Differential Cross Sections for Single Diffractive Dissociation using ALFA

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on behalf of the ATLAS Collaboration

ATLAS Paper
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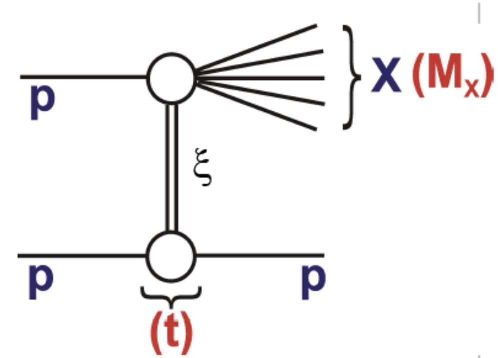
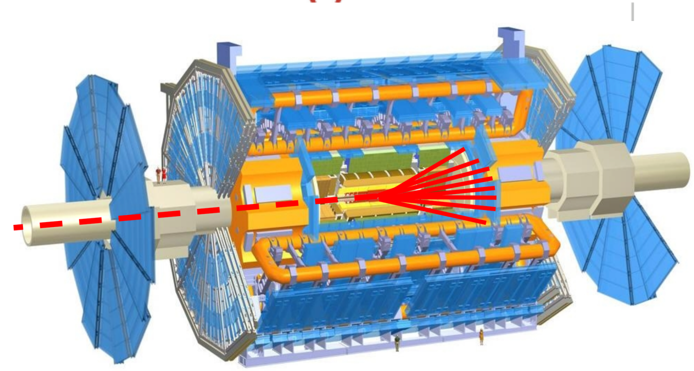
Measurement of Differential Cross Sections for Single Diffractive Dissociation in $\sqrt{s} = 8$ TeV pp collisions using the ATLAS ALFA Spectrometer

The ATLAS Collaboration

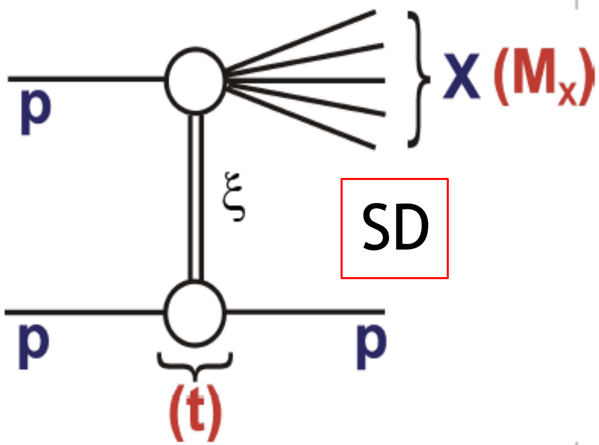
A dedicated sample of Large Hadron Collider proton-proton (pp) collision data at centre-of-mass energy $\sqrt{s} = 8$ TeV is used to study inclusive single diffractive dissociation, $pp \to Xp$. The intact final state proton is reconstructed in the ATLAS ALFA forward spectrometer, while charged particles from the dissociated system X are measured in the central detector components. Cross sections are measured differentially as functions of the proton fractional energy loss ξ, the four momentum transfer squared t, and $\Delta\eta$, a variable that characterises the rapidity gap separating the proton and the system X. The data are consistent with an exponential t dependence, $\mathrm{d}\sigma/\mathrm{d}t \propto e^{Bt}$ with slope parameter $B = 7.60 \pm 0.32$ GeV^{-2}. Interpreted in the framework of Regge phenomenology, the ξ dependence leads to a Pomeron intercept of $\alpha(0) = 1.07 \pm 0.09$.



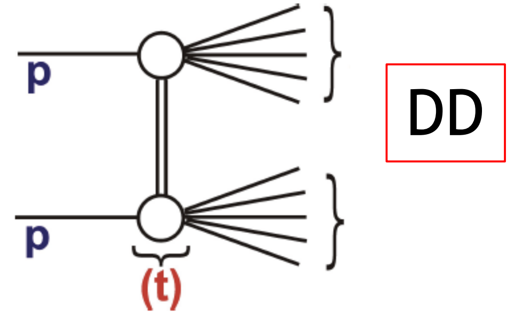


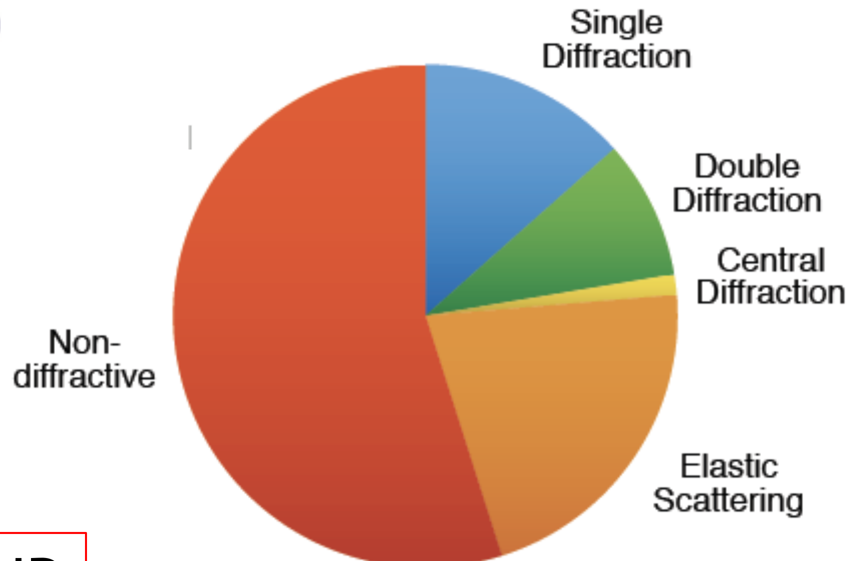
Workshop on Forward Physics & Diffraction at the LHC
UC Dublin, 10-13 June 2019

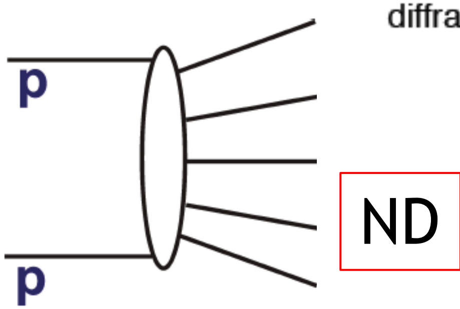
Orientation: Processes

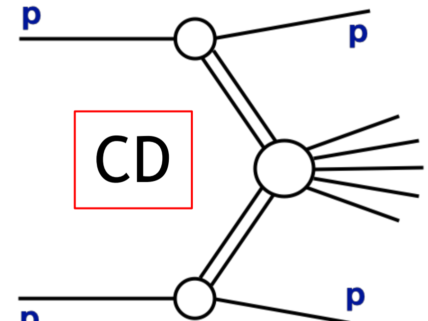


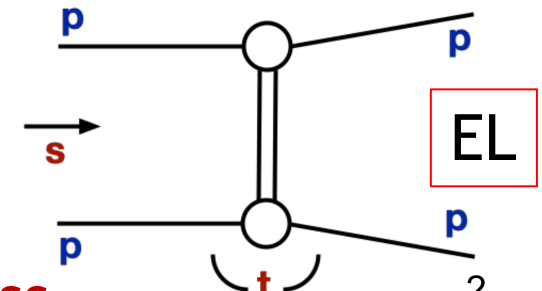
Decomposing the total cross section …







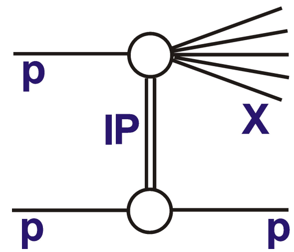




- Previously published inclusive LHC p-tagged data restricted to the elastic process

`Standard' Model of SD Cross Sections

1) Factorise SD into pomeron (IP) flux and total p+IP cross section



$$\xi = {M_X^2}/{s}$$

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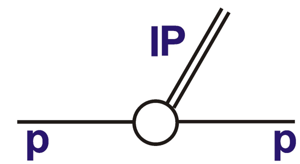

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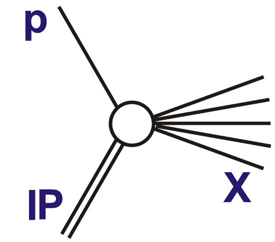
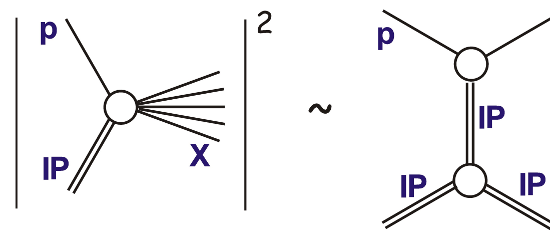
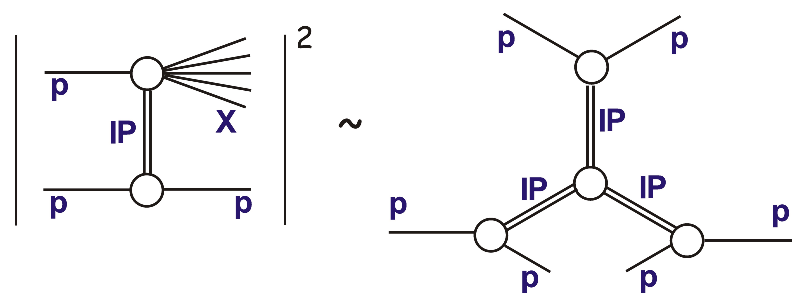


$$f_{IP/p}(\xi, t) \qquad \sigma_{tot}(IP + p \rightarrow X)$$

2) Relate total p+IP cross section to forward elastic amplitude via optical theorem



3) Calculate SD cross sections from triple pomeron amplitudes:

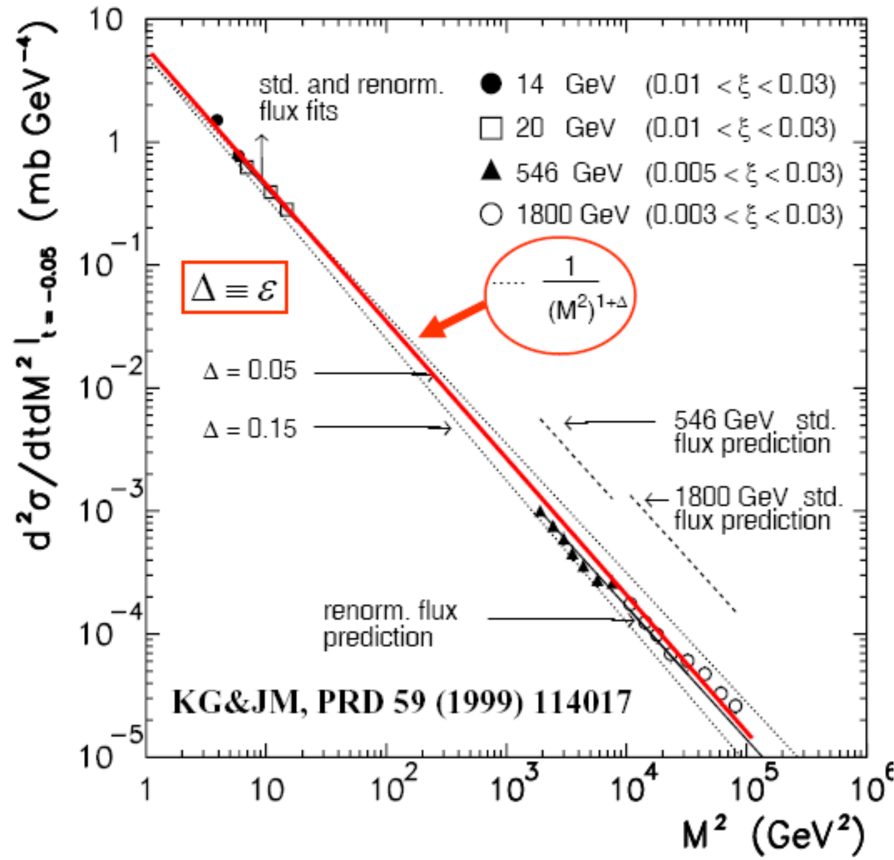


At fixed s: $$\boxed{\frac{d^2\sigma}{d\xi dt} \propto \left(\frac{1}{\xi}\right)^{2\alpha(t)-\alpha(0)} e^{B_0 t}}$$

… where the pomeron trajectory is $\alpha(t) = \alpha(0) + \alpha' t$

Note: PYTHIA default non-standard.
$\alpha(0) = 1$, const $\sigma(IP + p)$

Pre-LHC Data and Expectations



<u>Crudely, expect SD cross section:</u>

- scales with s at fixed Mx, t

- ~ $1/M_x^2$ at fixed s and t

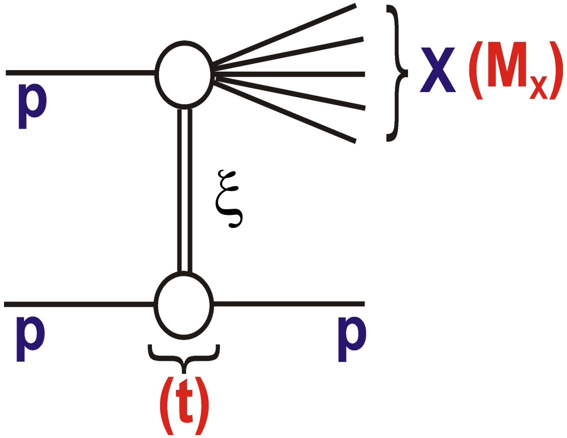
- ~ e^{bt} with b ~ 8 GeV^{-2} at fixed s and M_x

<u>More precisely:</u>

α(t) has been determined from many total, elastic and dissociation measurements at ISR, SPS, Tevatron, HERA … Small deviations from these scaling rules

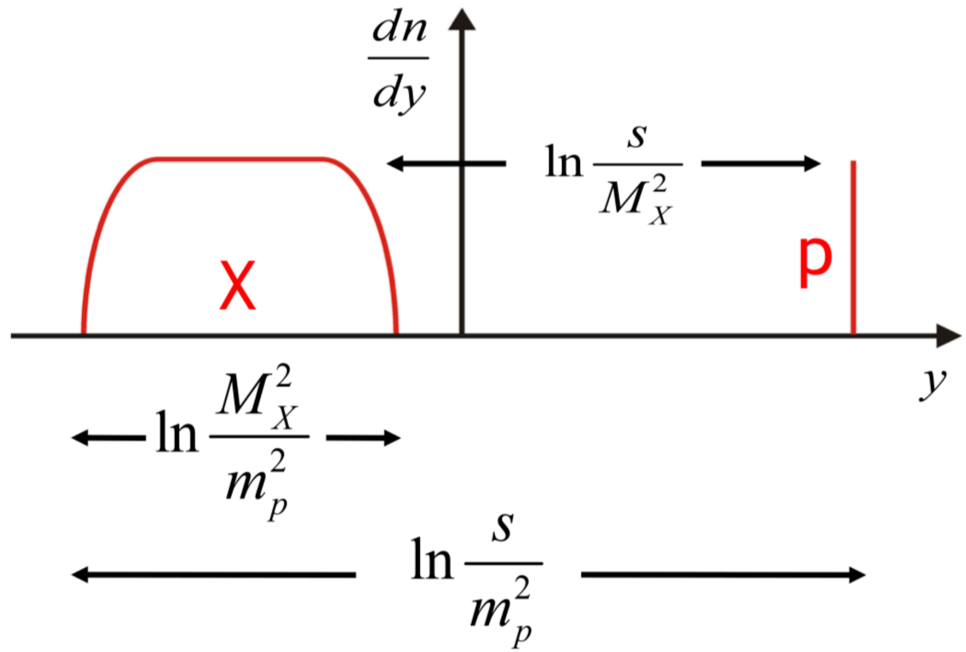
Lots of freedom for deviation from triple pomeron behavior (sub-leading terms, multiple exchanges / 'screening')

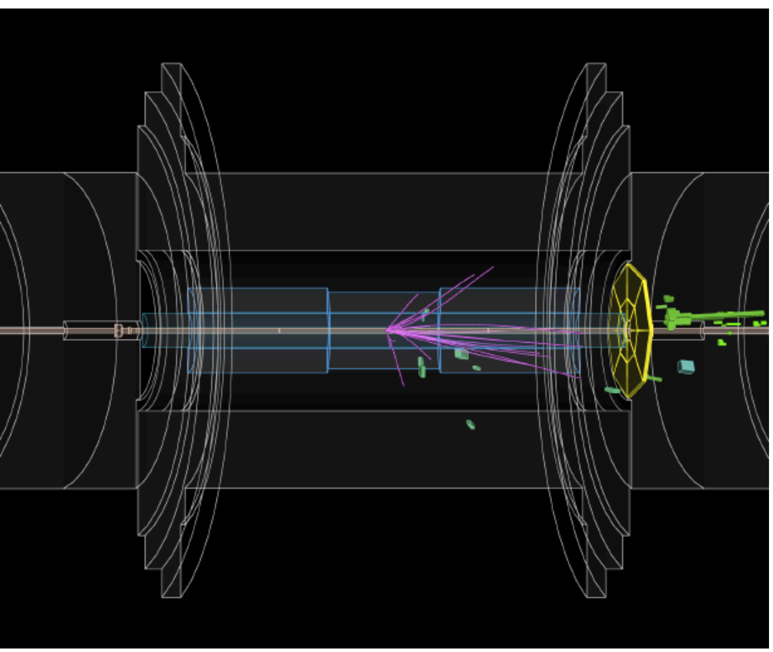
Relation to Rapidity Gaps



$$\Delta\eta \approx -\ln\xi$$

(Correlation limited by hadronisation fluctuations)



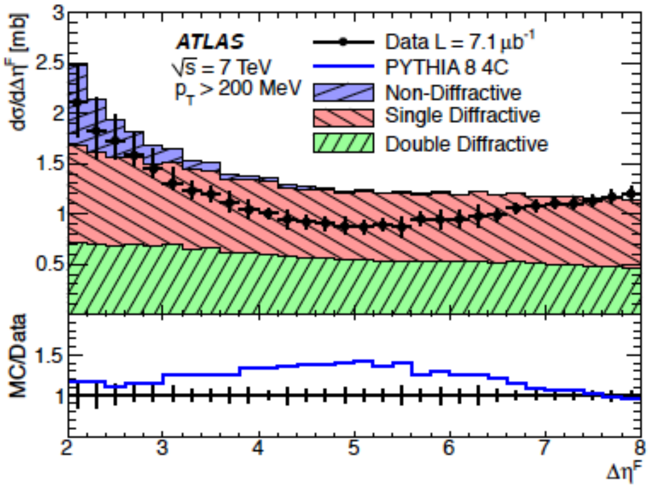


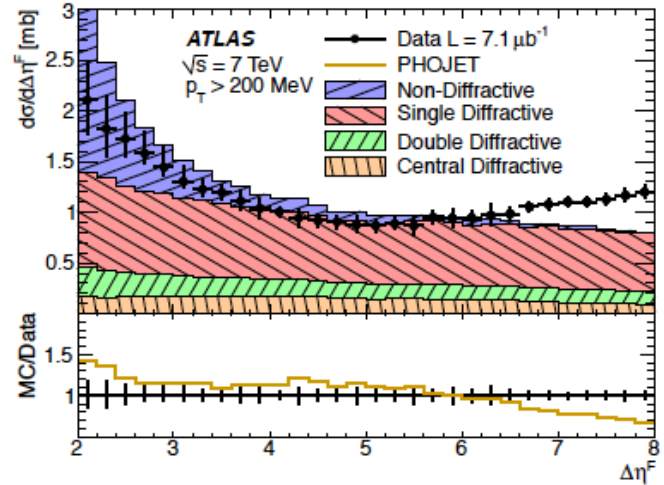
Example Large Rapidity Gap event in ATLAS

Gap size (extending to $\eta \sim 1$) implies $\xi \sim 10^{-4}$

Previous ATLAS Data / Motivation

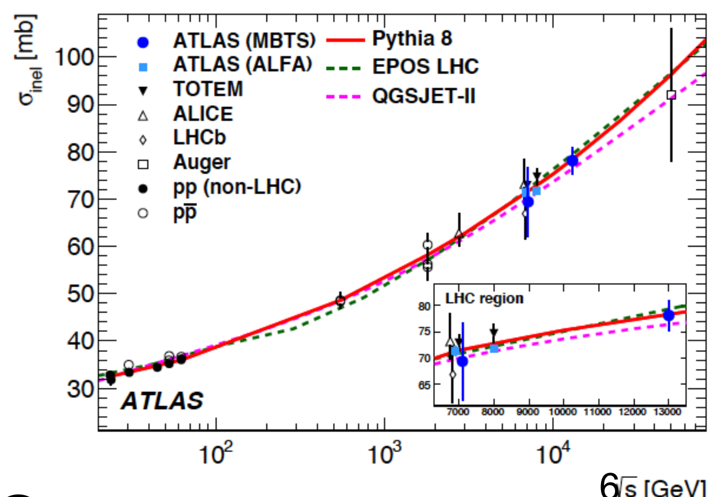
Inclusive Rapidity Gap spectra



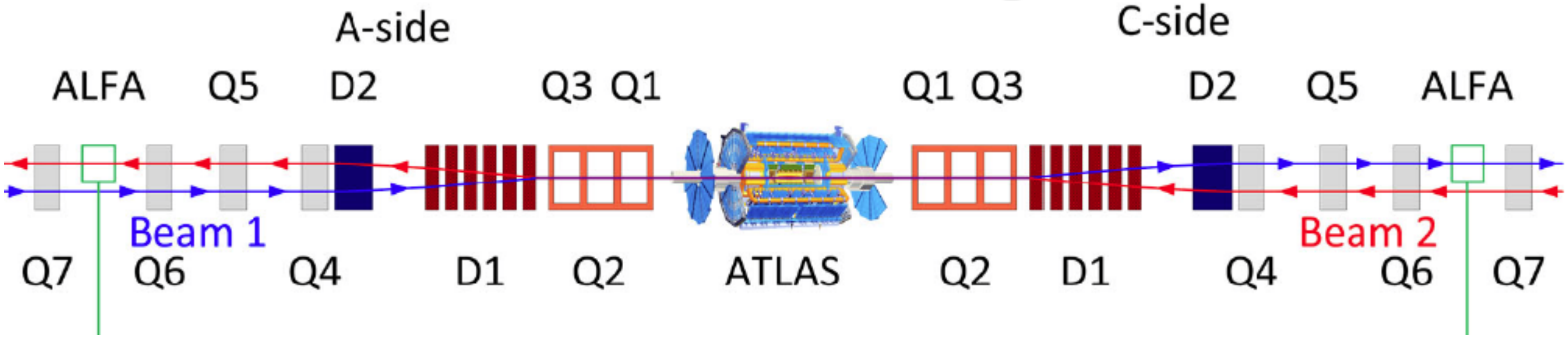


- Previous ATLAS constraints on SD come from large rapidity gap measurement (protons not tagged) … Large ambiguities - ND, DD

- **More motivations for better data:**
  - Precision on σ_{inel} (limited by low ξ extrapolation)
  - Pile-up modelling
  - Cosmic ray air showers
  - Confinement
  - String theory duality (AdS/CFT) ☺

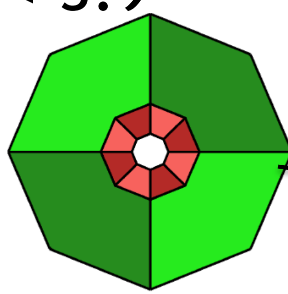


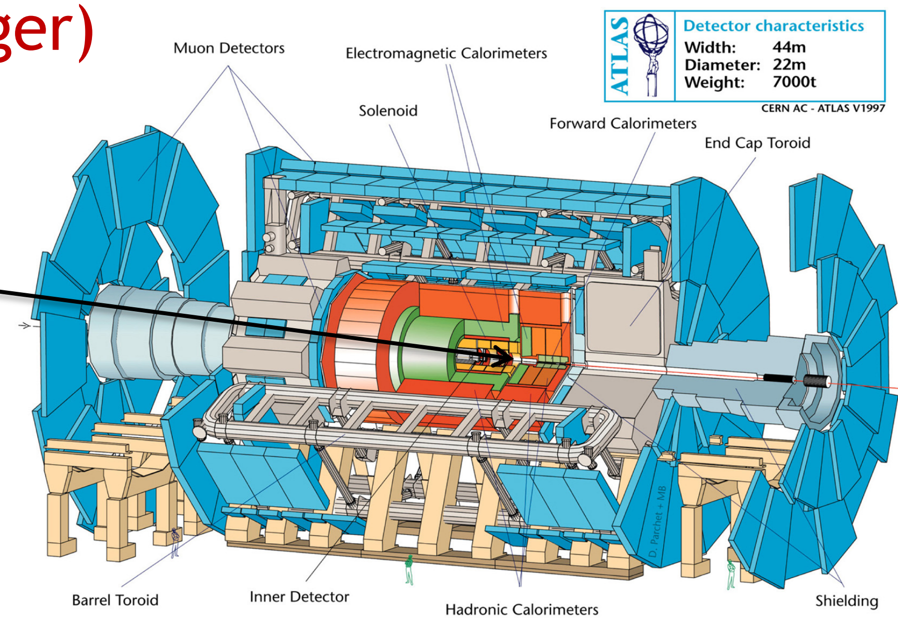
Detector Components



1) Directly tag outgoing proton in ALFA Roman pot spectrometer [4 stations at ~240m from interaction point].

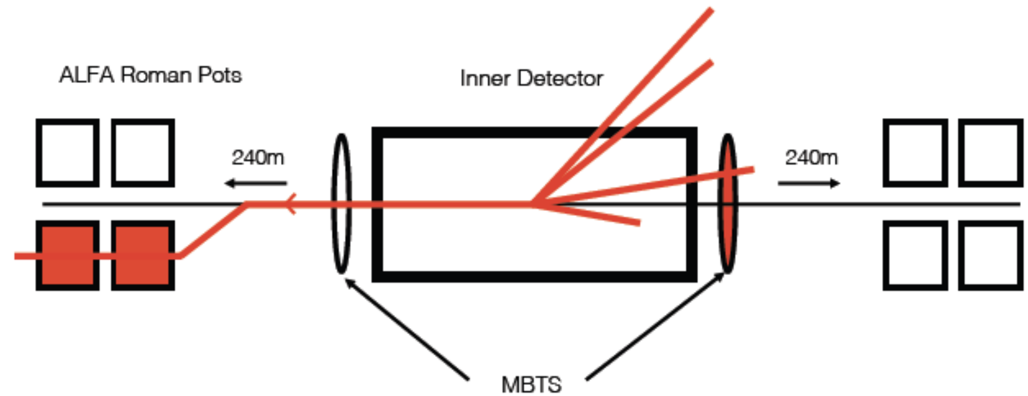
2) Dissociating proton yields charged particles in the Minimum Bias Trigger Scintillator (MBTS trigger)
$z = \pm\ 3.6\text{m},\ 2.1 < |\eta| < 3.9$





3) Charged particles measured precisely in inner tracking detector (ID) $|\eta| < 2.5$

Summary of Measurement Conditions

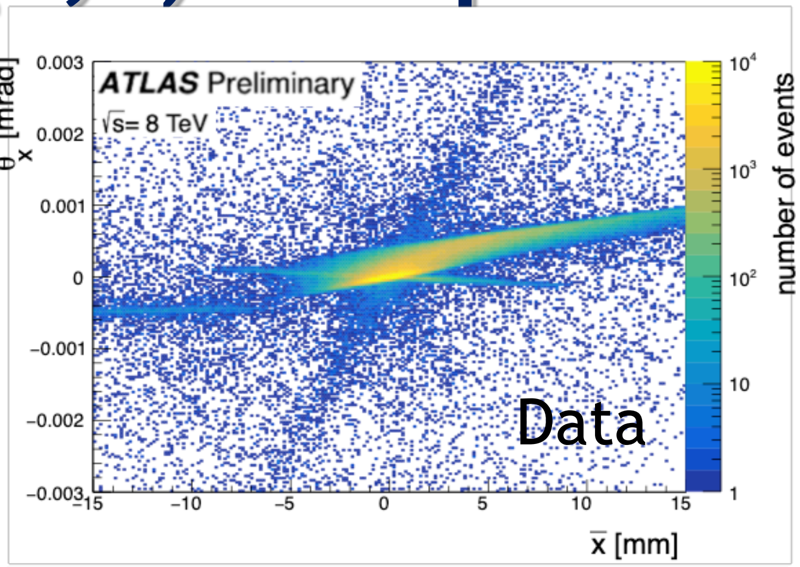


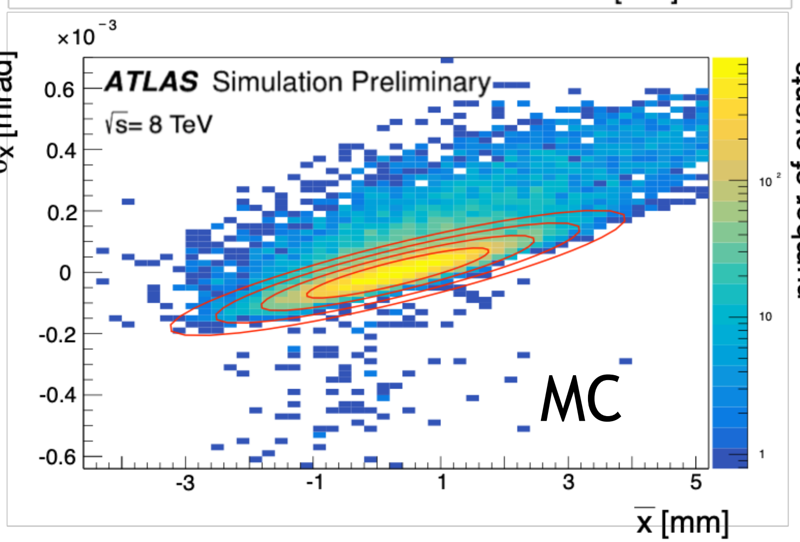
- Data from low lumi and pile-up run ($\mu = 0.08$, $\beta^* = 90$m … same as used in 8TeV ALFA elastic / total cross-section)
- Main MC sample PYTHIA8 A3 tune (DL flux - $\alpha(0) = 1.08$) PYTHIA8 A2 (S&S flux - $\alpha(0) = 1$) and HERWIG7 also considered

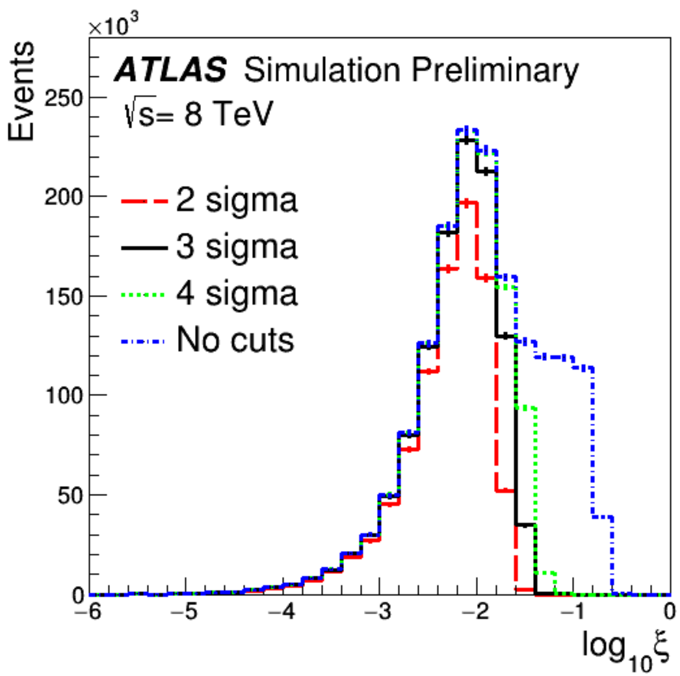
- Trigger: ALFA and MBTS signals on opposite sides of the IP
- ALFA Selection: Exactly one reconstructed proton with additional off-line selection for SD events (next slide)
- MBTS: At least 5 counters above noise threshold
- Inner Detector: $\geq$ 1 track with $p_T > 200$ MeV
- Reconstructed vertex

Final ALFA Selection: Mean x position v θ(x,z) of 2 pots

- SD events lie close to (0,0)
- Accept events within 3σ ellipse based on fit to SD MC
- Restricts analysis to $\xi \lesssim 0.03$







Variables Studied

- Four-momentum transfer squared t

- Reconstructed from $t = -p_T^2$ of proton in ALFA

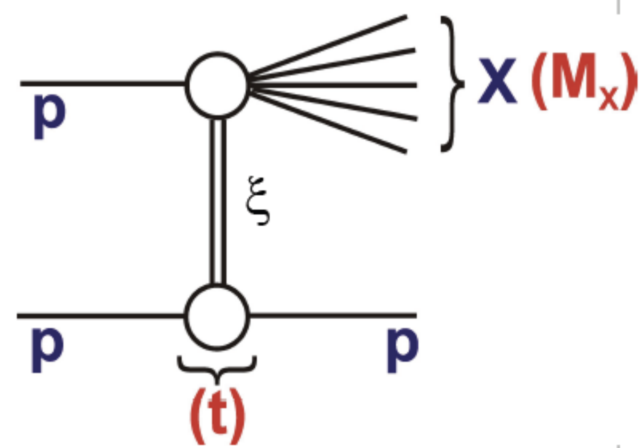
- Fractional proton energy loss, ξ

$$\xi = {}^{M_X^2}/_{s} = 1 - {}^{E_p'}/_{E_p} \ldots$$

- Reconstructed from ID tracks in approximation

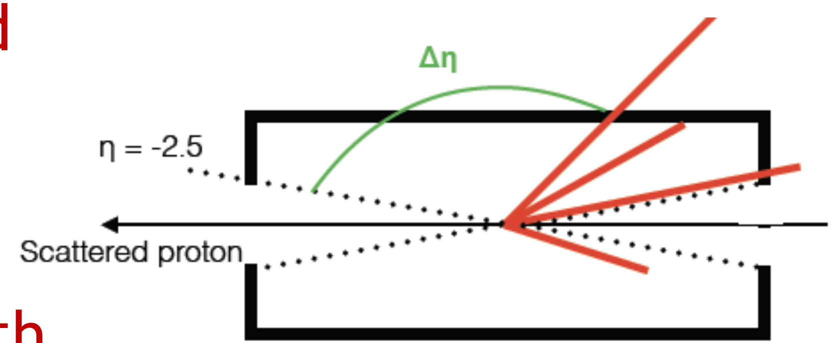
$$\xi^{\pm}_{EP_z} = \frac{\Sigma_i(E_i \mp p_{z,i})}{\sqrt{s}}$$

- Cross checked using reconstructed proton in ALFA



- (Visible) size of rapidity gap $\Delta\eta$

… between tracker edge on side with proton ($\eta = \pm 2.5$) and first ID track with p_T > 200 MeV

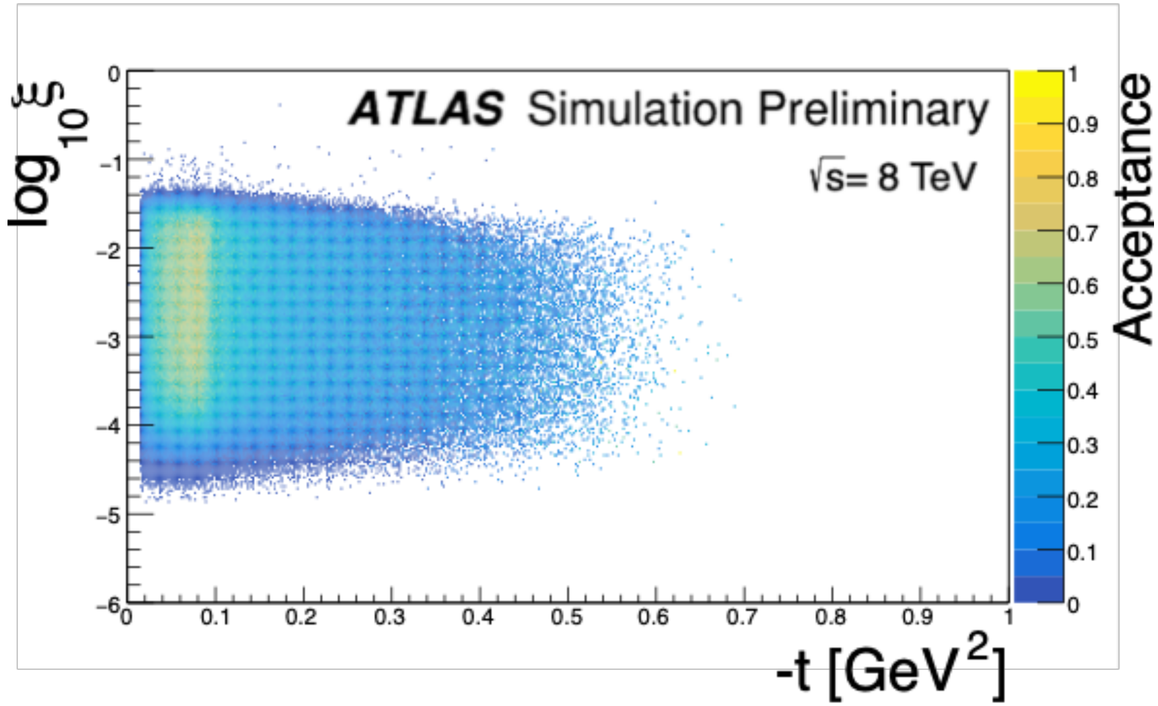


Acceptances / Fiducial Range (A3 MC)

- Lower limit in ξ determined by MBTS requirement

- Upper limit in ξ and range in t determined by ALFA acceptance

- Acceptance is a strong function of t due to ALFA geometry

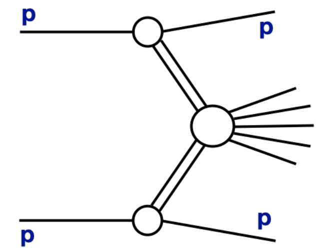


Fiducial Region of Measurement

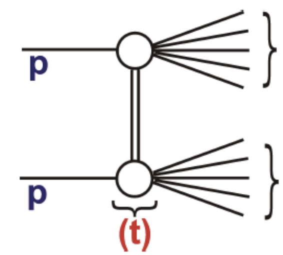
$0.016 < |t| < 0.43$ GeV^2
$-4.0 < \log_{10}(\xi) < -1.6$

$(80 < M_X < 1270$ GeV$)$

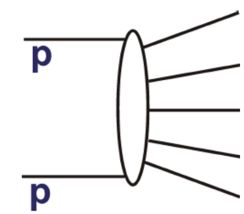
Backgrounds

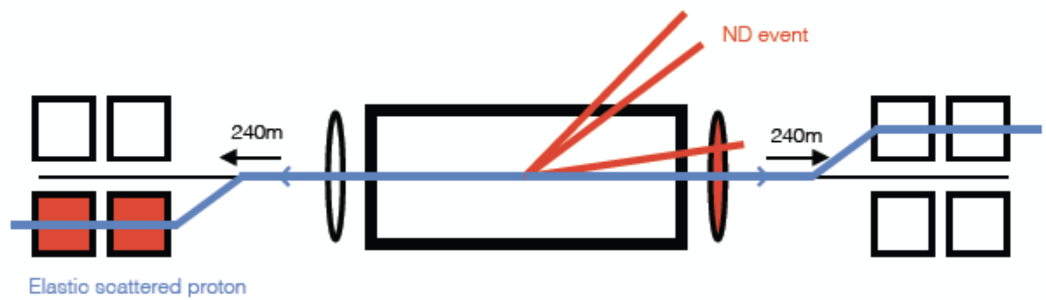


- Single source physics backgrounds are small (largest is CD, while DD, ND negligible)



- Largest background is due to uncorrelated ALFA versus ID/MBTS activity due to pile-up or beam-induced ALFA signals → `Overlay background'



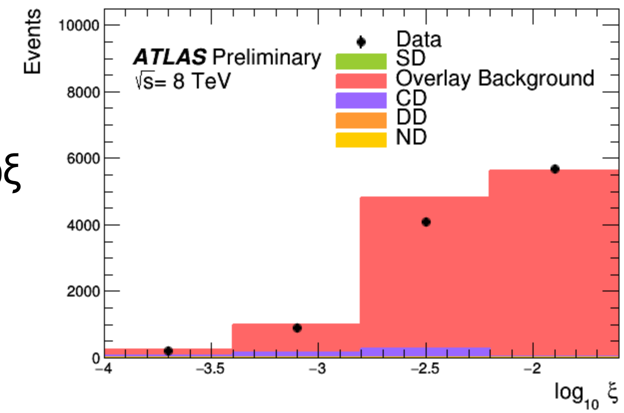


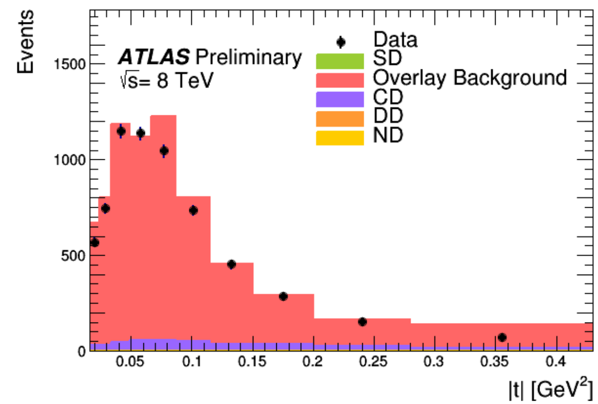
- Data-driven model of Overlay Background, assessing ALFA activity in strongly ND-enriched events (all 32 MBTS segments have signals, tracks throughout ID η range).
… 1 proton in ALFA in 0.8% of such events → Normalisation
… Shape in t from ALFA, shapes in ξ, $\Delta\eta$ from MC simulation

Control Region 1: for Overlay Background

- Same as nominal selection, except protons in exactly two ALFA armlets
  – Dominated by overlay of elastic scattering in ALFA and ND in the ID

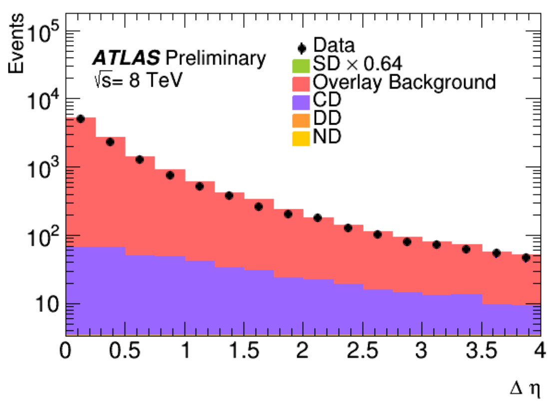
$\log_{10}\xi$

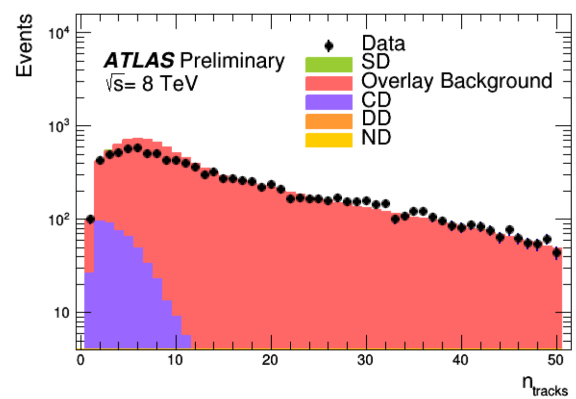




$|t|$

$\Delta\eta$





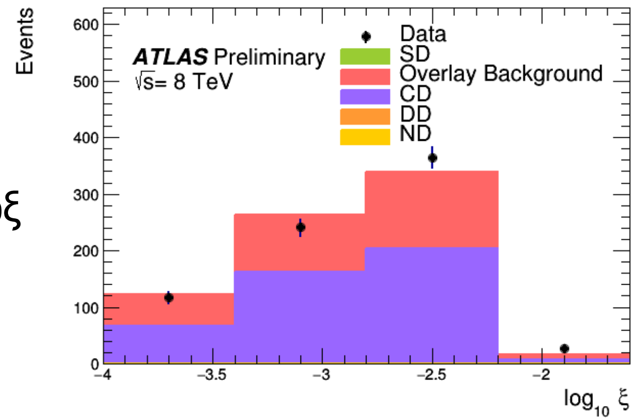
ID track multiplicity

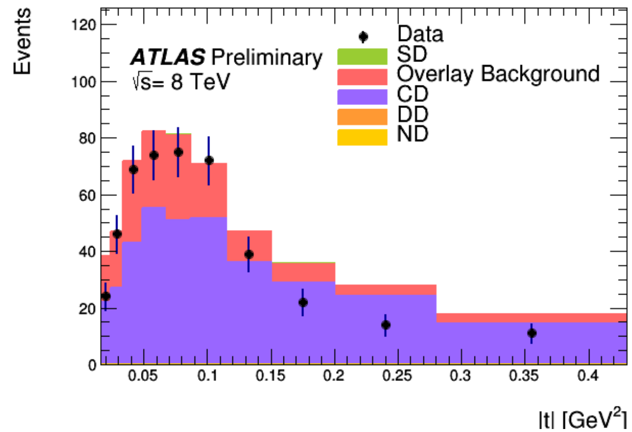
  – Good description of normalisation and shapes
  – Systematic errors obtained from residual differences between data and model in this control sample

Control Region 2: for CD Background

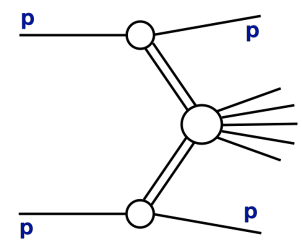
- Protons in exactly two ALFA armlets, 2 < #MBTS segments < 10

$\log_{10}\xi$

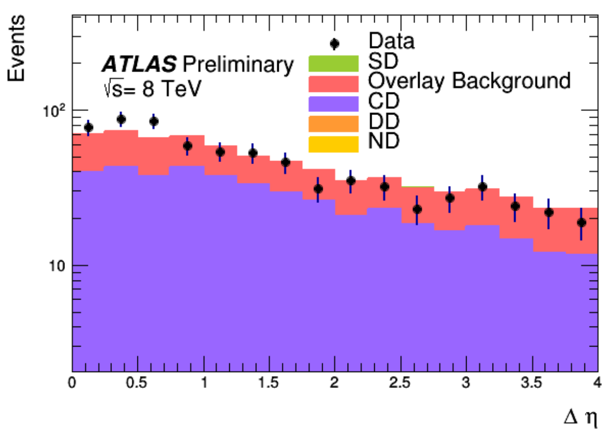


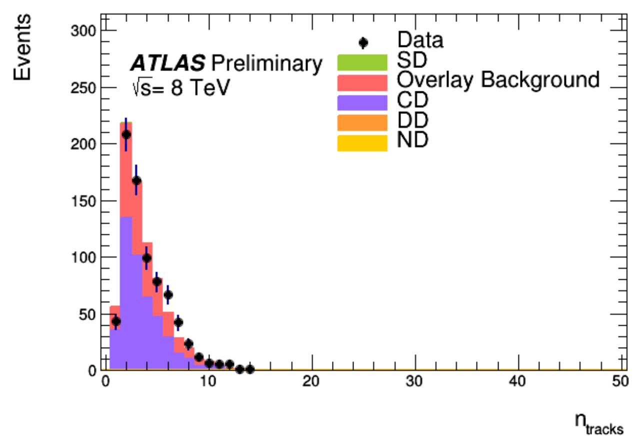


|t|



Δη

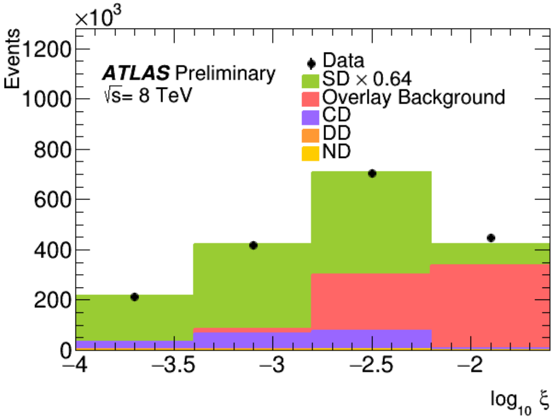


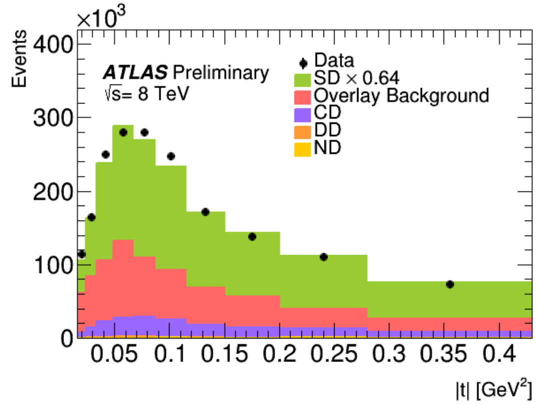


ID track multiplicity

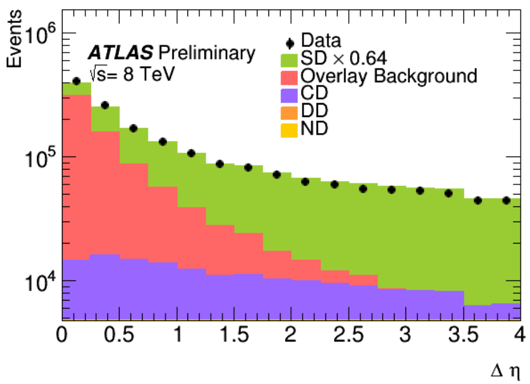
- Good description of normalisation and most shapes
- Reweight ξ to match ξ-ALFA distribution, preserving normalisation
- Systematic from either reweighting or not (& adjusting normalisation)

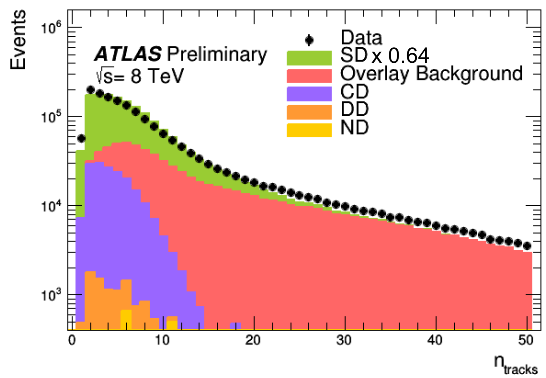
Uncorrected Distributions

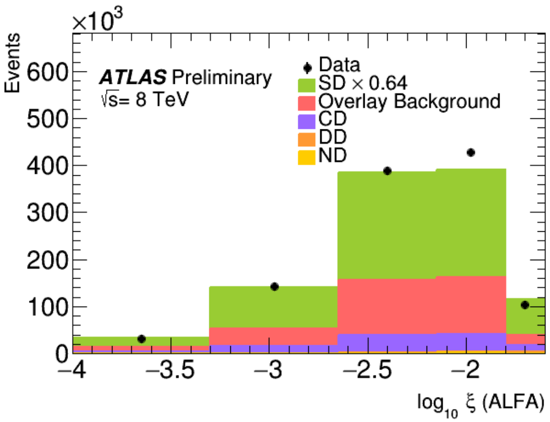




- Poor description with default PYTHIA8 SD normalisation.
- Adjust SD total cross section to the result from this measurement (factor 0.64) …

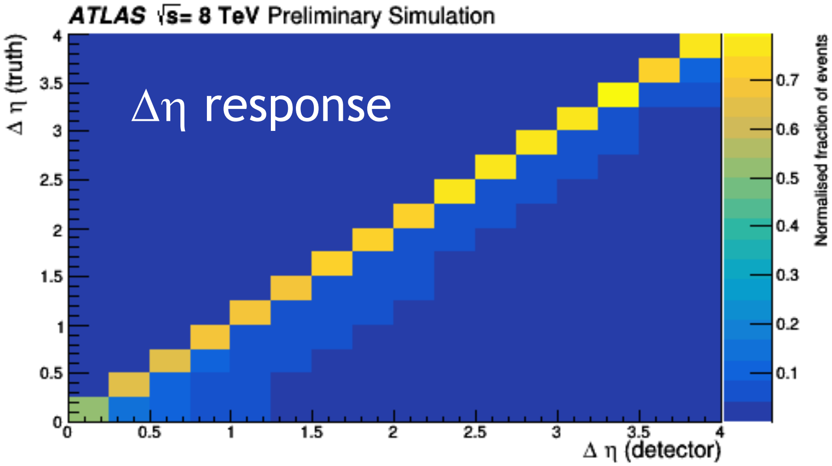


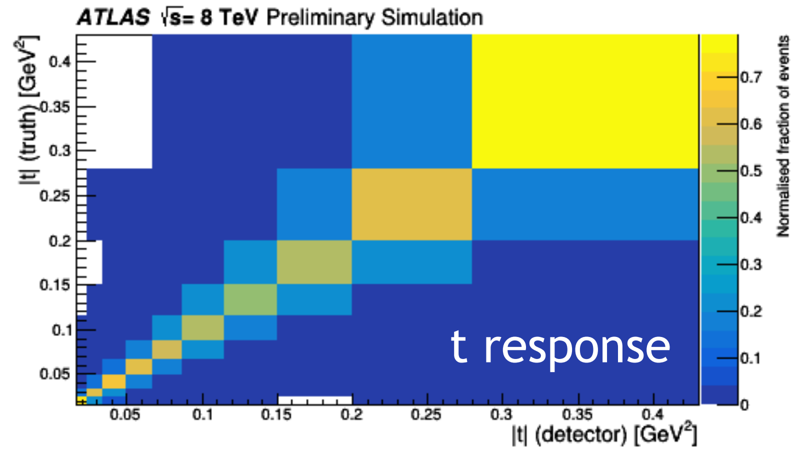




- Good desctiption of all distributions after renormalisation.
- ξ (ALFA) has very different background shapes and other systematics from ξ

Unfolding / Response Matrices

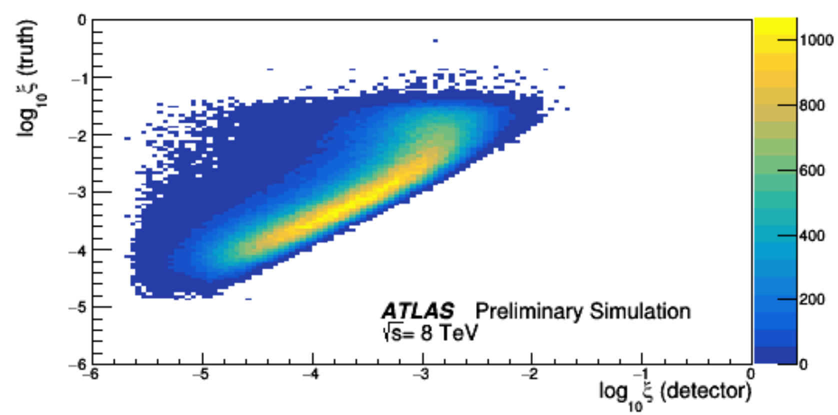




- t and $\Delta\eta$ are ~ diagonal
- ξ shows good correlation, but with shift due to missing neutrals and low pT / forward charged particles.

$$\xi^{\pm}_{EP_z} = \frac{\Sigma_i (E_i \mp p_{z,i})}{\sqrt{s}}$$

Response matrix for ξ after final linear recalibration factor



- Unfold with iterative Bayesian method (d'Agostini)

Systematic 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)

- Hadronisation uncertainty (PYTHIA8 v HERWIG7)

- CD background shape (reweight or not) and norm (cf CDF data)

- ALFA alignment and reconstruction (follow elastics methods)

- Lumi (1.5%)

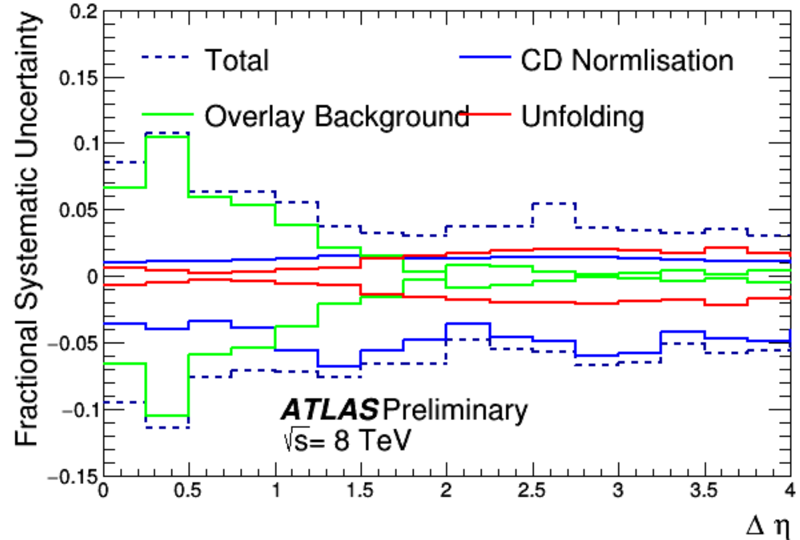
- MBTS thresholds (vary threshold)

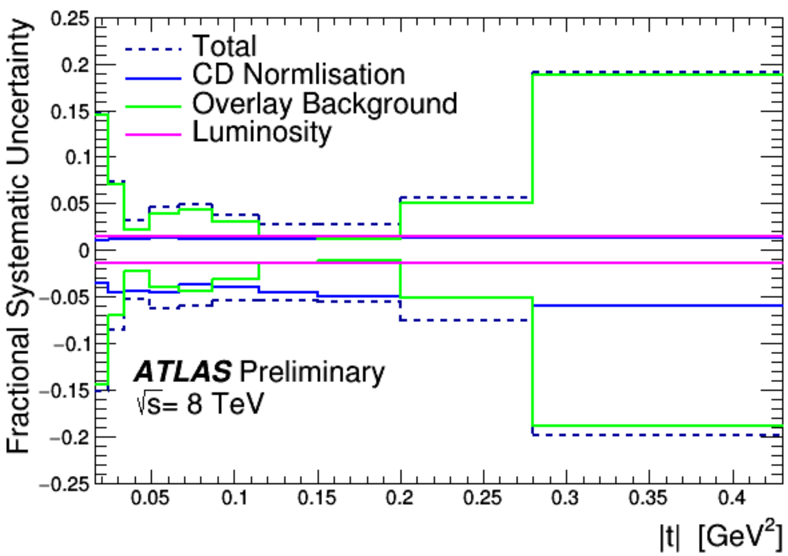
- ID track reconstruction (follow n_{ch} analysis methods)

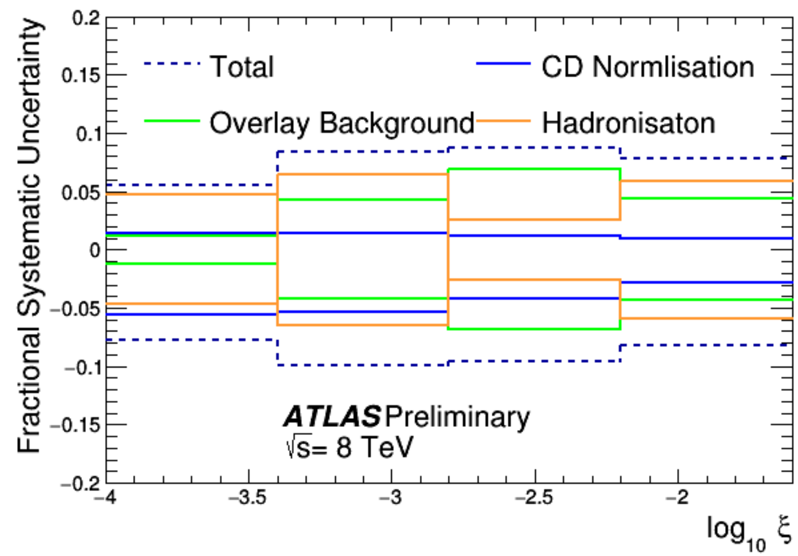
- Trigger efficiencies (vary reference sample)

Largest Uncertainties in each bin

- Overlay background dominates in many bins
- Hadronisation uncertainty significant for $\Delta\eta$
- Unfolding and CD normalisation also important in some regions







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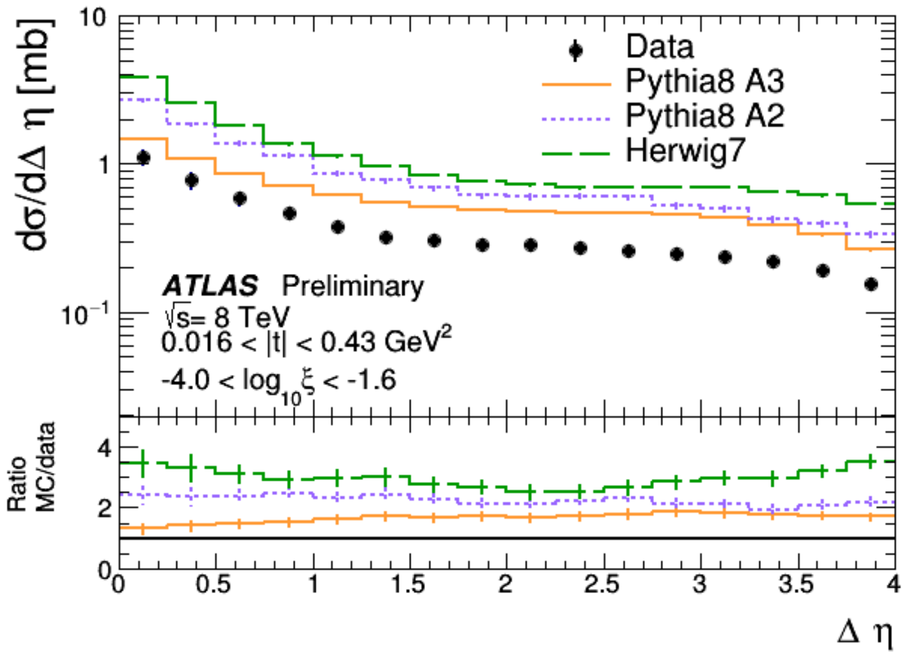
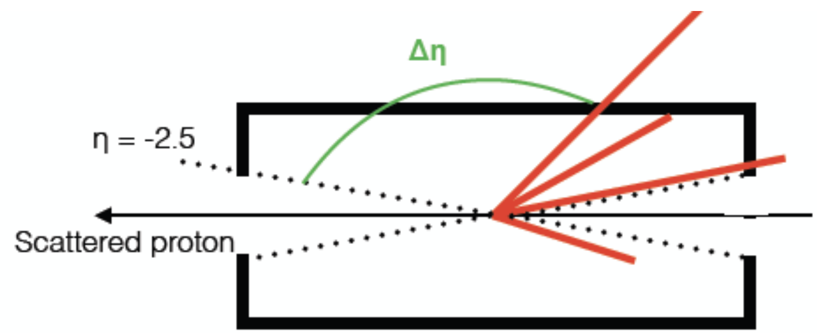
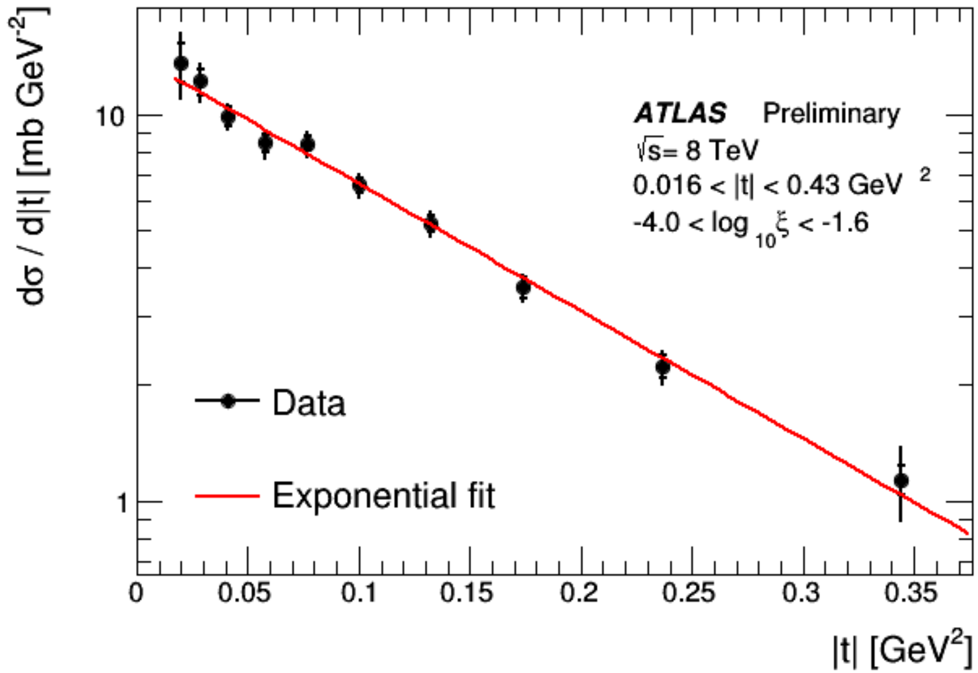
Results: Cross Section v Δη

- Gap defined by charged particles with p_T > 200MeV, relative to $|\eta|$ = $\pm$ 2.5
- Diffractive plateau visible
- 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 fiducial region ($\xi \sim 10^{-4}$ corresponds to $\Delta\eta \sim 4$)
- MC tunes predict a larger cross-section than the data (PYTHIA8 A3 *1.5, PYTHIA8 A2 *2.3, HERWIG7 *3)





Results: Cross Section v |t|



- Data consistent with expected exponential form

$$\frac{d\sigma}{dt} = Ae^{Bt}$$

- B = 7.60 ± 0.23(stat.) ± 0.22(syst.) GeV^{-2}
- Dominant uncertainty on fit result is overlay background and statistics (also arising from overlay background subtraction)

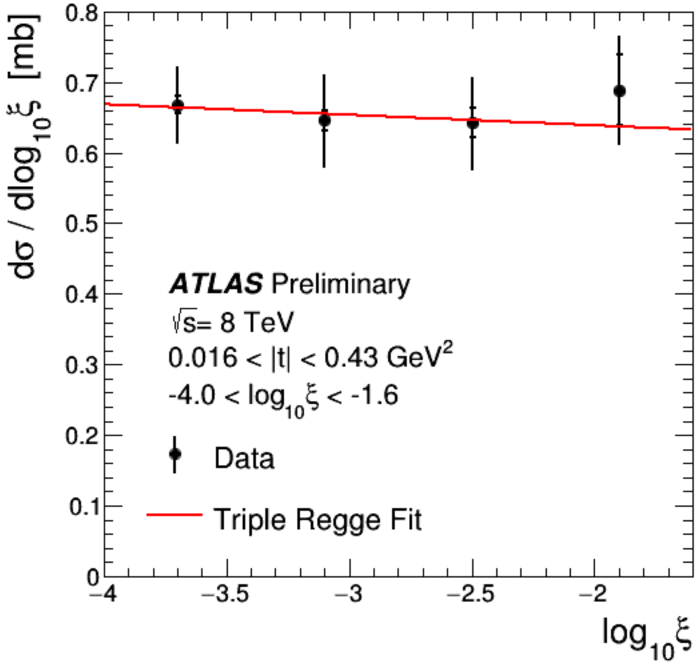
cf B(PYTHIA8 A2) = 7.82 GeV^{-2}, B(PYTHIA8 A3) = 7.10 GeV^{-2}

Broadly in line with expectations; high precision

Results: Cross Section v ξ

- Expected approximate $^{d\sigma}/_{d\xi}$ α $^{1}/_{\xi}$ dependence holds over two orders of magnitude in ξ
- Further interpreted in triple pomeron model: $$\frac{d\sigma_{SD}}{d\log_{10}(\xi)} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)-1} \frac{1}{B}\left(e^{Bt_{\text{high}}} - e^{Bt_{\text{low}}}\right)$$

where $B = B_0 - 2\alpha' \ln \xi$; fixed B_0 and $\alpha(t) = \alpha(0) + \alpha' t$



Fit yields:

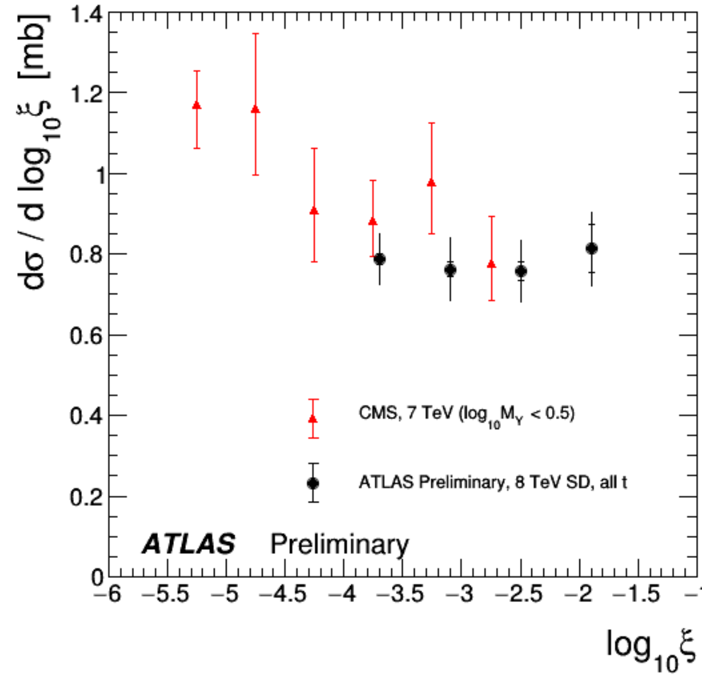
α(0) = 1.07 ± 0.02(stat.) ± 0.06(syst.) ± 0.06(α')

- Dominant uncertainty comes from using α' = 0.25 ± 0.25 GeV^{-2} in fit
- Unfolding, hadronisation & overlay background systematics also significant

cf in model above: PYTHIA8 A3 (DL): 1.14, PYTHIA8 A2 (SS): 1.00

Results: Cross Section v ξ

- Comparison of ATLAS data (extrapolated with factor 1.18 to cover full t range) with closest available published LHC data … CMS rapidity gap measurement with strong veto on forward energy flow (CASTOR)



- CMS data still contain DD admixture (unquantified but assumed small) and are at 7 TeV rather than 8 TeV

- Fair agreement and complementary ξ ranges

Results: Integrated SD Cross Section

- Cross section integrated over fiducial region ($0.016 < |t| < 0.43$ GeV^2, $-4.0 < \log_{10}\xi < -1.6$):

$$\sigma_{SD}(\xi, t \text{ fiducial}) = 1.59 \pm 0.13 \text{ mb}$$

- Small extrapolation (factor 1.18) for $0 < |t| < 0.016$ GeV^2 and 0.43 GeV^2 $< |t| < \infty$ yields integrated x-section for $-4.0 < \log_{10}\xi < -1.6$:

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

- "Total SD cross section" is ill defined (… e.g. up to which ξ?...)
  Extrapolation **<u>within context of PYTHIA model</u>** using average of A2 and A3 leads to:

$$\sigma_{SD} = 6.6 \text{ mb (no attempt at evaluating uncertainties)}$$

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

Summary

- Measurement of SD differential cross sections with ALFA-tagged protons at 8TeV

- No previous such measurements published at LHC

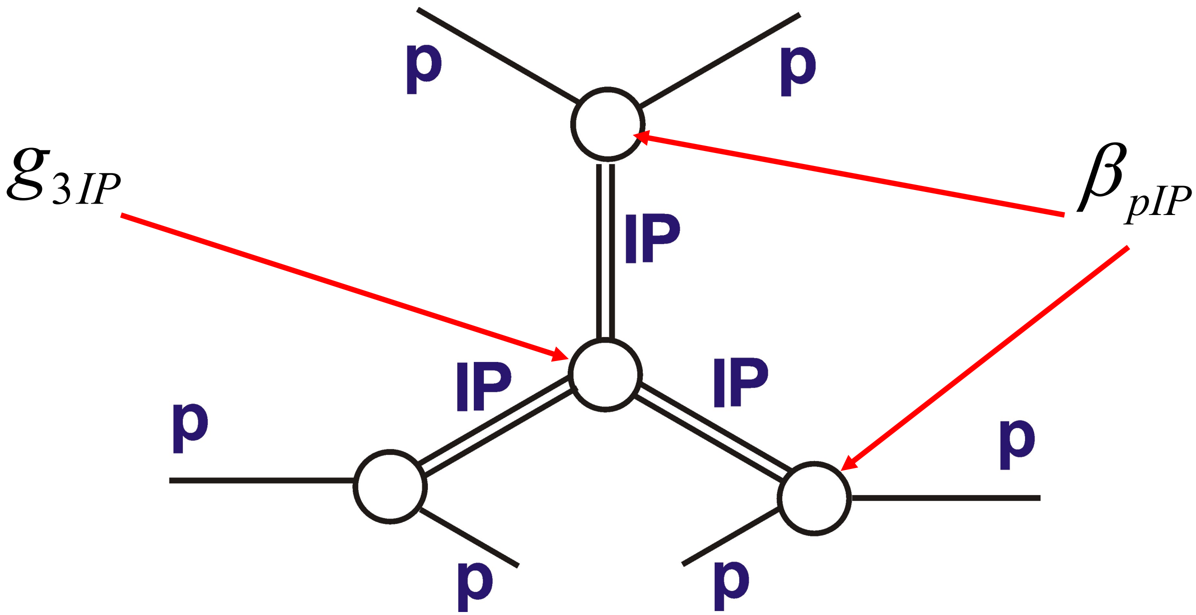
- Dynamics (ξ and t dependences) broadly as expected in soft phenomenological models, including those in PYTHIA8

- Normalisations of commonly used MC models all exceed the data

- Significant scope to improve constraints on pomeron trajectory with double differential ξ, t data and s dependence

Spares

Calculating Triple Pomeron Amplitudes



Need to know triple pomeron coupling $g_{3IP}(t)$ and pomeron proton coupling $\beta_{pIP}(t)$.

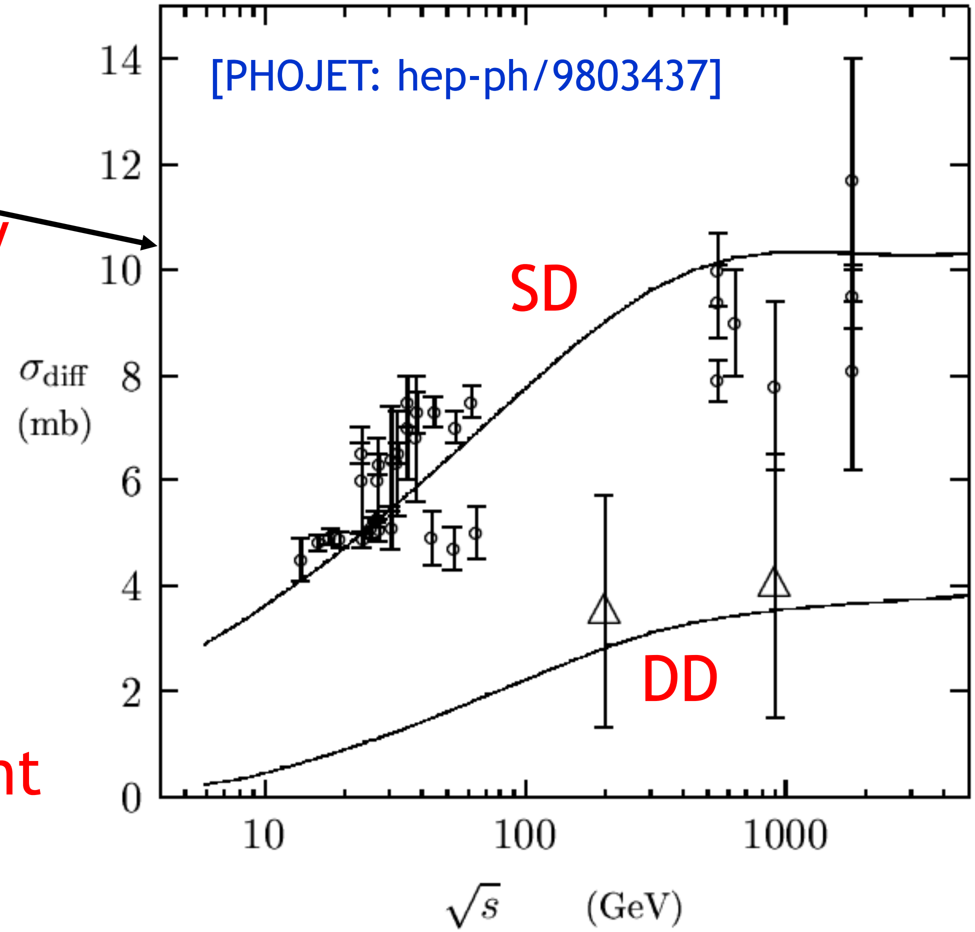
Pomeron `propagators' give dependences on M_X^2 and s via pomeron trajectory $\alpha(t) \sim 1.08 + 0.25\, t$

$$\frac{d\sigma}{dtdM_X^2} = \frac{1}{16\pi}\, g_{3IP}(t)\, \beta_{pIP}(t)^3\, s^{2\alpha(t)-2}\, M_X^{2[\alpha(0)-2\alpha(t)]} \xrightarrow[t\to 0]{} s^{0.16} \left(\frac{1}{M_X^2}\right)^{1.08} e^{B(\xi)t}$$

Remaining Difficulties

- This theory works fairly well, but is not universally accepted

- The data used to constrain couplings (especially g_{3IP}) are old and sometimes poor quality



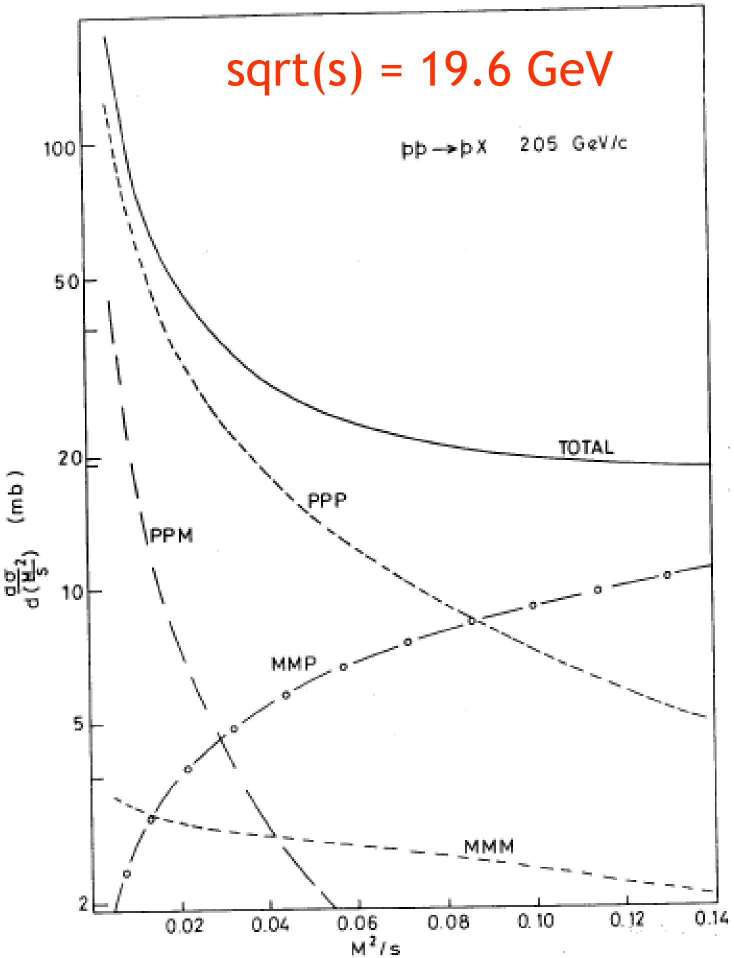
- Other exchanges in addition to the pomeron (e.g. ρ, π) become important for large ξ (>~ 10^{-2}) and small s

- There is a known enhancement in the low ξ resonance region

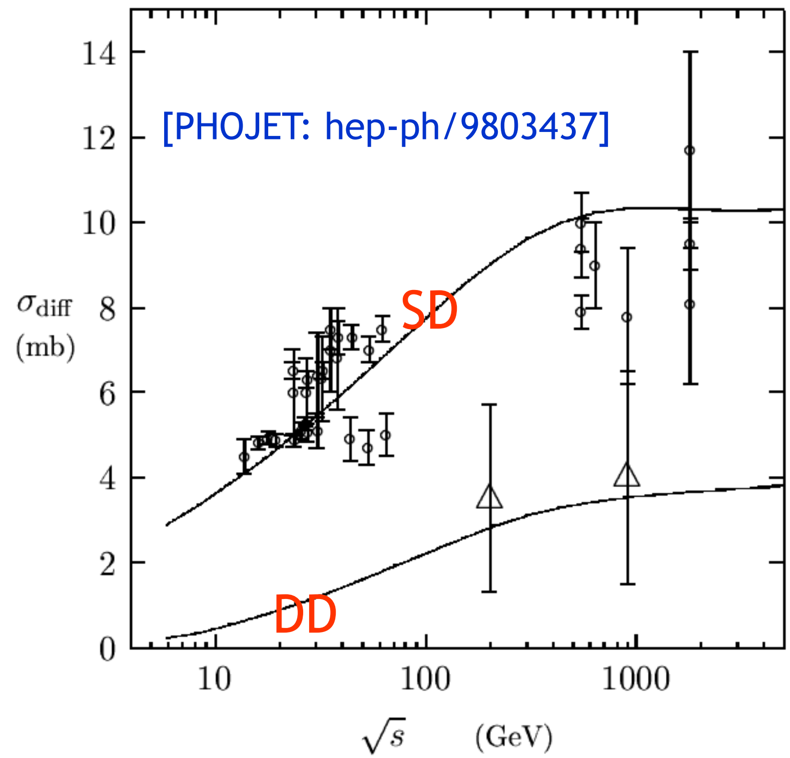
- The theory doesn't tell us where to stop at large ξ, i.e. how to merge SD with ND cross sections

Pre-LHC Data

Ancient (ISR) triple Regge phenomenology of pp → pX



Roberts & Roy: NP B77 (1974) 240
Field & Fox: NP B80 (1974) 367



- Sub-leading terms suppressed like 1/sqrt(s) or stronger … negligible at LHC,
- Perhaps influence assumed 3IP coupling in MC models?

PHOJET Implementation

- Cross section based on triple pomeron model with standard pomeron $\alpha(0) = 1.08$
- Sharp cut at steerable large ξ [default ~0.4?]
- No low ξ enhancement

PYTHIA Implementation

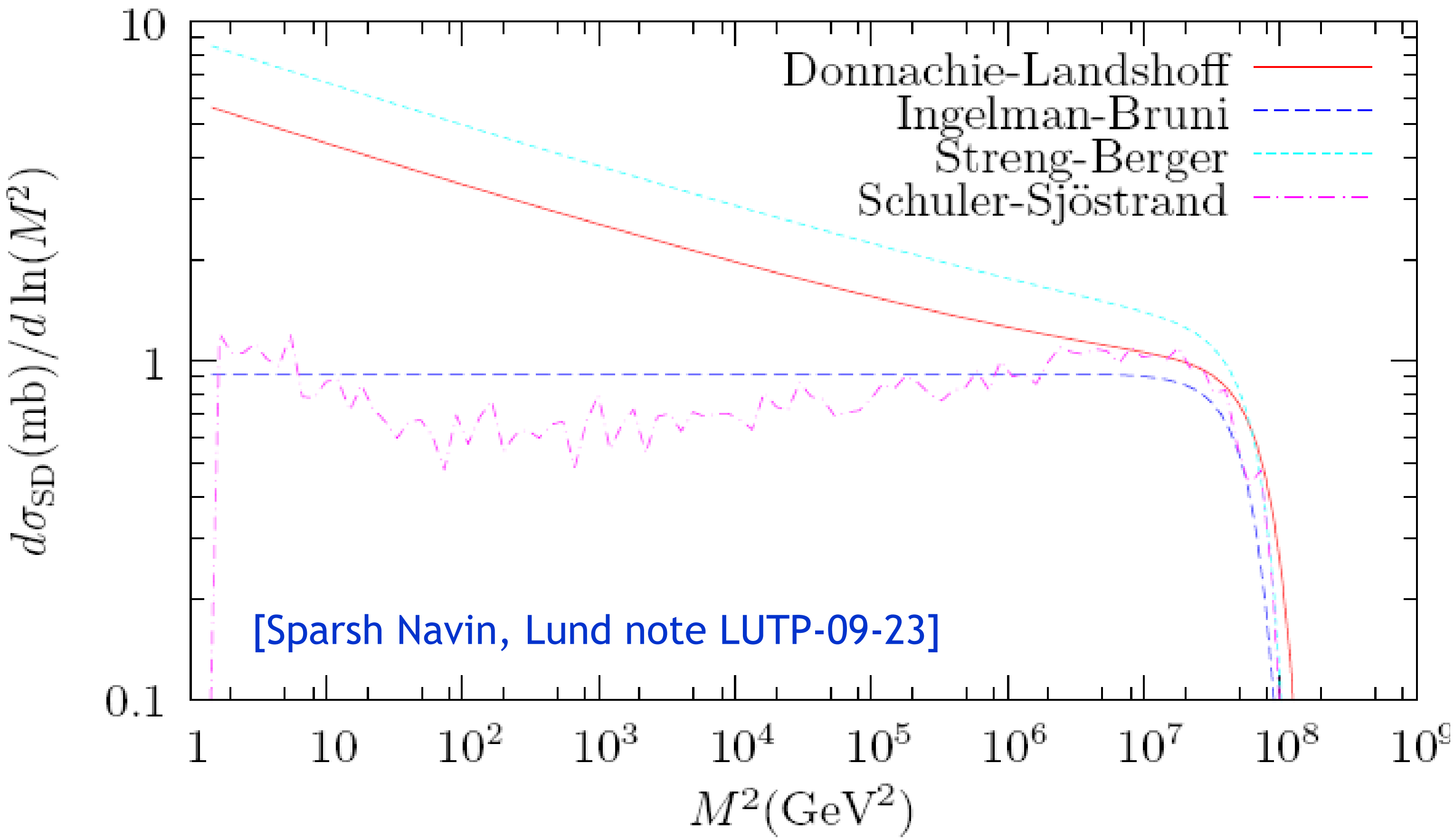
- Triple pomeron model. By default $\alpha(0) = 1$ (!)
- Fudge factors applied to suppress large ξ, give a low ξ enhancement and prevent X and Y systems overlapping in DD

$$\frac{d\sigma_{sd(AX)}(s)}{dt\, dM^2} = \frac{g_{3\mathbb{P}}}{16\pi} \beta^2_{A\mathbb{P}} \beta_{B\mathbb{P}} \frac{1}{M^2} \exp(B_{sd(AX)} t) F_{sd}$$

$$F_{sd} = \left(1 - \frac{M^2}{s}\right)\left(1 + \frac{c_{res} M^2_{res}}{M^2_{res} + M^2}\right)$$

- Exactly the same default in PYTHIA8, but now with 3 other parameterisations available

PYTHIA8 Pomeron Flux Models

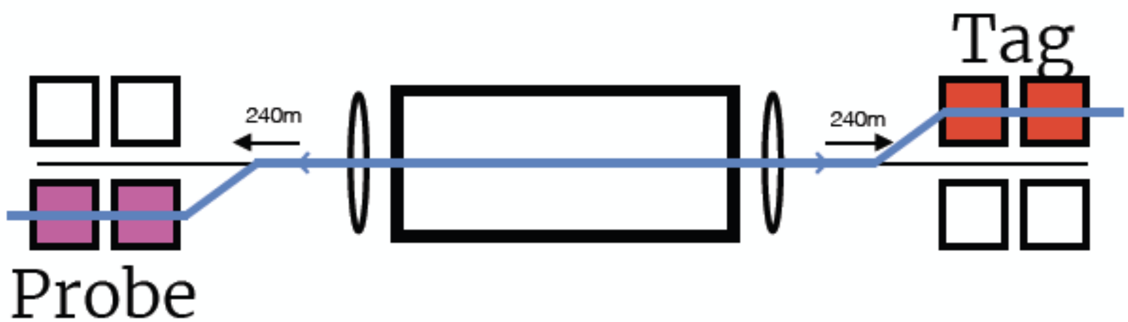


- Default Schuler & Sjostrand flux and more standard(?) Donnachie & Landshoff show significantly different ξ dependences when viewed over huge ξ range at LHC

- It would be a good idea to look at sensitivity to this choice.

ALFA Reconstruction Efficiency

- Apply `tag and probe' method used in elastic scattering analysis, exploiting back-to-back configuration of EL events and redundancy of 2 pots per arm (& many fibre layers in each)



	L1U	L1L	R1U	R1L
ϵ_{rec}				
Data:	0.9427	0.9123	0.9247	0.9179
MC:	0.9491	0.9177	0.9411	0.9391
Statistical uncertainty				
Data:	0.0009	0.0011	0.0010	0.0010
MC:	0.0007	0.0009	0.0008	0.0008
Systematic Uncertainty				
Data:	0.0086	0.0134	0.0092	0.0132
MC:	0.0102	0.0180	0.0081	0.0214
Total Uncertainty				
Data:	0.0086	0.0134	0.0093	0.0133
MC:	0.0103	0.0180	0.0082	0.0214

- Small inefficiencies (mainly due to showering) corrected for separately in data and MC

Armlet	$\epsilon^{\text{data}}/\epsilon^{\text{MC}}$
L1U	0.9933
L1L	0.9941
R1U	0.9826
R1L	0.9774