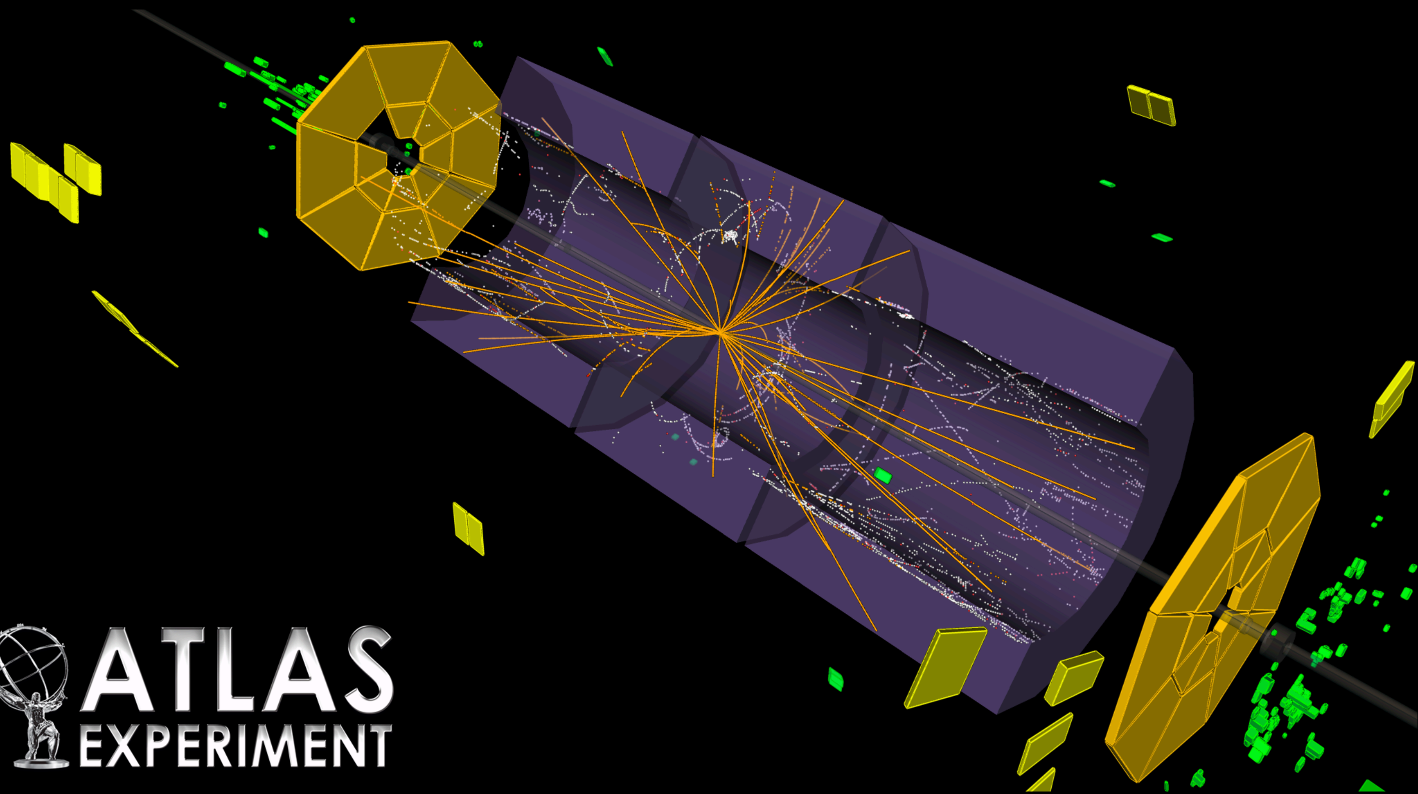
THE ROYAL SOCIETY
CELEBRATING 350 YEARS

UCL

Soft QCD results from ATLAS

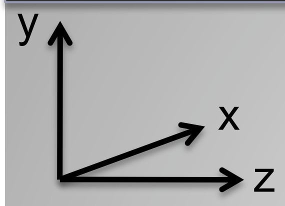
QCD@LHC : St Andrews, 22nd August 2011

Emily Nurse

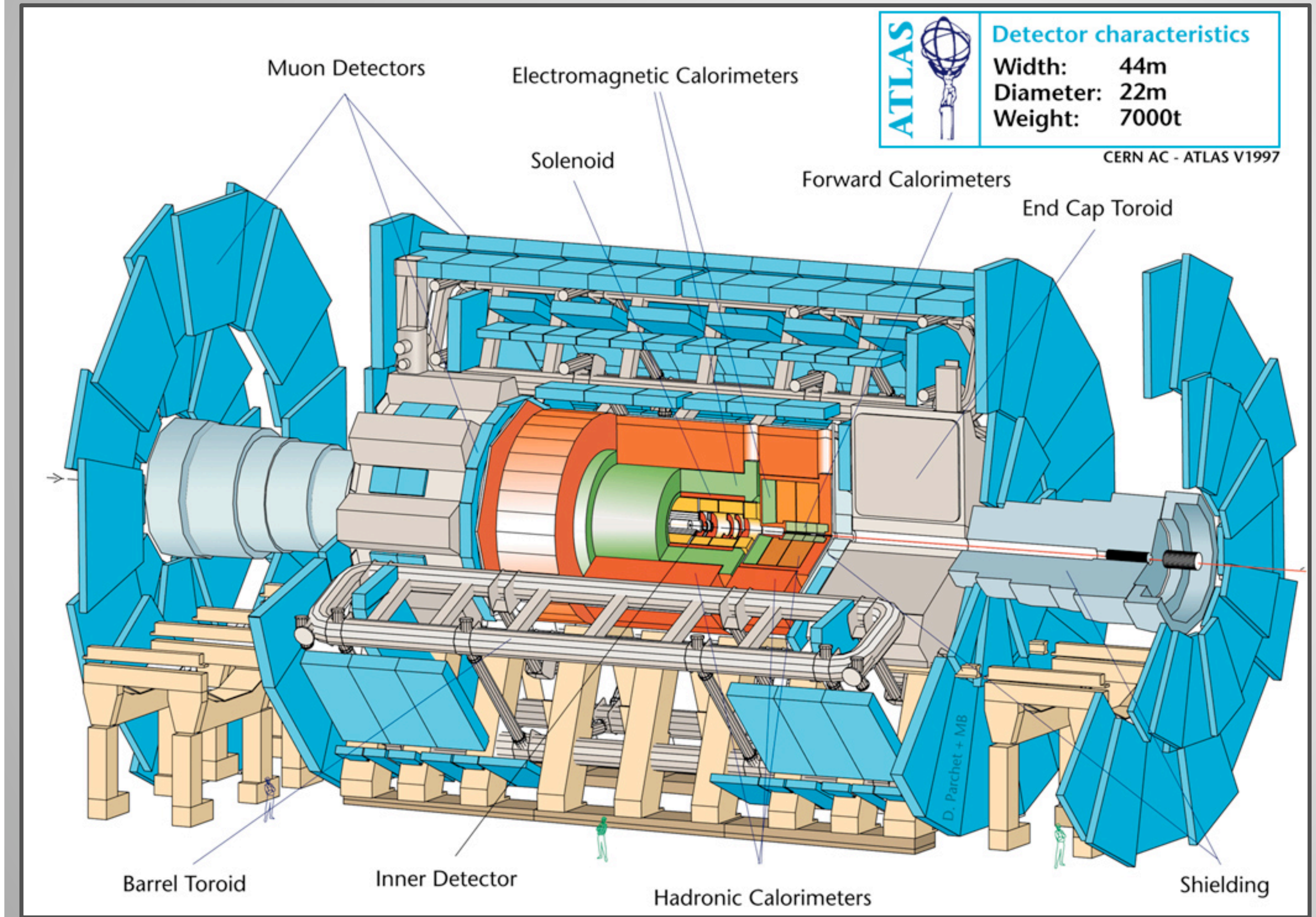


ATLAS EXPERIMENT

ATLAS



Φ = azimuthal angle around beam-axis {in xy plane}
θ = polar angle {w.r.t. beam-axis}
$\eta = -\ln\tan(\theta/2)$ {pseudo-rapidity}
p_T = momentum component transverse to beam



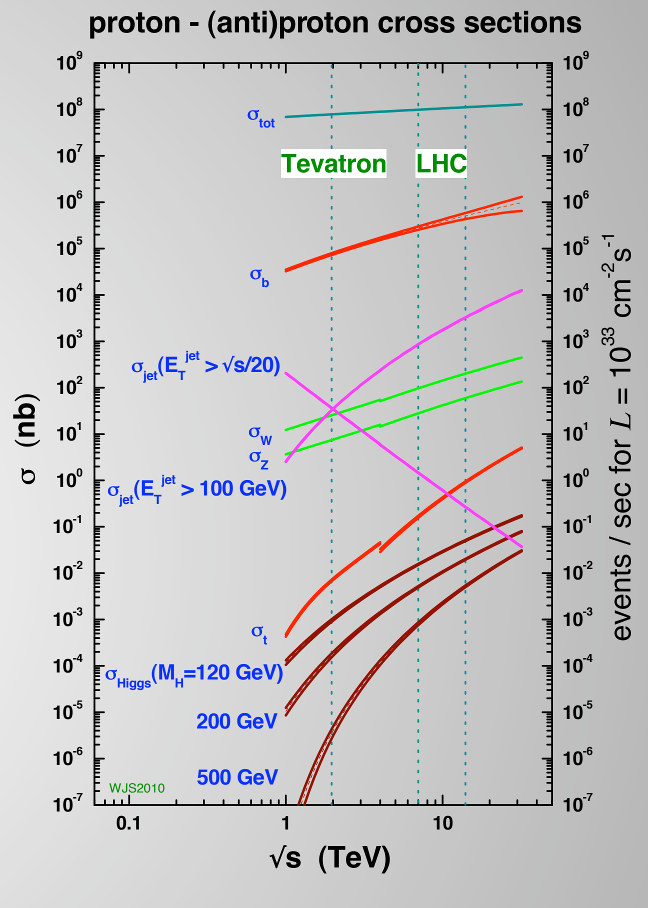
Inner Detector in 2 Tesla magnetic field reconstructs charged particle "tracks" with $|\eta| < 2.5$

Calorimeters absorb EM and hadronic particles with $|\eta| < 4.9$

used in soft QCD measurements

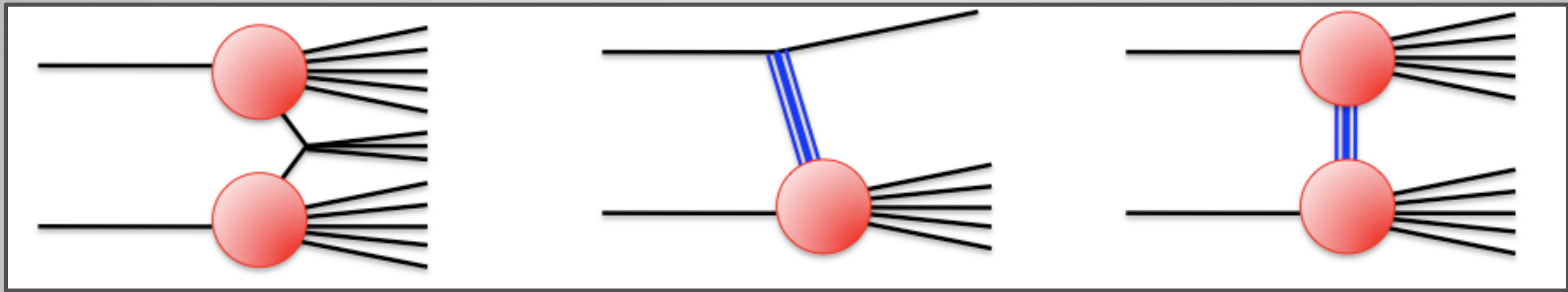
Dominant pp interactions

- The pp inelastic cross-section is much larger than that for "new" particle production (only 1 in every 10 billion interactions would produce a Higgs)
- Interactions dominated by soft (low momentum transfer) QCD processes
  - Perturbative QCD breaks down
  - We rely on phenomenological models, tuned to data



Thanks to James Stirling for plot!

Dominant pp interactions



Non-Diffractive (ND) σ~49 mb

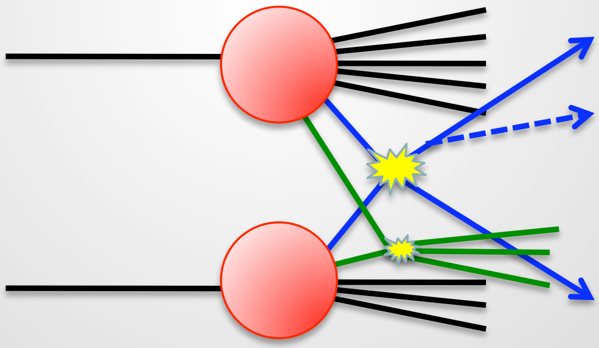
Single-Diffractive-Dissociation (SD) σ~14 mb

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

@ 7 TeV

Multiple Parton Interactions

(Underlying Event)



These soft-QCD processes are needed in Monte Carlo Event Generators

- ✓ To model pileup (up to ~20 extra pp interactions per bunch crossing)
- ✓ To model the soft processes occuring in the same pp interaction as an “interesting” event
- ✓ Affects E_T^{miss} resolution, lepton ID, jets, jet vetos, …

SOFT QCD RESULTS

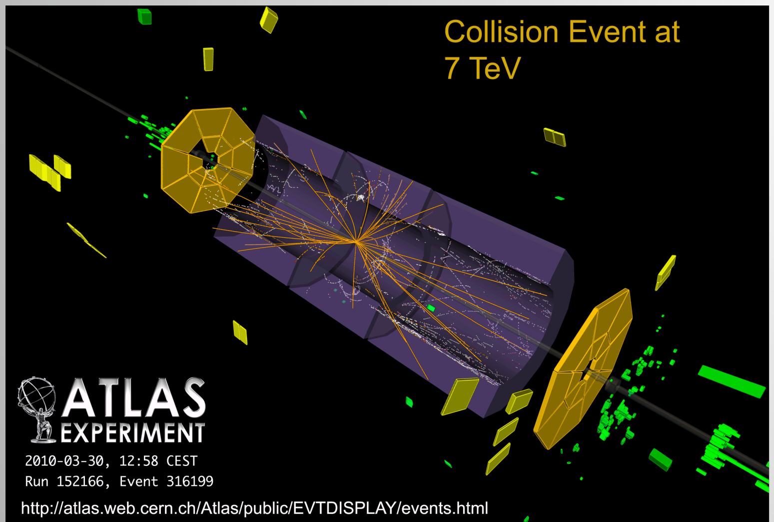
All NEW or UPDATED since QCD@LHC@Trento

1. Inelastic pp cross-section [arXiv:1104.0326, **accepted by Nature Comm**] (NEW)
2. pp cross-section differential in rapidity gap size [ATLAS-CONF-2011-059] (NEW)
3. Charged particle distributions [New J Phys (2011) 053033] (UPDATED : more phase-spaces)
4. Charged particle correlations [ATLAS-CONF-2011-055] (NEW)
5. Underlying Event with
   - charged particles [Phys.Rev.D 83, 052005 (2011)] (UPDATED :100 MeV particles)
   - charged+neutral particles [EPJC 71 (2011) 1636] (NEW)

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

Datasets

- Use only first few runs of 7 TeV data (7 → 190 μb^{-1}) + 0.9 TeV (7 μb^{-1}) and 2.36 TeV (0.1 μb^{-1}) data
- Generally we want to study *all* inelastic pp interactions
- Instantaneous luminosity *very* low for these runs : on average ~0.007 interactions per bunch crossing → 99.3% of crossings are empty!
- Need to "trigger" on inelastic interactions



- Minimum Bias Trigger Scintillator disks sensitive to any charged particle $2.09 < |\eta| < 3.84$
- 16 counters on each side of ATLAS

Measurement philosophy

- ✓ Correct measurements for detector inefficiencies and resolutions (e.g. present 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!
- ✓ Define the measured process purely in terms of the final state (e.g. we do not measure "non-single-diffractive" events)
  - Event selection well defined and reproducible

1. Inelastic pp cross-section

   [arXiv:1104.0326, **accepted by Nature Comm**]
2. pp cross-section differential in rapidity gap
3. Charged particle distributions
4. Charged particle correlations
5. Underlying Event with
   - charged particles
   - charged+neutral particles

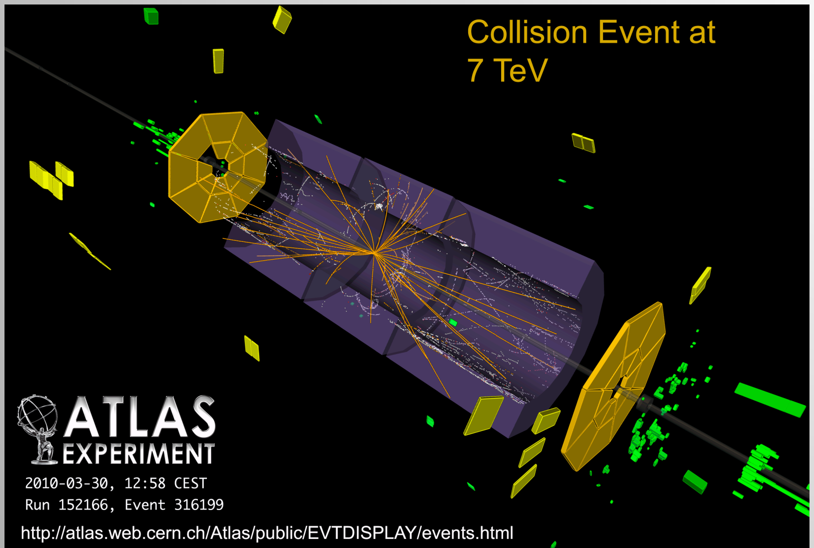
Inelastic cross-section measurement

- Proton-proton σ_{inel} vs $\sqrt{s}$ not well known, 7 TeV measurement needed!
- ATLAS has made a direct measurement of σ_{inel} with a new, simple method :

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

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

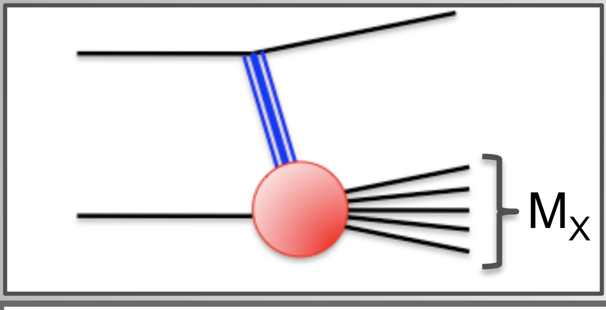
MBTS : $2.09 < |\eta| < 3.84$



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

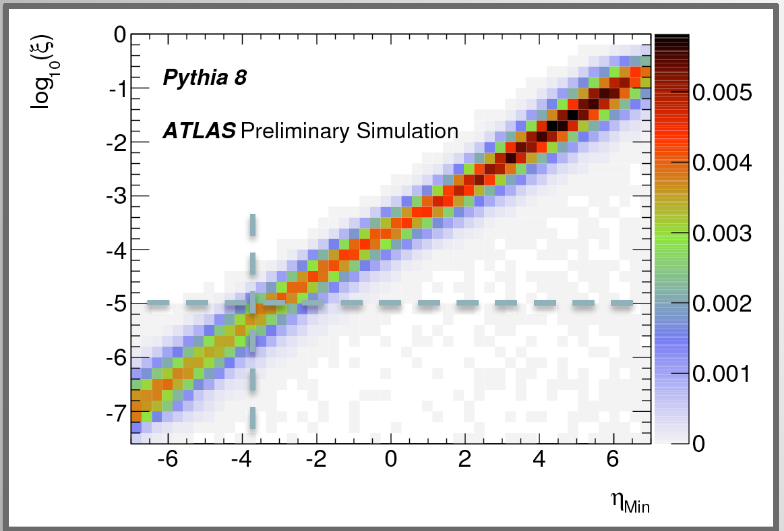
Inelastic cross-section measurement

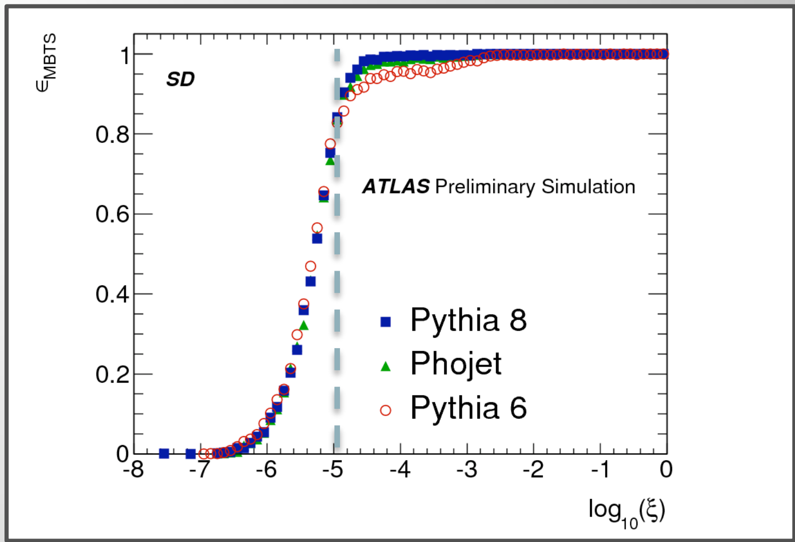
- MBTS : $2.09 < |\eta| < 3.84$
- Important : Blind to events with no particles with $|\eta| < 3.84$
- Solution: **Make measurement in a well defined phase-space region**



$\xi = M^2_X/s$

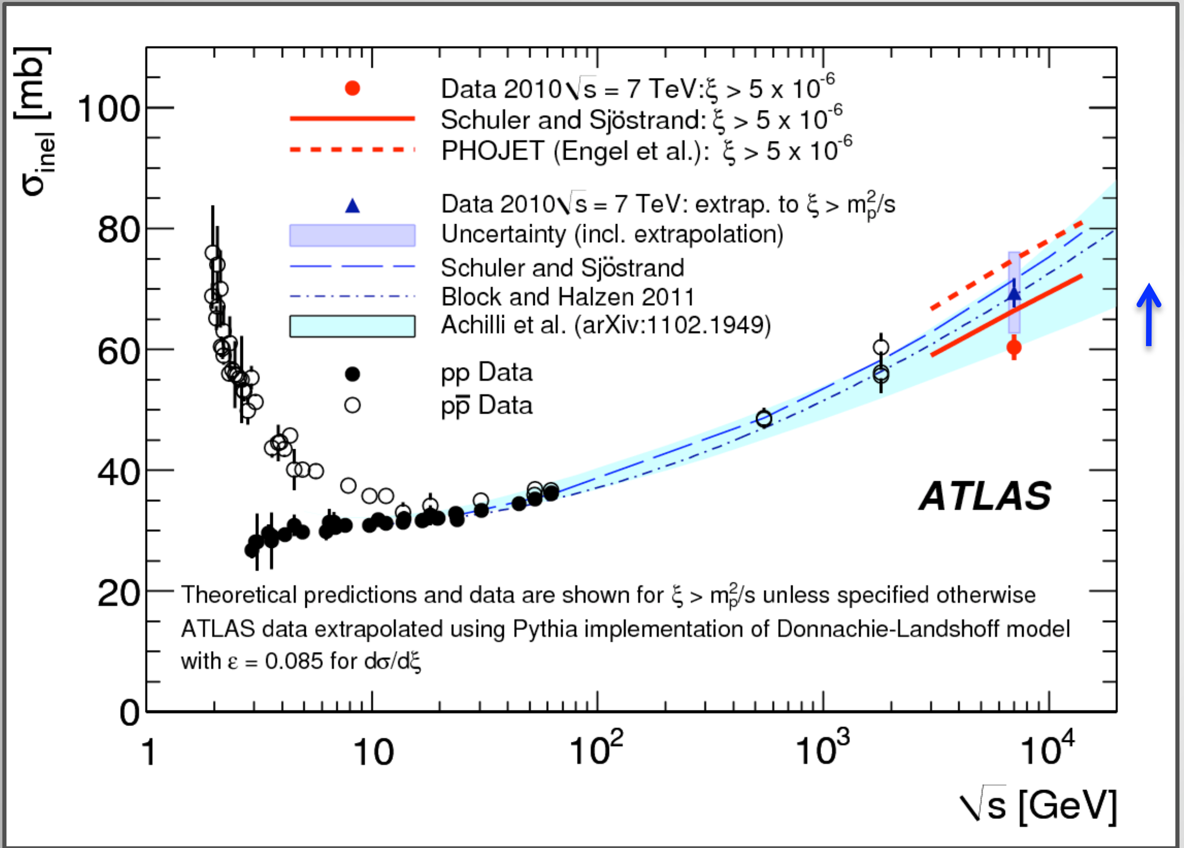
Restrict measurement to $\xi > 5\times10^{-6}$ ($M_X > 16$ GeV)





Inelastic cross-section measurement

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

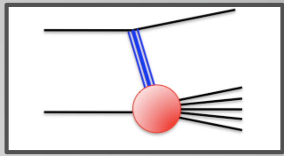


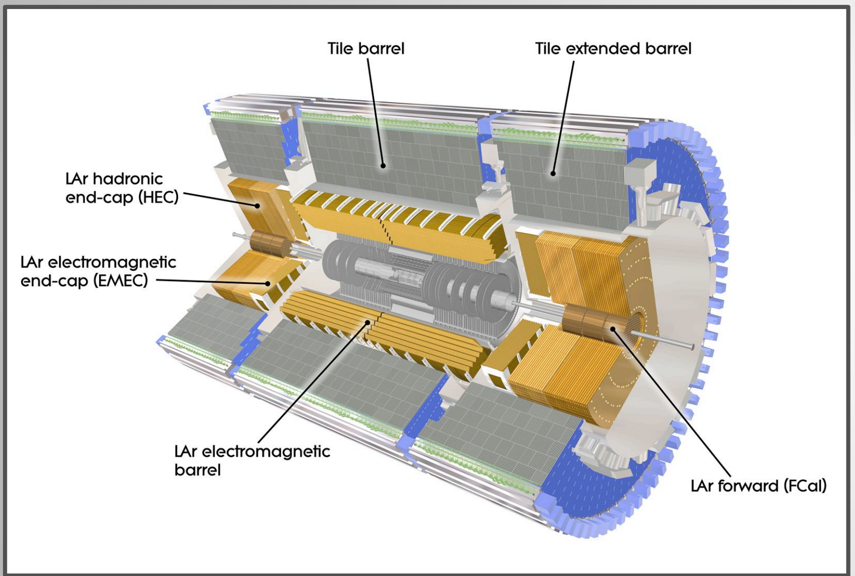
Extrapolation to full phase-space also included, with large uncertainty from range of models used

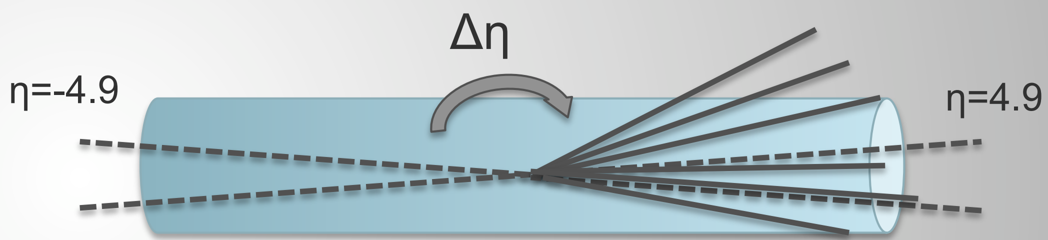
1. Inelastic pp cross-section
2. **pp cross-section differential in rapidity gap**
[ATLAS-CONF-2011-059]
3. Charged particle distributions
4. Charged particle correlations
5. Underlying Event with
   - charged particles
   - charged+neutral particles

Gap cross-section

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





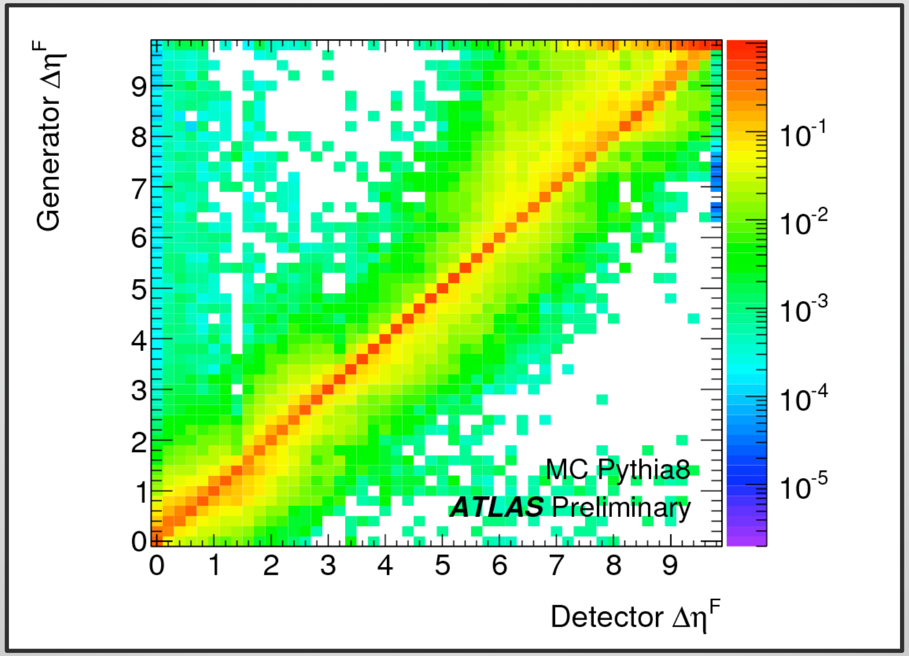


Calorimeters : |η| < 4.9
Inner Tracking Detector : |η| < 2.5

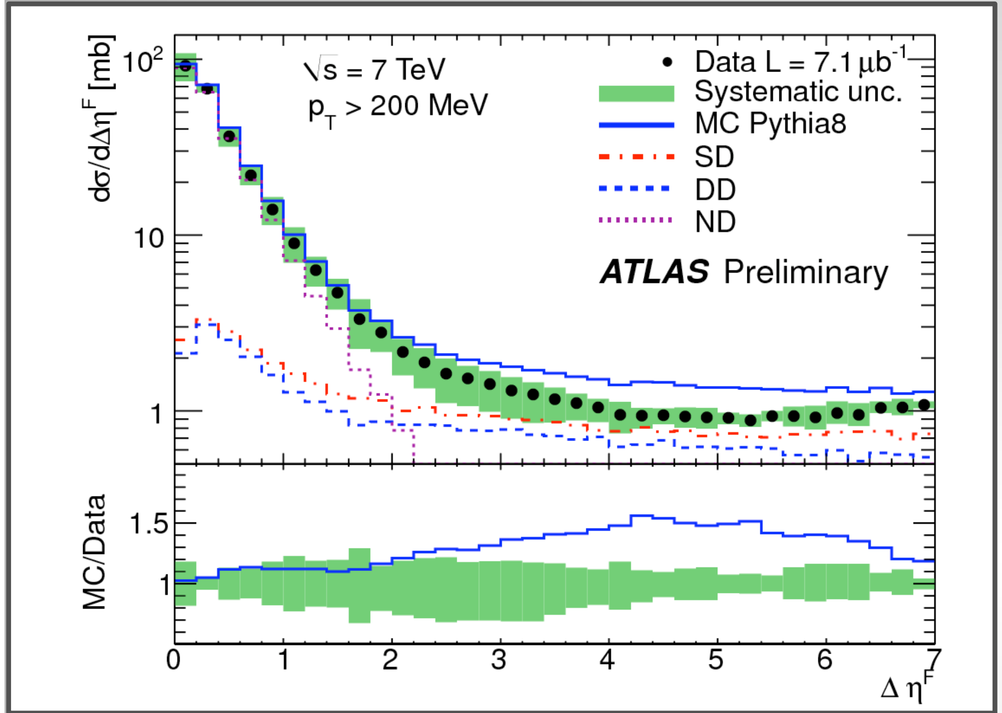
Gap cross-section

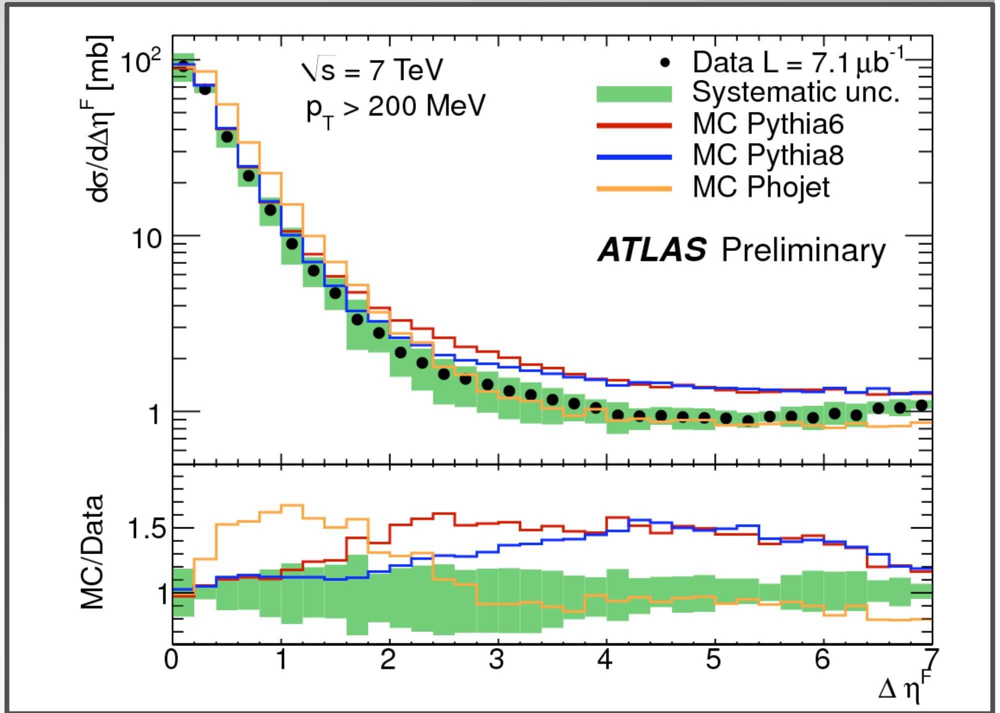
- Detector split into η rings (0.2 wide)
- Detector level : a ring is empty if :
  1. no calorimeter cells above noise threshold (|η|<4.9) and
  2. no Inner Detector tracks with p_T > 200 MeV (|η|<2.5)
- Generator level :
  1. no particles with p_T > 200 MeV

correct for detector effects



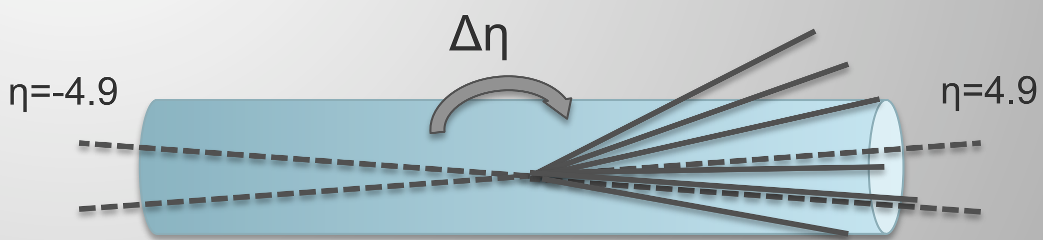
Gap cross-section





Dominant systematic uncertainties:

- MC model dependence of corrections
- Calorimeter energy-scale

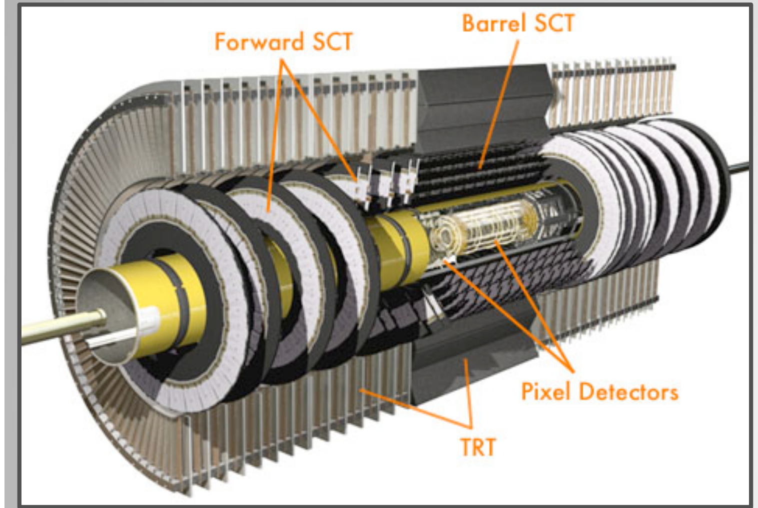


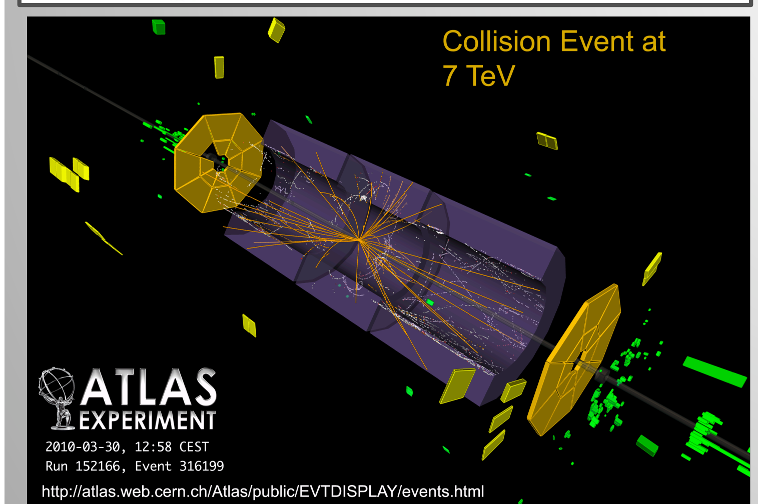
1. Inelastic pp cross-section
2. pp cross-section differential in rapidity gap
3. **Charged particle distributions**

   [New J Phys (2011) 053033]
4. Charged particle correlations
5. Underlying Event with
   - charged particles
   - charged+neutral particles

"Minimum bias" results

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





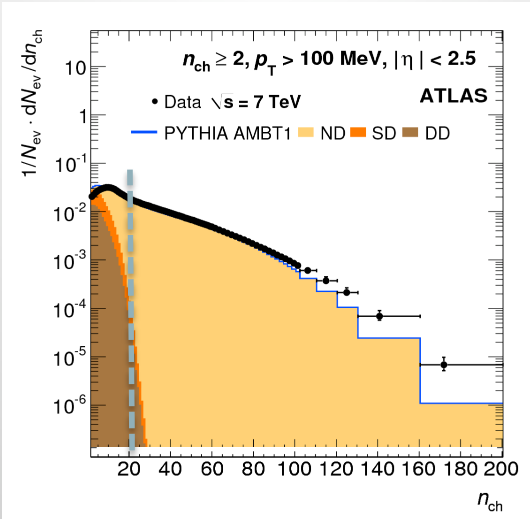
- Exact definition depends on detector (and analysis)
- ATLAS : Measurement made with Inner Detector Tracking (tracks with $|\eta| < 2.5$ and $p_T > 100$ MeV)
- Measure kinematics (multiplicity, p_T and η spectra, etc) of charged particles in "minimum bias" events

Phase spaces

Event selection well defined (and reproducible) :

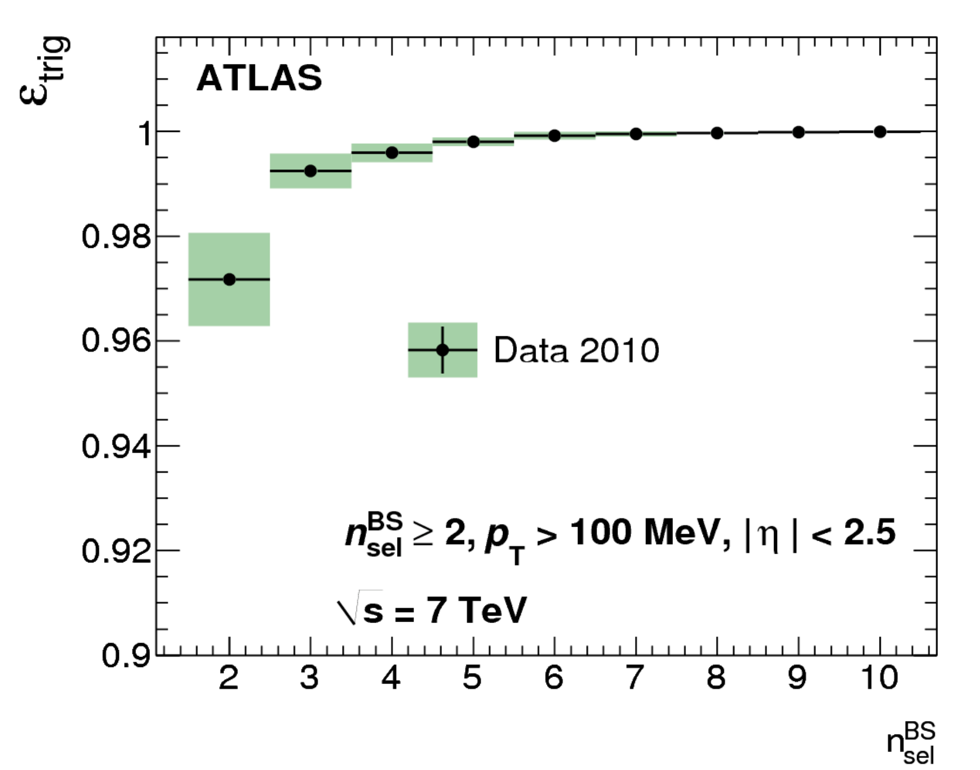
$\geq x$ charged particles (N_{ch}) with $p_T > y$ and $|\eta| < z$

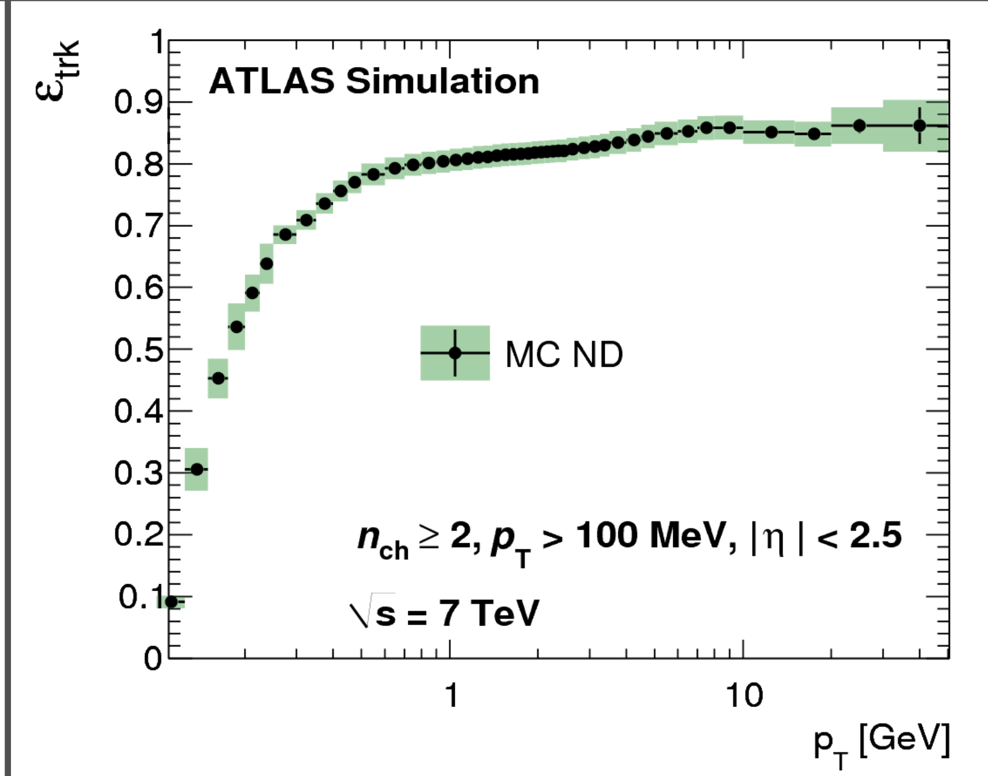
	Most inclusive		Diffraction suppressed		High p_T	ALICE/CMS comparison	
N_{ch} (≥)	2	1	20	6	1	1	1
p_T [MeV]	100	500	100	500	2500	500	1000
$\|\eta\|$	2.5	2.5	2.5	2.5	2.5	0.8	0.8



Correcting the data

- MBTS Trigger efficiency from data (small "control" sample recorded requiring presence of ID hits at L2 only)
- Tracking efficiency from MC with GEANT detector simulation (systematic uncertainties determined from comparisons with data)





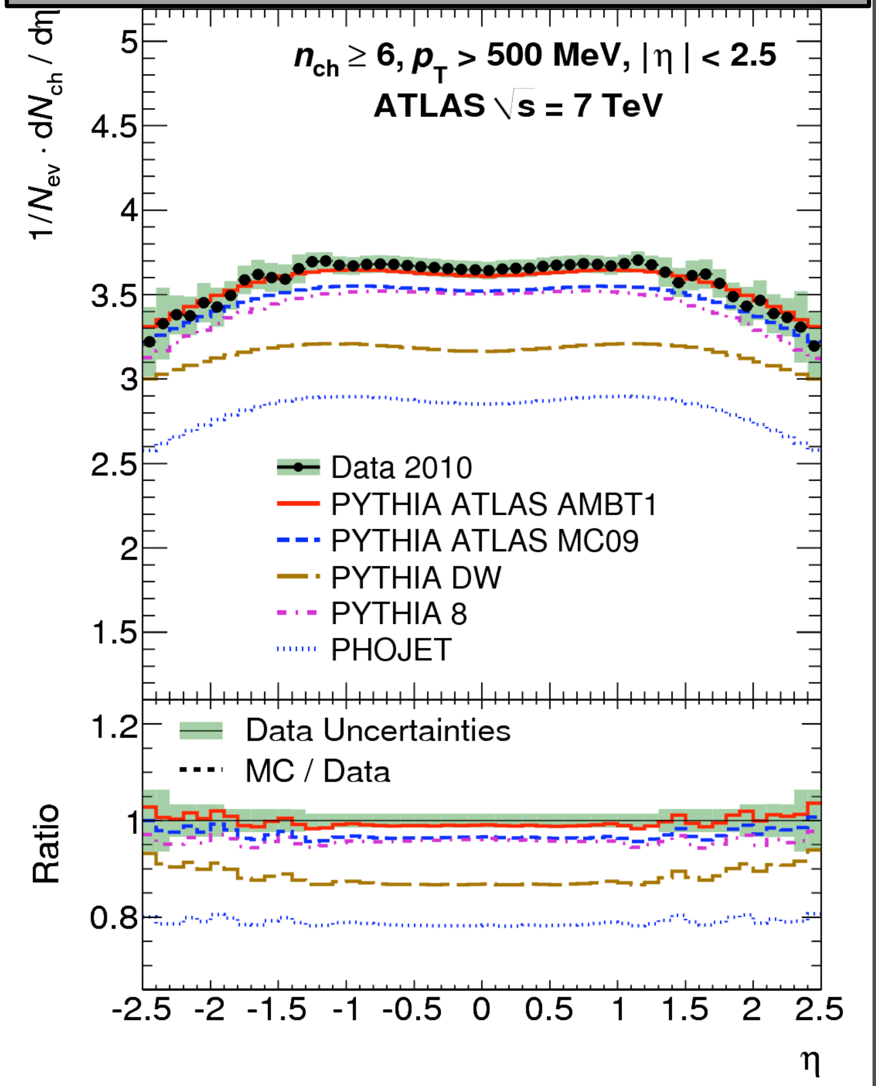
MC model comparisons

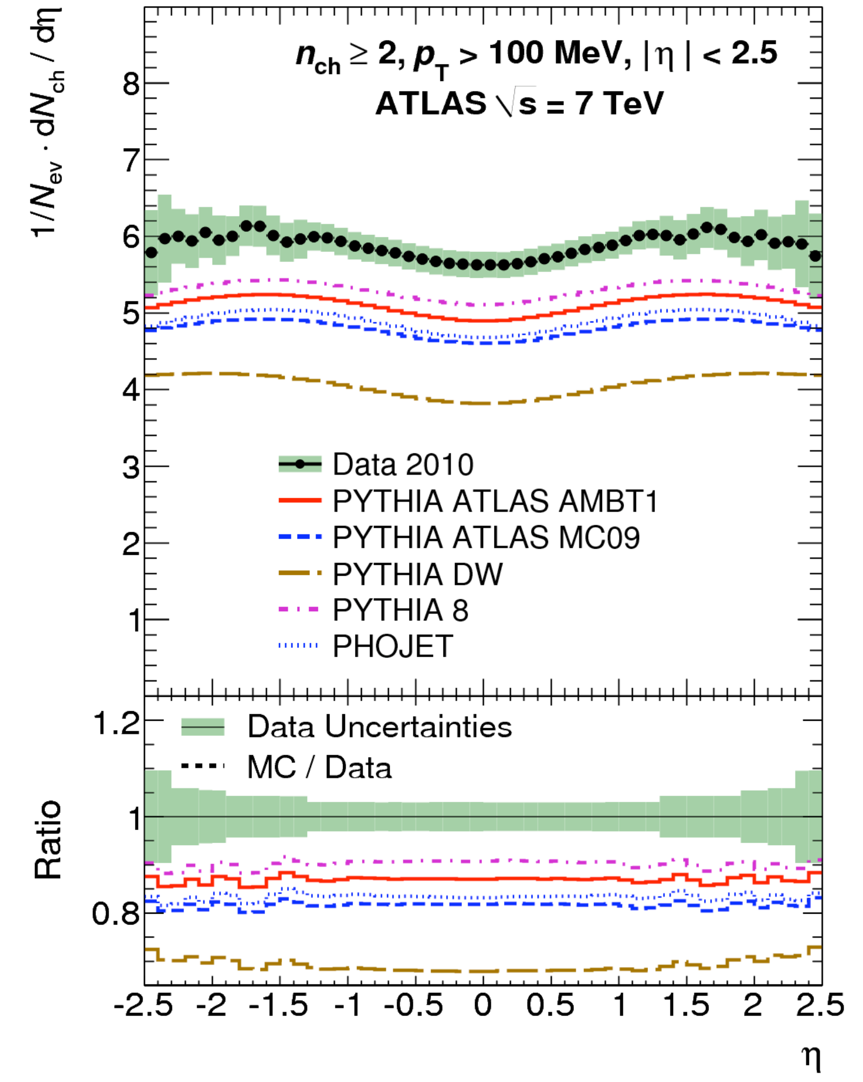
- Pythia and Phojet have “soft inclusive” models including diffraction
- Compare to various pre-LHC PYTHIA6 tunes, PYTHIA8 and PHOJET and…
- AMBT1 tune : Pythia v6.4.21 tuned to earlier version of diffraction suppressed data : $N_{ch} \geq 6$, $p_T > 500$ MeV, $|\eta| < 2.5$ [ATL-PHYS-PUB-2010-002]
  – More recently AMBT2 [ATL-PHYS-PUB-2011-008] - does a bit better in some distributions

See Andy Buckley’s dedicated ATLAS tuning talk
Thursday at 14:30

η spectra

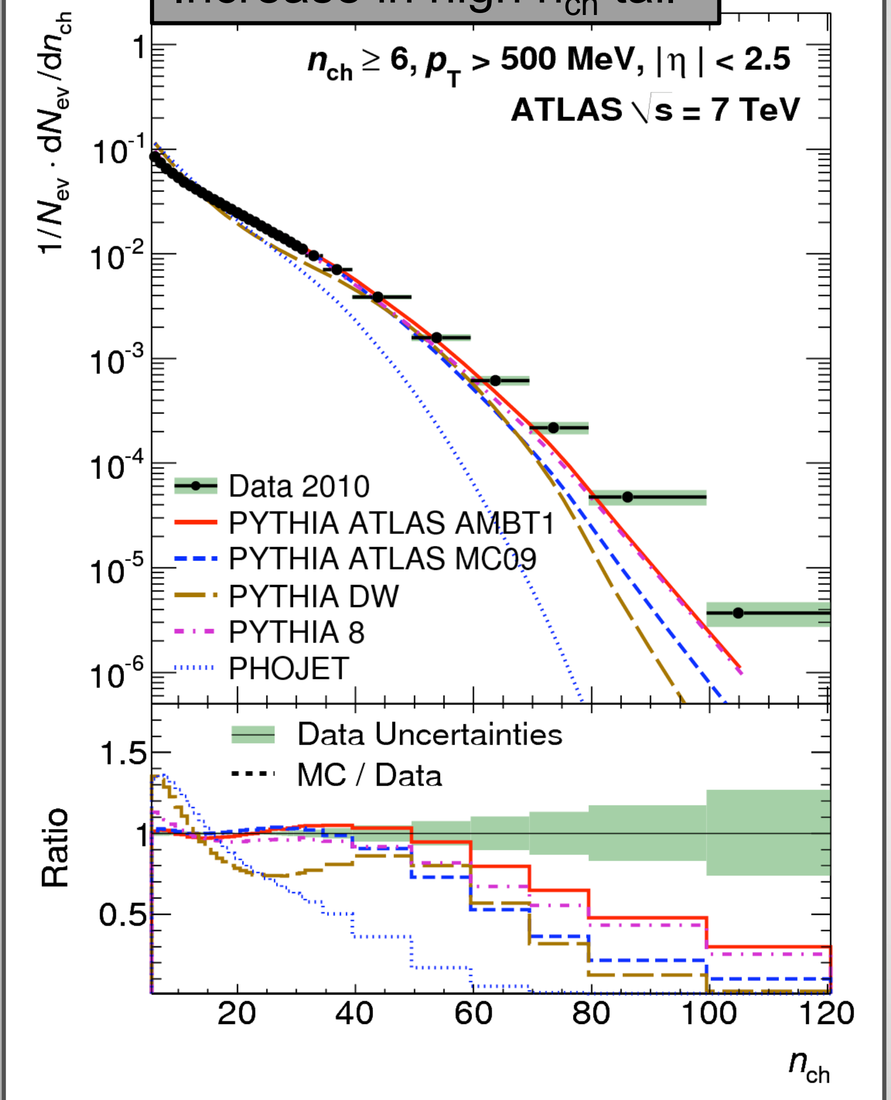
Slight increase in average multiplicity

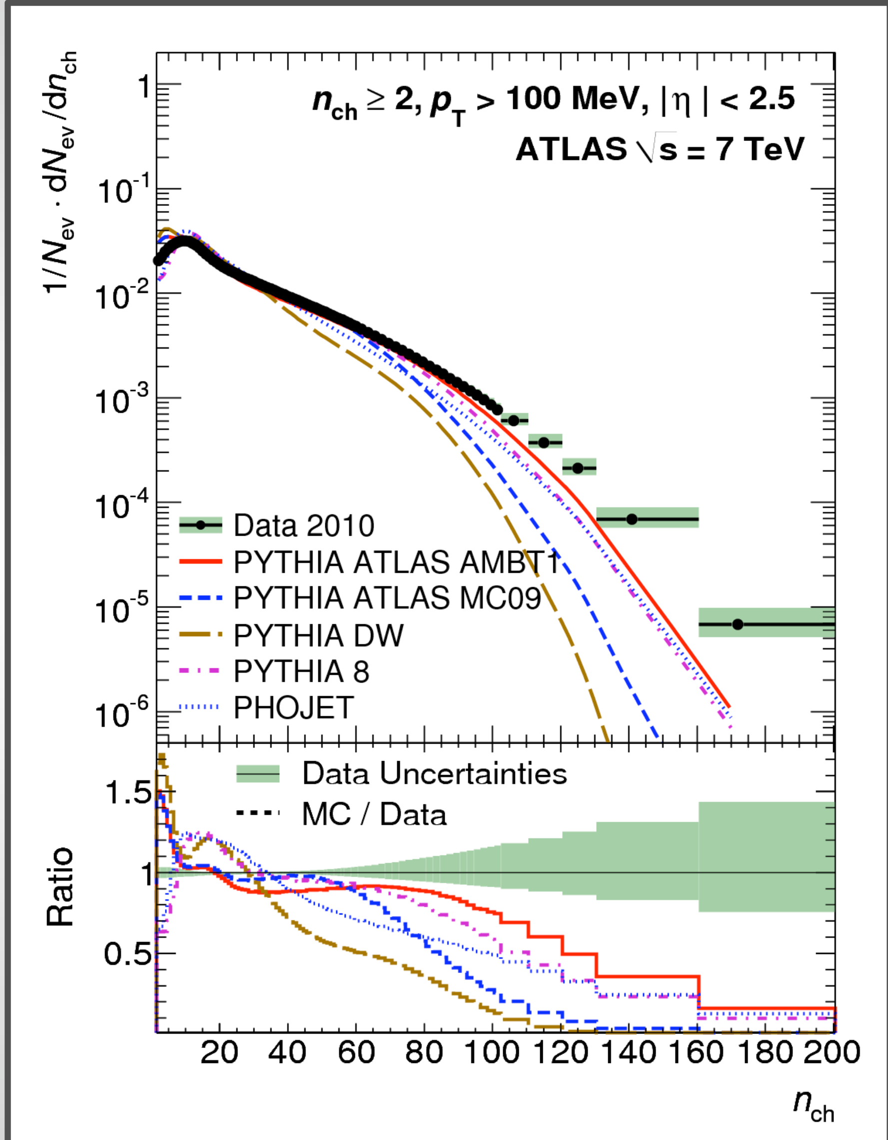




particle multiplicity

Increase in high n_{ch} tail





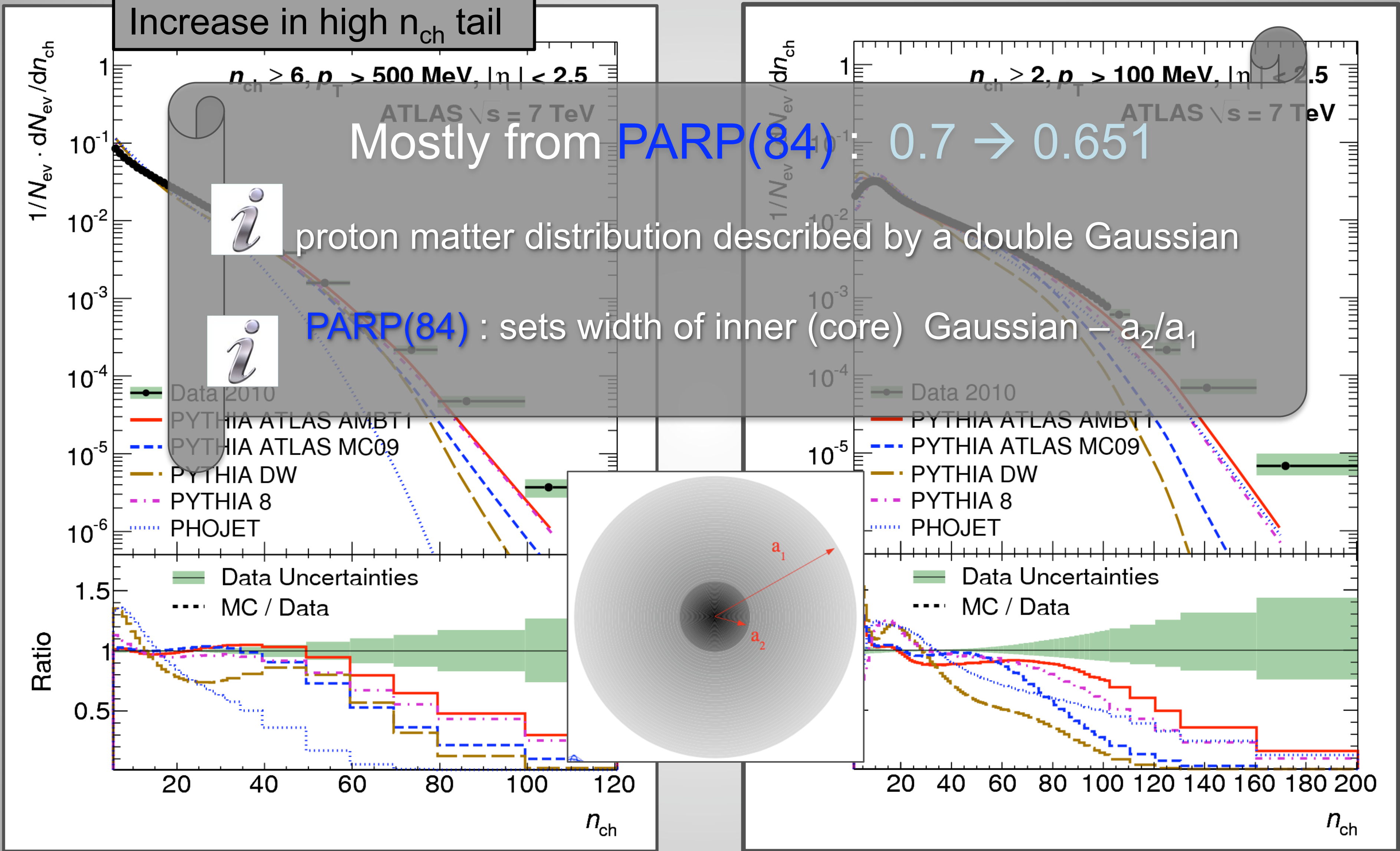
particle multiplicity

Increase in high n_{ch} tail

Mostly from PARP(84) : 0.7 → 0.651

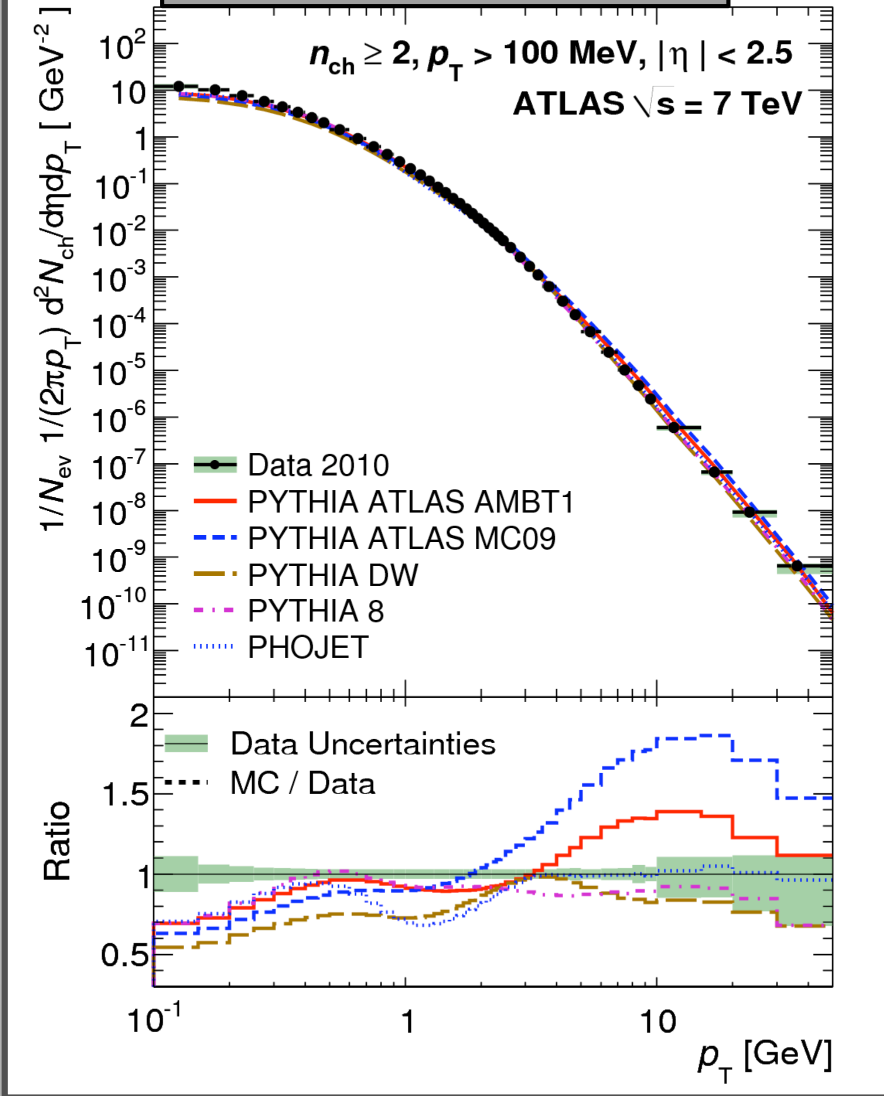
proton matter distribution described by a double Gaussian

PARP(84) : sets width of inner (core) Gaussian – a_2/a_1

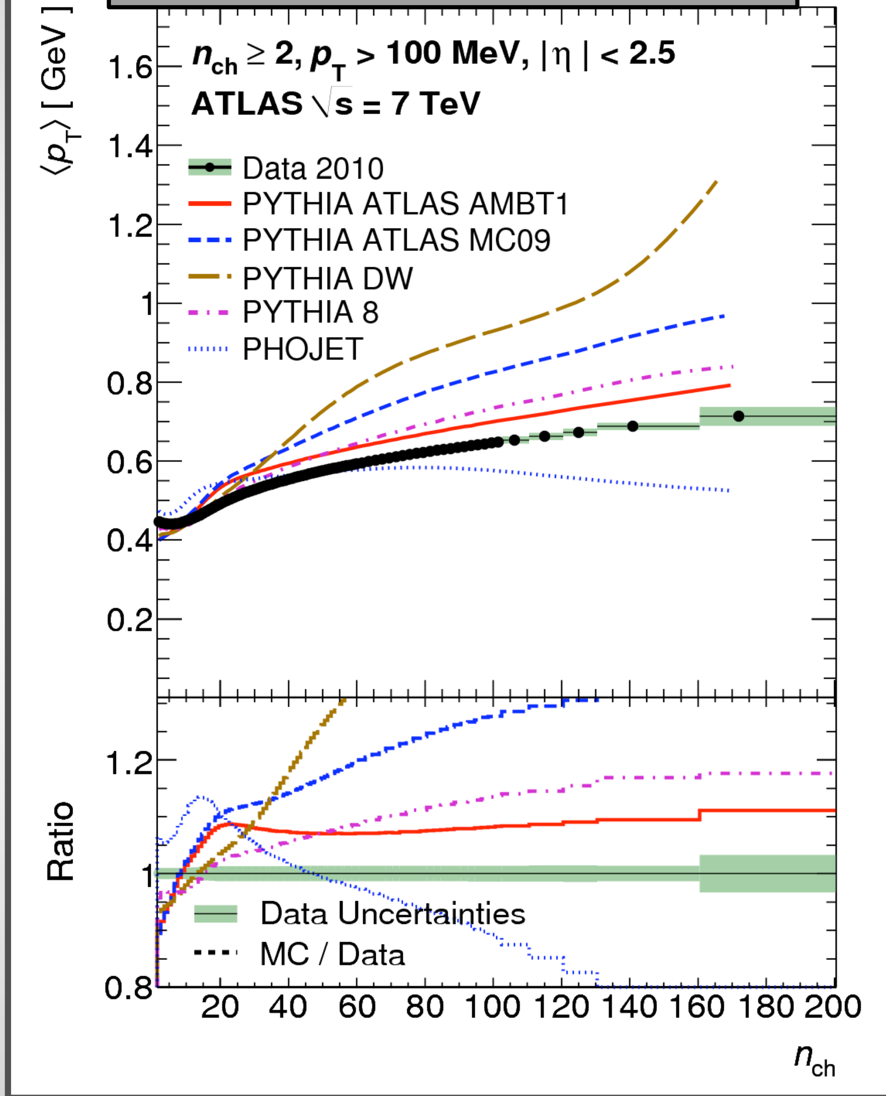


p_T spectra and $<p_T>$ vs n_{ch}

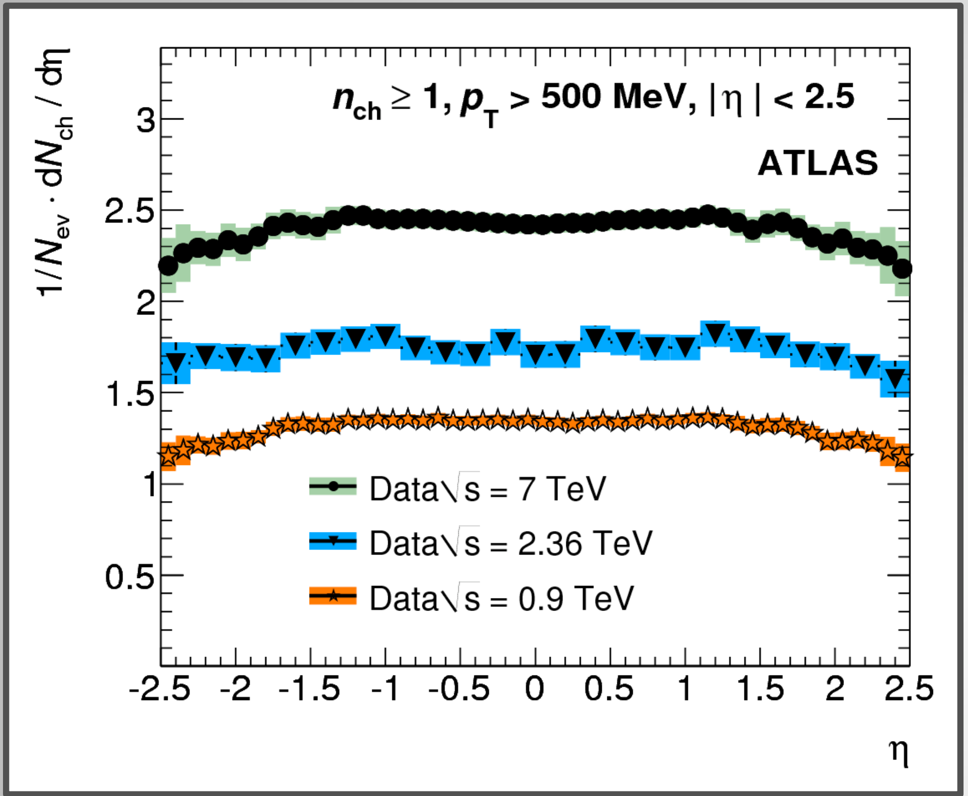
Decrease in high p_T tail

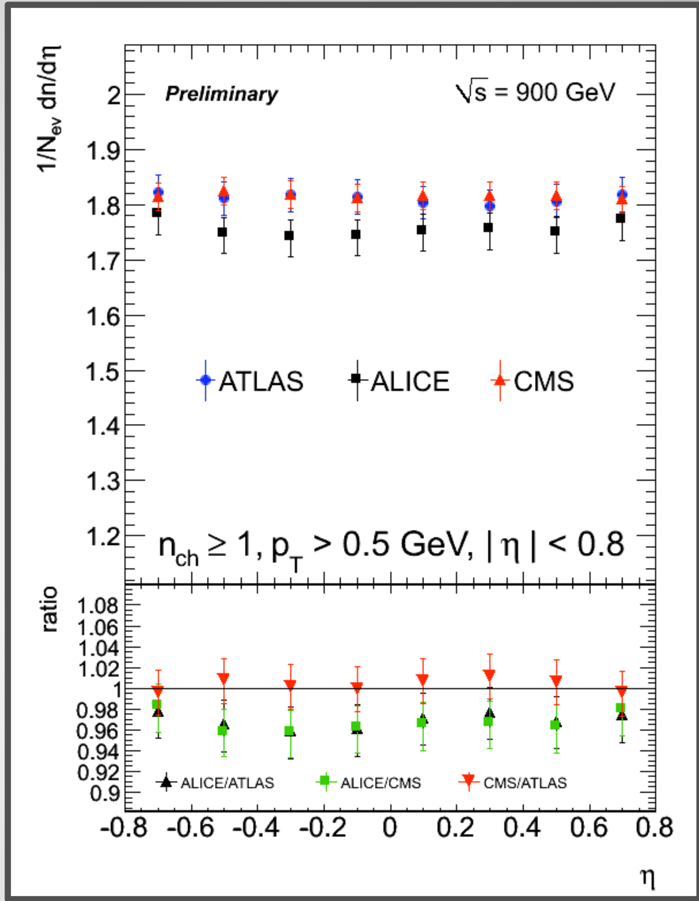


Decrease in $<p_T>$ at high n_{ch}



Results at 0.9, 2.36 and 7 TeV

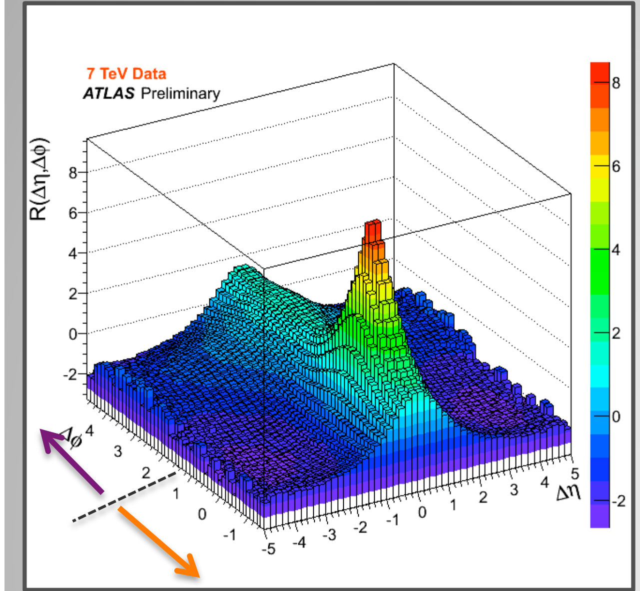




Comparison with CMS and ALICE!

1. Inelastic pp cross-section
2. pp cross-section differential in rapidity gap
3. Charged particle distributions
4. **Charged particle correlations**
   [ATLAS-CONF-2011-055]
5. Underlying Event with
   - charged particles
   - charged+neutral particles

Two particle correlations

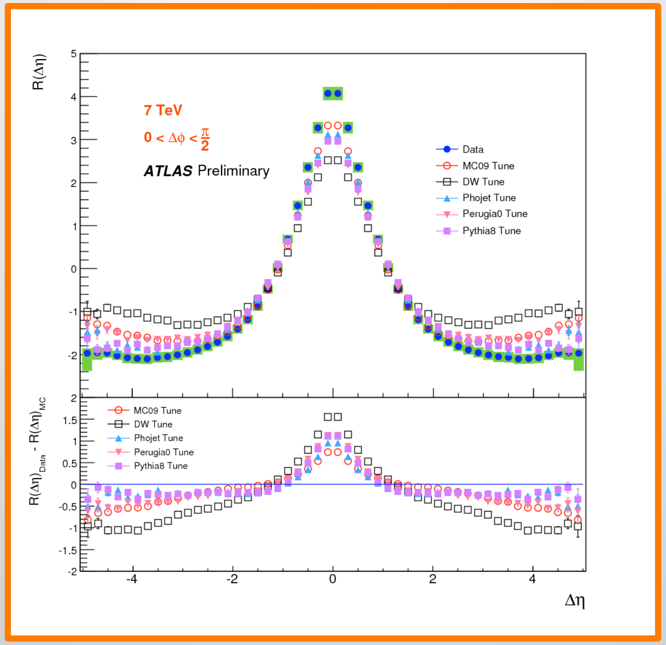


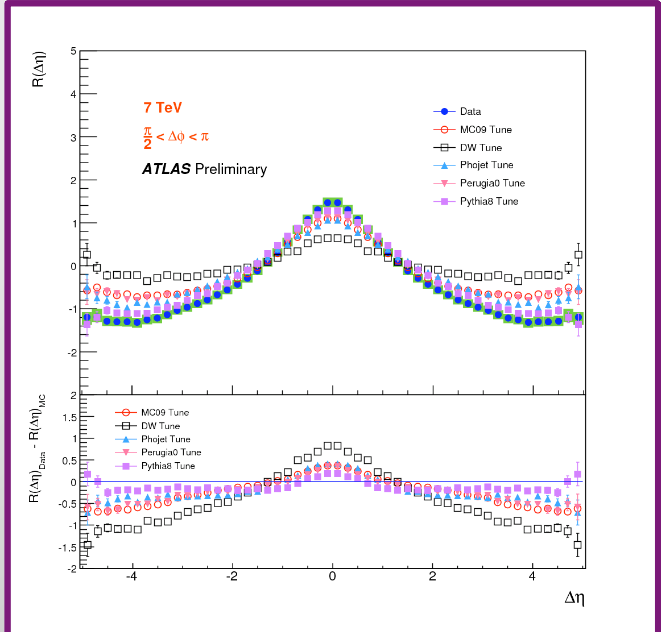
$R(\Delta\eta,\Delta\Phi) = (F(\Delta\eta,\Delta\Phi) - B(\Delta\eta,\Delta\Phi)) / B(\Delta\eta,\Delta\Phi)$ (+ normalisation factors)

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

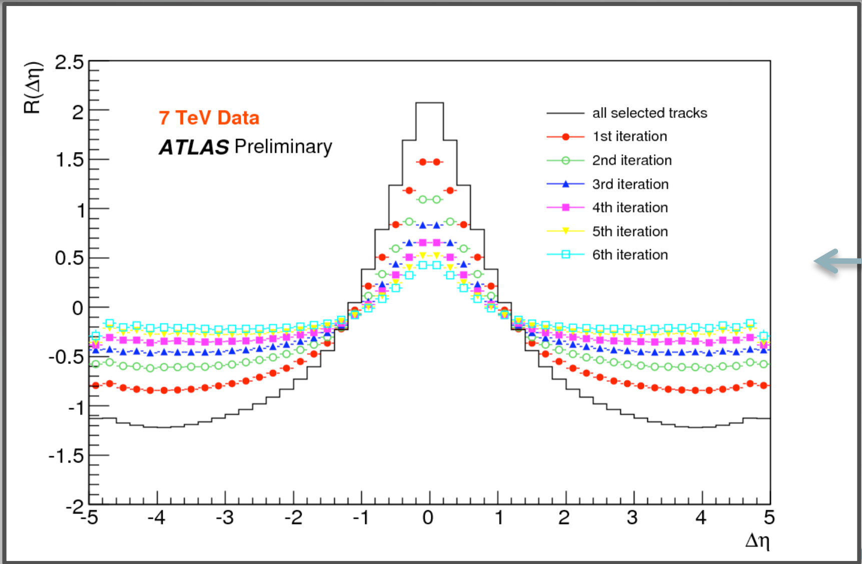
1D projections on Δη axis :
(ΔΦ projections not shown)

See Craig Buttar's dedicated talk
Tuesday at 15:00

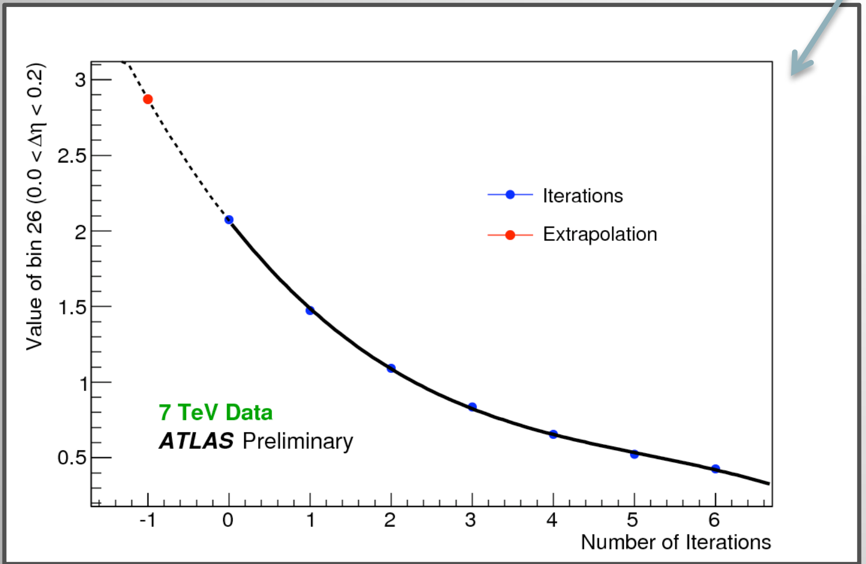


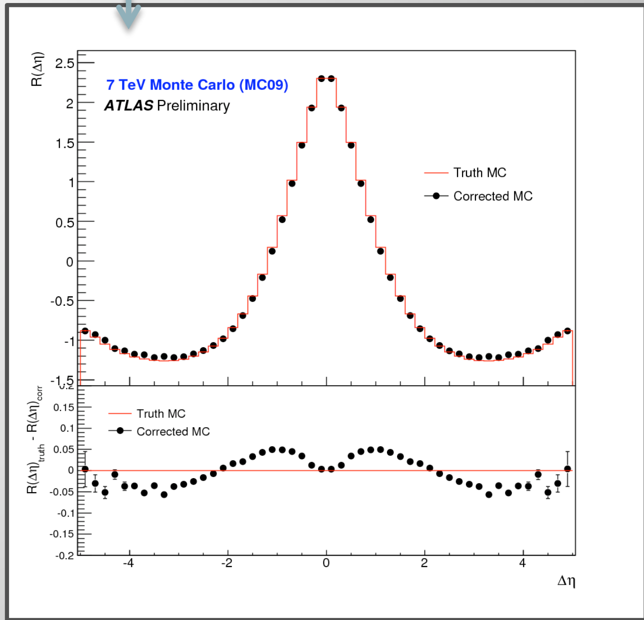


Two particle correlations : correction procedure



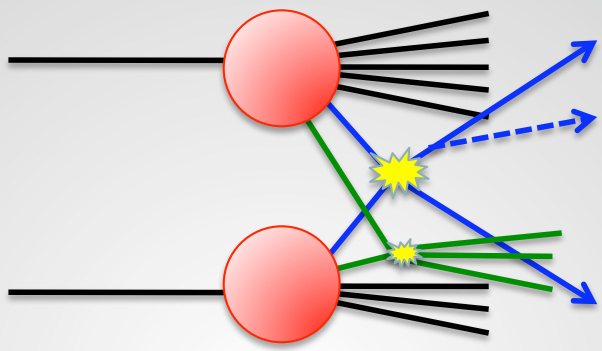
- In data :
  - ✓ Randomly throw tracks away according to known tracking efficiency
  - ✓ Iterate process 6 times $(\varepsilon_{trk})^6$
  - ✓In each bin, extrapolate back to -1: "truth"
- Test procedure on MC





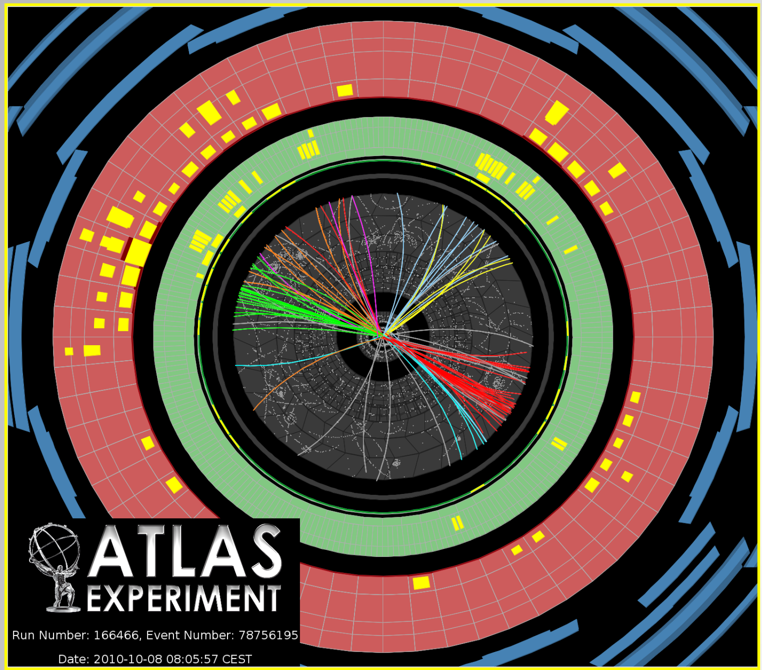
1. Inelastic pp cross-section
2. pp cross-section differential in rapidity gap
3. Charged particle distributions
4. Charged particle correlations
5. Underlying Event with
   - charged particles [Phys.Rev.D 83, 052005 (2011)]
   - charged+neutral particles [EPJC 71 (2011) 1636]

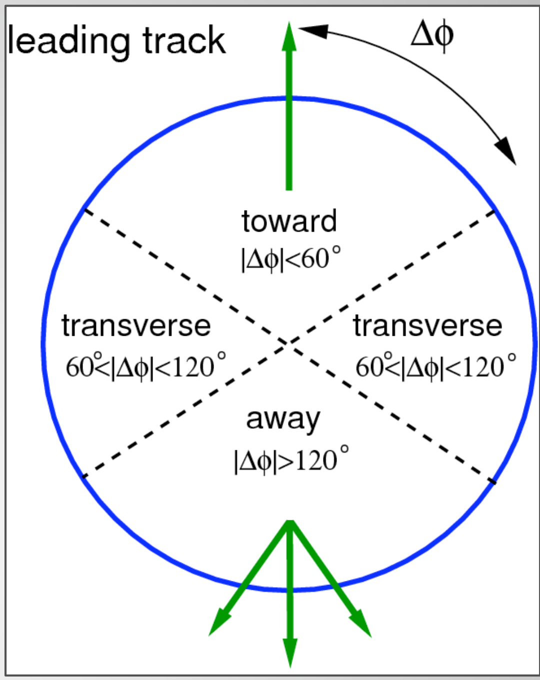
Multiple Parton Interactions



- Protons are made of quarks and gluons (partons)
- Additional partons *from the same proton* can interact (e.g. at the same time as Higgs production)
- Again : we rely on phenomenological models, tuned to data
- Need to measure distributions sensitive to Underlying Event (can include MPI, beam-beam remnants)

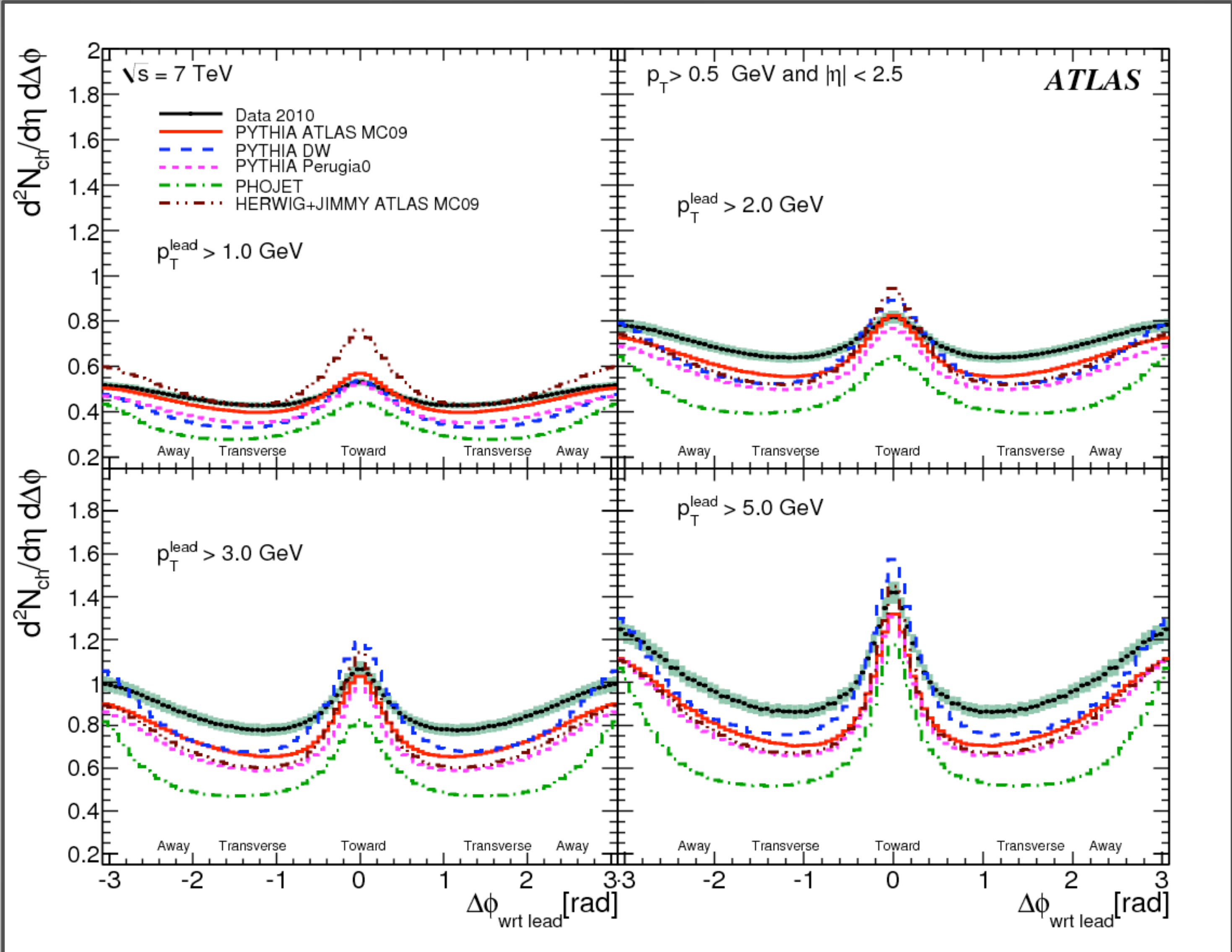
“Underlying Event” Measurements



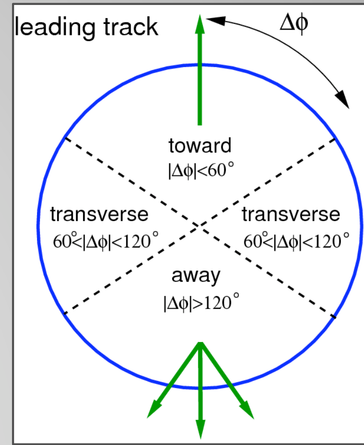


- Define the direction of the “hard scatter” as the highest p_T particle.
- Study the activity (# of particles or sum p_T) in the region “transverse” to the hard scatter

UE results

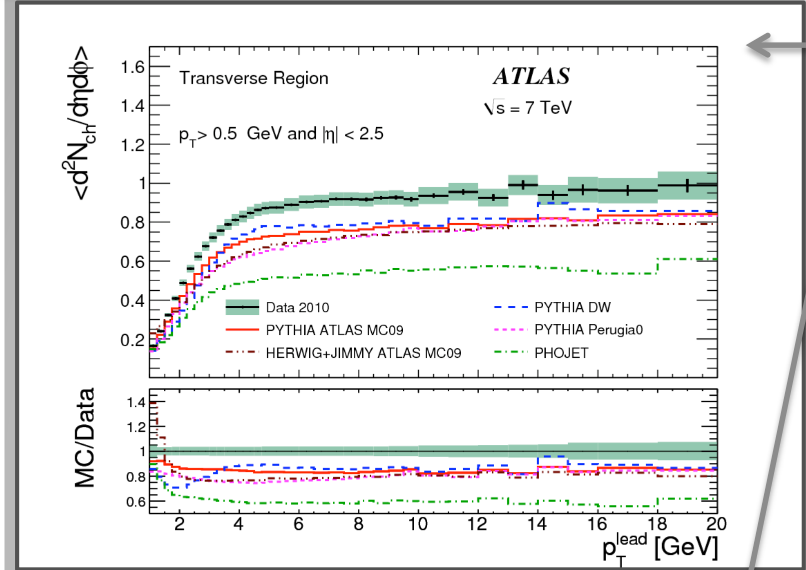


$\sqrt{s}$ = 7 TeV
p_T > 0.5 GeV and |η| < 2.5
ATLAS
Data 2010
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA Perugia0
PHOJET
HERWIG+JIMMY ATLAS MC09
p_T^{lead} > 1.0 GeV
p_T^{lead} > 2.0 GeV
p_T^{lead} > 3.0 GeV
p_T^{lead} > 5.0 GeV
$d^2N_{ch}/d\eta\, d\Delta\phi$
Away
Transverse
Toward
Transverse
Away
$\Delta\phi_{wrt\ lead}$[rad]

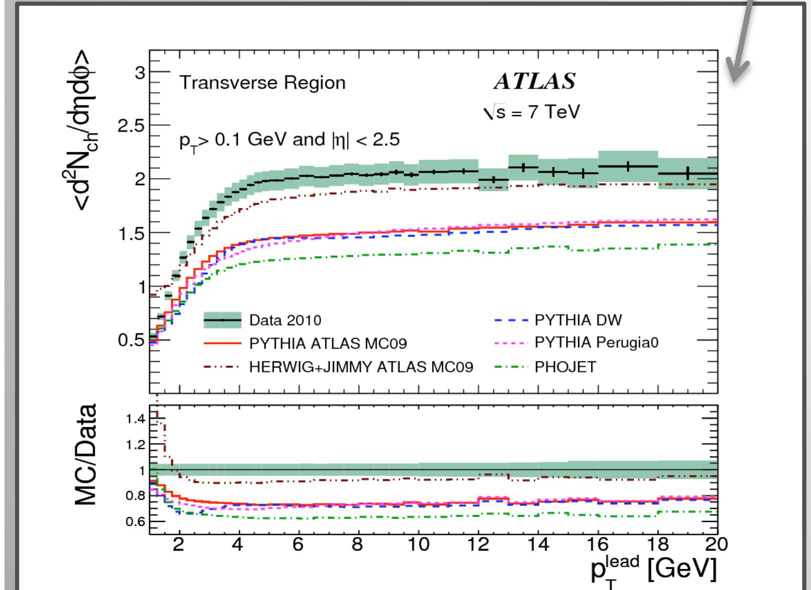


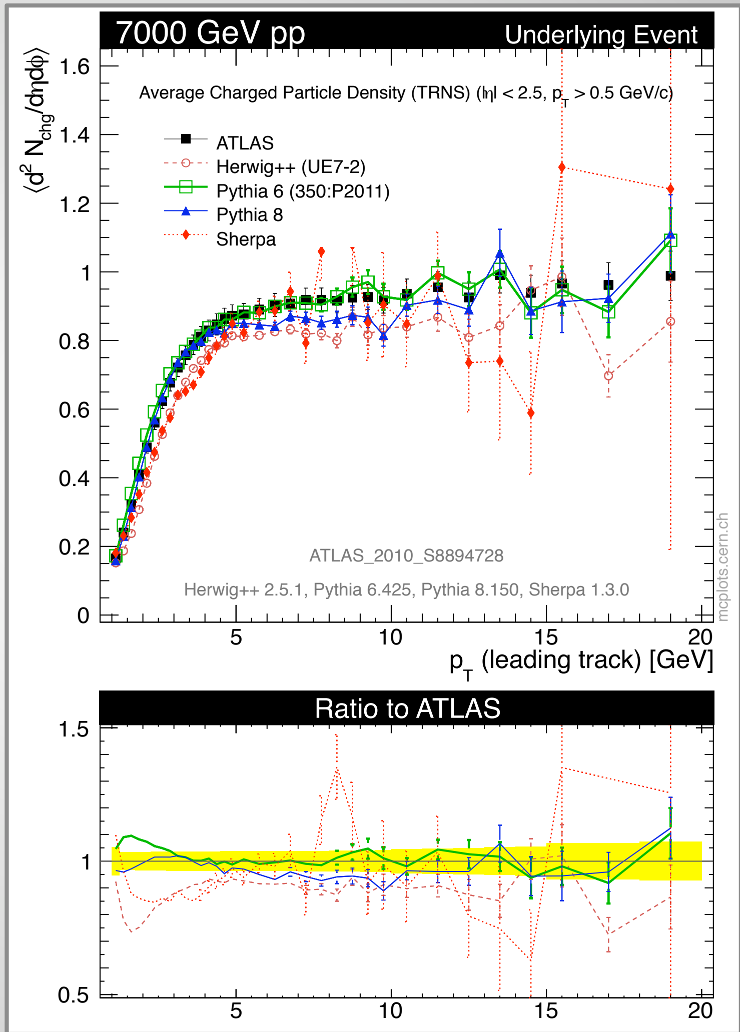
leading track
Δφ
toward
|Δφ|<60°
transverse
60°<|Δφ|<120°
transverse
60°<|Δφ|<120°
away
|Δφ|>120°

UE results

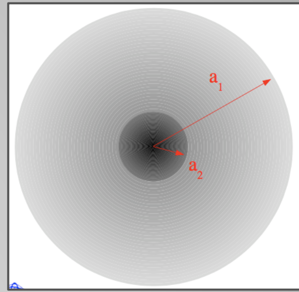


All pre-LHC tunes under-predict activity

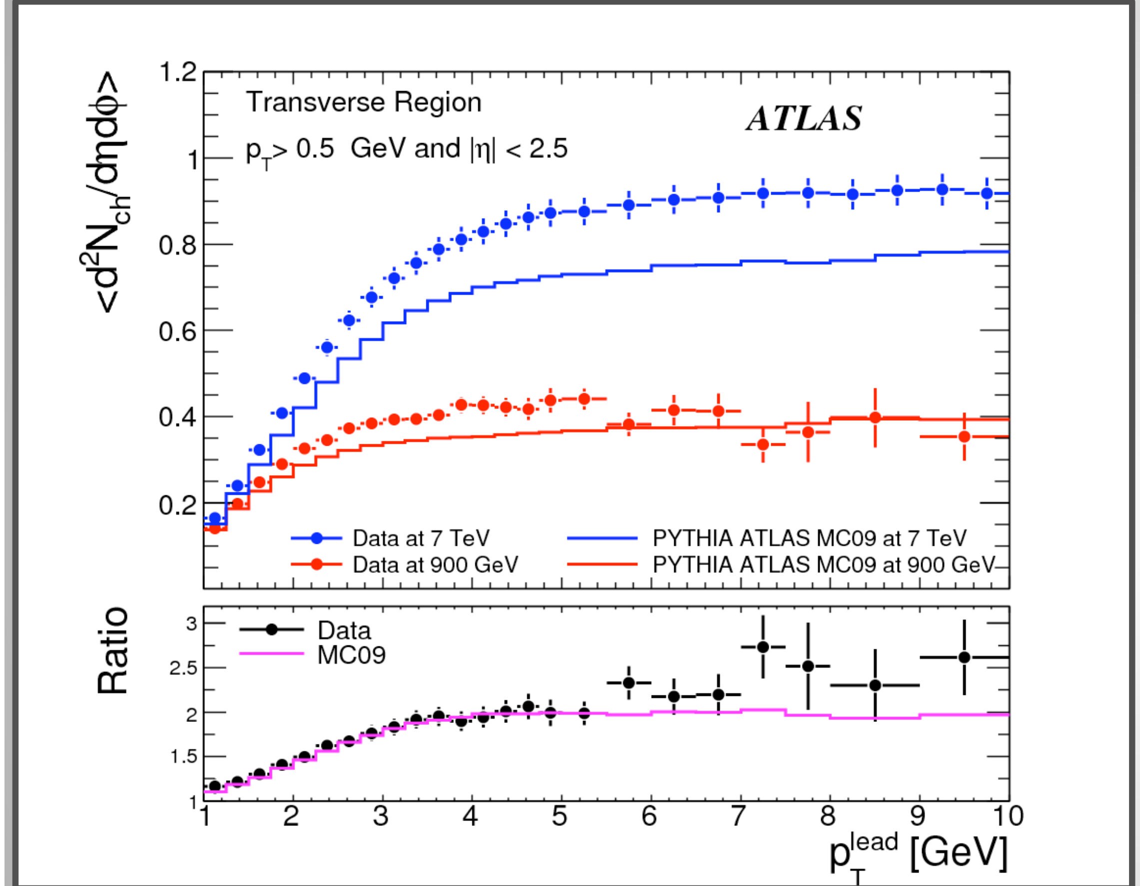


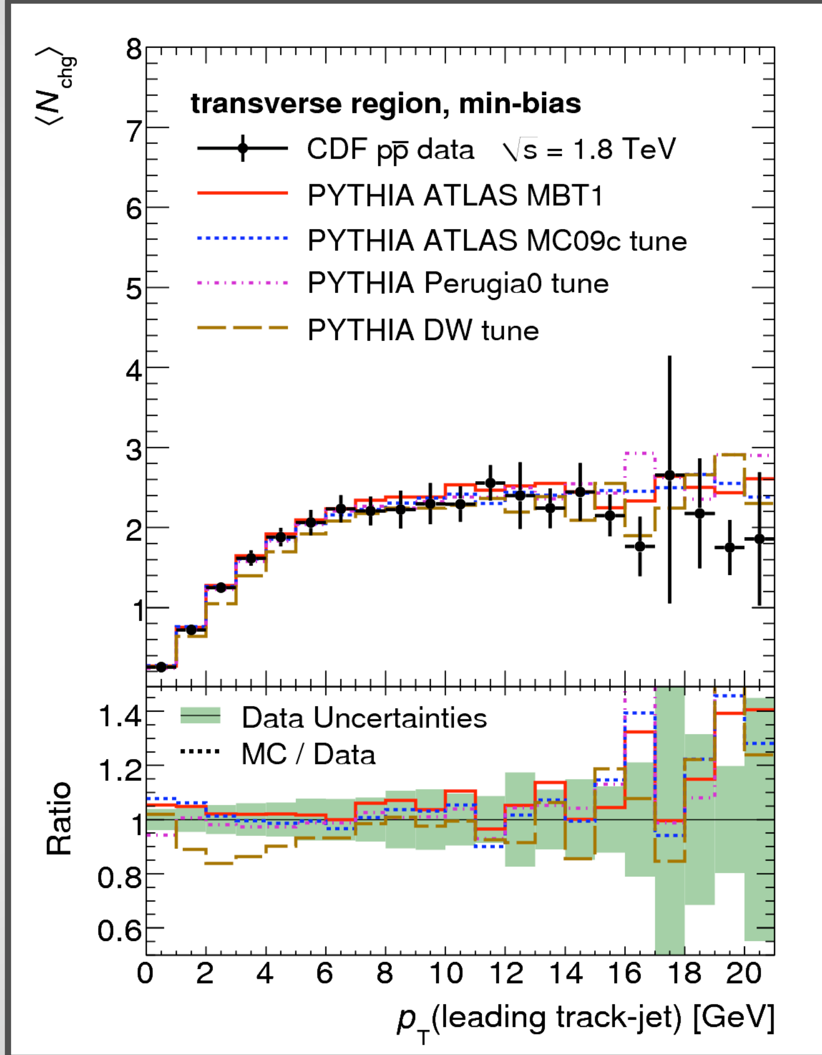


plot from mcplots.cern.ch



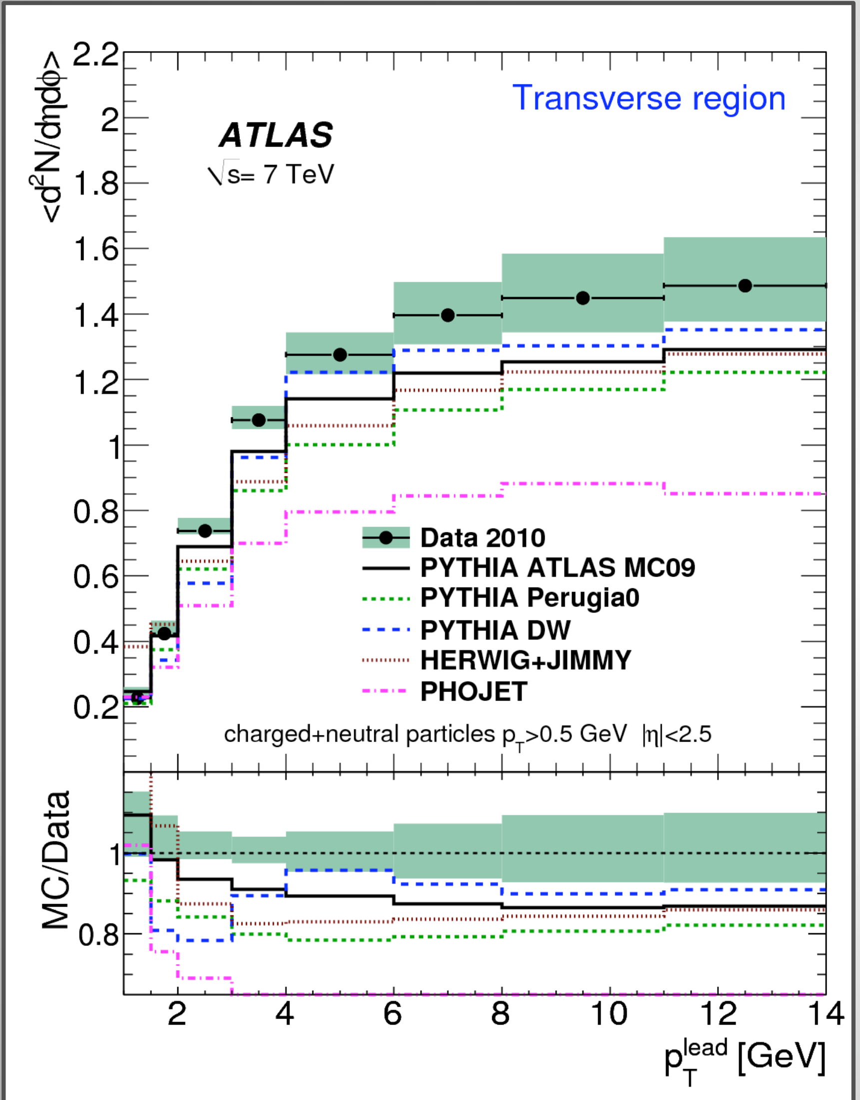
UE results



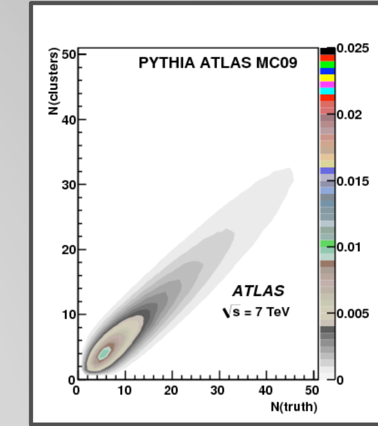


Inconsistency with Tevatron results? (1.8 TeV)
Inconsistency with ATLAS minbias results?

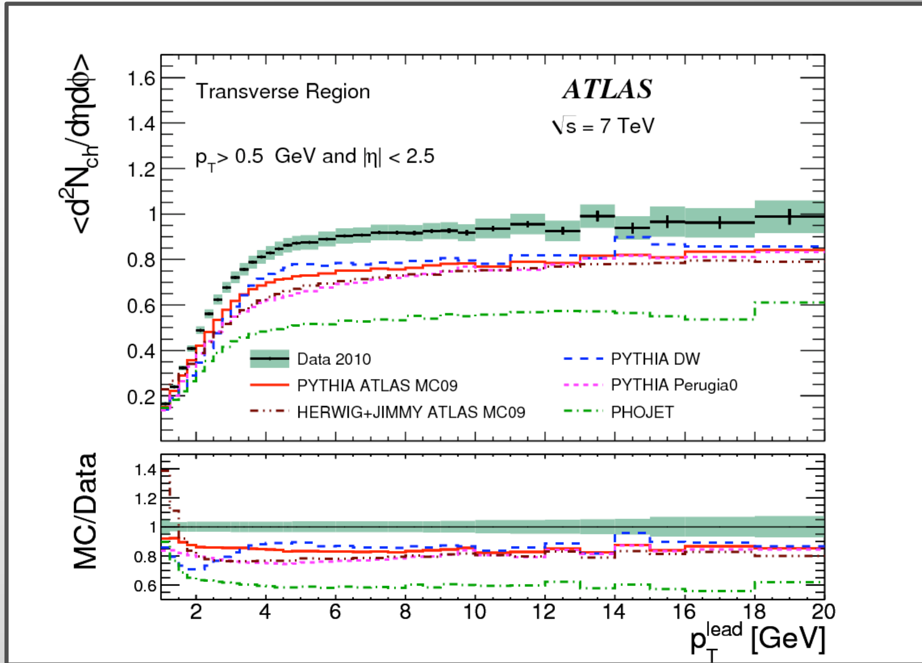
UE results with calorimeter



Count calorimeter clusters instead of tracks, also sensitive to neutral particles



compare to charged particle results



Summary

- Inelastic pp cross-section (new method!) and pp cross-section vs. $\Delta\eta$
  - cross-section lower than predictions
- Measurements of "minimum bias" and "underlying event" indicate a deficit of activity in models tuned to Tevatron data (tension with different energies, can this be resolved with new 2.76 TeV data?)
- Some tension between minimum bias and underlying event results (limitations in the models?)
- Models are being retuned (and new ones developed)
- Important to get it right as can affect : lepton ID, E_T^{miss} resolution, jets, jet vetos, high pileup simulations for upgrade, etc…

EXTRA SLIDES

TOTEM/ALPHA method

TOTEM Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC

The experimental method

- Well known **"luminosity independent"** method
  - Only method of practical use
- Total cross section and machine integrated Luminosity

$$N_{el} + N_{inel} = L\sigma_{tot}$$

- Total cross section and imaginary part of forward amplitude (Optical Theorem)

$$\left(\frac{dN_{el}}{dt}\right)_{t=0} = L\left(\frac{d\sigma}{dt}\right)_{t=0} = L\,\frac{\sigma_{tot}^2\left(1+\rho^2\right)}{16\,\pi}$$

- Combining the two, one writes the total cross section as a function of measurable quantities

$$\sigma_{tot} = \frac{16\pi\,(dN_{el}/dt)_{t=0}}{\left(1+\rho^2\right)\left(N_{el}+N_{inel}\right)}$$

- **Simultaneous measurement of low t elastic scattering and of inelastic interactions**

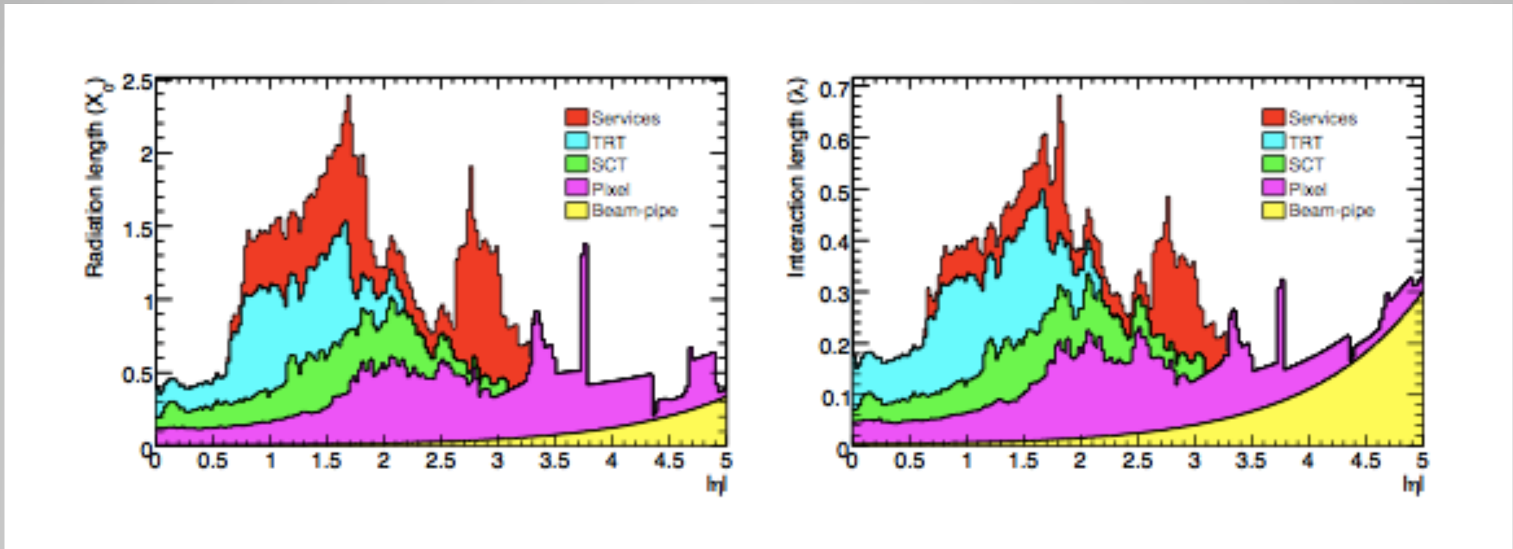
$$\rho = \mathcal{R}[f_{el}(0)]/\mathcal{I}[f_{el}(0)],$$

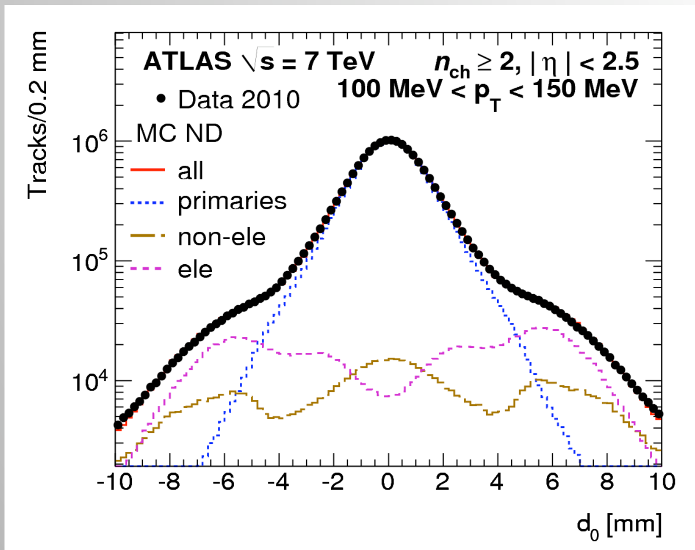
1st LHC Machine Experiments workshop on Luminosity Measurements

Marco Bozzo - 3

Cosmic ray measurements translate to pp with Glauber theory

Tracking





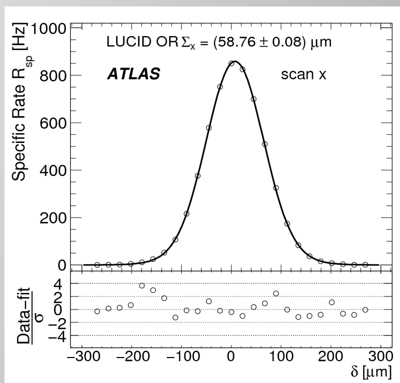
$\sigma(d_0)$ ~ 0.2 mm for 1 GeV (cut at 1.5 mm)

Van der Meer scans

$$\mathscr{L} = n_b f_r n_1 n_2 \int \hat{\rho}_1(x,y)\hat{\rho}_2(x,y)dxdy$$

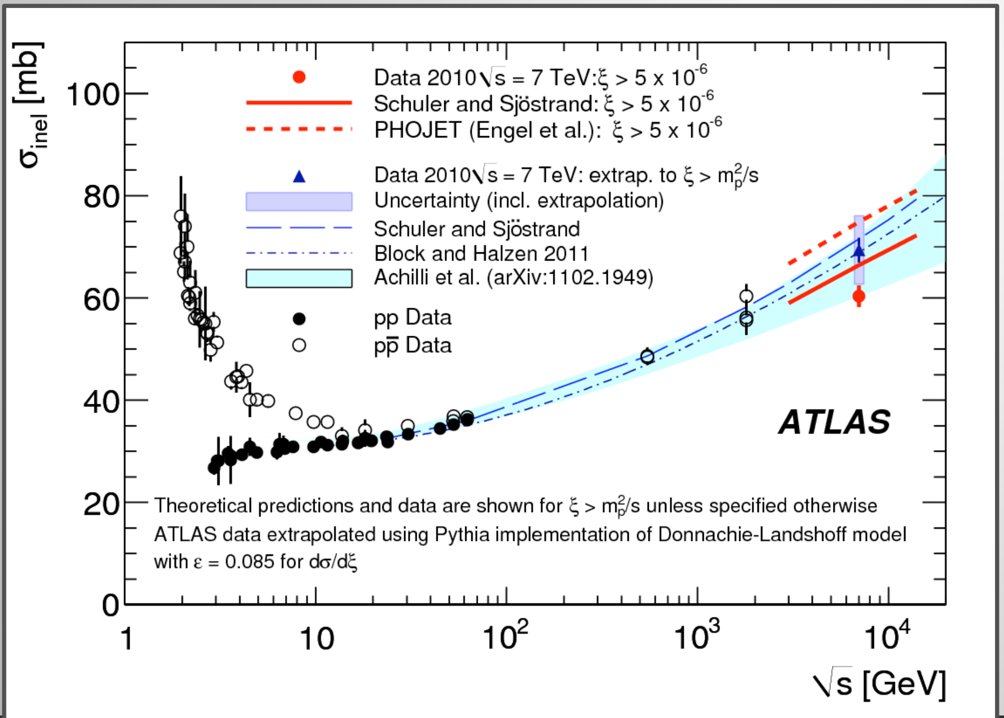
n_b = # bunches
f_r = revolution frequency
$n_{1,2}$ = # protons per bunch
$\rho_{1,2}$ = normalised particle density in transverse plane

- $\rho_{1,2}$ obtained from beam scans (where inelastic collisions are counted as beam separation is varied)
- Visible cross-section of luminosity detectors are normalised in special VdM runs and measured in subsequent runs.



Models

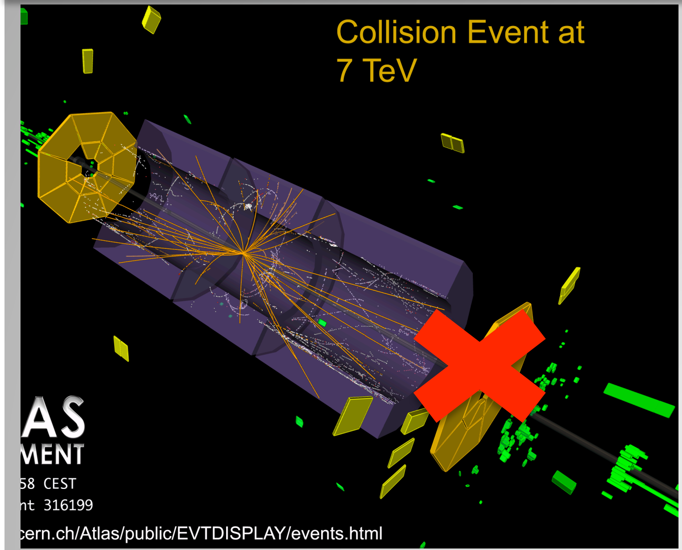
- Pythia (Schuler and Sjostrand) : Total cross-section from Regge theory: dominated at high energy by Pomeron exchange → DL paramerisation : $\sigma^{pp} = Xs^{\varepsilon} + Ys^{\eta}$ (ε = 0.081). Inelastic cross-section from optical theorem.
- Archilli *et al.* : Explicit calculation of inelastic cross-section dependent on average number of interactions (pQCD and soft gluon resummation)
- Phojet : Dual Parton Model (takes large N_{colour} limit) calculates cross-sections and uses Reggeon Field Theory. Uses a hard and soft pomeron with explicit cut-off of 3 GeV.

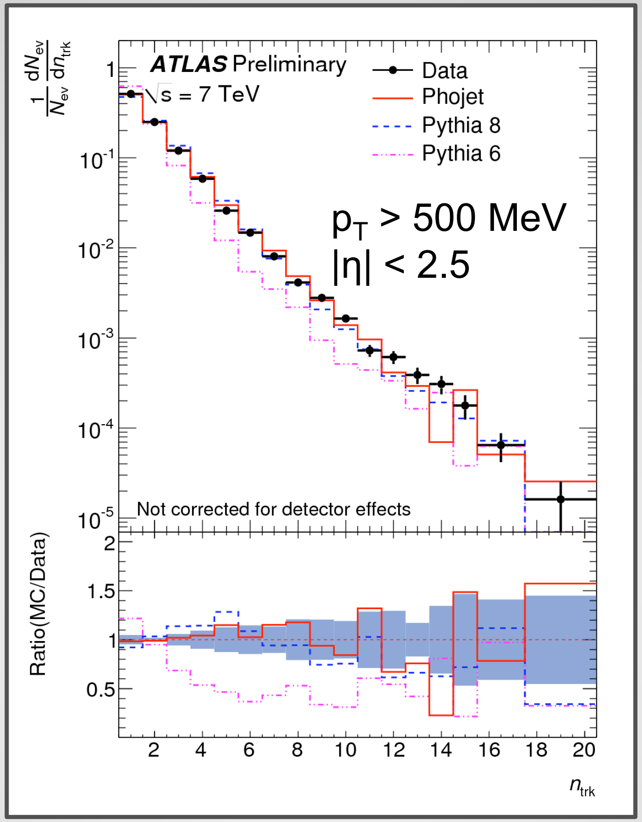


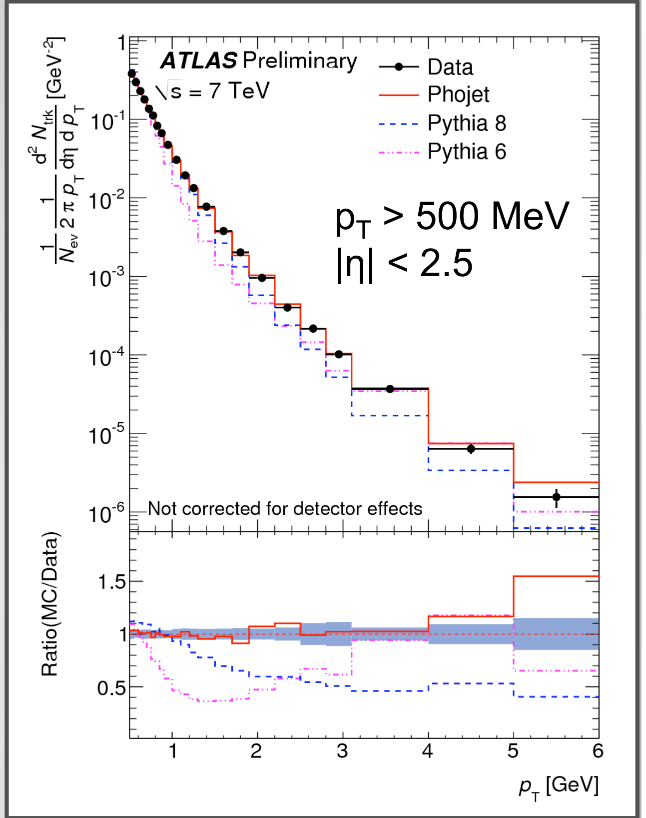
Extrapolation based on Donnachie +Landshoff :
$d\sigma_{sd}/d\xi \sim (1 + \xi) / \xi^{(1+\varepsilon)}$ with ε = 0.085

Diffraction enhanced minbias

no detector corrections yet! compared to full Sim MC!







Pythia diffractive model

- PYTHIA 6 :
  - For $M_X - M_p < 1$ GeV : isotropic 2-body decay of diffractive system
  - Otherwise : parton extracted from proton and string forms
- PYTHIA 8 only :
  - For $M_X > 10$ GeV : Pomeron←→ proton interactions occur using a Pomeron PDF, standard Pythia parton showering, MPI etc is then used

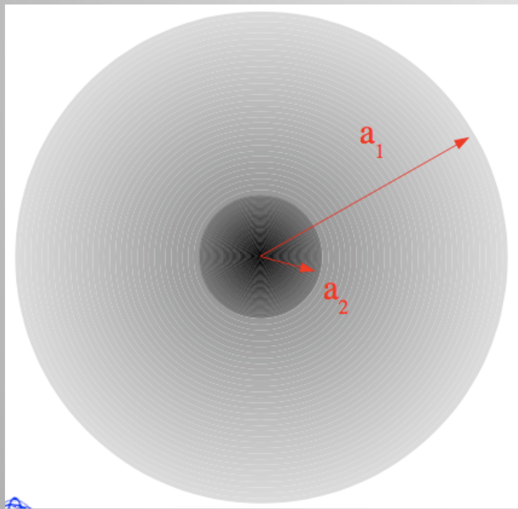
Pythia ND model

Regularisation of divergence in low p_T QCD 2→2 scattering via
$\alpha_S^2(p_T^2)/p_T^4 \rightarrow \alpha_S^2(p_T^2 + p_{T0}^2)/(p_T^2 + p_{T0}^2)^2$

Screening : Wavelength of exchanged particle becomes too large to resolve colour

p_{T0} = PARP(82) (E_{COM} / 1.8 TeV) $^{PARP(90)}$

(smaller p_{T0} → more low p_T activity)



Matter distribution of protons described by double Gaussian

PARP(83) = fraction in core Gaussian
PARP(84) = a_2 / a_1

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

PARP(X) = tunable parameters

Colour reconnection

Colour reconnection :

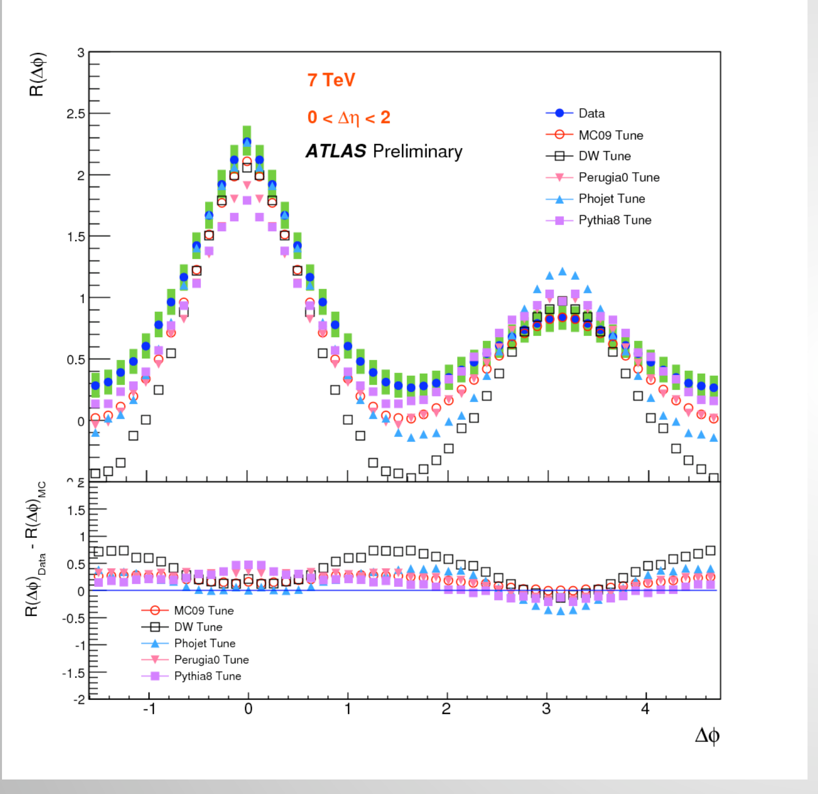
- Probability that a string piece *does not* participate in colour annealing : $(1 - \text{PARP}(78))^{n_{MI}}$ (n_{MI} =# of MPI)
- Suppression factor for colour annealing : $1 / (1 + \text{PARP}(77)^2 \cdot p_{avg}^2)$

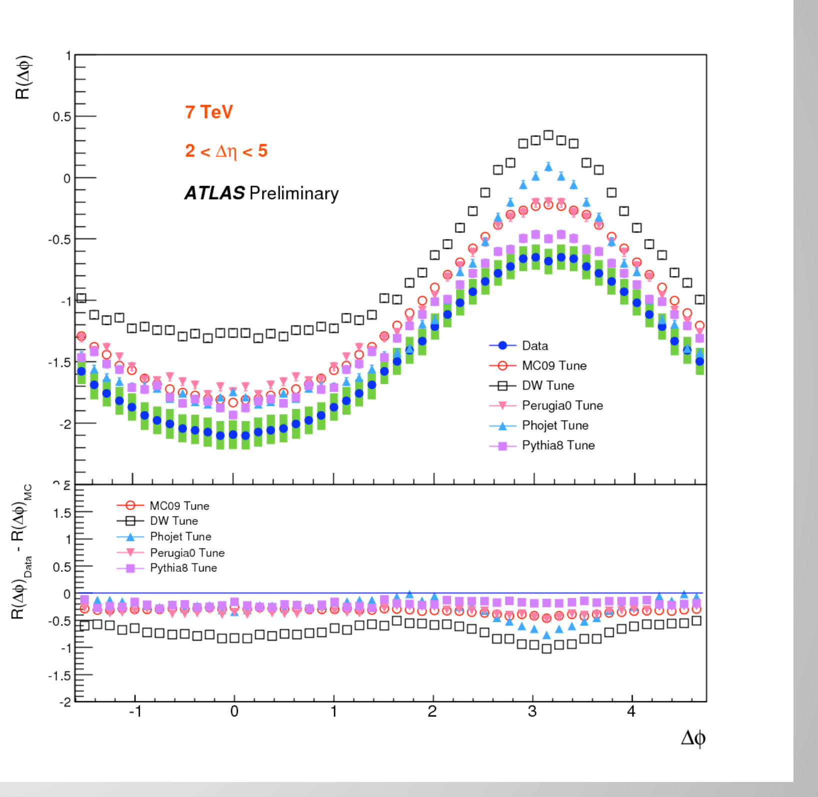
Mostly from PARP(77) : 0 → 1.016

PARP(77) : colour-reconnection suppression factor for high momentum hadrons

colour-reconnection leads to less hadrons for a given parton final state

2pc delta-phi projections





Minbias comparisons