Soft QCD @LHC

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UK LHC HEP Forum

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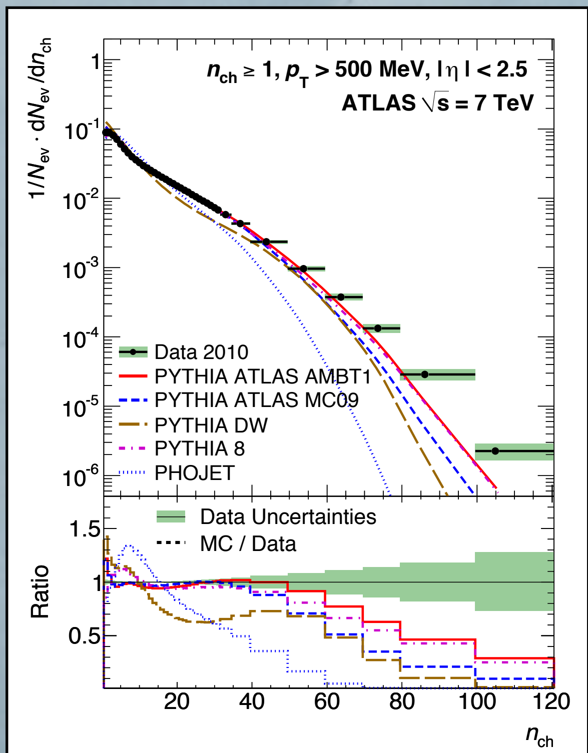
Outline

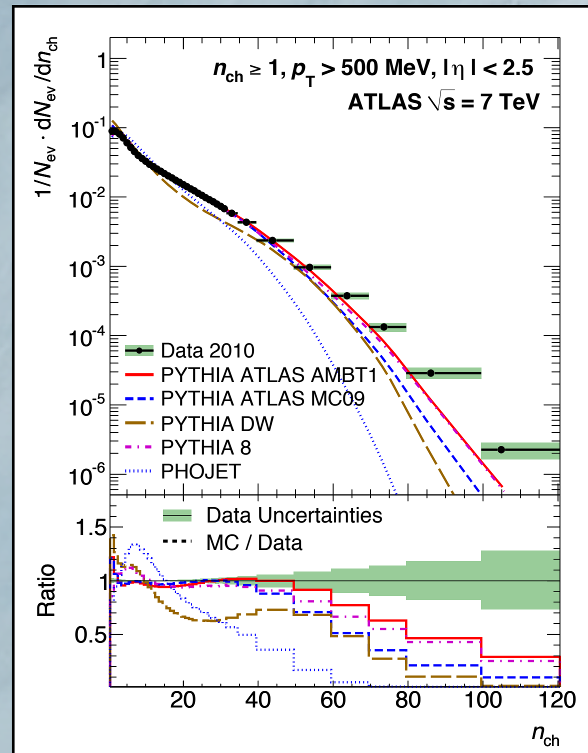
- Soft QCD program at the LHC is extremely large. Not possible to cover anywhere near all of it in 25 minutes. A few areas
  - Minimum Bias Results
  - Min Bias with particle ID
  - Correlations and Event Shape Results
  - Underlying Event Results

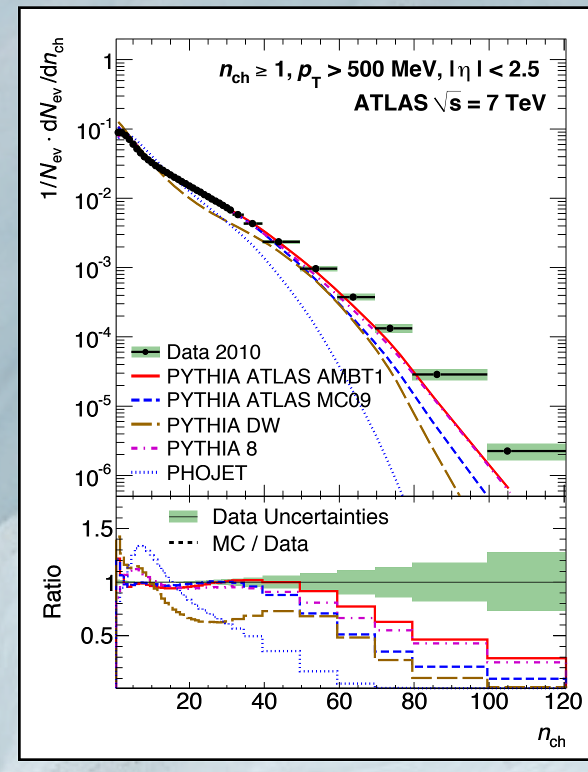
Minimum Bias

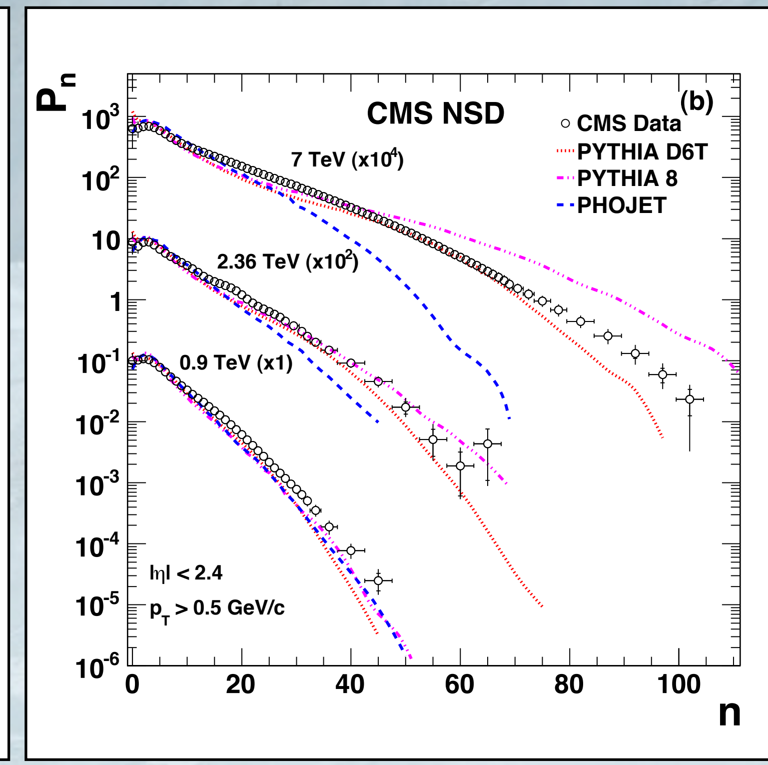
- Minimum bias is **experimentally** defined (by the trigger or some other phase-space cuts).
- It is a measure of what happens *on average* when you collide two protons
- It is important because it forms a background to the higher pT physics.
- Multiple independent collisions (a.k.a pile-up) are min bias, which provides a background plus noise contamination of signal
- Fluctuations in the “average” event can look like signal
- Therefore we need min bias to be well modelled by Monte Carlo = compare measurements to different MC tunes.

Charged particle multiplicity distributions

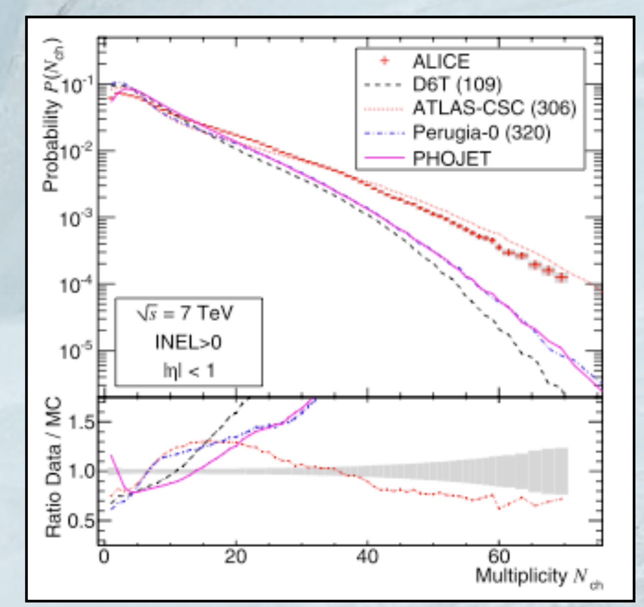


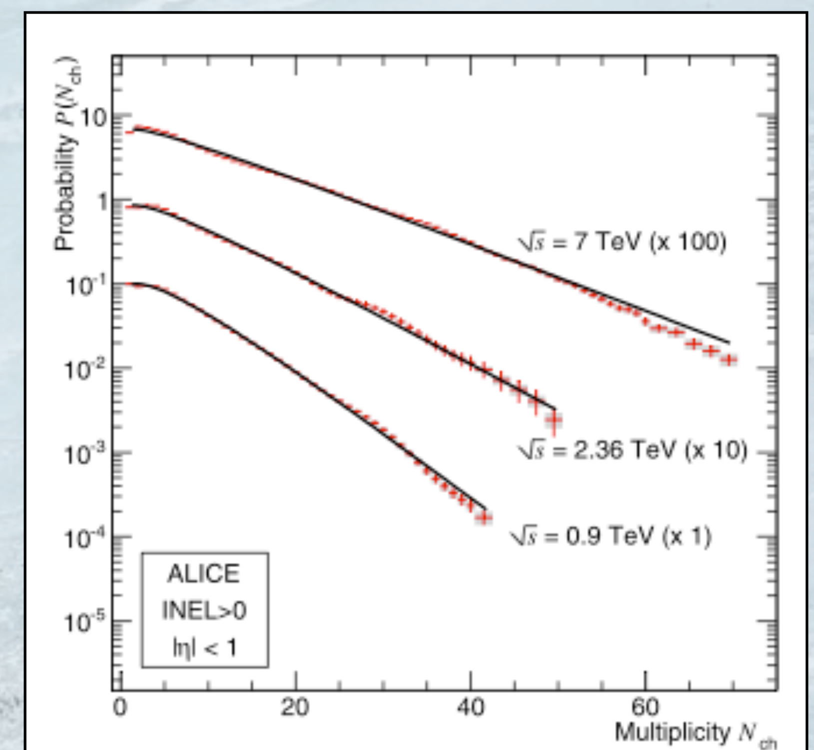




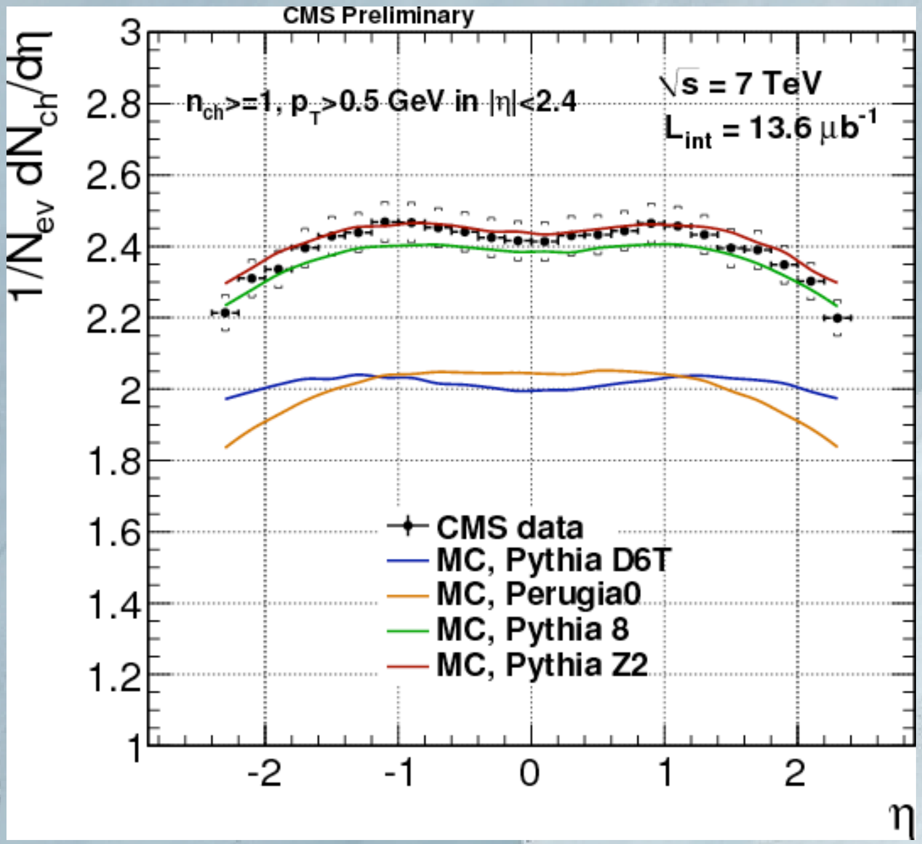


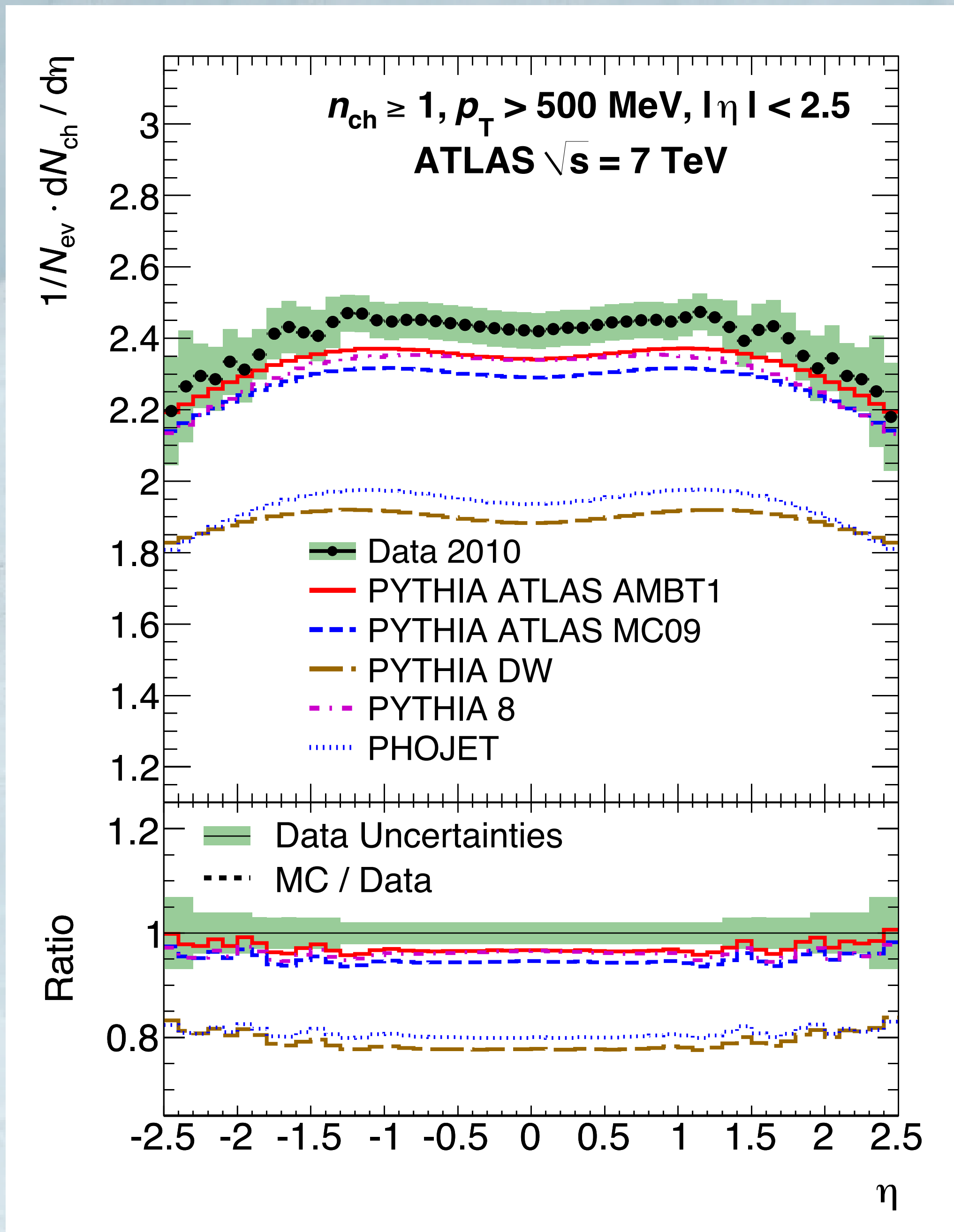
Note slight differences between phase space and event definition. |η| < 2.5 (ATLAS), 2.4 (CMS) or 1.0 (ALICE). ATLAS and ALICE use events with > 1 charged particle inside their η acceptance, whereas CMS define "non-single diffractive" sample





Pseudo-Rapidity distributions

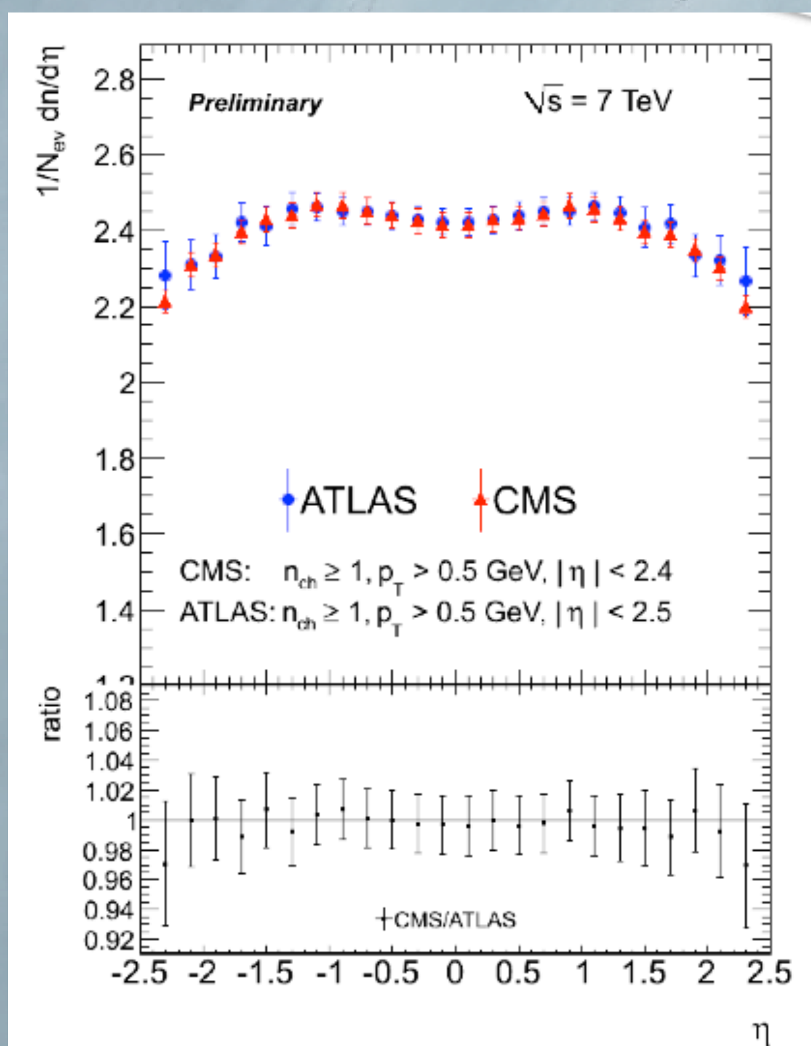


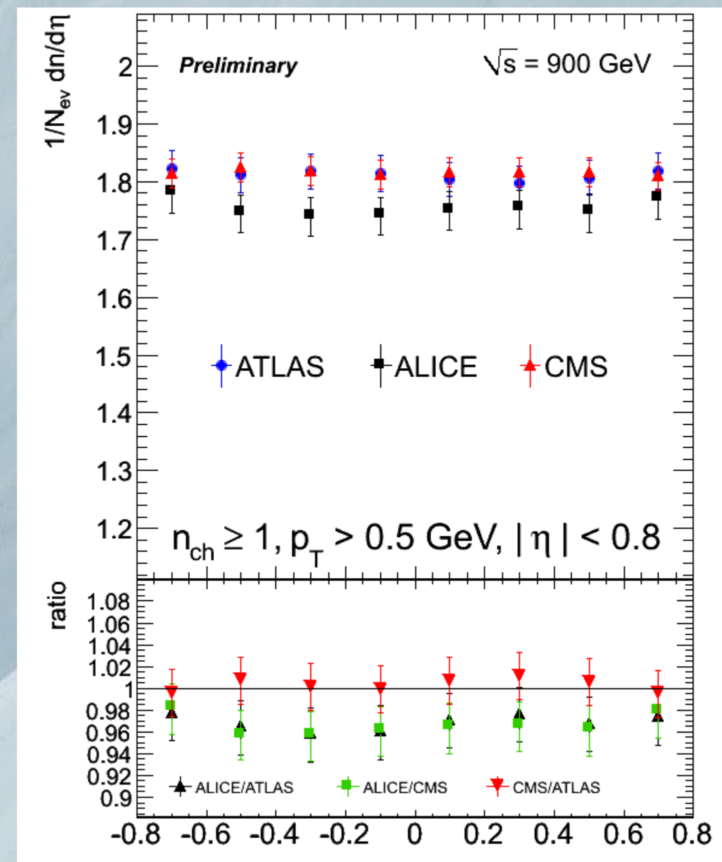


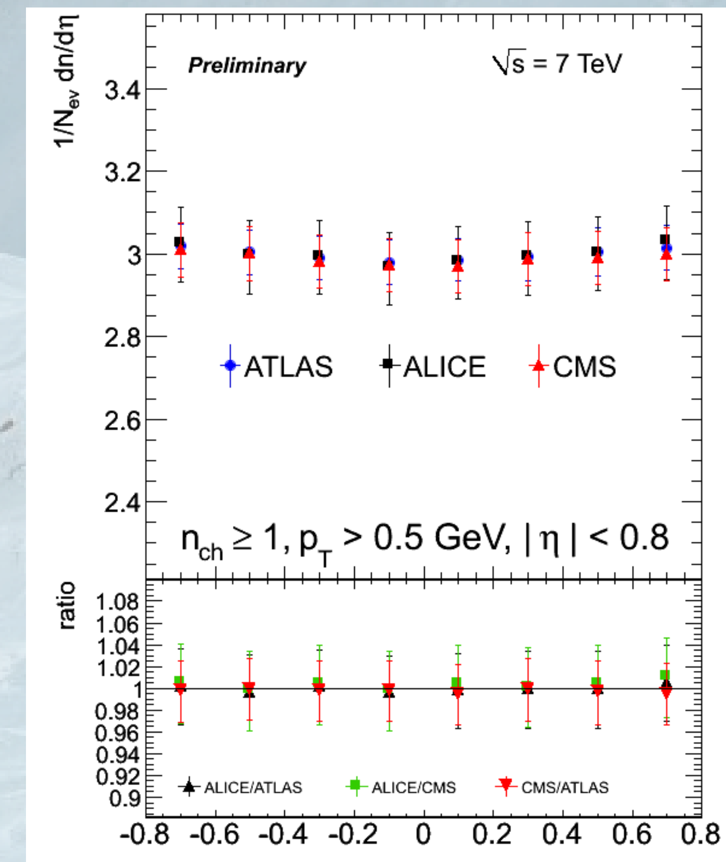
- More similar event definitions this time

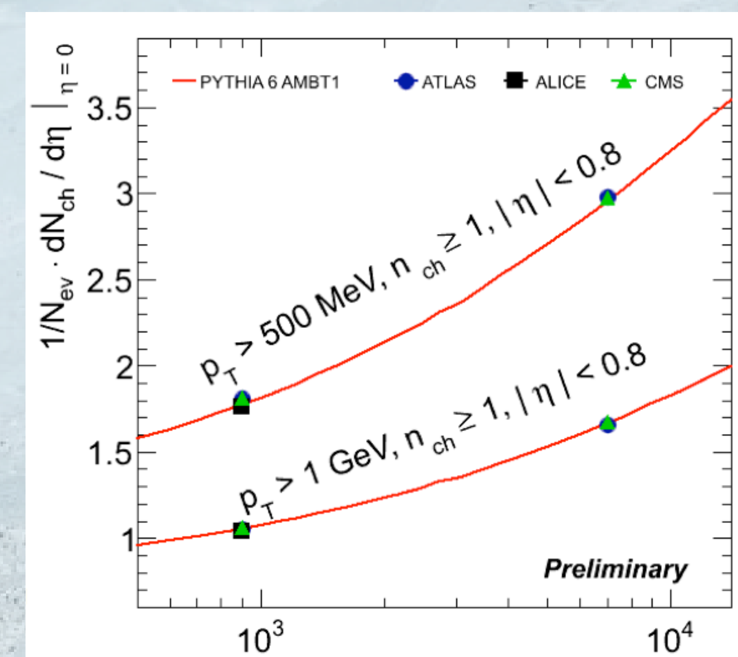
Common plots

- ALICE, ATLAS and CMS defined a common set of cuts for easy comparison of MB results: $|\eta| < 0.8$, pT > 500 MeV or 1 GeV. All events with Nch > 1





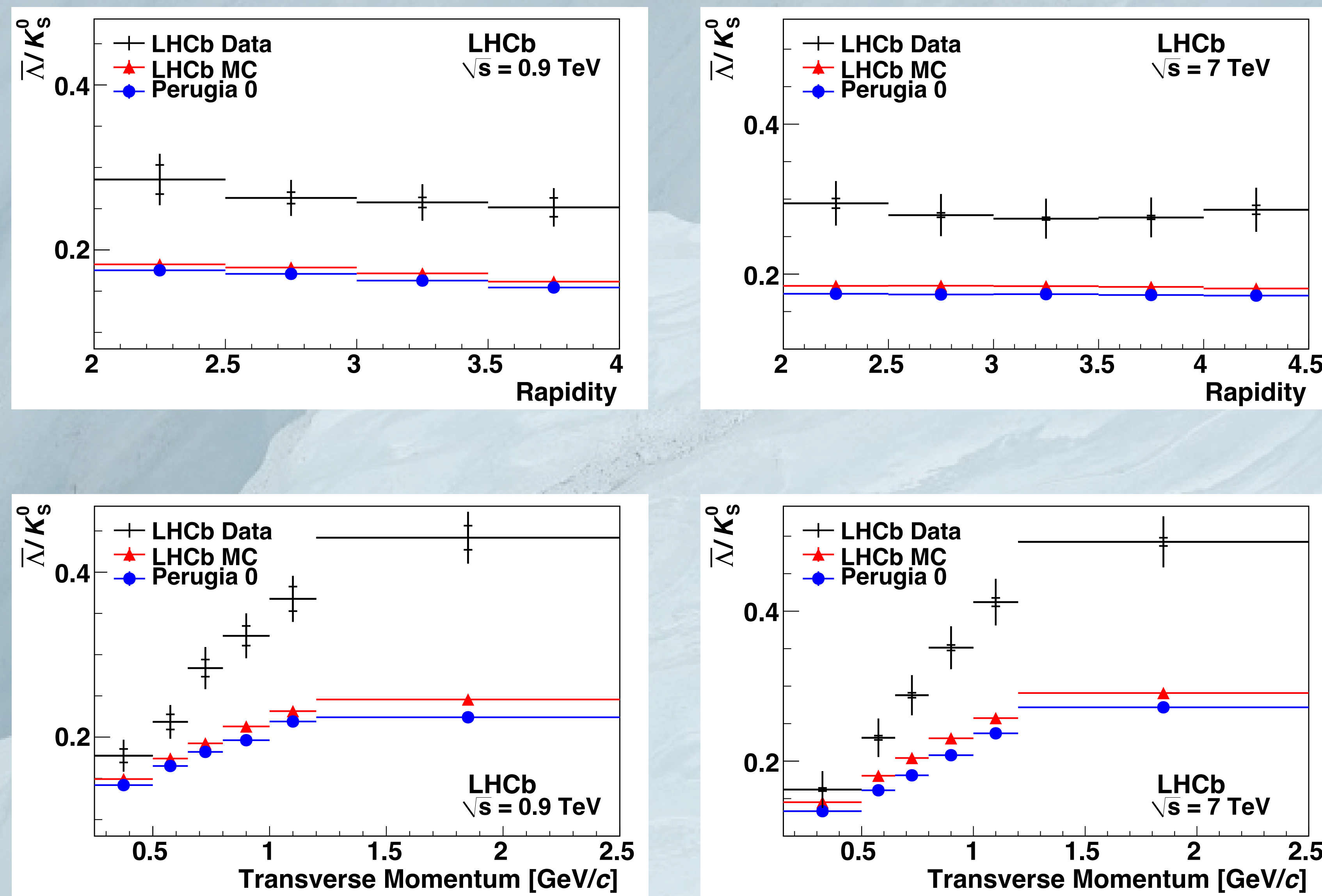




Min Bias with Particle ID

Min Bias with Particle ID

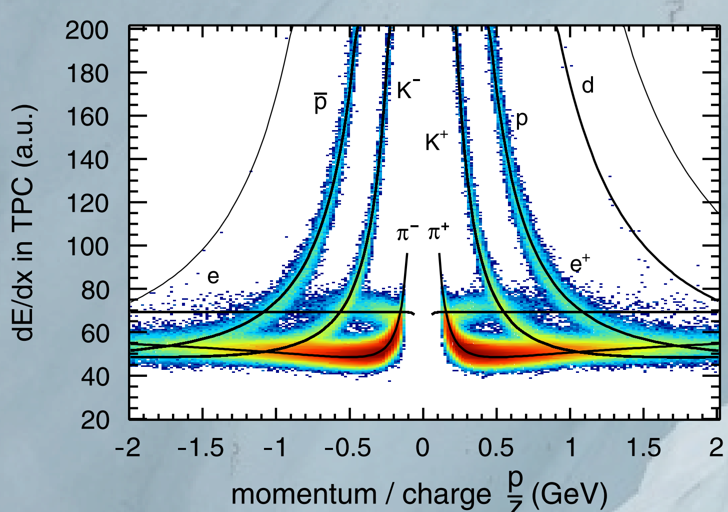
- Particle ID can provide useful input to hadronisation models
- Are the pT spectra of individual particle species well modelled?
- Ratio of e.g. Δ / Ks shows baryon production rate relative to meson
- pbar/p ratio gives an indication of baryon production (two baryons in initial beams)



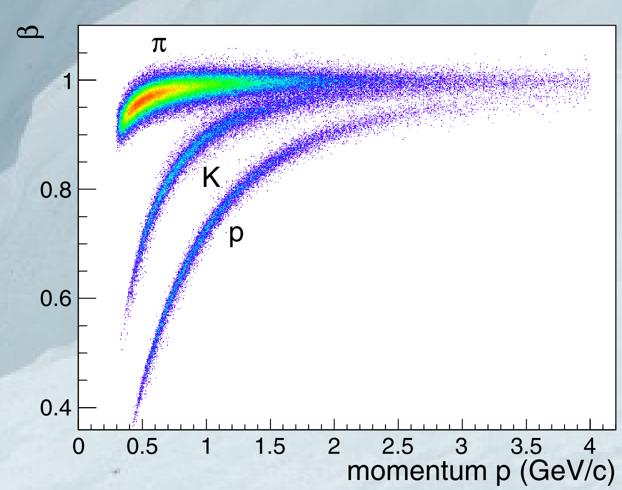
Generators not doing a great job of this

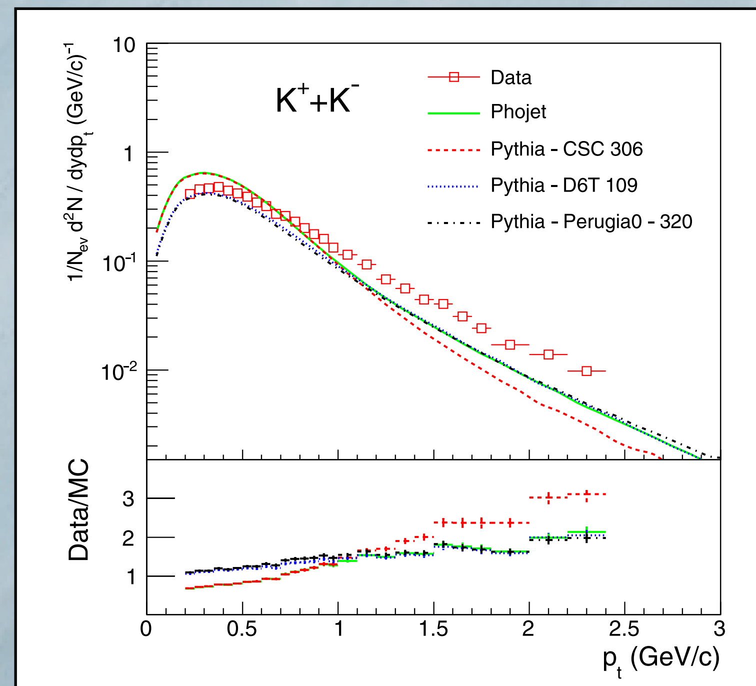
Min Bias with Particle ID

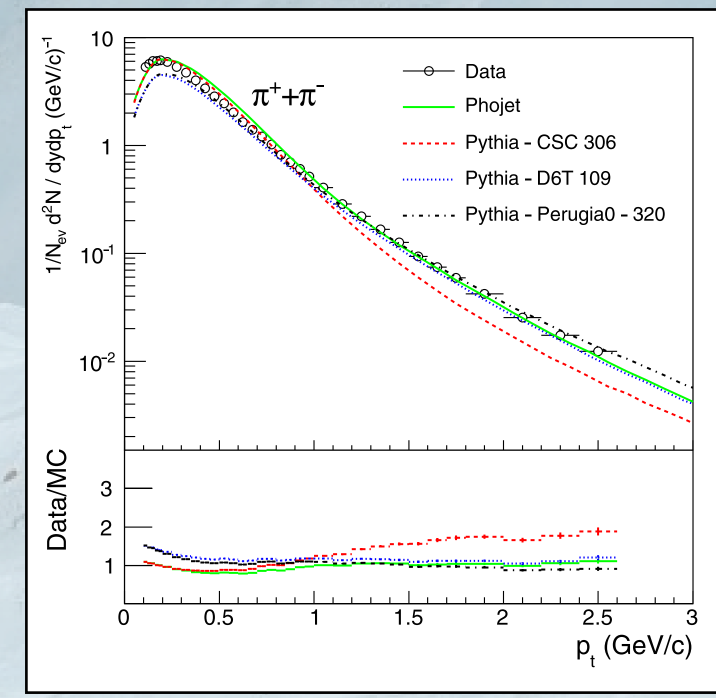
- Alice have measured π, k and p pT spectra at 900 GeV collision energy



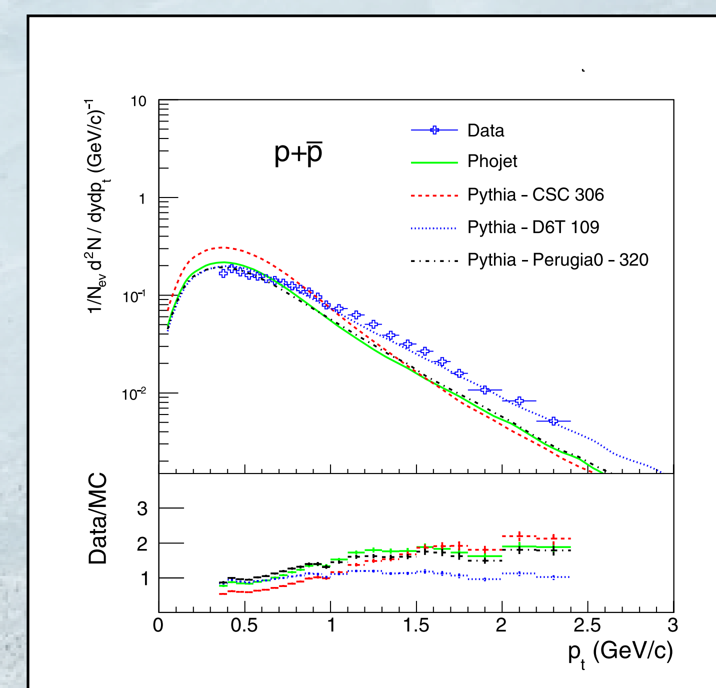
Particle Id by dE/dx and time of flight (ß=length travelled/ time)





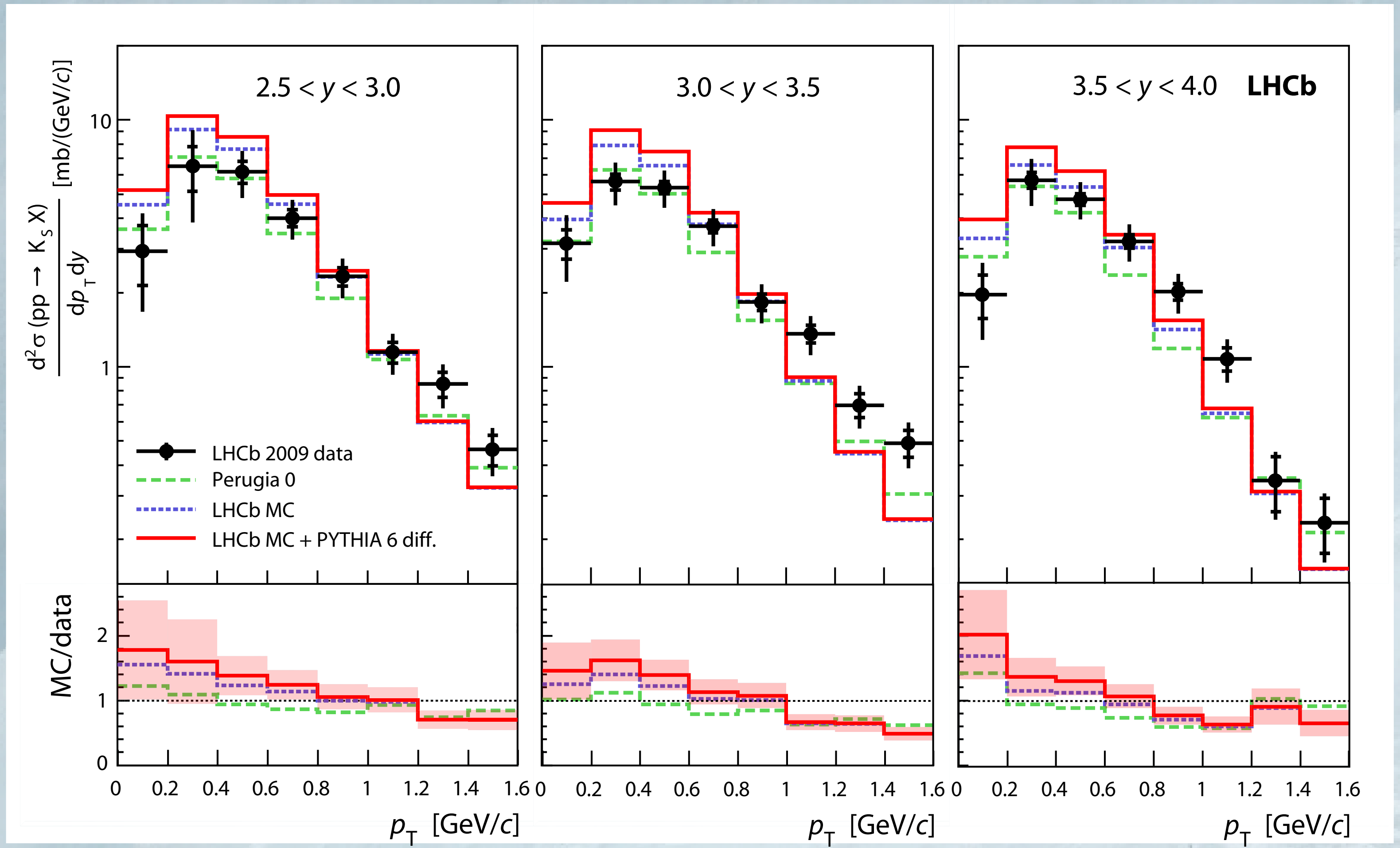


Comparison to MC shows different discrepancies for different species



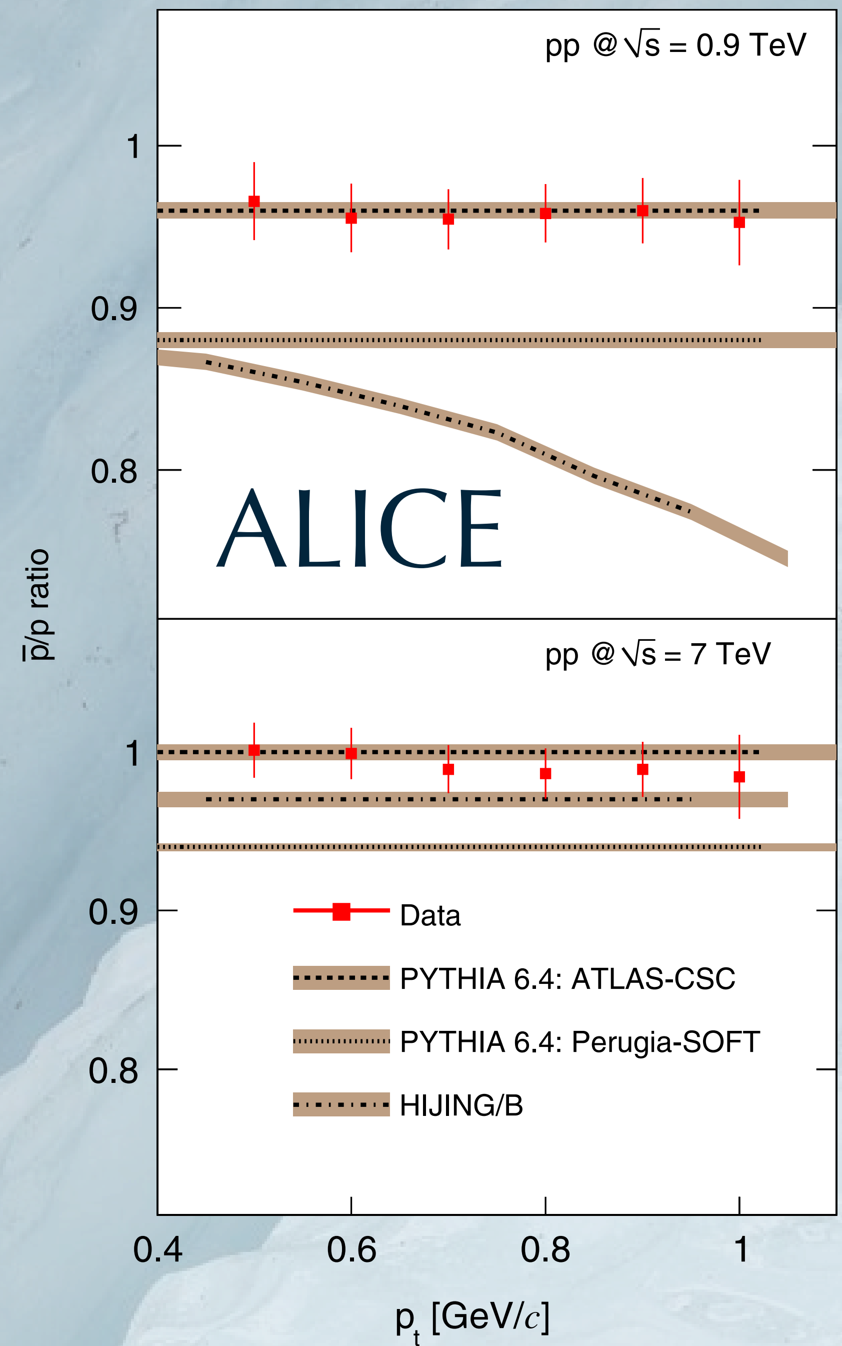
Min Bias with Particle ID

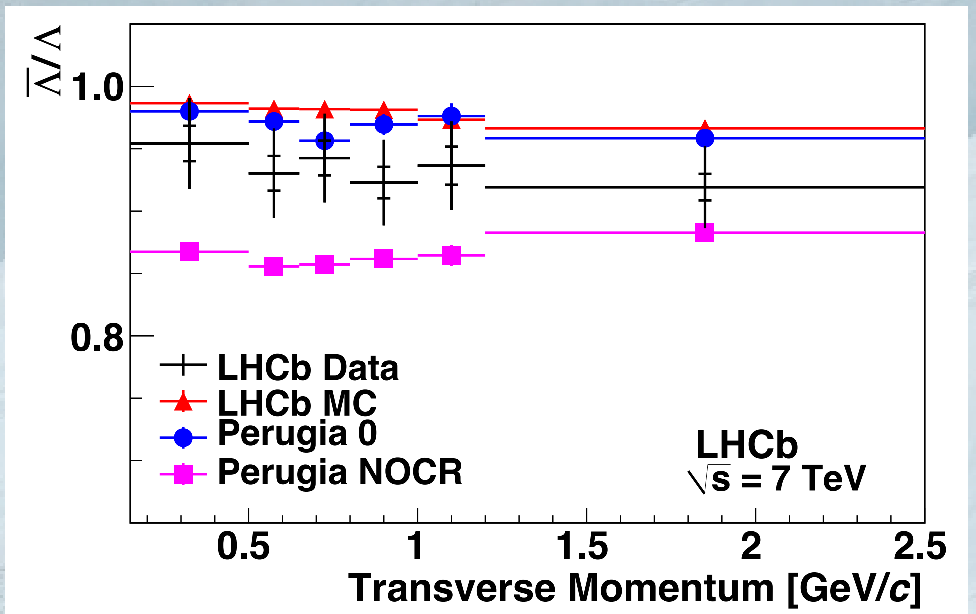
- LHCb performed a similar measurement for neutral Ks @ 900 GeV

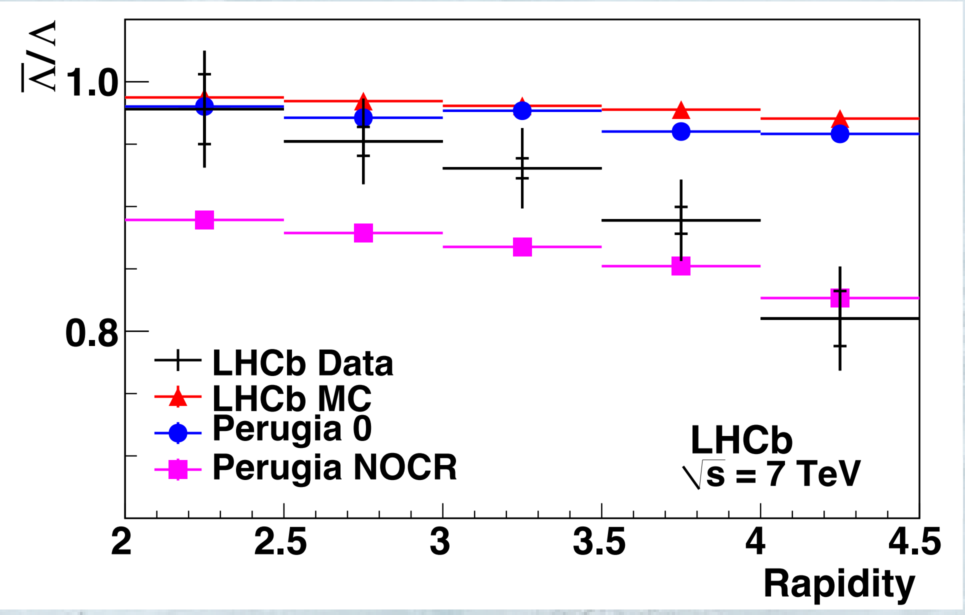


Min Bias with Particle ID

- ratio of p/pbar production gives an indication of baryon production (beam baryon number = 2)
- Lambda/Lambda-bar production shows similar







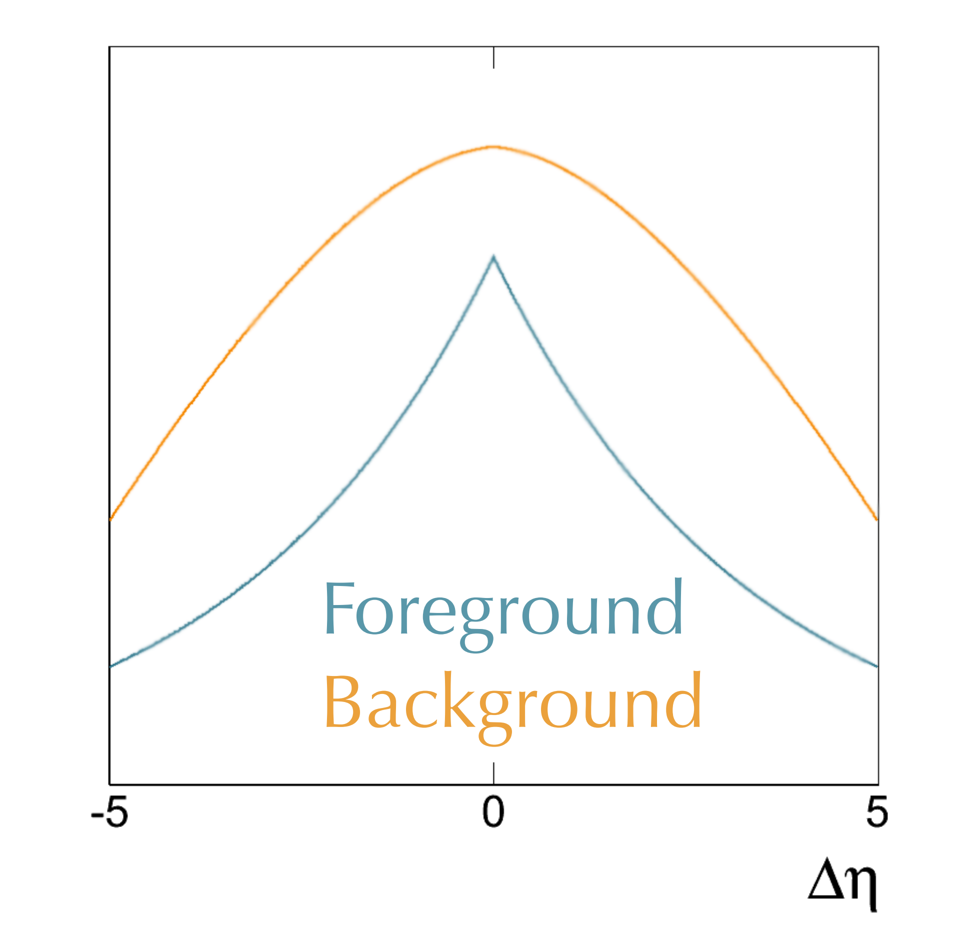
Correlations & Event Shapes

Two-Particle Correlations

- The existence of correlations between final state particles is an indication that there is a common origin for their production.
- Simple example: decays of clusters could give rise to particles close together in η and ϕ.
- Another example: if radiation is emitted at a given angle, ϕ_0, then there will tend to also be emission close to π-ϕ_0 because of momentum conservation.
- In general, the pattern of correlations can be quite complicated. Models of soft QCD dynamics (as encapsulated in Monte Carlo generators) need to be able to describe this.

Two-Particle Correlations

- Two particle correlations consist of a **foreground** and a **background**.
- Foreground = take **Δη** and **Δϕ** between each pair of particles in an event. Fill a 2D histogram with those values
- Falls with **Δη** because of phase space, but there is also structure (e.g. peak at 0,0)



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

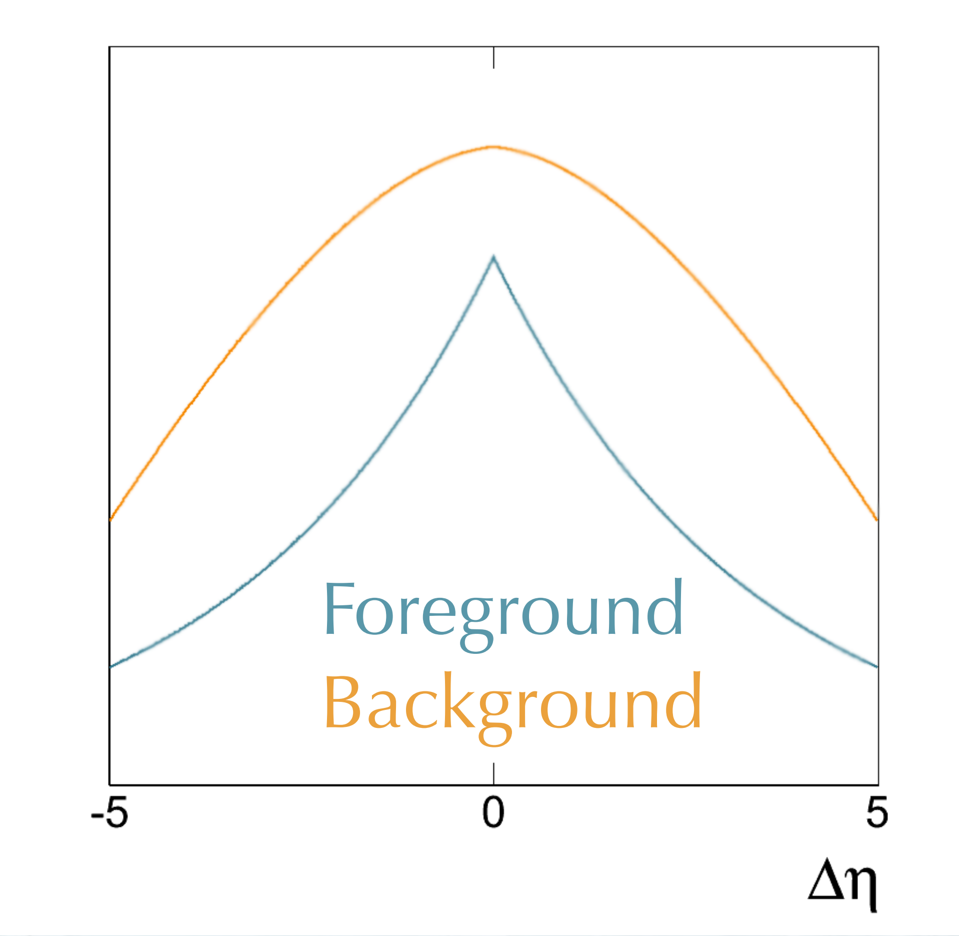
Foreground is normalised by dividing by total number of events

Means that each track has the same weight in the distribution , regardless of the track multiplicity of the event

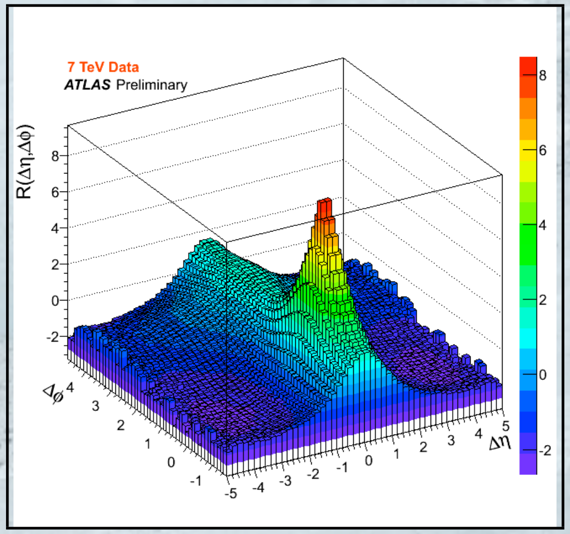
N_{ch} = number of (charged) particles in the event

Two-Particle Correlations

- For the background take the **Δη** and **Δϕ** between particle pairs in **independent** events.
- Accounts for the phase space effect plus some other detector effects
- **Divide** the foreground by the background to give the observable

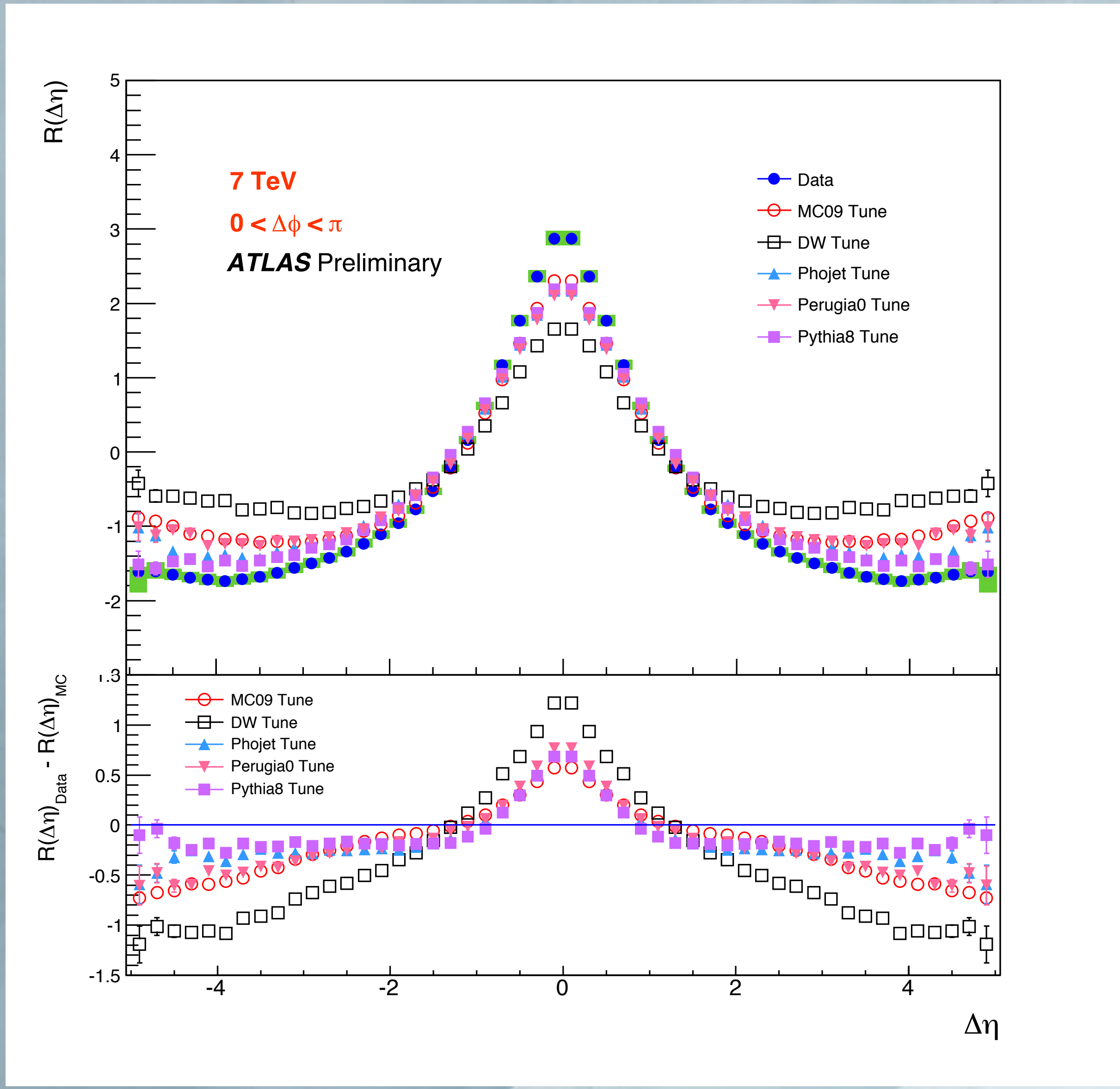


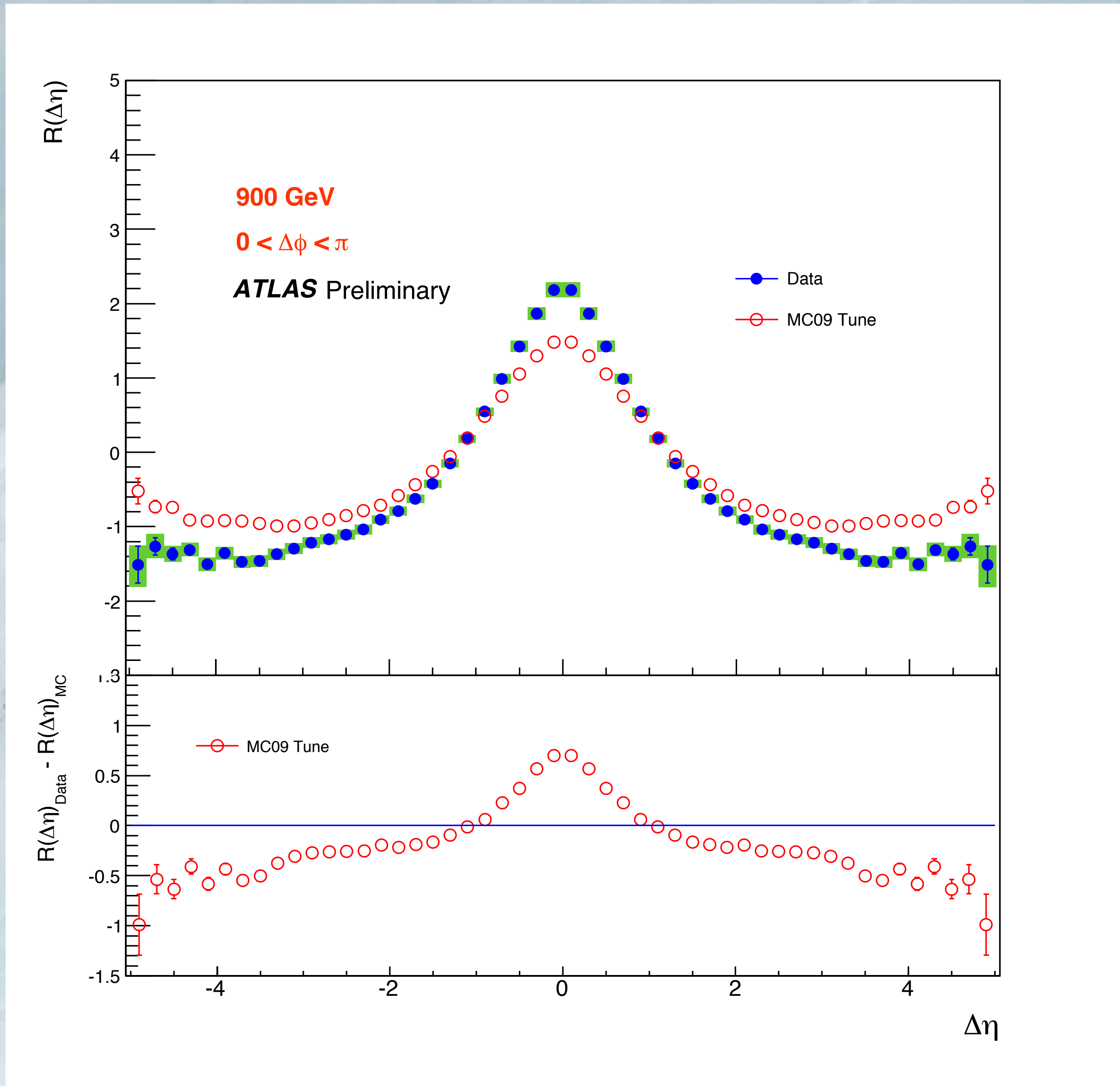
$$B\left(\Delta\eta\right)=\int_{-2.5}^{2.5}\int_{-2.5}^{2.5}\mathrm{d}\eta_1\mathrm{d}\eta_2\delta\left(\eta_1-\eta_2-\Delta\eta\right)\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_1}\left.\frac{\mathrm{d}N_{ch}}{\mathrm{d}\eta}\right|_{\eta=\eta_2}$$



Note the different normalisation: the background is normalised by dividing by the number of entries (= the no. of tracks) to give unit integral

Two-Particle Correlations

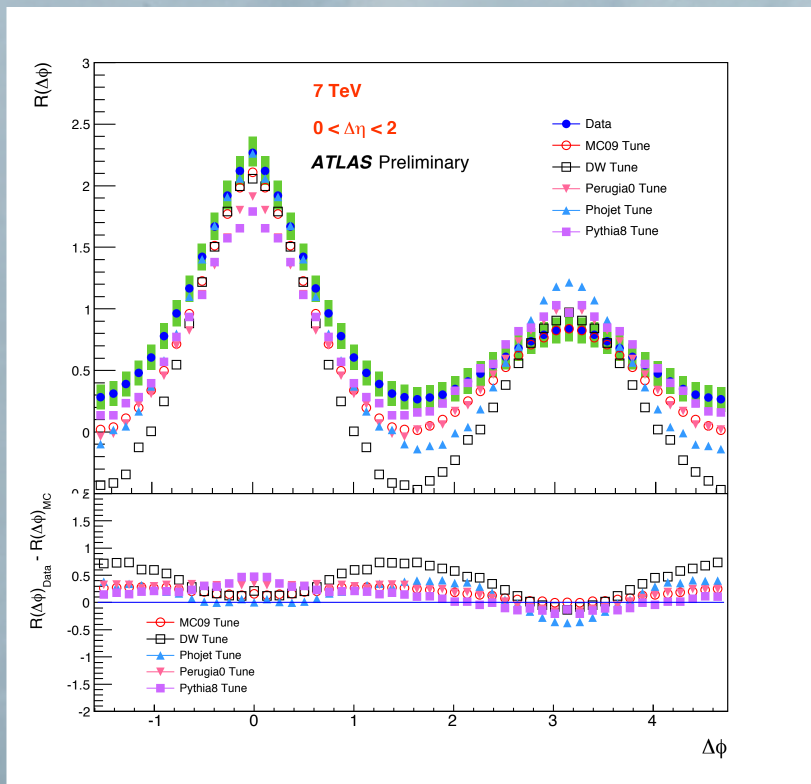


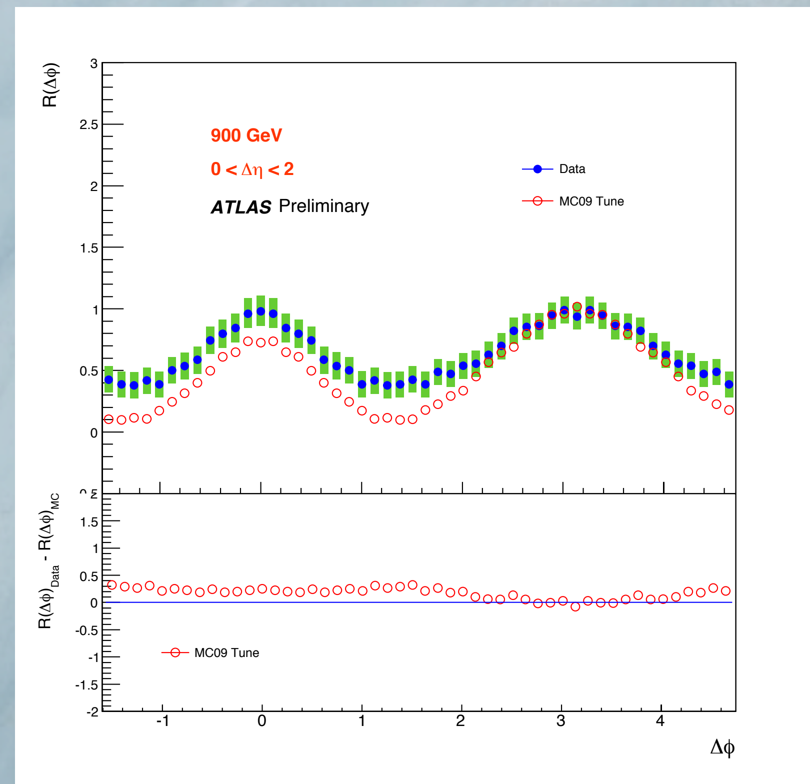


Easier to compare to MC by integrating over Δϕ

Δη distribution (by integrating the foreground and background separately over {0, π} at 7 TeV and 900 GeV)

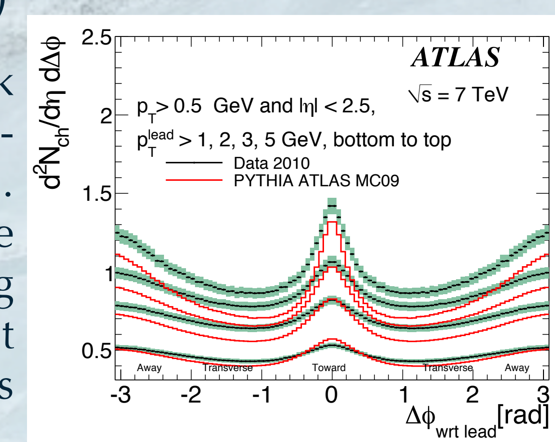
Two-Particle Correlations





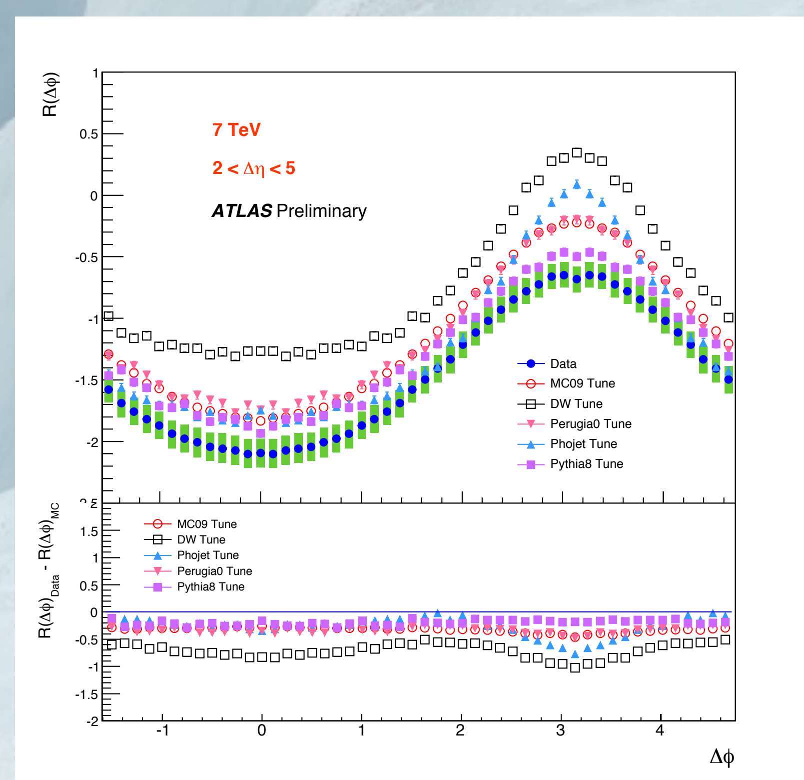
$\Delta\phi$ distribution (by integrating the foreground and background separately $\Delta\eta$ over {0, 2} at 7 TeV and 900 GeV)

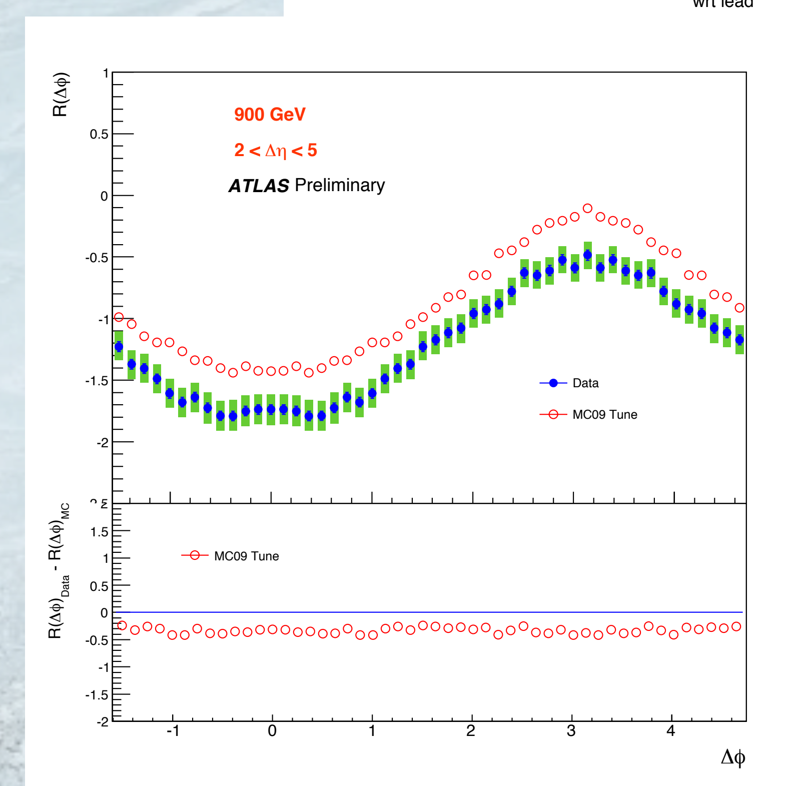
Double peak due to back-to-back recoil. Similar to some underlying event distributions



$\Delta\phi$ distribution (by integrating the foreground and background separately $\Delta\eta$ over {2, 5} at 7 TeV and 900 GeV)

Integrating over $\Delta\phi$ region that does not include main peak - we see the away side recoil, but a dip on the near side

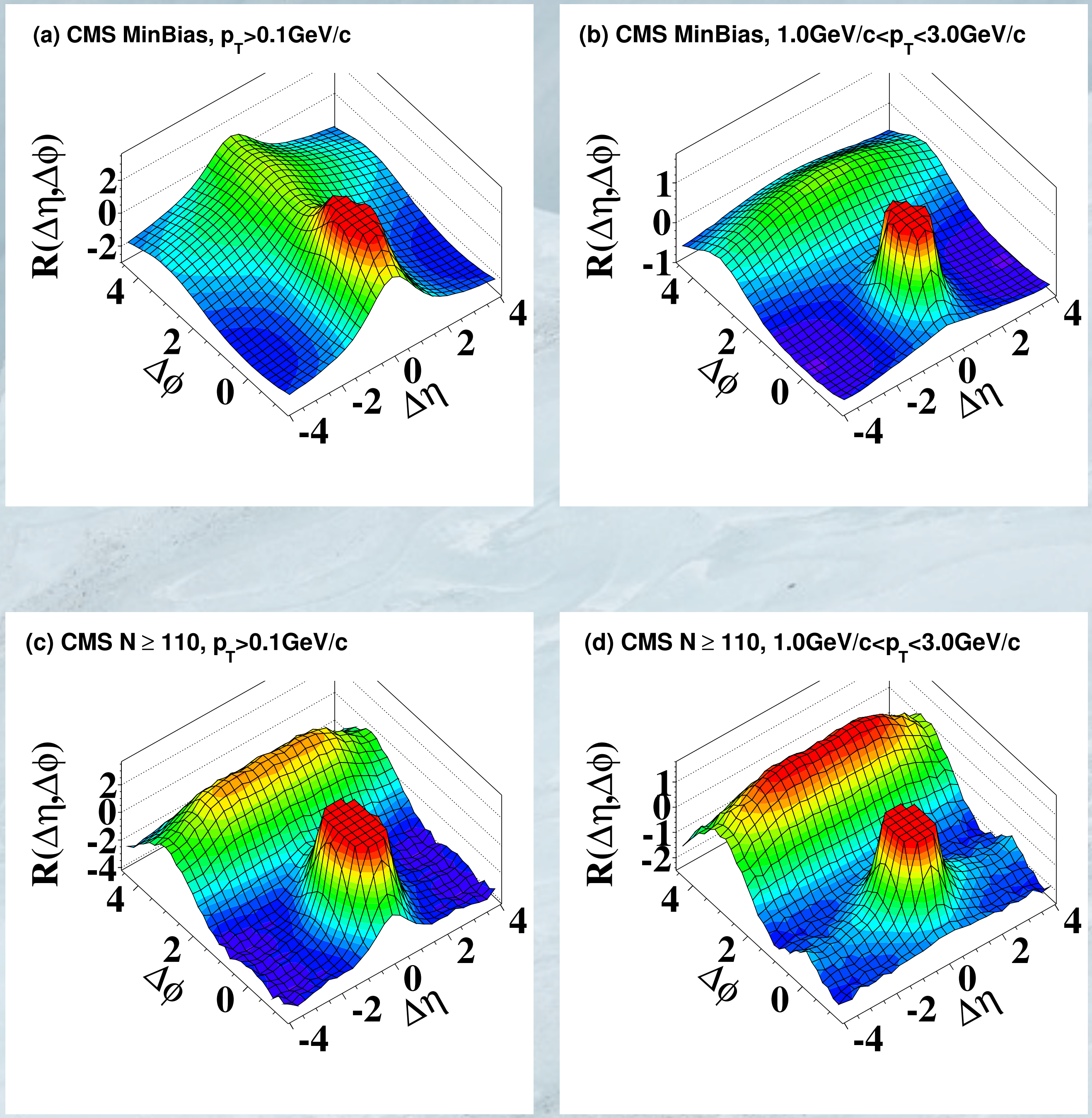




Two-particle Correlations at higher multiplicity

- In a specific region of phase space, Nch(pT > 400 MeV) ≥ 110, and for particles with 1 GeV < pT < 3 GeV, CMS observe an interesting ridge showing long range correlations between tracks

- Interpretation is open for debate...



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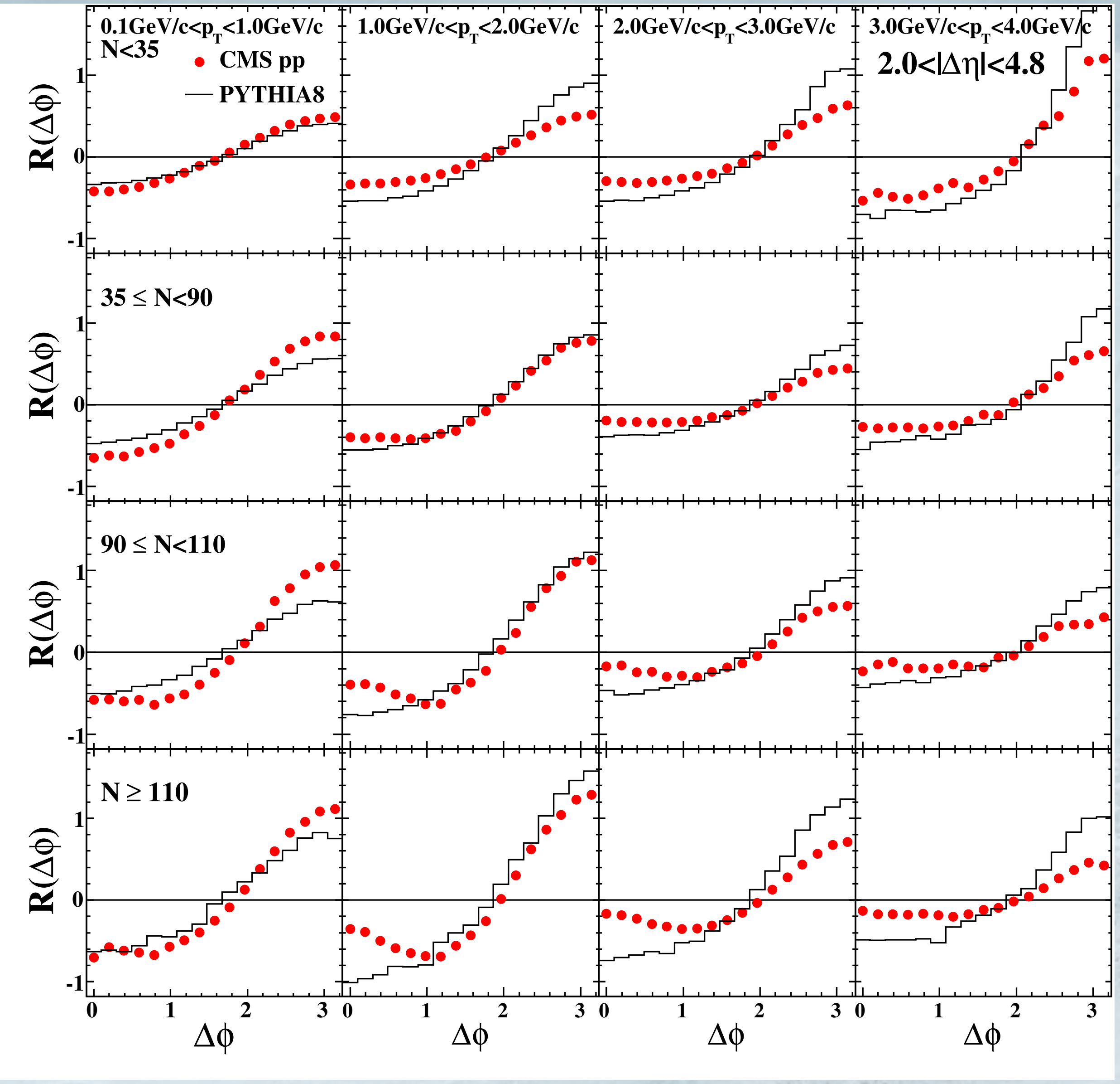
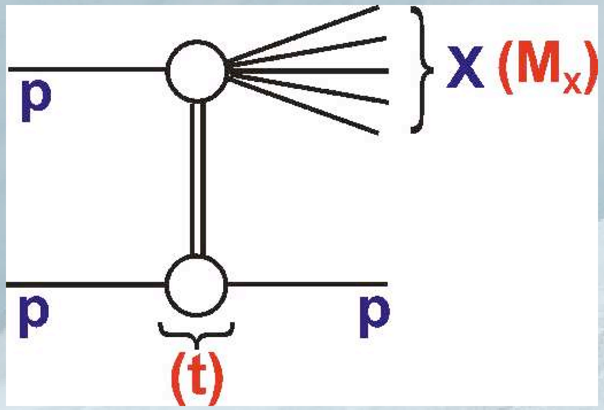
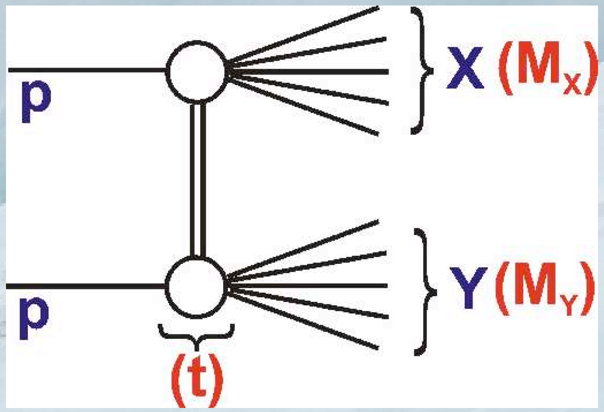


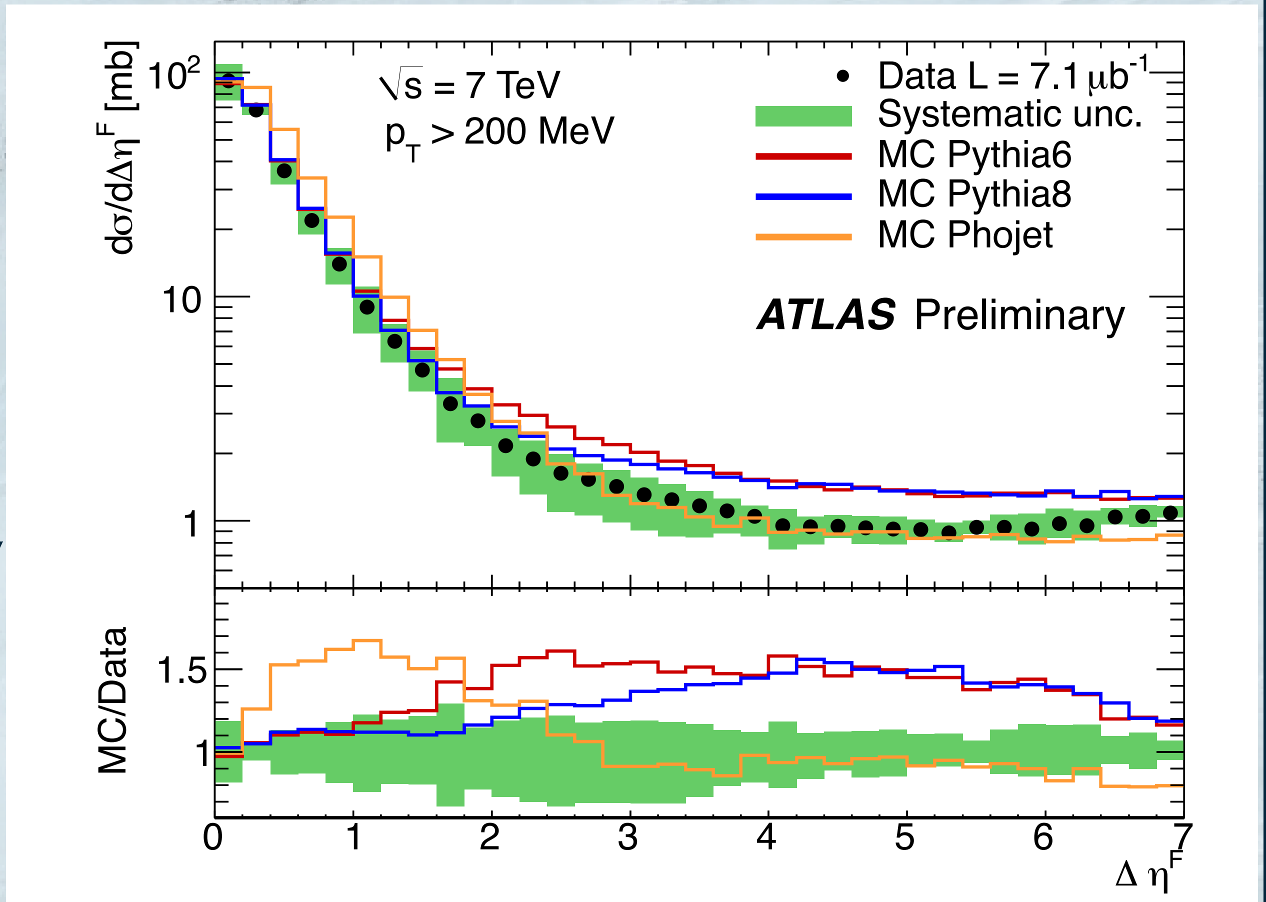
Same 2D plot in profile

Soft Diffraction

- Diffraction is the low t (momentum exchange) limit of scattering processes.
- Results from the exchange of (composite) colourless objects - a large and important contribution to the total cross section
- Exchange of colour singlet is typically accompanied by a rapidity "gap" devoid of radiation in the detector.
- ATLAS has measured the cross section as a function of that gap size
- Gap defined as a region with no track of pT > 200 MeV and no calorimeter cell with an energy deposit above a noise pedestal.
- The noise pedestal is defined such that the probability for a noisy cell to exceed the threshold is 0.00014

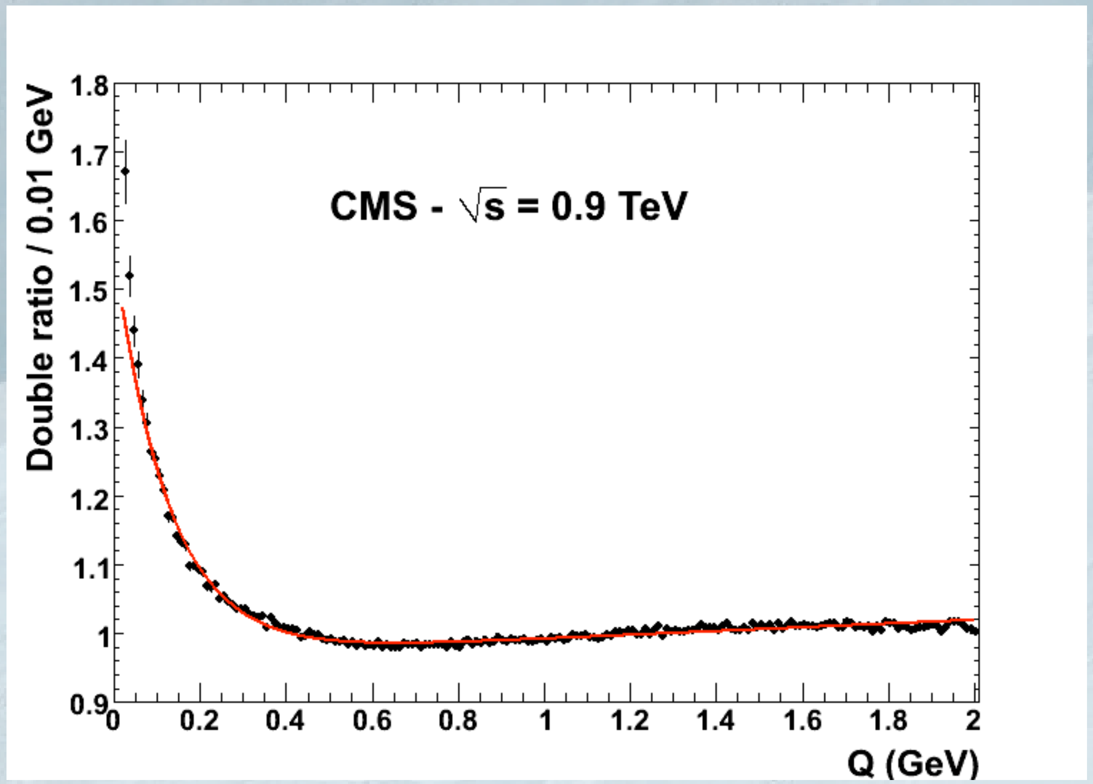


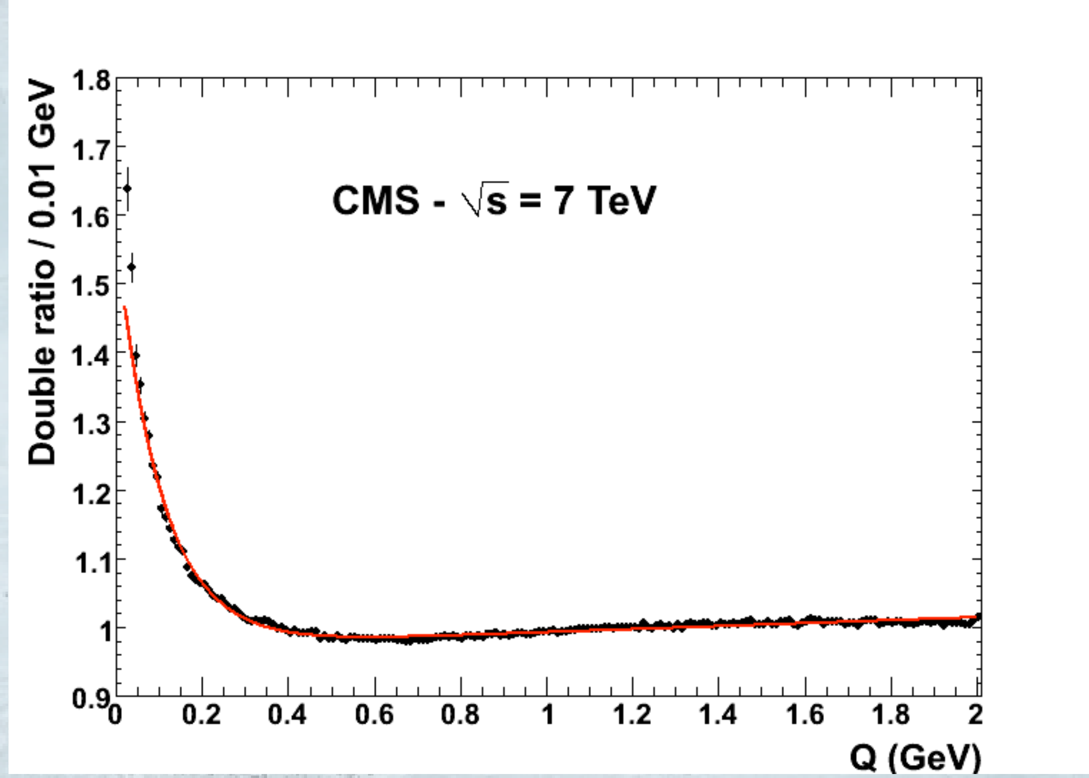




Bose Einstein Correlations

- Determine dN/dQ ($Q^2 = (p_1 - p_2)^2$) for all pairs of like-sign charged particles in each event.
- Do same for un-correlated particles (mixed events)
- Take the ratio
- Final state pions are **bosons**, therefore they may originate from the same quantum state (hence require like-signed particles)
- This would show up as an increase as Q->0

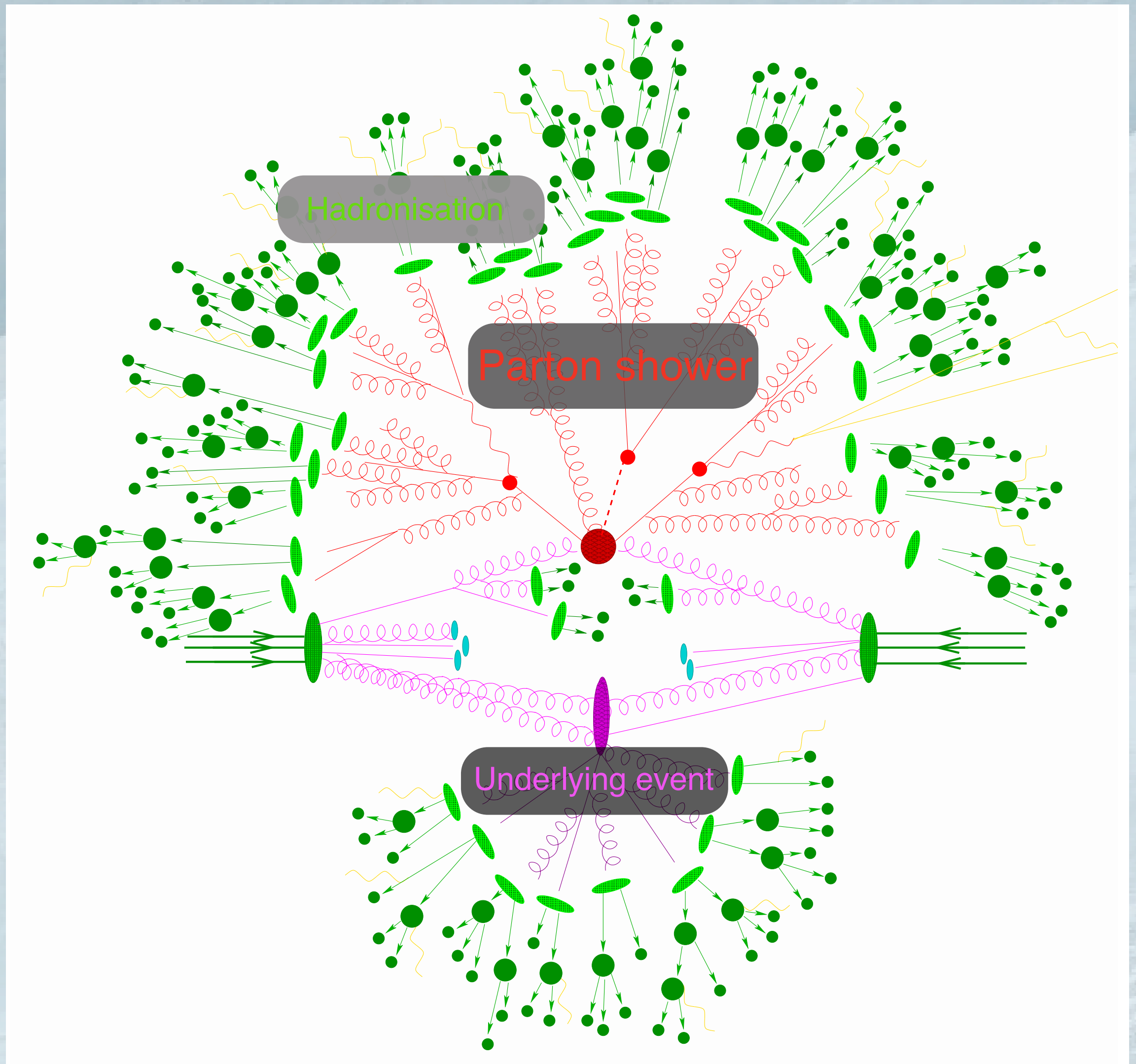




Underlying Event Mearurements

Underlying Event

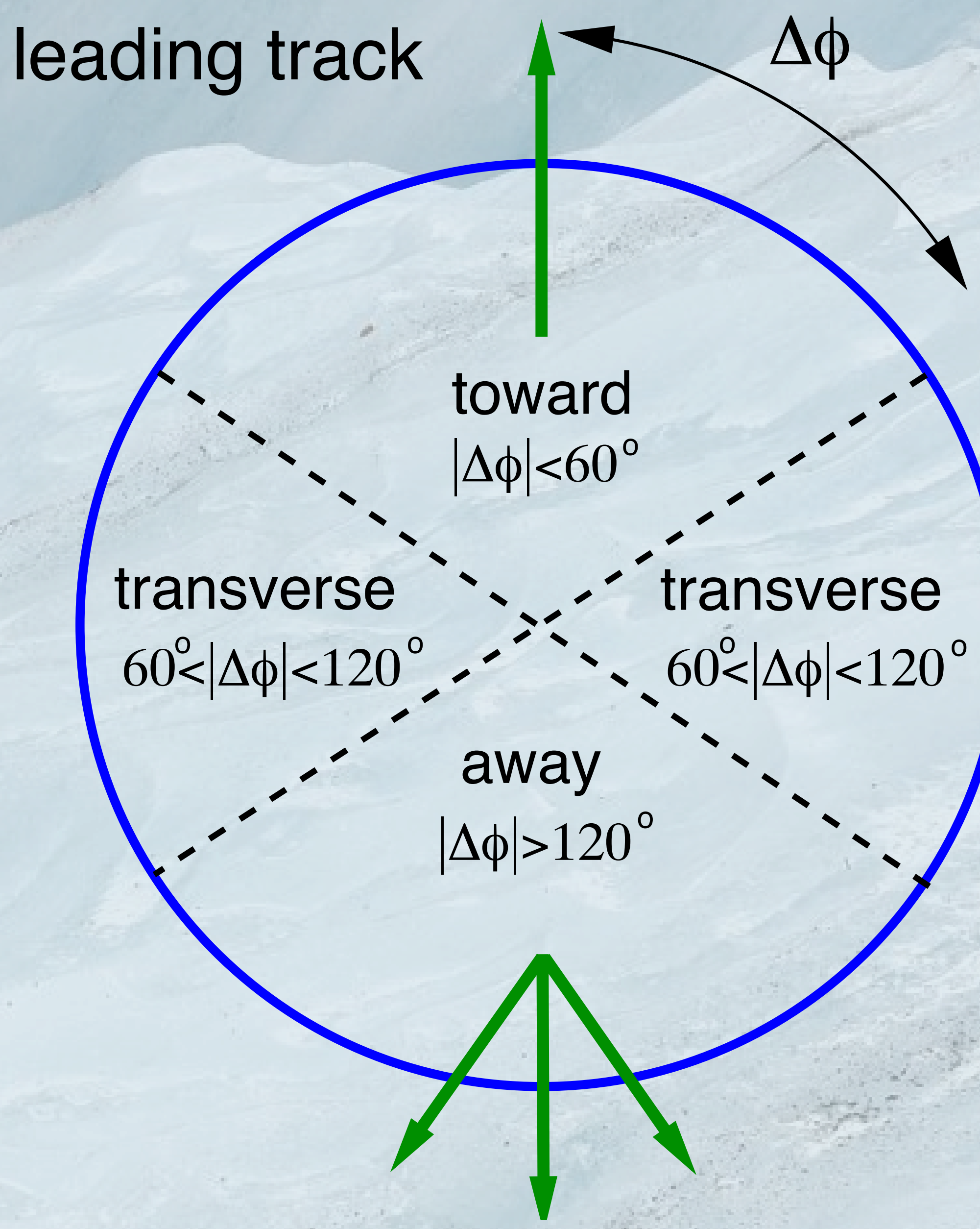
- Underlying event is a **feature** of (Monte Carlo) **models** that describes what happens to the part of the proton that does not participate in the hard scatter
- Secondary soft interactions between the proton remnants
- Important because it can add radiation to your final state, fake your signal, mess up your jets
- Related to, but **not** the same as min bias



- There are a set of observables to which the underlying event models can be compared and their parameters tuned...

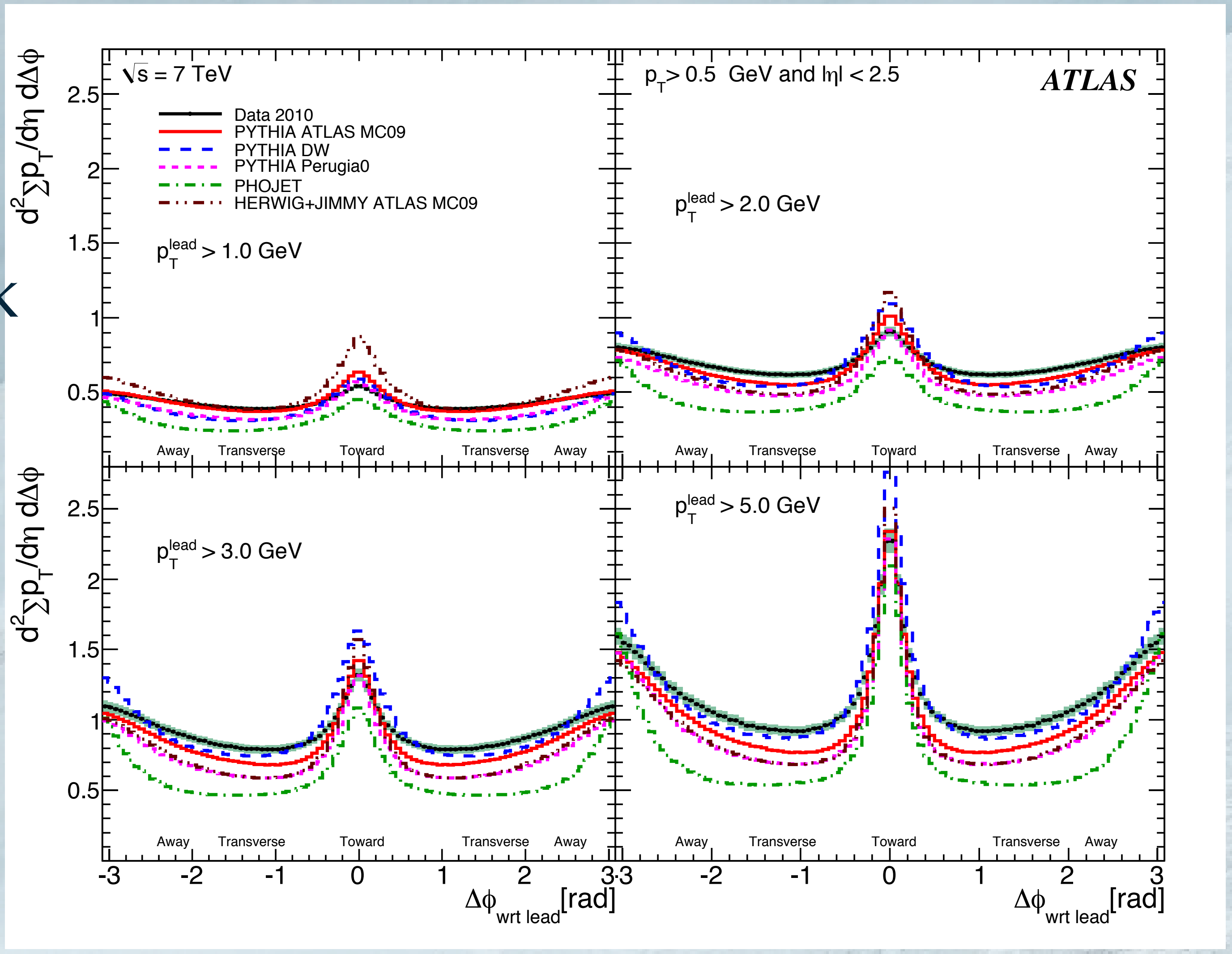
Underlying Event

- Identify leading particle or track or calo-cluster in each event
- Define 3 regions relative to this:
  - Toward: $|\Delta\phi| < 60^\circ$
  - Away: $|\Delta\phi| > 120^\circ$
  - Transverse: $60^\circ < |\Delta\phi| < 120^\circ$
- Determine pT sum, multiplicity, av. pT of tracks and other observables in each region



Underlying event

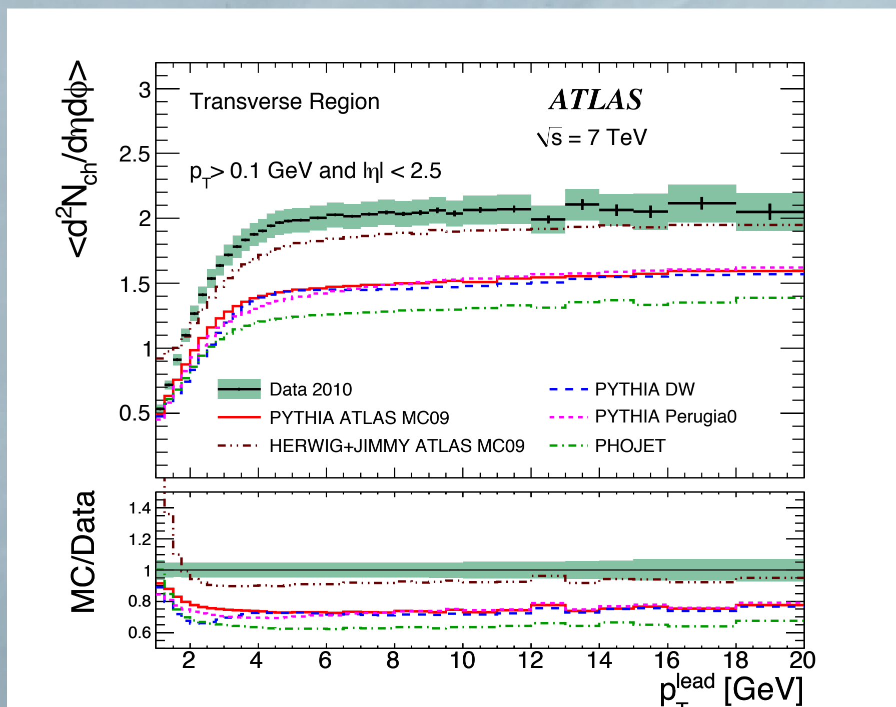
- Shows Δϕ distribution of pT from leading track
- Spike at Δϕ = 0->radiation correlated to the leading track
- Increase as Δϕ-> π corresponds to recoil radiation
- This structure gets more obvious as lead pT increases (emergence of jets)
- Note the dip in between (the transverse region)

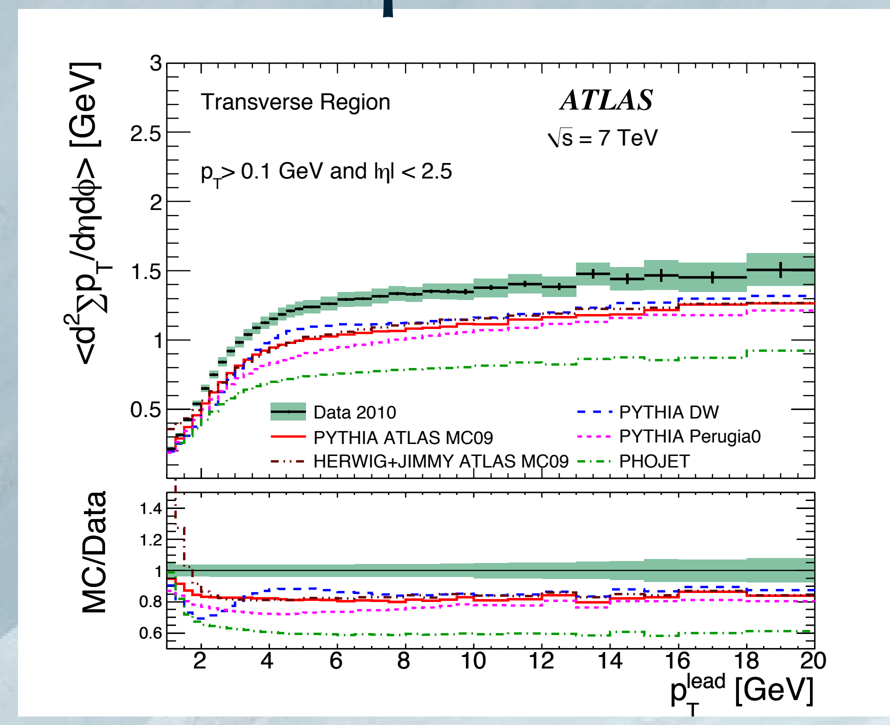


Transverse Region

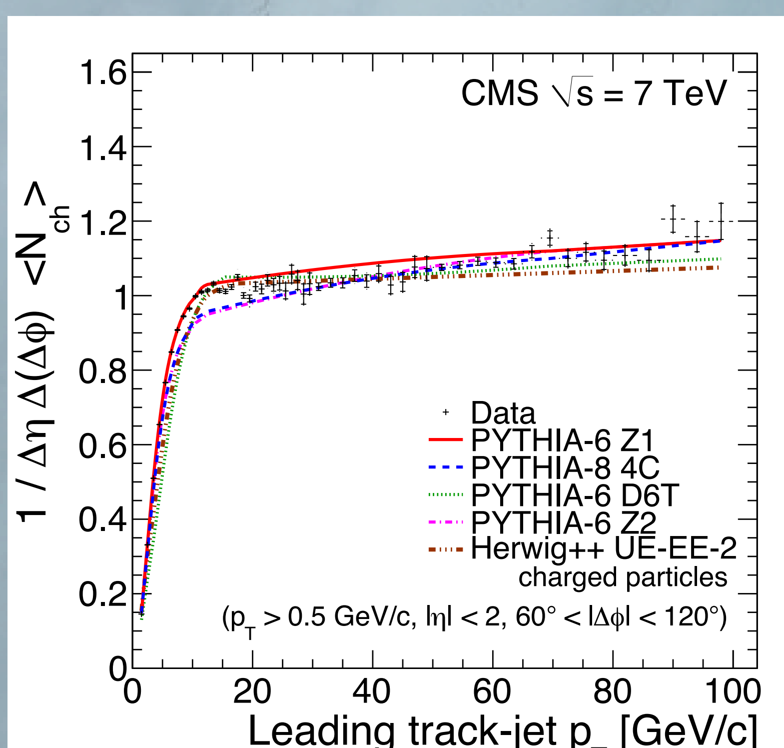
Av. Multiplicity

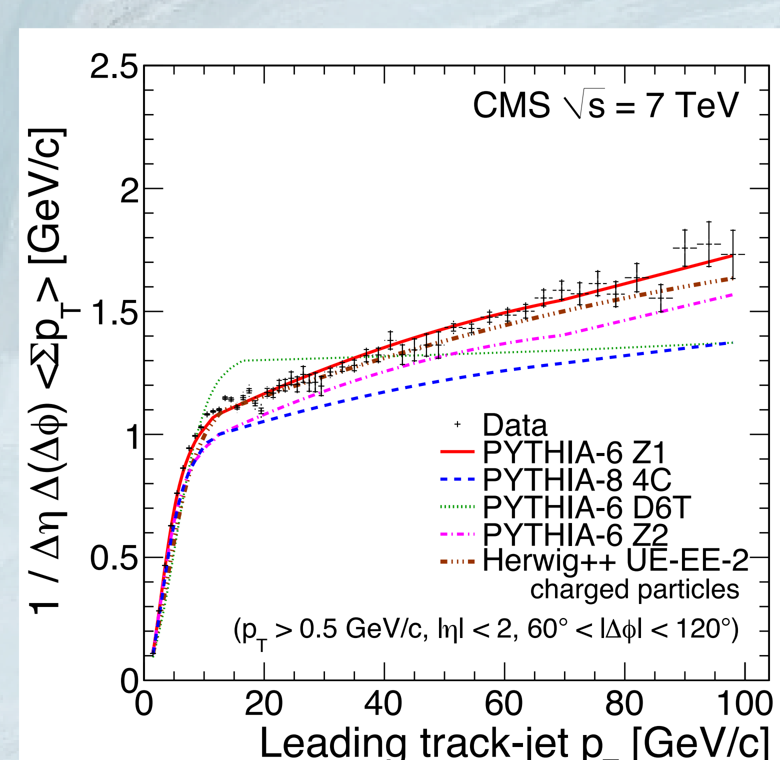
Av. pT sum





Lead Track



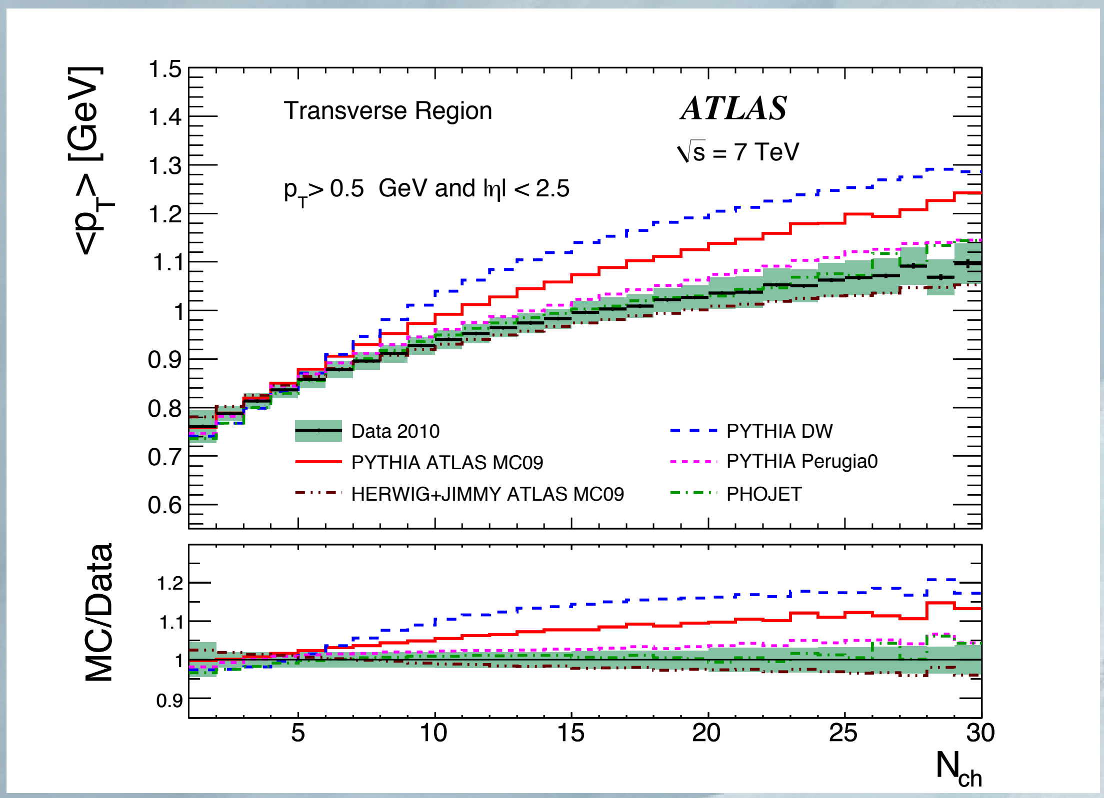


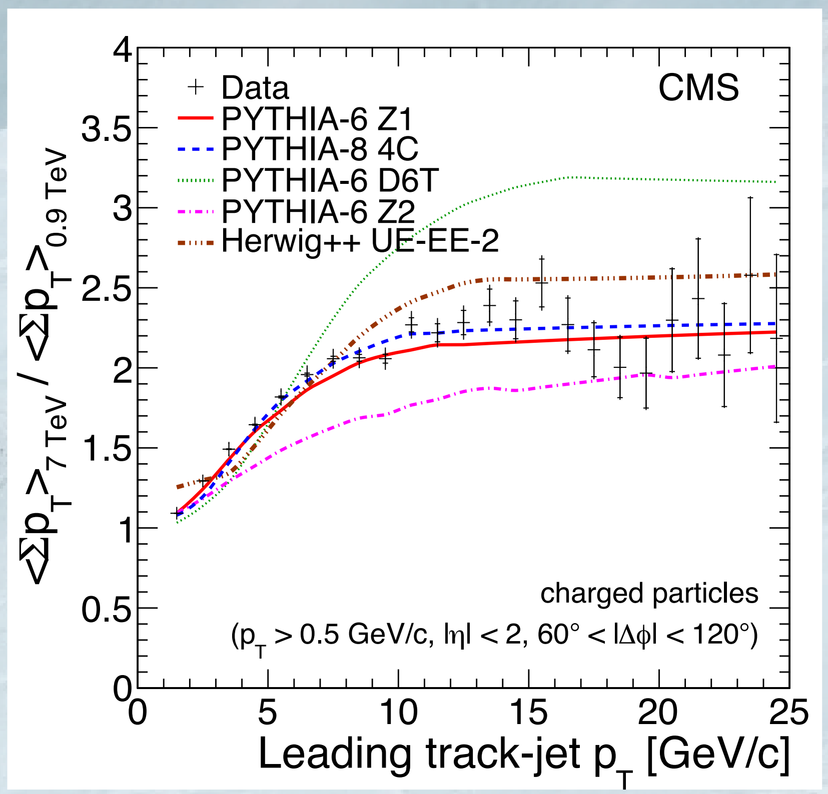
Lead Track Jet

(difference to lead track shows in different x axis scale)

Transverse Region

Av. pT per particle

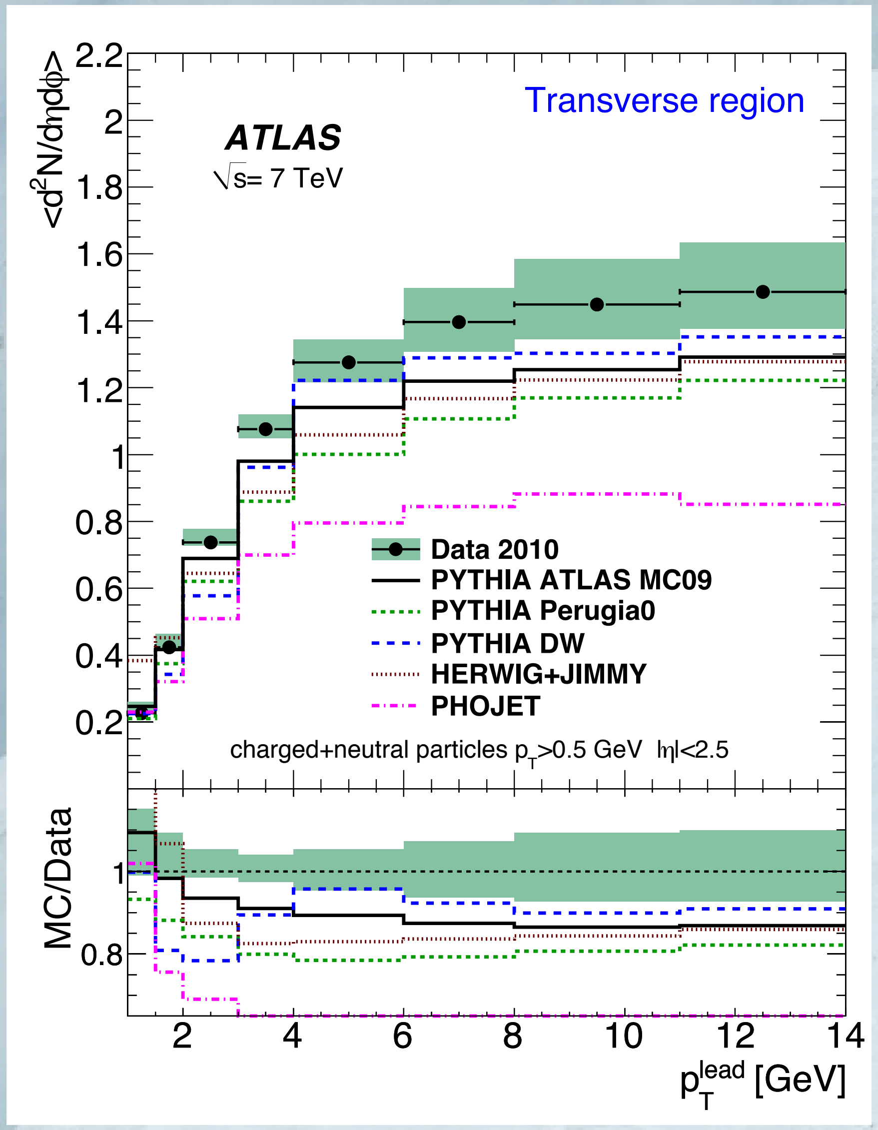


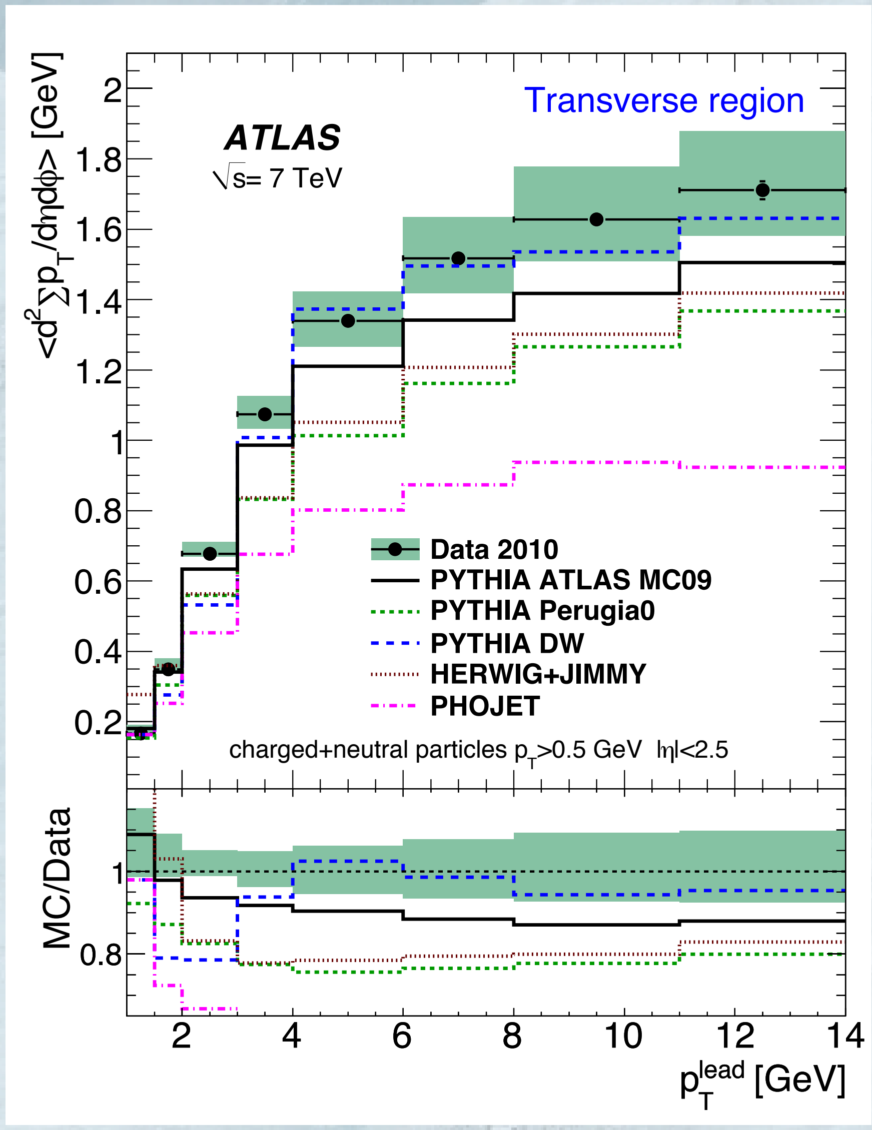


- Pythia overshoots <pT>, Herwig undershoots (a bit)
- Ratio of pT sum at 900GeV: 7 TeV. Shows energy evolution of the underlying event

Neutral particles

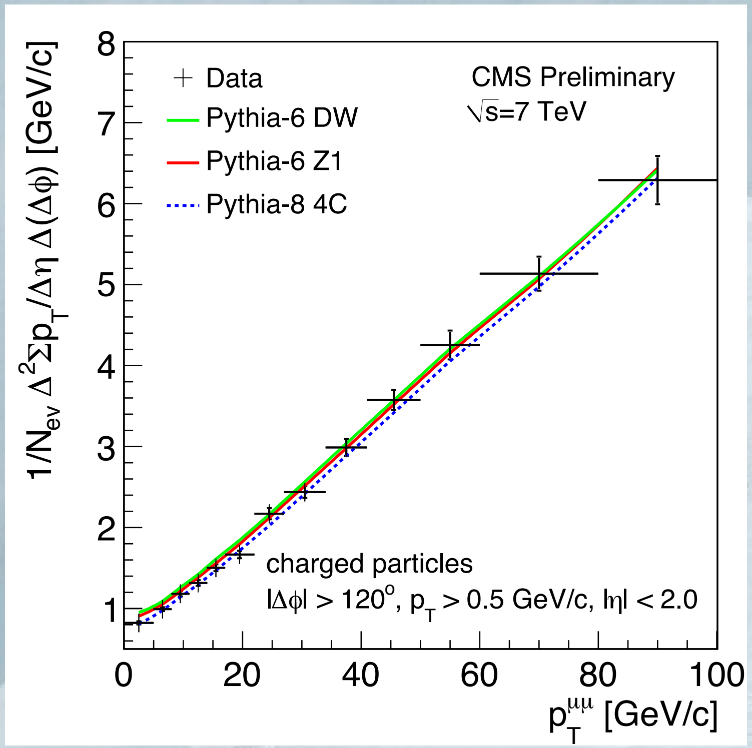
- ATLAS has performed the same measurement using neutral particles in the calorimeter together with tracks for charged particles



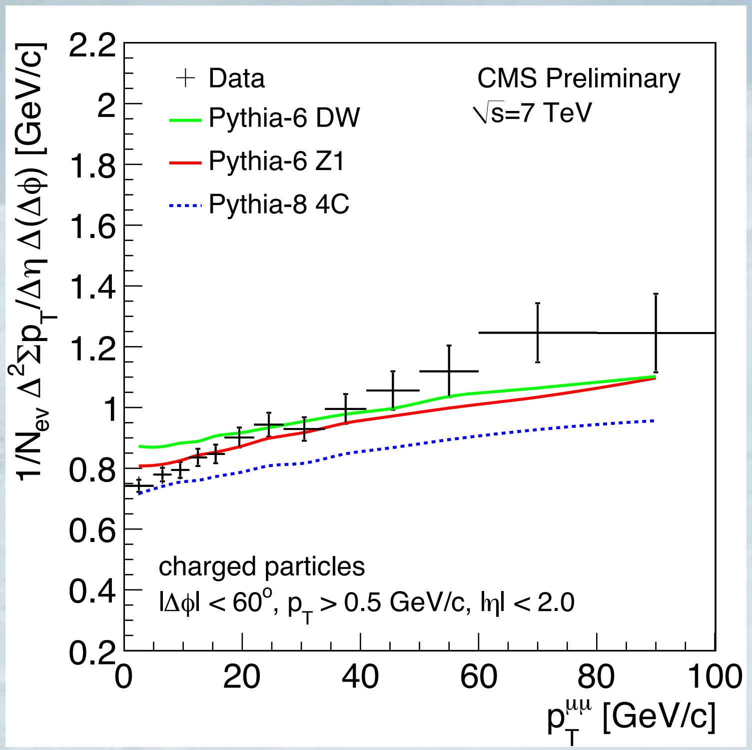


Drell Yan

- CMS have a preliminary measurement of UE in Drell-Yan μμ production.
- Here the direction of the di-μ system is the towards region and is most sensitive to the underlying event (because an electro-weak interaction is responsible for the μ)



Away



Towards

Conclusion

- The first year of data from the LHC has lead to a panoply of new soft physics results
- These valuable results have already fed into Monte Carlo tuning efforts, and will continue to do so
- Could only show a small selection here
- More coming in the future...