Minimum Bias & Underlying Event Studies at ATLAS: Review of Measurements and MC tuning

Yuri Kulchitsky (JINR)

on behalf of the ATLAS Collaboration

12th International workshop on Multiple Partonic Interactions at the LHC

11 – 15 October 2021, LIP Lisbon

STUDY OF MINIMUM-BIAS EVENTS

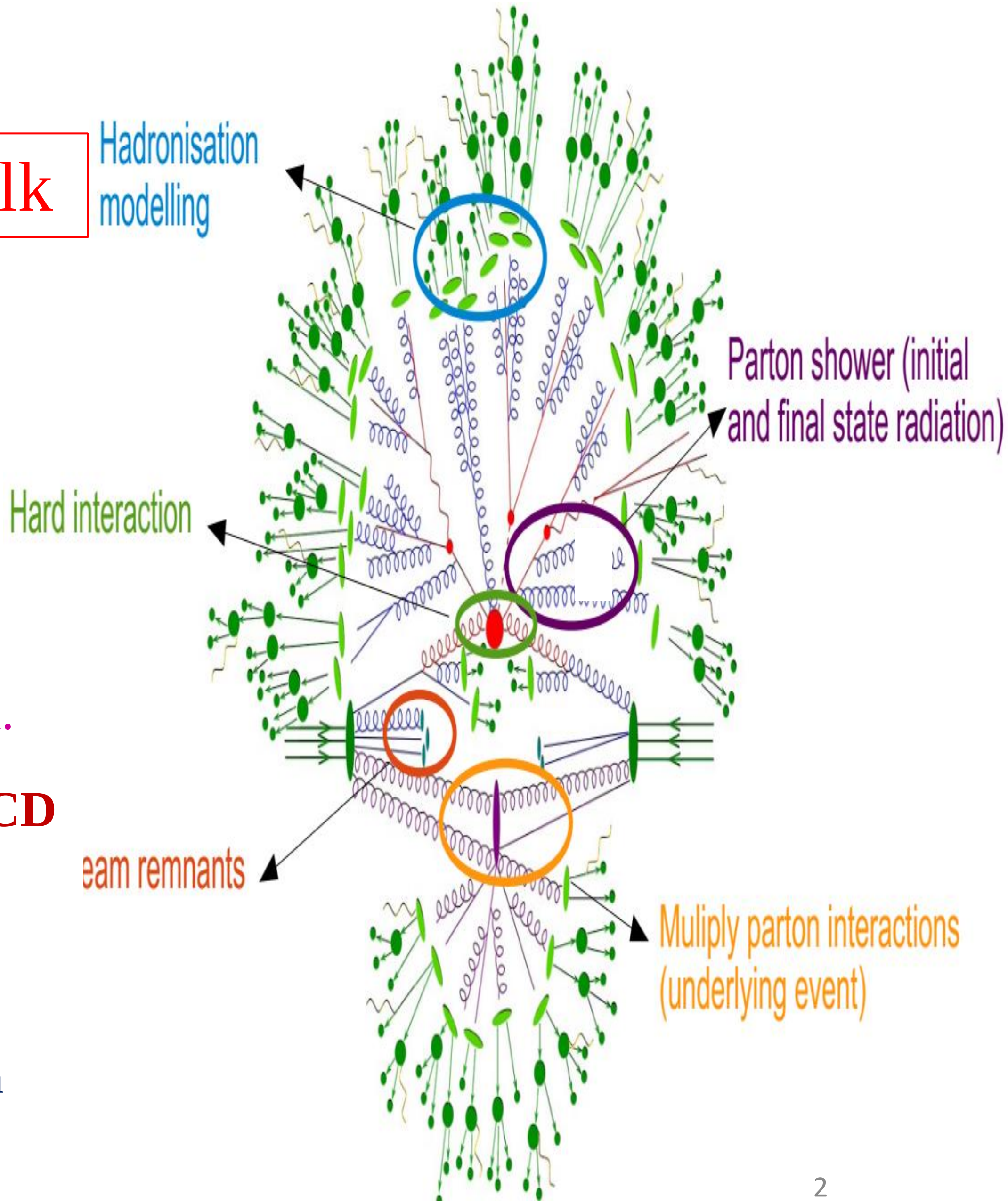
Understanding of soft-QCD interactions has direct impact on:

- **precision measurements;**
- **searches for new physics**

For pp interactions at 13 TeV

- Study Charged-particle distributions
- Study Underlying event distributions
- Monte-Carlo generators tuning

In this talk



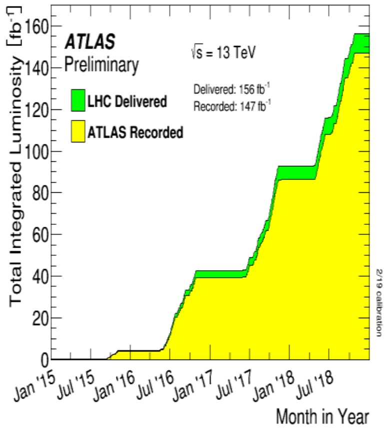
- Study Bose–Einstein correlations (BEC)
- Study an inelastic cross section,
- Study particle correlations, hadronization and colour reconnection.

Provides insight into strong interactions in non-perturbative QCD regime:

- Soft QCD results used in Monte-Carlo generators tuning,
- Soft QCD description essential for simulating Underlying Event: Multiple Parton Interactions (MPI) Initial & Final State gluon Radiation (ISR, FSR)

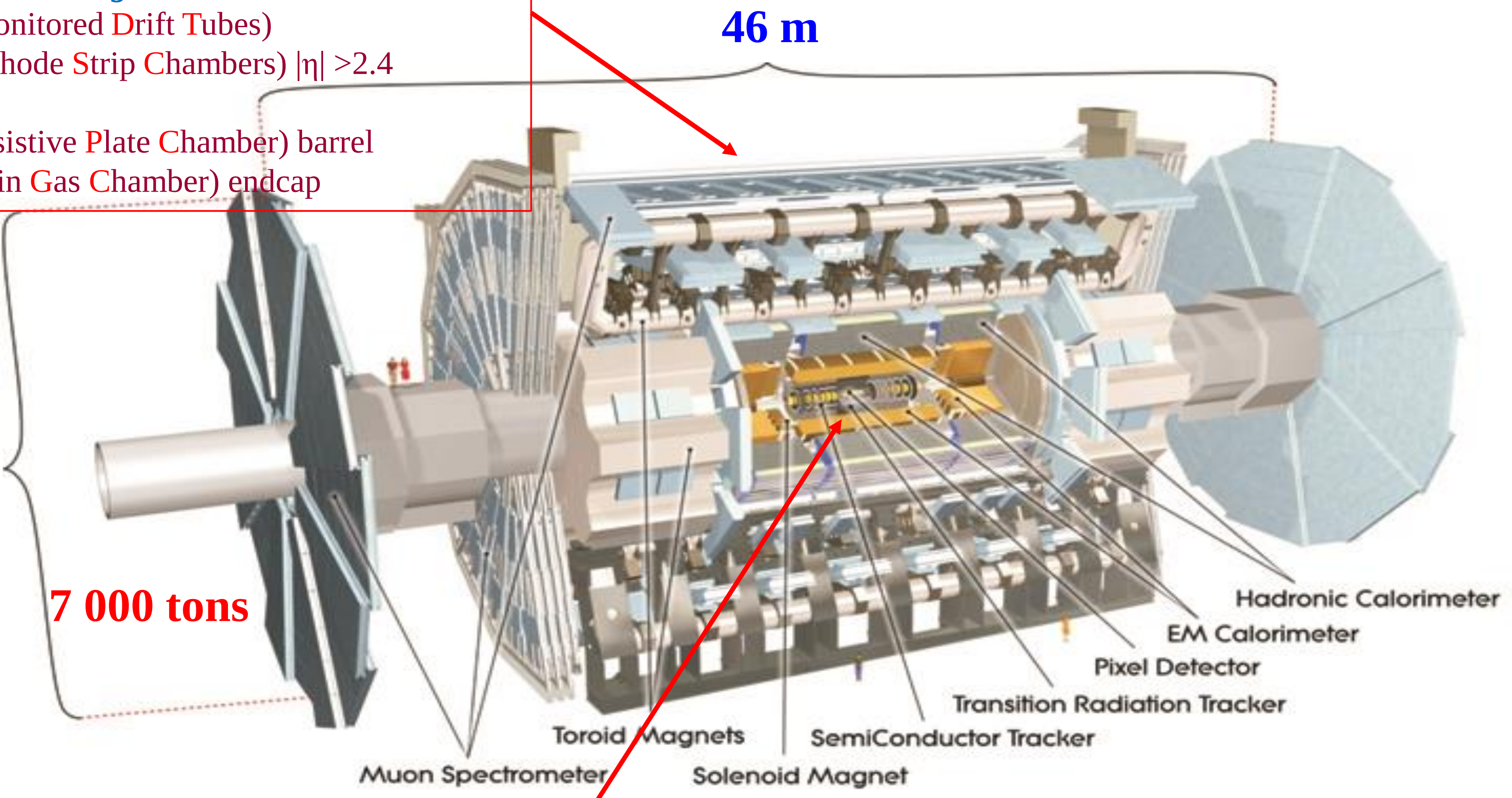
A TOROIDAL LHC APPARATUS (ATLAS)

Subdetector	Operational Fraction
AFP	93.8%
ALFA	99.9%
CSC Cathode Strip Chambers	95.3%
Forward LAr Calorimeter	99.7%
Hadronic End-Cap Lar Cal	99.5%
LAr EM Calorimeter	100 %
LVL1 Calo Trigger	99.9%
LVL1 Muon RPC Trigger	99.8%
LVL1 Muon TGC Trigger	99.9%
MDT Muon Drift Tubes	99.7%
Pixels	97.8%
RPC Barrel Muon Chambers	94.4%
SCT Silicon Strips	98.7%
TGC End-Cap Muon Cha	99.5%
Tile Calorimeter	99.2%
TRT Transit Rad Tracker	97.2%



Air-core Muon spectrometer
(*μ Trigger/tracking and* ***Toroid Magnets***)
Precision Tracking:
MDT (Monitored Drift Tubes)
CSC (Cathode Strip Chambers) |η| >2.4
Trigger:
RPC (Resistive Plate Chamber) barrel
TGC (Thin Gas Chamber) endcap

25 m



Inner Detector (ID) Tracking in **2T Solenoid Magnet**
Silicon Pixels 50x400 μm^2
Silicon Strips (SCT) 40 μm rad stereo strips
TransitionRadiation Tracker (**TRT**) ≤36 points/track

Two Level Trigger system
L1 hardware: **100 kHz, 2.5 μs** latency
HLT farm: merge the former **L2** and **Event Filter**
1.5 kHz, 0.2 s latency

CHARGED-PARTICLE DISTRIBUTIONS

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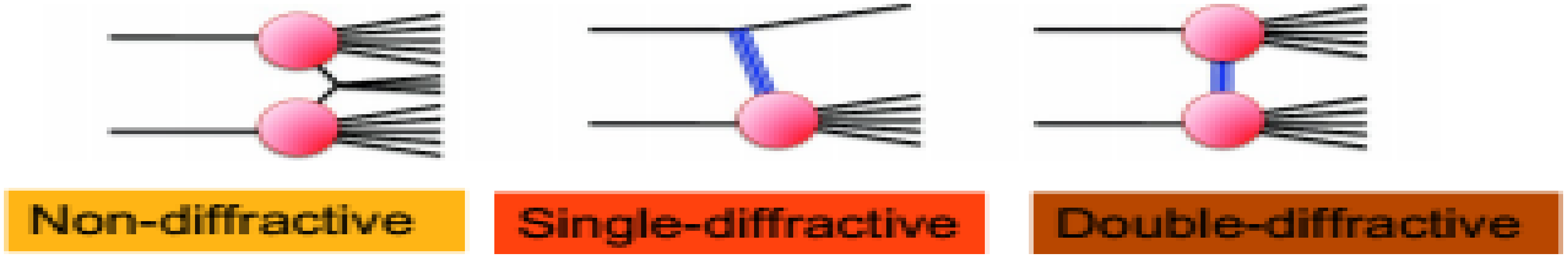
ATLAS EXPERIMENT

The composition of inelastic p-p collisions:



Perturbative QCD describes only the hard-scattered partons, all the rest is predicted with **phenomenological models.**

ND: QCD motivated models with many parameters; Pile-up is Background; **SD+DD** modelled with large uncertainties

Strange baryons with 30<τ<300 ps are excluded.

Measure spectra of primary charged particles corrected to particle level

Multiplicity vs. η — Multiplicity vs. p_T — Multiplicity distributions

$$\frac{1}{N_{ch}}\cdot\frac{dN_{ch}}{d\eta},\quad \frac{1}{N_{ev}}\cdot\frac{1}{2\pi p_T}\cdot\frac{d^2N_{ch}}{d\eta dp_T},\quad \frac{1}{N_{ev}}\cdot\frac{dN_{ev}}{dn_{ch}},\quad \langle p_T\rangle \text{ vs. } n_{ch}$$

Measurement do not apply model dependent corrections & allow to tune models to data measured in well defined kinematic range

The MC generators used to compare to the corrected data

Generator	Version	Tune	PDF	Focus of Tune
PYTHIA 8	8.185	A2	MSTW2008LO	MB
PYTHIA 8	8.186	MONASH	NNPDF2.3LO	MB/UE
EPOS	3.4	LHCv3400		MB
QGSJET-II	II-04	Default		

All the events are processed through the ATLAS detector simulation program (based on GEANT4)

MC MODELLING OF THE MB & UE

- **Pythia 8.18/8.21:** MPI and hadronisation modelling are phenomenological and even the perturbative parton shower formalism has some configurational freedom, many parameter tuning of **Pythia 8** have been performed:
  - *I.* ***ATLAS's*** dedicated ***UE tune*** is **Pythia 8 A14**. Its was optimised for the description of ***several UE and jet radiation observables*** with an ***emphasis on high-scale events***.
  - II. The **Pythia 8 Monash** ***MB/UE tune*** is used. It was ***constructed*** using ***Drell–Yan and UE data*** from ***ATLAS***, but also ***data from CMS***, ***from the SPS***, and from the ***Tevatron*** *in order* ***to constrain energy scaling***.
  - III. The ***ATLAS MB tune*** **Pythia 8 A2** was used for ***deriving detector corrections***. This was tuned using ***ATLAS MB data at 7 TeV*** for the ***MPI parameters***.
  - **IV. New Pythia 8 A3** tune is suitable for inclusive QCD modelling for **Run 3**. The **Pythia 8 A3** uses the ***ATLAS*** **Run 2** charged particle distribution and inelastic cross section results in addition to the **Run 1** used previously to construct ***MB tunes***. **A3** uses the same **NNPDF 2.3LO PDF** and provides a demonstration that an ***acceptable description*** of data can be achieved by using the ***Donnachie-Landshoff model for diffraction***.
- **EPOS 3.4:** provides an implementation of a ***parton-based Gribov-Regge theory*** which is ***an effective QCD-inspired field theory describing hard and soft scattering simultaneously***. **EPOS** gives a ***very good description*** of ***ATLAS's 13 TeV MB data***, including the tails of distributions where ***UE physics*** should be involved, but as it lacks a dedicated hard scattering component it is unclear how accurate its description of ***UE correlations*** can be.
- **QGSJET-II** provides a phenomenological treatment of hadronic and nuclear interactions in the ***Reggeon field theory*** framework. The soft and semihard parton processes are included within the "***semihard Pomeron***" approach.
- **Herwig 7.0.1:** the ***default tune*** has been used. This tune, like its **Herwig++** predecessors, is ***based on LHC*** and ***Tevatron UE measurements***, as well as ***double parton scattering data***. It provides a good description of all these observables for $\sqrt{s}$ ***from Tevatron 300 GeV to LHC 7 TeV***.

$dN_{ch}/d\eta$ and Average Multiplicity Distributions

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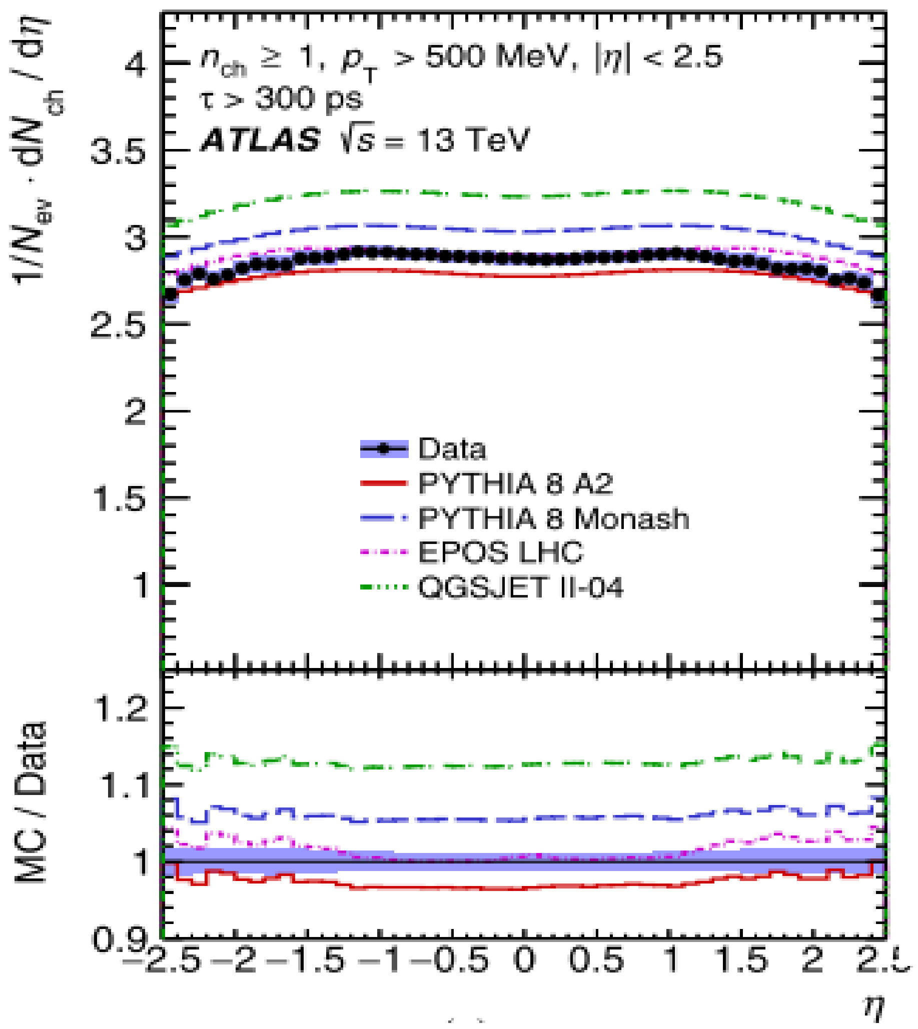
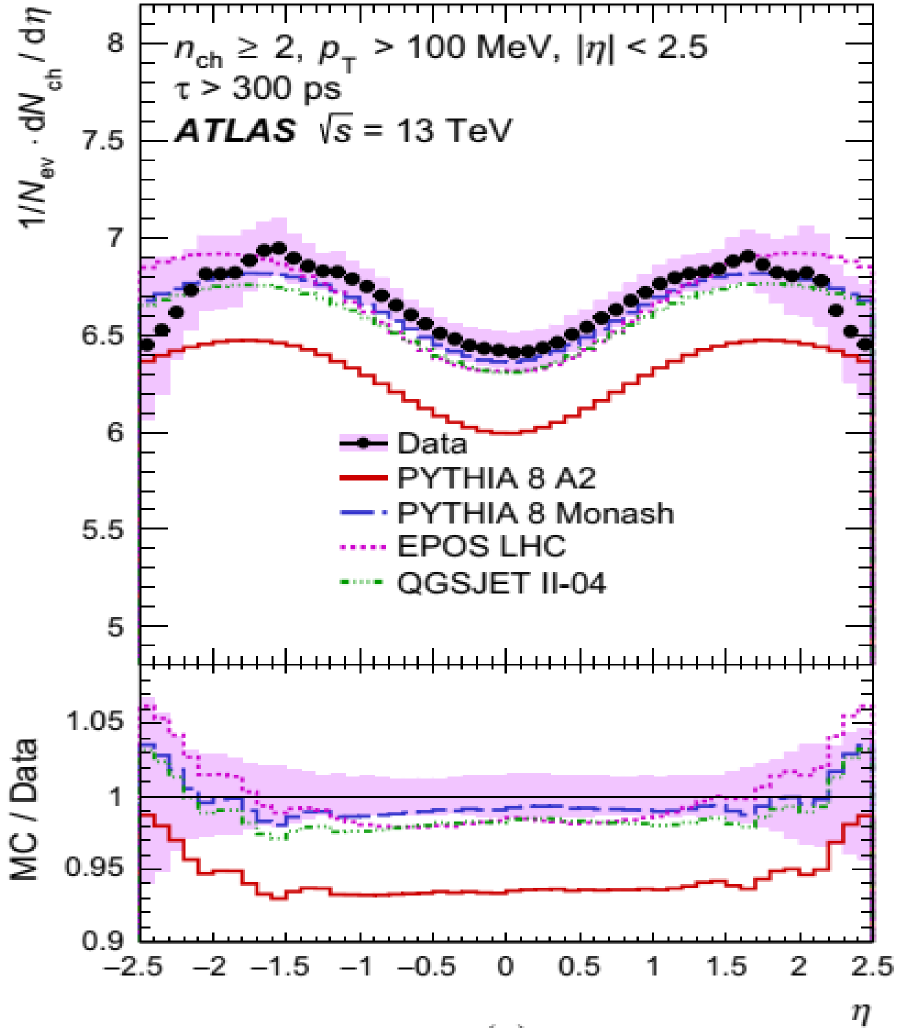


For p_T>500 MeV:

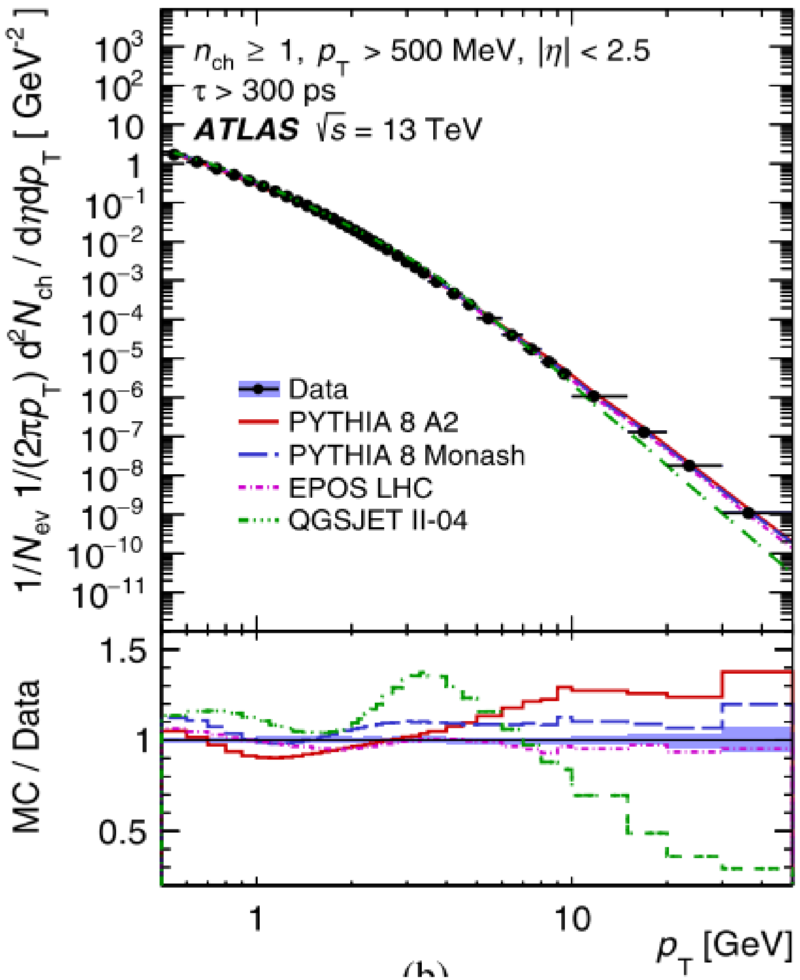
- Has the ***same shape*** in Models but different normalisation
- **EPOS** and **Pythia 8 A2** give remarkably good predictions

For p_T>100 MeV:

- **PYTHIA 8 MONASH, EPOS and QGSJET- II** give a good description for $|\eta|$<1.5
- The prediction from **PYTHIA 8 A2** has the same but lies below the data



Primary charged-particle multiplicities as a function of η for events with $n_{ch}\geq1$, p_T>500 MeV and $n_{ch}\geq2$, p_T>100 MeV.

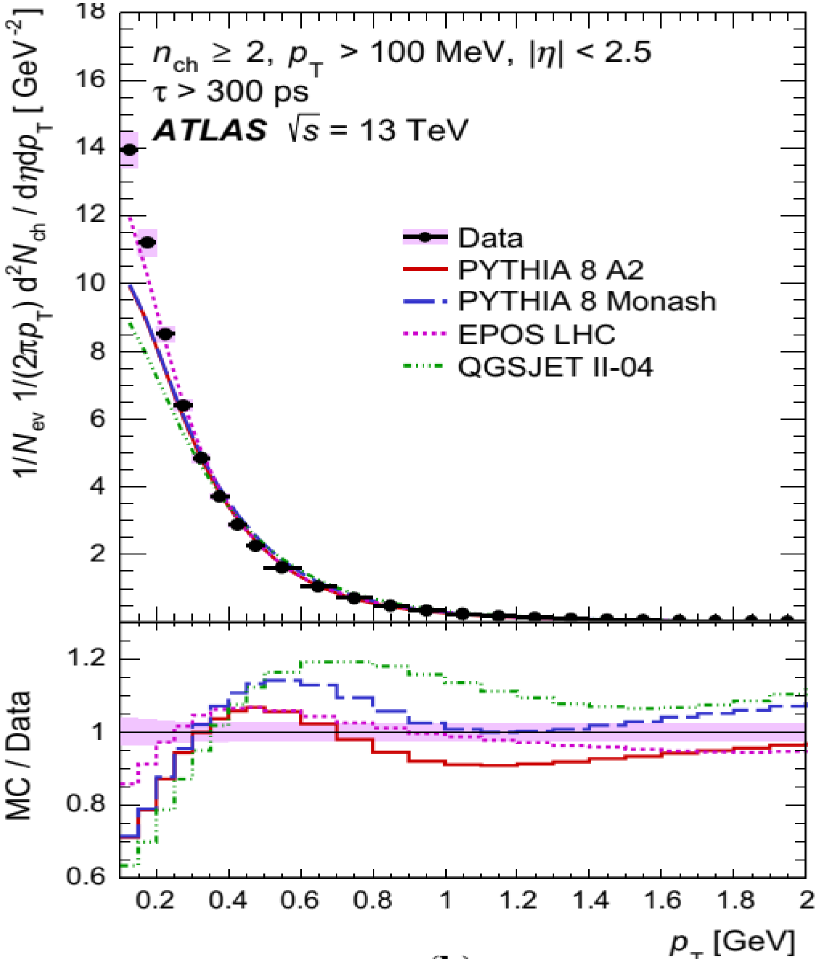


For p_T>500 MeV:

- Measurement ***spans 10 orders*** of magnitude
- **EPOS and Pythia 8 Monash** give remarkably good predictions

For p_T>100 MeV:

- **EPOS** describes the data well for p_T>300 MeV, but for p_T< 300 MeV, the data are underestimated by up to 15%.
- MC show similar mismodelling **at low momentum** but with larger discrepancies up to 35% for **QGSJET- II**
- MC mostly overestimate the charged-particle multiplicity for p_T>400 MeV
- **PYTHIA 8 A2** overestimates only in the intermediate p_T region and underestimates the data slightly for p_T>800 MeV



Primary charged-particle multiplicities as a function of p_T for events with n_{ch}≥1, p_T>500 MeV and n_{ch}≥2, p_T>100 MeV in $|\eta|$<2.5.

❑ The energy dependence predicted by the models does not usually work (***tuned when new energy regime reached***)

MULTIPLICITIES VERSUS N_{CH}

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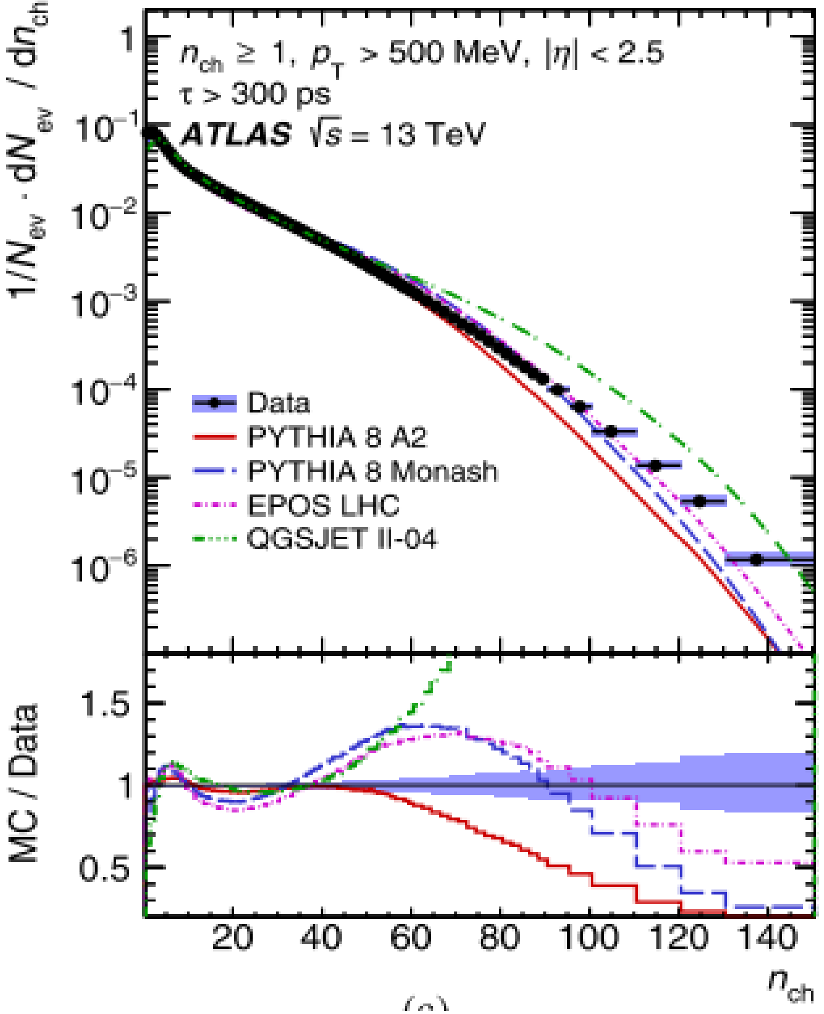
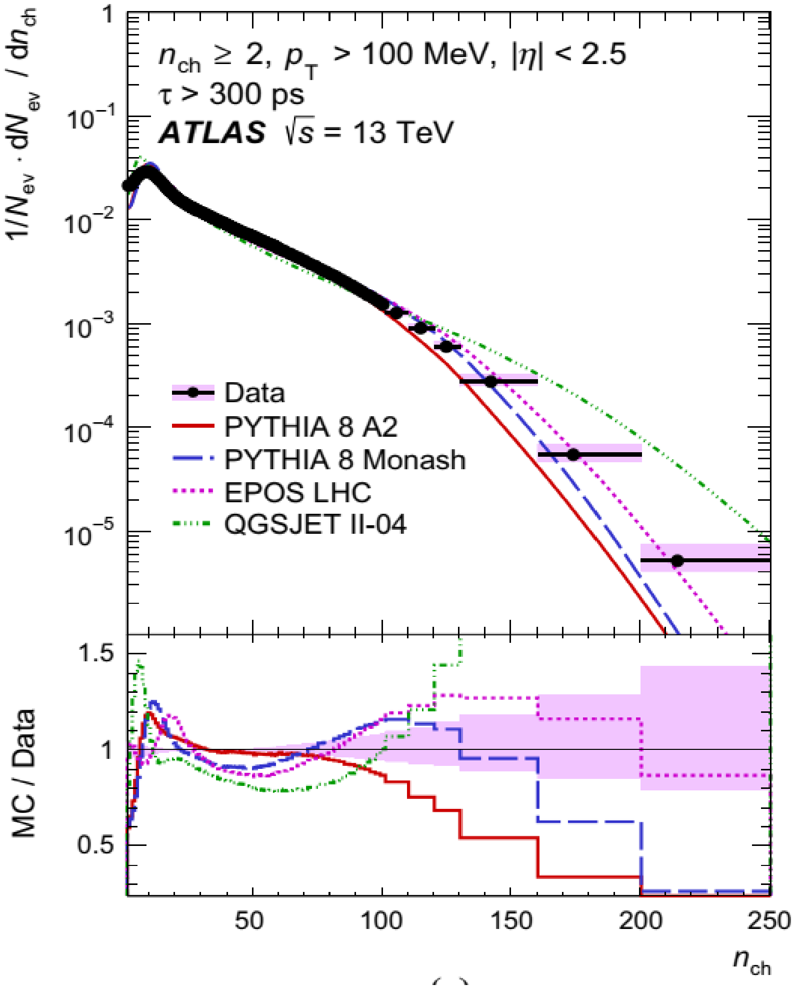


For p_T>500 MeV & p_T>100 MeV:

- The form of the measured distribution is reproduced reasonably by all models.
- **PYTHIA 8 A2** describes the data well for middle n_{ch} but underestimates it for higher
- For middle n_{ch} **PYTHIA 8 MONASH, EPOS, QGSJET-II** underestimate the data by up to 10-20%.
- **PYTHIA 8 MONASH, EPOS** overestimate the data for higher n_{ch} and drop below the measurement in the very high-n_{ch} region
- **QGSJET-II** overestimates the data significantly



Primary charged-particle multiplicities versus n_{ch} for events with $n_{ch}\geq1$, p_T>500 MeV & $n_{ch}\geq2$, p_T>100 MeV in $|\eta|<2.5$

The charged-particle multiplicity distribution. The high-*n*ch region has significant contributions from events with numerous MPI.

Colour reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization

MEAN TRANSVERSE MOMENTUM <p_T> VERSUS N_{CH}

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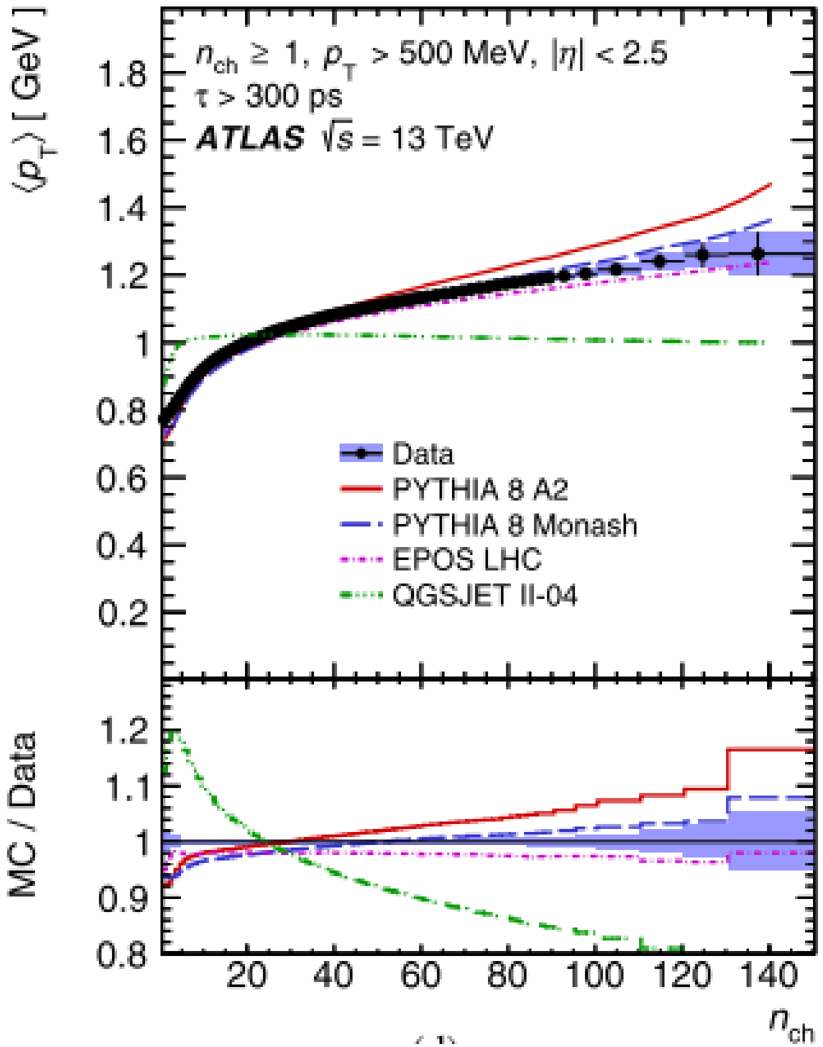
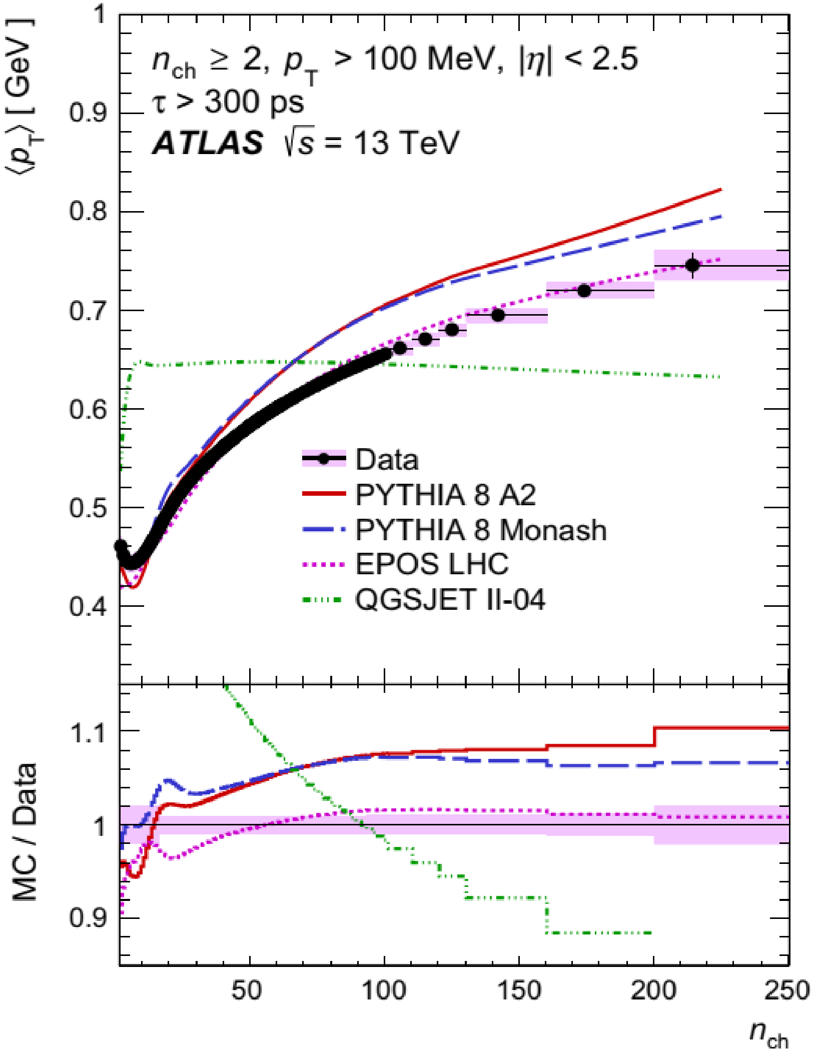


For p_T>500 MeV & p_T>100 MeV:

- Increases towards higher n_{ch}, as modelled by a *colour reconnection mechanism* in **PYTHIA 8** and by the *hydrodynamical evolution model* in **EPOS**
- The **QGSJET- II** generator, which has *no model for colour coherence effects*, describes the data poorly.
- For low n_{ch}, **PYTHIA 8 A2, EPOS** underestimate the data
- For higher n_{ch} all generators overestimate the data
- **EPOS** describes the data reasonably well and to within 2%



Primary charged-particle the <p_T> vs. n_{ch} for events with n_{ch}≥1, p_T>500 MeV and n_{ch}≥2, p_T>100 MeV in $|\eta|$<2.5

Colour reconnection: strings from independent parton interactions do not independently produce hadrons, but fuse before hadronization

AVERAGE PRIMARY CHARGED-PARTICLE MULTIPLICITY

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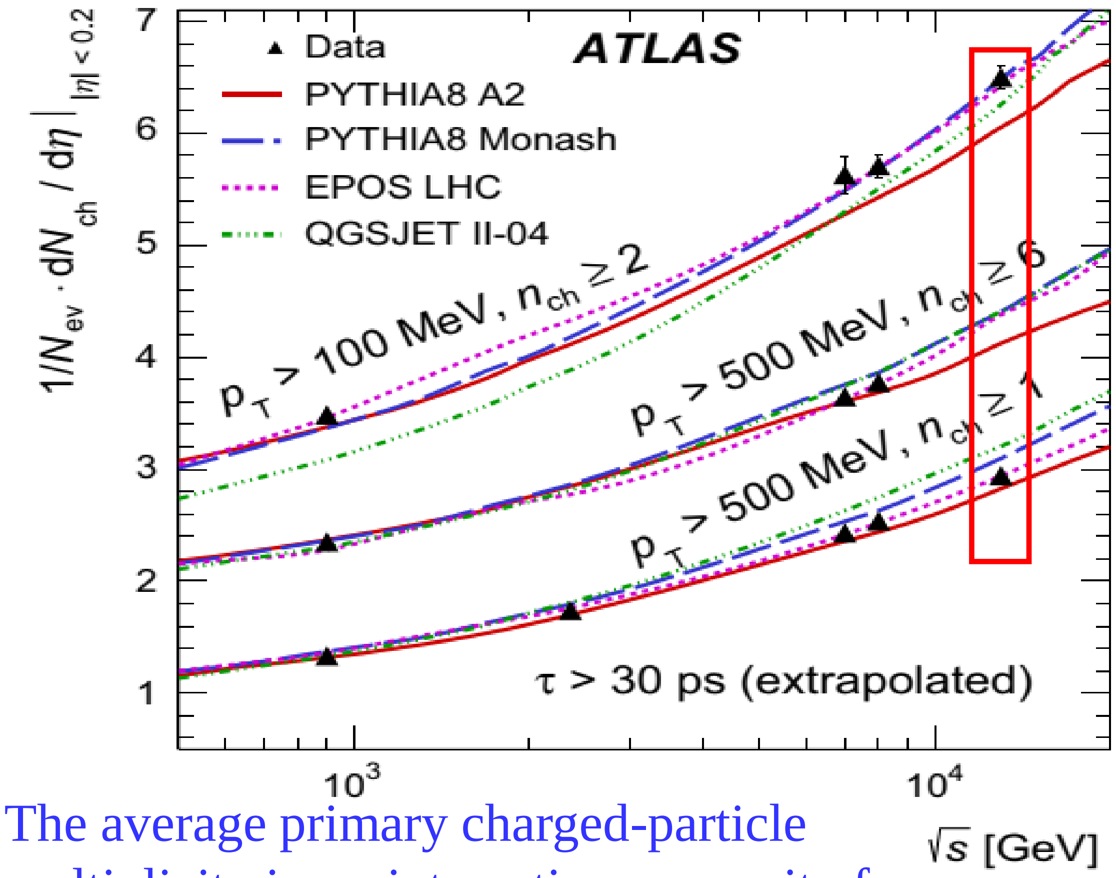


The average primary charged-particle multiplicity in *pp* interactions per unit of η for $|\eta|<0.2$ as a function of the energy

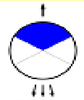
- The values for the other *pp* energies are taken from previous ATLAS analyses.
- The results have been extrapolated to include charged strange baryons (charged particles with a mean lifetime of $30<\tau<300$ ps).
- The data are shown as *black triangles* with *vertical errors bars* representing the total uncertainty.
- They are compared to various MC predictions which are shown as *coloured lines*.

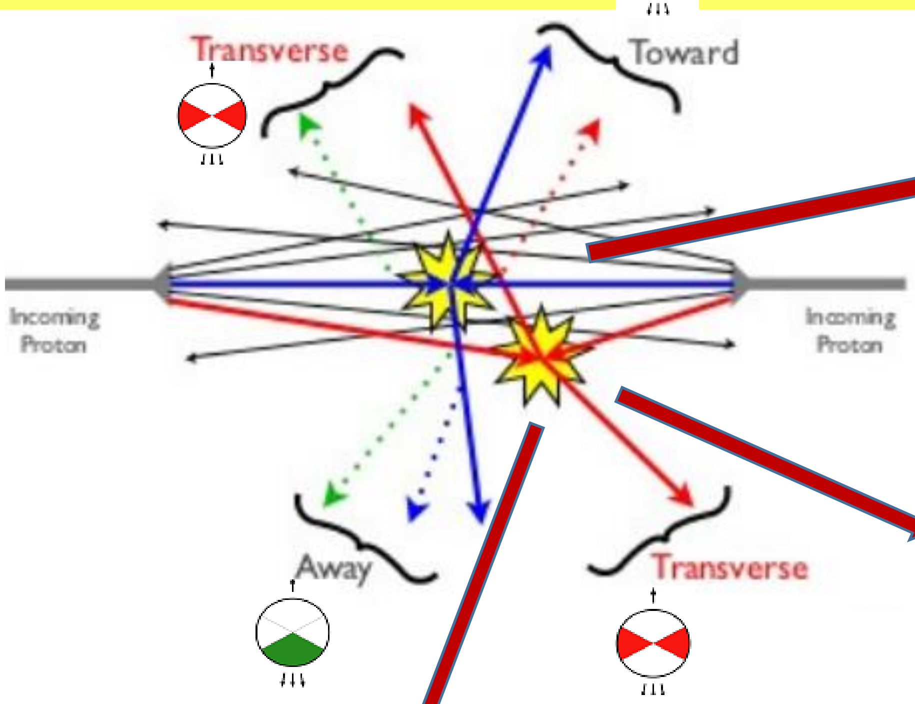
❑ It is related to the average energy density in pp-interactions and it gives reference for heavy-ion collisions

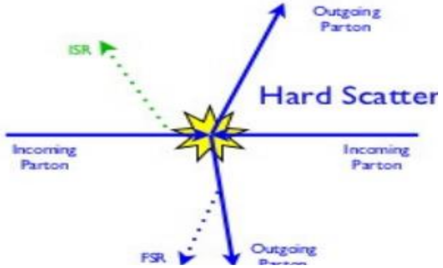
➢ For p_T**>100 MeV** the predictions from **EPOS and PYTHIA8 MONASH** match the data well; the predictions from **PYTHIA8 A2** the match is not as good as was observed when measuring particles with p_T>500 MeV

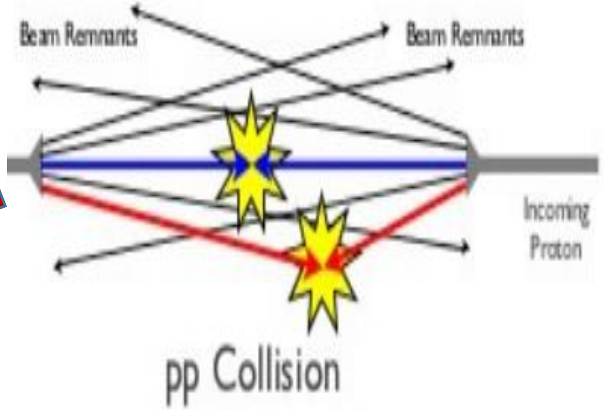
➢ For p_T**>500 MeV** the predictions from **EPOS and PYTHIA8 A2** match the data well

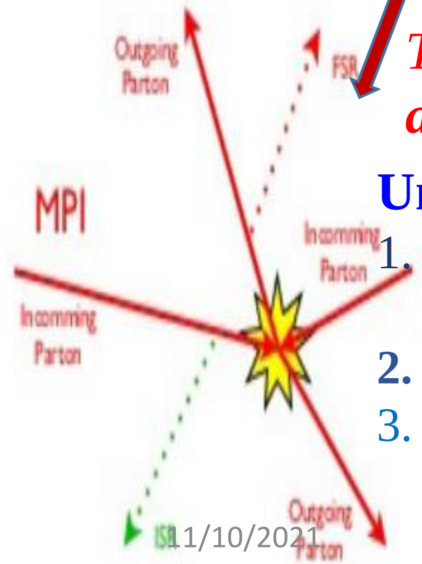
UNDERLYING EVENT (UE)











*The **UE** is defined as the activity*
accompanying any hard scattering

Underlying event:

1. Additional hard scatters in the same pp collision, termed **M**ultiple **P**arton **I**nteractions (**MPI**)
2. **I**nitial **&** **F**inal **S**tate gluon **R**adiation (**ISR, FSR**)
3. Partons not participating in a hard scattering process (**beam-proton remnants**)

Motivation

- Underlying event irreducible background at LHC
- Not understood from first principles in Monte-Carlo models
- Data need for test and constrain model parameters, motivate development
- Analysis are sensitive to multiple parton interactions
- New way of measuring UE using event shapes in Drell-Yan events
- Study of the UE with leading track

It is important to have a **good understanding** of

- primary short-distance hard scattering process
- **accompanying** interactions of the rest of the pp-collision: collectively termed the **UE**

- accurate description of **UE** properties by empirical tuning of MC

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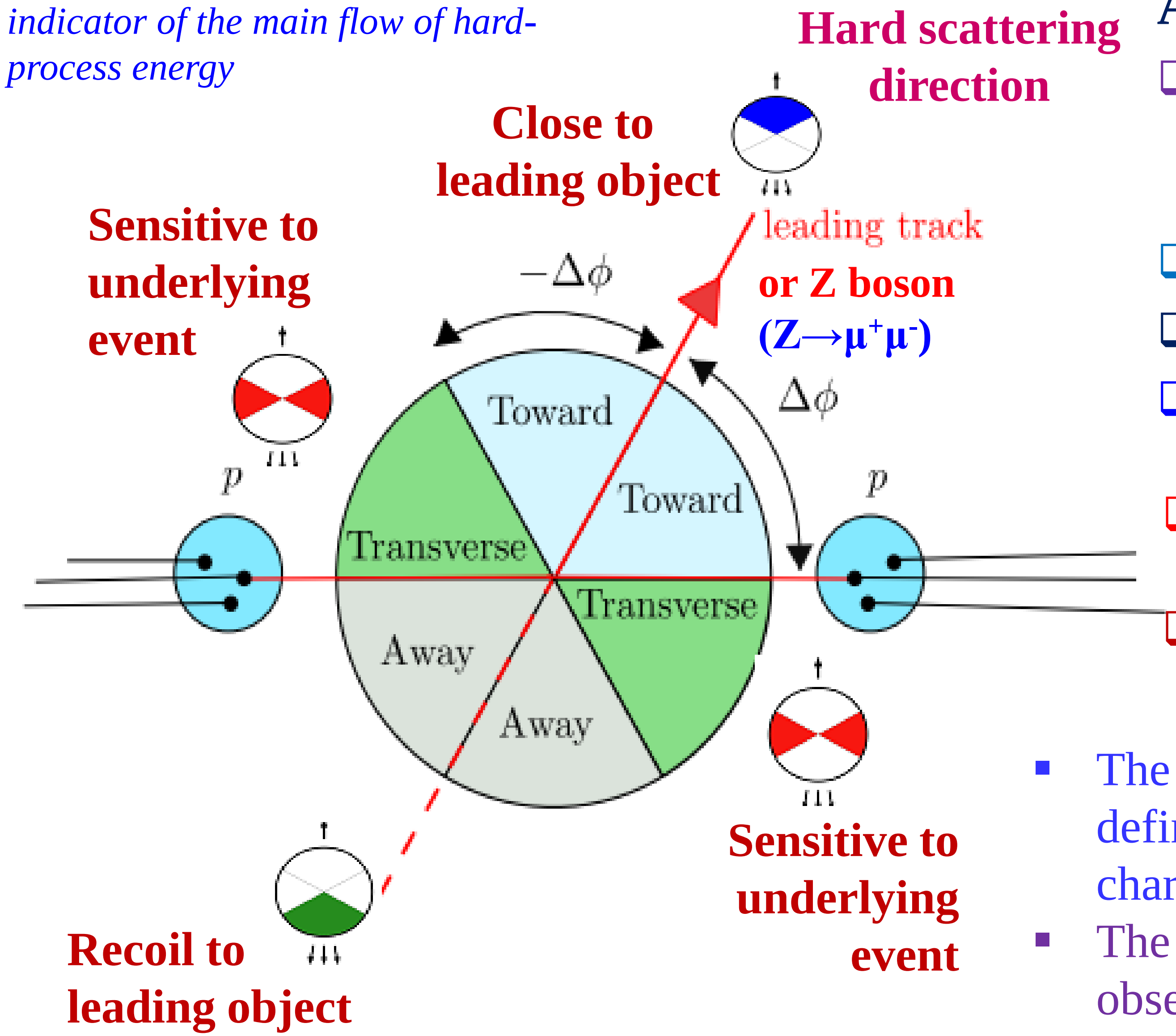
A leading object is a convenient indicator of the main flow of hard-process energy



Analysis based on *Leading track:*

- The distributions were constructed using charged particles with **p_T>0.5 GeV in $|\eta|$<2.5** in events with leading track with **$p_T \geq 1$ GeV**
- Results presented at particle level
- The tracking effic. uncertainty is about ≤**2%**
- No correction for secondary tracks is performed

- It is impossible to uniquely separate the **UE** from the **hard scattering process** on an event-by-event basis
- Observables can be defined which are particularly **sensitive** to the properties of the **UE**

- The **more** and the **less** active sides of the transverse region defined in terms of their relative scalar sums of primary charged-particle p_T and termed **trans-max** & **trans-min**.
- The difference between **trans-max** & **trans-min** observables termed the **trans-diff.**

MC MODELLING OF THE UE & OBSERVABLES

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The tunes use data from different experiments to constrain different processes. Some tunes are focused on describing the **MB** distributions better. The rest models are tuned to describe the **UE** distributions or double parton scattering (**DPS**) distributions

Generator	Version	Tune	PDF	Focus of Tune
PYTHIA 8	8.185	**A2**	MSTW2008LO	**MB**
PYTHIA 8	8.186	**Monash**	NNPDF2.3LO	**MB/UE**
PYTHIA 8	8.185	**A14**	NNPDF2.3LO	**UE**
Herwig++	7.0.1	**UE-MMHT**	CTEQ6L1	**UE/DPS**
EPOS	3.4	**LHC**		**MB**

As a physics process related to the bulk structure of protons and not calculable from first-principles perturbative QCD, the underlying event is modelled in MC event generator programs by **various phenomenological approaches**.

In this analysis the observable definitions restrict the effect of diffractive scattering, i.e., colour-singlet exchange, to play a minor role.

The data are compared with the MC predictions, after passing the generated events through the ATLAS detector simulation (based on GEANT4)

Definition of the measured observables

Observable	Name	Definition
$<d^2N_{ch}/d\eta d\varphi>$	Average track multiplicity density	Mean number of charged particles per unit η–φ
$<d^2\sum p_T/d\eta d\varphi>$	Average scalar p_T sum density	Mean scalar pT sum of charged particles per unit η–φ
$<\text{mean } p_T>$	Average mean p_T density	Mean per-event average pT of charged particles

DISTRIBUTIONS OF *AVERAGE TRACK MULTIPLICITY* VS p_T^{lead} : TRANS-MIN REGION

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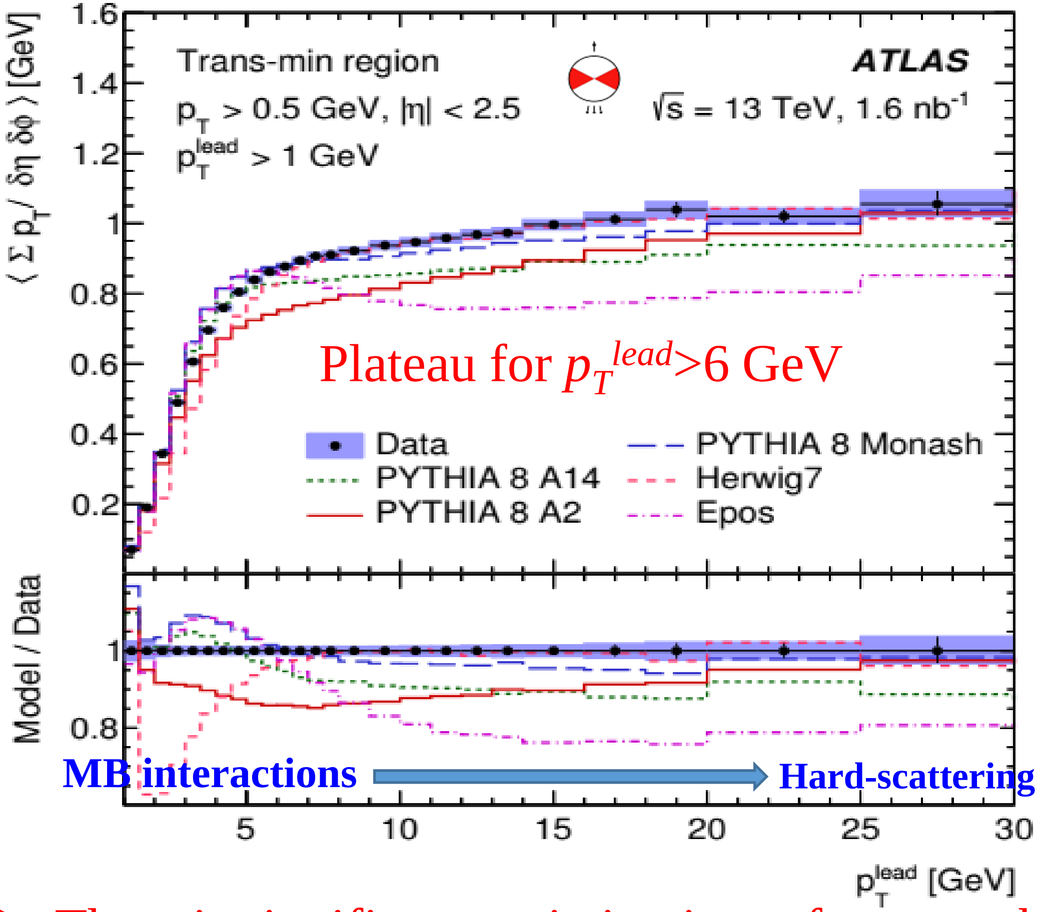

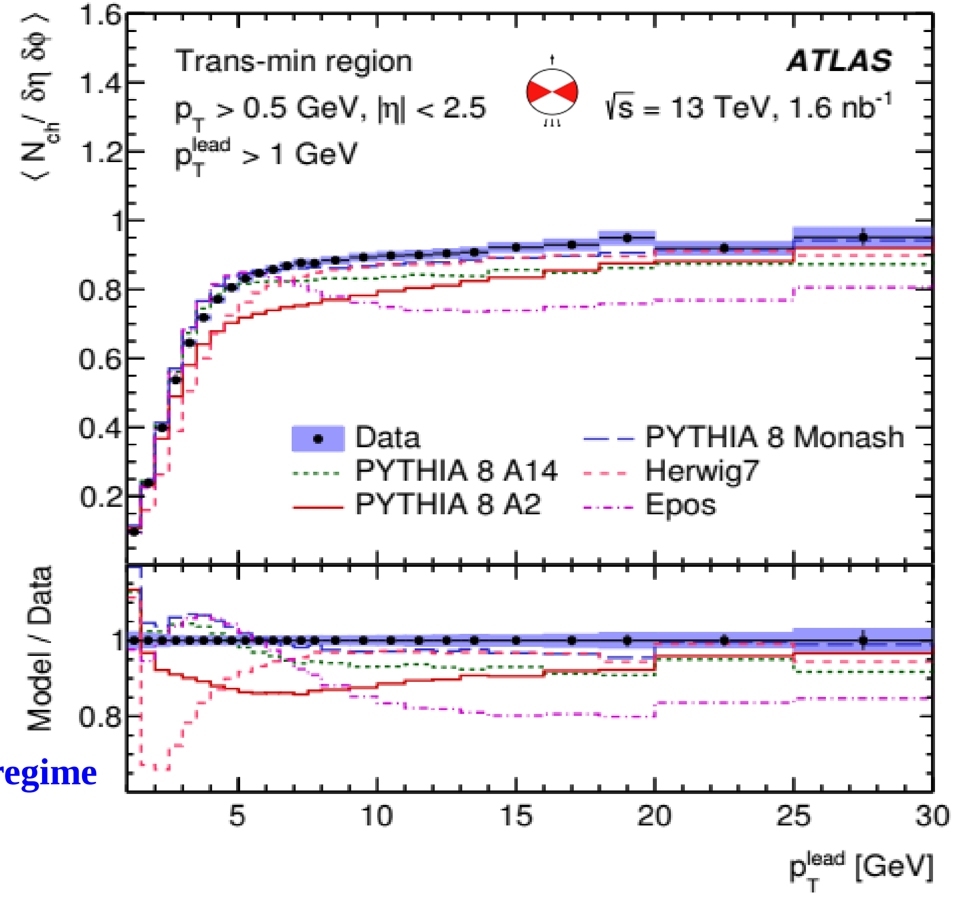

Mean densities of charged-particle multiplicity N_{ch} (right) and Σp_T (left) as a function of leading charged-particle $\mathbf{p_T^{lead}}$

Focuses on the UE-dominated transverse region, and its per-event specialisations trans-min, -max & -diff

The **trans-min** is the most sensitive to MPI effects, i.e. the pedestal

- ► There is significant variation in performance between the models
- ► **Pythia 8 Monash** & **Herwig 7** giving the best description of data in the plateau region of trans-min
- ► **Epos** overestimates in the “ramp" region to the pedestal effect plateau, on the plateau it underestimates the pedestal height by around 20%
- ► **Herwig 7 and Pythia 8 A2** mismodel the transition region

- The development of this from **low** to **high** $\mathbf{p_T}$ corresponds to the smooth transition from **MB interactions** to the **hard-scattering regime** focused on by most LHC analyses
- The **correlation distributions** characterize **how soft QCD effects co-evolve with the hard process** through this transition

AVERAGE P_T VS N_{CH} OR P_T^{LEAD} : TRANSVERSE REGION

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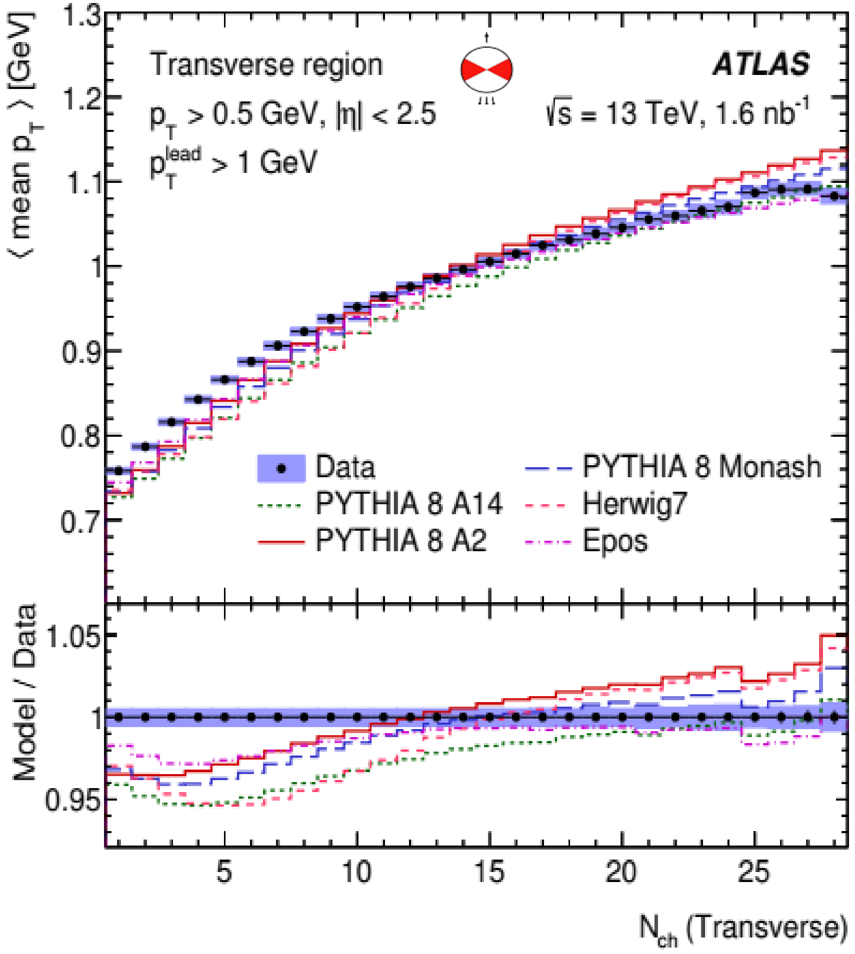

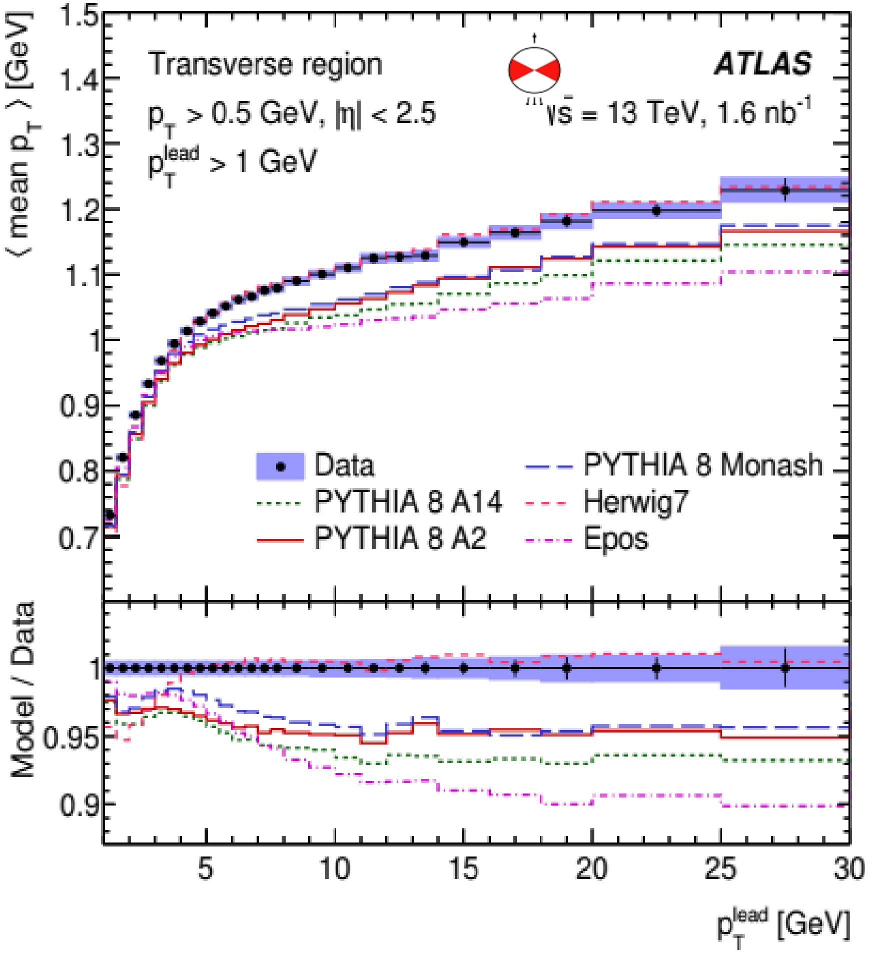

- Mean charged-particle average transverse momentum as a function of charged-particle multiplicity in transverse region N_{ch} (Transvers) and as a function of p_T^{lead}
- The best modelling is from **Epos**, whose maximum undershoot is ~3% at low N_{ch} but which follows the data closely in all region definitions for higher transverse multiplicities

- The **per-event mean transverse momentum** of charged particles in the **transverse azimuthal regions** is of interest since it ***illustrates the balance in UE physics between the Σp_T and multiplicity observables***.
- This balance is affected in some MC models by colour-reconnection or -disruption mechanisms, which stochastically reconfigure the colour structures in the hadronising system into energetically favourable states and typically increase the p_T per particle.

AVERAGE N_{CH} AND VS N_{CH} OR ΣP_T VS P_T^{LEAD}

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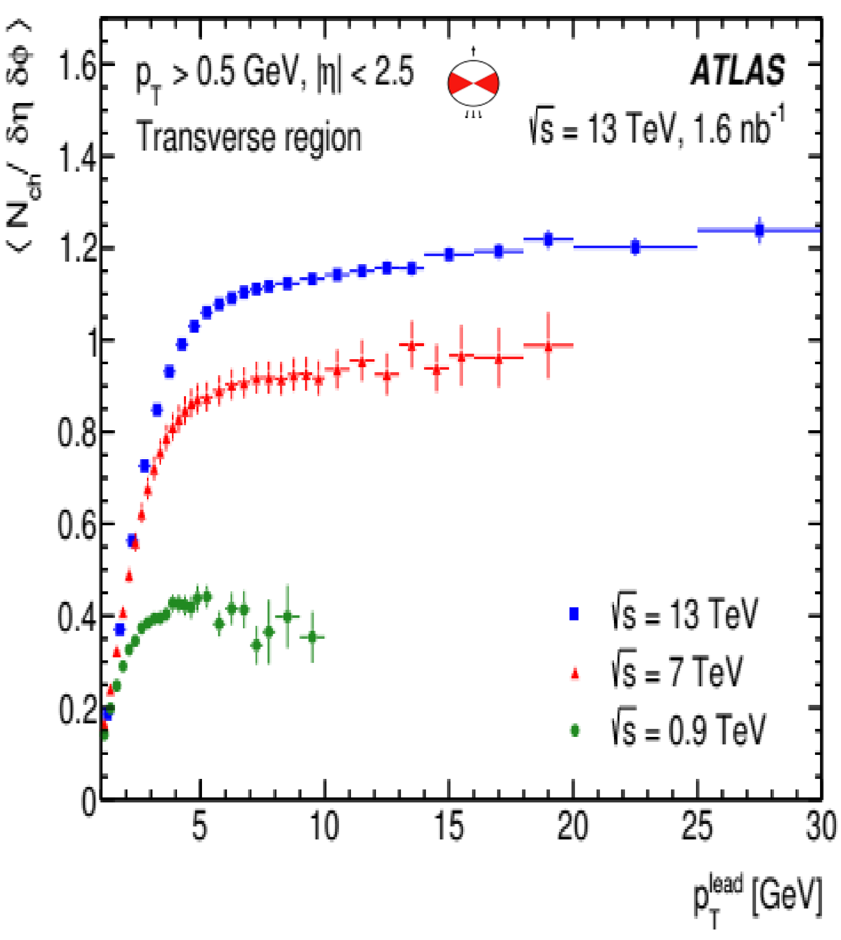
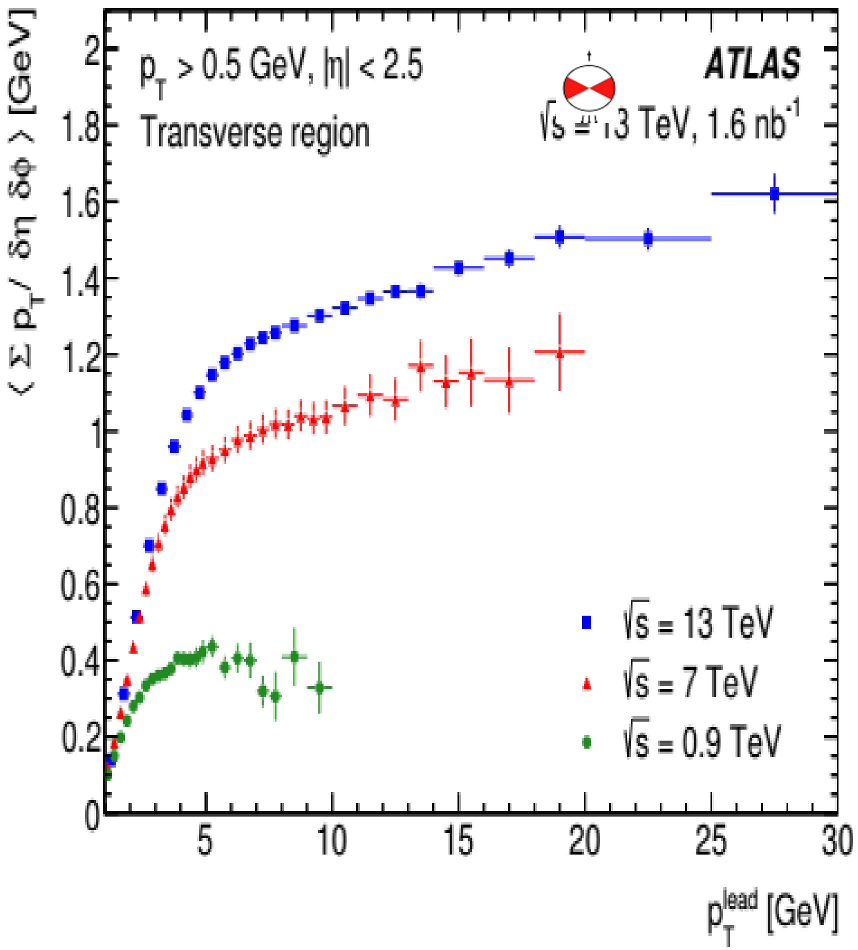


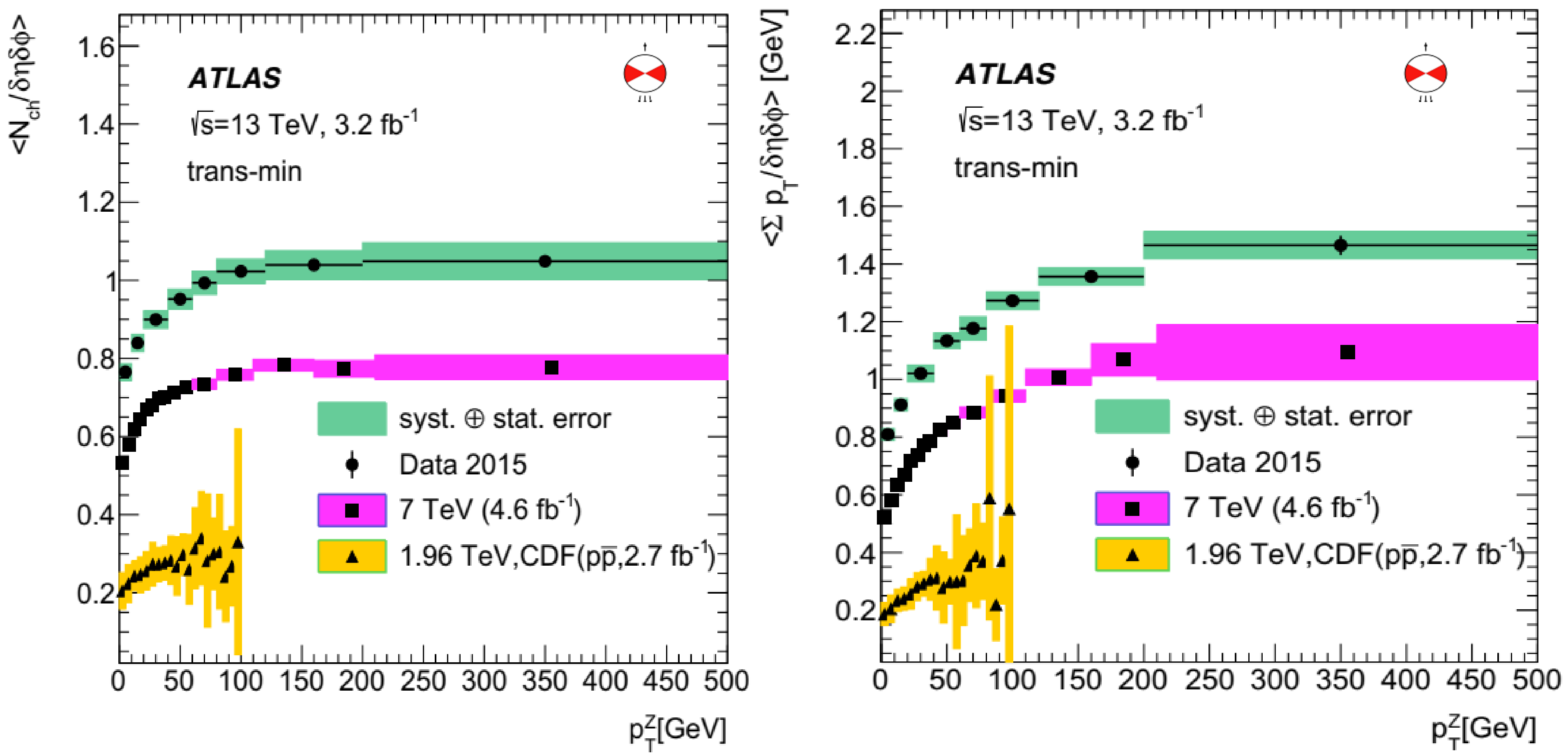


- Mean charged-particle multiplicity and Σp_T densities as a function of transverse momentum of the leading charged particle measured for 0.9; 7 TeV and 13 TeV
- The fiducial acceptance definitions of the 0.9 and 7 TeV measurements did not exclude charged strange baryons, but this effect is limited to a few percent at most

- The presented measurement improves upon previous ATLAS measurements of the underlying event using leading-track alignment, both in the reach in p_T^{lead} and the precision achieved
- An increase in UE activity of approximately 20% is observed when going from 7 TeV to 13 TeV pp collisions

AVERAGE N_{CH} AND ΣP_T VS. P_T^Z

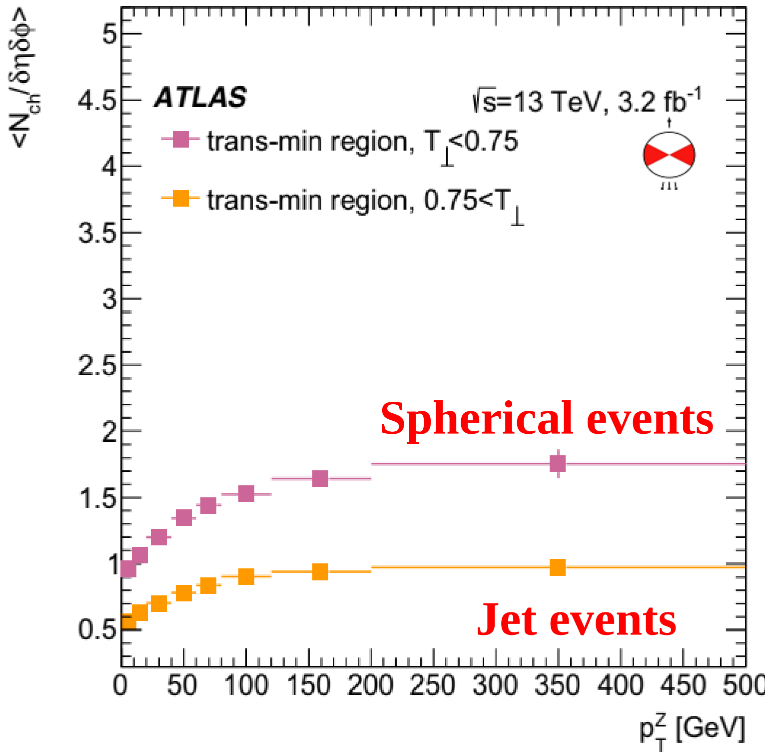
Eur. Phys. J. C (2019) 79:666

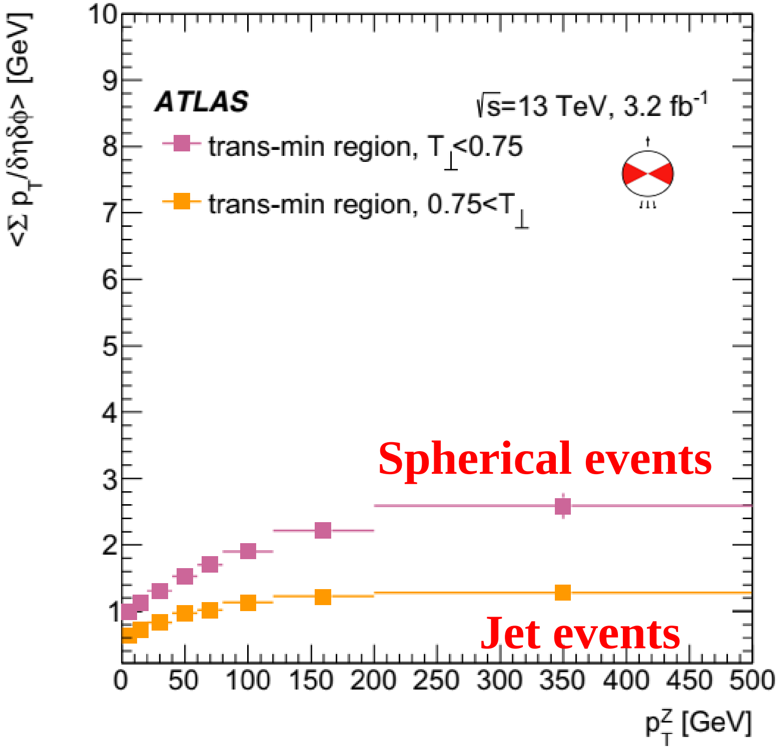


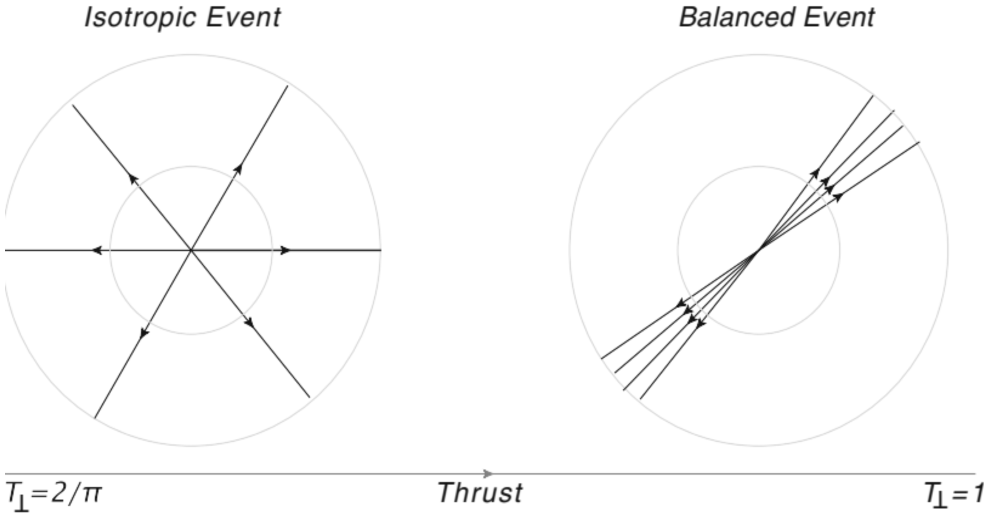
Mean charged-particle multiplicity and Σp_T densities as a function of transverse momentum of the leading charged particle measured for 1.96; 7 TeV and 13 TeV energies.

- ❑ Figure presents a comparison of the measurement of the UE activity in Z boson events.
- ❑ The CDF measurements at √s=1.96 TeV are included.
- ❑ All measurements show qualitatively the same behaviour, a growing UE activity with higher values of p_T^Z.

UNDERLYING EVENT IN Z BOSON: TRANSFER TRUST







The mean number of charged particles and the mean of the scalar sum of the transverse momentum of those particles per unit η–φ space as a function of p_T^Z in the trans-min region separated in $T_\perp$

Transverse thrust $$T = \max_{\vec{n}_T} \frac{\sum |\vec{p}_T \cdot \vec{n}_T|}{\sum p_T},$$

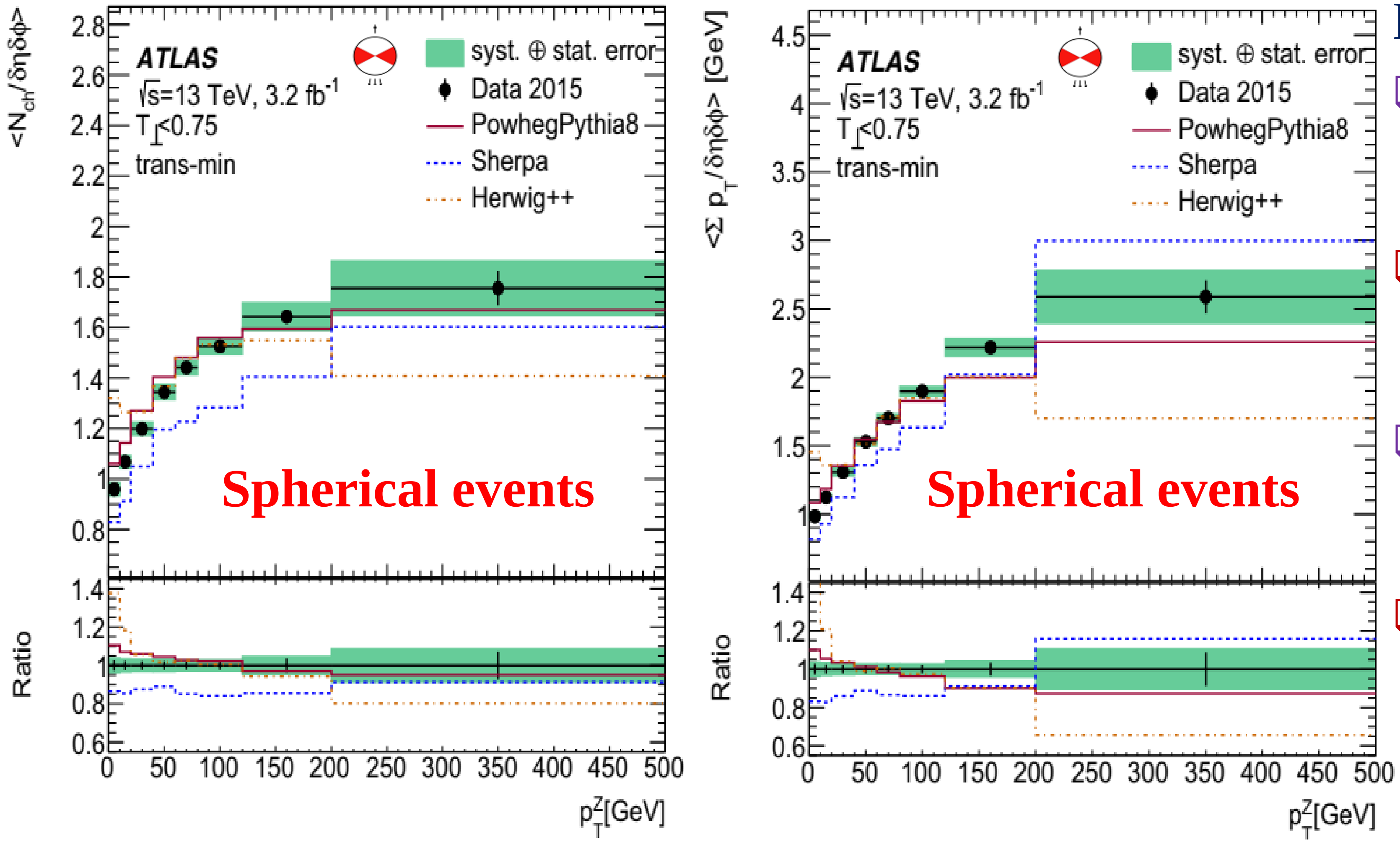
runs over all charged particles, $\vec{n}_T$ the **thrust axis**, $\vec{n}_T$ maximizes the expression. For $n_{sel} \geq 2$. The solution for is found iteratively: $$\vec{n}_T^{(j+1)} = \frac{\sum \varepsilon(\vec{n}_T^{(j)} \cdot \vec{p}_T)\vec{p}_T}{|\sum \varepsilon(\vec{n}_T^{(j)} \cdot \vec{p}_T)\vec{p}_T|},$$

where $\varepsilon(x>0)=1$ and $\varepsilon(x<0)=-1$.

- ➢ The UE activity is higher for events with lower $T_\perp$.
- ➢ Lower values of $T_\perp$ also increase the dependence on p_T^Z in the trans-min region.
- ➢ The slope of the UE activity in the trans-min region as a function of p_T^Z for events of high $T_\perp$ is like the inclusive measurement.

UNDERLYING EVENT IN Z BOSON & MC: $T_\perp$<0.75

Eur. Phys. J. C (2019) 79:666



In the ***low*** ***$T_\perp$ region:***

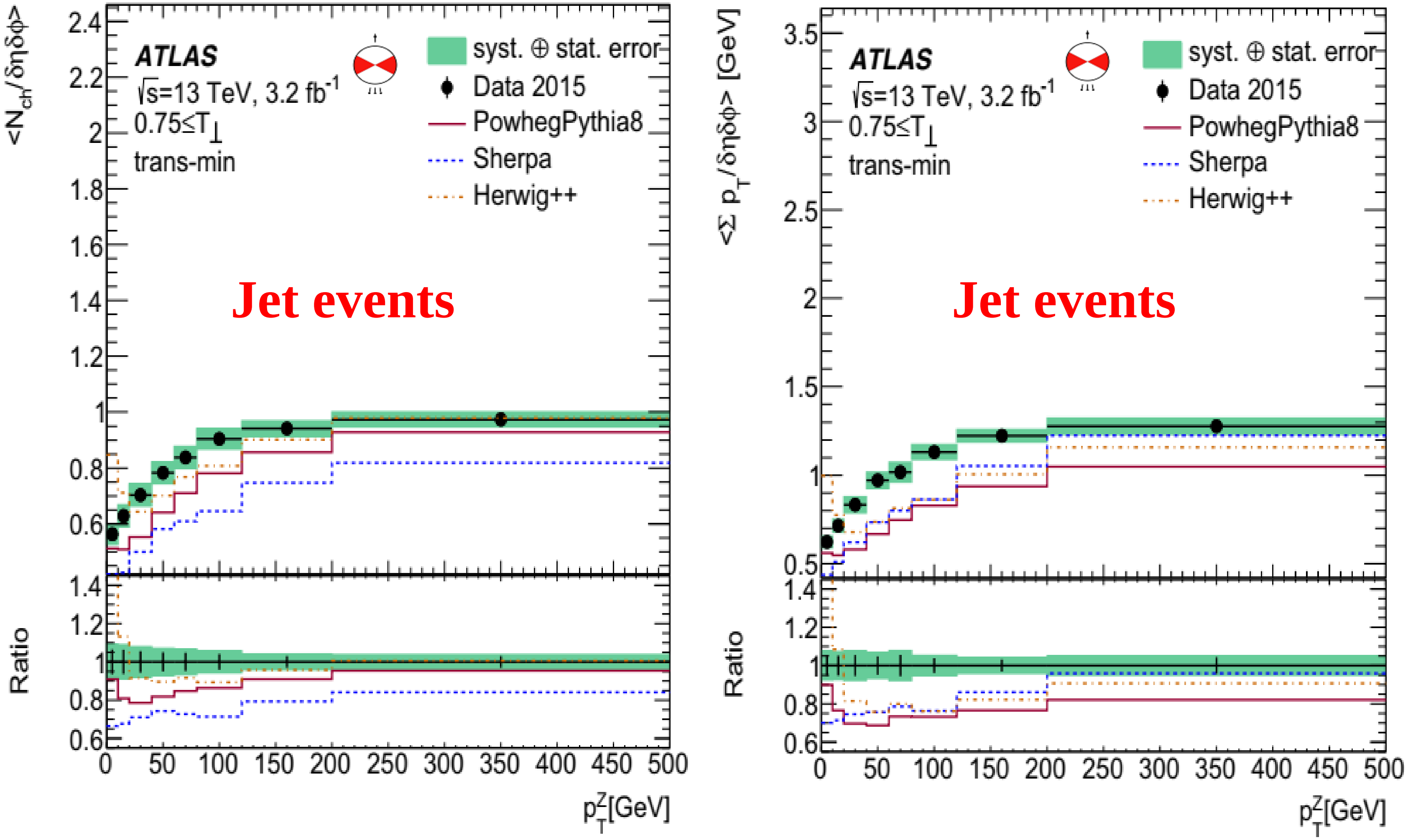
- The prediction by **Sherpa** improves, e. g. for N_{ch} the discrepancy shrinks from about 30% to roughly 10%.
- Referring to the same observable, **Powheg+Pythia** agrees with data for p_T^Z>80 GeV within the uncertainties
- The agreement of **Powheg+Pythia** with data is better for $T_\perp$<0.75 than for the inclusive measurement.
- The predictions of **Herwig++** in the **trans-min region** improve with higher values of p_T^Z and in events of lower $T_\perp$

Comparison of measured arithmetic means of the N_{ch} and Σp_T as functions of p_T^Z for $T_\perp$<0.75 for the trans-min region

- Predictions of **Powheg+Pythia**, **Sherpa** and **Herwig++** are compared with the data.

UNDERLYING EVENT IN Z BOSON AND MC: 0.75≤$T_\perp$

Eur. Phys. J. C (2019) 79:666



In the ***high*** $T_\perp$ ***region:***

- All generators underestimate the UE activity.
- **Sherpa** provides the best description of the data in <mean p_T>. Apart from the toward region, it tends to a constant underestimation but agrees with the overall shape.

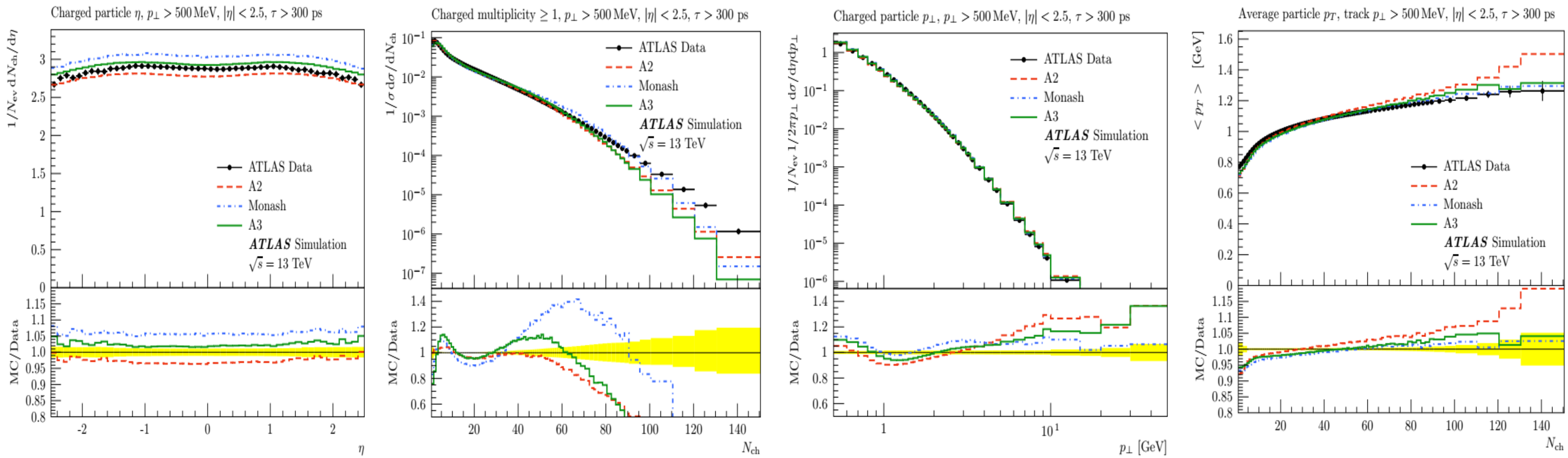
Comparison of measured arithmetic means of the N_{ch} and Σp_T as functions of p_T^Z for 0.75≤$T_\perp$ for the trans-min region

- Predictions of **Powheg+Pythia**, **Sherpa** and **Herwig++** are compared with the data.

RUN 3: PLANS

ATL-PHYS-PUB-2016-017

- The typical variables used to study the soft phenomena using **MB** samples are usually tuned in event generators using these **MB** measurements, because there is a variability in modelling since non-perturbative QCD is used.
  - These variables for new collision energy will be measurement in **Run 3**
- The **MB/UE** results from **Run 2** are exploited for **Run 3:**
- The ***Pythia 8 A3** tune* is suitable for inclusive QCD modelling for **Run 3** and it uses the ATLAS **Run 2** charged-particle distribution & inelastic cross section results in addition to the **Run 1** used for construction of ***MB tunes***



The ***Pythia 8 A3**, **A2** & **Monash tune*** predictions compared with ATLAS charged particle distributions **at 13 TeV**

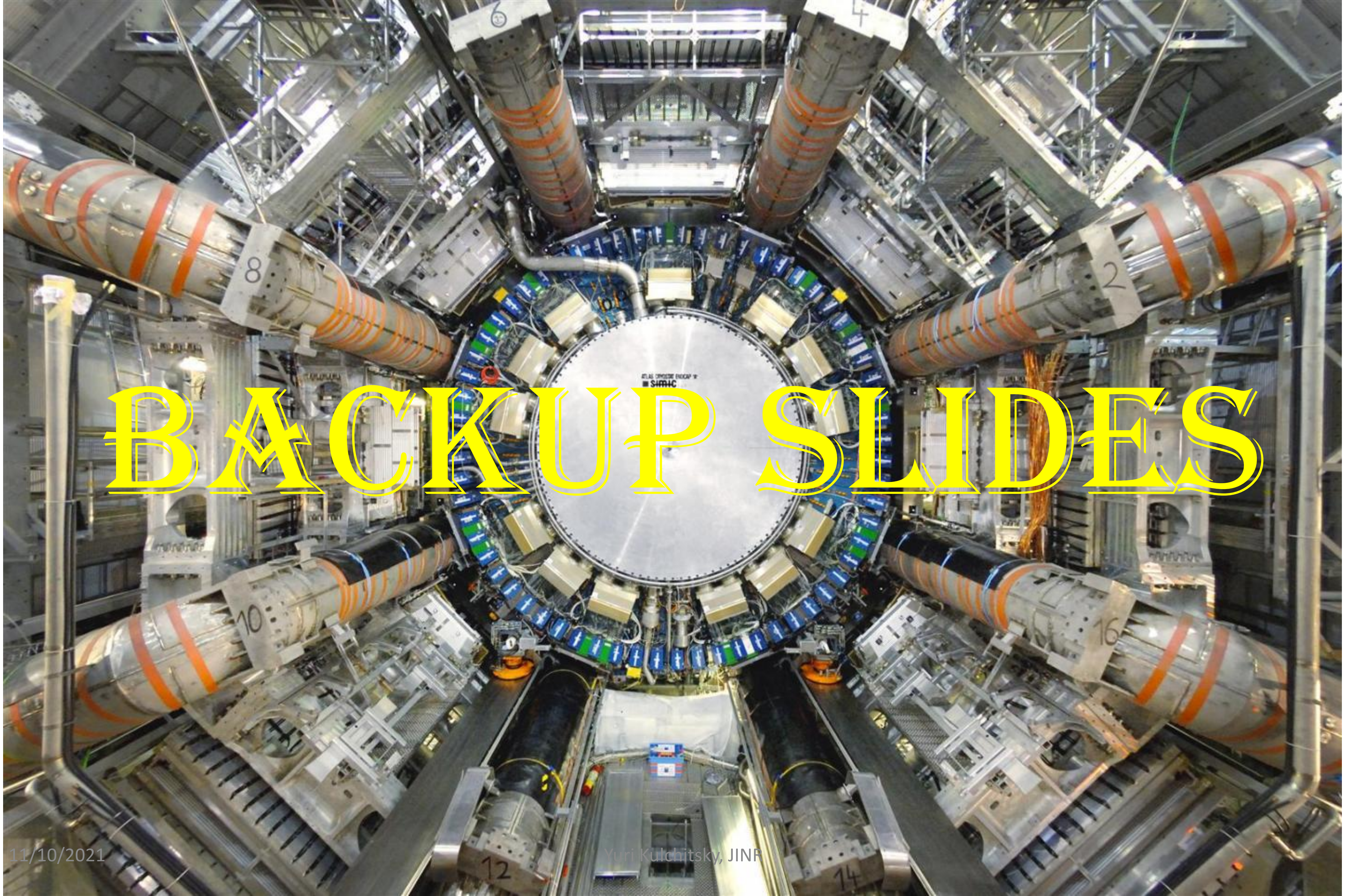
SUMMARY

- **Measurements the distributions of**
  - the charged-particle multiplicity dependences on pseudorapidity, multiplicity and transverse momentum,
    - the dependence of the mean transverse momentum on multiplicity

  are done for study the soft phenomena using MB: $n_{ch}\geq 1$, $p_T>500$ MeV & $n_{ch}\geq 2$, $p_T>100$ MeV, $|\eta|<2.5$ at 13 TeV
- The results are compared to the predictions from several MC event generators
- There variables are tuned in event generators using these MB measurements, because there is a variability in modelling since non-perturbative QCD is used
- That we plan to measure them in **Run 3** because for every collision energy, we need to measure these variables and ***tune MC generators***
- **Underlying event** analysis at $\sqrt{s}$=13 TeV are presented for **leading track** & **Z boson** the distributions of
  - the charged-particle multiplicity, its dependence on p_T and η
  - the dependence of the mean transverse momentum on multiplicity are measured
- The reasonable agreement of tunes used in ***Atlas MC*** with the data
- **New MC tune**: **Pythia 8 A3 tune** was prepared for result predictions at **Run 3**

THANKS A LOT, TO ATLAS COLLEAGUES!

THANK YOU VERY MUCH FOR ATTENTION!



Backup Slides

PUBLICATIONS

Minimum-bias Events

- ATLAS Collaboration, *Charged-particle distributions at low transverse momentum in √s=13 TeV pp interactions measured with the ATLAS detector at the LHC;* Eur. Phys. J. C (2016) 76:502
- ATLAS Collaboration, *Charged-particle distributions in √s=13 TeV pp interactions measured with the ATLAS detector at the LHC;* Physics Letters B 758 (2016) 67–88

Underlying Event

- ATLAS Collaboration, *Measurement of charged-particle distributions sensitive to the underlying event in √s=13 TeV proton-proton collisions with the ATLAS detector at the LHC;* JHEP03 (2017) 157
- ATLAS Collaboration, *Measurement of distributions sensitive to the underlying event in inclusive Z boson production in pp collisions at √s=13 TeV with the ATLAS detector*, Eur. Phys. J. C (2019) 79:666

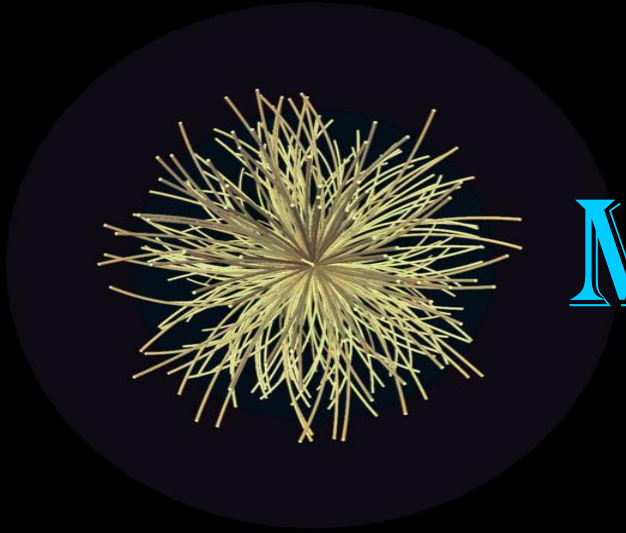
MC tuning

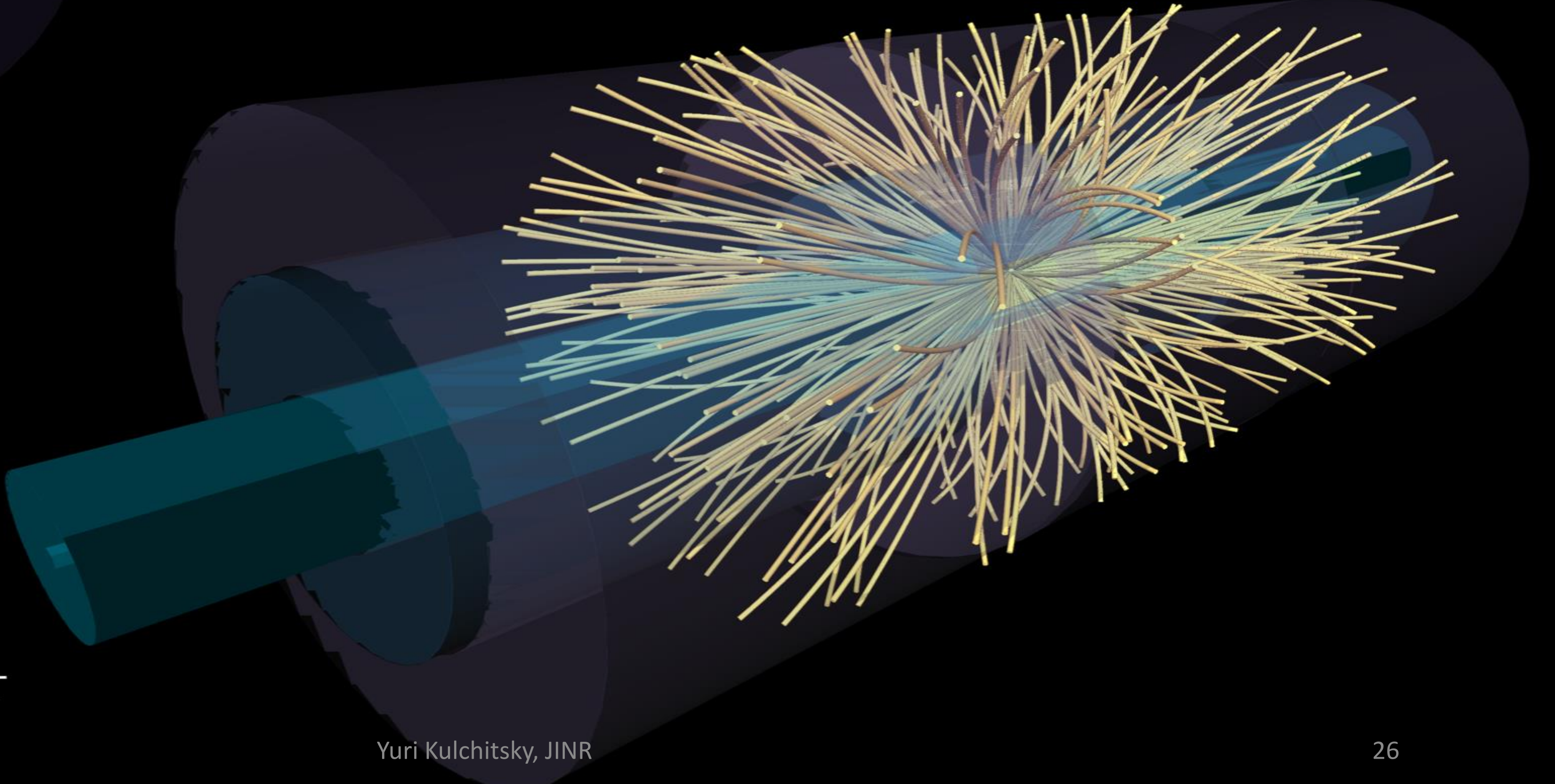
- The ATLAS collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model; ATL-PHYS-PUB-2016-017*

319 reconstructed charged-particles

The shown tracks are from a single vertex and have $p_T > 0.4$ GeV

MINIMUM-BIAS EVENTS





ATLAS EXPERIMENT

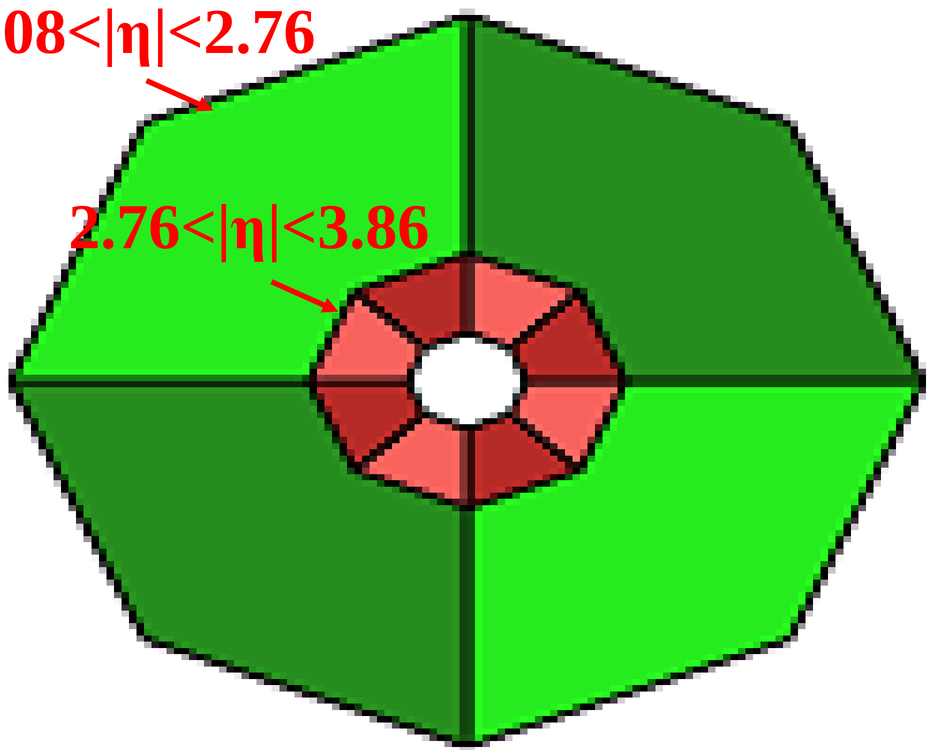
Run: 312837
Event: 135456971
2016-11-14 07:42:28 CEST

Minimum-bias Events

- ATLAS Collaboration, *Charged-particle multiplicities in pp interactions at $\sqrt{s}$=900 GeV measured with the ATLAS detector at the LHC*; *Phys. Lett. B* 688 (2010) 21-42
- ATLAS Collaboration, *Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC*; *New J. Phys.* 13 (2011) 053033
- ATLAS Collaboration, *Charged-particle distributions in pp interactions at $\sqrt{s}$=8 TeV measured with the ATLAS detector*; *Phys. Lett. B* 758 (2016) 67-88

MINIMUM BIAS TRIGGER SCINTILLATOR

24 independent wedge-shaped plastic scintillators (12 per side) read out by PMTs, $2.08<|\eta|<3.86$*



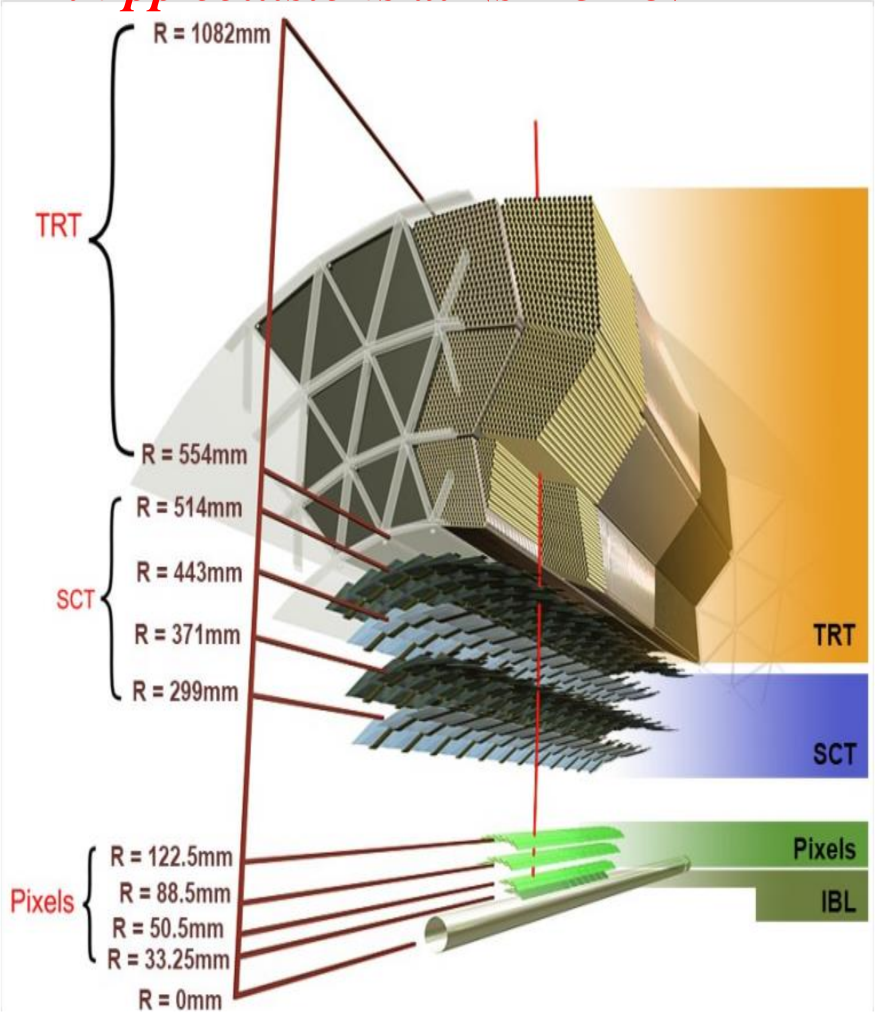
* Pseudorapidity is defined as $\eta = -\frac{1}{2} \ln(\tan(\theta/2))$, θ is the polar angle with respect to the beam.

- Designed for triggering on min bias events, >99% efficiency
- MBTS timing used to veto halo and beam gas events
- Also being used as gap trigger for various diffractive subjects

INNER DETECTORS (ID)

The focus of ATLAS is high-p_T physics and provides a window onto important *softer QCD processes*.
These have intrinsic interest but also the searches for new physics.

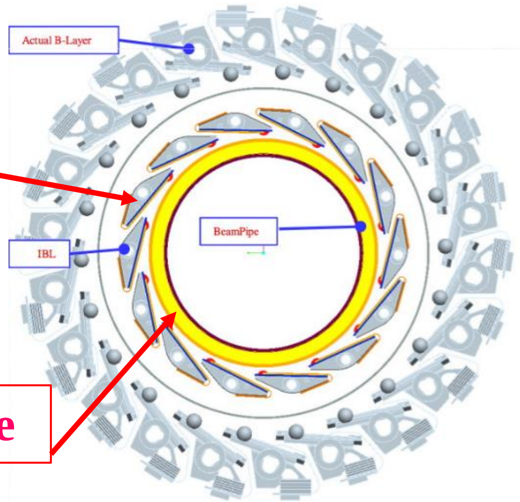
- ***Charged-particle distributions at √s=13 TeV in pp interactions***
- ***Charged-particle distributions sensitive to the underlying event in pp collisions at √s=13 TeV***



ATLAS tracking detectors:
Pixels, SCT & TRT

- **New innermost 4-th layer** for the Pixel detector
  [**IBL** = Insertable B-Layer]
- Required complete removal of the ATLAS Pixel volume
- IBL fully operational

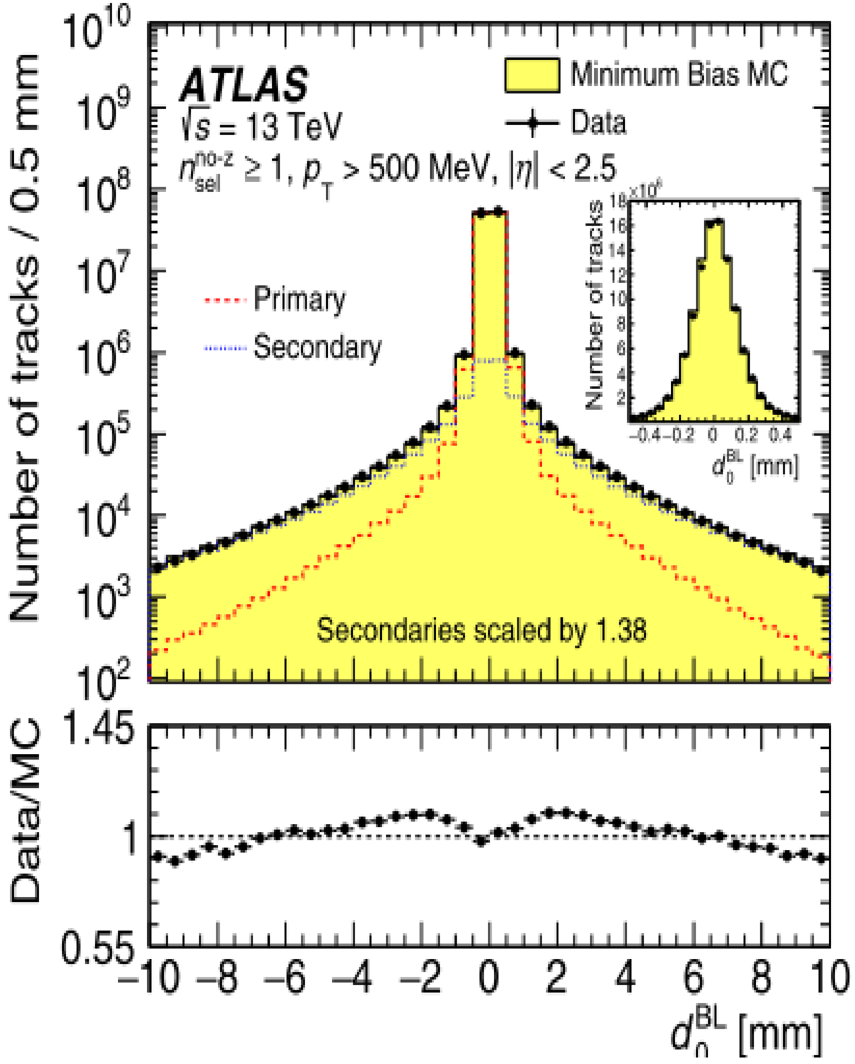
New Be beam pipe

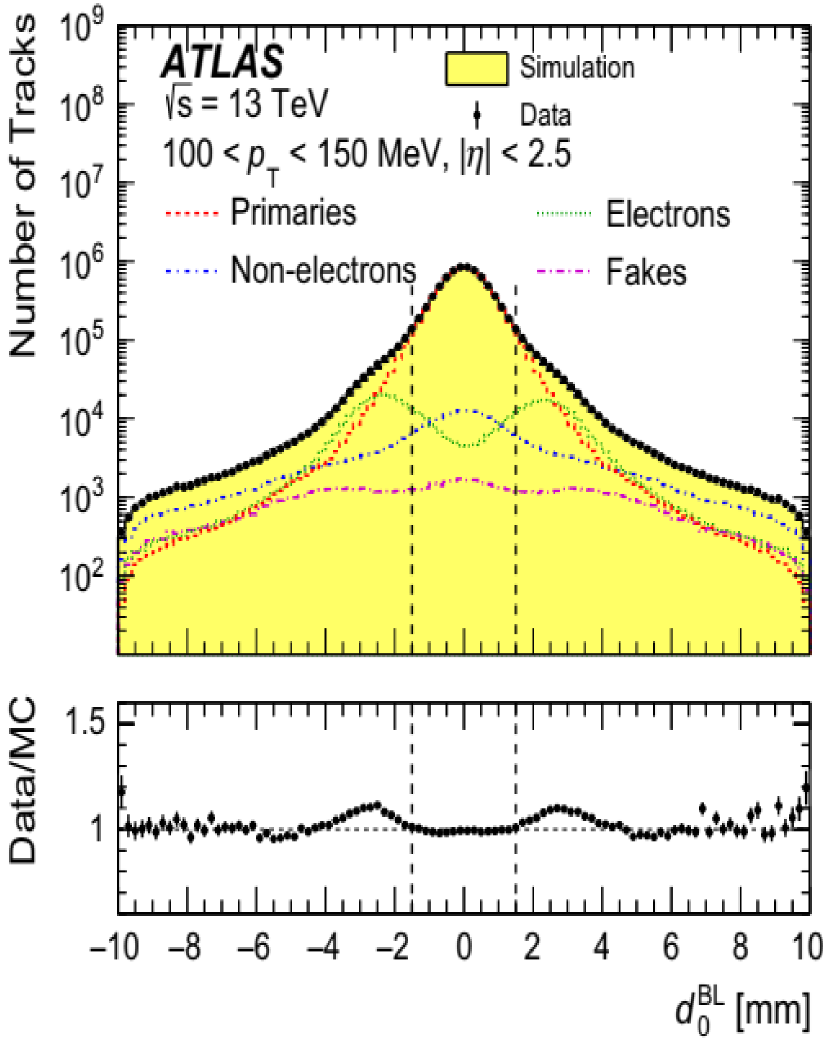


Two times better tracks impact parameters resolution at 13 TeV!

DISTRIBUTIONS OF IMPACT PARAMETER D_0

Eur. Phys. J. C (2016) 76:502
Phys. Let. B 758 (2016) 67–88





- The d_0^{BL} distribution is shown for **p_T>500** MeV and **100<p_T<150 MeV** without applying the cut on the transverse impact parameter.
- The position where the cut is applied is shown as dashed black lines at ±1.5 mm.
- The simulated d_0^{BL} distribution is normalised to the number of tracks in data and the separate contributions from primary, fake, electron and non-electron tracks are shown as lines using various combinations of dots and dashes.

Comparison between **data & PYTHIA 8 A2** simulation for the transverse impact parameter d_0^{BL} distribution. The error bars on the points are the statistical uncertainties of the data.

MINIMUM-BIAS EVENT SELECTION CRITERIA

Eur. Phys. J. C (2016) 76:502
Phys. Let. B 758 (2016) 67–88

ATLAS EXPERIMENT

Events pass the data quality criteria. "Good events":

- **all ID sub-systems nominal conditions,**
- **stable beam,**
- **defined beam spot**

- **Trigger:**
  - Accept on signal-arm Minimum Bias Trigger Scintillator for minimum-bias triggers
- **Vertex:**
  - Primary vertex (2 tracks with p_T>100 MeV),
  - Veto to any additional vertices with ≥4 tracks,
- **Tracks:** At least 2 tracks with p_T>100 MeV, $|\eta|<2.5$;
  - At least 1 first Pixel layer hit;
  - At least 2, 4, or 6 SCT hits for p_T>100, 300, 400 MeV respectively;
  - IBL hit required if expected (if not expected, next to innermost hit required if expected);
  - Cuts on the transverse impact parameter: $|d_0^{BL}|<1.5$ mm (w.r.t beam line);
  - Cuts on the longitudinal impact parameter: $|\Delta z_0 \sin\Theta|<1.5$ mm, where Δz_0 is difference between z_0^{tracks} & z^{vertex};
  - Track fit χ^2 probability >0.01 for tracks with p_T>10 GeV.

Correct distributions for detector effects:

- where possible the data used to reduce the MC dependencies
- Monte Carlo derived corrections for tracking

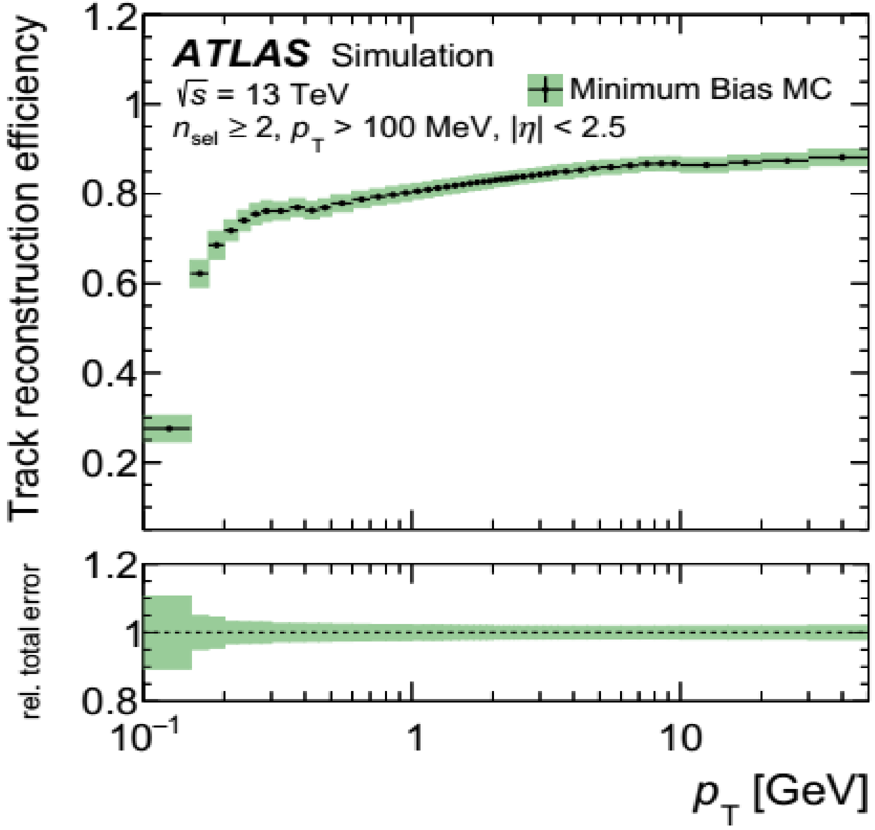
Eur. Phys. J. C (2016) 76:502
Phys. Let. B 758 (2016) 67–88

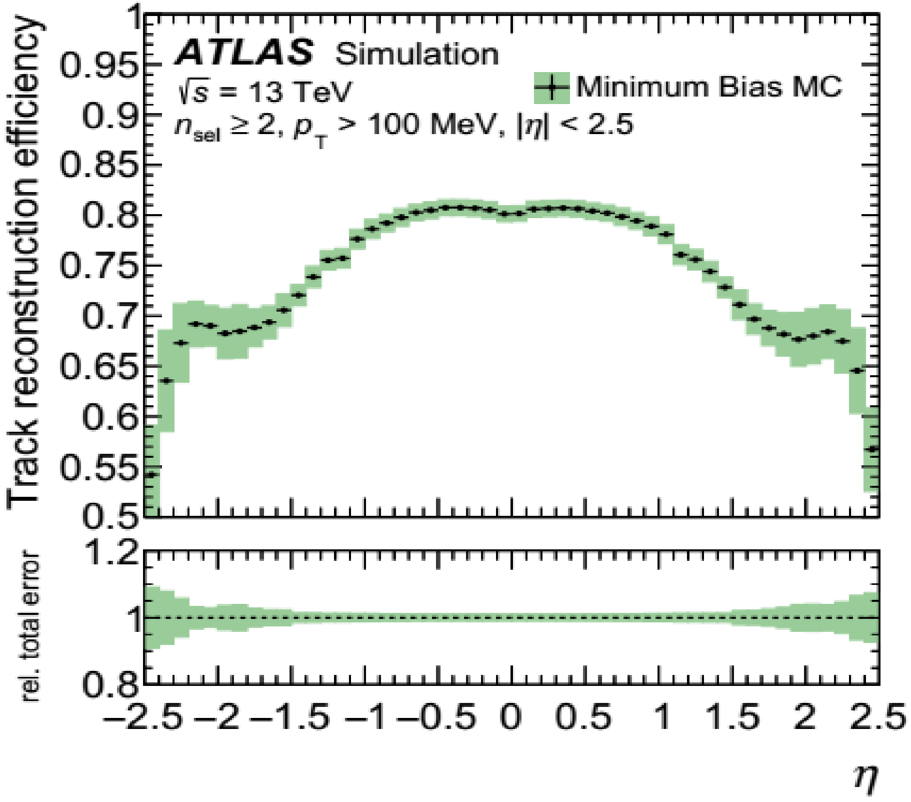
Performed corrections on:

1. The reconstruction track efficiency – $\varepsilon(p_T,\eta)$,
2. The fraction of non-primary (secondaries and fake) tracks – $f_{nonp}(p_T,\eta)$,
3. The fraction of tracks for which the corresponding primary particles are outside the kinematic range – $f_{okr}(p_T,\eta)$,
4. The strange barion tracks – $f_{sb}(p_T,\eta)$,

We use the formula, **as in MB studies**:

$$w_i(pT,\eta) = \frac{(1 - fnonp(p_T,\eta) - fokr(p_T,\eta) - fsb(p_T,\eta))}{\varepsilon(p_T,\eta)}$$





The primary track reconstruction efficiency integrated over p_T (left), integrated over η (middle) and as function of p_T and η (right). The green shaded error band includes the total systematic and statistical uncertainty

Systematic Uncertainties

Eur. Phys. J. C (2016) 76:502
Phys. Let. B 758 (2016) 67–88

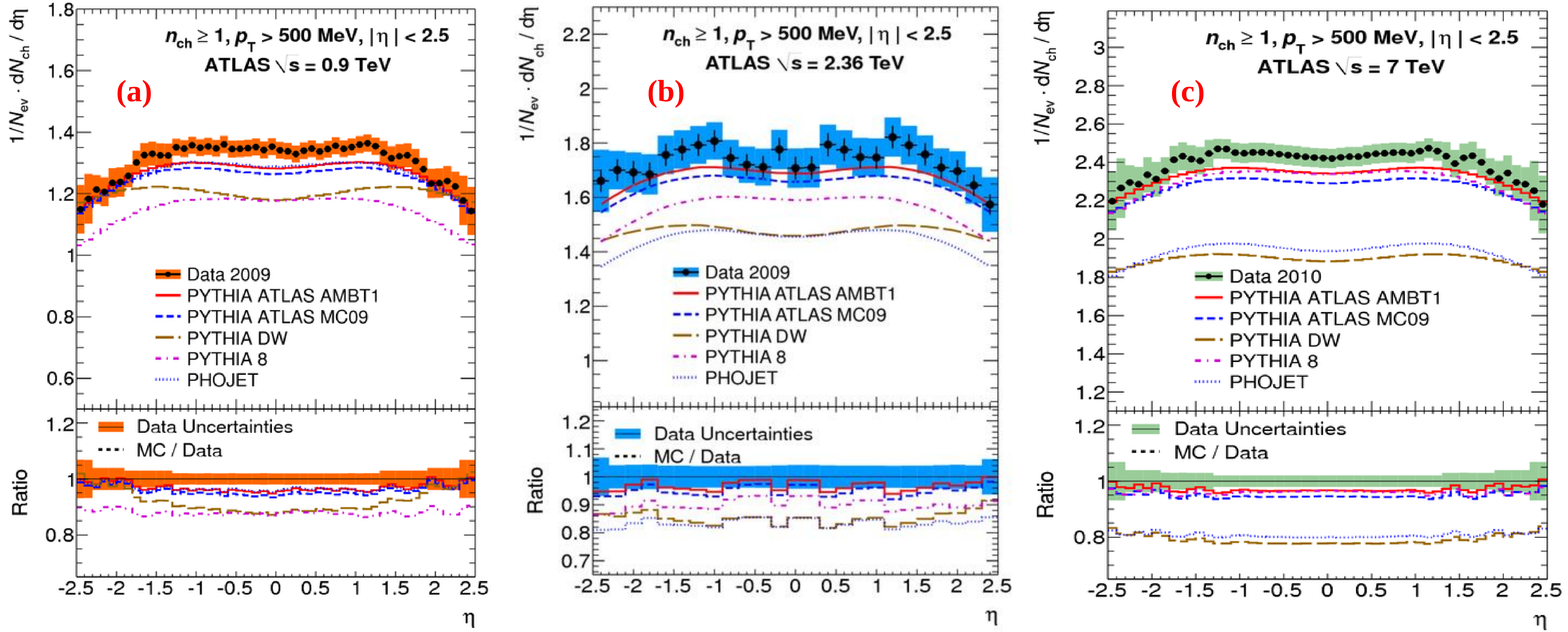
ATLAS EXPERIMENT

The dominant uncertainty is due to material effects on the track reconstruction efficiency. Uncertainties due to imperfect detector alignment are taken into account and are less than 5% at the highest track p_T values. Resolution effects on the transverse momentum can result in low-p_T particles being reconstructed as high-p_T tracks. The track background uncertainty is dominated by systematic effects in the estimation of the contribution from secondary particles. The non-closure systematic uncertainty is estimated from differences in the unfolding results using PYTHIA 8 A2 and EPOS simulations.

Distribution	$\frac{1}{N_{ev}} \cdot \frac{dN_{ch}}{d\|\eta\|}$	$\frac{1}{N_{ev}} \cdot \frac{1}{2\pi p_T} \cdot \frac{d^2 N_{ch}}{d\eta d p_T}$	$\frac{1}{N_{ev}} \cdot \frac{dN_{ev}}{dn_{ch}}$	$\langle p_T \rangle$ vs. n_{ch}
Range	0–2.5	0.1–50 GeV	2–250	0–160 GeV
Track reconstruction	1 %–7 %	1 %–6 %	0 %–$^{+38\,\%}_{-20\,\%}$	0 %–0.7 %
Track background	0.5 %	0.5 %–1 %	0 %–$^{+7\,\%}_{-1\,\%}$	0 %–0.1 %
p_T spectrum	–	–	0 %–$^{+3\,\%}_{-9\,\%}$	0 %–$^{+0.3\,\%}_{-0.1\,\%}$
Non-closure	0.4 %–1 %	1 %–3 %	0 %–4 %	0.5 %–2 %

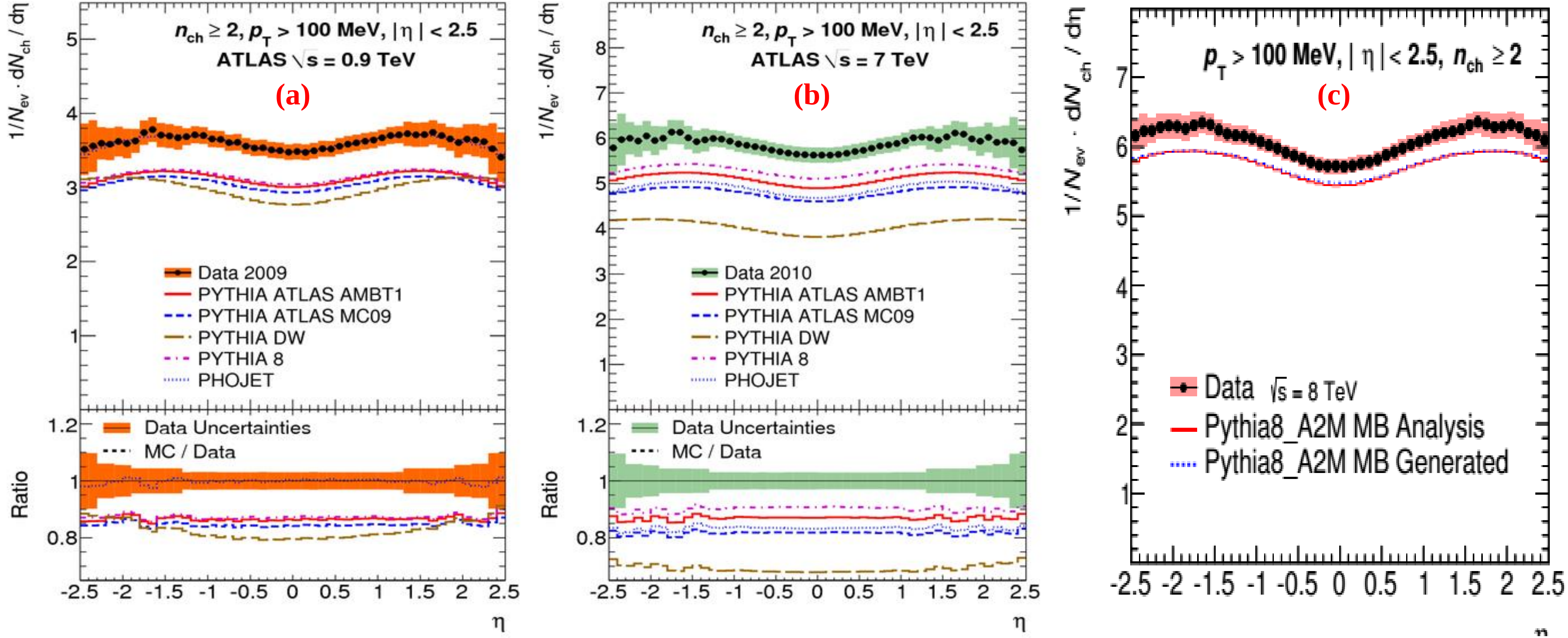
Summary of the systematic uncertainties in the η, p_T, n_{ch} and p_T vs. n_{ch} observables for p_T>100 MeV. The uncertainties are given at the minimum and the maximum of the phase space.

CHARGED-PARTICLE MULTIPLICITIES AS A FUNCTION OF η



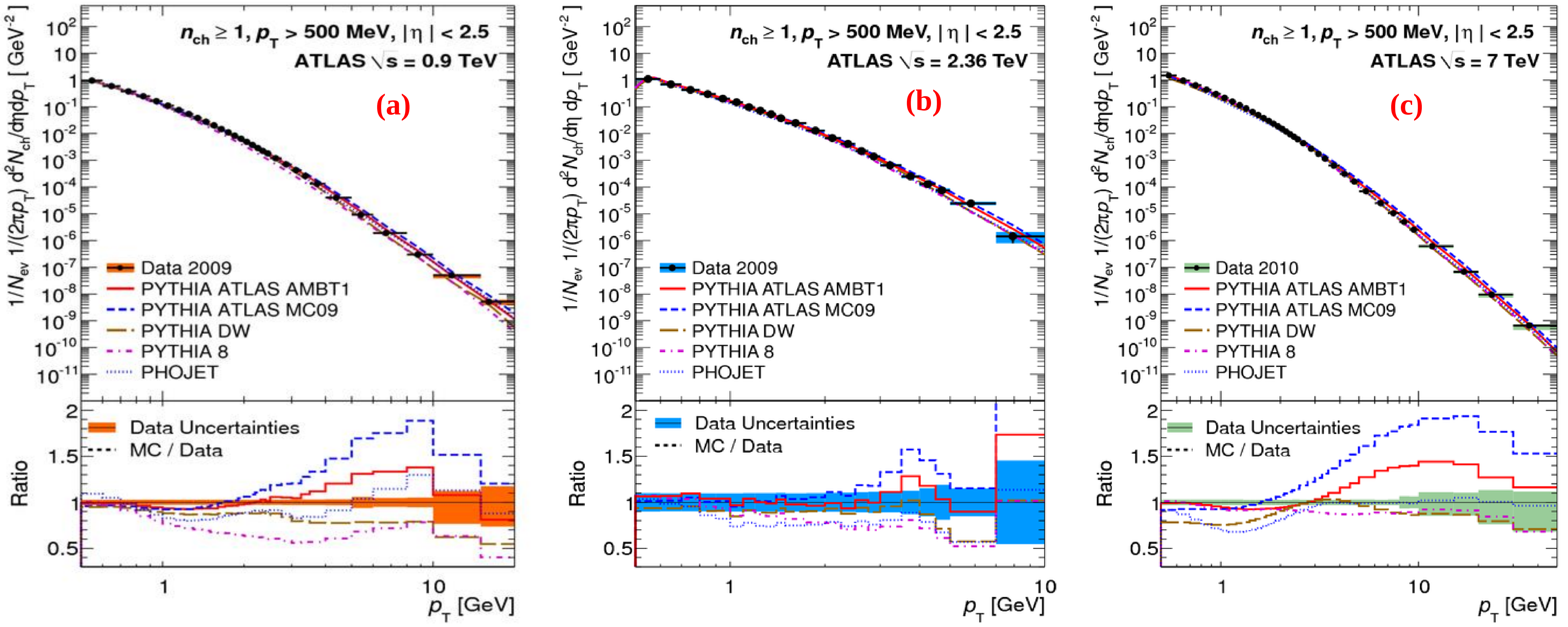
Charged-particle multiplicities as a function of the pseudorapidity for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s} = 0.9$ (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models.

CHARGED-PARTICLE MULTIPLICITIES AS A FUNCTION OF THE η II



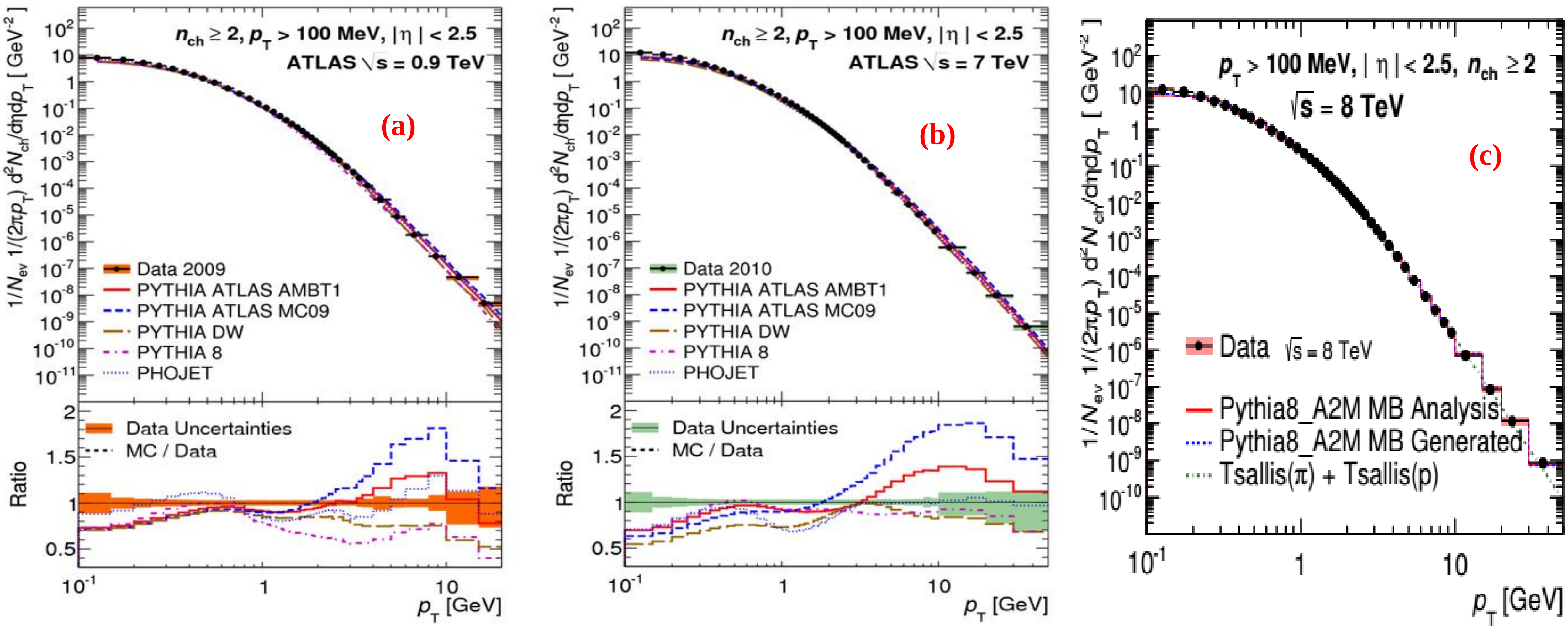
Charged-particle multiplicities as a function of the pseudorapidity for events with $n_{ch} \geq 2$, $p_T > 100$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$=0.9 (a), 7 (b) and 8 TeV (c). The dots represent the data and the curves the predictions from different MC models

CHARGED-PARTICLE MULTIPLICITIES AS A FUNCTION OF P_T



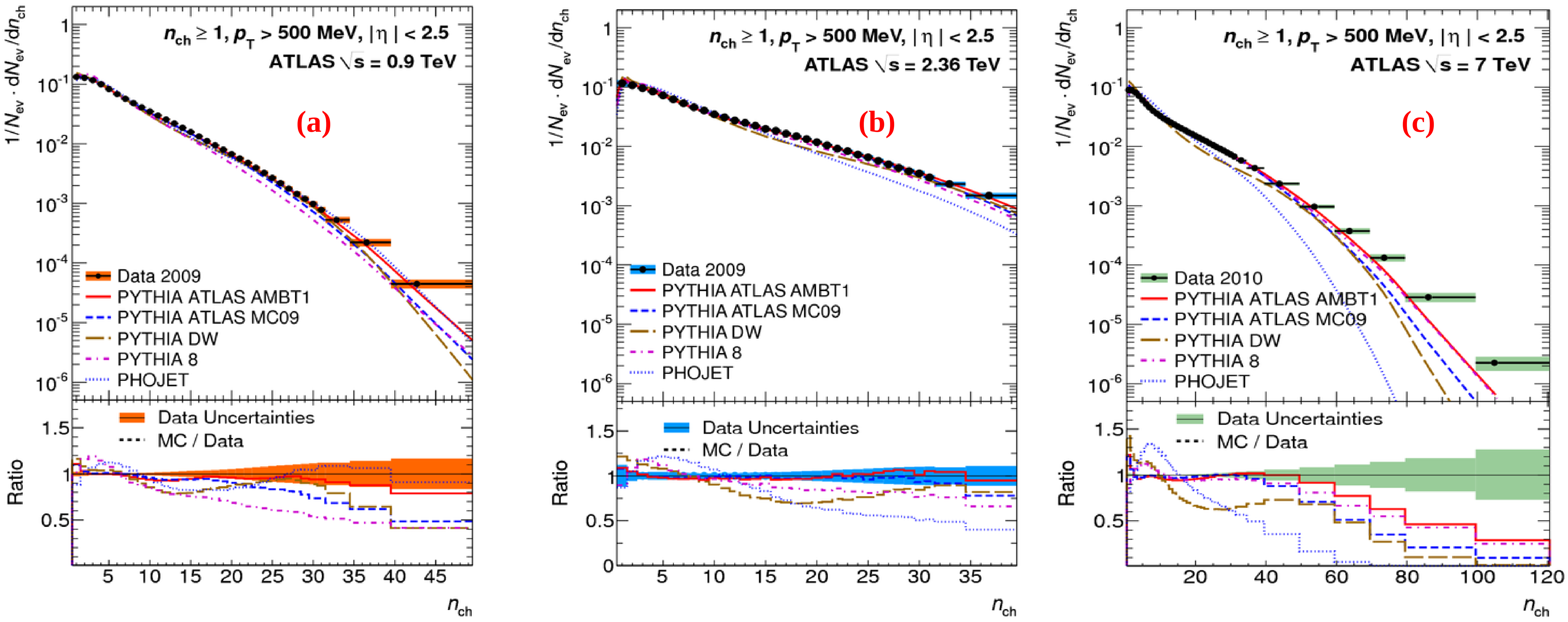
Charged-particle multiplicities as a function of the transverse momentum for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$= 0.9 (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models.

CHARGED-PARTICLE MULTIPLICITIES AS A FUNCTION OF THE P_T II



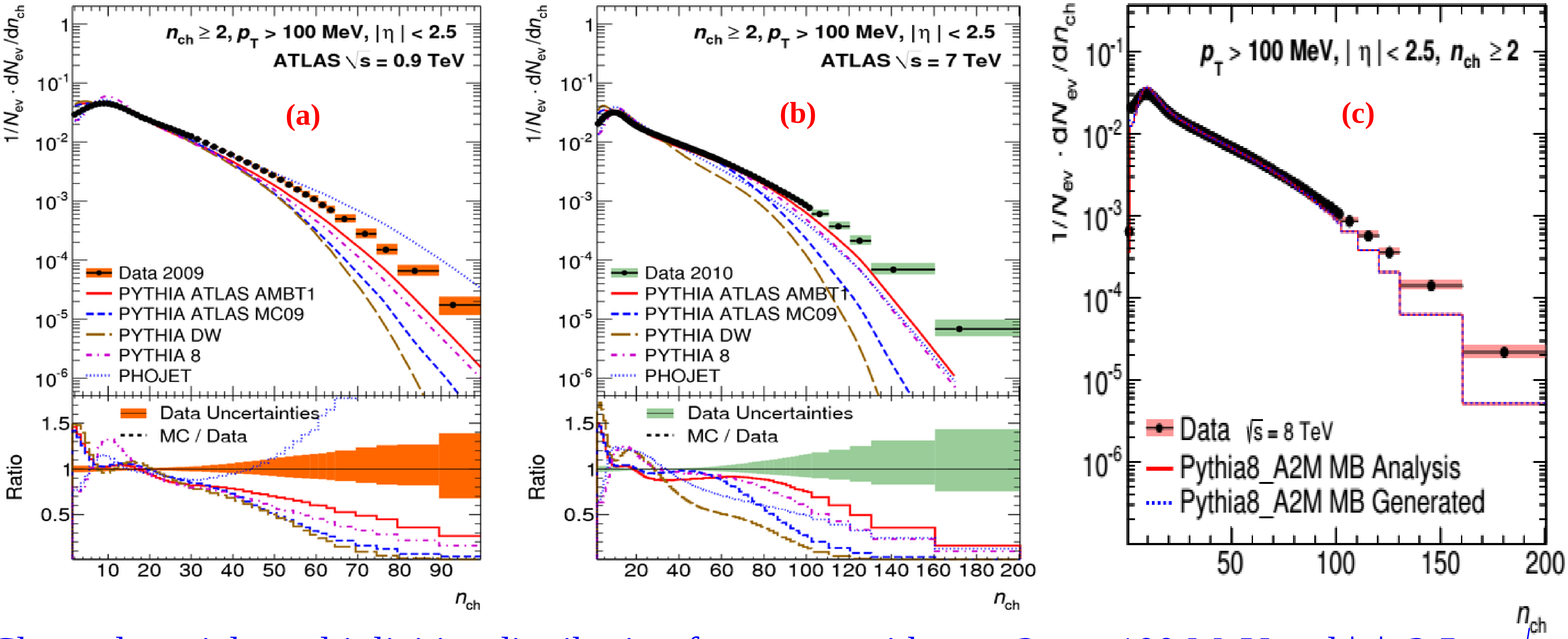
Charged-particle multiplicities as a function of the transverse momentum for events with $n_{ch} \geq 2$, p_T>100 MeV and |η|<2.5 at √s=0.9 (a), 7 (b) and 8 TeV (c). The dots represent the data and the curves the predictions from different MC models.

CHARGED-PARTICLE MULTIPLICITIES DISTRIBUTION



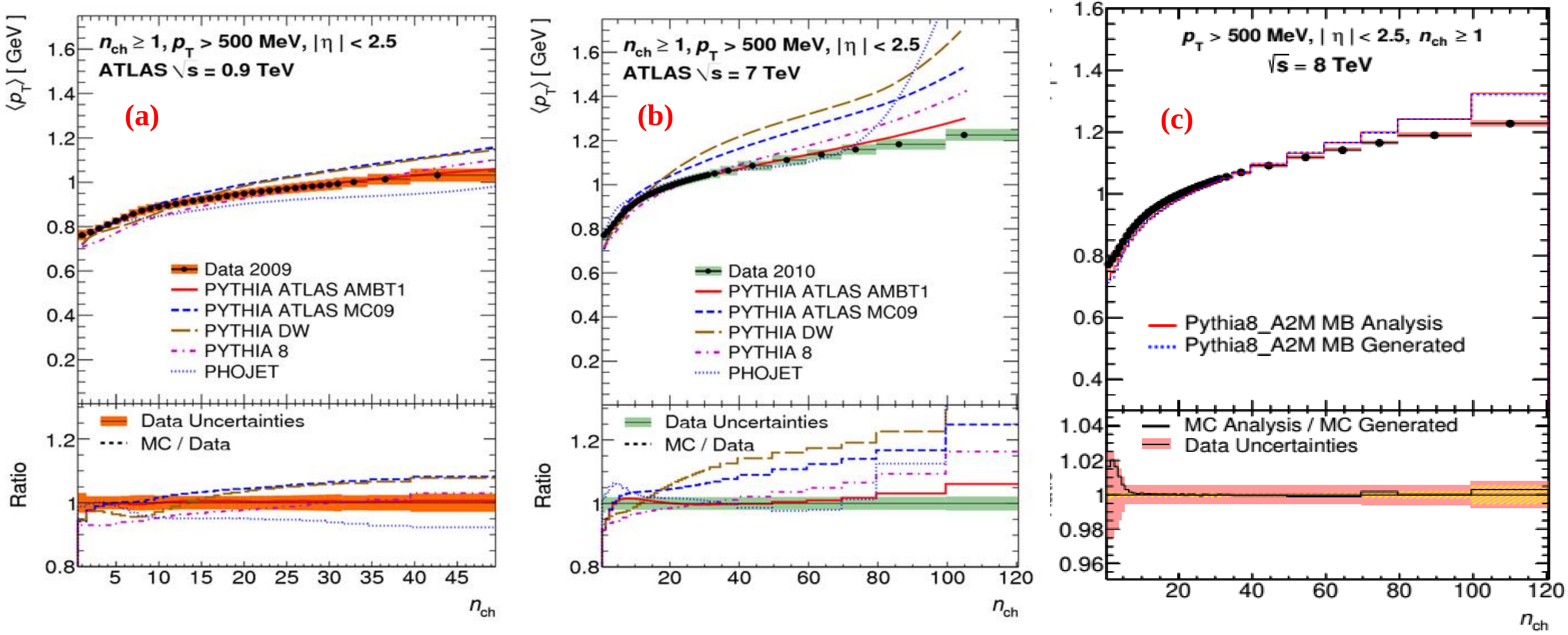
Charged-particle multiplicities distribution for events with $n_{ch} \geq 1$, p_T>500 MeV and |η|<2.5 at √s=0.9 (a), 2.36 (b) and 7 TeV (c). The dots represent the data and the curves the predictions from different MC models.

CHARGED-PARTICLE MULTIPLICITIES DISTRIBUTION II



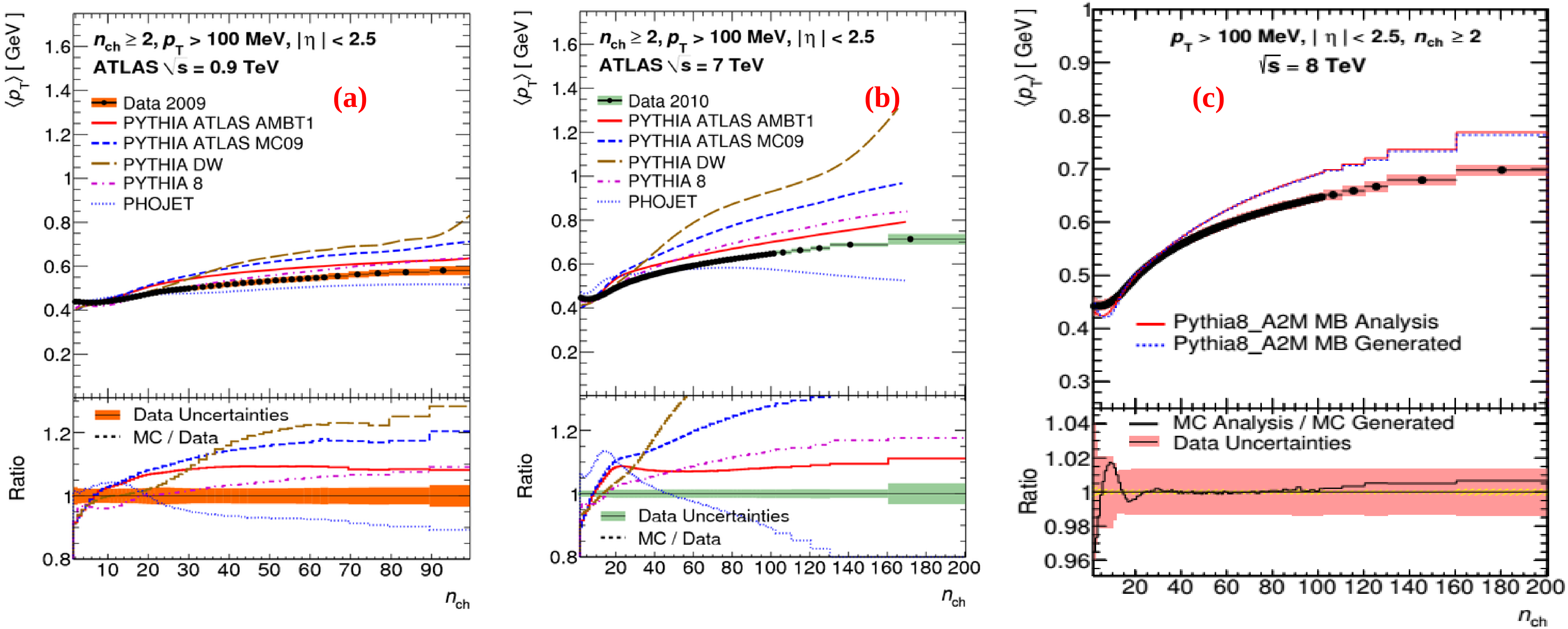
Charged-particle multiplicities distribution for events with $n_{ch} \geq 2$, $p_T > 100$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$= 0.9 (a), 7 (b) and 8 TeV (c). The dots represent the data and the curves the predictions from different MC models.

AVERAGE TRANSVERSE MOMENTUM AS A FUNCTION MULTIPLICITIES



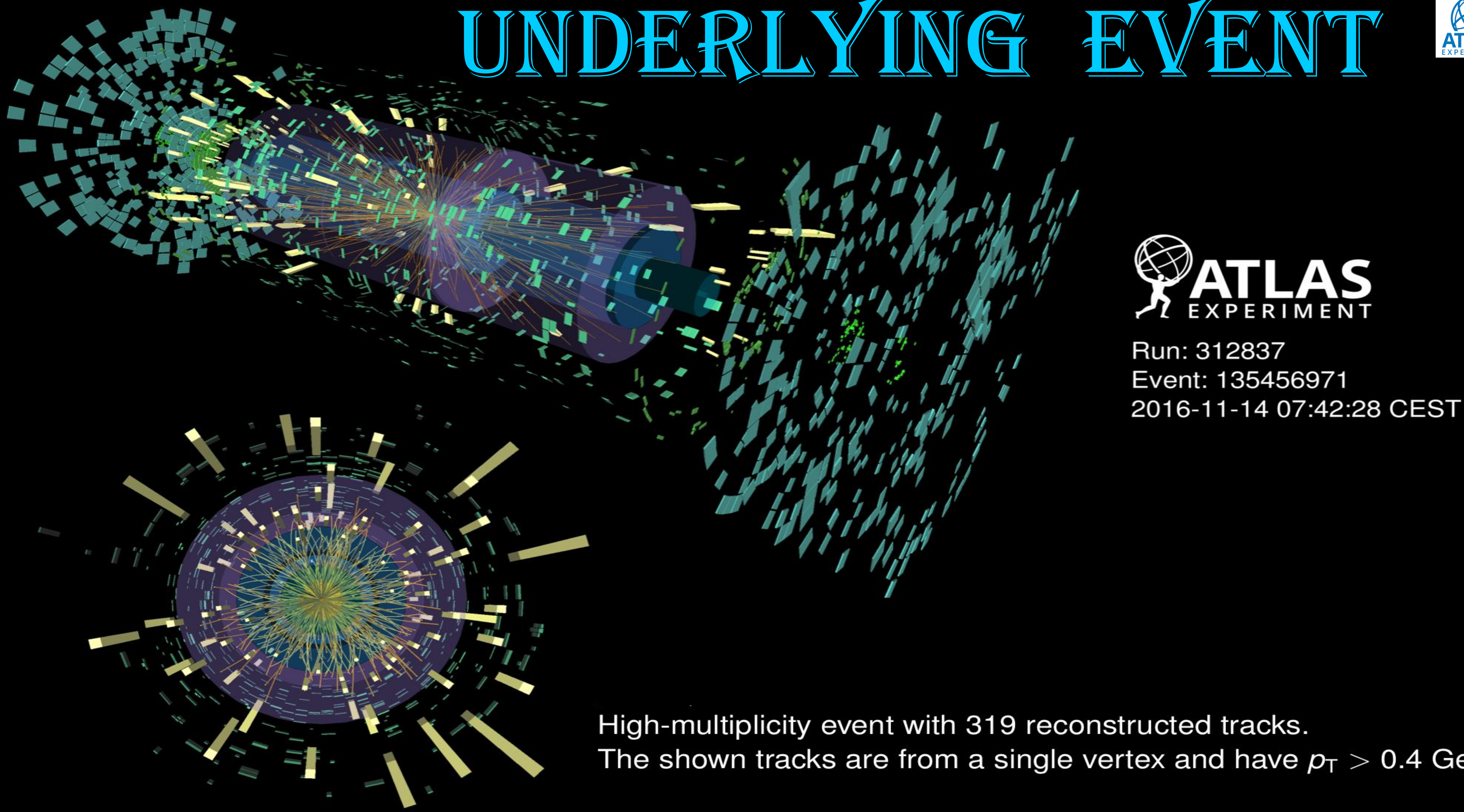
Average transverse momentum as a function of the number of charged particles in the event for events with $n_{ch} \geq 1$, $p_T > 500$ MeV and $|\eta| < 2.5$ at $\sqrt{s}$=0.9 (a), 7 (b) and 8 TeV (c). The dots represent the data and the curves the predictions from different MC models.

AVERAGE TRANSVERSE MOMENTUM AS A FUNCTION MULTIPLICITIES II



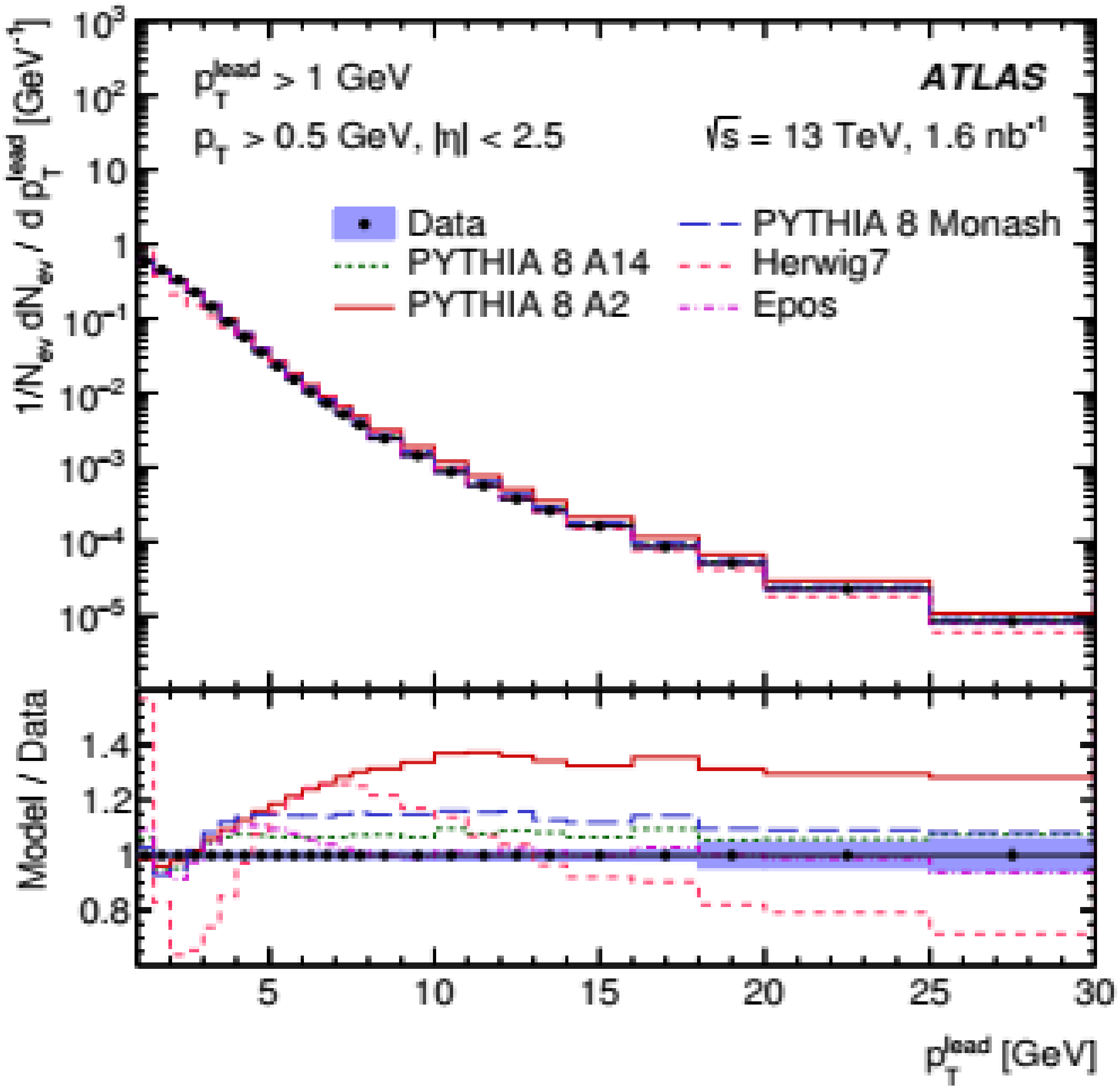
Average transverse momentum as a function of the number of charged particles in the event for events with $n_{ch} \geq 1$, p_T>100 MeV and |η|<2.5 at √s=0.9 (a), 7 (b) and 8 TeV (c). The dots represent the data and the curves the predictions from different MC models.

Underlying Event



High-multiplicity event with 319 reconstructed tracks.
The shown tracks are from a single vertex and have $p_{\mathrm{T}} > 0.4$ GeV

LEADING CHARGED-PARTICLE p_T^{lead}



- This is a steeply falling distribution, with a change of slope for p_T^{lead}>5 GeV: a form which is broadly modelled by all generators.
- The **Pythia 8 A14** and **Monash** tunes, as well as **Epos**, model the distribution within 15% out to p_T^{lead} =30 GeV, while the **Pythia 8 A2** minimum-bias tune predicts too hard a spectrum in the high p_T^{lead} tail. **Herwig 7** peaks strongly at the lowest p_T^{lead} and alternates between under- and over-shooting the data at higher scales, finally producing a softer tail than seen in data.

❖ Unit-normalised distribution of the transverse momentum of the leading charged particle, p_T^{lead}>1 GeV, compared to various generator models.

SYSTEMATIC UNCERTAINTIES

JHEP03 (2017) 157

- Several categories of systematic uncertainties that may influence the distributions after corrections and unfolding were quantified.
- The sources of uncertainty and the methods used to estimate them were the following:
- trigger and vertexing: the systematic uncertainties were found to be negligible;
- track reconstruction: the uncertainties in track reconstruction efficiency principally arise from imperfect knowledge of the material in the inner detector;
- non-primary particles: the systematic uncertainties were propagated by modification of track weights;
- Unfolding: the systematic uncertainties associated with the HBOM unfolding have two distinct sources – Non-closure and Parameterisation.

	Range of values			
Observable	Material	Non-primaries	Non-closure	Parameterisation
N_{ch} or $\sum p_{\mathrm{T}}$ vs. $\Delta\phi$	0.9%	0.6%	0–0.6%	0–0.4%
N_{ch} or $\sum p_{\mathrm{T}}$ vs. $p_{\mathrm{T}}^{\mathrm{lead}}$	0.5–1.0%	0.3–0.6%	0–2.5%	0–0.4%
$\langle \mathrm{mean}\ p_{\mathrm{T}} \rangle$ vs. N_{ch}	0–0.5%	0–0.5%	— 0.5% (combined) —	
$\langle \mathrm{mean}\ p_{\mathrm{T}} \rangle$ vs. $p_{\mathrm{T}}^{\mathrm{lead}}$	0–0.4%	0–0.3%	— 0.5% (combined) —	

Summary of systematic uncertainties for each class of UE observable, broken down by origin.

AVERAGE TRACK MULTIPLICITY & P_T SUM VS $|\Delta\phi|$

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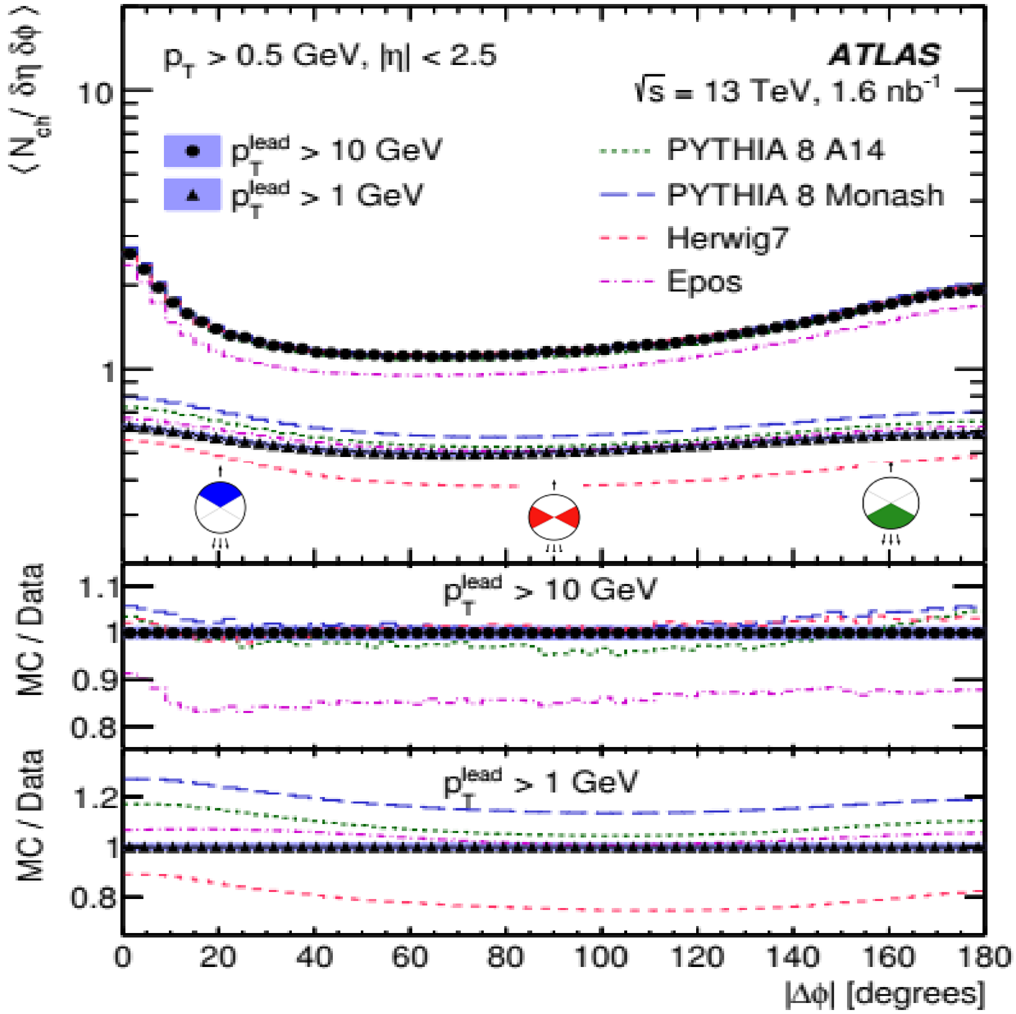

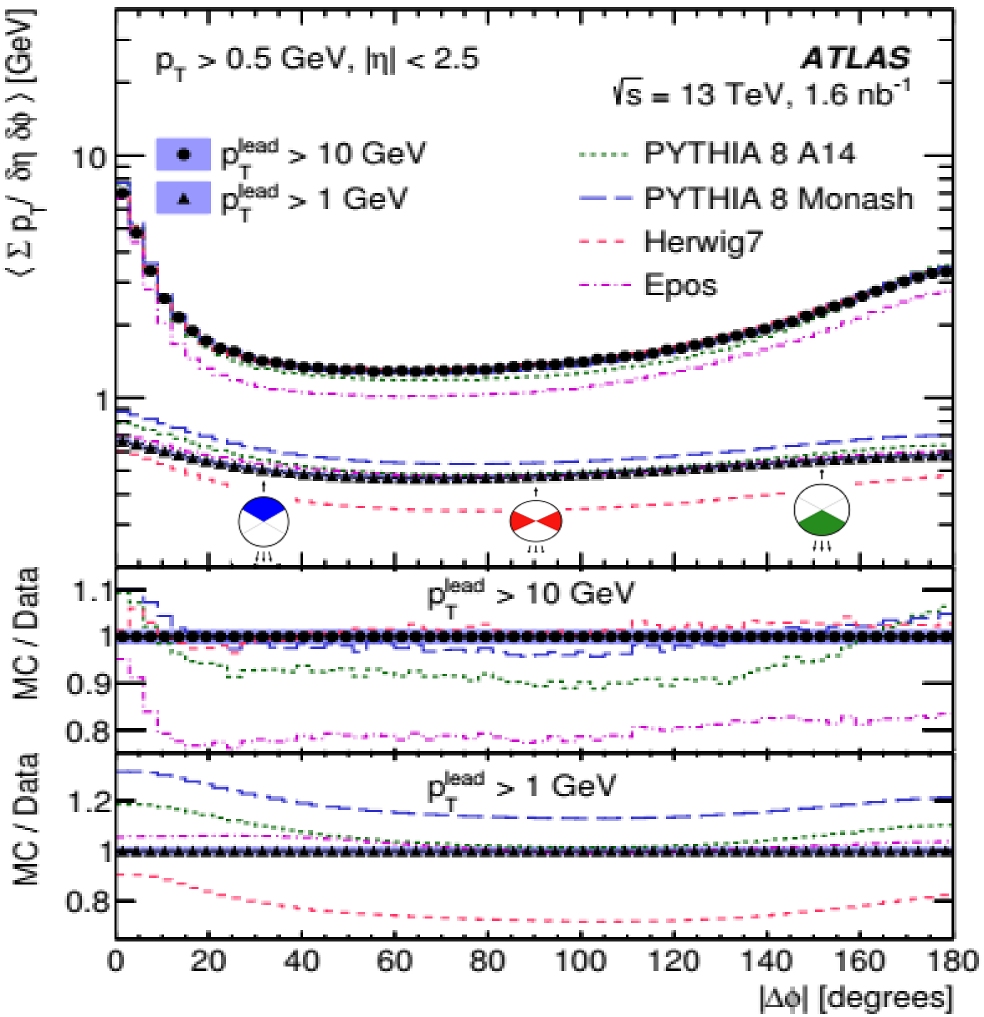

Comparison of particle level data and MC predictions for the $|\Delta\phi|$ (with respect to the leading charged particle) distributions of average track multiplicity density (left) and average scalar p_T sum density of tracks (right) for p_T^{lead} >1 GeV and p_T^{lead} >10 GeV, with comparisons to MC.

- For p_T^{lead} **>1 GeV:** **Epos** performs best, **Pythia 8 A14 & Herwig 7** significantly undershoots; **Monash** is above the data
- For p_T^{lead} **>10 GeV**: **Herwig 7 & Monash** perform best, with a slight undershoot from **Pythia 8 A14 &** a large one from **Epos**

Distributions of average track multiplicity vs P_T^{LEAD}: trans-max region

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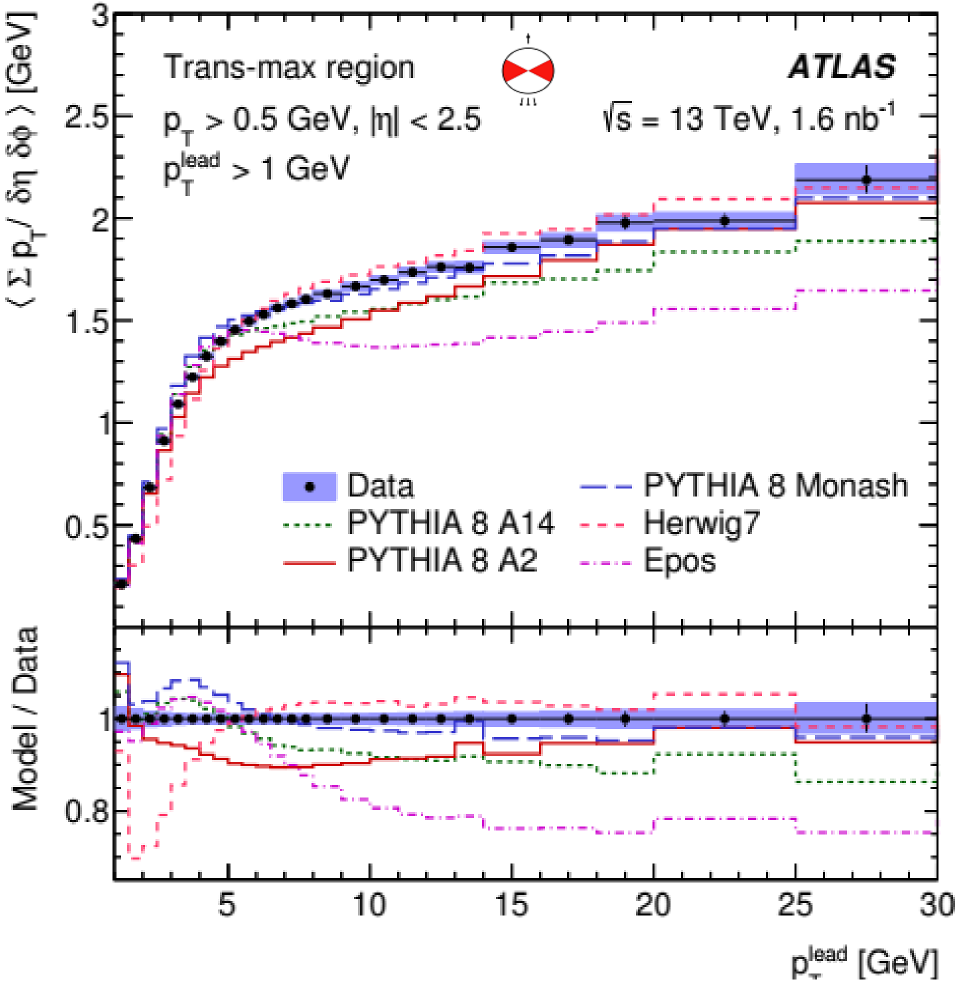
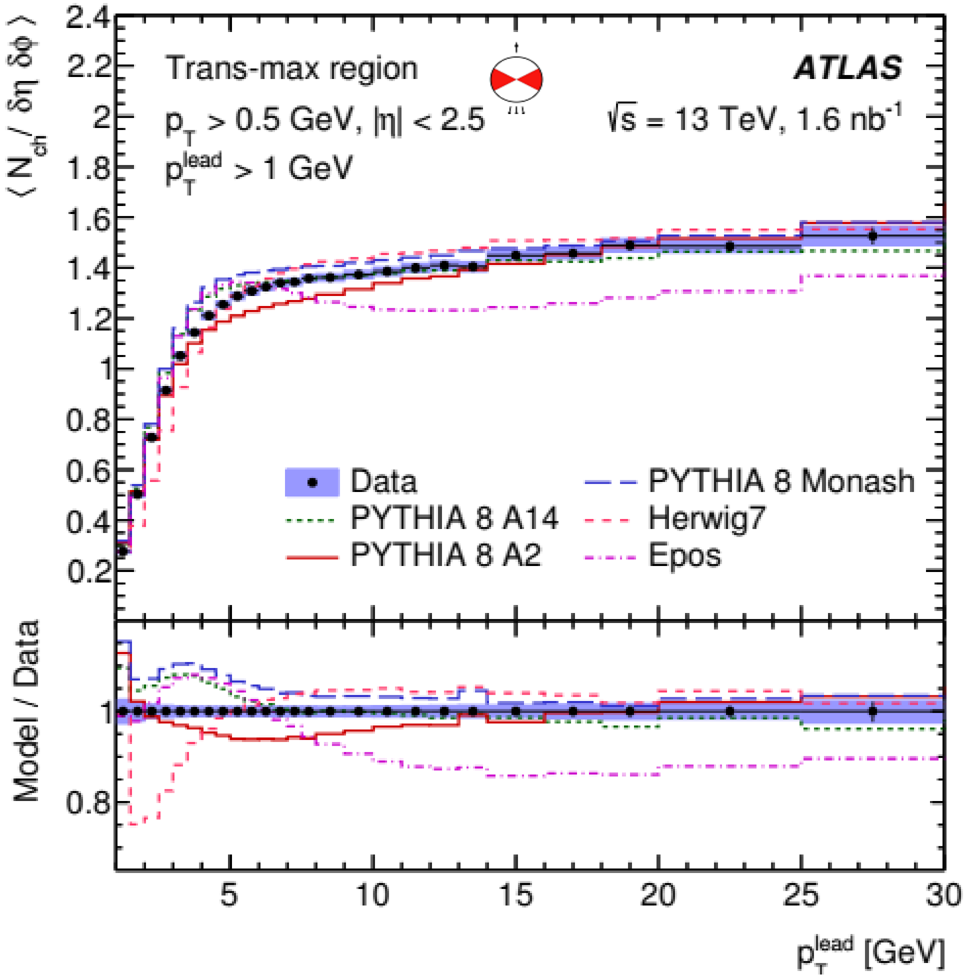


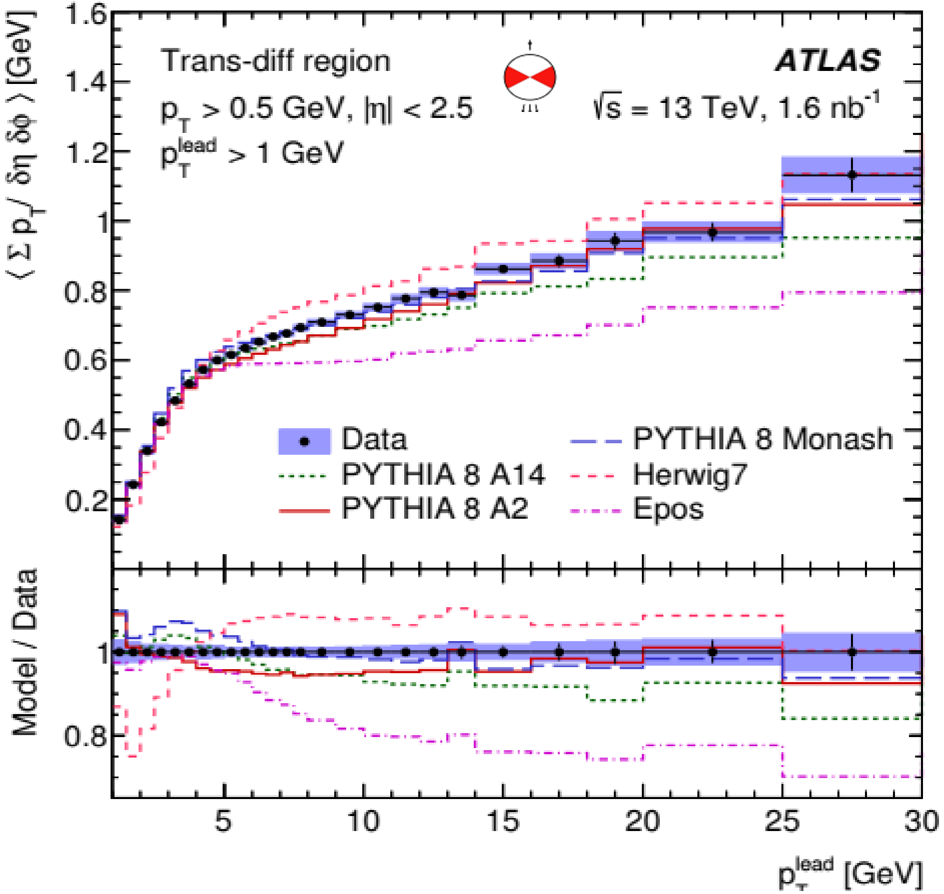


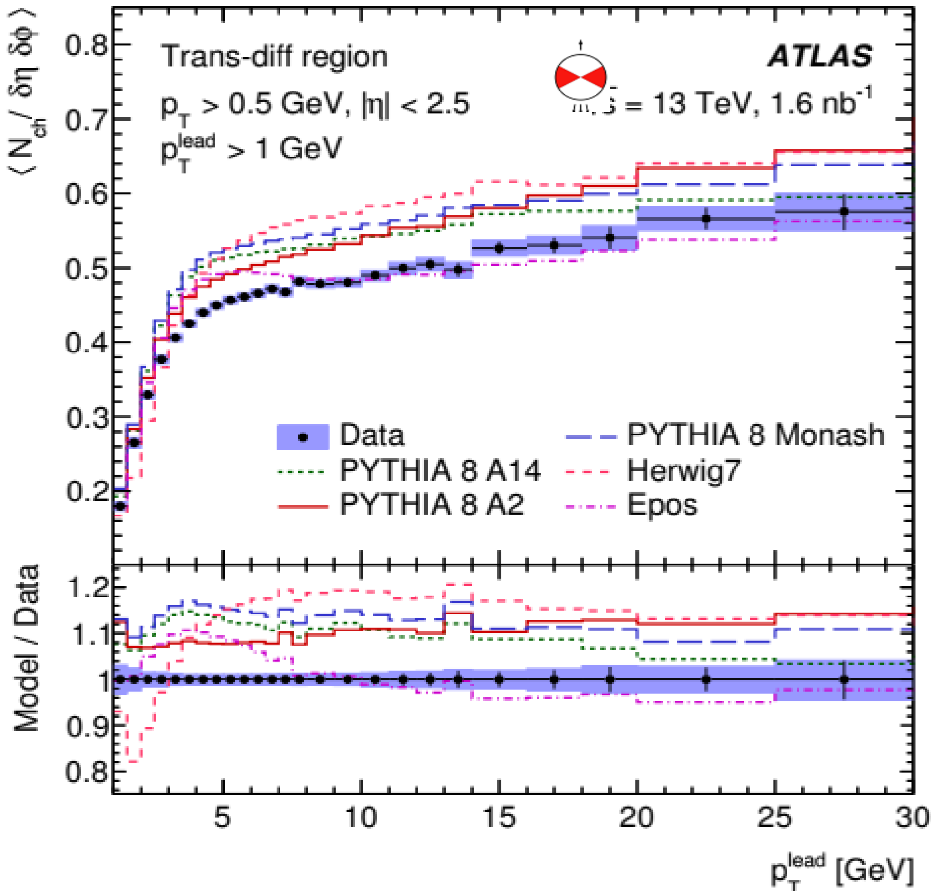
- Mean densities of charged-particle multiplicity N_{ch} (right) and Σp_T (left) as a function of leading charged-particle $\mathbf{p_T^{lead}}$
- Focuses on the UE-dominated transverse region, and its per-event specialisations trans-min, -max & -diff
  - The trans-max includes both MPI and hard-process contaminations

- The predictions cluster together more tightly in the process-inclusive trans-max region , with all generators other than Epos providing a description of the N_{ch} density data within a few percent for $p_T^{lead} \geq 10$ GeV
- **Epos** continues to undershoot the data significantly
- **Pythia 8 A14** also significantly undershoots the Σp_T density data, by around 10% as compared to **Epos** 20%.

DISTRIBUTIONS OF AVERAGE TRACK MULTIPLICITY VS p_T^{lead} : TRANS-DIFF REGION

JHEP03 (2017) 157



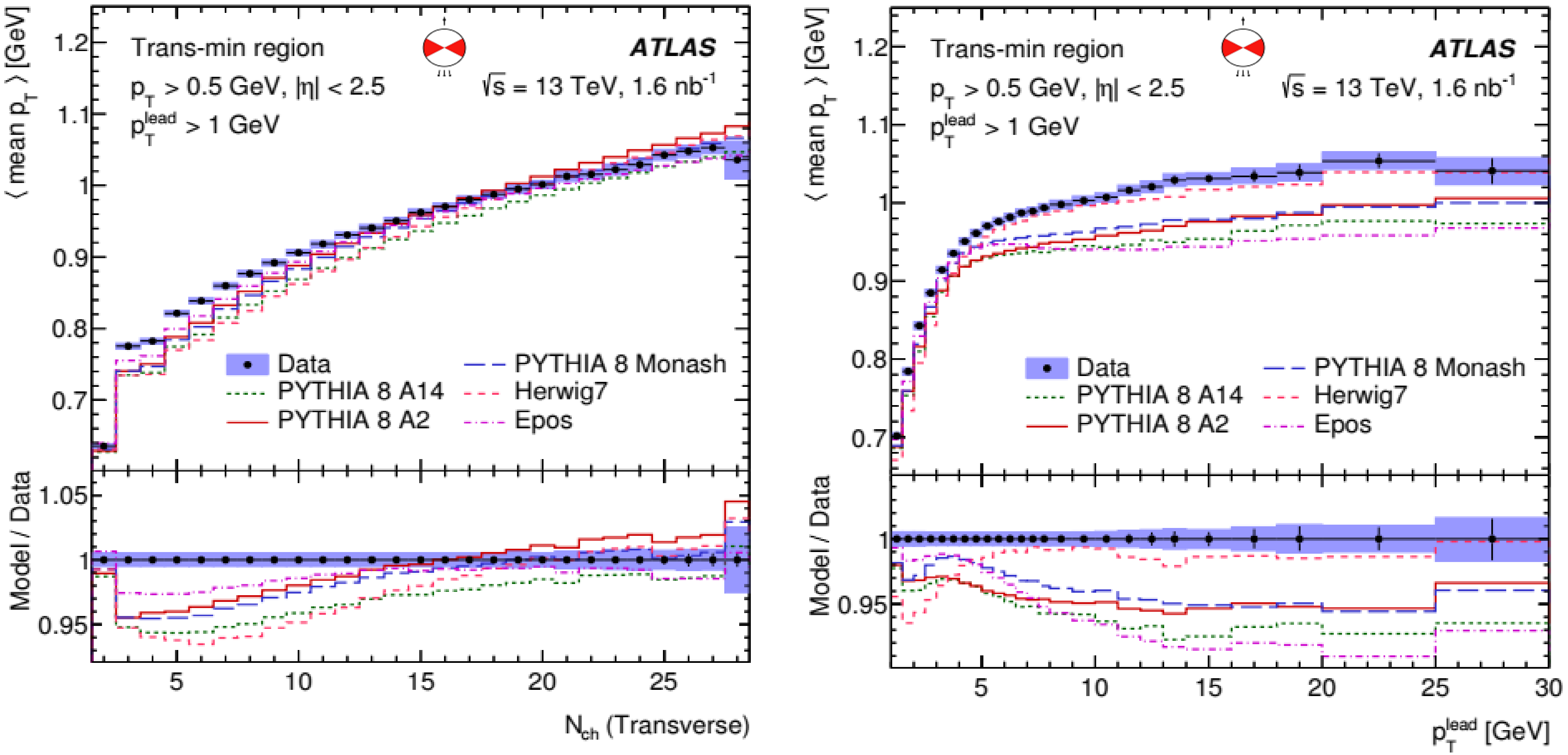


- Mean densities of charged-particle multiplicity N_{ch} and Σp_T as a function of leading charged-particle $\mathbf{p_T^{lead}}$
  - Focuses on the UE-dominated transverse region, and its per-event specialisations trans-min, -max & -diff
- The trans-diff is hence the clearest measure of those contaminations

- The trans-diff gives a clearer view of **how non-MPI contributions to the UE are modelled**, with mostly flat ~10% overshoots from all models other than **Epos** in N_{ch} density, and a spread of performance in describing the Σp_T density evolution.
- The best performance: **Pythia 8 Monash and A2** tunes; with **Herwig 7 and Pythia 8 A14** wrong by 5-10%
- **Epos** prediction is again separated from the ATLAS data by **more than 20%**
- **There is no obvious best model for all observables**

AVERAGE p_T VS N_{CH} OR p_T^{LEAD} : TRANS-MIN REGION

JHEP03 (2017) 157

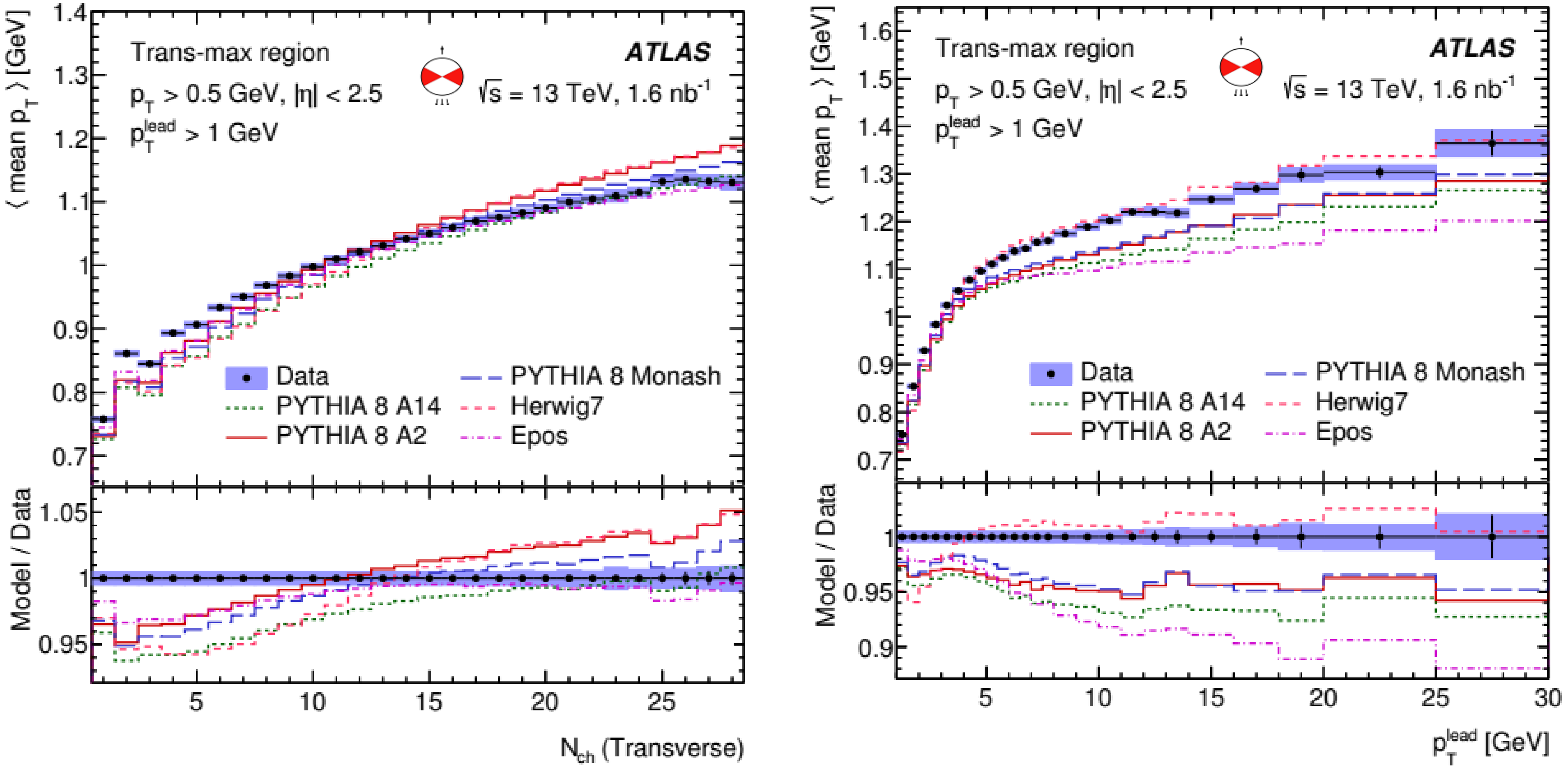


Mean charged-particle average transverse momentum as a function of charged-particle multiplicity in transverse region N_{ch} and as a function of p_T^{lead}

- The **Monash** tune is the best performing **Pythia 8** configuration, with a performance like that of **Epos**, while **Pythia 8 A14** undershoots in the low-multiplicity events and **Pythia 8 A2** overshoots at high-multiplicities – notably the regions not included in each tune's construction.

AVERAGE p_T VS N_{CH} OR p_T^{LEAD} : TRANS-MAX REGION

JHEP03 (2017) 157

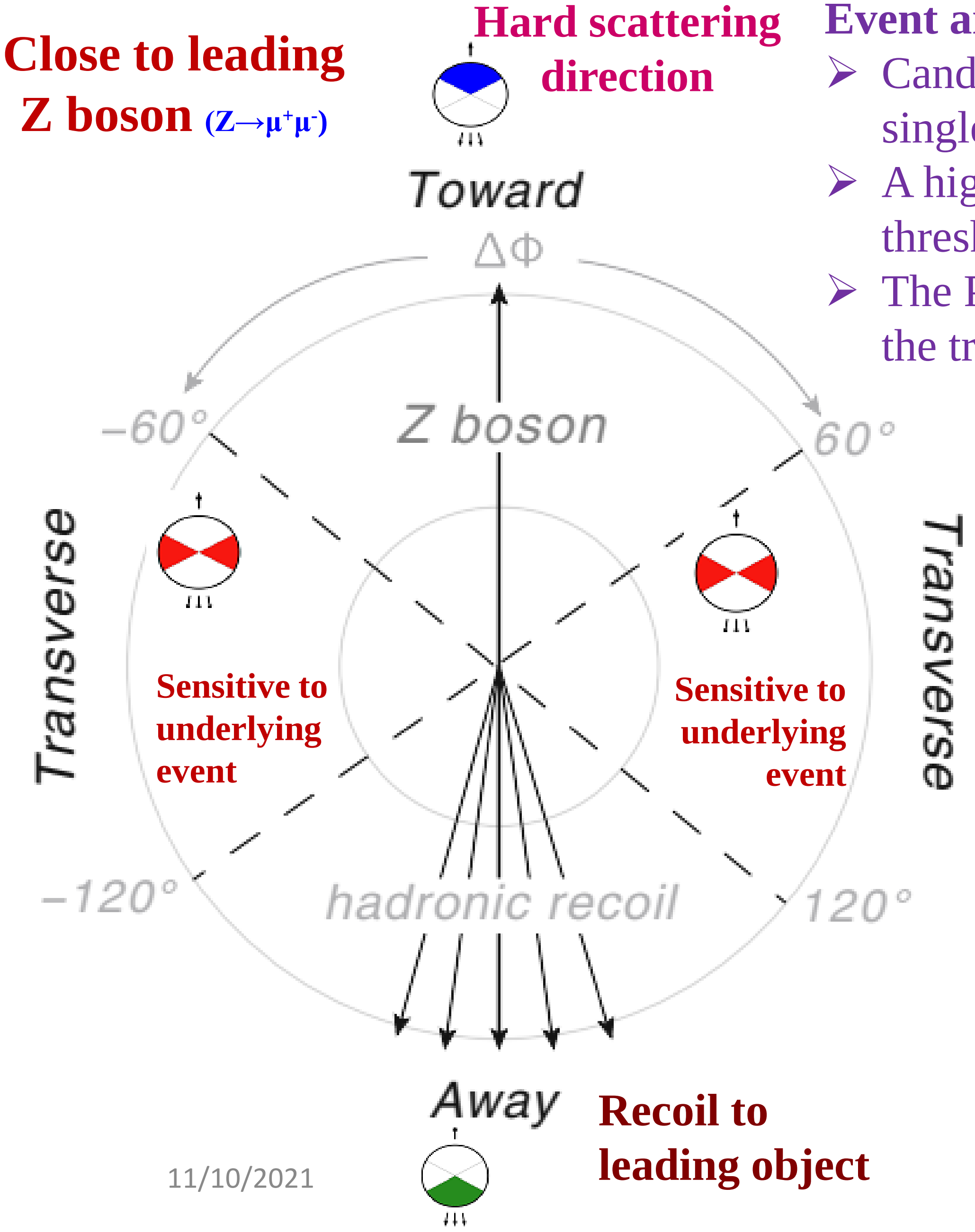


Mean charged-particle average transverse momentum as a function of charged-particle multiplicity in transverse region N_{ch} and as a function of p_T^{lead}

- Herwig 7 shows the largest variations, from a ~7% undershoot at low N_{ch} to a 5% overshoot at $N_{ch} \approx 30$.

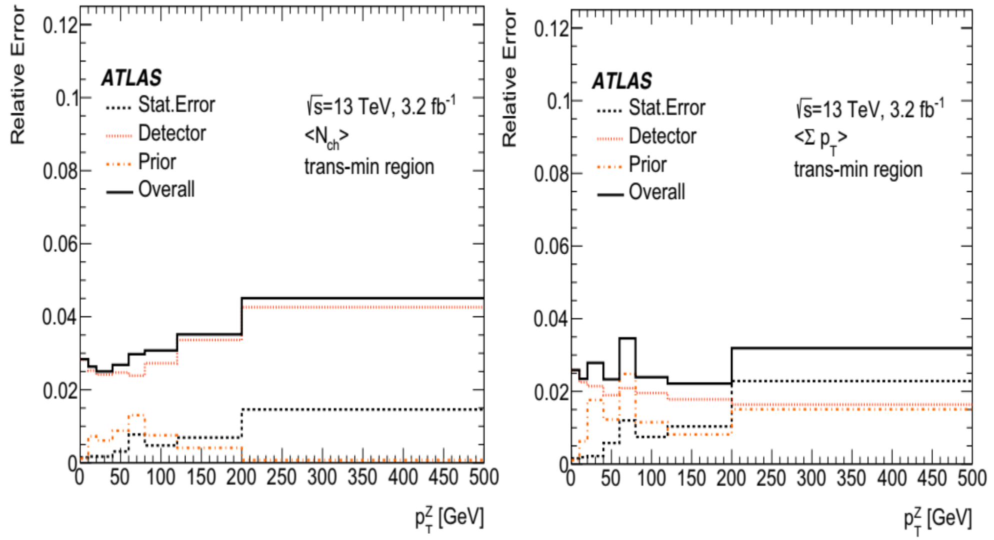
Underlying event in inclusive Z boson production

Eur. Phys. J. C (2019) 79:666



Event and track selection:

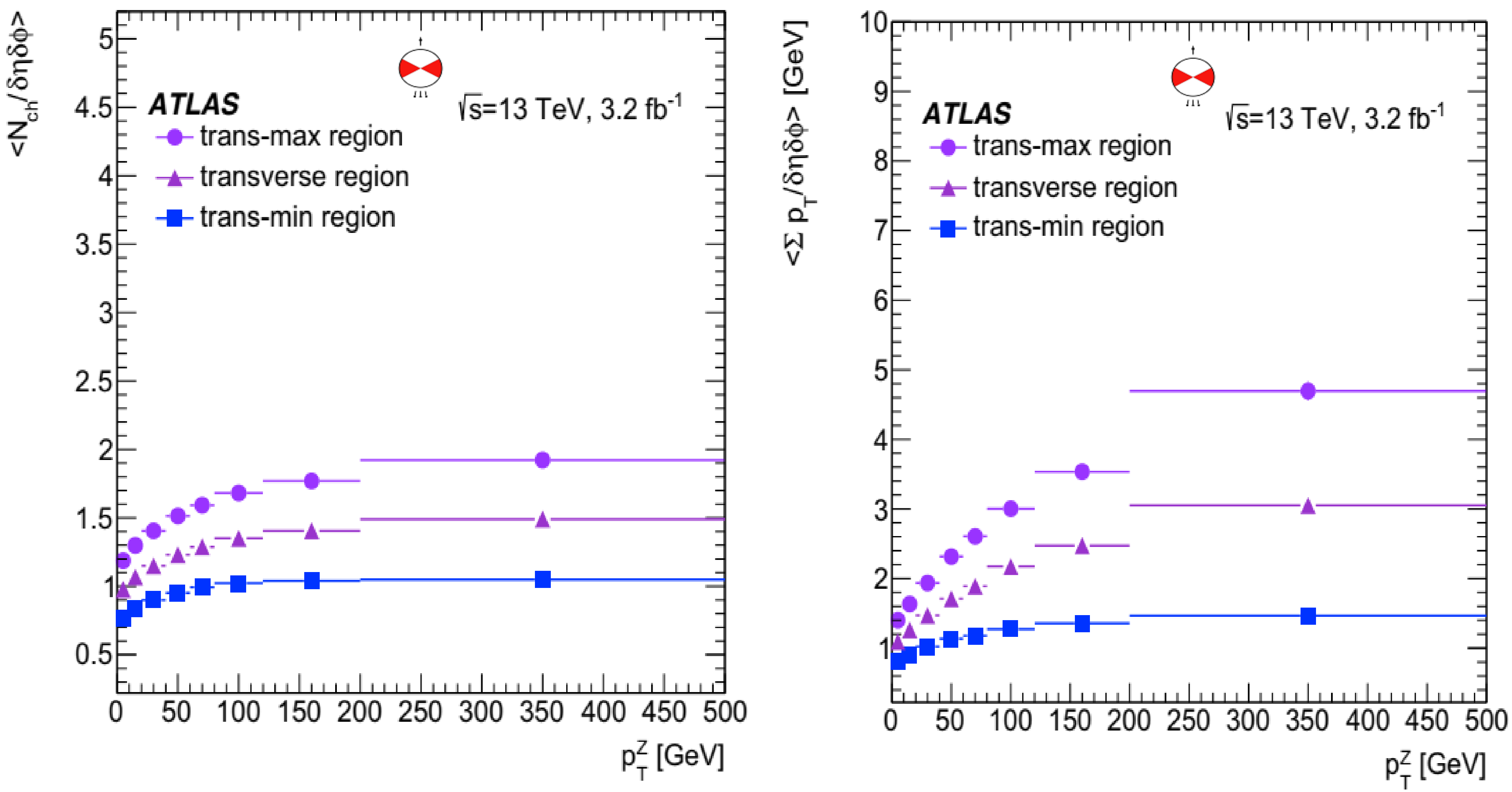
- Candidate Z→μμ events are selected by requiring that at least one out of two single-muon triggers be satisfied
- A high-threshold trigger requires a muon to have p_T>40 GeV, whilst a low-threshold trigger requires p_T>20 GeV and the muon to be isolated.
- The PV is defined as the reconstructed vertex in the event with the highest ΣpT of the tracks, consistent with the BS position and with at >1 tracks with p_T>400 MeV



A summary of the systematic uncertainties in the arithmetic mean of the N_{ch} and p_T spectra in the trans-min region as a function of p_T^Z

The fiducial volume definition of the measurement, the particle-level definition. The selection criteria for the signal muons limited by the detector geometry, the cut on the dimuon invariant mass m^{ll} yields a low background contamination.

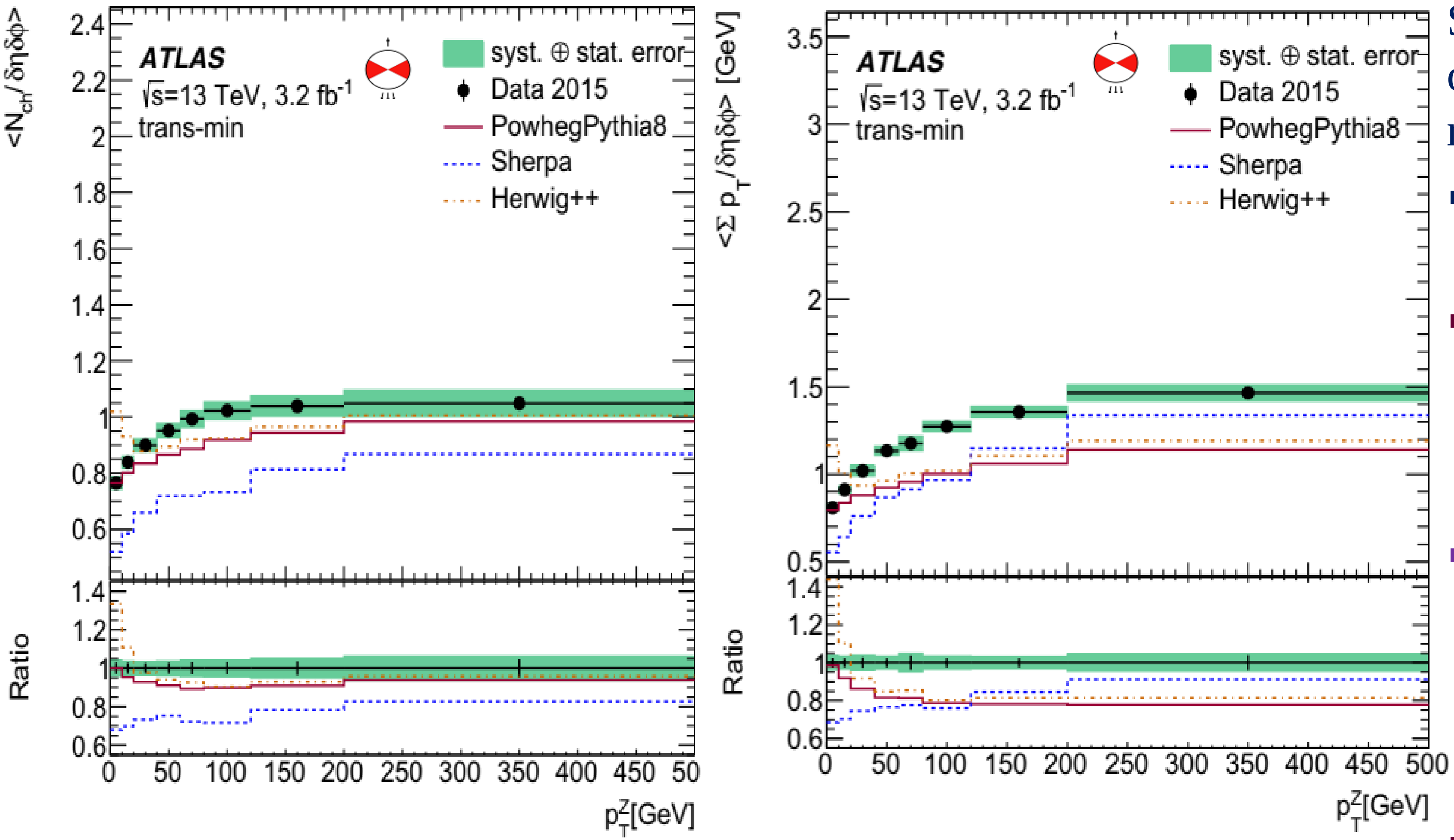
Fiducial volume (for muon selection)	$p_T^{\mu} > 25$ GeV, $\|\eta\| < 2.4$, 66 GeV $< m^{\mu\mu} < 116$ GeV
Particle-level definition	$p_T > 0.5$ GeV, $\|\eta\| < 2.5$, charge $\neq 0$, stable (i.e. a proper lifetime of $c\tau > 10$ mm)



- In the trans-min region, the UE sensitive variables N_{ch} and p_T rise slowly with increasing Z boson transverse momentum.
- The observables in the trans-max region have a strong dependence on p_T^Z because it is heavily contaminated with the Z boson hadronic recoil leaking into the transverse region.

The mean number of charged particles and the mean of the scalar sum of the transverse momentum of those particles per unit η–φ space as a function of p_T^Z in the **full transverse region** and for the **trans-min and trans-max regions** inclusively in $T_\perp$

UNDERLYING EVENT IN Z BOSON: TRANS-MIN REGION



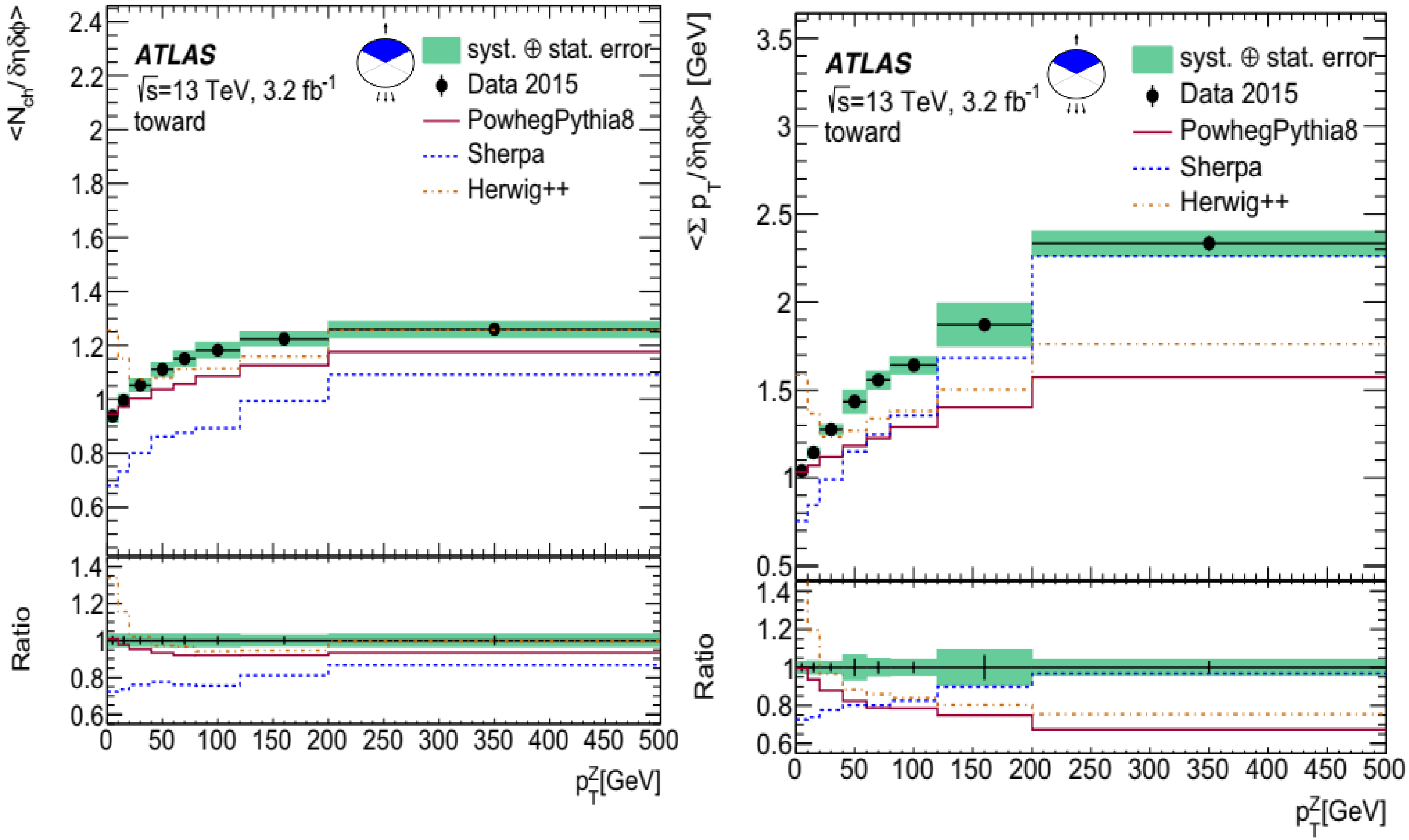
Show comparisons with the predictions of MC for the trans-min and towards regions inclusively in *T*⊥.

- The predictions fail to describe the data in either of the regimes.
- For p_T^Z>20 GeV, **Herwig++** predicts a slower rise in UE activity with rising p_T^Z than in the measured distributions.
- **Powheg+Pythia, Sherpa** qualitatively describe the 'turn-on' effect of the UE activity, i.e. a steeper slope at low p_T^Z which vanishes at higher values of p_T^Z .
- For **Powheg+Pythia**, the rise of the UE activity is underestimated, and hence the discrepancy with data grows with p_T^Z and stabilizes around p_T^Z =100 GeV.

- Comparison of measured arithmetic means of the N_{ch} and Σp_T as functions of p_T^Z for the trans-min region inclusively in $T_\perp$.
- Predictions of **Powheg+Pythia, Sherpa and Herwig++** are compared with the data.

UNDERLYING EVENT IN Z BOSON: TOWARDS REGION

Eur. Phys. J. C (2019) 79:666



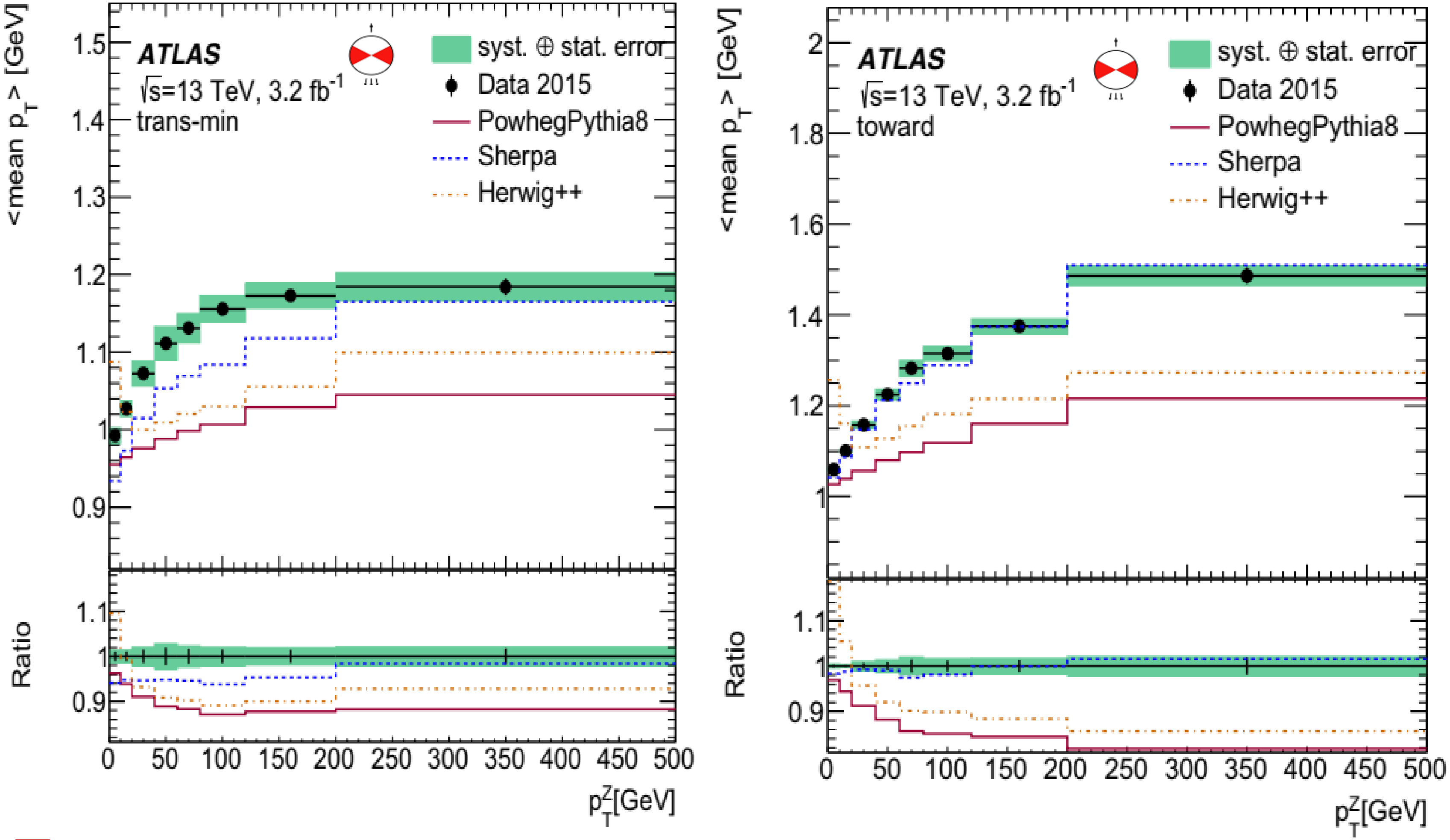
Show comparisons with the predictions of MC for the trans-min and towards regions inclusively in $T_\perp$.

- The predictions fail to describe the data in either of the regimes.
- For p_T^Z>20 GeV, **Herwig++** predicts a slower rise in UE activity with rising p_T^Z than in the measured distributions.
- **Powheg+Pythia, Sherpa** qualitatively describe the 'turn-on' effect of the UE activity, i.e. a steeper slope at low p_T^Z which vanishes at higher values of p_T^Z .
- For **Powheg+Pythia**, the rise of the UE activity is underestimated, and hence the discrepancy with data grows with p_T^Z and stabilizes around p_T^Z =100 GeV.

- Comparison of measured arithmetic means of the N_{ch} and Σp_T as functions of p_T^Z for the towards region inclusively in $T_\perp$.
- Predictions of **Powheg+Pythia**, **Sherpa** and **Herwig++** are compared with the data.

UNDERLYING EVENT IN Z BOSON: <p_T> VS p_T^Z

Eur. Phys. J. C (2019) 79:666

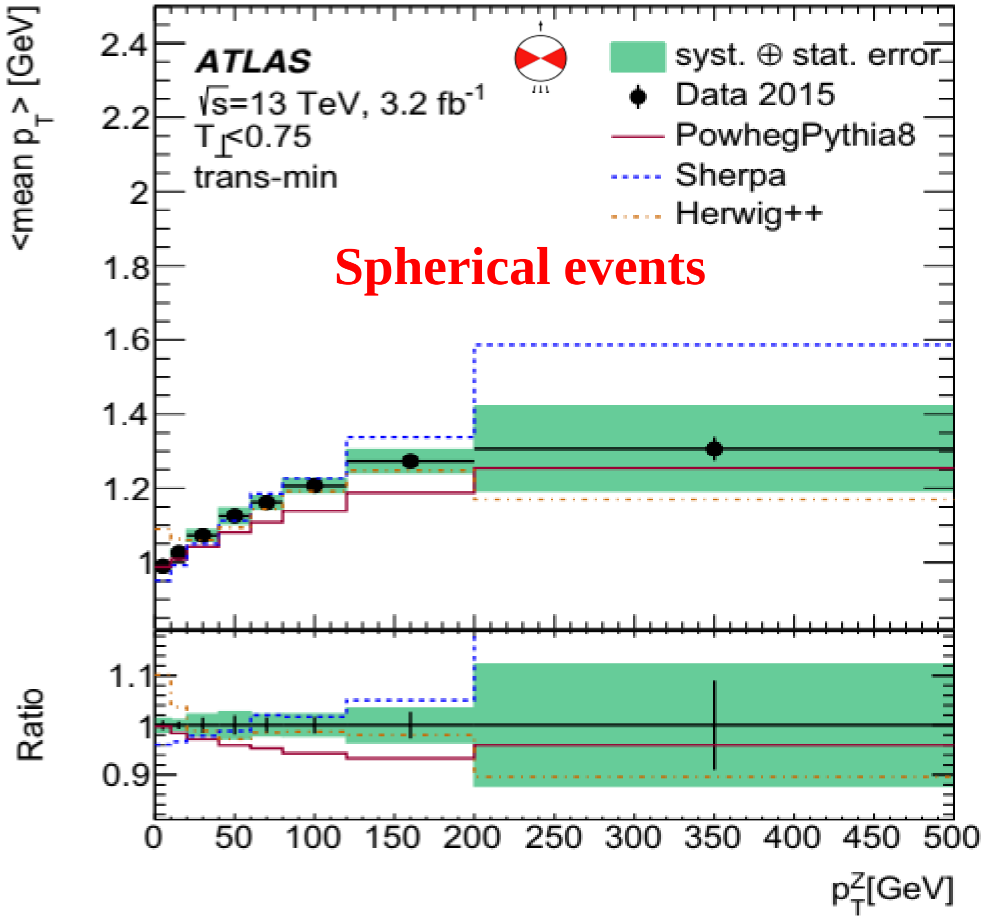


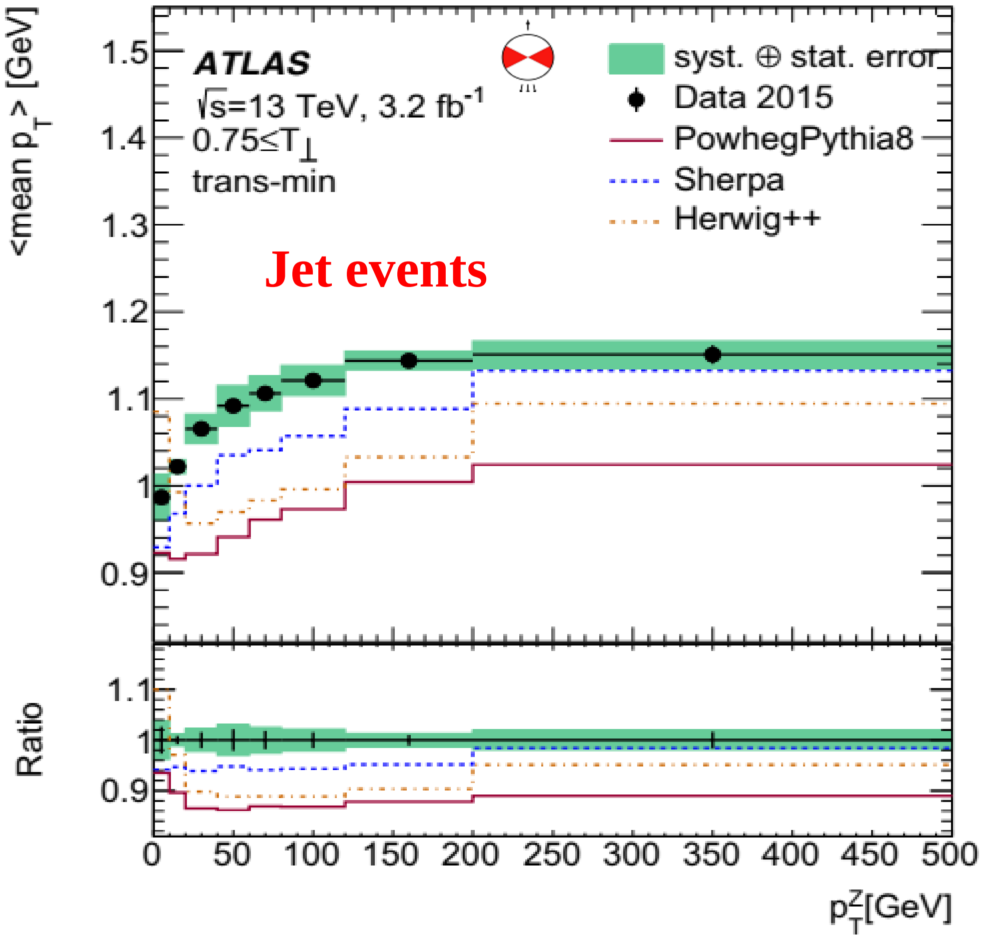
In the toward region of the mean of the mean p_T is **Sherpa** in good agreement with the data.

- Comparison of measured arithmetic means of mean p_T as functions of p_T^Z for the trans-min and towards regions inclusively, and in regions of $T_\perp$.
- Predictions of **Powheg+Pythia, Sherpa** and **Herwig++** are compared with the data.
- The ratios shown are predictions over data.

UNDERLYING EVENT IN Z BOSON & MC: <p_T> VS p_T^Z FOR RANGES OF $T_\perp$

Eur. Phys. J. C (2019) 79:666





- Comparison of measured arithmetic means of mean p_T as functions of p_T^Z for ranges of $T_\perp$ in the trans-min region.
- Predictions of Powheg+Pythia, Sherpa and Herwig++ are compared with the data.
- The ratios shown are predictions over data.

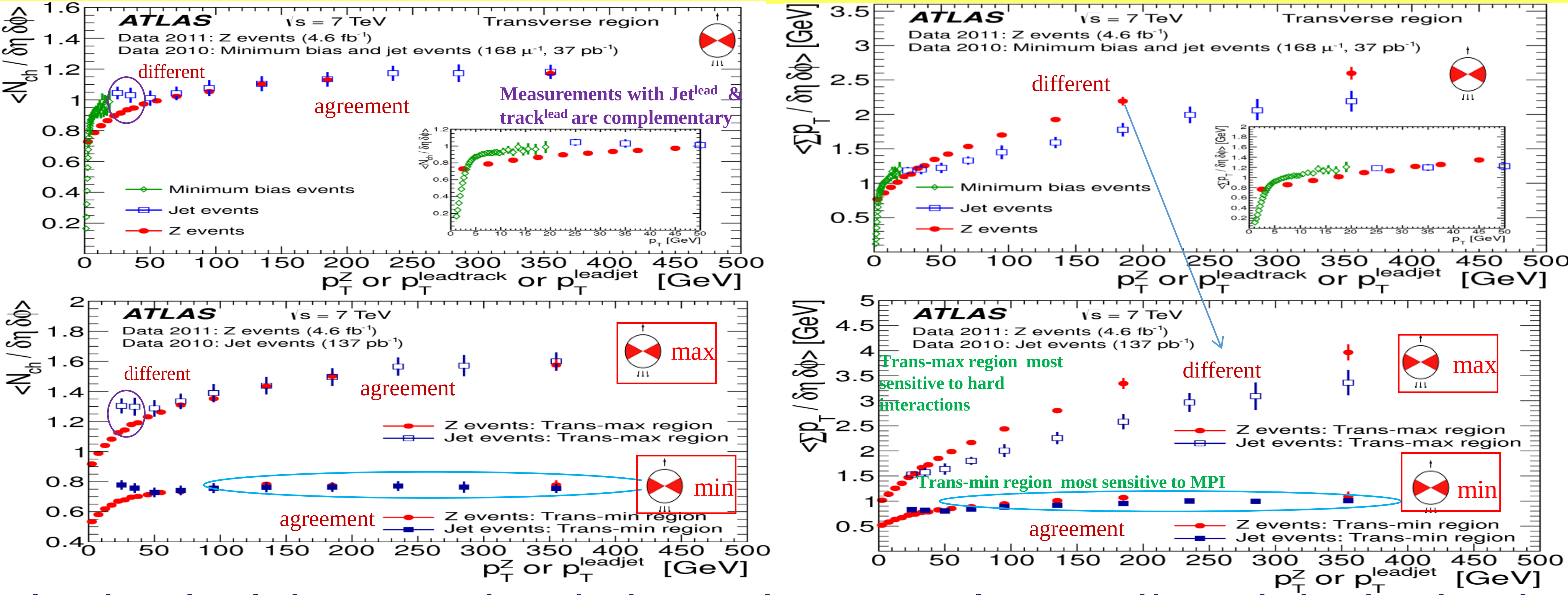
UNDERLYING EVENT: PUBLICATIONS AT 0.9 – 7 TEV

Underlying Event

- ATLAS Collaboration, *Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in pp collisions at √s=**7** TeV with the ATLAS detector; Eur. Phys. J. C 74 (2014) 3195*
- ATLAS Collaboration, *Measurement of the underlying event in jet events from √s=**7** TeV proton–proton collisions with the ATLAS detector; Eur. Phys. J. C 74 (2014) 2965*
- ATLAS Collaboration, *Underlying event characteristics and their dependence on jet size of charged-particle jet events in pp collisions at √s=**7** TeV with the ATLAS detector; Phys. Rev. D* 86 (2012) 072004
- ATLAS Collaboration, *Measurements of underlying-event properties using neutral and charged particles in pp collisions at 900 GeV and 7 TeV with the ATLAS detector at the LHC; Eur. Phys. J. C* 71 (2011) 1636
- ATLAS Collaboration, *Measurement of underlying event characteristics using charged particles in pp collisions at √s=900 GeV and 7 TeV with the ATLAS detector, Phys. Rev. D 83 (2011) 112001*

UNDERLYING EVENT: *Z AND JETS* AT 7 TEV

EPJC 74 (2014) 3195
EPJC 74 (2014) 2965

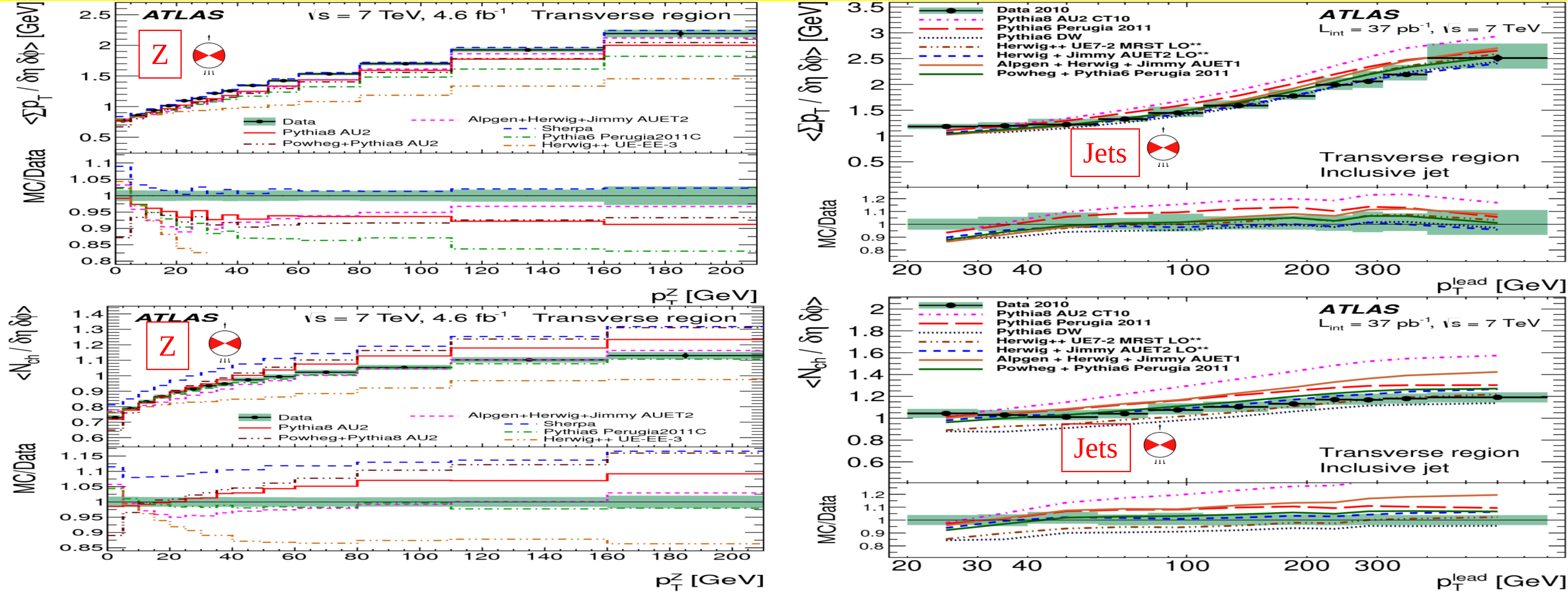


Charged particle multiplicity average values and scalar p_T sum density average values compared between leading charged particle (*MB*), leading jet and *Z* boson events, respectively as functions of leading track p_T, leading jet p_T and *Z* boson p_T.

- ► Data **are compatible** between the **different definitions**
- ► **Transition** between **leading track and jet**
- ► In the track density distribution**, Z-bosons and jets agree well at high p_T**

UNDERLYING EVENT: *Z AND JETS* AT 7 TEV

EPJC 74 (2014) 3195
EPJC 74 (2014) 2965



Comparison of particle level data and MC predictions for average scalar p_T sum density of tracks and average track multiplicity density values as a function of Z and leading jet transverse momentum.

- ► For Jets: **Not perfect agreement** between **data and simulation** **Herwig** better than **Pythia6**
- ► For Z: Good description given by **Sherpa**, followed by **Pythia 8**, **ALPGEN** and **POWHEG**