Diffractive Studies at the LHC & Possible Scenario at the EIC

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Outline

- Introduction
- Existing Diffractive Studies at the Large Hadron Collider (LHC)
- Relevance with Electron-Ion Collider (EIC)
- Summary

Introduction

Hadron-Hadron Collisions

Elastic Scattering

- Initial state hadrons and absolute values of their momenta remains intact.
- Change in directions via a colourless exchange.
- Quantum numbers of the interacting systems remains same.

Inelastic Scattering

Diffractive

- Also mediated by colourless exchange via **pomeron**s.
- The rapidity gaps (RG: the regions with no particles) exists and are not exponentially suppressed.

Non-Diffractive

- mediated by coloured exchange
- The final phase-space is filled with particles with no RG or with exponentially RG.

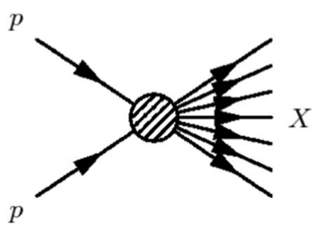
- *~25% of the total inelastic proton-proton cross-sections at the high energies may be attributed to diffractive processes*

Phy. Rev. D92 (2015) 012003

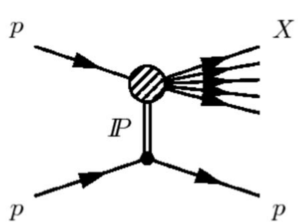
Inelastic hadron collisions

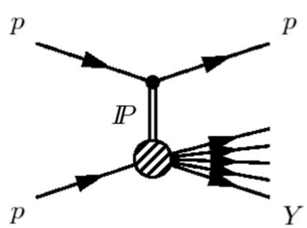
Inelastic Hadron Collisions

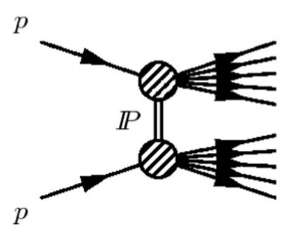
- **Non-Diffractive (ND)**

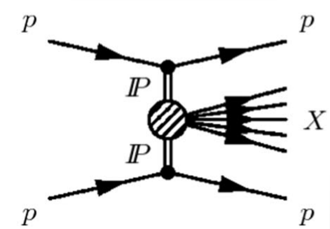


- **Diffractive**
  - **Single Dissociation (SD)**
  - **Double Dissociation (DD)**
  - **Central Dissociation (CD)**





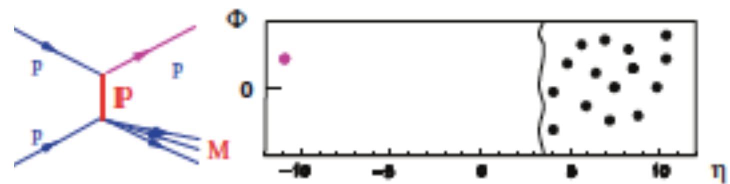




Diffractive Processes

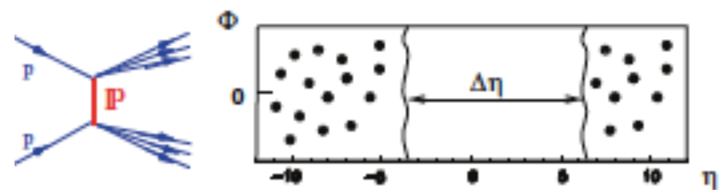
- **Single diffractive** (SD) processes:

  One of the initial state hadron remains intact and the other one dissociates and hadronizes resulting in a final state with a forward proton on one side and a system of particles on the other side.



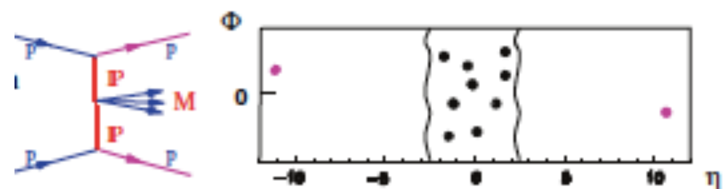
- **Double diffractive** (DD) processes

  Both initial state hadrons dissociates and hadronize resulting in system of particles on both sides of the rapidity gap.



- **Central diffractive** (CD) processes

  Both protons remain intact and a system of particles is produced in central region with rapidity gaps b/w both protons and central system.



What motivates?

- The inclusive diffractive processes can not be calculated within perturbative quantum chromodynamics (QCD) and are commonly described by models based on the Regge theory.
- The predictions of such models differs while extrapolation from Tevatron energies to LHC energies.
- The diffractive cross-section measurements at the LHC provide a valuable inputs for understanding diffraction and improving its theoretical description.
- These studies are also crucial for proper modelling of the full final state of hadronic interactions in event generators and help to improve the simulation of underlying event as well as total inelastic cross-section.

Diffractive Measurements @LHC

- Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s}$ = 8 TeV pp collisions using ATLAS ALFA spectrometer

CERN-EP-2019-190 (submitted to JHEP)

- Measurement of diffractive dissociation cross sections in pp collisions at $\sqrt{s}$ = 7 TeV

Phy. Rev. D92 (2015) 012003

- Measurement of inelastic, single- and double-diffraction cross-sections in proton-proton collisions at the LHC with ALICE

Eur. Phy. J. C73 (2013) 2456

Results from ALICE experiment

Measurement of inelastic, single- and double-diffraction cross-sections in proton-proton collisions at the LHC with ALICE

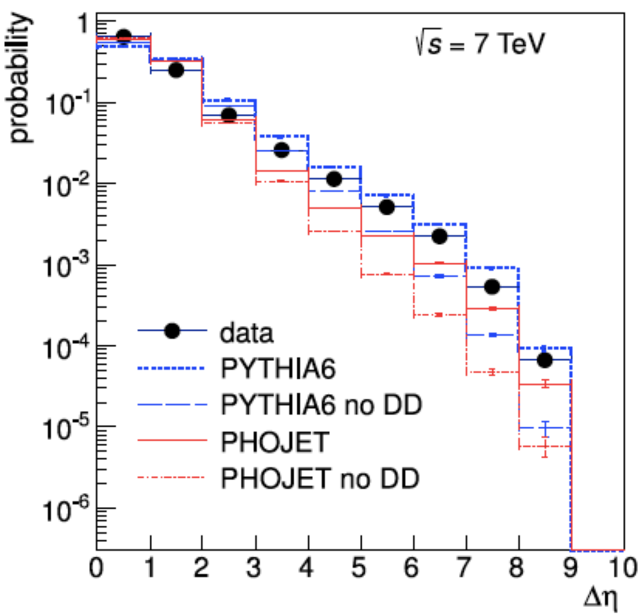
Eur. Phy. J. C73 (2013) 2456

- At different centre-of-mass energies $\sqrt{s}$ = 0.9 TeV, 2.76 TeV & 7 TeV
- Reports the measurements of inelastic pp cross-section with a precision better than 6% and emphasizes the importance of diffraction processes in such measurements.
- The nucleon-nucleon inelastic cross section (a basic parameter used as input for model calculations to determine the number of participating nucleons and number of nucleon-nucleon binary collisions in heavy-ion collisions).
- The uncertainties on diffractive processes may dominate over all the overall systematic uncertainties in LHC measurements (particle momentum distributions, cross sections, etc.) → **Need of precise measurements**

Results from ALICE experiment

Eur. Phy. J. C73 (2013) 2456

- Data collected with low beam current and low luminosity (leads to small corrections for beam backgrounds and small event pileup in a given bunch crossing)
- At $\sqrt{s}$ = 7 TeV, minimum average number of collisions per bunch crossing = 0.1
- The LRG distributions are compared for data and various simulations (PYTHIA6 and PHOJET, in particular)
- To illustrate the sensitivity to DD, the events are also simulated without DD.



Results from ALICE experiment

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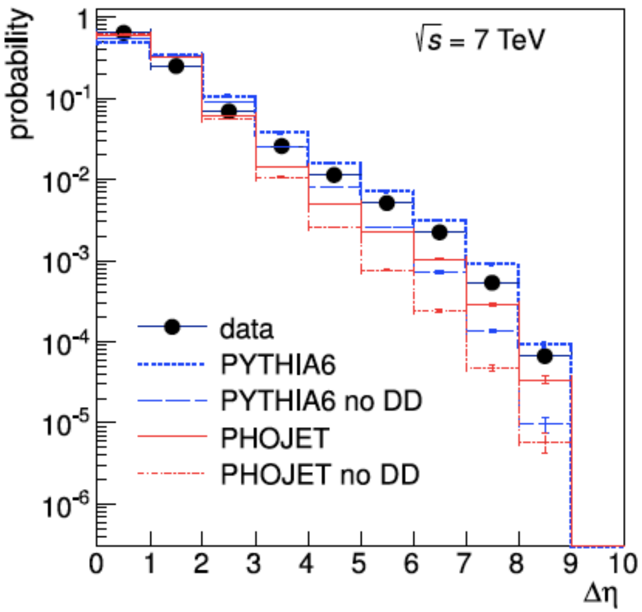
- The gap width distributions at large Δη values are not described by simulations without DD.
- The default DD fraction overestimates the distributions in in PYTHIA6 and underestimates in PHOJET.
- The simulations by two generators are **adjusted** by varying the DD fraction so as to match with data distributions.



Results from ALICE experiment

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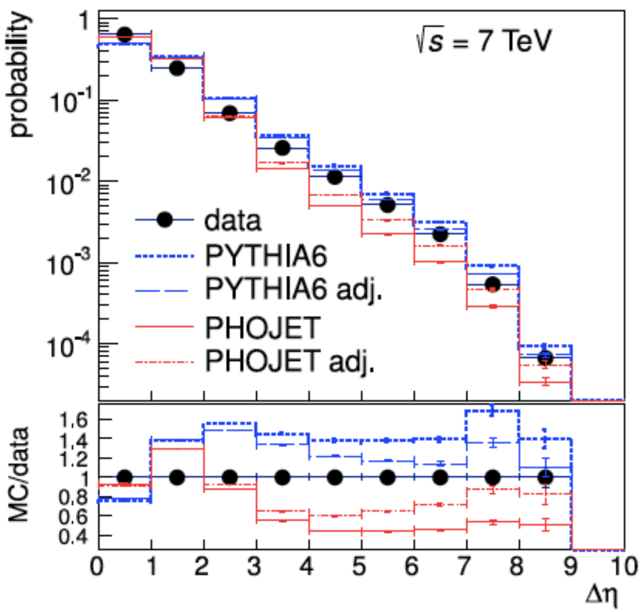
- After **adjustments**, PYTHIA6 still overestimates the data and PHOJET still underestimates the data.
- BUT, the agreement is close to 10%, which is better as compared to without adjustments.



Results from ALICE experiment

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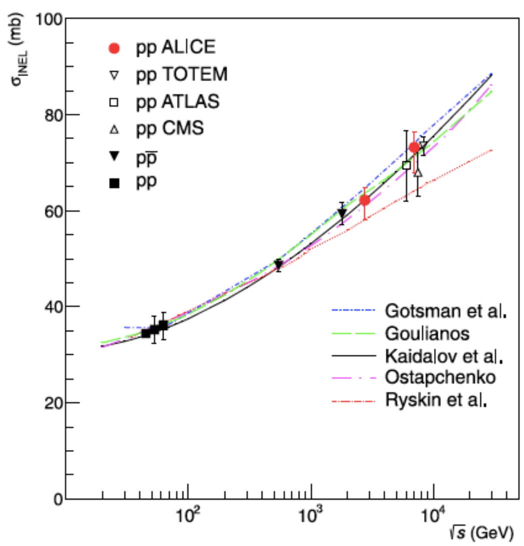
	$\sqrt{s}$ = 0.9 TeV	$\sqrt{s}$ = 2.76 TeV	$\sqrt{s}$ = 7 TeV
$\sigma_{SD}/\sigma_{INEL}$	0.21 ± 0.03	$0.20^{+0.07}_{-0.08}$	$0.20^{+0.04}_{-0.07}$
$\sigma_{DD}/\sigma_{INEL}$	011 ± 0.03	0.12 ± 0.05	$0.12^{+0.05}_{-0.04}$
σ_{INEL} (mb)	-	$62.8^{+2.4}_{-4.0}(mod.) \pm 1.2(lumi)$	$73.2^{+2.0}_{-4.6}(mod.) \pm 2.6(lumi)$
σ_{SD} (mb)	-	$12.2^{+3.9}_{-5.3}$	$14.9^{+3.4}_{-5.9}$
σ_{DD} (mb)	-	7.8 ± 3.2	9.0 ± 2.6

- Forward Multiplicity Detector (FMD) of ALICE was not used during data taking at $\sqrt{s}$ = 2.76 TeV, which leads to large systematic uncertainties.
- The inelastic cross section is not measured at $\sqrt{s}$ = 0.9 TeV.

Results from ALICE experiment

Experiment	σ_{INEL} (mb)	$\sigma_{\mathrm{INEL}}^{\xi>5\times10^{-6}}$ (mb)
ALICE	$73.2^{+2.0}_{-4.6}$(model) $\pm$ 2.6(lumi)	$62.1^{+1.0}_{-0.9}$(syst) $\pm$ 2.2(lumi)
ATLAS	69.4 $\pm$ 6.9(model) $\pm$ 2.4(exp)	60.3 $\pm$ 0.5(syst) $\pm$ 2.1(lumi)
CMS	68.0 $\pm$ 4.0(model) $\pm$ 2.0(syst) $\pm$ 2.4(lumi)	60.2 $\pm$ 0.2(stat) $\pm$ 1.1(syst) $\pm$ 2.4(lumi)
TOTEM	$73.5^{+1.8}_{-1.3}$(syst) $\pm$ 0.6(stat)	

Excluding lower mass diffraction contribution with M_X > 15.7GeV



- Comparable with other LHC experiments
- Slightly higher values than CMS & ATLAS
- Comparable with model predictions which predicted non-LHC data fairly well

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Results from ALICE experiment

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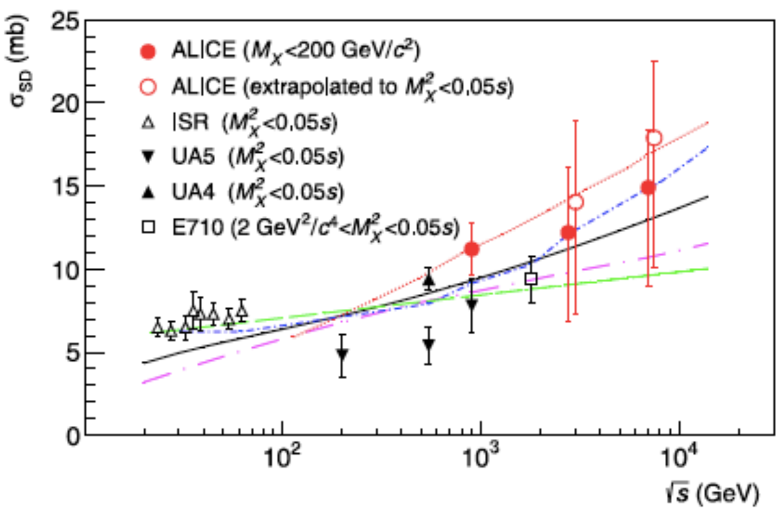
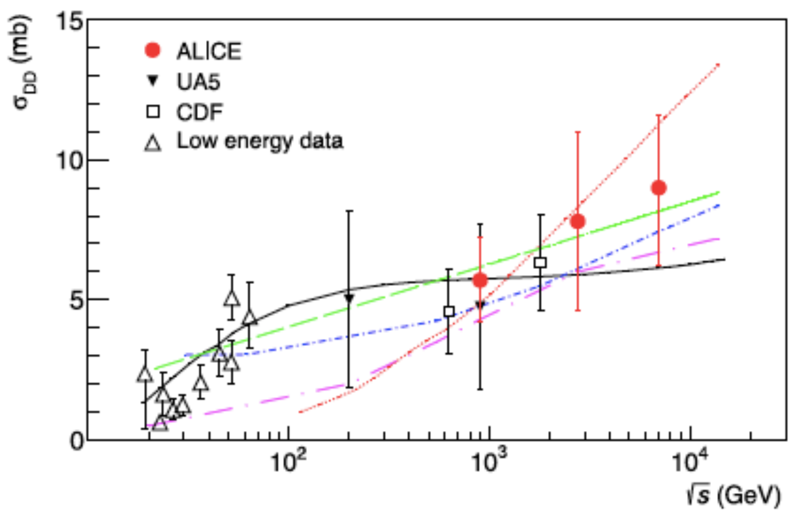
$\sqrt{s}$ (TeV)	σ_{SD} (mb)	σ_{DD} (mb)
0.9	$11.2^{+1.6}_{-2.1}$(syst)	5.6 ± 2.0(syst)
2.76	$12.2^{+3.9}_{-5.3}$(syst) ± 0.2(lumi)	7.8 ± 3.2(syst) ± 0.2(lumi)
7	$14.9^{+3.4}_{-5.9}$(syst) ± 0.5(lumi)	9.0 ± 2.6(syst) ± 0.3(lumi)





- UA measurement of 52.5(±?) mb for inelastic cross-section is used @ 0.9 TeV
- The results are extrapolated to facilitate comparison with other measurements.
- Good agreement within (large) uncertainties

Results from CMS experiment @ 7 TeV

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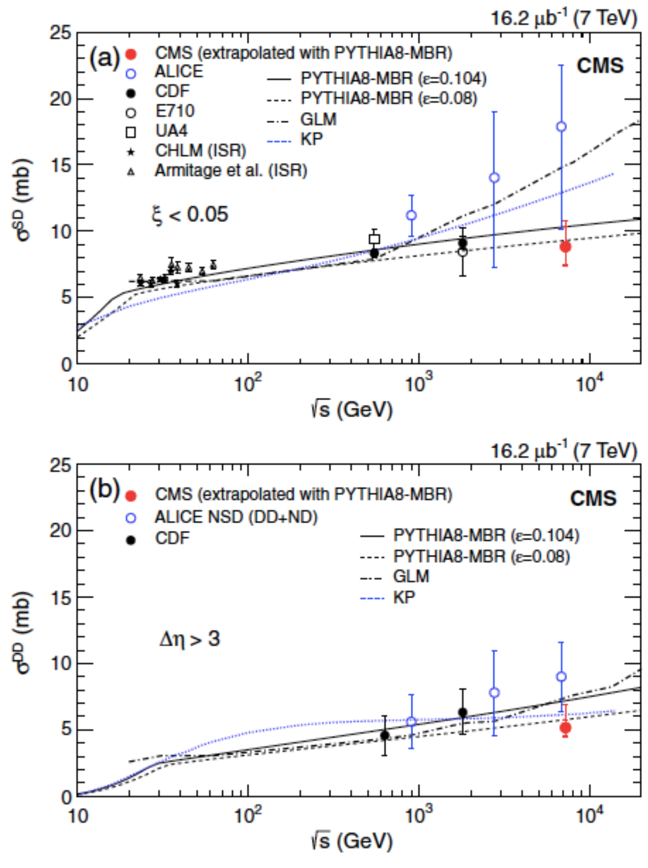
- Measurement using $\sqrt{s}$ = 7 TeV pp collisions
- Differential cross sections are measured as a function of ξ_X ($=M_X{}^2/s$)
- Regions defined by masses (M_X, M_Y) of final state systems separated by LRG:
    - $-5.5 < \log_{10} \xi \leq -2.5$
    - $\log_{10} M_Y < 0.5$ (dominated by SD)
    - $0.5 < \log_{10} M_Y < 1.1$ (dominated by DD)
- CASTOR forward calorimeter is used to discriminate b/w the regions
- The cross section values are corrected and are extrapolated to the region of lower diffractive masses using PYTHIA8 MBR.

Results from CMS experiment @ 7 TeV

$$\sigma_{SD} = 8.84 \pm 0.08(stat)^{+1.49}_{-1.38}(syst)^{+1.17}_{-0.37}(extrap)$$

$$\sigma_{DD} = 5.17 \pm 0.08(stat)^{+0.55}_{-0.57}(syst)^{+1.62}_{-0.51}(extrap)$$

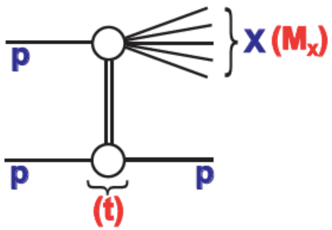
- CMS results are in agreement with weakly (?) rising SD/DD cross-section with energy as predicted by models.
- Results are comparable with those measured by ALICE within (large) uncertainties although ALICE values are significantly high.
- The difference in DD cross section measurements are possibly due to ND contribution as per definition (in ALICE)



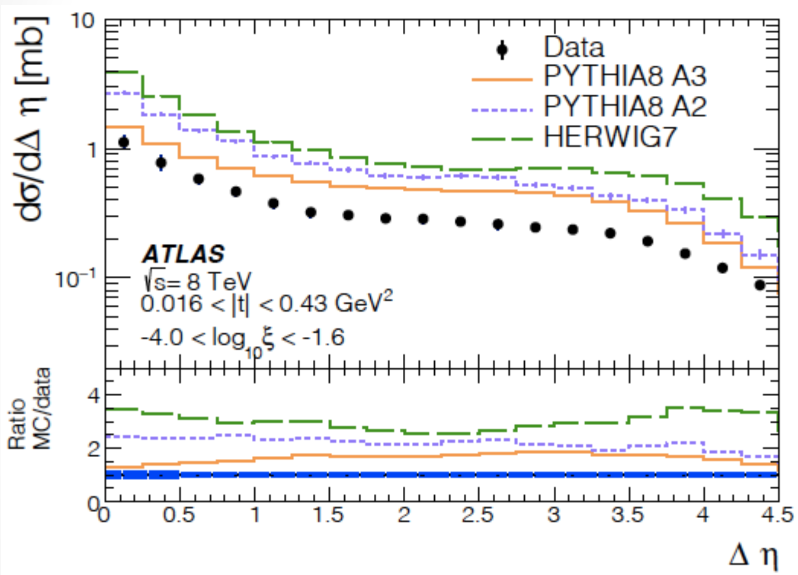
Results from ATLAS experiment @ 8TeV

CERN-EP-2019-190 (submitted to JHEP)

- Measurement is using √s = 8 TeV pp collisions
- Low luminosity data (2012) with pileup less than 0.08
- Focus on single diffractive dissociation (pp→pX) **only**
- Final state proton reconstructed using ATLAS ALFA Forward Spectrometer & charged particles from dissociated system are measured in central detector
- Cross sections are measured differentially as functions of:
  - Proton fractional energy loss (ξ)
  - Squared momentum transfer (t)
  - Large rapidity gap (Δη) between proton (p) and diffractive system (X)



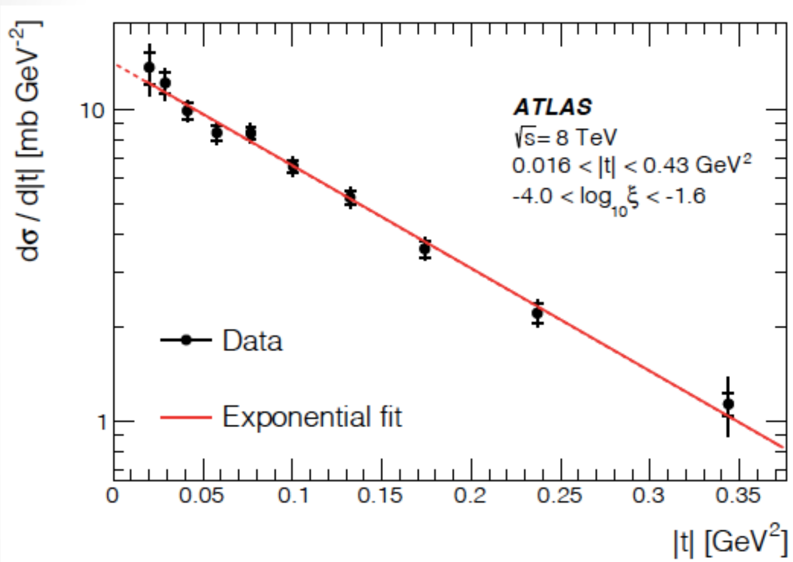
Results from ATLAS experiment @ 8TeV



- The plateau (a characteristic of rapidity gap distributions diffractive in soft diffractive processes may be observed.
- PYTHIA8 exceed the measurement by factors of 2.3 for A2 tune and 1.5 for A3 tune (due to different pomeron intercepts) which is also compatible with other ATLAS measurements.
- Fair description of shape (A2 is better!)
- HERWIG7 also predicts the shape, but exceeds the measurement by bigger factor due to definition of SD process being adopted in model.

CERN-EP-2019-190 (submitted to JHEP)

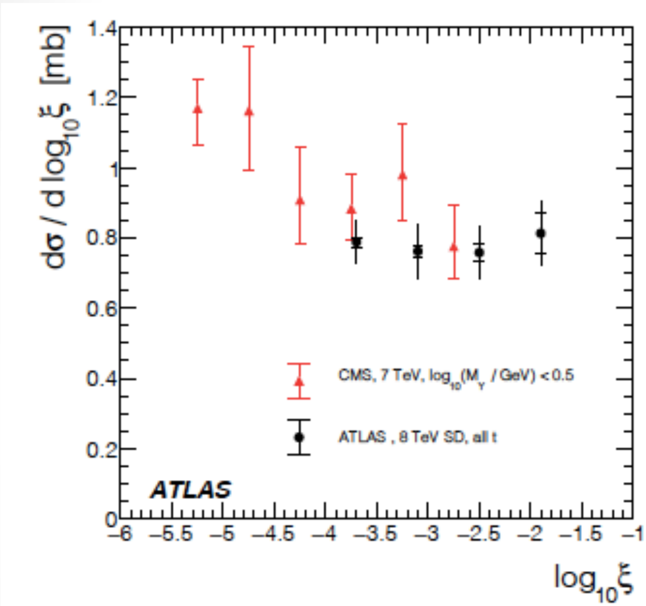
Results from ATLAS experiment @ 8TeV



- The data points are plotted at averaged value of |t| in each bin
- The fit (shown) is of the form $d\sigma/dt \propto e^{Bt}$
- B = 7.65 ±0.26 (stat.) ± 0.22 (syst.) GeV^{-2}
- The result is compatible with other model predictions.

CERN-EP-2019-190 (submitted to JHEP)

Results from ATLAS experiment @ 8TeV



- The ALTAS (@8 TeV) results are compared with CMS (@ 7 TeV) results.
- The technique adopted by CMS also includes the SD processes with small DD admixture.
- Different (but overlapping) regions are covered with a good agreement in the overlap region.
- SD cross section is calculated in full fiducial range and extrapolated to whole range

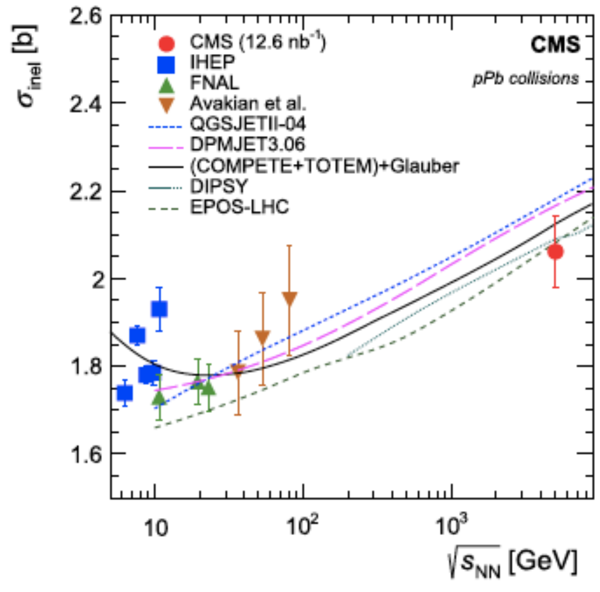
$-4.0 < \log_{10} \xi \leq -1.6$
$0.016 < |t| \leq 0.43$ (GeV^2)

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 (Schuler–Sjöstrand)	3.69	4.35
Pythia8 A3 (Donnachie–Landshoff)	2.52	2.98
Herwig7	4.96	6.11

CERN-EP-2019-190 (submitted to JHEP)

Inelastic cross-section (p-Pb) collisions

$$\sigma_{\text{inel}}(\text{pPb}) = 2061 \pm 3(\text{stat}) \pm 34(\text{syst}) \pm 72(\text{lumi})\ \text{mb}.$$



- Proton–lead collisions at a centre-of-mass energy per nucleon pair of 5.02Te with the CMS detector
- The values are corrected for photon-induced contributions, experimental acceptance, and other instrumental effects.
- Results are comparable with model predictions
- ALICE has a similar measurement with central value of cross section in range 2090-2120 b.
- The comparison is NOT shown due to possibility of different acceptance region and difference in several corrections.

PLB 759 (2016) 641-662

Relevance with EIC

- Expected centre-of-mass energy ~ 20-140 GeV
- & luminosity of the order of ~ 10^{34} $cm^{-2}s^{-1}$
- Extension of available kinematic range in x and Q^2
- Significant contribution of diffractive processes is expected
- Precise **diffractive measurements**

  - Important for understanding of strong interactions
  - Information about confinement mechanism
  - Accurate extraction of diffractive parton distributions functions (DPDFs) and Nuclear Diffractive PDFs (nDPDFs)

Summary

- Several diffractive processes measurements at LHC from different experiments at various collision energies
- Diffractive measurements are important for complete understanding of QCD and are helpful for improving theoretical understanding
- EIC is expected to provide a good opportunity for diffractive measurements.