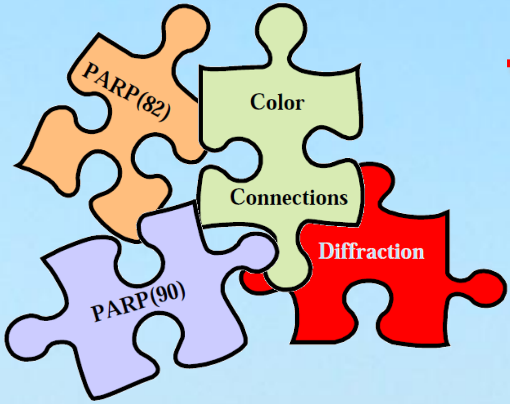
ATLAS results on inelastic pp collisions and the underlying event



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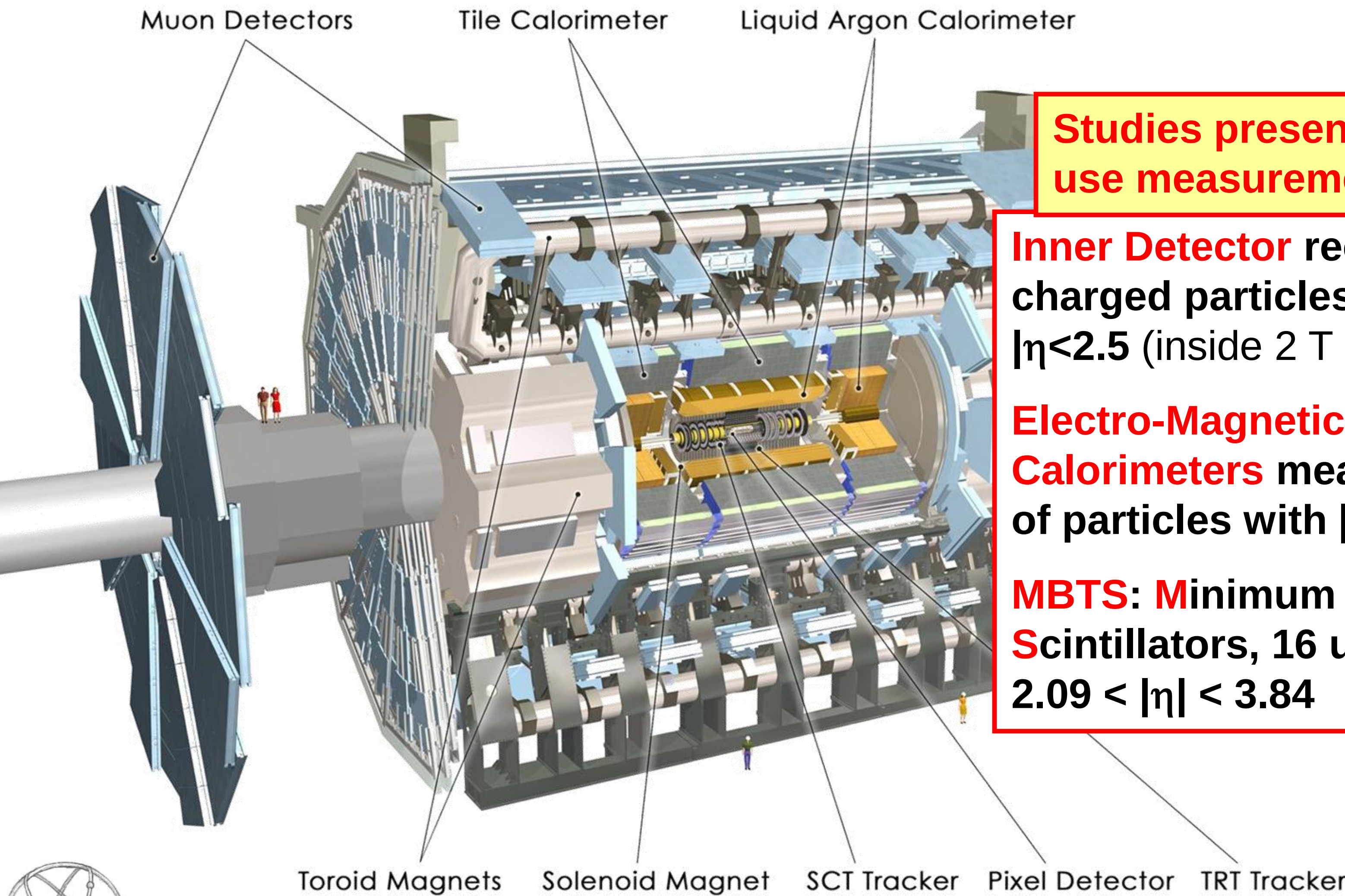
University of Iowa

Outline:

ATLAS & inelastic pp collisions
Inelastic cross-section measurement
Charged particle distributions
The Underlying Event

The ATLAS detector



Studies presented today use measurements of:

Inner Detector reconstructs charged particles tracks with |η<2.5 (inside 2 T solenoid field)

Electro-Magnetic and Hadronic Calorimeters measure energy of particles with |η|<4.9

MBTS: Minimum Bias Trigger Scintillators, 16 units covering 2.09 < |η| < 3.84

ϕ = azimuthal angle in tranverse plane (perpendicular to beam-axis)
θ = angle w.r.t. beam-axis
$\eta = -\ln \tan(\theta/2)$ (pseudo-rapidity)

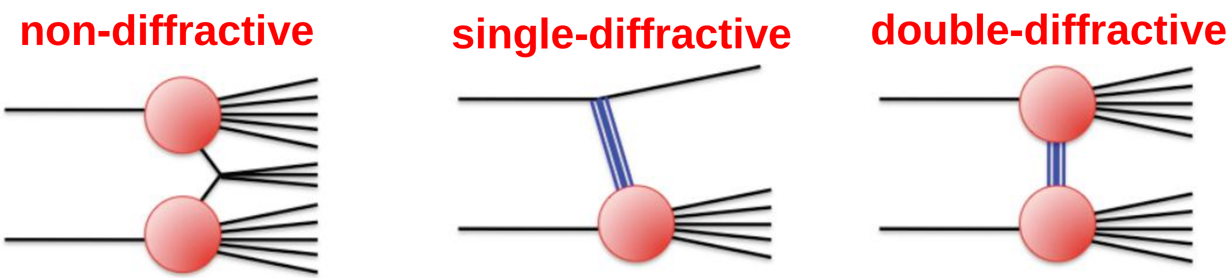
Inelastic pp collisions

p-p interactions are dominated by soft (low momentum transfer) QCD processes

Soft QCD can not be predicted using perturbative QCD model!

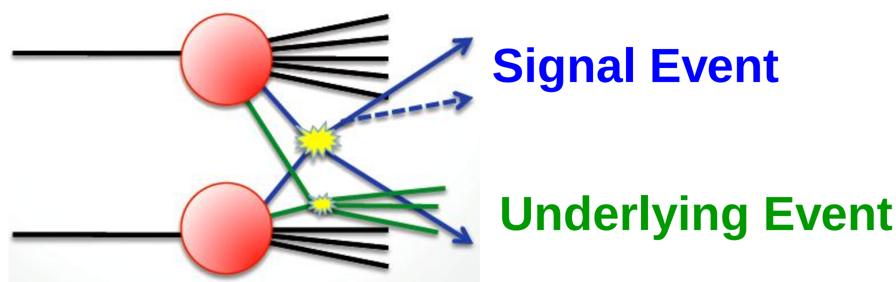
Rely on phenomenological models that need to be tuned to data

Inelastic pp collisions are the result of a combination of non-diffractive and diffractive p-p processes: $\sigma_{total\text{-}inelastic} = \sigma_{sd} + \sigma_{dd} + \sigma_{nd\text{-}inelastic}$



<u>Knowledge on soft-QCD processes needed:</u>

- To model pileup (up to ~20 p-p interactions per bunch crossing)
- To model the soft processes occuring in the *Underlying Event*
- Affects E^T_{miss} resolution, lepton ID, jet reconstruction, ...

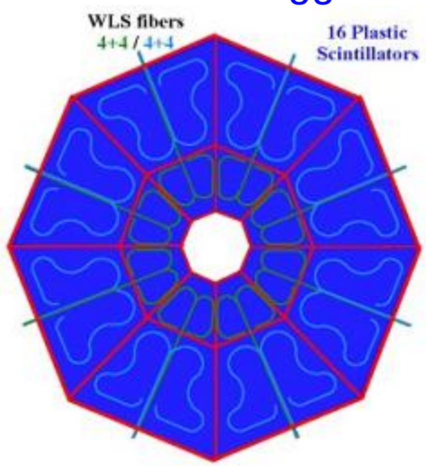


Inelastic cross-section measurement

No good predictions for proton-proton σ_{inel} at $\sqrt{s}$=7 TeV

Direct measurement of σ_{inel} using events counted by Minimum Bias trigger (≥ 2 MBTS hits):

Minimum Bias Trigger Scintillators



$\sigma_{inel} = (N_{evts} - N_{BG})/\varepsilon \times L$

N_{evts} : # events with ≥ 2 MBTS hits

N_{BG} : background, mainly non-colliding events

ε : detector efficiency

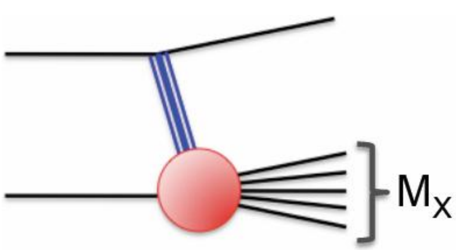
L : luminosity (from van Der Meer scans)

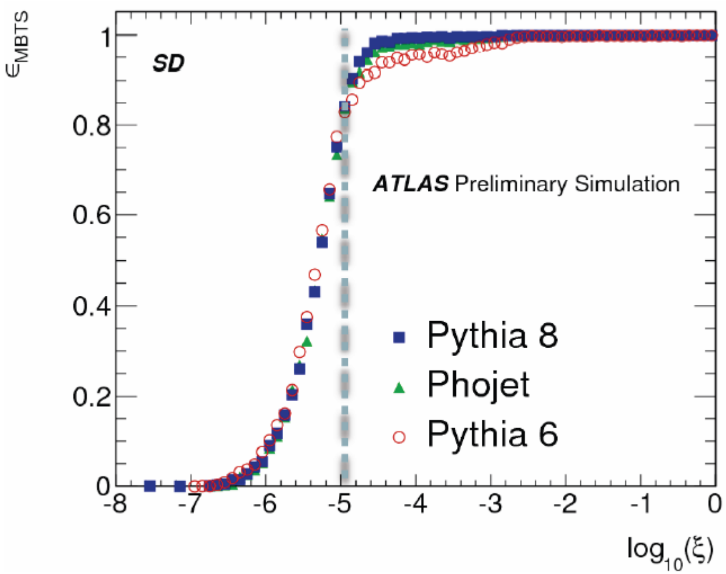
Main problem : Blind to events with particles in |η| > 3.84 region

Solution: Make measurement in a well defined phase-space region:

σ_{inel} measured for $\xi > 5 \times 10^{-6}$ (M_X > 15.7 GeV)

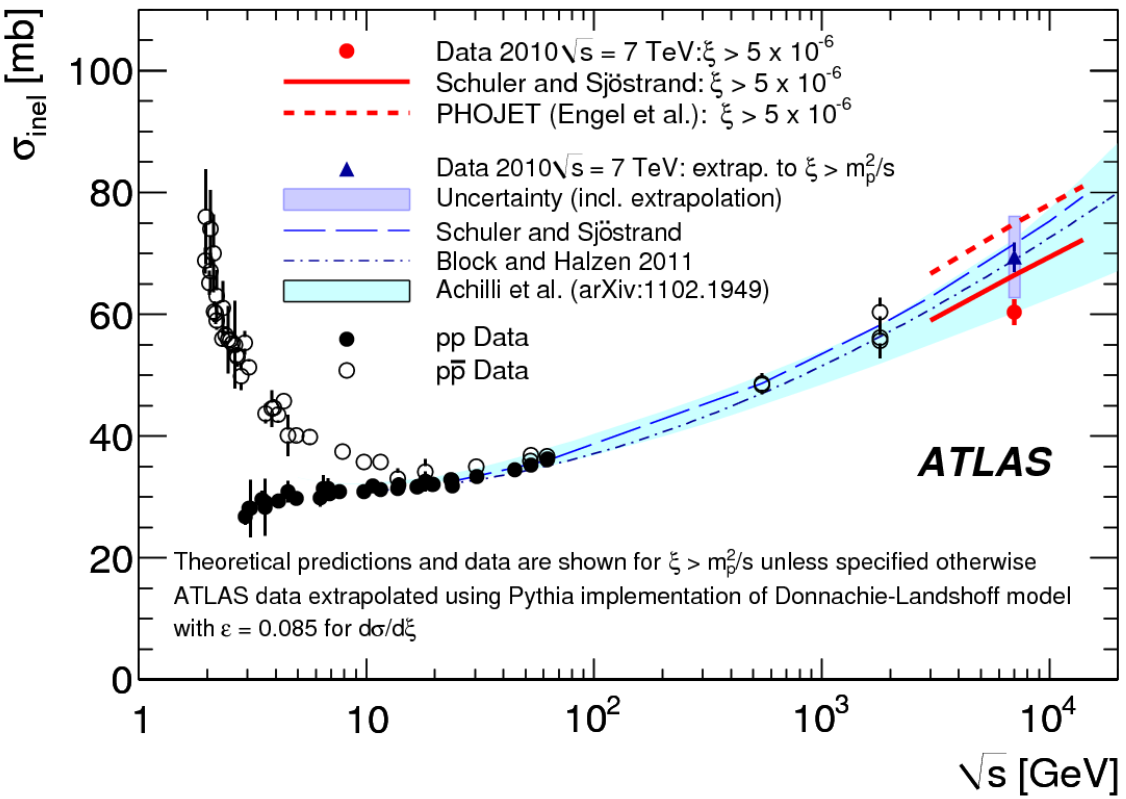
$\xi = M^2_X/s$





Inelastic cross-section measurement

$\sigma_{inel}(\xi > 5 \times 10^{-6}) = 60.3 \pm 0.05(\text{stat}) \pm 0.5(\text{syst}) \pm 2.1(\text{lumi})$ mb



Systematic uncertainties on σ_{inel} measurement:

Source	Uncertainty (%)
Trigger Efficiency	0.1
MBTS Response	0.1
Beam Background	0.4
f_D	0.3
MC Multiplicity	0.4
ξ-Distribution	0.4
Material	0.2
Luminosity	3.4
Total	3.5

Dominated by luminosity uncertainty

Full inelastic cross-section using model predictions:

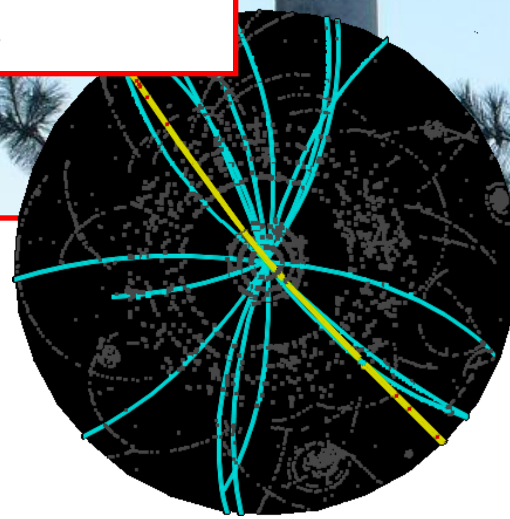
$\sigma_{inel} = 69.4 \pm 2.4(\text{exp}) \pm 6.9(\text{extr.})$ mb

Extrapolation uncertainty from range of models used

Minimum Bias measurements

***"Minimum Bias Events"*: ≥1 hits in the Minimum Bias Trigger Scintillators**

Charged particles are measured from tracks reconstructed in the Inner Detector



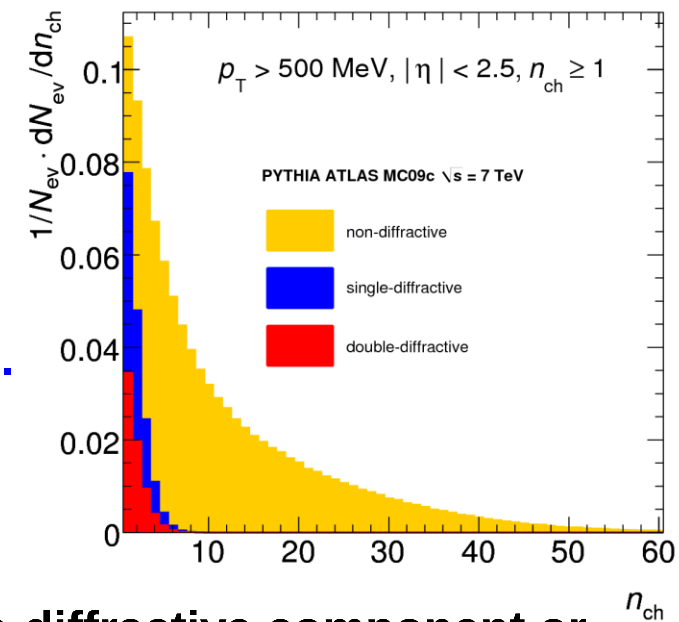
Apply event-level and track-to-particle corrections to measure the distributions of **stable charged particle from the primary p-p interaction**

Particle distributions in Minimum Bias events

Minimum Bias events consist of non-diffractive, single-diffractive and double-diffractive events:

Relative contributions of the different components depend on event and track selection criteria!
Predictions of relative fractions rely on non-pertubative QCD models and have large uncertainty...

<u>PYTHIA tune "*ATLAS MC09c*":</u> main reference of model predictions before ATLAS measurements at √s=7 TeV



Rather than using MC predictions to remove single-diffractive component or extrapolate to regions of phasespace inaccessible by the ATLAS detector, measurements are made in well-defined regions of phase-space:

	Most inclusive		Diffraction suppressed		High p_T	ALICE/CMS comparison	
N_{ch} ≥	2	1	20	6	1	1	1
p_T [MeV] ≥	100	500	100	500	2500	500	1000
|η| ≥	2.5	2.5	2.5	2.5	2.5	0.8	0.8

*used to produce updated model parameters for new pythia tune "*ATLAS AMBT1*"

Measurement strategy

Event and track selection are chosen to match the kinematic range of charged particles for the specific phase-spaces

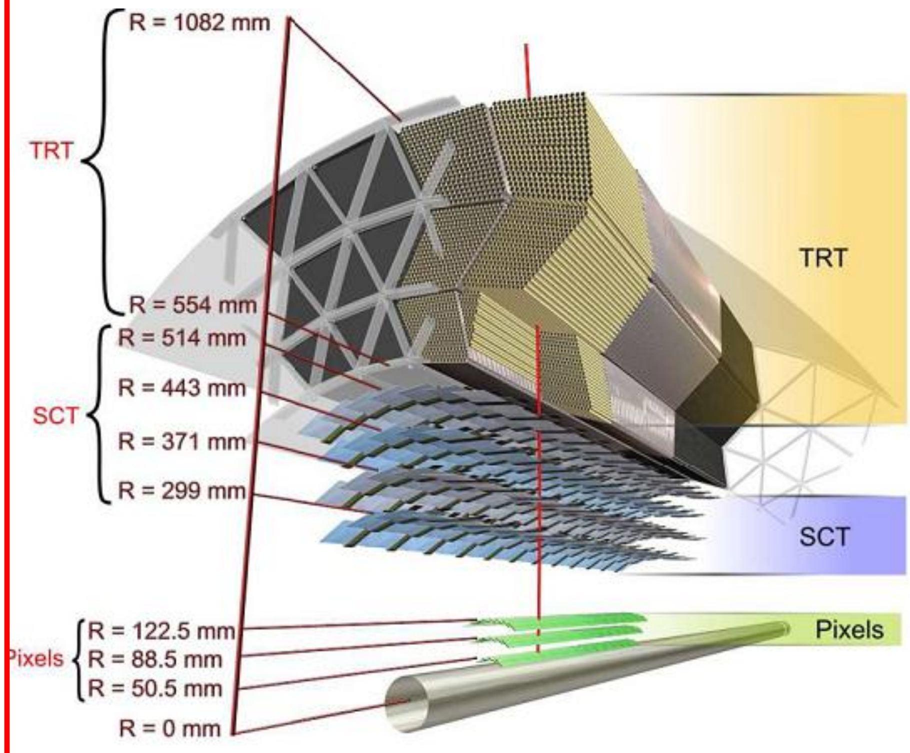
Phase-space $n_{ch} \geq 1$, $|\eta| < 2.5$, $p_T > 500$ MeV

Event-level requirements:

- **MBTS1 trigger**
- =1 primary vertex in event*
- pile-up veto**: reject events with a second primary vertex with 4 or more tracks
- **≥1 "primary track" in event**

"Primary track" selection:

- **track $p_T > 500$ MeV** and **track $|\eta| < 2.5$**
- a minimum of one Pixel and **six SCT** (Semiconductor Tracker) hits on the track
- $|d0_{PV}| < 1.5$ mm and $|z0_{PV}|\sin\theta < 1.5$ mm, impact parameters w.r.t primary vertex



*Single primary vertex in event shown to reduce contribution from beam-background and pile-up events to neglible level

**studies were done with early data, before pile-up became significant

Event-level corrections

Event-level correction uses **trigger and vertex efficiency derived from data to** **correct for missing events due to event selection critera**

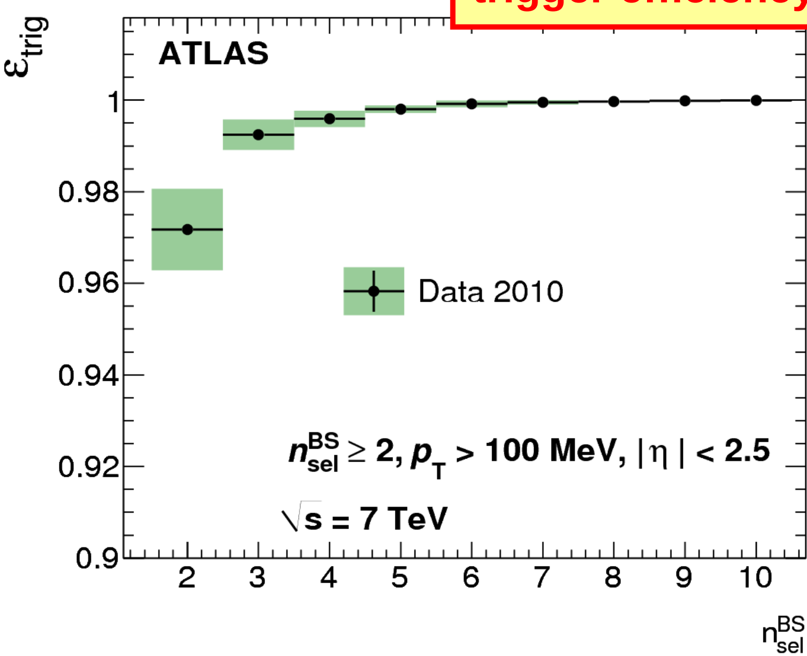
Corrections derived seperately for all different phase-spaces

Measure trigger efficiency of MBTS with respect to control trigger

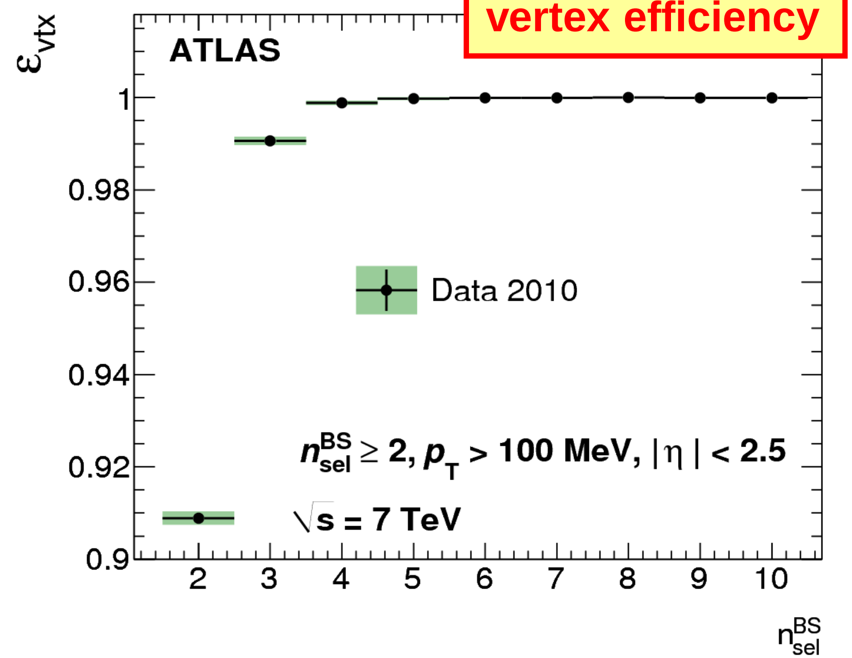
Control trigger: random trigger coincident with colliding bunches with at least 4 pixel clusters and at least 4 SCT space points measurements

MBTS trigger almost fully efficient for chosen phasespace except for slightly lower efficiency in low multiplicity events

trigger efficiency



vertex efficiency



Primary vertex reconstruction requires at least two tracks with: p_T > 100 MeV, $|d0_{BS}|$< 4 mm, ≧ 1 pixel hit and ≧ 4 SCT-hits and ≧ 6 SCT+Pixel hits

Vertex reconstruction efficiency measured in data using all triggered events

For n^{BS}_{Sel}<3, vertex reconstruction efficiency is corrected in bins of η

Track-to-particle corrections

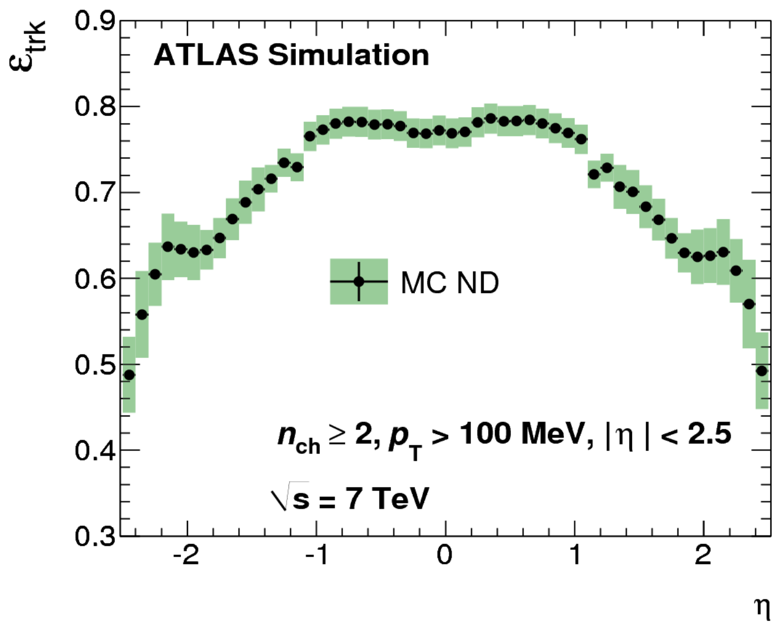
Track-to-particle correction uses track reconstruction efficiency derived from simulation

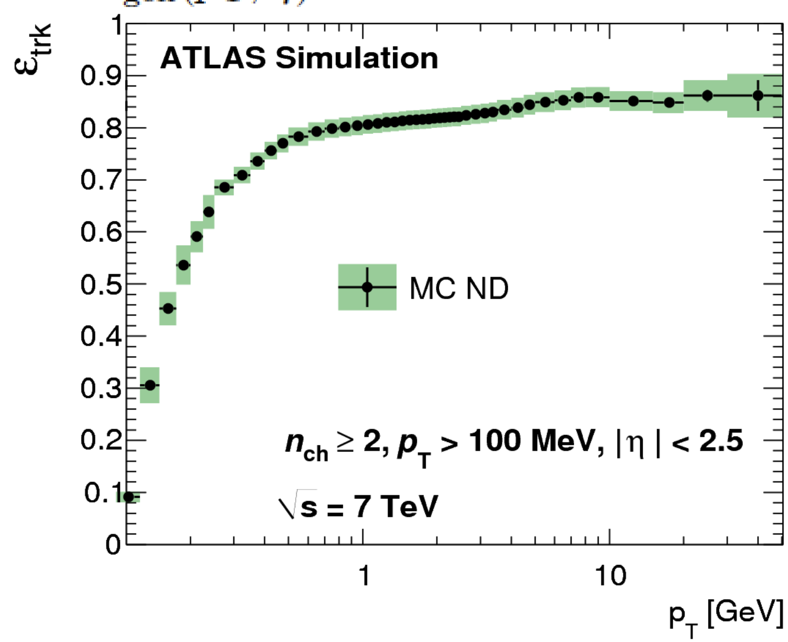
Systematic uncertainty of tracking efficiency based on data/simulation comparison

Track reconstruction efficiency is determined from MC sample using 10 million non-diffractive events at 7 TeV collisions from ATLAS MC09 tune

Efficiency based on track-truth matching between track and MC particle within a ΔR cone of 0.05

$$\epsilon_{\mathrm{bin}}(p_{\mathrm{T}}, \eta) = \frac{N_{\mathrm{rec}}^{\mathrm{matched}}(p_{\mathrm{T}}, \eta)}{N_{\mathrm{gen}}(p_{\mathrm{T}}, \eta)}$$



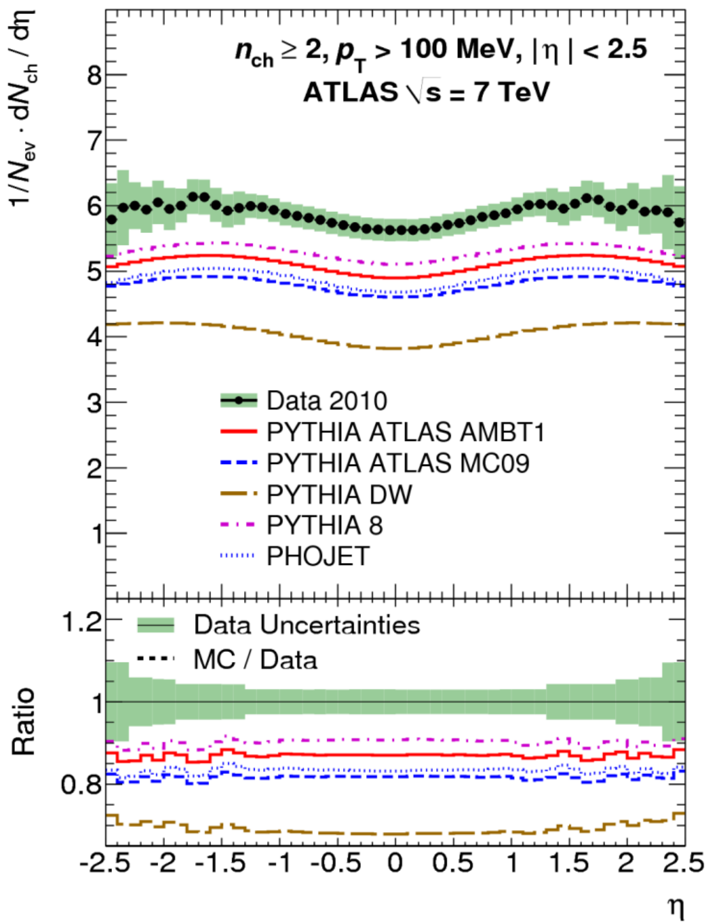


Correction for track reconstruction efficiency is made using 2D efficiency vs p_T and eta to remove model dependence from p_T and eta distributions

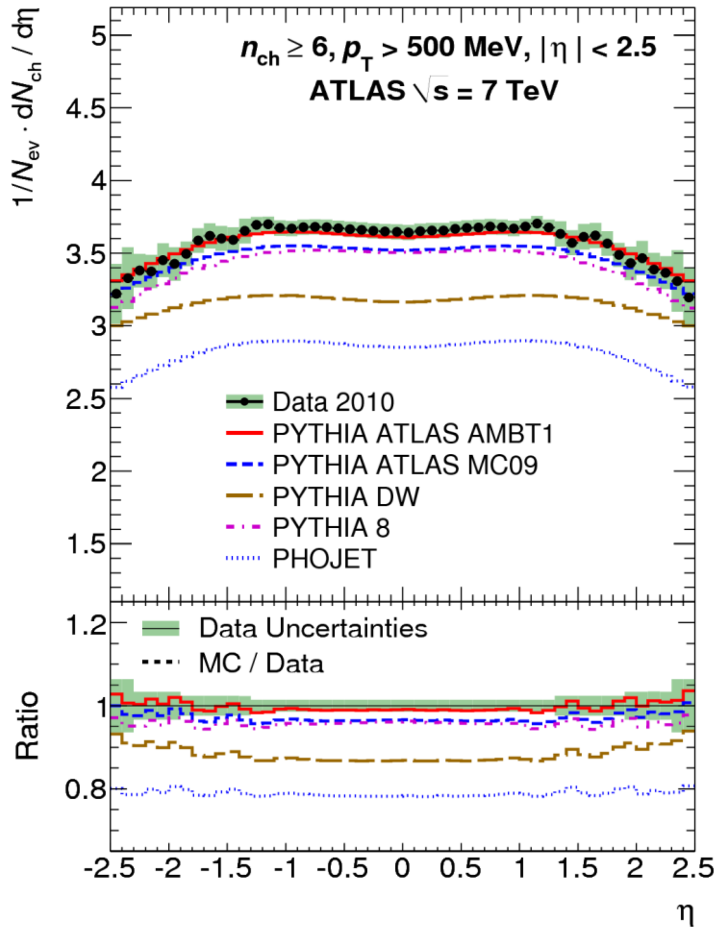
Track reconstruction efficiency derived seperately for all phase-spaces

Charged particle multiplicity vs η

"most-inclusive" phase-space

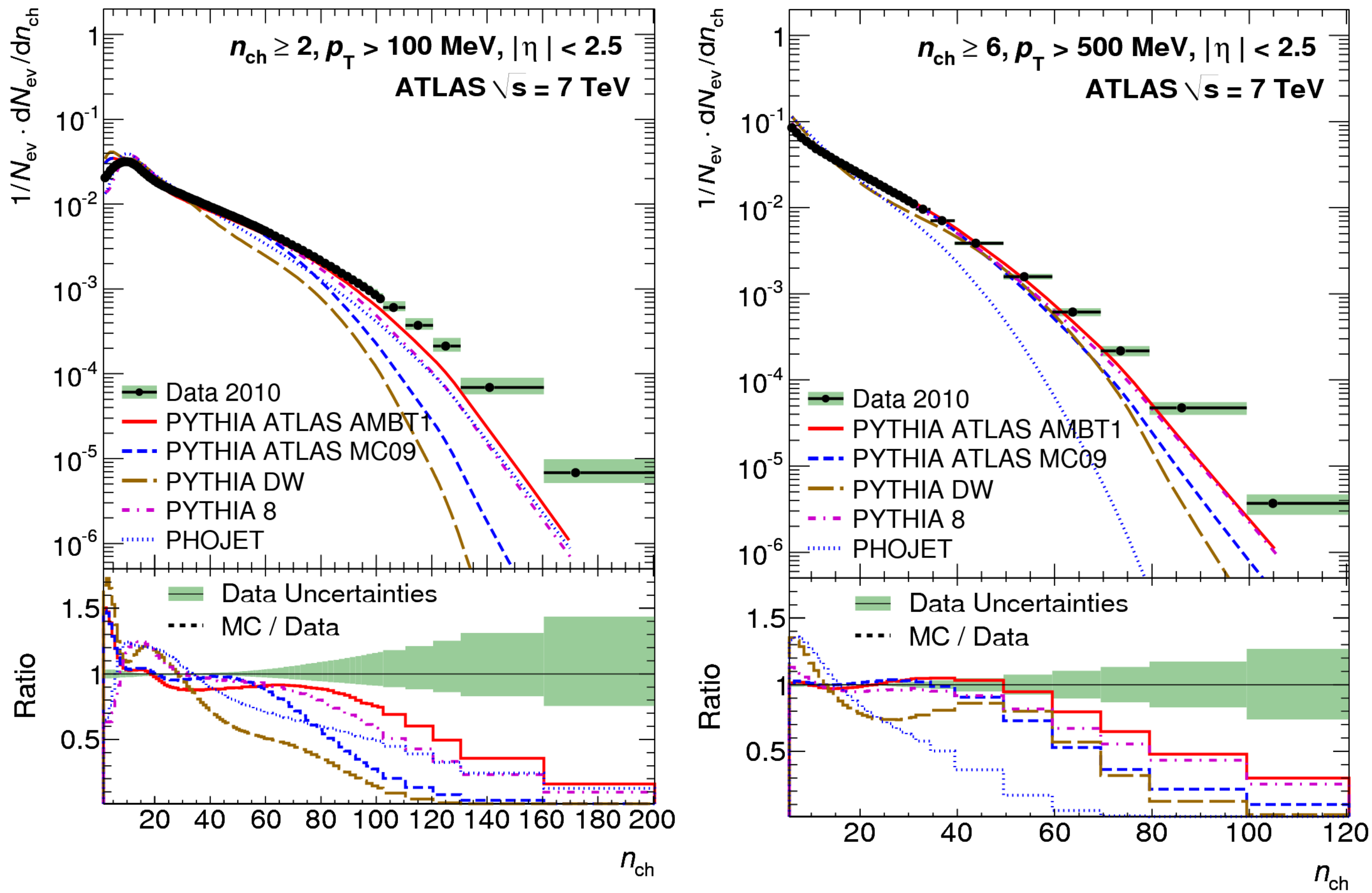


"diffraction surpressed" phase-space



Don't forget that AMBT1 prediction was tuned to match results in diffraction surpressed phase-space!

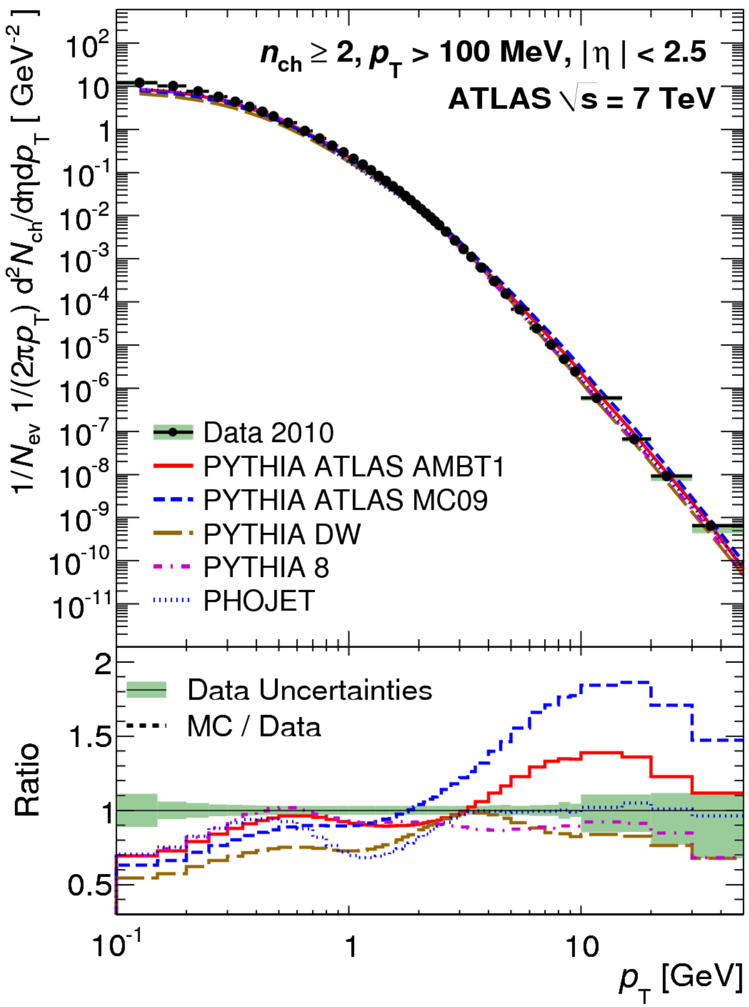
Charged particle multiplicy: N_{ch} spectra

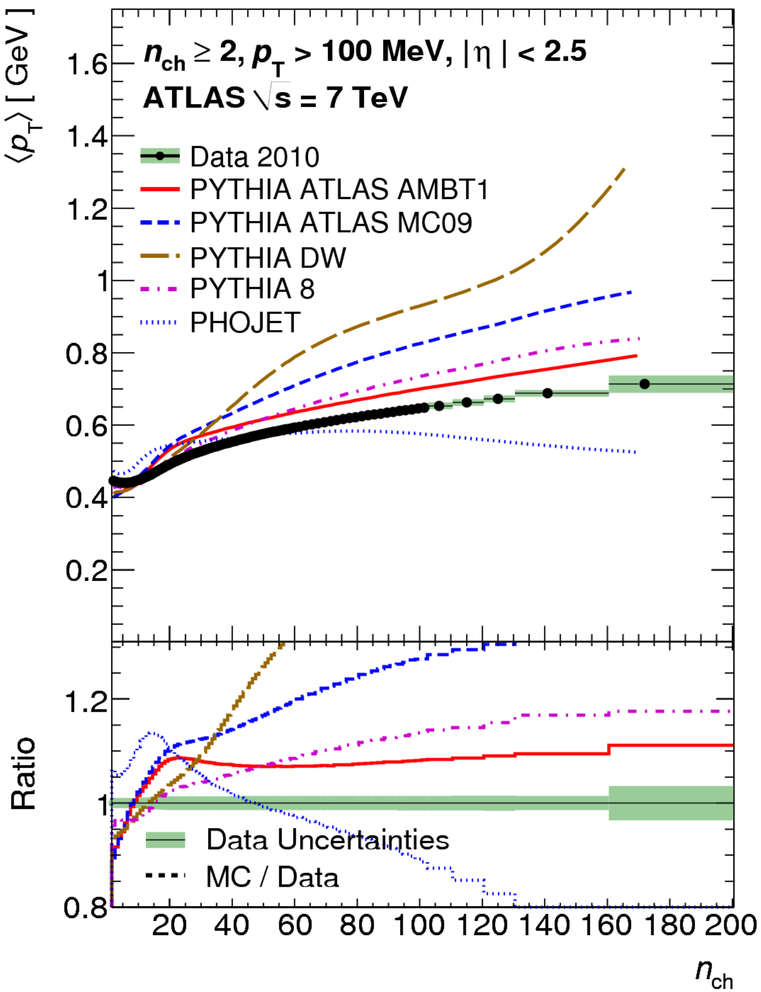


Excess of model over data at lower n_{ch} -> highly influenced by the modelling of diffractive events

AMBT1 tune improved description at high n_{ch}

p_T results



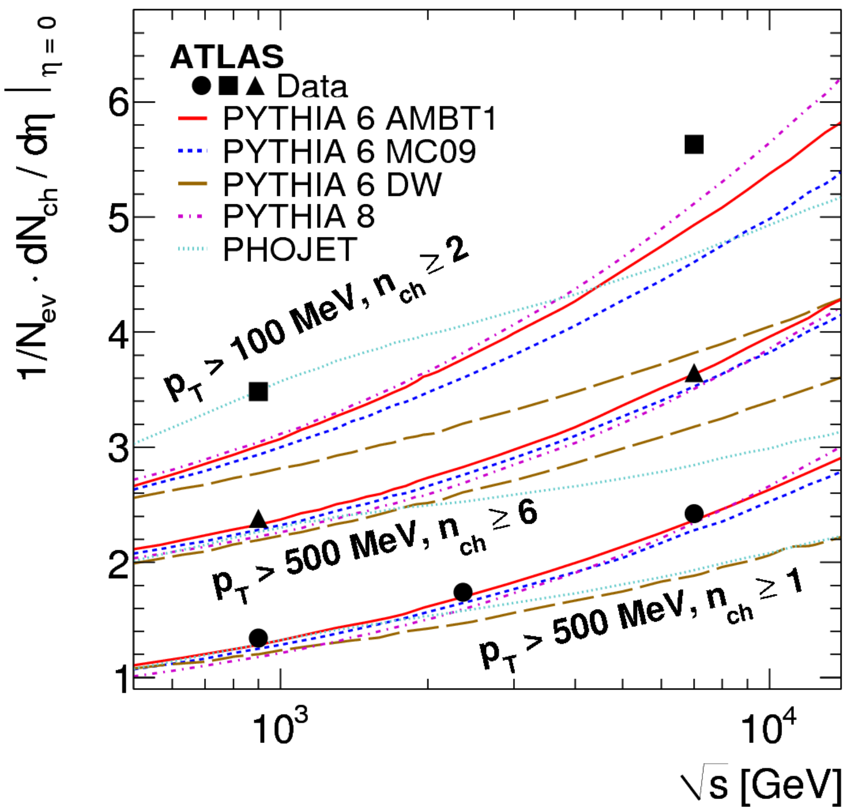


Simulation predicts a significantly harder spectrum at p_T>4 GeV

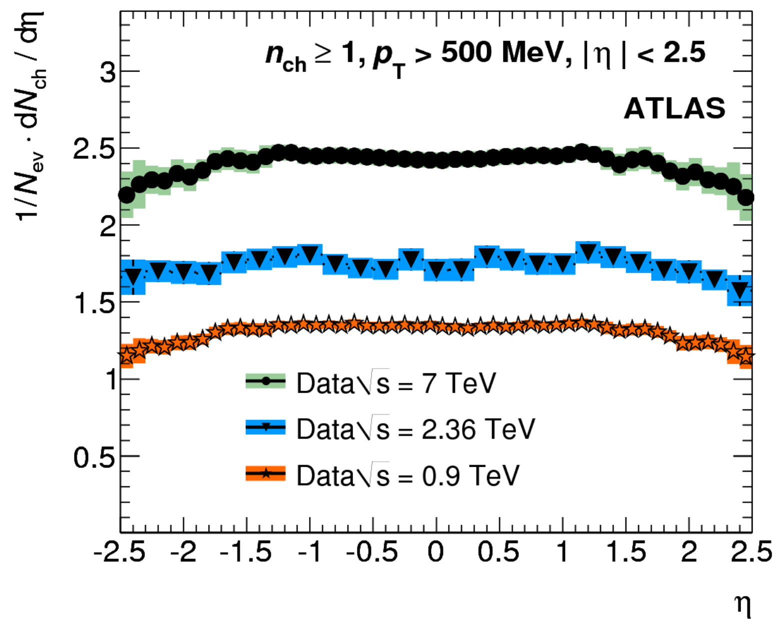
Average p_T vs n_{ch} lower than predicted

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

Measurement results for $1/N_{ev} \cdot dN_{ch}/d\eta$ at $\eta=0$ for all phase-spaces:



Minimum bias measurements made at $\sqrt{s}$ = 0.9, 2.36 and 7 TeV

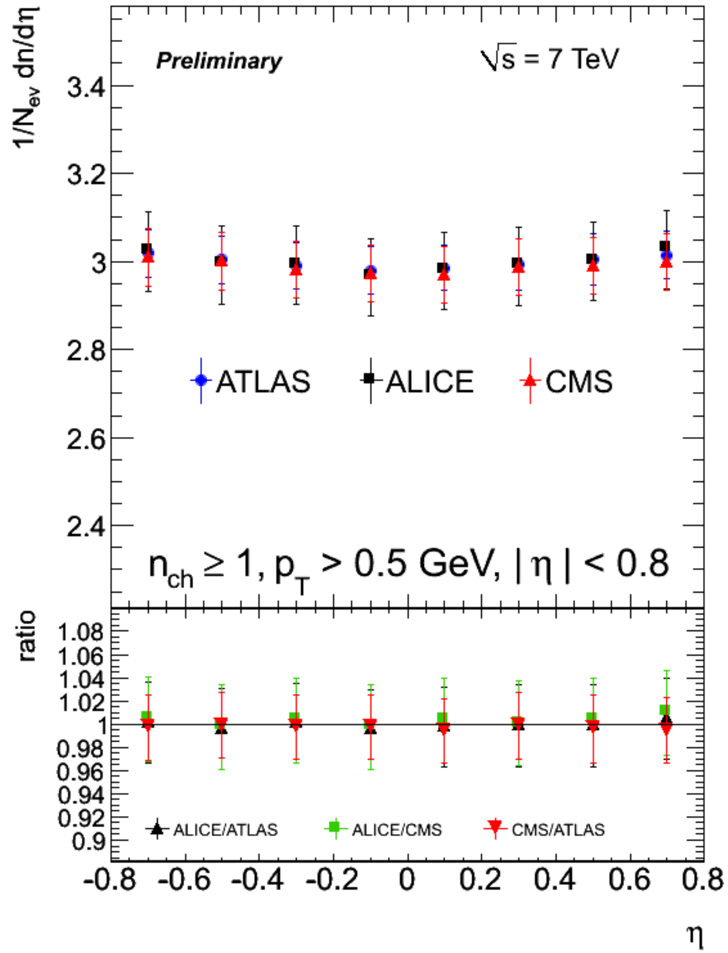


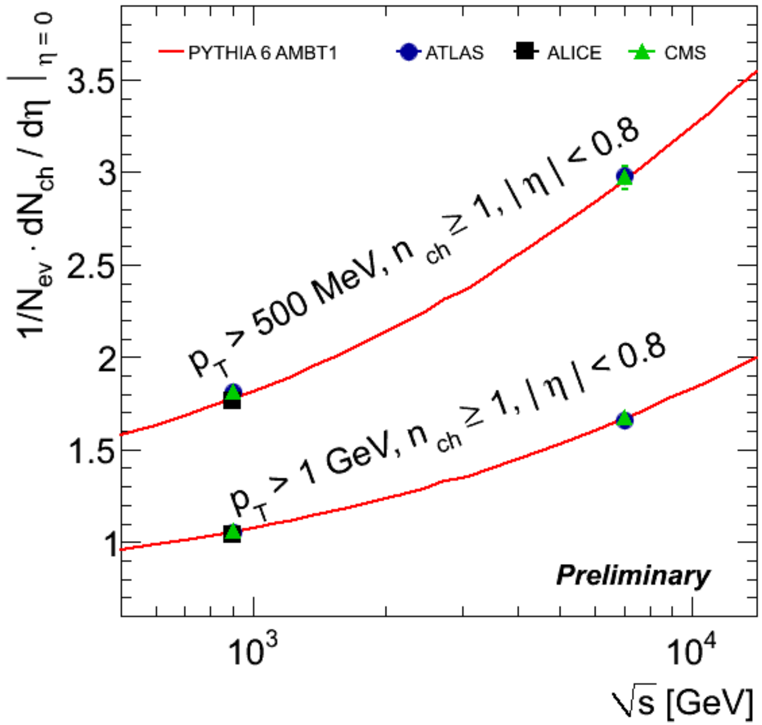
PYTHIA6 AMBT1 tune gives good description of energy dependence of the multiplicity for all phase-spaces except low-pt

Diffraction still not well understood, low-p_T region to be included in future tuning results

ATLAS/ALICE/CMS comparison

Common phase-spaces chosen by the *LHC's* "Minimum Bias & Underlying Event working group": p_T>500 MeV, $n_{ch} \geq 1$, $|\eta|<0.8$ and p_T>1 GeV, $n_{ch} \geq 1$, $|\eta|<0.8$





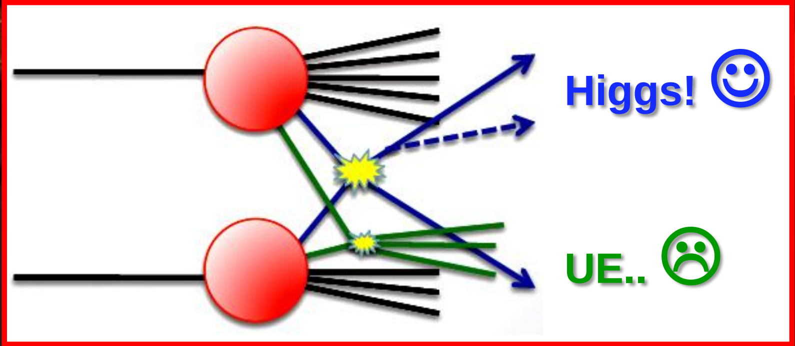
Good agreement of the measured charged particle multiplicity between the LHC experiments!

The Underlying Event

"Underlying Event": **everything else besides the hard scattering process**

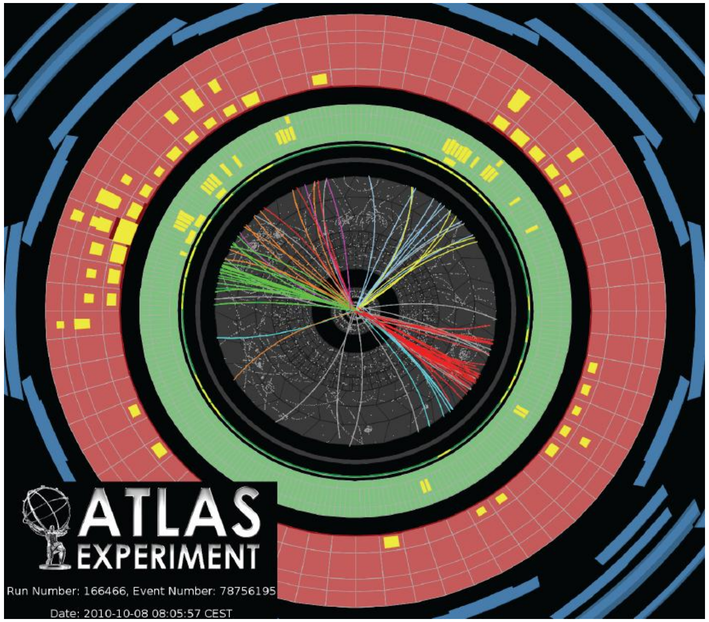
UE: additional partons *from the same proton* interact at the same time as signal interaction

As before: low momentum transfer, relying on phenomenological models tuned to data



Underlying Event measurements

Measure distributions sensitive to Underlying Event to understand Underlying Event properties at $\sqrt{s}$=7 TeV



Two **independent measurements** of UE in ATLAS:

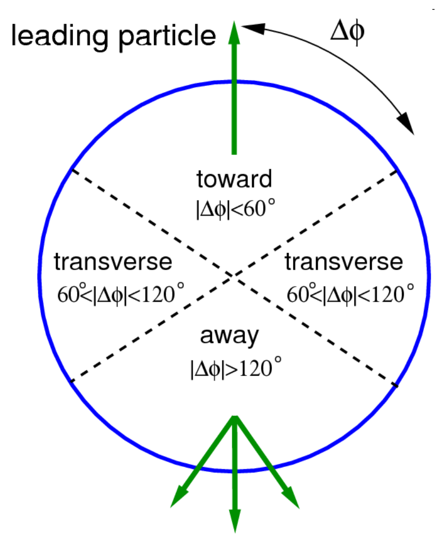
Track-based:

Use precise position measurements in the inner detector to reconstruct tracks of charged particles

Cluster-based:

Use granularity of the calorimeters to reconstruct three-dimensional energy depositions associated with indivual particles; charged & neutral!

Underlying Event measurements



Underlying Event activity is characterized by activity in φ region transverse to the leading particle *(=highest p_T track/cluster)*

Track-based UE: corrections for vertex, trigger and tracking efficiency similar as for minimum bias studies

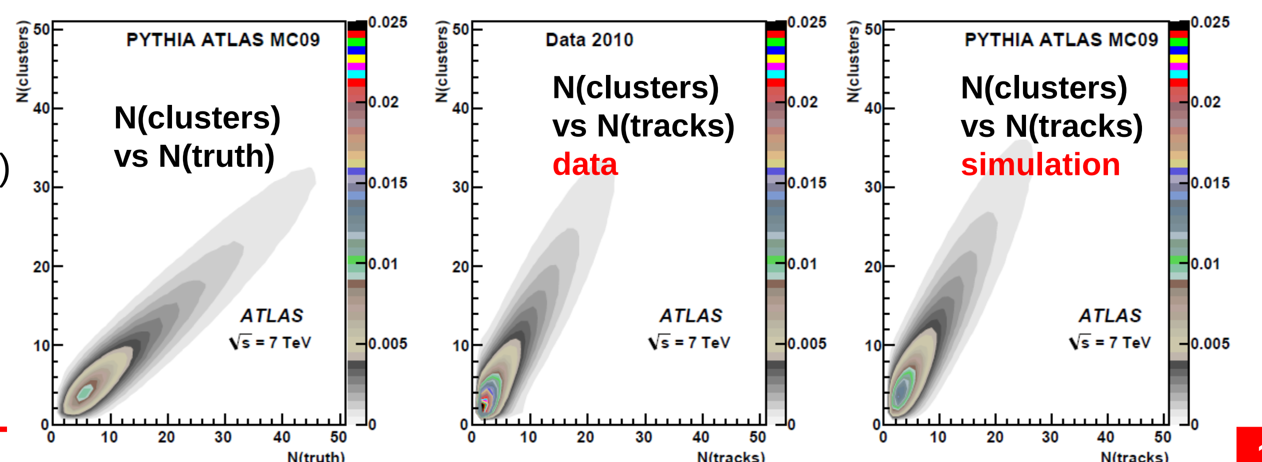
Cluster-based UE: cluster distributions are corrected to the stable-particle level using correction factor derived from MC:

$$C = \frac{A^{\mathrm{gen}}}{A^{\mathrm{det}}}$$

A^{gen}: number of generated stable-produced primary particles

A^{det}: number of measured calorimeter clusters

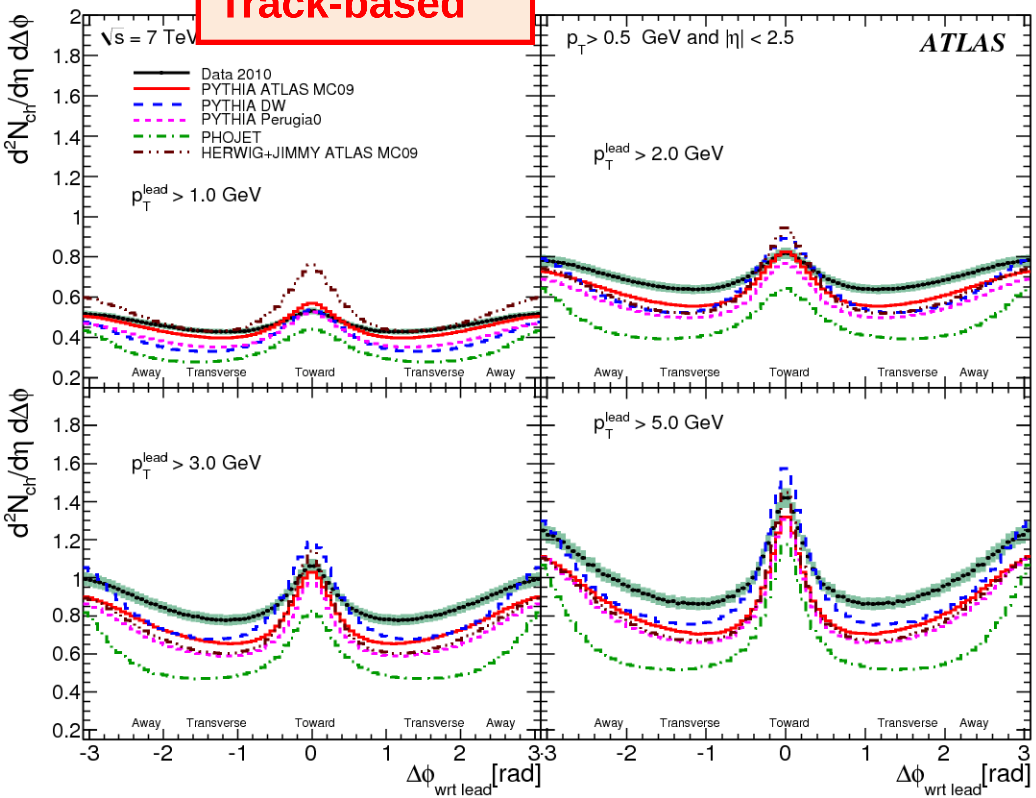
Cross-check using data/simulation comparison of N(clusters) vs N(tracks)



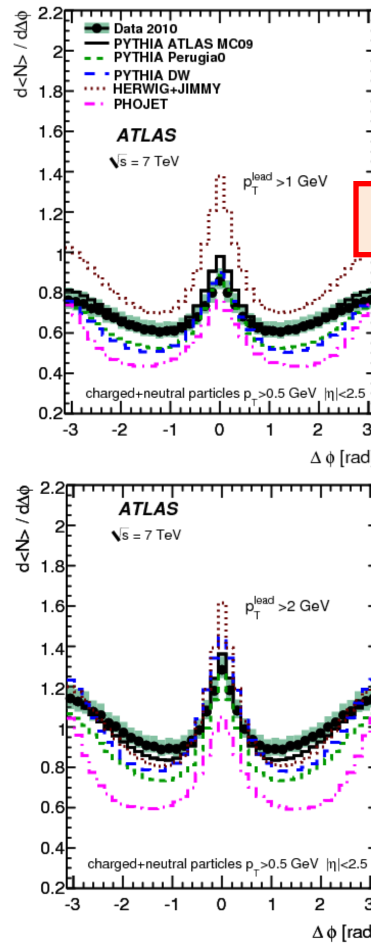
Particle density versus $\Delta\phi_{\text{wrt lead}}$

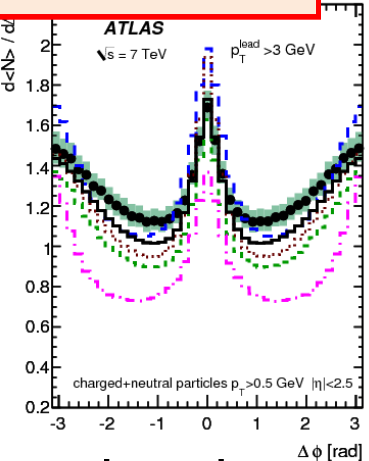
charged particles

Track-based



Cluster-based





charged +neutral particles

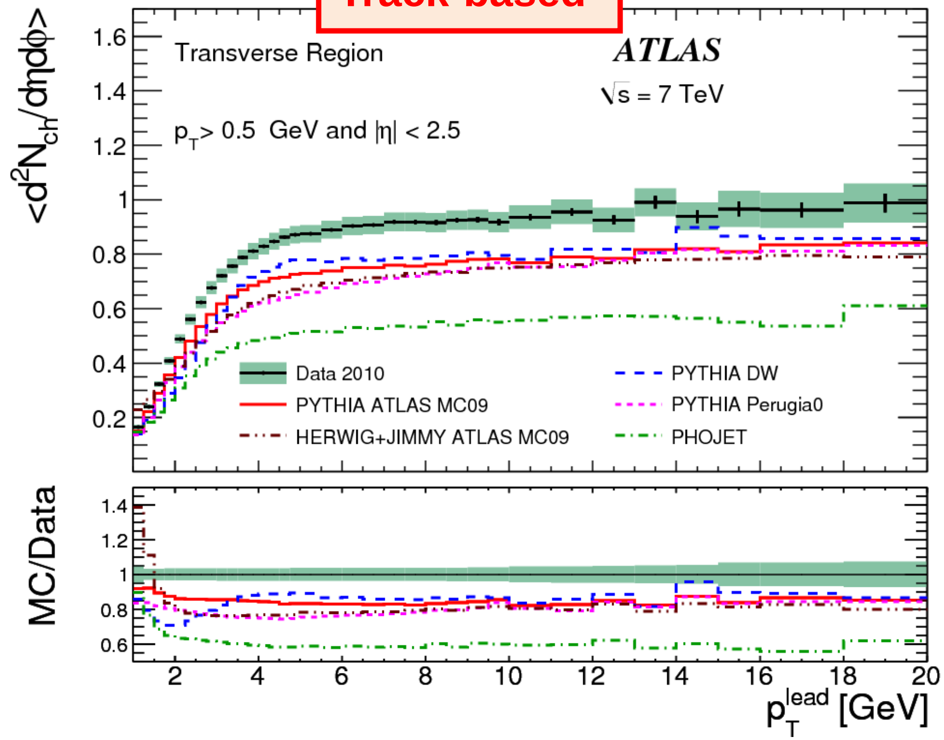
As the p_T of the leading track increases, the development of 'jet-like' region of higher density is observed adjacent to and opposite the leading track

Particle density is higher and has a different angular distribution than was predicted from the various Monte Carlo generators

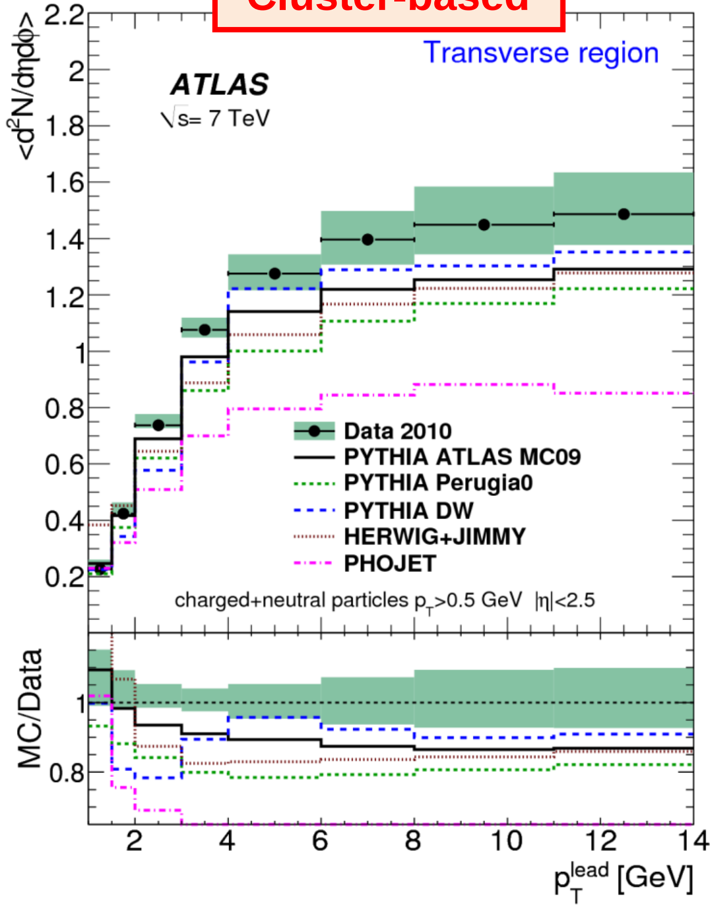
Particle density versus p_T^{lead}

Particle number density vs p_T^{lead} in the transverse region:

Track-based

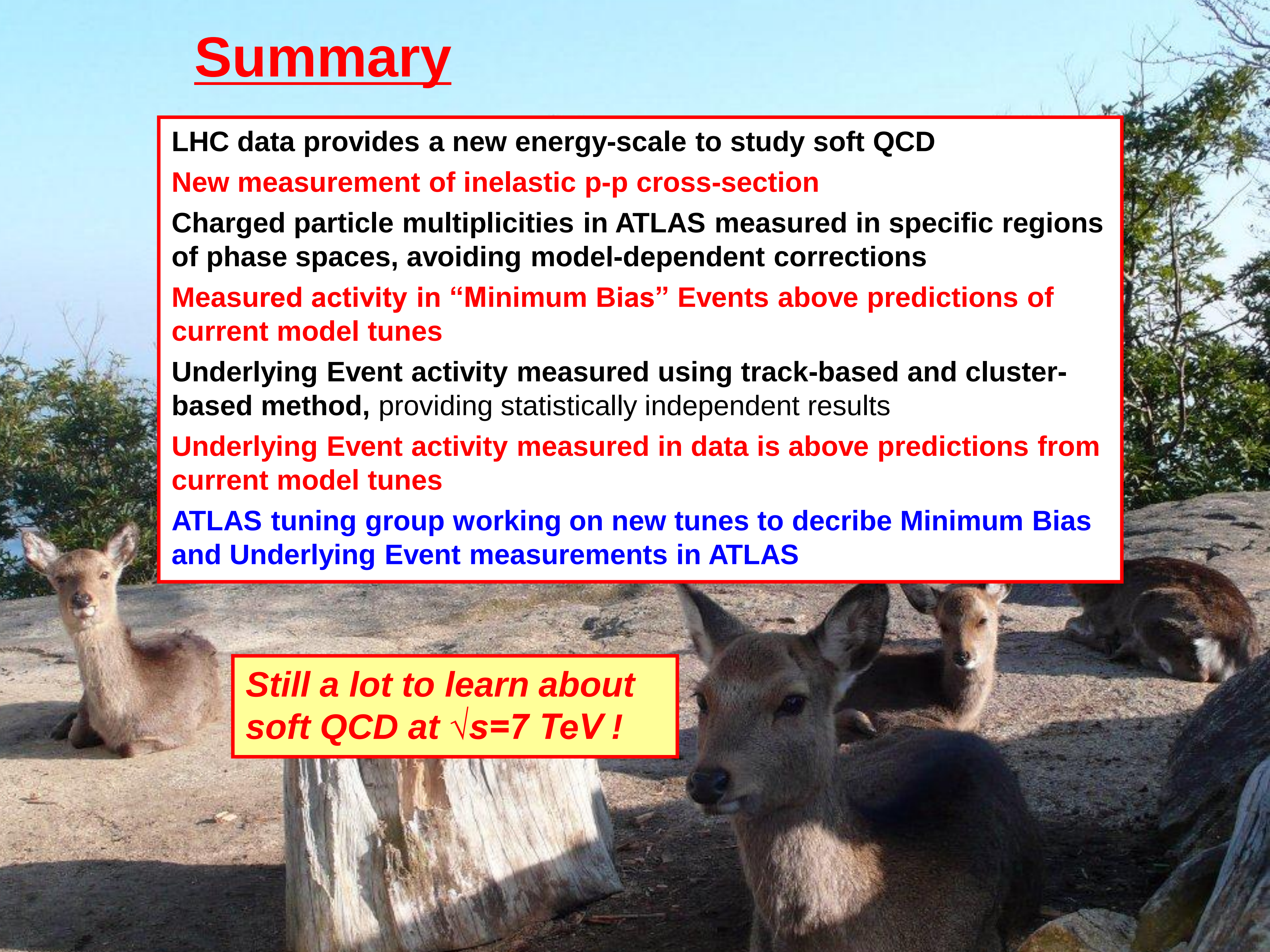


Cluster-based



Particle density is higher than predicted by any of the MC tunes

ATLAS tuning group currently working on new Pythia tune to improve description of Underlying Event results



Summary

LHC data provides a new energy-scale to study soft QCD

New measurement of inelastic p-p cross-section

Charged particle multiplicities in ATLAS measured in specific regions of phase spaces, avoiding model-dependent corrections

Measured activity in “Minimum Bias” Events above predictions of current model tunes

Underlying Event activity measured using track-based and cluster-based method, providing statistically independent results

Underlying Event activity measured in data is above predictions from current model tunes

ATLAS tuning group working on new tunes to decribe Minimum Bias and Underlying Event measurements in ATLAS

Still a lot to learn about soft QCD at $\sqrt{s}$=7 TeV !

References (in order of appearance in this talk!)

"Measurement of the inelastic proton–proton cross-section at √s=7 TeV with the ATLAS detector"

published 6 September 2011 in **Nature Comm. 2 (2011) 463**

"Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC"

published 18 May 2011 in **New J Phys 13 (2011) 053033**

Common plots from LHC MB & UE working-group:

http://lpcc.web.cern.ch/LPCC/index.php?page=mb_ue_wg_docs

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

published 31 May 2011 in **Phys. Rev. D 83, 112001**

"Measurements of underlying-event properties using neutral and charged particles in pp collisions at √s=900 GeV and √s=7 TeV with the ATLAS detector at the LHC"

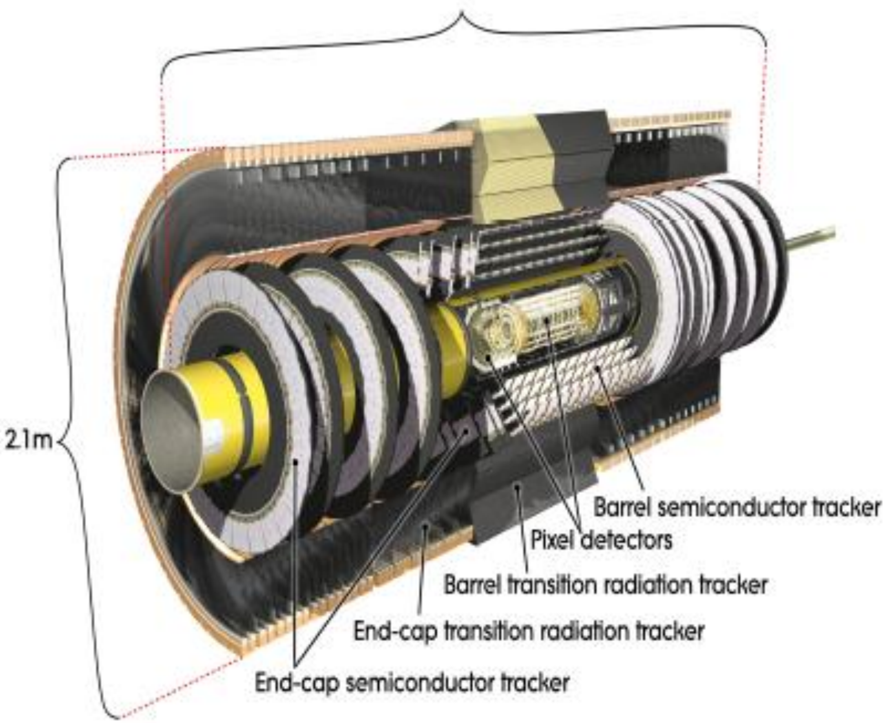
published 10 May 2011 in **EPJC 71 (2011) 1636**

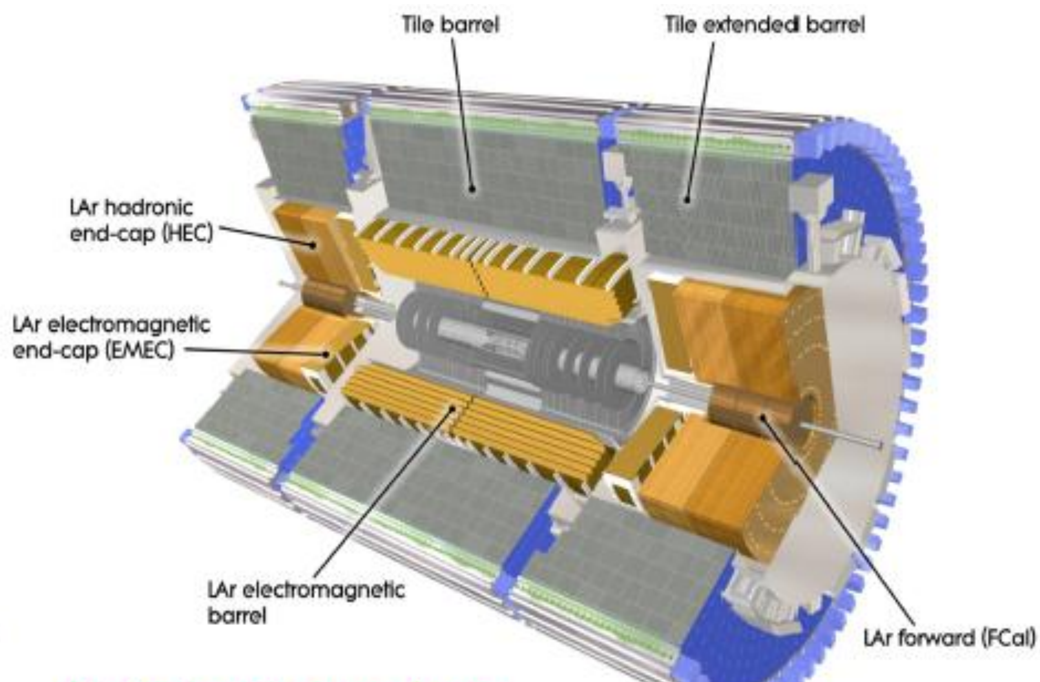
Backup!

ATLAS tracking and calorimeter

Tracking system

Pixel and SCT up to |η| < 2.5
TRT up to |η| < 2.0
(immersed in 2.0 T field)





Calorimeter system

Electromagnetic calorimeter up to |η| < 3.2
- with presampler up to |η| < 1.8

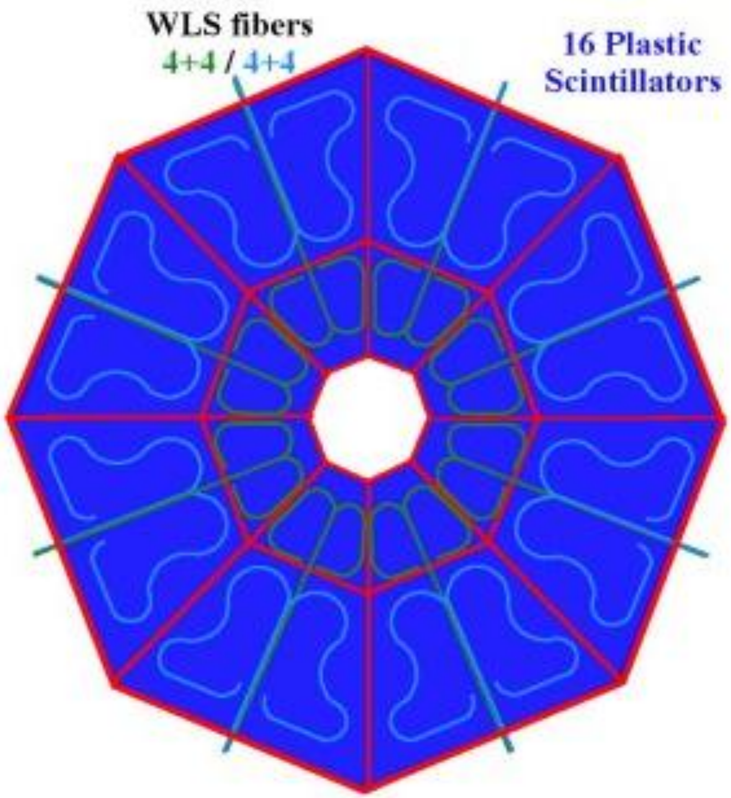
Hadronic calorimeter consists of
- Tile calorimeter up to |η| < 1.7
- Hadronic endcap for 1.5 < |η| < 3.2

Minimum Bias Trigger

Minimum Bias Trigger Scintillators (MBTS)

2 units in η (2.09 < η < 2.82, 2.82< η < 3.84)

z = -3560 mm, 8 units in φ

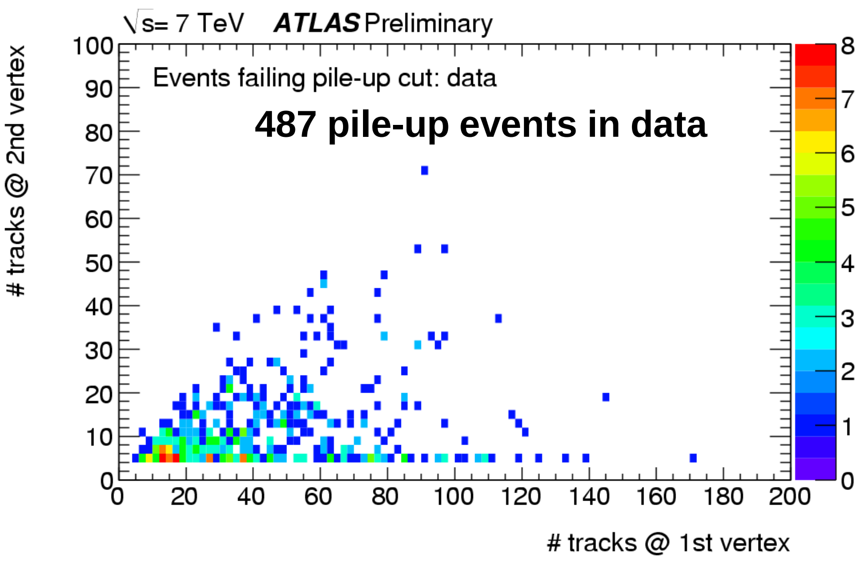


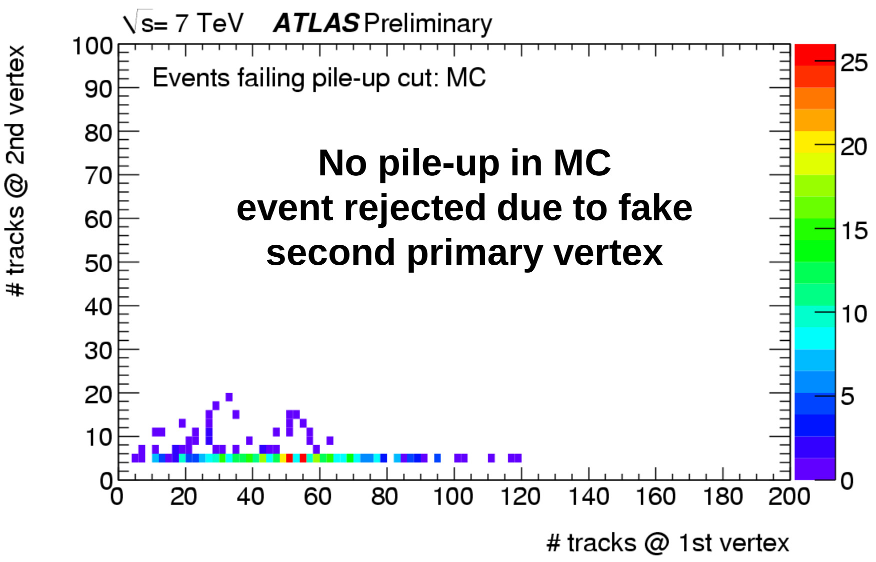
Used for Inelastic cross-section measurement and as trigger for minimum bias events

Pile-up veto

Take into account possibility of multiple proton-proton interactions inside same bunch crossing by allowing reconstruction of multiple primary vertices

pile-up veto: reject events with a second primary vertex with 4 or more tracks





Expected fraction of pile-up events is 10^{-3} at LHC conditions for this data

487 events were removed by pile-up veto, corresponding to 0.1% of our data

Fraction of removed events that are not true pile-up is estimated to be 0.03%.

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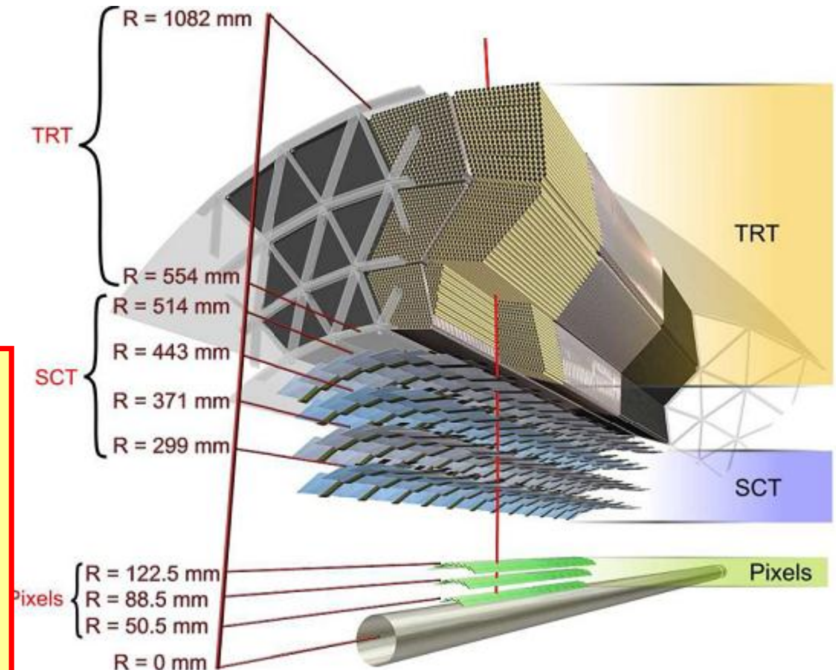
Track reconstruction

Charged particle with p_T>0.5 GeV passing through full ATLAS inner detector produces on average:

- 3 silicon pixel hits
- 8 SemiConductor Tracker (SCT) hits
- (2 overlapping silicon strips per SCT module)
- ~30 Transition Radiation Tracker (TRT) hits



"Primary track" definition

- **track p_T > 500 MeV and track $|\eta|$< 2.5**
- **a minimum of one Pixel and six* SCT (Semiconductor Tracker) hits on the track**
- **$|d0_{PV}|$ < 1.5 mm and $|z0_{PV}|\sin\theta$ < 1.5 mm,** impact parameters with respect to primary vertex

Rate of secondaries passing primary track cuts measured from data using fit of d0 distribution

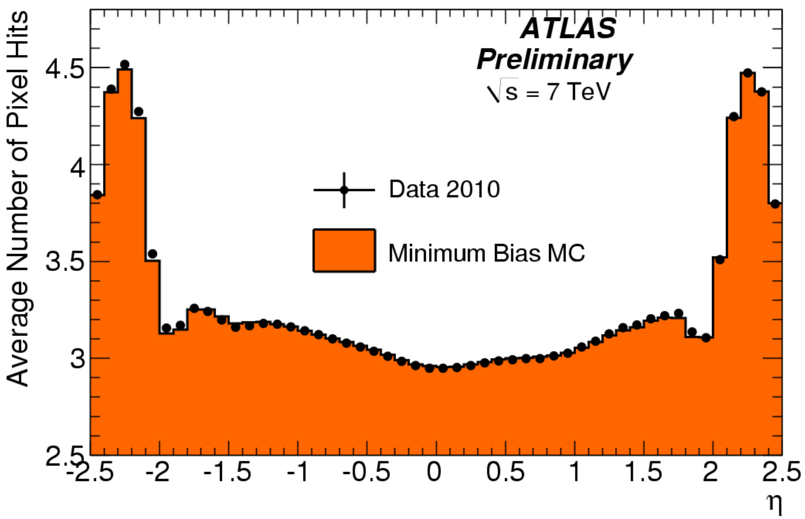
Track reconstruction efficiency determined from simulation

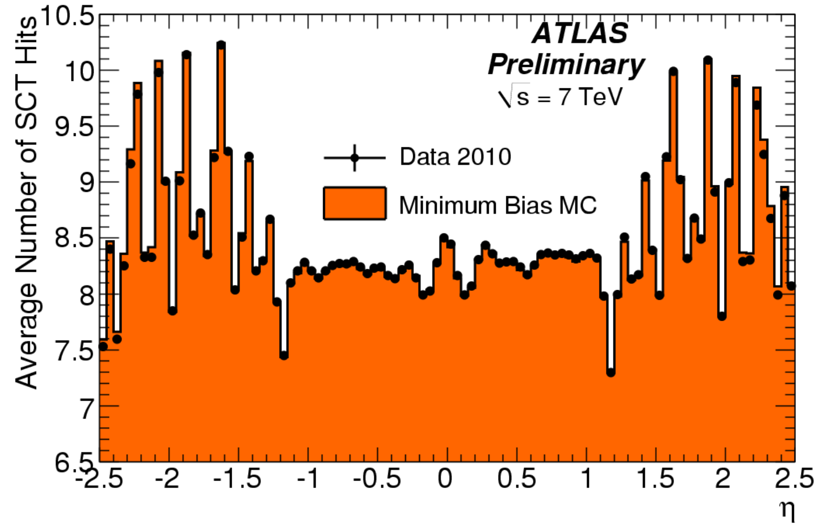
Simulation of the ATLAS silicon detectors found to describe the data to high accuracy

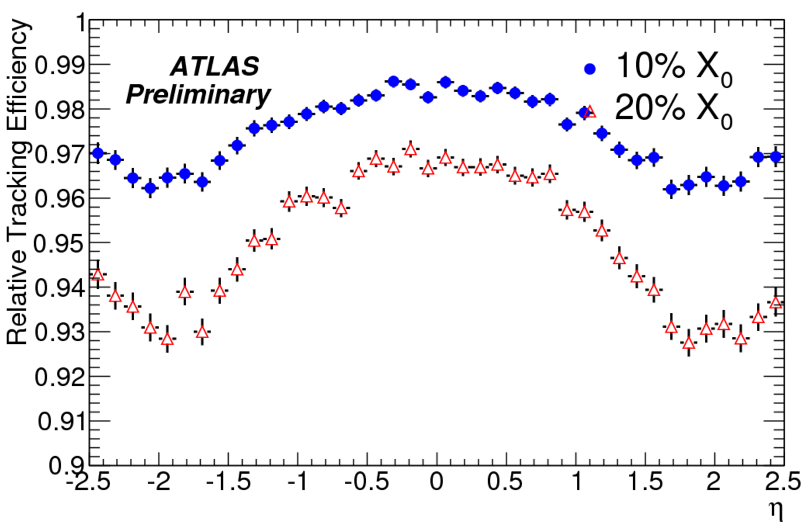
Differences between simulation and data are expressed as systematic uncertainty on tracking efficiency

Data/simulation comparison

Good agreement between data and MC for number of silcion hits on track:







Largest systematic uncertainty comes from material description in simulation

upper limit of 10% uncertainty on material gives 3% uncertainty on track reconstruction efficiency

Disagreement between data/simulation adds increased uncertainty in specific eta regions

Minimum Bias Correction procedure

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Events lost due to trigger and vertex requirements are corrected using a weight per event:

$$w_{\mathrm{ev}}(n_{\mathrm{Sel}}^{\mathrm{BS}}) = \frac{1}{\varepsilon_{\mathrm{trig}}(n_{\mathrm{Sel}}^{\mathrm{BS}})} \cdot \frac{1}{\varepsilon_{\mathrm{vtx}}(n_{\mathrm{Sel}}^{\mathrm{BS}})}$$

where $\varepsilon_{\mathrm{trig}}(n_{\mathrm{Sel}}^{\mathrm{BS}})$ and $\varepsilon_{\mathrm{vtx}}(n_{\mathrm{Sel}}^{\mathrm{BS}})$ are the trigger and vertex reconstruction efficiencies.

The p_T and η distributions of selected tracks are corrected by using a weight for each track:

$$w_{\mathrm{trk}}(p_{\mathrm{T}}, \eta) = \frac{1}{\varepsilon_{\mathrm{bin}}(p_{\mathrm{T}}, \eta)} \cdot (1 - f_{\mathrm{sec}}(p_{\mathrm{T}})) \cdot (1 - f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta))$$

where ε_{bin} is the track reconstruction efficiency, $f_{\mathrm{sec}}(p_{\mathrm{T}})$ is the fraction of secondaries and $f_{\mathrm{okr}}(p_{\mathrm{T}}, \eta)$ is the fraction of the selected tracks produced by particles outside the kinematic range

The 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}

$M_{Nch,Nsel}$ is populated from MC but the resulting distribution is n_{ch} used to re-populate the matrix and the correction is re-applied to remove model dependence. This procedure is repeated till it converges after four iterations

Minimum Bias systematics

Largest contribution for Minimum Bias systematics comes from tracking efficiency correction:

Systematic Uncertainty	Size	Region
Material	$\pm 2 - 15\%$	decreases with p_T, increases with $\|\eta\|$
χ^2 prob. cut	$\pm 10\%$	flat, only for $p_T > 10$ GeV
Resolution	$\pm 5\%$ negligible -7%	$100 < p_T < 150$ MeV $0.15 < p_T < 10$ GeV $p_T > 10$ GeV
Track Selection	$\pm 1\%$	flat in p_T and η
Truth Matching	$\pm 1\%$	only for $\sqrt{s} = 2.36$ TeV Pixel Tracks
Efficiency correction factor	$\pm 4\%$	only for $\sqrt{s} = 2.36$ TeV ID Track
Alignment and other high p_T	-3% to -30%	only for $p_T > 10$ GeV averaged over η , increases with increasing p_T

Table 5: The systematic uncertainties on the track reconstruction efficiency for $\sqrt{s} = 0.9$ TeV, $\sqrt{s} = 7$ TeV and $\sqrt{s} = 2.36$ TeV Pixel Track and ID Track methods. Unless otherwise stated, the systematic is similar for all energies and phase-space regions. All uncertainties are quoted relative to the track reconstruction efficiency.

The ATLAS Minium Bias Tune 1

ATLAS MBT1: Adaption of ATLAS MC09c tune to the new LHC data

Tune 6 model parameters for multiple particle interaction (MPI) and color reconnection (CR)

Parameter	Related model	MC09c value	scanning range	AMBT1 value
PARP(62)	ISR cut-off	1.0	fixed	1.025
PARP(93)	Primordial kt	5.0	fixed	10.0
PARP(77)	CR suppression	0.0	0.25 − − − 1.15	1.016
PARP(78)	CR strength	0.224	0.2 − − − 0.6	0.538
PARP(83)	MPI (matter fraction in core)	0.8	fixed	0.356
PARP(84)	MPI (core of matter overlap)	0.7	0.0 − − − 1.0	0.651
PARP(82)	MPI (p_T^{min})	2.31	2.1 − − − 2.5	2.292
PARP(90)	MPI (energy extrapolation)	0.2487	0.18 − − − 0.28	0.250

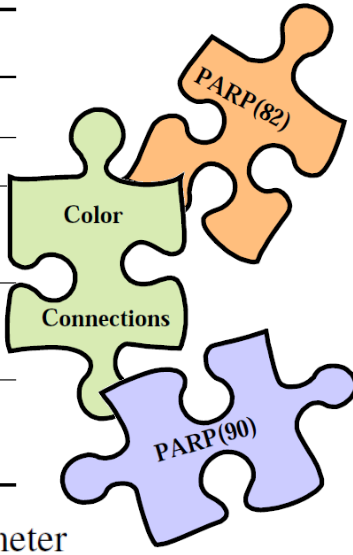
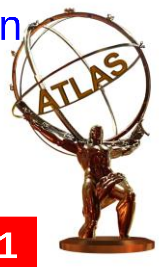


Table 5: Comparison of MC09c and resulting optimised parameters (AMBT1). The range for parameter variations in AMBT1 are also given.

Inclusion of new parameter (parp77) for suppression of color reconnection in fast moving strings to describe <pt> vs nch

Force tuning of interesting regions using weights and regions of the data distribution

CDF data included in tuning to remain consistent with previous measurements



UE track-based systematics

TABLE II. Summary of systematic uncertainties, shown for the lowest-, intermediate- and highest-p_T bins. For the analysis with 7 TeV (900 GeV) center-of-mass energy data, the lowest-p_T bin refers to $p_T^{lead} = 1.0 - 1.5$ GeV, the intermediate p_T bin refers to $p_T^{lead} = 9 - 10$ GeV ($4 - 5$ GeV), and the highest p_T bin refers to $p_T^{lead} = 18 - 20$ GeV ($9 - 10$ GeV). The uncertainties shown are from the transverse region charged $\sum p_T$ distribution, and all the other profiles are estimated to have comparable or less systematic uncertainty. Each uncertainty is given relative to the profile value at that stage in the correction sequence and they are an average over all of the phase-space values. In the cases where the uncertainties are different for 900 GeV and 7 TeV analysis, the 900 GeV value is shown in parentheses.

Leading charged particle bin	Lowest-p_T	Intermediate-p_T	Highest-p_T
Systematic uncertainty on unfolding			
PYTHIA/PHOJET difference	4%	2%	2%
PYTHIA unfolding stat. uncertainty	< 0.1%	1% (2%)	4% (5%)
Systematic uncertainties from efficiency corrections			
Track reconstruction	3%	4%	4%
Leading track requirement	1%	< 0.1%	< 0.1%
Trigger and vertex efficiency	——	< 0.1% (everywhere)	——
Total from efficiency corrections	2.5%	4%	4%
Systematic uncertainty for bin migration			
Bin migration due to mismeasured p_T	-	2.5% (0%)	5% (0%)
Total systematic uncertainty	4.5%	4.5% (5%)	8% (6.5%)

MC-based unfolding procedure: to take into account that migration of the leading track from the lower-p_T bins to higher ones is possible

due to the steeply-falling p_T spectrum in minimum bias events, the number of events in low-p_T bins of these profiles is much higher than in the higher-p_T bins

UE cluster-based correction procedure

A bin-by-bin correction procedure for all measured observables:

$$p_{\mathrm{T}}^{\mathrm{lead}} \;;\; d\langle N\rangle/d\Delta\phi \;;\; \langle d^2N/d\eta d\phi\rangle \;;\; \langle d^2\sum p_{\mathrm{T}}/d\eta d\phi\rangle$$

Observed cluster distributions are corrected to the stable-particle level using a correction factor: (derived seperately for each observable)

$$C = \frac{A^{\mathrm{gen}}}{A^{\mathrm{det}}}$$

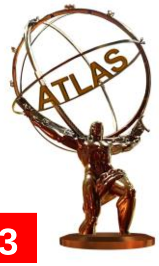
number of generated stable-produced primary particles

number of measured calorimeter clusters

Factor derived from simulated event generated with PYTHIA MC09 model
✓model dependence included in systematics

Correction factor includes the effects for:
- ✓**event selection**
- ✓**reconstruction efficiency**
- ✓**bin migrations**
- ✓**smearing,** including the case when the leading particle is mis-identified and a cluster corresponding to a subleading is used to define the event orientation

Typical value of bin-by-bin correction factors around 1.3
Largest contributor is the reconstruction inefficiency of topological clusters, leads to a correction factor of approximately 1.2 on average



UE cluster-based systematics

Systematic uncertainties for calorimeter cluster-based underlying event measurements

Check	$d\langle N\rangle/d\Delta\phi$	$\langle d^2N/d\eta d\phi\rangle$	$\langle d^2\sum p_T/d\eta d\phi\rangle$
Energy scale	$\pm 4.3\%$	$\pm 4\%$	$\pm 5.6\%$
Additional material	$+3.5\%$	$+3\%$	$+3.6\%$
Model dependence	$\pm 3.5\%$	$\pm 5\%$	$\pm 4.5\%$
Multiplicity reweighting	$\pm 4.5\%$	$\pm 10\%$	$\pm 11\%$
Resolution reweighting	$\pm 0.4\%$	$\pm 6\%$	$\pm 6\%$

Table 1. A summary of the most important systematic uncertainties. The table lists the values of contributions from different groups of systematic checks. Only the largest values are shown, taken from the bins with the largest effect when the systematic variation was applied.