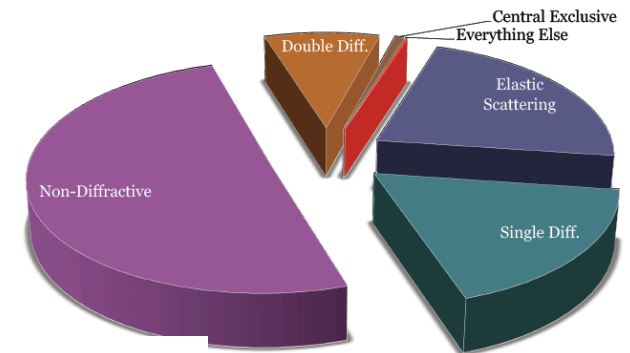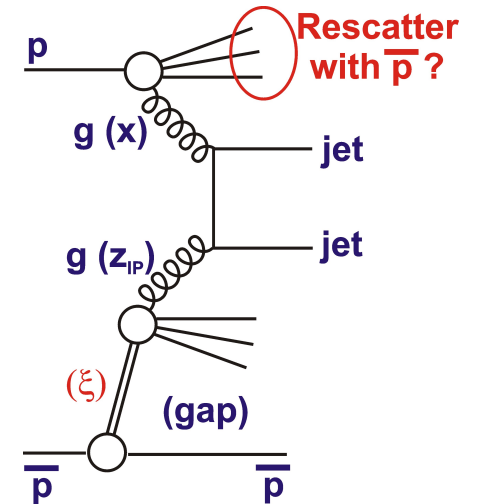# Recent Diffractive and Related Measurements with the ATLAS Detector

Paul Newman
(University of Birmingham)
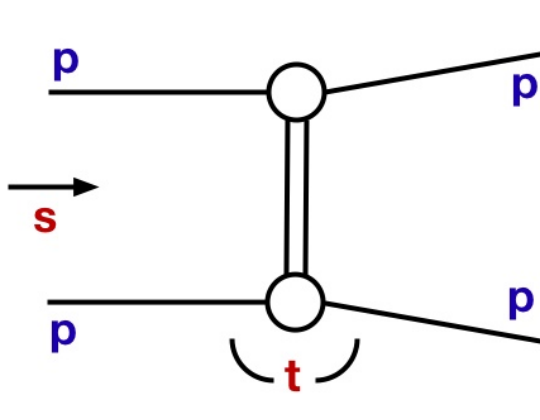**for the ATLAS Collaboration**

Low x Workshop, Gyongyos, Hungary
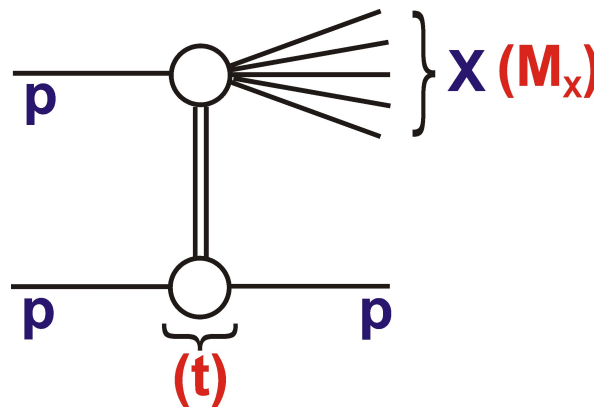**6-10 June 2016**

→ Total Inelastic Cross Section at 13 TeV **NEW!**
→ Diffractive Dijet Cross Sections
→ Via a bit of elastic and soft diffractive measurements
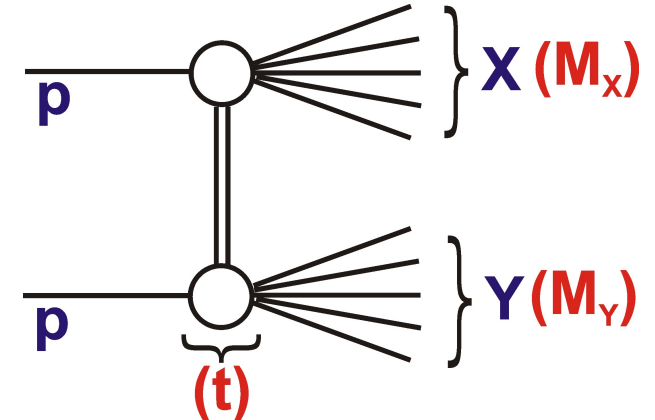
1

Decomposing the pp Cross Section

Elastic

1 degree of freedom
→ scattering angle / t

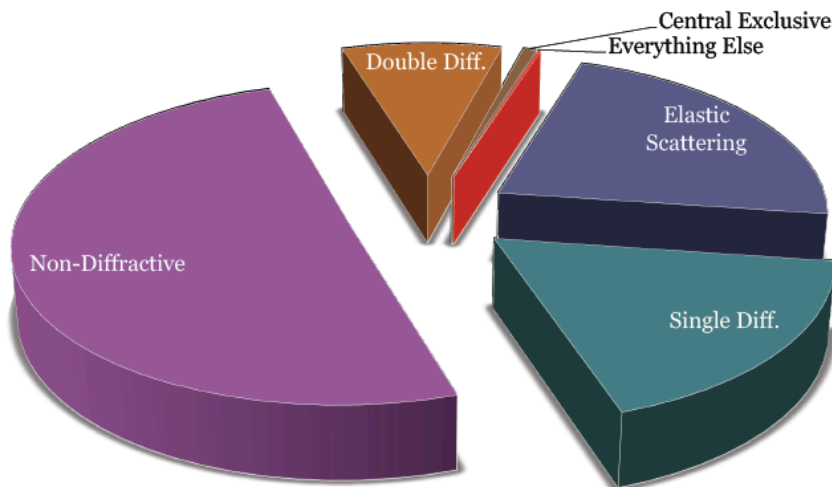**Single diffractive dissociation**

Also M_X

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

Double diffractive dissociation

Also M_Y

$$\xi_Y = \frac{M_Y^2}{s}$$

At LHC, M_X, M_Y can be as large as 1 TeV → plenty of phase space to produce jets and other hard probes

Central Exclusive

Everything Else

Double Diff.

Elastic Scattering

Non-Diffractive

Single Diff.

Diffractive Channels:
& Rapidity Gap Kinematics
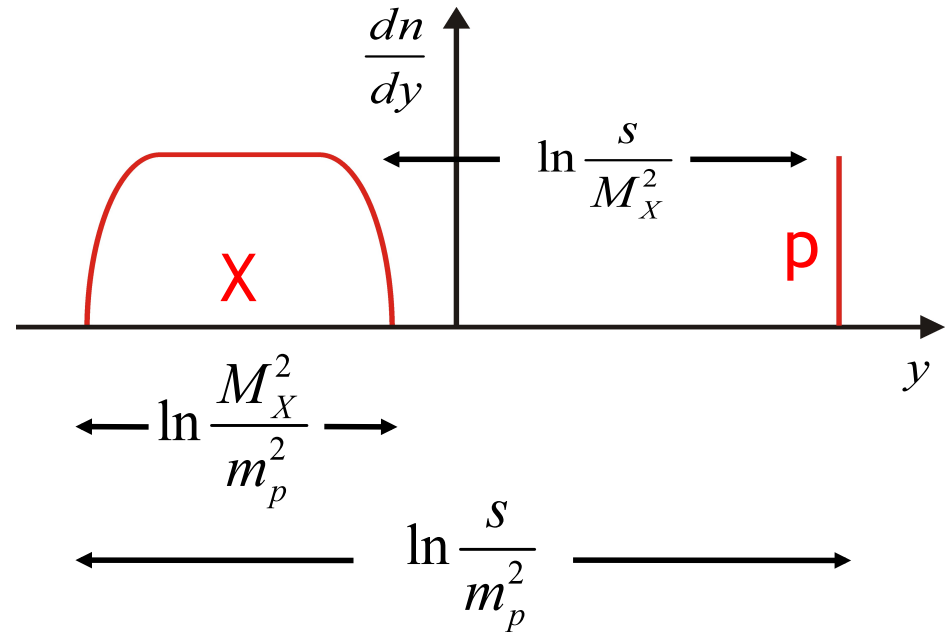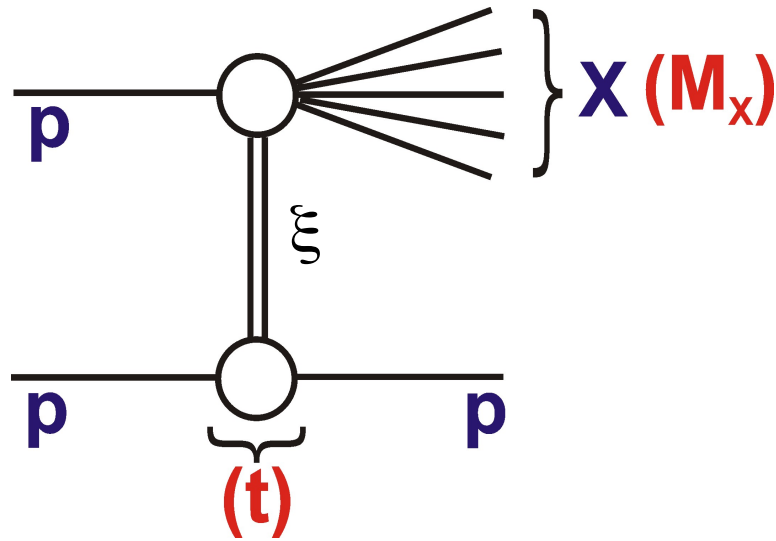
- Protons not tagged directly

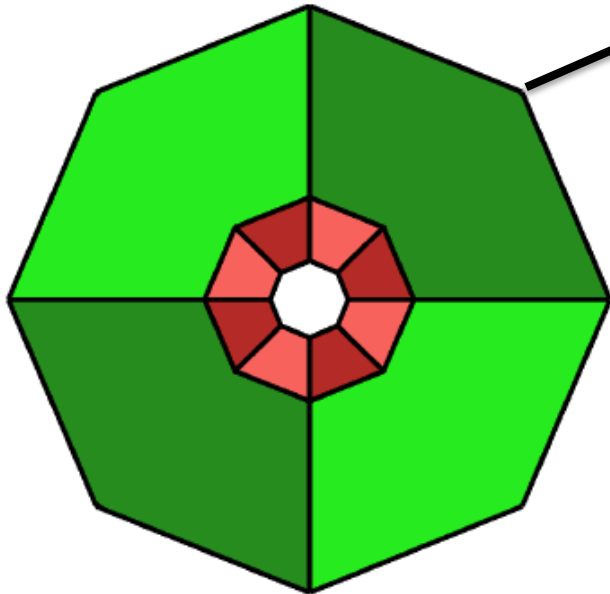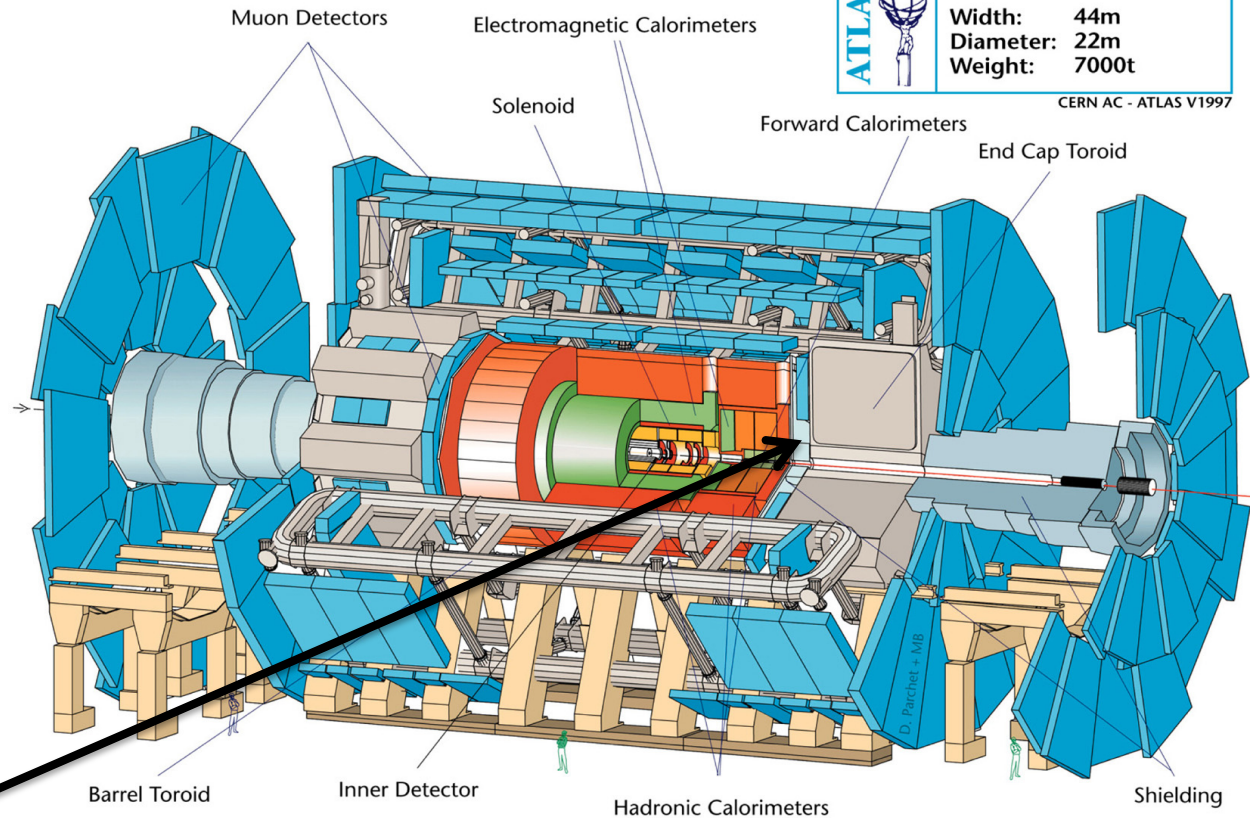- ξ variable strongly correlated with empty rapidity regions

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

          ... exploited in both measurements to be shown

- Correlation limited by hadronisation fluctuations

ATLAS

Both measurements
rely on minimum bias
samples triggered using
the MBTS scintillators

Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

$z = \pm 3.6m$, $2.1 < |\eta| < 3.8$
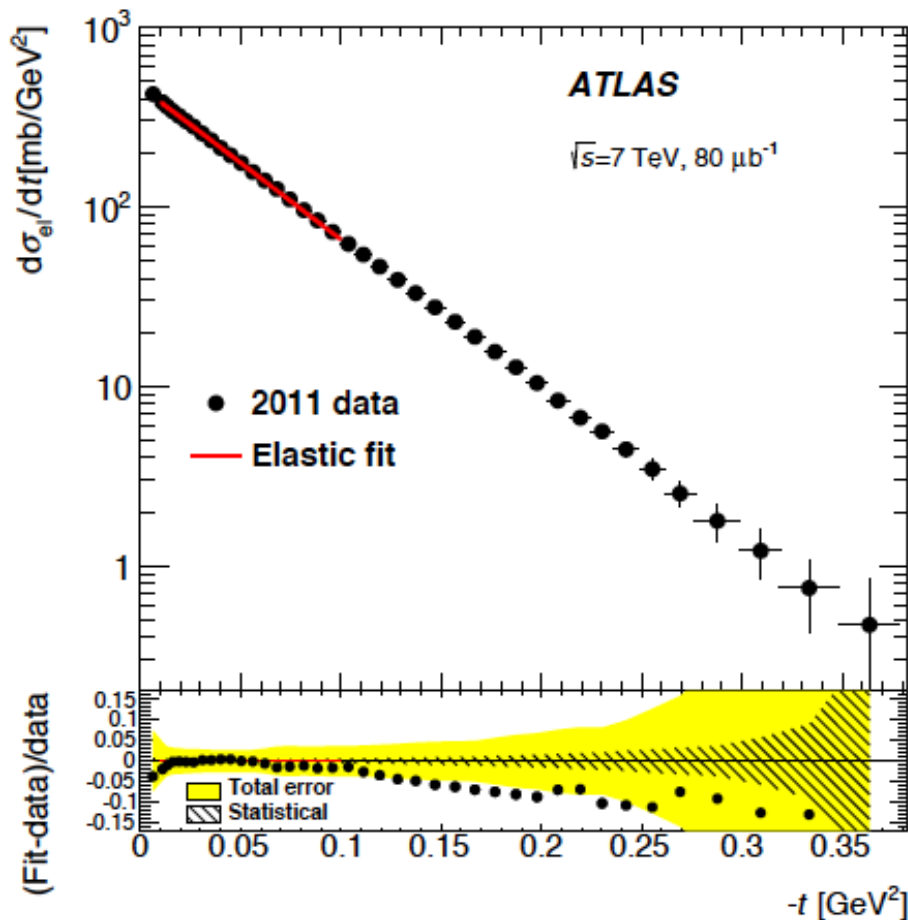
Run 1 version had 2 x 8-fold segmentation

Replaced for Run 2 – 8 fold segmentation
nearest beam-pipe, 4-fold further out

Motivation:
Total and elastic cross sections

Measurements of the elastic cross section and its t-dependence (eg in ALFA) determine total cross section via optical theorem
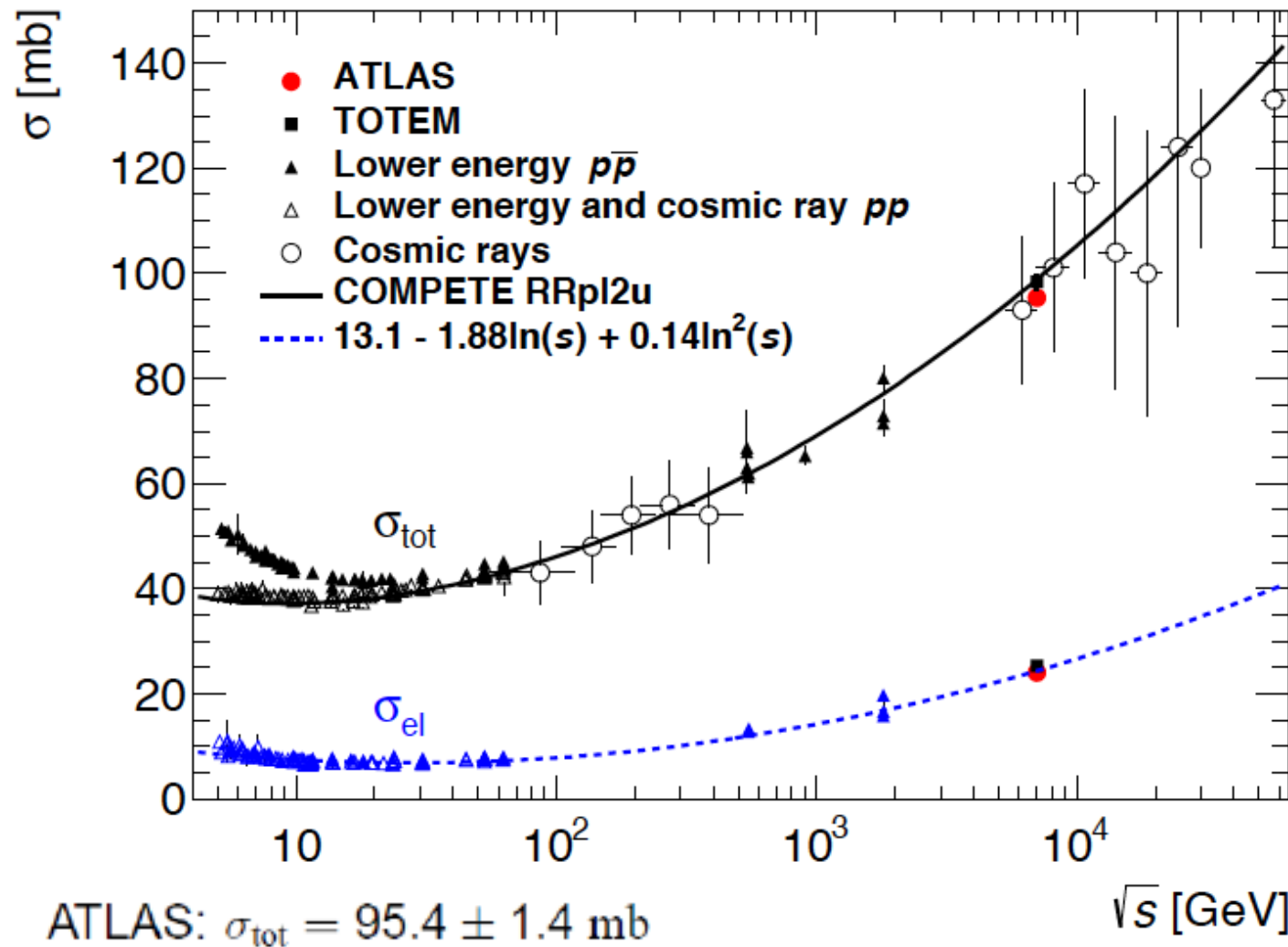

ATLAS

$\sqrt{s}$=7 TeV, 80 µb⁻¹

• 2011 data
— Elastic fit

Total error
Statistical

$-t$ [GeV²]

At fixed s: $\dfrac{d\sigma}{dt} = \dfrac{d\sigma}{dt}\bigg|_{t=0} e^{Bt}$

B=19.73±0.24 GeV⁻² (ALFA)

$$\sigma_{TOT}^2 = \frac{16\pi(hc)^2}{1+\rho^2} \cdot \frac{d\sigma_{EL}}{dt}\bigg|_{t=0}$$

[ρ~0.1 = phase of Coulomb-nuclear interference at t=0]

Nucl Phys B889 (2014), 486

Total, Elastic and Inelastic Cross Sections

ATLAS: $\sigma_{tot} = 95.4 \pm 1.4$ mb

Consistent with fits to previous data (with either a logarithmic or power law dependence).

$[\alpha_{IP}(0) \sim 1.08]$

- σ_{tot} & σ_{el} indirectly determine total inelastic cross section σ_{inel}
- Direct σ_{inel} measurement tests self-consistency (expt & theory).
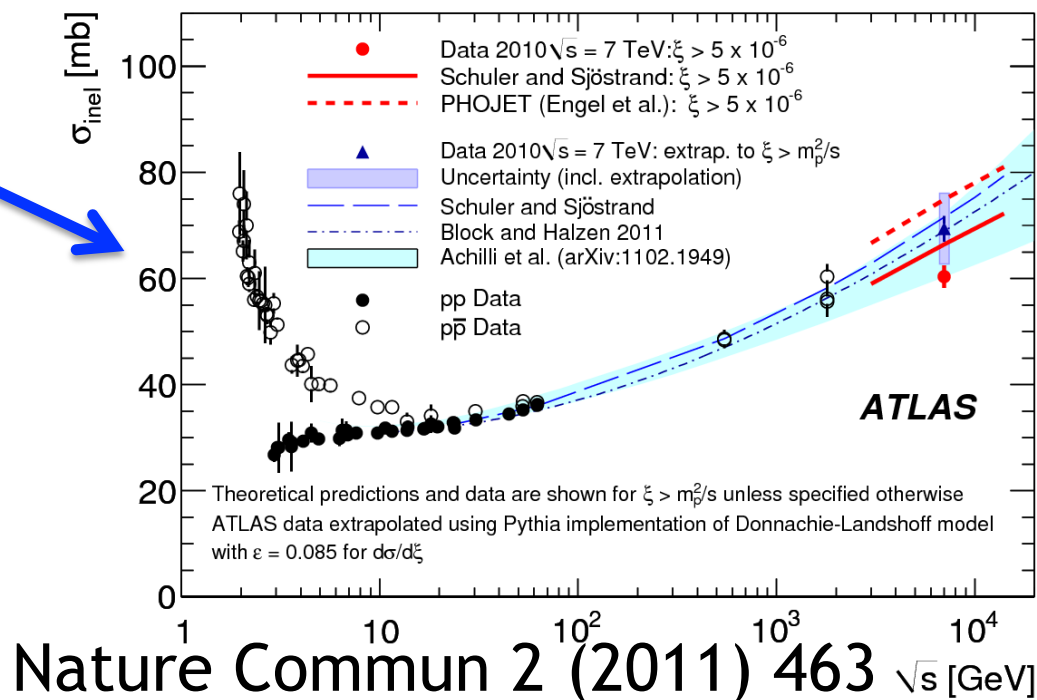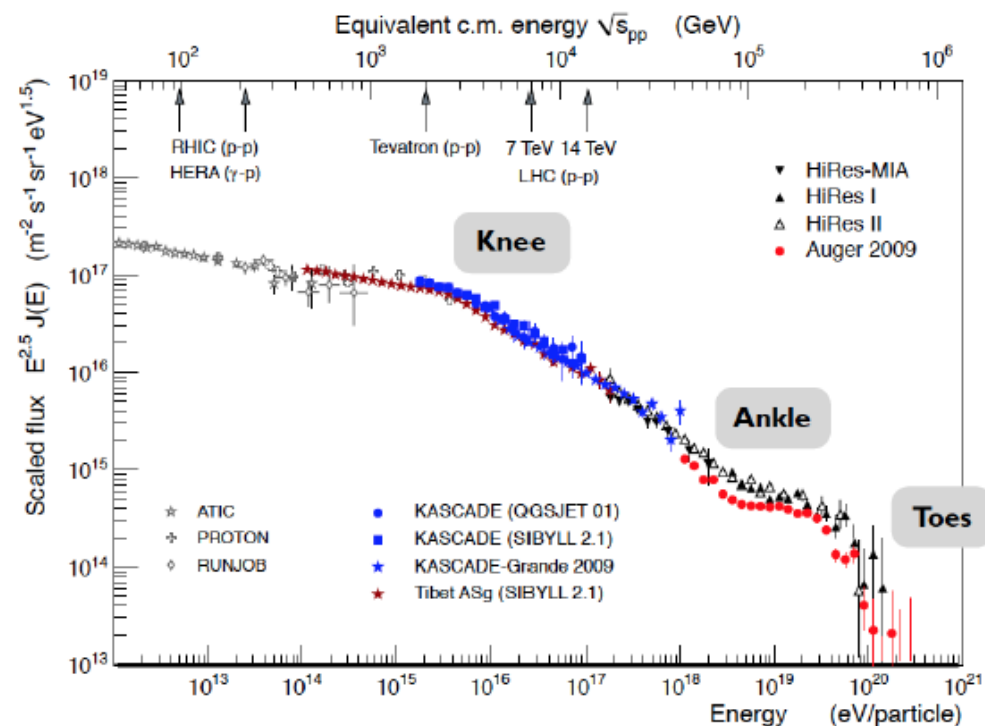
Total Inelastic Cross Section

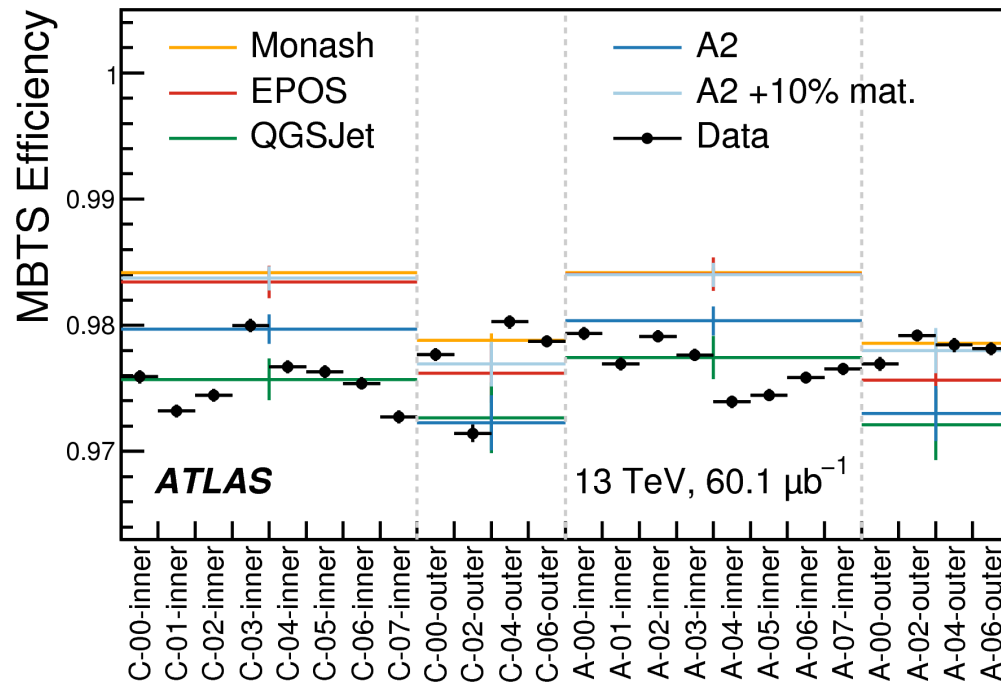- Crucial quantity for understanding cosmic ray air showers

- Ingredient for modelling pile-up (and lumi) at LHC

Repeat and refine 7 TeV procedure using a short low pile-up run at 13 TeV taken in June 2015

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


Nature Commun 2 (2011) 463

Controlling MBTS Efficiency with Data

- Efficiencies for each MBTS counter measured relative to tracks in inner detector where possible and calorimeter clusters where not.
→MC efficiencies tuned accordingly

- Trigger efficiencies monitored relative to independent LUCID and LHCf triggers

- Efficiency / acceptance depends on MBTS segment multiplicity
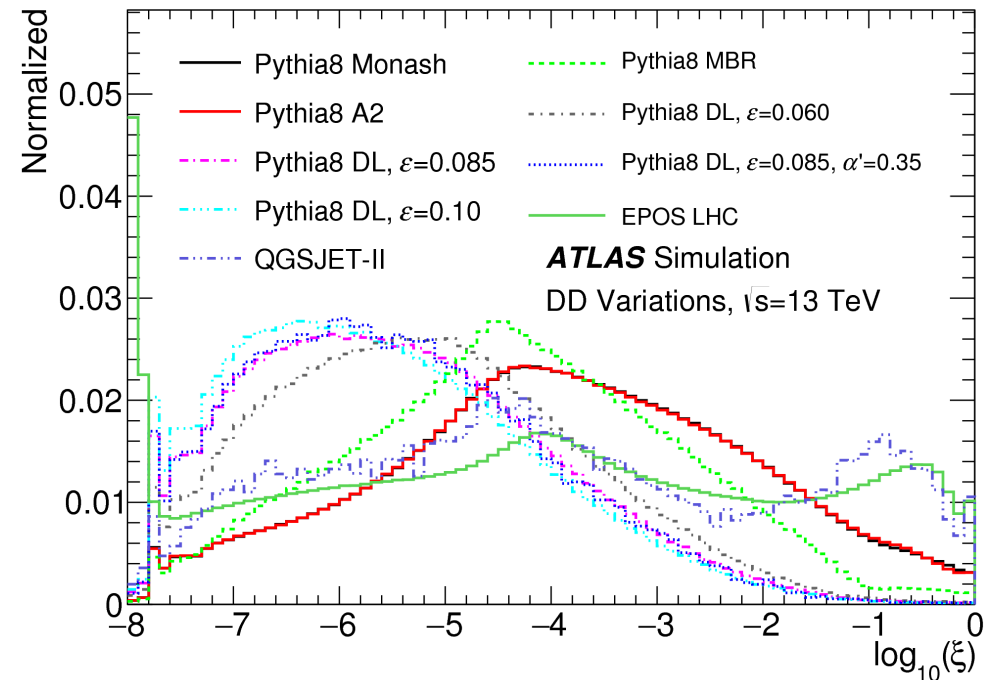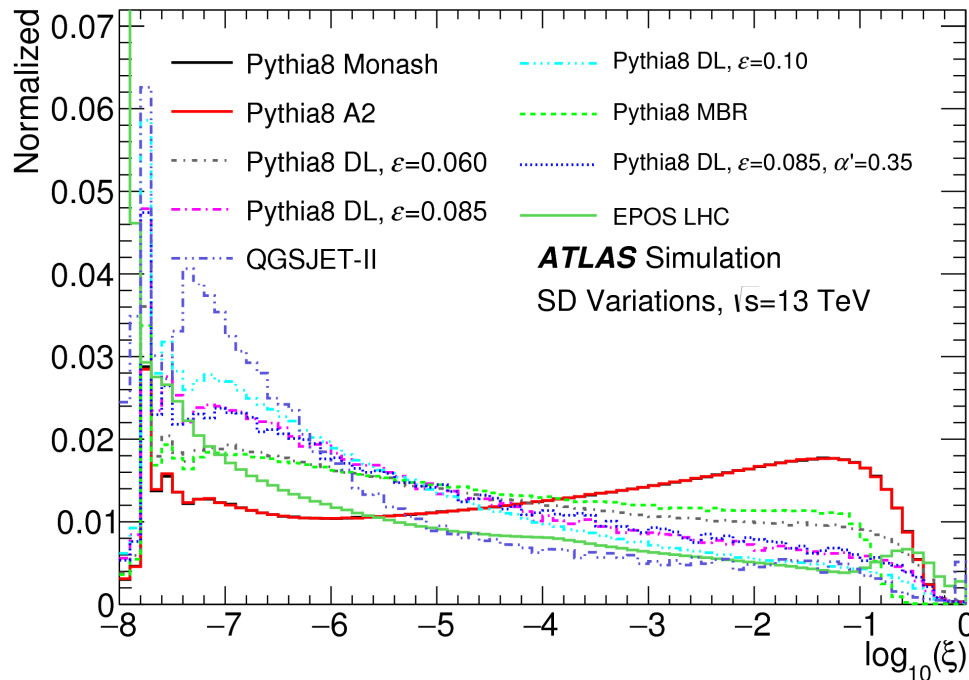
- Analysis selection is $N_{MBTS} \geq 2$
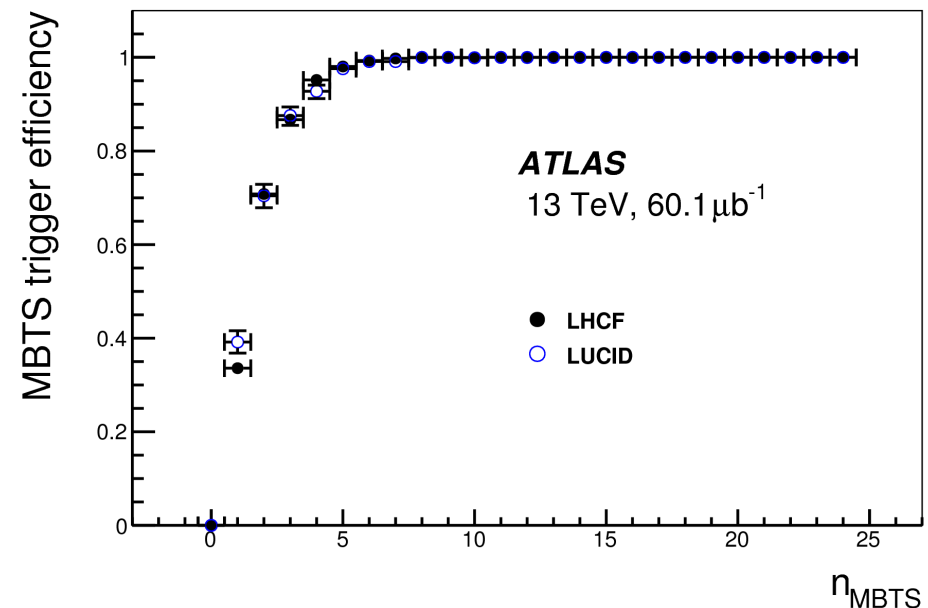
What we can't see: low mass diffraction

$$\Delta\eta \approx -\ln\xi$$
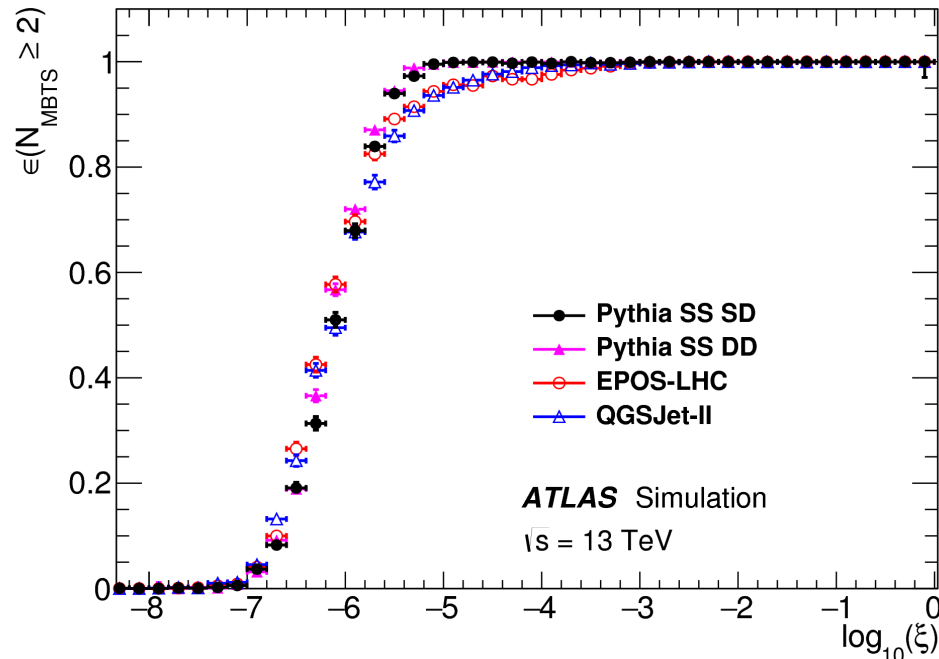
Acceptance limit of MBTS ($|\eta| <\sim 4$) corresponds to $\xi \sim 10^{-6}$

Cross section for $\xi < 10^{-6}$ poorly constrained

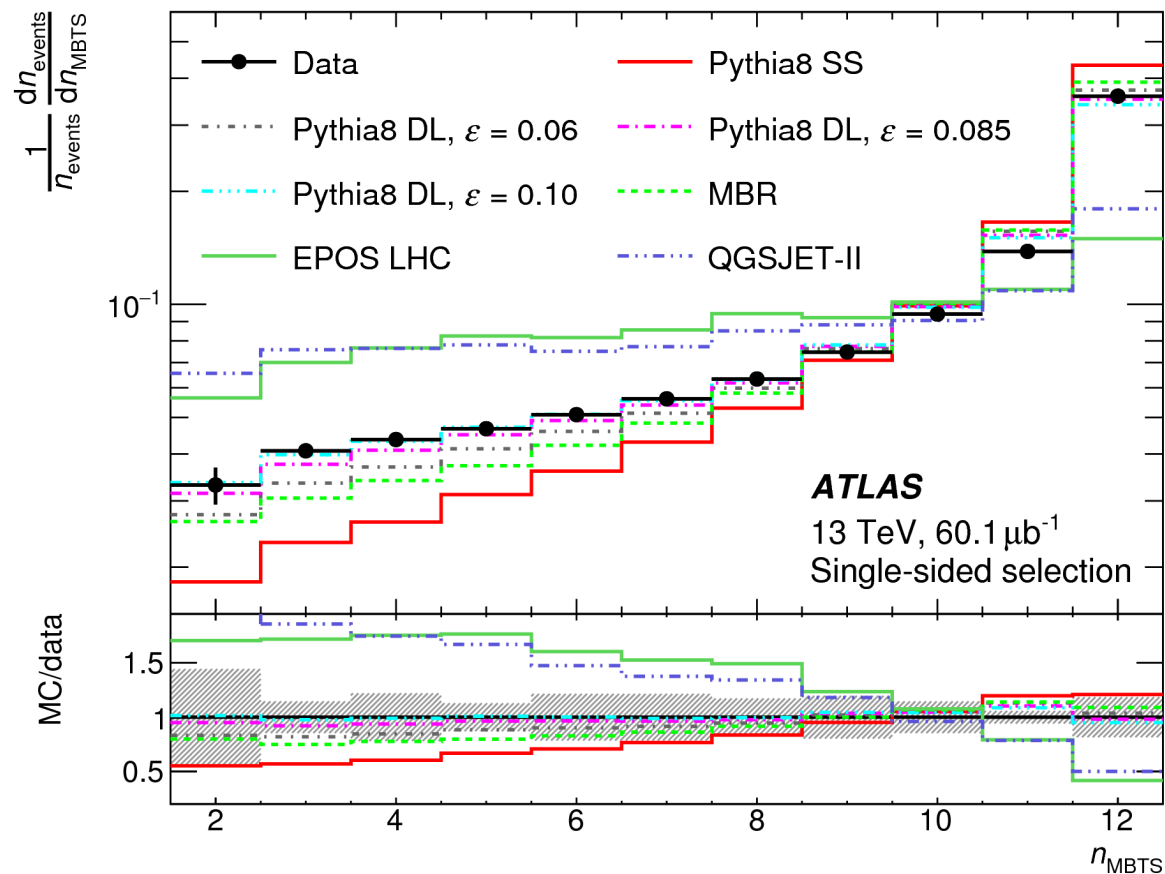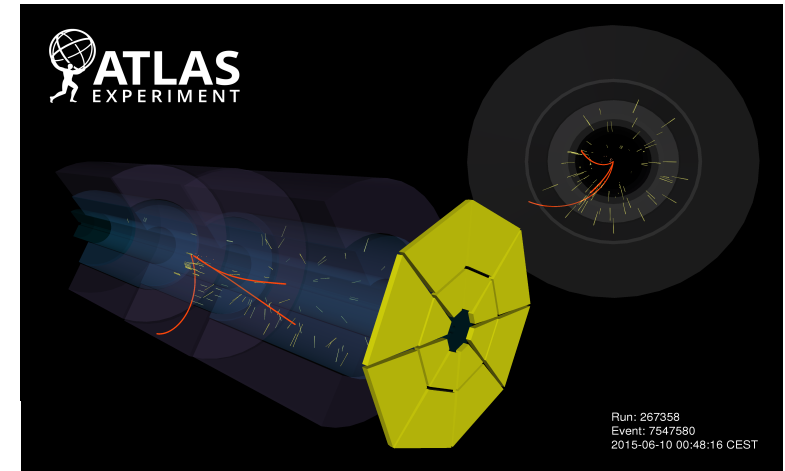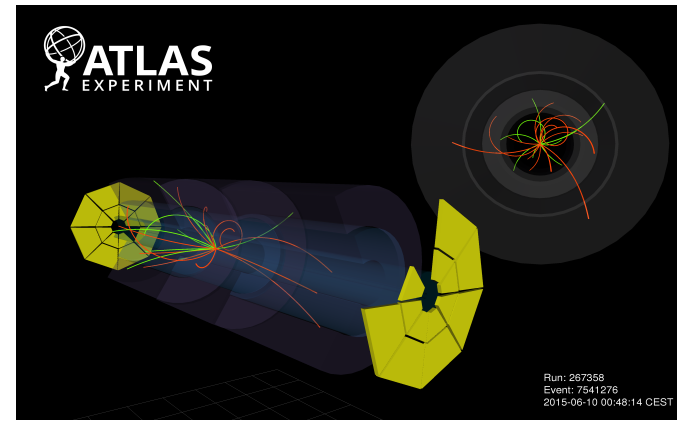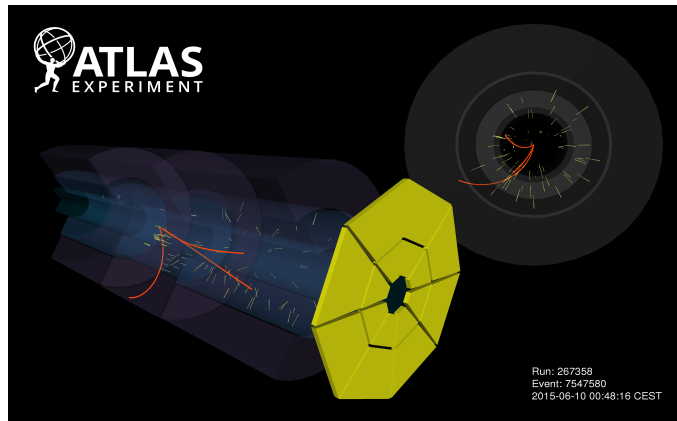# Benchmarking Diffractive MC models

"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

Tuning Diffractive MC models

R_{SS} = Ratio of single sided to double sided MBTS samples ... used to tune fractions of events considered diffractive in each MC model

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

Data 2015
Pythia8 SS
Pythia8 DL, ε=0.085
Pythia8 DL, ε=0.060
Pythia8 DL, ε=0.10
Pythia8 MBR
EPOS LHC
QGSJET-II

ATLAS
$\sqrt{s}$=13 TeV, L=60.1μb^{-1}
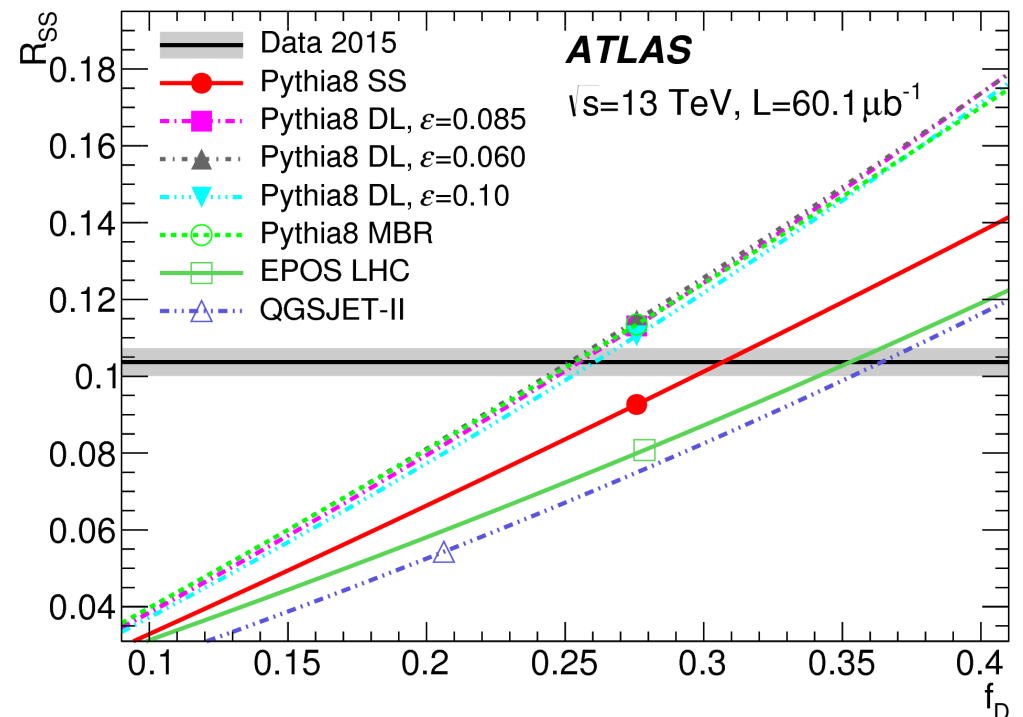
Fiducial Cross Section Extraction

$$\sigma_{\mathrm{inel}}^{\mathrm{fid}}\left(\xi > 10^{-6}\right) = \frac{N - N_{\mathrm{BG}}}{\epsilon_{\mathrm{trig}} \times \mathcal{L}} \times \frac{1 - f_{\xi < 10^{-6}}}{\epsilon_{\mathrm{sel}}}$$

- N_{BG}: Small background from beam-gas, radiation & activation, determined using triggers in non-colliding bunches

- $(1-f_{\xi<10\text{-}6})/\epsilon_{\mathrm{sel}} = C_{\mathrm{MC}}$ = MC acceptance and migration correction

- Luminosity from final calibration of Van der Meer scan
  → 1.9% error ... cf was 9% in preliminary result ☺

Factor	Value	Rel. uncertainty
Number of events passing the inclusive selection (N)	4159074	−
Number of background events (N_{BG})	51187	±50%
Integrated luminosity [$\mu\mathrm{b}^{-1}$] ($\mathcal{L}$)	60.1	±1.9%
Trigger efficiency (ϵ_{trig})	99.7%	±0.3%
MC correction factor (C_{MC})	99.3%	±0.5%

Cross Section in Fiducial Range

Source	Value
This measurement	68.2 ± 0.8 (exp.) ± 1.3 (lum.) mb
PYTHIA8 DL, $\varepsilon = 0.06$	71.0 mb
PYTHIA8 DL, $\varepsilon = 0.085$	69.1 mb
PYTHIA8 DL, $\varepsilon = 0.1$	68.1 mb
PYTHIA8 SS	74.4 mb
EPOS LHC	71.2 mb
QGSJET-II	72.7 mb

For $\xi > 10^{-6}$ ...

Due to final lumi calibration, cross section increased by 3mb relative to preliminary result and lumi uncertainty decreased from 5.9mb to 1.3mb

- Donnachie-Landshoff implmentation in PYTHIA8 consistent with data within $\sim 2\sigma$ for $\alpha_{IP}(0) = 1.06 \ldots 1.14$

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

Extrapolation to Full Inelastic Cross Sec

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

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

$$\sigma^{7\,\text{TeV}}(\xi < 5 \times 10^{-6}) = \sigma_{\text{inel}}^{7\,\text{TeV}} - \sigma^{7\,\text{TeV}}(\xi > 5 \times 10^{-6})$$
$$= 11.0 \pm 2.3 \text{ mb}$$

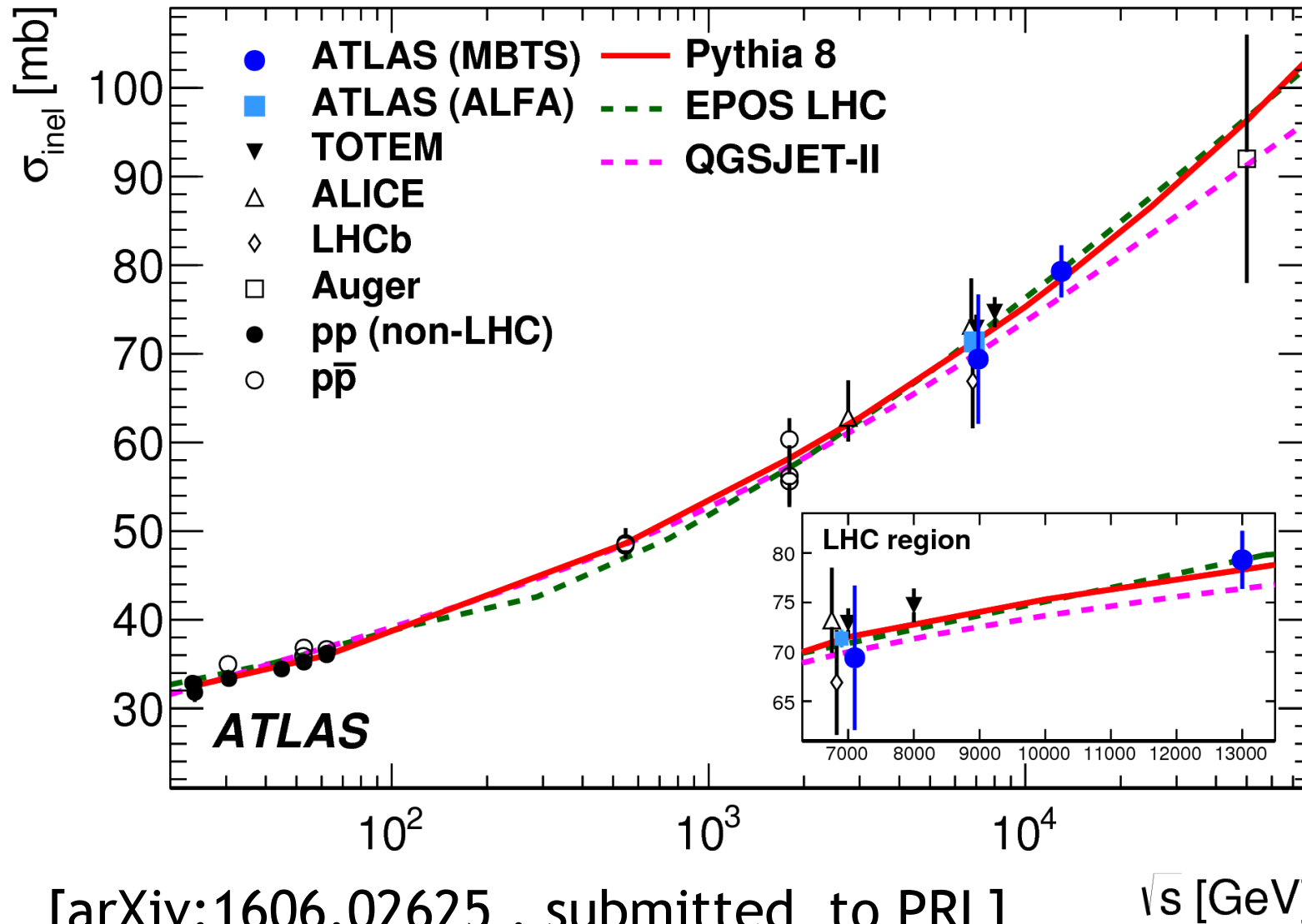from ALFA result

previous fiducial MBTS result

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

... extrapolation uncertainty reduced from 3.8 mb in prelim result to 2.5 mb in final
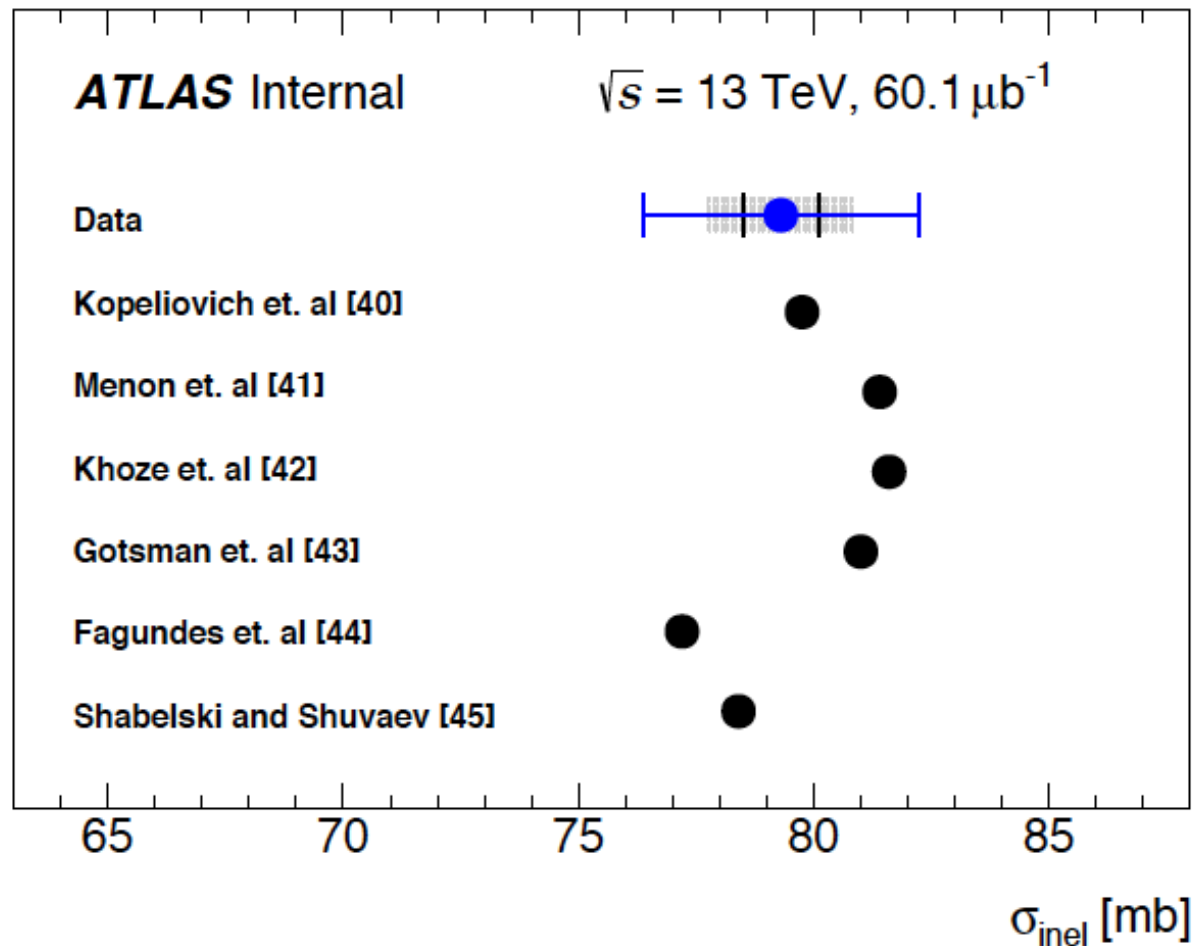
Extrapolation to Full Inelastic Cross Sec

$$\sigma_{inel} = 79.3 \pm 0.8 \text{ (exp.)} \pm 1.3 \text{ (lum.)} \pm 2.5 \text{ (extrap.) mb.}$$

First LHC total cross-xec result at 13 TeV

Increase by 11±4% compared with 7 TeV ALFA point

[arXiv:1606.02625 , submitted to PRL]

Total Inelastic Cross Section v Models

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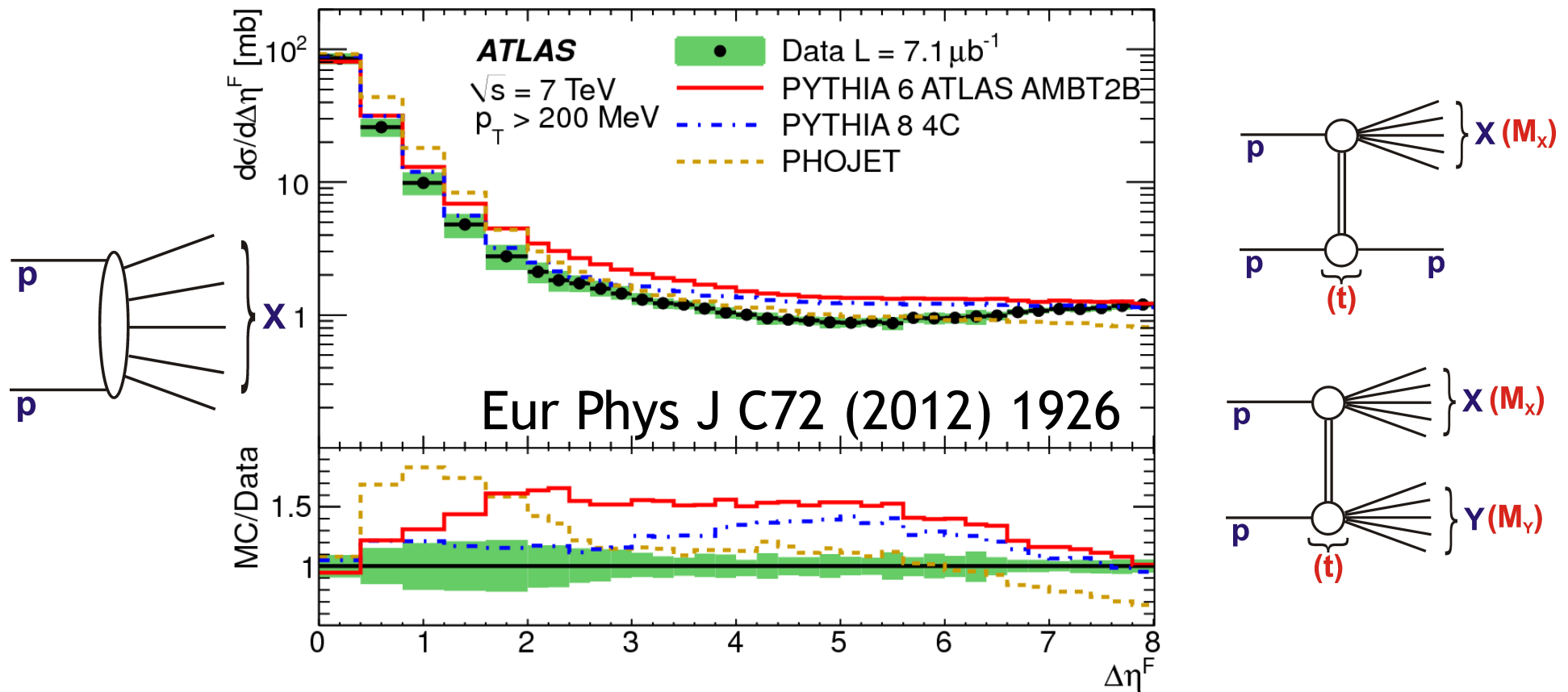
Rapidity gap cross-sections

Method developed by ATLAS to measure hadron Level cross section as a function of $\Delta\eta^F$: forward or backward rapidity gap extending to limit of instrumented range: i.e. including $\eta = \pm 4.9$
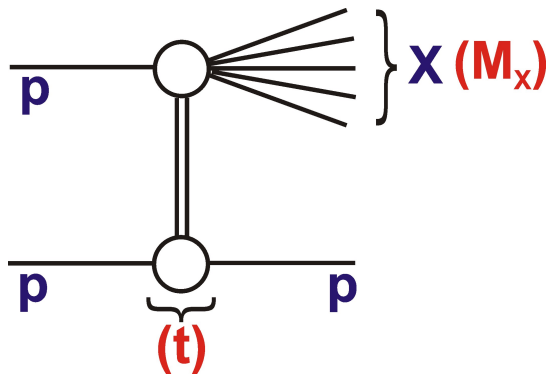
... no statement on $\eta > \sim 4.9$
... large $\Delta\eta^F$ sensitive to SD + low M_Y DD

$\Delta\eta^F \sim 6$ event in ATLAS

Implies $\xi \sim 10^{-4}$
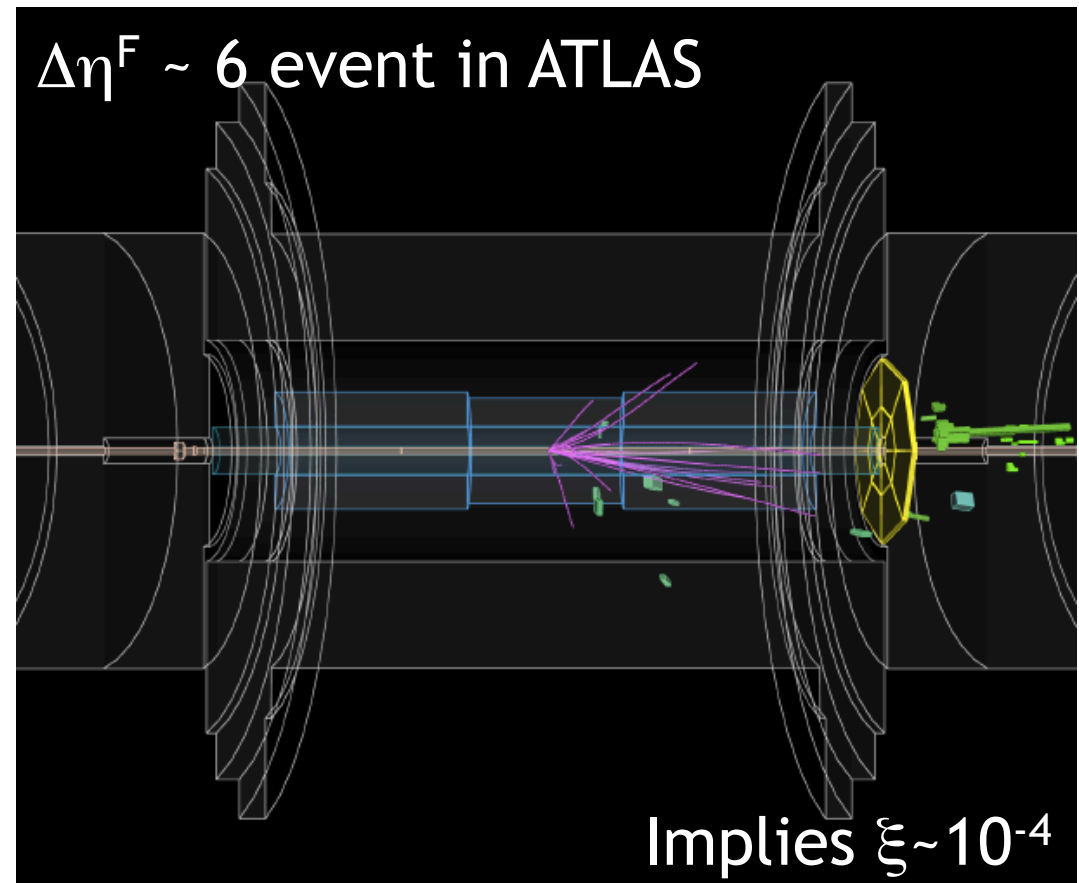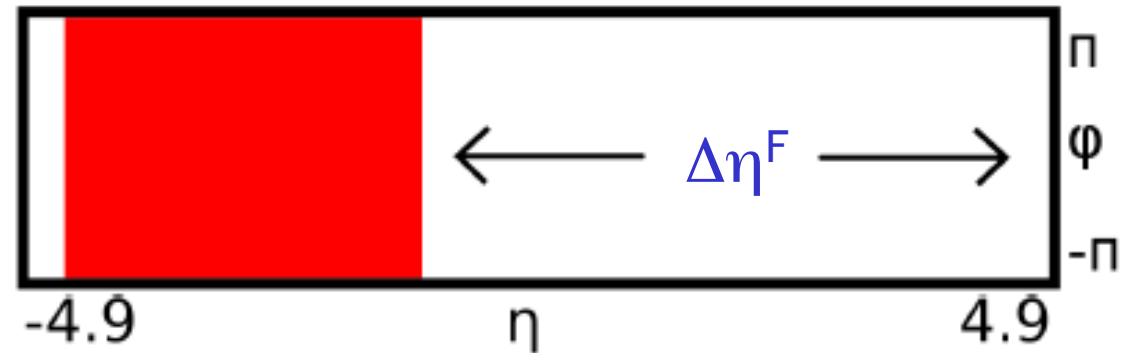
Inclusive Differential Gap Cross Section

Eur Phys J C72 (2012) 1926

- Large $\Delta\eta^F$: Diffractive plateau with ~1mb per unit gap size, consistent with soft pomeron ($\alpha_{IP}(0) = 1.058 \pm 0.036$)
- Small $\Delta\eta^F$: sensitive to hadronisation fluctuations / MPI in ND

18

Can the same method be applied to hard diffractive processes?...

Hard Diffraction: Structure of Vacuum Exchange
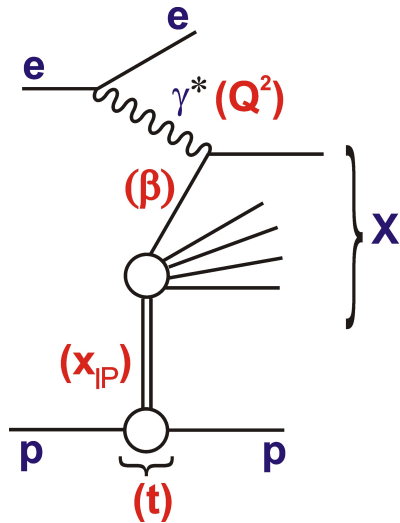
Diffractive DIS at HERA → **Diffractive parton densities (DPDFs) dominated by gluon, which extends to large momentum fractions**
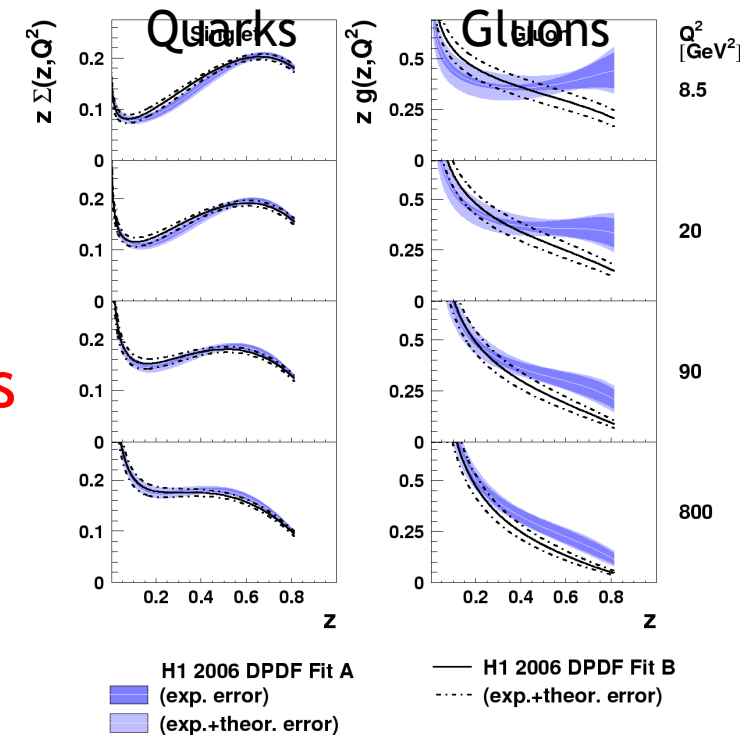
... NLO predictions based on HERA DPDFs give impressive description of all HERA 'hard' diffractive data, eg jet production ...
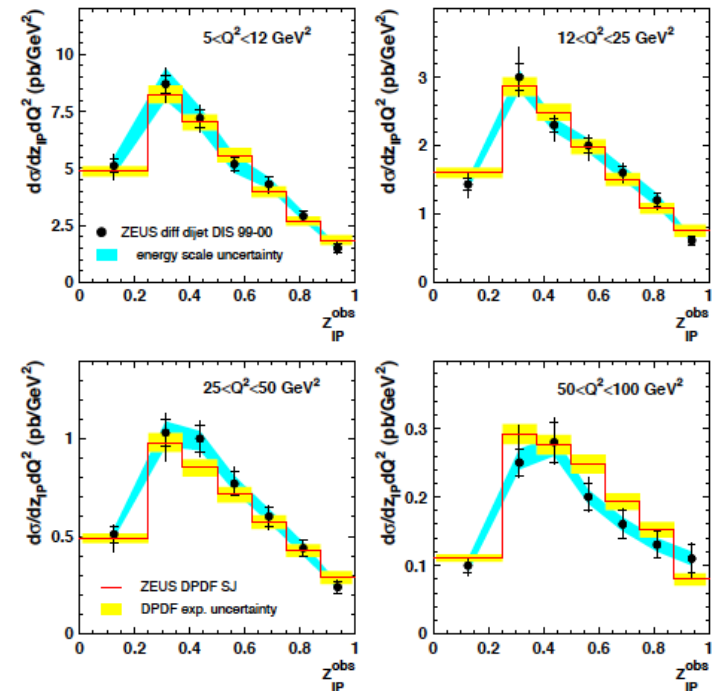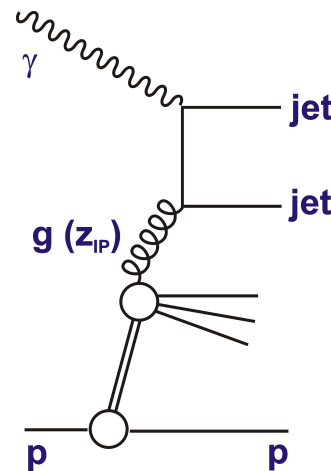
→ DPDFs used in many models in pp(bar)

... but in pp(bar)

Spectacular failure in comparison of Tevatron proton-tagged diffractive dijets with HERA DPDFs   [PRL 84 (2000) 5043]

CMS data suggest similar effect [Phys Rev D87 (2013) 012006]

... rescattering (absorptive corrections / related to MPI ...) breaks factorisation ... `rapidity gap survival probability' ~ 0.1

LHC hard diffraction sensitive to both DPDFs and gap survival probability →
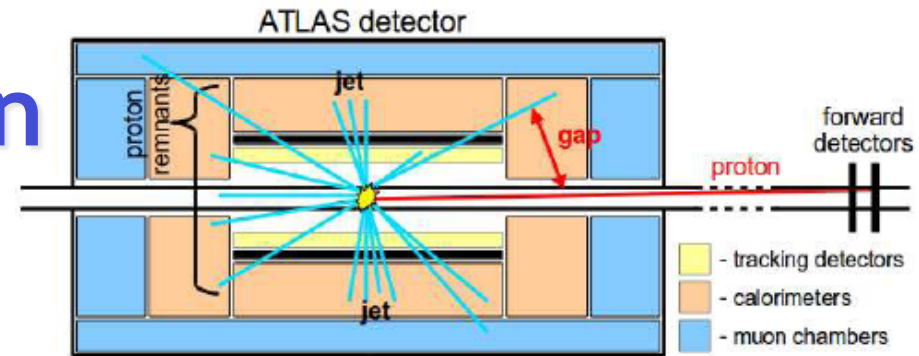**Here: First results from ATLAS:**
    ... dijets with large rapidity gaps ...
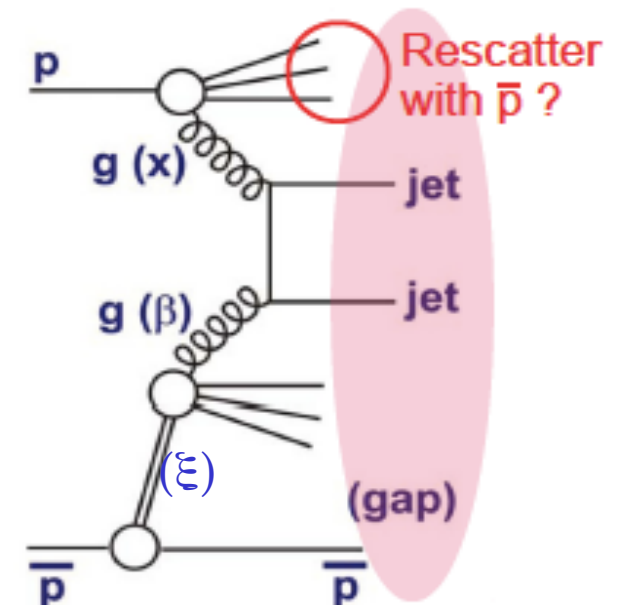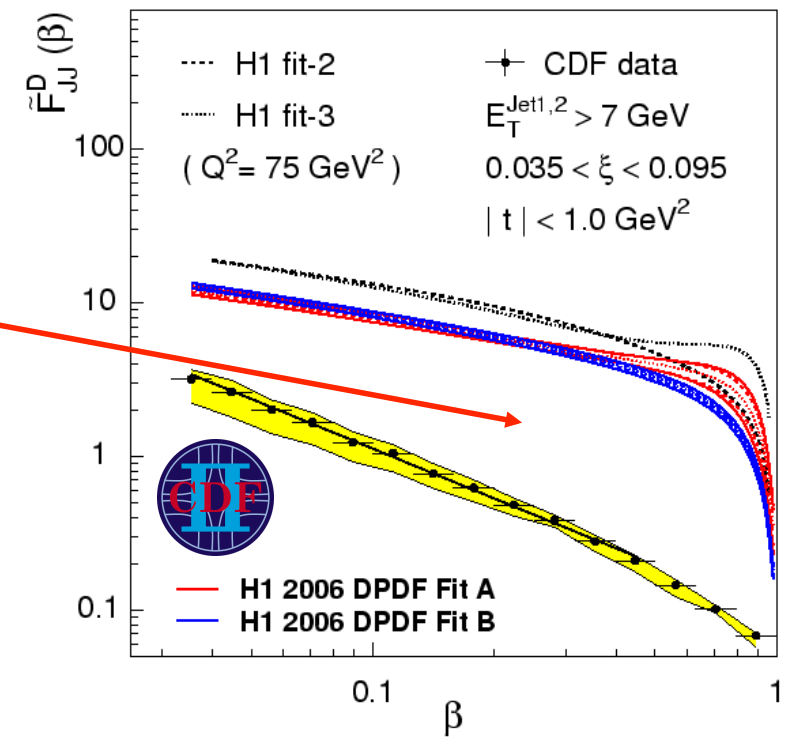
Kinematics & Selection

- Low pile-up data sample from 2010 with $\sqrt{s}$ = 7 TeV and integrated luminosity of 6.8 nb^{-1}.

- Triggered using either MBTS or calorimeter jet triggers

- Jets with anti-k_T algorithm, p_T > 20 GeV, $|\eta|$ < 4.4, R=0.4, 0.6

- Gaps characterised using $\Delta\eta^F$, based on tracks ($|\eta|$ < 2.5) and calo cells ($|\eta|$ < 4.8) that are >5σ out of noise distribution.

- Corrected cross sections correspond to gaps with no neutral particle with p > 200 MeV and no charged particle with p > 500 MeV or p_T > 200 MeV.

- Uncertainty dominated by jet energy scale

Models

- POMWIG: Dedicated hard diffraction
model with standard factorisable pomeron
approach:
Cross section ingredients are proton PDFs,
pomeron Flux and DPDFs

- PYTHIA8: Inclusive model with hard
and soft ND, DD and SD contributions;
smoothly interfaced.
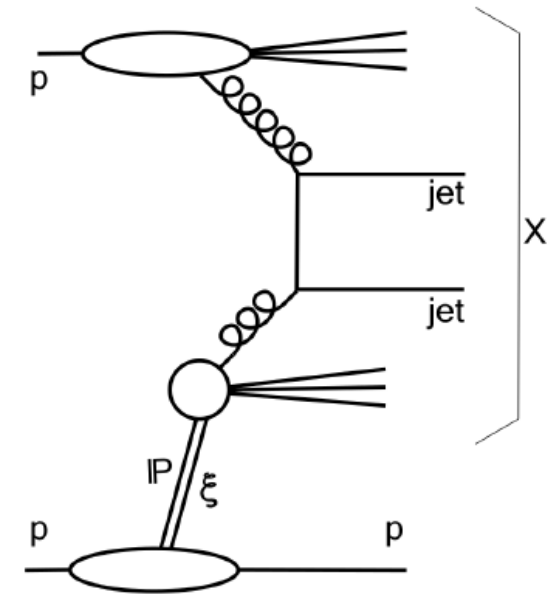
- Both models use HERA DPDFs (H12006-FitB)

- Neither model includes rapidity gap destruction effects

- Alternative ND model from POWHEG-NLO interfaced to PYTHIA

Constraining ξ

$$\tilde{\xi} \simeq M_X^2/s = \sum p_T e^{\pm\eta} / \sqrt{s}$$

... approximation to ξ which is relatively insensitive to losses of parts of X system into the beam-pipe
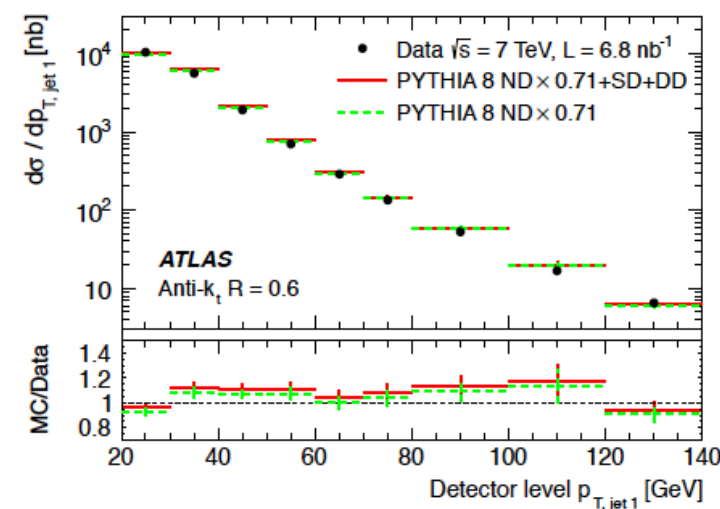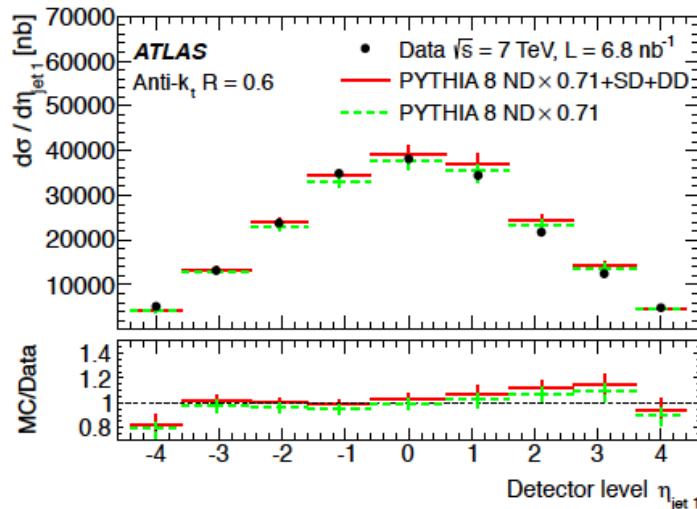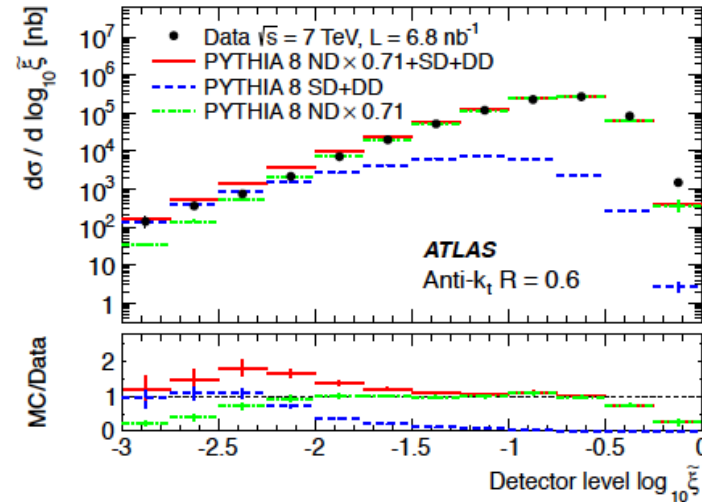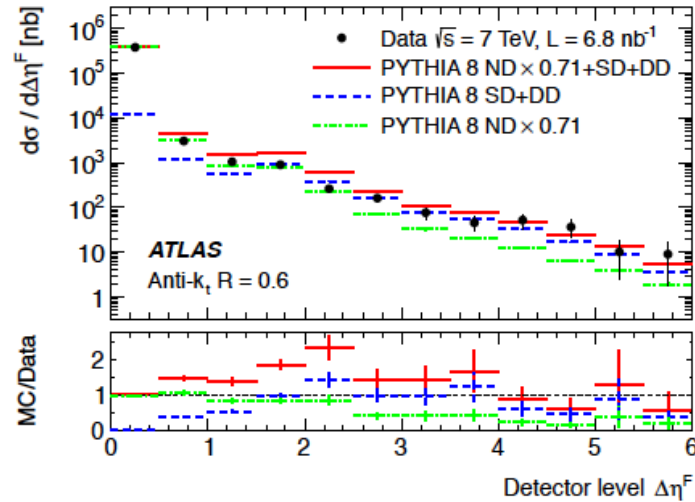

[PYTHIA8]

(truth level)

ATLAS Simulation
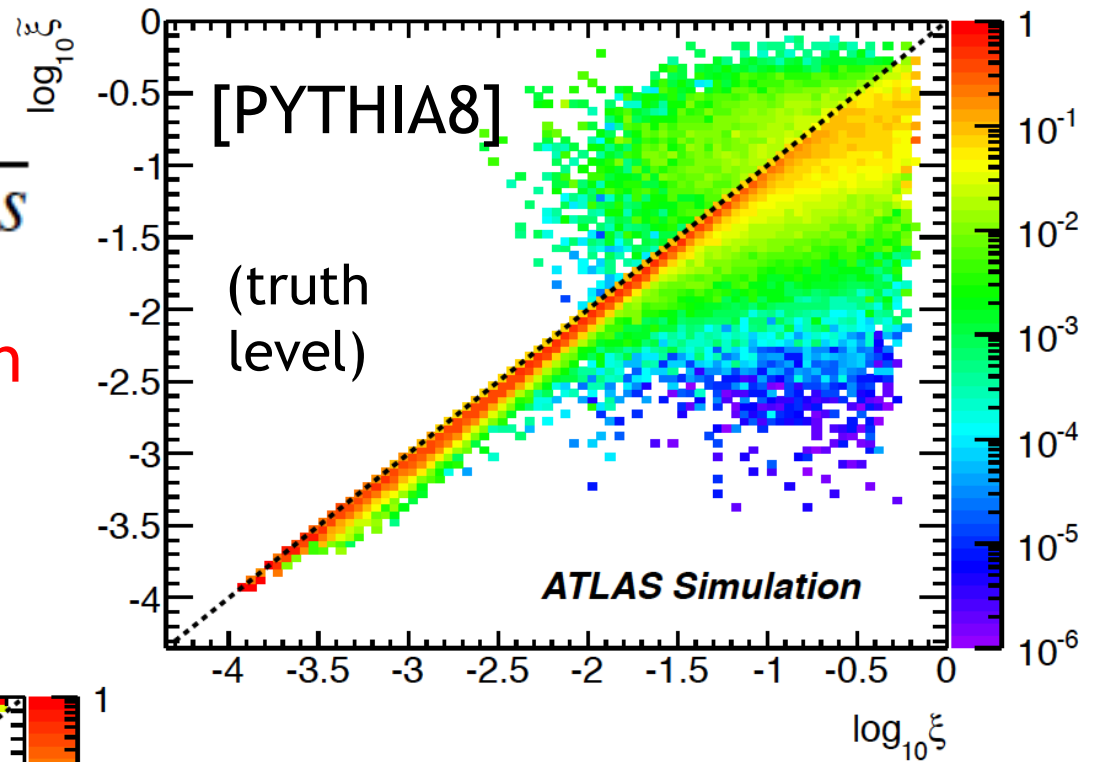
$\tilde{\xi}$ close to true ξ at truth level up to ~10^{-2} (slightly smaller, as only include particles in fiducial region).

Experimental resolution on log $\tilde{\xi}$ approximately 10%.

[PYTHIA8]

ATLAS Simulation

Detector level log$_{10}\tilde{\xi}$

23
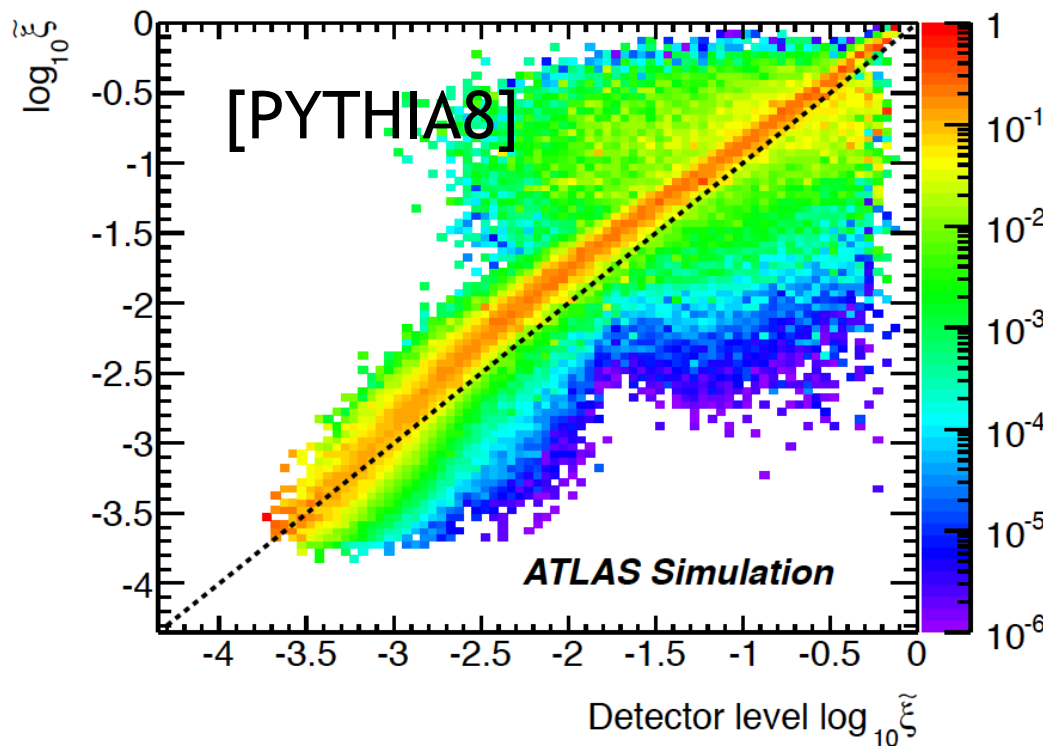
Unorrected Data (Control Distributions)

PYTHIA8 MC: ND scaled x 0.71 to match first bin of $\Delta\eta^F$, added to SD and DD 'out of the box' → Satisfactory descriptions of all relevant distributions; used for unfolding.

Corrected Data Compared with Non-Diffractive Models

- Kinematic suppression of large gaps → no clear diffractive plateau (unlike minimum bias case)
- ND models matched to data at small gap sizes give contributions compatible with data up to largest $\Delta\eta_F$ and smallest ξ … no clear diffractive signal …
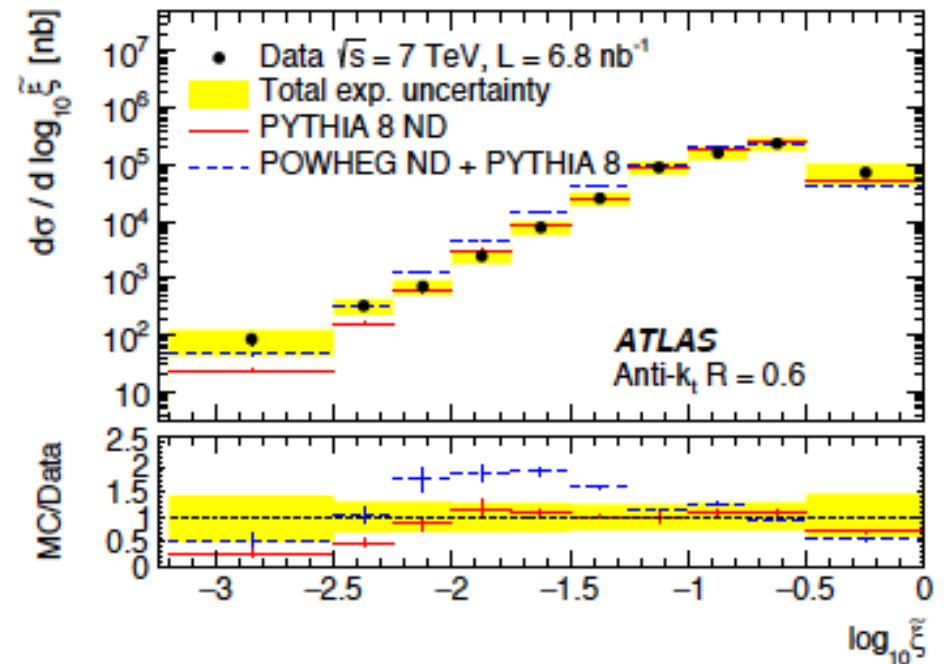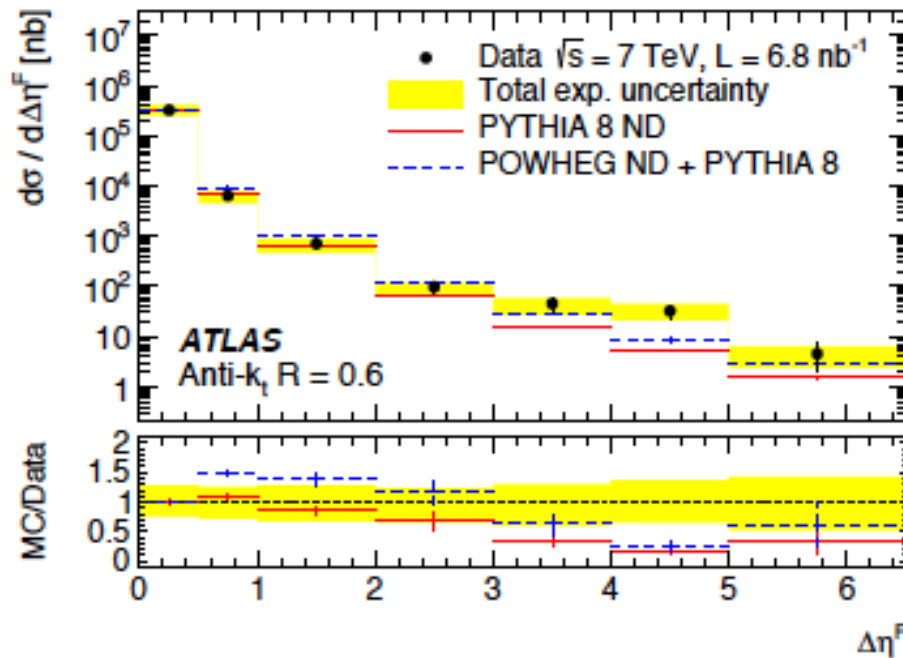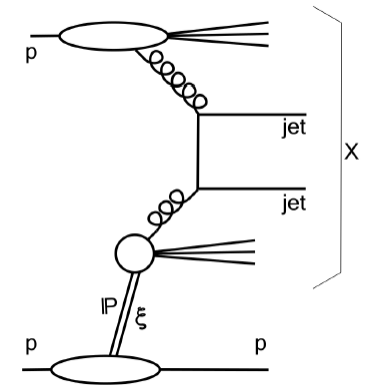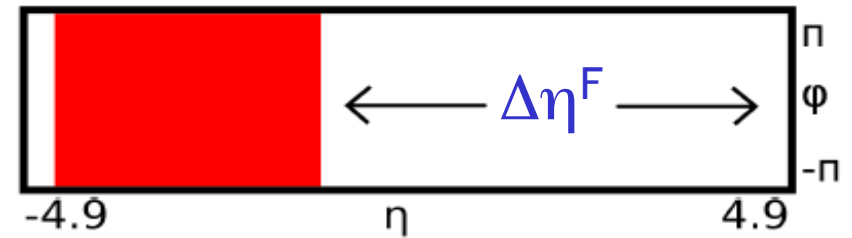
# Evidence for Diffractive Contribution

Focusing on small ξ, whist simultaneously requiring large gap size ($\Delta\eta_F > 2$) gives best sensitivity to diffractive component

→ Models with no SD jets are below data by factor >~3

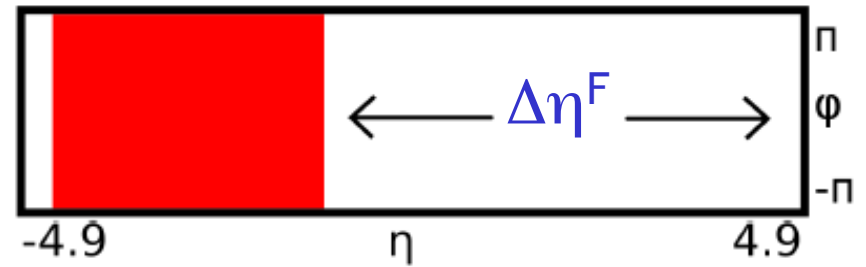→ Comparison of smallest ξ with DPDF-based model (POMWIG) leads to rapidity gap survival probability estimate ...
- Model dependence not investigated in detail
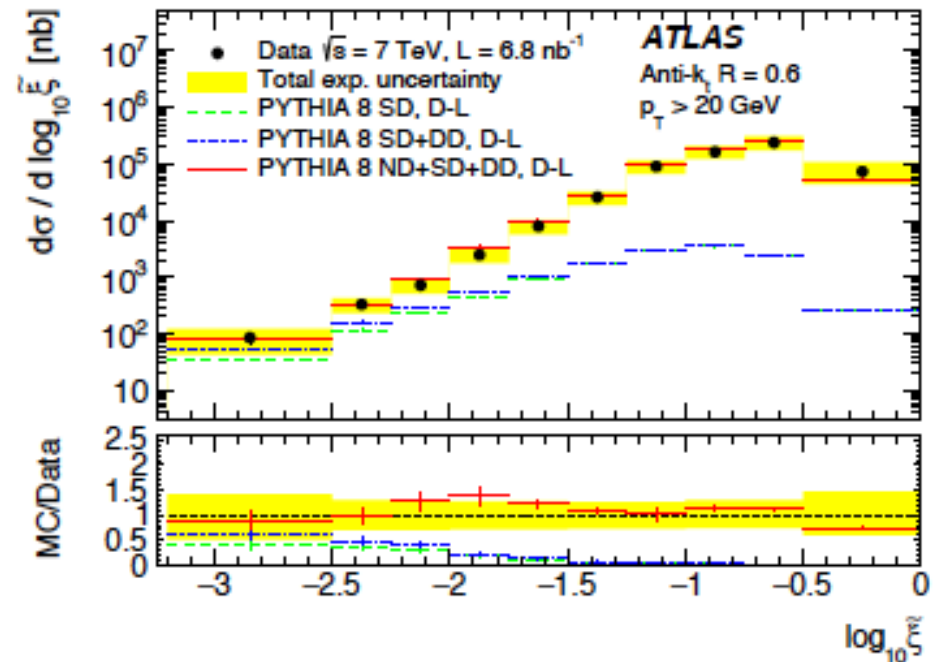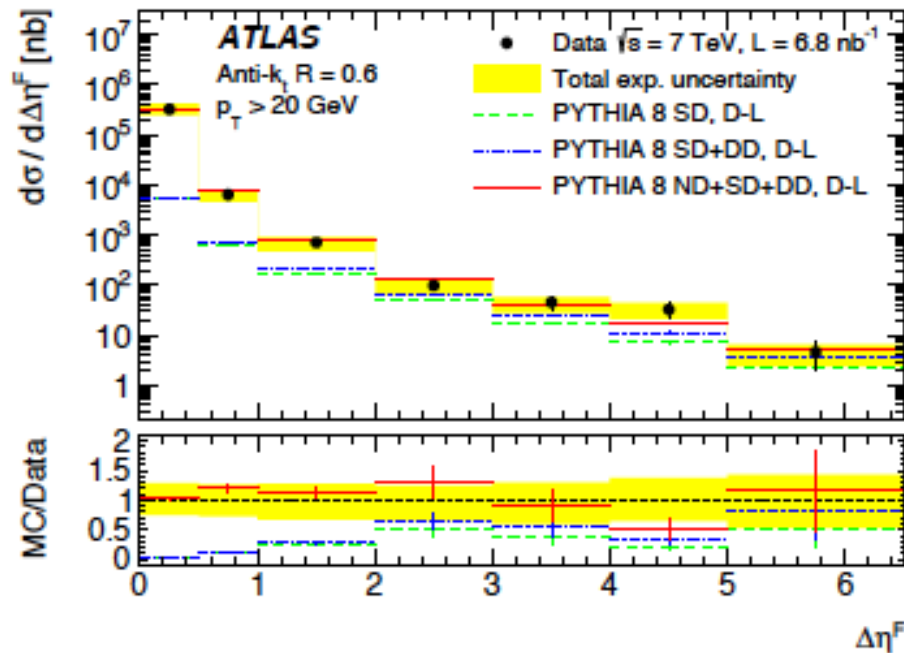- In context of POMWIG, using anti-k_T with R=0.6:
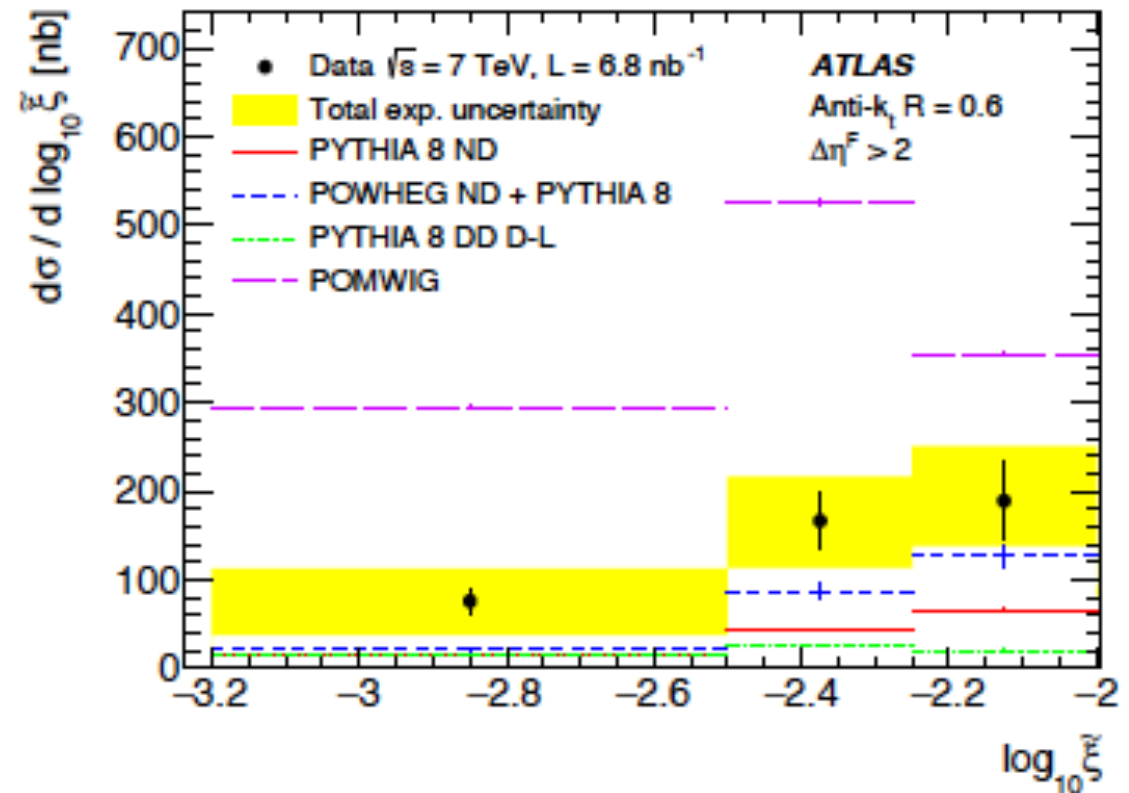
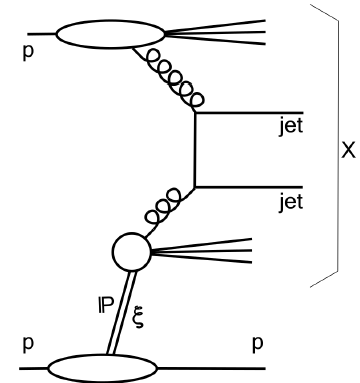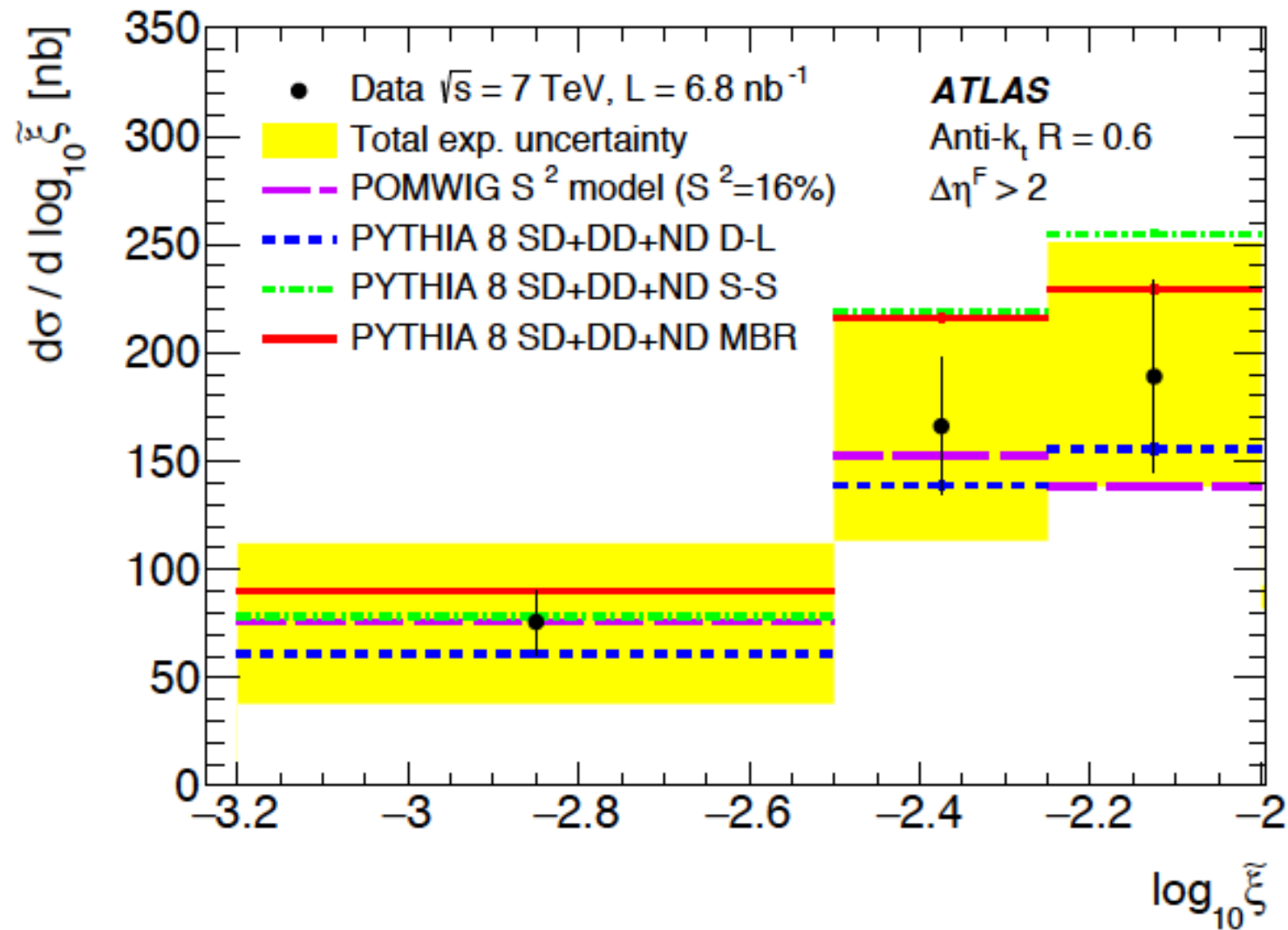$$S^2 = 0.16 \pm 0.04 \,(\text{stat.}) \pm 0.08 \,(\text{exp. syst.}) \,,$$

Comparison with Full PYTHIA8

'Off-the shelf' PYTHIA8 ND*0.71 + SD + DD does a good job at all $\Delta\eta_F$ and ξ, with no need for a gap survival factor (though ND dominates, so compatible with a wide range of S^2 values).
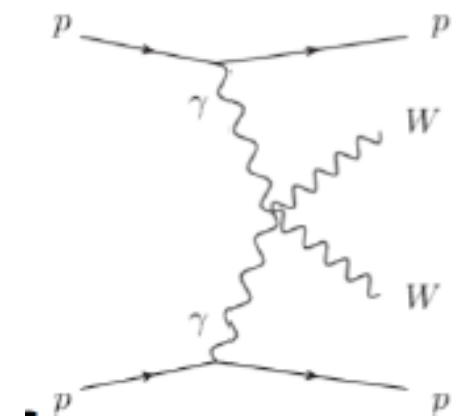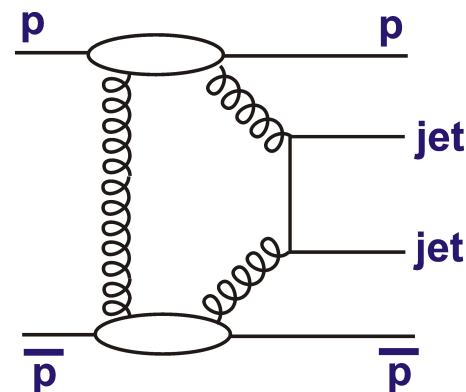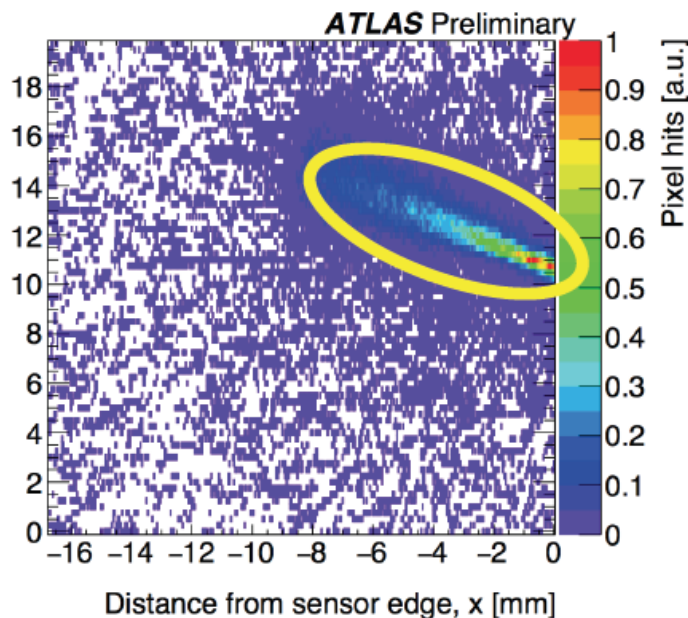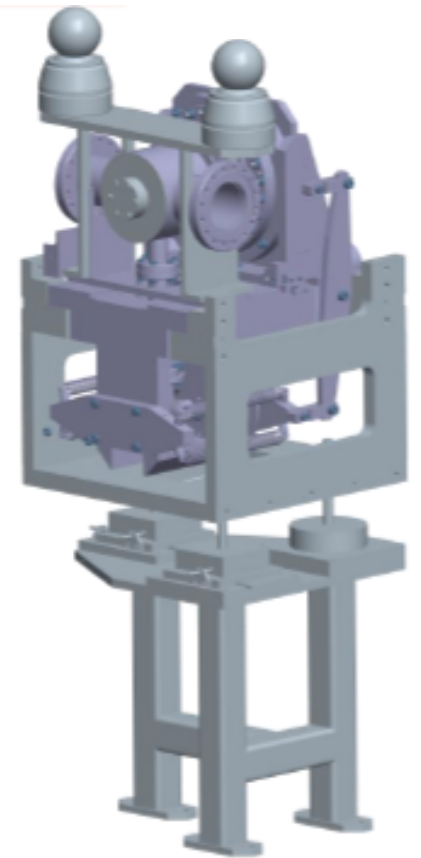
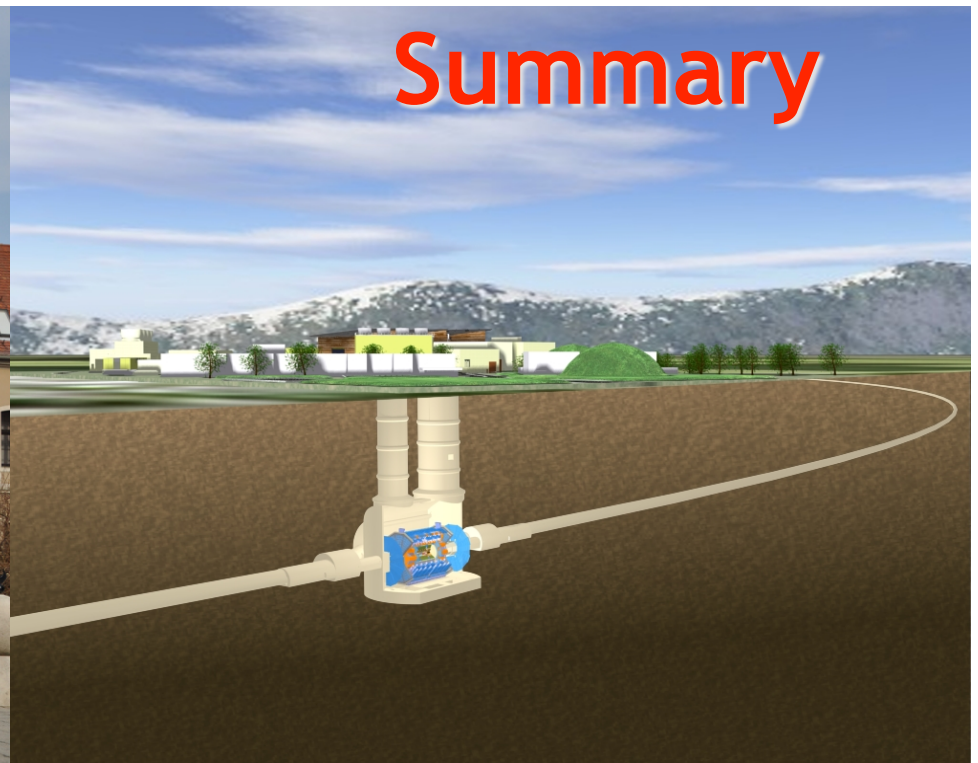# Diffractive Models Focusing on $\Delta\eta^F > 2$

Phys Lett B754 (2016), 214

Future ATLAS Diffraction

- Further progress will require proton tagging to unfold ND and DD from SD

- Short term: ongoing ALFA analysis

- Medium term = AFP, first arm commissioning underway → SD physics in 2016/17

- Longer term: AFP with two arms & high lumi → ra exclusive (or exotic) processes ...

Direct Inelastic Cross Section Measurement at √s = 13 TeV

- Significant improvement in precision (9% → 2%) over prelim.
- Some discrimination between models
- Consistent with indirect extractions using optical theorem

Dijet Cross Sections Differential in Gap Size at √s = 7 TeV

- Evidence for diffractive contribution
- Understanding limited by poorly known non-diff contribution
- Future prospects with proton spectrometers (ALFA, AFP)
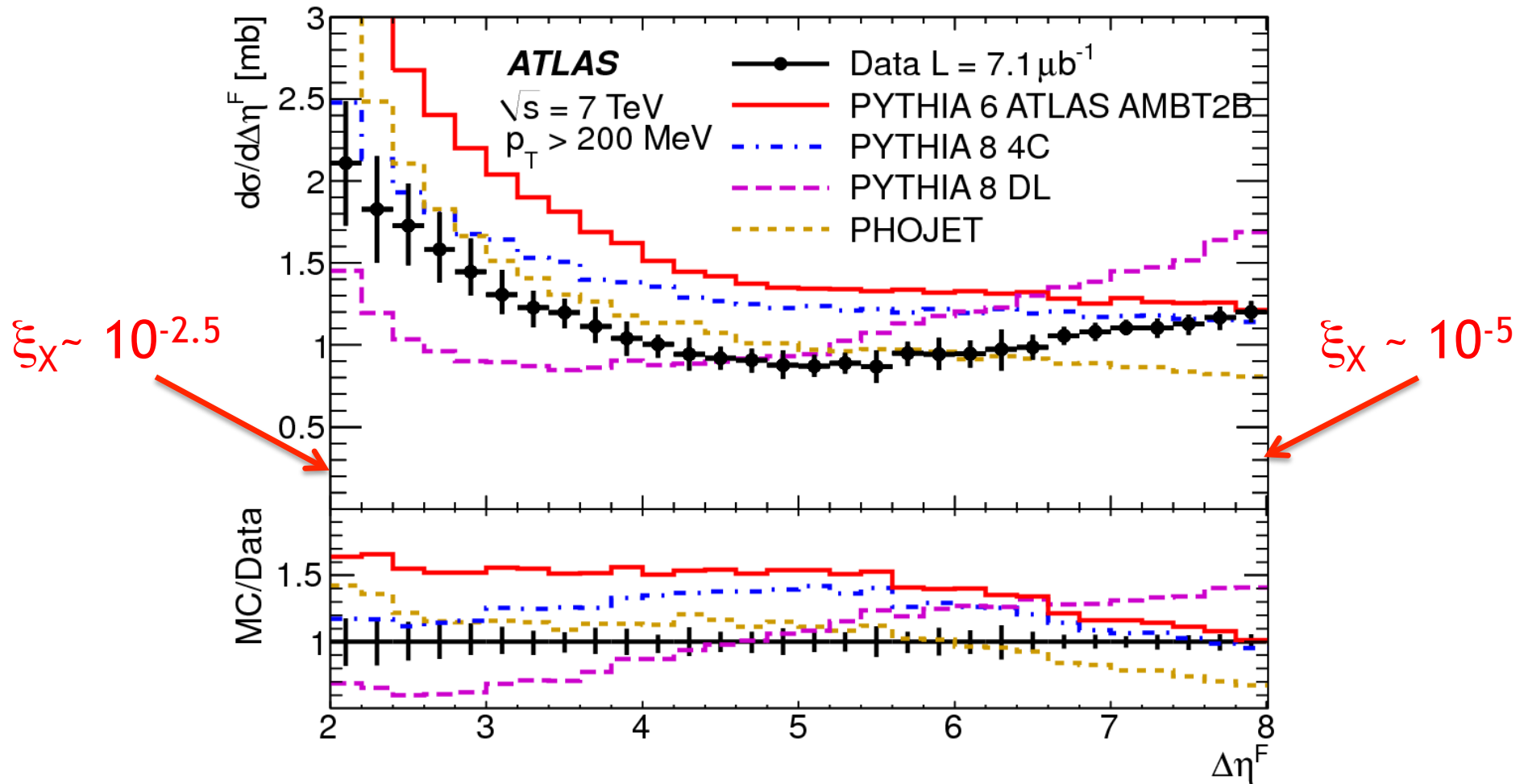
Investigating Low Mass Extrapolations
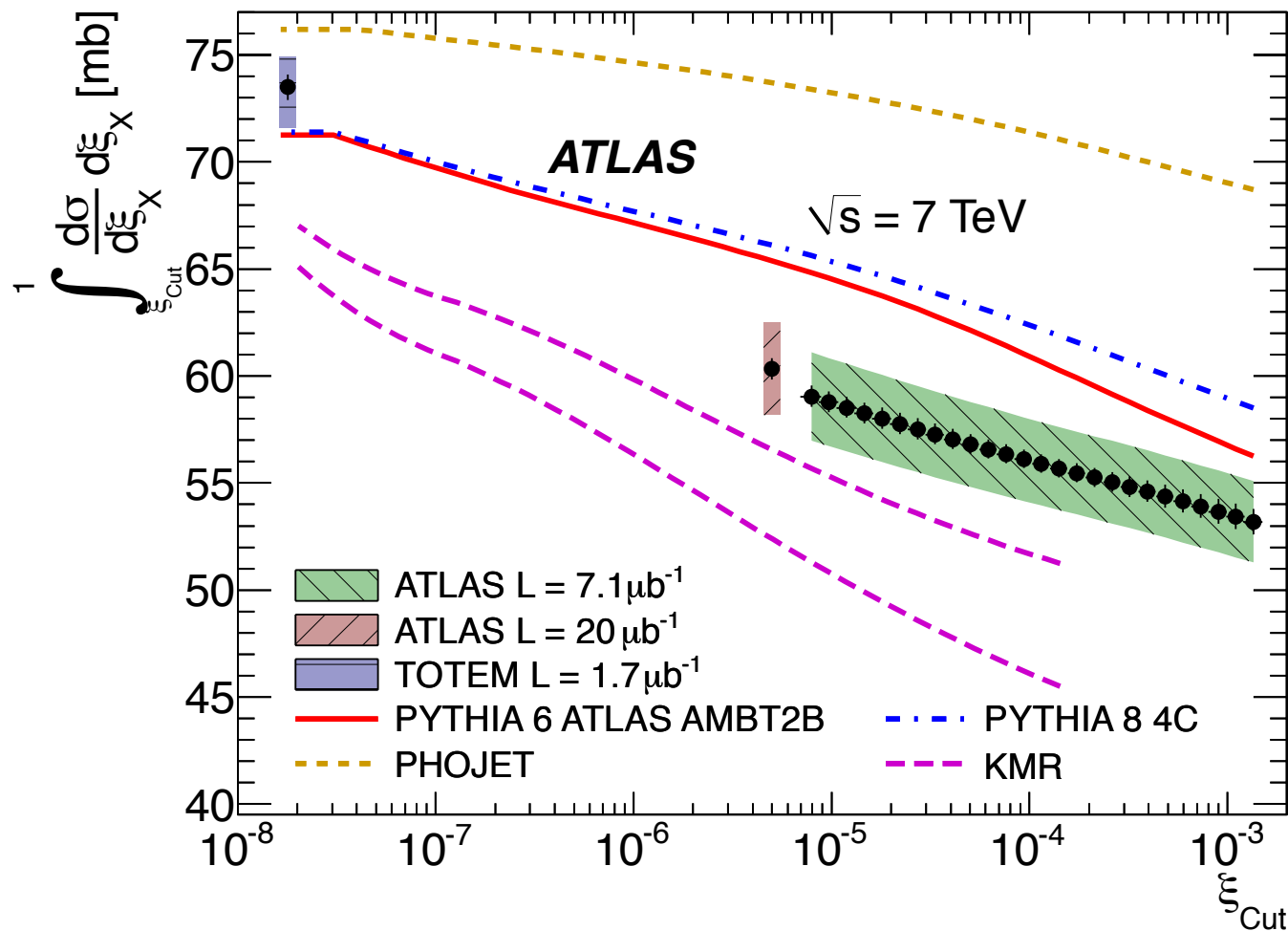
[Inelastic cross section excluding diffractive channels with $\xi < \xi_{cut}$]

- Integrating ATLAS gap cross section up to some max $\Delta\eta^F$ (equivalently min ξ_X) and comparing with TOTEM indicates that small ξ_X region underestimated in PHOJET and PYTHIA:
- 14 mb with $\xi < 10^{-5}$, compared to 6 (3) mb in PYTHIA (PHOJET)

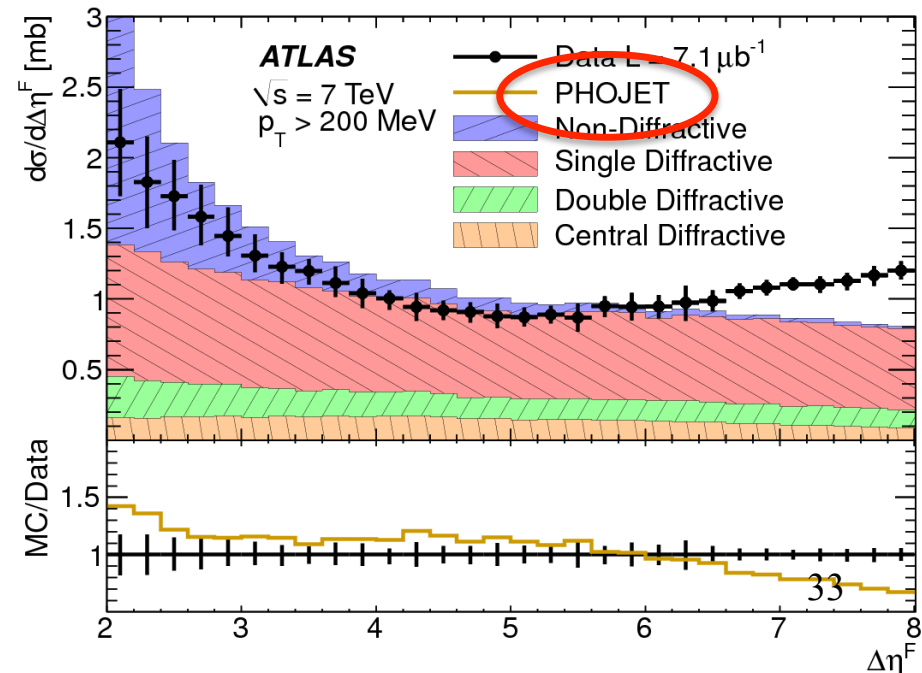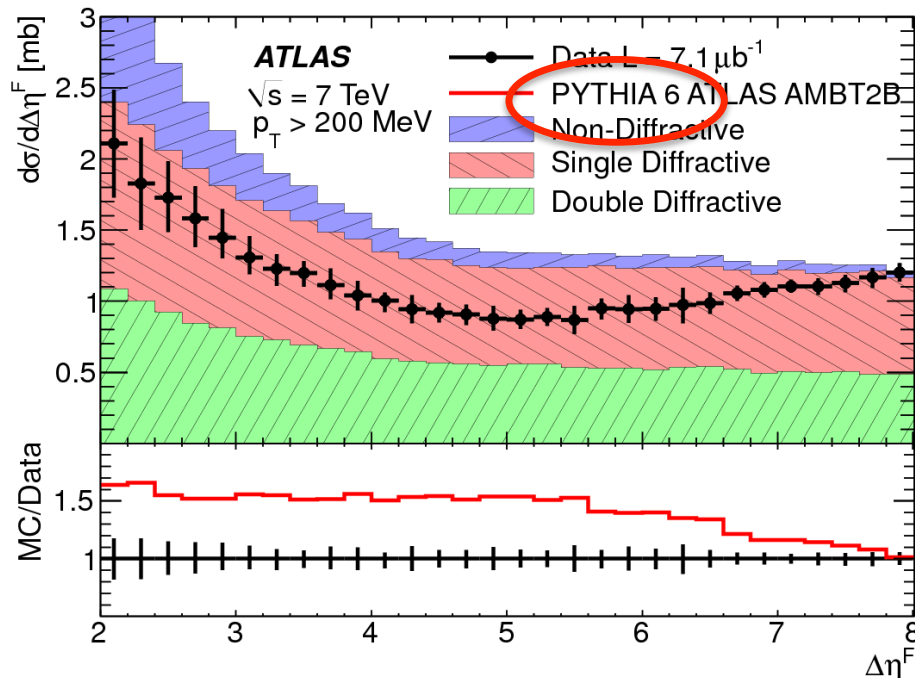# Large Gaps and Diffractive Dynamics

- Default PHOJET, PYTHIA have $\alpha_{IP}(0) = 1$; DL has $\alpha_{IP}(0) = 1.085$
- Fit to large $\Delta\eta^F$ data: $\alpha_{IP}(0) = 1.058 \pm 0.003$ (stat) ± 0.036 (syst)
- CMS also favour intermediate value of $\alpha_{IP}(0)$

Large Gaps and Diffractive Dynamics

-Diffractive plateau with ~ 1 mb per unit of gap size for $\Delta\eta^F > 3$
- Broadly described by models
- $\alpha_{IP}(0) = 1.058 \pm 0.036$ (ATLAS)
- Further significant progress will require proton tagging to unfold SD from DD and ND

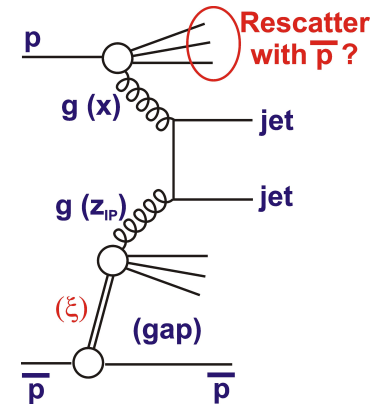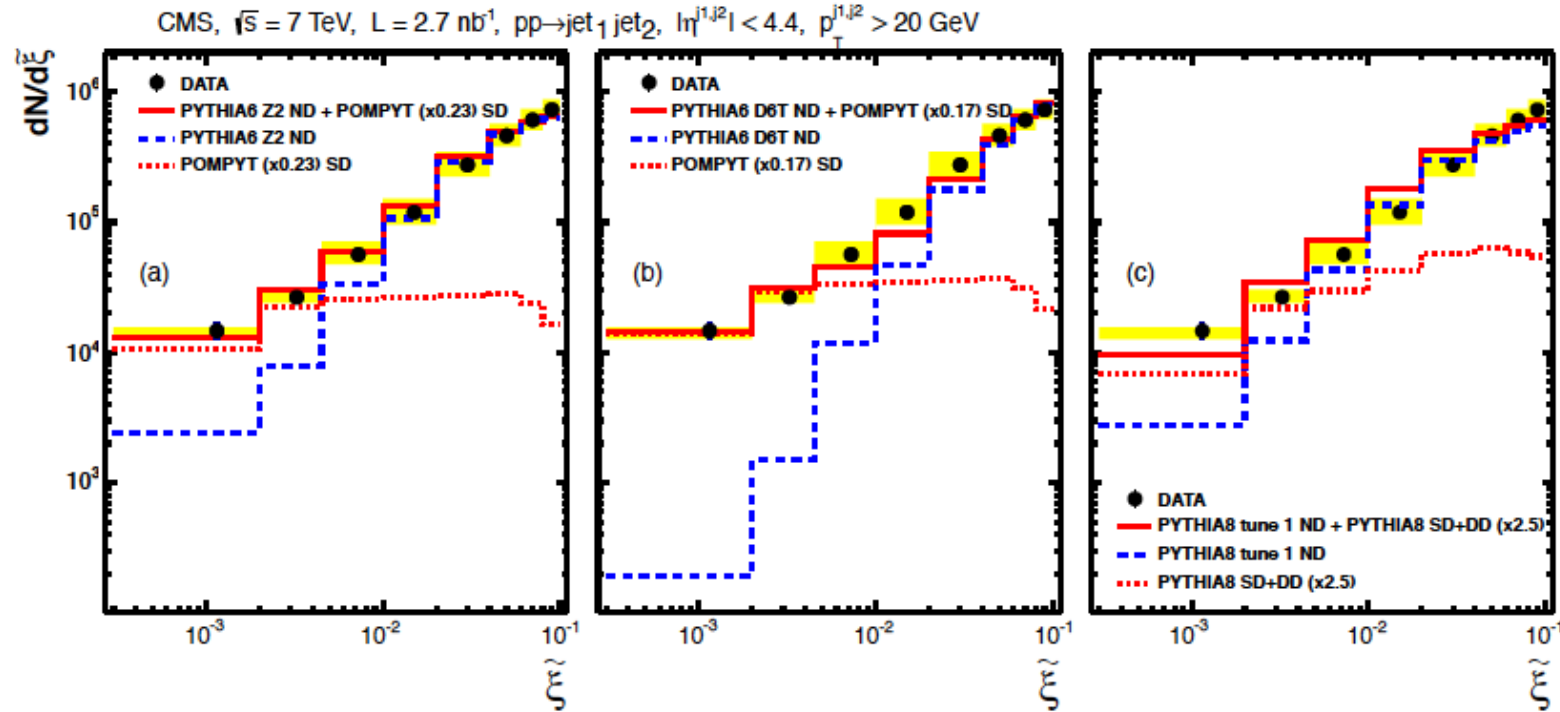# CMS Dijets with Low ξ

CMS, $\sqrt{s}$ = 7 TeV, L = 2.7 nb^{-1}, pp→jet$_1$jet$_2$, |$\eta^{j1,j2}$| < 4.4, $p_T^{j1,j2}$ > 20 GeV

(a)
- DATA
- PYTHIA6 Z2 ND + POMPYT (x0.23) SD
- PYTHIA6 Z2 ND
- POMPYT (x0.23) SD

(b)
- DATA
- PYTHIA6 D6T ND + POMPYT (x0.17) SD
- PYTHIA6 D6T ND
- POMPYT (x0.17) SD

(c)
- DATA
- PYTHIA8 tune 1 ND + PYTHIA8 SD+DD (x2.5)
- PYTHIA8 tune 1 ND
- PYTHIA8 SD+DD (x2.5)
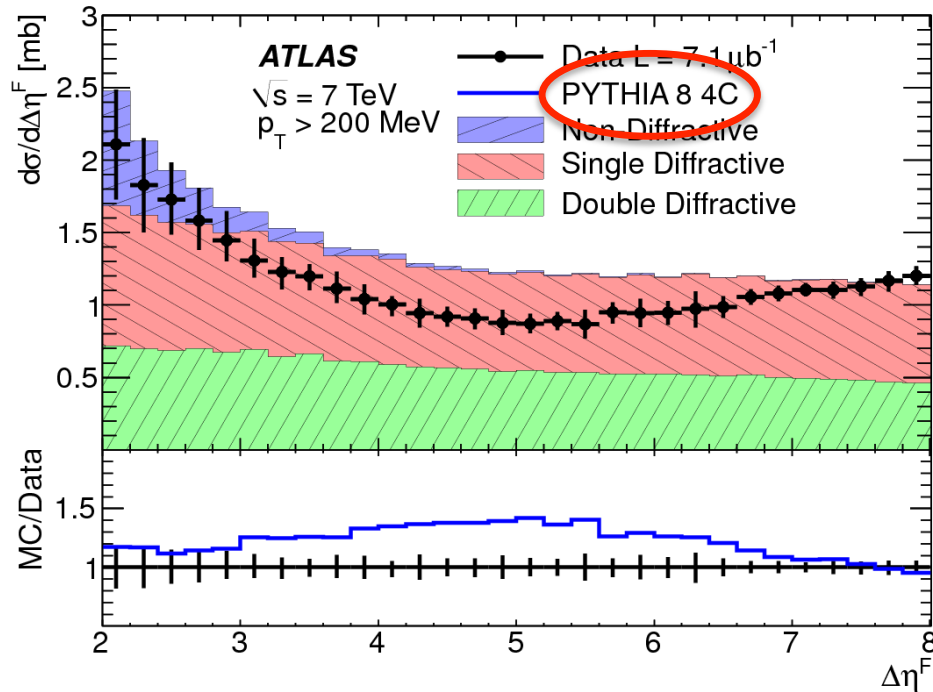
Uncorrected data prior to rapidity gap selection

- Diffractive signal required at low ξ (Data > PYTHIA ND)

- Fit linear combination of PYTHIA (ND) and POMPYT / PYTHIA8-SD+DD (DPDF-based diffractive models)

→ Best description from PYTHIA6 with POMPYT x 0.23

→ PYTHIA8, SD/DD contribution has to be multiplied by a factor ~2.5 and still gives inferior description

Comparison between CMS and ATLAS

Using first ever LHC run at 7TeV (avoiding pile-up)

- Agreement on overall characteristics

- Cross sections defined slightly differently

- ATLAS: $\Delta\eta^F$ extends from $\eta = \pm4.9$ to 1st particle with $p_t > 200$ MeV

- CMS: $\Delta\eta^F$ extends -from $\eta = \pm4.7$ to 1st -particle with $p_t > 200$ MeV