Minimum Bias and Underlying Event Measurements with ATLAS

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(on behalf of the ATLAS Collaboration)

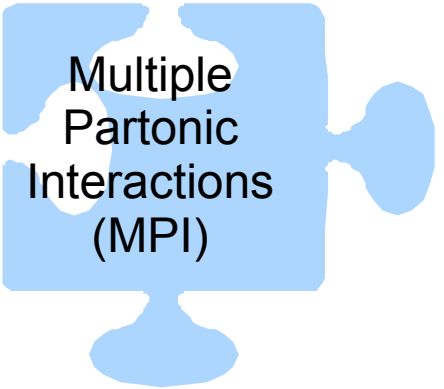
Workshop on Multi-Parton Interactions at the LHC

DESY, Hamburg

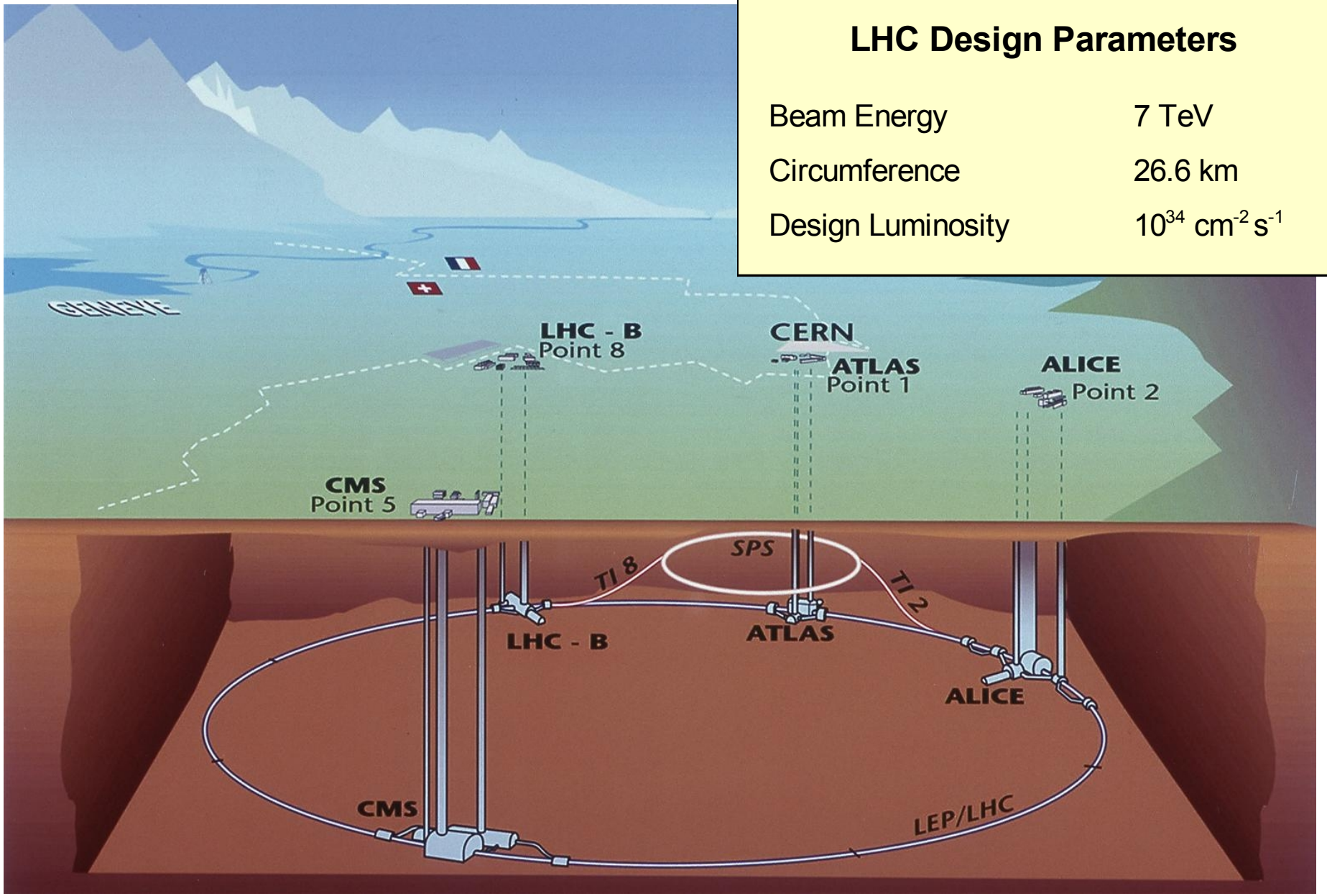
21 November 2011

Outline

- LHC / ATLAS
- QCD at the LHC
- Charged particle distributions
- Two-particle correlations
- Azimuthal ordering of hadrons
- K^0_s and Λ production
- Underlying Event
- Summary



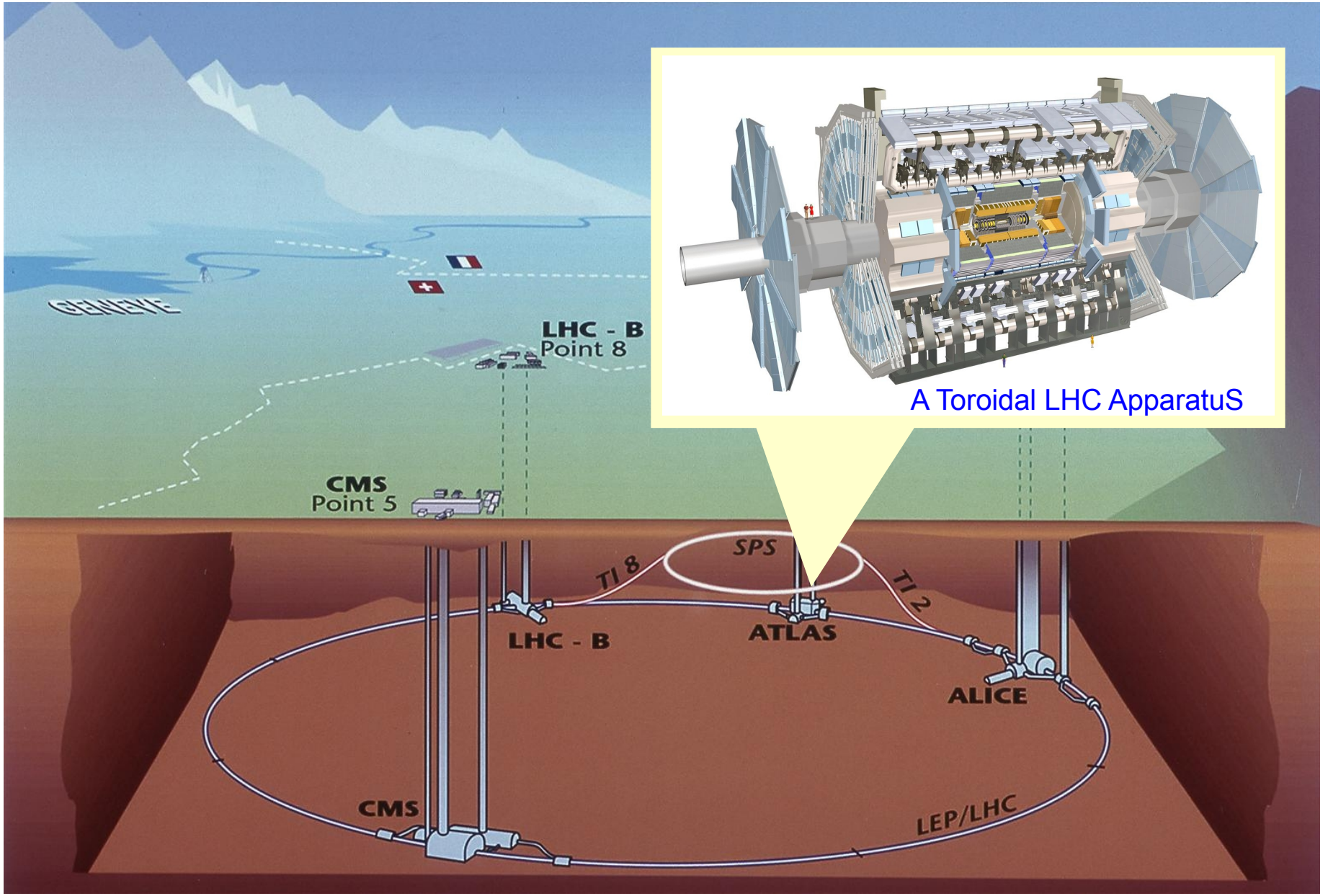
The LHC



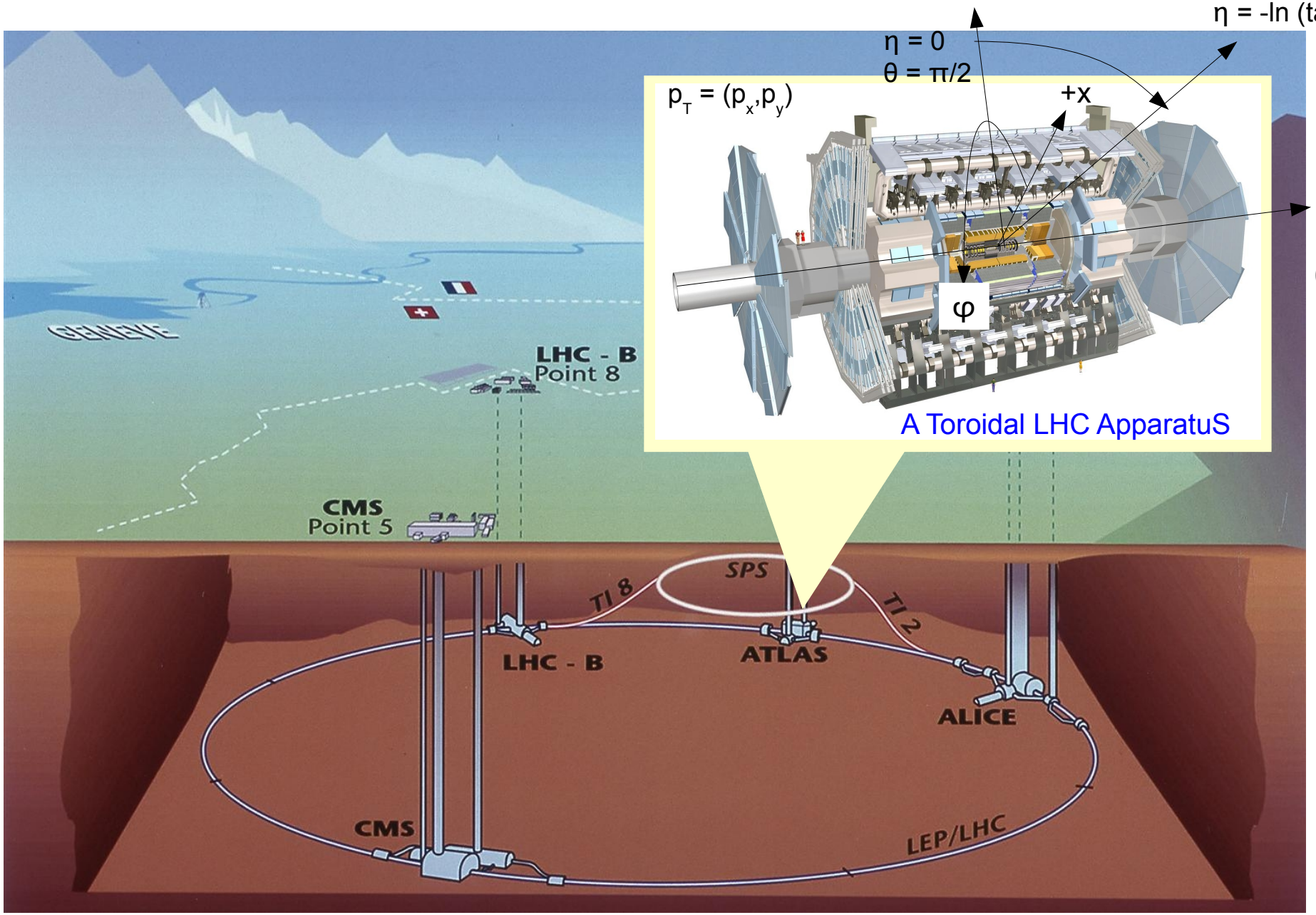
LHC Design Parameters

Beam Energy	7 TeV
Circumference	26.6 km
Design Luminosity	10^{34} cm^{-2} s^{-1}

ATLAS


GENEVE
LHC - B
Point 8
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
A Toroidal LHC ApparatuS

ATLAS


η = -ln (tan θ/2)
η = 0
θ = π/2
$p_T = (p_x,p_y)$
+x
+z
η = +∞
θ = 0
φ
A Toroidal LHC ApparatuS
GENEVE
LHC - B
Point 8
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC

ATLAS

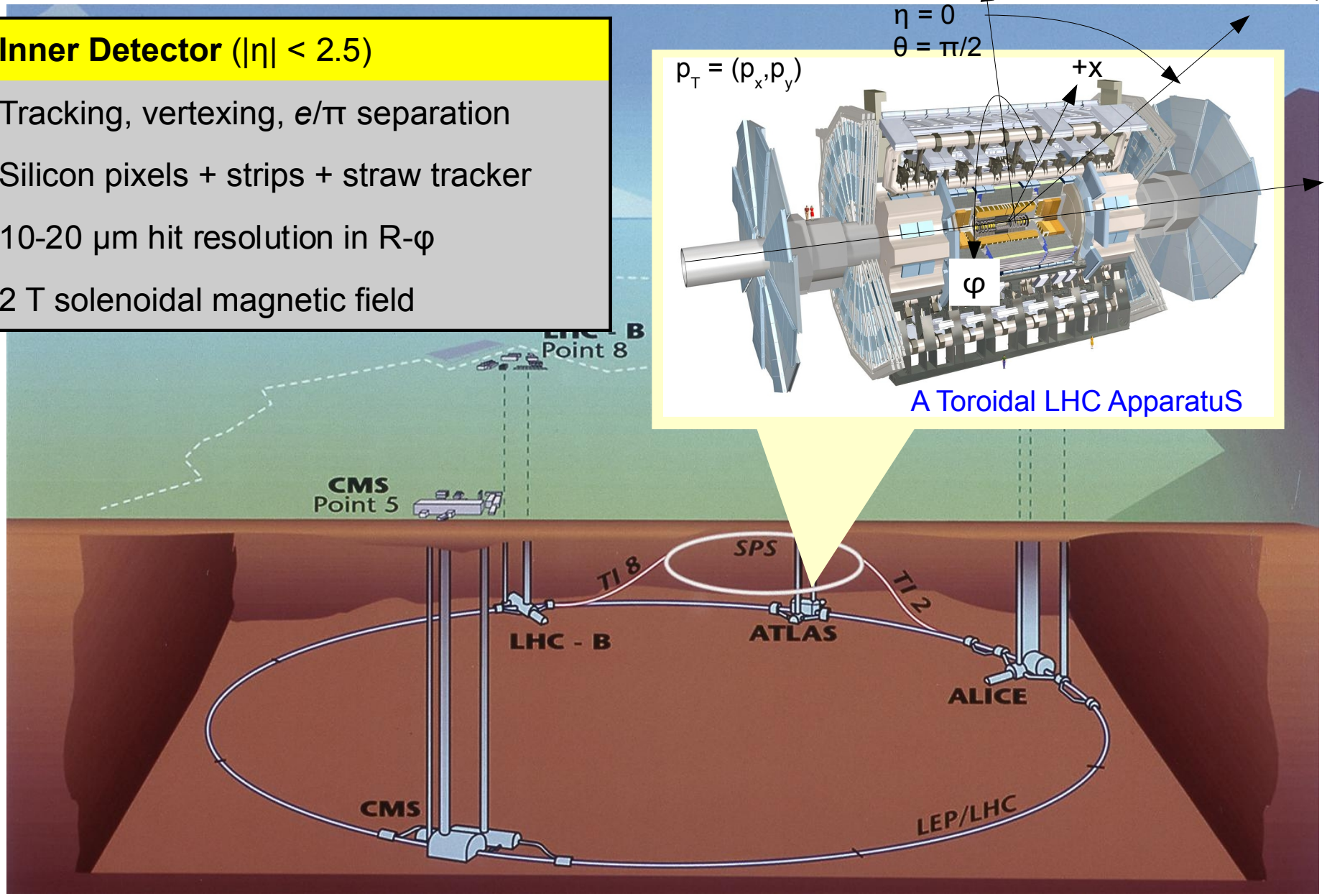
Inner Detector ($|\eta| < 2.5$)

Tracking, vertexing, e/π separation

Silicon pixels + strips + straw tracker

10-20 μm hit resolution in R-φ

2 T solenoidal magnetic field



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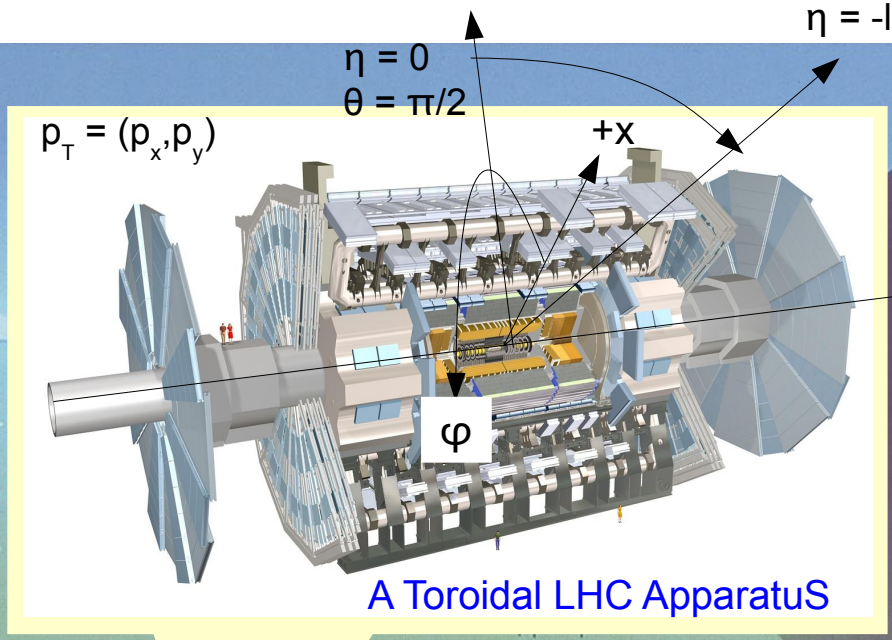


MBTS ($2.09 < |\eta| < 3.84$)

Minimum Bias Trigger Scintillators

Trigger

Eight sectors in φ, two rings in η

ATLAS

Inner Detector (|η| < 2.5)

Tracking, vertexing, *e*/π separation

Silicon pixels + strips + straw tracker

10-20 μm hit resolution in R-φ

2 T solenoidal magnetic field

Electromagnetic Calorimeter (|η| < 3.2)

Trigger, e/γ reco and id.

Pb/Liquid Argon (LAr) accordion

σ/E ≈ 10%/√E (GeV) ⊕ 0.7%

Hadronic Calorimeter (|η| < 5.0)

Trigger, jets and E_t^{miss}

Fe/Scintill. tiles (central), Cu/W LAr (fwd)

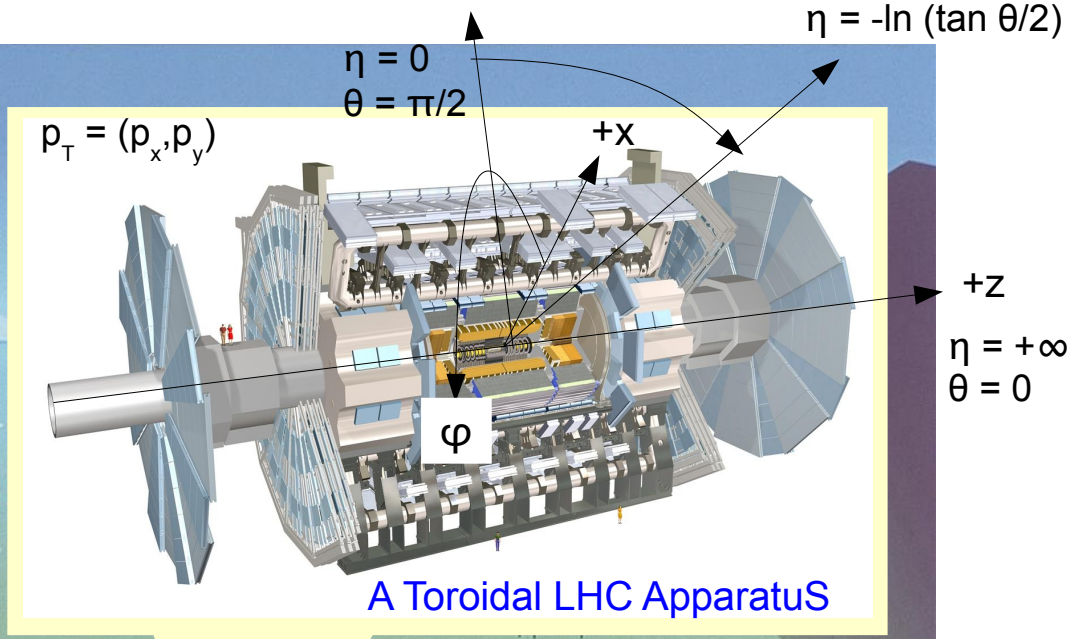
σ/E ≈ 50%/√E (GeV) ⊕ 3%

MBTS (2.09 < |η| < 3.84)

Minimum Bias Trigger Scintillators

Trigger

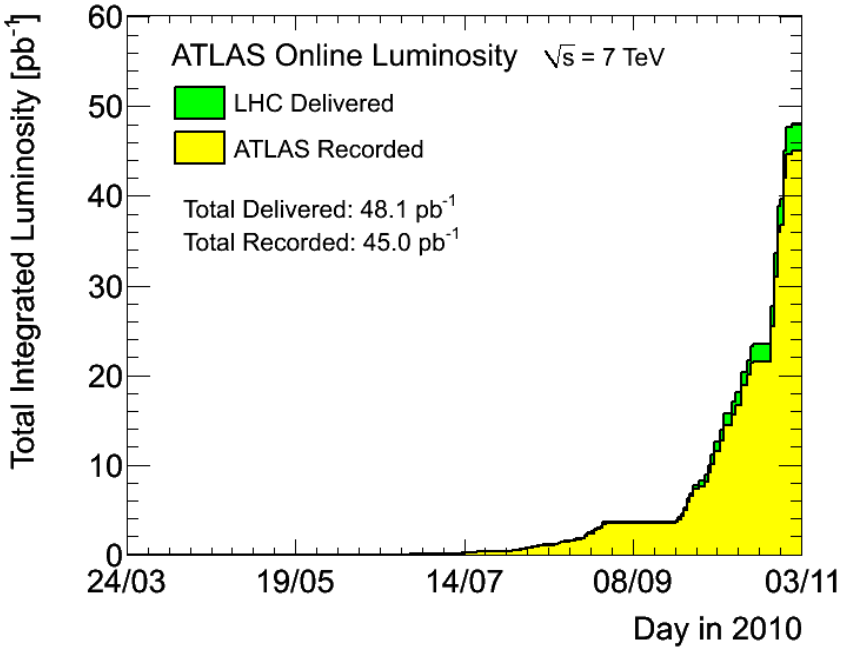
Eight sectors in φ, two rings in η

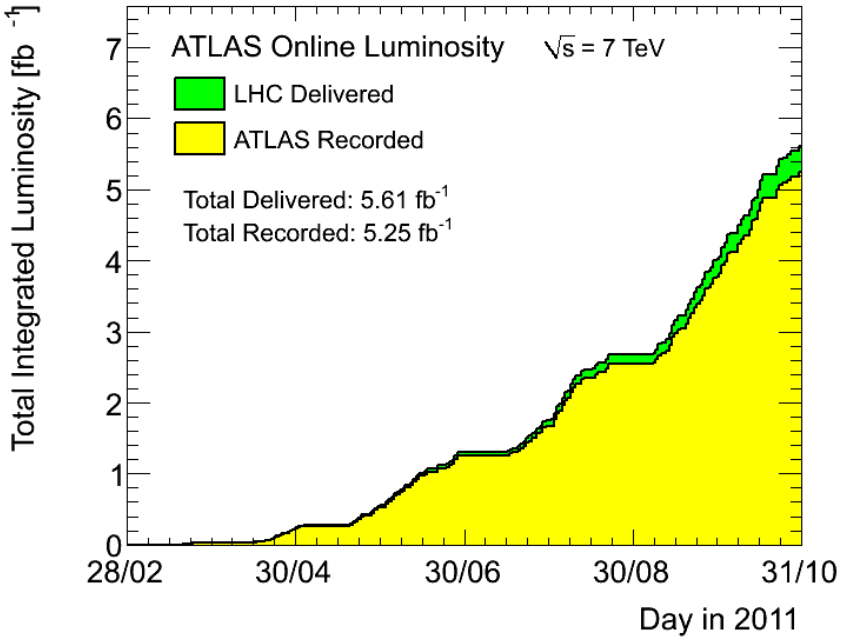


ATLAS data collection

ATLAS pp collisions recorded thus far:

Integrated Luminosity	Center-of-mass Energy
7 μb^{-1}	900 GeV
0.1 μb^{-1}	2.36 TeV
0.25 pb^{-1}	2.76 TeV
> 5 fb^{-1}	7 TeV





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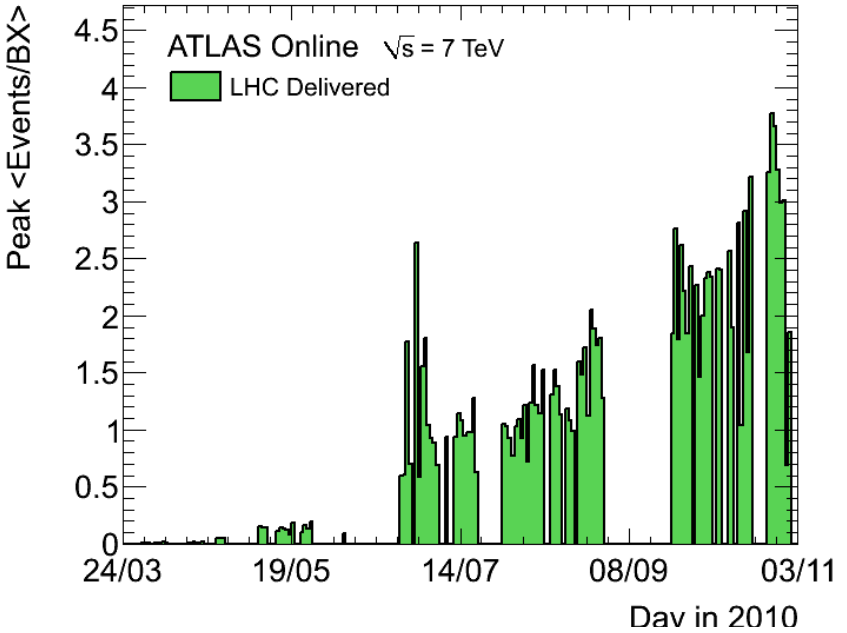
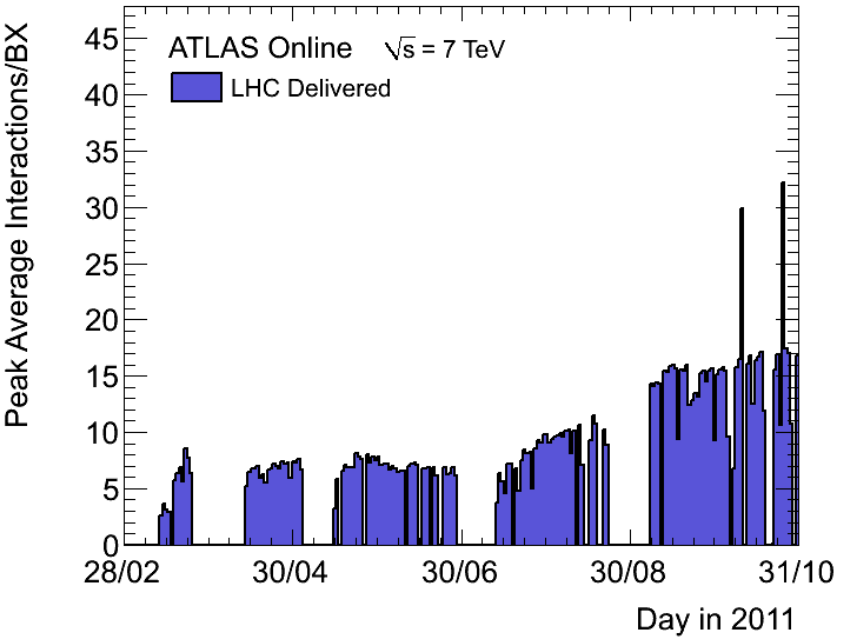


All results presented here use only data from beginning of 2010 or before (≤ 230 μb^{-1})

- √s = 0.9, 2.36, 7 TeV
- ~ 0.007 interactions / bunch crossing on average
- Need to trigger on inelastic interactions



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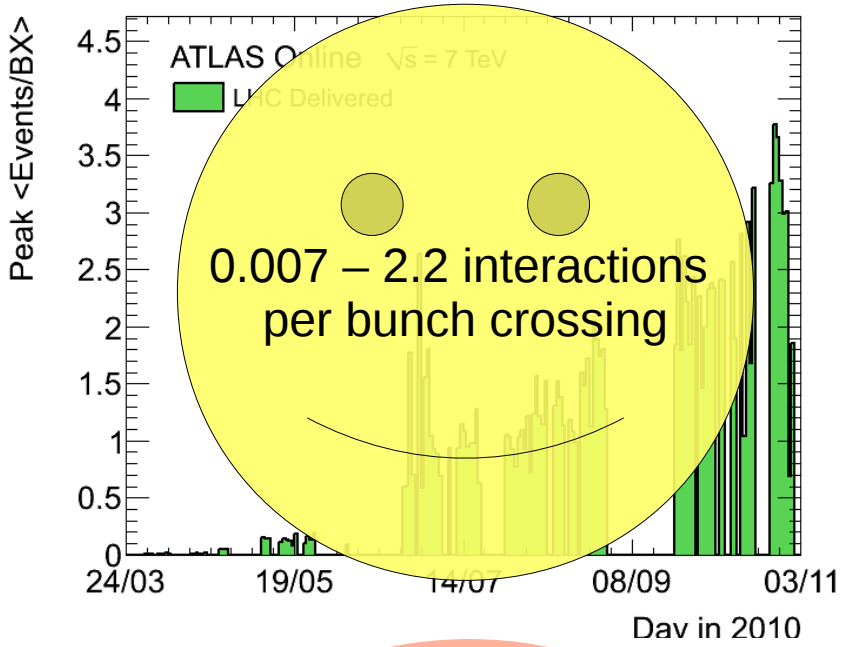

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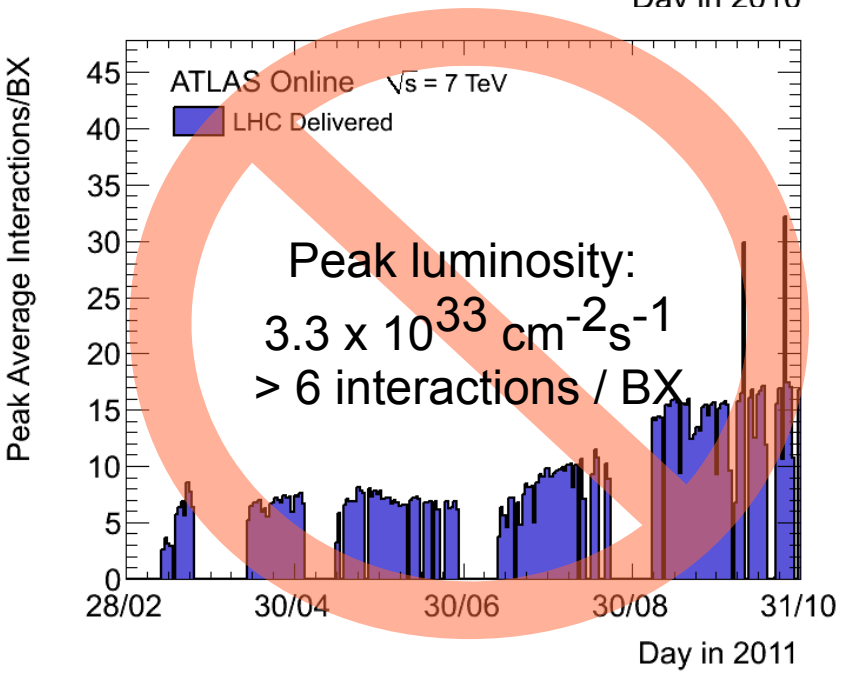
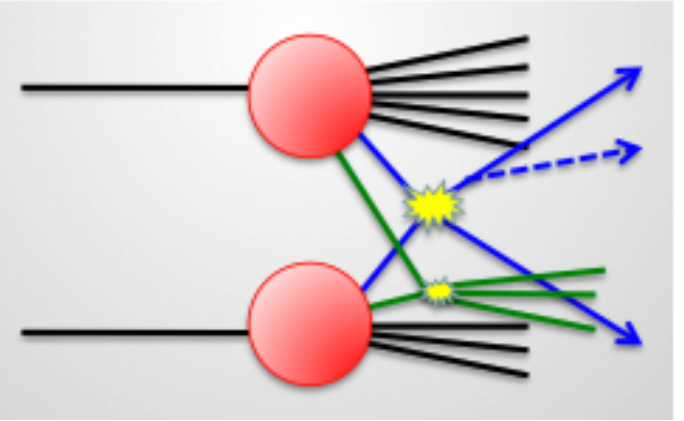


Collision event at 7 TeV

(Non-perturbative) QCD at the LHC

Essentially all physics at LHC connected to quark and gluon interactions

- Hard processes (high p_T): well described by perturbative QCD
- Soft interactions (low p_T): require non-perturbative phenomenological models
  - 'Minimum bias' (MB) interactions
  - Multiple Parton Interactions (MPI)
  - Underlying Event (UE) of hard scatter



High-p_T interaction

Underlying Event

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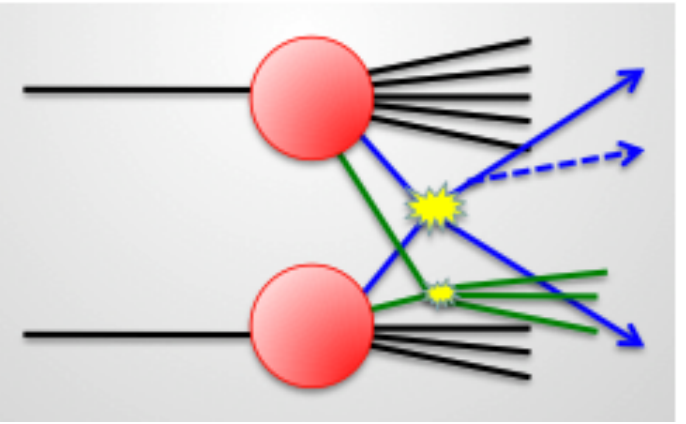
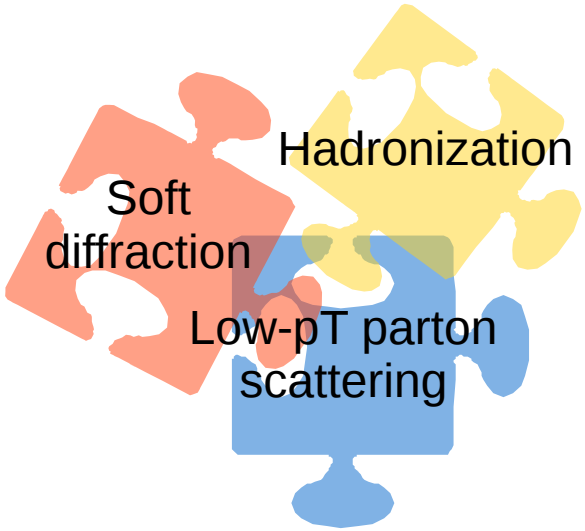




Phenomenological models need to be tuned to data

- Non-perturbative effects difficult to separate experimentally
- Must still preserve description of hard processes
- Difficult to describe MB + UE with same parameters

ATLAS soft-QCD measurements

- Charged-particle multiplicities, New J Phys 13 (2011) 053033
- Two-particle angular correlations, ATL-CONF-2011-055
- **NEW!** Azimuthal ordering of charged hadrons, not yet available
- **NEW!** Strange particle production, arXiv:1111.1297 [hep-ex]
- Underlying event with charged particles, Phys. Rev. D 83, 112001
- Underlying event with charged and neutral particles, EPJC 71 (2011) 1636
- ** Rapidity gap cross sections, ATL-CONF-2011-059
- ** Inelastic pp cross-section, Nature Comm. 2 (2011) 463

More can be found here:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Soft_QCD

** see talk by P. Newman, Wed. at 11 AM

Measurement commandments

ATLAS soft-QCD

1) Thou shalt correct measurements for detector inefficiencies and resolutions.

2) Thou shalt not extrapolate into unseen regions of phase space.

3) Thou shalt not make model-dependent corrections.

4) Thou shalt select events in a well-defined and reproducible way.

CHARGED-PARTICLE MULTIPLICITIES

- New J Phys 13 (2011) 053033

Two-particle angular correlations

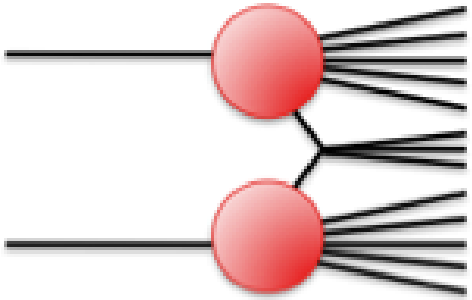
Azimuthal ordering of charged hadrons

Strange particle production

Underlying event with charged, neutral particles

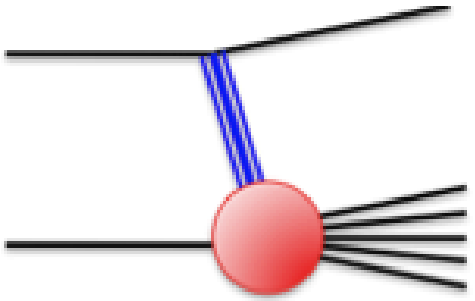
Minimum bias at the LHC

$$\sigma_{TOT} = \sigma_{ELAS} + \sigma_{SD} + \sigma_{DD} + \sigma_{ND} + \sigma_{CD}$$



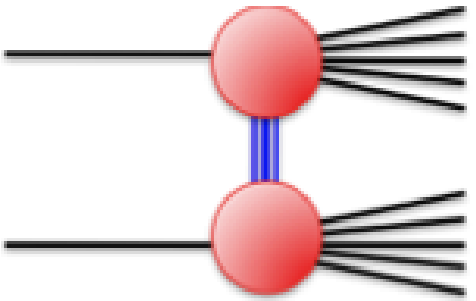
Non-diffractive

@ 7 TeV: σ_{ND} ~ 49 mb



Single-diffractive

σ_{SD} ~ 14 mb



Double-diffractive

σ_{DD} ~ 9 mb

- "Minimum bias": experimentally defined to select events with the minimum possible requirements that ensure an inelastic collision occurred

- Exact definition depends on experiment (and analysis)

“Minimum bias” at ATLAS

- Select 'minimum bias' events: ≥ 1 hit(s) anywhere in the MBTS
  - MBTS: 2.09 < |η| < 3.84
  - Consists of ND, SD and DD events
    - Relative contributions depend on event and track selection criteria
    - Predictions of relative fractions have large uncertainty
- Charged particles are measured from tracks reconstructed in the ID
  - Measure kinematics: multiplicity (n_{ch}), p_T and η spectra, $\langle p_T \rangle$
  - Measure properties in various phase spaces

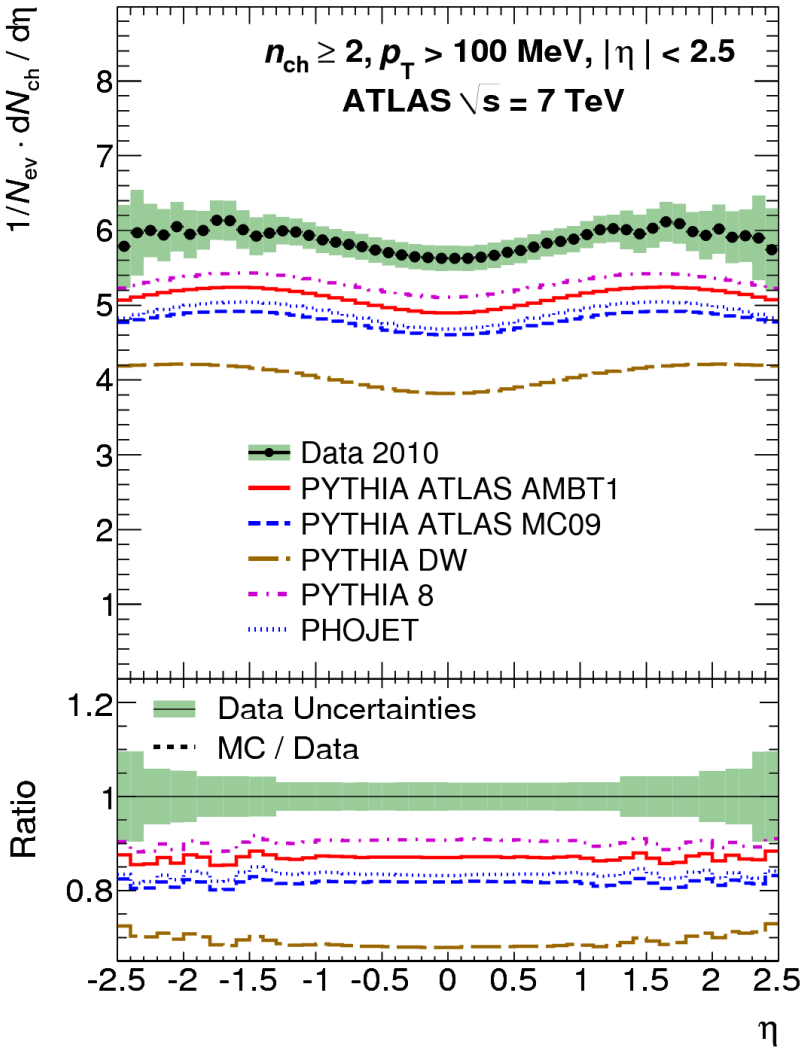
	Most inclusive		Diffraction suppressed		High pT	ALICE/CMS Comparison	
$n_{ch} \geq$	2	1	20	6	1	1	1
p_T [MeV] >	100	500	100	500	2500	500	1000
|η| <	2.5	2.5	2.5	2.5	2.5	0.8	0.8

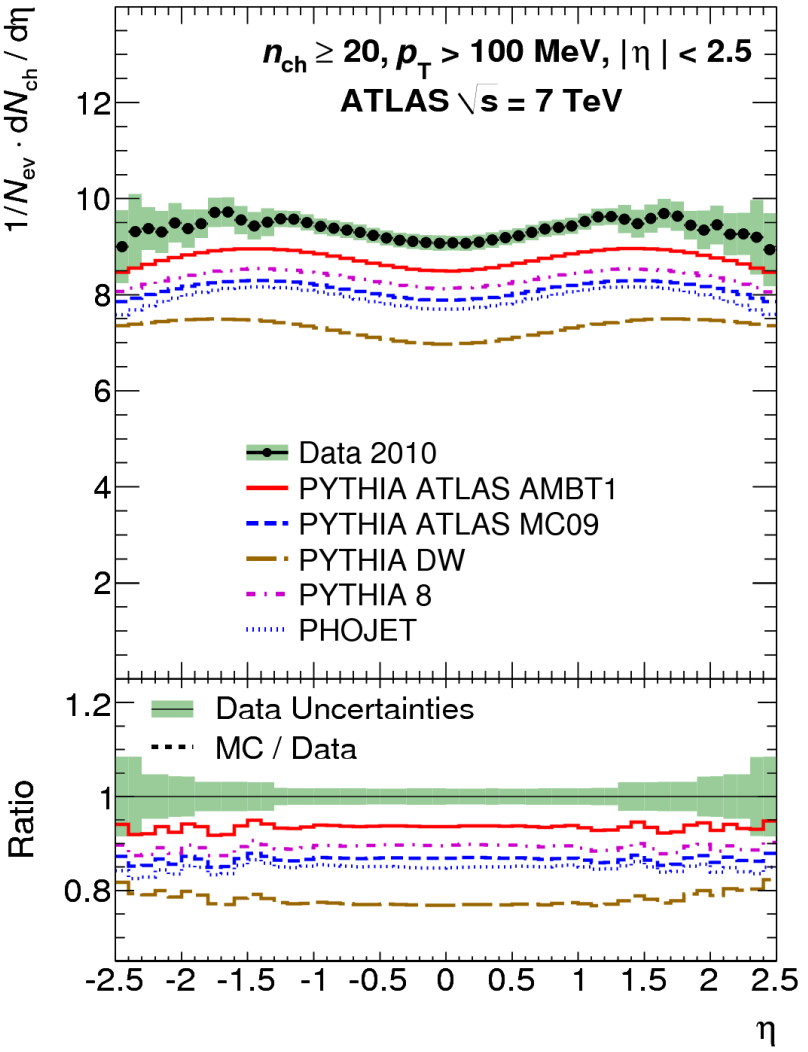
Used for AMBT2b Pythia tune

Used for AMBT1 Pythia tune

Charged particle multiplicity vs. η

All models underestimate pseudorapidity density, both in inclusive and diffraction-suppressed samples

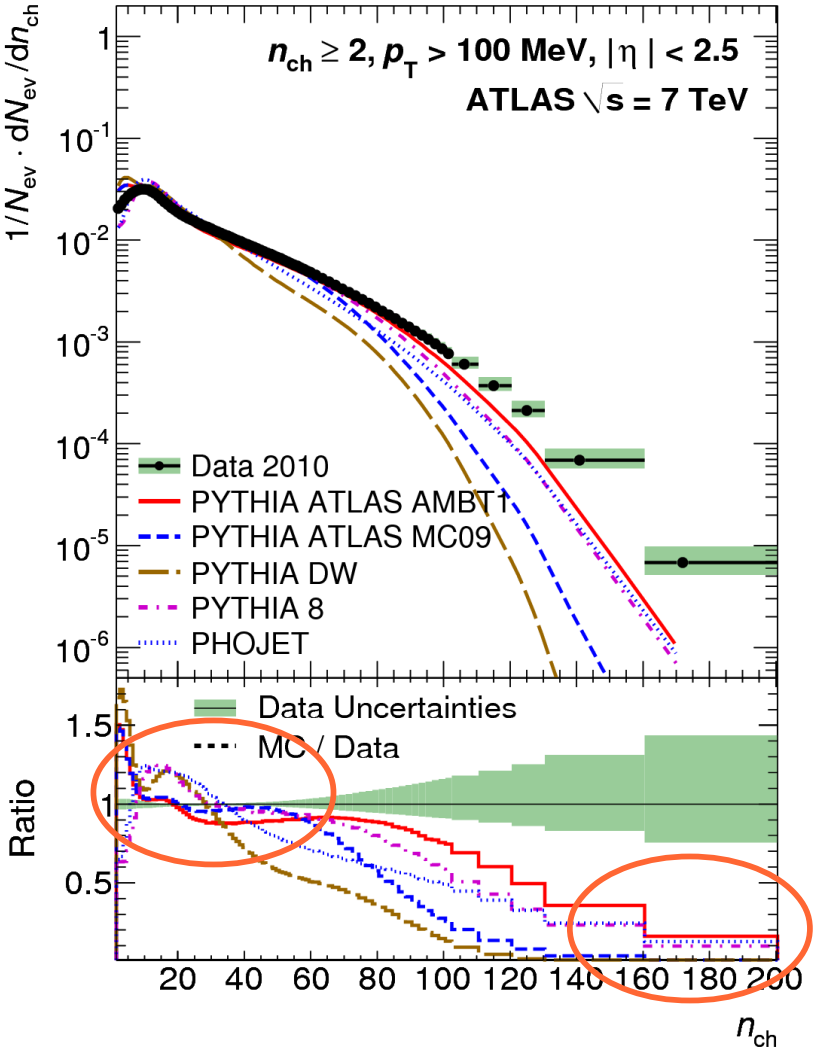


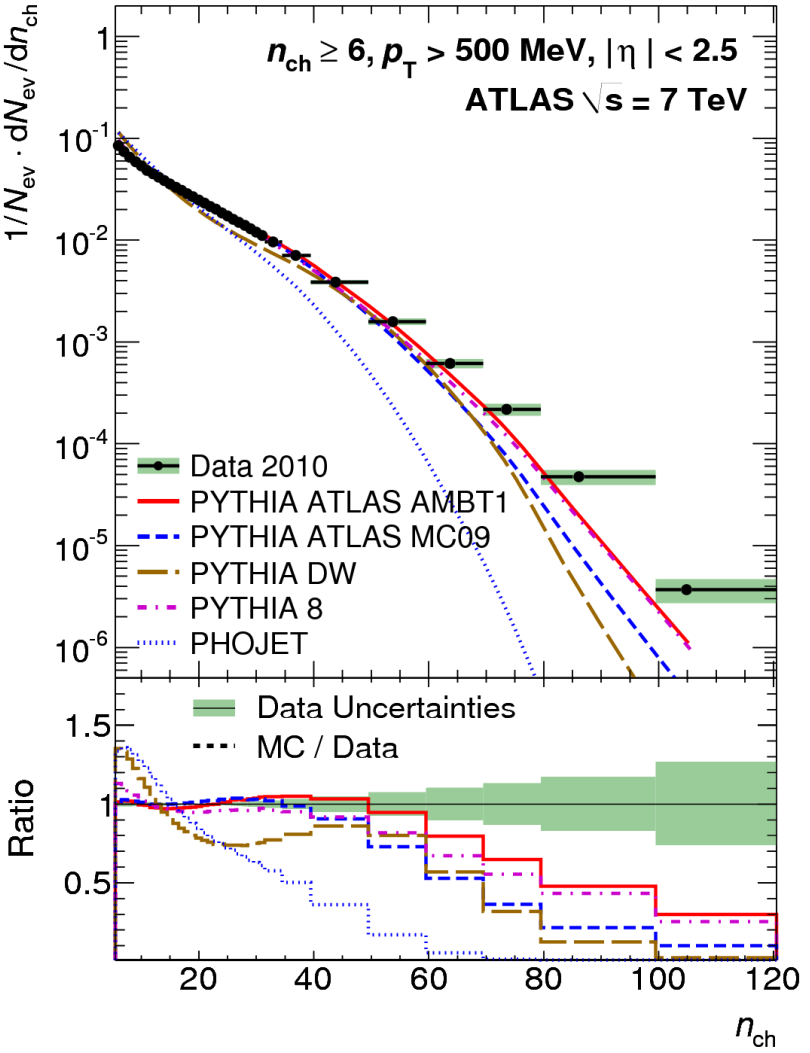


Charged particle multiplicity

Excess of models over data at low n_{ch}

Highly influenced by modeling of diffractive events

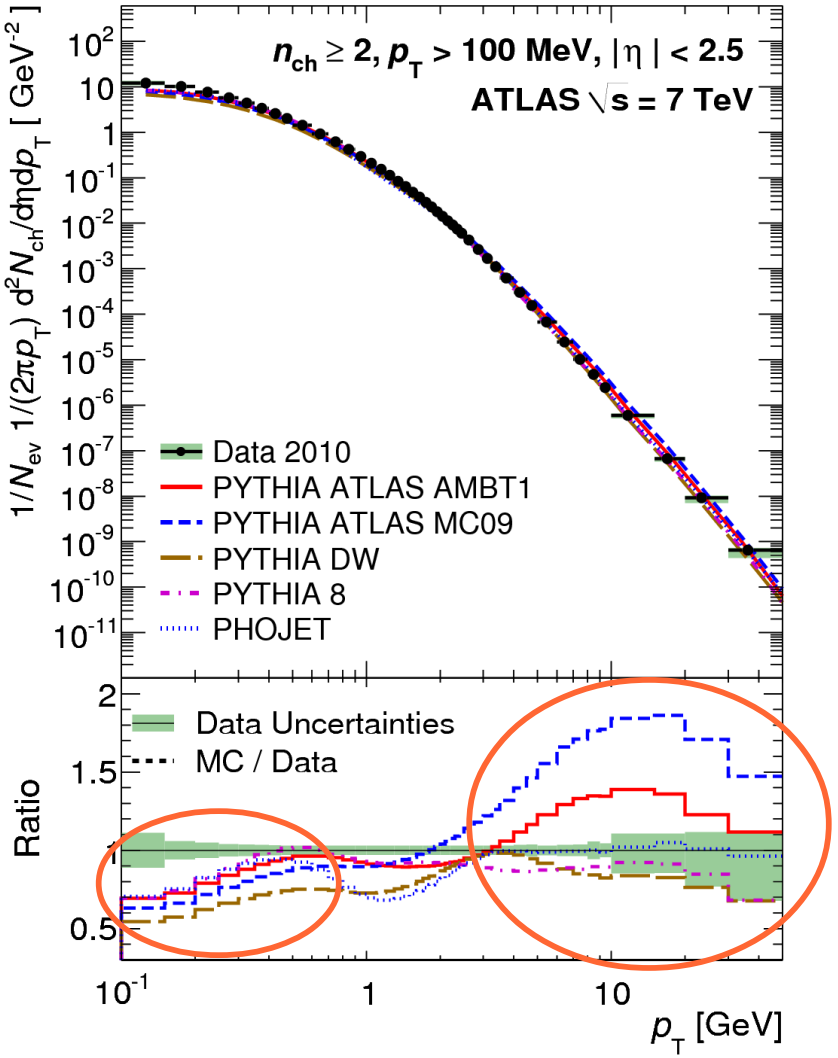


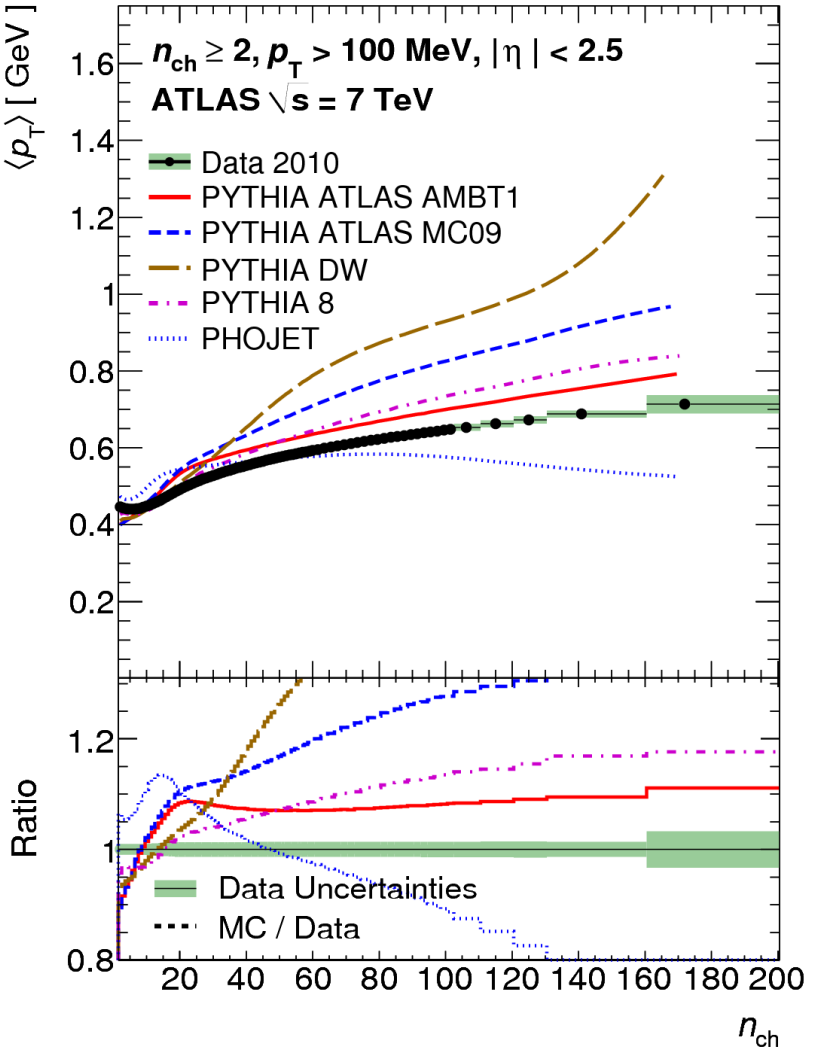


Charged particle multiplicity vs. p_T

Simulation predicts significantly harder spectrum for p_T > 3 GeV

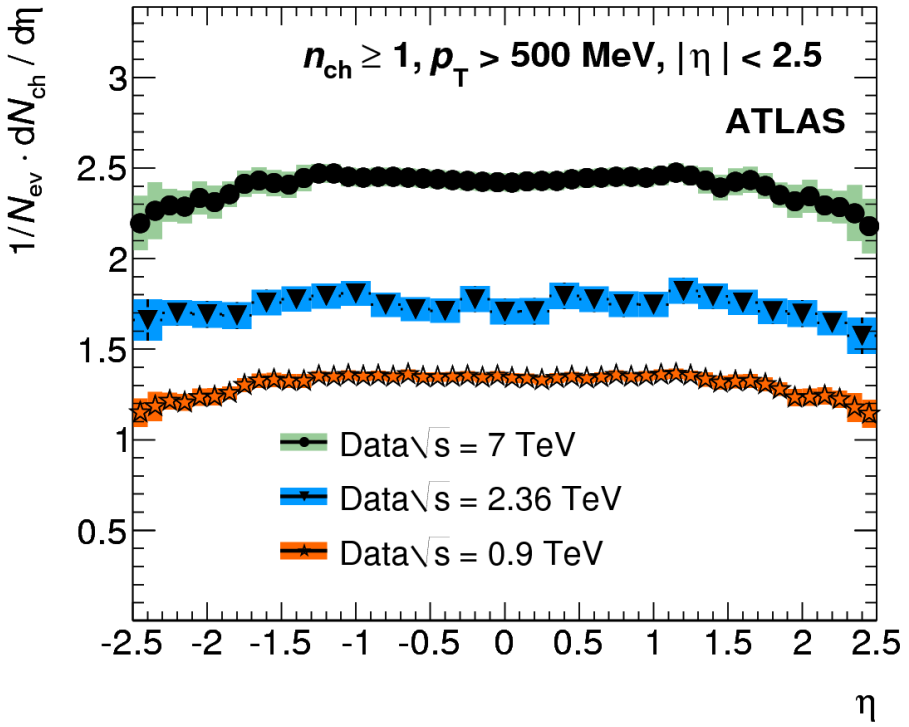
Data lower than predicted

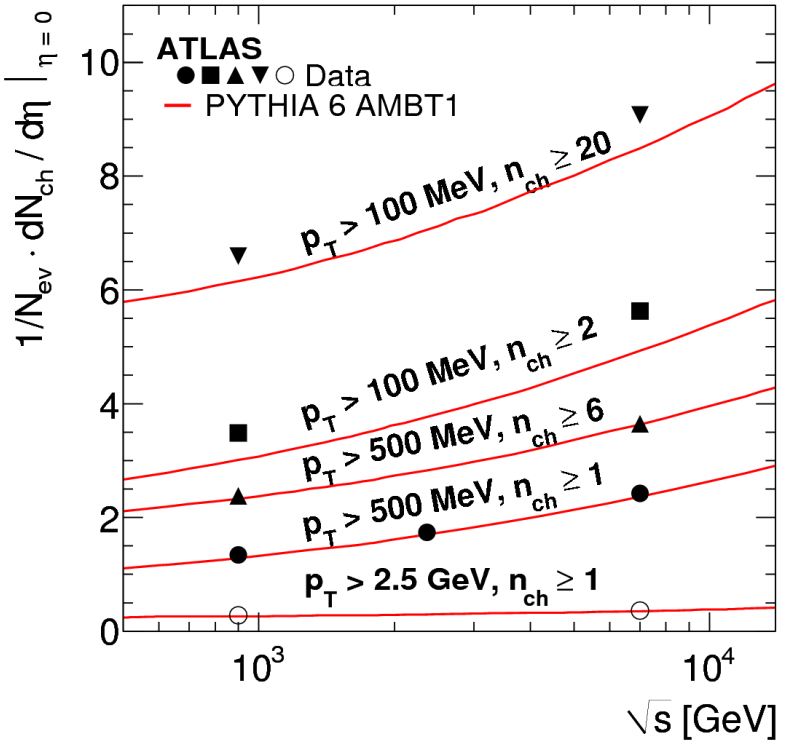




Pseudorapidity density vs. √s

- Charged particle distributions measured in various phase spaces and CM energies
  - Study energy dependence of particle production
  - Compare $1/N_{ev}\ dN_{ch}/d\eta$ at $\eta=0$ as a function of √s
- Pythia 6 AMBT1 tune gives good description of energy dependence for phase spaces without low-pT region
- See talk by D. Kar at 3:40 pm for latest results from tuning





Charged-particle multiplicities

TWO-PARTICLE ANGULAR CORRELATIONS

- ATL-CONF-2011-055

Azimuthal ordering of charged hadrons

Strange particle production

Underlying event with charged, neutral particles

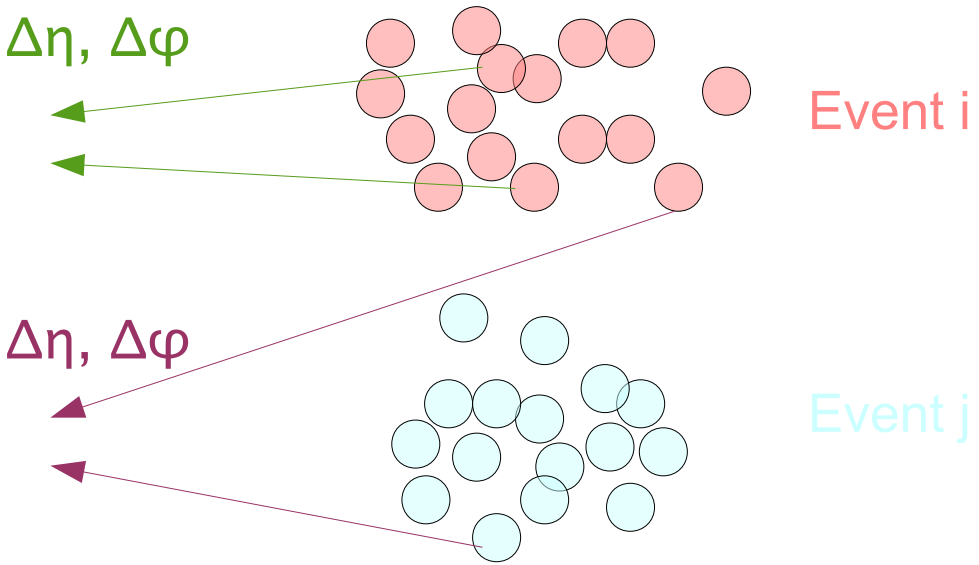
Two-particle correlations

- Sensitive to underlying mechanisms for soft particle production
  - Correlations between final states can indicate a common origin of production
  - Gives indication about multi-particle dynamics in HI
- Two-particle angular correlation function:

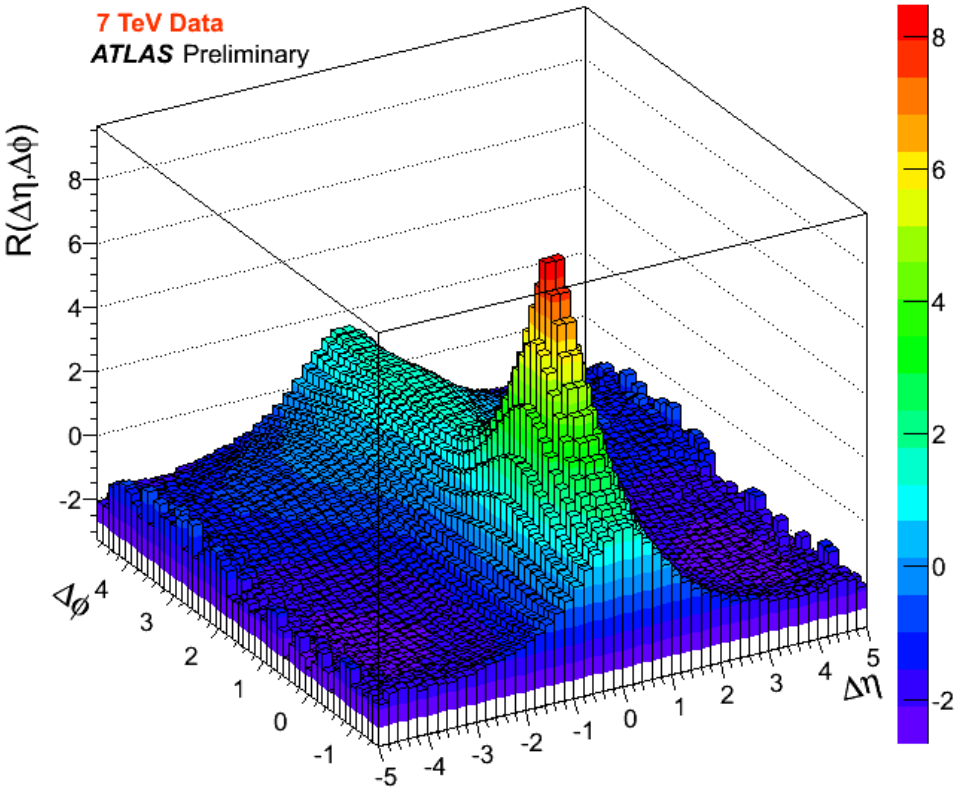
$$R(\Delta\eta, \Delta\phi) = \frac{\langle (N_{ch} - 1)\, F(N_{ch}, \Delta\eta, \Delta\phi) \rangle_{ch}}{B(\Delta\eta, \Delta\phi)} - \langle N_{ch} - 1 \rangle_{ch}$$

Foreground (F): all particle pairs in same event (correlated + uncorrelated pairs)

Background (B): particle pairs from different events (uncorrelated pairs)



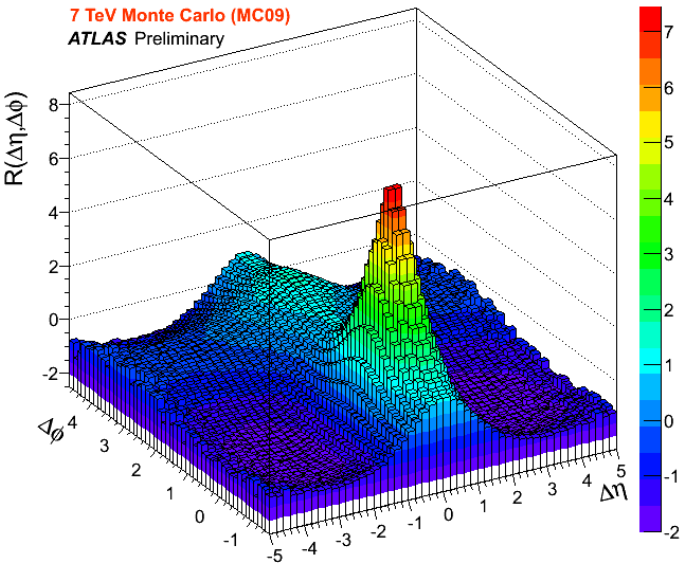
Results



Narrow peak at (Δη,Δφ) ≈ (0,0): contribution from higher p_T

Ridge at Δφ ≈ π: momentum conservation

Gaussian ridge at Δη ≈ 0: decay of particles with lower p_T



Pythia predicts a similar structure, but fails to reproduce the strength of the correlation

Charged-particle multiplicities

Two-particle angular correlations

AZIMUTHAL ORDERING OF CHARGED HADRONS

Strange particle production

Underlying event with charged, neutral particles

Azimuthal ordering

- Charged-particle measurements show limitations of phenomenological models
  - Models cannot describe measured observables in all regions of phase space
  - Some discrepancies can be reduced by tuning, but
  - New formulation of certain components of models (e.g. fragmentation) is likely needed

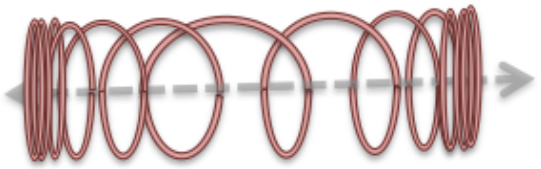
- Two main hadronization models used in multi-purpose MC generators:
  - String (Lund) fragmentation model, e.g. PYTHIA, PHOJET
  - Cluster model, e.g. HERWIG

- Idea: replace standard Lund string with a helix-like ordered gluon chain
  - J. High Energy Phys. 9809 014 (1998)
  - p_T of direct hadron is entirely constrained by spiral structure of QCD string
  - Corresponds to optimal packing of soft gluons in phase space under helicity conservation requirements
  - Imposes correlations between adjacent breakup points along string
  - Observable effects in inclusive p_T distribution and azimuthal ordering of direct hadrons

Observables

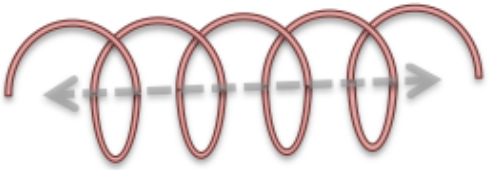
- Define two types of power spectra according to expected structure of helix field:

~ original proposal



$$S_\eta(\xi) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j \exp(i(\xi \eta_j - \phi_j)) \right|^2$$

static, regular helix



$$S_E(\omega) = \frac{1}{N_{ev}} \sum_{event} \frac{1}{n_{ch}} \left| \sum_j \exp(i(\omega X_j - \phi_j)) \right|^2$$

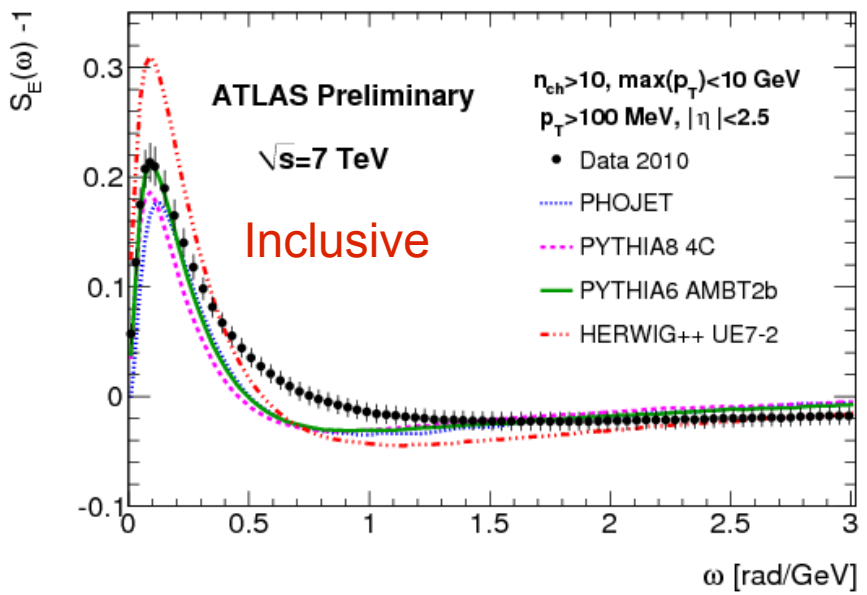
$$X_j = 0.5\, E_j + \sum_{k=0}^{k<j} E_k$$

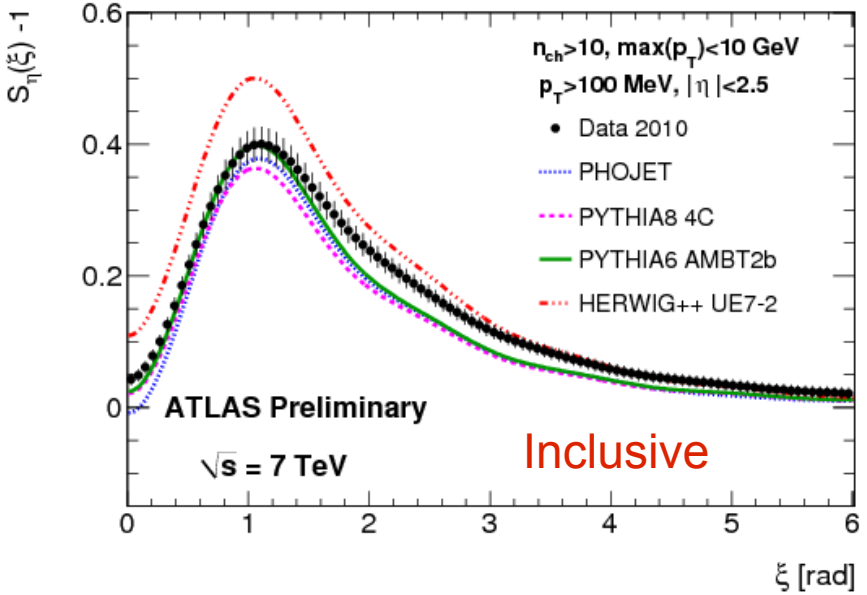
(energy distance along string)

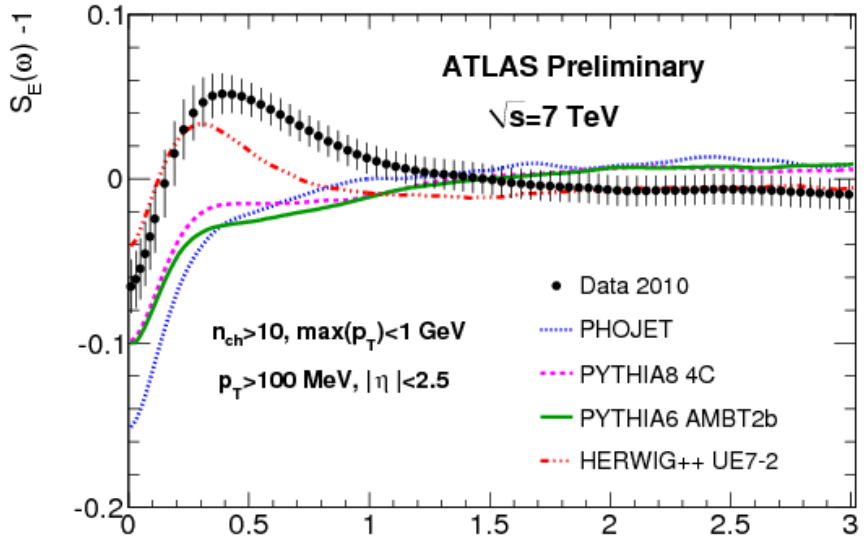
- Measure power spectra in 'inclusive' sample, as well as two sub-samples:
  - "Inclusive": p_T > 100 MeV, veto events containing any track with p_T > 10 GeV
  - "Low-pT enhanced": p_T > 100 MeV, veto events containing any track with p_T > 1 GeV
  - "Low-pT depleted": p_T > 500 MeV, veto events containing any track with p_T > 10 GeV

Results

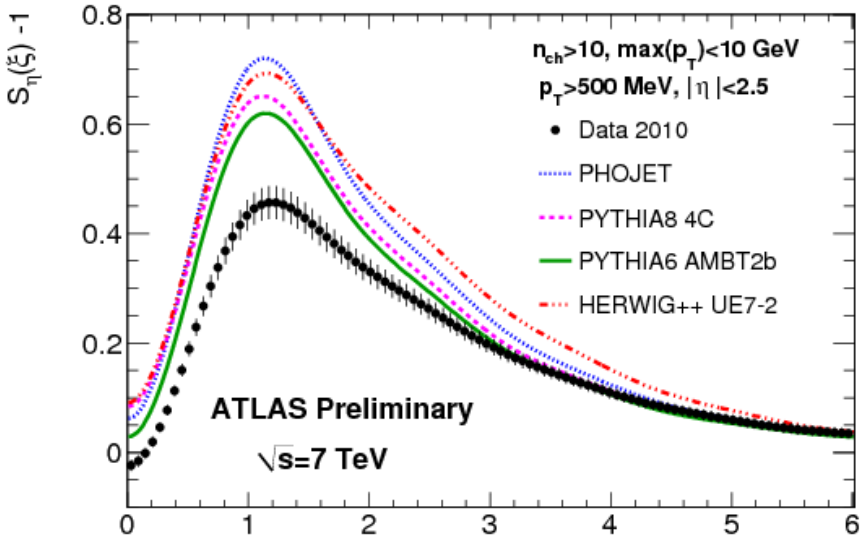
Clear enhancement of data over models in S_E ($0.5 < \omega < 1$ rad/GeV)







Low-p_T enhanced



Low-p_T depleted

Pythia variations

Low-pT enhanced:

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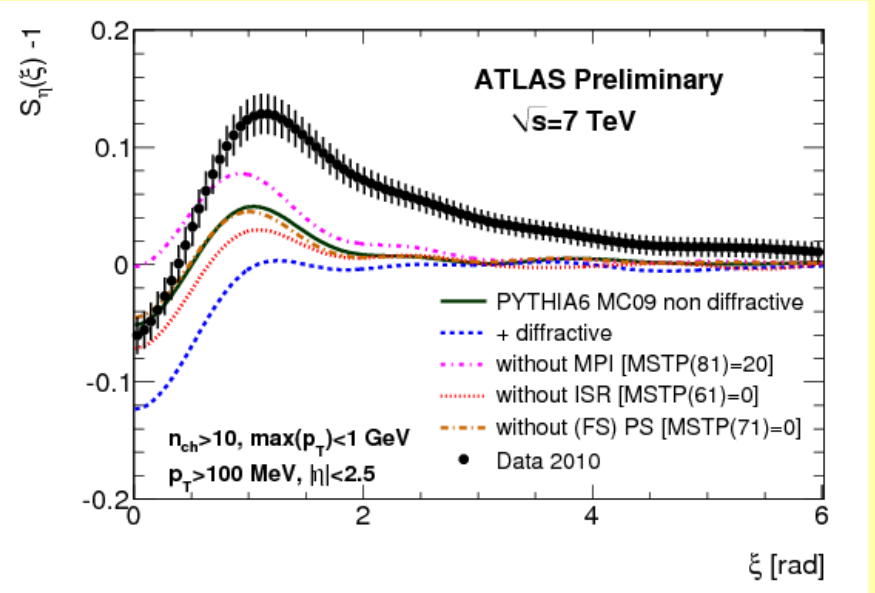
- Modeling of diffractive events is major source of discrepancy between data and models
- MPI scheme pulls model prediction away from data



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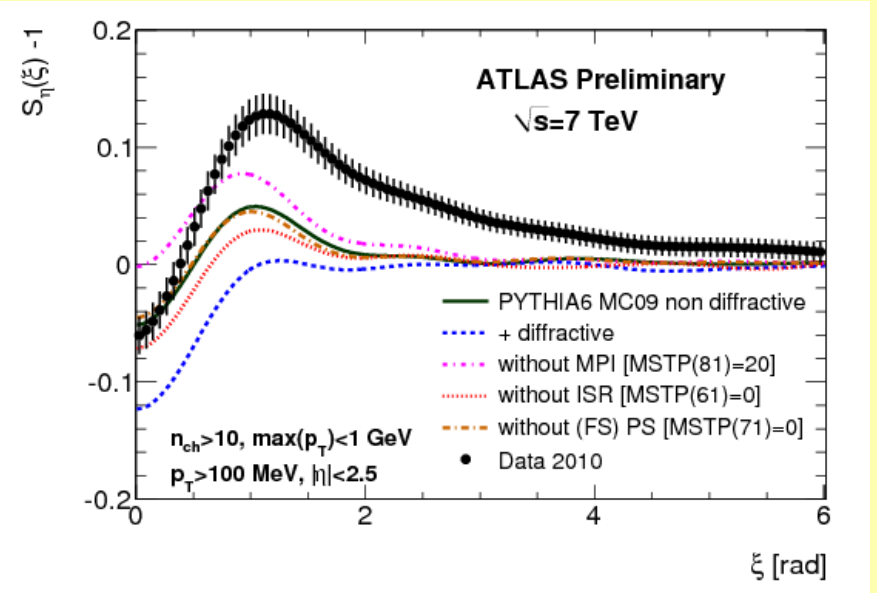
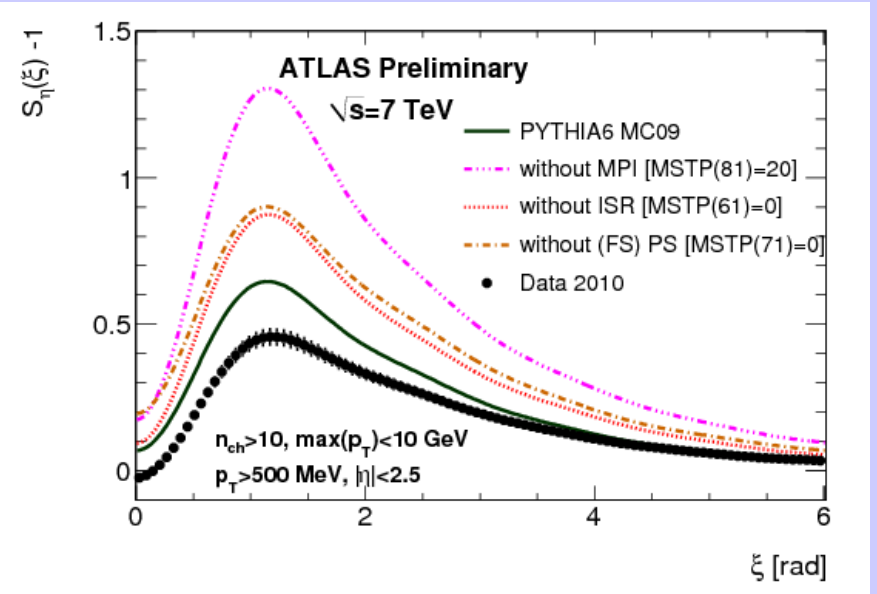
- Extreme variation of model parameters cannot provide reasonable description of data
- Modeling of diffractive events is major source of discrepancy between data and models
- MPI scheme pulls model prediction away from data



Low-pT depleted:

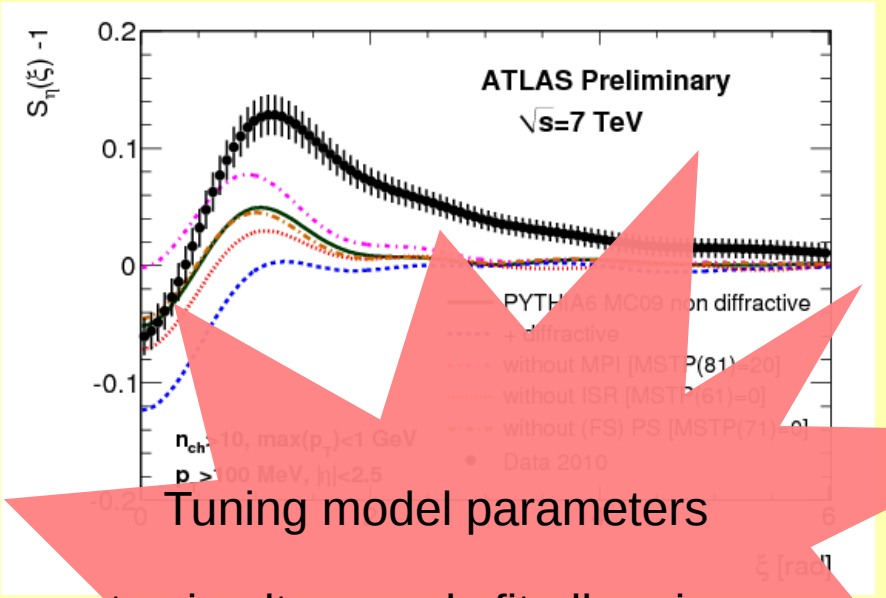
- Higher rate of MPI is required to describe the data



Pythia variations

Low-pT enhanced:

- Extreme variation of model parameters cannot provide reasonable description of data
- Modeling of diffractive events is major source of discrepancy between data and models
- MPI scheme pulls model prediction away from data



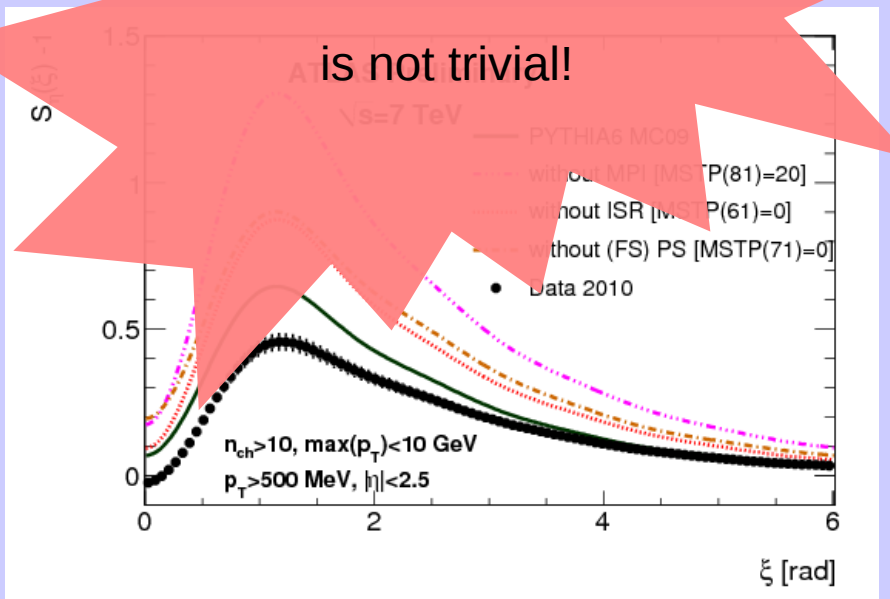
Tuning model parameters

to simultaneously fit all regions

is not trivial!

Low-pT depleted:

- Higher rate of MPI is required to describe the data



Charged-particle multiplicities

Two-particle angular correlations

Azimuthal ordering of charged hadrons

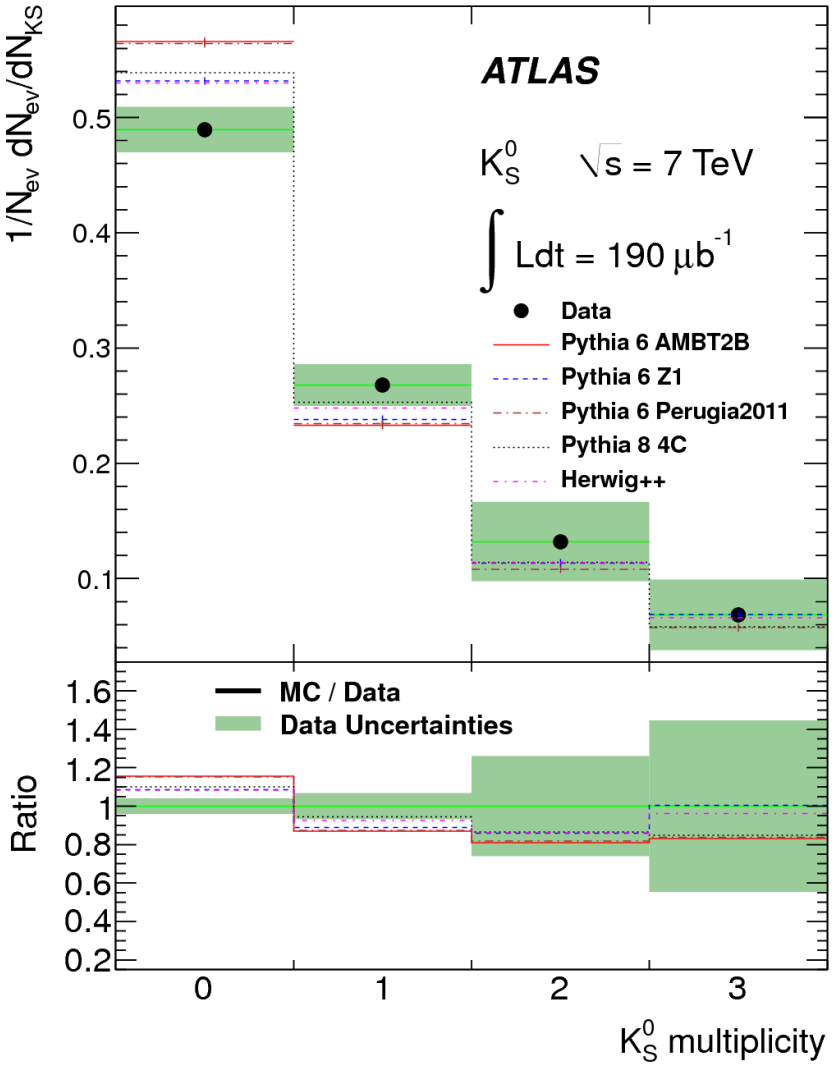
STRANGE PARTICLE PRODUCTION

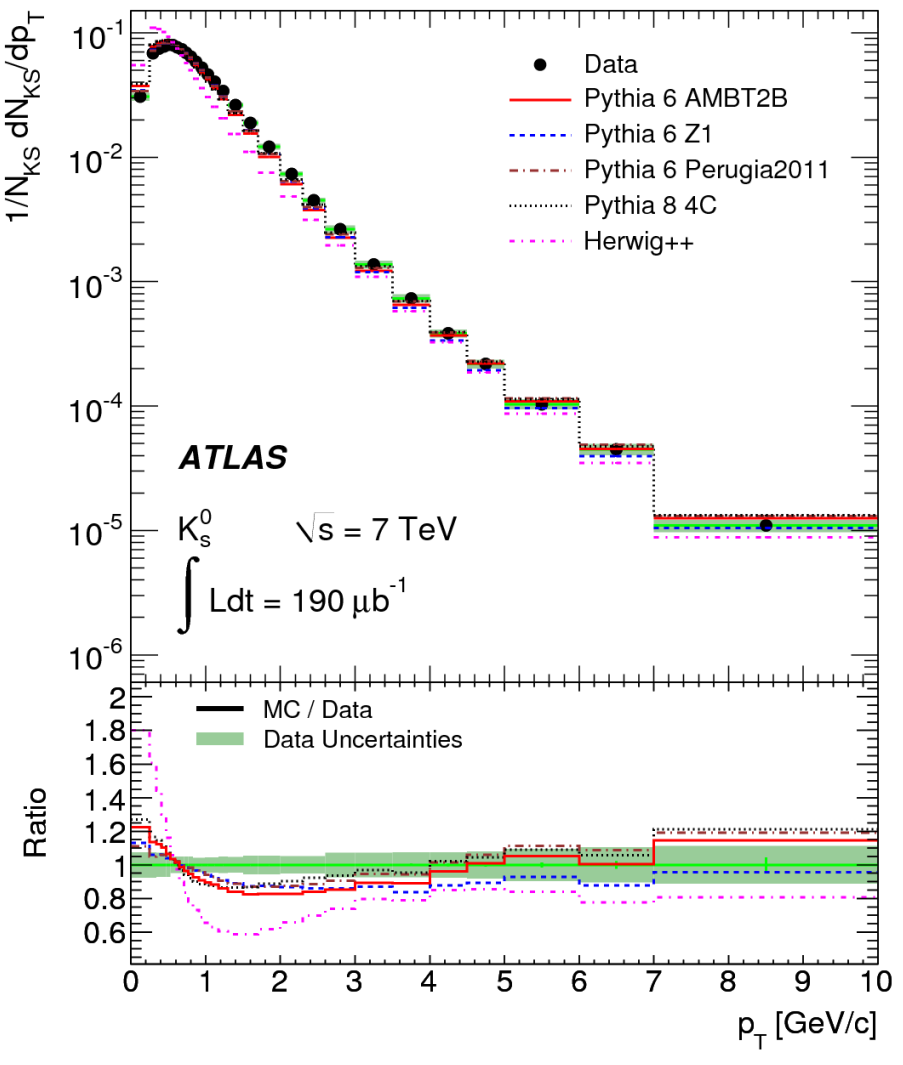
- arXiv:1111.1297 [hep-ex]

Underlying event with charged, neutral particles

K^0_s production

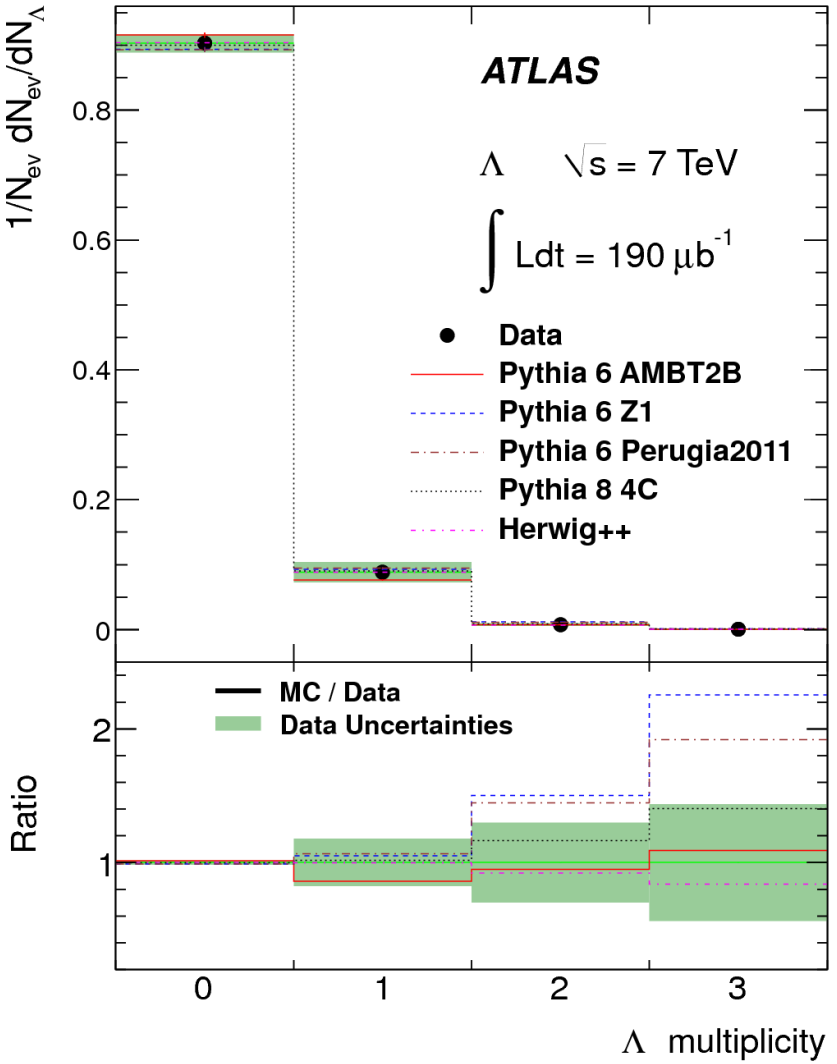
K^0_s mesons are required to have a flight distance between 4 mm and 450 mm and to decay to two charged pions with $|\eta| < 2.5$ and $p_T > 100$ MeV

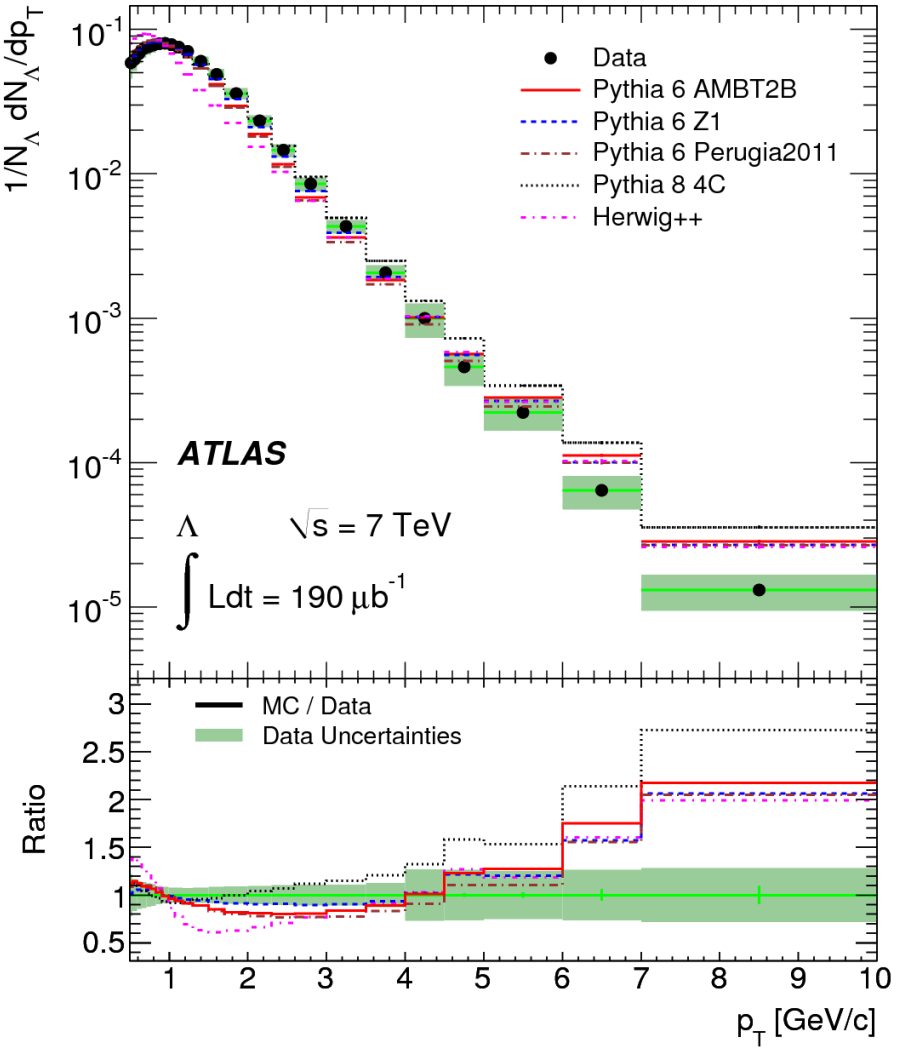




Λ production

Λ baryons are required to have p_T > 500 MeV, flight distance between 17 mm and 450 mm and to decay to a proton and a pion with $|\eta| < 2.5$ and p_T > 100 MeV





Charged-particle multiplicities

Two-particle angular correlations

Azimuthal ordering of charged hadrons

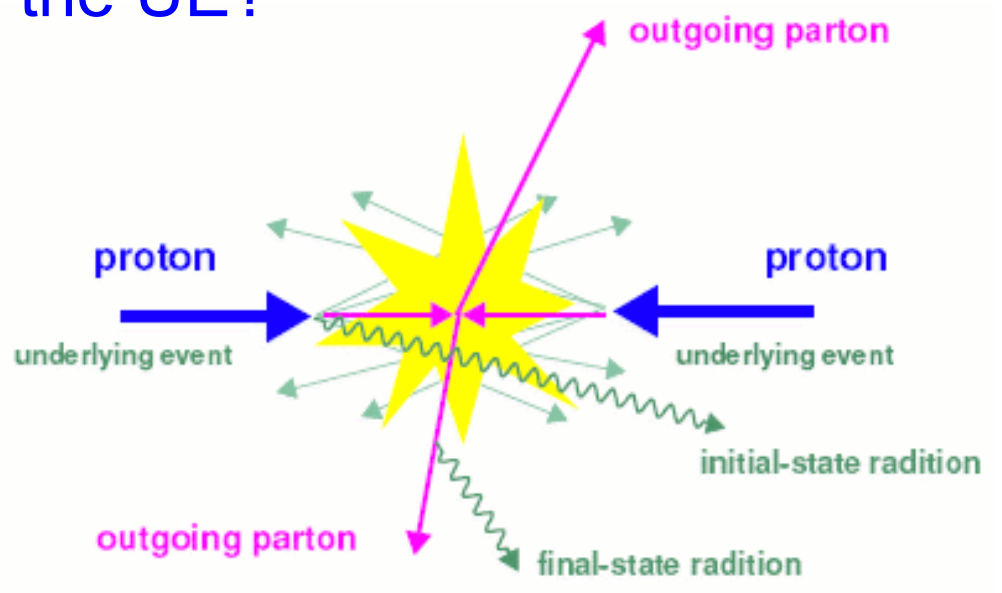
Strange particle production

UNDERLYING EVENT WITH CHARGED, NEUTRAL PARTICLES

- Phys. Rev. D 83, 112001
- EPJC 71 (2011) 1636

Underlying Event

What is the UE?



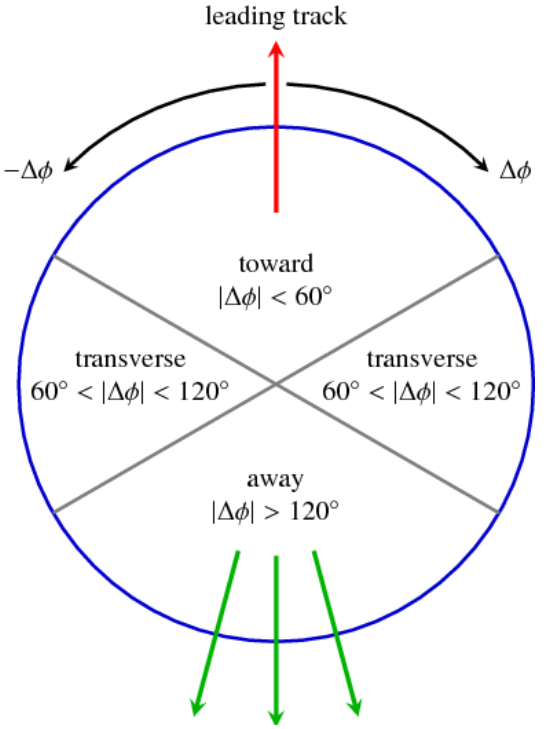
CMS PAS QCD-08-005

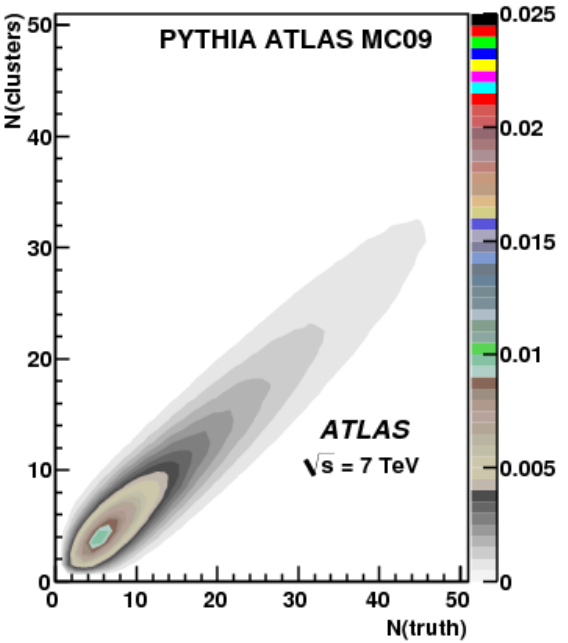
Everything BUT the hard scatter!

- Additional partons from the same proton interacting at the same time as signal (high-pT) interaction
  - Can include MPI, beam-beam remnants, ISR/FSR, etc.
  - Characterized by low momentum transfer → rely on models tuned to data
- Modeling of UE important for precise high-pT measurements
  - Important ingredient for jet and lepton isolation, energy flow, jet tagging, etc

Underlying Event at ATLAS

- UE characterized by activity in φ region transverse to the leading particle (= highest pT track or cluster)
  - # particles
  - Σp_T
  - $\langle p_T \rangle$
- Track-based measurement:
  - Reconstruct ID tracks of charged particles
  - Corrections for vertex, trigger and tracking efficiency similar as for minimum bias studies
- Cluster-based measurement:
  - Use energy depositions in calorimeters associated to charged and neutral particles
  - Correct cluster distributions to stable-particle level using correction factor derived from MC
  - Cross-check using data/simulation comparison of N(clusters) vs. N(tracks)



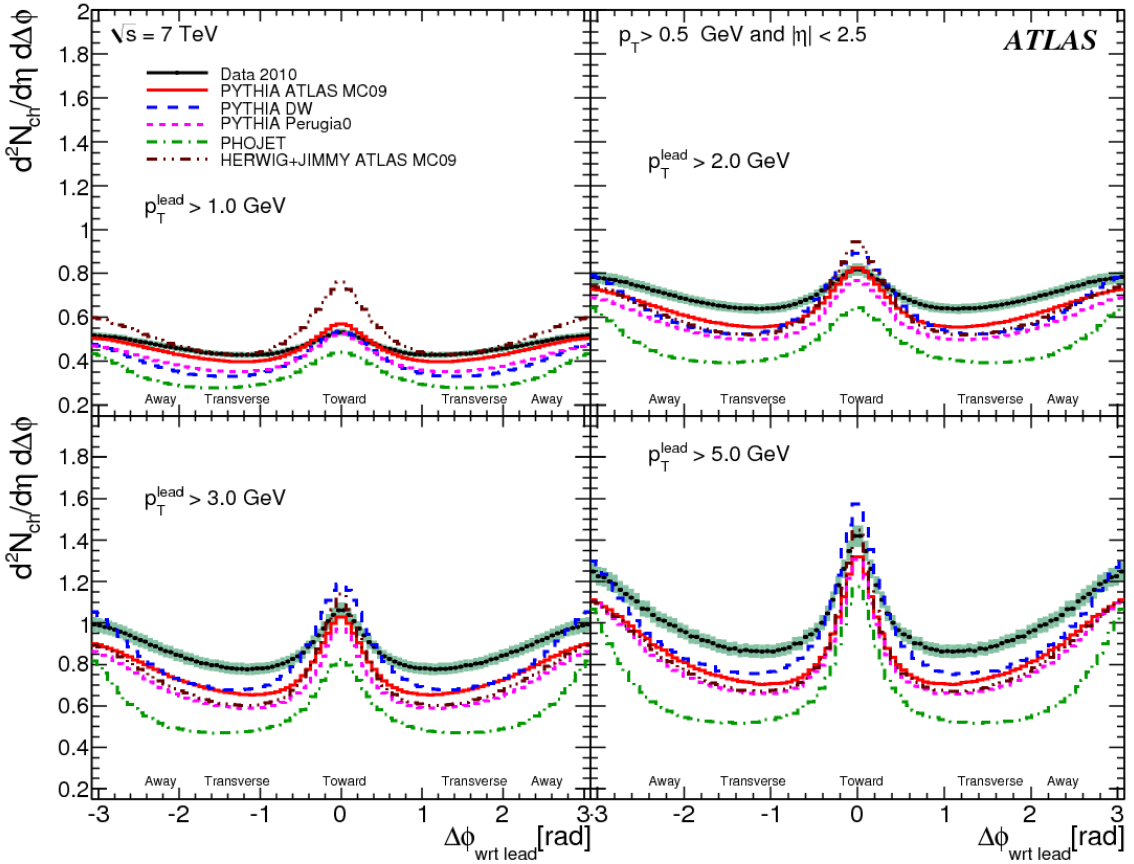


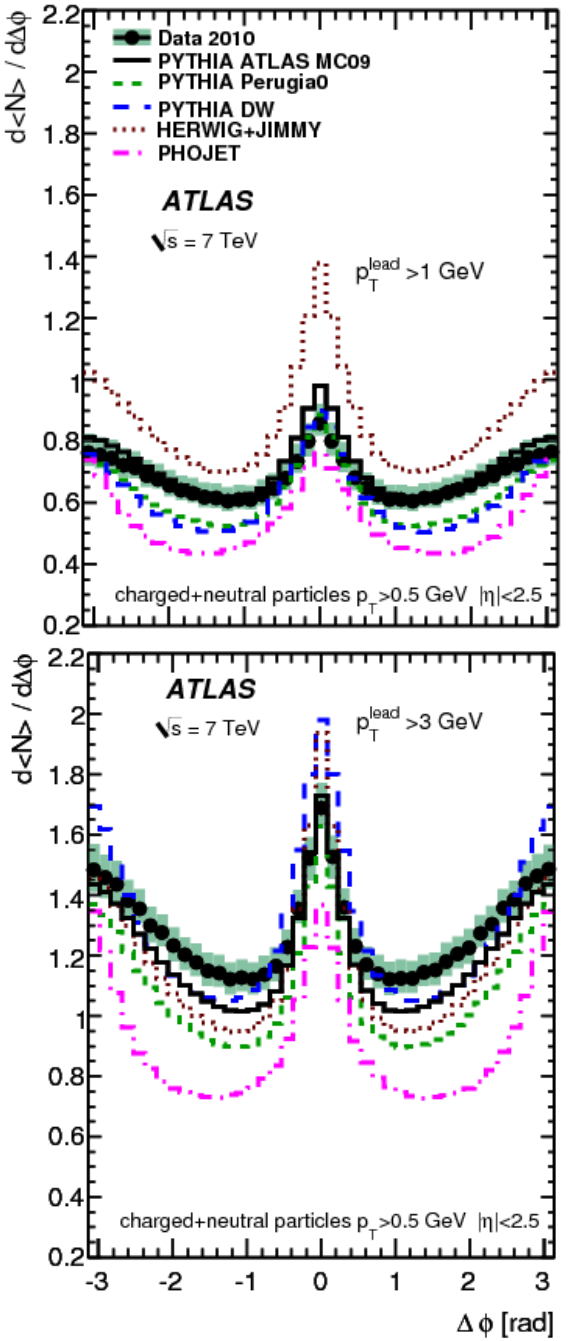
Particle density vs. Δφ

Cluster method

- Development of 'jet-like' region of higher density as p_T of leading track/particle increases (toward, away)
- Particle density is higher and has a different angular distribution than predicted by MC

Track method

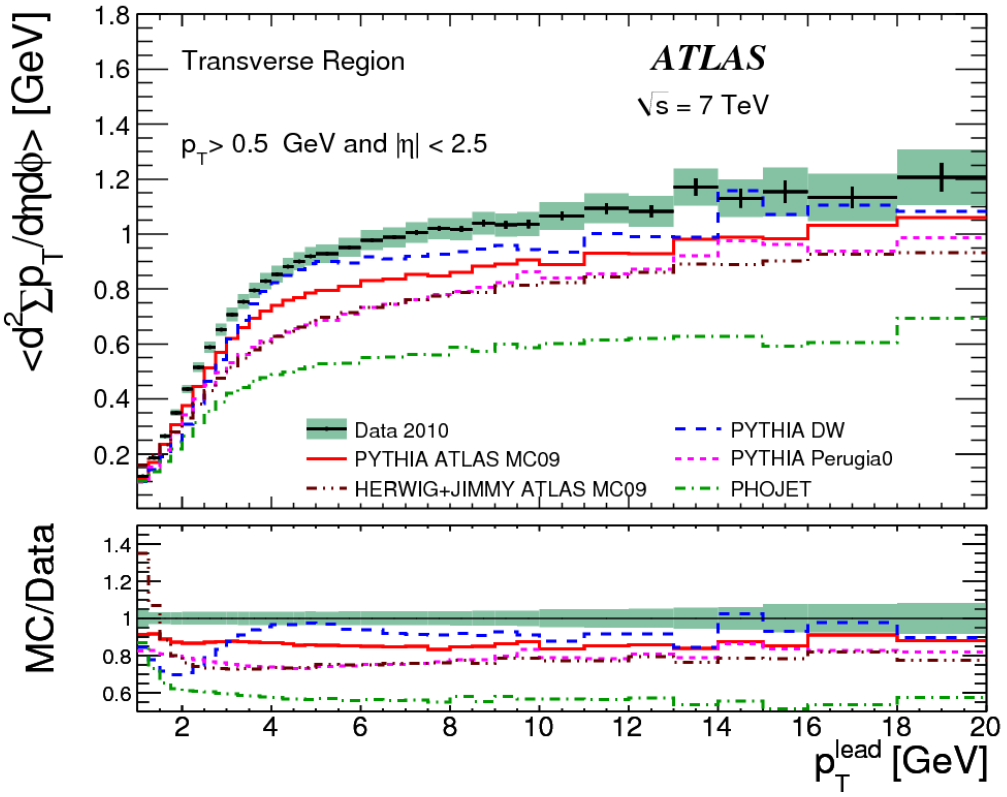




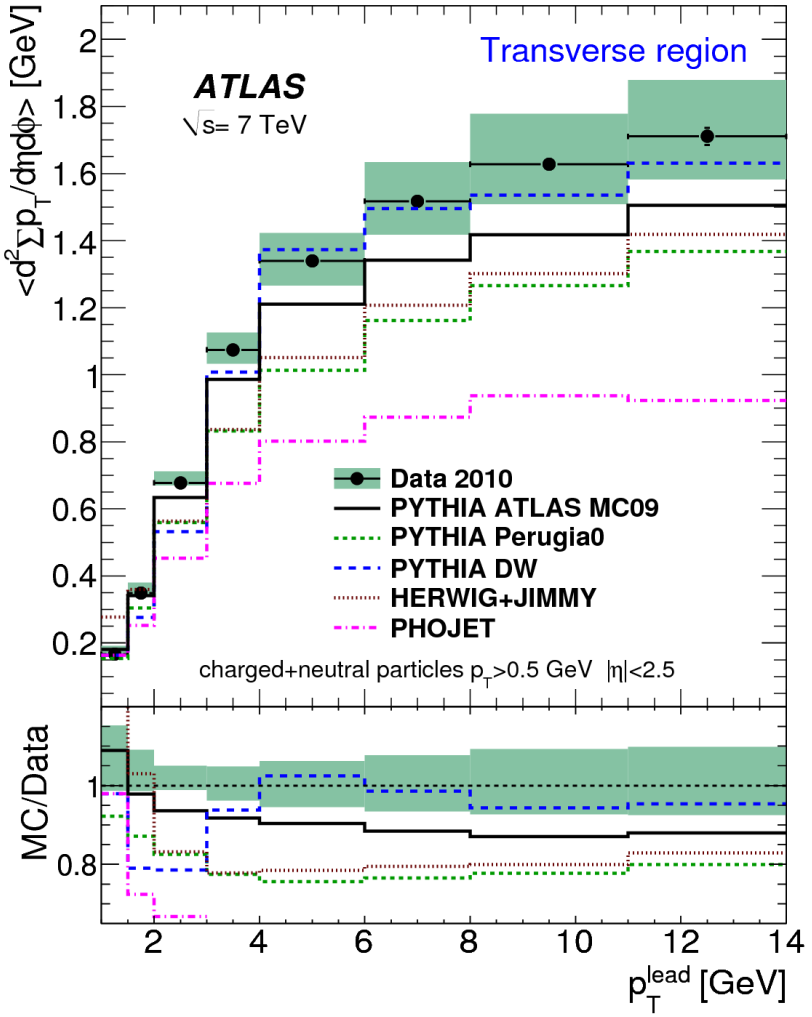
Σp_T vs. p_T^{lead}

Σp_T is higher than predicted by any of the MC tunes

Track method

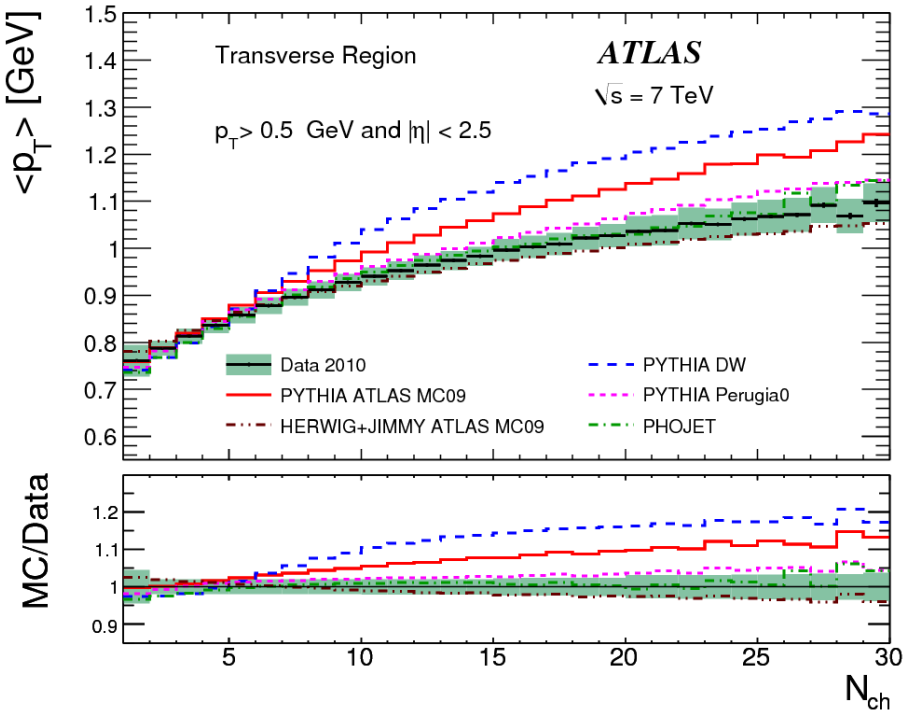


Cluster method

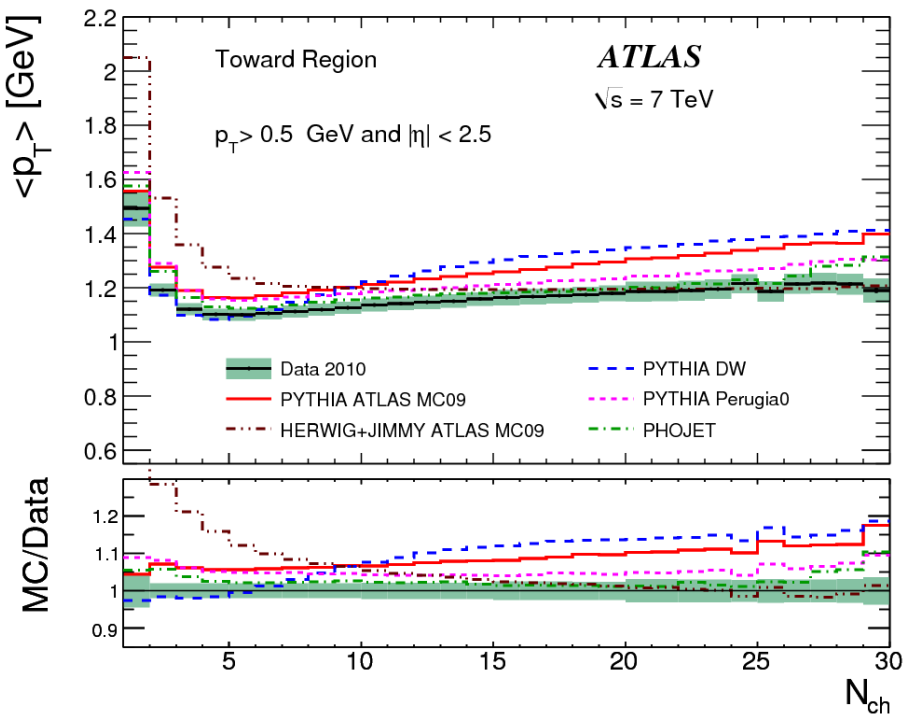


$\langle p_T \rangle$ versus n_{ch}

$\langle p_T \rangle$ is overestimated in toward region



Track method

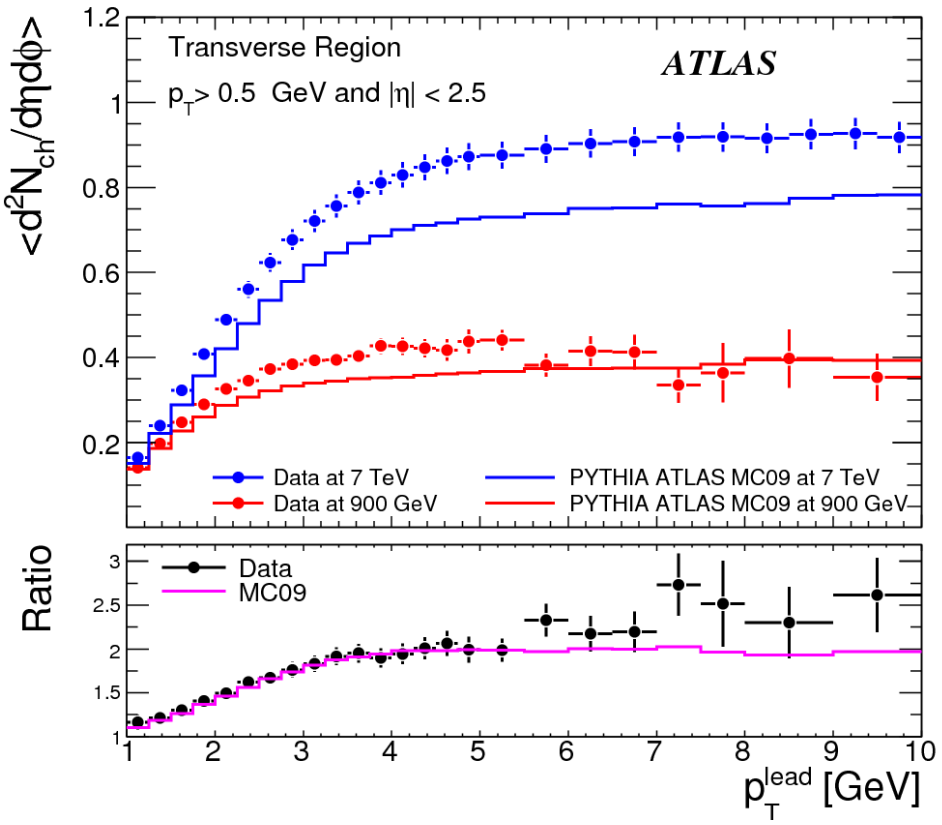


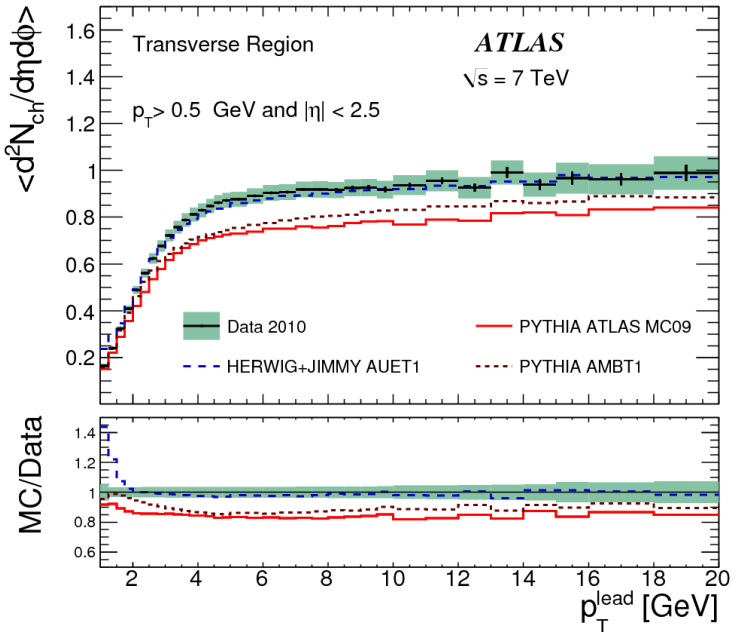
Track method

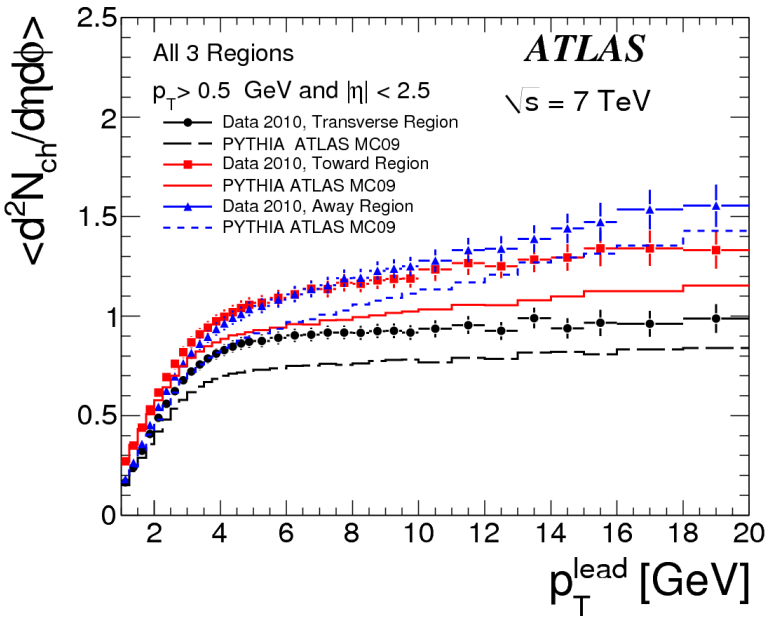
Particle density versus p_T^{lead}

New Pythia tunes from ATLAS tuning group to improve description of UE results.

See talk by D. Kar at 3:40 pm today.







Ongoing studies

- Forward-backward correlations
- Forward energy flow
- UE with track jets
- UE in Z events
  - High statistics 2011 data sample
  - $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels
  - Leading jet up to 1 TeV

Stay tuned for new results!

Summary

- LHC data provides a new energy scale for studying non-perturbative QCD
- Charged particle multiplicities measured by ATLAS in various regions of phase space
  - Measurements indicate a deficit of activity in models tuned to Tevatron data
- New measurement of the azimuthal ordering of charged hadrons
  - Shows features consistent with string fragmentation represented by a helix-like ordered gluon chain
- Underlying Event activity measured using track-based and cluster-based methods, providing statistically independent results
  - Activity measured in data is above predictions from current model tunes
- MB + UE measurements expose limitations in models that prevent a simultaneous description of all regions of phase space

There is still much to learn about non-perturbative QCD at $\sqrt{s}$ = 7 TeV!

References

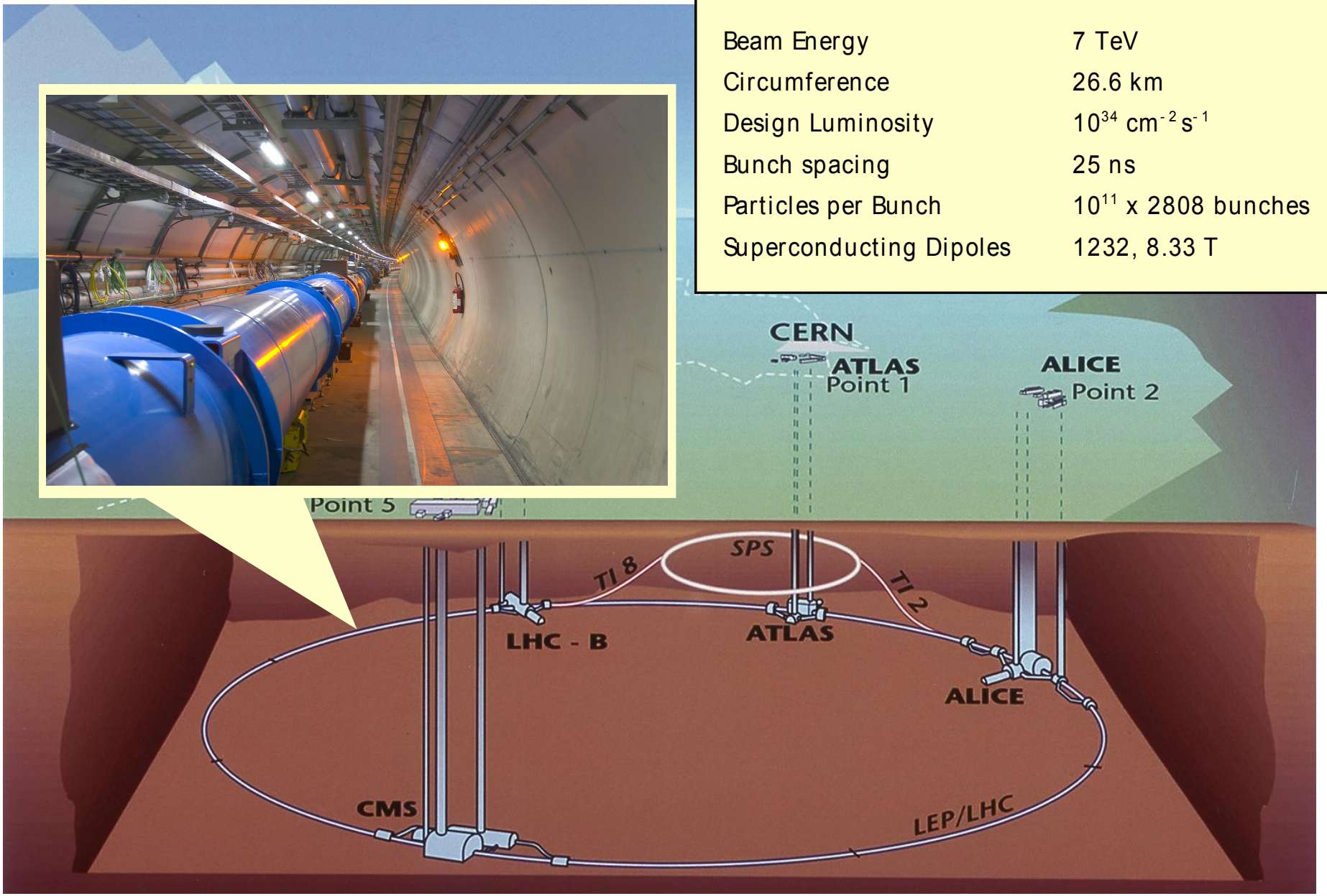
- "Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC", published 18 May 2011 in New J Phys 13 (2011) 053033
- Common plots from LHC MB & UE working-group: http://lpcc.web.cern.ch/LPCC/index.php?page=mb_ue_wg_docs
- "Measurement of inclusive two-particle angular correlations in proton-proton collisions at √s=900 GeV and 7 TeV", 6 April 2011, ATL-CONF-2011-055
- "Measurement of the azimuthal ordering of charged hadrons with the ATLAS detector", reference not yet available
- "K^0_s and Λ production in pp interactions at √s = 0.9 and 7 TeV measured with the ATLAS detector at the LHC", arXiv:1111.1297 [hep-ex] , submitted to Phys. Rev. D
- "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
- "Measurement of underlying event characteristics using charged particles in pp collisions at √s=900 GeV and 7 TeV", published 31 May 2011 in Phys. Rev. D 83, 112001

BACKUP SLIDES

The LHC

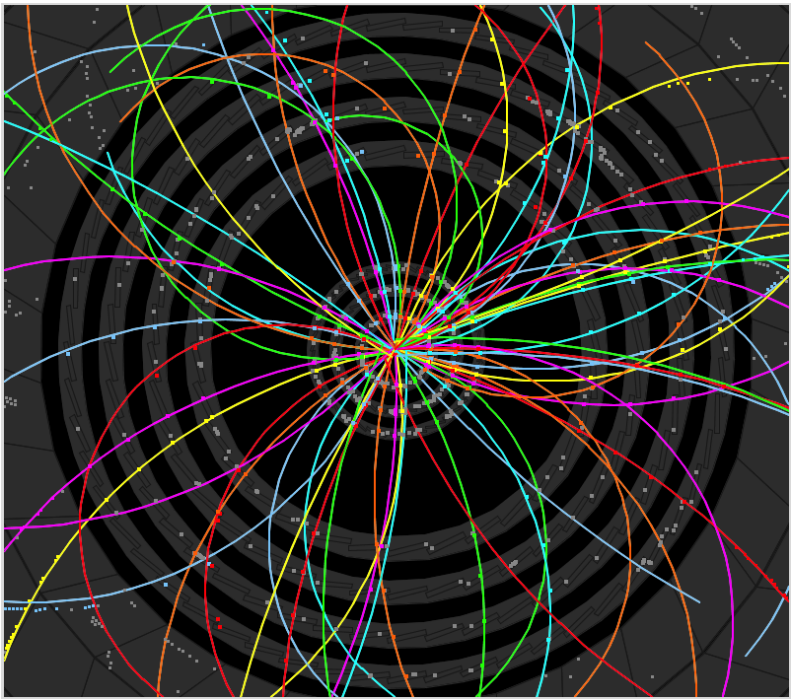
LHC Design Parameters

Beam Energy	7 TeV
Circumference	26.6 km
Design Luminosity	10^{34} cm^{-2}s^{-1}
Bunch spacing	25 ns
Particles per Bunch	10^{11} x 2808 bunches
Superconducting Dipoles	1232, 8.33 T



Minimum bias: Measurement strategy

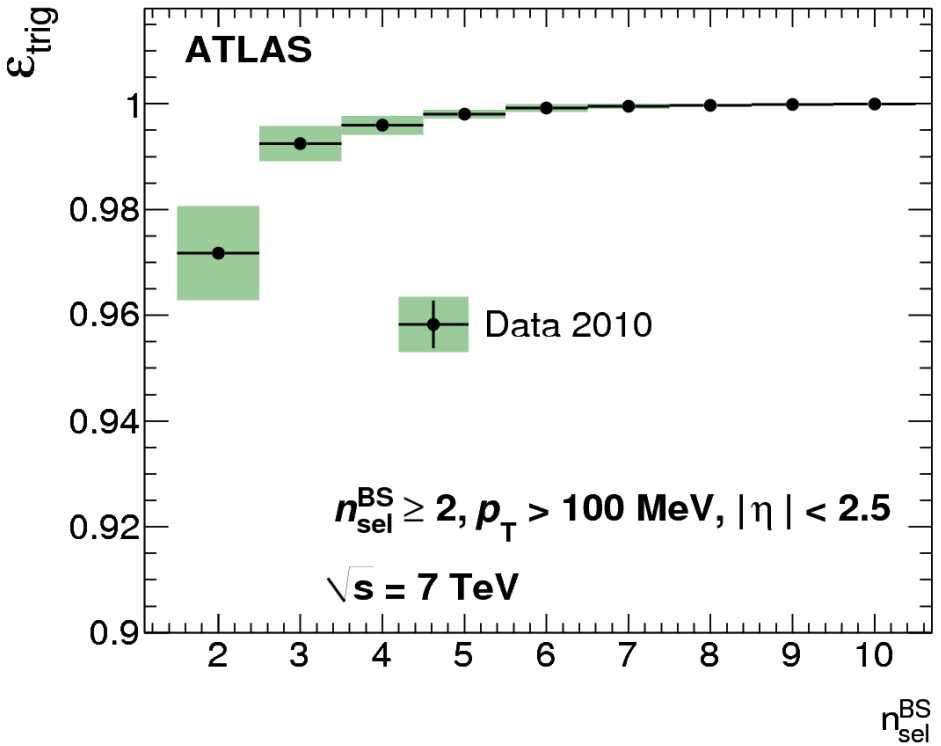
- Event selection
  - Single-arm MBTS trigger (≥1 hit anywhere)
  - Pile-up veto: reject events with a second primary vertex with 4 or more tracks
  - Number of selected tracks within given phase space
- Track selection
  - p_T and η within given phase space
  - A minimum of one hit in first layer of pixel detector, if expected
  - A minimum of one pixel hit and 2/4/6 strip hits (p_T-dependent)
  - $|d_0^{PV}|$, $|z_0^{PV}| \sin\theta < 1.5$ mm (impact parameters w.r.t. primary vertex)

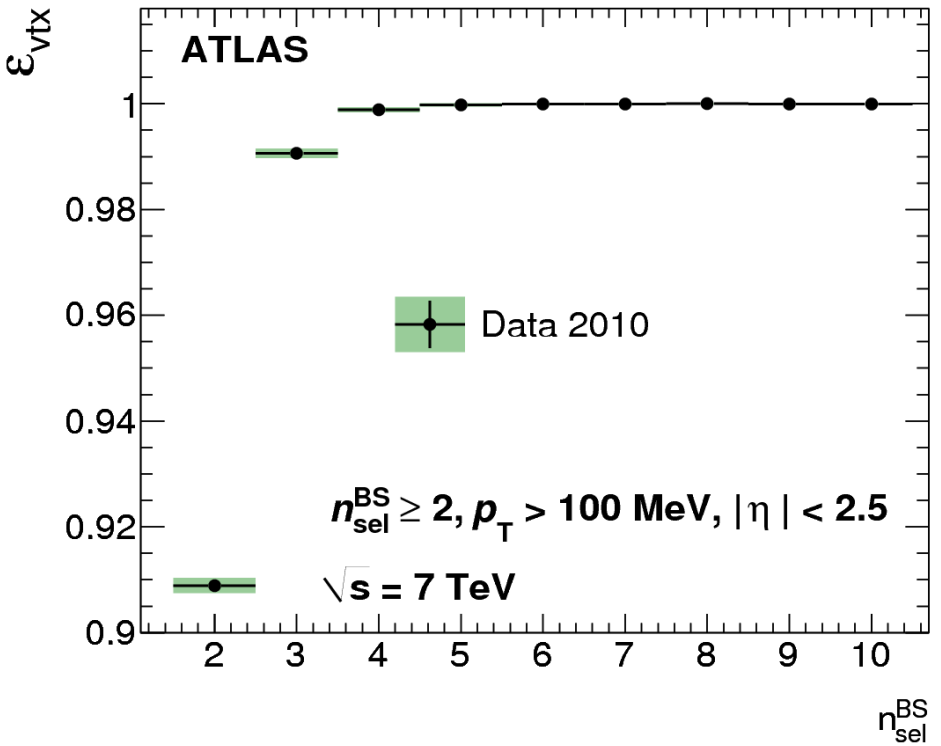


Apply corrections at event and track level to measure distributions of stable charged particles coming from the primary pp interaction

Minimum bias: Event-level corrections

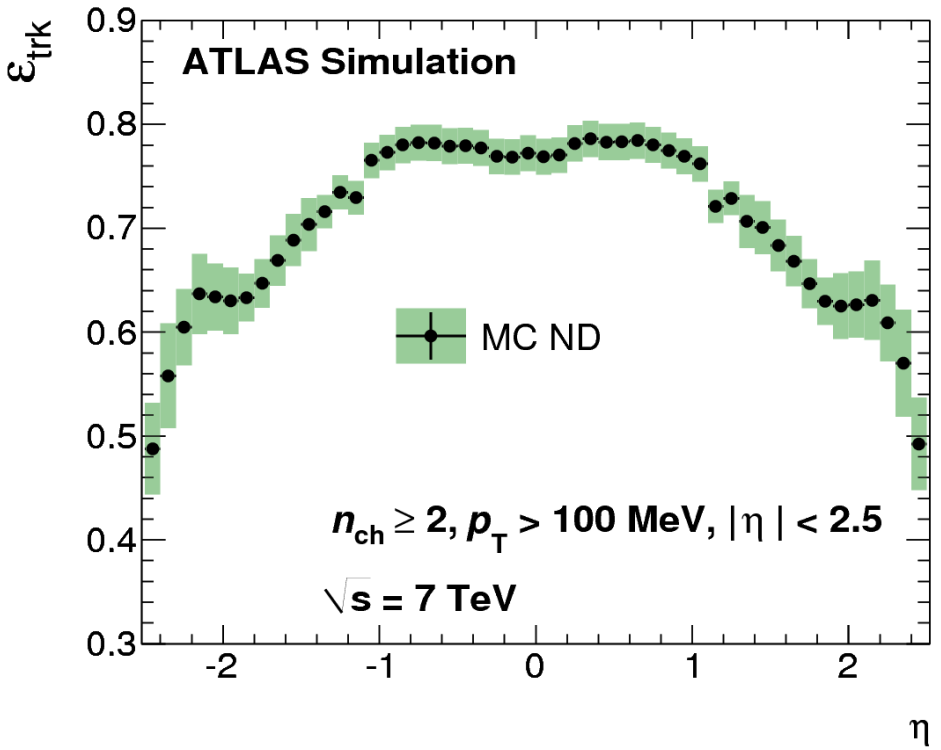
- Correct for missing events due to trigger and vertex requirements
- Both vertex and trigger corrections derived from data
  - Measure trigger efficiency of MBTS w.r.t. control trigger using ID
  - Vertex reconstruction efficiency measured using all triggered events

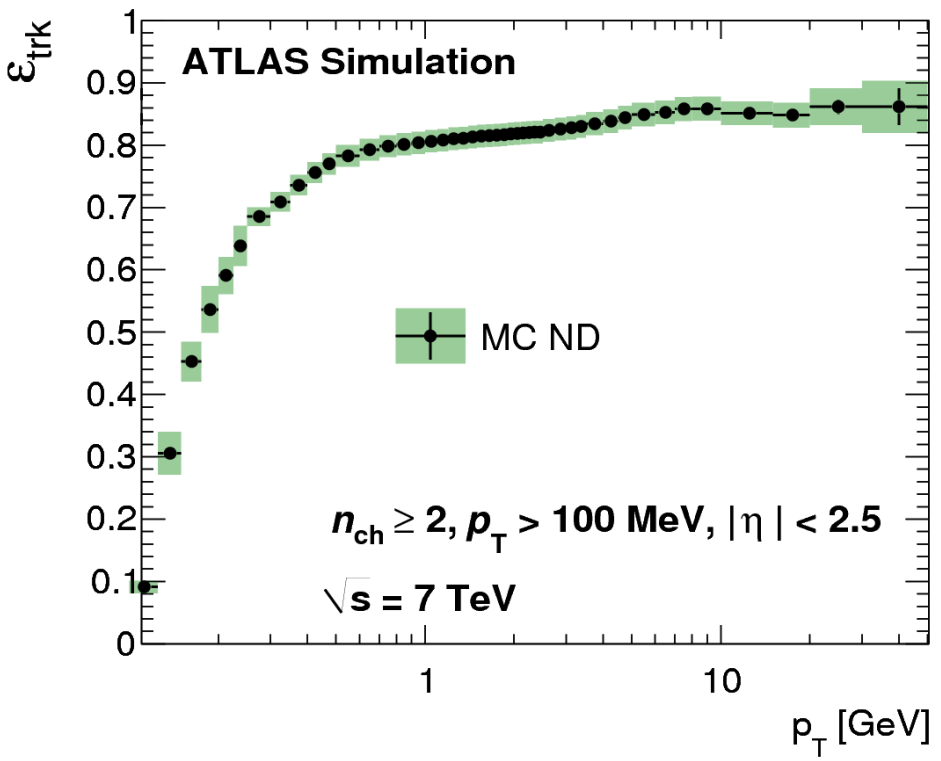




Minimum bias: Track-level correctioms

- Tracking efficiency (ε_{trk}) derived from MC with GEANT detector simulation
  - Systematic uncertainty determined from comparisons with data
- Correction is applied in 2D (pT, η) to remove model dependence
  - Also correct for non-primaries and particles outside of kinematic range





Pythia 6 Tunes

- ATLAS MC09
  - Main reference before ATLAS measurements at $\sqrt{s}$ = 7 TeV

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- ATLAS MBT1
  - Tuned using diffraction-suppressed phase-space
  - $n_{ch} \geq 1$, pT > 500 MeV, $|\eta| < 2.5$
  - ATL-PHYS-PUB-2010-002

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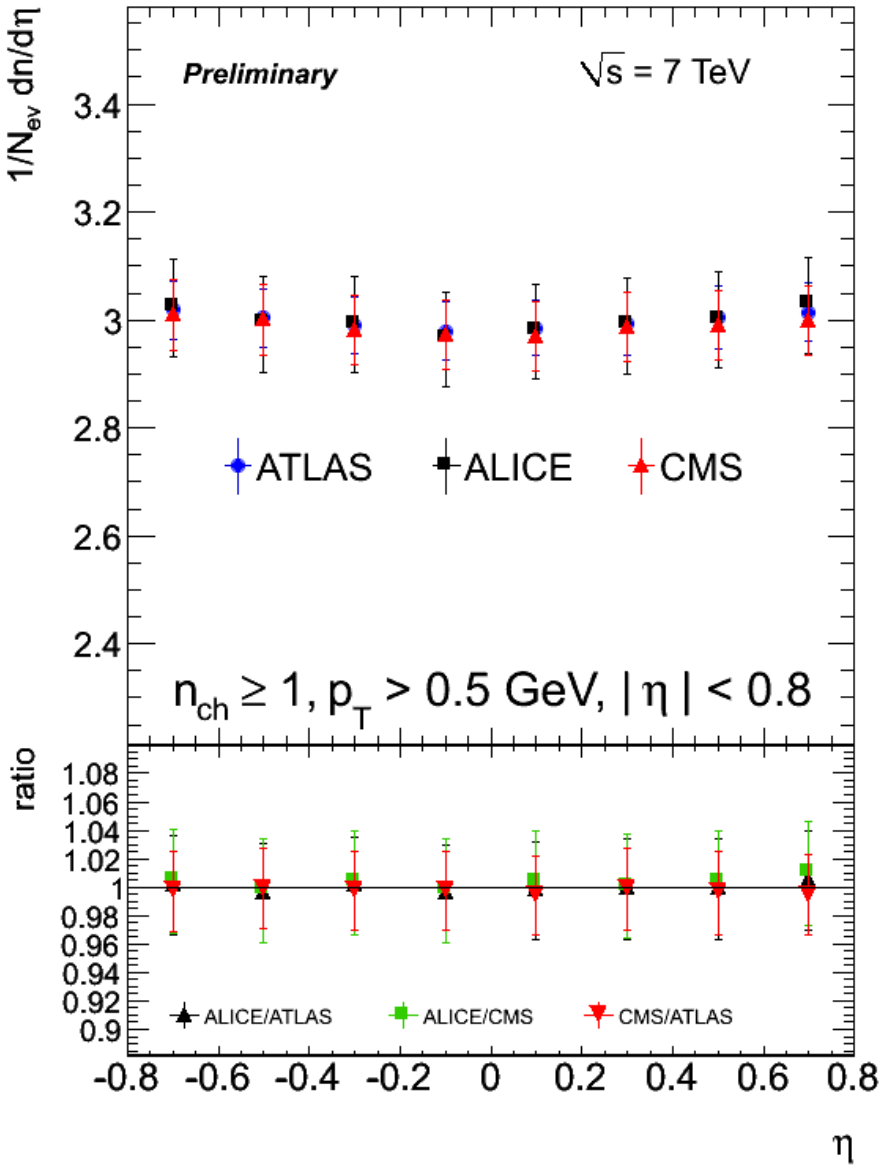
- ATLAS MBT2, MBT2B, UET2B
  - Not discussed here
  - See talk by D. Kar at 3:40 pm today

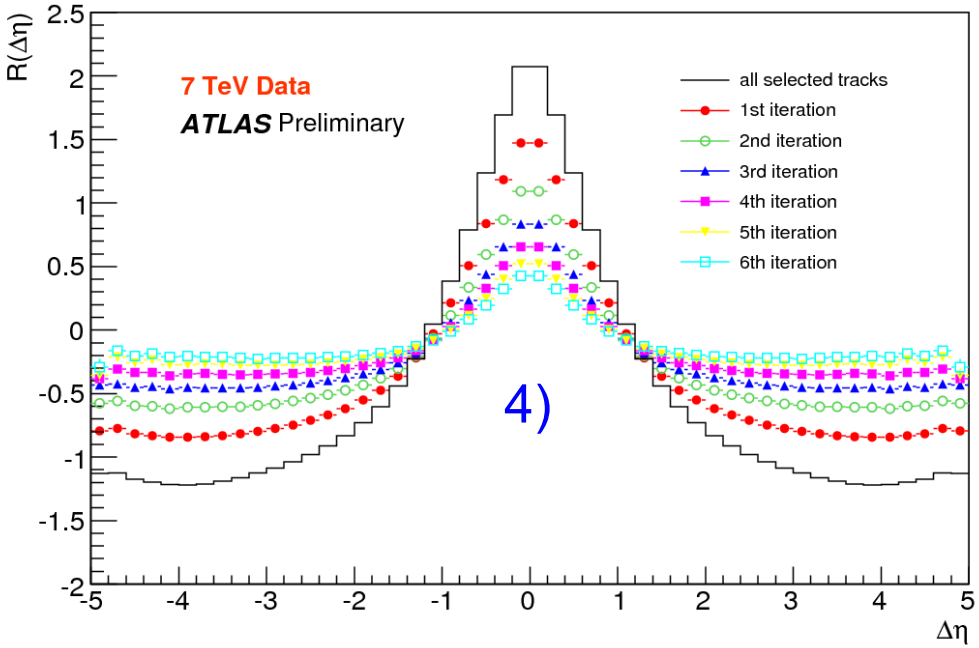
Minimum bias: ATLAS/ALICE/CMS comparison

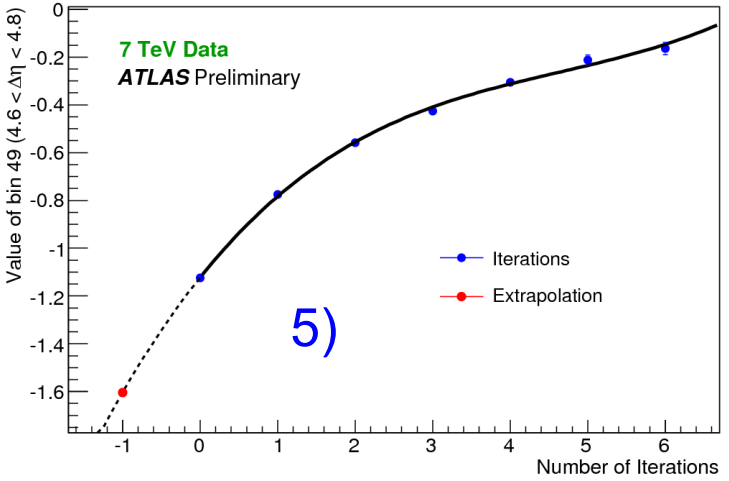
- Common phase spaces chosen by the LHC Minimum Bias & Underlying Event working group:
  - $n_{ch} \geq 1$, $p_T > 500$ MeV, $|\eta| < 0.8$
  - $n_{ch} \geq 1$, $p_T > 1$ GeV, $|\eta| < 0.8$
- Good agreement on measured charged particle multiplicity between LHC experiments!

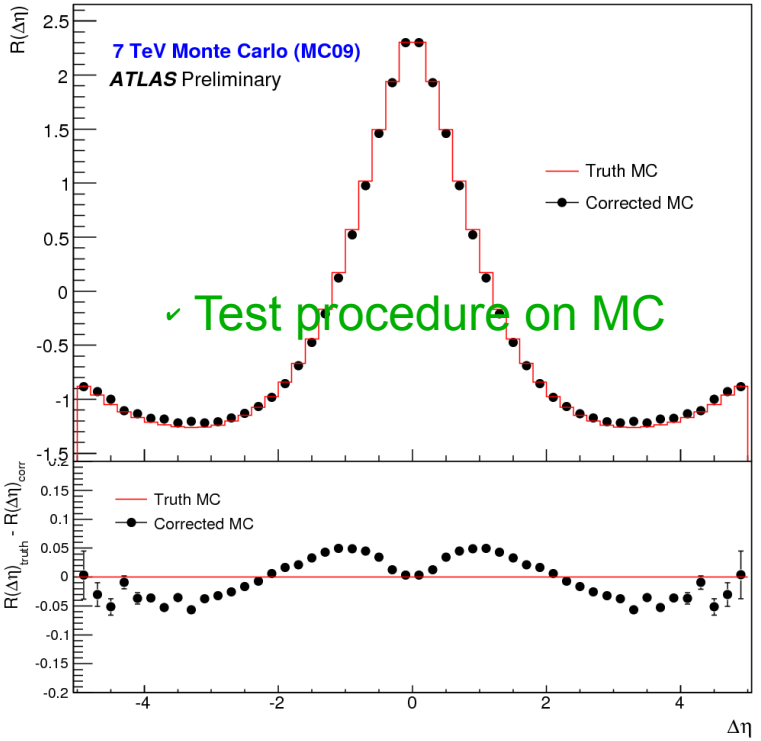


Angular correlations: Correction strategy

1) Apply event-level corrections (track + vertex)
2) Compute observable R(Δη,Δφ)
3) Randomly throw away tracks according to tracking efficiency
4) Repeat 6 times (ε_{trk}^{6})
5) In each bin, extrapolate back to -1th iteration: "truth"

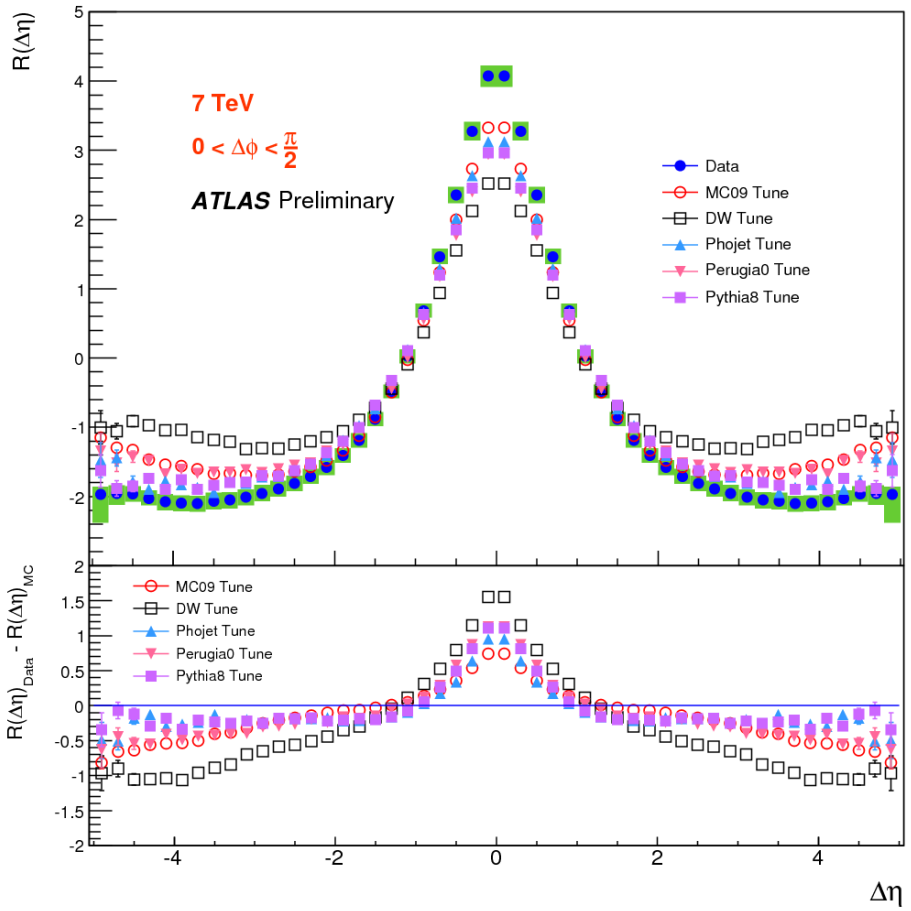




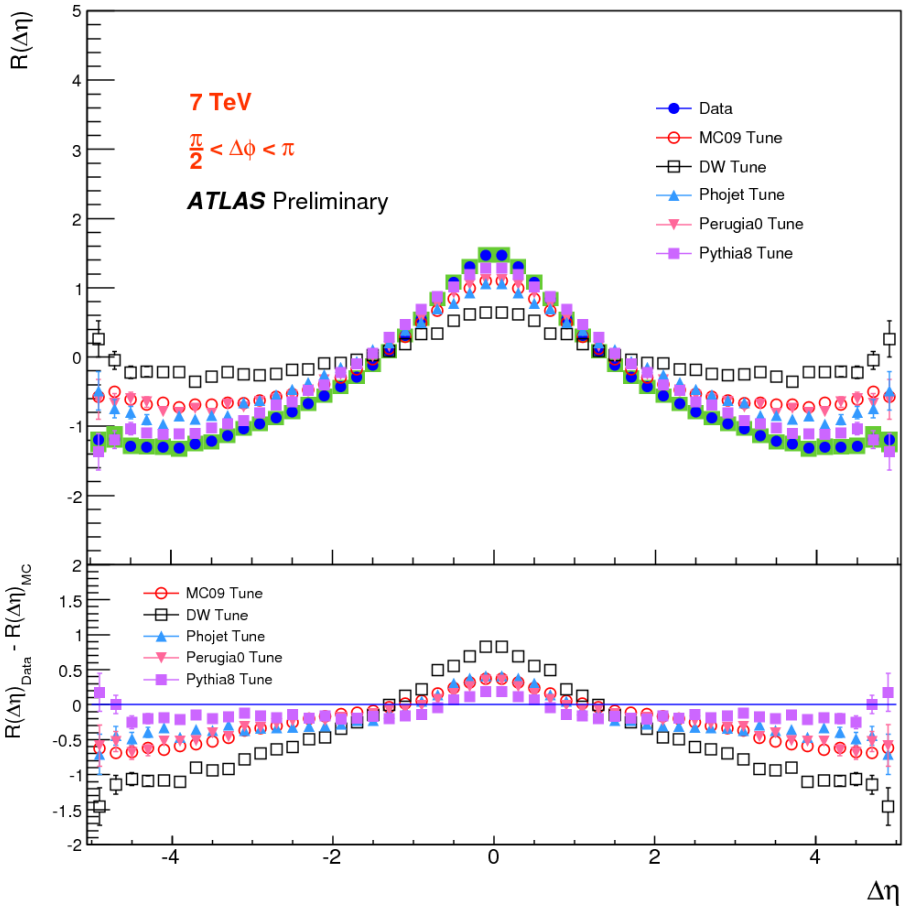


Angular correlations: Correlations in Δη

Near-side correlation
(Integrated over 0 < Δφ < π/2)

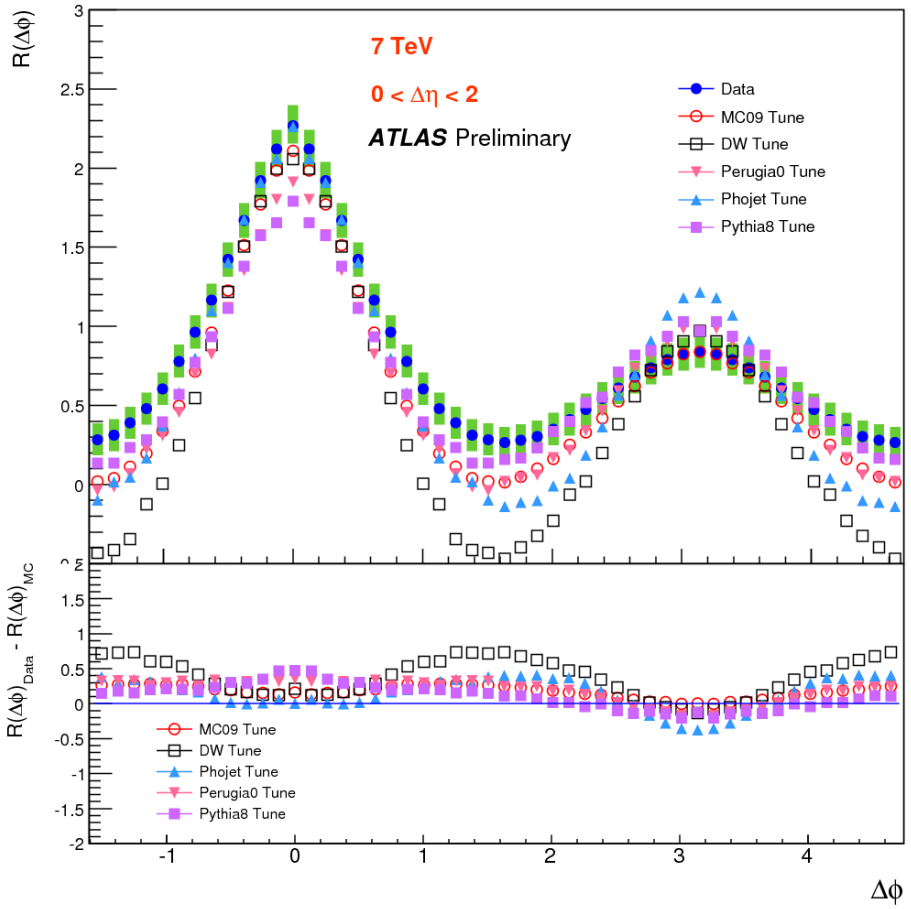


Away-side correlation
(Integrated over π/2 < Δφ < π)

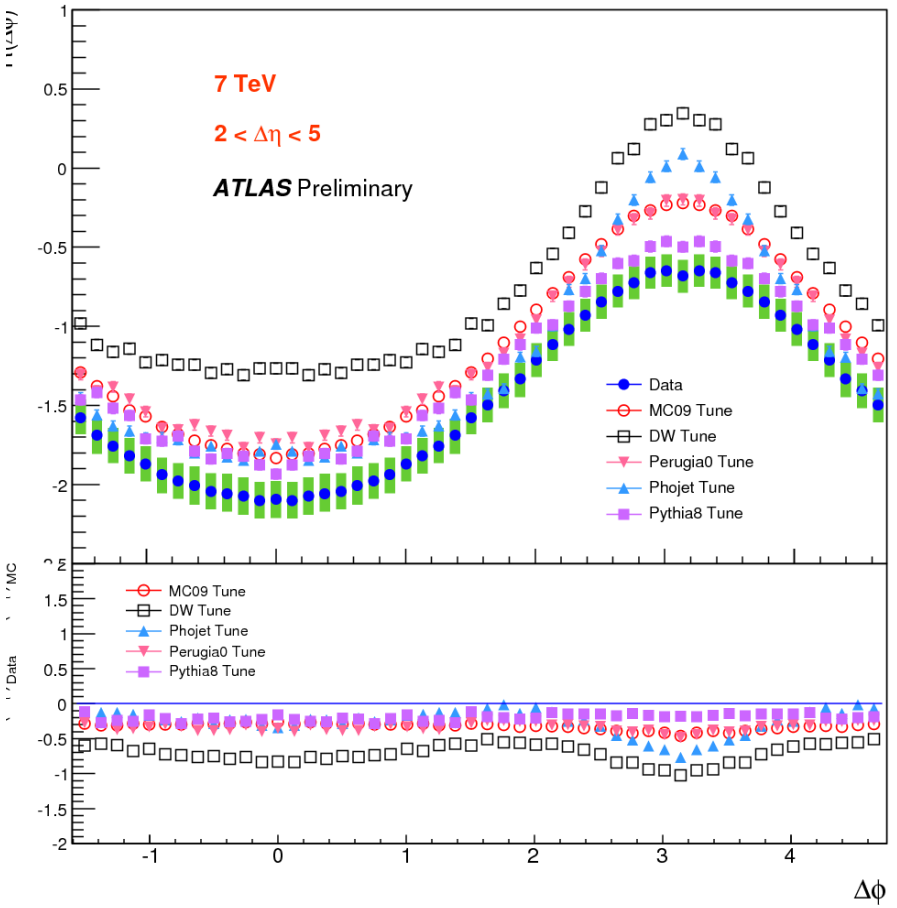


Angular correlations: Correlations in Δφ

Short-range correlation
(Integrated over 0 < Δη < 2)



Long-range correlation
(Integrated over 2 < Δη < 5)

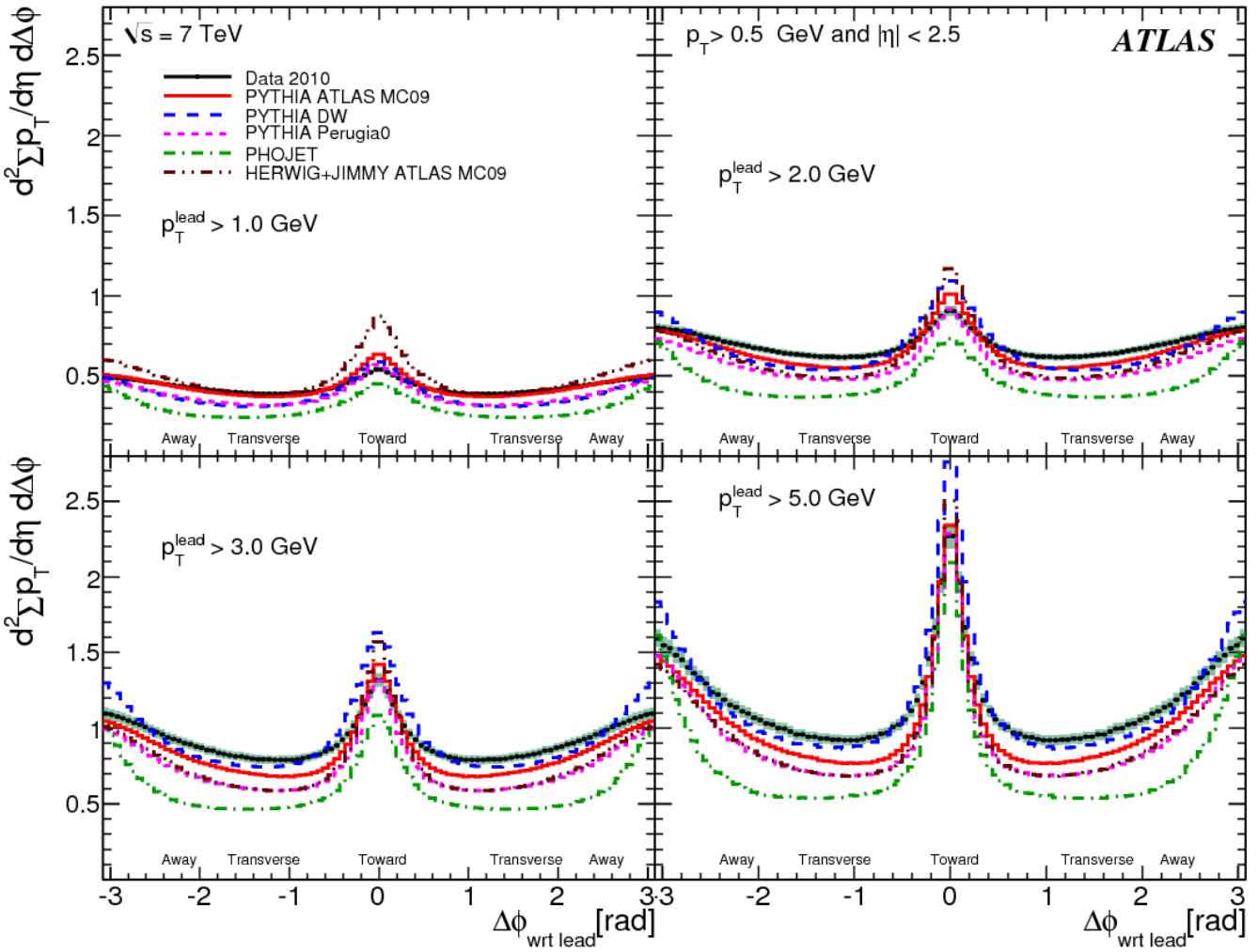


Azimuthal ordering: Measurement strategy

- Event selection (inclusive sample)
  - At least one triggered counter in MBTS (minimum bias)
  - Exactly one reconstructed vertex with at least three tracks
  - At least six tracks passing slightly modified minimum bias selection (p_T > 100 MeV)
  - n_{tr} is stochastically unfolded to $n_{ch} \rightarrow n_{ch} > 10$
  - Veto events containing any track with p_T > 10 GeV
- Low-pT enhanced sample
  - Veto events containing any track with p_T > 1 GeV
  - Effects of parton showering and lateral boost are diminished
  - Transverse activity in these events expected to be sensitive to hadronization
- Low-pT depleted sample
  - Use higher track p_T cut, p_T > 500 MeV
  - Significantly reduced contribution from diffractive pp interactions

Correct for detector effects using deconvolution technique similar to 2-particle correlation study

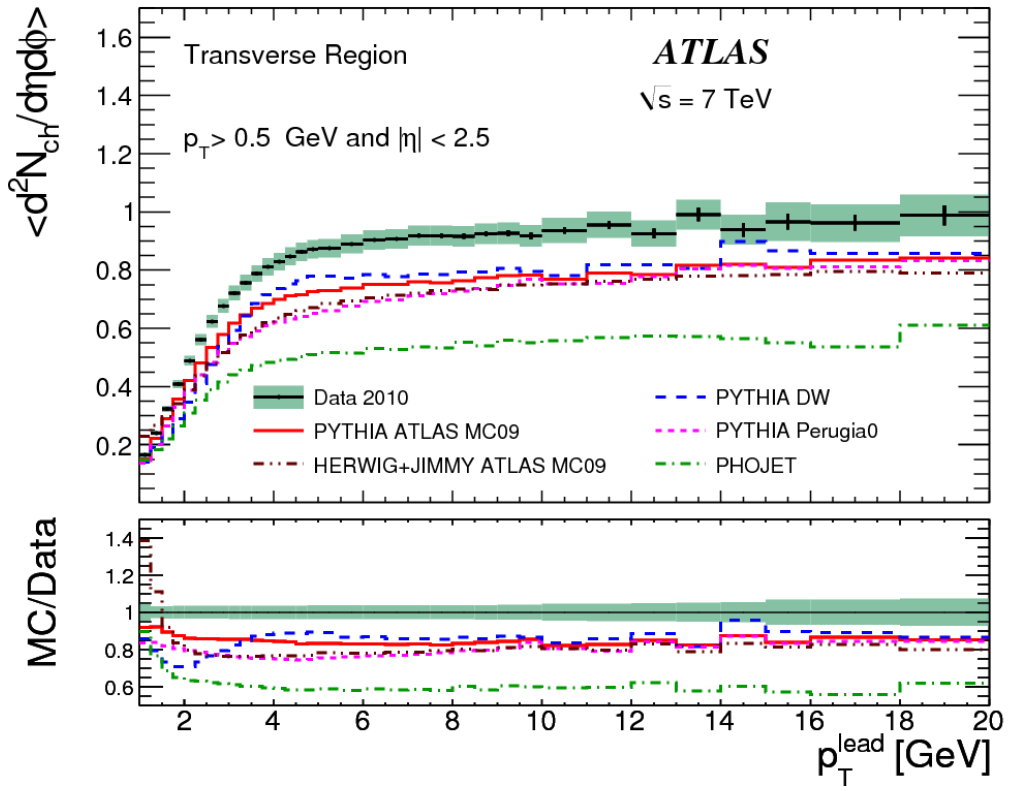
Underlying Event: Σp_T vs. $\Delta\varphi$



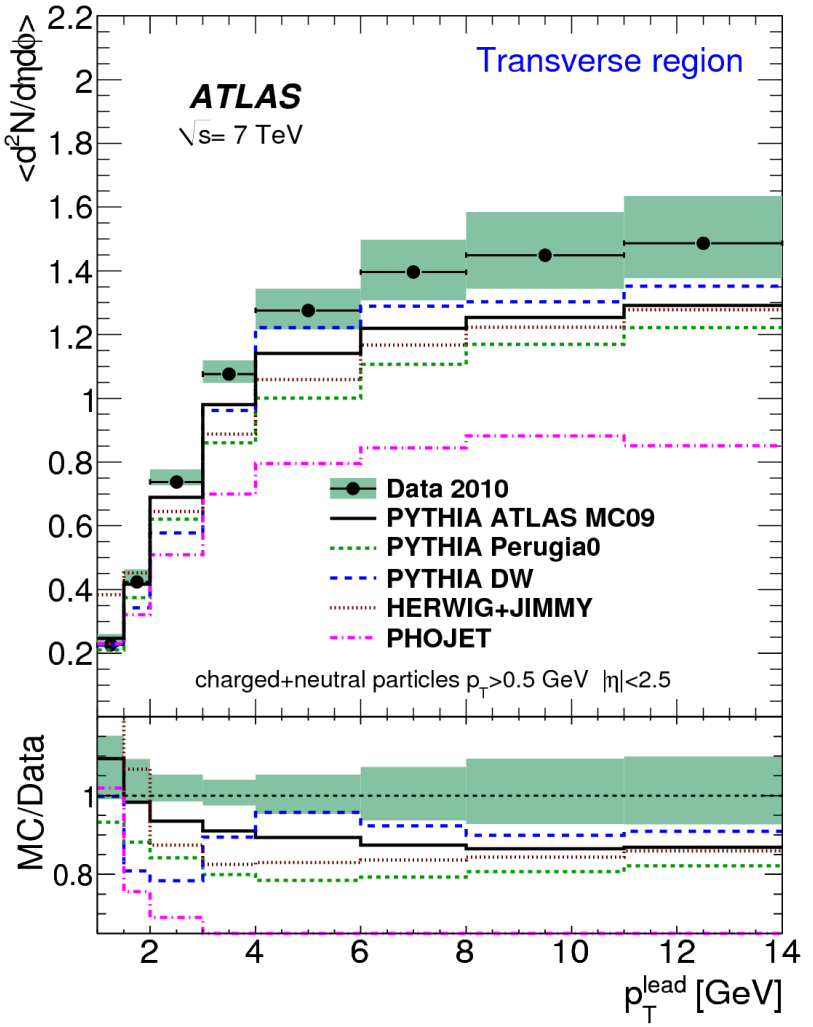
Underlying Event: Particle density vs. p_T^{lead}

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

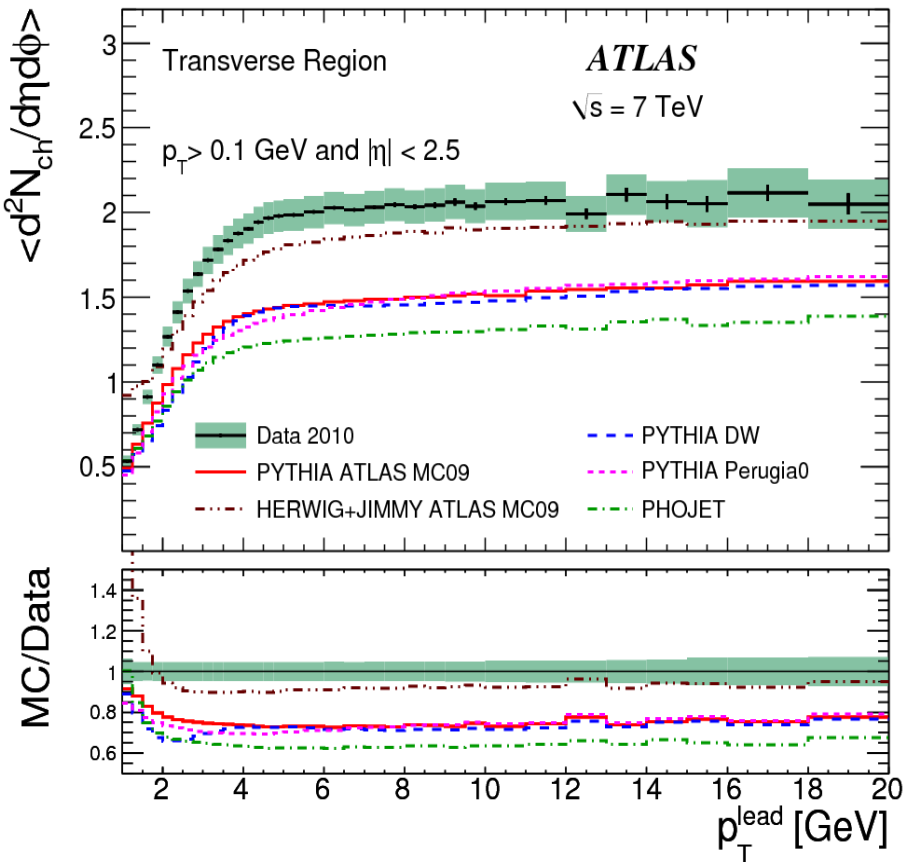
Track method

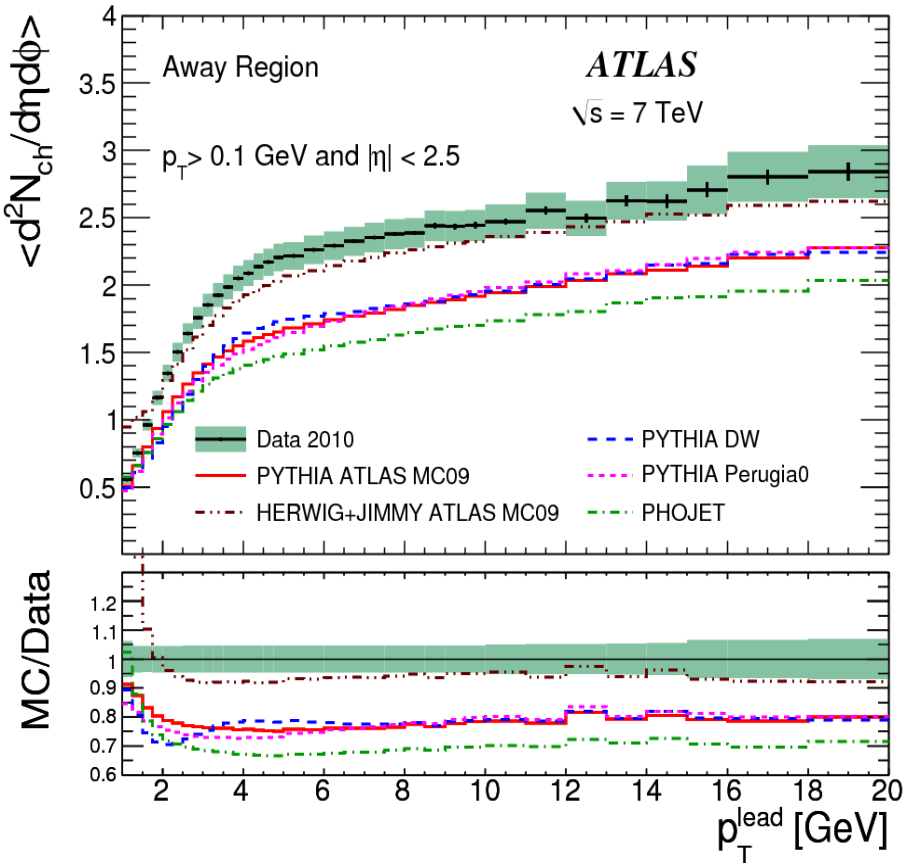


Cluster method

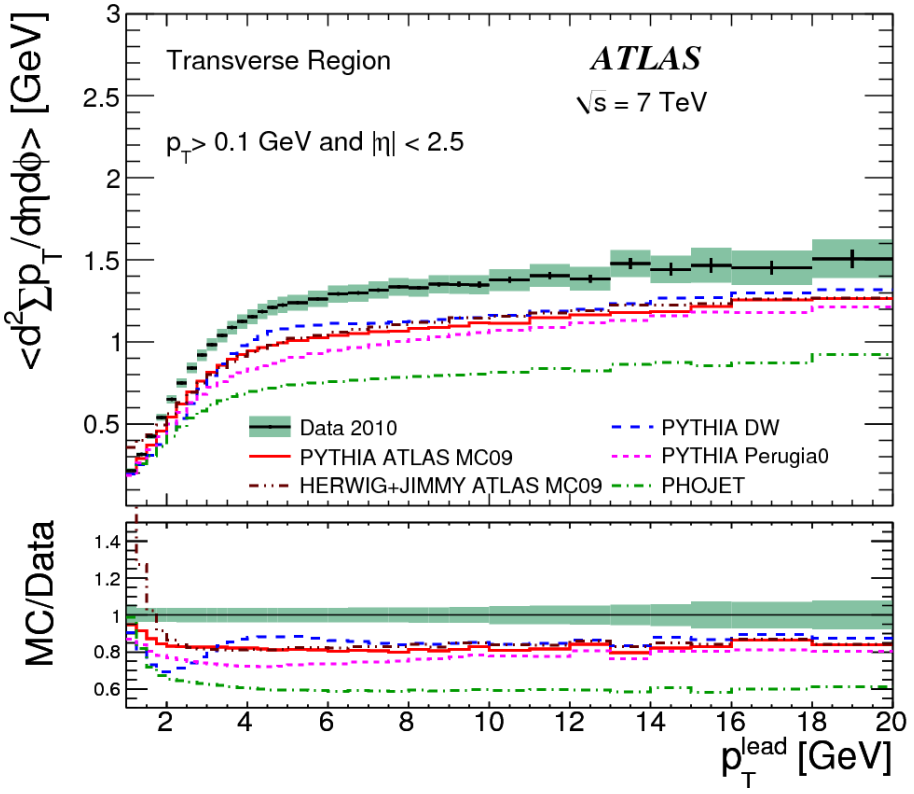


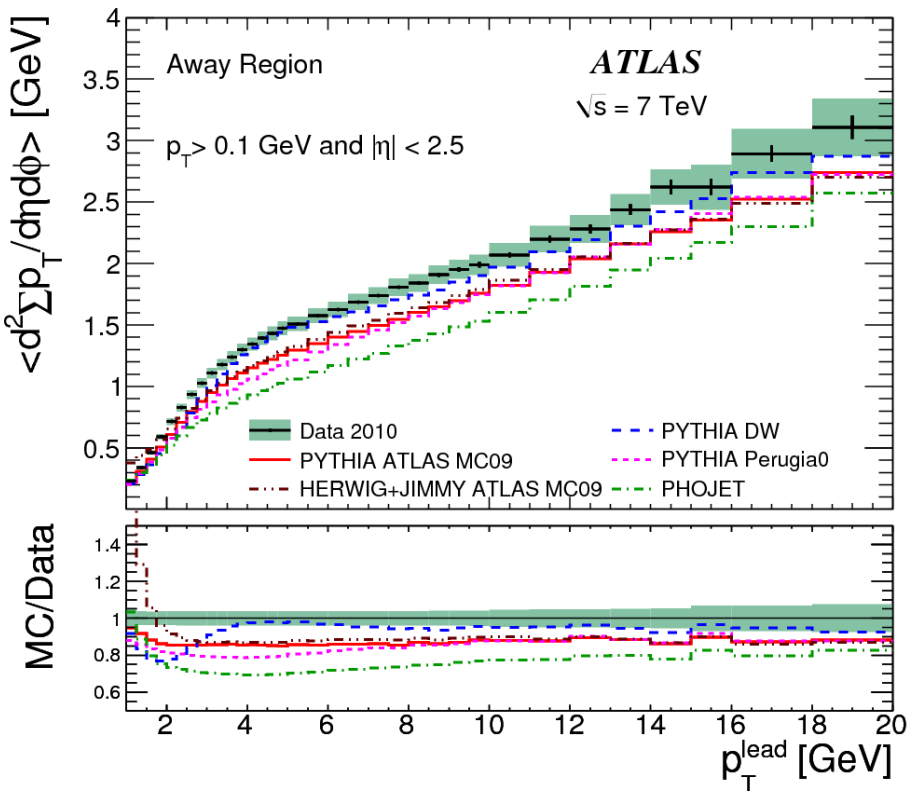
Underlying Event: Particle density vs. p_T^{lead}





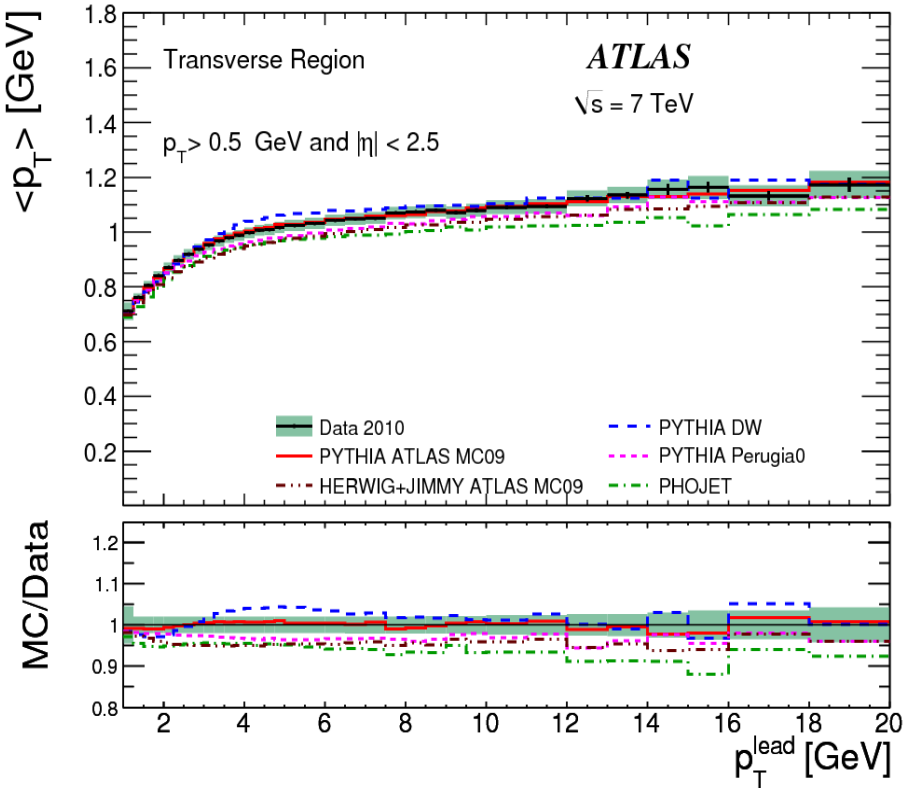
Underlying Event: Σp_T vs. p_T^{lead}



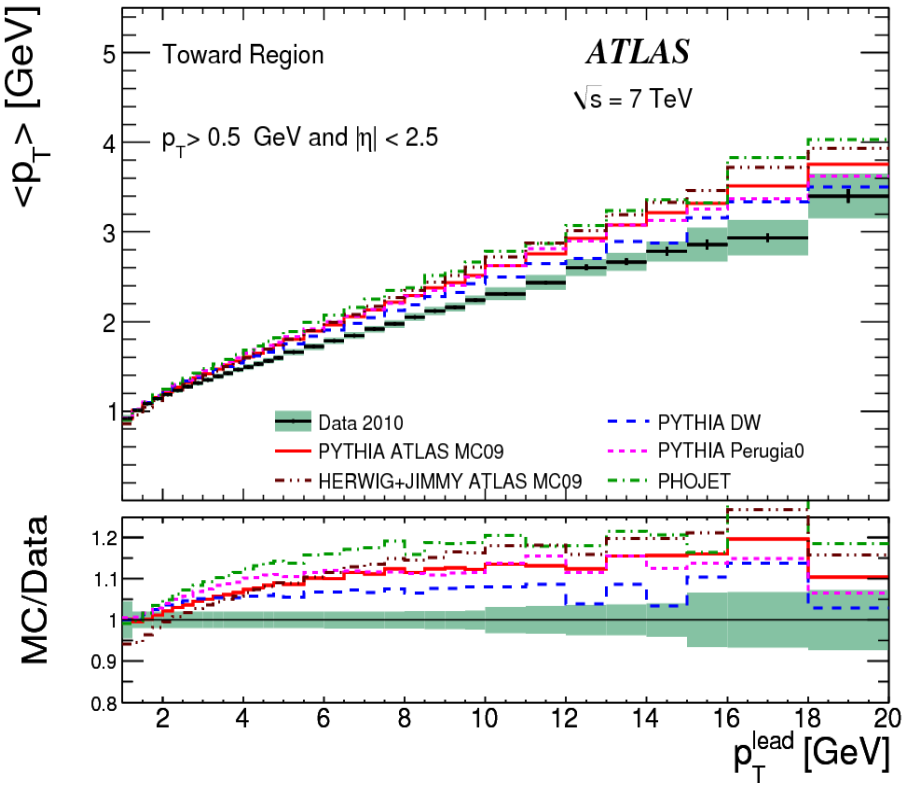


Underlying event: $\langle p_T \rangle$ versus p_T^{lead}

$\langle p_T \rangle$ is overestimated in toward region



Track method



Track method