Early Run 2 Soft QCD Results from the ATLAS Collaboration

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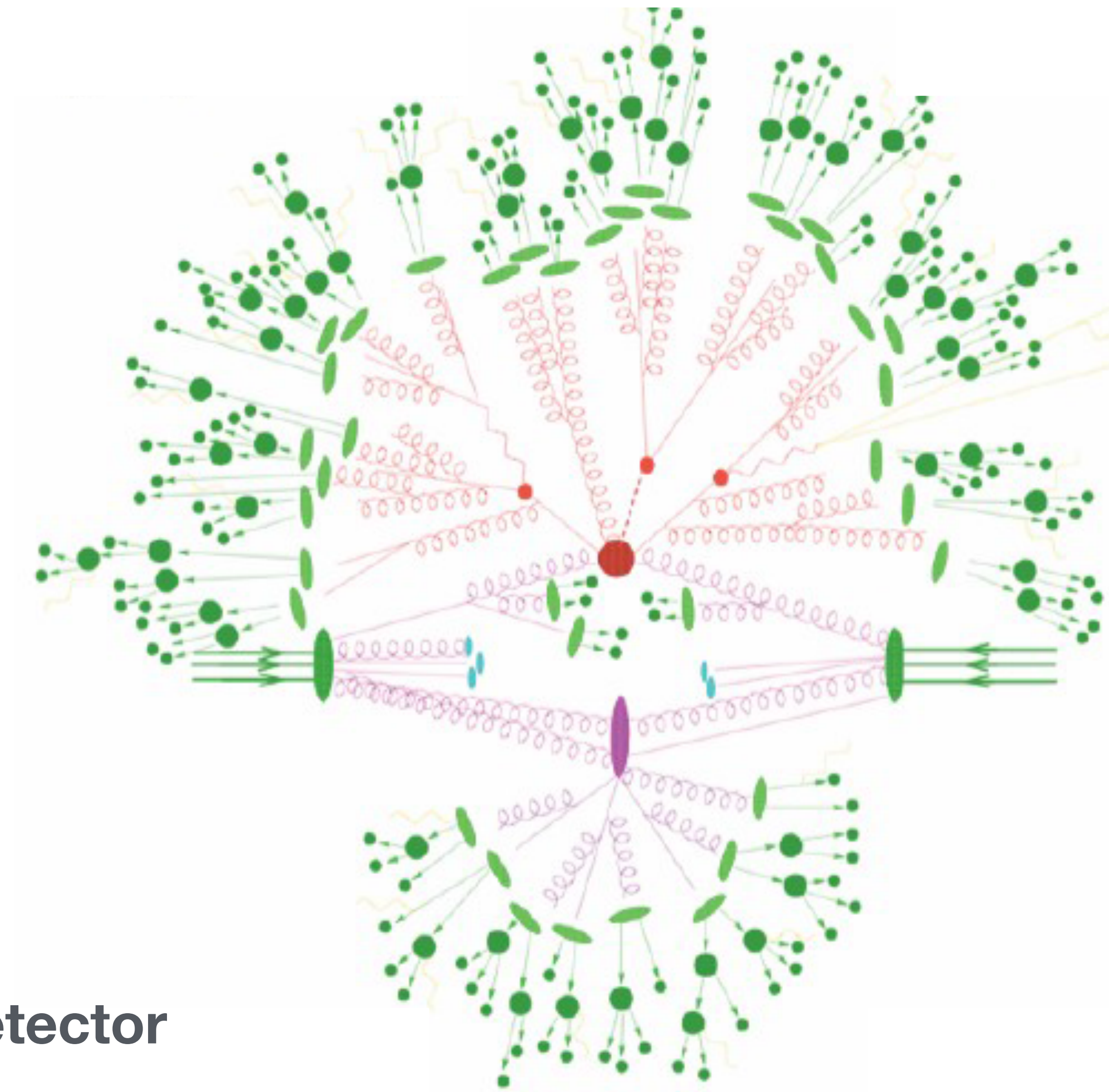
on behalf of the ATLAS Collaboration

Oct 9, 2015 XLV International Symposium on Multiparticle Dynamics (ISMD2015), Munich, Germany

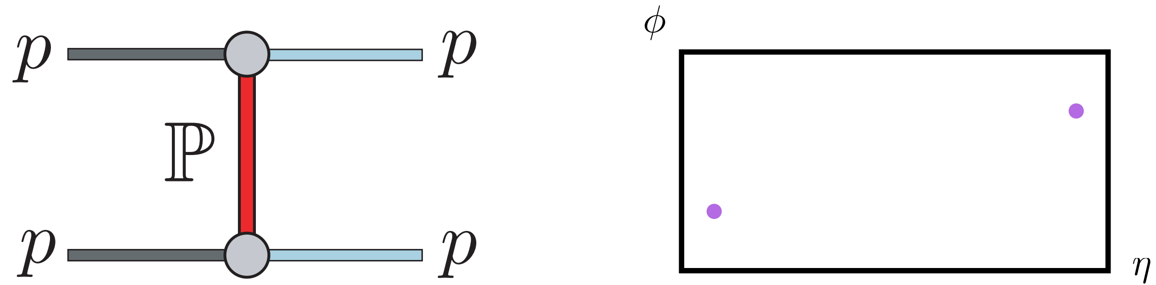
Overview

- **Understanding and modelling of QCD interactions have direct impact on the potential precision measurements and new physics searches.**
- **Soft QCD interaction is only phenomenologically modelled and not predicted by pQCD. Non-predictable free parameters are tuned using data.**
- **Commencement of the LHC Run2 at the new energy frontier at 13 TeV.**
  - Low-μ runs: ideal place to measure various properties of soft QCD interactions (negligible pile-up)
- **This talk will cover the following measurement results released this summer using the ATLAS Detector (Minimum Bias Trigger Scintillators and the Inner Detector).**
  - Fiducial/total inelastic cross section [ATLAS-CONF-2015-038]
  - “Minimum Bias” charged particle distributions [ATLAS-CONF-2015-028]
  - Underlying event [ATL-PHYS-PUB-2015-019]



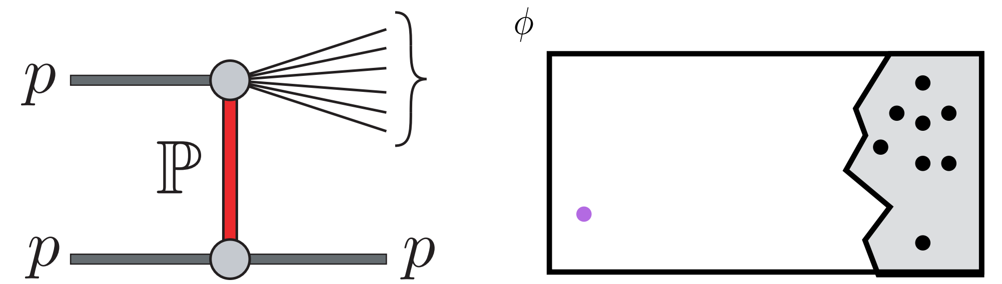
Soft QCD Interaction Categories

Elastic

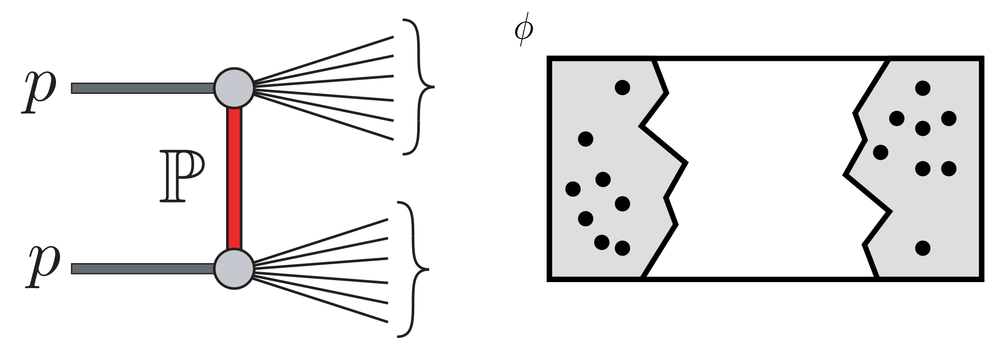


Inelastic

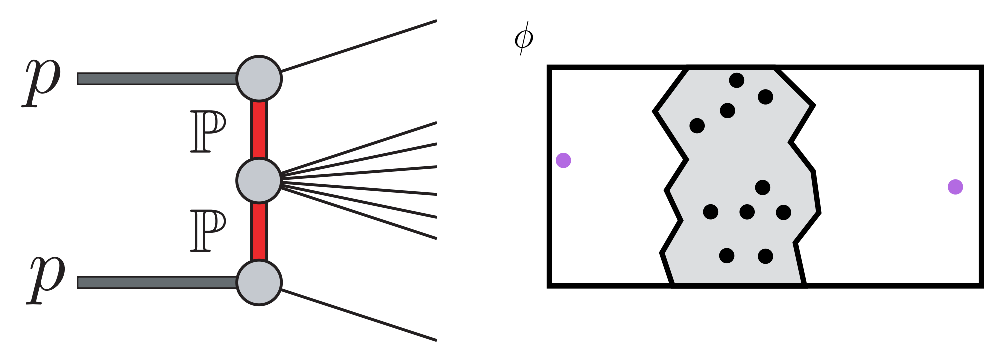
Single-Diffractive (SD)



Double-Diffractive (DD)



Central-Diffractive (CD)

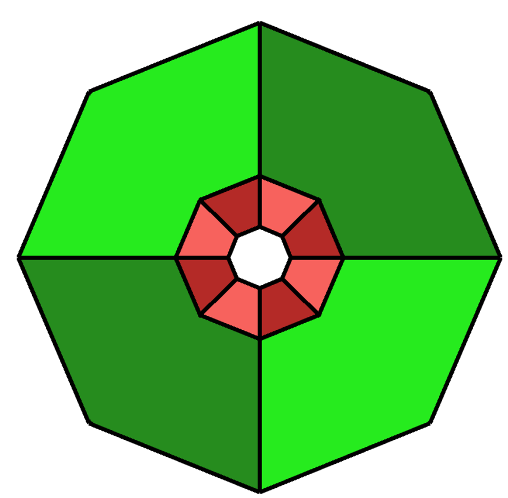


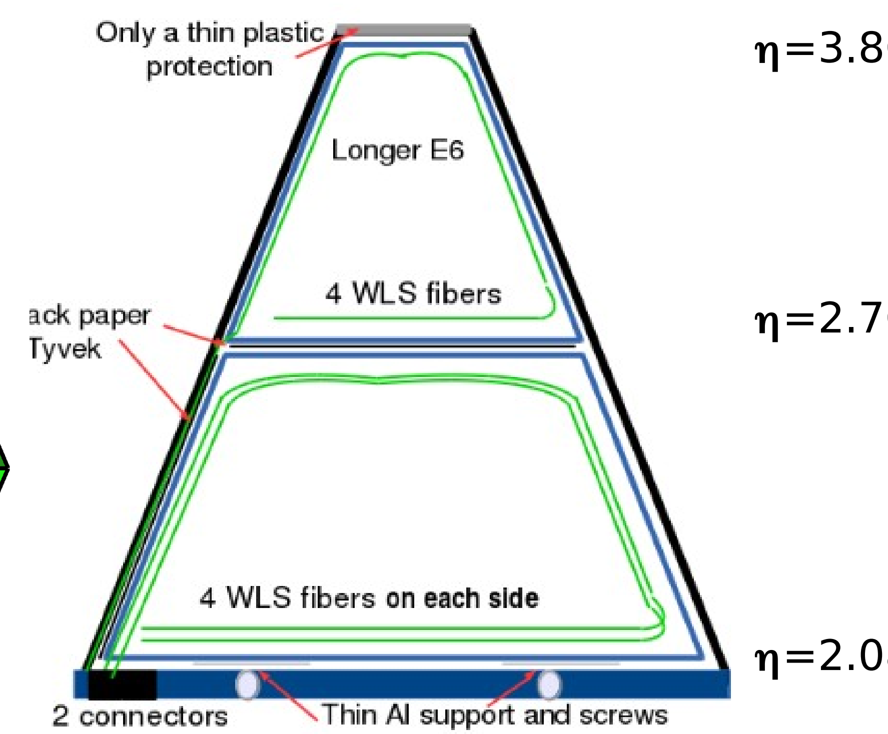
Non-Diffractive (ND)

Everything else (~ *t*-channel gluon exchange)

Inelastic Cross Section Measurement

- **LHC has two types of inelastic cross section measurement.**
  - Elastic events in Roman Pot detectors (TOTEM, ATLAS-ALFA)
    - Optical theorem to derive total and elastic cross section
    - ATLAS-ALFA (7 TeV): σ_{inel} = 71.34 ± 0.90 mb
      [Nuclear Physics, Section B (2014), pp. 486-548, [arXiv:hep-ex/1408.5778]]
    - Requires special run conditions with different beam optics
  - Inelastic event counting (all LHC experiments)
    - Define fiducial region of events where the detector has high efficiency
    - Use low-μ collision runs
- **ATLAS measurement w/ MBTS**
  - Scintillator tiles located in front of end-cap calorimeters
  - Refurbished for Run2
  - Slightly extended η range of 2.08 < $|\eta|$ < 3.86
  - Modified segmentation
    - Outer panel: 4 sections per side
    - Inner panel: 8 sections per side
    - Total: (4+8)×2 sides = 24 channels in total



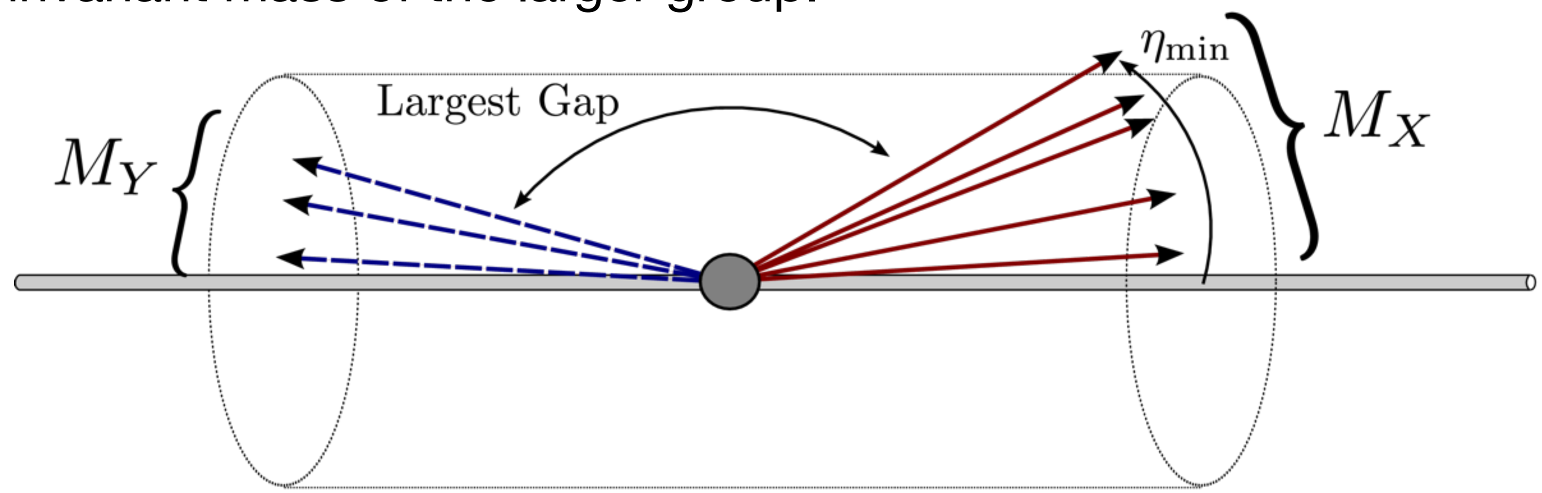


Inelastic Cross Section Measurement

[ATLAS-CONF-2015-038]

- Dividing final state hadrons into two groups *X*, *Y* using the larget rapidity gap.
- Define the following varialbe using the invariant mass of the larger group.

$$\tilde{\xi} = \frac{\tilde{M}_X^2}{s}$$



[Fiducial Cross Section]

Data-based Estimations

Total Events

BG Subtraction

Migration of Small ξ into the fiducial

$$\sigma_{\rm inel}(\tilde{\xi} > 10^{-6}) = \frac{N - N_{\rm BG}}{\epsilon_{\rm trig} \times L} \times \frac{1 - f_{\tilde{\xi}<10^{-6}}}{\epsilon_{\rm sel}}$$

MC-based Corrections

Trigger Eff.

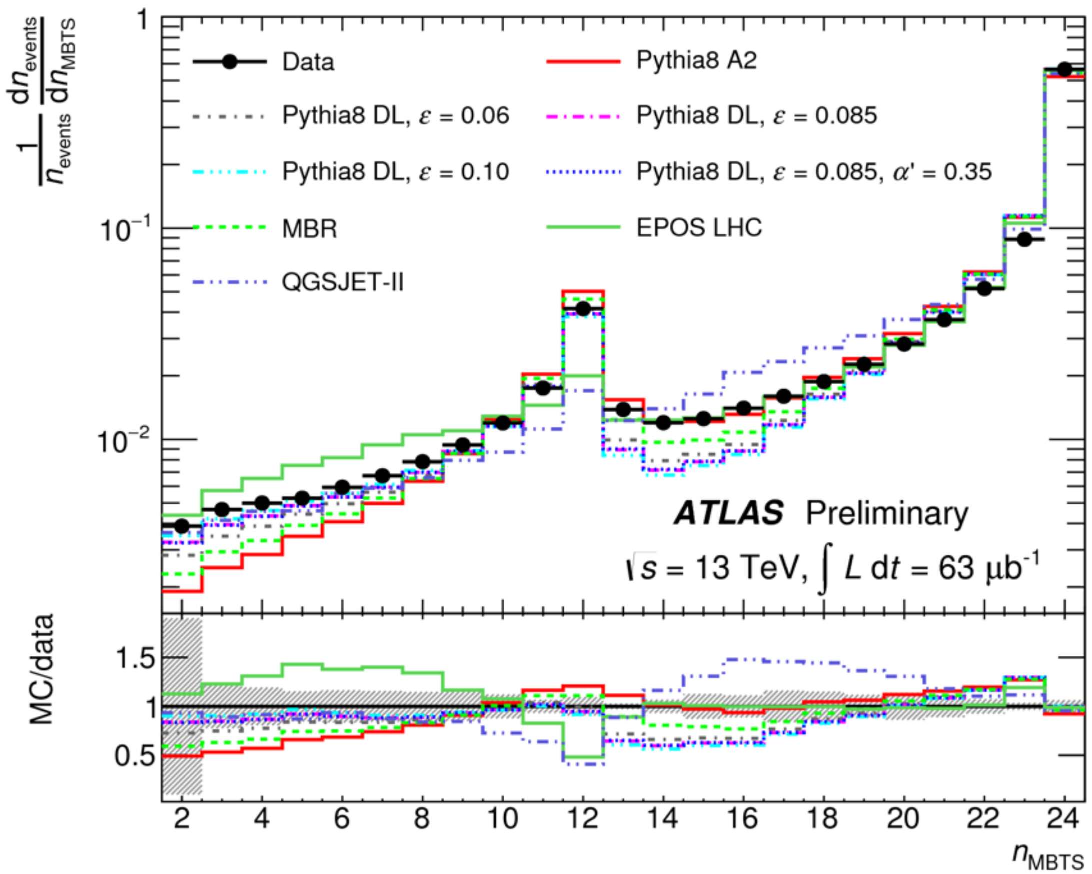
Luminosity

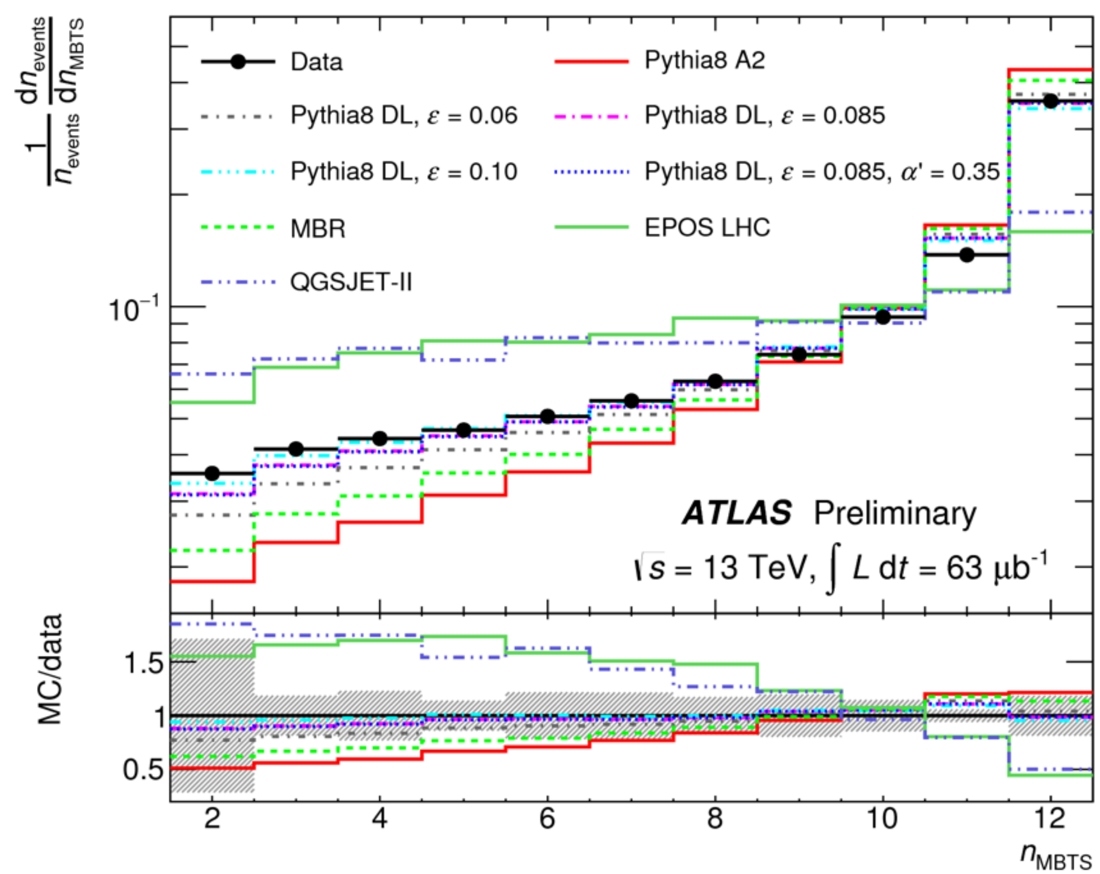
Event selection efficiency

→ Extrapolated to $\sigma_{\rm inel}(\rm total)$ (model-dependent)

MBTS Hit Multiplicity Distribution

[ATLAS-CONF-2015-038]





- **Compared MBTS hit multiplicity distribution with various MC models.**
  - **Pythia8: A2 Schuler & Sjöstrand / Donnachie & Landshoff (DL) / MinBias Rockfeller (MBR)**
  - **EPOS-LHC**
  - **QGSJET-II**
- **Pythia8 Donnachie & Landshoff model w/ (α'=0.25, ϵ = 0.085) gives a good description.**
  → Used as the central value model.

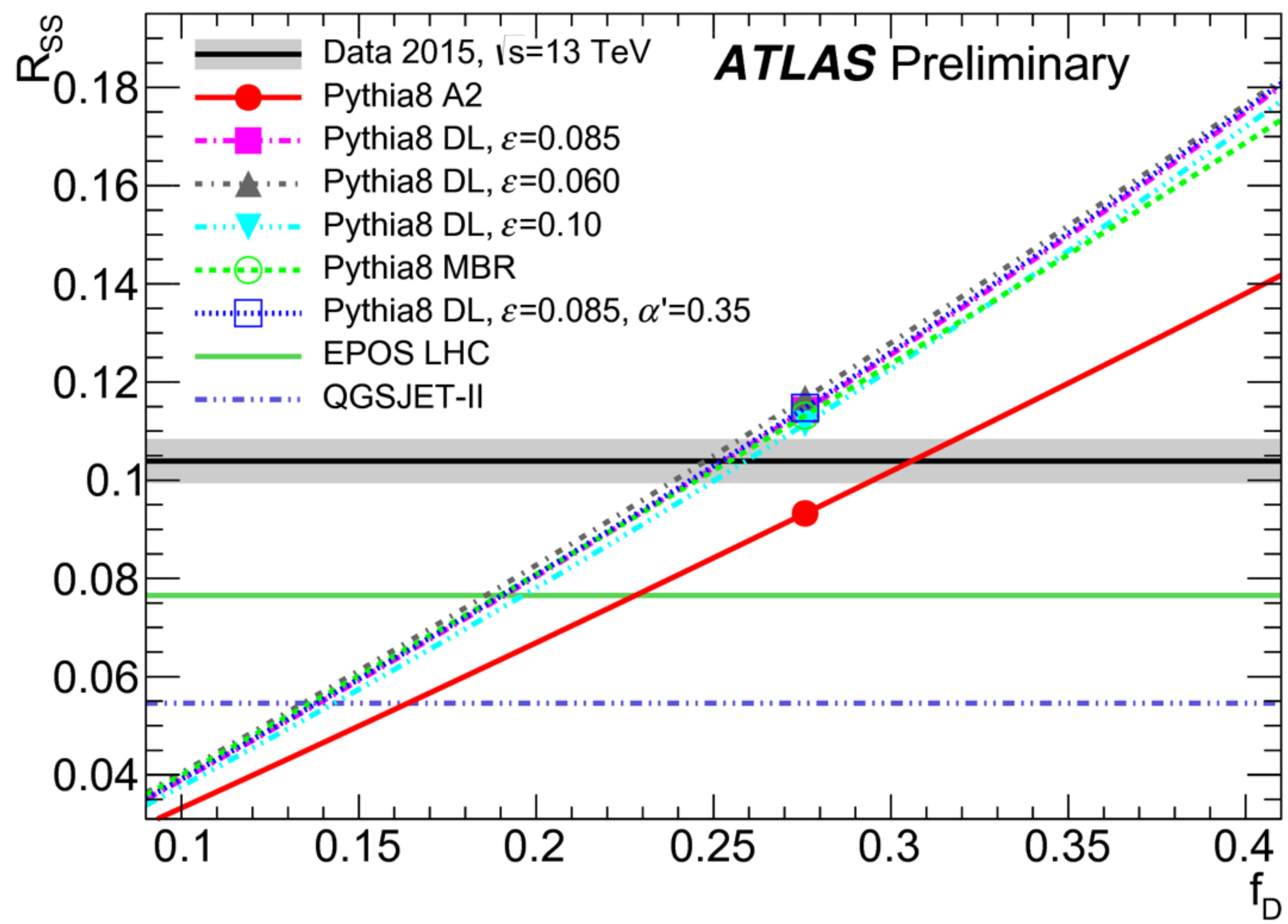
Pomeron-Regge trajectory: $\alpha(t) = 1 + \epsilon + \alpha' t$

- **Variance of the models are considered as the uncertainty of the extrapolation to calculate the total cross section from the fiducial cross section.**

Constraints on the fraction of SD+DD

[ATLAS-CONF-2015-038]

- R_{SS}: Fraction of the events that only either side of MBTS's has activity
- R_{SS} = 10.4 ± 0.5 % (data)
- Using Pythia8, the fraction of (SD+DD) cross section to the total inelastic cross section, f_D, was varied to reproduce the measured R_{SS}.
  - Systematic uncertainty was set with setting extreme cases of $\sigma_{SD} = 0$ and $\sigma_{DD} = 0$ within the tuning of the R_{SS}.
  - For Pythia8: f_D = 25-32 %. (nominal: 27.5%)
- R_{SS} prediction
  - QGSJET-II : 5.5%
  - EPOS (LHC) : 7.6%
- Pythia8 f_D constraint is applied to extract the variation of the fiducial acceptance.

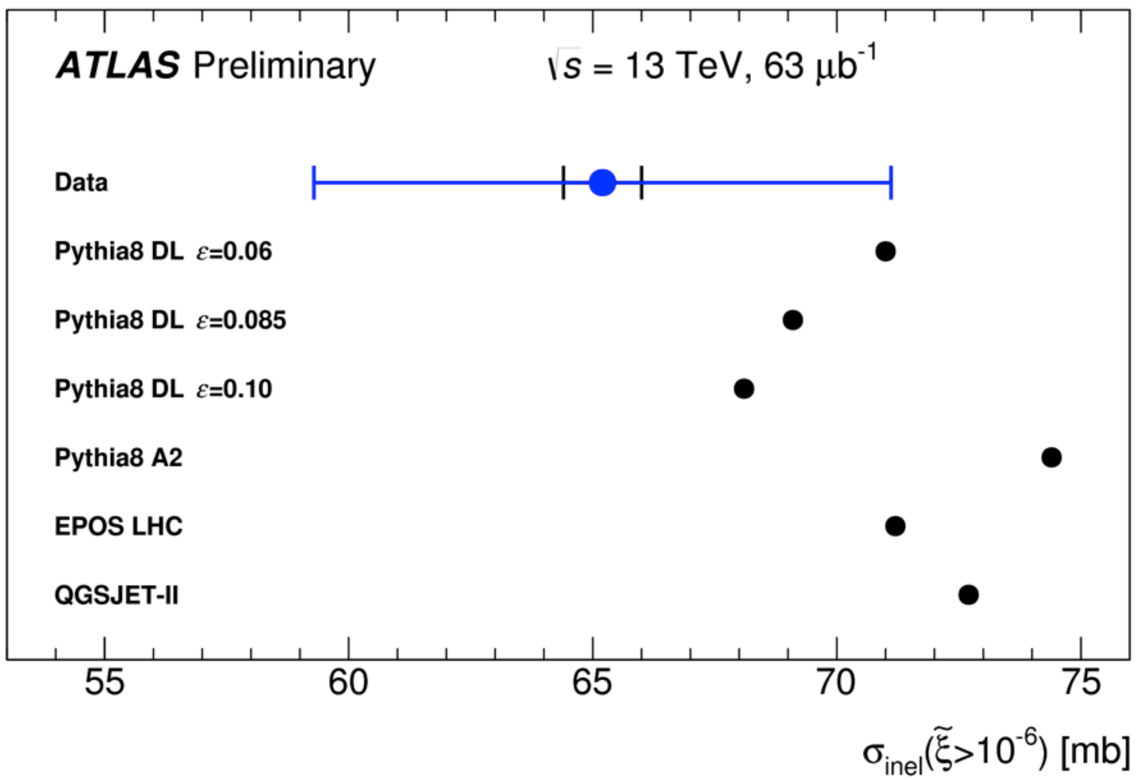


Inelastic Cross Section

[ATLAS-CONF-2015-038]

Factor	Value	Rel. unc.
Number of selected events (N)	4159074	–
Number of background events (N_{BG})	43512	±100 %
Luminosity [μb^{-1}] (L)	62.9	±9 %
Trigger efficiency (ϵ_{trig})	99.7%	±0.1 %
MC Correction factor ($(1 - f_{\tilde{\xi}<10^{-6}})/\epsilon_{\mathrm{sel}}$)	0.993	±0.5 %

Fiducial



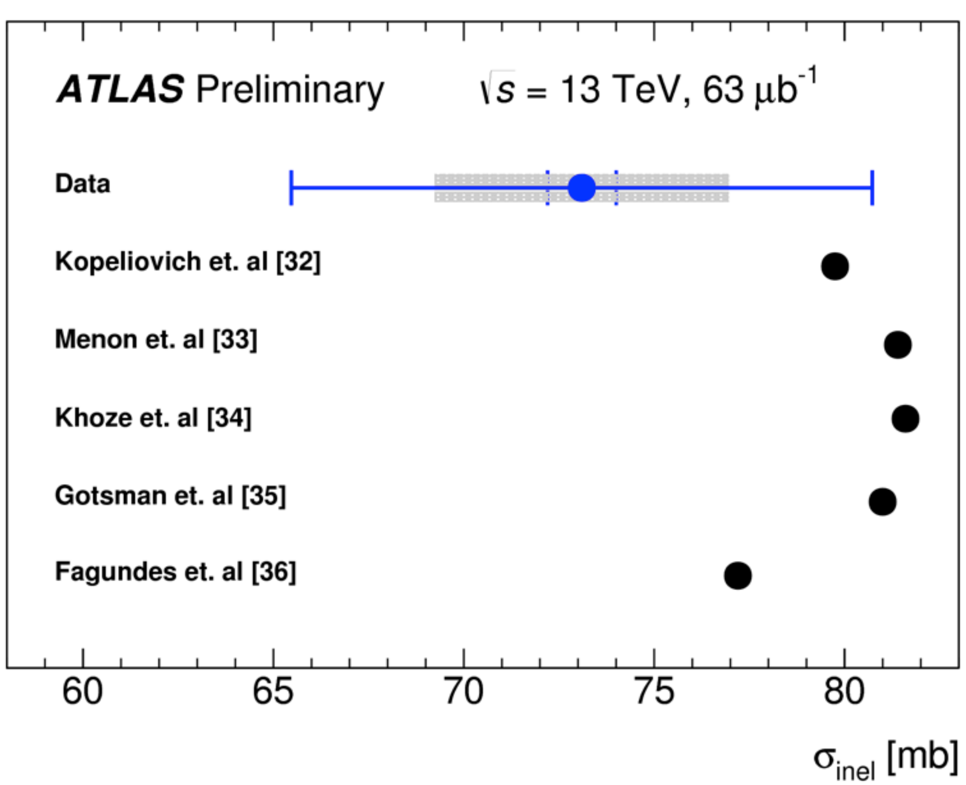
Fiducial Cross Section

$$\sigma_{\mathrm{inel}}(\tilde{\xi} > 10^{-6}) = 65.2 \pm 0.8\ (\mathrm{exp.}) \pm\ 5.9\ (\mathrm{lum.})\ \mathrm{mb}$$

Extrapolation to the total cross section (model-dependent)

- Extimate the fraction of events in $\xi > 10^{-6}$ using MC after adjusting R_{SS}.
- Model dependence is taken as systematic uncertainty.

Total

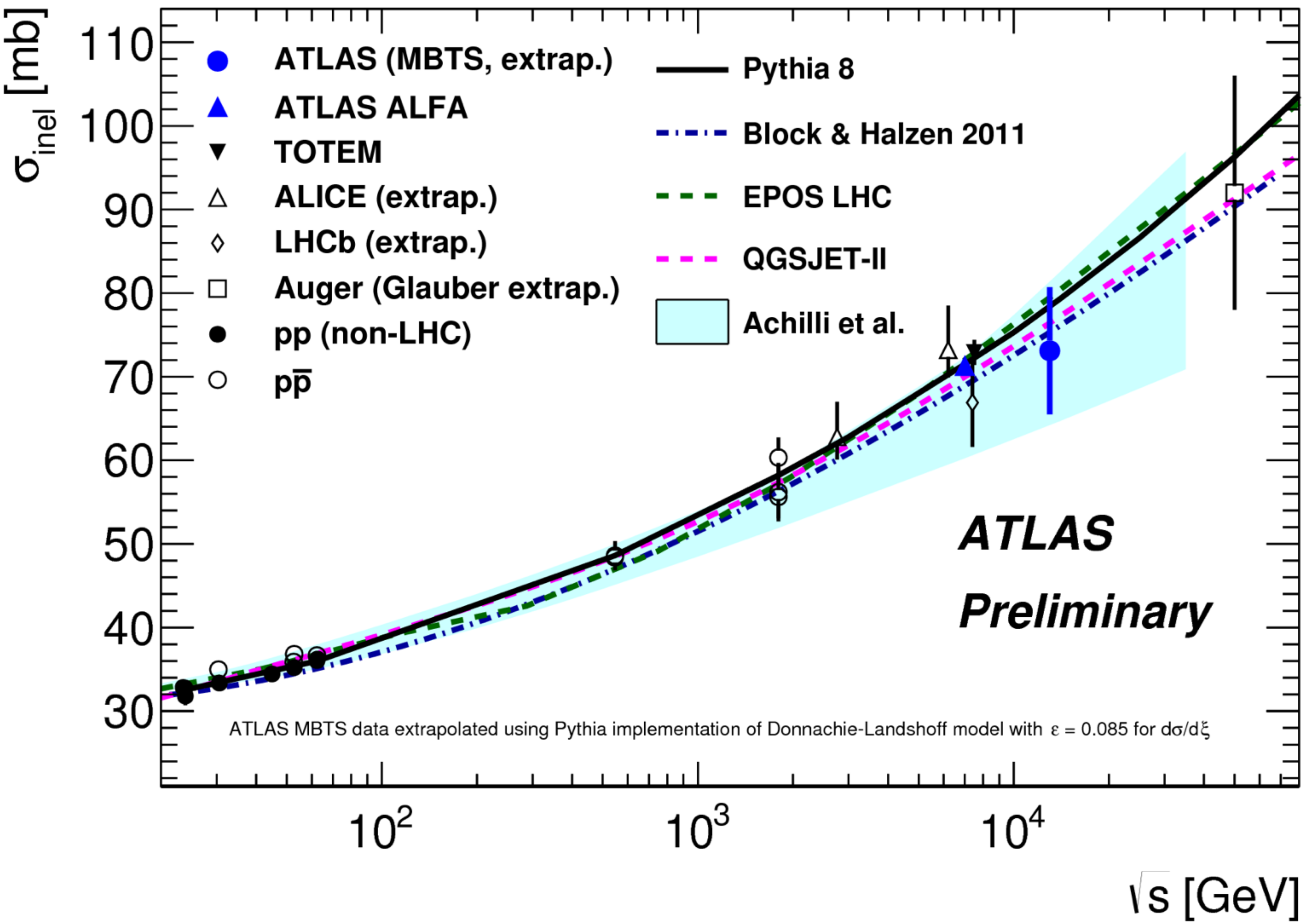


Extrapolated Total Cross Section

$$\sigma_{\mathrm{inel}} = 73.1 \pm 0.9\ (\mathrm{exp.}) \pm 6.6\ (\mathrm{lum.}) \pm 3.3\ (\mathrm{extr.})\ \mathrm{mb}$$

pp Total Inel. Cross Section vs. √s

[ATLAS-CONF-2015-038]



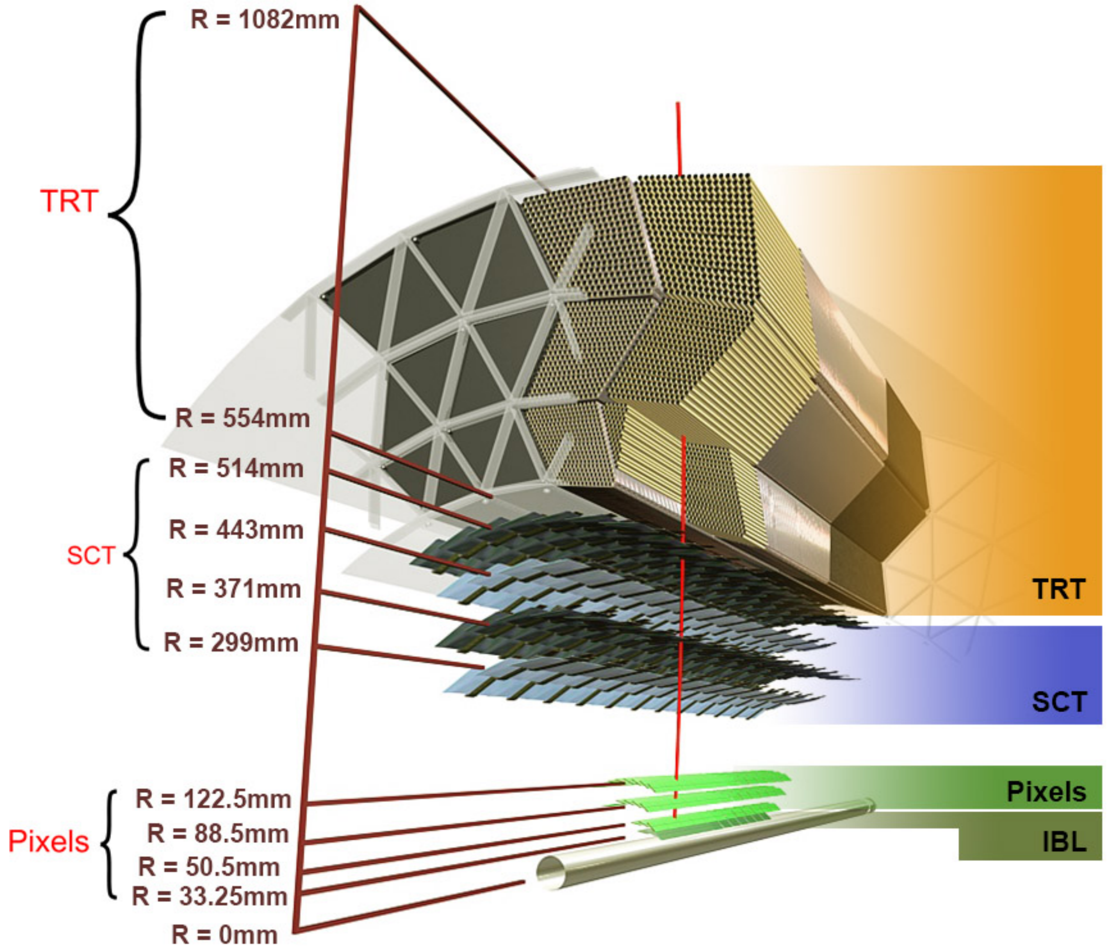
“Minimum Bias” Charged Particle Multiplicity

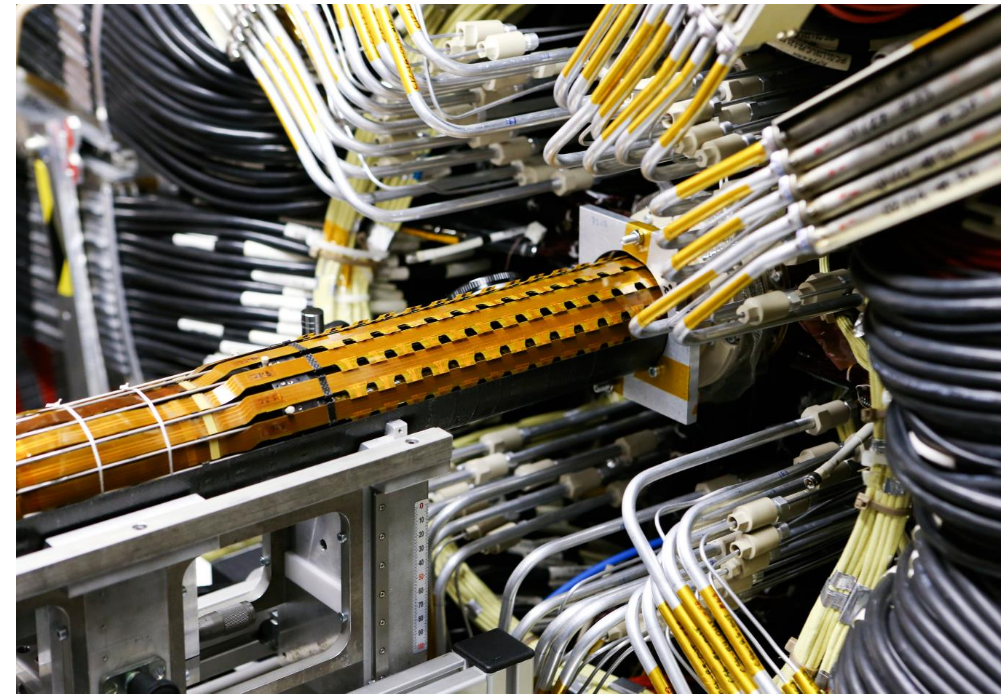
[ATLAS-CONF-2015-028]

- Accurate description of low-energy strong interaction processes is necessary for simulating pile-up collisions.
- Inclusive measurements (w/o model-dependent corrections): giving results in well-defined fiducial region. Results are suitable for tuning MC generators.
- $\sqrt{s}$ = 13 TeV low-μ runs. ~170 μb^{-1}. Pile-up: ~0.005.
- Observables
  - $\frac{1}{N_{\mathrm{ev}}} \frac{dN_{\mathrm{ch}}}{d\eta}$ **Charged track pseudorapidity distribution**
  - $\frac{1}{N_{\mathrm{ev}}} \frac{1}{2\pi p_{\mathrm{T}}} \frac{d^2 N_{\mathrm{ch}}}{d\eta d p_{\mathrm{T}}}$ **Charged track pseudorapidity-momentum distribution**
  - $\frac{1}{N_{\mathrm{ev}}} \frac{dN_{\mathrm{ev}}}{dN_{\mathrm{ch}}}$ **Primary track multiplicity distribution**
  - $\langle p_{\mathrm{T}} \rangle$ vs. N_{ch} **Average p_{T} as a function of charged track multiplicity**

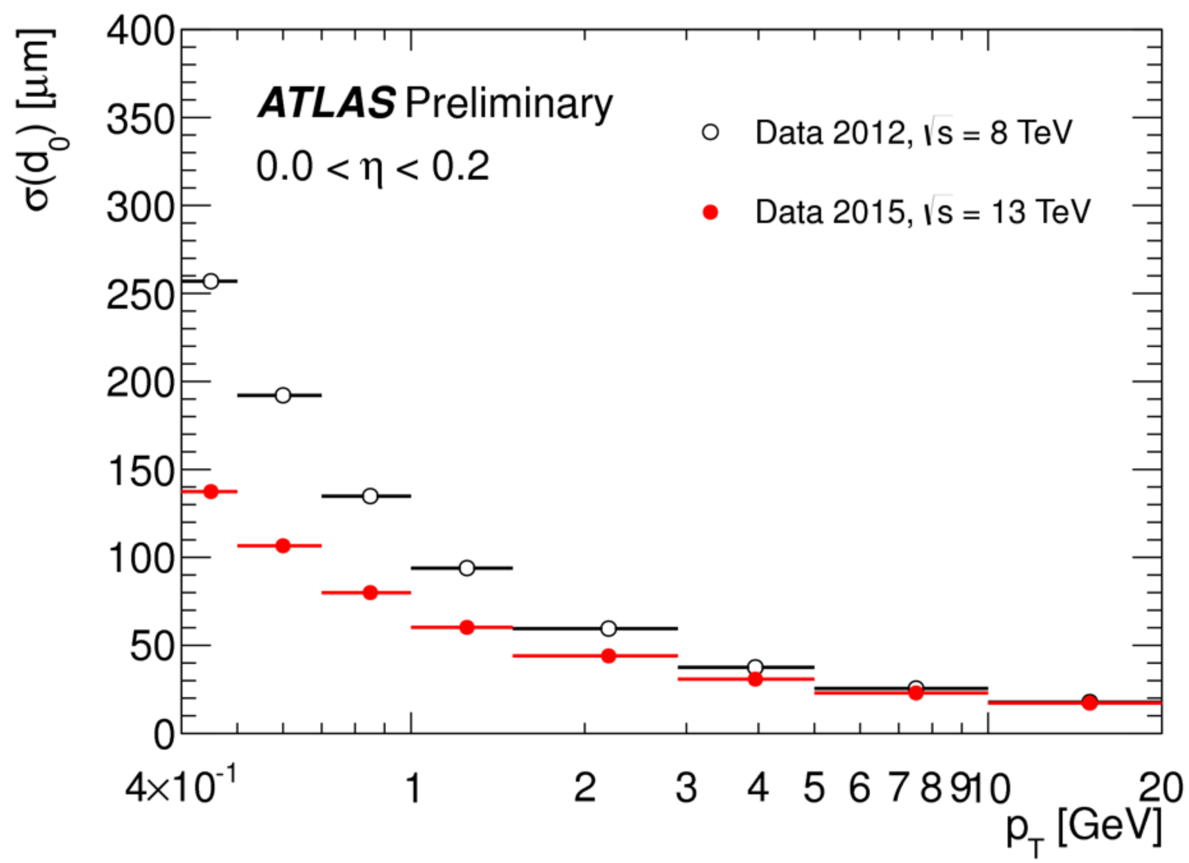
Run2 Inner Detector

[ATLAS-CONF-2015-028]





Insertable B-Layer (IBL)

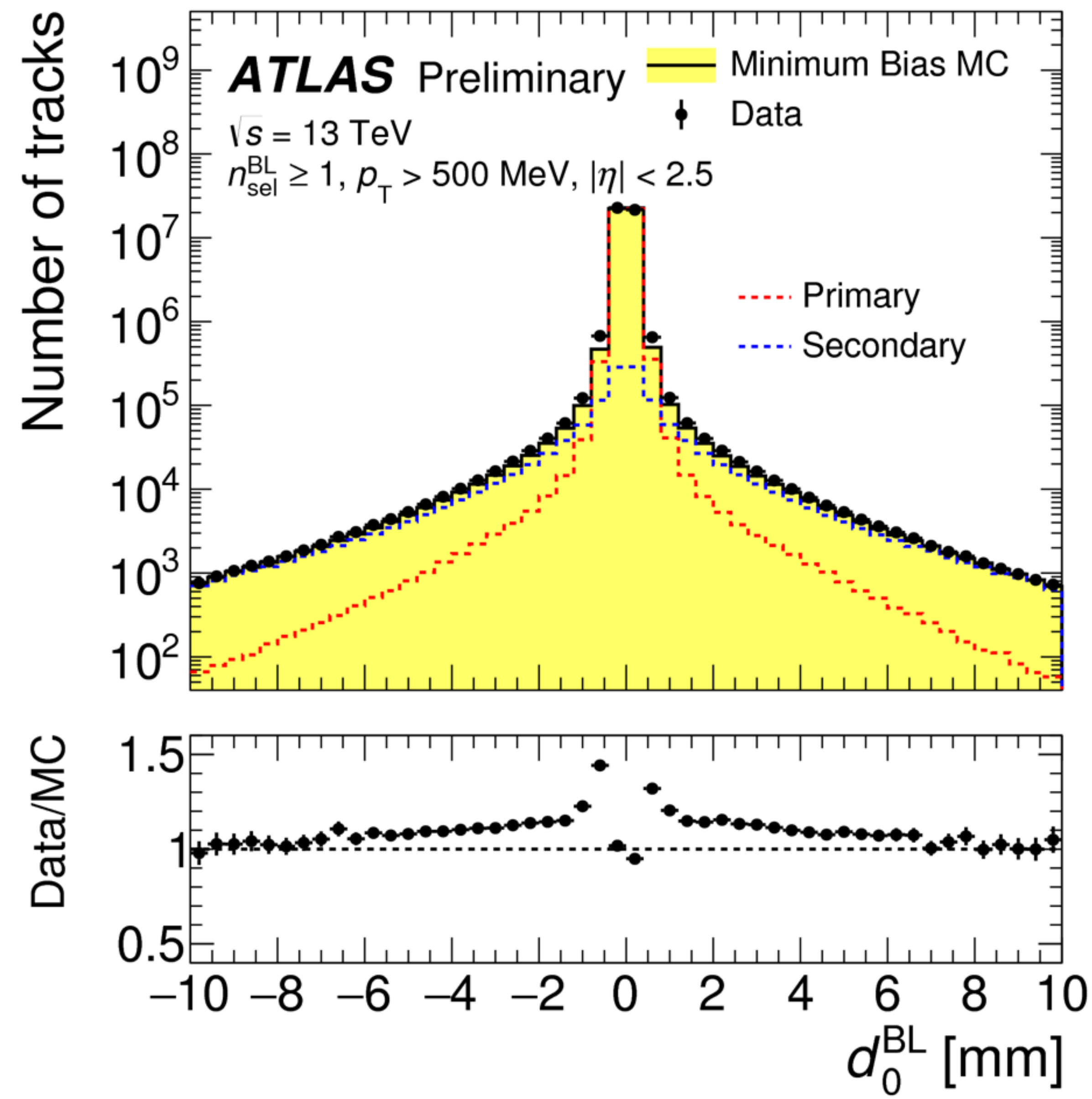


- **Existing Detectors**
  - Pixel: 3 Barrel + 3 Endcap layers, 1.7k modules 80Mpx
  - Silicon Strip (SCT): 4k modules
  - Transition Radiation Tracker (Drift Tube): 360k straws
- **Run2: New Pixel Layer "IBL" at R = 33 mm.**
  - 12 Mpx, 50×250 μm^2 pixel size
  - New smaller Beam Pipe (inner radius : 23.5 mm)
- **2 T solenoid magnet, |η| < 2.5**

Minimum Bias Analysis

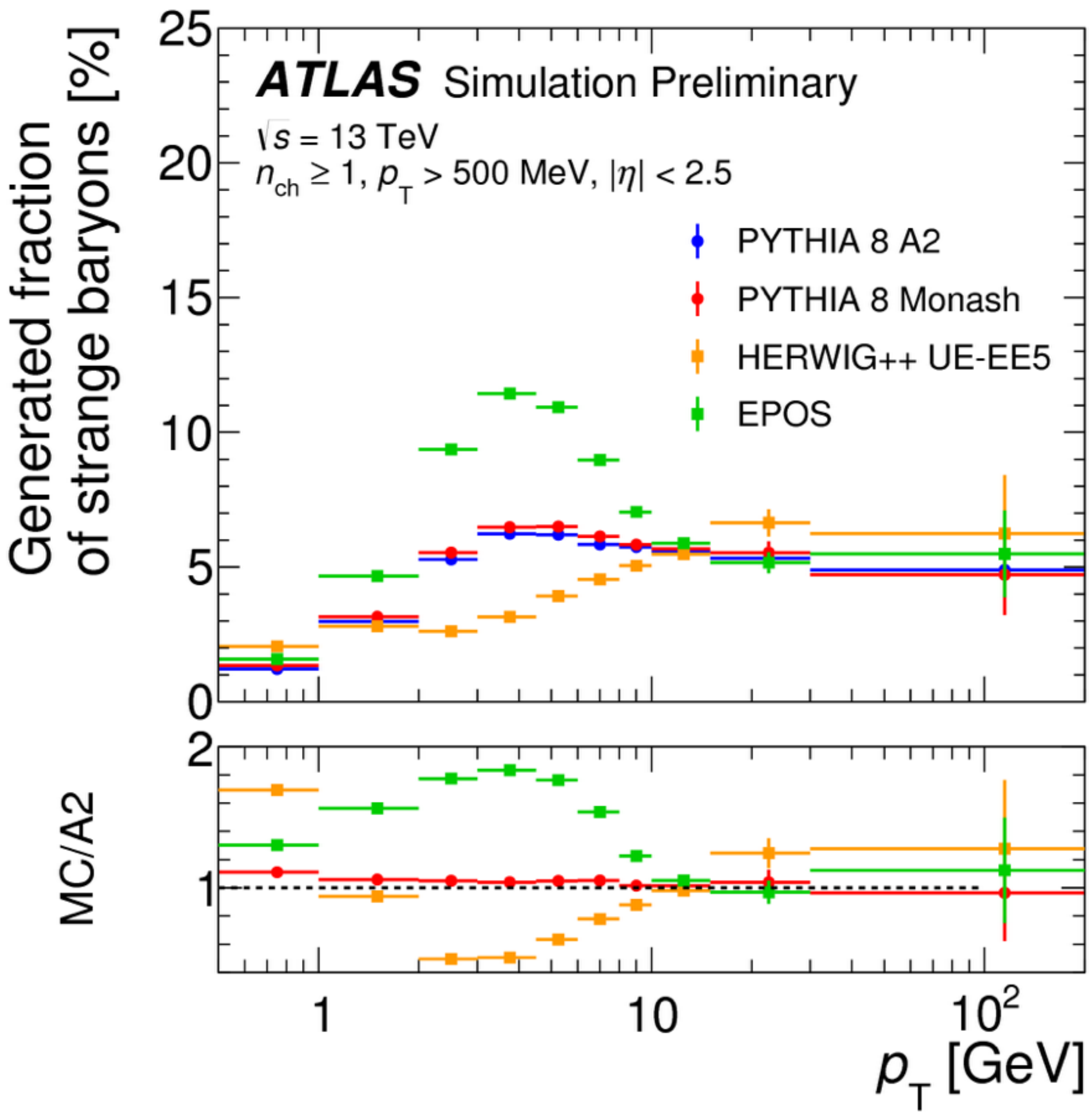
[ATLAS-CONF-2015-028]

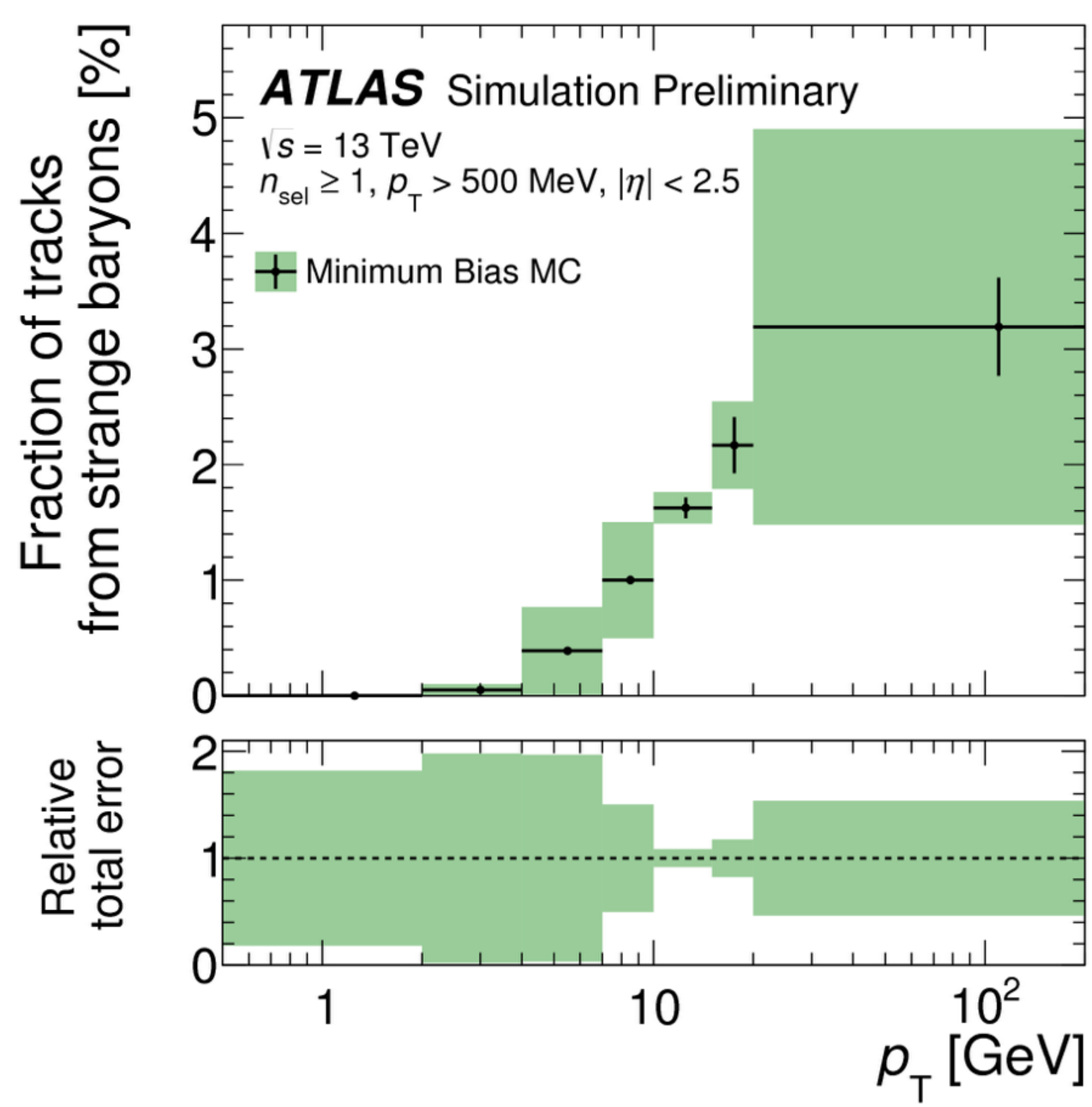
- **Trigger**
  - Level-1: Minimum Bias trigger (MBTS), ≥1 hits in either side
- **Event Selection**
  - Track Reconstruction
    - Track acceptance: $p_T > 0.5$ GeV, $|\eta| < 2.5$ (≥ 1 tracks)
    - ≥ 1 Pixel Hits and ≥ 6 SCT Hits
    - $|d_0^{BL}| < 1.5$ mm and $|\Delta z_0 \cdot \sin\theta| < 1.5$ mm
    - χ^2 probability > 0.01 for $p_T > 10$ GeV
  - Primary vertex (≥ 2 tracks w/ $p_T > 100$ MeV)
    - 1 primary vertex (Pile-up veto)
- **Extraction of primary particle yield**
  - Primary: with lifetime > 300 ps, either directly produced from pp collisions, or decay product of mother particles with lifetime < 30 ps.
  - Fitting of d_0^{BL} distribution in $5 < |d_0^{BL}| < 9.5$ mm to estimate the fraction of secondary particle yield.
  - Subtract secondary yield at the primary track selection region.
- **Corrections**
  - Event (trigger, vertex eff.) and track efficiency corrections
  - Bayesian unfolding for p_T distribution



Strange Baryons

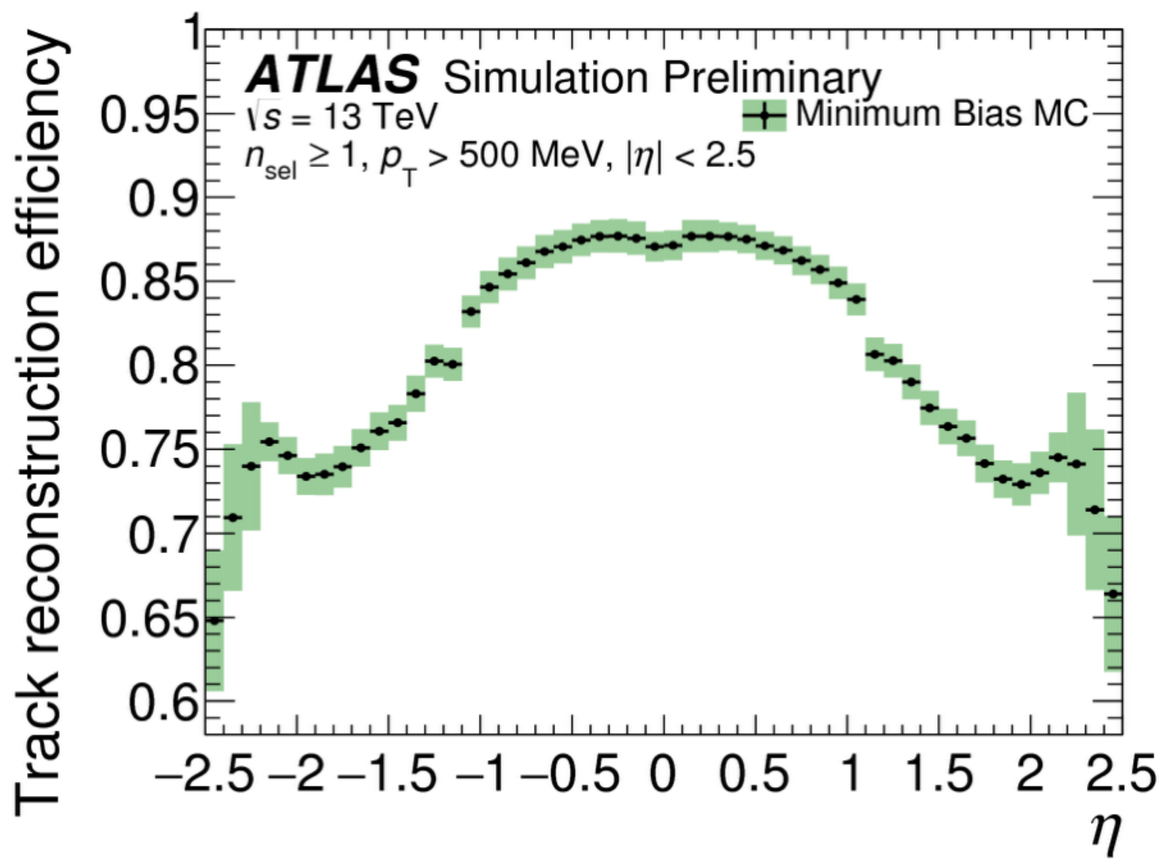
- **Defining primary particles as the particles with lifetime > 300 ps.**
  - Either directly produced from pp collisions, or decay product of mother particles with lifetime < 30 ps.
- **In Run1 analyses, strange baryons were included as primary particles. In Run2 13 TeV results, strange baryons were excluded.**
  - MC generator dependence is very large for strange baryons.
  - Reconstruction efficiency is low.

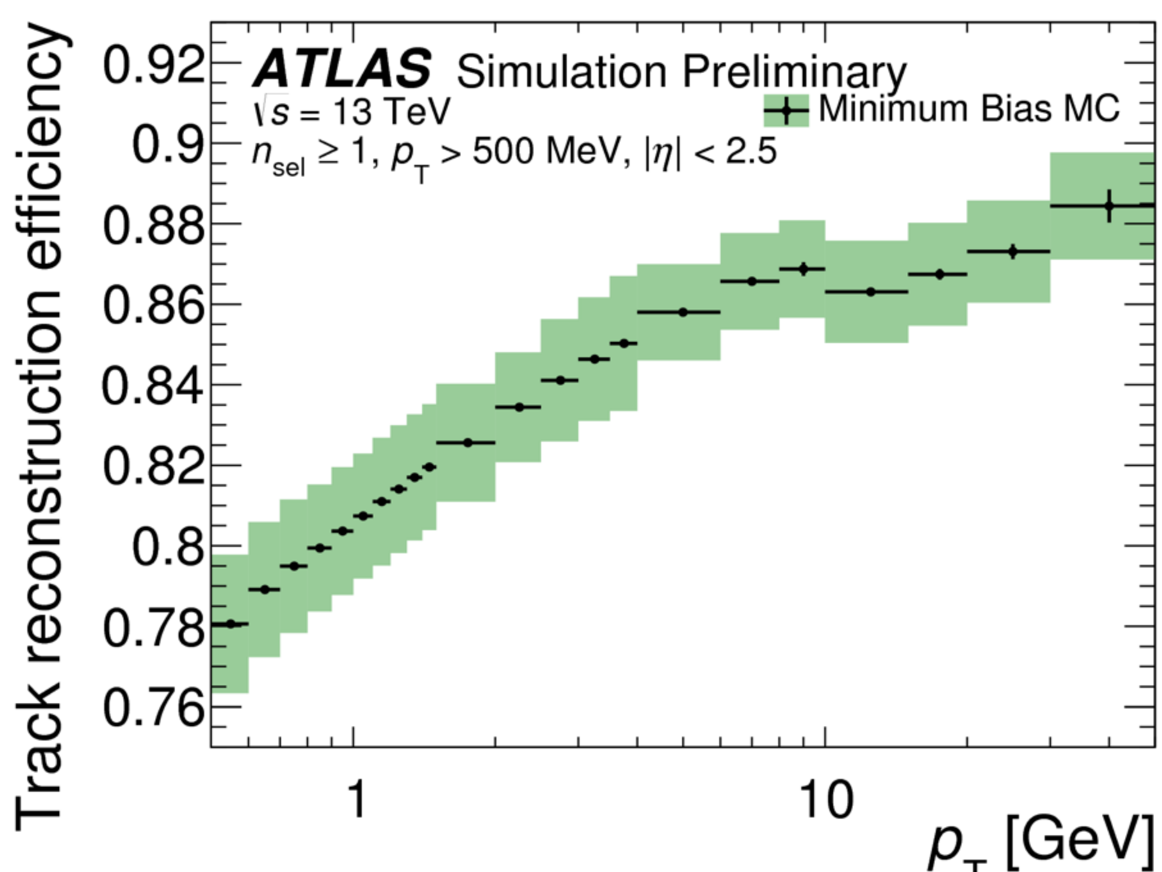


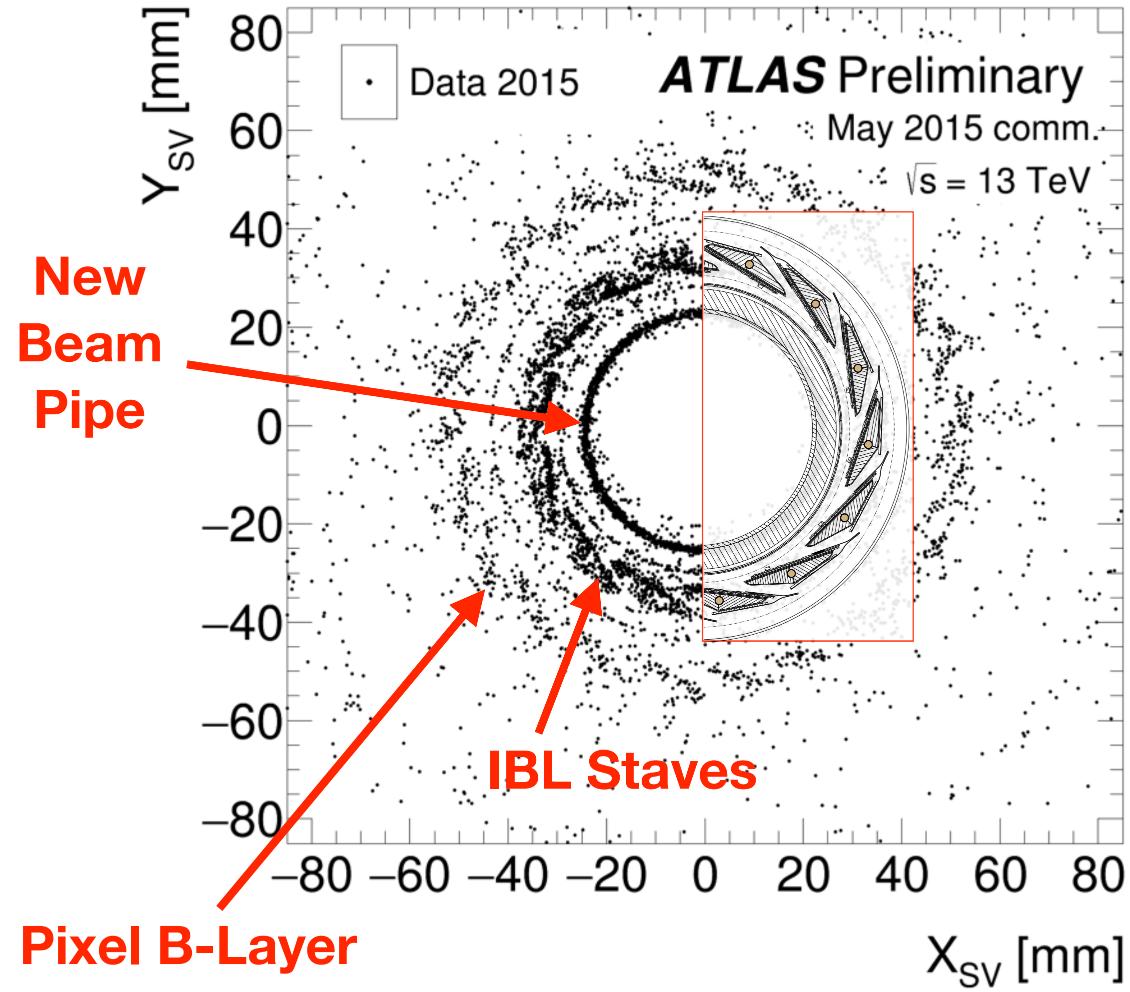


Tracking Efficiency

[ATLAS-CONF-2015-028]



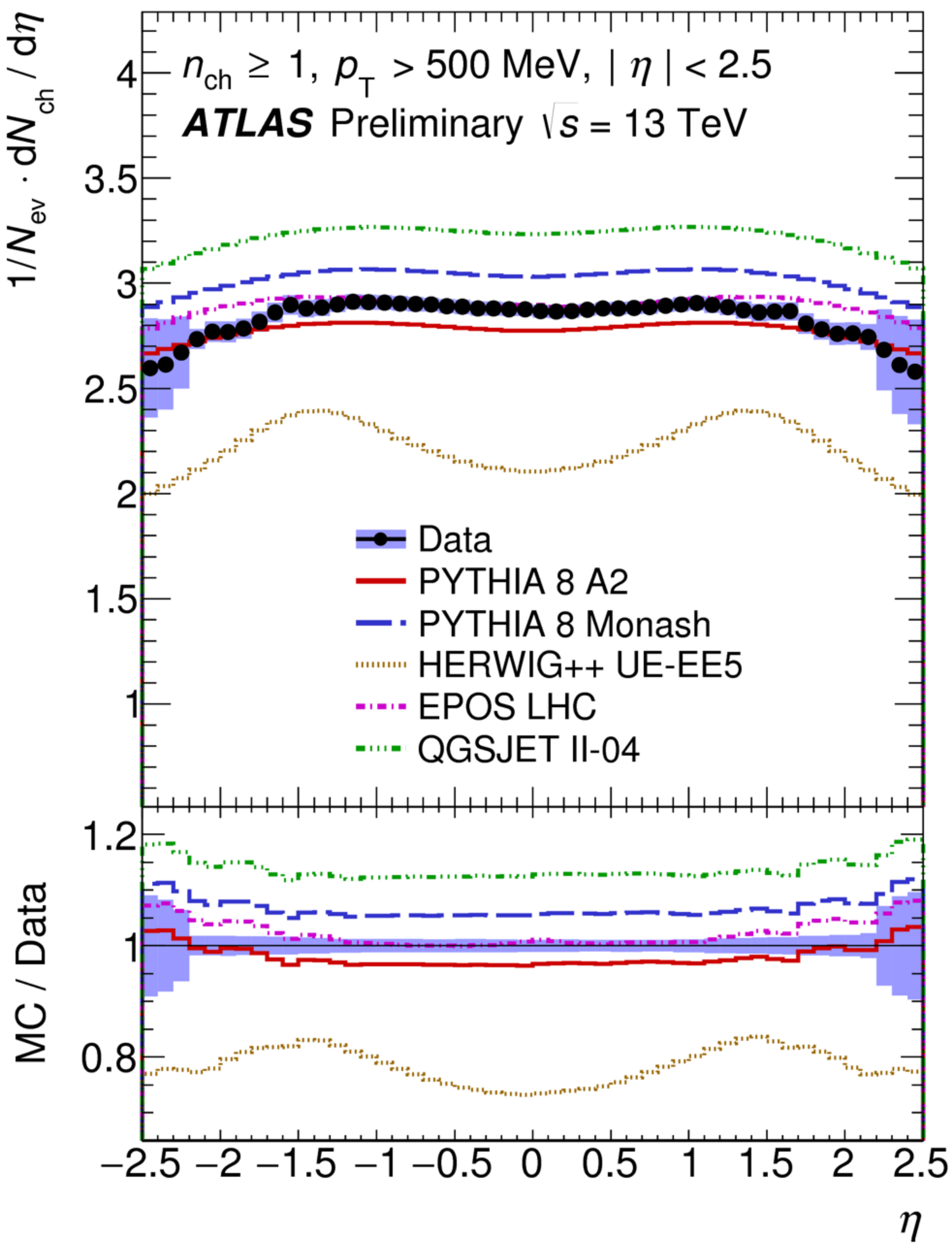




- **Track reconstruction efficiency was estimated using simulation.**
- **Uncertainty is dominated by the material description of the Inner Detector.**
  - (1.1% at mid-rapidity, 5% at $|\eta| > 2.2$)
  - The dominant uncertainty of the analysis
- **Materials were examined using hadronic interaction, photon conversion, and the Pixel→SCT track extension efficiency.**

Result: Pseudorapidity Distribution

[ATLAS-CONF-2015-028]

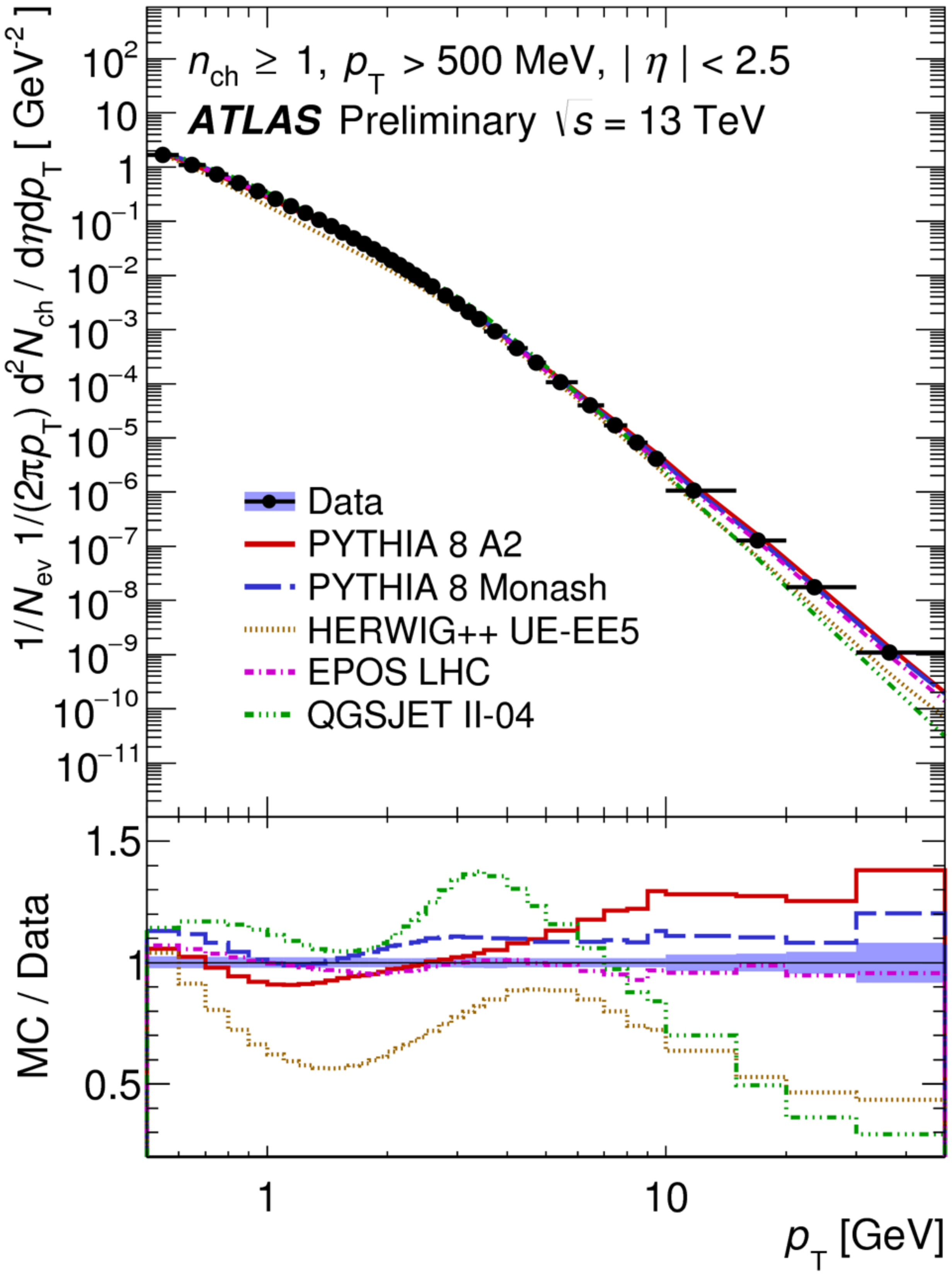


$$\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ch}}}{d\eta}$$

- **Data is roughly constant at |η| < 1.0, and decreasing at forward η.**
- **EPOS describes well the mid-rapidity data, but over-predicts at |η| > 1.5.**
- **QGSJET-II and Pythia8 (Monash) over-predict by ~15% and ~5%, respectively.**
- **Pythia8 (A2) under-predicts by 3% at mid-rapidity, but the description at |η| > 2 is good.**

Result: p_T Distribution

[ATLAS-CONF-2015-028]

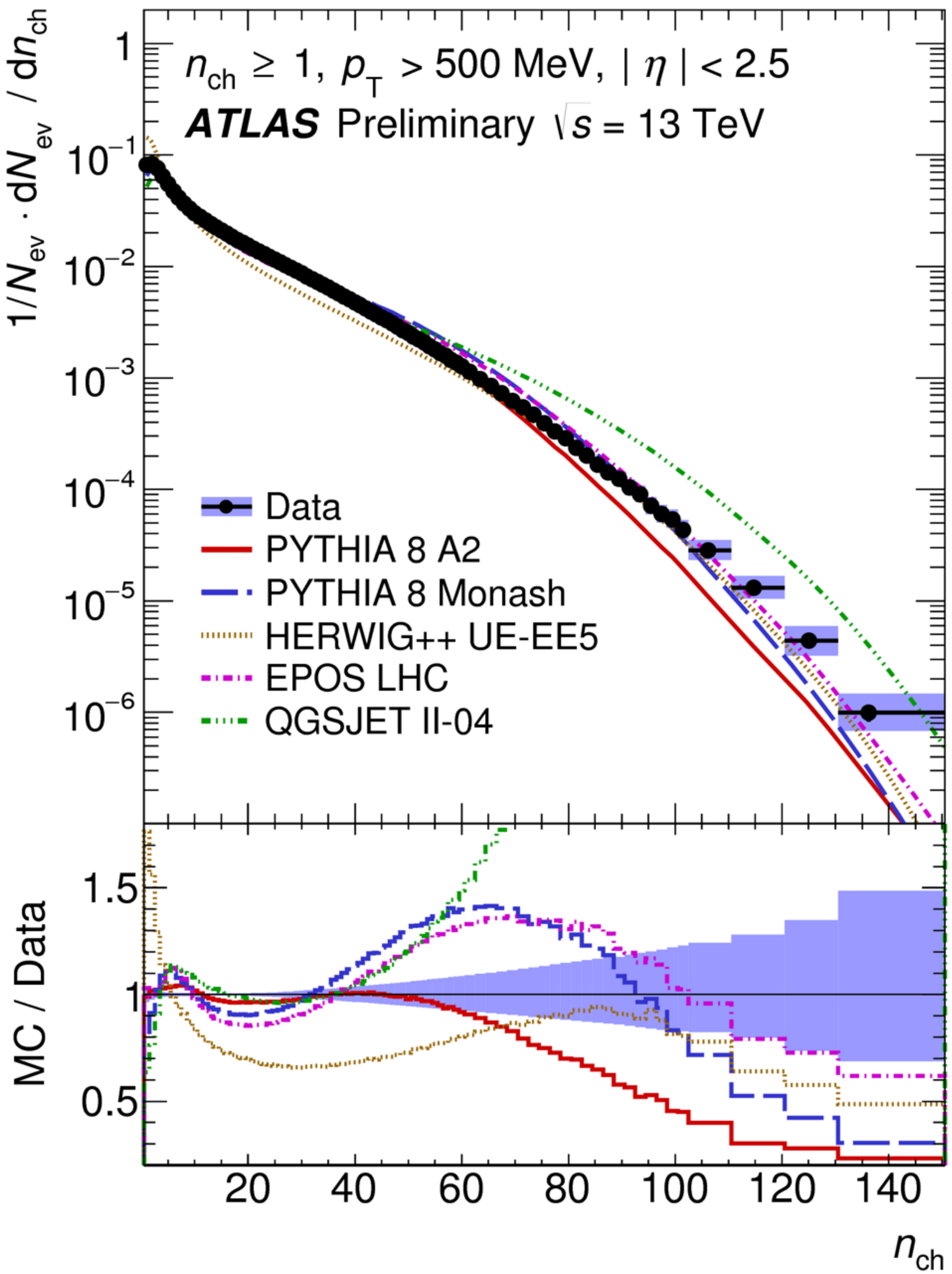


$$\frac{1}{N_{\mathrm{ev}}}\frac{1}{2\pi p_{\mathrm{T}}}\frac{d^2N_{\mathrm{ch}}}{d\eta dp_{\mathrm{T}}}$$

- **EPOS describes the data well.**
- **Pythia8 tunes are reasonable, but slightly over-predicting at high p_T region.**
- **QGSJET-II is poor over the entire spectrum.**

Result: Charged Particle Multiplicity

[ATLAS-CONF-2015-028]

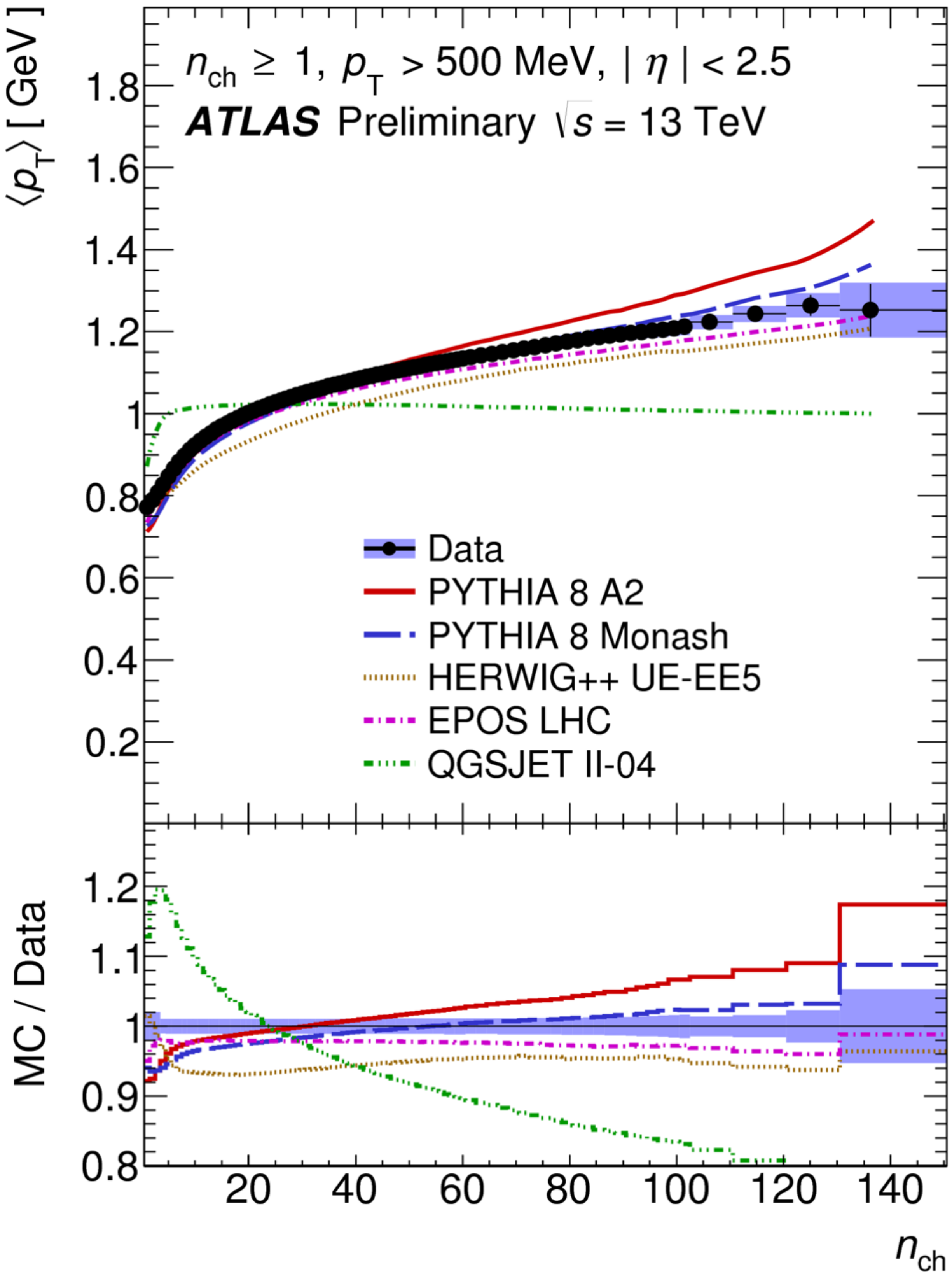


$$\frac{1}{N_{\rm ev}} \frac{dN_{\rm ev}}{dN_{\rm ch}}$$

- **Pythia8 (A2) describes the data in N_{ch} < 50, but under-predicts at larger N_{ch}.**
- **Pythia8 (Monash), EPOS, and QGSJET-II are reasonable at N_{ch} < 30, but over-predict at mid-multiplicity region.**
- **Pythia8 (Monash) and EPOS are under-predicting at N_{ch} > 100, but QGSJET-II under-predicts at high N_{ch}.**

Result: Average p_T vs. Multiplicity

[ATLAS-CONF-2015-028]

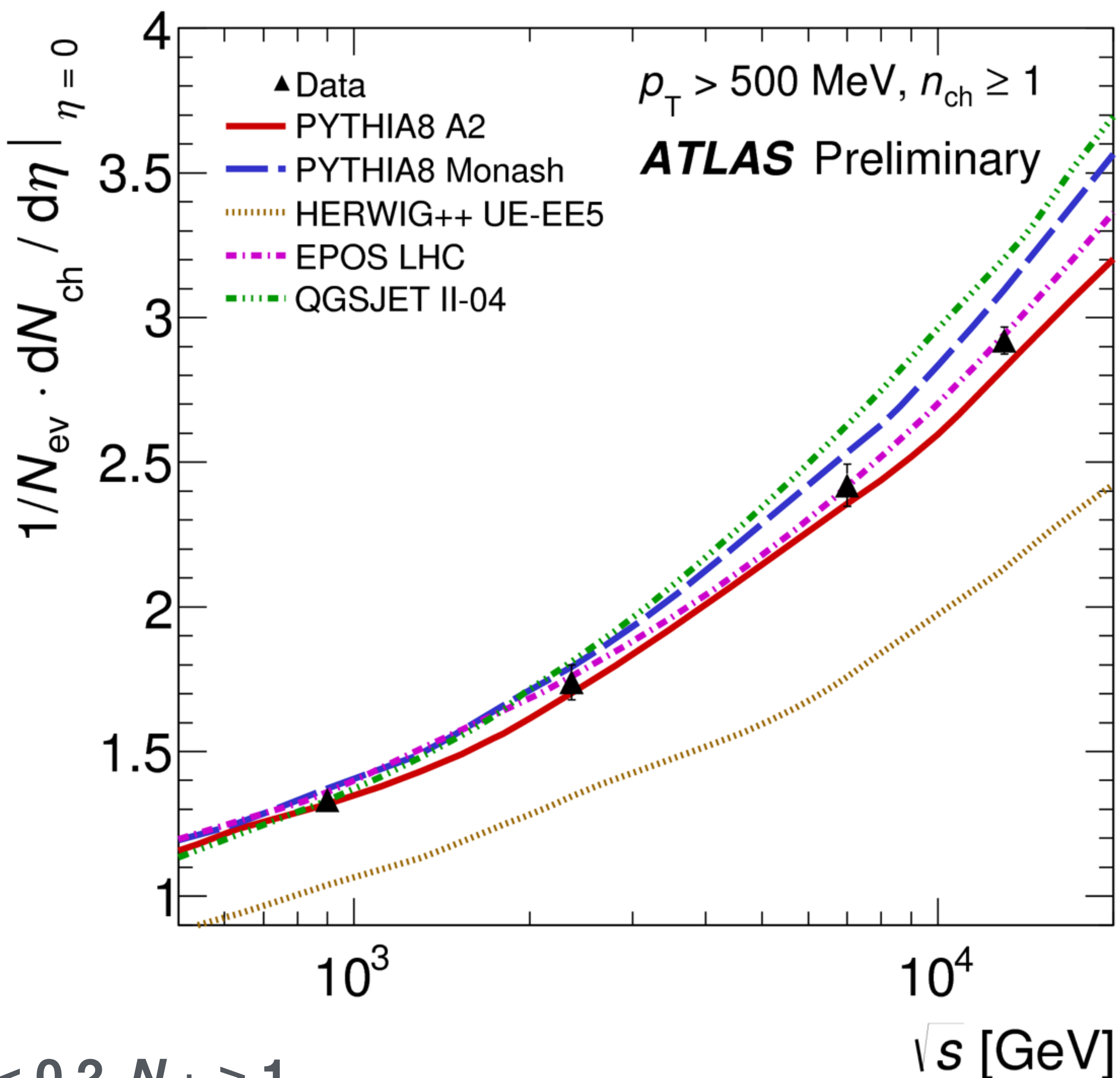


$$\langle p_T \rangle \text{ vs. } N_{ch}$$

- **Average p_T increasing with N_{ch}: color reconnection effects.**
  - If large N_{ch} events are dominated by MPI events, without color reconnection the average p_T should be approximately flat.
  - With color reconnection the particle multiplicity decreases at a given number of MPIs. Hence the momentum per each track increases.
- **EPOS slightly under-predicts <p_T>, but the dependence on N_{ch} is good.**
- **Pythia8 tunes predict steeper slope than data, under-predicting <p_T> at low N_{ch}.**
- **QGSJET-II precits almost flat <p_T> at ~1 GeV (no color reconnection model).**

Charged Particle Multiplicity Dependence on √s

[ATLAS-CONF-2015-028]

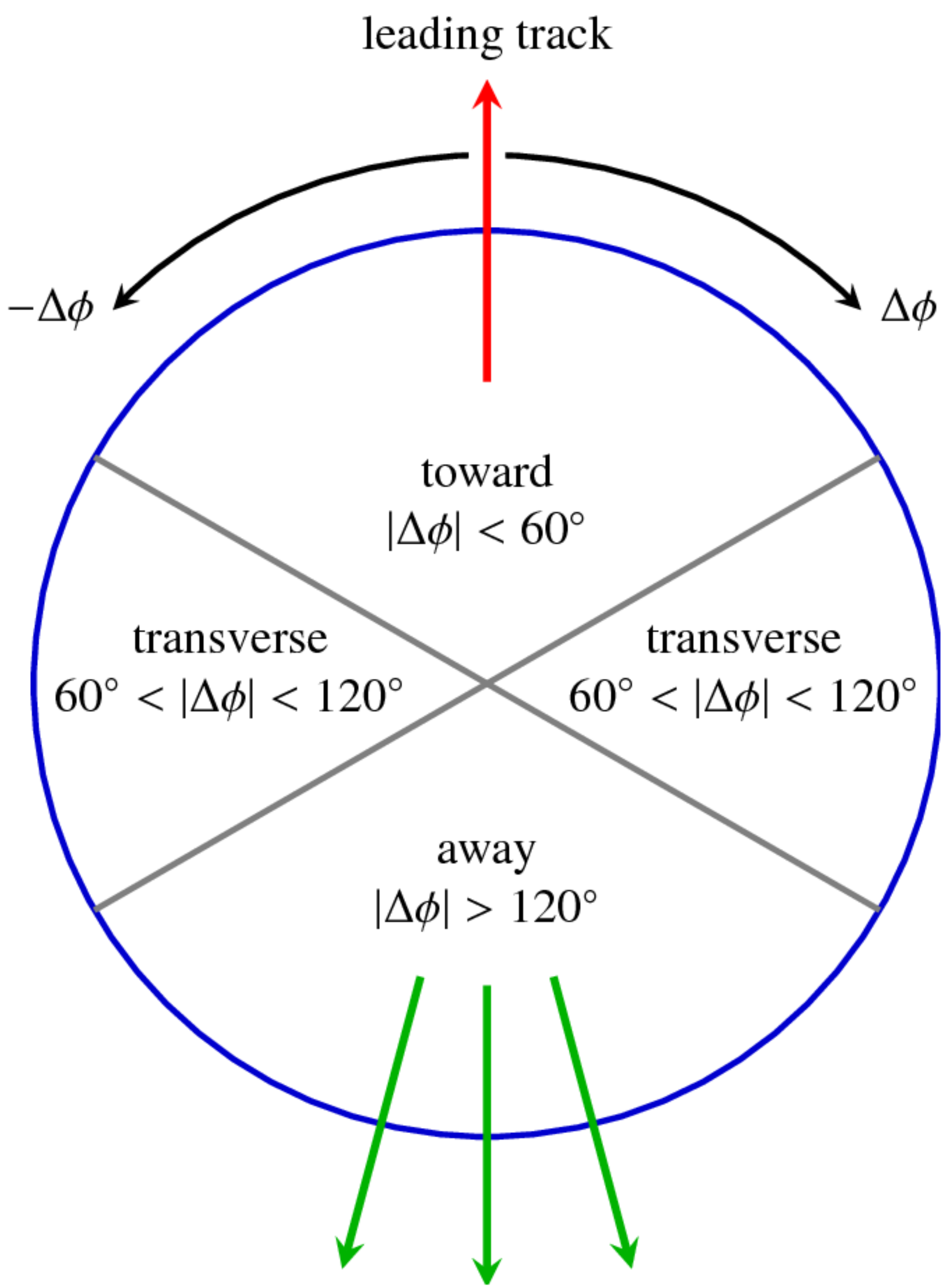


The 13 TeV data are corrected for different treatment of strange baryons (1.5% correction)

- ***p_T* > 0.5 GeV, |η| < 0.2, *N_{ch}* ≥ 1**
- ***N_{ch}*(13 TeV) / *N_{ch}*(8 TeV) ~ 1.2**
- ***N_{ch}*(13 TeV) / *N_{ch}*(900 GeV) ~ 2.2**

Underlying Event at $\sqrt{s}$ = 13 TeV

[ATL-PHYS-PUB-2015-019]



- **Underlying Event (UE)**
  - Activity accompanying any hard scattering in a collision event.
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Initial/Final State Radiations (ISR, FSR)
- **Kinematics definitions**
  - Define the zero degree to the ϕ-direction of the leading track.
  - Divide ϕ-segments into 3 regions
    - **"Toward"** : $|\Delta\phi| < 60°$
    - **"Transverse"** : $60° < |\Delta\phi| < 120°$
    - **"Away"** : $|\Delta\phi| > 120°$
  - The transverse region is sensitive to UE.
- **Observables**
  - $\frac{d^2 N_{\mathrm{ch}}}{d\eta d|\Delta\phi|}(|\Delta\phi|)$: Track multiplicity density
  - $\frac{d^2 \sum p_{\mathrm{T}}}{d\eta d|\Delta\phi|}(|\Delta\phi|)$: Scalar sum of track p_{T} density

Monte Carlo samples

Generator	Version	Tune	PDF	Focus	
PYTHIA 8 [18]	8.186	A2 [19]	MSTW2008LO [20]	MB	ATLAS MB Tune
PYTHIA 8	8.186	Monash [21]	NNPDF2.3LO [22]	MB/UE	Author's Tune
PYTHIA 8	8.186	A14 [23]	NNPDF2.3LO	UE/Shower	ATLAS UE Tune
HERWIG++ [24]	2.7.1	UEEE5 [25]	CTEQ6L1 [26]	UE	Author's Tune
EPOS [27]	3.1	LHC [28]		MB	AstroParticle Phys. Model

A spin-off of Minimum Bias charged track multiplicity analysis.

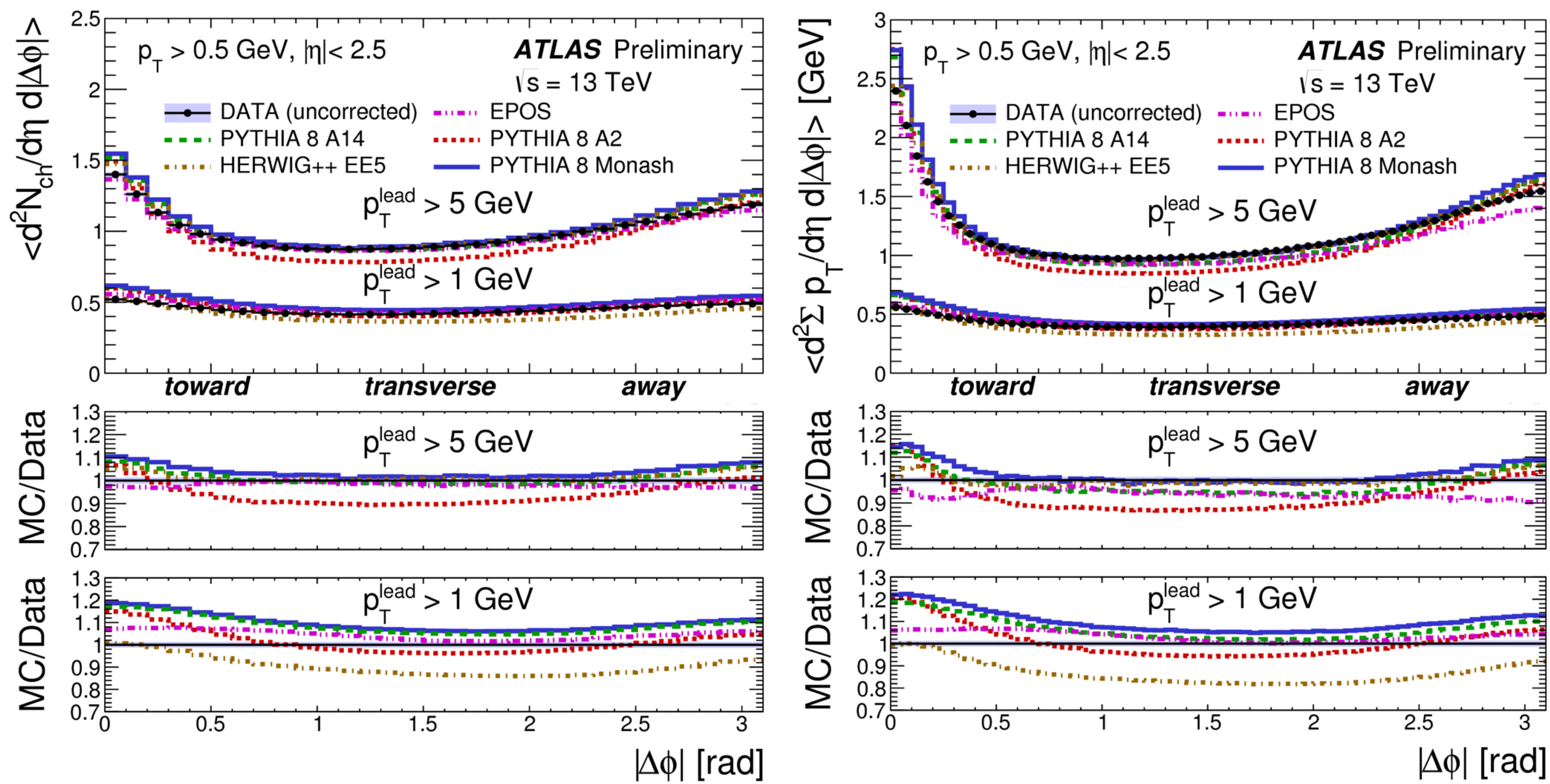
- The same data set as the Minimum Bias analysis (low-μ runs, 170 μb^{-1}).
- Minimum Bias scintillator trigger (MBTS).
- $p_T > 0.5$ GeV, $|\eta| < 2.5$ + same quality cuts (see p.12)
- Pile-up veto
- Leading track $p_T > 1$ GeV (*additional requirement*).

Detector-level data/MC comparison

- MC samples are re-weighted for primary vertex Z-distribution.

Underlying Event at $\sqrt{s}$ = 13 TeV

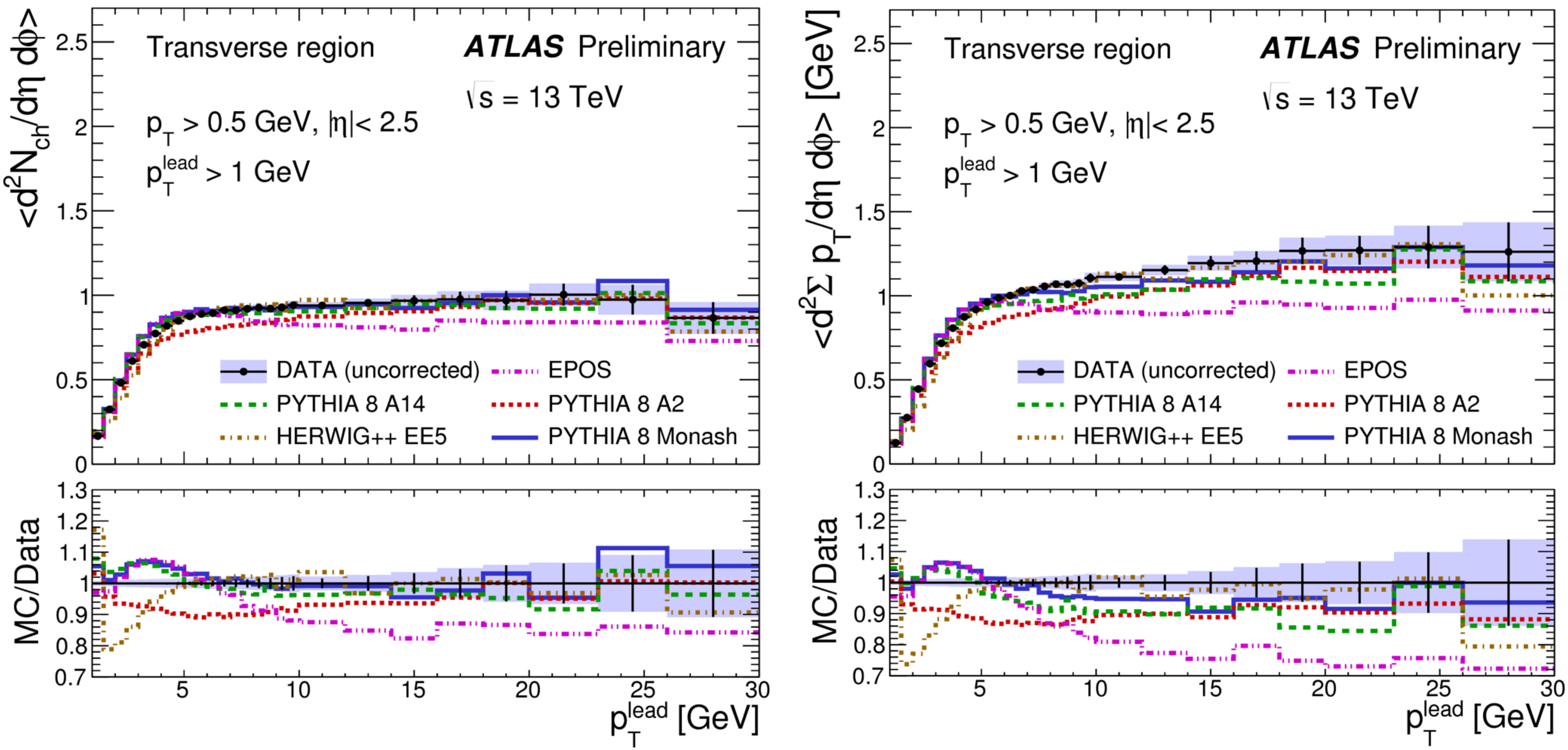
[ATL-PHYS-PUB-2015-019]



- **Pythia8 (A2) and EPOS are good at 1 GeV leading p_T cut.**
- **"UE Tunes": Pythia8 (Monash), Pythia8 (A14), and HERWIG++ (UEEE5) are good at 5 GeV leading p_T cut.**

Underlying Event at $\sqrt{s}$ = 13 TeV

[ATL-PHYS-PUB-2015-019]



- Approximate "plateau" at leading p_T > 6 GeV.
- Pythia8 (A14), Pythia8 (Monash), HERWIG++ (UEEE5) are close to data, but none of MC samples used is good at describing the rise-up behavior.
- EPOS is significantly less at high leading p_T by ~15%.

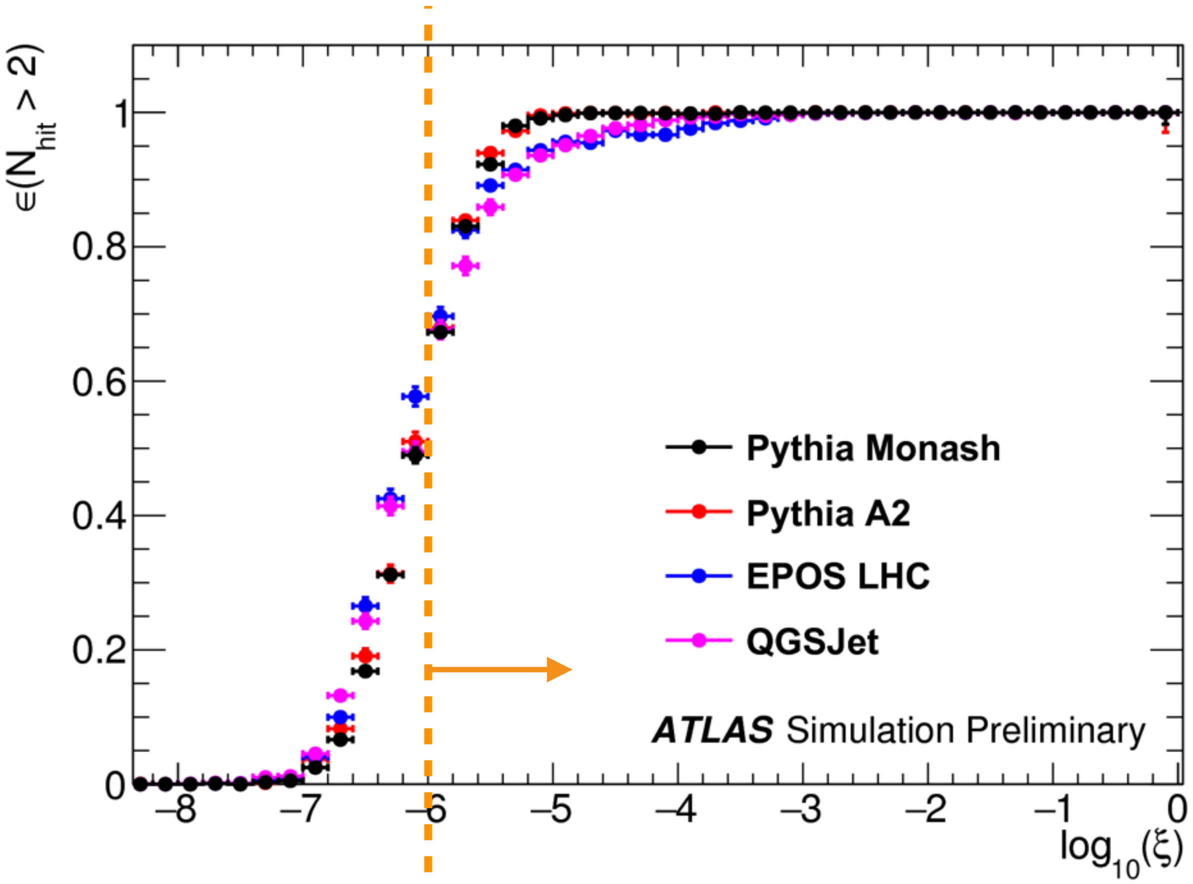
Summary

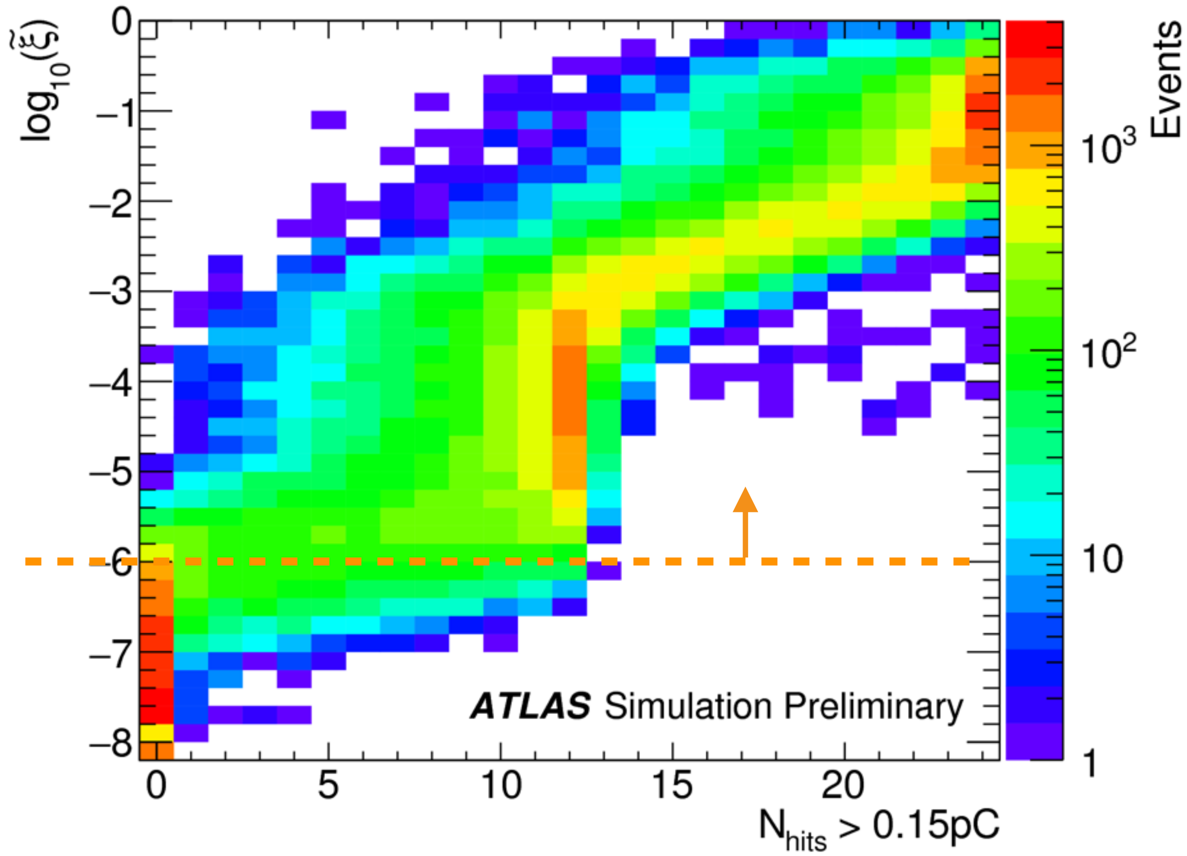
- Early Run2 soft QCD results with the upgraded/refurbished ATLAS (especially in tracking) has been presented.
- Results are timely and robust.
- Measurements in wide $\sqrt{s}$ range (0.9-13 TeV) in a single experiment.
- MC tunes based on lower center of mass energy generally show good modelling, giving confidence in multi-parton interaction extrapolation at $\sqrt{s}$ = 13 TeV.
- Hard QCD/SM channels → Next Talk by Nicola!

Backup

Selection Efficiency and Migration Corrections

ϵ_{sel}



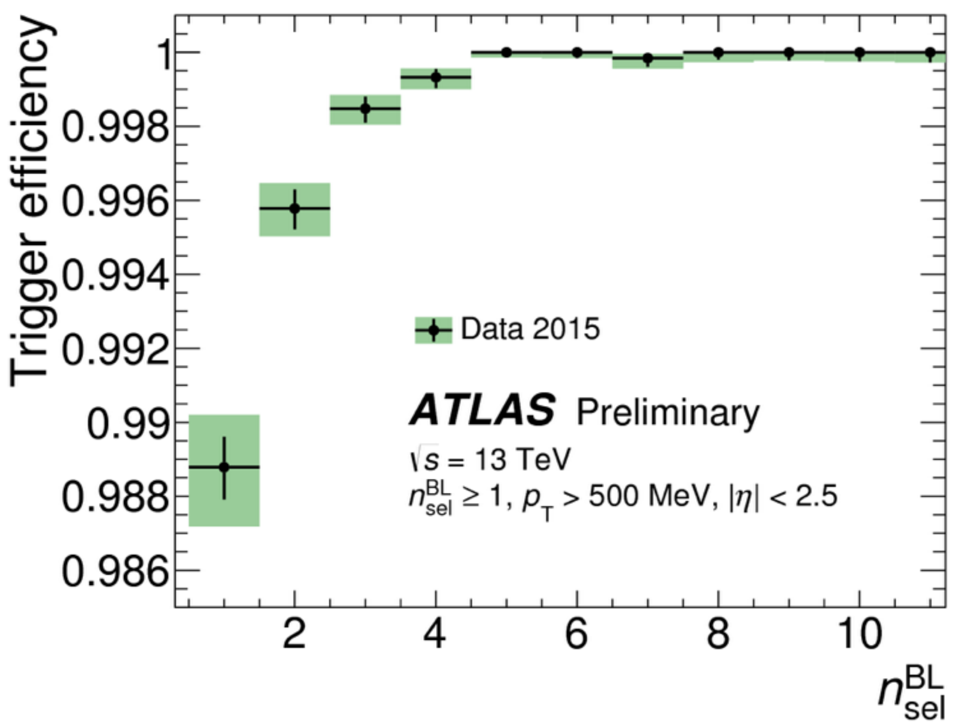


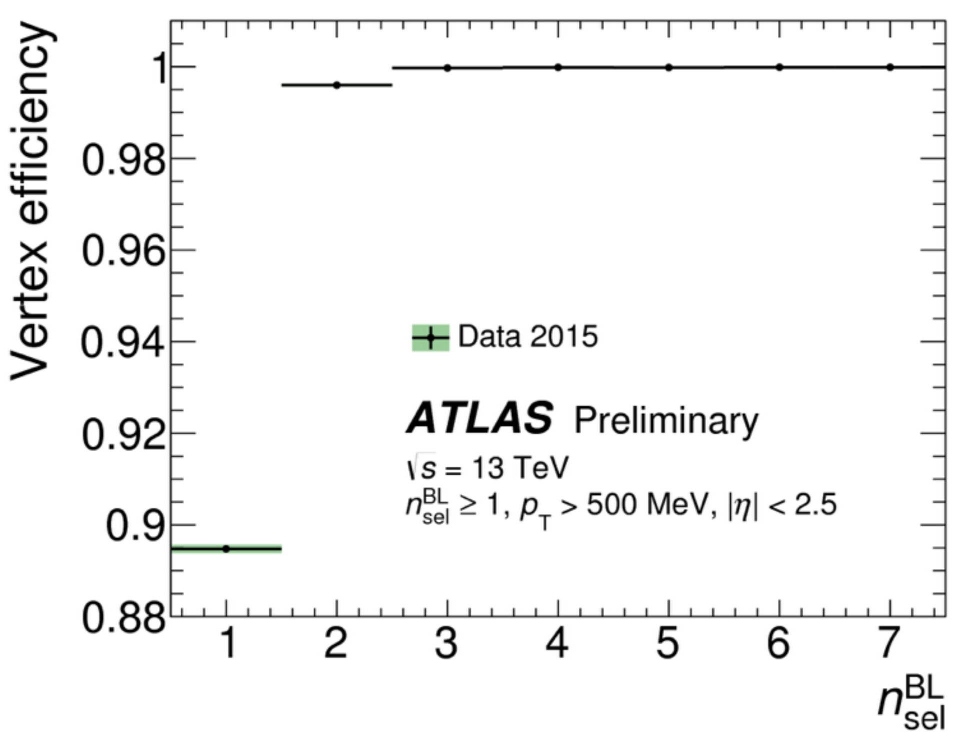
Minimum Bias MC Samples

Generator	Version	Tune	PDF	7 TeV data MB	7 TeV data UE	
PYTHIA 8	8.185	A2	MSTW2008LO [19]	yes	no	ATLAS MB Tune
PYTHIA 8	8.186	MONASH	NNPDF2.3LO [20]	yes	yes	Author's Tune
HERWIG++	2.7.1	UE-EE-5-CTEQ6L1	CTEQ6L1 [21]	no	yes	Author's Tune
EPOS	3.1	LHC	N/A	yes	no	AstroParticle Phys.
QGSJET-II	II-04	default	N/A	yes	no	AstroParticle Phys.

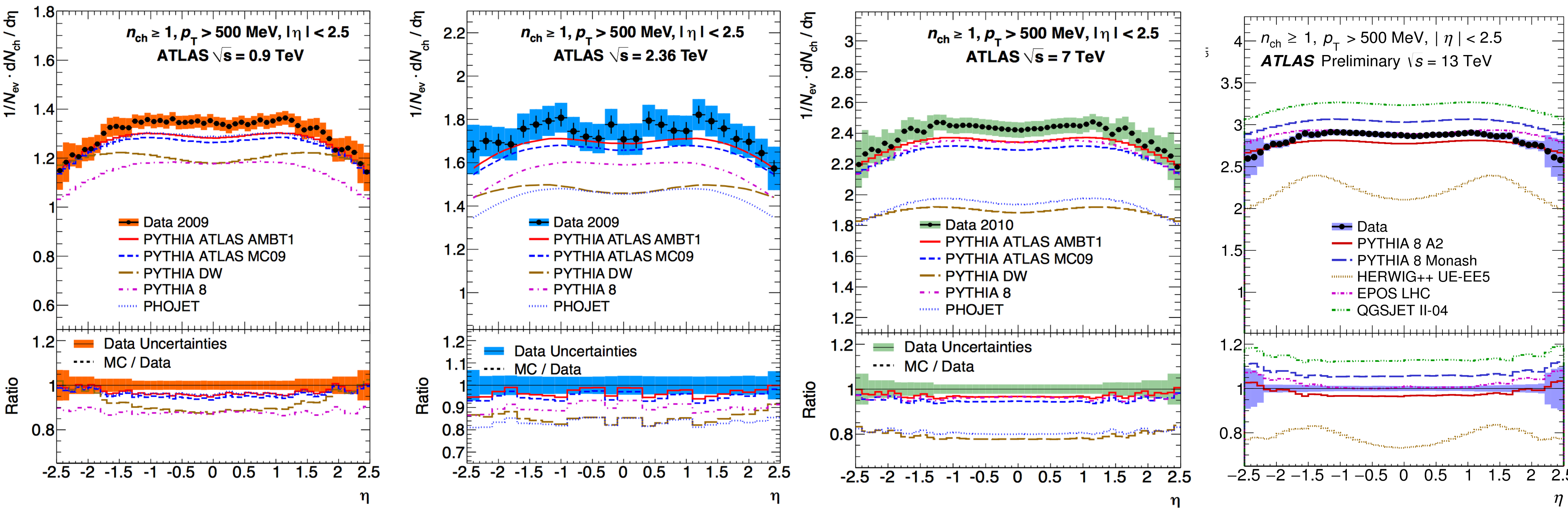
Corrections

- **Event-level corrections**
  - Trigger efficiency (data-driven)
  - Vertex reconstruction efficiency (data-driven)
- **Track-level corrections**
  - Track reconstruction efficiency (simulation)
  - Subtraction of :
    - Secondary particles (data-driven using MC shape),
    - Strange baryons (simulation), and
    - Migration from the out-of-kinematic range (simulation)
- **Bayesian unfolding for p_T distribution**
- **MC samples: re-weighted for primary vertex *Z*-distribution.**

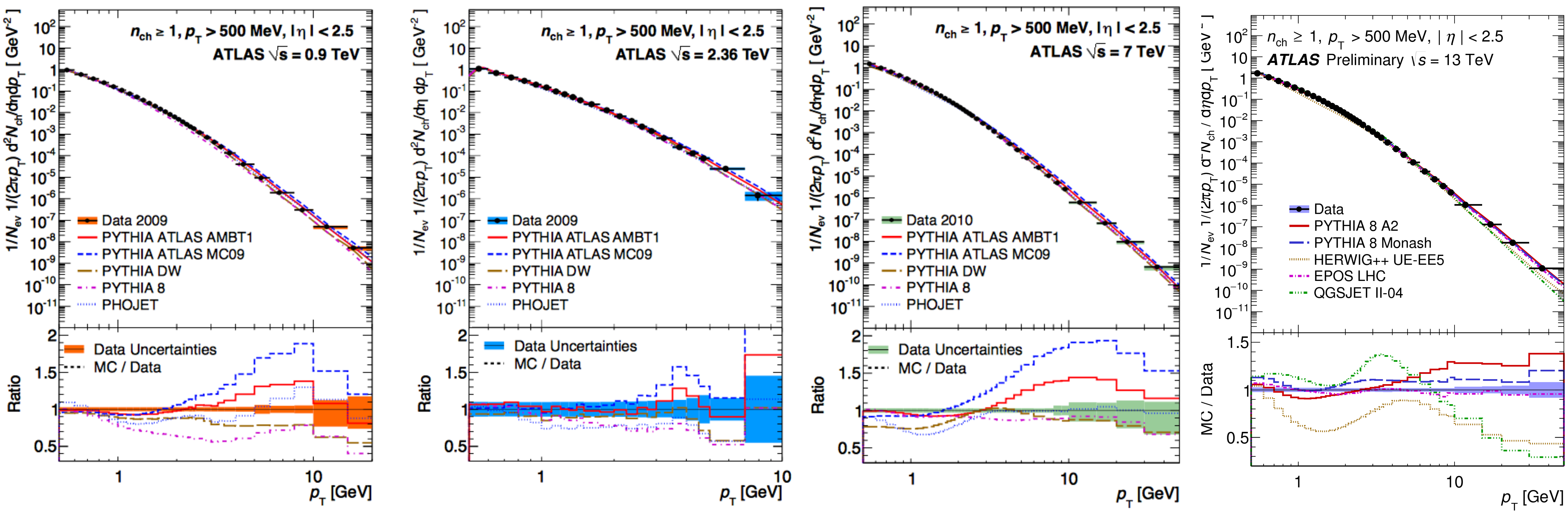




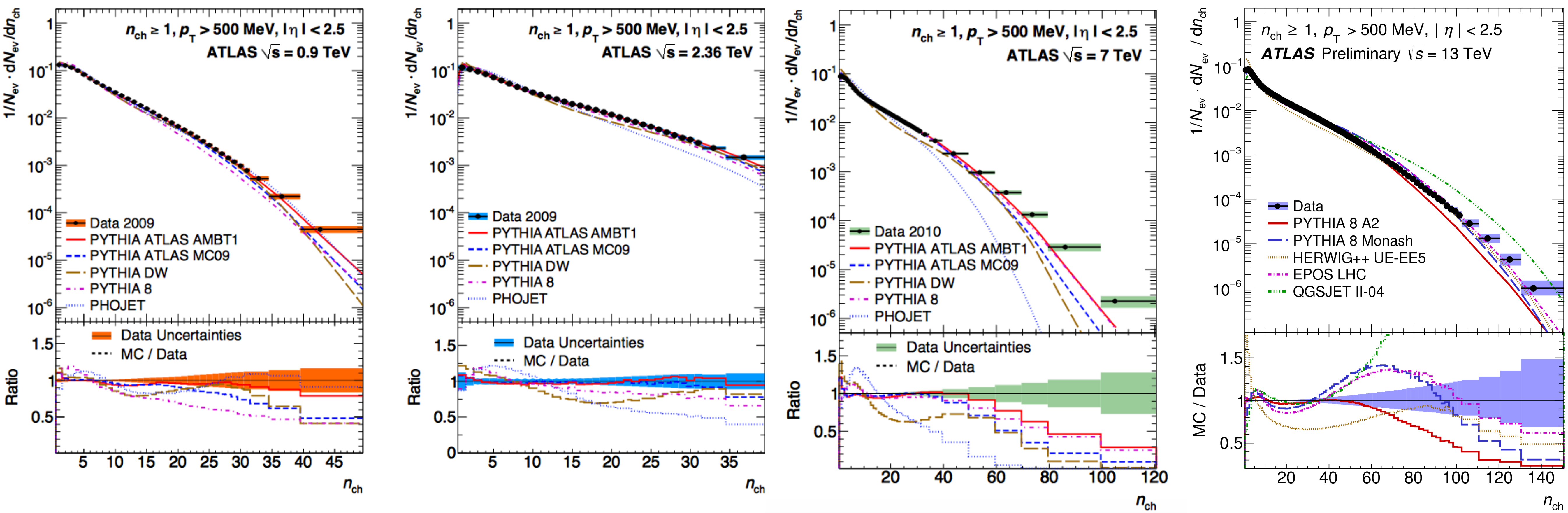
√s Dependence: Pseudorapidity Distribution



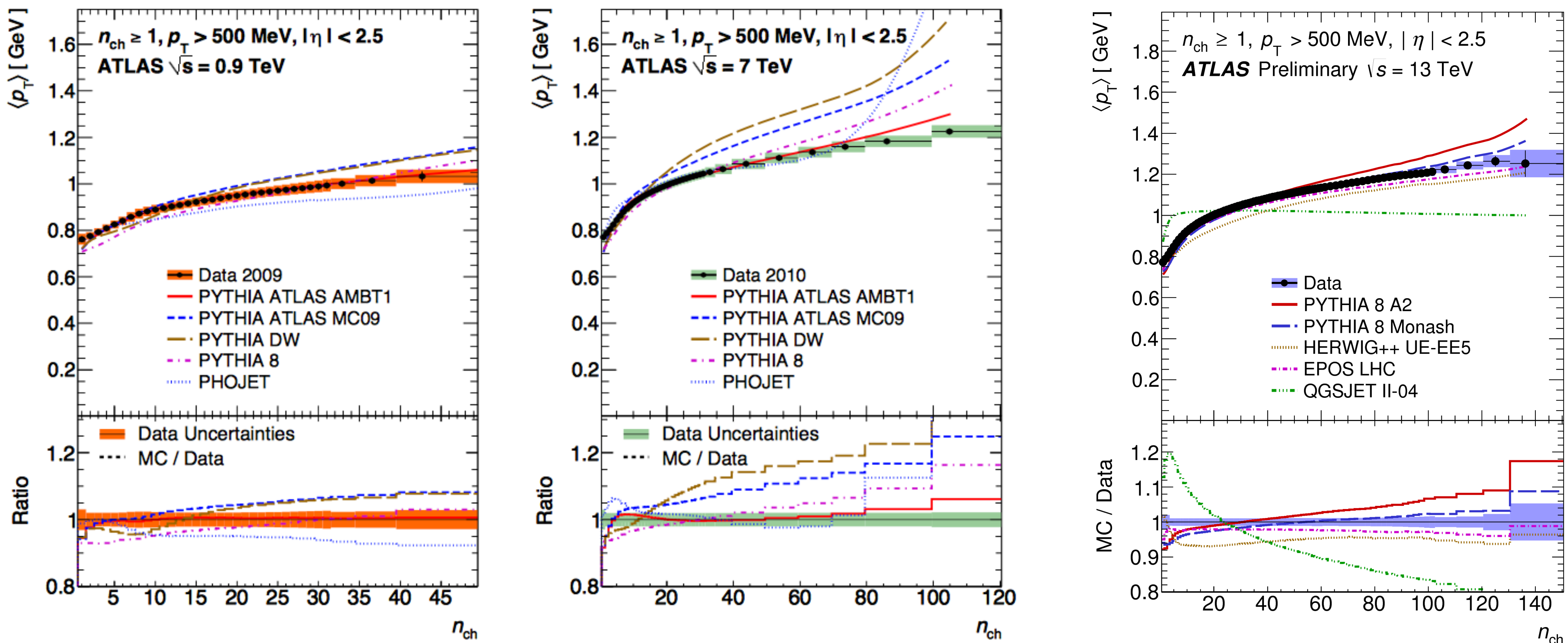
$\sqrt{s}$ Dependence: p_T Distribution



$\sqrt{s}$ Dependence: Multiplicity Distribution



$\sqrt{s}$ Dependence: Average p_T vs.Multiplicity



The measurement of ⟨pT⟩ as a function of charged multiplicity at s = 2.36 TeV is not shown because different track reconstruction methods are used for determining the p_T and multiplicity distributions