# Soft QCD Physics in *pp* collisions at ATLAS

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# Introduction

Soft interactions: ($p_T$ < few GeV) require non-perturbative phenomenological models

"Soft QCD" dominates Minimum Bias physics

Minimum Bias is a mixing of non-diffractive and diffractive *pp* processes:

$$\sigma_{total-inelastic} = \sigma_{sd} + \sigma_{dd} + \sigma_{nd-inelastic}$$

Predictions of charged particle multiplicities at LHC energies based on previous experiments

Diffractive cross-sections and differential distributions known very roughly

MB measurement may help to better understand tracking, detector, simulation, reconstruction

MB measurement better performed at low luminosity to remove effect of overlapping collisions (pile-up)

# Measurement strategy – I

- results of this analysis submitted and accepted in NJP (New Journal of Physics):
  - arXiv 1012.5104
  - public page: *https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/MinBias_02/*
  - HEPDATA: *http://hepdata.cedar.ac.uk/view/p7918*
- phase spaces studied at 900 GeV and 7 TeV:
  - $n_{ch}$ >= 1, $p_T$ > 500 MeV, $|\eta|$ < 2.5
  - $n_{ch}$ >= 6, $p_T$ > 500 MeV, $|\eta|$ < 2.5
  - $n_{ch}$ >= 2, $p_T$ > 100 MeV, $|\eta|$ < 2.5
  - $n_{ch}$ >= 20, $p_T$ > 100 MeV, $|\eta|$ < 2.5
  - $n_{ch}$ >= 1, $p_T$ > 2.5 GeV, $|\eta|$ < 2.5
  - $n_{ch}$ >= 1, $p_T$ > 500 MeV, $|\eta|$ < 0.8
  - $n_{ch}$ >= 1, $p_T$ > 1.0 GeV, $|\eta|$ < 0.8
- event sample:
  - at $\sqrt{s}$ = 7 TeV: ~190 $\mu b^{-1}$
  - at $\sqrt{s}$ = 900 GeV: ~7 $\mu b^{-1}$

# Measurement strategy – II

- single primary vertex in event to reduce contribution from beam-background and events with multiple proton-proton interactions
- event level requirements:
  - single-arm trigger “MBTS1”: at least one hit in the Minimum Bias Trigger Scintillator
  - primary vertex in event
  - pile-up removal: reject events with a second primary vertex with 4 or more tracks
  - at least 1 “primary track” in event
- “primary track” selection:
  - track $p_T$ > 500 MeV and track $|\eta| < 2.5$
  - at least 1 Pixel and 2, 4, 6 SCT hits on the track depending on $p_T$ < 100, 200, and >= 300 MeV
  - $|d0_{PV}| < 1.5$ mm and $|z0_{PV}| \sin\theta < 1.5$ mm impact parameters with respect to primary vertex
- event level correction uses trigger and vertex efficiencies derived from data
- track-to-particle correction uses track reconstruction efficiency derived from simulation
- systematic uncertainty of tracking efficiency based on data/simulation comparison

# Trigger efficiency

Trigger efficiency measured from data versus number of selected primary tracks (using Beam Spot instead of primary vertex for the $d_0$ cut)

***Control trigger*** (0.9 TeV / 7 TeV)

Random trigger with at least 7 (4) pixel clusters, 7 (4) SCT hits and one track with $p_T$ > 200 MeV

***Minimum Bias Trigger Scintillator***

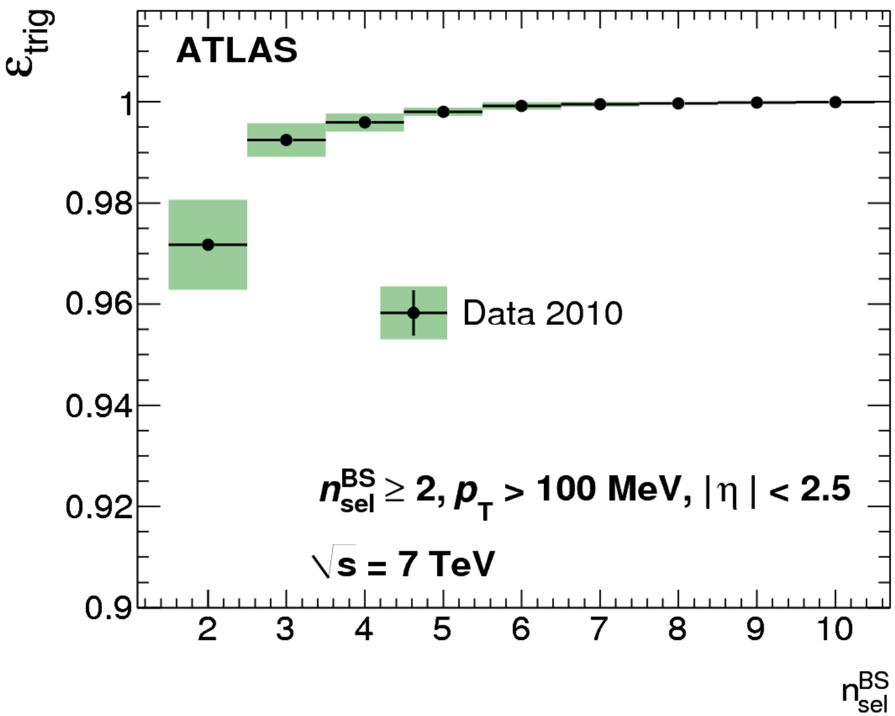
2 stations in front of LAr end-cap cryostats at $z = \pm 3.56$ m

Eight sectors in azimuth and two rings $2.09 < |\eta| < 3.84$

**Beam Spot**

$n_{sel}^{BS}$: number of tracks passing "good track" criteria using $|d_0^{BS}| < 4$ mm instead of $d_0^{PV}/z_0^{PV}$ cut

$$\varepsilon_{trig} = \frac{\text{control trigger \& MBTS}}{\text{MBTS}}$$

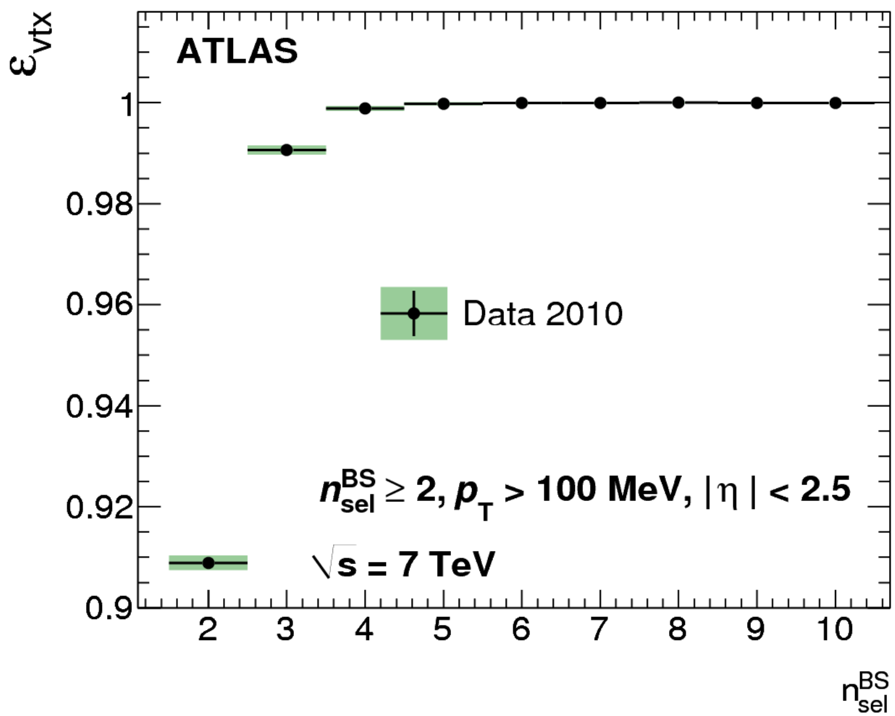


# Vertex reconstruction efficiency

$$\varepsilon_{vtx} = \frac{\text{triggered events with reconstr. vertex}}{\text{triggered events}}$$

*Primary vertex reconstruction uses beamspot position and at least two tracks with:*

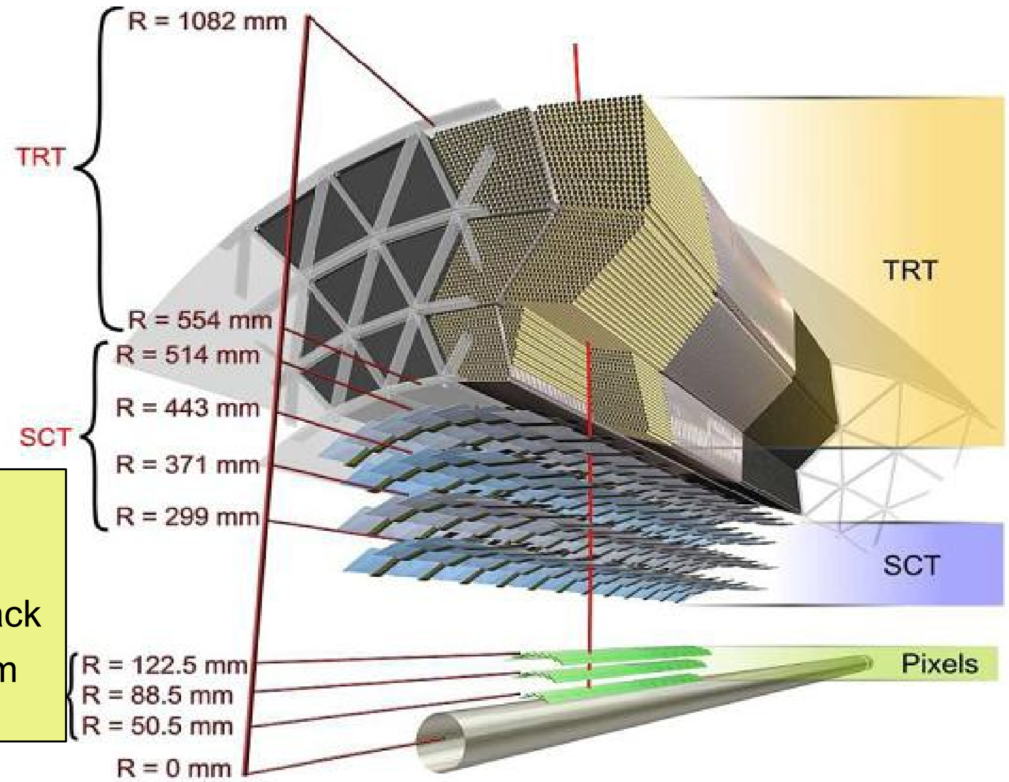
- track $p_T > 100$ MeV
- $|d0_{BS}| < 4$ mm
- at least 1 Pixel hit and 4 SCT hits
- at least 6 Pixel+SCT hits



# Track reconstruction

Charged particles with $p_T > 500$ MeV traversing the full Inner Detector produce on average:

- 3 Pixel hits
- 8 SCT hits
- ~30 TRT hits




***Primary track:***

- track $p_T > 500$ MeV and track $|\eta| < 2.5$
- at least 1 Pixel and 6 SCT hits on the track
- $|d0_{PV}| < 1.5$ mm and $|z0_{PV}| \sin\theta < 1.5$ mm

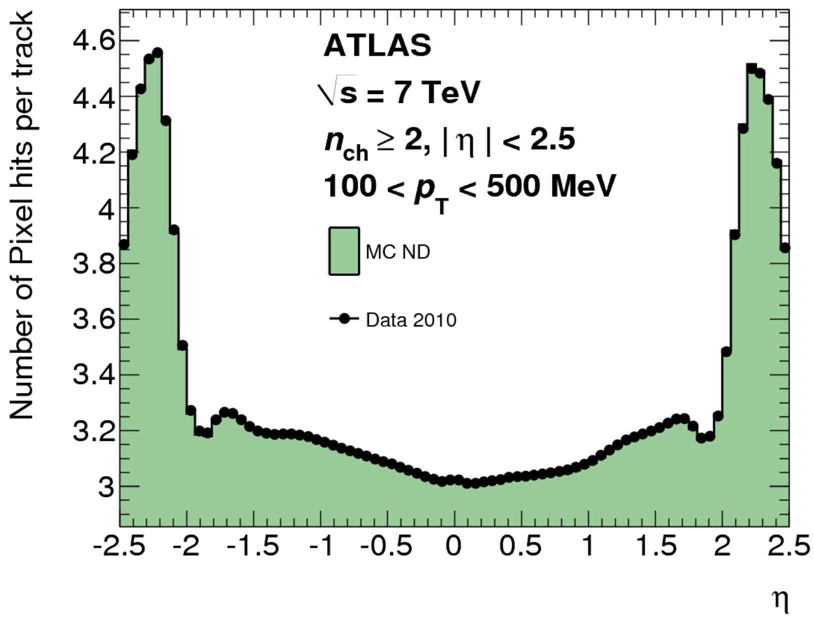
*Track reconstruction efficiency determined from simulation*

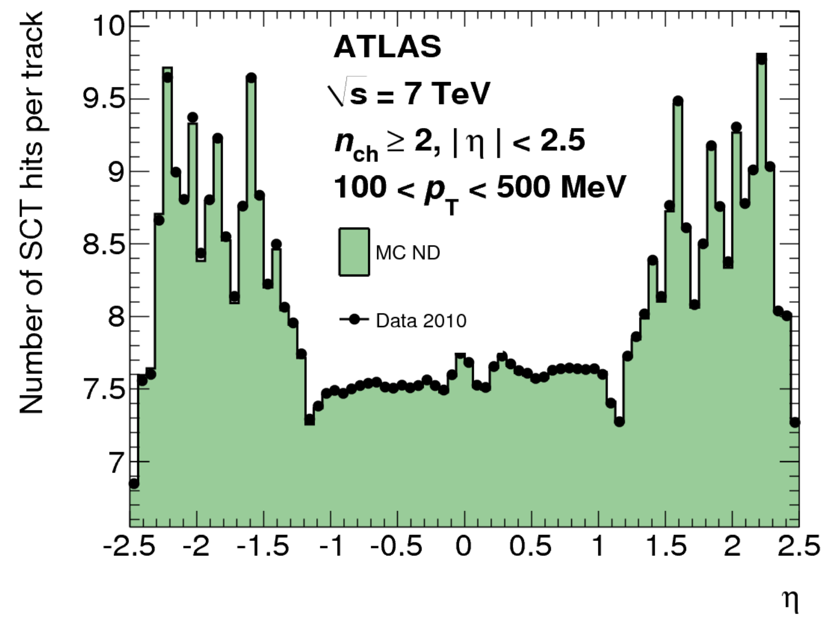
*Differences between simulation and data are expressed as systematic uncertainty on tracking efficiency*

# Data-simulation comparison

Very good agreement between data and MC

First ATLAS publication measured up to 500 MeV: these plots show that the models works well even for lower $p_T$ tracks



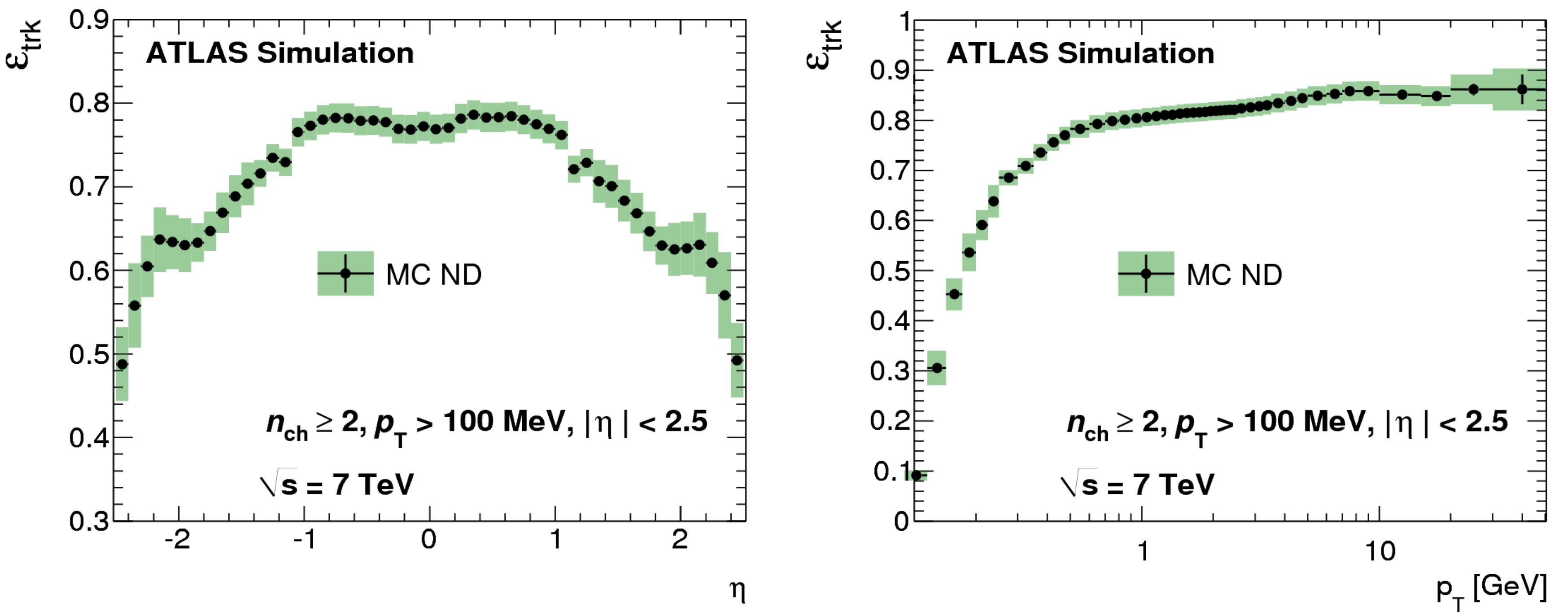



# Track reconstruction efficiency

$$\varepsilon_{trk(p_T,\eta)} = \frac{N_{rec}^{matched}(p_T,\eta)}{N_{gen}(p_T,\eta)}$$

***$N_{rec}^{matched}(p_T,\eta)$:*** number of reconstructed tracks matched to a generated charged particle

***$N_{gen}(p_T,\eta)$:*** number of generated charged particles



# Correction procedure

Events lost due to trigger and vertex requirements corrected using an event-by-event weight:

$$w_{ev}(n_{sel}^{BS}) = \frac{1}{\varepsilon_{trig}(n_{sel}^{BS})} \cdot \frac{1}{\varepsilon_{vtx}(n_{sel}^{BS}, x)}$$

$x$ is either $\Delta z$ between tracks or the $\eta$ of the tracks

$p_T$ and $\eta$ distributions of selected tracks are corrected for using a track-by-track weight:

$$w_{trk}(p_T, \eta) = \frac{1}{\varepsilon_{trk}(p_T, \eta)} \cdot [1 - f_{nonp}(p_T)] \cdot [1 - fokr(p_T, \eta)]$$

$f_{nonp}$ fraction of non-primary tracks

$f_{okr}$ fraction of tracks for which the corresponding primary particle is outside the kinematic range

$n_{ch}$ distribution from the data is obtained by using a matrix $M_{Nch,Nsel}$, that relates the number of selected tracks $n_{sel}$ to the number of charged particles $n_{ch}$

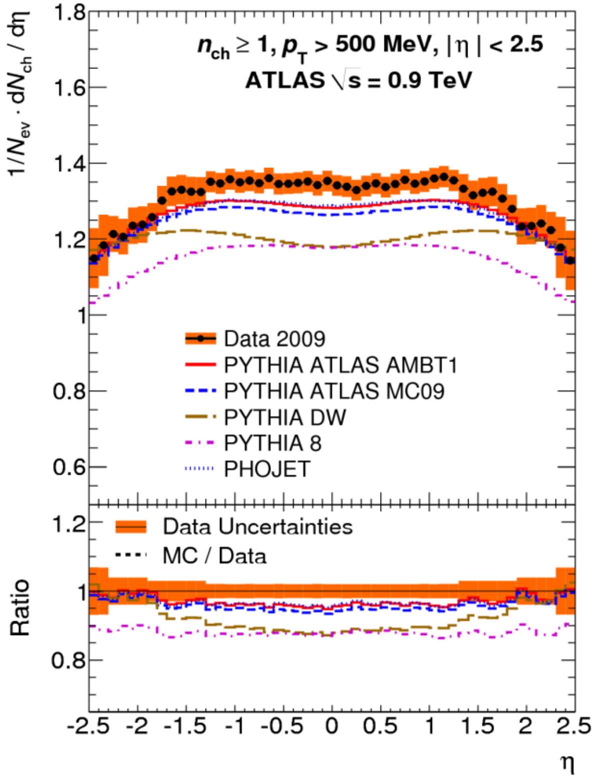
An iterative procedure is applied, using both MC and re-applying corrections

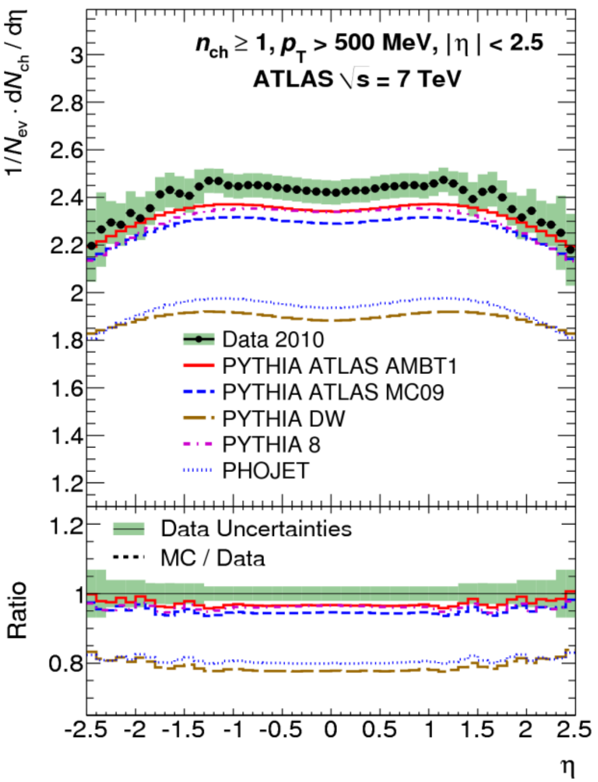
The procedure converges after 4 iterations

# Minimum bias distributions for $n_{ch}$ >= 1, $p_T$ > 500 MeV

Charged particle multiplicities as a function of the pseudorapidity

AMBT1 PYTHIA6 tune gives the best shape and normalization description of the data, although it was tuned for $n_{ch} > 6$



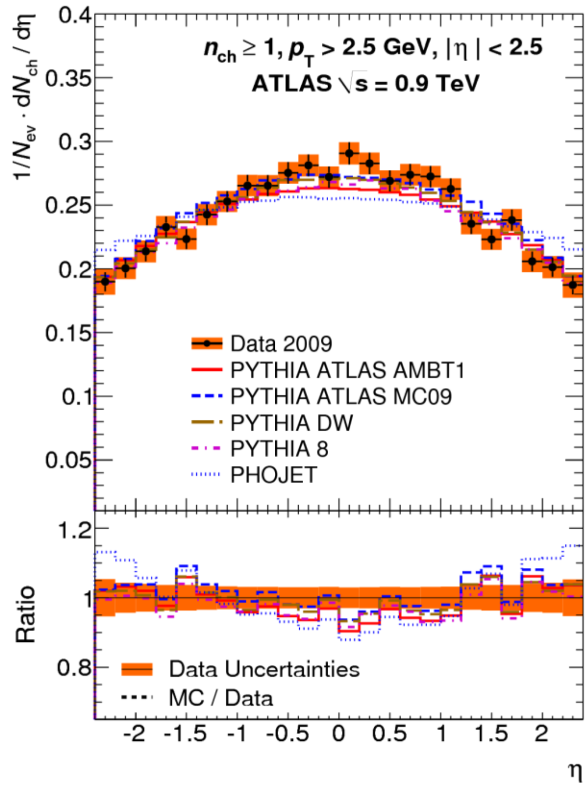



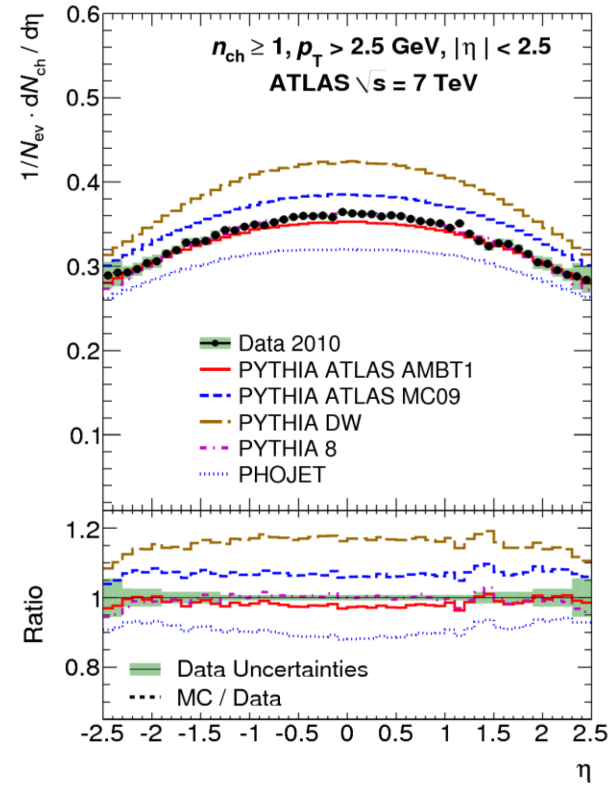
# Minimum bias distributions for $n_{ch}$ >= 1, $p_T$ > 2.5 GeV

Charged particle multiplicities as a function of the pseudorapidity

Phase space with "hard" component

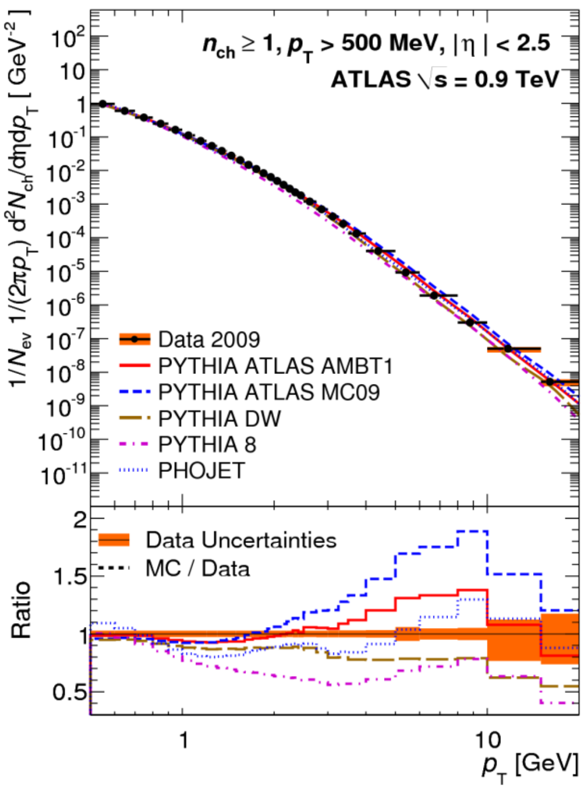
Much better description of data at $\sqrt{s}$ = 900 GeV

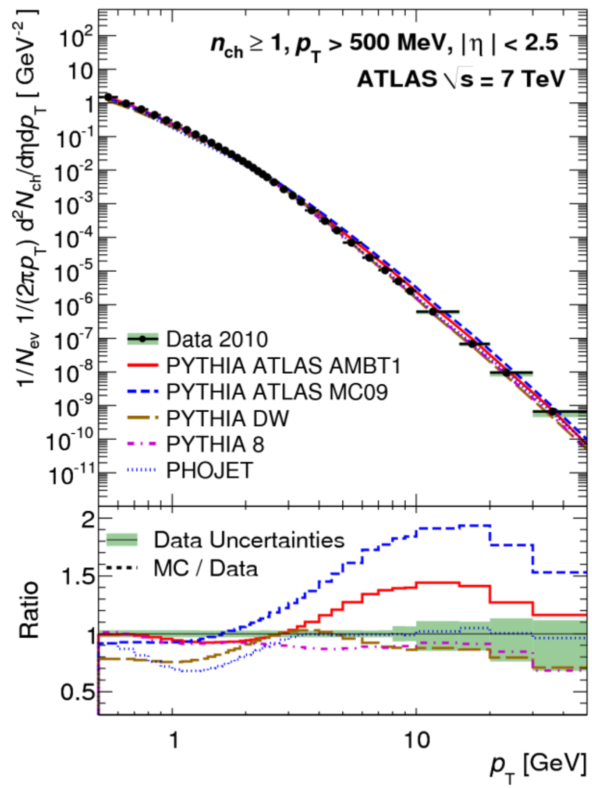


# Minimum bias distributions for $n_{ch} >= 1, p_T > 500$ MeV

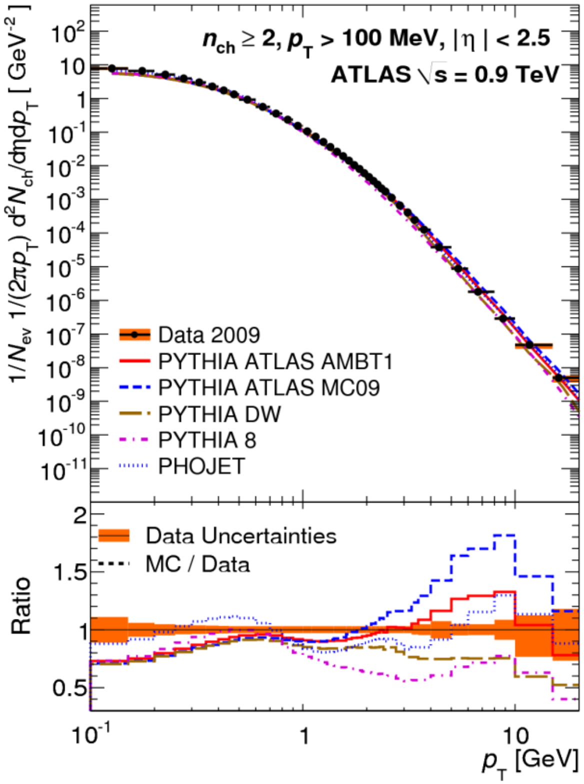
- Charged particle multiplicities as a function of the transverse momentum
- The observed spectrum is not described by any of the models over the whole range

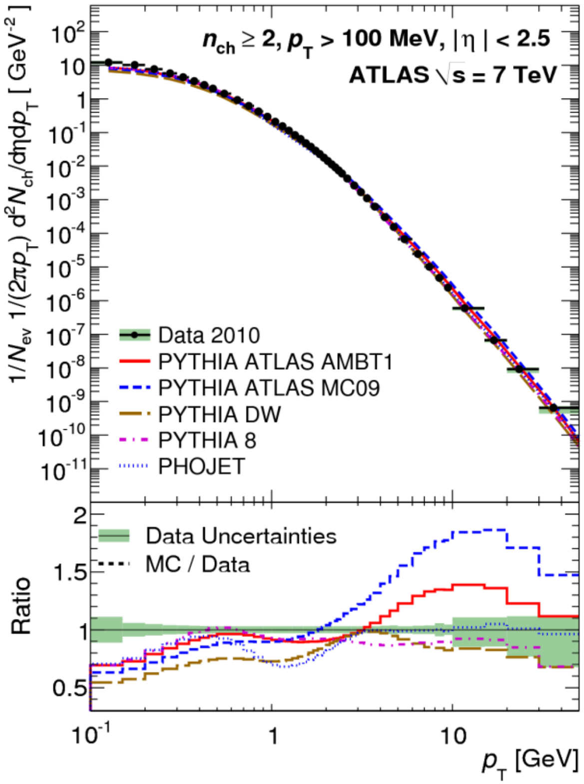


# Minimum bias distributions for $n_{ch} >= 2$, $p_T > 100$ MeV

- Charged particle multiplicities as a function of the transverse momentum
- At 900 GeV PHOJET describes the data best over the whole range
- At 7 TeV at high $p_T$ the agreement of PYTHIA8 and PHOJET with data is quite good



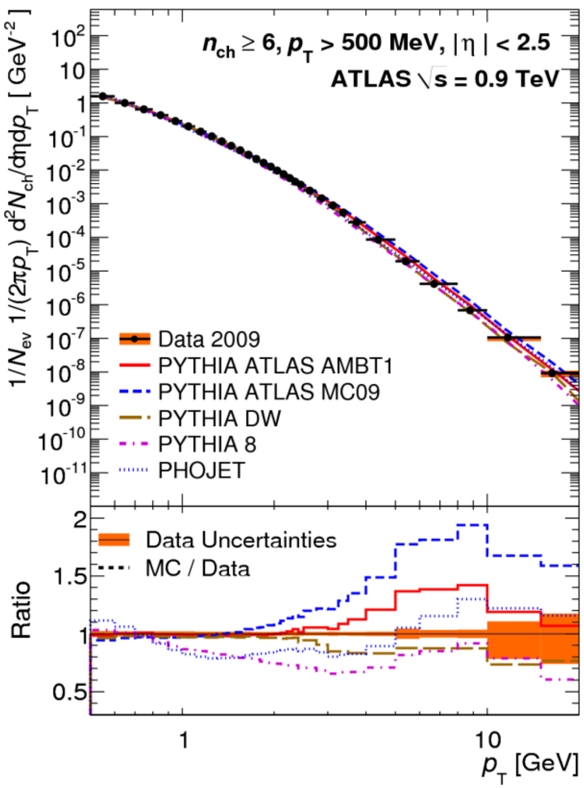



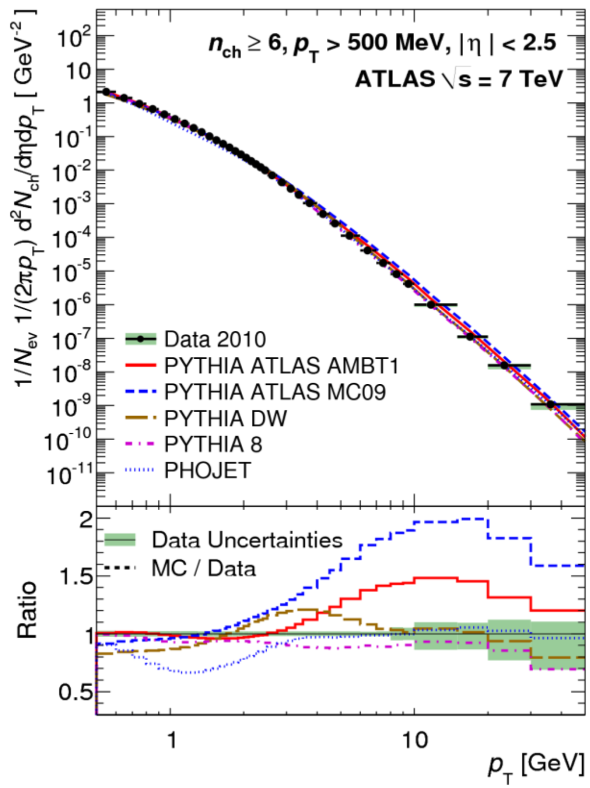
# Minimum bias distributions for $n_{ch} >= 6, p_T > 500$ MeV

Charged particle multiplicities as a function of the transverse momentum

This selection has the smallest contribution from diffractive events

Considerable improvement in the agreement with data between the older MC09 and the newly tuned AMBT1

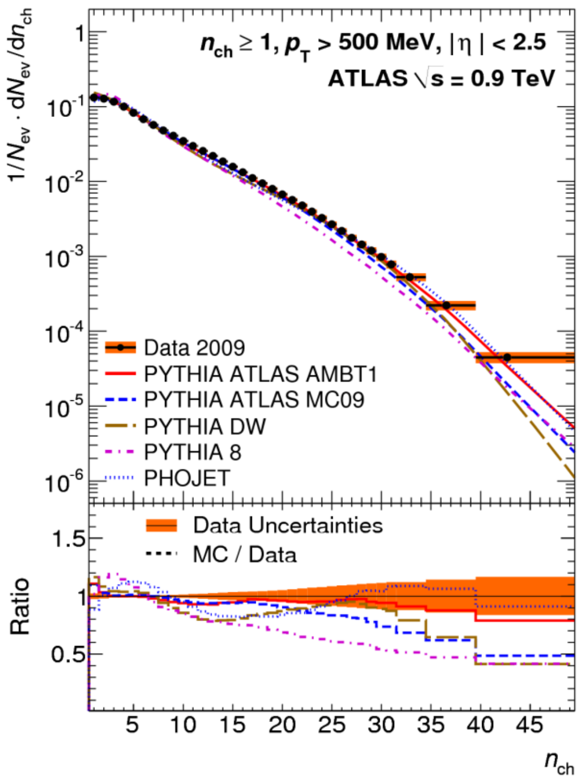


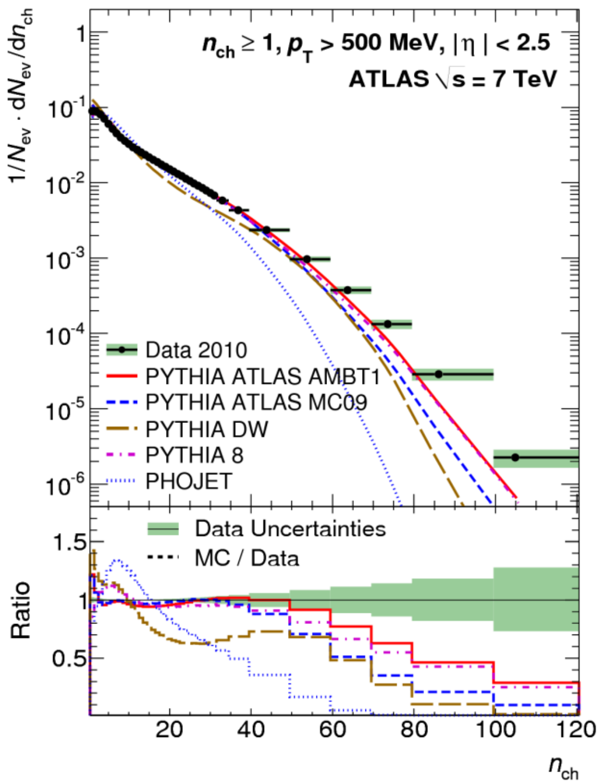



# Minimum bias distributions for $n_{ch} >= 1, p_T > 500$ MeV

Charged particle multiplicities as a function of the number of particles

AMBT1 PYTHIA6 tune seems to provide the best agreement with data

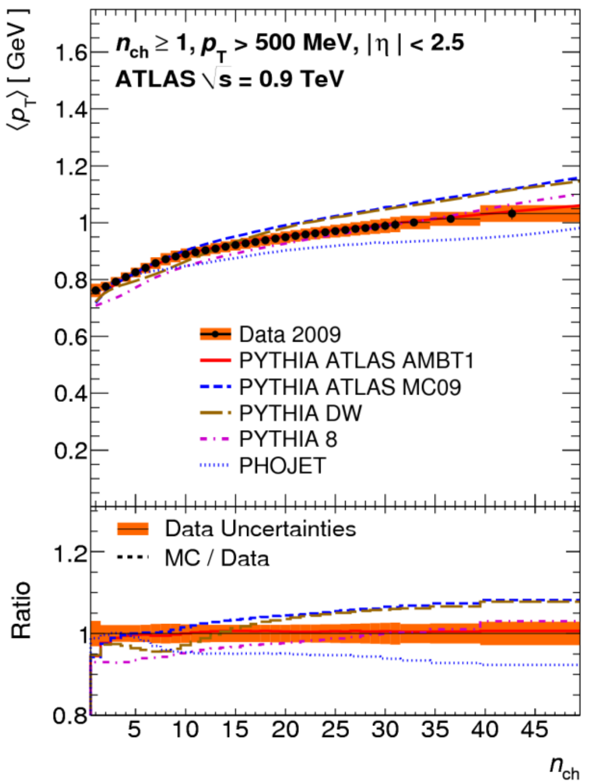


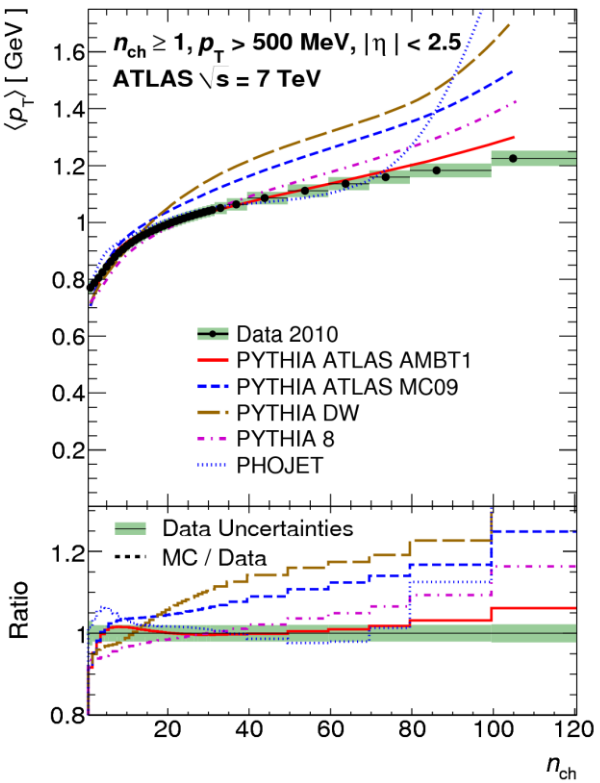



# Minimum bias distributions for $n_{ch}$ >= 1, $p_T$ > 500 MeV

Average transverse momentum as a function of the number of charged particles

AMBT1 tune gives the best description of the data

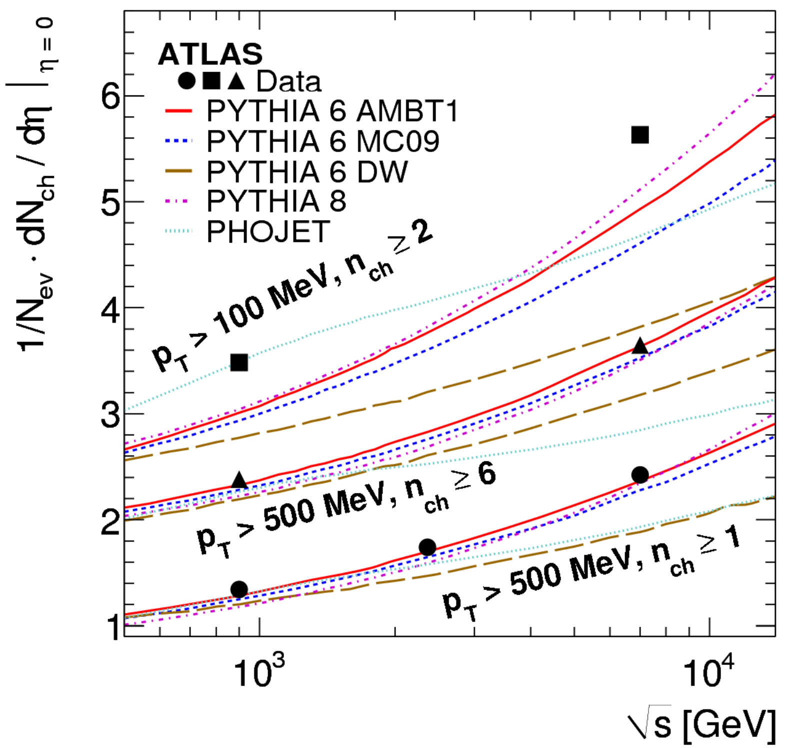


# Minimum bias results as function of $\sqrt{s}$

Mean number of charged particles in the central region

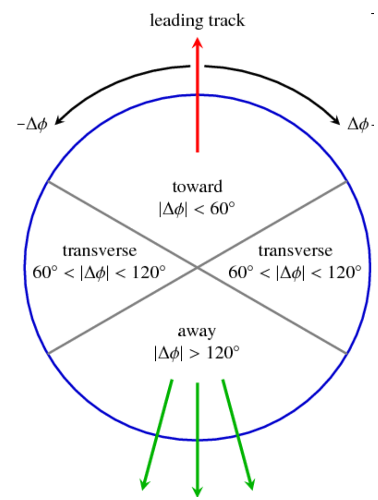
Computed by averaging over $|\eta| < 0.2$



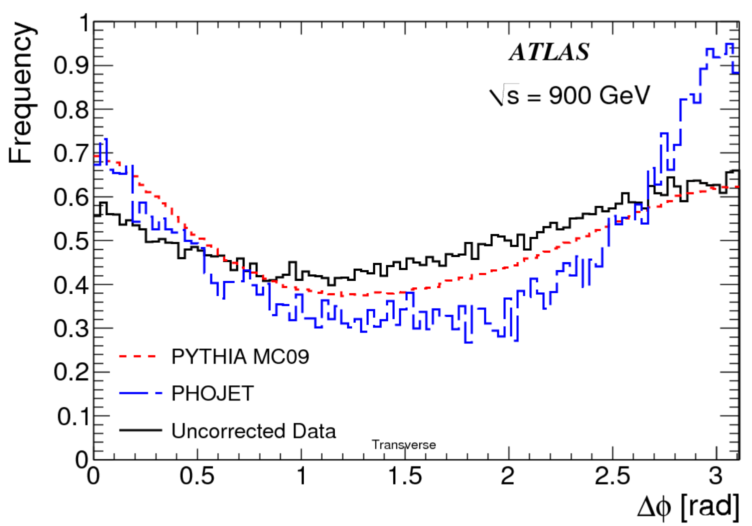
# Track based Underlying Event studies

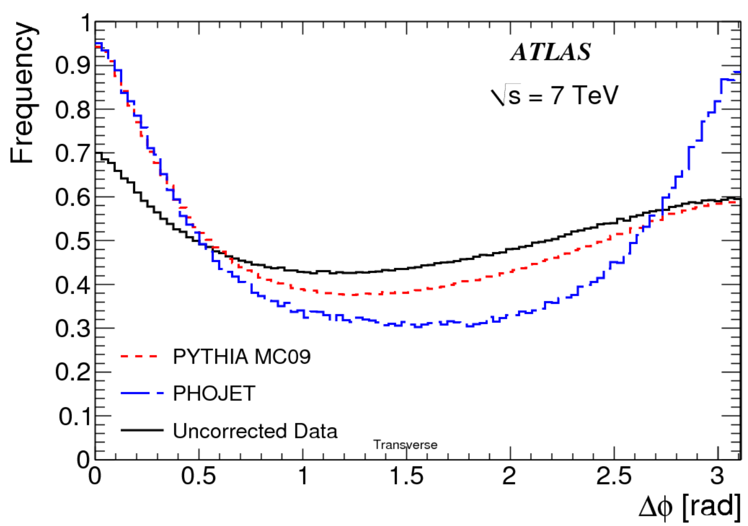
*"Underlying Event": everything else than hard scattering process*

The $\varphi$ region transverse to the leading tracks is assumed to be principally filled by the underlying events

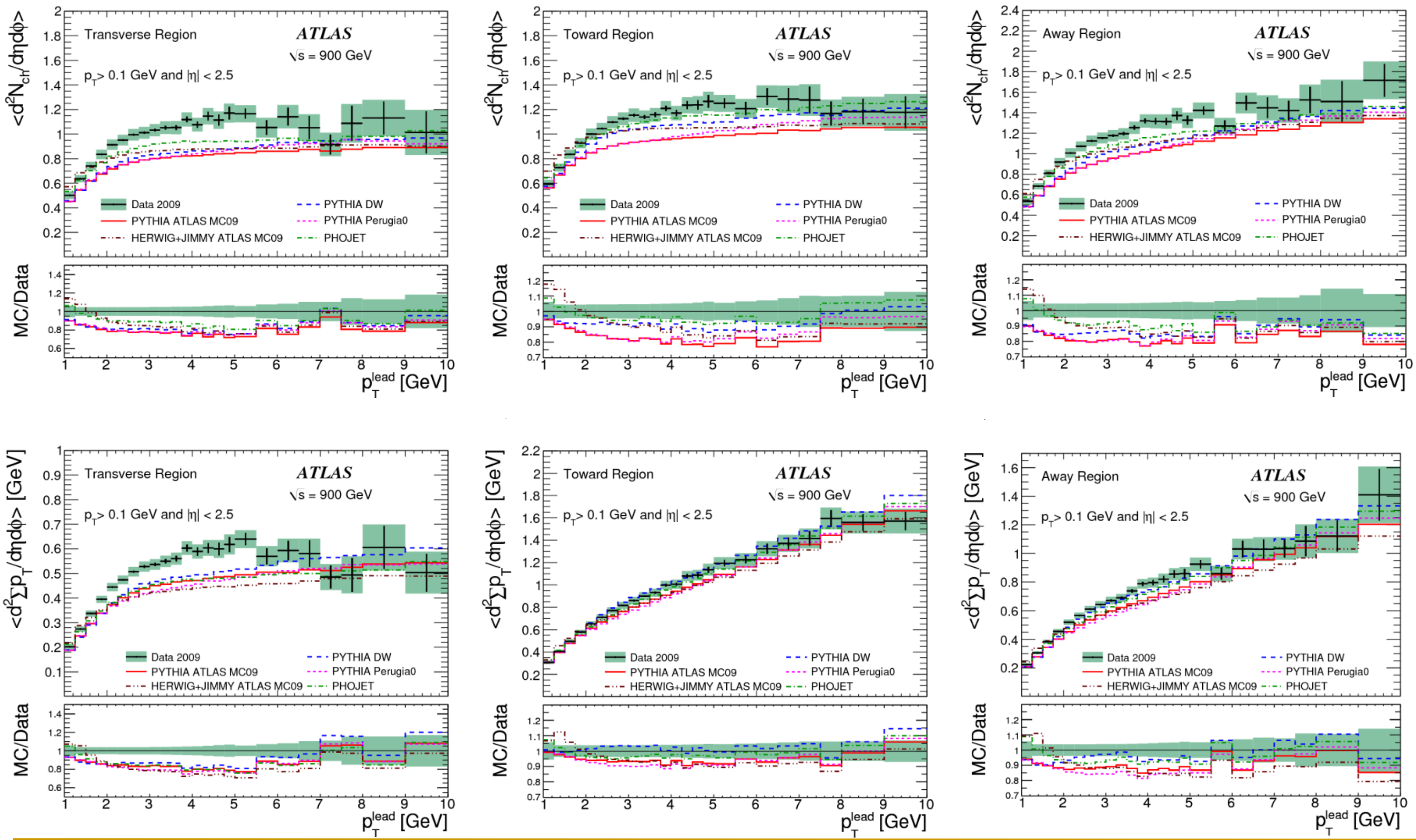



Corrections for trigger, vertex and tracking efficiencies same as for minimum bias studies

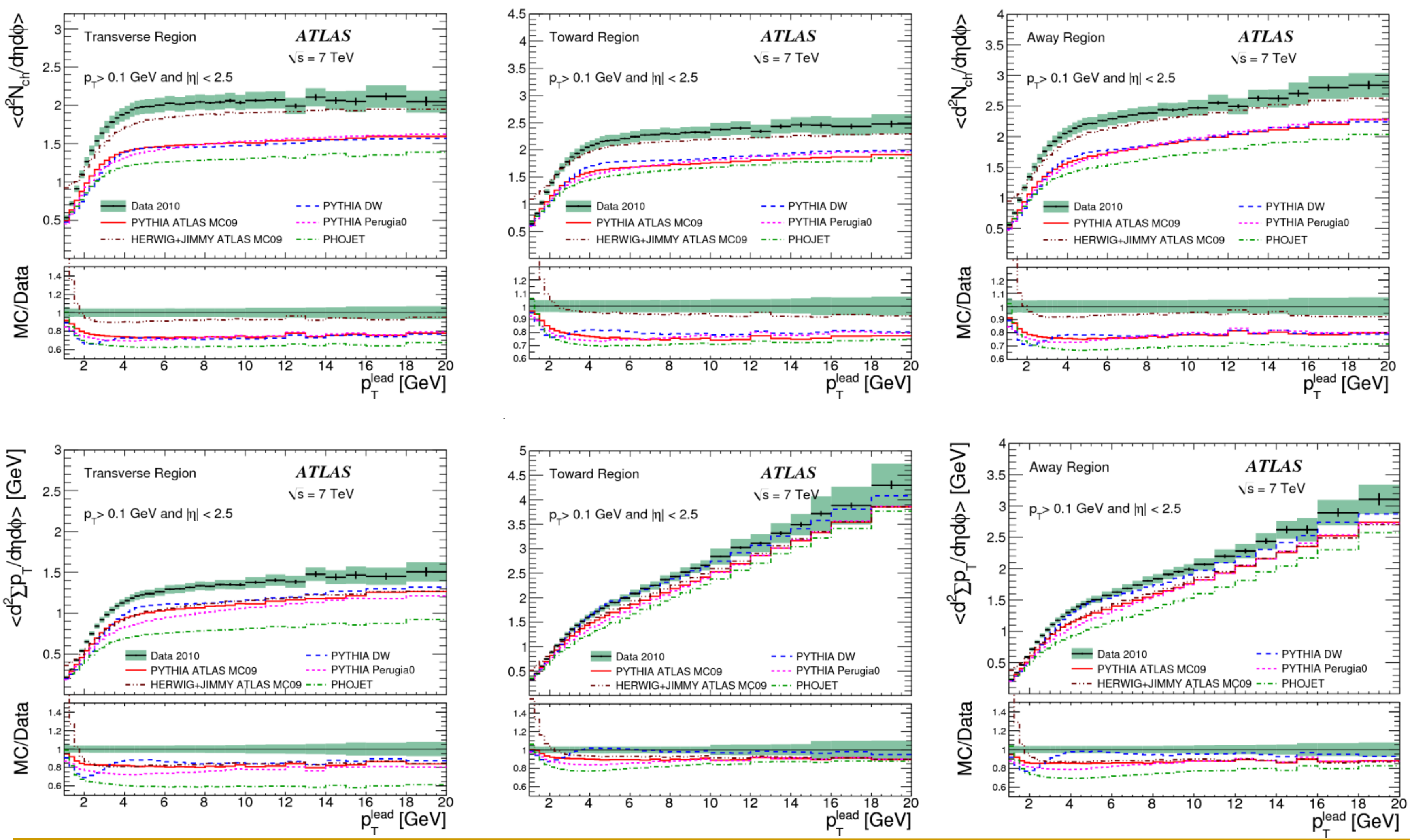


# Charged particle number and $p_T$ density at $\sqrt{s}$ = 900 GeV and $p_T$ > 100 MeV

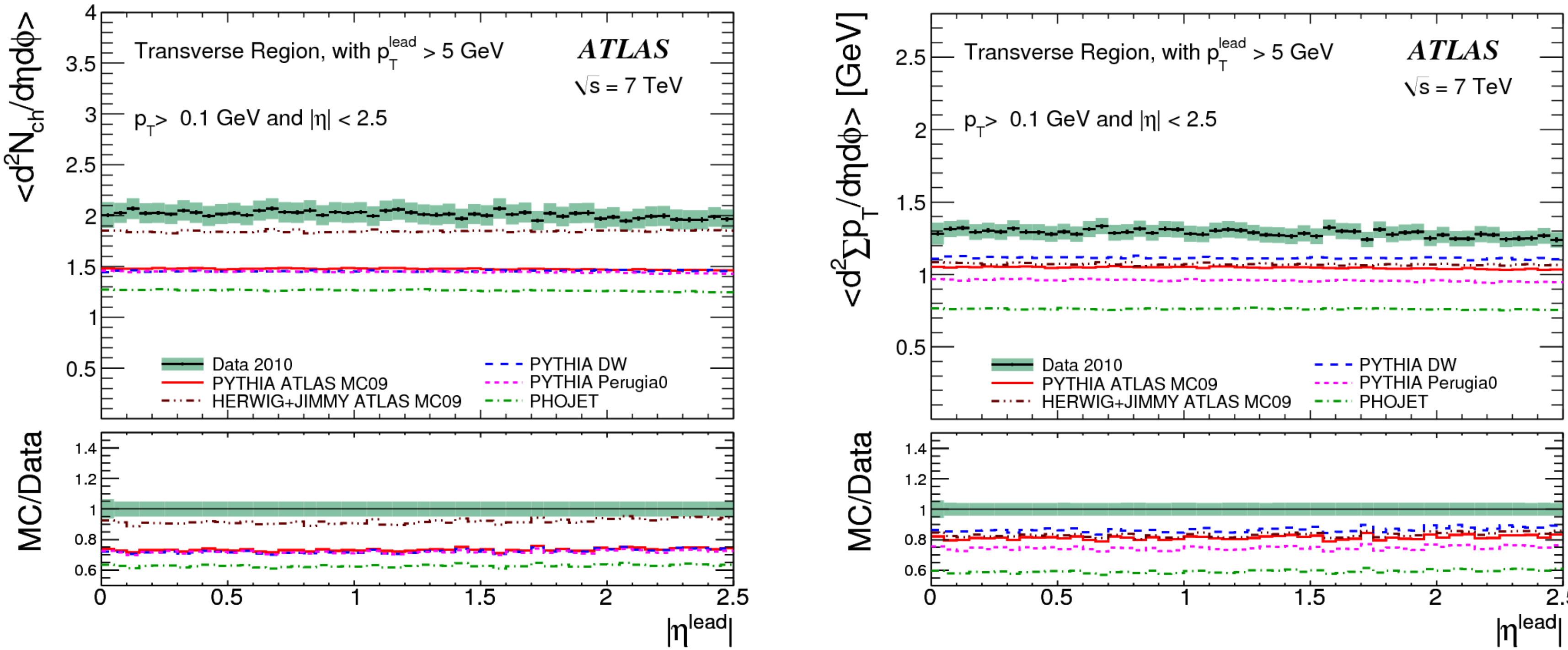


# Charged particle number and $p_T$ density at $\sqrt{s}$ = 900 GeV and $p_T$ > 100 MeV



# Charged particle number and $p_T$ density

- Charged particle multiplicity and $p_T$ densities as a function of the leading charged particle pseudorapidity
- Results are shown for $\sqrt{s}$ = 7 TeV only. The available statistics at $\sqrt{s}$ = 900 GeV was not sufficient for a robust analysis
- Multiplicity and $\Sigma p_T$ are seen to be independent of $\eta$ for the transverse region plateau, suggesting that the average impact parameters in $pp$ collisions do not depend strongly on $\eta$ of the leading particle for a given $p_T$

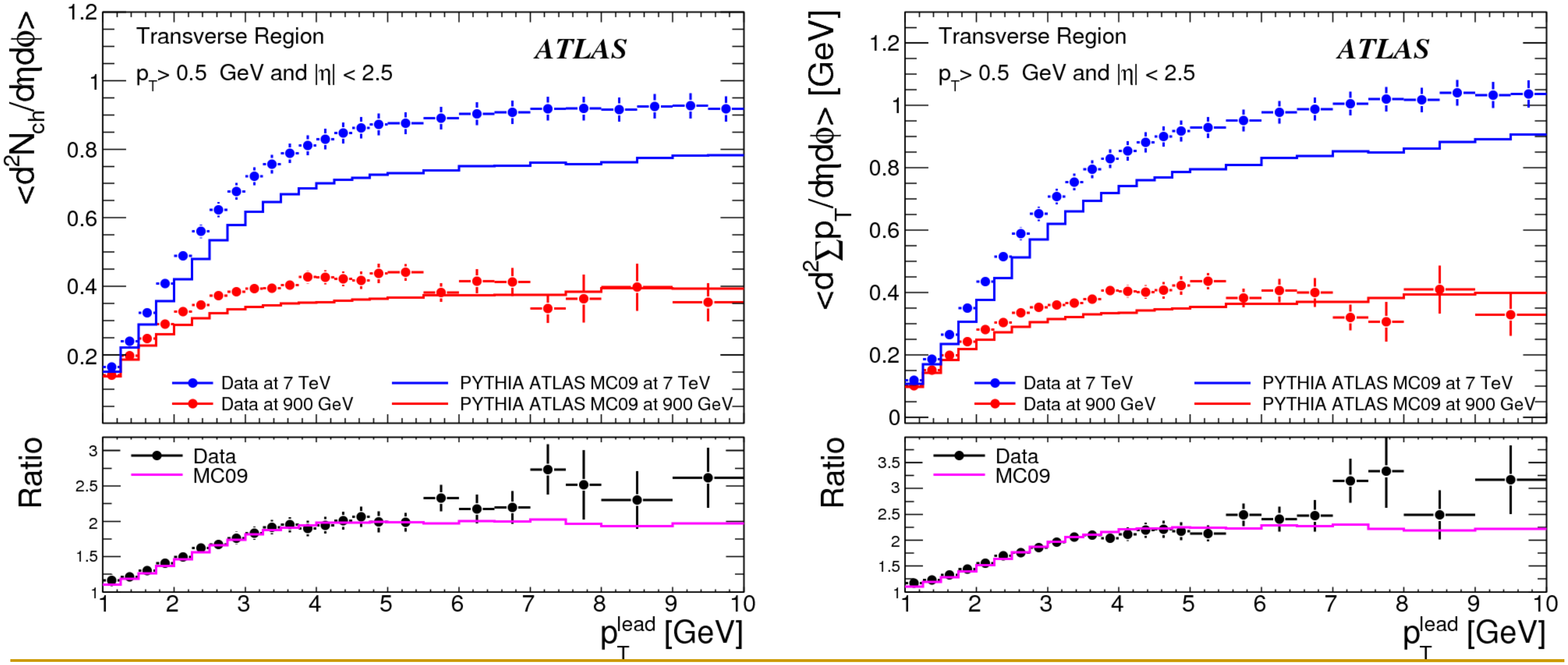


# Underlying event results as function of √s

Charged particle multiplicity and $p_T$ densities

Activity increases by approximately a factor 2 going from 900 GeV to 7 TeV, roughly consistent with the increase predicted by MC

Better agreement between data and MC at 900 GeV



# Conclusions

- results for Minimum Bias and Underlying Events in *pp* collisions at $\sqrt{s}$ = 900 GeV and $\sqrt{s}$ = 7 TeV at ATLAS have been presented
- a specific phase-space has been chosen, without subtracting single diffractive component, in order to have model-independent measurements
- charged primary particles in kinematic range $|\eta| < 2.5$ and $p_T > 100$, 500 MeV, $|\eta| < 0.8$ and $p_T > 1$, 2.5 GeV for some MB measurements
- charged particle multiplicity studied in events with at least one primary charged particle ($n_{ch} >= 1$) and diffractive limited phase-space ($n_{ch} >= 6$)

# References


**“Charged particle multiplicities in *pp* interactions measured with the ATLAS detector at the LHC”**

- *http://cdsweb.cern.ch/record/1317794/files/1012.5104v1.pdf*

**“Measurement of underlying event characteristics using charged particles in *pp* collisions at *s*=900 GeV and 7 TeV with the ATLAS detector”**

- *http://cdsweb.cern.ch/record/1309895/files/UE-tracks.v4.pdf*

**“Central charged-particles multiplicities in *pp* collisions with *n*<0.8 and pT>0.5 and 1 GeV measured with the ATLAS detector at the LHC”**

- *http://cdsweb.cern.ch/record/1317333/files/ATLAS-CONF-2010-101.pdf*

**“Measurement of the Inelastic Proton-Proton Cross Section at sqrt(s) = 7 TeV with the ATLAS Detector”**

- *https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-002/*

# Back-up

# UE with Calorimeter Clusters

**Measurement using calorimeters:**

- sensitive to a complete final state including neutrals (about extra 40%)
- useful for many high precision jet measurements based on energy deposition
- 175k channels for electromagnetic, 20k channels for hadronic calorimeter
- excellent transverse and longitudinal sampling allowing the reconstruction of topological clusters (Topoclusters) in 3D closely related to single particles

# UE with Calorimeter Clusters

**Selection for cluster based analysis:**

- same trigger and vertex requirements as track-based
- Topocluster quality:
  - clustering method (4-2-0):
    - ✓ seeded by cells with $|E| > 4$ x (noise level)
    - ✓ neighboring cells with $|E| > 2$ x (noise level) iteratively added (in 3D)
    - ✓ all neighbors around cluster with $|E| > 0$ added
  - hadronic calibration
  - energy scale measured with $E/p$ and $\pi^0$ mass
  - $|\eta| < 2.5$
  - $p_T > 500$ MeV
  - cluster cleaning:
    - ✓ leading cell energy < 90%
    - ✓ energy sampling max not in region without good calibration
    - ✓ fraction of energy associated with problematic cells < 50%

# Correction procedure

**Selection for cluster based analysis:**

- unfold the observable distributions by bin-by-bin correction from detector level to hadron level (charged and neutral)
- take into account:

− event selection

− cluster selection

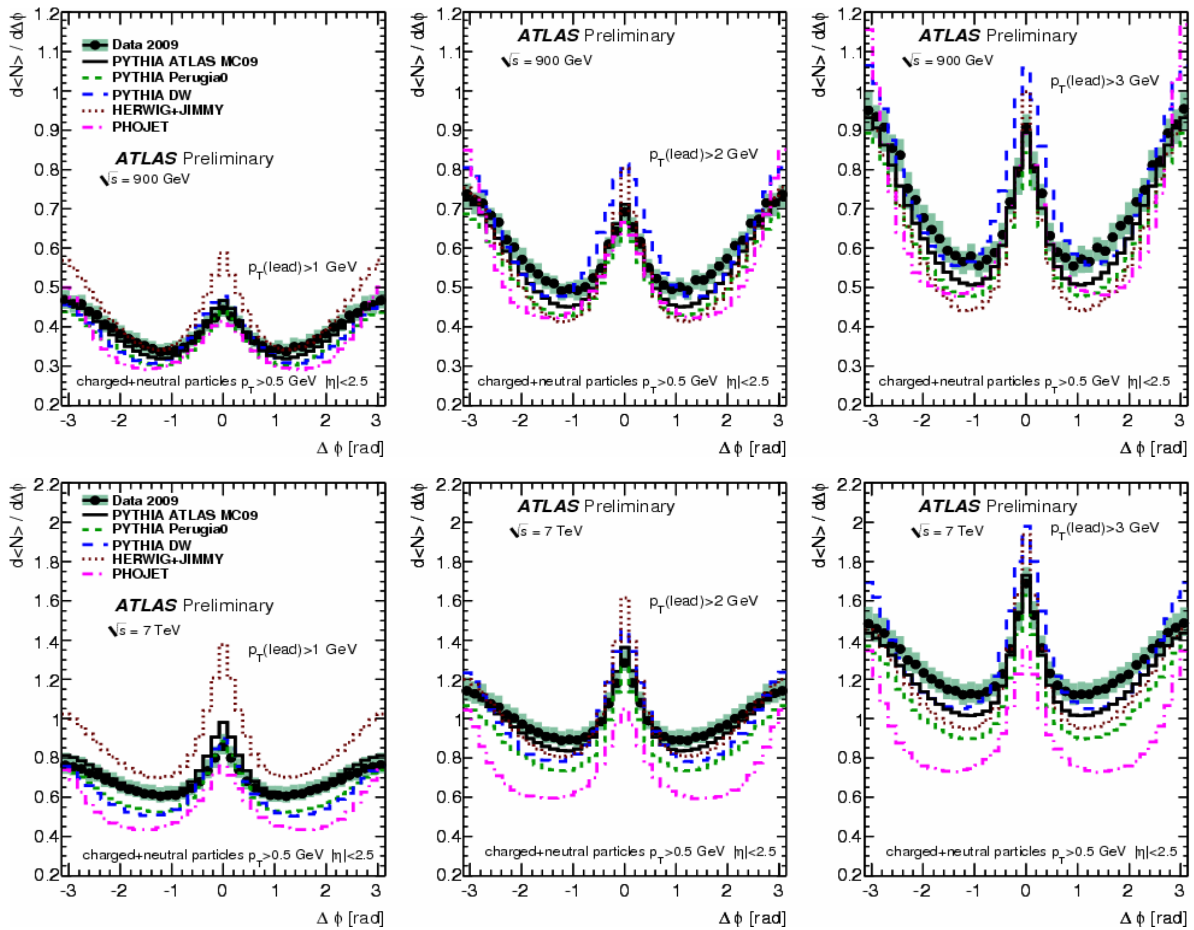
− bin-by-bin migration

− smearing

- minimize the resolution smearing by choosing bin sizes larger than resolutions in each bin
- control model dependence using alternative MCs
- not apply correction for diffraction
- reweight the low multiplicity region with track multiplicity, reweight the resolution tail of $p_{T(Lead)}$ with leading track $p_T$ distribution

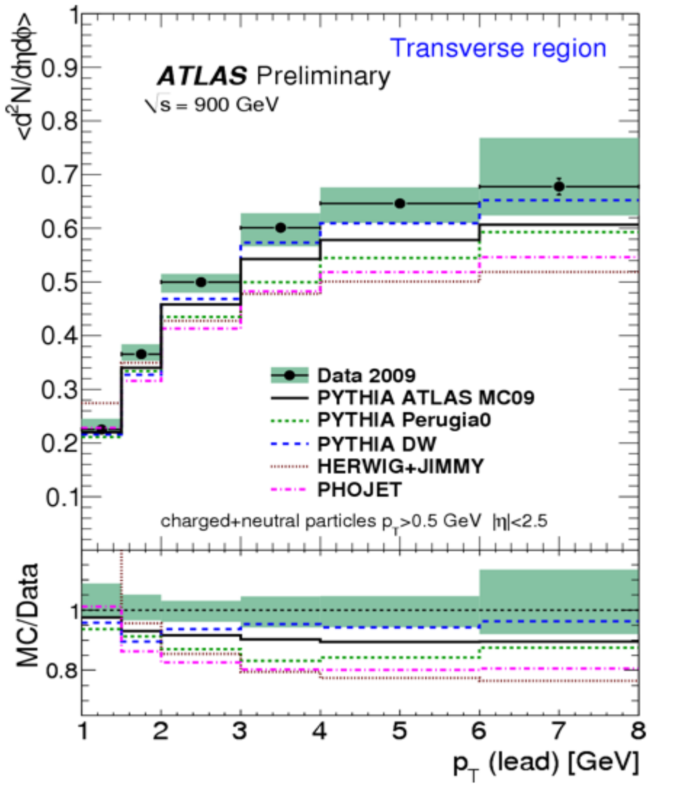
# UE with Calorimeter Clusters

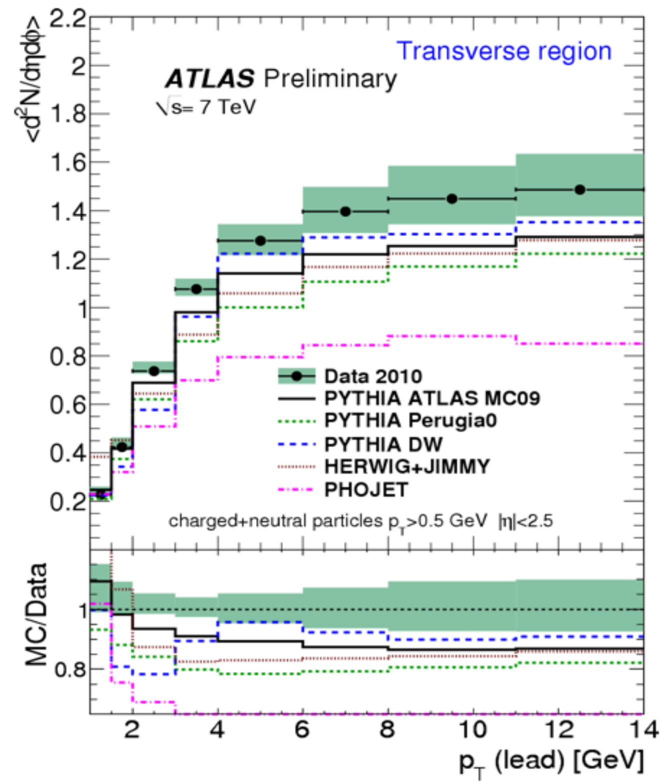
MC tunes don't describe data well
~40% increase in particle density due to neutrals



# Charged particle number at $p_T$ > 500 MeV

Lower particle density in MC tunes
Larger discrepancies at 7 TeV



# Charged particle $p_T$ density at $p_T$ > 500 MeV

Lower particle $p_T$ density in MC tunes
Larger discrepancies at 7 TeV (PHOJET worst)