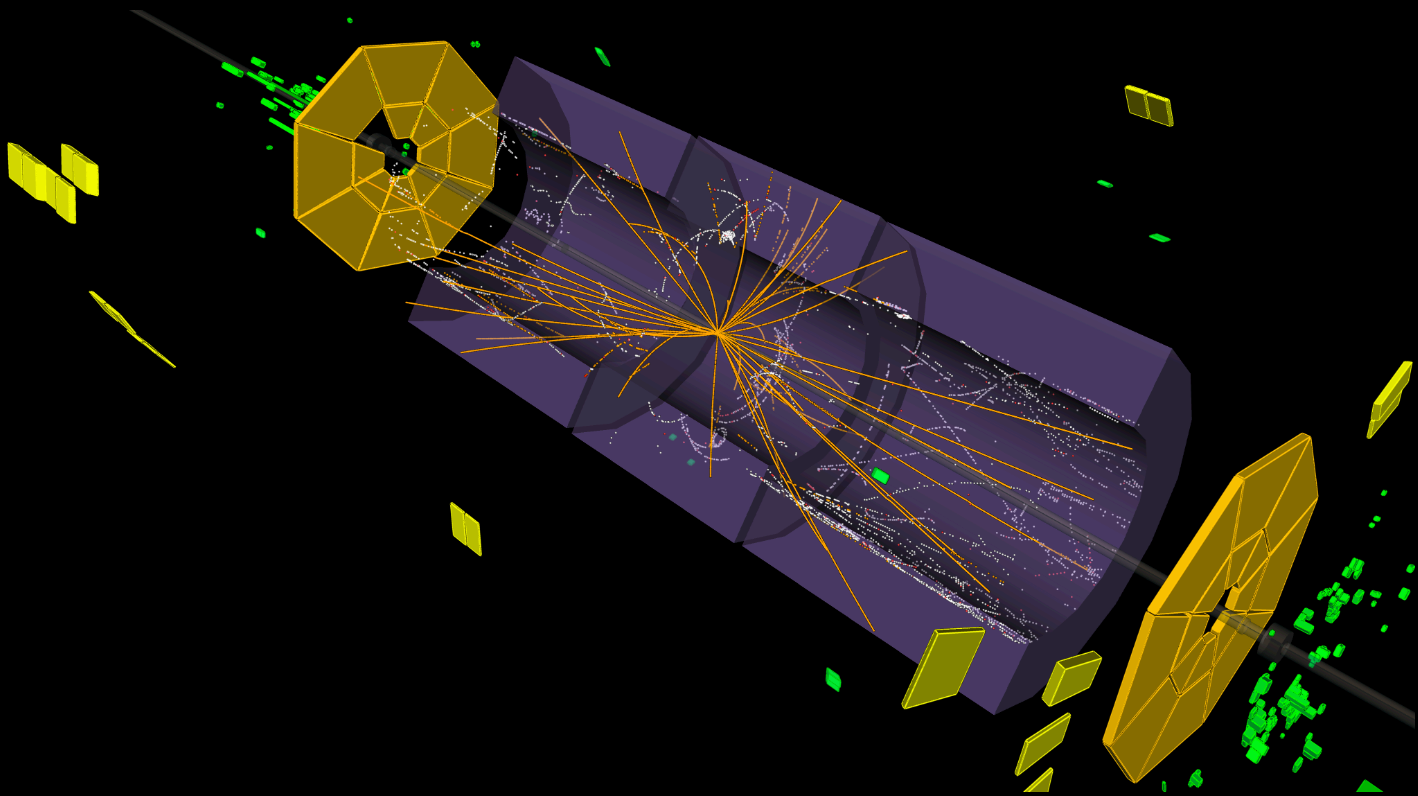
Soft-QCD at Hadron Colliders

1st November 2011

Emily Nurse

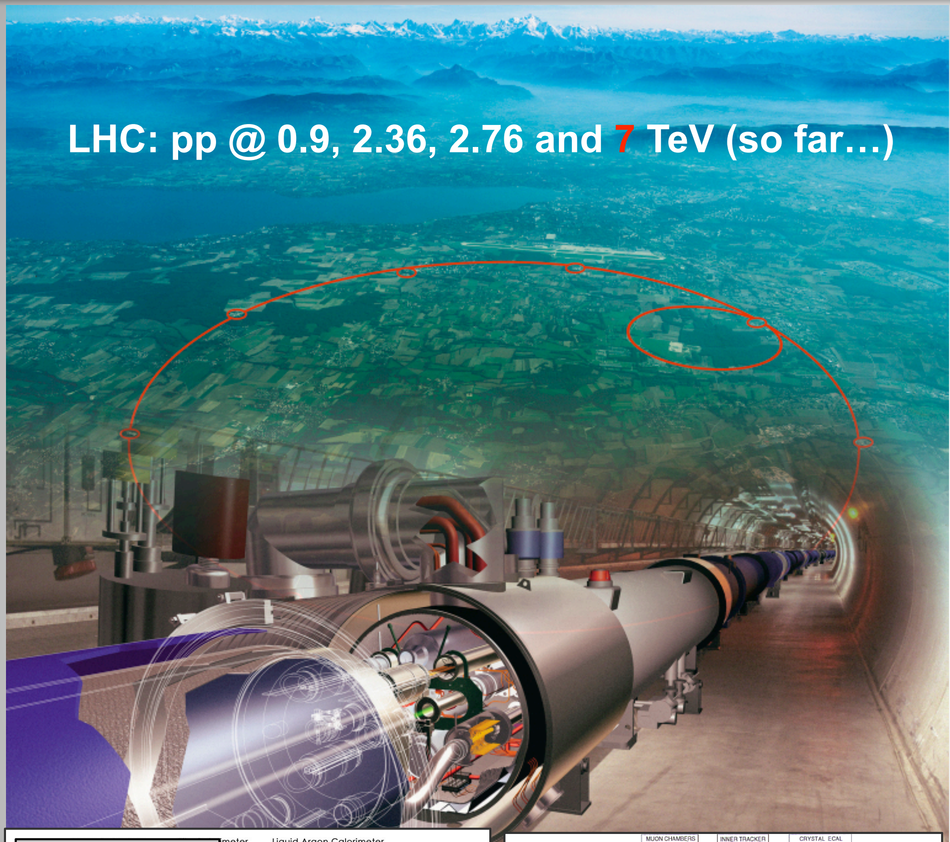


Outline

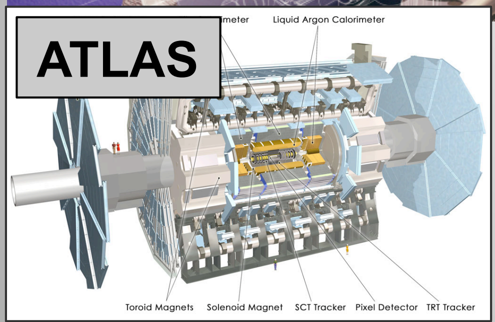
- Hadron Colliders (quick recap)
- What is soft-QCD? Why do we care?
- soft-QCD models / Monte Carlo Event Generators
- A selection of soft-QCD measurements

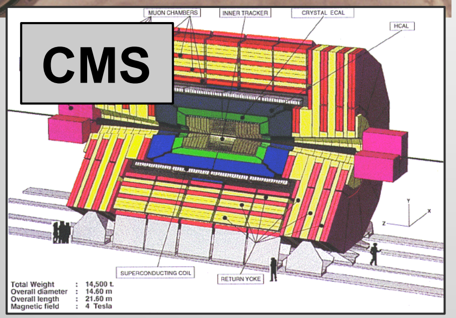
Hadron colliders : recap

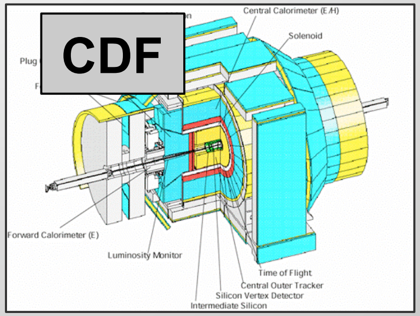
LHC: pp @ 0.9, 2.36, 2.76 and 7 TeV (so far…)

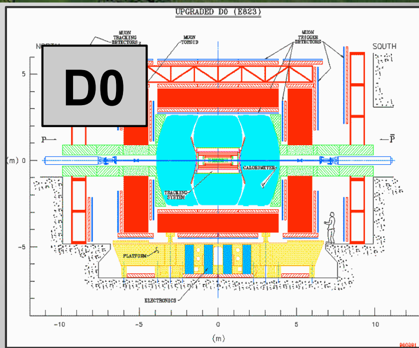


Tevatron: $p\bar{p}$ @ 0.3, 0.63, 0.546, 0.9, 1.8 and 1.96 TeV









What is soft-QCD?

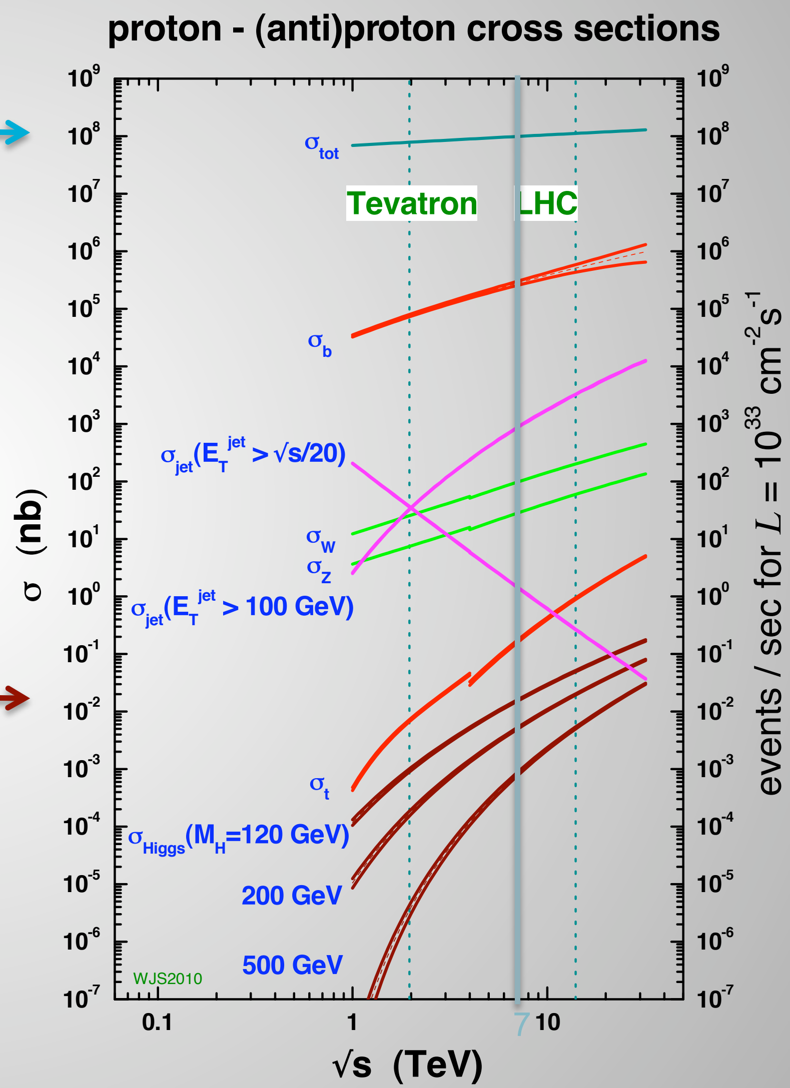
- QCD = Quantum ChromoDynamics (i.e. the strong force)
- *soft* = low momentum transfer
- These are the dominant types of interaction at hadron colliders

What is soft-QCD?

cross-section for any interaction (dominated by soft-QCD)

cross-section for Higgs production

At the LHC only 1 in every ~10 billion interactions would produce a Higgs (if it exists at all…)

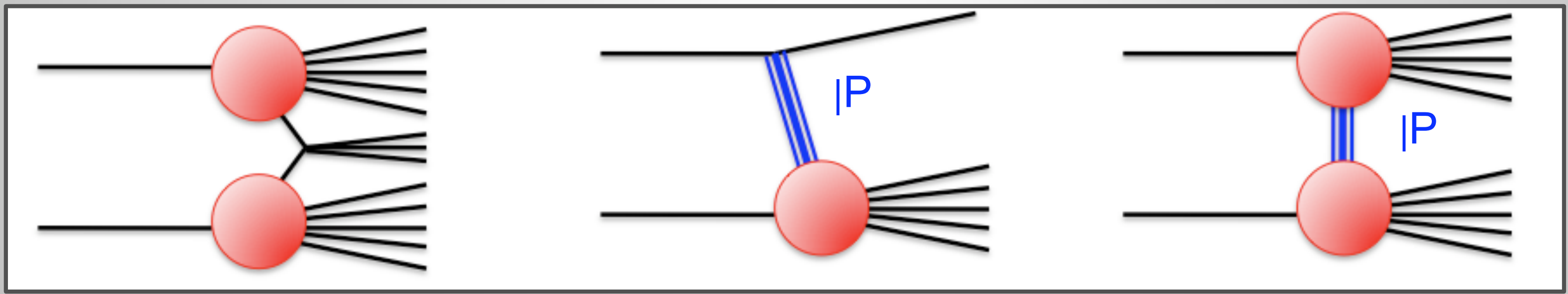


What is soft-QCD?

Elastic interaction: $A(p_A) + B(p_B) \rightarrow A(p_A') + B(p_B')$

Inelastic interaction: $A + B \rightarrow \Sigma x_i \, (\neq A + B)$

Dominant processes in inelastic hadron-hadron interactions :



Non-Diffractive (ND) σ~49 mb

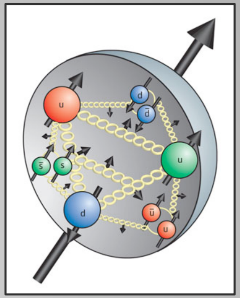
Single-Diffractive-Dissociation (SD) σ~14 mb

Double-Diffractive-Dissociation (DD) σ~9 mb

@ 7 TeV

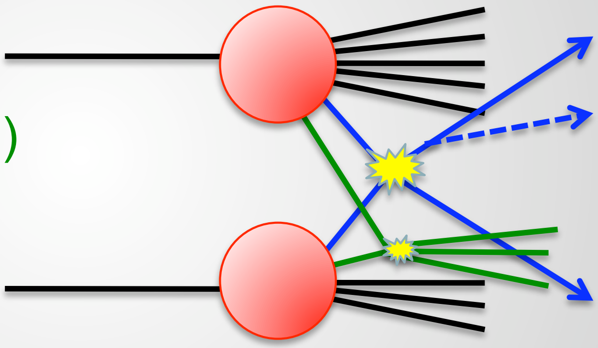
|P = Pomeron (quantum numbers of the vacuum)

What is soft-QCD?



Soft-QCD processes also occur in the same proton-proton interaction as a (more interesting) hard interaction:

Multiple Parton Interactions (MPI)



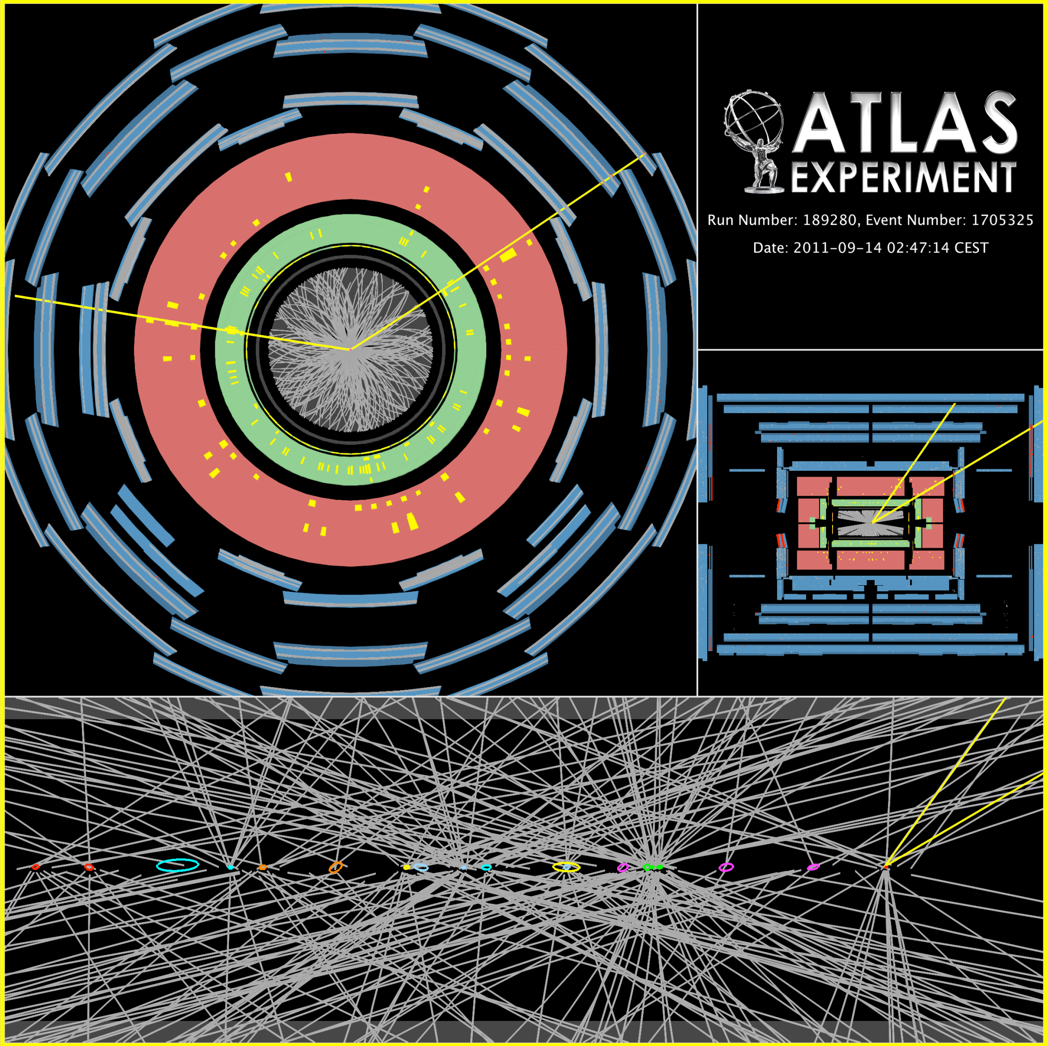
The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

Why do we care ?

- These processes cannot be calculated from first principles (the strong coupling blows up at low scales and perturbative calculations are not possible). What is going on at these scales?
- soft-QCD affecting the high p_T physics program at hadron colliders:
  - Pileup: LHC ~20 proton-proton interactions at the same time, they will almost always be soft-QCD processes
  - Multi Parton Interactions: An interesting parton-parton interaction will have many additional parton-parton interactions occurring in the same proton-proton interaction, they will almost always be soft-QCD processes
  - Therefore we had better have a good model of these processes! Can affect simulations of lepton ID, E_T^{miss} resolution, jets, jet vetos,…

Pileup

Important for understanding 20 pp interactions on top of your Higgs!!



Monte Carlo Event Generators

- See Glen Cowan's course next week for all the details
- In brief:
  - Theoretical tools that simulate events at colliders
  - Extensively used to simulate signal and background processes, to help us understand our data and enable us to make measurements
  - High p_T interactions are calculated using perturbation theory
  - Soft-QCD processes use phenomenological models with theoretical motivation that must be *validated against data*
  - These models contain parameters that must be *tuned to the data*
  - It is therefore necessary to make measurements of soft-QCD processes

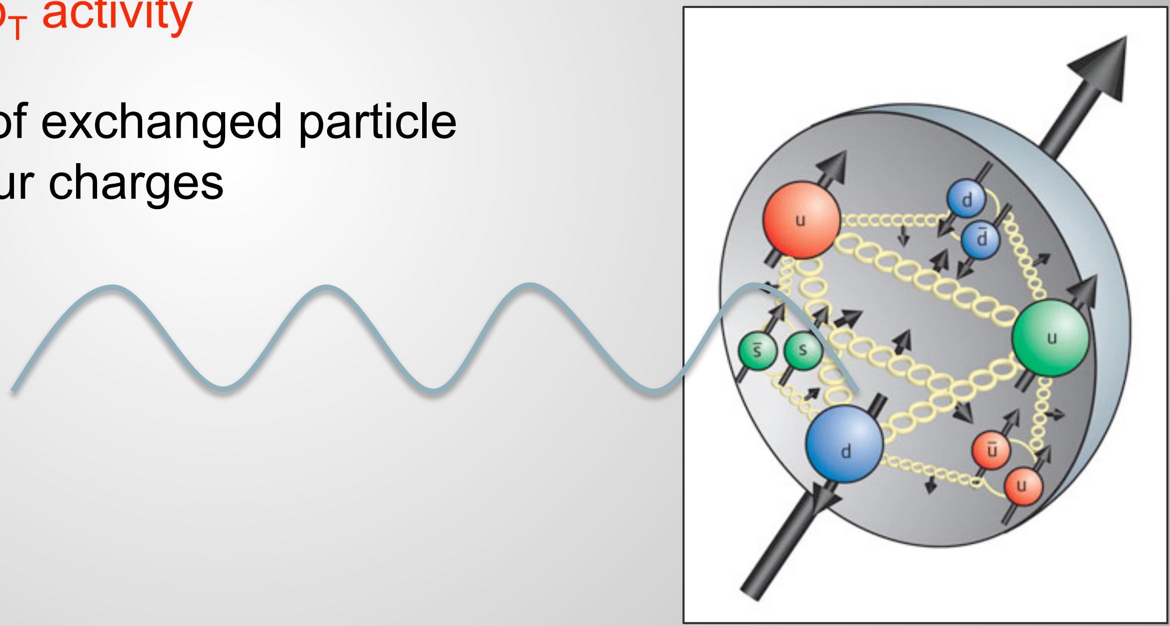
Soft-QCD models

e.g. Pythia

QCD 2→2 scattering	$\sim \alpha_S^2(p_T^2)/p_T^4$
Dampen divergence at low p_T →	$\sim \alpha_S^2(p_T^2 + p_{T0}^2)/(p_T^2 + p_{T0}^2)^2$

smaller p_{T0} → more low p_T activity

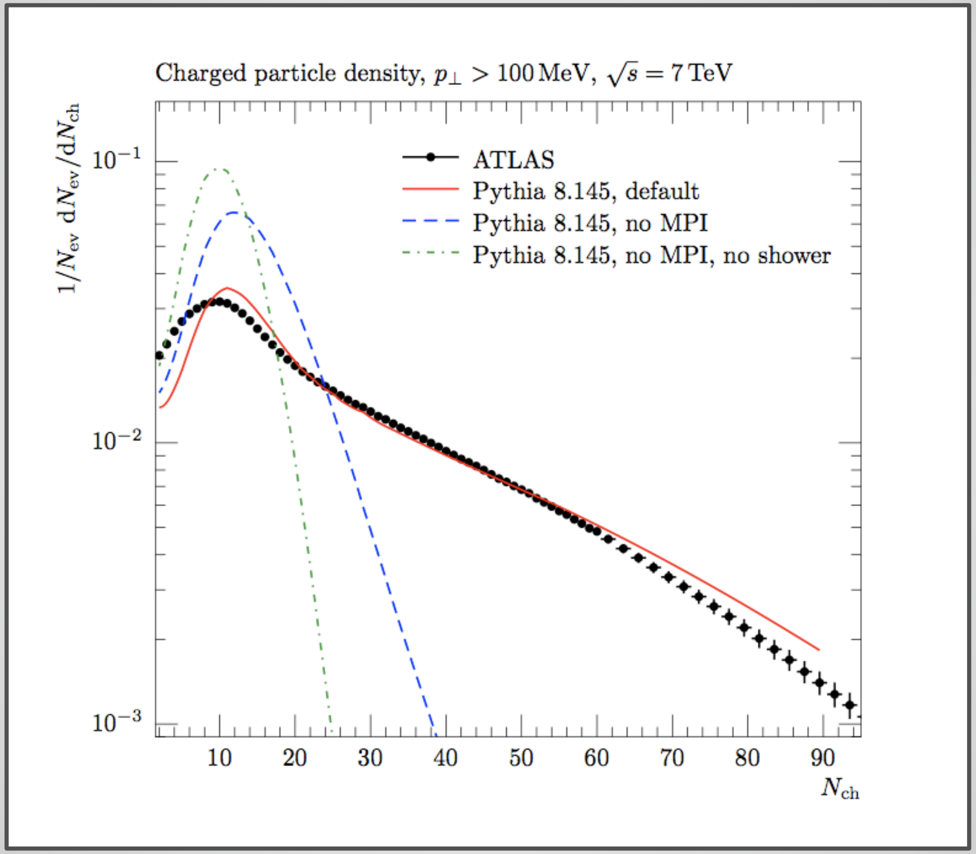
Screening : At low p_T wavelength of exchanged particle becomes too large to resolve colour charges



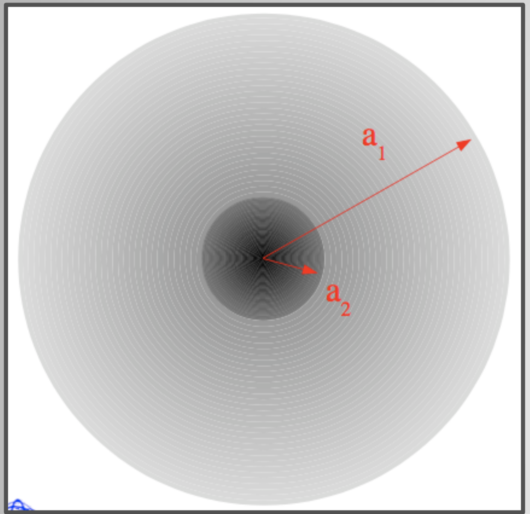
$p_{T0} = P_1 (E_{COM} / 1.8\ \text{TeV})^{P_2}$

Multiple Parton Interactions

The soft-QCD models need to include MPI



Soft-QCD models



Matter distribution in proton described by double Gaussian

P_3 = fraction in core Gaussian
$P_4 = a_2 / a_1$

(denser matter distribution → more multiple interactions → more activity)

Experimental Measurements

1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

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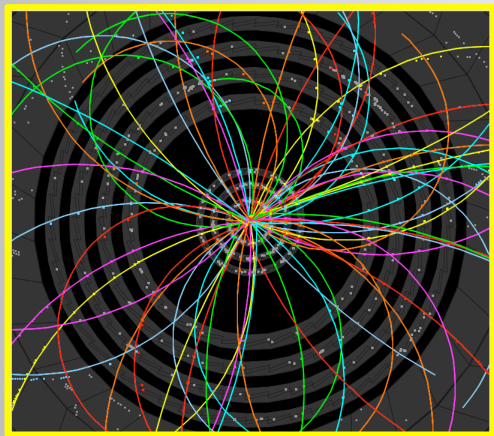
Minimum bias measurements

Minimum bias *adj.* experimental term, to select events with the minimum possible requirements that ensure an inelastic collision occurred.

- Exact definition depends on detector (and analysis)
- Typically measure kinematics (multiplicity, p_T and η spectra, etc) of charged particles in "minimum bias" events using central tracking detectors
- Monte Carlo parameters will be tuned to these distributions



Charged particles moving through a magnetic field will bend by an amount inversely proportional to p_T

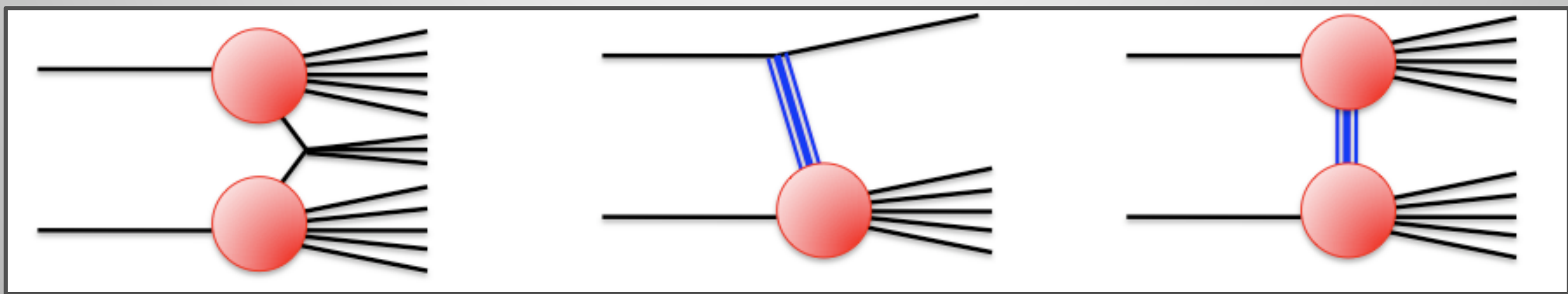
e.g. ATLAS: (a) At least two charged particles with $p_T > 100$ MeV, $|\eta| < 2.5$ (most inclusive)
(b) At least six charged particles with $p_T > 500$ MeV, $|\eta| < 2.5$ (suppresses diffraction)

definition of minimum bias in each analysis

Measurement philosophy

How should you do a measurement that is optimally useful for theory validation and MC tuning?

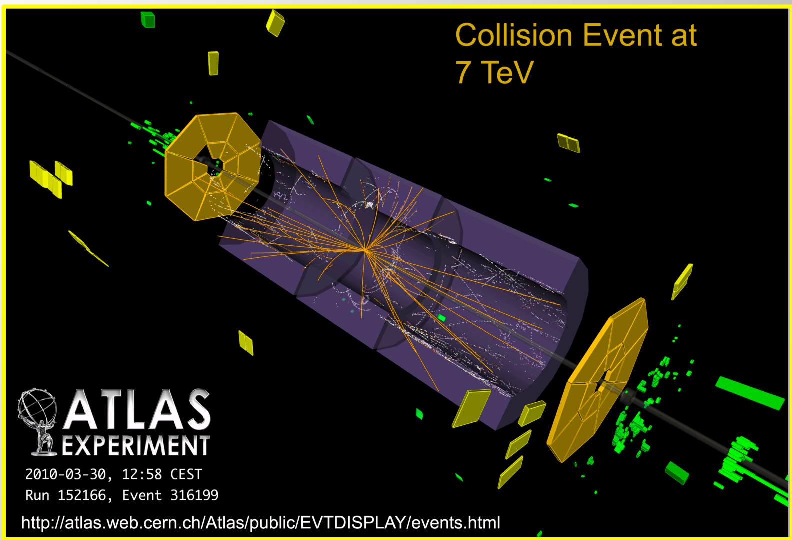
- ✓ Correct measurements for detector inefficiencies and resolutions (e.g. measure p_T spectrum of *charged particles*, not of *ATLAS tracks*)
- ✓ *No extrapolations* into regions not "seen" by ATLAS (such as very low p_T or far-forward particles)
  - We measure what we see, not what the MC tells us we should have seen!
- ✓ No corrections for diffractive events (rather make reproducible cuts that suppress diffraction) ~~Non-Single-Diffractive~~
  - On an event-by-event basis we do not know what process occurred



Triggering the events

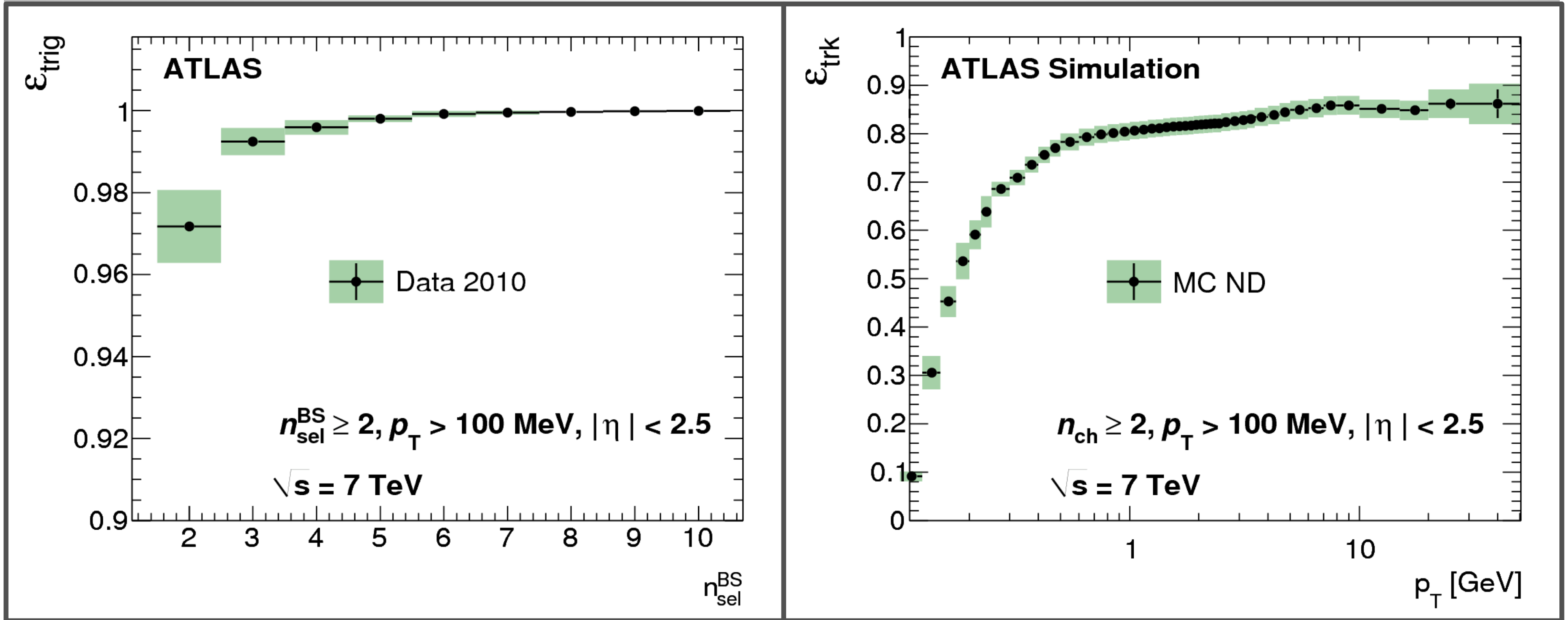
- Measurement performed with early data
- Few interactions per crossing (mean ~ 0.007)
  - ~ No additional interactions
  - But … 99.3% of beam crossings have no interaction!
- Need to “trigger” on inelastic interactions
- Use Minimum Bias Trigger Scintillators (very inclusive)

Minimum Bias Trigger Scintillator disks trigger on any charged particle with $2.09 < |\eta| < 3.84$

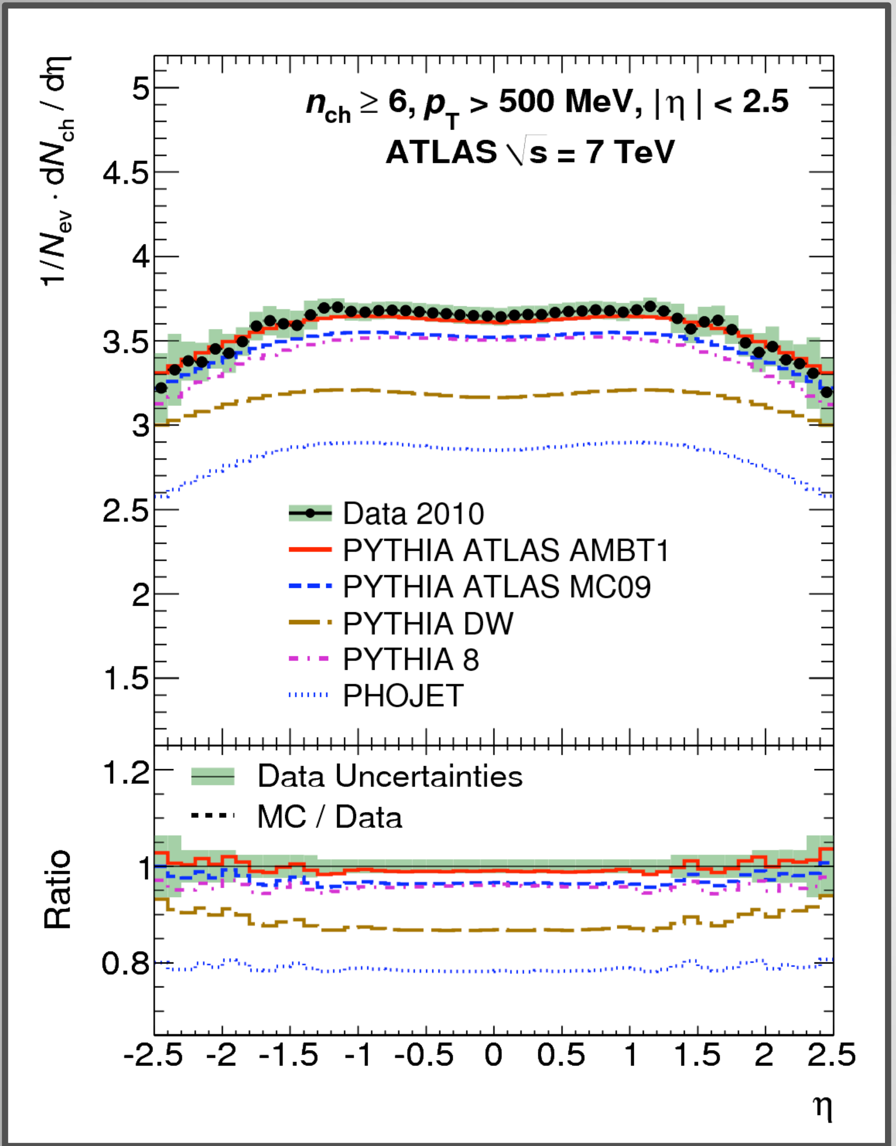


Correcting the data

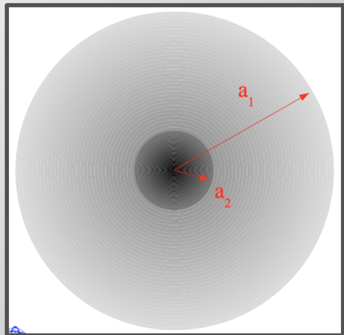
- Trigger efficiency from data (small "control" sample recorded with different trigger)
- Tracking efficiency from Monte Carlo with GEANT detector simulation (systematic uncertainties determined from checks with data)



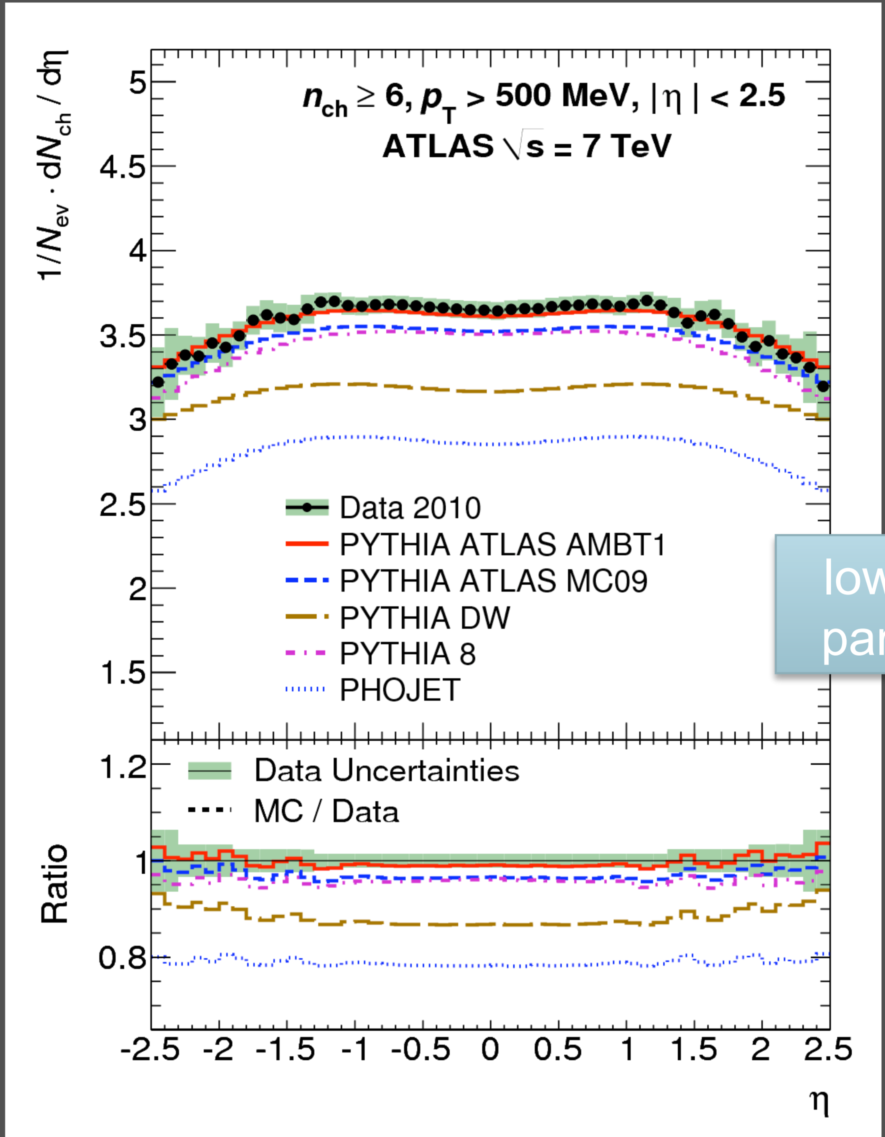
η spectra



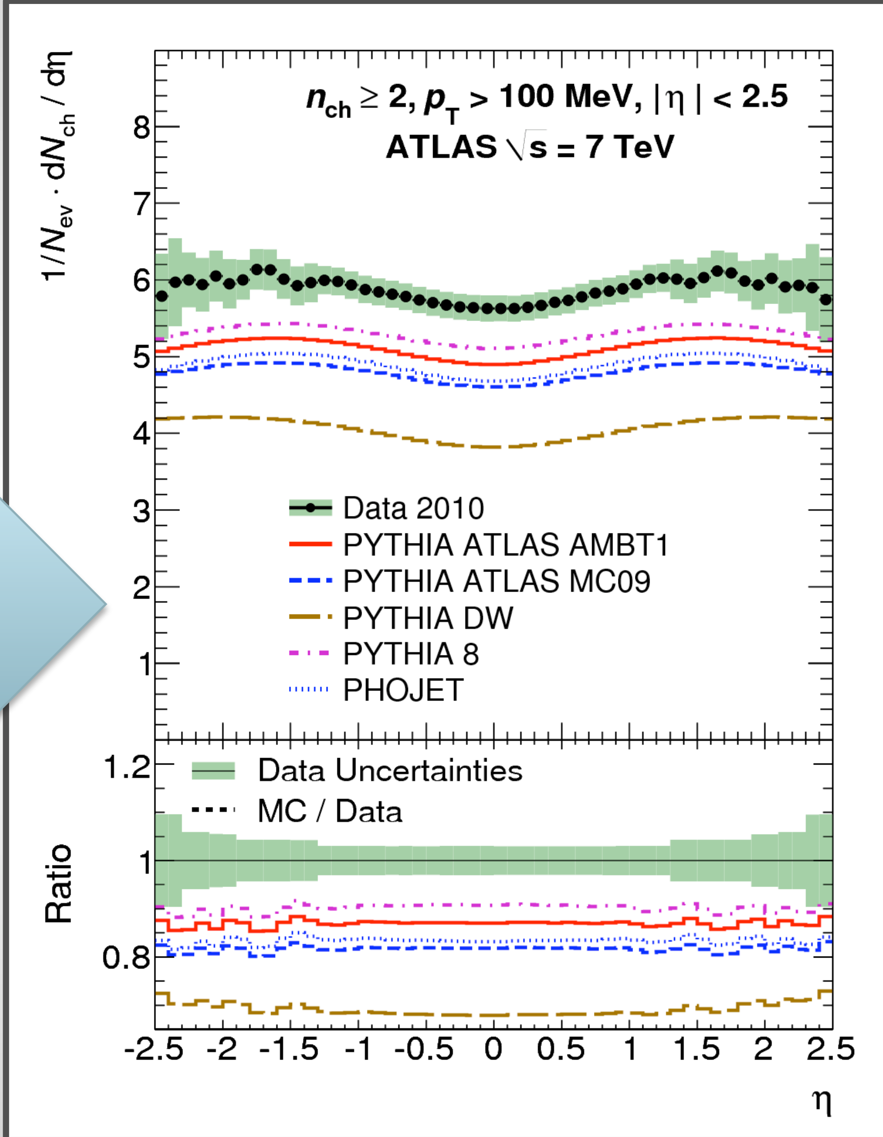
- $dN_{ch}/d\eta$: Number of charged particles per unit η
- All but Pythia AMBT1 are tuned to Tevatron data
- Slight increase in activity in AMBT1 (achieved by a denser proton)



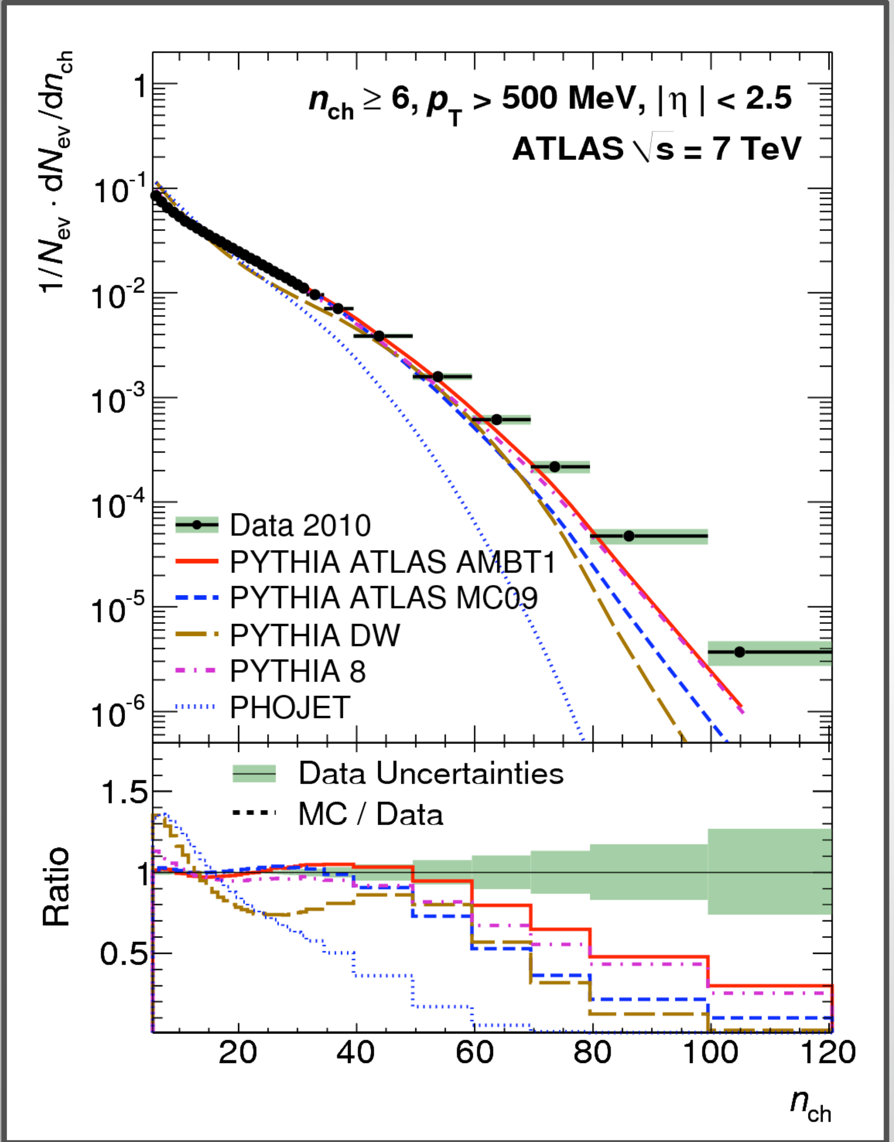
η spectra

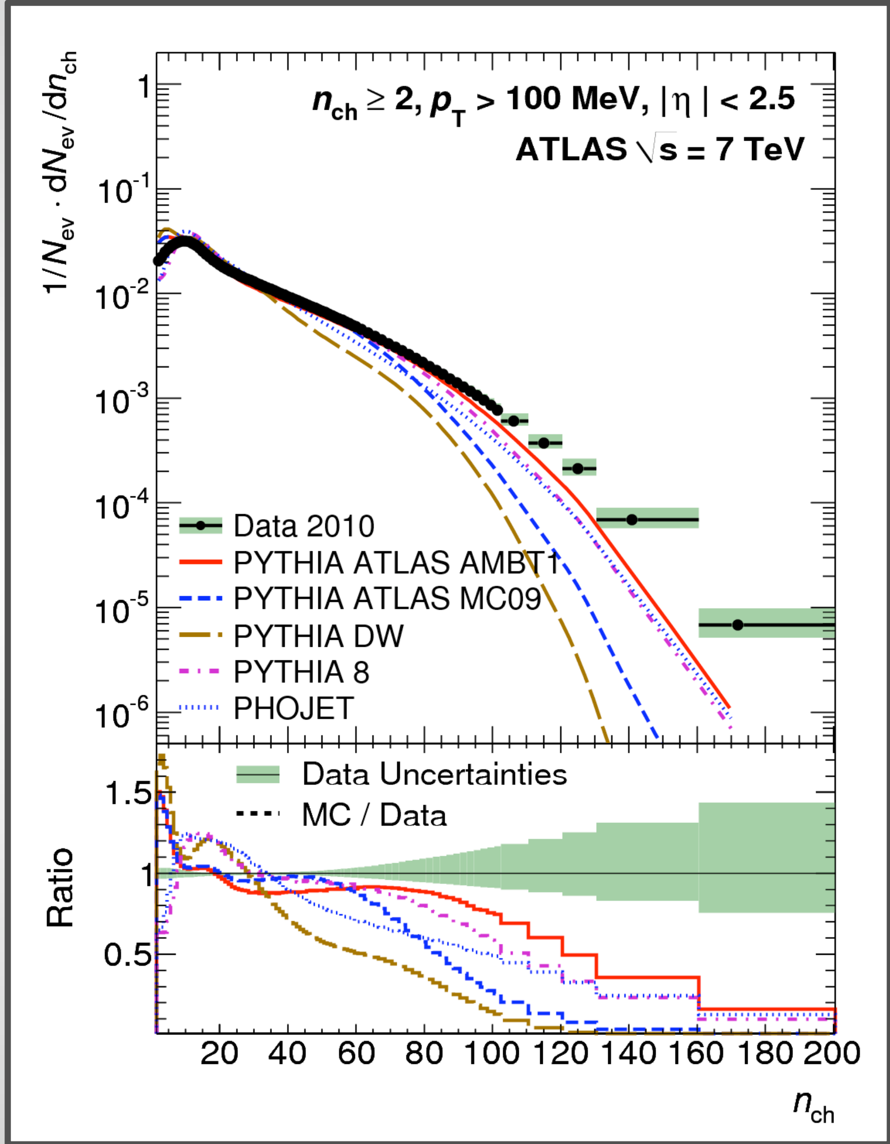


lower p_T particles

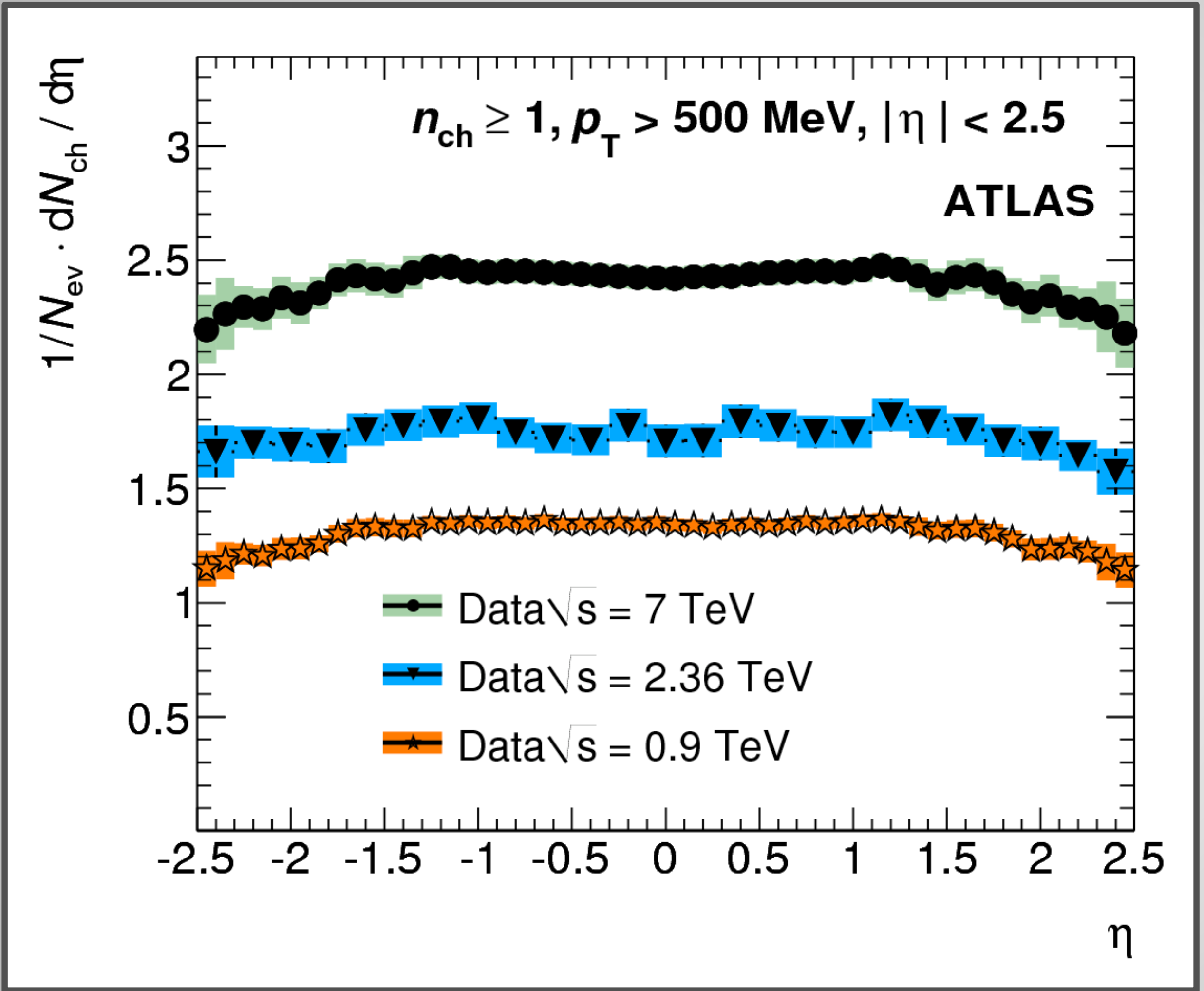


particle multiplicity





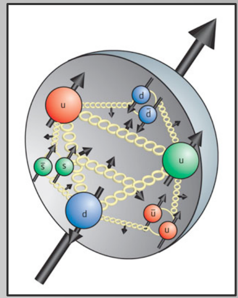
Results at 0.9, 2.36 and 7 TeV



Higher energy → probing more partons

1. Minimum Bias
2. **Underlying Event**
3. Total cross-section
4. Diffractive cross-sections
5. Particle Correlations

Reminder : Underlying Event



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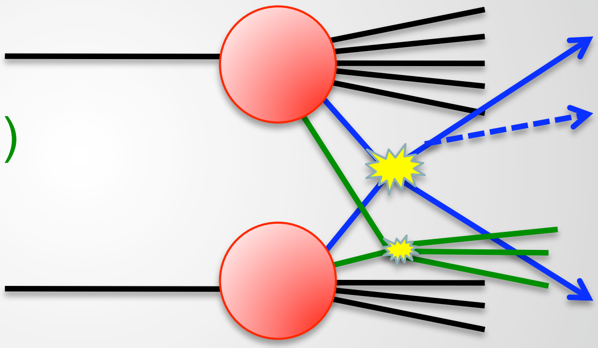
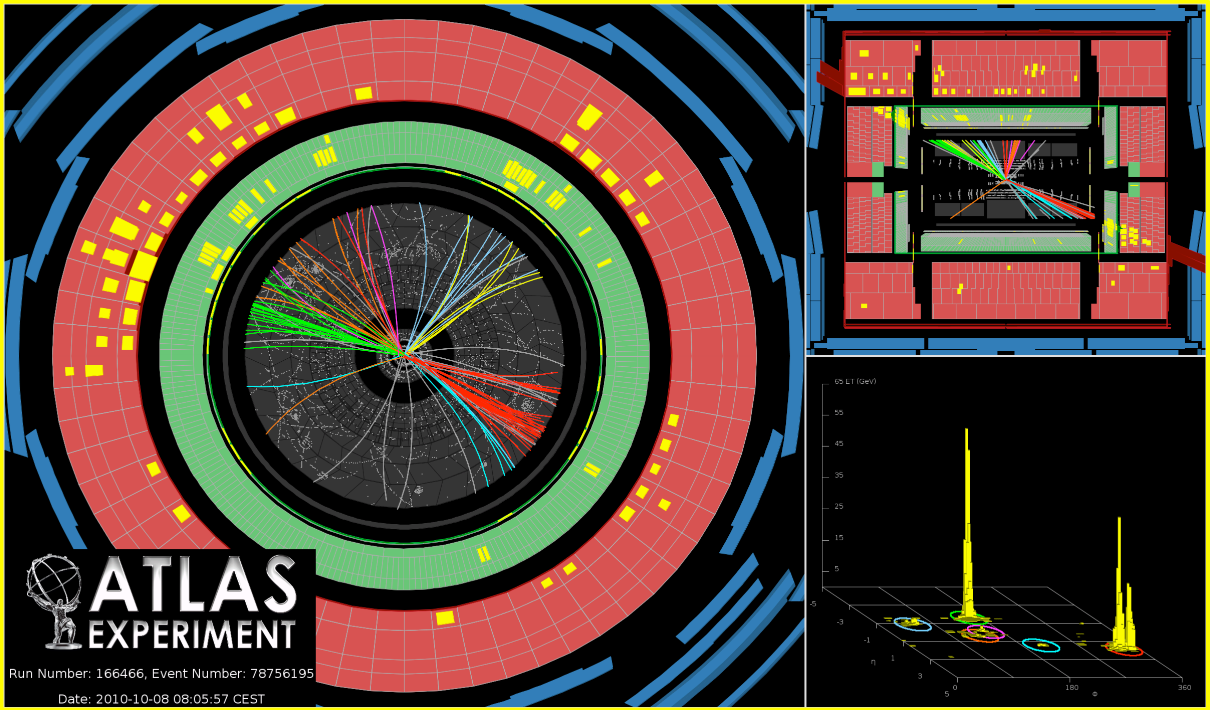
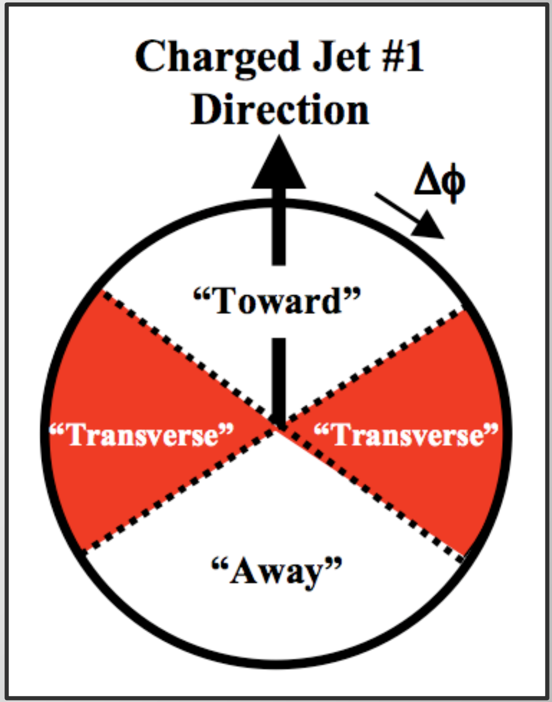


The Underlying Event (UE) is everything not associated with the hard parton-parton interaction

Underlying Event Measurements

- How can we make measurements of the particle activity from the Underlying Event ?
  - Simple technique pioneered by CDF during Tevatron Run I
  - e.g. in di-jets : the activity from the hard parton-parton interaction produces two back-to-back jets (in the transverse plane)





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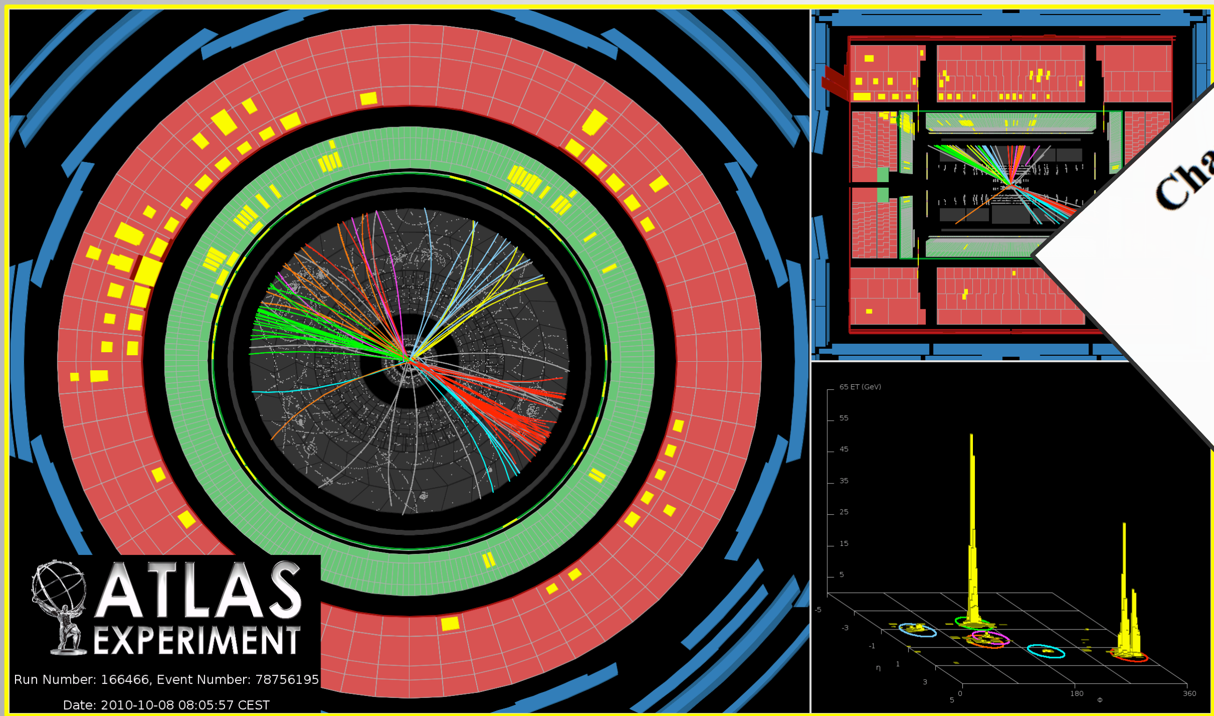
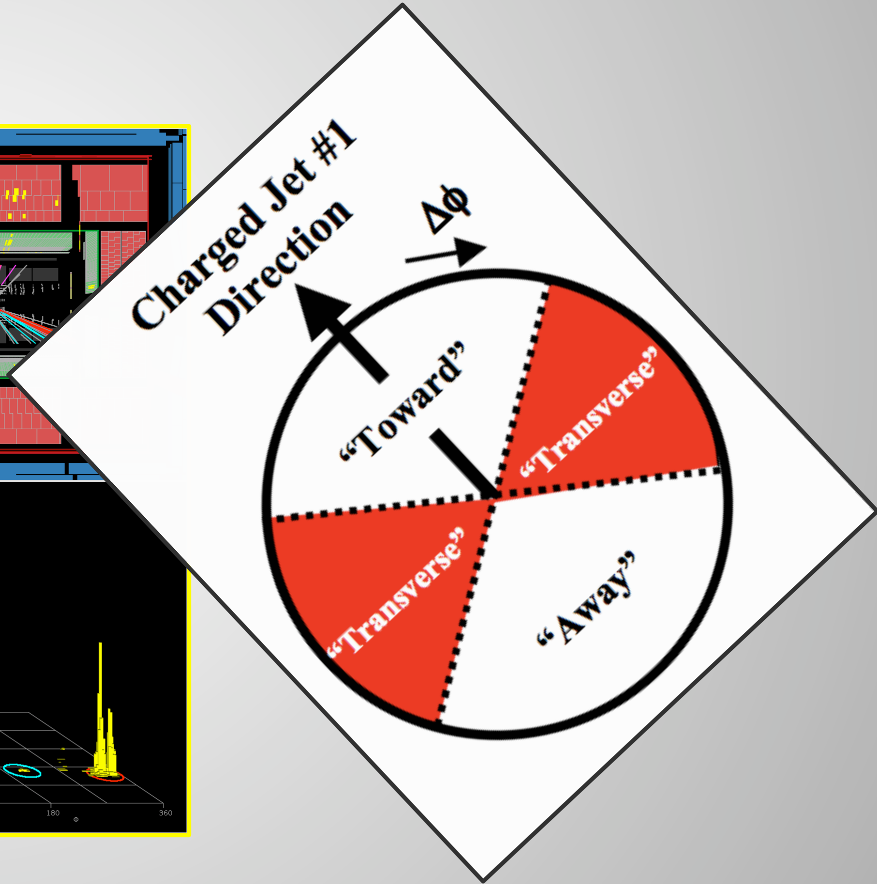
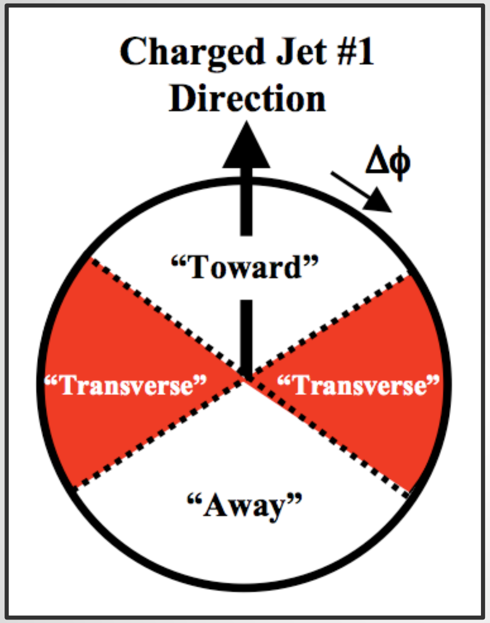
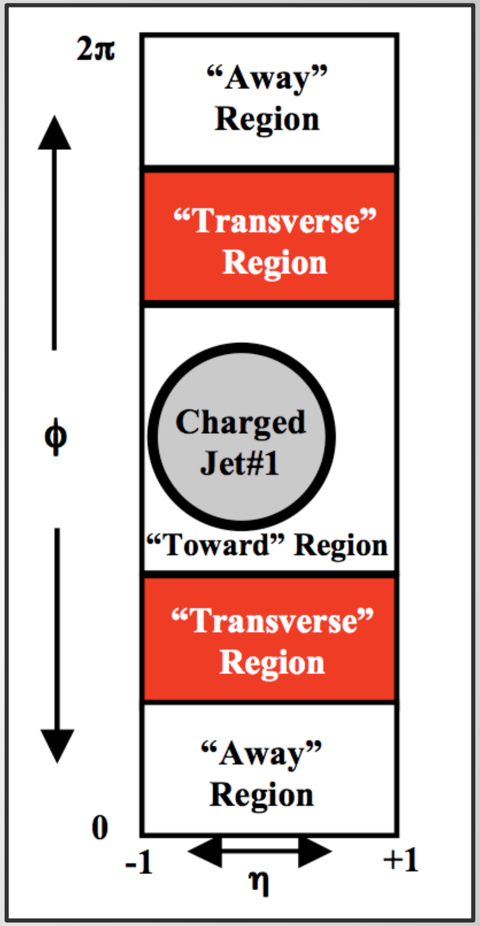




Underlying Event Measurements

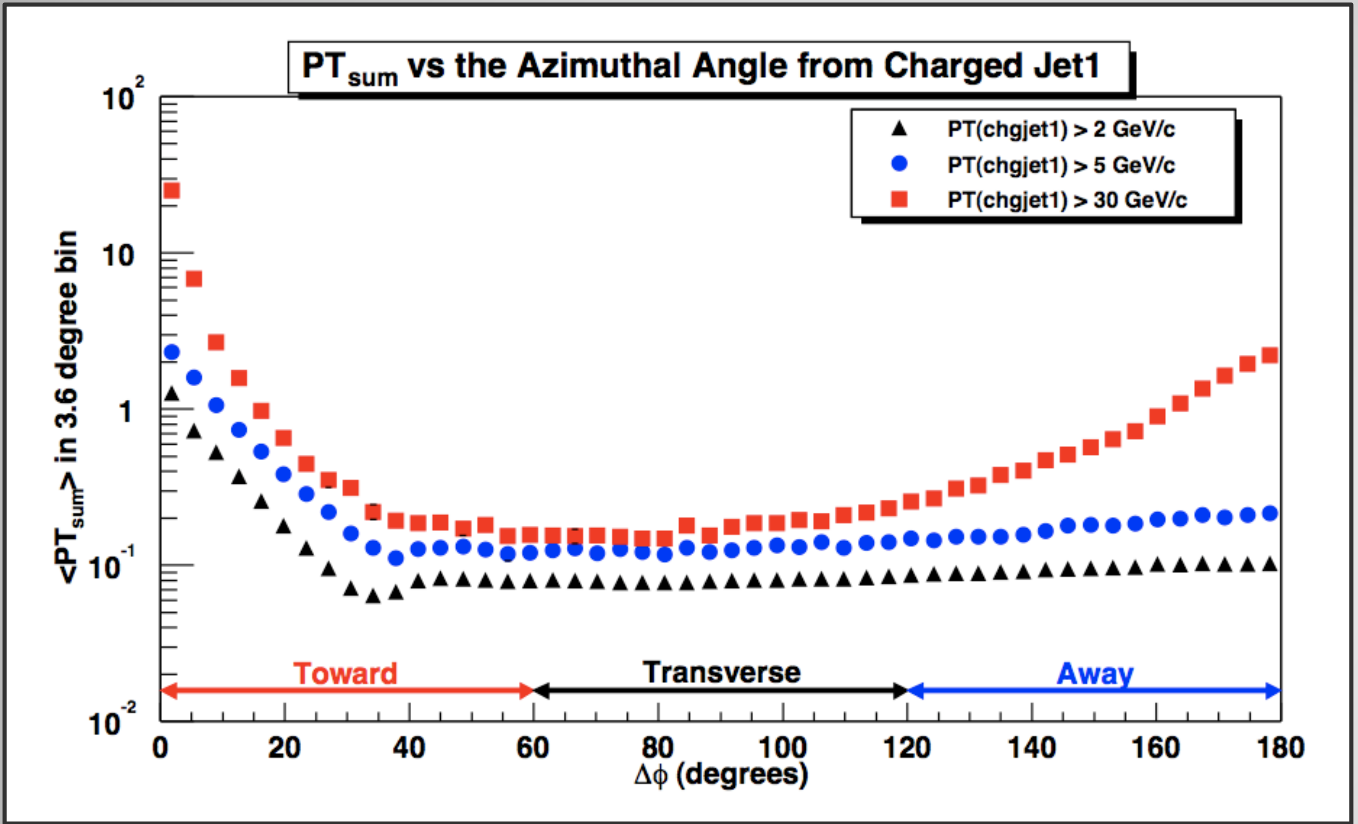
60° < |ΔΦ| < 120°

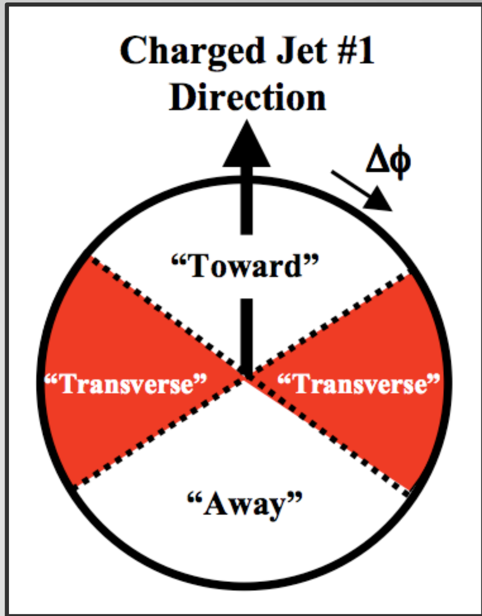




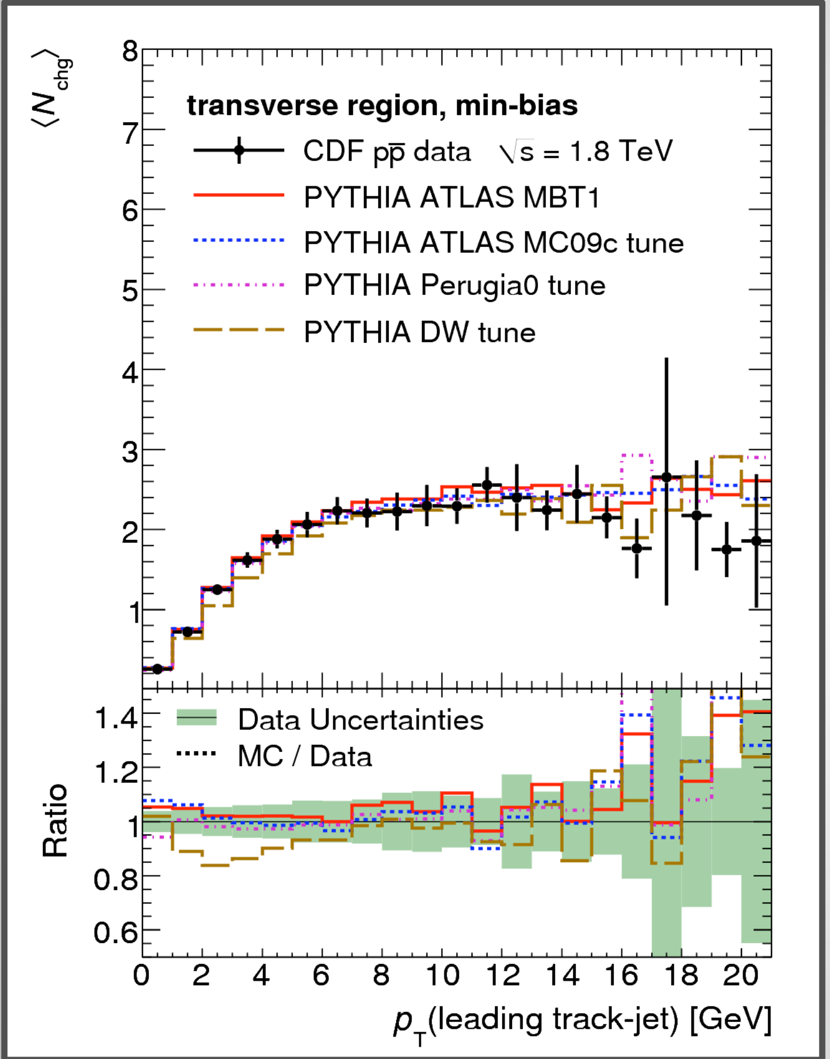
- Define the direction of the "hard scatter" (highest p_T jet /particle)
- Study the activity (# of particles or Σp_T) in the region "transverse" to the hard scatter

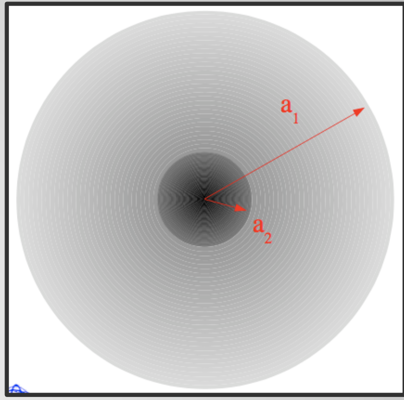
Underlying Event Measurements





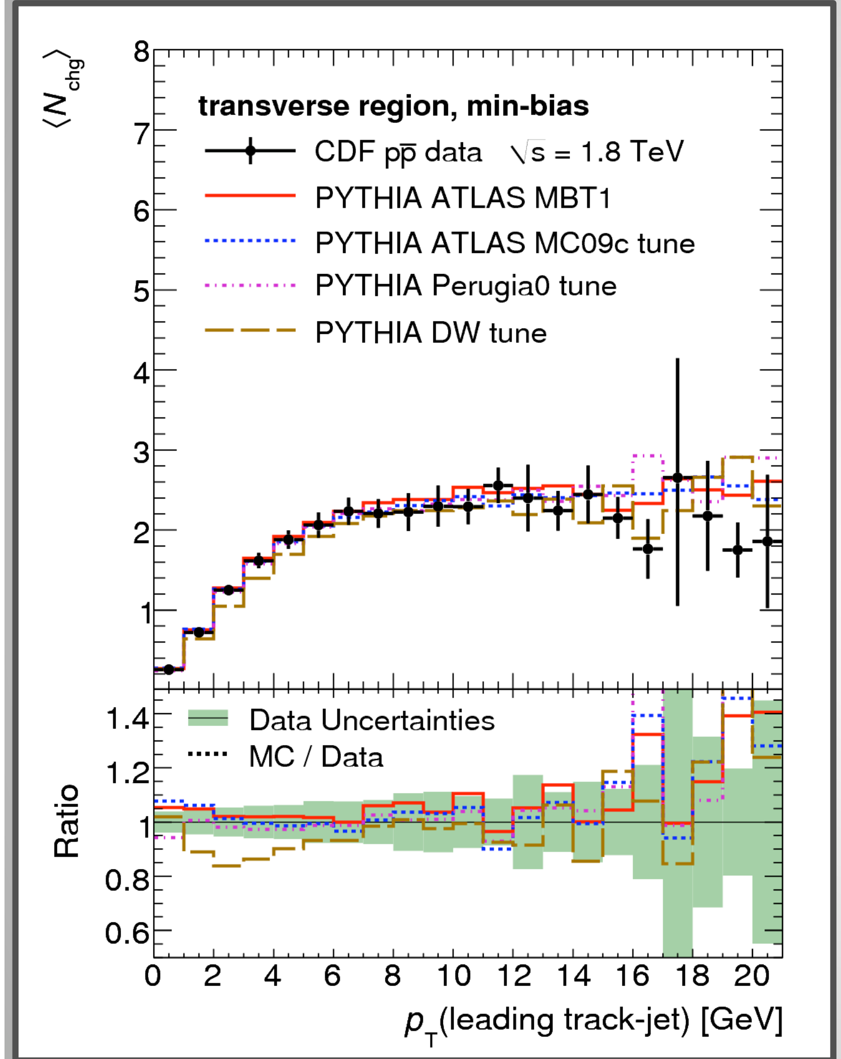
Underlying Event Measurements

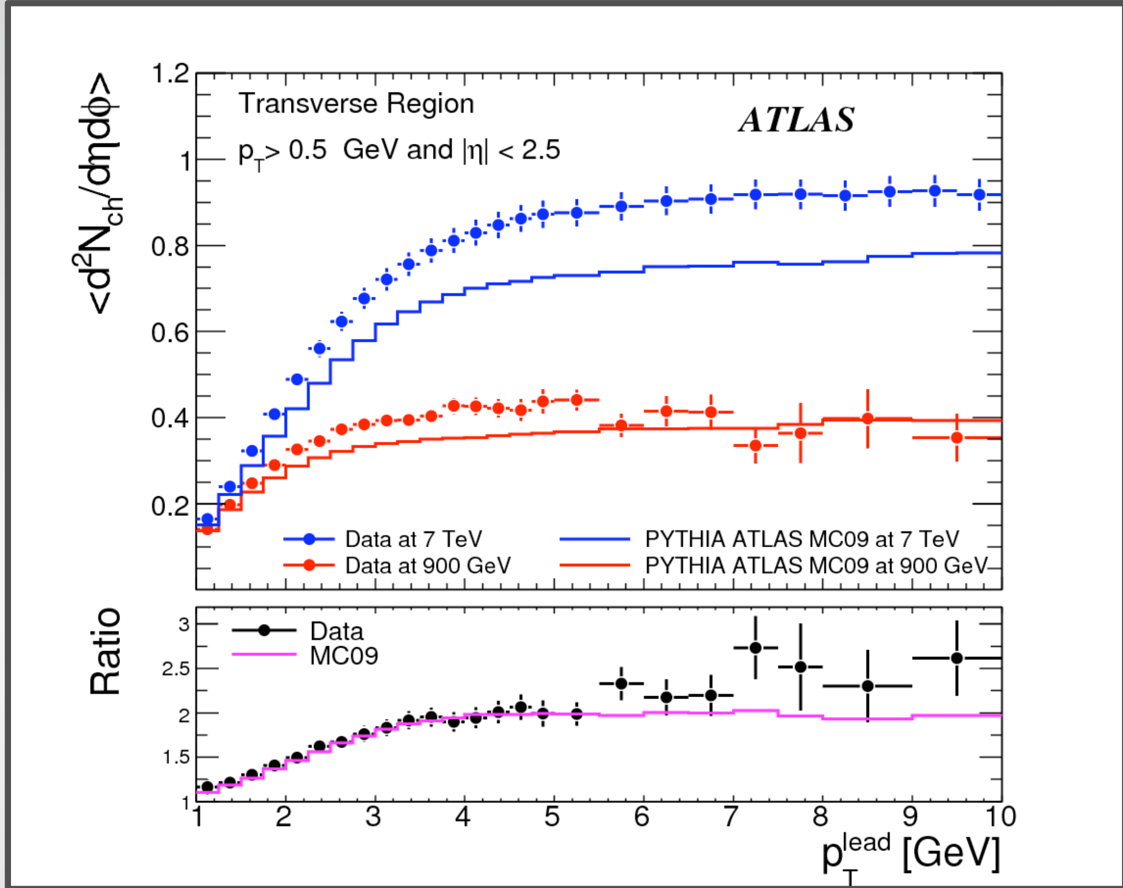




Proton matter distribution

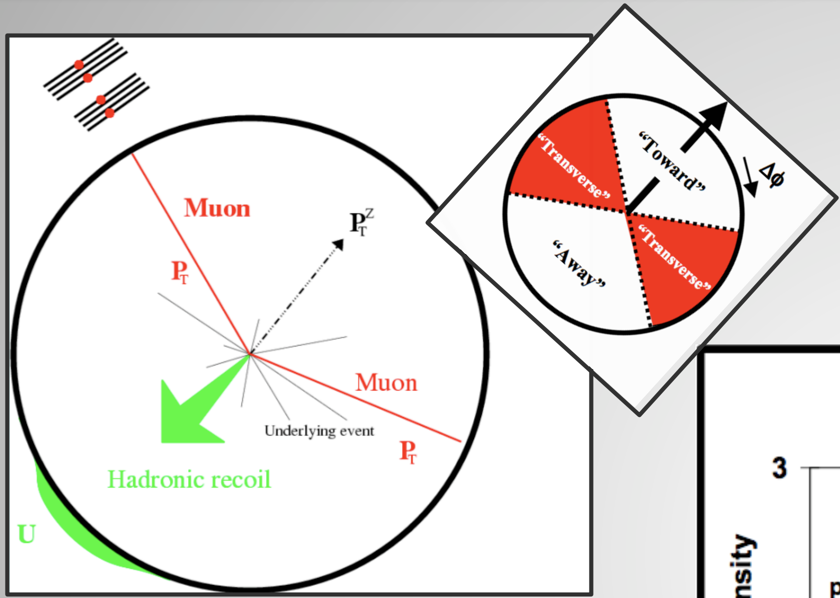
Underlying Event Measurements

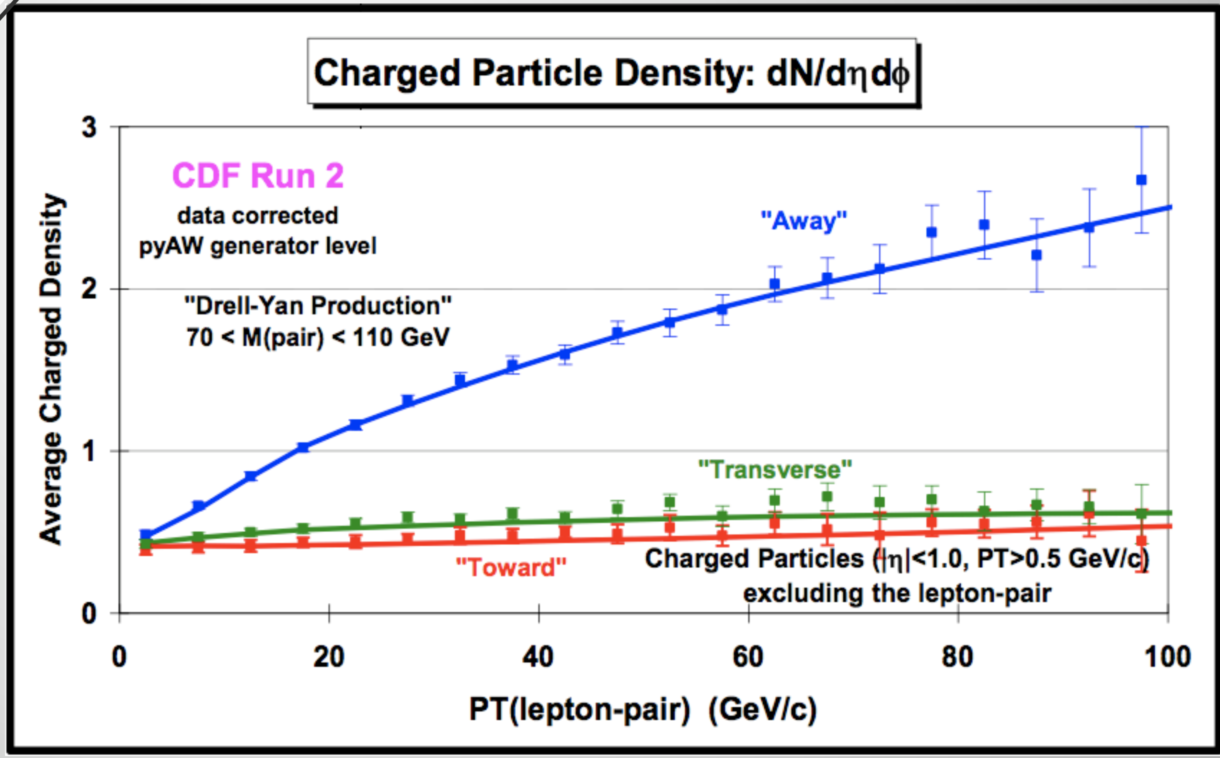




Inconsistency between LHC and Tevatron results? Currently analysing 2.76 TeV LHC and 0.9 TeV Tevatron data to resolve the issue

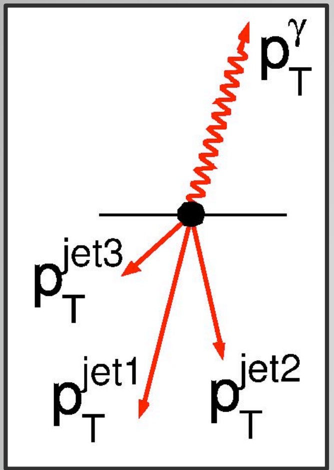
Underlying Event in Z→ℓℓ

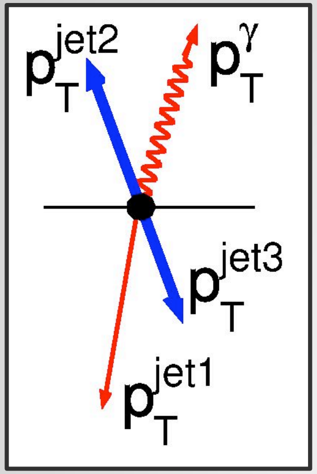


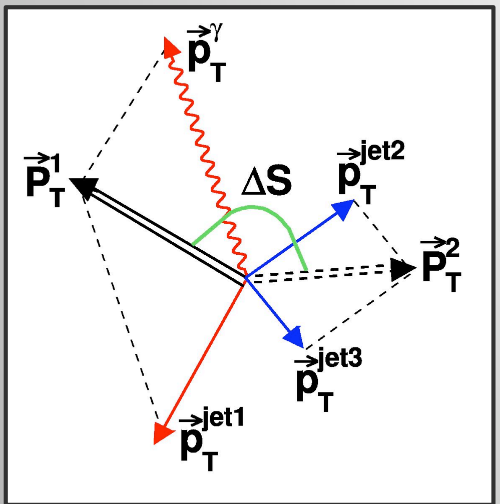


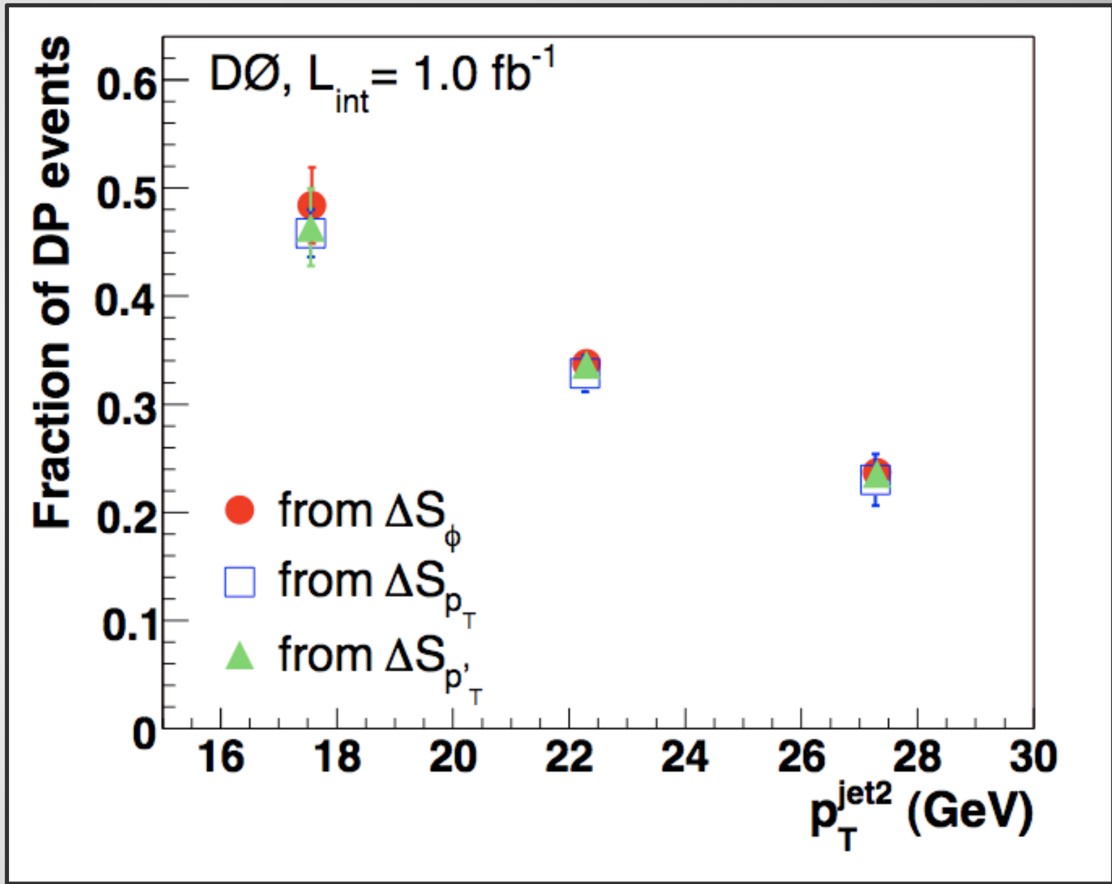
Double parton scattering

The high p_T tails of the Underlying Event… (not really soft-QCD anymore)







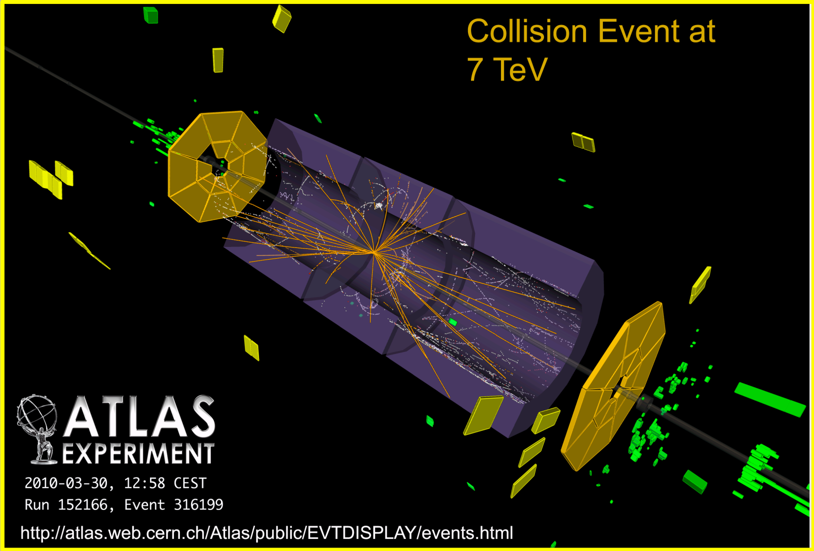


1. Minimum Bias
2. Underlying Event
3. **Total cross-section**
4. Diffractive cross-sections
5. Particle Correlations

Inelastic cross-section measurement

$$\sigma_{inel} = \frac{N^{evts} - N^{bck}}{\varepsilon \times \mathcal{L}}$$

1. N^{evts} : count inelastic collisions
2. ε : Correct for detector efficiency
3. $\mathcal{L}$: Normalise with luminosity



Minimum Bias Trigger Scintillators :
$2.09 < |\eta| < 3.84$

N^{evts} = # events with ≥ 2 counters above threshold

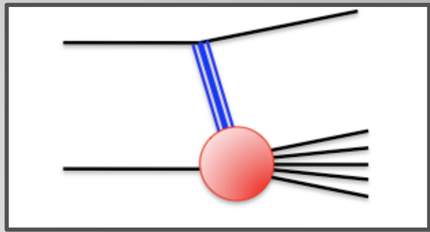
σ_{inel} $(\xi > 5\times10^{-6})$ = 60.3 ± 0.05(stat) ± 0.5(syst) ± 2.1(lumi) mb

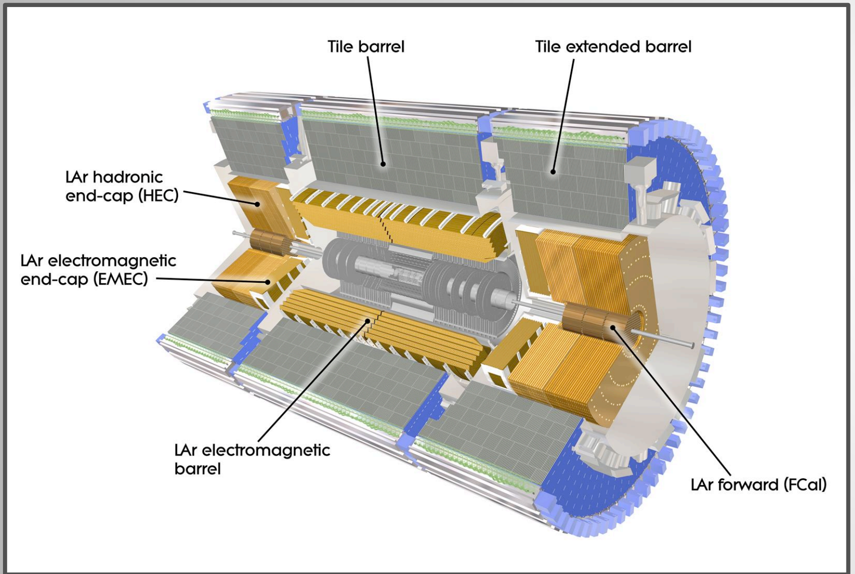
Measurement restricted to region in which we are sensitive (e.g. at least one charged particle with $|\eta| < 3.84$)

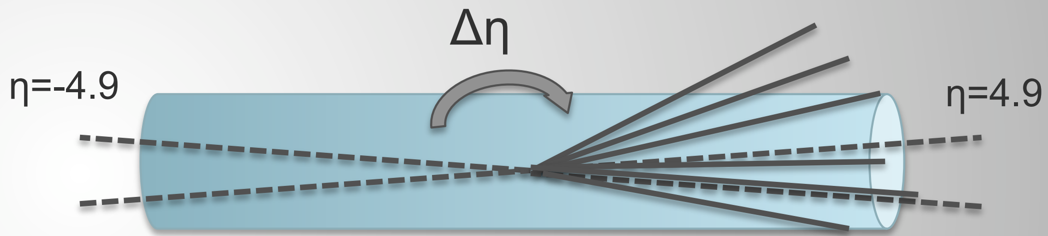
1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. **Diffractive cross-sections**
5. Particle Correlations

Gap cross-section

- Diffractive events tend to have large "rapidity gaps"
- Measure σ vs Δη (large Δη dominated by diffraction)

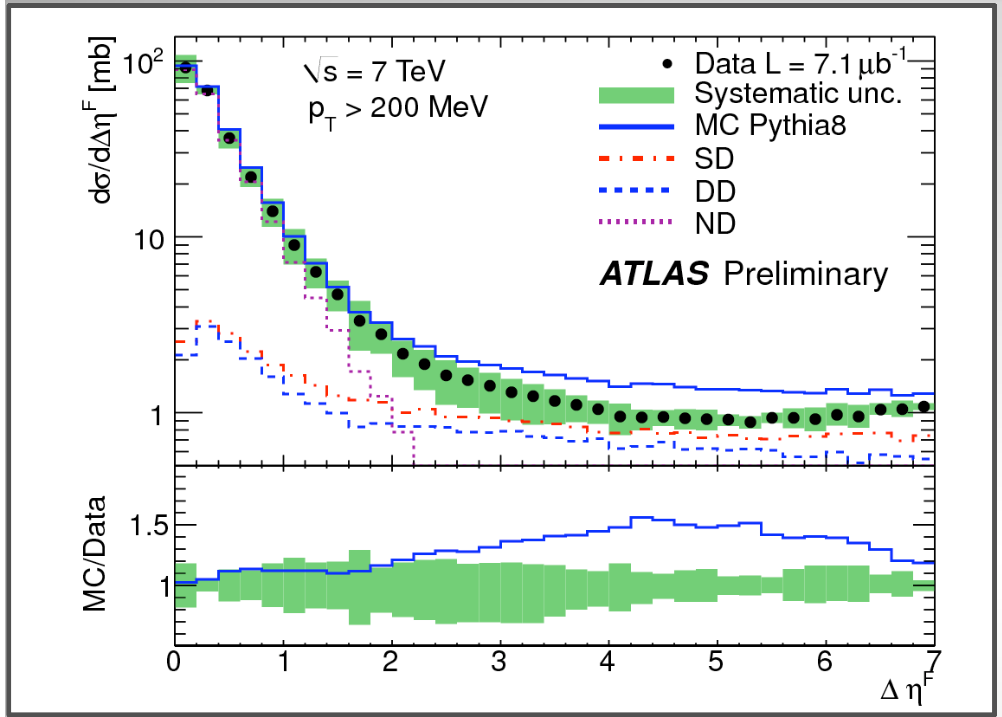


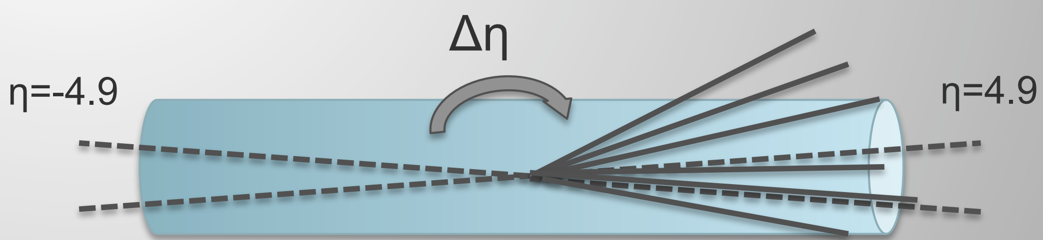




Calorimeters : |η| < 4.9
Inner Tracking Detector : |η| < 2.5

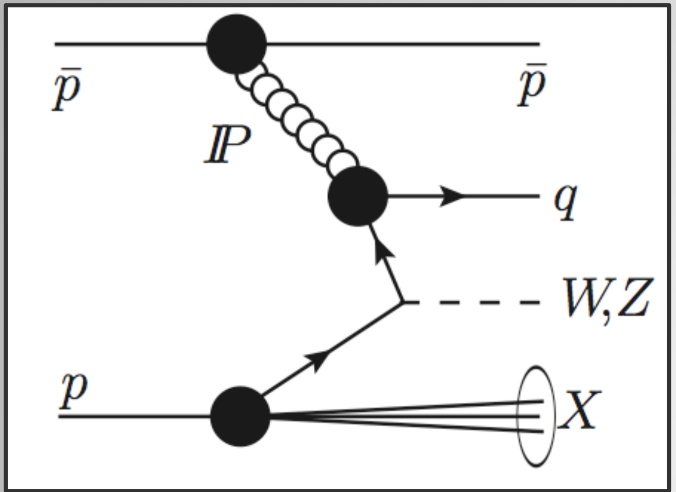
Gap cross-section

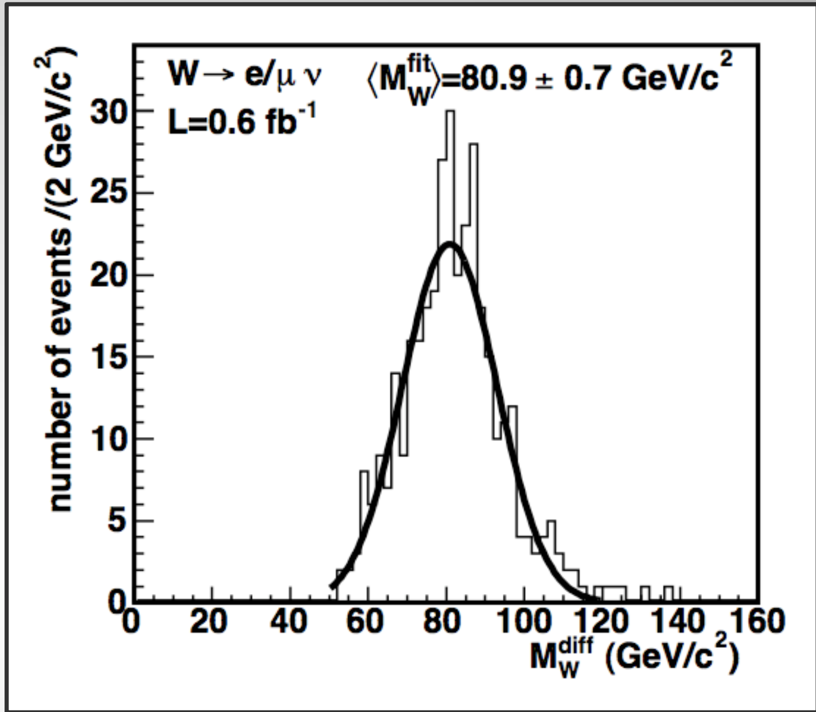


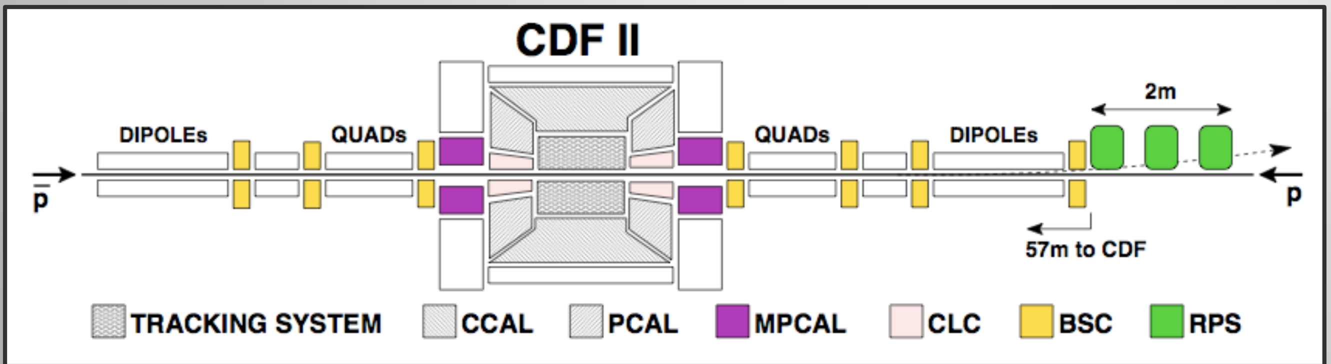


Other diffractive processes

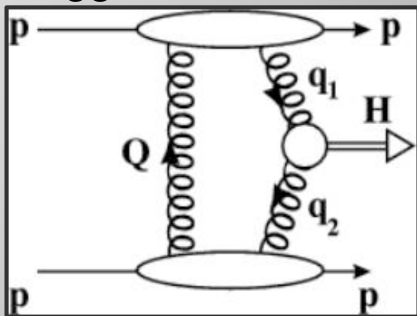
Not really soft-QCD anymore….





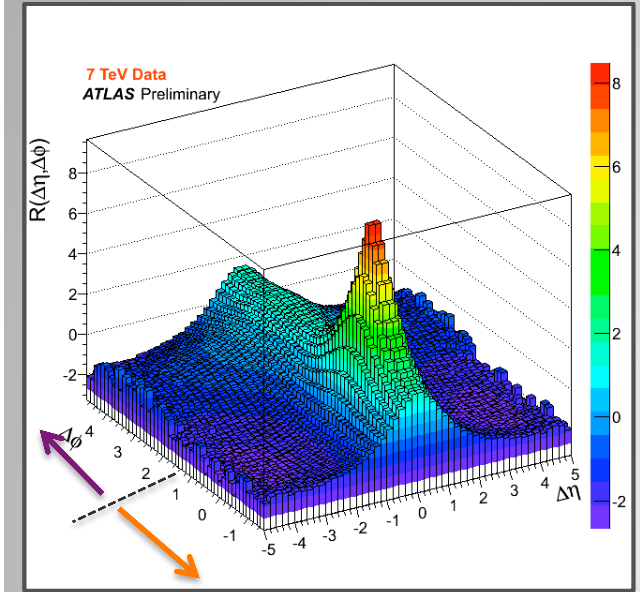


Higgs?



1. Minimum Bias
2. Underlying Event
3. Total cross-section
4. Diffractive cross-sections
5. **Particle Correlations**

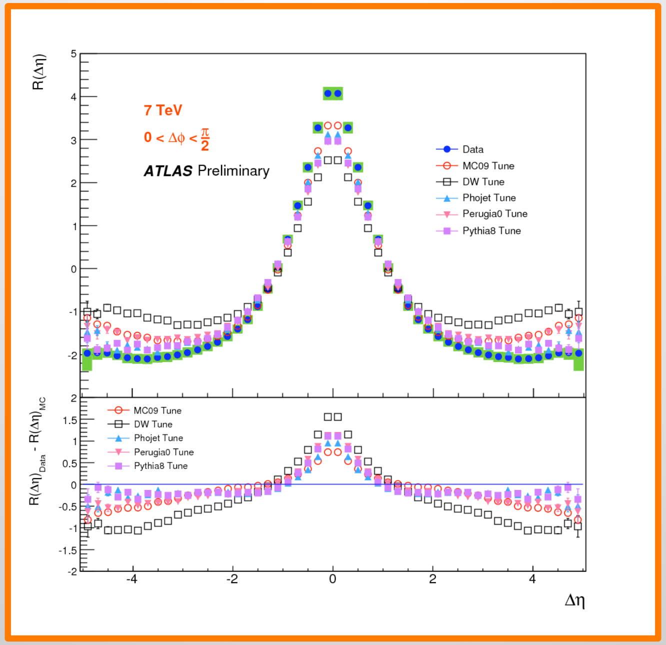
Two particle correlations

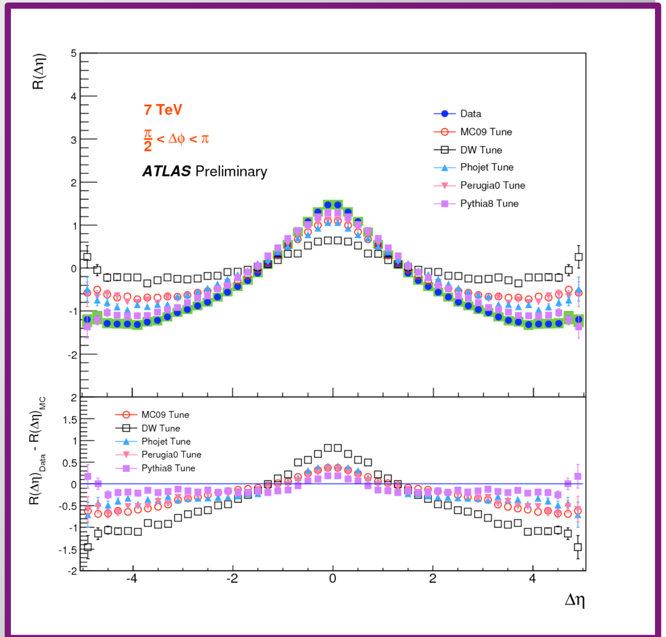


$R(\Delta\eta,\Delta\Phi) = (F(\Delta\eta,\Delta\Phi) - B(\Delta\eta,\Delta\Phi)) / B(\Delta\eta,\Delta\Phi)$ (+ normalisation factors)

F : all particle pairs in same event
B : pair particles from different events

1D projections on Δη axis :
(ΔΦ projections not shown)





Summary

- Soft-QCD processes must be measured to help constrain phenomenological models and tune Monte Carlos
- Many measurements including
  - Minimum Bias
  - Underlying Event
  - Total cross-section
  - Diffraction
  - Particle correlations
- Models are being retuned (and new ones developed) to improve the description
  - Some tension is seen between LHC and Tevatron data
- Important to get it right as can affect : lepton ID, E_T^{miss} resolution, jets, jet vetos,…