

Study of Soft QCD Phenomena and Double Parton Interaction with the ATLAS Detector at LHC



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On behalf of the ATLAS Collaboration



Introduction

- QCD is our best theory to describe strong interactions. Many of its predictions were confirmed by experiments for decades.
- But the **non perturbative** nature of strong interactions at energies **below ~ 1 GeV** prevents QCD from being predictive for various processes and observables.
- These include **hadron spectrum, underlying event, parton shower, hadronization, diffractive interactions etc.**
- LHC offers large and various data sets to study strong interactions: **proton-proton Minimum Bias events (MB), hadronic jets, proton diffractive scattering, Heavy Ion collisions (HI), proton-Heavy Ion collisions (p-HI).**
- Measuring strong interactions in their non perturbative regime:
 - **Improves our knowledge.**
 - **Helps in tuning empirical model or finding better ones.**
- This talk:
 - I. **Study of double parton scattering (DPS) in proton collisions.**
 - II. **Strange hadrons in underlying events.**
 - III. **Exclusive $\pi^+\pi^-$ production in double diffraction events.**
 - IV. **Ordered hadron chains.**

DPS : Cross-Section

- If the two scattering partons belonging to the same proton were independent, we could write:

$$\sigma_{AB}^{\text{DPS}} = \text{prob}(\text{A}) \times \text{prob}(\text{B}) = \sigma_A \times \frac{\sigma_B}{\sigma_{\text{inel}}}$$

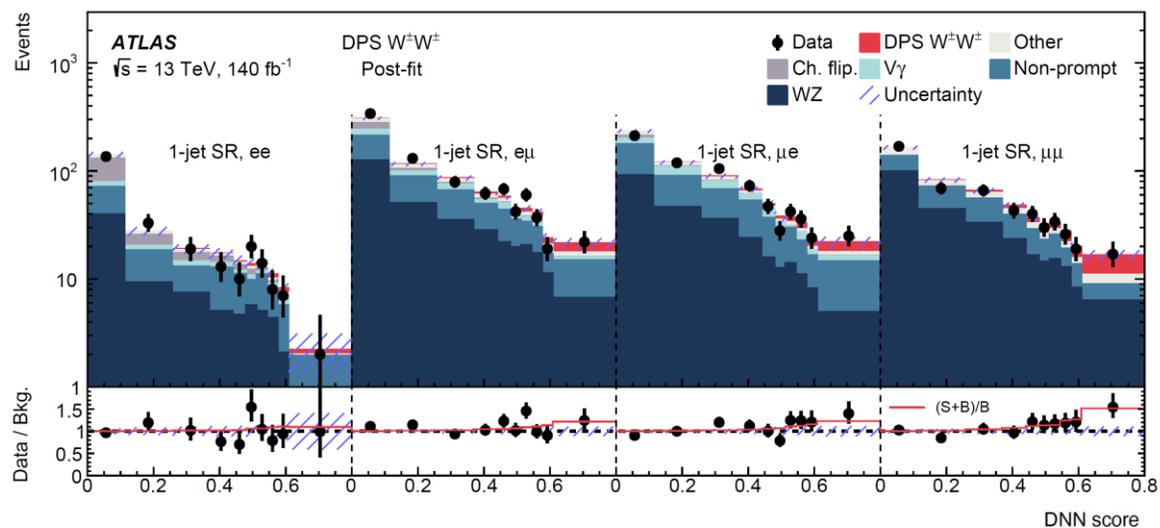
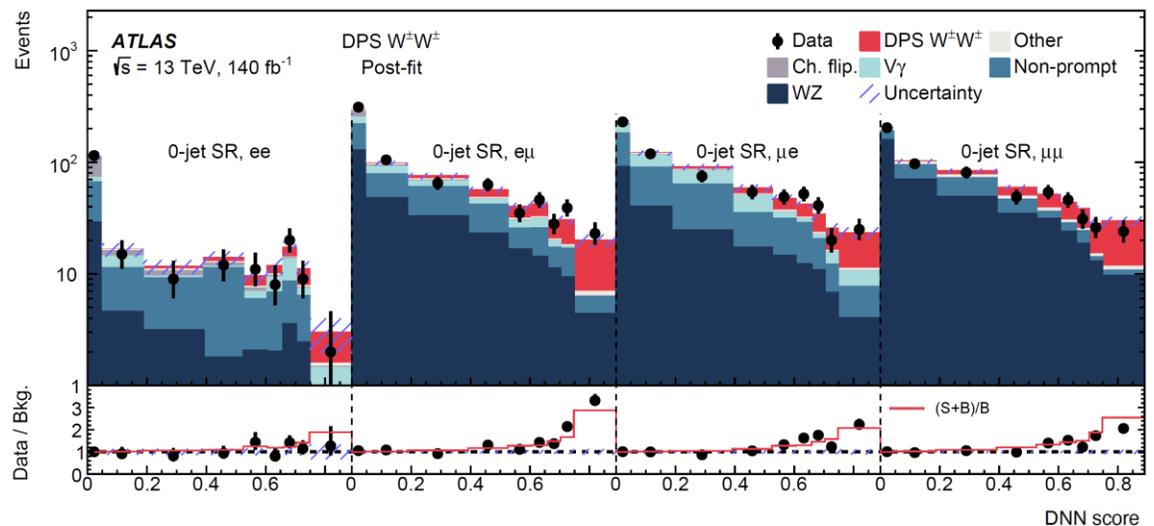
- But partons are correlated. This is parametrized by replacing σ_{inel} by σ_{eff} . **These correlations are what we want to learn about by measuring DPS.**

$$\sigma_{AB}^{\text{DPS}} = \frac{1}{1 + \delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}$$

- $\delta_{AB} = 0$ unless A and B are identical, and thus indistinguishable. In this case, cross section should be divided by 2, giving $\delta_{AB} = 1$.
- This analysis: **Production of $W^\pm W^\pm$ in DPS.**

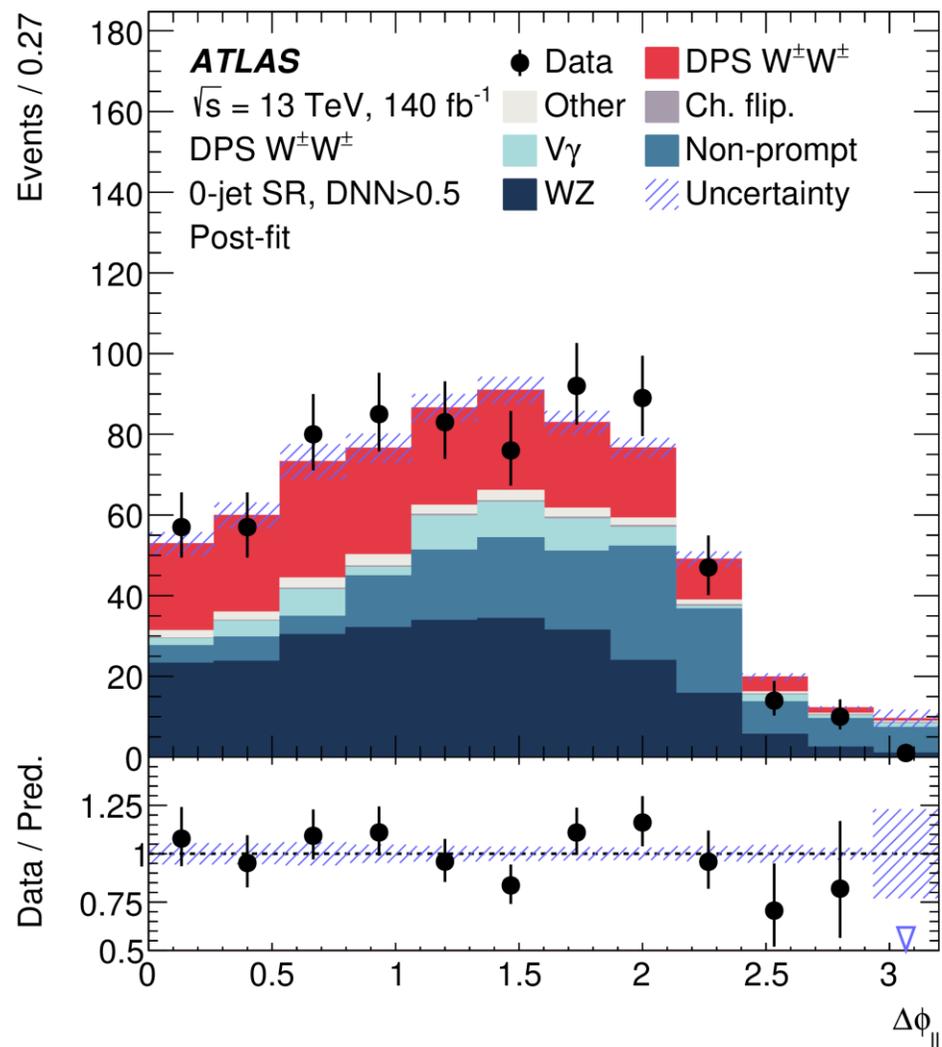
I

Post fit Signal DNN scores in the 8 signal regions, with obtained normalisations and nuisance parameters



- 140 fb^{-1} from LHC Run 2
- $\sqrt{s} = 13 \text{ TeV}$
- Single e^\pm and μ^\pm triggers with threshold $\sim 20 - 26 \text{ GeV}$

Post fit $\Delta\Phi_{||}$ for DNN score higher than 0.5



ArXiv:2505.08313

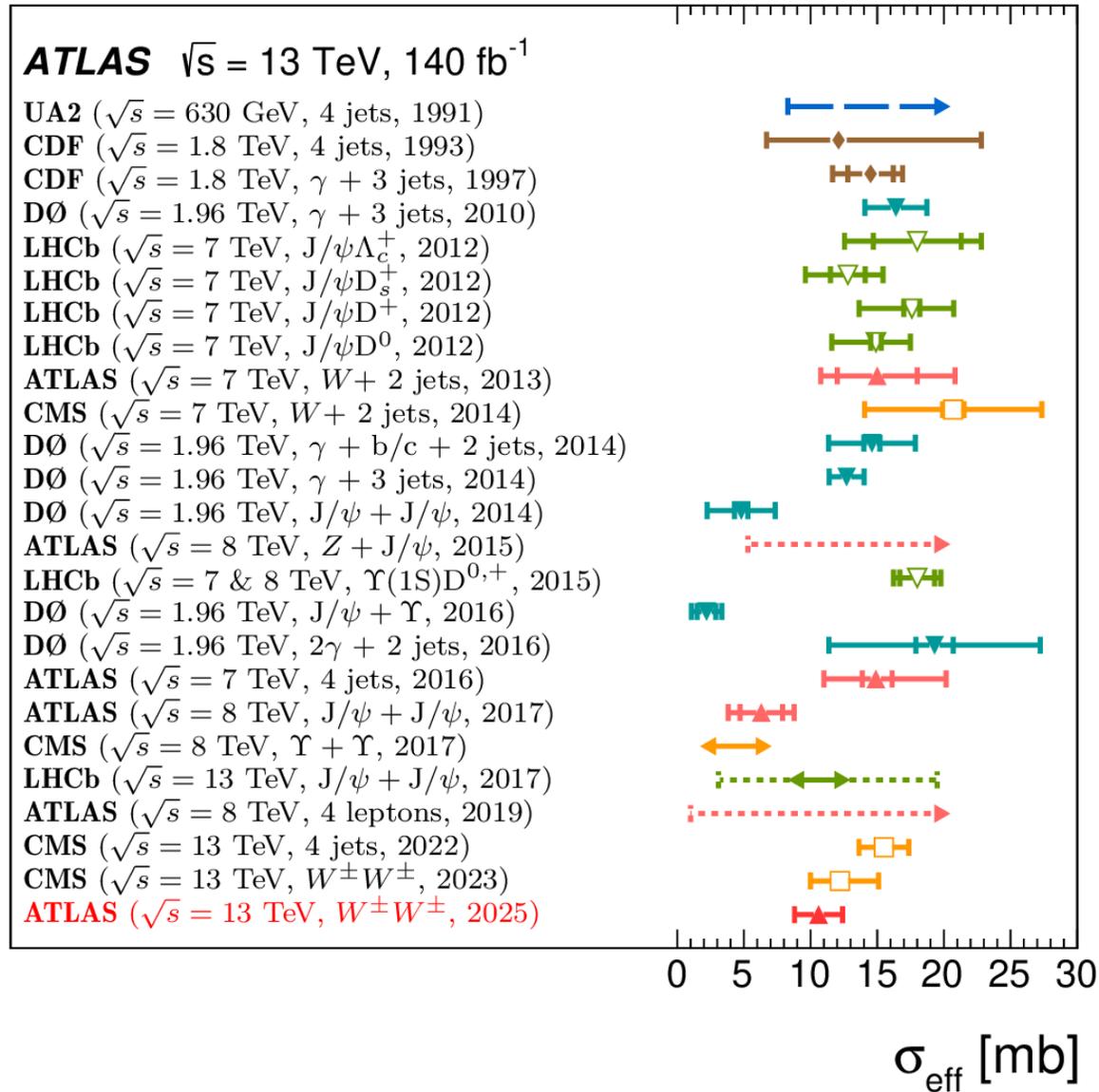
I

- Background-only hypothesis is rejected with an observed significance of **8.8 σ** .
- Measured fiducial cross section:

$$\sigma_{\mathcal{B}}(W^{\pm}W^{\pm}) = 4.59 \pm 0.64 \text{ fb}$$
- Leading to:

$$\sigma_{\text{eff}} = 10.6 \pm 1.8 \text{ mb}$$
 (compared to $\sigma_{\text{inel}}(13 \text{ TeV}) = 78.1 \pm 2.9 \text{ mb}$
[Phys. Rev. Lett. **117**, 182002](#))
- ATLAS result confirms the small value of σ_{eff} , and thus, **the expected large parton correlations**.

Experiment (energy, final state, year)

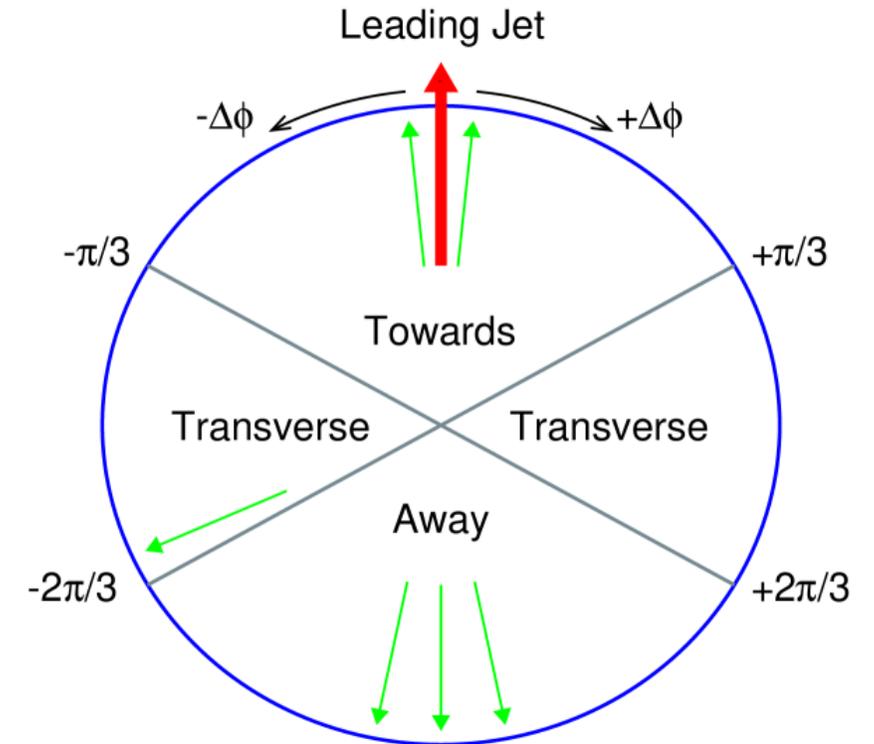


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II

Underlying Events (UE)

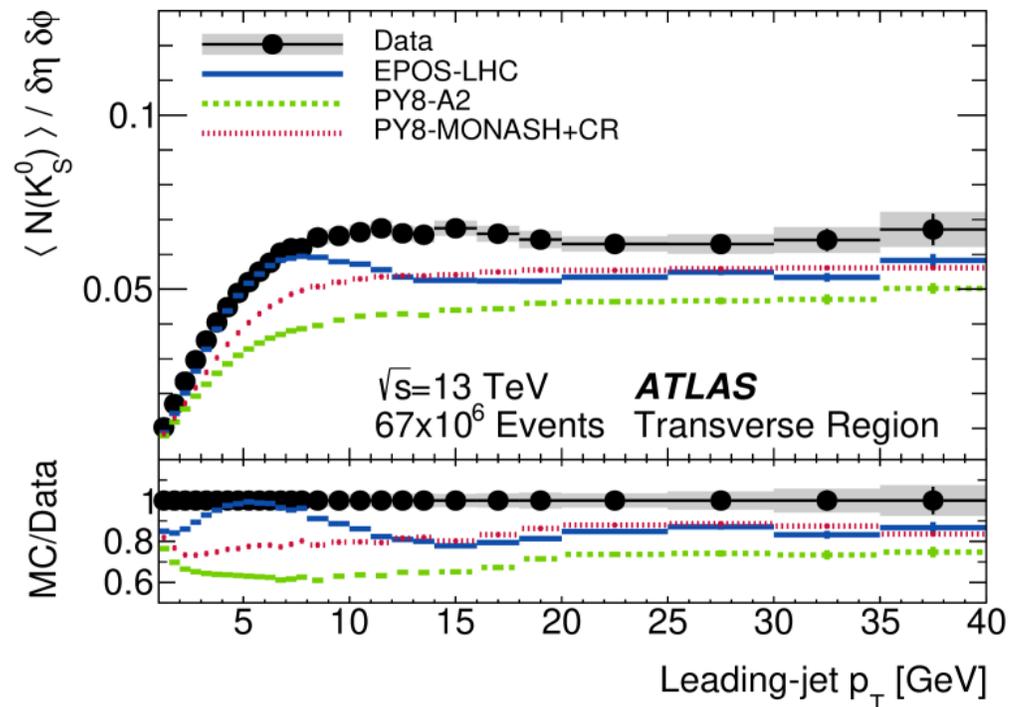
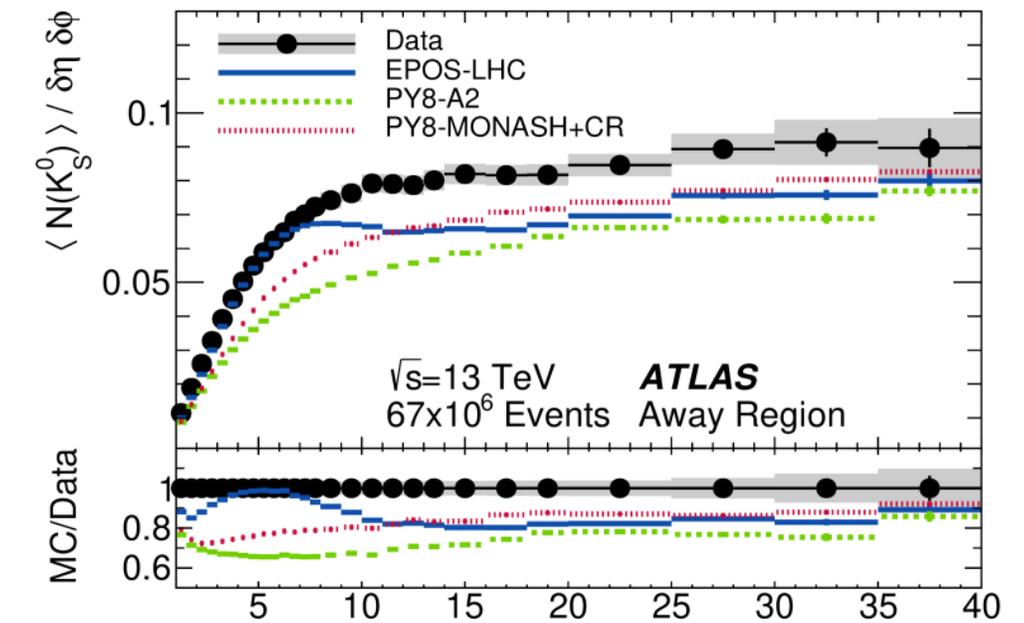
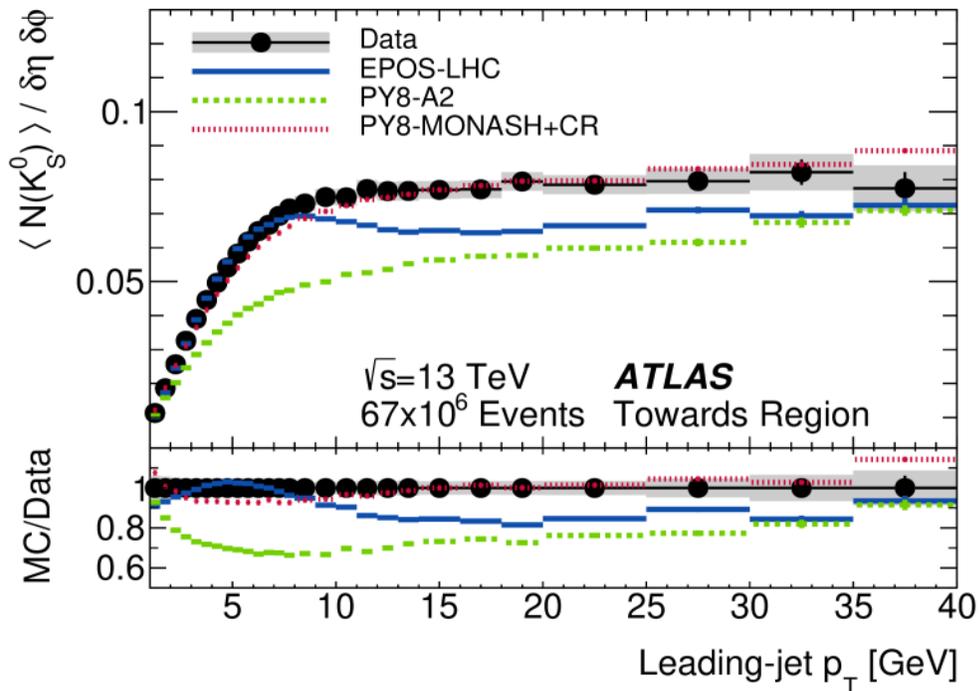
- UE arises from initial and final-state radiation, color reconnection between spectator and final state partons, Multi-Parton Interactions (MPI) and beam remnants for diffractive scattering.
- UE is important for a correct modeling of proton-proton collisions and their (non trivial) extrapolation to hadron-hadron collisions, especially for studies of air-shower triggered by high energy cosmic rays.
- Preserve UE from pileup \Rightarrow Very low luminosity run: **$0.003 < \langle \mu \rangle < 0.03$**
- The less biased events: **Minimum bias events** (130 M recorded events).
- Strange particles to probe UE:
 - $m_s \sim \Lambda_{QCD}$, predictions are difficult, so we need measurements.
 - K_S^0 and Λ are the lightest strange meson and baryon: **Easiest to produce and easy to tag** with their decay vertex (V0).



[Eur. Phys. J. C 84 \(2024\) 1335](#)

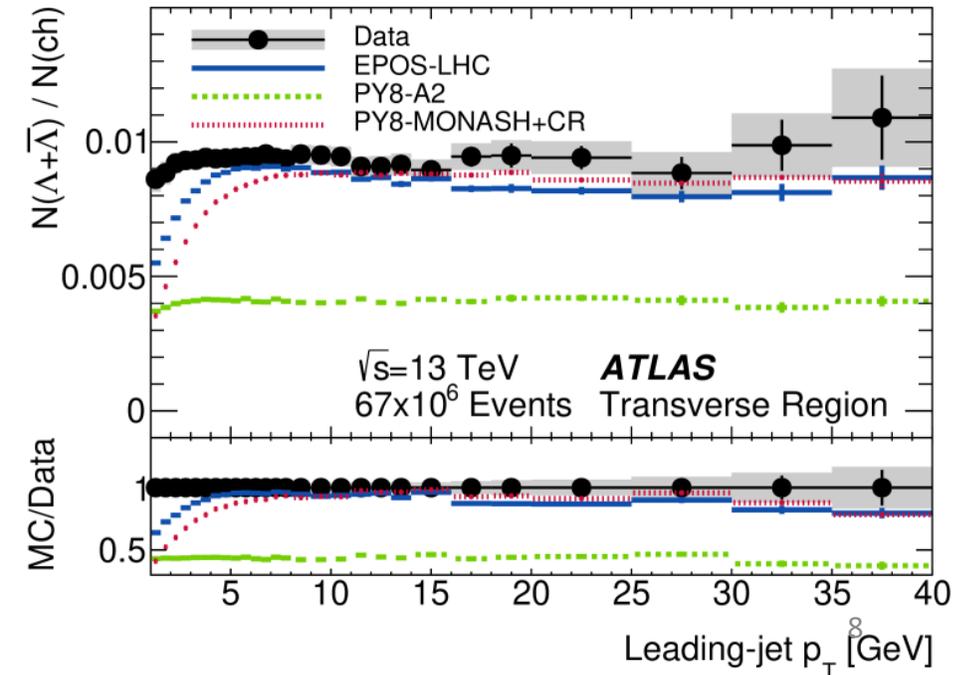
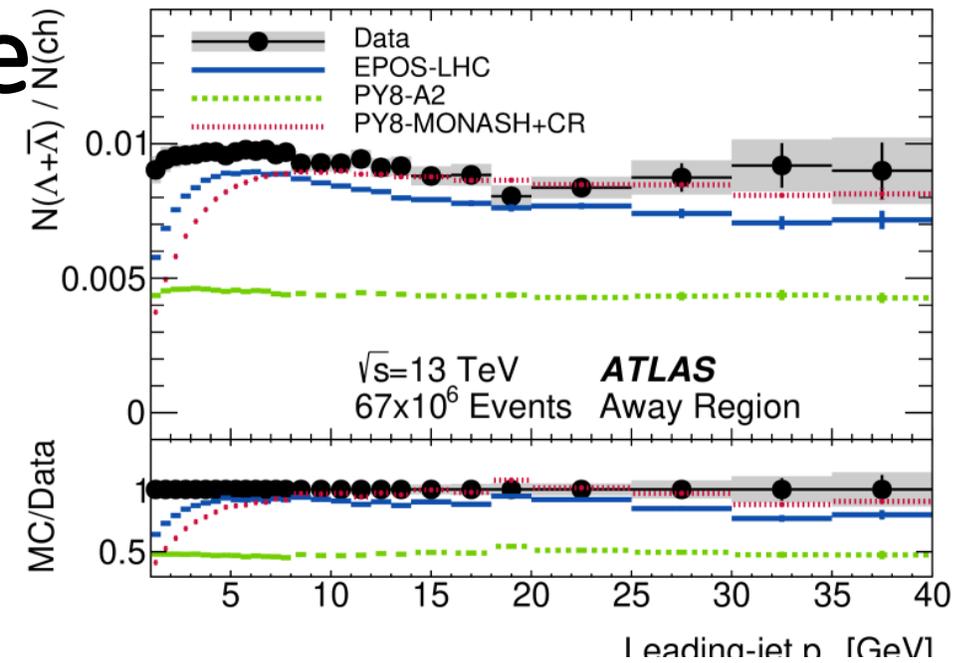
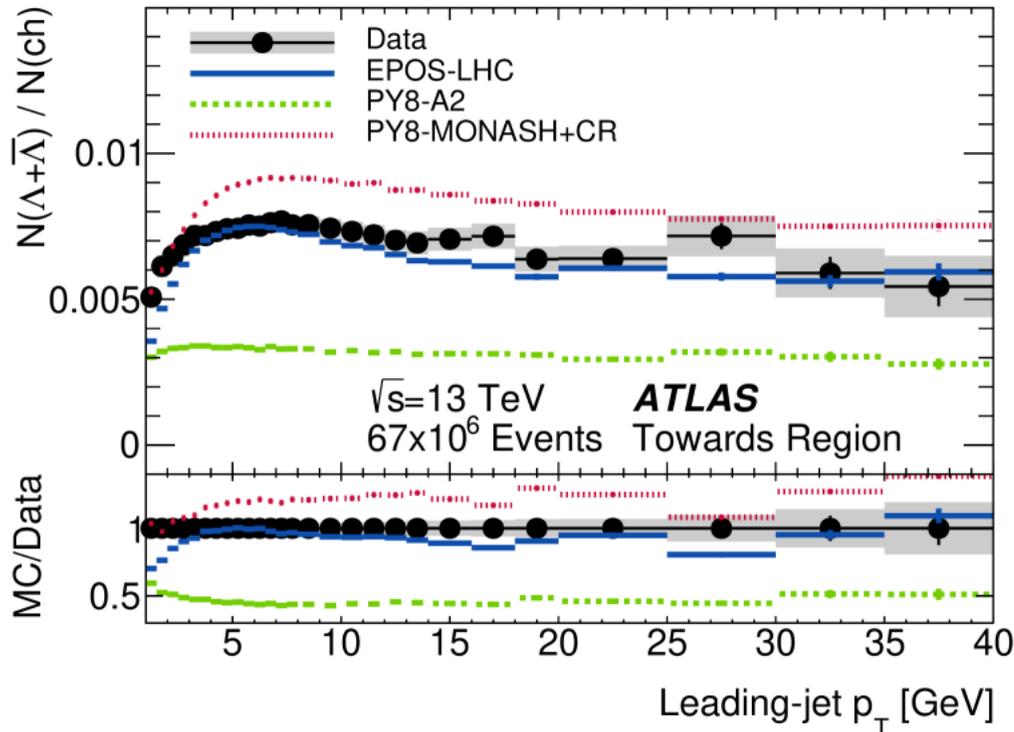
II K_S^0 per event

- The increasing of strange hadrons yield in the soft regime: **Confirms the impact parameter b picture of MPI**: Higher P_T leading jet means smaller b, and so larger MPI.
- The yield then saturates for totally **«central collisions»**, when $b = 0$ in hard regime.



II Λ per prompt charged particle

- Strange hadrons yield normalised by prompt charged particles varies much less with P_T than when normalised by event: **MPI independent from hadronisation.**
- EPOS LHC better at soft than at hard regime: **It needs a better modeling for hard processes.**



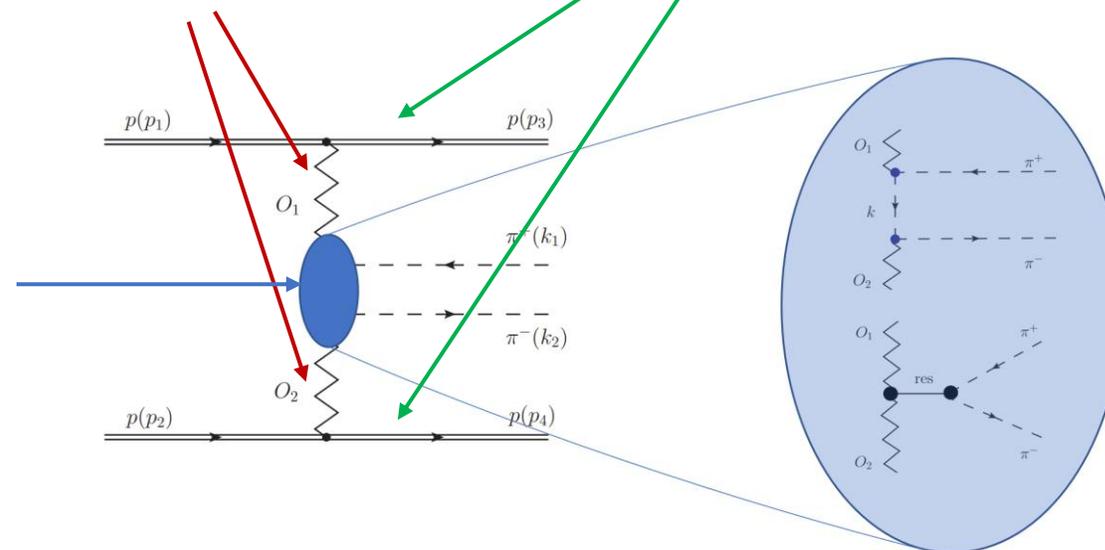
III

Exclusive Central $\pi^+ \pi^-$ Production in Double Diffractive Events

- Elastic and diffractive proton-proton events are dominated by low momentum transfer (below ~ 1 GeV). Perturbative QCD can not describe them.
- Double Diffractive event :

Central produced system
Detected in ATLAS detector

Pomerons



Outgoing protons

Detected in ALFA stations

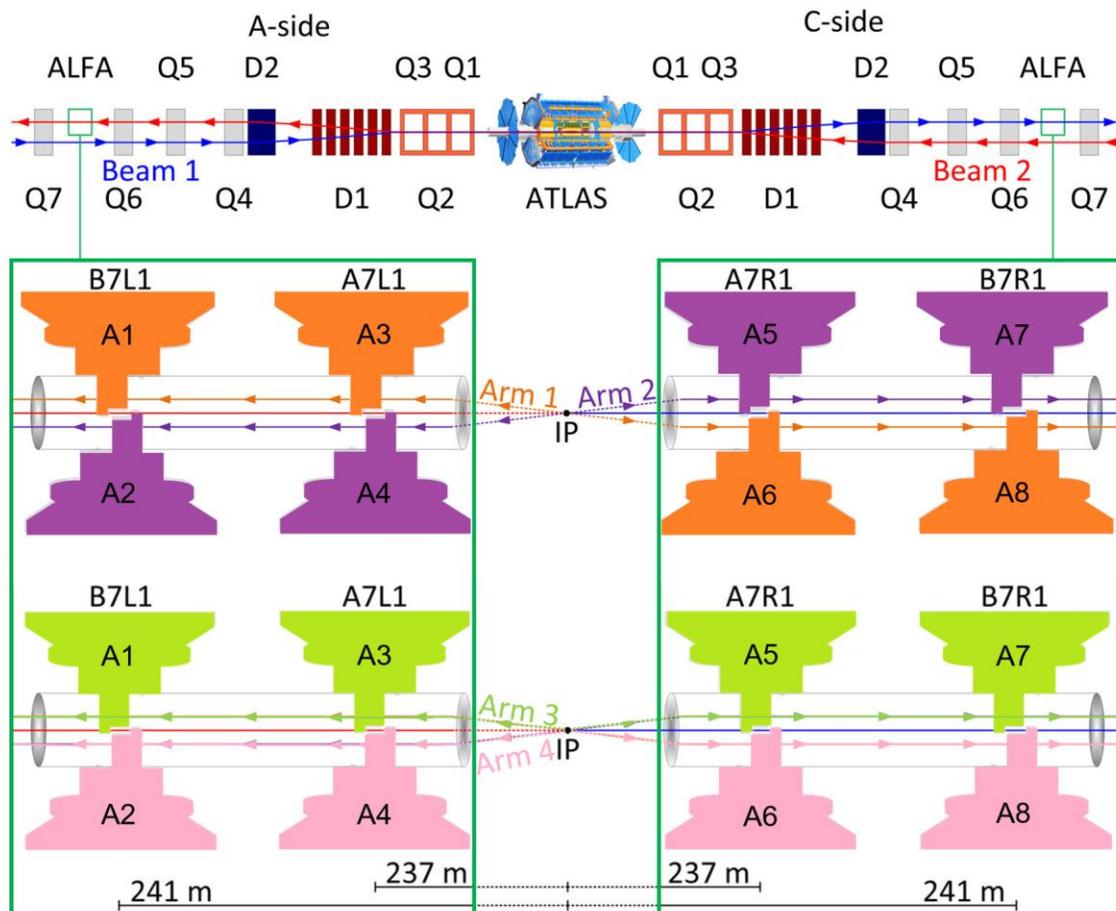
Used for trigger

[Eur. Phys. J. C 83 \(2023\) 627](#)

- Measurement of central system helps in understanding pomeron structure and interactions.

III

The Absolute Luminosity For ATLAS Stations (ALFA)



- 4 vertical stations.
- Located at $z = \pm 237$ and ± 241 m.
- Each station has 2 Roman Pots.
- Each Roman Pot contains a fiber tracker and trigger scintillators.
- Typical tracker dimensions: $\sim 10 \times 10 \text{ cm}^2$.
- Measures angles of \sim few tens of μrad .

III

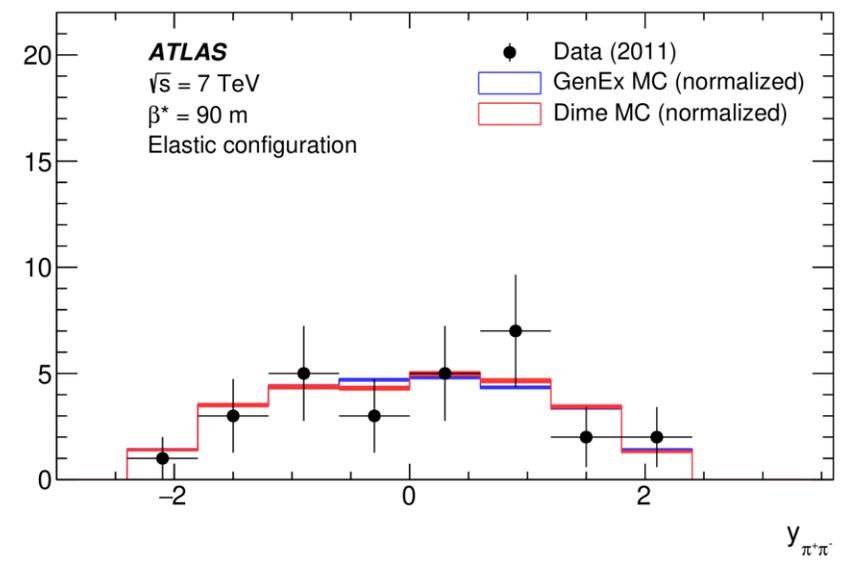
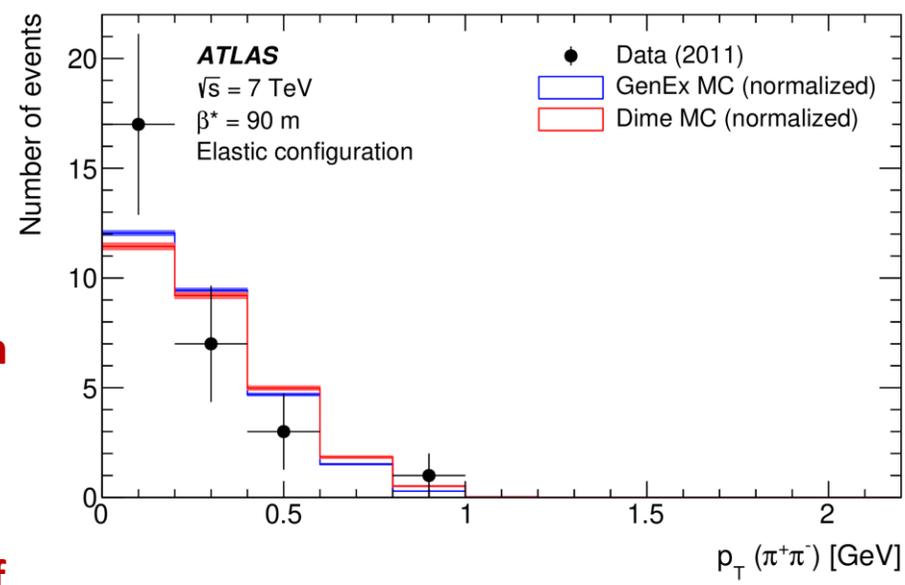
- $80 \mu\text{b}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$
- Low luminosity, $\mu = 0.035$
- $\beta = 90 \text{ m}$

- Outgoing proton momentum measured using LHC optics.
- Pion pair momentum measured by the ATLAS Inner Detector tracker.

- Main backgrounds:
 - Beam halo
 - Other diffractive events
- Main selection cuts:
 - Minimal central activity
 - Total momentum balance

- **First exclusive measurement with tagged protons.**
- **Limited uncertainties prevent model tuning.**
- **This result shows the potential of exclusive diffraction.**

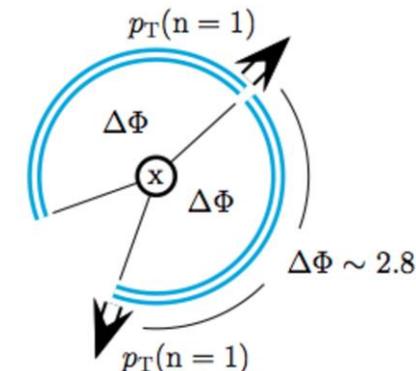
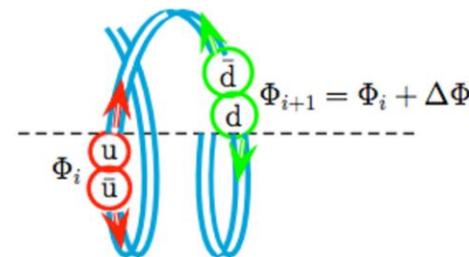
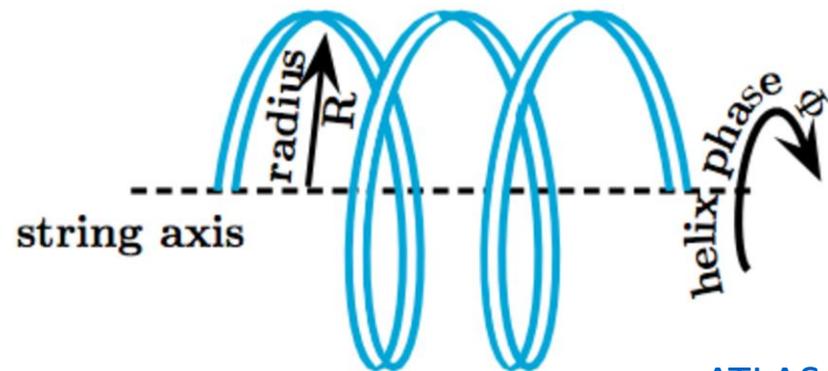
Exclusive $\pi^+\pi^-$ cross-section [μb]	
Elastic configuration	
Measurement	$4.8 \pm 1.0 \text{ (stat)} \quad {}^{+0.3}_{-0.2} \text{ (syst)} \pm 0.1 \text{ (lumi)} \pm 0.1 \text{ (model)}$
GENEX $\times 0.22$ (absorptive correction)	1.5
DIME	1.6
Anti-elastic configuration	
measurement	$9 \pm 6 \text{ (stat)} \quad {}^{+1}_{-1} \text{ (syst)} \pm 1 \text{ (lumi)} \pm 1 \text{ (model)}$
GENEX $\times 0.22$ (absorptive correction)	2
DIME	3



IV

Study of Ordered Hadron Chains in Proton-Proton, Proton-Lead and Lead-Lead Collisions

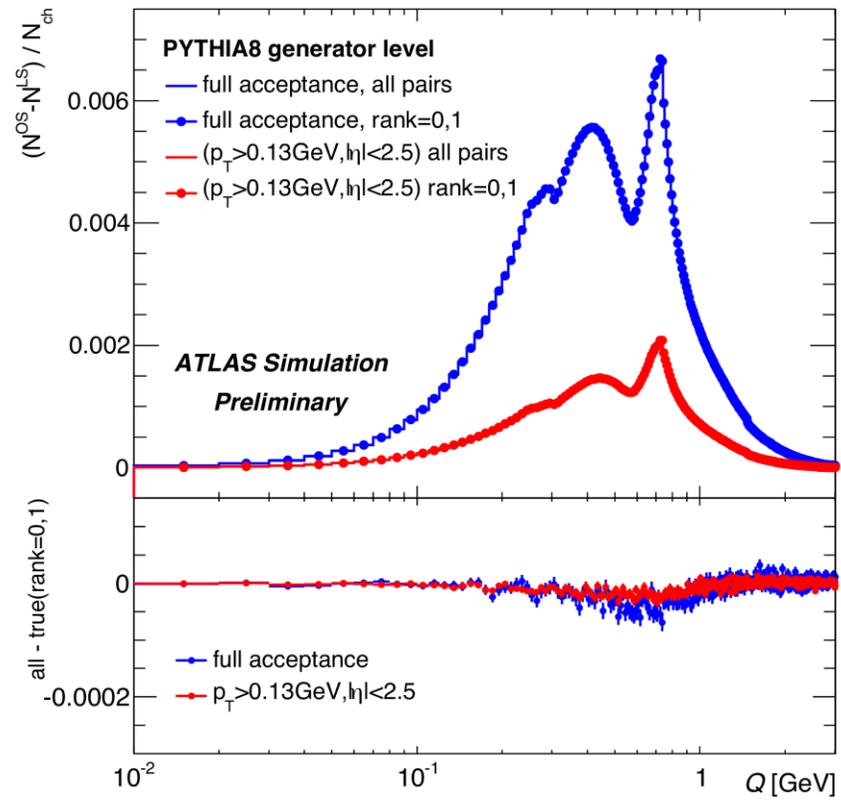
- Hadron correlations inform us about **hadron formation mechanisms**.
- Already observed Like-Sign (LS) hadron correlations may point to hadron production in **quantized fragmentation of 3 dimensional QCD strings**:
 - String parameters $\Delta\varphi$ and κR fitted with LHC run 1 proton-proton ATLAS data.
 - Mass spectrum of light mesons reproduced in 3D helical QCD string which break at a regular $\Delta\varphi$ intervals.
 - The model predicts most probable momentum difference between hadrons as a function of the distance of their breaking points along the helical string \Rightarrow **Study of adjacent hadrons**.



IV

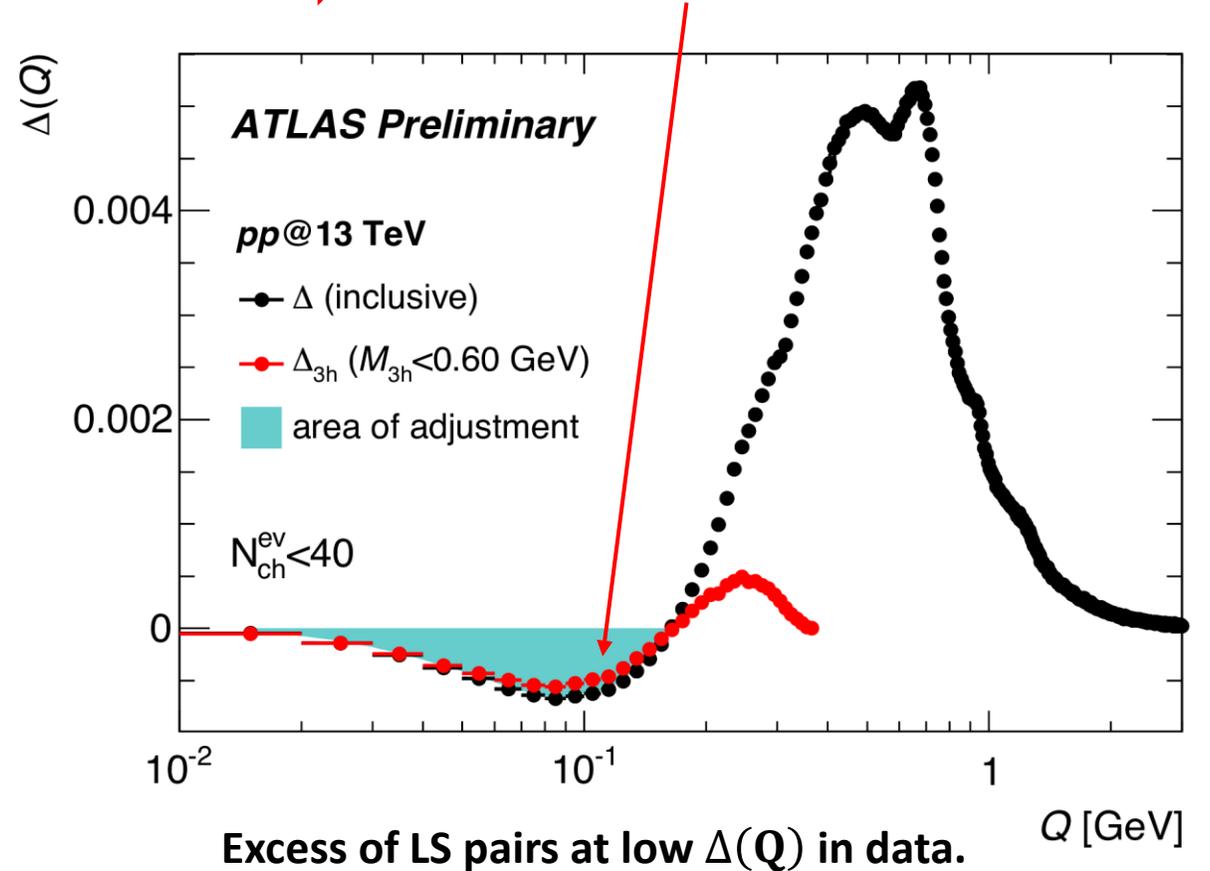
- **Adjacent LS hadrons: Forbidden by charge conservation.**
- **Non adjacent hadrons: Equal amount of LS and opposite sign charge (OS).**
- $\Delta(Q) = \frac{1}{N_{ch}} [N^{OS}(Q) - N^{LS}(Q)]$ informs us about adjacent hadrons.
- **Q: 4-momentum difference for hadron pairs.**

• **Shortest hadron chain to study helical string: 3 hadrons.** ➔ **Excess seems to come from hadron triplets.**



Excess not observed in Pythia.

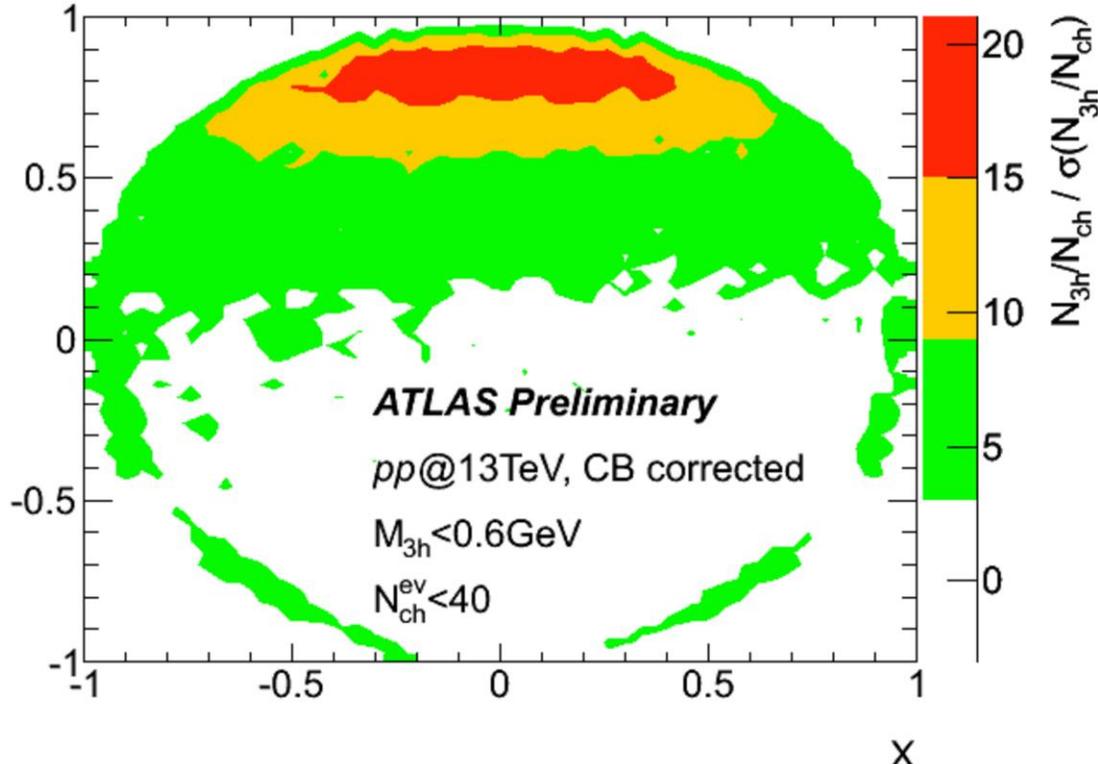
ATLAS-CONF-2022-055



Excess of LS pairs at low $\Delta(Q)$ in data.

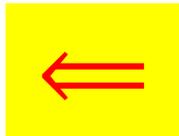
IV

Momentum difference between hadron chain should have a visible pattern in Dalitz plot:



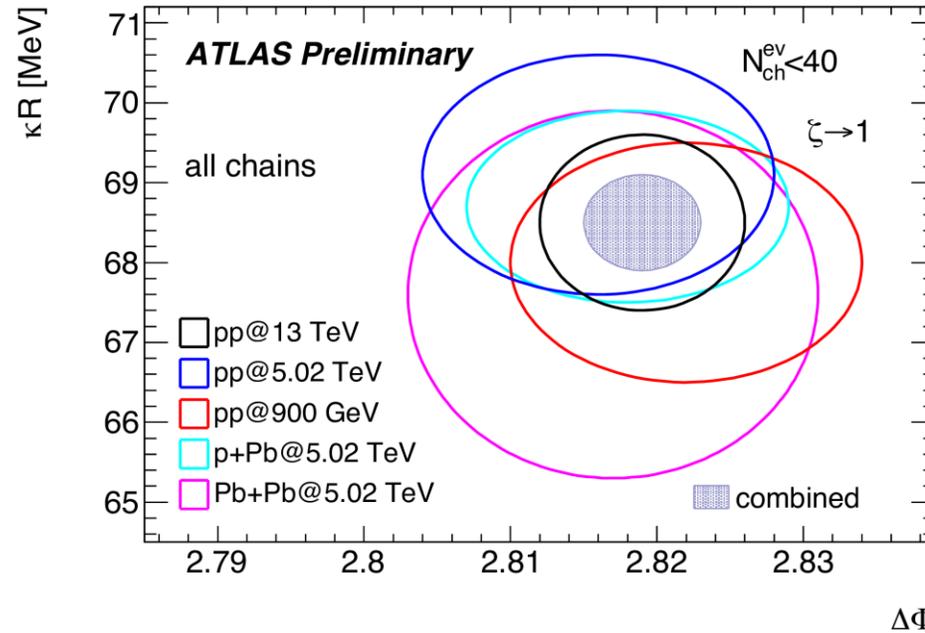
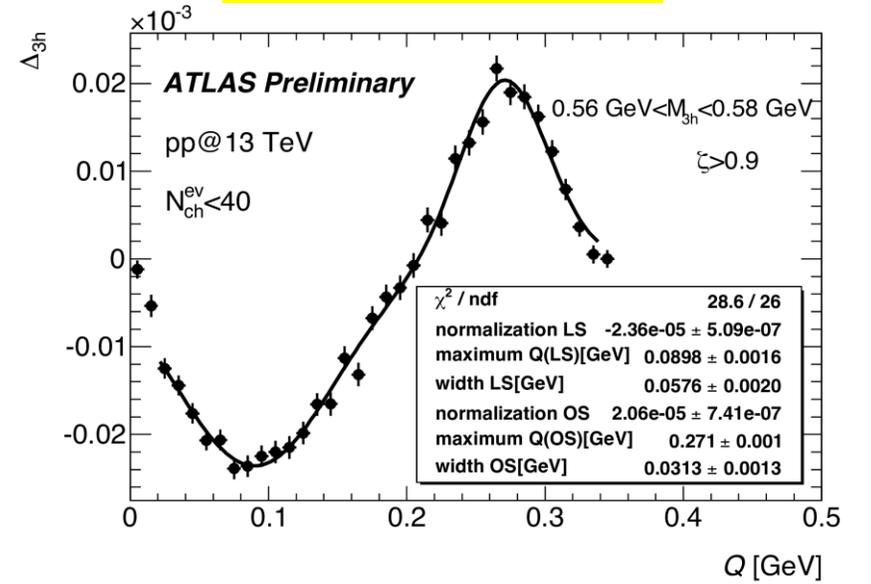
Significance of the excess observed in data.

In excellent agreement with results of fits using light meson masses.



...and string parameters determined with various Run 2 data sets.

Triplet $\Delta(Q)$ fitted...



ATLAS-CONF-2022-055

Conclusions

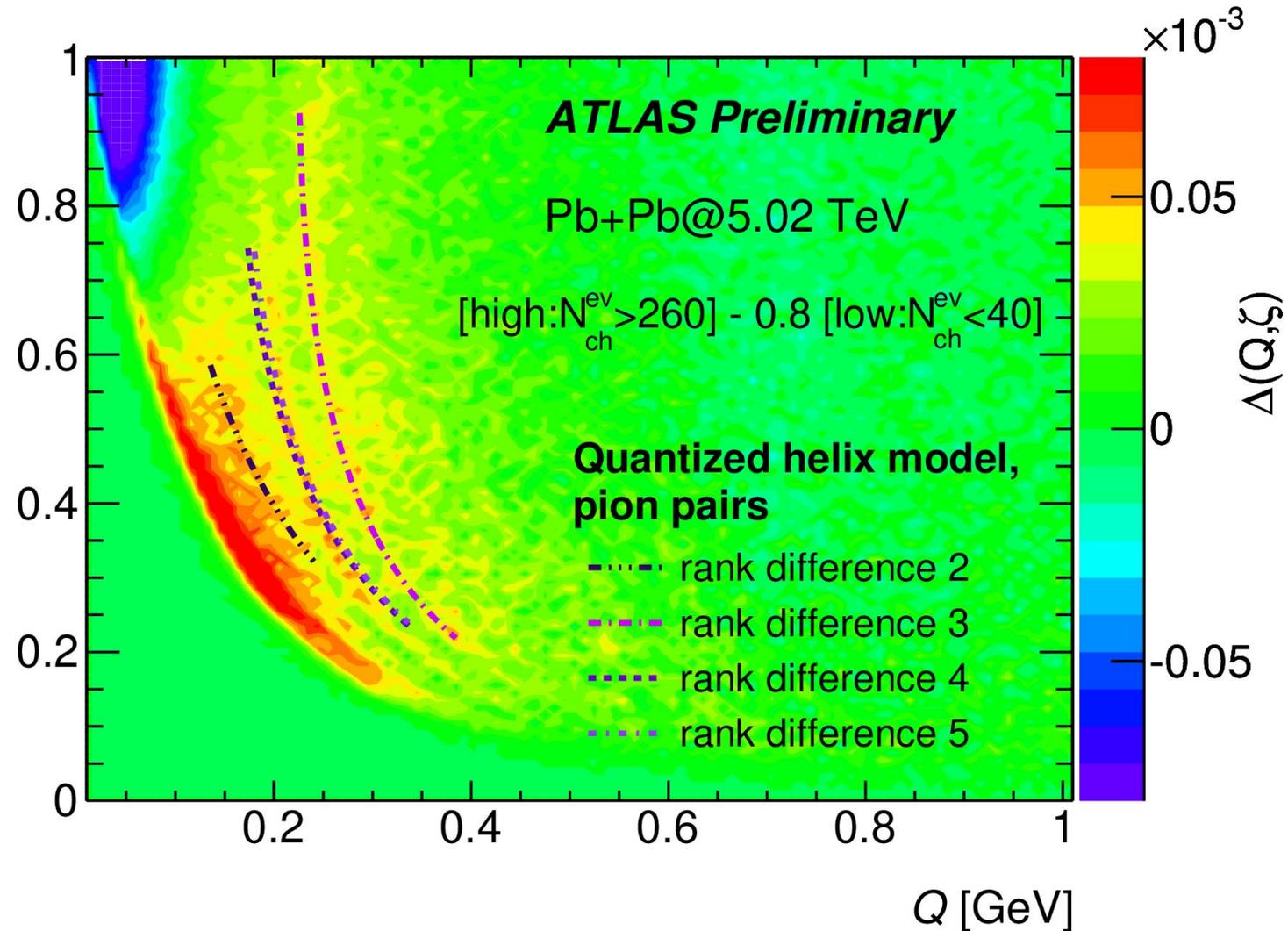
- Observation of $W^\pm W^\pm$ production in Double Parton Scattering, and measurement of σ_{eff} .
- EPOS-LHC seems to provide the best underlying event modeling, but needs tuning for hard processes.
- First observation of an exclusive production ($\pi^+ \pi^-$) in central diffraction using tagged forward protons.
- Correlations between hadrons seem to arise from quantum effects in the fragmentation of helical QCD strings.
- ATLAS Collaboration actively investigates strong interactions, especially in their non perturbative regime. These measurements contribute to model tuning and improve our knowledge in the most difficult sector of the Standard Model.

Backup

IV

$$\zeta(\vec{p}_i, \vec{p}_j) = \min\left(\frac{|\vec{p}_j|}{|\vec{p}_i|}, \frac{|\vec{p}_i|}{|\vec{p}_j|}\right)$$

- In Lead-lead collisions: observation of strip pattern.
- This pattern is reproduced by the quantized helix model.
- A hint for future studies of long range correlations (Ridge effect ?)...



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Why Study DPS ?

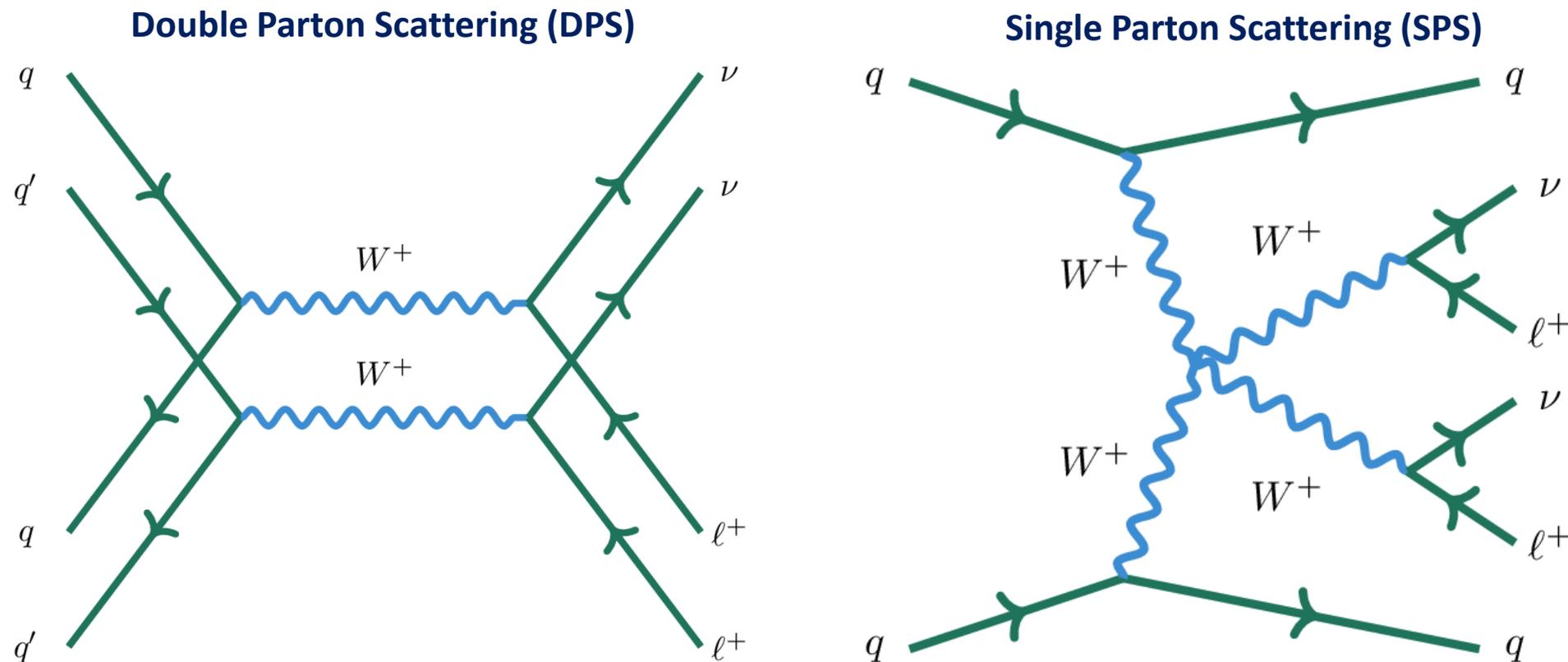
$$d\hat{\sigma}_{Y+Z}^{(\text{DPI})}(s) = \frac{m}{2\sigma_{\text{eff}}(s)} \int dx_{i_1} dx_{j_1} dx_{i_2} dx_{j_2} [f_{i_1 j_1}(x_{i_1}, x_{j_1}, \mu_F) \\ \times f_{i_2 j_2}(x_{i_2}, x_{j_2}, \mu_F) d\hat{\sigma}_{i_1 i_2 \rightarrow Y}(x_{i_1}, x_{i_2}, s) d\hat{\sigma}_{j_1 j_2 \rightarrow Z}(x_{j_1}, x_{j_2}, s)]$$

- $f_{ij}(x_i, x_j, \mu_F)$: **Double Parton Distribution Function (DPDF)**.
- To integrate over x , we have to take into account the **correlation between momenta** of the two partons belonging to the same proton:

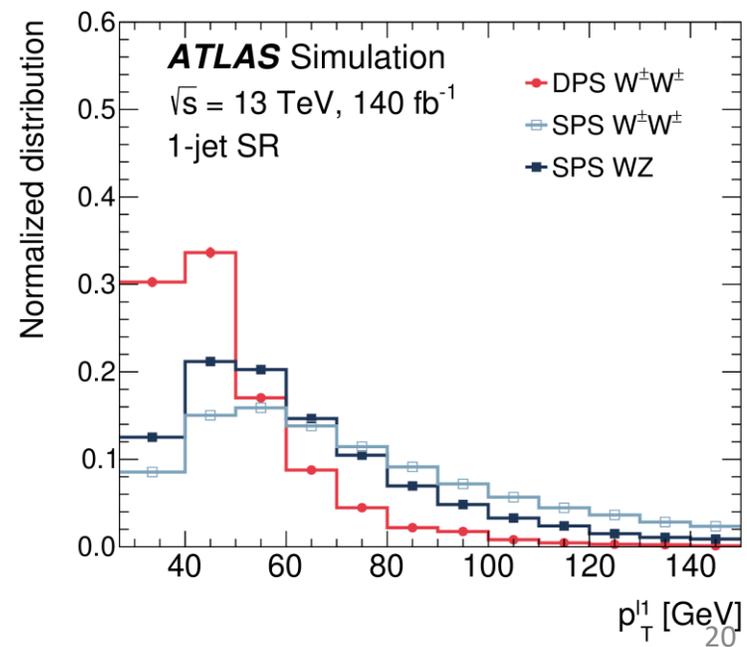
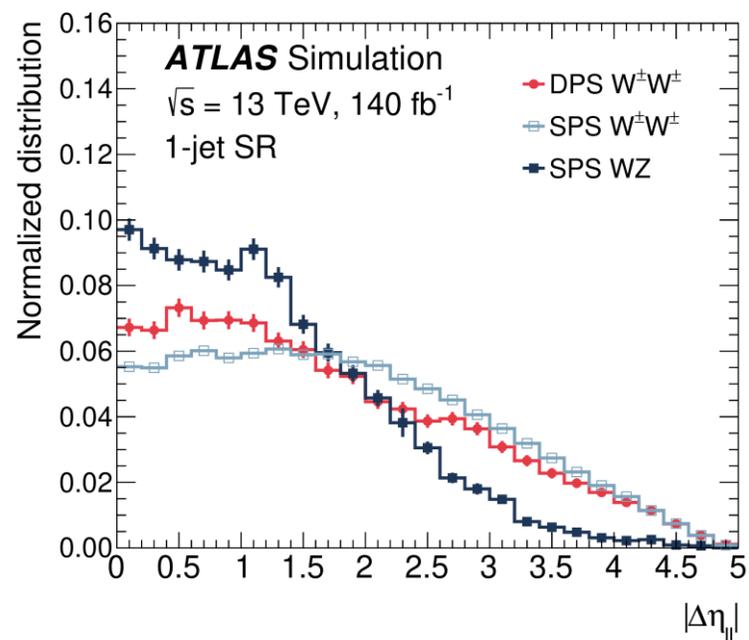
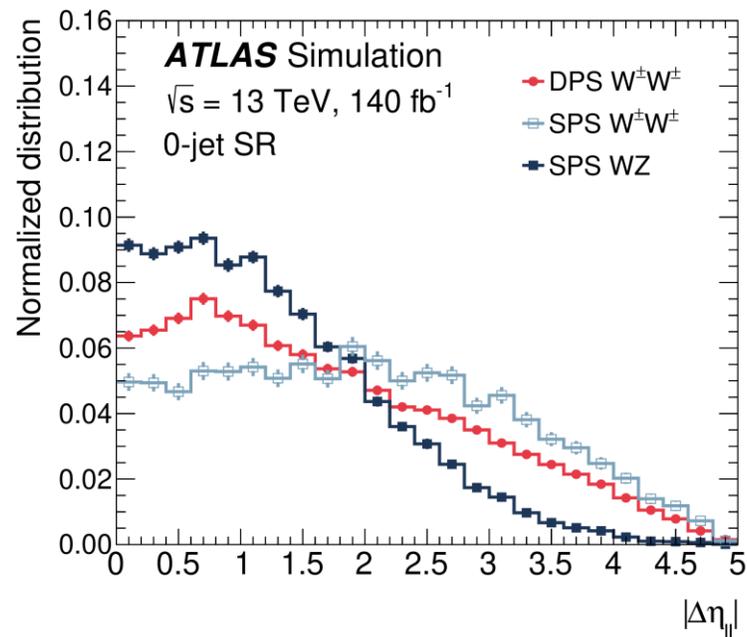
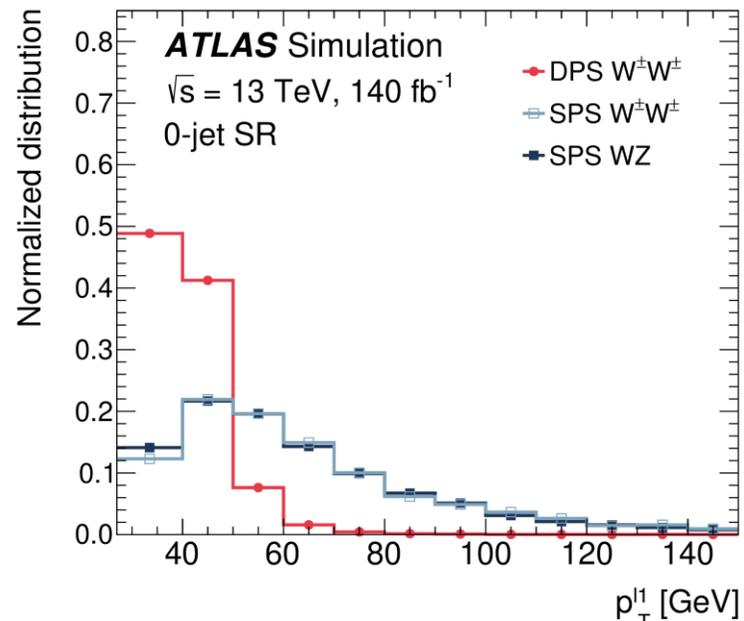
$$f_{ij}(x_i, x_j, \mu_F) = f_i(x_i, \mu_F) f_j(x_j, \mu_F) \boxed{(1 - x_i - x_j) \Theta(1 - x_i - x_j)}$$

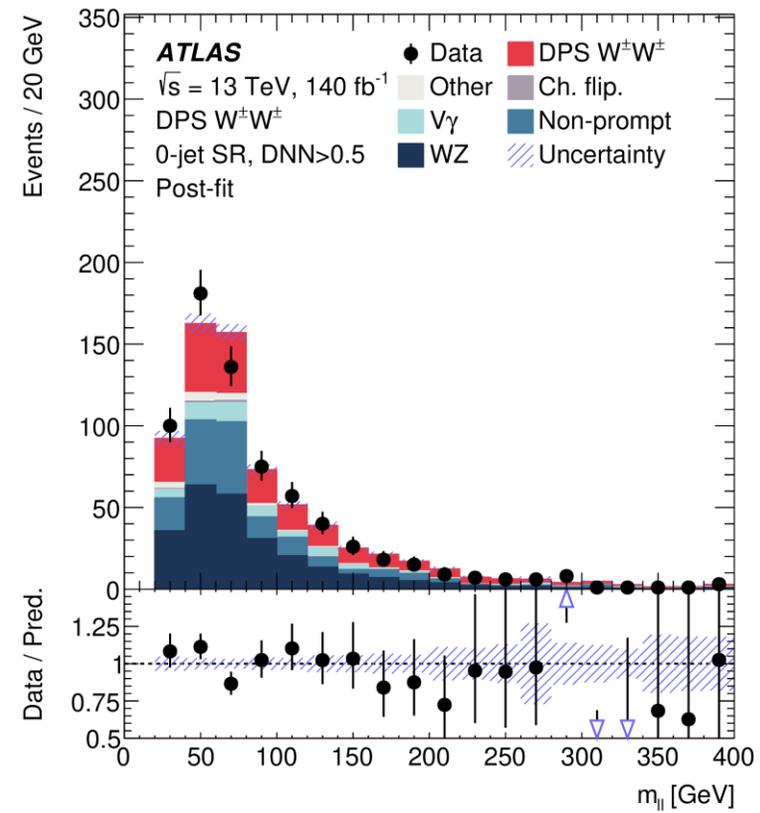
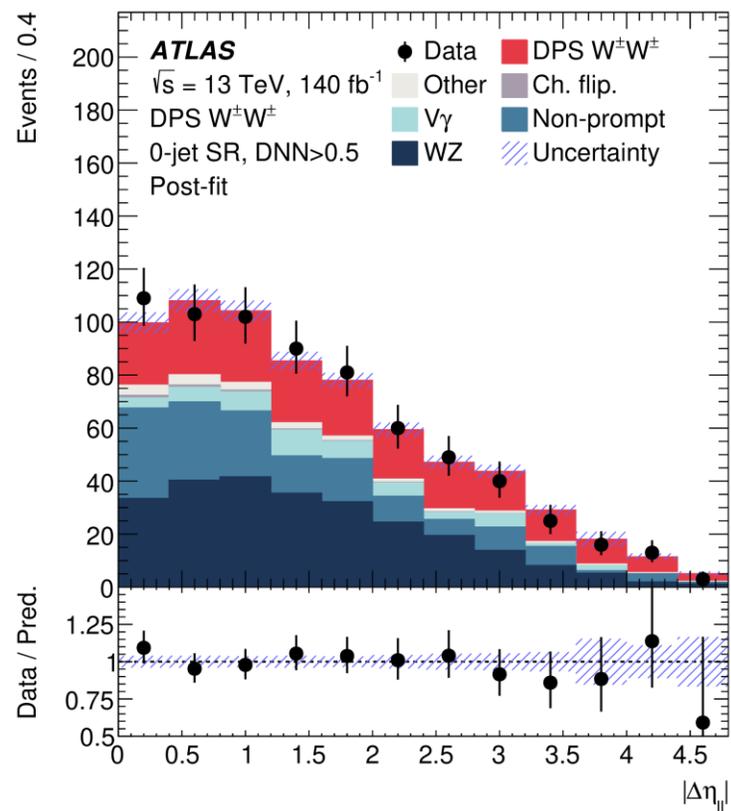
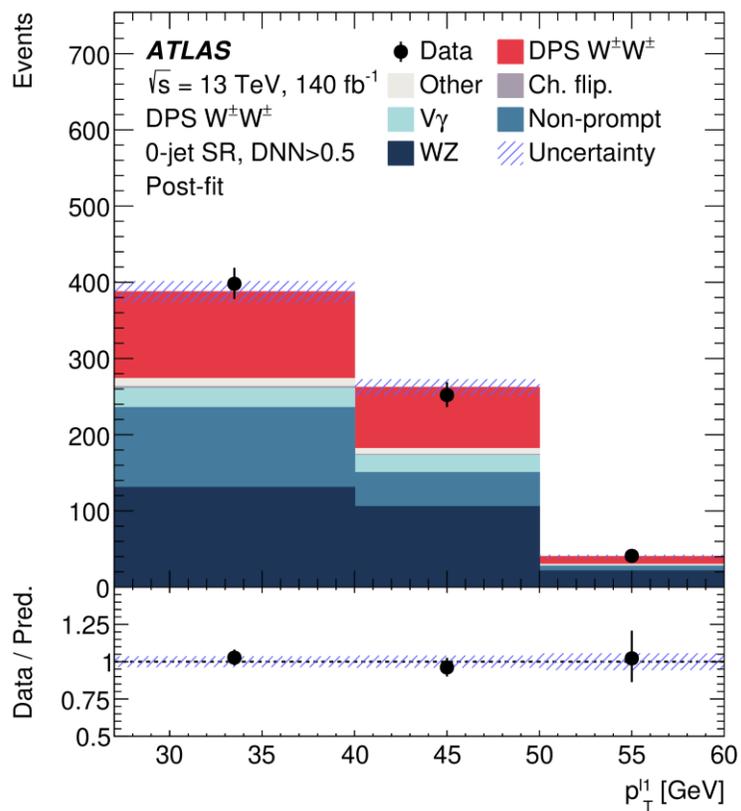
- **Spin and Color correlations** between partons are also taken into account.
- The only remaining parton correlation is their **correlation in transverse plane**.
- **Measuring DPS cross-sections inform us on the transverse dimension of hadrons.**

W^+W^+ Feynman Diagrams



- Same-sign W s SPS production has smaller cross-section than opposite-sign W s.

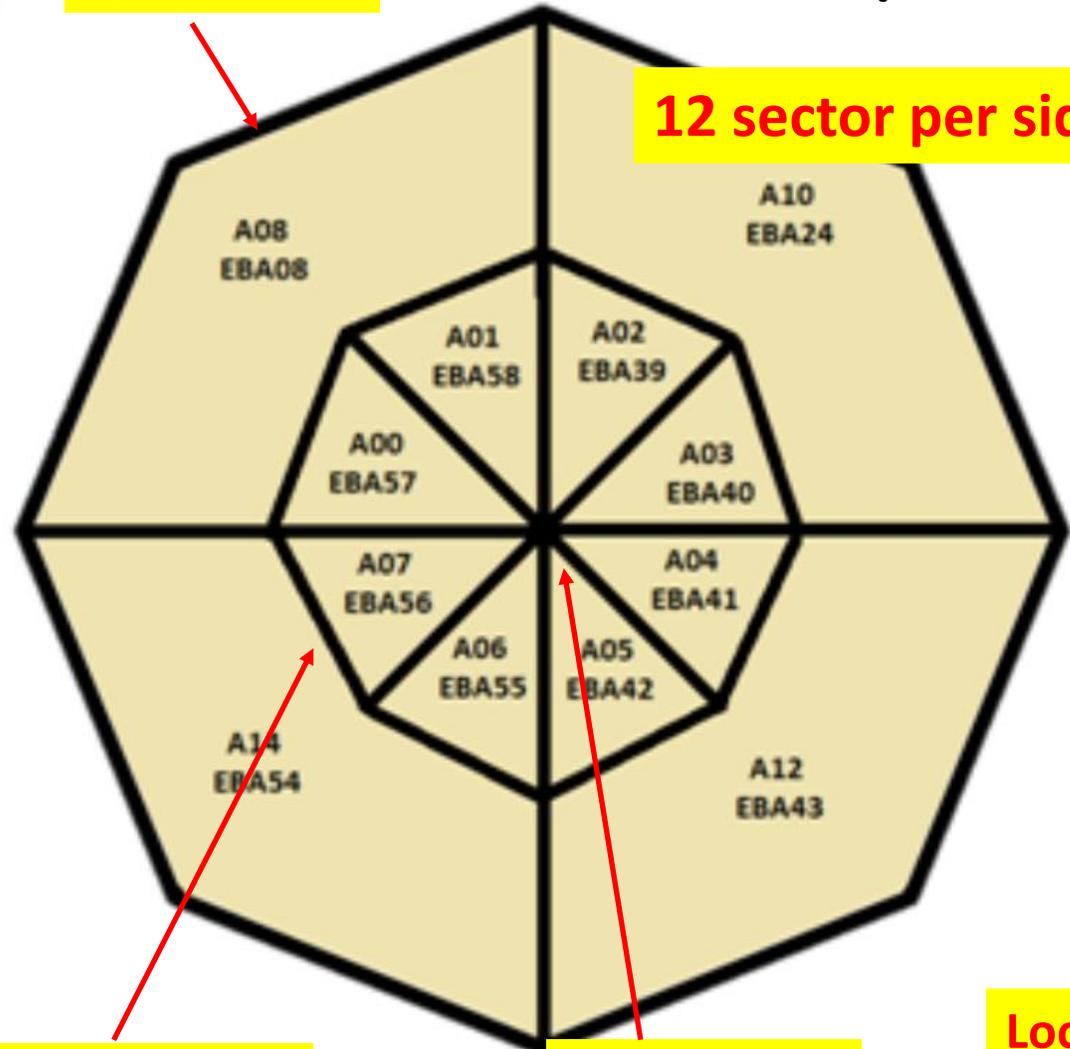
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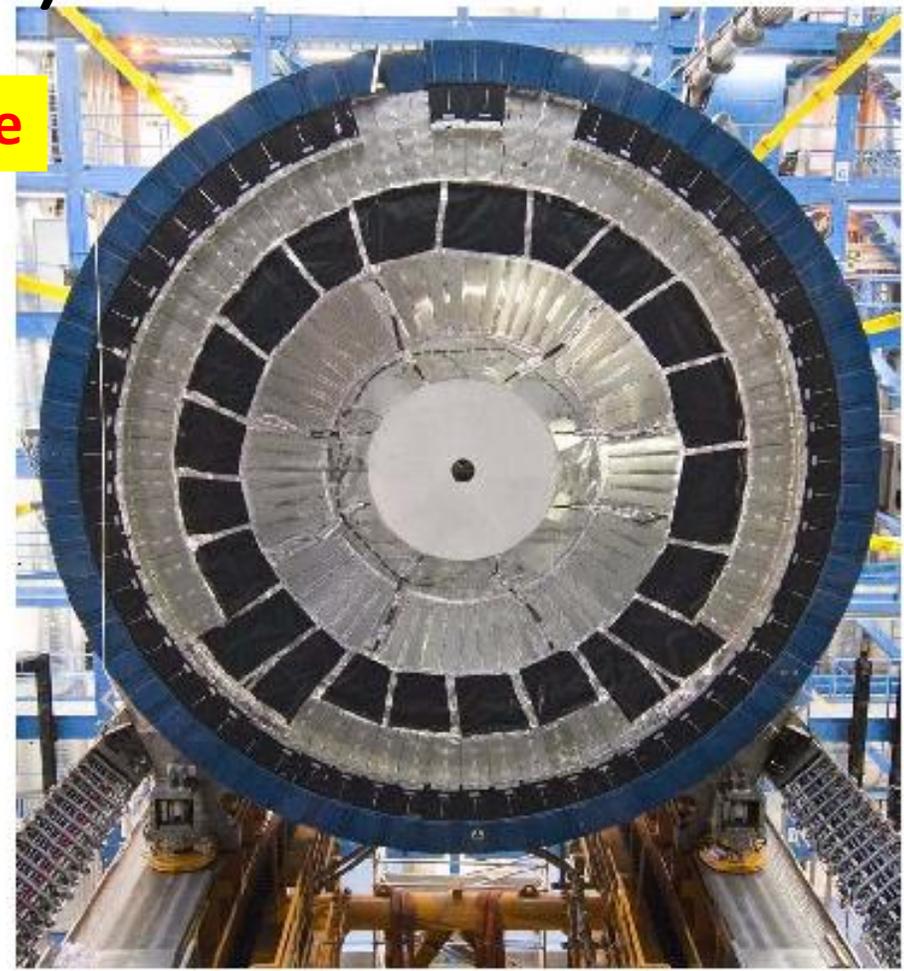
II

The ATLAS Minimum Bias Trigger Scintillators (MBTS)

$\eta = 2.07$



12 sector per side



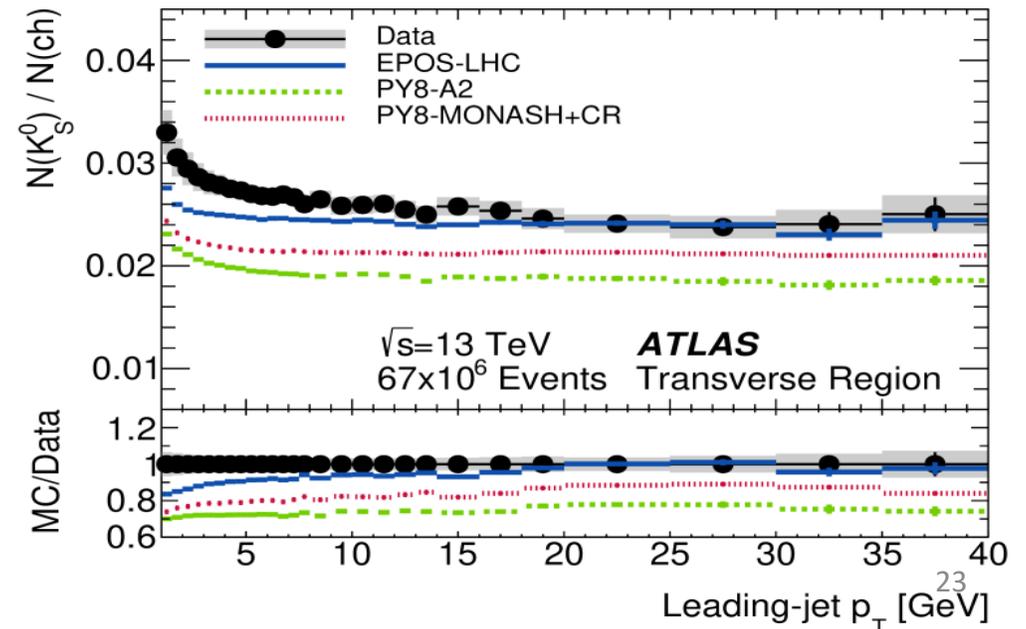
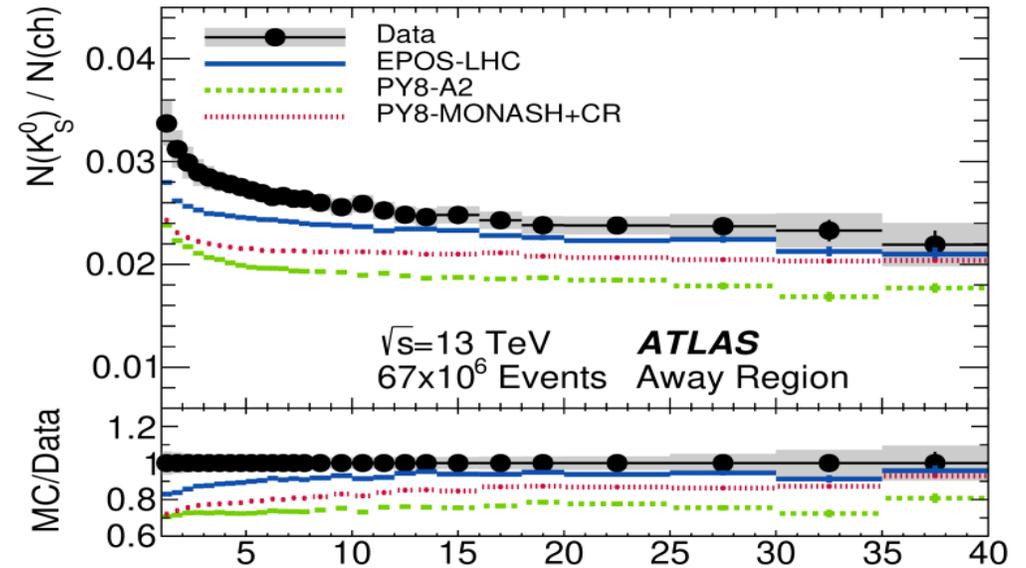
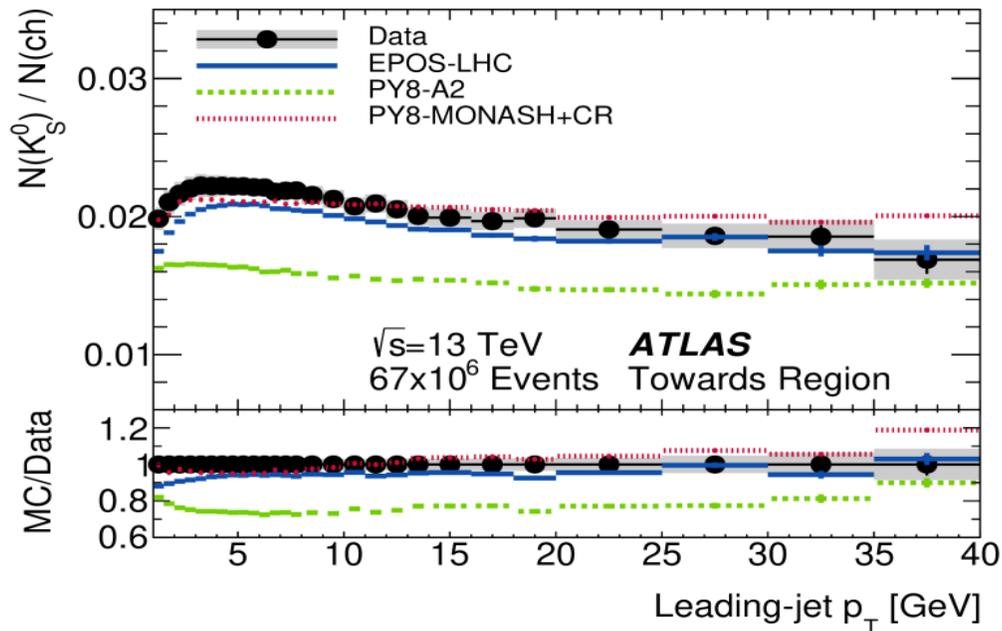
Located at $z = \pm 3.56$ m, on end-cap cryostats front side

$\eta = 2.76$

$\eta = 3.86$

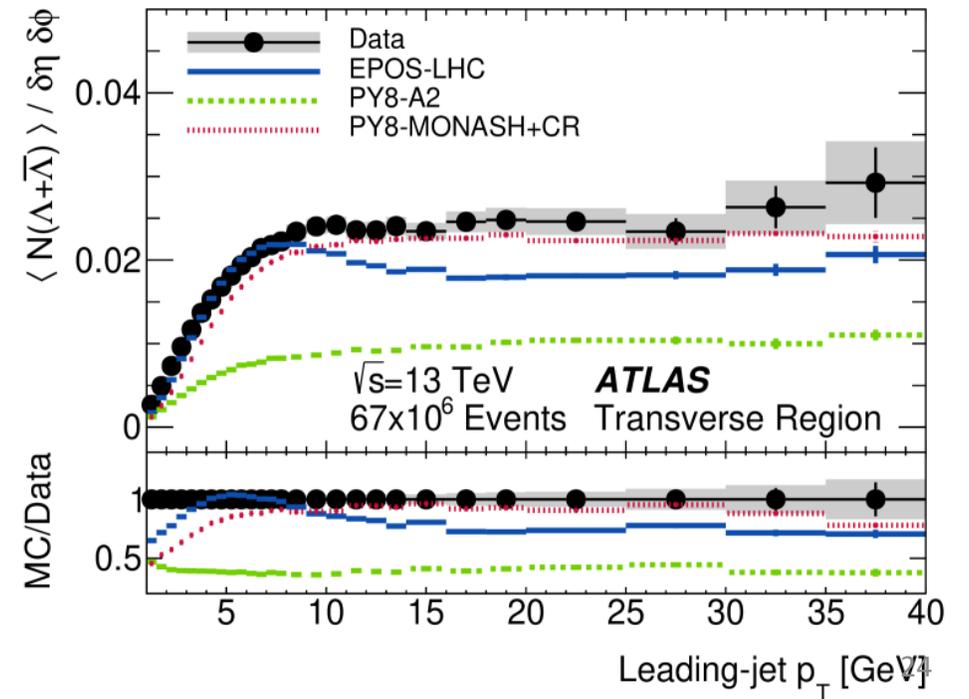
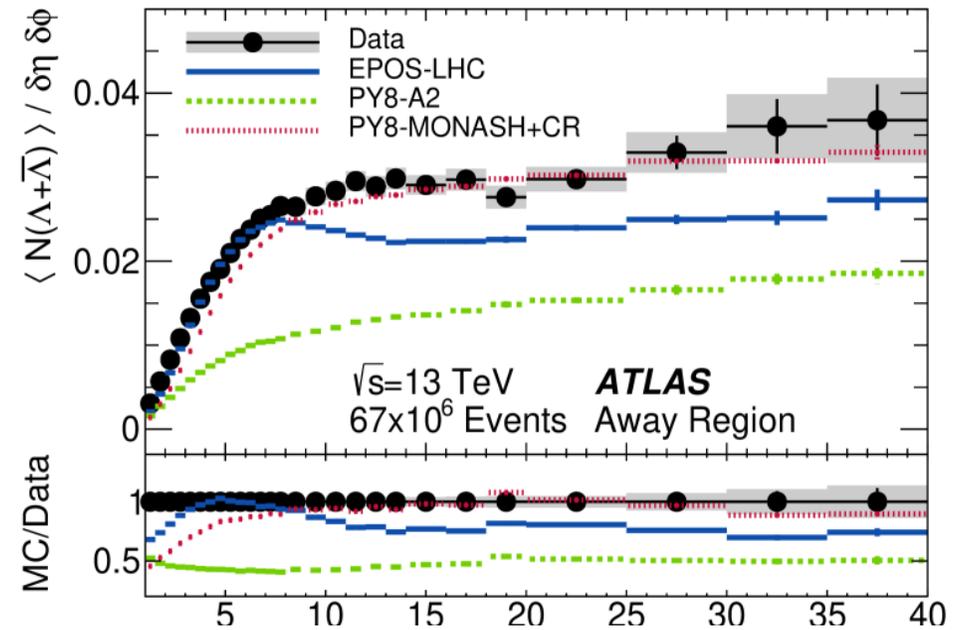
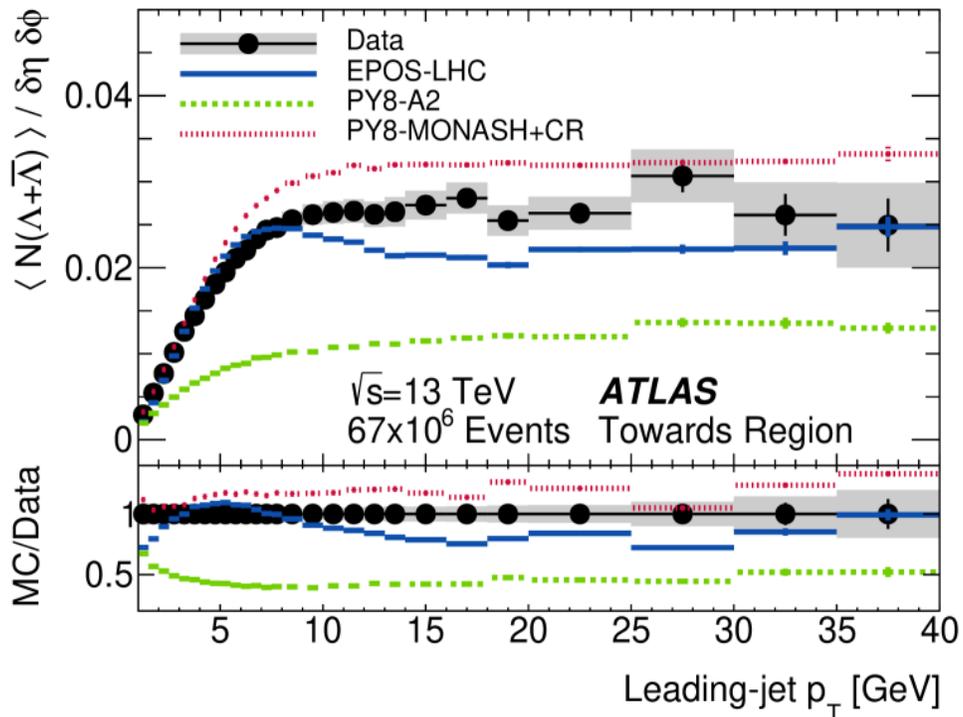
II K_S^0 per prompt charged particle

- Data: Soft to hard transition less distinct.
- Soft regime:
 - EPOS LHC agreement not as good as event-normalisation.
 - PYTHIA Monash + CR is again better in the Towards region.
- Hard regime:
 - PYTHIA Monash + CR reproduces data in the Towards region.
 - All models reproduce data shape.



II Λ per event

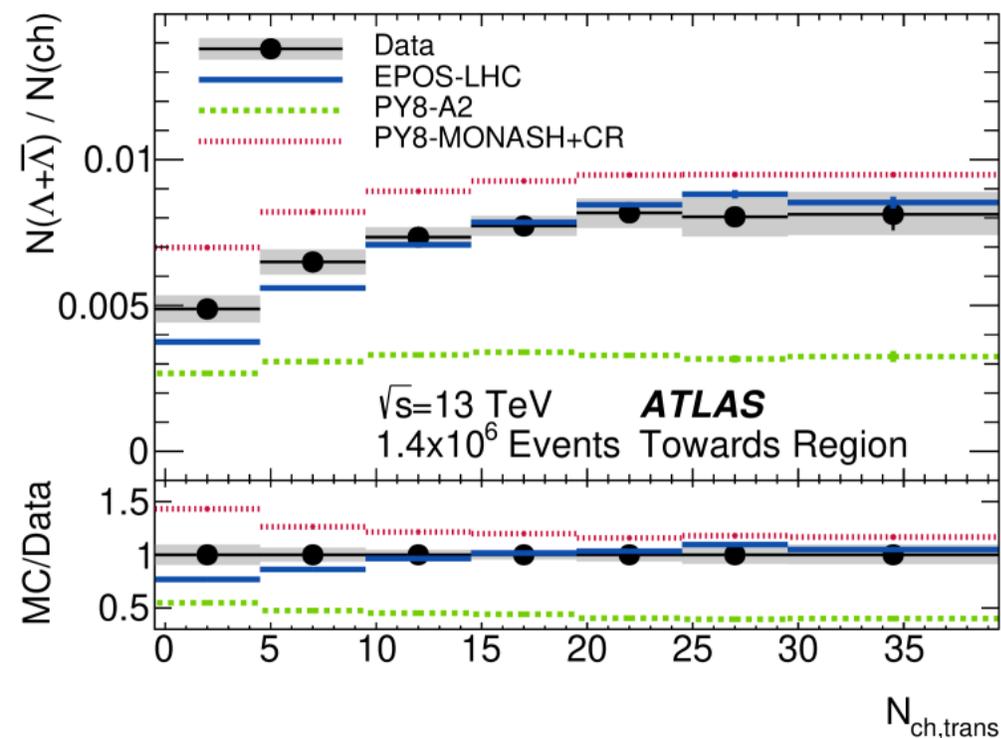
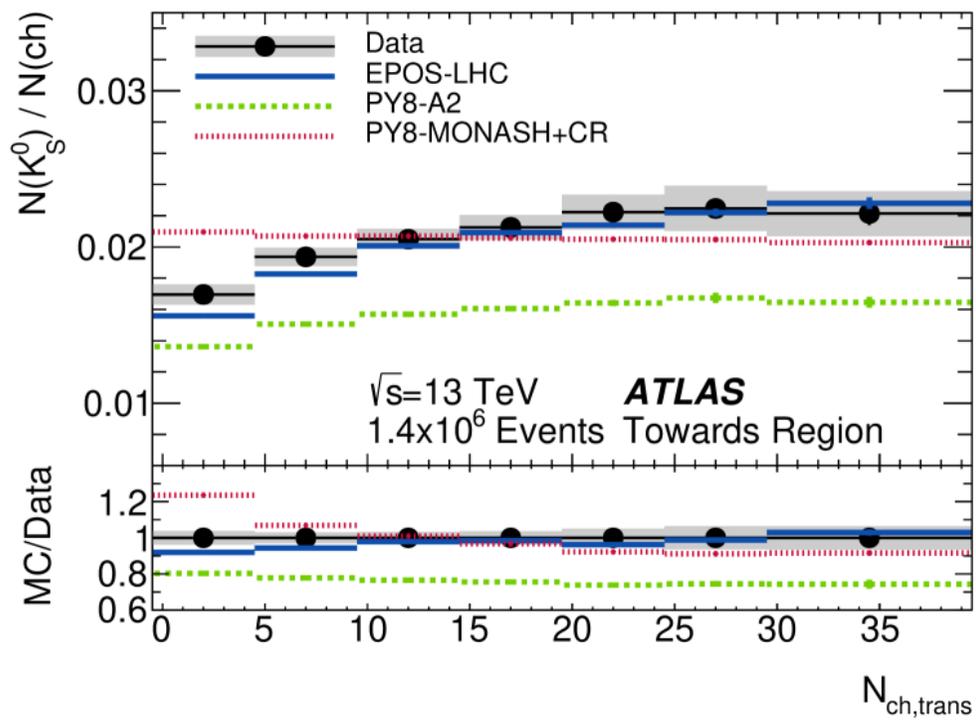
- Data: **Soft and hard regime**. Transition around leading jet P_T of 10 GeV.
- Soft regime:
 - EPOS LHC is the closest to data.
 - **PYTHIA Monash + CR is better in the Towards region.**
- Hard regime:
 - EPOS LHC shows a dip absent from data and other models.
 - **PYTHIA A2 models well the data shape.**
 - **PYTHIA Monash + CR models well the Away and Transverse regions.**



II

Results for events with leading jets $10 \text{ GeV} < P_T \leq 40 \text{ GeV}$ (1)

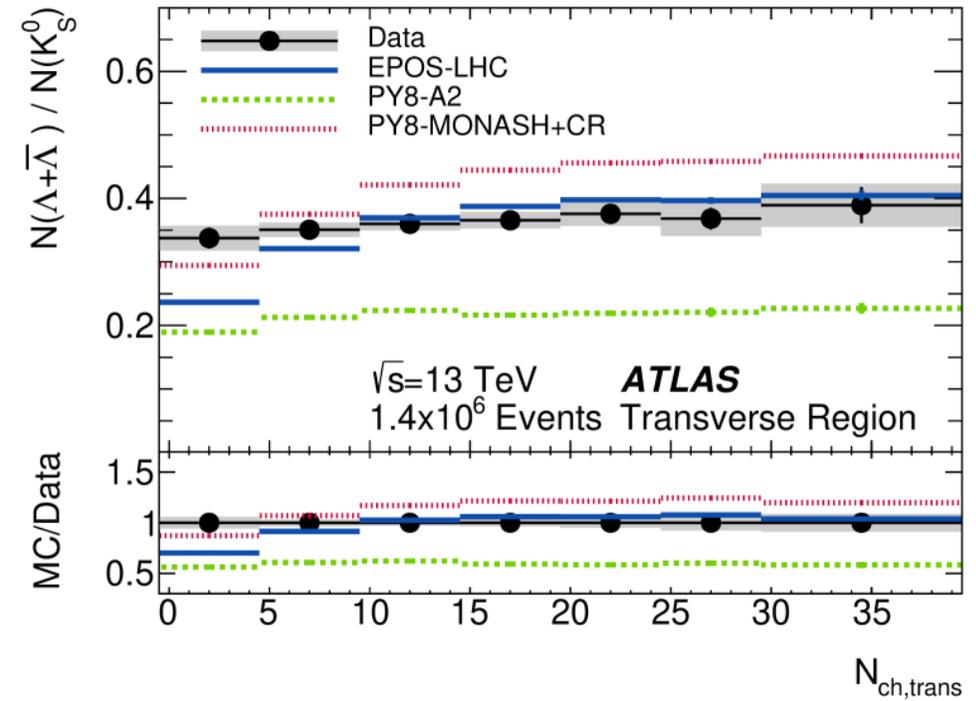
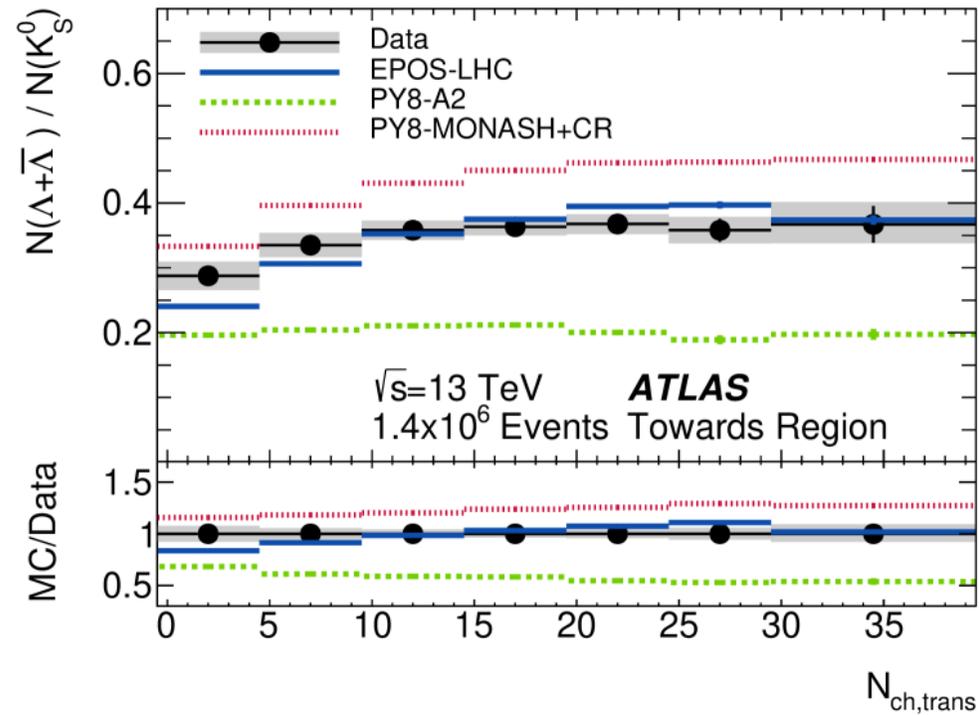
- Events acquired with the double hemisphere trigger.
- Number of prompt charged particle in Transverse region used as MPI proxy.



EPOS LHC is the closest to data.

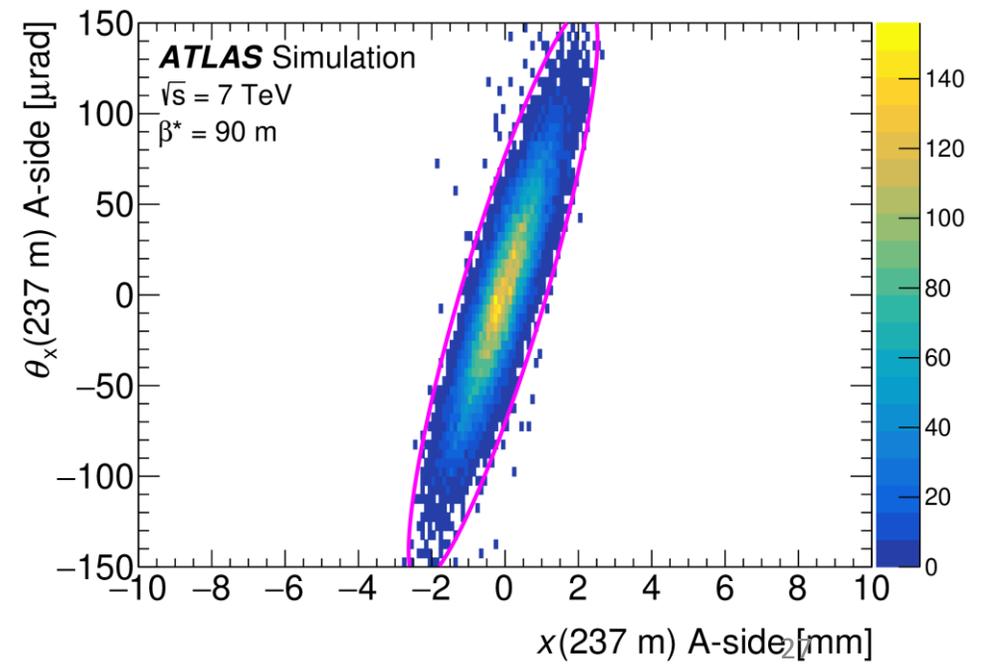
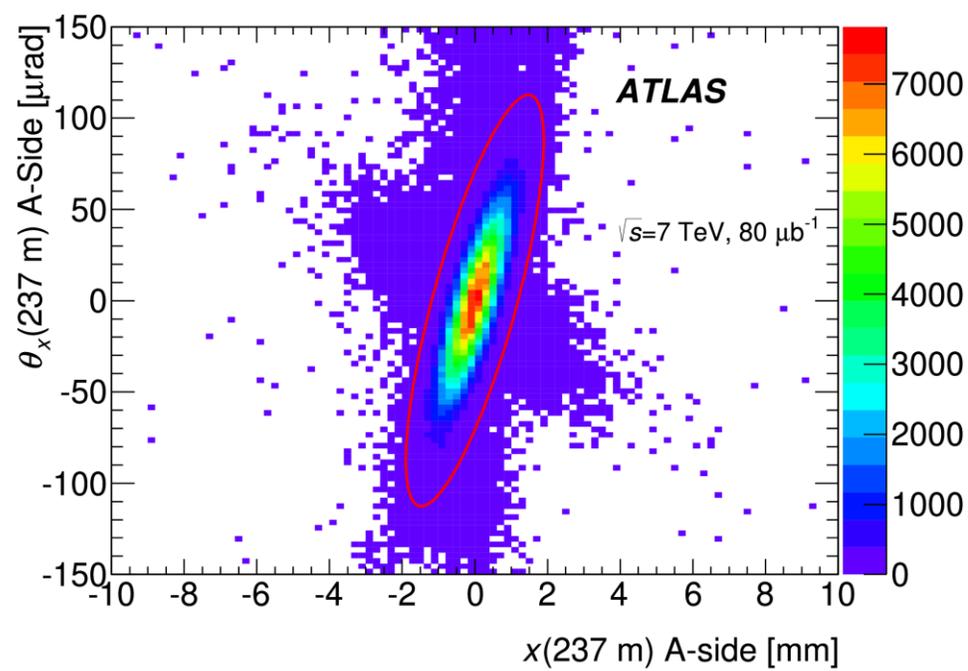
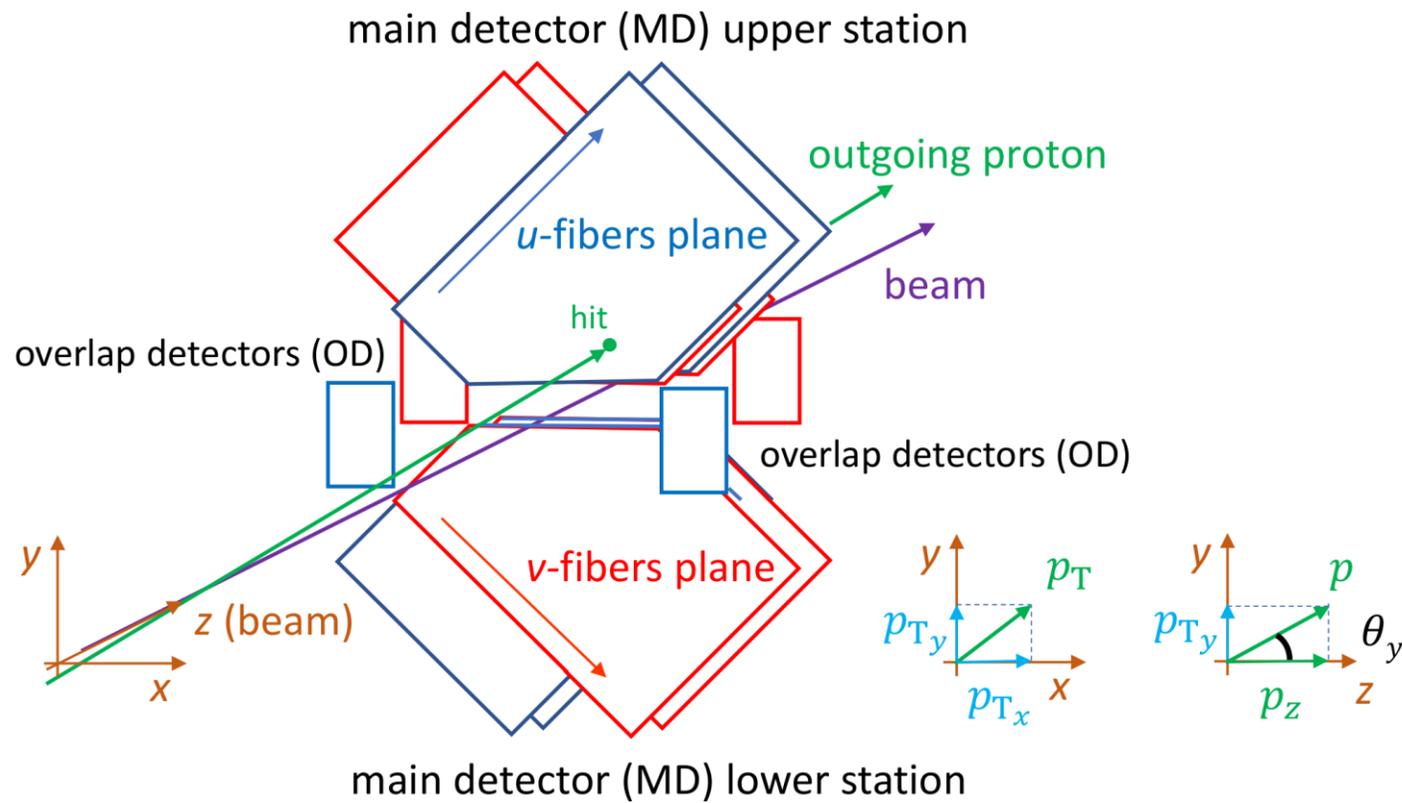
II

Results for event with leading jets $10 \text{ GeV} < P_T \leq 40 \text{ GeV}$ (2)

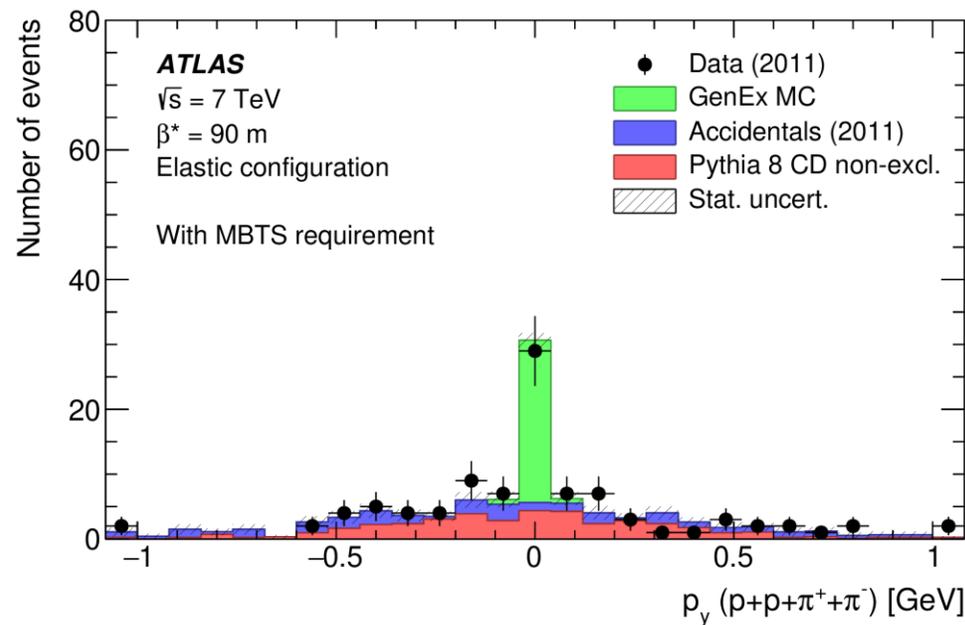
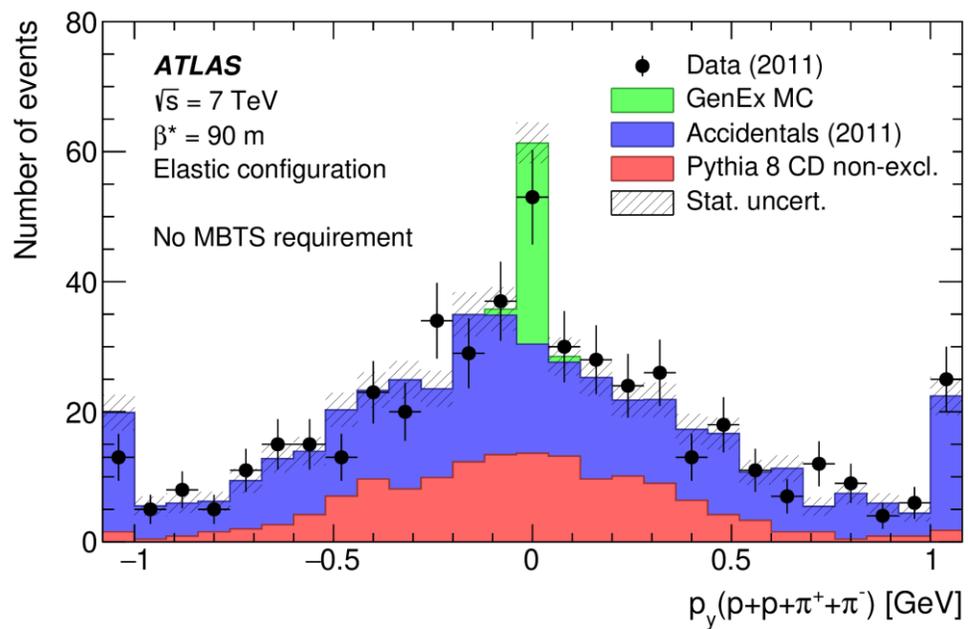
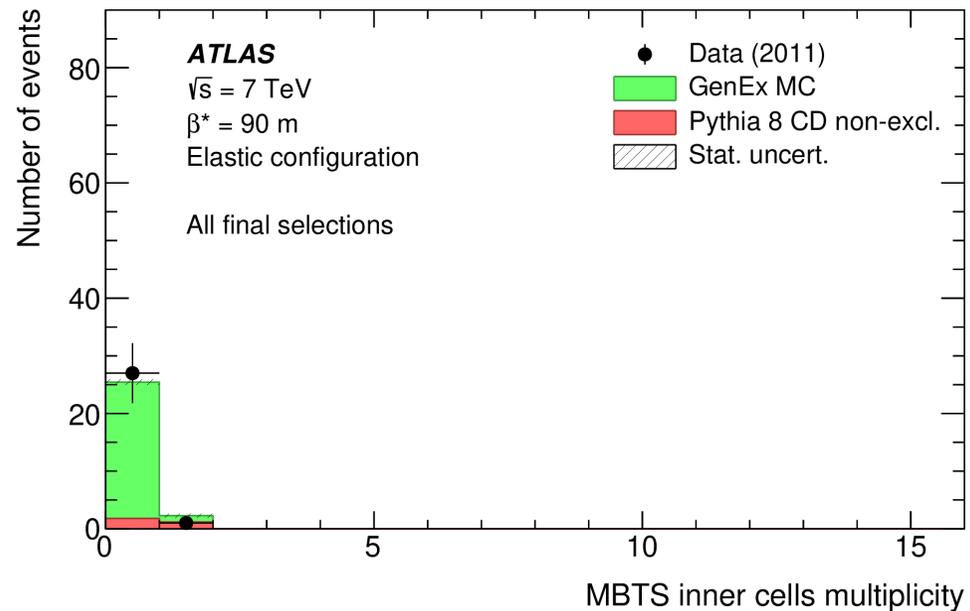
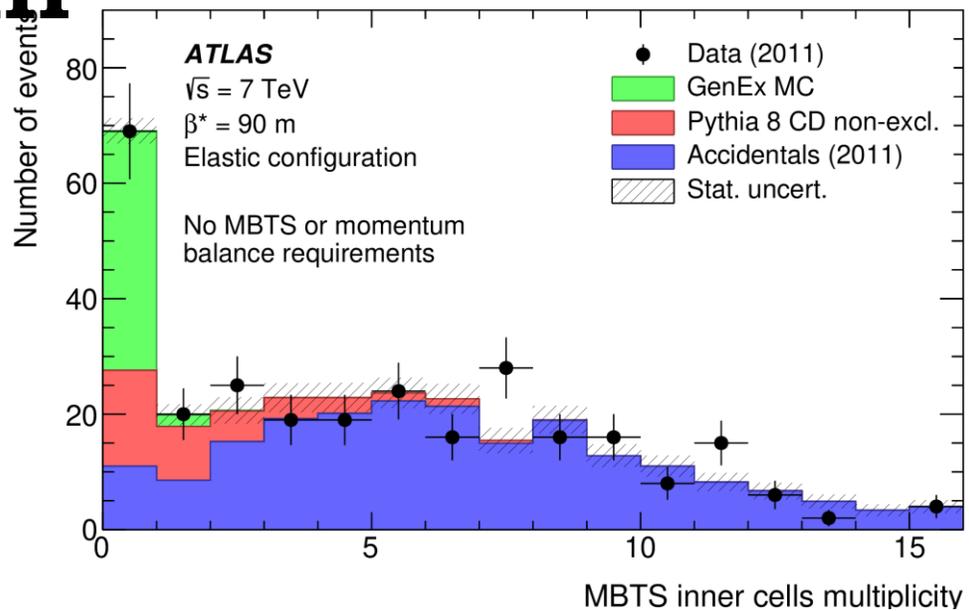


PYTHIA A2 reproduces the shape of the data.

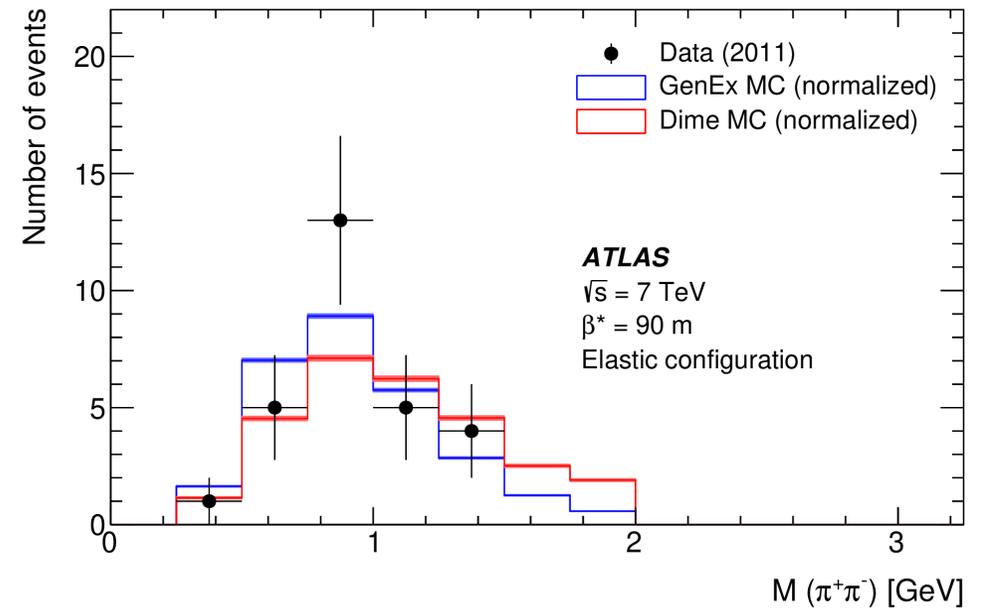
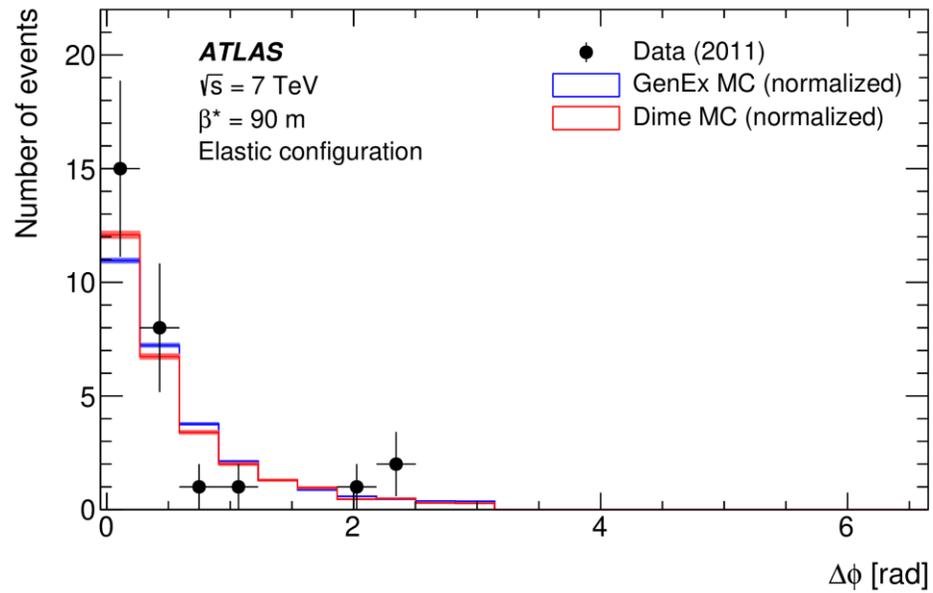
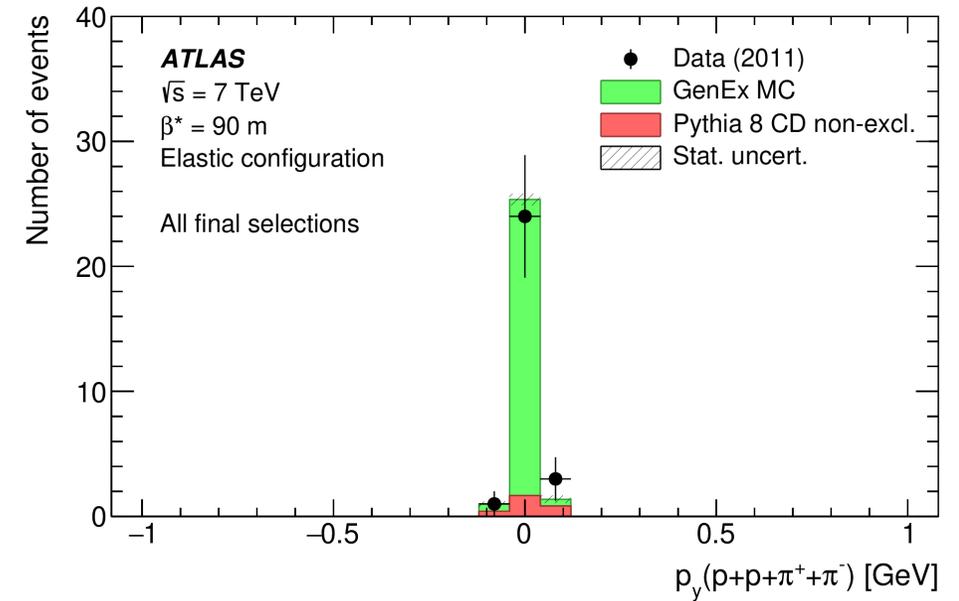
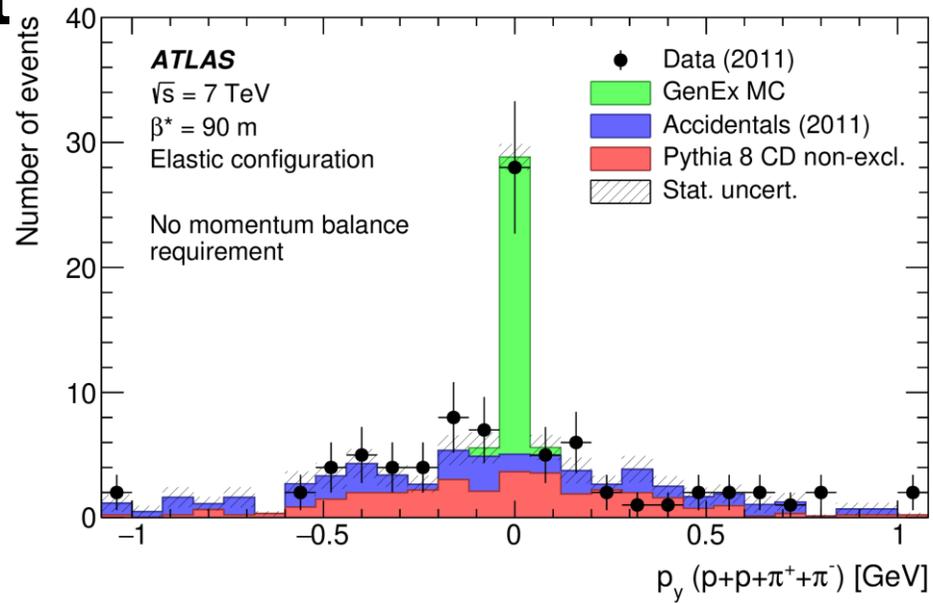
III



III



III



IV

collision system	\sqrt{s}	integrated luminosity	$\langle \mu \rangle$	number of events
<i>pp</i>	0.9 TeV	53.9 pb ⁻¹	0.005	4.4×10^6
<i>pp</i>	5.02 TeV	31.4 nb ⁻¹	0.47	8.2×10^6
<i>pp</i>	13 TeV	14.0 nb ⁻¹	0.003 - 0.321	65.5×10^6
<i>p+Pb</i>	5.02 TeV	0.27 nb ⁻¹	0.0002-0.005	18.7×10^6
Pb+Pb	5.02 TeV	19.3 pb ⁻¹	0.002 - 0.003	9.3×10^6