Study of Particle Correlations in ATLAS

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Outline

1. Motivation for soft QCD
2. Minimum bias events
3. Particle correlations studies :
   - 3.1. $\Delta\Phi$: Angular correlations between charged particles
   - 3.2. Inclusive two particle angular correlations
   - 3.3. Other ongoing studies

4. Conclusions

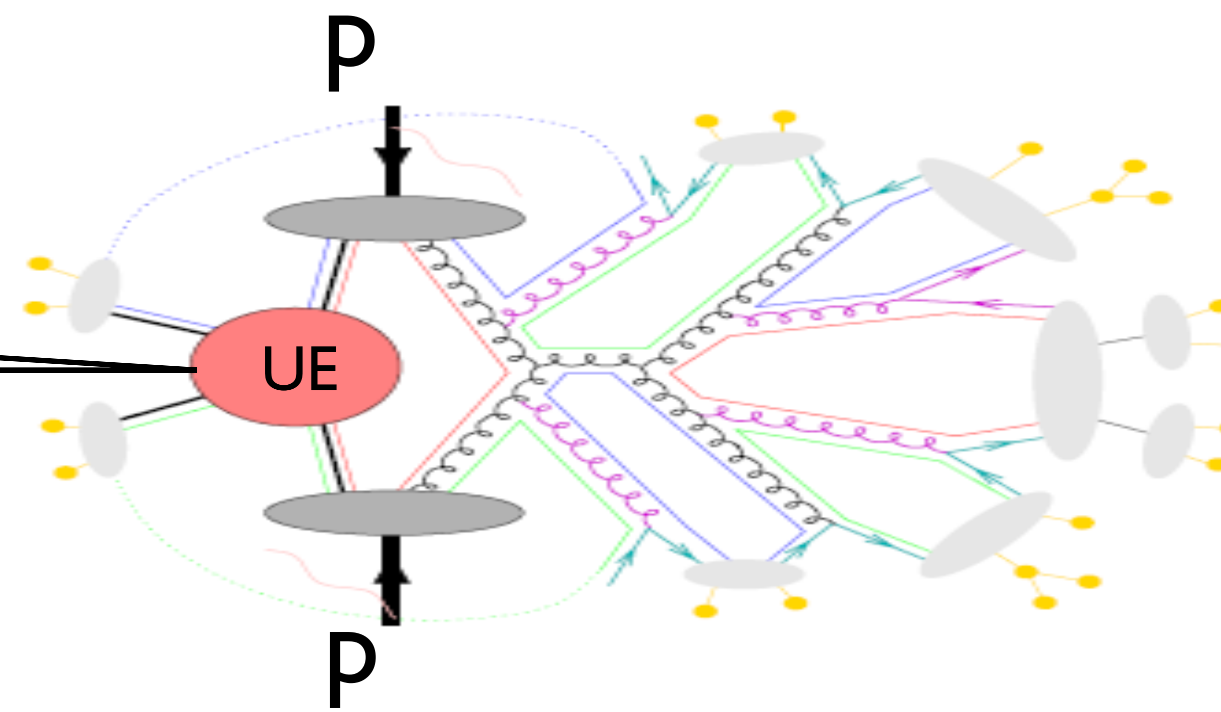
Motivation for soft QCD

'Soft' processes involving low momentum transfer between initial and final states are modeled empirically with many parameters that need tuning.

Valid soft QCD models are necessary for high p_T physics.
Understand dynamics of multi-particle production and soft radiation.

Underlying Events (UE)

- multi-parton interactions
- beam-beam remnants
- ISR and FSR

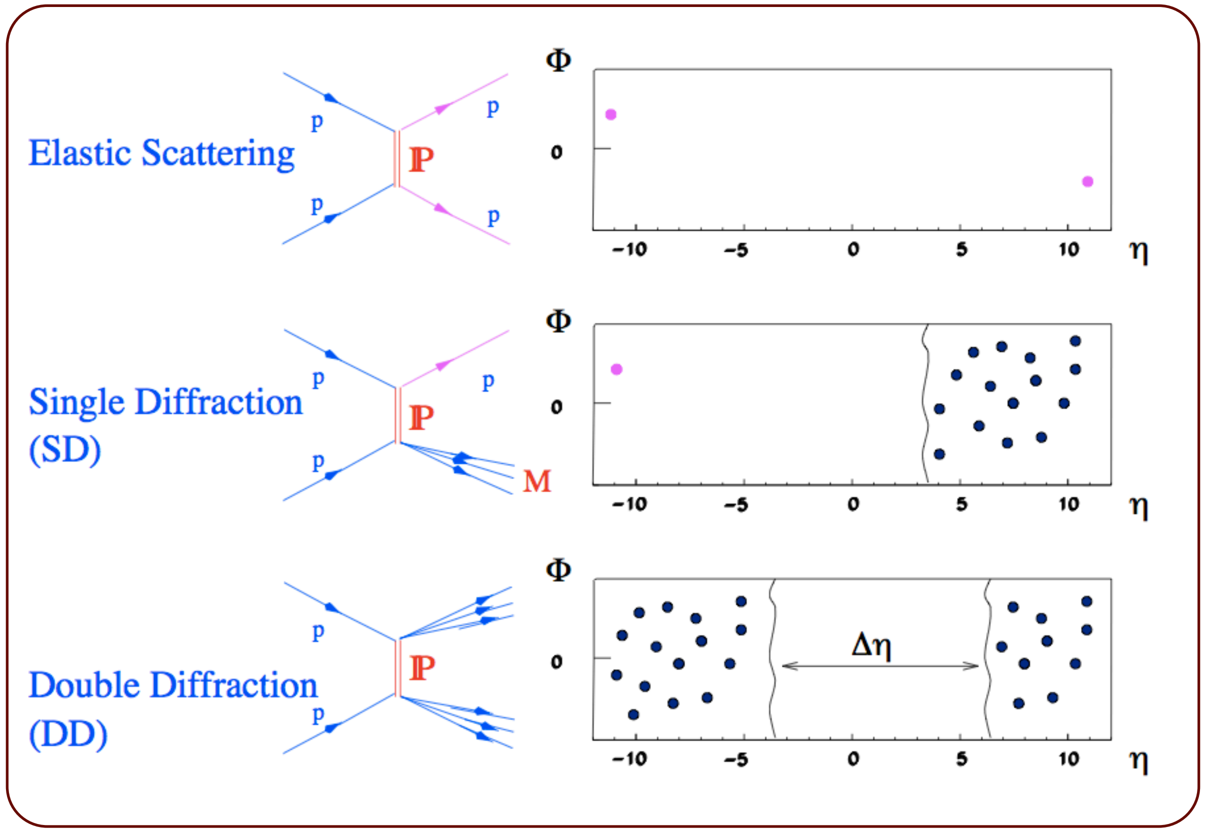


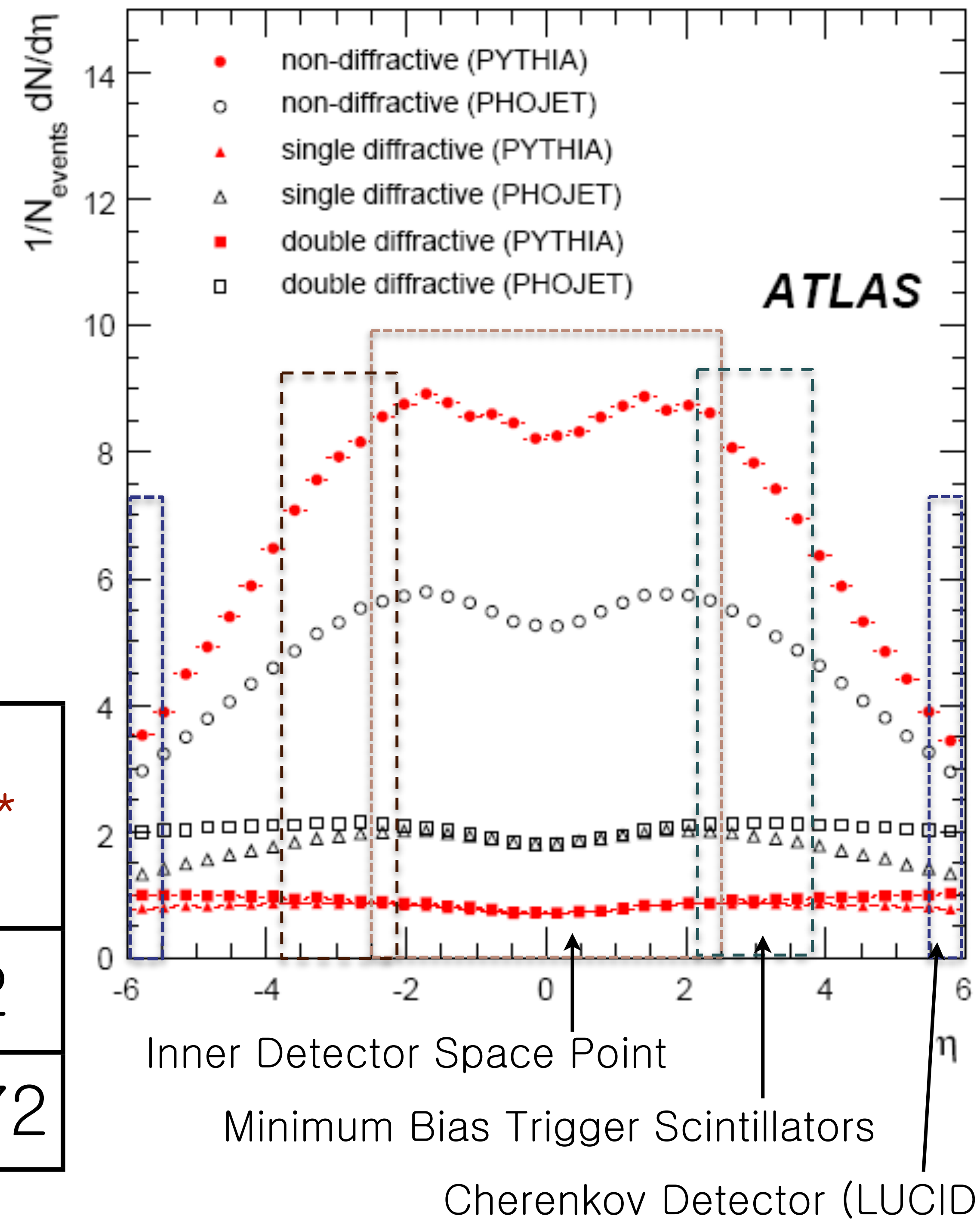
Correlation studies between final state particles allows us to investigate the particle production process.

Minimum bias events

Minimum bias events are dominated by soft QCD interactions.

A dedicated minimum bias trigger is used for data.



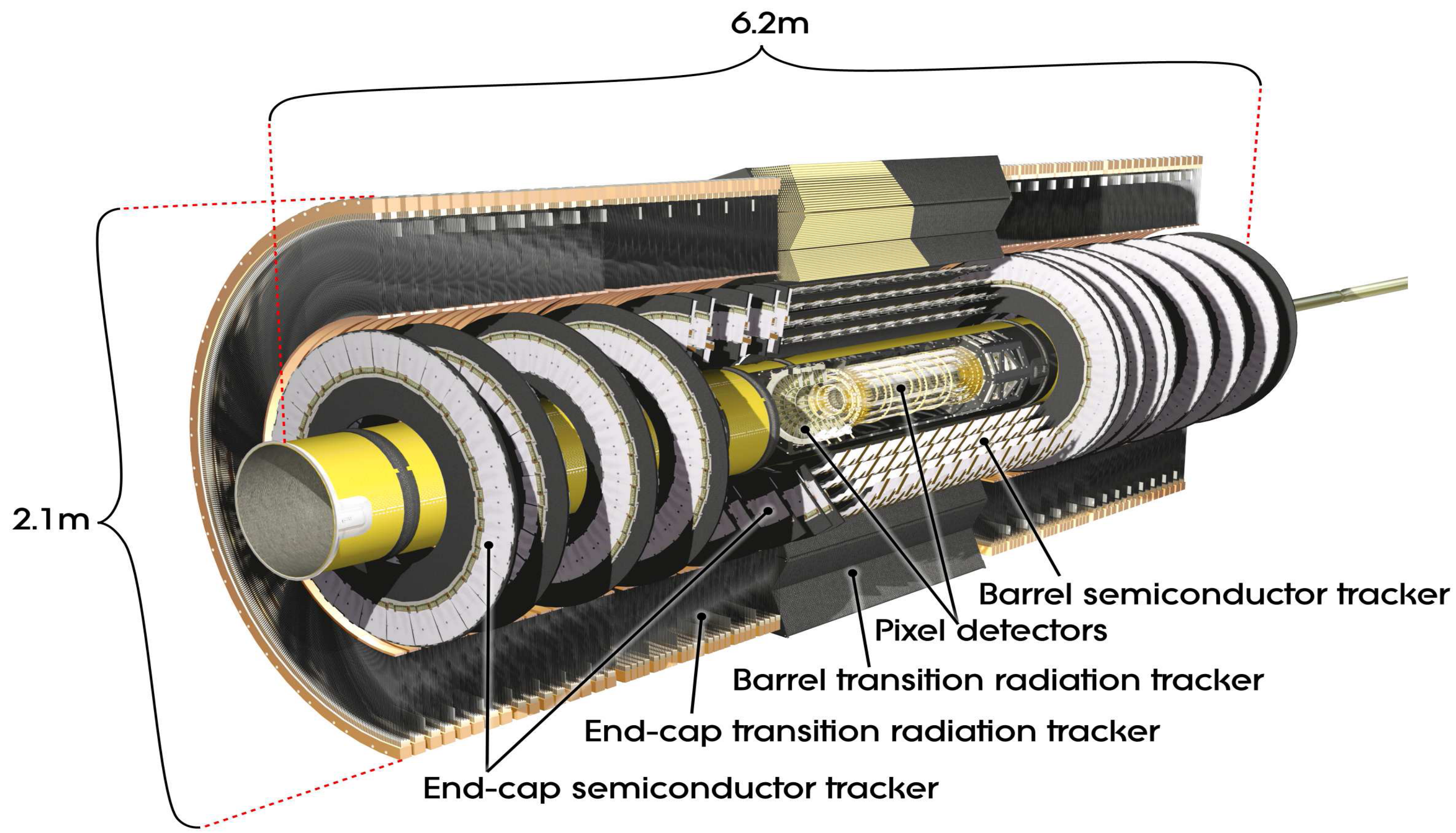


Energy √s	Integrated Luminosity	Events*
900 GeV	7 μb^{-1}	357532
7 Tev	190 μb^{-1}	10066072

* After event selections described in next slide

arXiv:1012.5104v2 [hep-ex], New J. Phys. 13,053033 (2011) Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC

Event and Track Selection



Event Selection

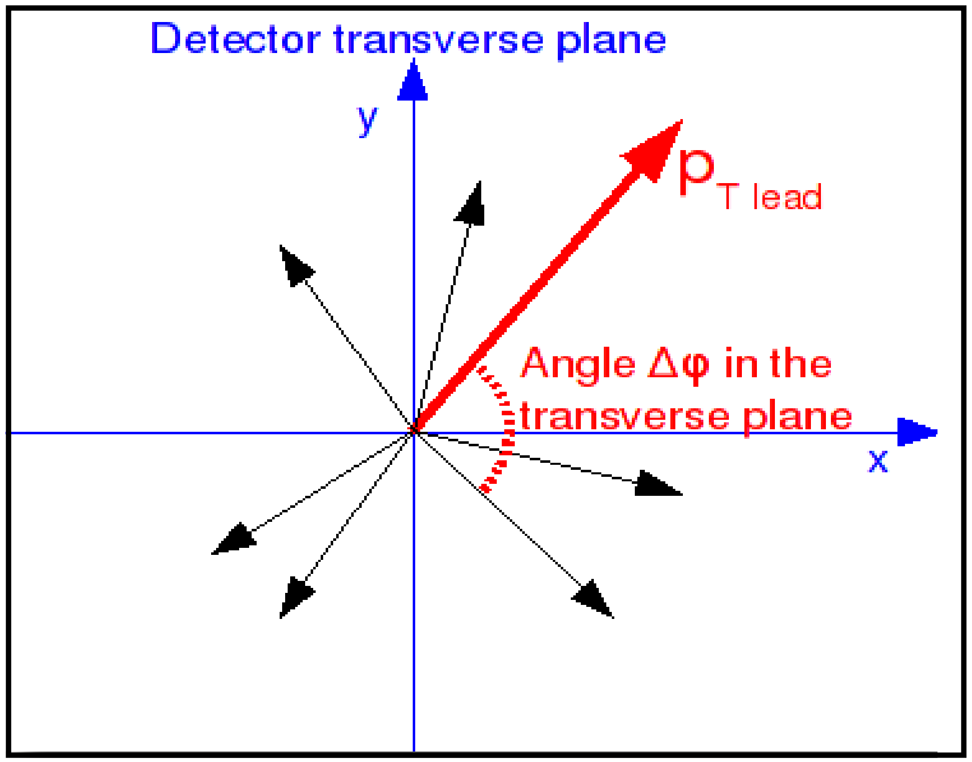
- ATLAS fully operational with nominal magnetic field
- Passes level 1 Minimum Bias trigger
- At least one primary vertex
- No second vertex with more than 4 tracks

Track Selection

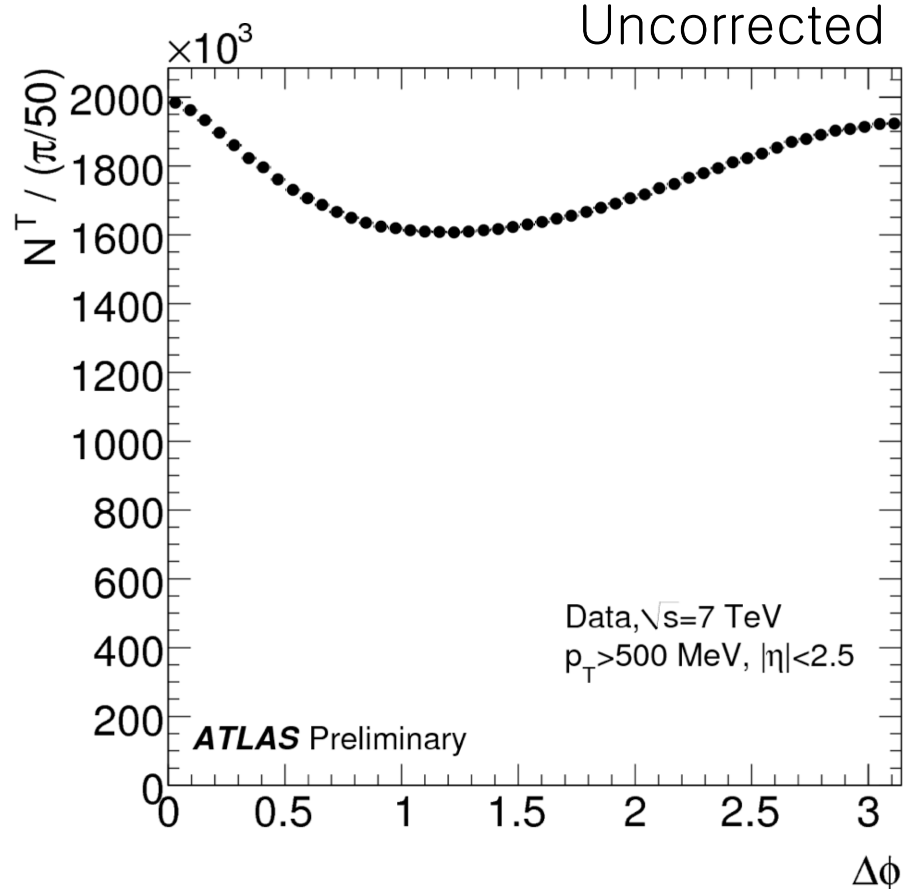
- At least 2 tracks with p_T>100 MeV, $|\eta|$<2.5
- At least one hit in any layer with 1 first Pixel (b) layer hit when expected & 2, 4, or 6 SCT (Silicon Tracker) hits for p_T>100, 200, 300 MeV respectively
- Cuts on the transverse ($|d_0|$< 1.5mm) and longitudinal($|z_0 \sin \theta|$ < 1.5mm) impact parameters w.r.t. the primary vertex
- If p_T>10 GeV, require fit probability χ^2/ndf $\geq$ 0.01

Particle Correlations : ΔΦ

"Angular correlations between charged particles from proton-proton collisions at $\sqrt{s}$ = 900 GeV and $\sqrt{s}$ = 7 TeV measured with ATLAS detector"
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-082/



Uncorrected



Leading Particle : has highest p_T
Non-leading Particle : all others

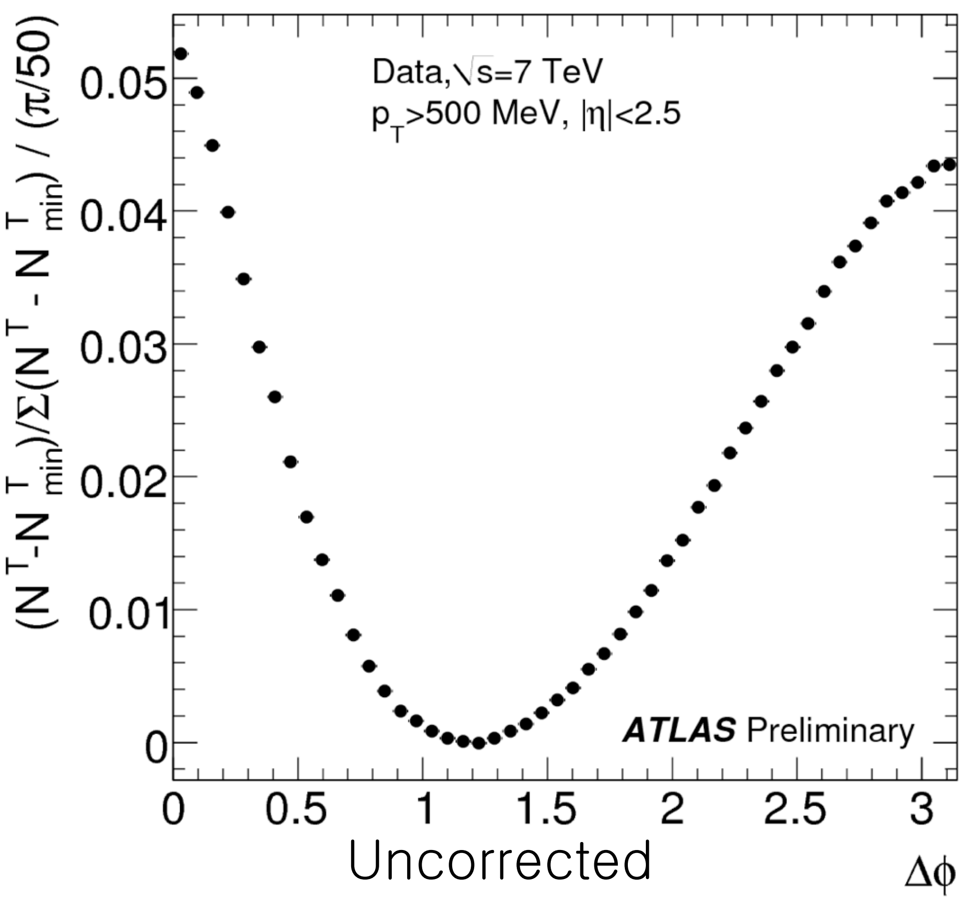
$$\Delta\Phi \equiv |\Phi_{\text{non-leading}} - \Phi_{\text{leading}}|$$

angle in transverse plane between leading and non-leading

ΔΦ Correlations : Observables

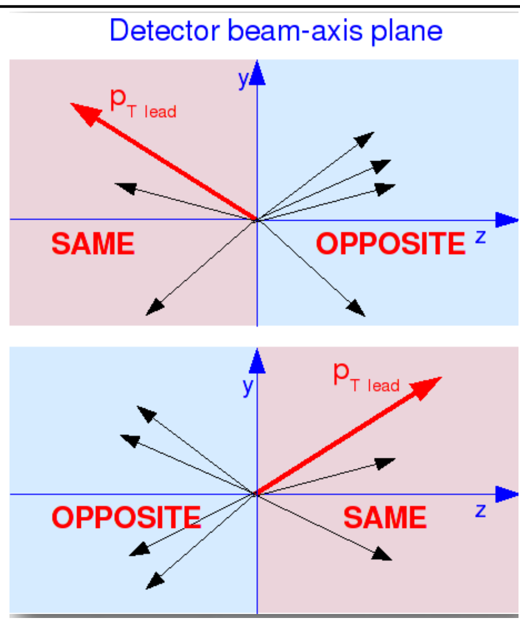
ΔΦ Crest Shape

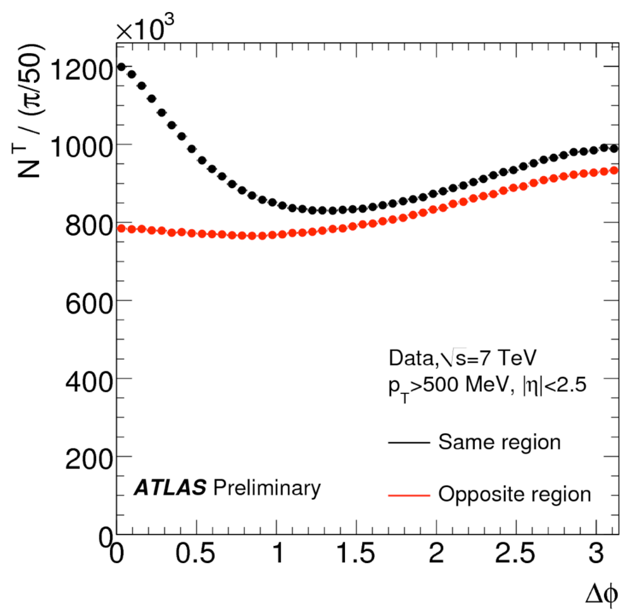
1. ΔΦ for all non-leading particles
2. Estimate minimum from a second degree polynomial fit
3. Subtract minimum from each bin and normalize to unit area

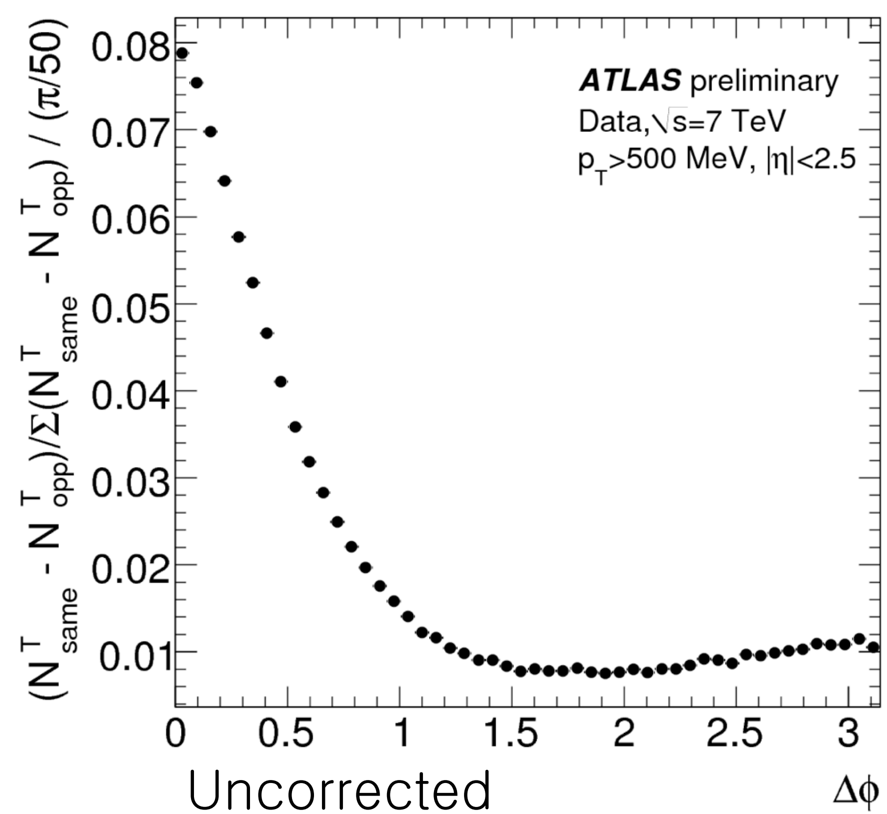


ΔΦ Same minus Opposite

1. Same and opposite sign regions depending on η of leading particle







2. Make ΔΦ for same and opposite non leading particles
3. Subtract opposite from same and normalize

$\Delta\Phi$ Correlations : Corrections

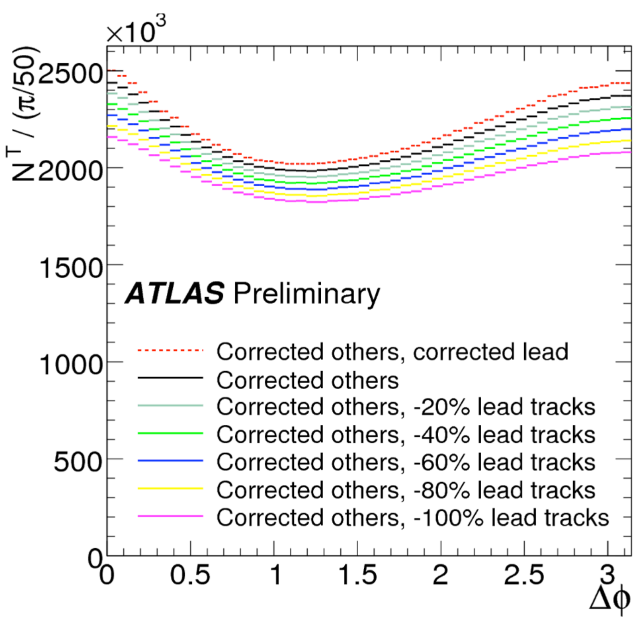
Corrections are applied to make measurements comparable to particle level Monte Carlo

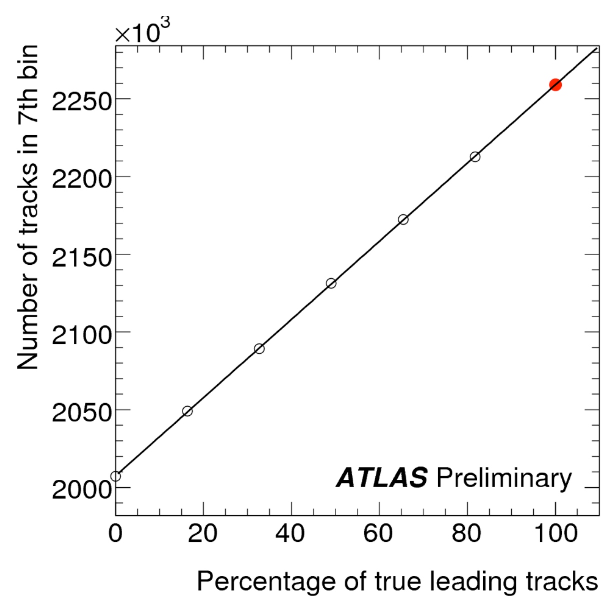
Track level correction weight

$$w_{trk} = \frac{1}{\epsilon_{trk}(p_T,\eta)} \cdot (1 - f_{sec}(p_T)) \cdot (1 - f_{okr}(p_T,\eta)) \cdot (1 - f_{fake})$$

Track level correction are applied for the tracking efficiency, fraction of secondaries, fraction of selected tracks with primaries beyond kinematic range, and the fraction of fake tracks.

Leading track correction





A bin by bin correction based on shape changes with extra loss of leading tracks are applied

ΔΦ Correlations : Uncertainties

Systematic uncertainties arise due to :

- Choice of MC models
- Efficiency corrections at track level

Systematic uncertainties, summary table

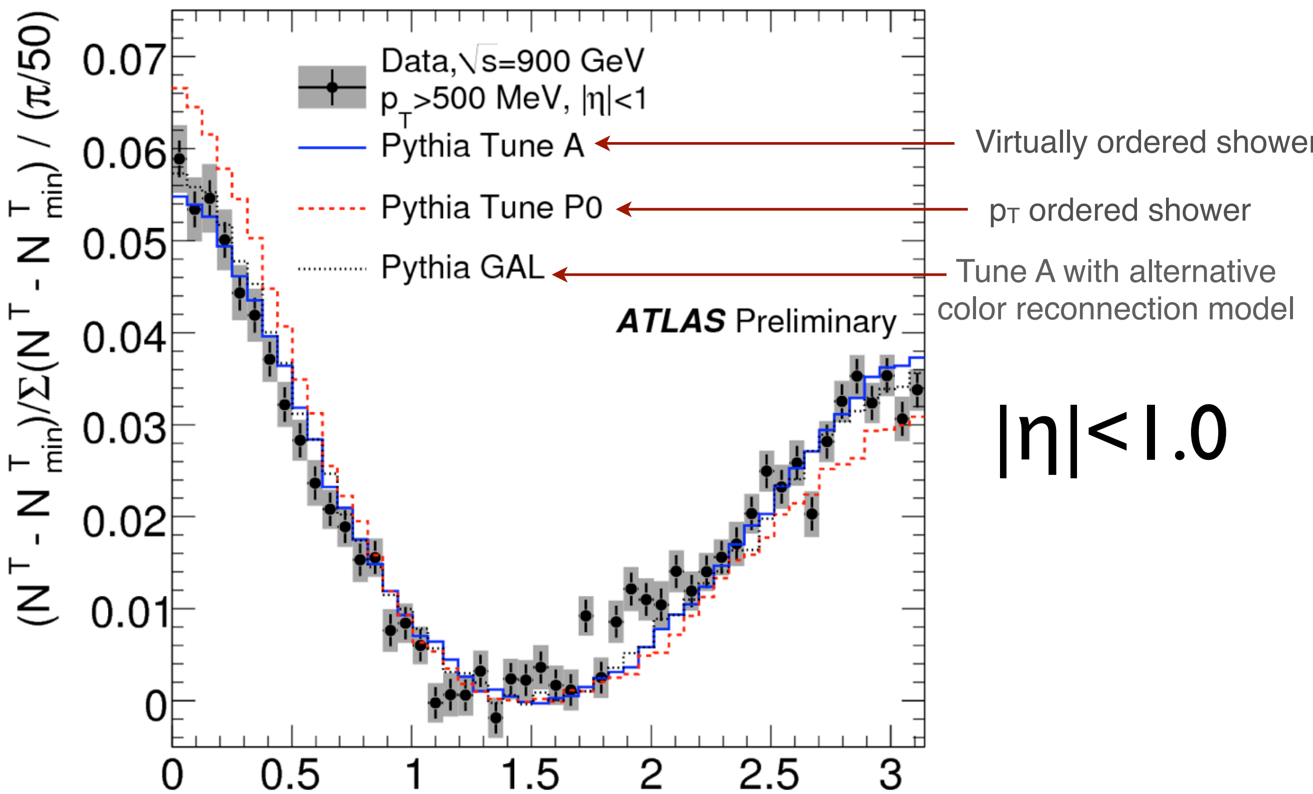
Source of systematic uncertainty	Implemented	Relative uncertainty in first bins
Event selection inefficiency	bin-by-bin	1%-3%
Bias remaining after corrections	2% in first 4 bins	2%
Resolution - phase space boundaries	bin-by-bin	1%-2%
Resolution - leading track	bin-by-bin	0.1%-0.2%
Efficiency of leading tracks	bin-by-bin	0.1%-0.2%
Efficiency of non-leading tracks	0.2% in each bin	0.2%
ϕ dependence of the tracking efficiency	6×10^{-5} in each bin	0.1%-0.2%
Choice of the d_0^{PV} cut	9×10^{-5} in each bin	0.1%-0.3%
Statistical uncertainty		900 GeV: 3%-4%
		7 TeV: 0.3%-0.4%

Statistical uncertainty from limited MC statistics and systematic uncertainties are combined in quadrature to provide total uncertainty.

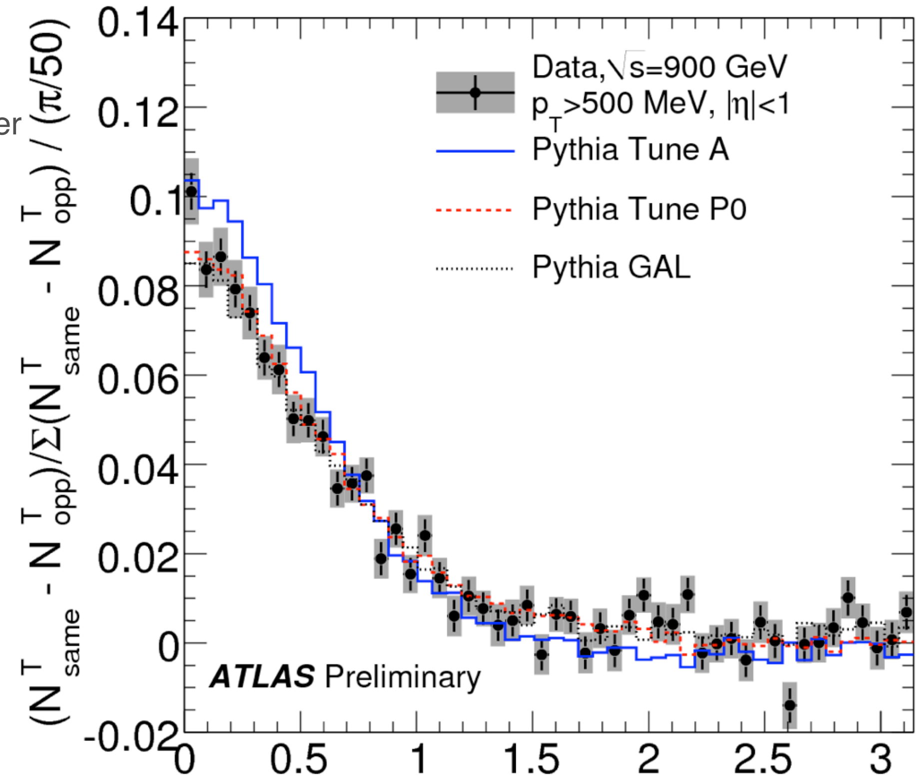
ΔΦ Correlation Results : 900 GeV

p_T>500 MeV

ΔΦ Crest Shape

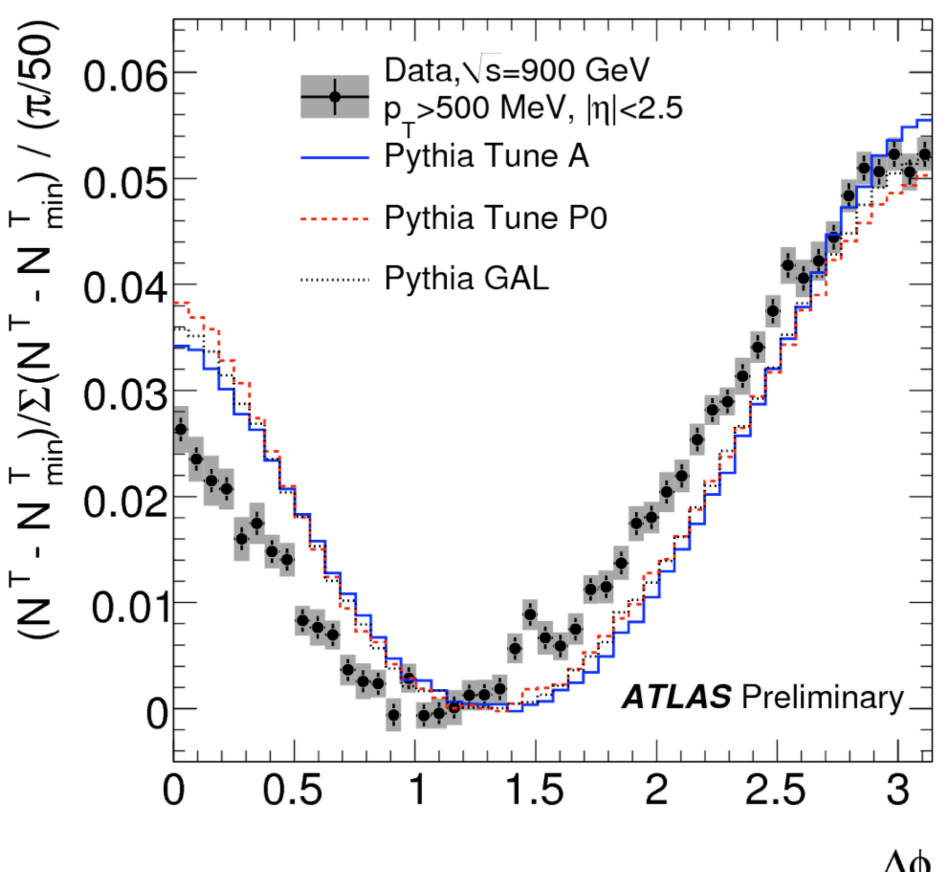


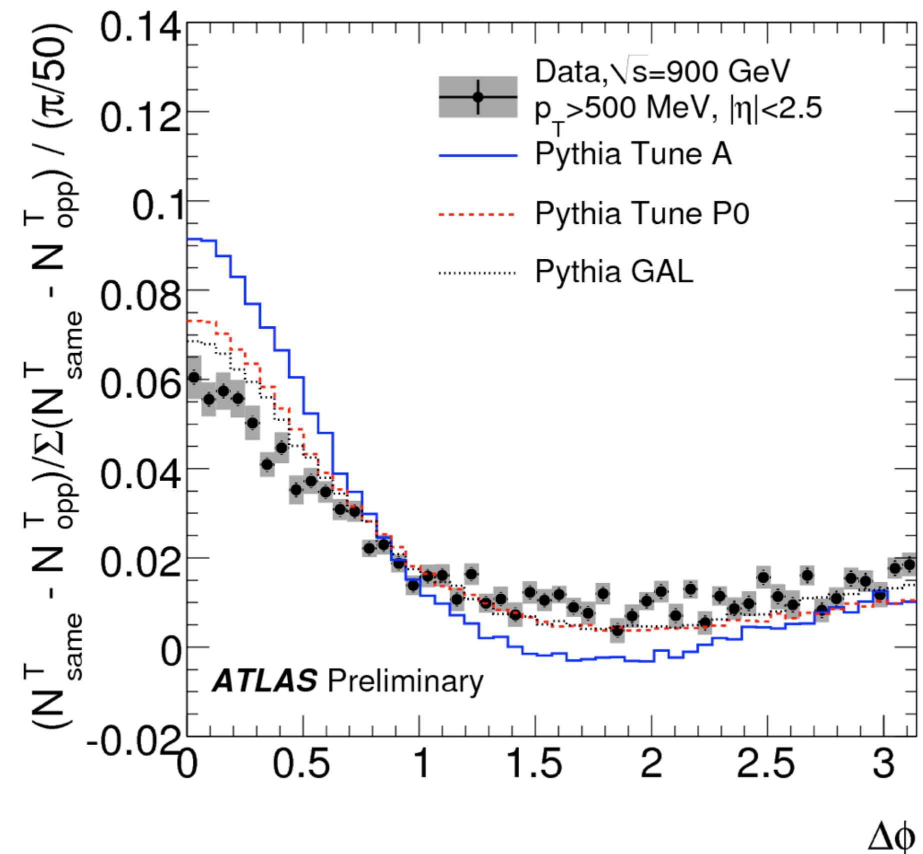
ΔΦ Same minus Opposite



$|\eta|$<1.0

$|\eta|$<2.5



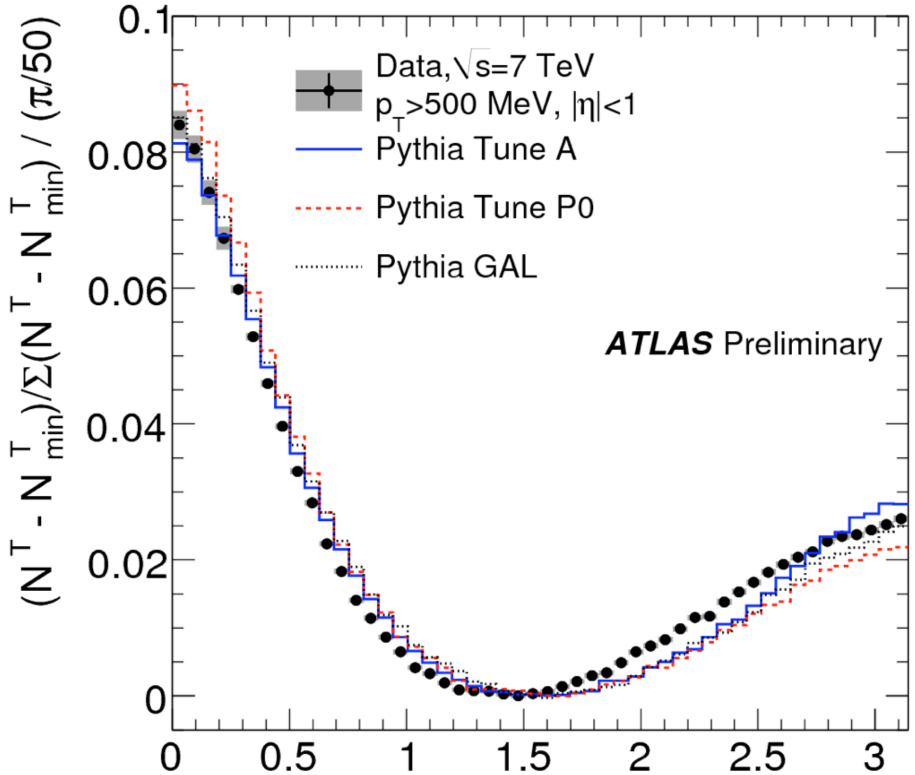


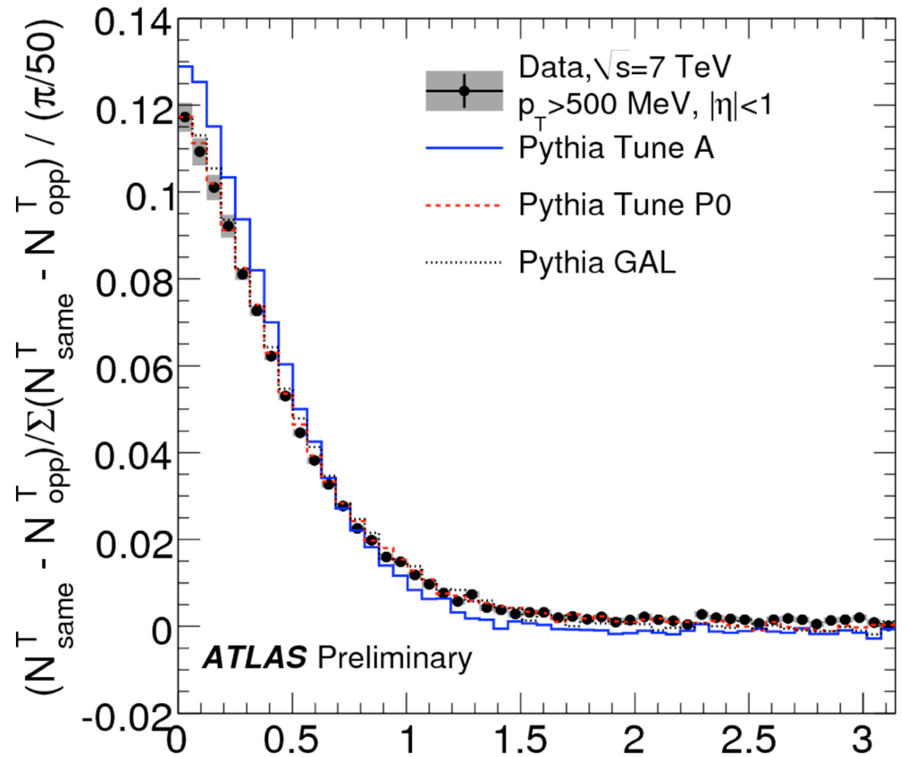
ΔΦ Correlation Results : 7 TeV

p_T>500 MeV

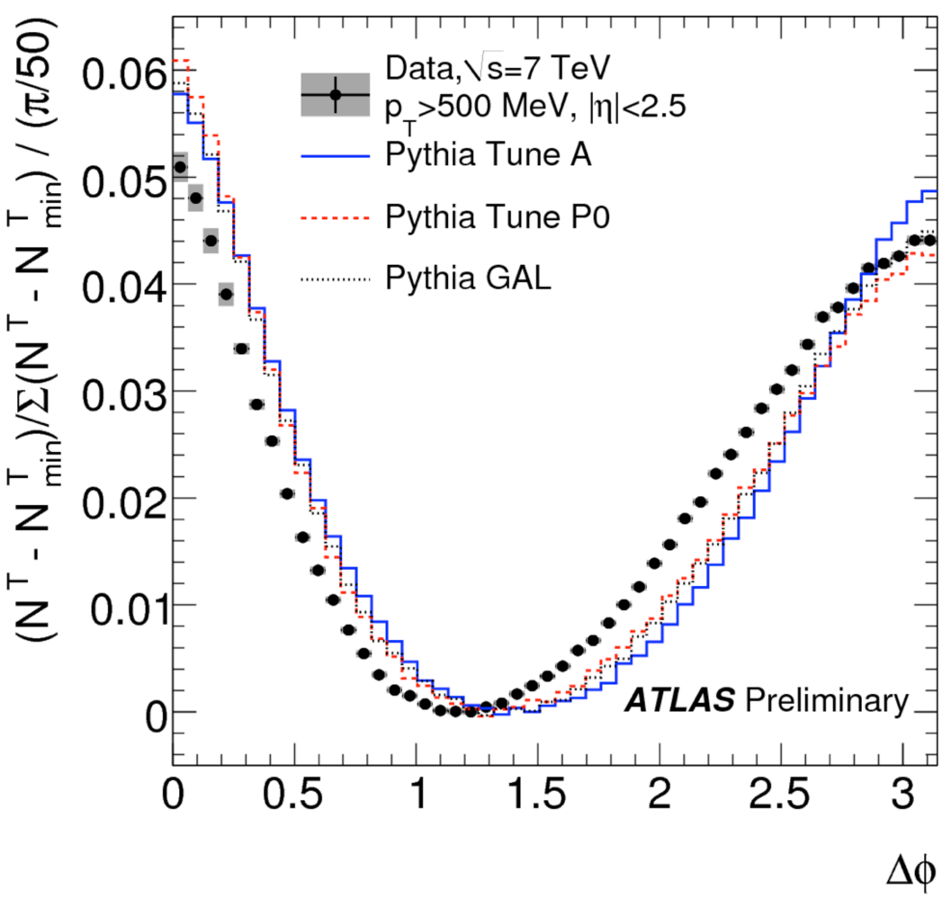
ΔΦ Crest Shape

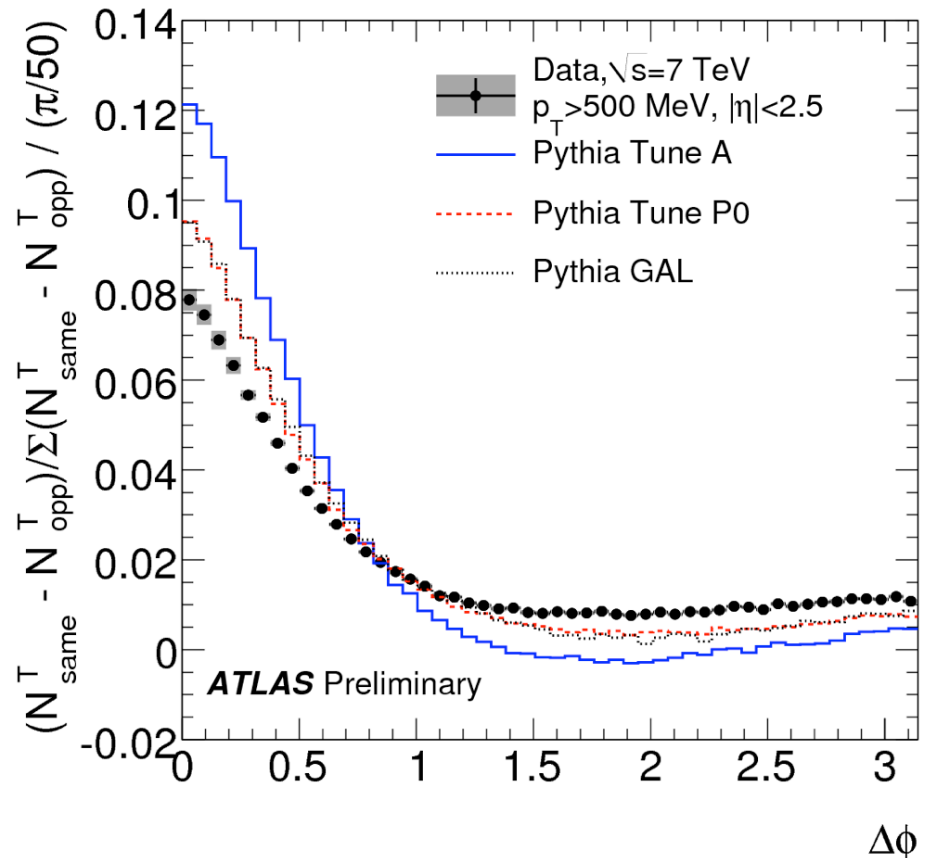
ΔΦ Same minus Opposite





|η|<1.0





|η|<2.5

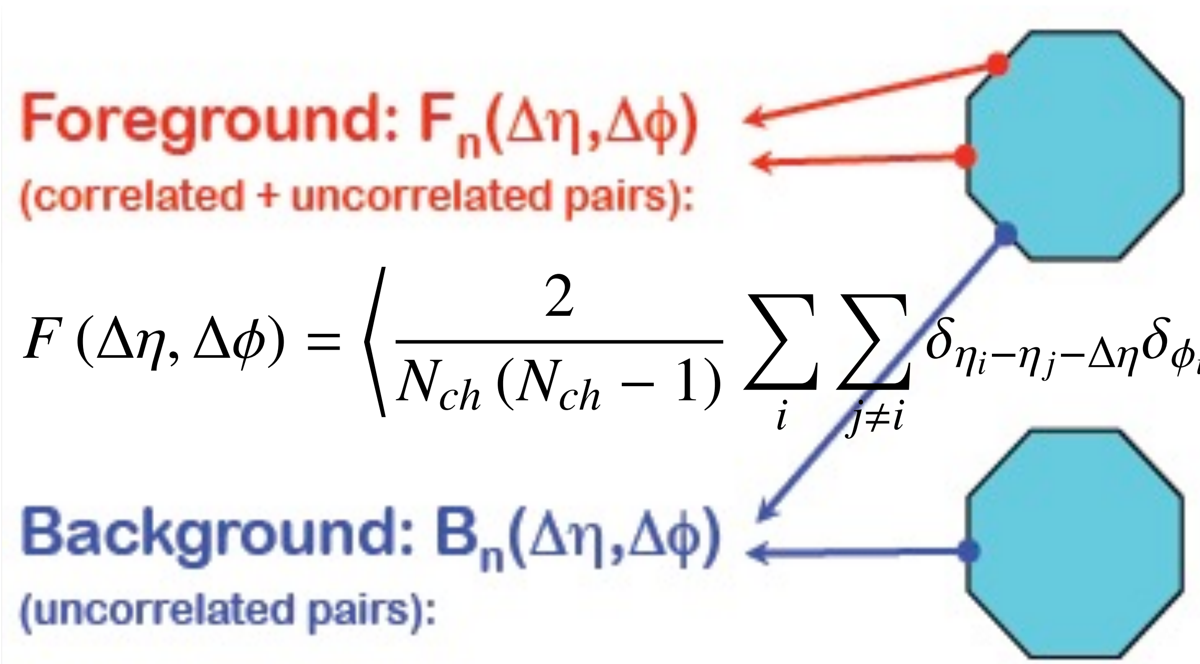
Inclusive Two Particle Correlations: Observable

“Measurement of Inclusive Two-Particle Angular Correlations in Proton-Proton Collisions at $\sqrt{s}$ = 900 GeV and 7 TeV”
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-055/

Inclusive two particle correlation function is given by:

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

where $\langle ... \rangle_{ch}$ indicates an average over contributions from all particle multiplicities.



$$F\left(\Delta\eta,\Delta\phi\right)=\left\langle\frac{2}{N_{ch}\left(N_{ch}-1\right)}\sum_{i}\sum_{j\neq i}\delta_{\eta_i-\eta_j-\Delta\eta}\delta_{\phi_i-\phi_j-\Delta\phi}\right\rangle$$

Correlations between particle pairs emitted in the same event. Normalized by number of events.

$$B\left(\Delta\eta\right)=\int_{-2.5}^{2.5}\int_{-2.5}^{2.5}\mathrm{d}\eta_1\mathrm{d}\eta_2\delta\left(\eta_1-\eta_2-\Delta\eta\right)\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_1}\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_2}$$

Correlations between particles pairs emitted in different events. Normalized by integral.

Inclusive Two Particle Correlations: Corrections

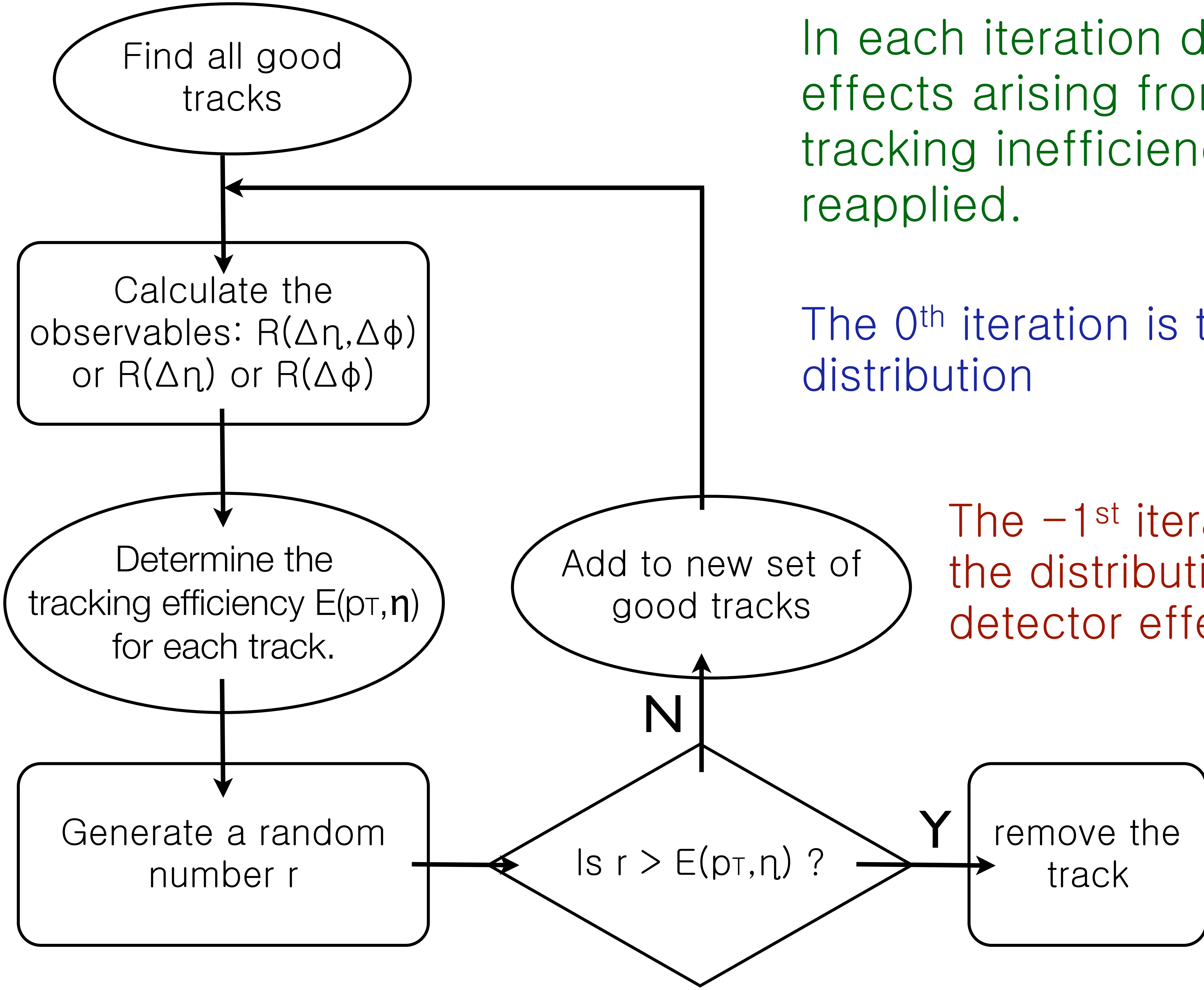
The foreground and multiplicity distributions are weighted by :

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

To correct for the vertex and trigger selection efficiencies.

Tracking efficiencies are accounted for using a data driven iterative probabilistic track removal method described in the following slides.

Inclusive Two Particle Correlations: Corrections

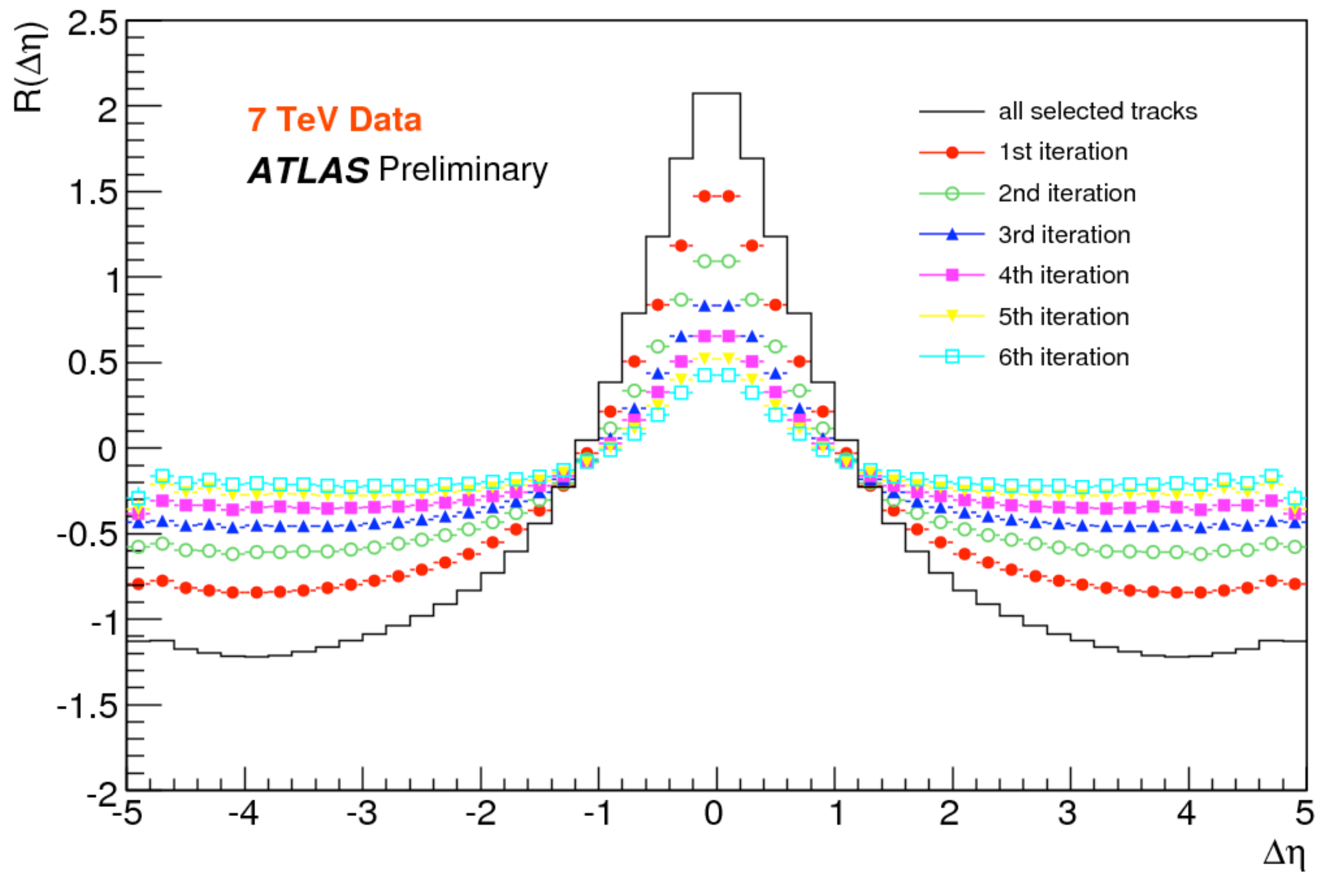


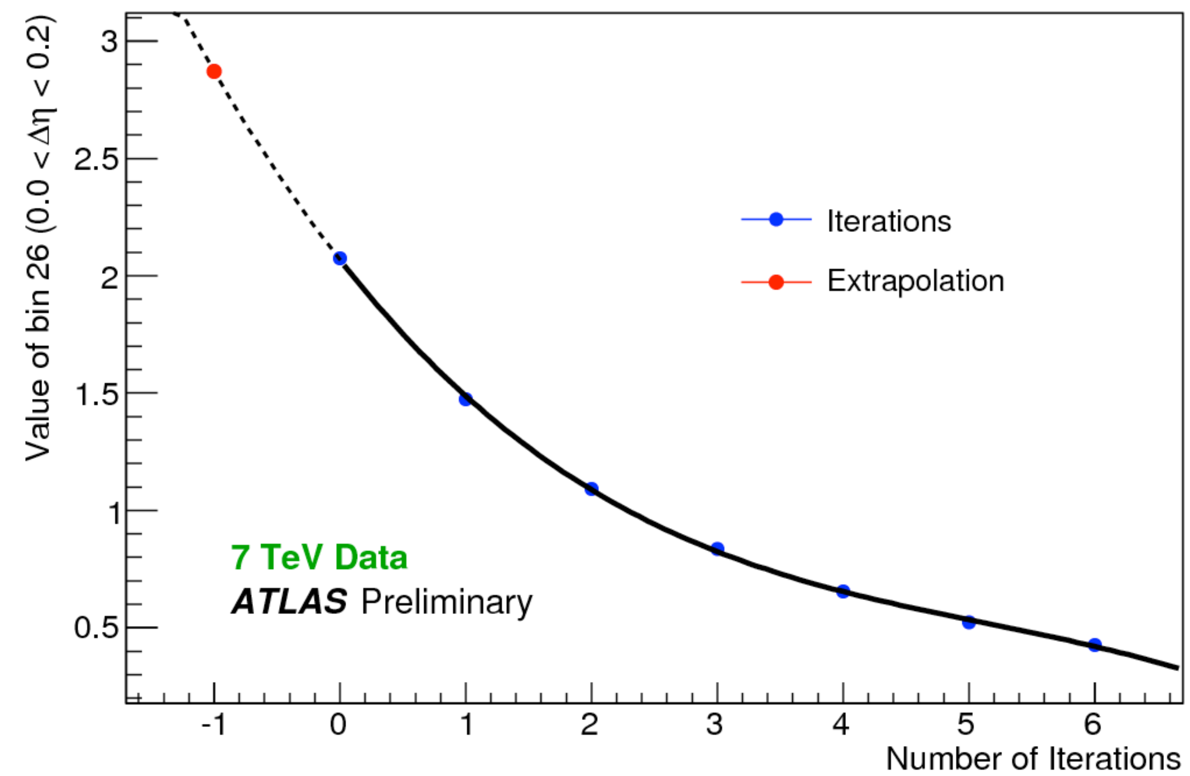
In each iteration detector effects arising from tracking inefficiencies are reapplied.

The 0^{th} iteration is the original distribution

The -1^{st} iteration is the distribution without detector effects

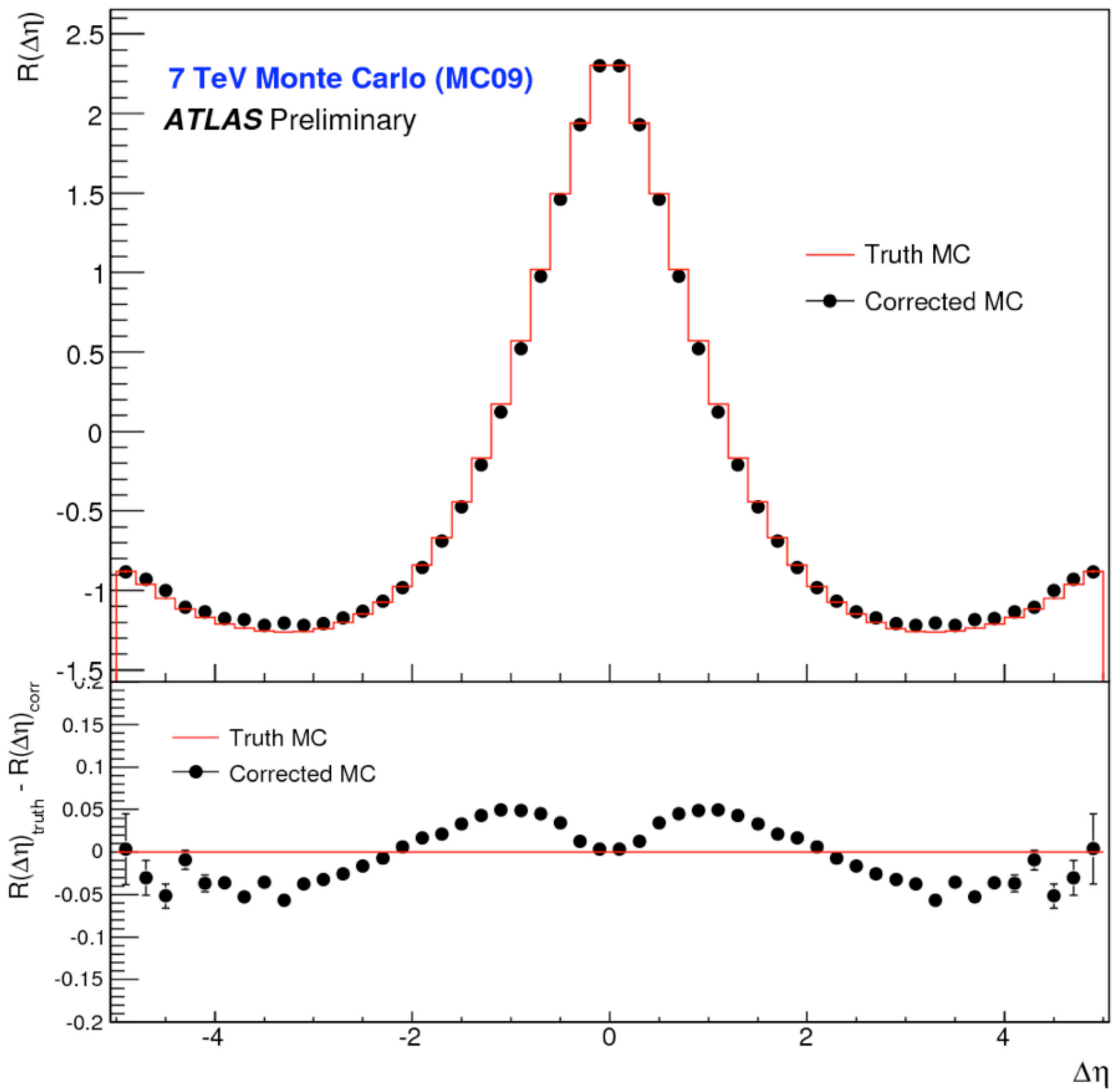
Inclusive Two Particle Correlations: Corrections



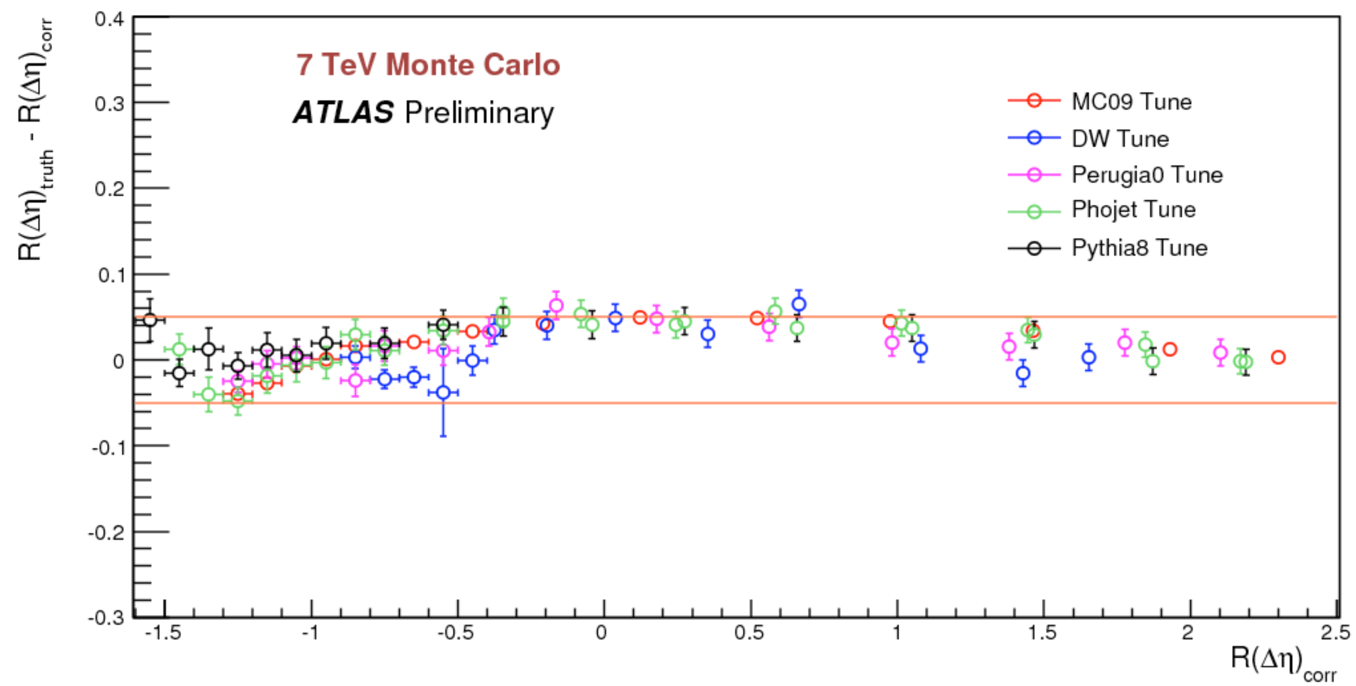


- Values of the observable R in each bin is plotted against the iteration number.
- Third order polynomial fit extrapolates the value to the -1^{st} iteration for each bin
- Same procedure is used for all observables at all energies.

Inclusive Two Particle Correlations: Corrections



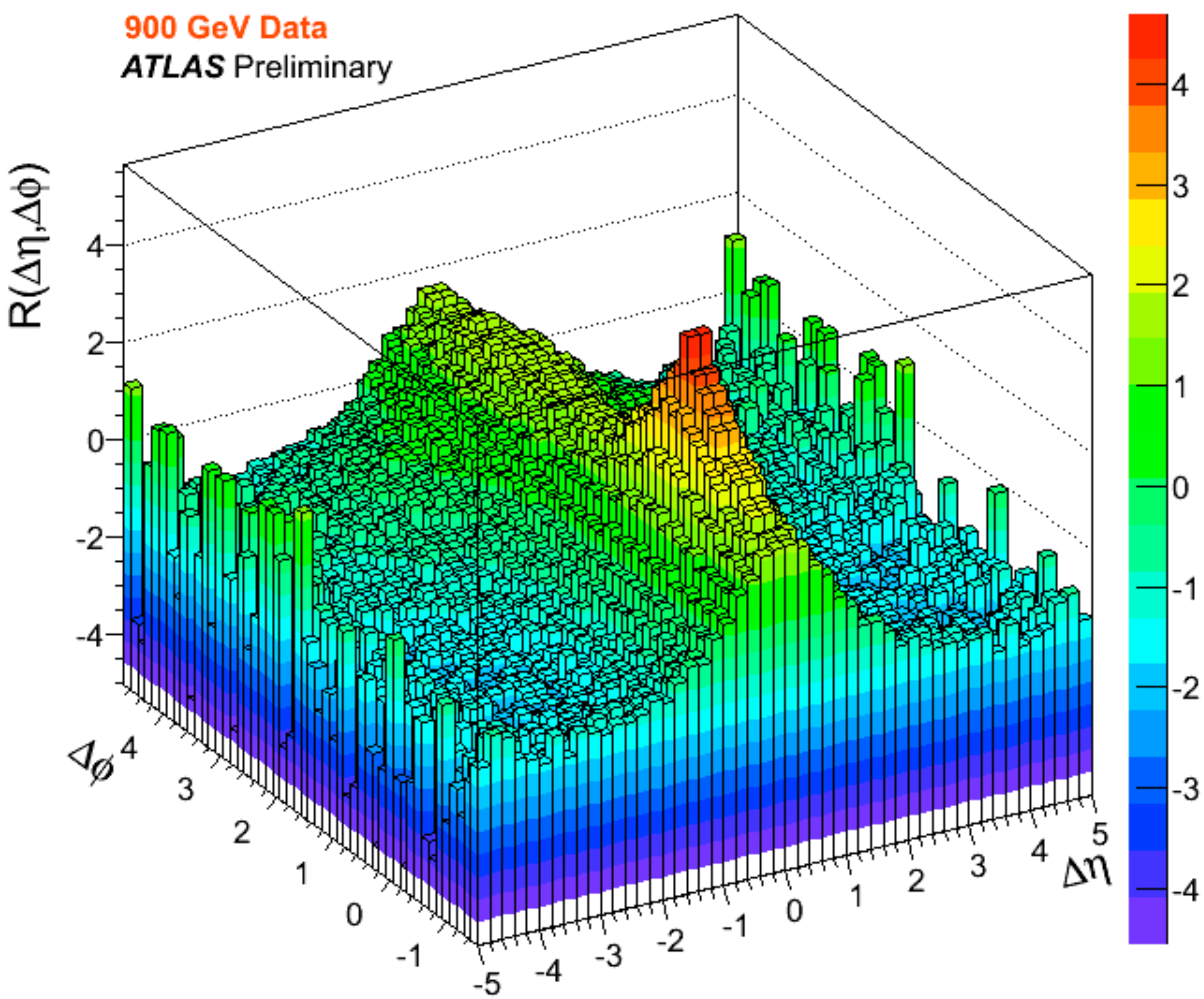
The procedure is validated against Monte Carlo



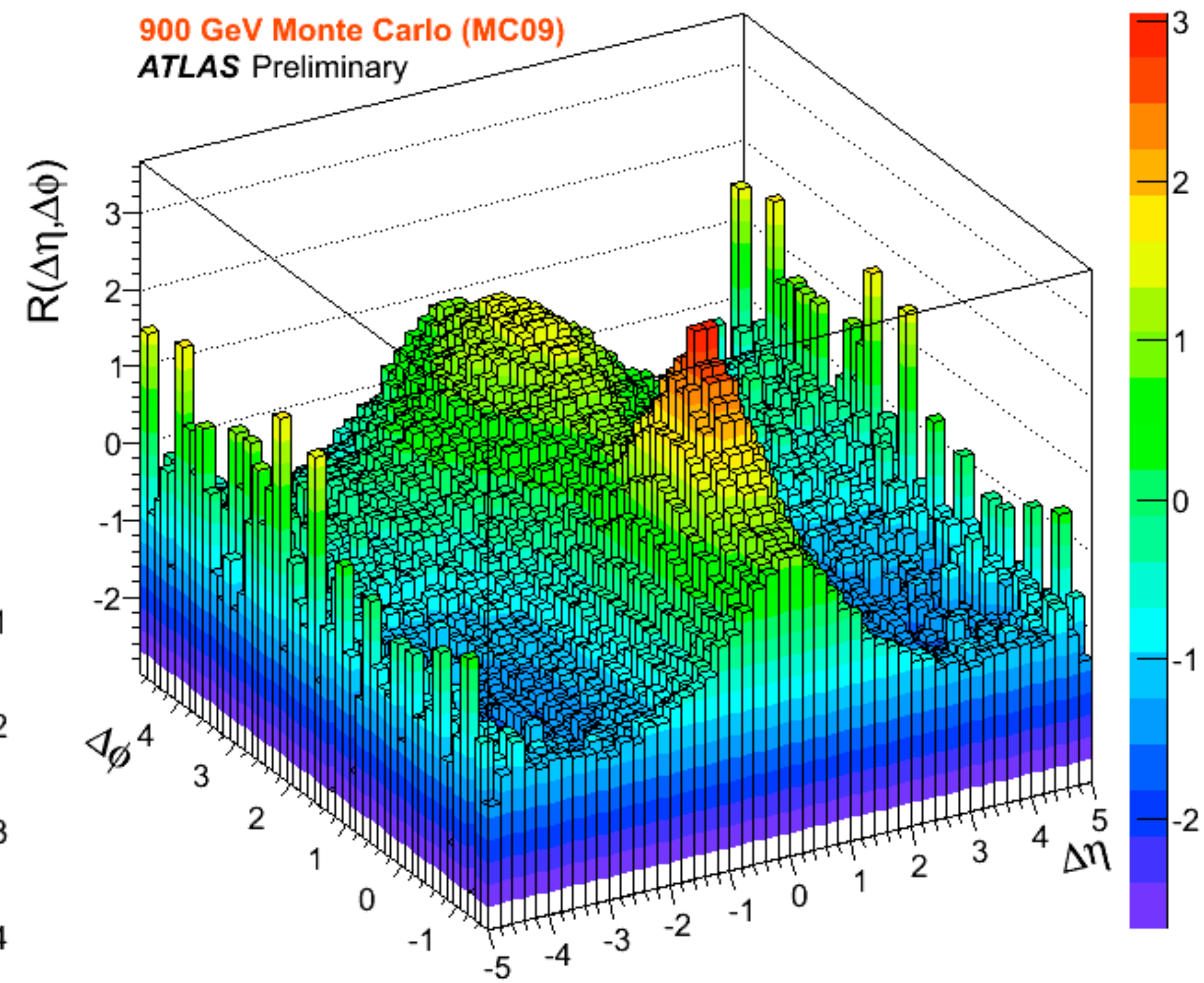
Systematic uncertainty of 0.05 is assigned for all bins of R

This arises from non-closure in MC and is independent of tune.

Inclusive Two Particle Correlations: Results

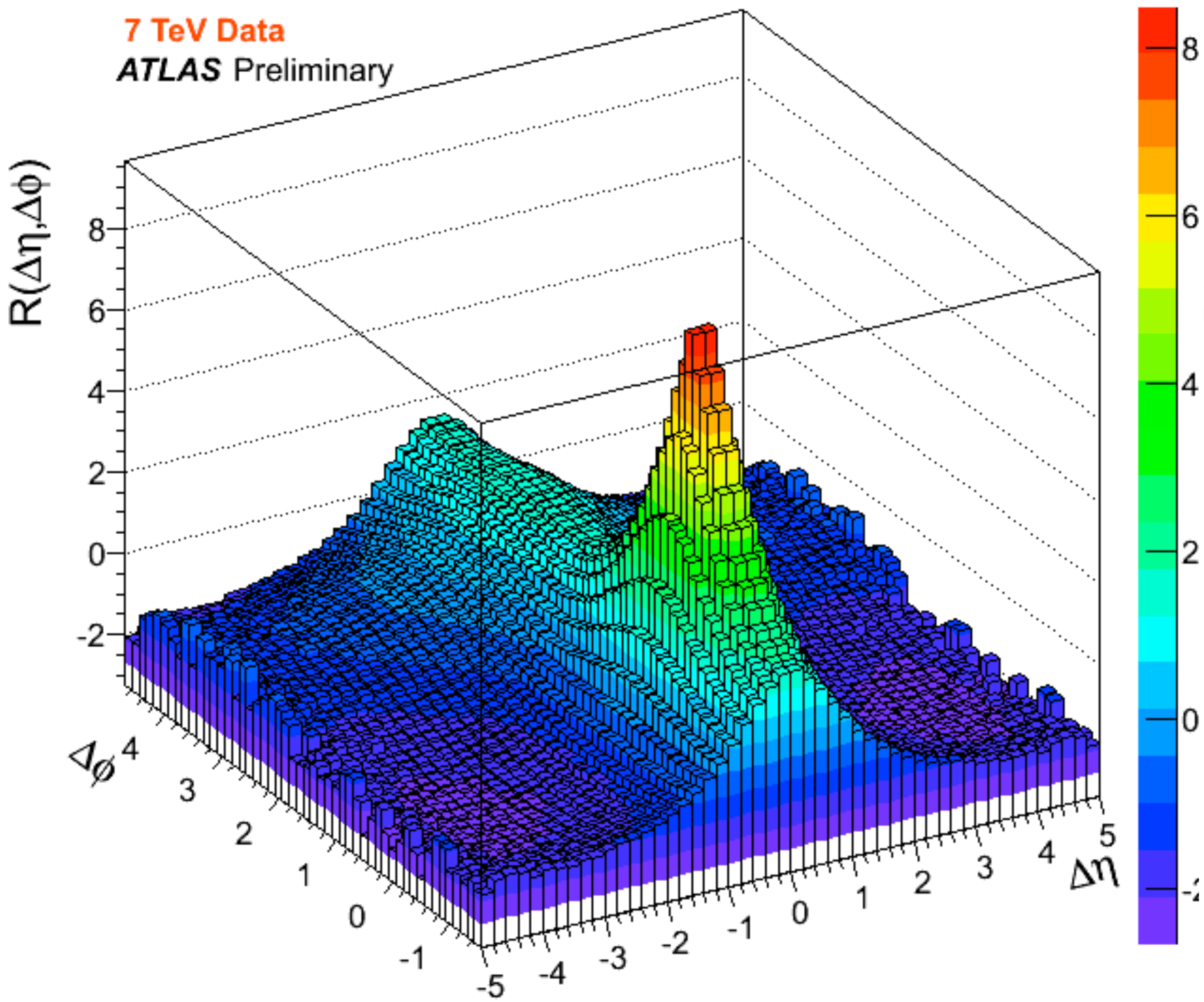


R(Δη,Δϕ) in 900 GeV Data

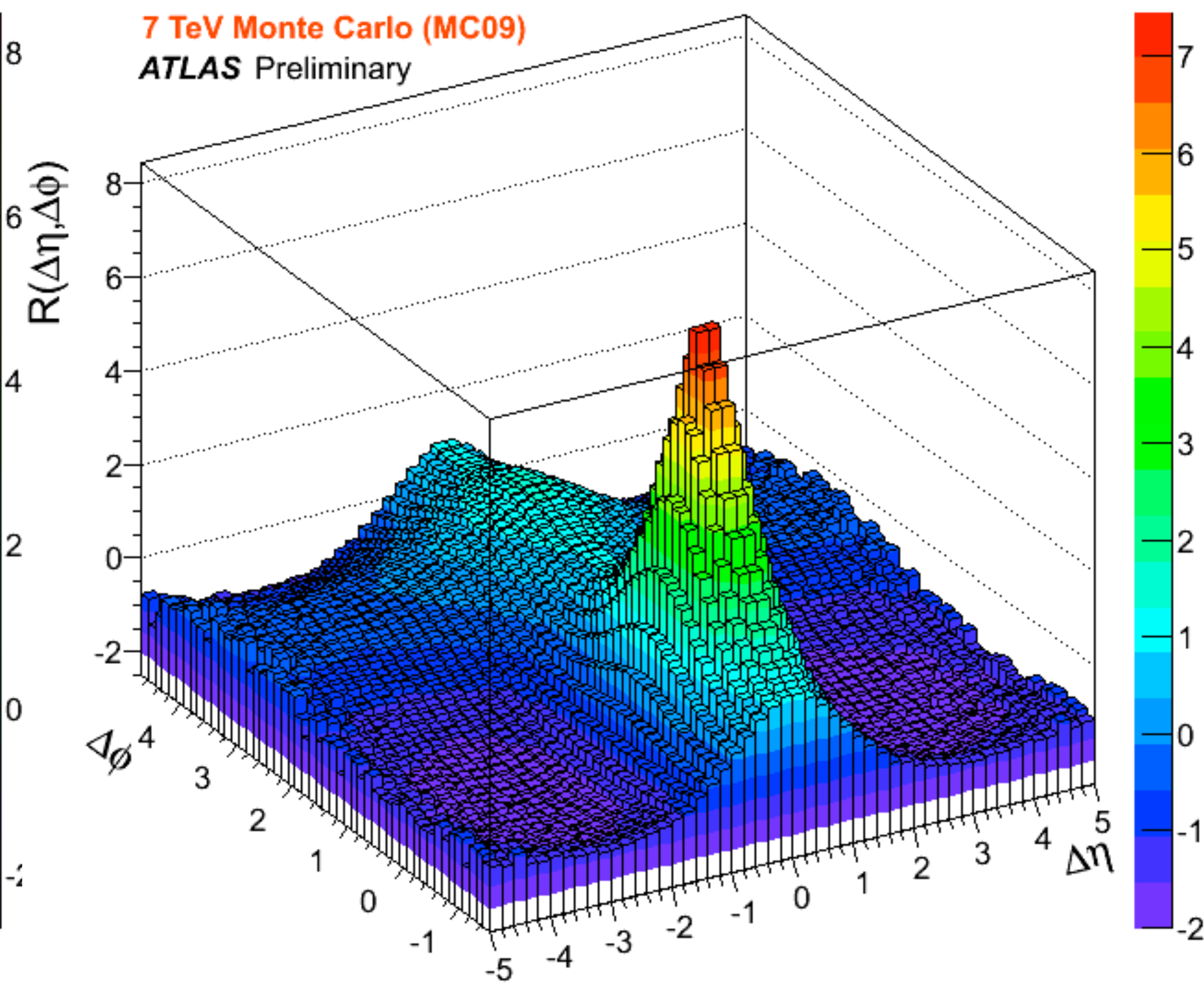


R(Δη,Δϕ) 900 GeV Monte Carlo (MC09)

Inclusive Two Particle Correlations: Results



R(Δη,Δϕ) in 7 TeV Data

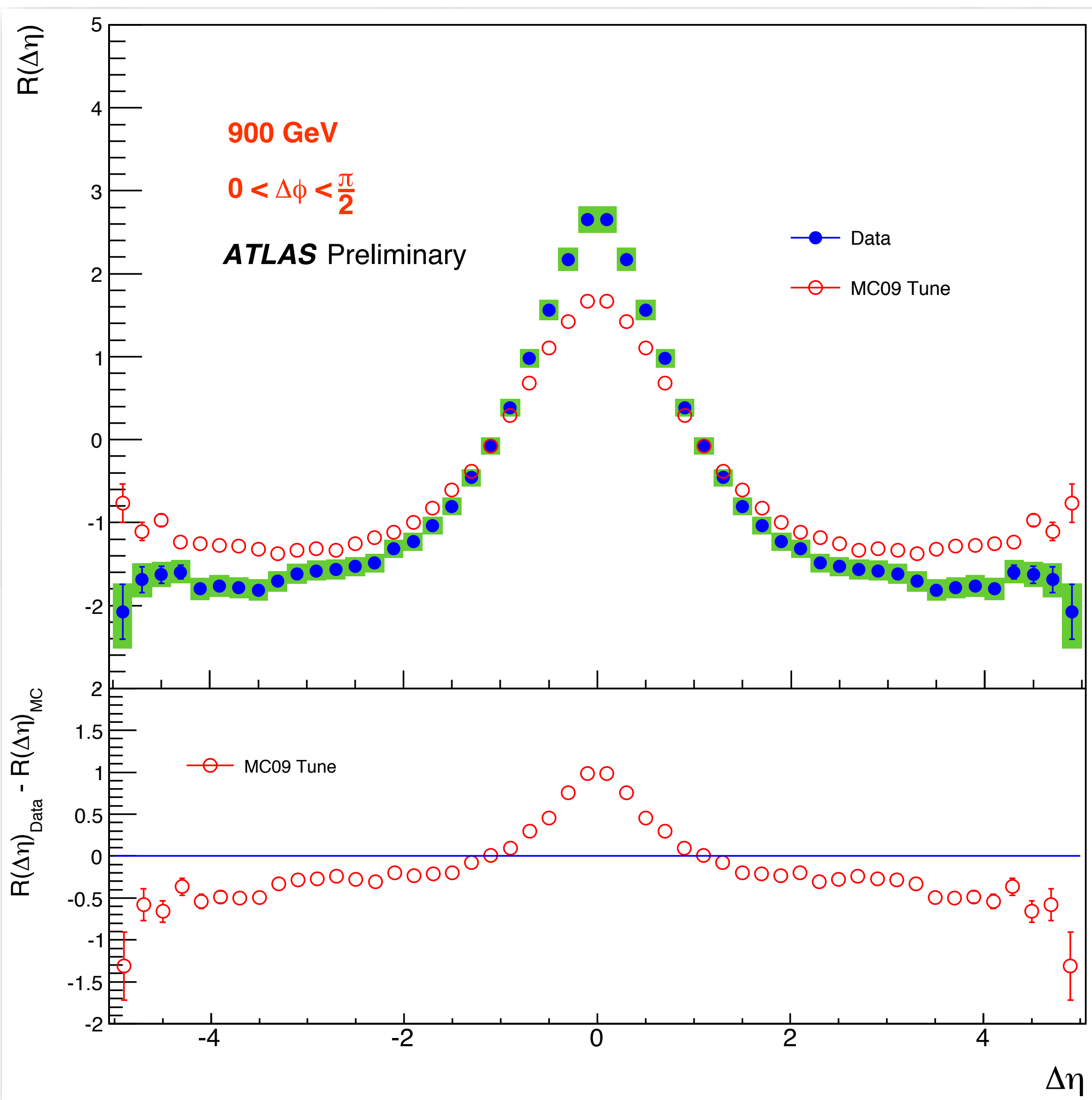


R(Δη,Δϕ) 7 TeV Monte Carlo (MC09)

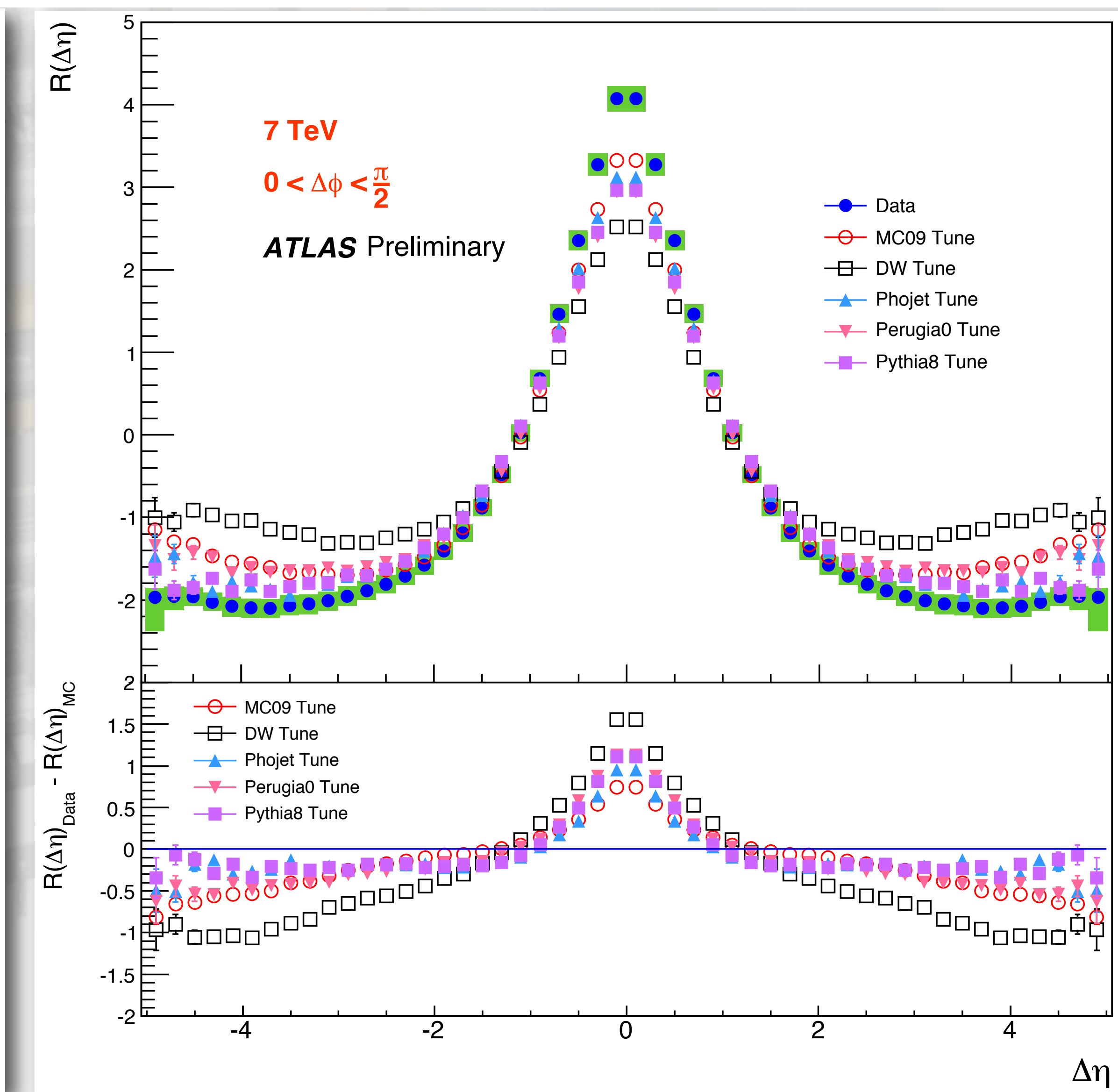
Inclusive Two Particle Correlations: Results

Near-side correlations: integrating $0 < \Delta\phi < \pi/2$.

Dominated by the peak at (0,0). At 7 TeV, Pythia 8 and Phojet have better agreement in the tails of the distribution while MC09 is closer in the peak.



R(Δη) in 900 GeV Data and MC

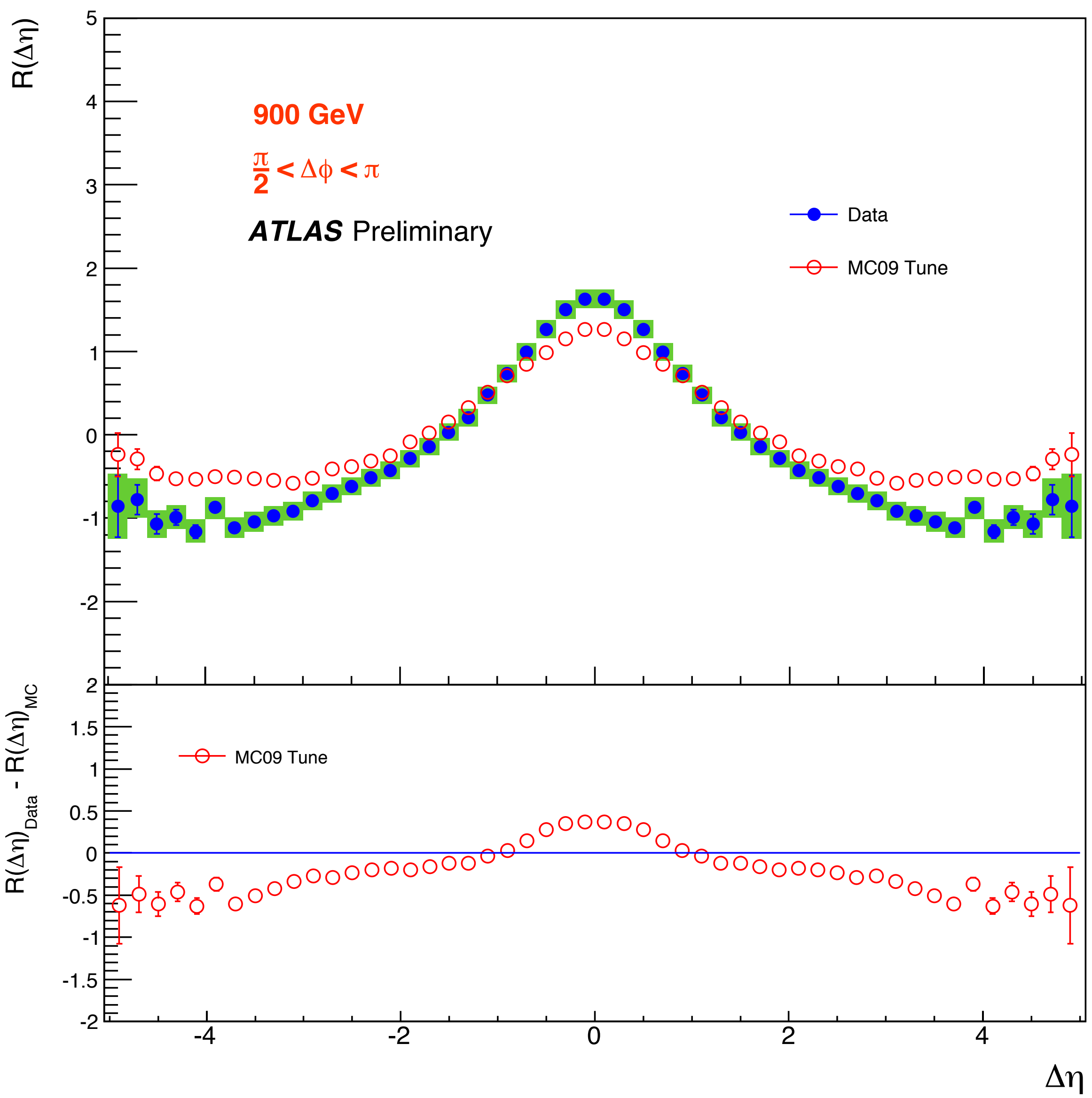


R(Δη) in 7 TeV Data and MC

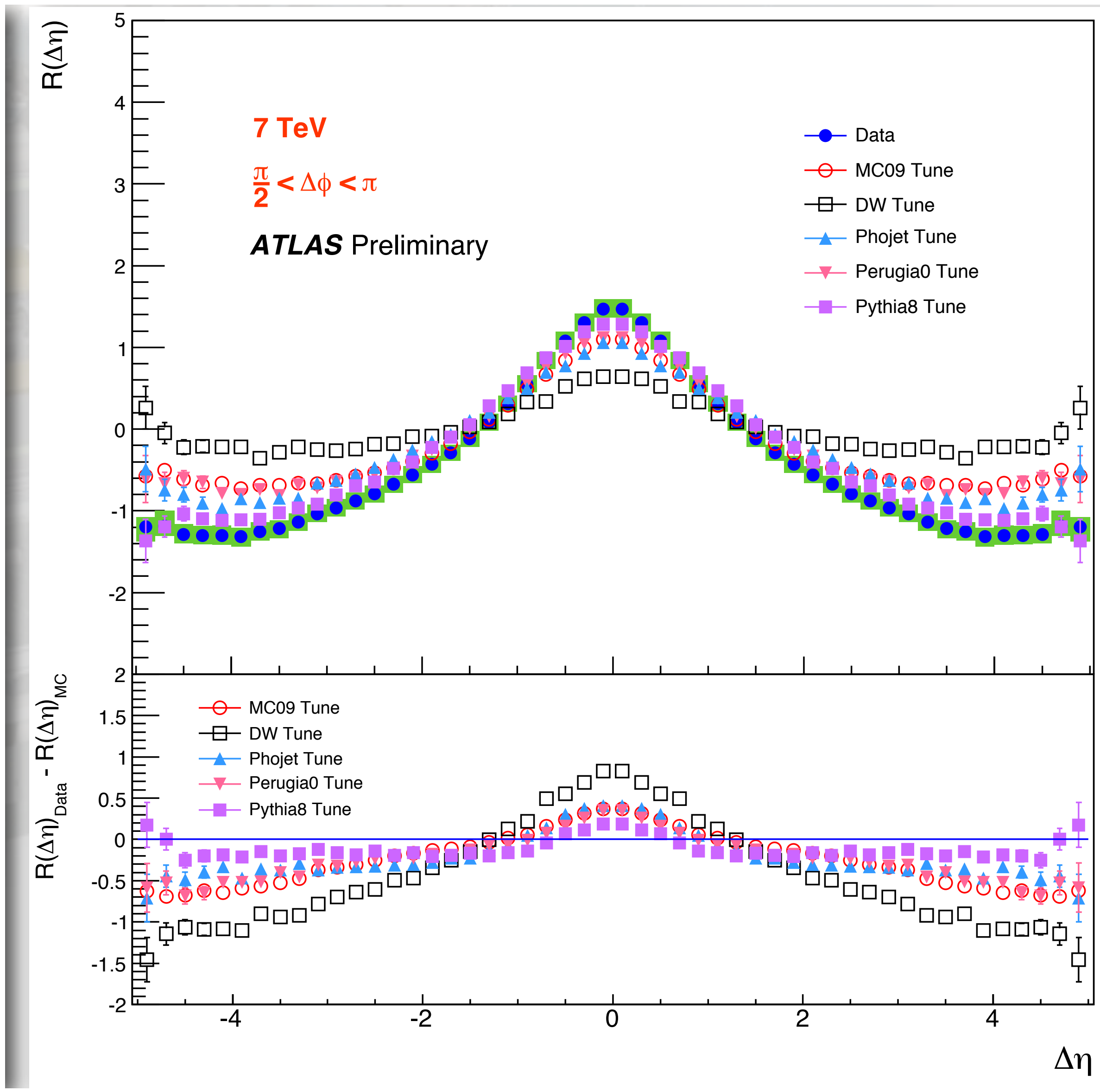
Inclusive Two Particle Correlations: Results

Away-side correlations: integrating $\pi/2 < \mathbf{\Delta\Phi} < \pi$

Dominated by the ridge structure around $\mathbf{\Delta\Phi}=\pi$. Except for DW, the tunes perform better in these distributions.



R(Δη) in 900 GeV Data and MC

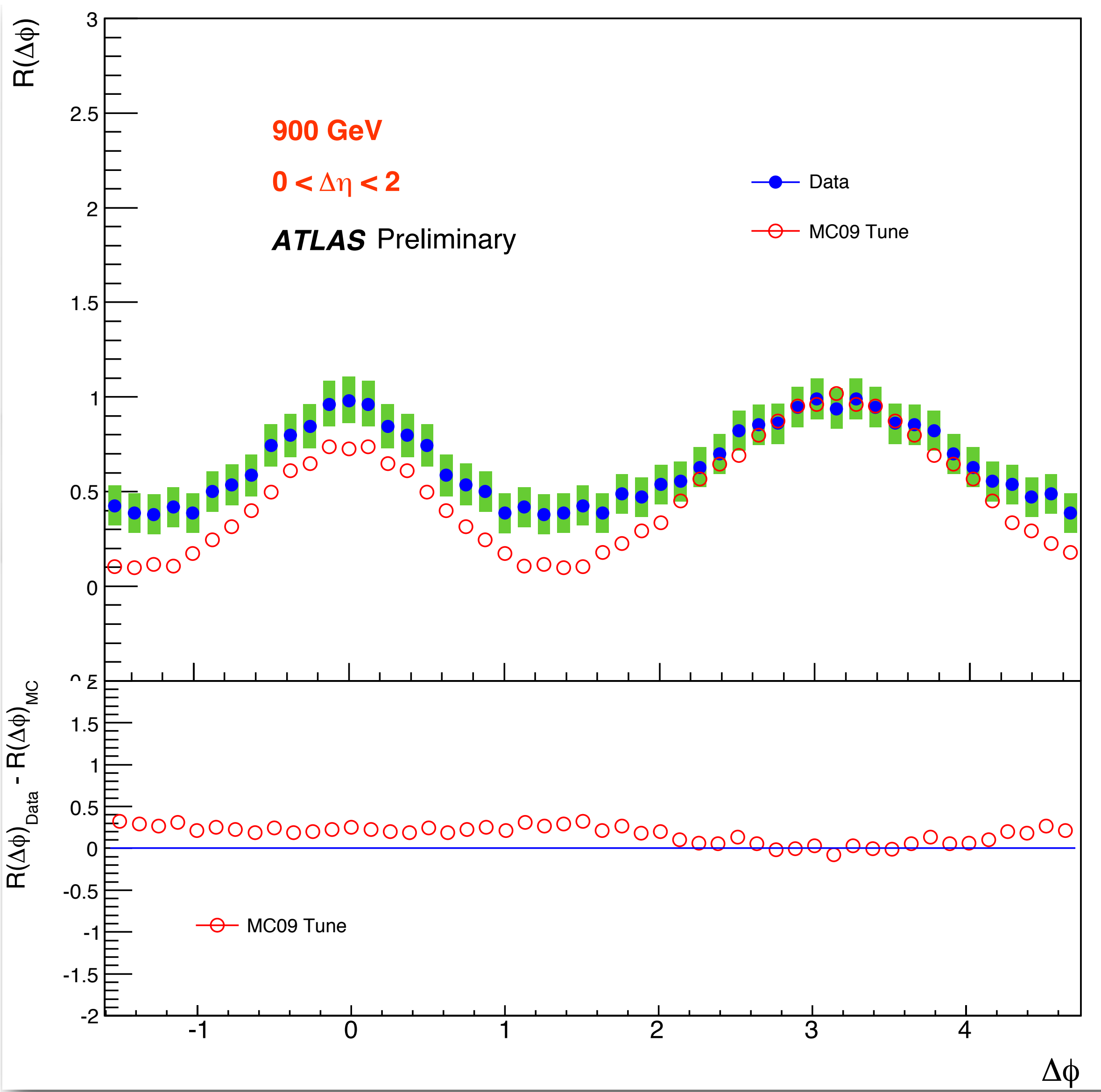


R(Δη) in 7 TeV Data and MC

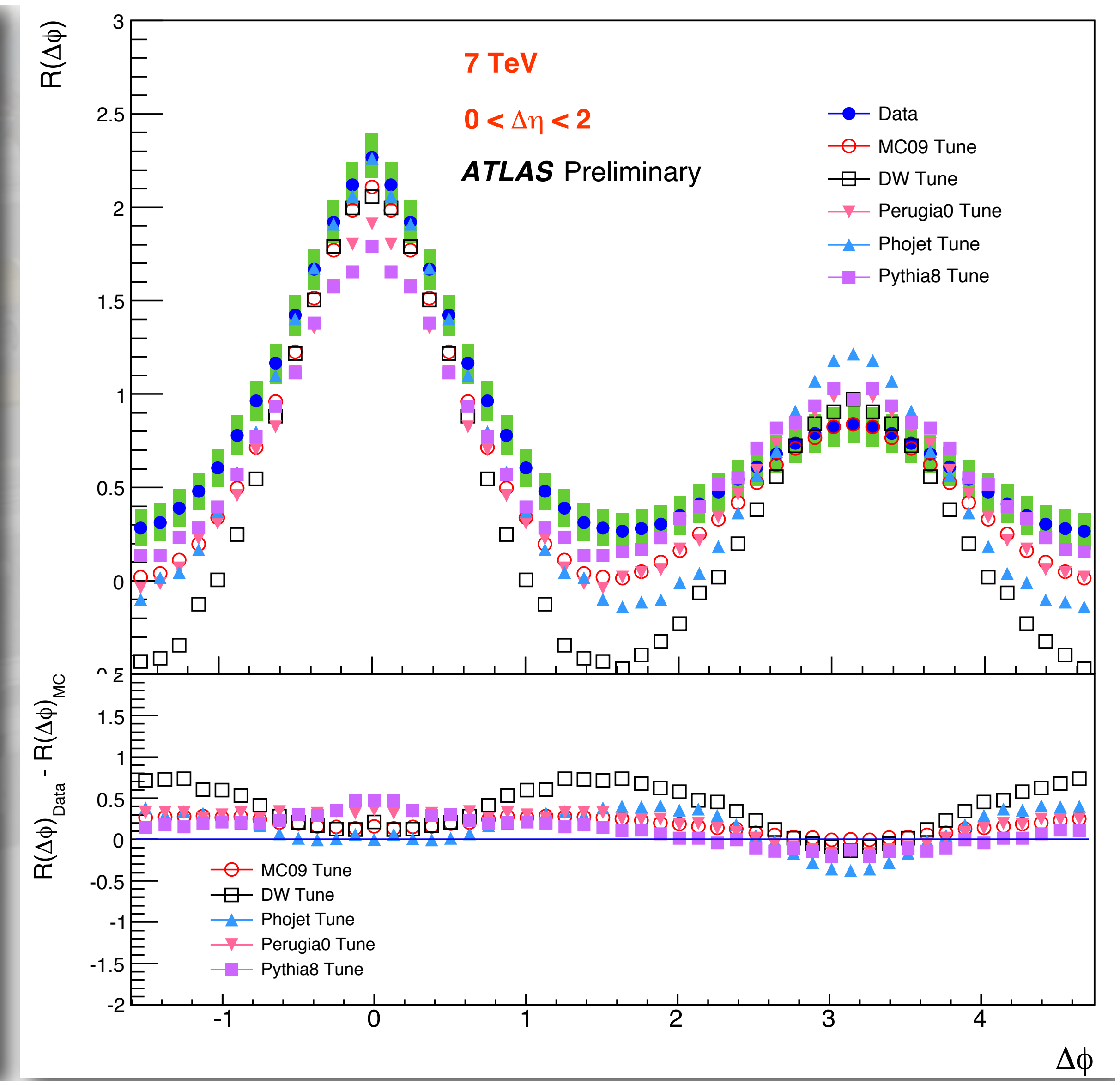
Inclusive Two Particle Correlations: Results

Short-range correlations: integrating $0 < \Delta\eta < 2$.

Two-peak structure. Similar to underlying event distributions. Back-to-back recoil. Most of the tunes agree well with data in a small region around $\Delta\phi=\pi$.



R(ΔΦ) in 900 GeV Data and MC

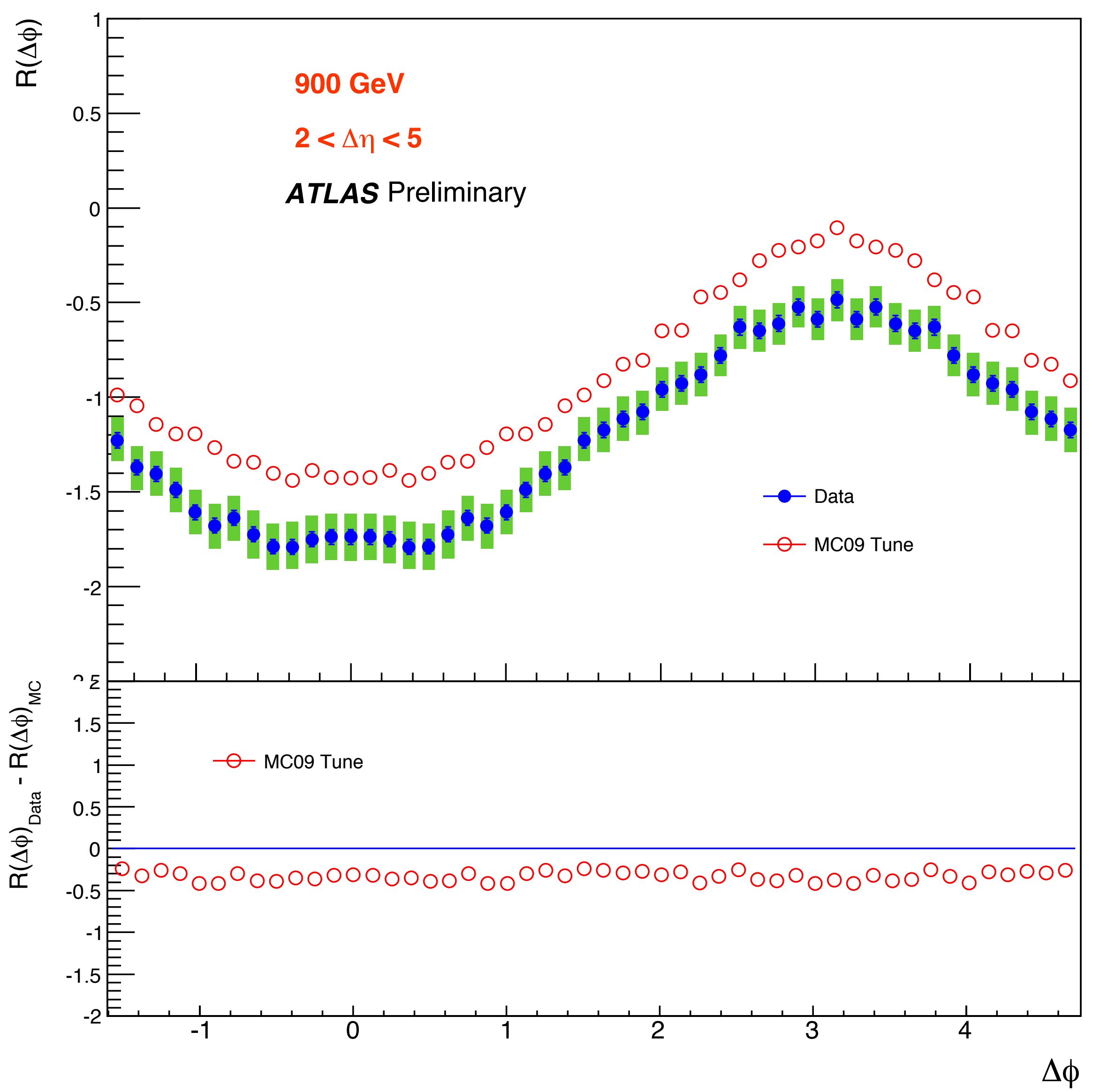


R(ΔΦ) in 7 TeV Data and MC

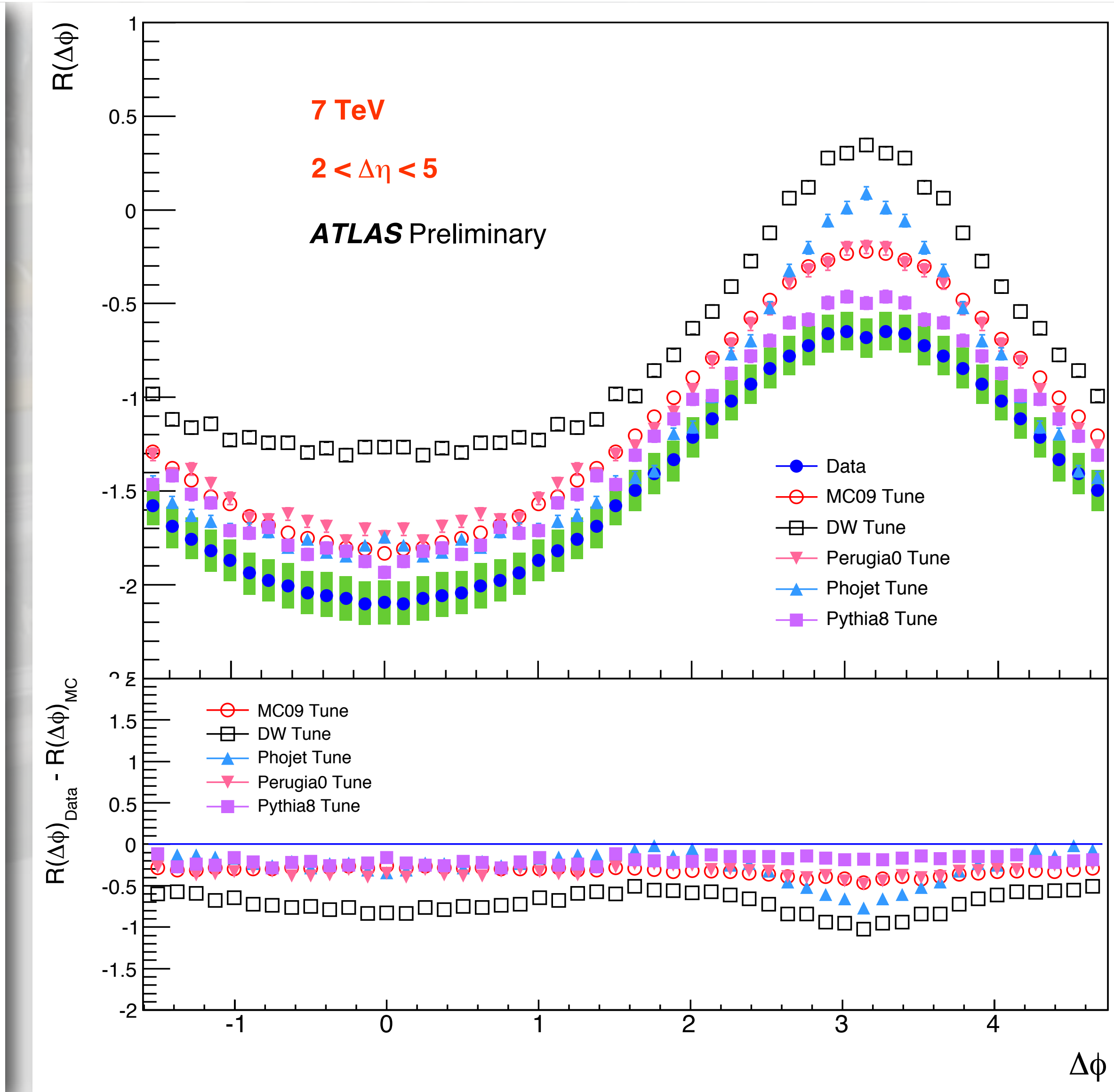
Inclusive Two Particle Correlations: Results

Long-range correlations: integrating $2 < \Delta\eta < 5$.

Underlying structure away from the peak at (0,0). The absolute difference between data and the different models is flat across **ΔΦ**. Pythia 8 is best and DW tune is worst.



R(ΔΦ) in 900 GeV Data and MC



R(ΔΦ) in 7 TeV Data and MC

Ongoing Studies

Several Studies of Particle Correlations at ATLAS

- Two-particle Correlations and Ridge Effect. High Multiplicity Studies
- Forward-backward correlations, p_T-dependence
- Bose-Einstein Correlations
- Multiplicity distribution, its moments, and KNO scaling
- Dynamical Fluctuations and Genuine Correlations
- Thermalization and Very High Multiplicities
- Two-particle Azimuthal Correlations
- Azimuthal Fourier Analysis

Lots of analyses and papers to come!

Conclusions

- Angular correlations studies showed discrepancies in the observable between data and most Monte Carlo tunes
- Emergence of jet structure is poorly described by the present Monte Carlo
- Two particle correlation studies showed complex structure in both energies
- None of the Monte Carlo models reproduced the strength of the correlations observed in data
- More measurements are underway to study particle production in the soft regime.

Special Thanks to :

All the members of

The Correlations and Fluctuations group at ATLAS

and specifically,

Cristina Oropeza Barrera

Camille Belanger-Champagne

Edward Sarkisyan Grinbaum

for helping with this presentation.

Backup Slides

Reference : MC Generators and Tunes

PYTHIA 6, actually 6.4.21 (P6): p_T–ordered parton shower, MRST LO* p.d.f.,multiple parton–parton scattering, string fragmentation

PYTHIA ATLAS AMBT1: P6 tuned by ATLAS to the low–multiplicity data

PYTHIA ATLAS MC09 (reference) P6 tune: parameters tuned to underlying events and minimum bias data from Tevatron at 630 GeV to 1. 8 TeV (ATLAS optimization), used to determine ATLAS detector acceptances and efficiencies, to correct the data

PYTHIA ATLAS MC09c tune: MC09 optimizing0 the strength of the color reconnection to describe p_T dependence on n_{ch} in the CDF data at 1.96 TeV

PYTHIA Perugia0 P6 tune: soft QCD part is tuned using only minimum bias data from Tevatron and CERN ppbar data

PYTHIA DW P6 tune: uses the virtuality–ordered showers and used to describe the CDF II underlying events and Drell–Yan process data

PYTHIA 8: includes new features such as hard scattering in diffractive systems, up–to–date LO p.d.f. set, possibility to use one p.d.f. set for hard scattering and another one for the rest, more underlying–event processes (J/ψ, DY,…)

PHOJET: two–component Dual Parton Model with soft hadronic processes by Pomeron exchange and semi–hard processes by perturbative parton scattering

Reference : PYTHIA Tunes

10.1103/PhysRevD.82.074018

Tunes using Q2-ordered model

- 100: A: Rick Field's Tune A to Tevatron Underlying-Event Data. Uses the "old" UE and shower models, with a double-gaussian matter profile, 1 GeV of primordial kT, and near-maximal color correlations. [Oct 2002]
- 103: DW: Rick Field's Tune DW to Tevatron Underlying-Event and Drell-Yan Data. Similar to Tune A, but has 2 GeV of primordial kT and uses a very small renormalization scale for initial-state radiation (i.e., more ISR radiation). It also has completely maximal color correlations. [Apr 2006]
- 104: DWT: Variant of DW using the Pythia 6.2 default collider energy scaling (has worse agreement with Tevatron energy scaling quantities than DW). [Apr 2006]
- 106: ATLAS-DC2 ("Rome"): first ATLAS tune of the Q2-ordered showers and old UE framework. Does not give very good agreement with Tevatron min-bias quantities.
- 107: A-CR: variant of Tune A using the Pythia 6.2 default color connections but with the new "color annealing" color reconnection model applied as an afterburner. Is intended as an example of strong color reconnections. [Mar 2007]
- 108: D6: Rick Field's Tune D6 to Tevatron data, using CTEQ6L1 PDFs.
- 110: A-Pro: Tune A with LEP tune from Professor. [Oct 2008]
- 113: DW-Pro: Tune DW with LEP tune from Professor. [Oct 2008]
- 114: DWT-Pro: Tune DWT with LEP tune from Professor. [Oct 2008]
- 116: ATLAS-DC2-Pro: ATLAS-DC2 with LEP tune from Professor. [Oct 2008]
- 117: A-CR-Pro: Tune A-CR with LEP tune from Professor. [Oct 2008]
- 118: D6-Pro: Tune D6 with LEP tune from Professor. [Oct 2008]
- 129: Pro-Q20: Tune of the Q2-ordered showers and old UE framework made with Professor, an automated tuning tool. [Feb 2009]

Tunes intermediate between Q2- and pT-ordered models

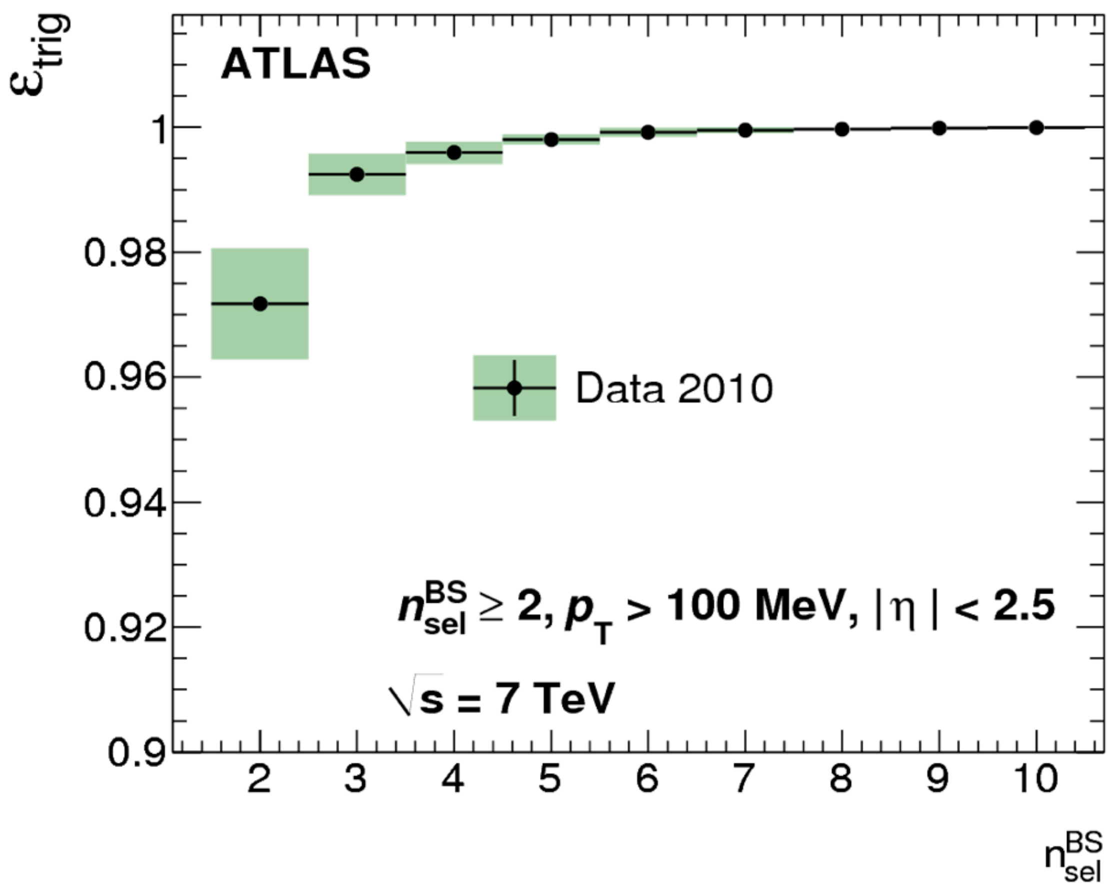
- 201: A-PT: Retune of Tune A with pT-ordered final-state showers. [Mar 2007]
- 211: A-PT-Pro: Tune A-PT with LEP tune from Professor. [Oct 2008]
- 221: Perugia A-PT: "Perugia" update of A-PT-Pro. [Feb 2009]
- 226: Perugia A6-PT: "Perugia" update of A-PT-Pro, using CTEQ6L1 PDFs. [Feb 2009]

Tunes using pT-ordered model

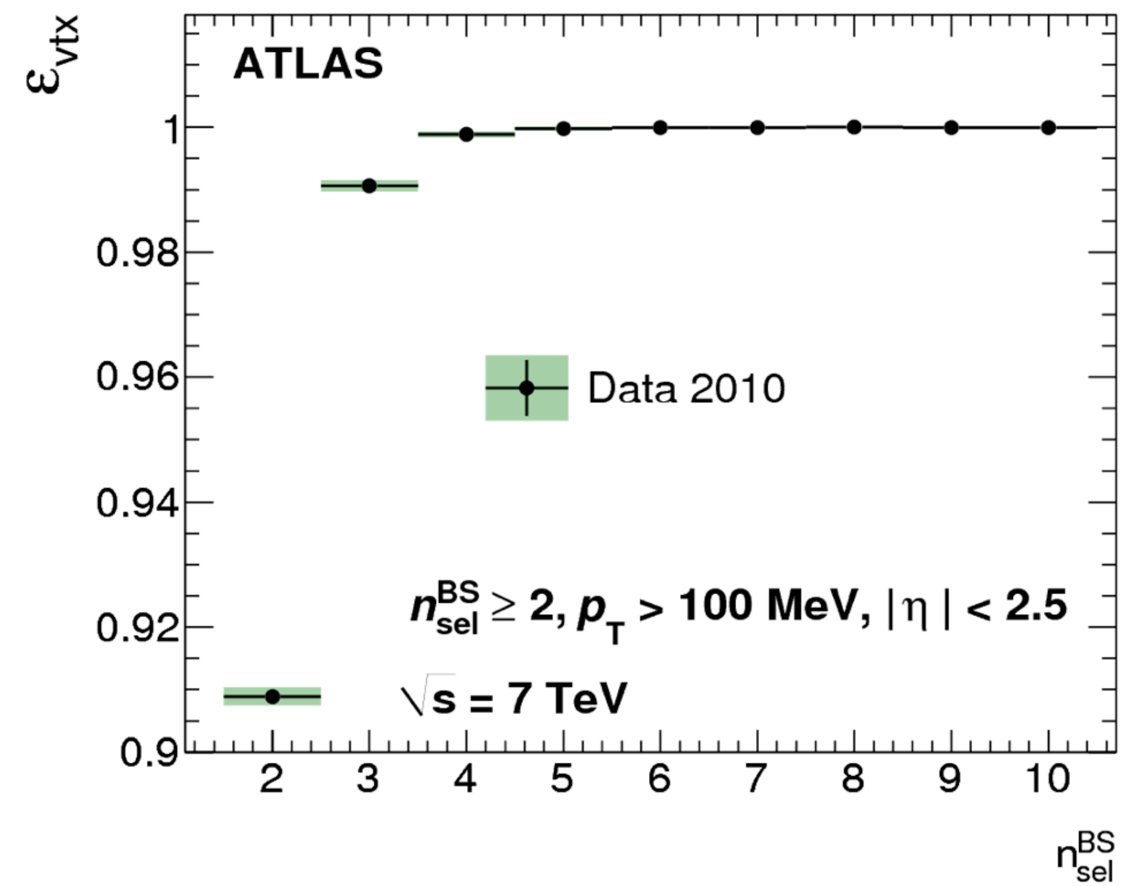
- 300: S0: First Sandhoff-Skands Tune of the "new" UE and shower framework, with a smoother matter profile than Tune A, 2 GeV of primordial kT, and "colour annealing" color reconnections. Uses the default Pythia energy scaling rather than that of Tune A. [Apr 2006]
- 303: S0A: A variant of S0 which is identical to S0 at the Tevatron, but which uses the Tune A energy scaling of the UE activity. [Apr 2006]
- 304: NOCR: Sandhoff-Skands "best try" without color reconnections. Gives less good agreement with Tevatron data. [Apr 2006]
- 306: ATLAS-CSC: first ATLAS tune of the pT-ordered showers and new UE framework. Does not give very good agreement with Tevatron min-bias quantities.
- 313: S0A-Pro: A variant of S0A revamped with a comprehensive retune of the fragmentation parameters to LEP data (by the "Professor" tool, hence the name). [Oct 2008]
- 314: NOCR-Pro: NOCR with LEP tune from Professor. [Oct 2008]
- 320: Perugia 0: "Perugia" update of S0-Pro. [Feb 2009]
- 321: Perugia HARD: Systematically "hard" variant of Perugia 0. [Feb 2009]
- 322: Perugia SOFT: Systematically "soft" variant of Perugia 0. [Feb 2009]
- 323: Perugia 3: Variant of Perugia 0 with different ISR/MPI balance and different collider energy scaling. [Feb 2009]
- 324: Perugia NOCR: "Perugia" update of NOCR-Pro. [Feb 2009]
- 325: Perugia X: Variant of Perugia 0 using MRST LO* PDFs. [Feb 2009]
- 326: Perugia 6: Variant of Perugia 0 using CTEQ6L1 PDFs. [Feb 2009]
- 327: Perugia 2010: Variant of Perugia 0 with updated fragmentation parameters and more FSR off ISR. [Apr 2010]
- 328: Perugia K: Variant of Perugia 2010 using a K-factor of 1.5 on the QCD scattering cross sections in the UE. [Apr 2010]
- 329: Pro-pT0: Tune of the pT-ordered showers and new UE framework made with Professor, an automated tuning tool. [Feb 2009]

Efficiencies

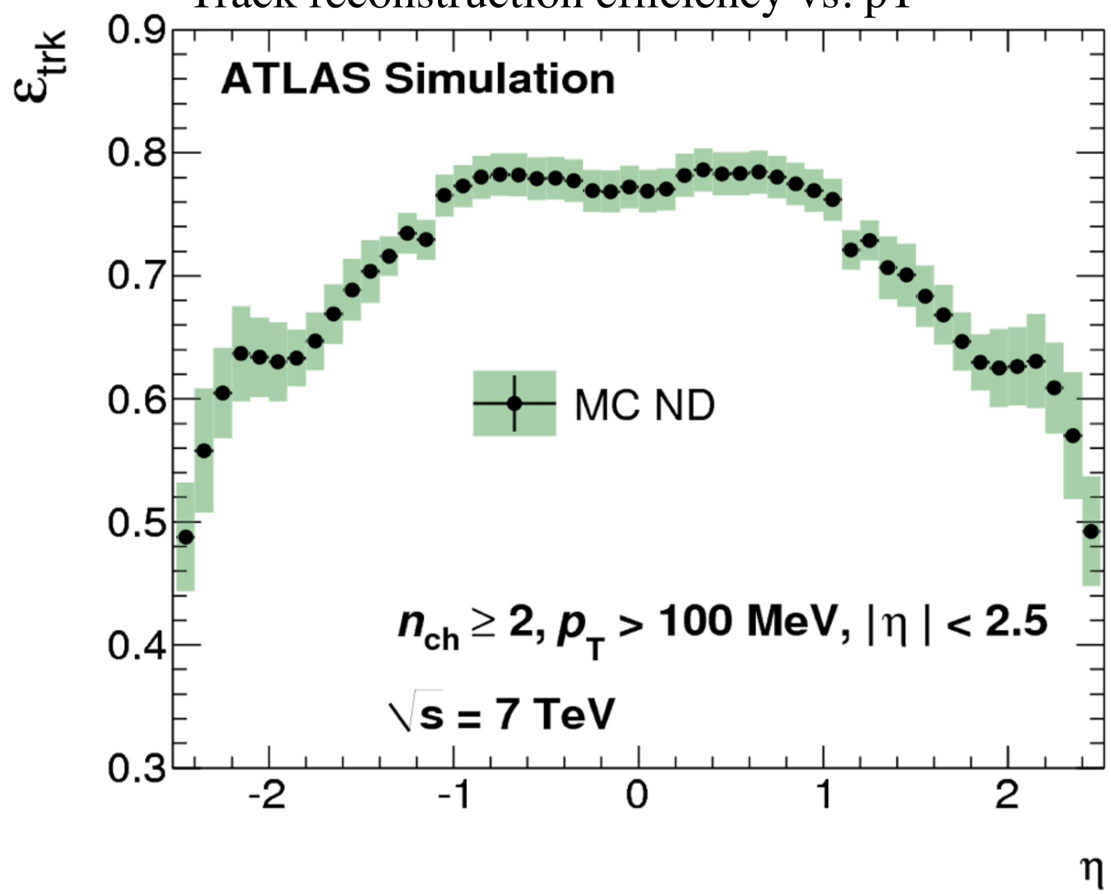
Trigger efficiency



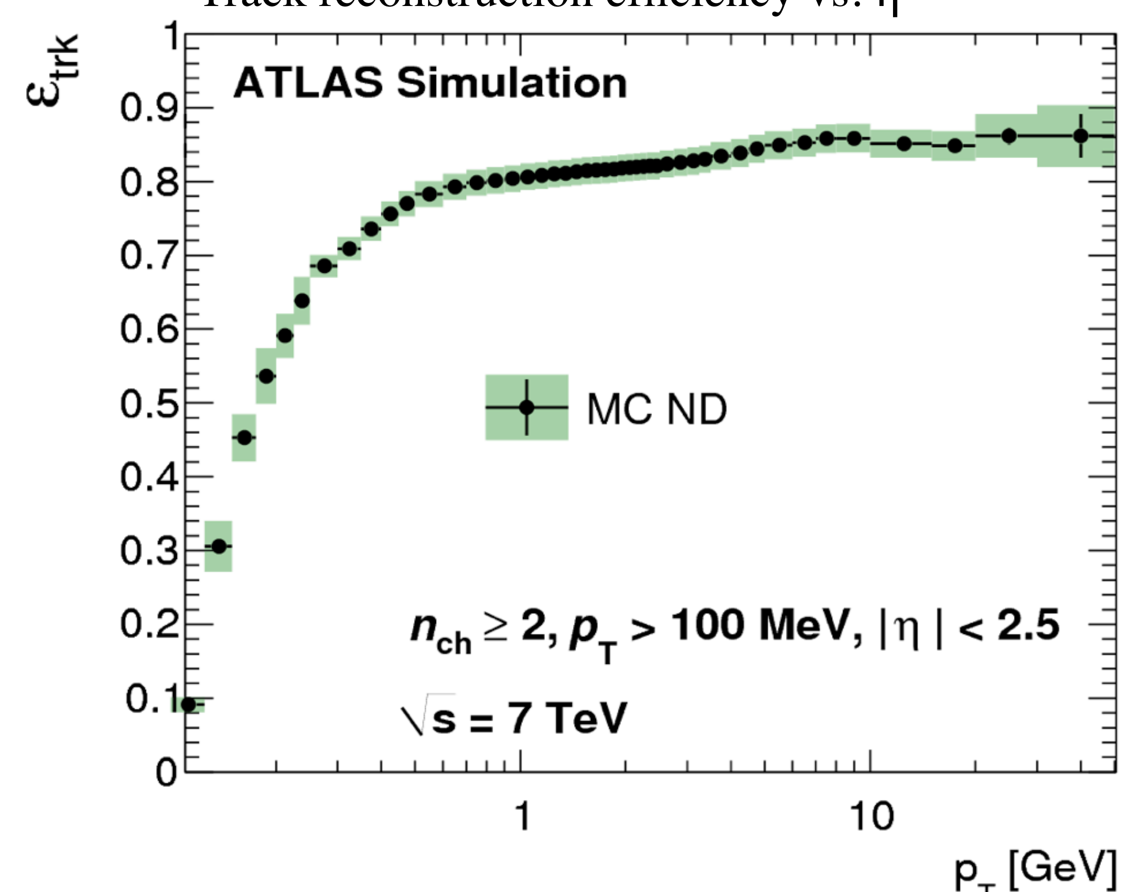
Vertex reconstruction efficiency



Track reconstruction efficiency vs. pT

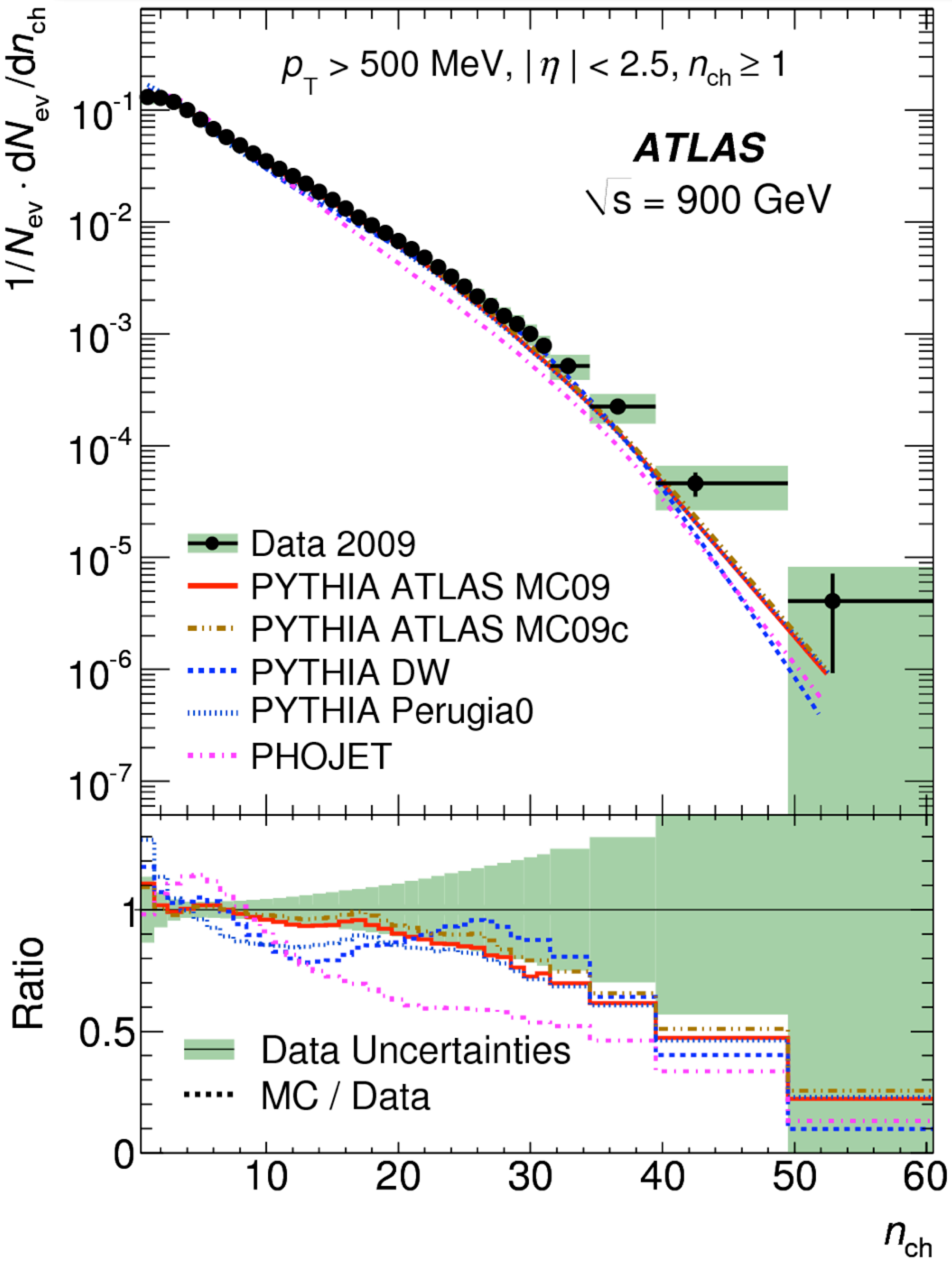


Track reconstruction efficiency vs. η

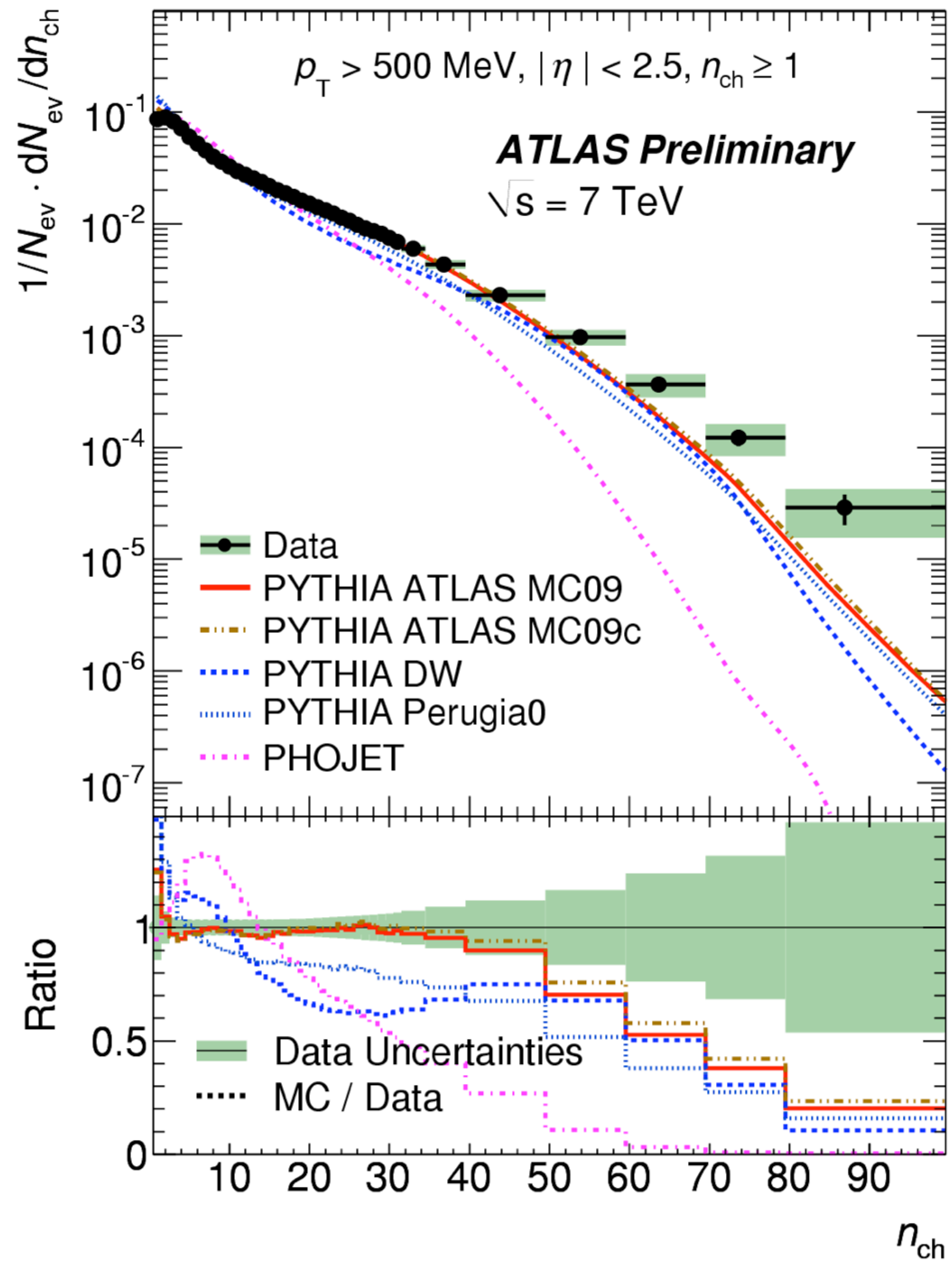


Minimum Bias Measurements in ATLAS

Multiplicity Distribution for $\sqrt{s}$=900 GeV

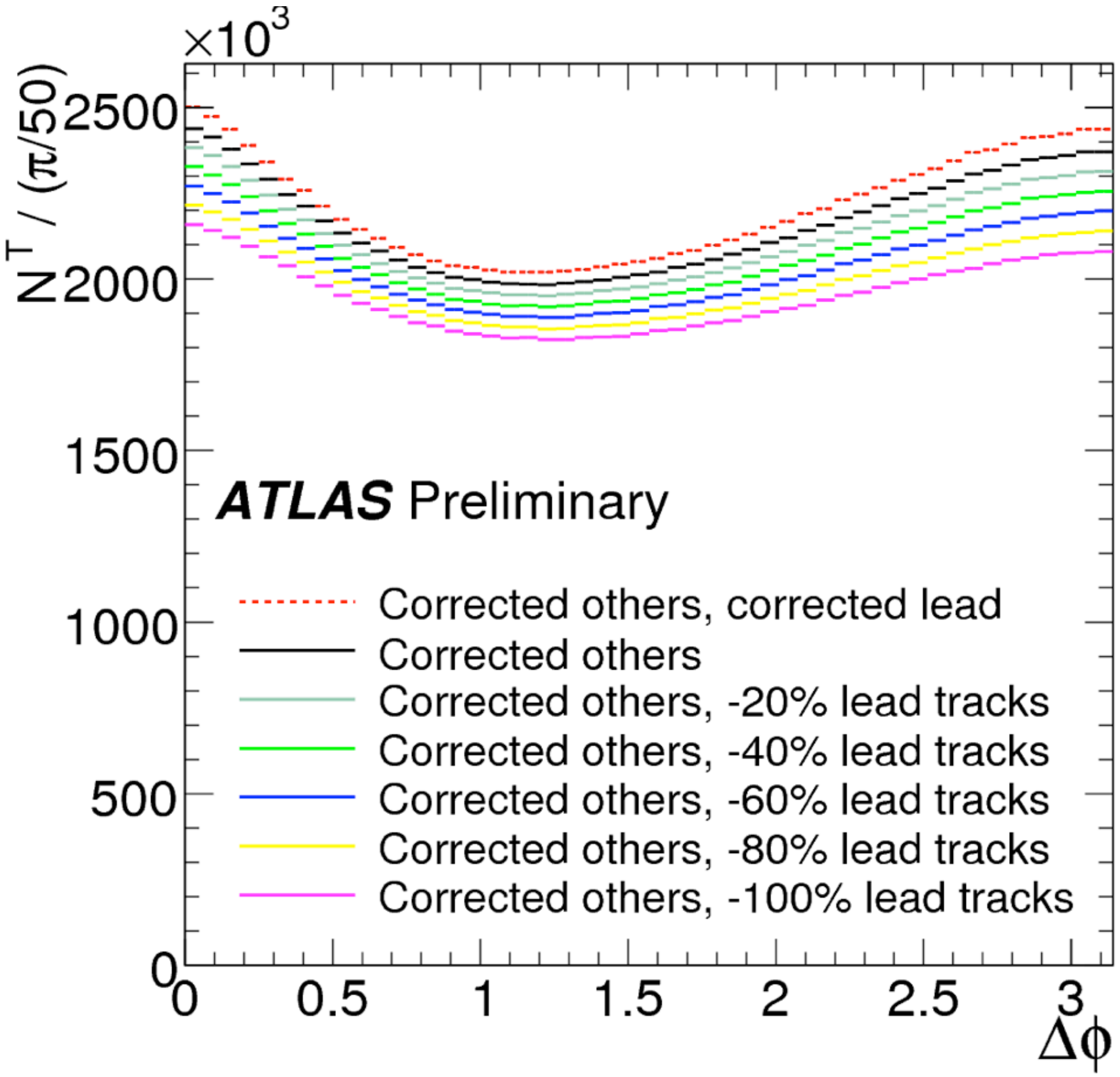


Multiplicity Distribution for $\sqrt{s}$=7 TeV

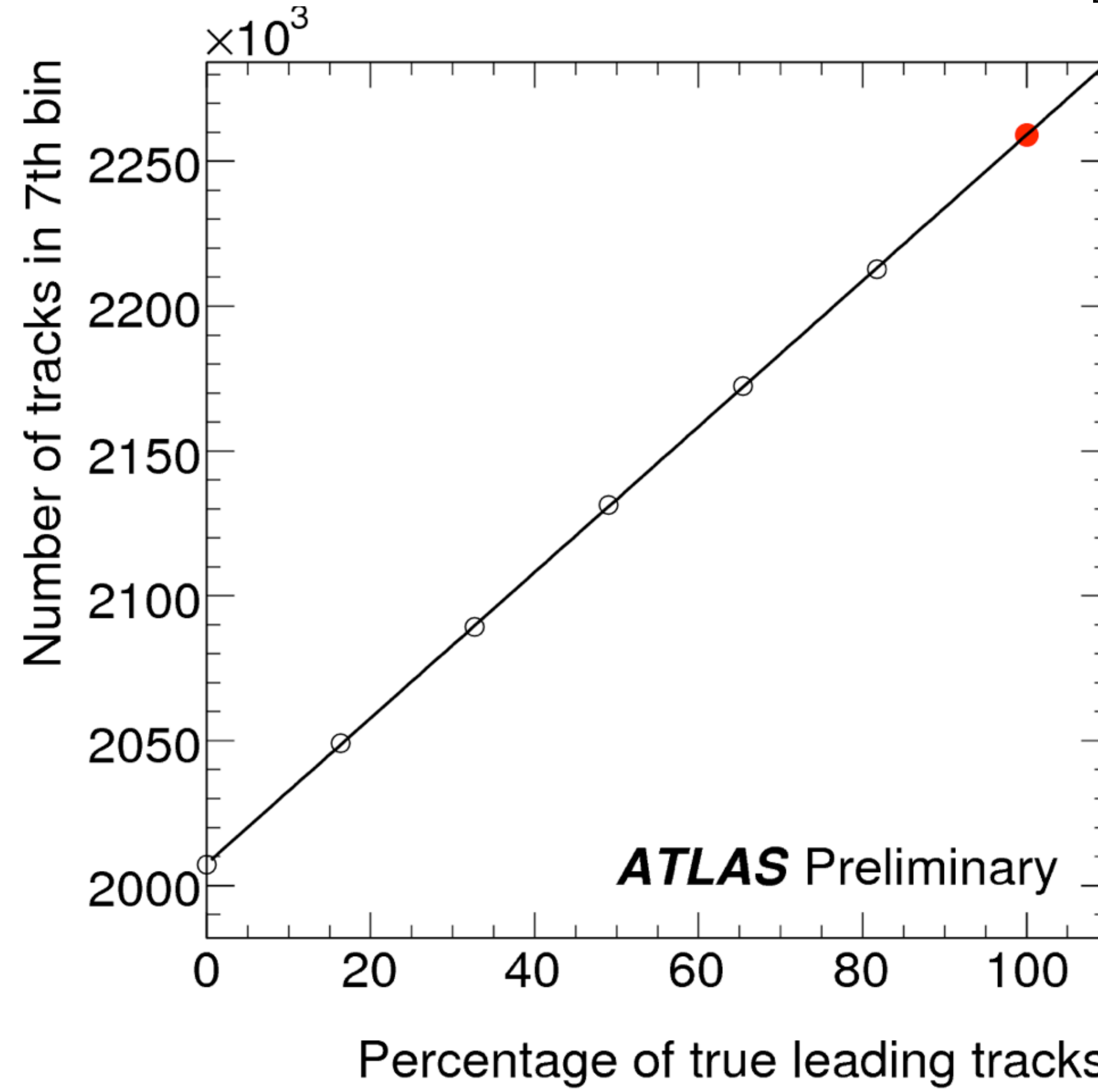


ΔΦ Correlations : Bin by bin Correction

3



The black line of this figure shows the Delta phi distribution for the 7 TeV data, corrected for the inefficiency of the non-leading tracks. The lines below that one (olive-green, green, blue, yellow and magenta) show the Delta phi distributions obtained if one disregards the leading track in 20%, 40%, 60%, 80% and 100% of randomly selected events. (These are also corrected for the inefficiency of the non-leading tracks.) The red dashed line (which lies above all other curves) represents the Delta phi distribution obtained after correcting for the effect of the lost leading particle.



Number of entries in one of the bins from adjacent figure. For the black empty circles the (x) represents the fraction of events, where the leading track was not disregarded, normalized in the way that the point of no disregarded leading tracks lies at the value of x = 81%, which is the reconstruction efficiency of the leading particle. The full red circle represents the number of entries with a perfect tracking efficiency. This number is obtained by extrapolating to x=100%.