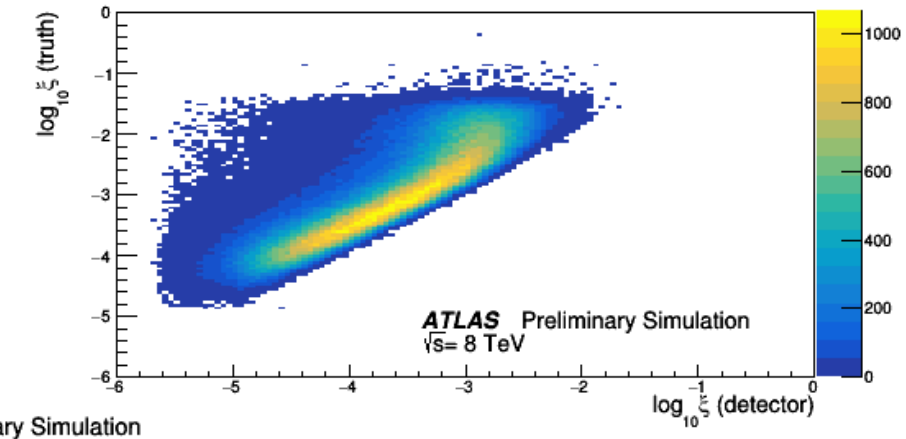
signal

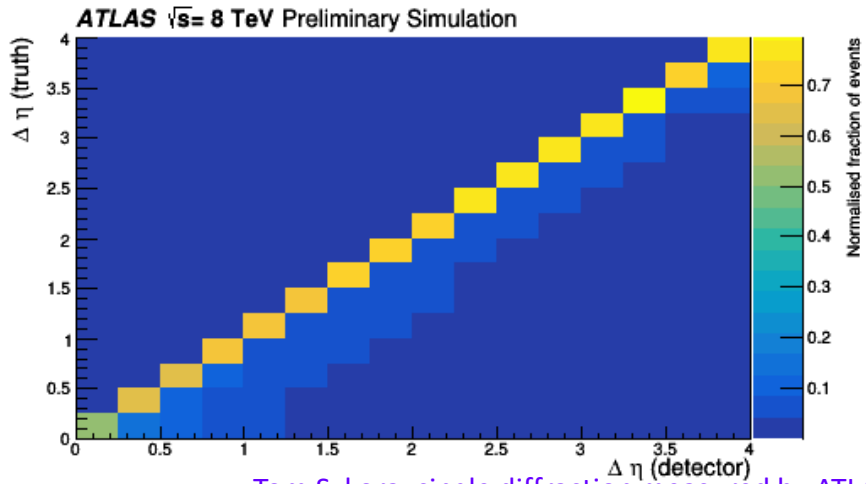
- **PYTHIA8 A3**
  - proton PDF = NNPDF23 LO
  - pomeron PDF = H1 2006 Fit B
    - flux: intercept α(0) = 1.07,
      slope α' = 0.25 (Donnachie-Landshoff)
  - **SD** for unfolding
  - **CD**, **DD**, **ND** for background subtraction
  - **EL** for ALFA reconstruction efficiency

systematics

- **PYTHIA 8 A2**
  same as A3 tune, but Schuler-Sjostrand flux
  with intercept α(0) = 1.00
- **HERWIG 7.1.3**
  - proton PDF = MMHT2014lo68cl
  - pomeron PDF - α(0), α' not extracted







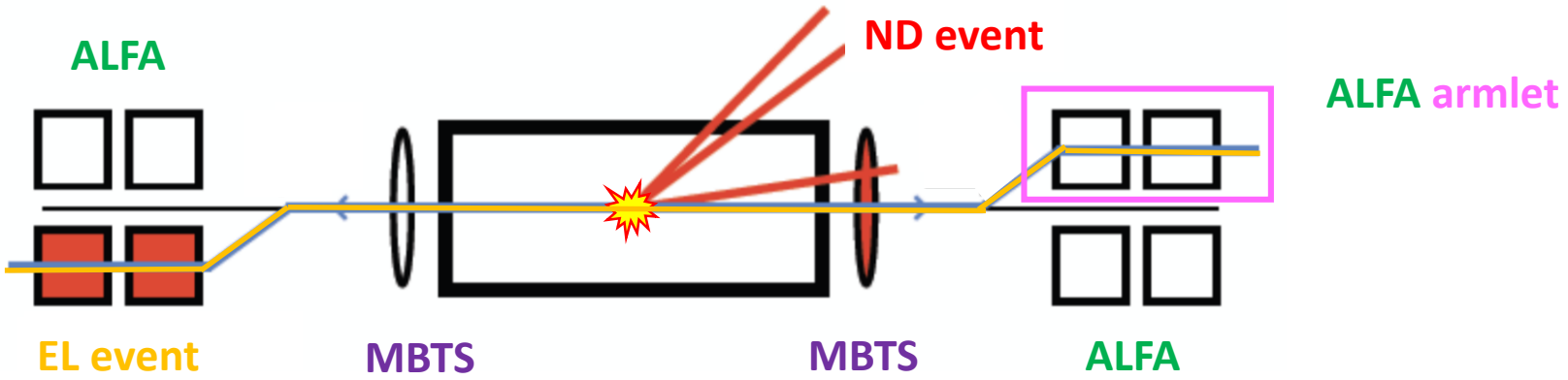
signal background

- **single event contamination** due to **ND**, **CD**, **DD**, **EL** processes **is small/zero**:

  ND < 1%, **CD ~ 9%**, **DD** < 1%, **EL** = 0%

- **not** the case **for events overlay** (= combination of two uncorrelated events)

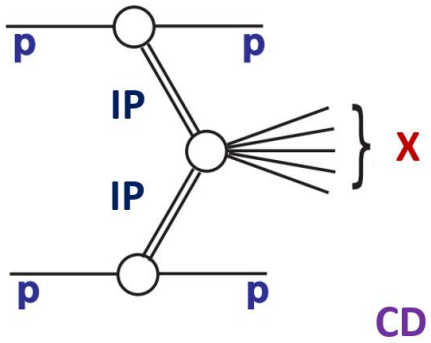
  ALFA (elastics / beam halo proton) + **ID**/**MBTS** (Minimum Bias events) **~ 25%**



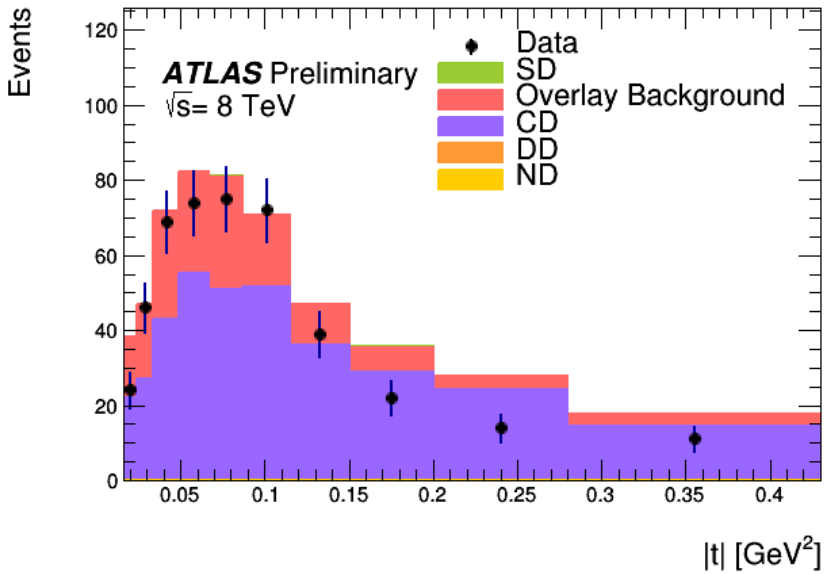
  - (overlay background) estimated by data-driven technique assessing **ALFA** activity in strongly **ND**-enriched events, selected as:
    - all 32 **MBTS** segments have signals
    - at least 1 track with $p_T > 200$ MeV and $|\Delta\eta| < 0.5$

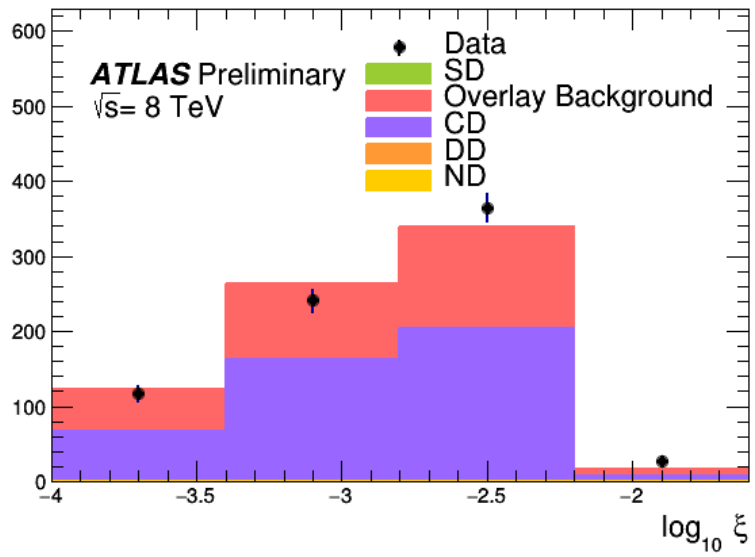
- **ALFA**, 1 proton, 0.8% of such events, gives **normalization**
- **shape** in t from **ALFA** data
- **shapes** in ξ, $\Delta\eta$ based on MC events that pass all analysis selection cuts except for number of protons

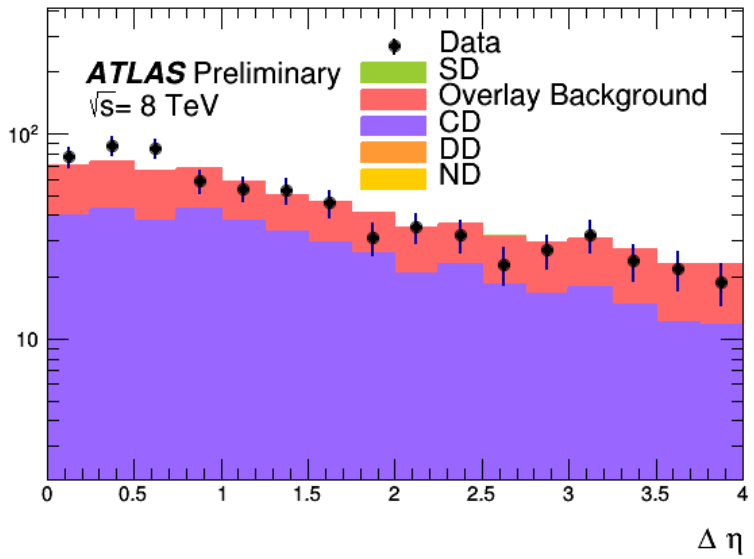
background due to CD



- the second largest source of signal background (9%)
- obtained from MC control region (**CD**-enriched sample)
  - protons in exactly two **ALFA armlets**
  - 2-10 **MBTS** segments fired



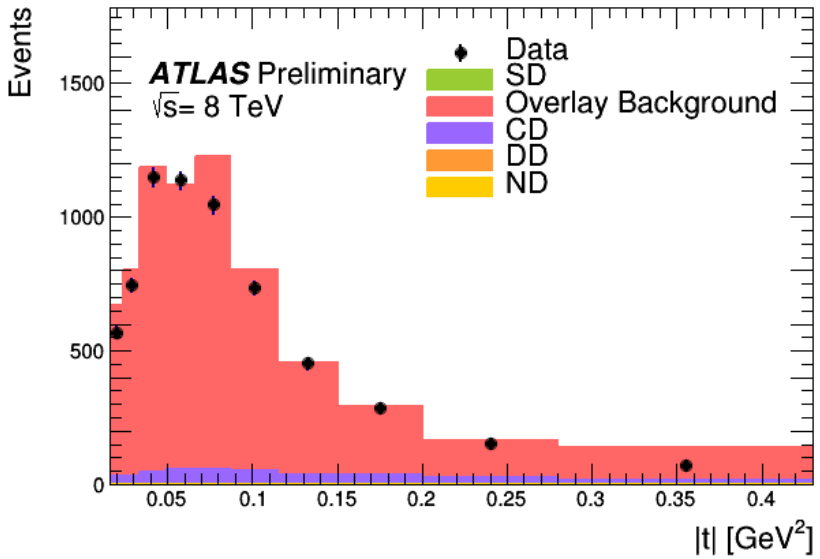


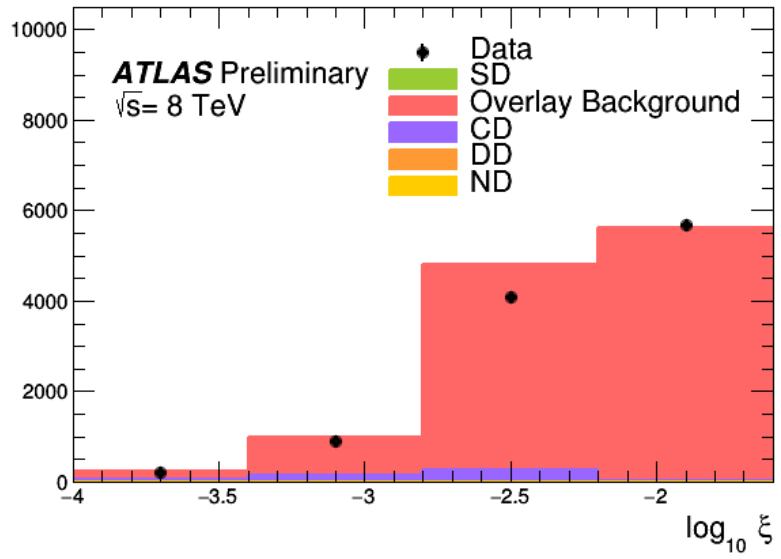


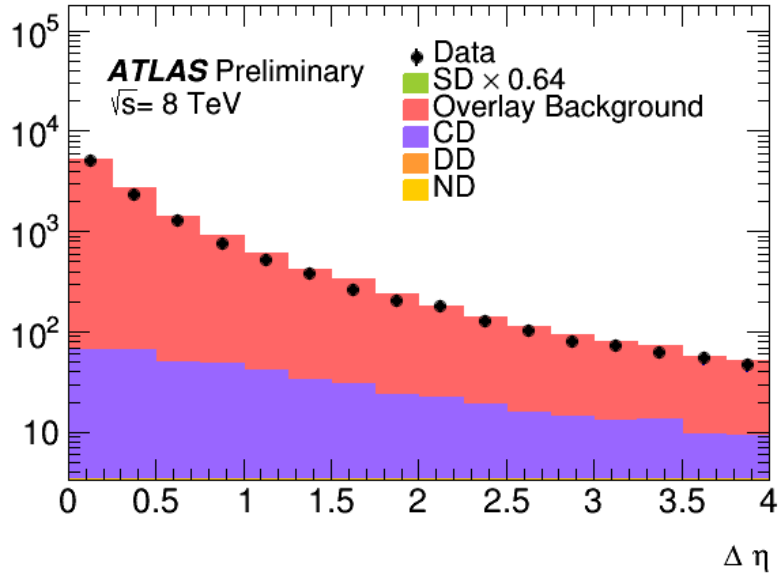
- **good** description of **normalizations** and **shapes**
- reweight ξ distributions to match the data, preserving normalization

background due to overlay events

- biggest source of signal background (25%)
- same as nominal selection, but with protons **in exactly two ALFA armlets** - dominated by elastics **p** in **ALFA** + **ND** in **ID**

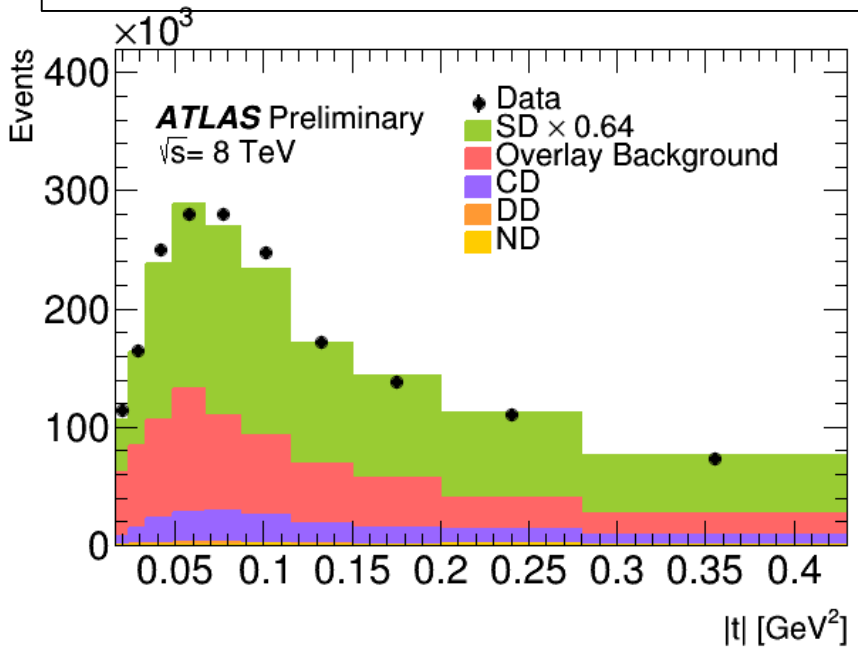


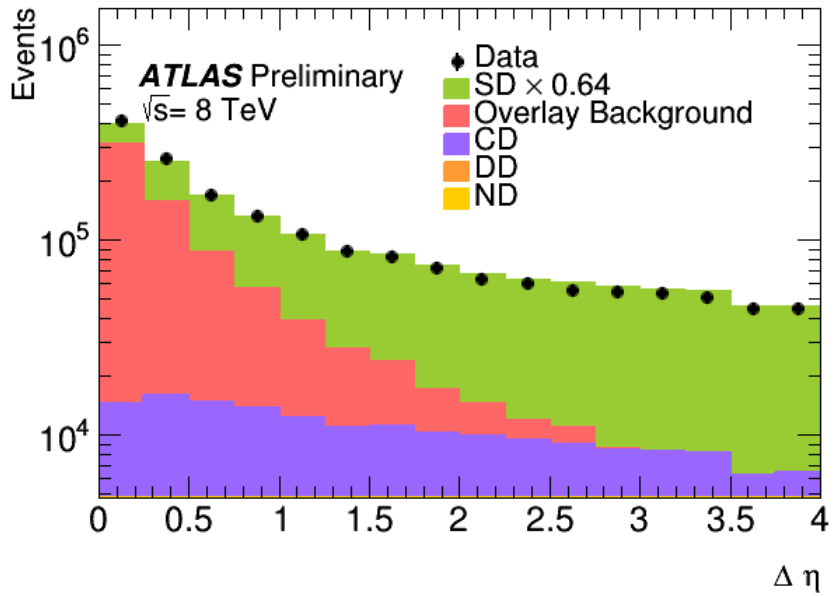


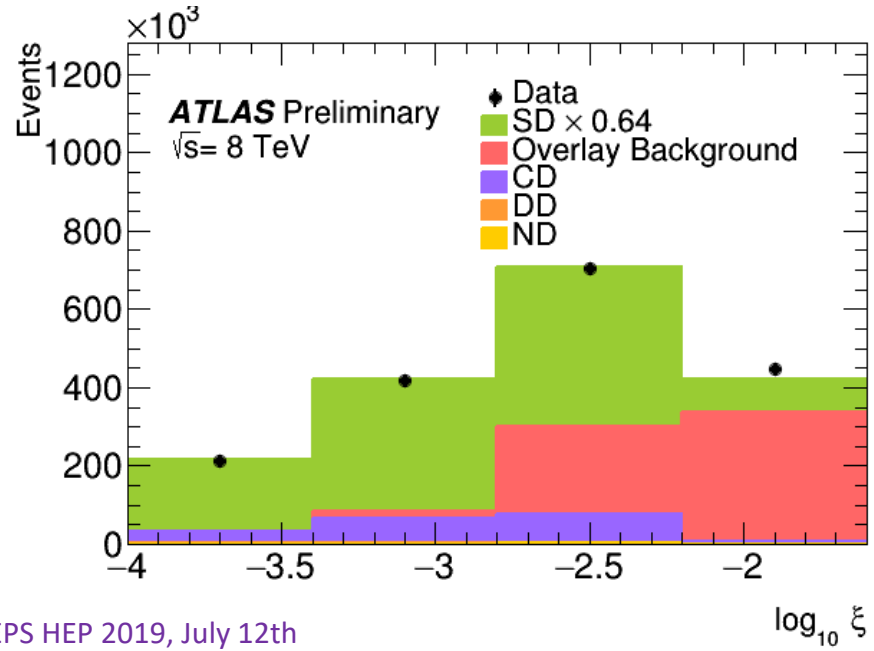


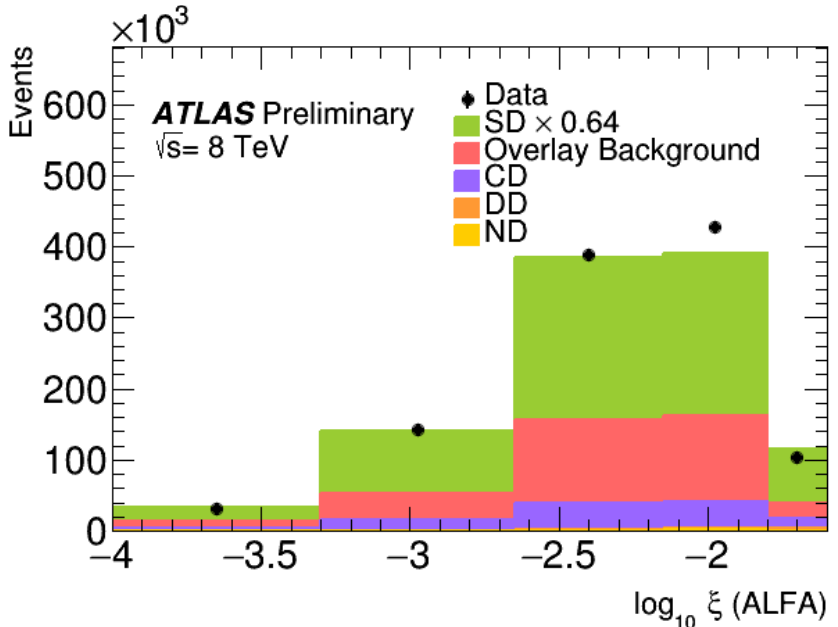
- **good** description of normalization and shapes
- **systematic errors** obtained from residual differences between data and model in this control sample

uncorrected (detector level) distributions







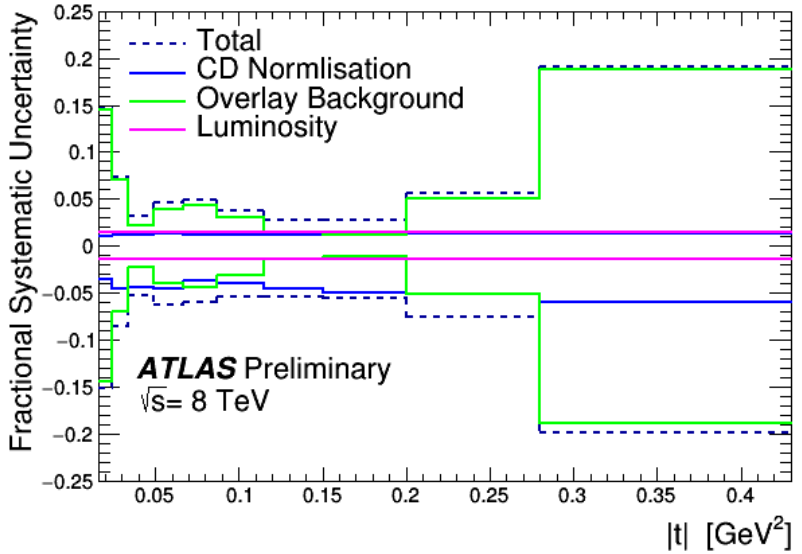


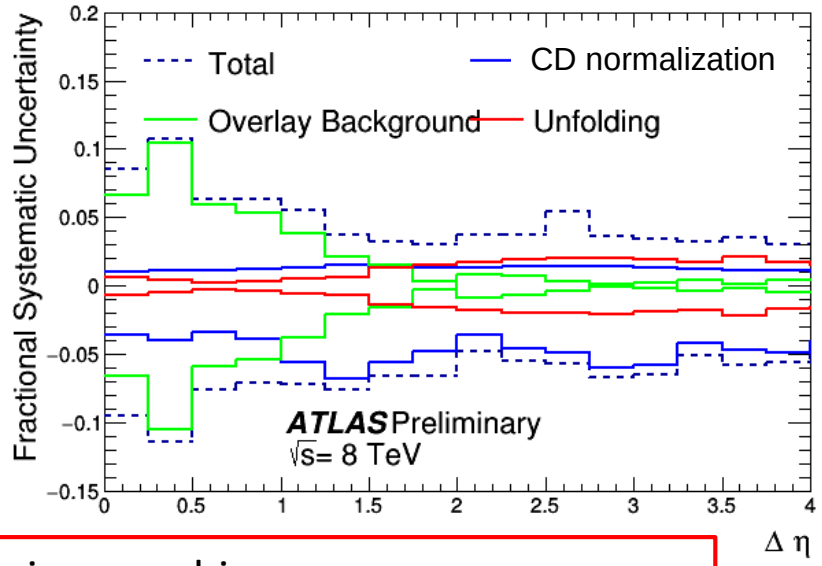
- poor description with default PYTHIA8 SD normalization
- adjust SD total cross section to the result from this measurement by the factor 0.64

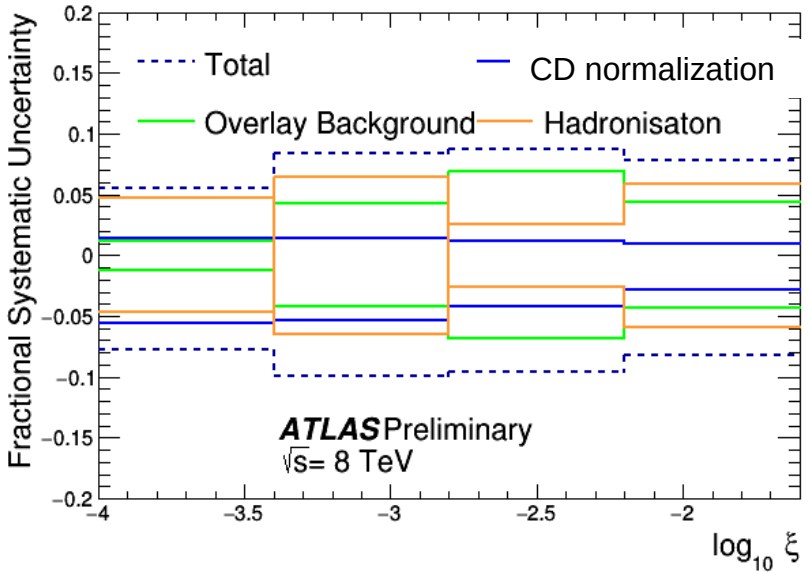
- good description of all distributions after renormalization
- ξ (ALFA) has very different background shapes and other systematics from ξ

systematics uncertainty sources

- overlay background subtraction
- CD background shape and normalization
- ALFA alignment and reconstruction
- hadronization uncertainty
- luminosity (1.5%)
- MBTS thresholds
- ID track reconstruction
- trigger efficiencies
- unfolding

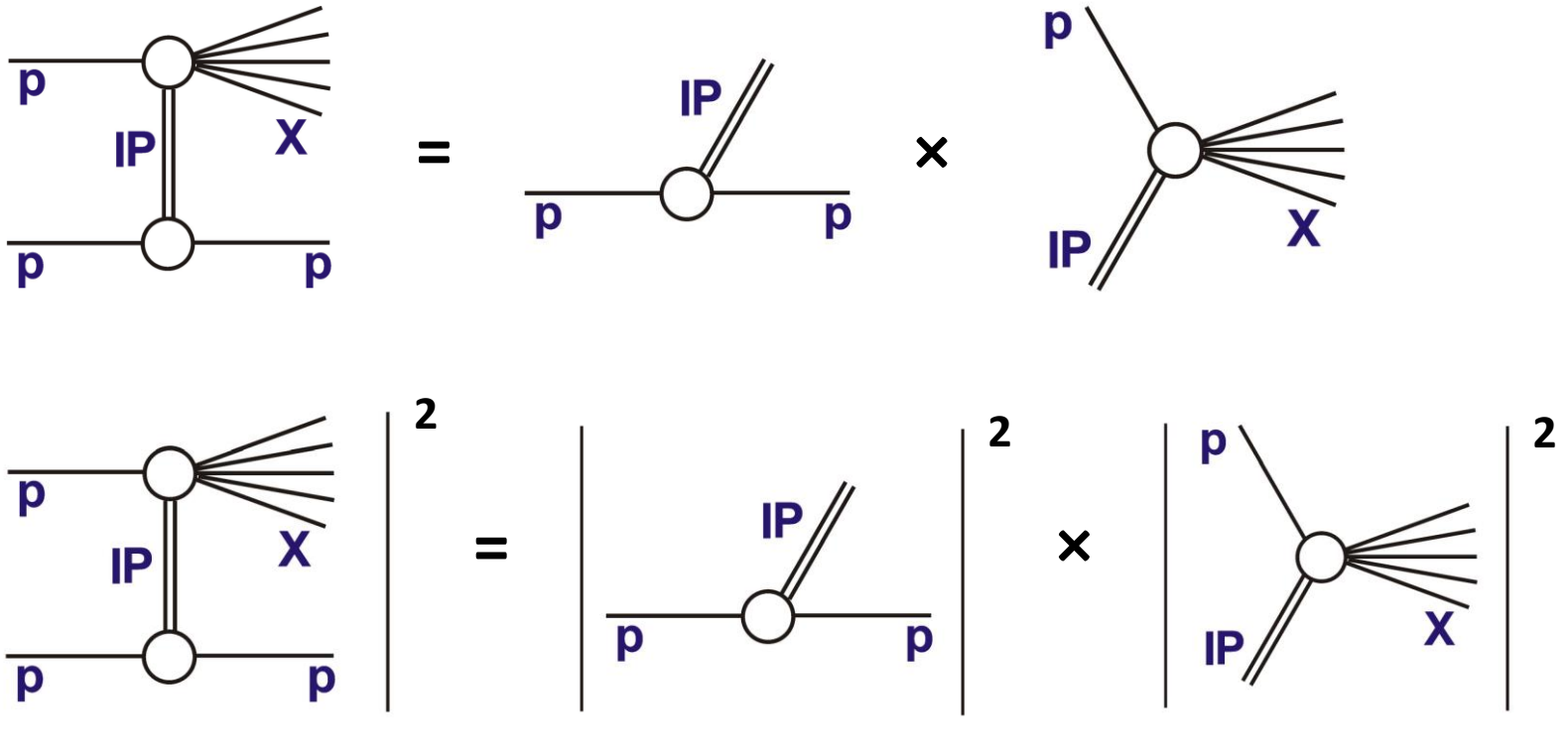


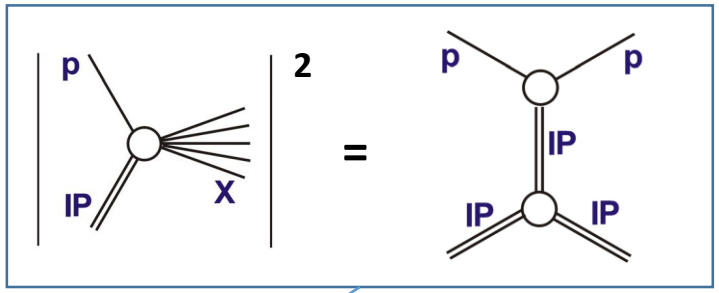


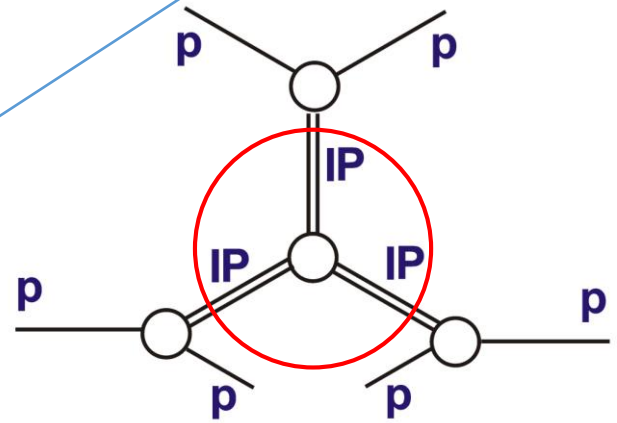


- overlay background dominates in many bins
- hadronization uncertainty significant for ξ
- unfolding and CD normalization also important in some regions

interpretation of results in terms of Regge theory







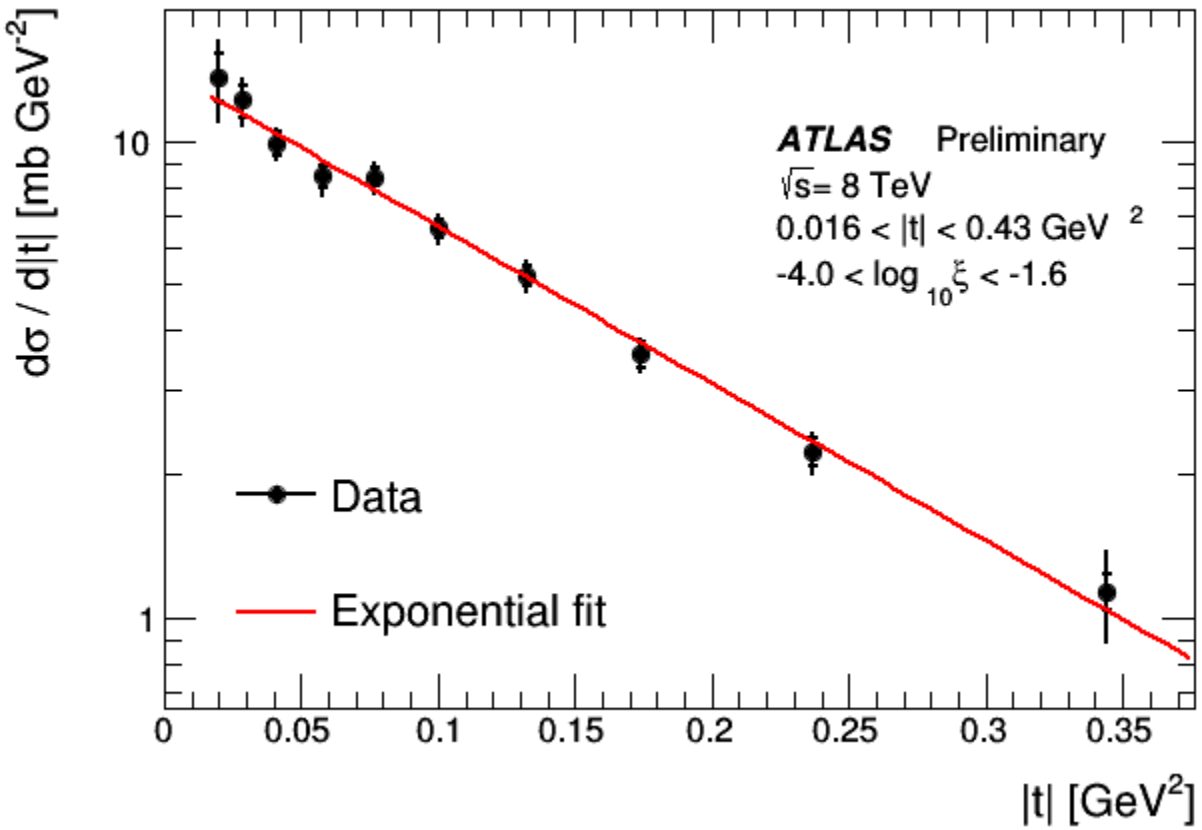
triple pomeron

for fixed **s**

$$\frac{d\sigma_{SD}}{dt\,d\xi} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} \qquad e^{Bt};\ \alpha(t) = \alpha(0) + \alpha' \cdot t$$ – **pomeron Regge trajectory**

for a detailed description see e.g. K. Goulianos and J. Montanha
PHYSICAL REVIEW D 59 114017

differential cross section as function of t



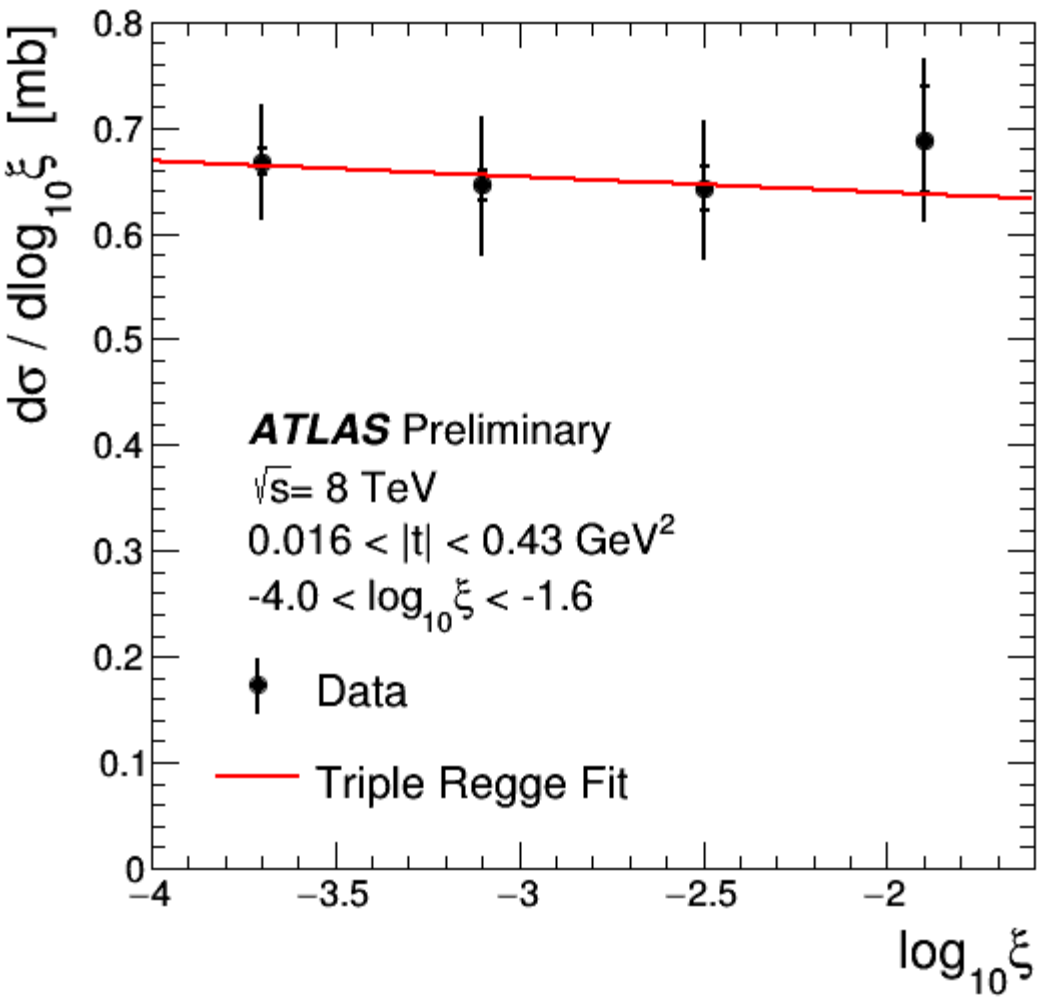
- data corrected using Bayesian unfolding
- expected fit in exponential form

$$d\sigma_{SD}/dt \propto e^{Bt}$$

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

- the largest contribution to the uncertainty on B arises from the overlay background subtraction
- cf. **$B_{\text{PYTHIA 8 A3}}$ = 7.10 GeV^{-2}, $B_{\text{PYTHIA 8 A2}}$ = 7.82 GeV^{-2}**
- in line with expectations; high precision

differential cross section as function of ξ



- data corrected using Bayesian unfolding
- expected behaviour of differential cross section

$$d\sigma_{SD}/d\xi \propto \int_{t_{min}}^{t_{max}} \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{Bt}\, dt$$

t_{min}, t_{max} – fiducial region

- fit gives

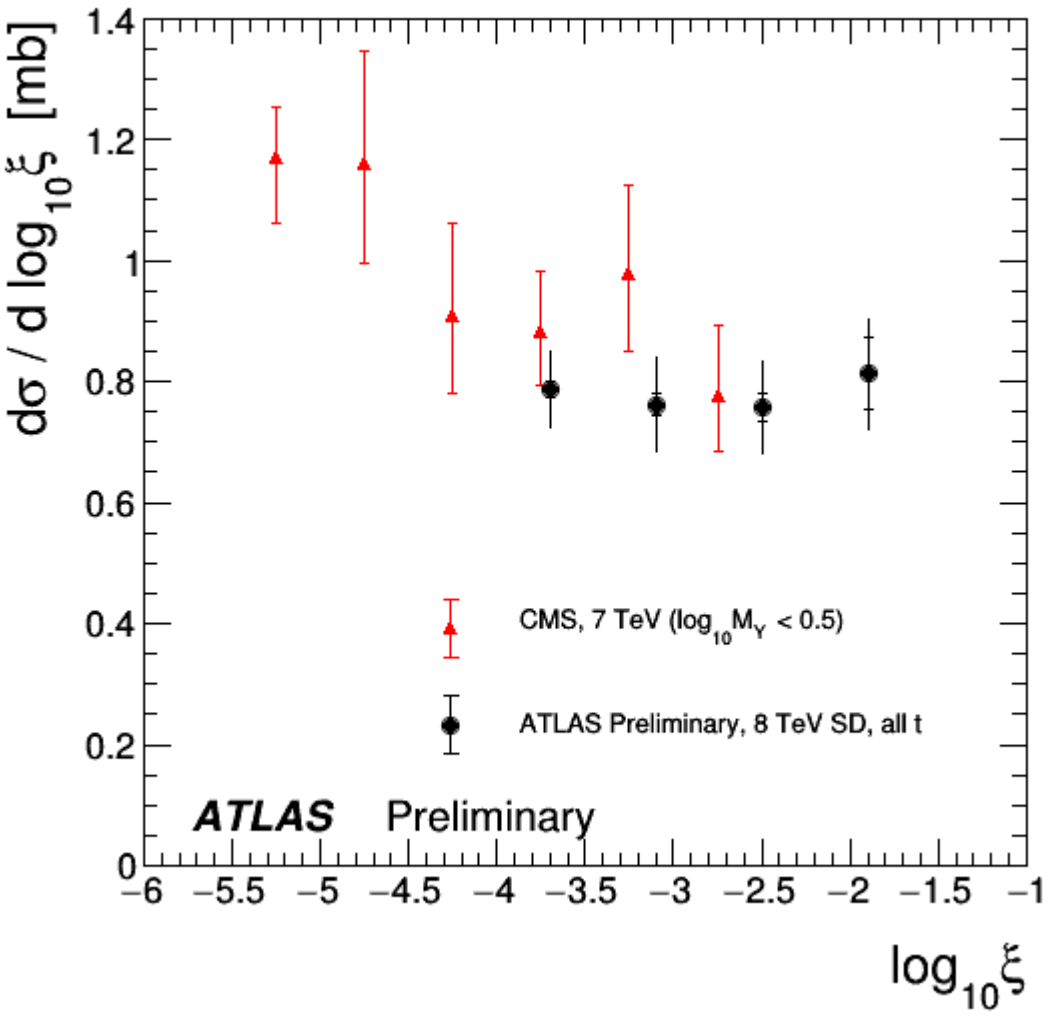
$\alpha(0) = 1.07 \pm 0.02$ (stat.) ± 0.06 (syst.) ± 0.06 (α')

- **triple Pomeron model** form

$$d\sigma_{SD}/d\xi \propto (1/\xi)^{\alpha(0)-1}$$

- dominant uncertainty comes from $\alpha' = 0.25 \pm 0.25$ GeV^{-2} in fit
- unfolding, hadronization & overlay background systematics also significant
- cf. **$\alpha(0)_{\text{PYTHIA 8 A3}} = 1.14$, $\alpha(0)_{\text{PYTHIA 8 A2}} = 1.00$**

ATLAS – CMS comparison of $d\sigma_{SD}/d\log_{10}\xi$

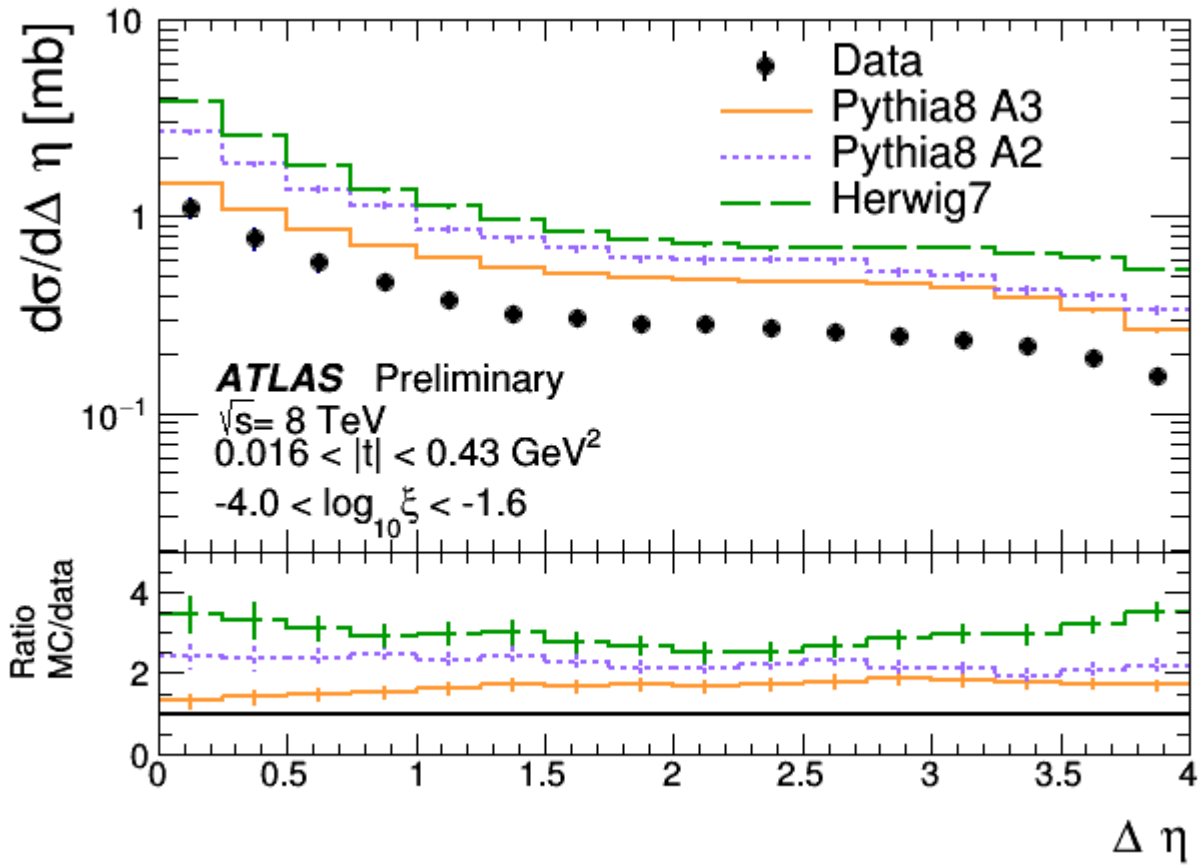


ATLAS data (at **8** TeV) extrapolated to full ***t***-range using the ***t***-slope measured in **this analysis**

CMS data (at **7** TeV) rapidity gap analysis using CASTOR as a veto, some contamination from DD, assumed to be small
Phys. Rev. D92 (2015) 012003

- good agreement in overlapping ξ-range
- complementary ξ ranges

differential cross section as function of $\Delta\eta$



- data corrected using Bayesian unfolding
- gap defined by particles with $p_T > 200$ MeV & $|\eta| < 2.5$
- diffractive plateau visible ($\Delta\eta \sim -\ln \xi$)
- shape at low gaps due to stacking up of high ξ events with small gaps beyond acceptance
- shape at high gaps due to edge of ξ

all MC generator tunes predict larger cross sections than data, Pythia8 A3 ~ 1.5x, Pythia8 A2 ~ 2.3x, Herwig7 ~3x

integrated cross section, data and data-MC comparison

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

$$\sigma_{SD}^{\text{fiducial}(\xi,t)} = 1.59 \pm 0.03\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{mb}$$

- extrapolating to the full ***t*** range assuming the measured slope parameter ***B*** leads to a cross section

$$\sigma_{SD}^{\text{fiducial}(\xi)} = 1.88 \pm 0.15\ \text{mb}$$

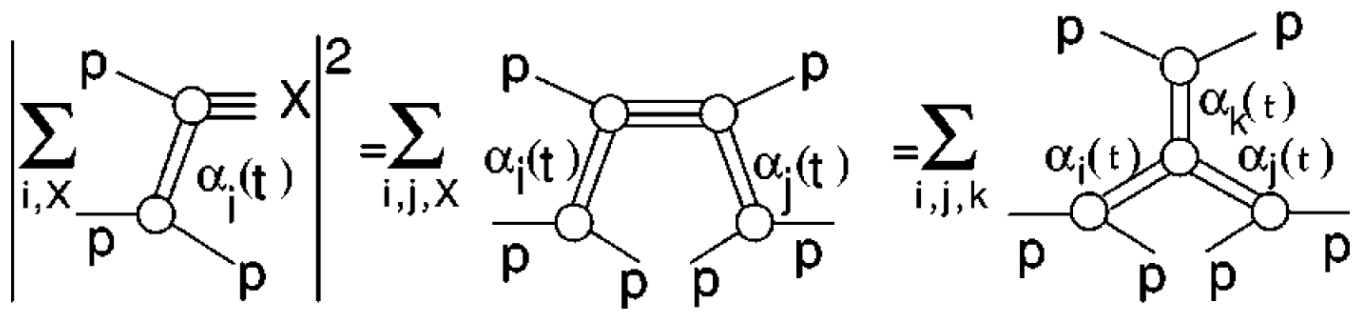
- data vs MC comparison

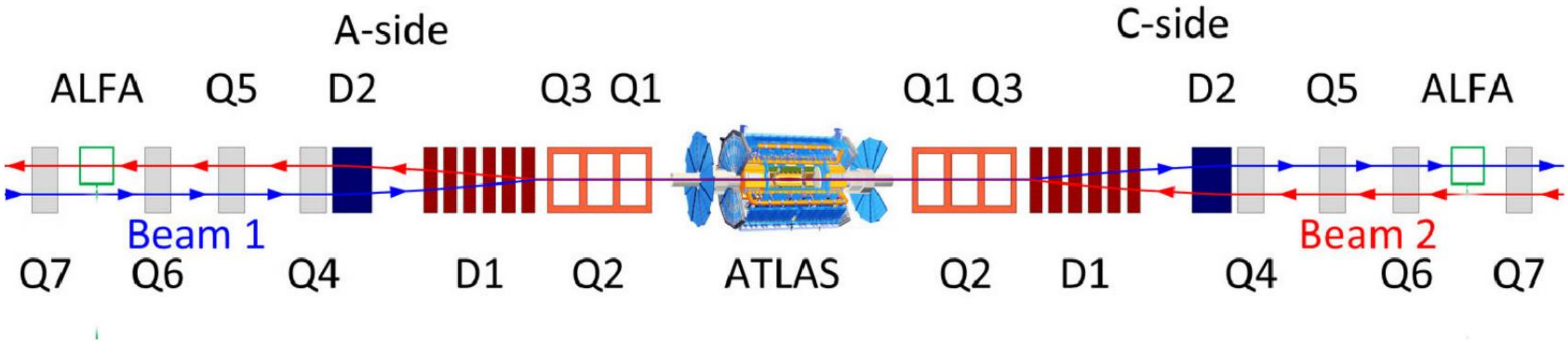
Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t-\text{extrap}}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
PYTHIA8 A2 (Schüler-Sjostrand)	3.69	4.35
PYTHIA8 A3 (Donnachie-Landshoff)	2.52	2.98
HERWIG7	4.96	6.11

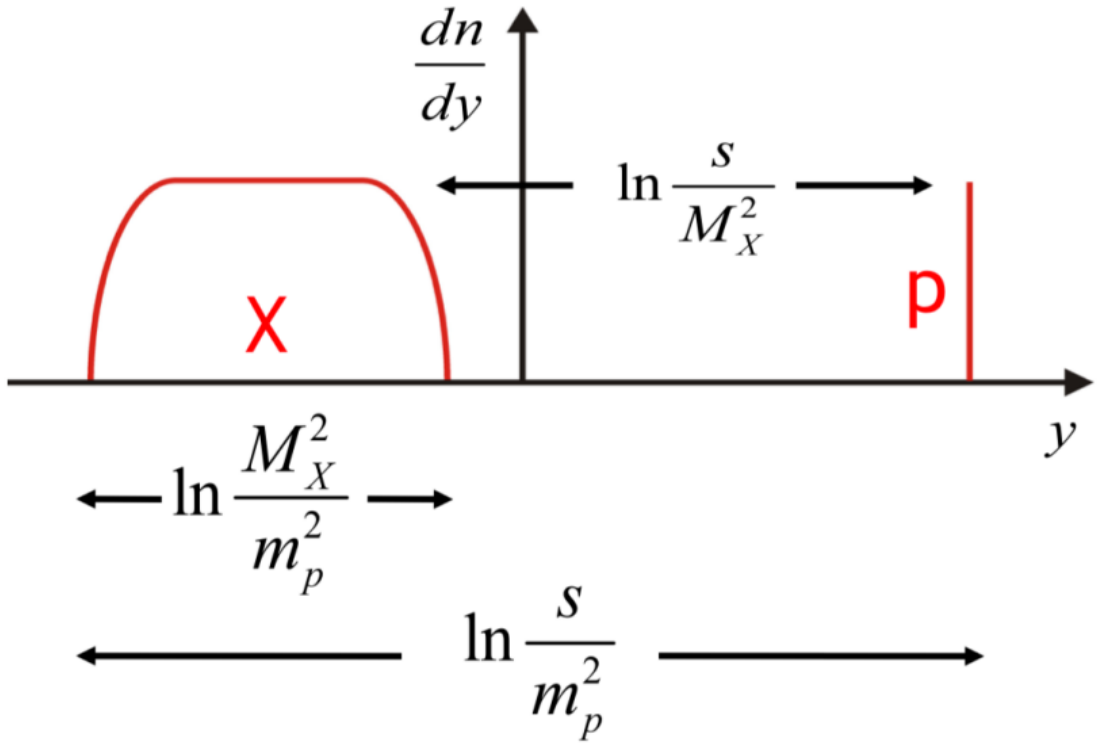
summary

- **ATLAS** performed a measurement of the inclusive single diffractive dissociation process **p + p → X + p at √ s = 8 TeV** using **proton tagging**
- for the first time at LHC the final state protons in **SD** measurement are directly reconstructed, greatly reducing backgrounds from ND and DD compared to previous LHC analyses based on rapidity gaps
- differential cross sections are measured as a function of t, ξ and the visible gap size $\Delta\eta$
- normalization of all MC generators (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 ± 0.23 (stat.) ± 0.22 (syst.) GeV^{-2}
  - from a fit to ξ distribution the measured
    α(0) = 1.07 ± 0.02 (stat.) ± 0.06 (syst.) ± 0.06 (α')
- good agreement in the overlap ξ region with the CMS results
- details available in **ATLAS-CONF-2019-012**

backup


$\left|\sum_{i,X}\right|^2 = \sum_{i,j,X} = \sum_{i,j,k}$
p
X
$\alpha_i(t)$
$\alpha_j(t)$
$\alpha_k(t)$


A-side
C-side
ALFA
Q5
D2
Q3
Q1
Q1
Q3
D2
Q5
ALFA
Beam 1
Beam 2
Q7
Q6
Q4
D1
Q2
ATLAS
Q2
D1
Q4
Q6
Q7


$\frac{dn}{dy}$
$\ln\frac{s}{M_X^2}$
X
p
y
$\ln\frac{M_X^2}{m_p^2}$
$\ln\frac{s}{m_p^2}$

systematics uncertainty sources

- overlay background subtraction (from control region)
- unfolding (residual non-closure when taking PYTHIA8 after reweight to match data, unfolded using un-reweighted MC)
- hadronization uncertainty (PYTHIA8 vs HERWIG7)
- CD background shape (reweight or not) and normalization (cf. CDF data)
- ALFA alignment and reconstruction (follows elastics methods)
- luminosity (1.5%)
- MBTS thresholds (vary threshold)
- ID track reconstruction (follow n_{ch} analysis methods)
- trigger efficiencies (vary reference sample)

integrated cross section, data and data-MC comparison

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

$$\sigma_{SD}^{\text{fiducial}(\xi,t)} = 1.59 \pm 0.03\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{mb}$$

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

$$\sigma_{SD}^{\text{fiducial}(\xi)} = 1.88 \pm 0.15\ \text{mb}$$

- data lies between PYTHIA 8 A2 and PYTHIA 8 A3 → extrapolation to the full t and full ξ ranges done by scaling data by averaged extrapolation factors from A2 and A3 in the measured range

$$\sigma_{SD}^{\text{extrap}} \sim 6.6\ \text{mb}$$ uncertainties are deemed inestimable due to very poorly constrained low and high ξ behaviour

- data vs MC comparison

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