Minimum bias and underlying event measurements with ATLAS

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University of Glasgow

(on behalf of the ATLAS Collaboration)

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Outline:

I. Introduction:

- The Large Hadron Collider – LHC
- ATLAS

II. ("soft") QCD measurements with ATLAS:

- Minimum bias events
  - charged particle densities
  - charged particle multiplicities
  - correlations
- The underlying event
  - track & calorimeter based measurements

III. Conclusions

The Large Hadron Collider: ATLAS data collection

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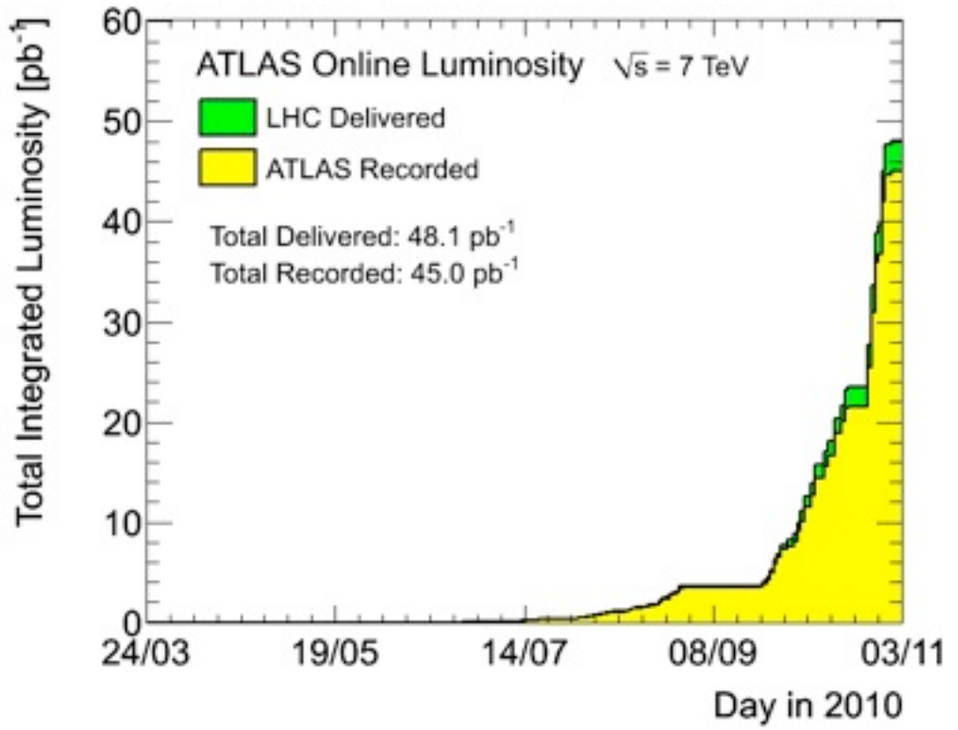
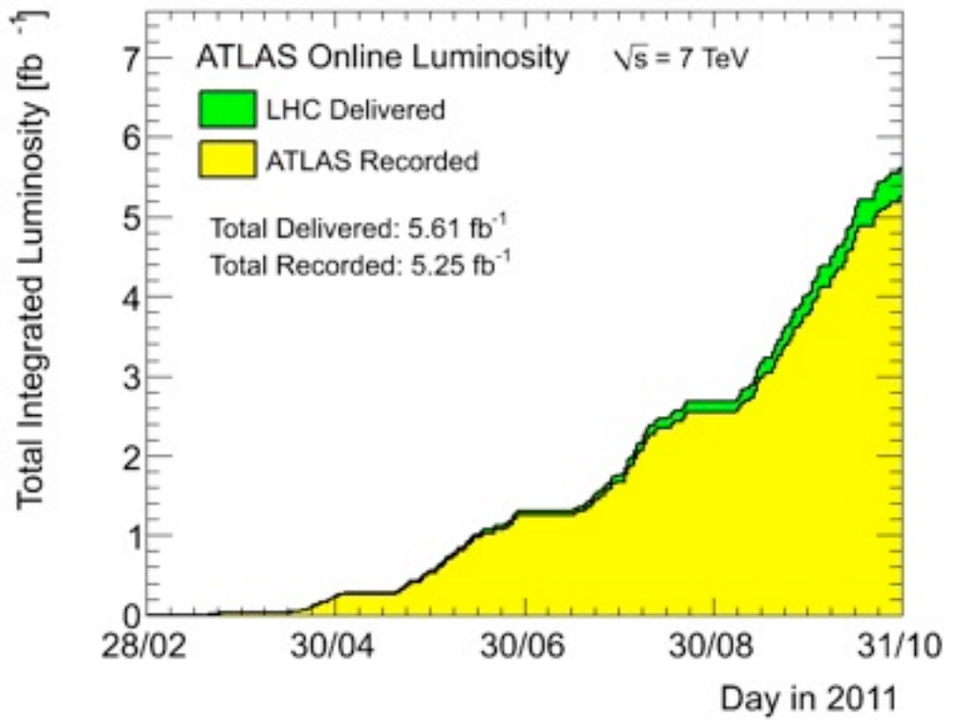
LHC News: http://lpc.web.cern.ch/lpc/

- **ATLAS pp collisions recorded thus far:**

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





- **2012: expect to accumulate ~15fb^{-1} of p-p collisions at $\sqrt{s}$ = 8 TeV.**

ATLAS luminosity (public plots): https://twiki.cern.ch/twiki/bin/view/AtlasPublic

The Large Hadron Collider: ATLAS data collection

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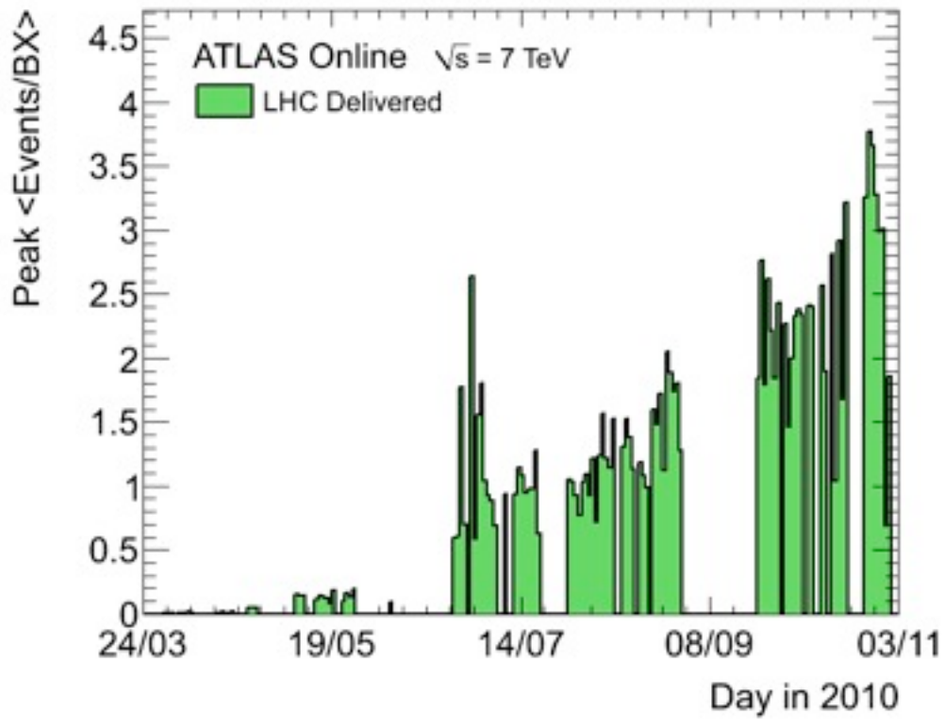

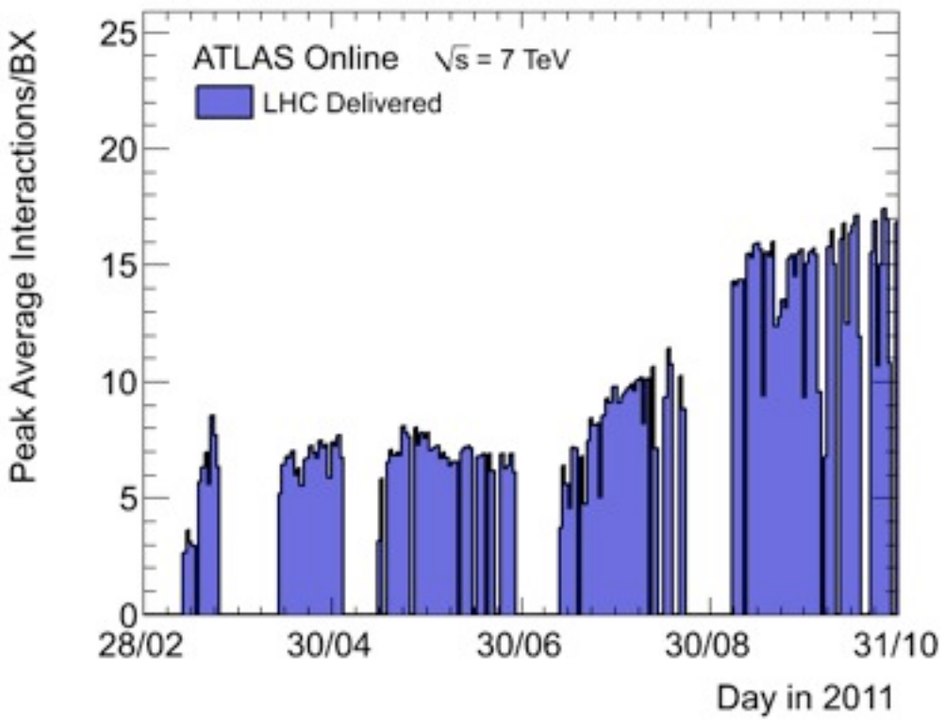

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ATLAS: A Toroidal LHC ApparatuS

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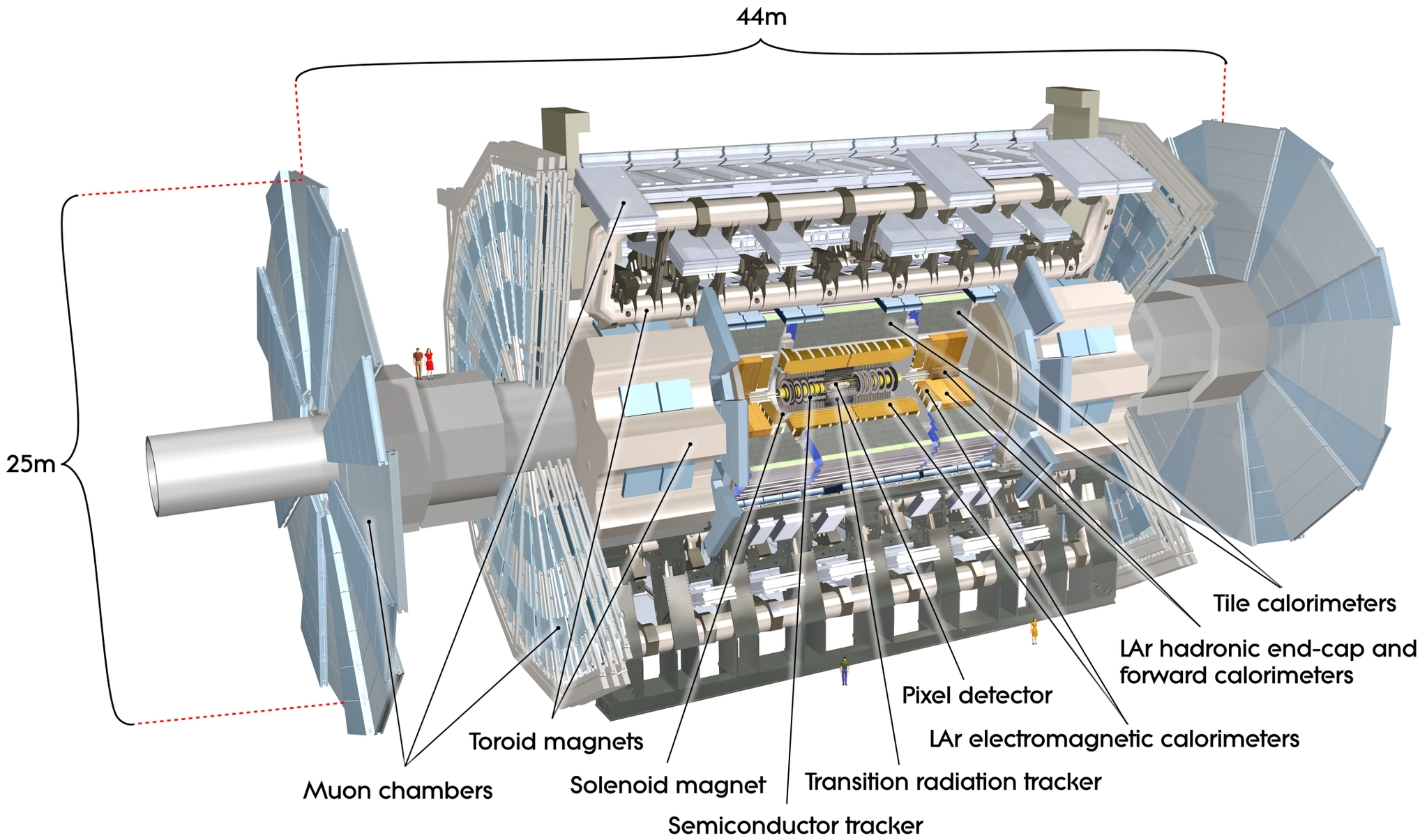
Electromagnetic and hadronic calorimeters:

sensitive to electrons/photons ($|\eta|<3.2$) and hadrons ($|\eta|<4.9$) that have E_T > a few hundred MeV.



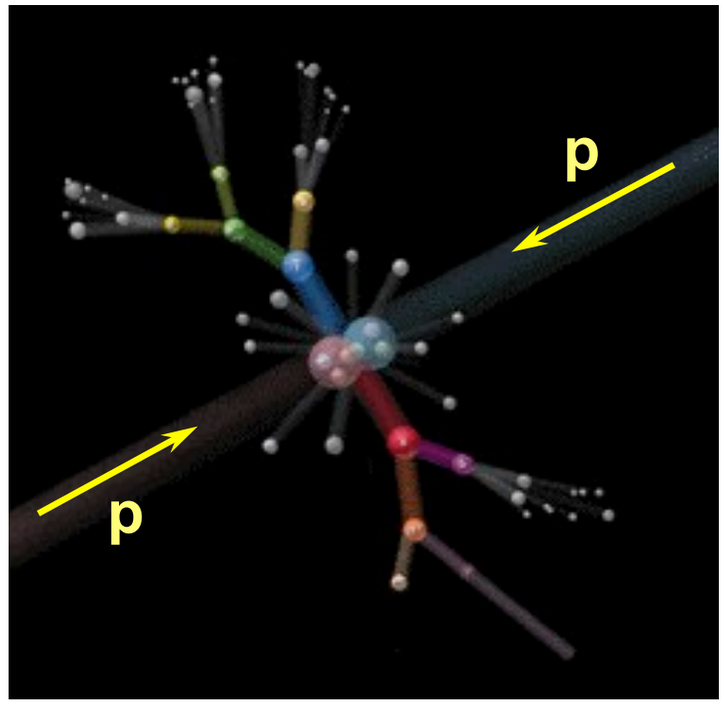
Inner tracking detectors:

sensitive to charged particles with p_T > 100MeV and $|\eta|$ <2.5

The ATLAS Collaboration, G. Aad *et al.*, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003

QCD at the LHC

- Essentially all physics at high-energy hadron colliders are connected to the interactions of quarks and gluons (small & large transferred momentum).
  - Hard processes (high-p_T): well described by perturbative QCD
  - Soft interactions (low-p_T): require non-perturbative phenomenological models



- Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…
- Inelastic hadronic events are dominated by “soft” partonic interactions.
- On average, inelastic hadron-hadron collisions have low transverse energy, low multiplicity.
- Most pile-up events are (soft) inelastic collisions.

Minimum bias and underlying event

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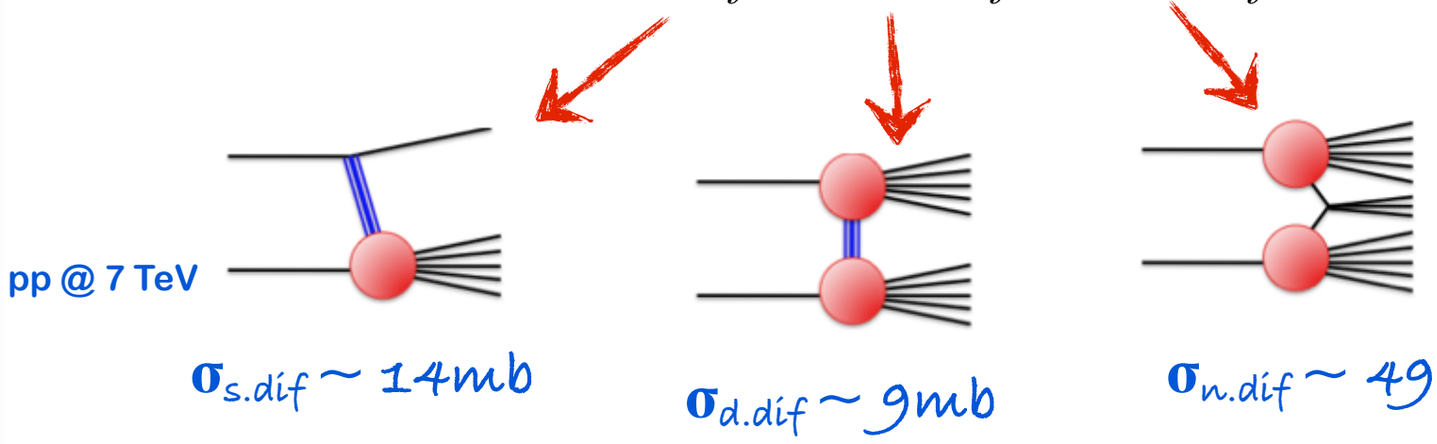
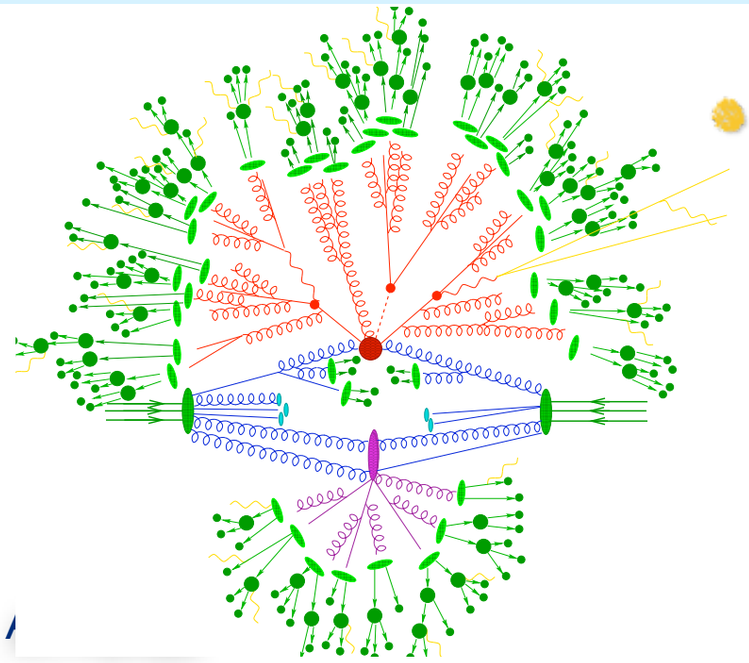
- Minimum bias: **experimentally defined to select events with the minimum possible requirements to ensure an inelastic collision occurred.**

$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$



- Note: exact definition depends on experiment (and analysis).

- The underlying event: **All particles from a single particle collision except the process of interest** (typically a hard process).



- parton showers (ISR/FSR)
  - multiparton interactions
    - beam remnants
      - colour field connecting hard-scatter to beam remnants

ATLAS soft-QCD measurements

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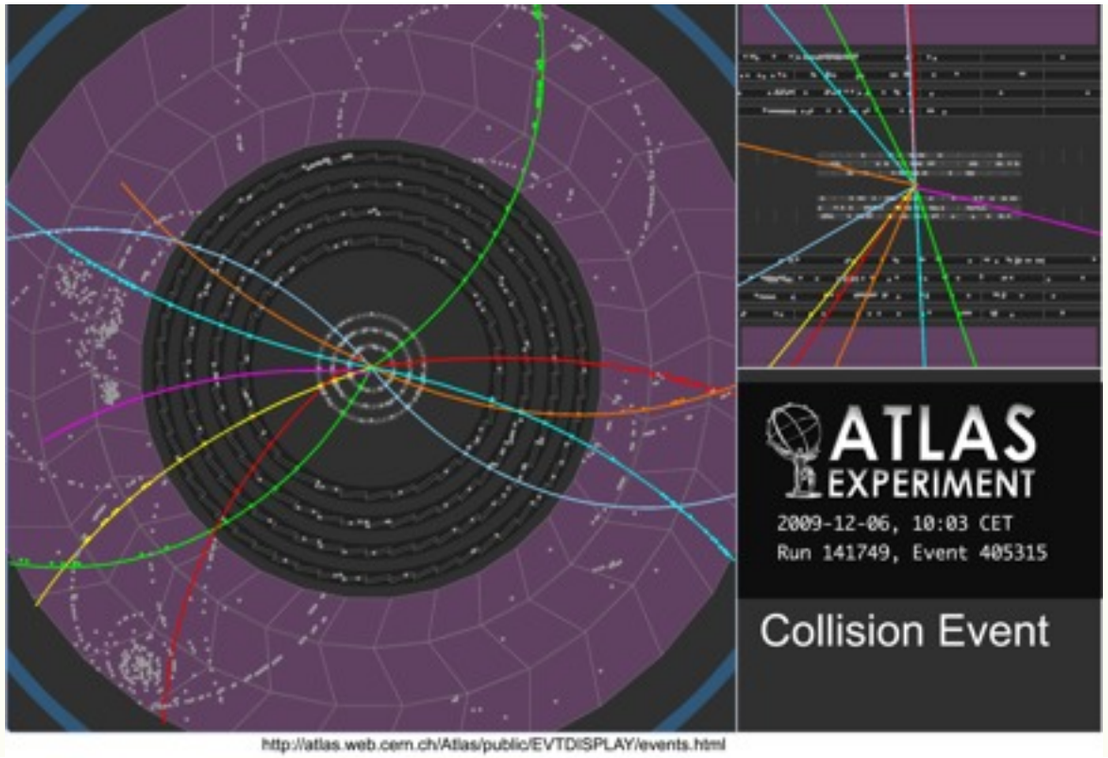
- NEW! Two-particle angular correlations: arXiv:1203.3549 [hep-ex] (submitted to JHEP)
- NEW! Forward-backward correlations: arXiv:1203.3100 [hep-ex] (submitted to JHEP)
- NEW! Azimuthal ordering of charged hadrons: arXiv:1203.0419 [hep-ex] (submitted to PRD)
- Ks and Λ production : Phys Rev D 85 (2012) 012001
- Rapidity gap cross sections: arXiv:1201.2808 [hep-ex] (submitted to EPJC)
- Charged particle multiplicities: New J Phys 13 (2011) 053033 and Phys Lett B 688 (2010) 21
- Underlying event with charged particles: Phys Rev D 83 (2011) 112001
- Underlying event with charged and neutral particles: EPJC 71 (2011) 1636
- Inelastic p-p cross section: Nature Comm 2 (2011) 463

More can be found at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#Soft_QCD

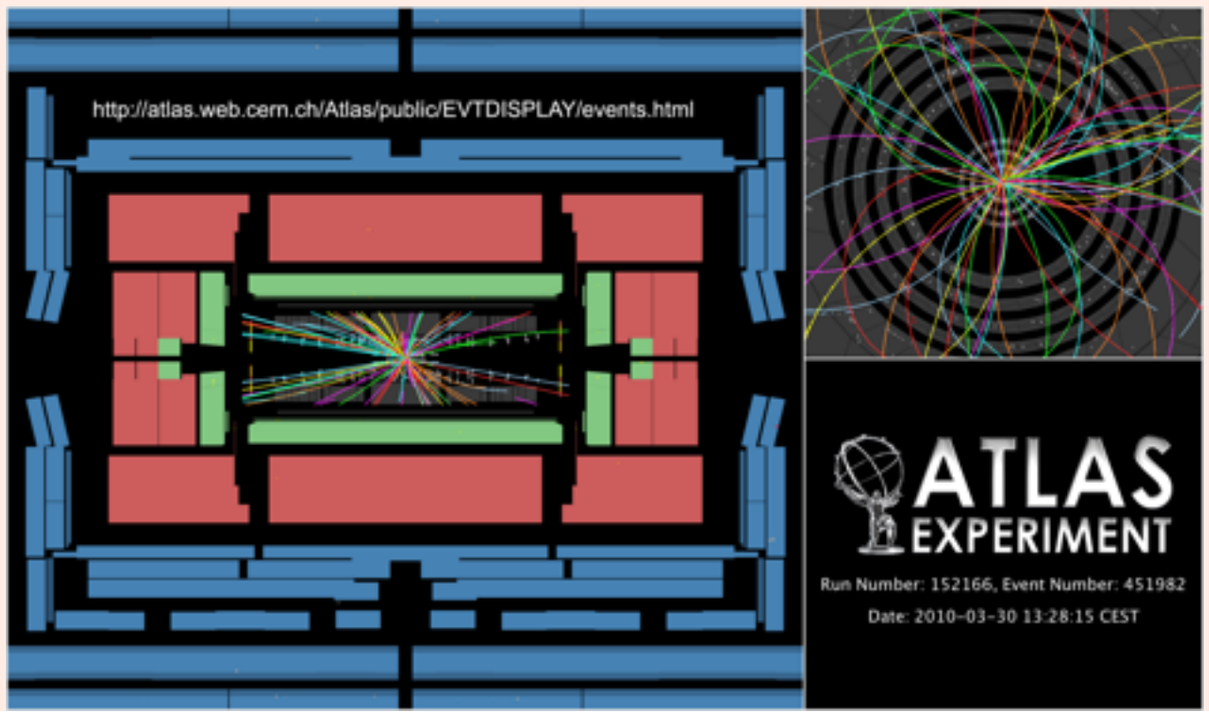
Measuring “minimum bias” events at ATLAS



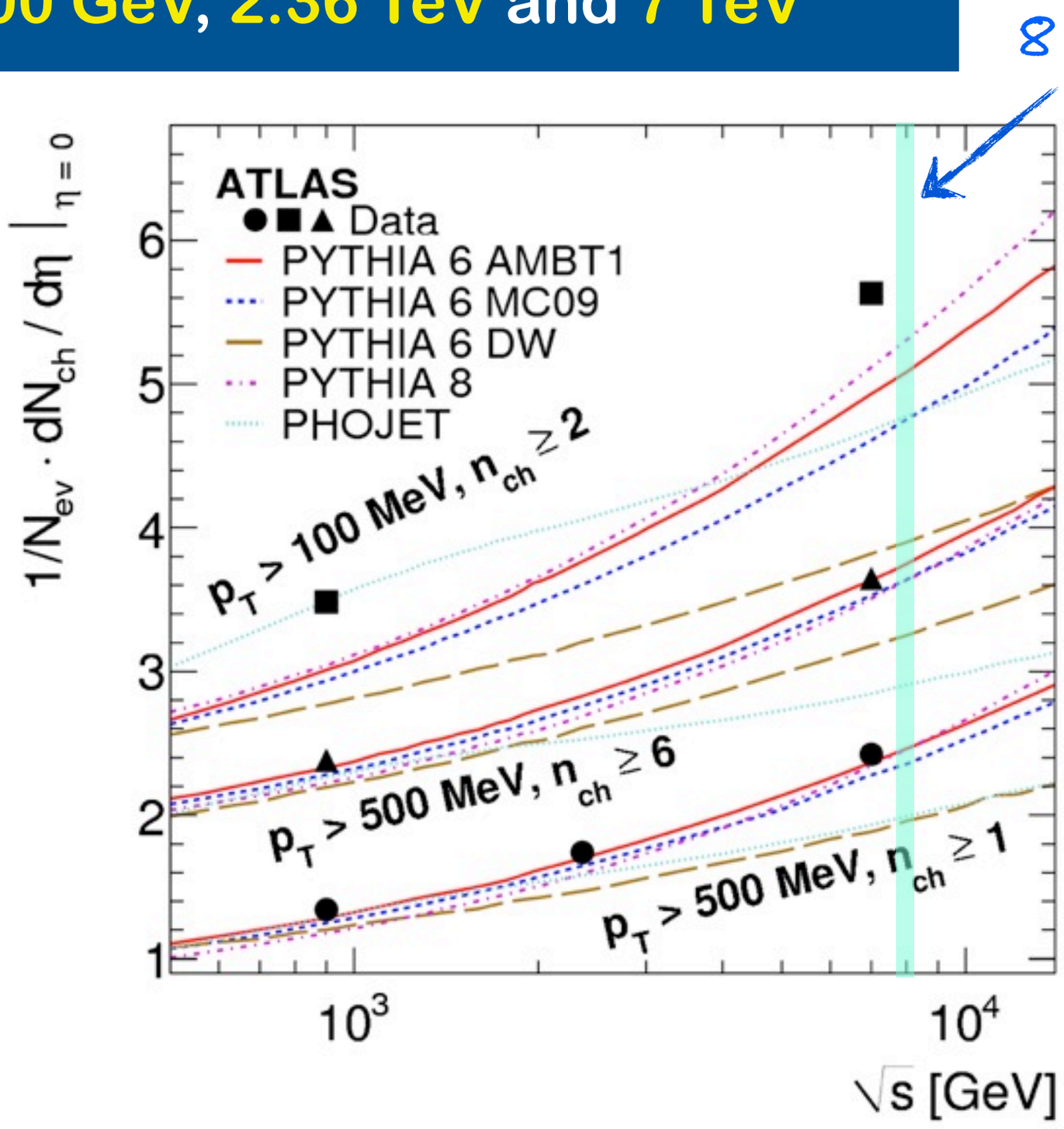
- Event display: pp collision at $\sqrt{s}$=900GeV
- First physics publication with ATLAS measurements: Phys Lett B **688**, Issue 1, 21–42

- Event display: pp collision at $\sqrt{s}$=7 TeV
- Results for 7 TeV p–p collisions as well as 2.36 TeV and 900 GeV can be found in:

New J Phys 13 (2011) 053033

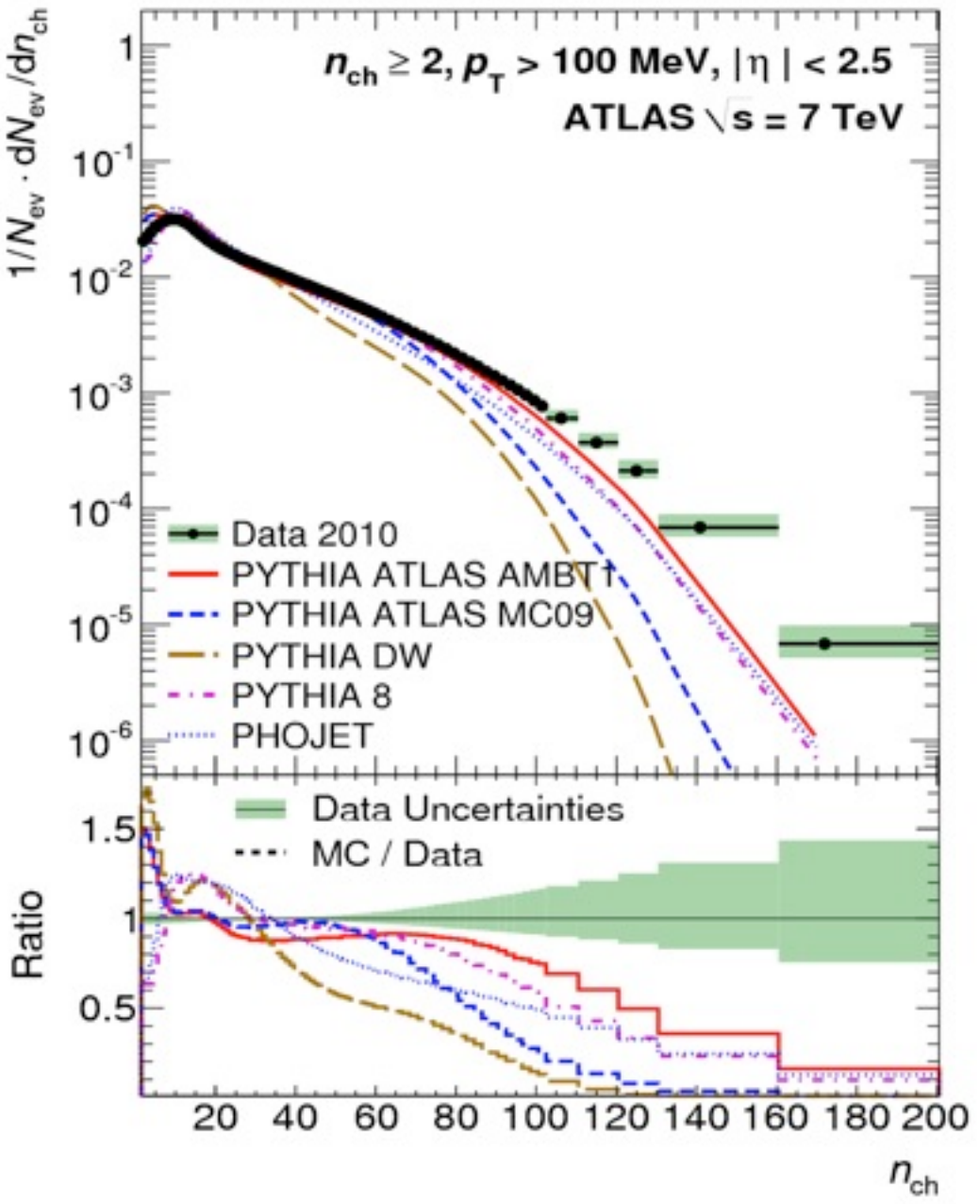


Charged particle density in η: √s=900 GeV, 2.36 TeV and 7 TeV



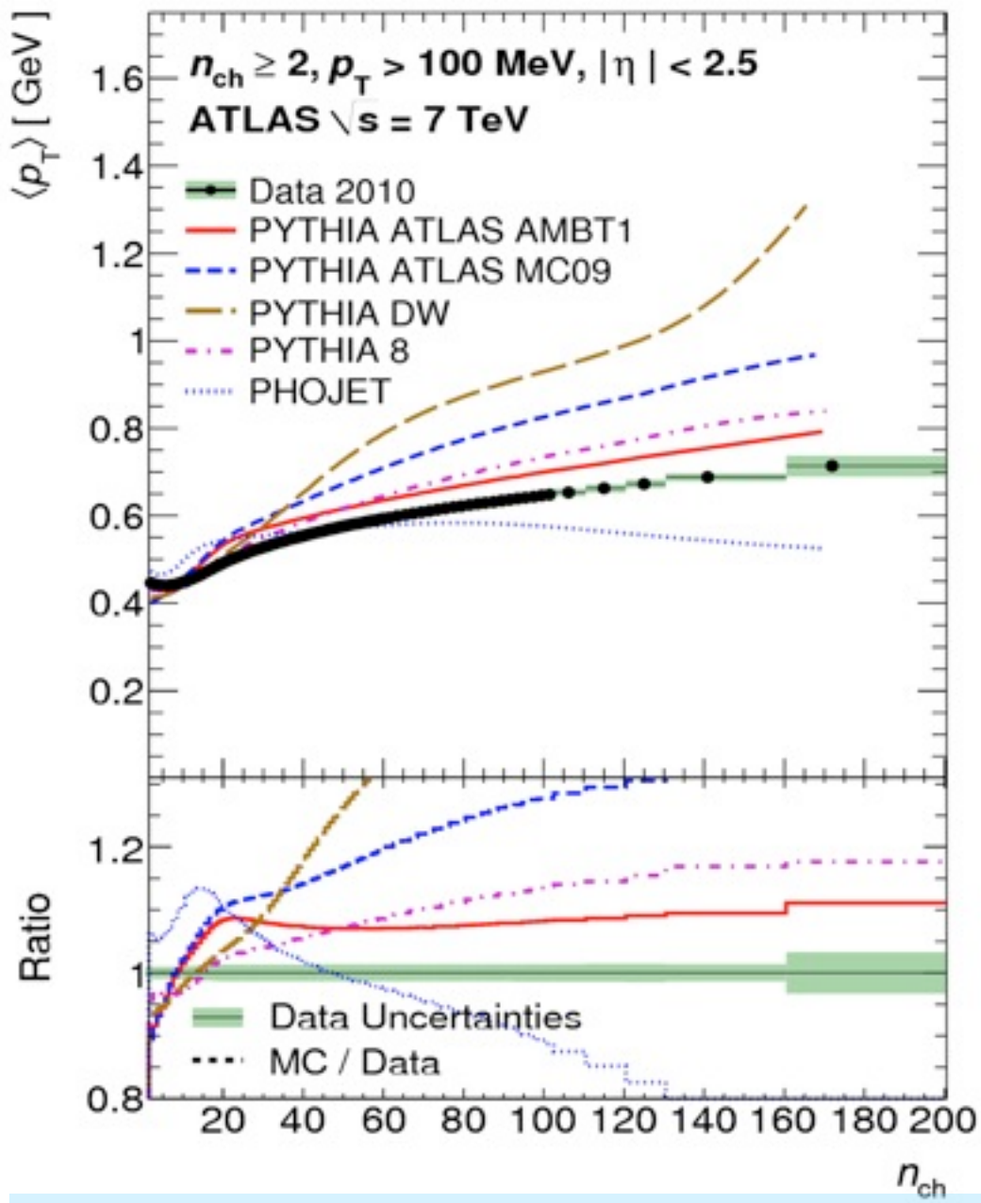
- Measurements at different c.m. energies are crucial for an accurate understanding (prediction) of the evolution of inelastic hadronic processes.

Charged particle multiplicity distributions



- Charged particle multiplicity distributions: high n_{ch} tail not described by MC tunes! Problems also in low n_{ch} bins.

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



- As low-p_T particles are added to the measurements, MC models no longer describes the data. Generated particles are, on average, harder than what we see in the data.

Forward-backward correlation

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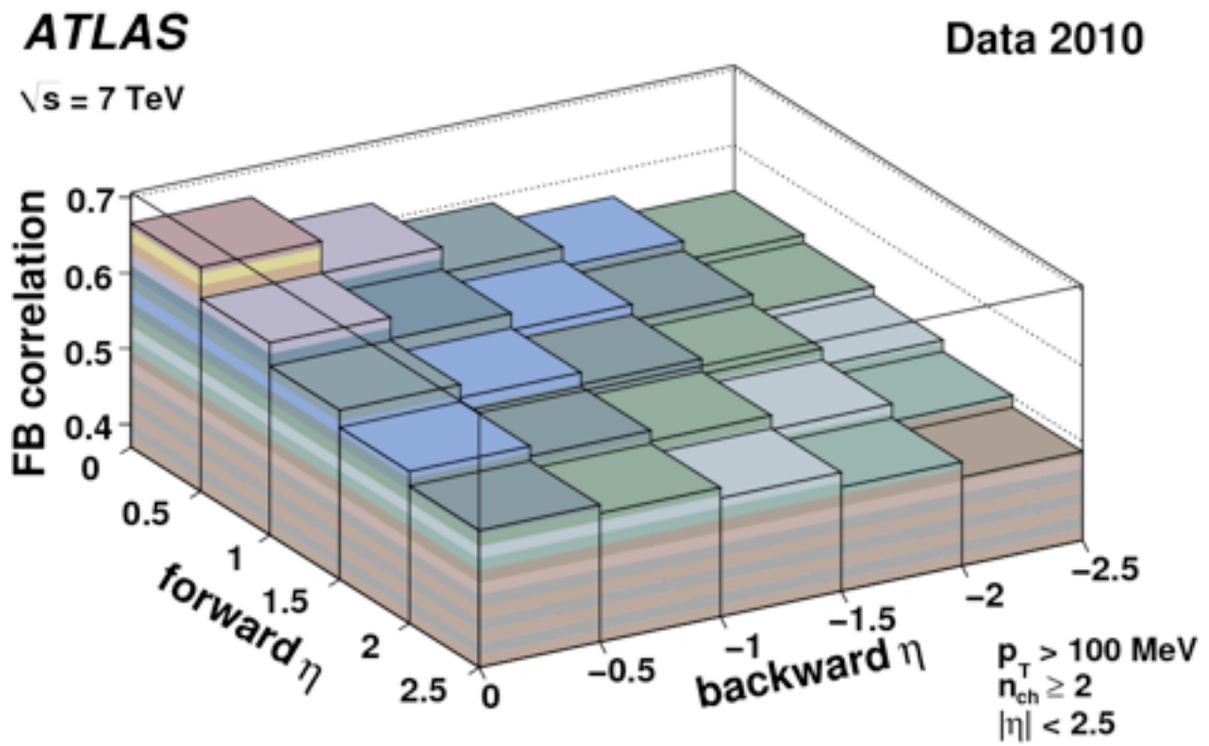
- Measurement of the correlation between charged particle multiplicities in the forward and backward regions of the ATLAS detector.

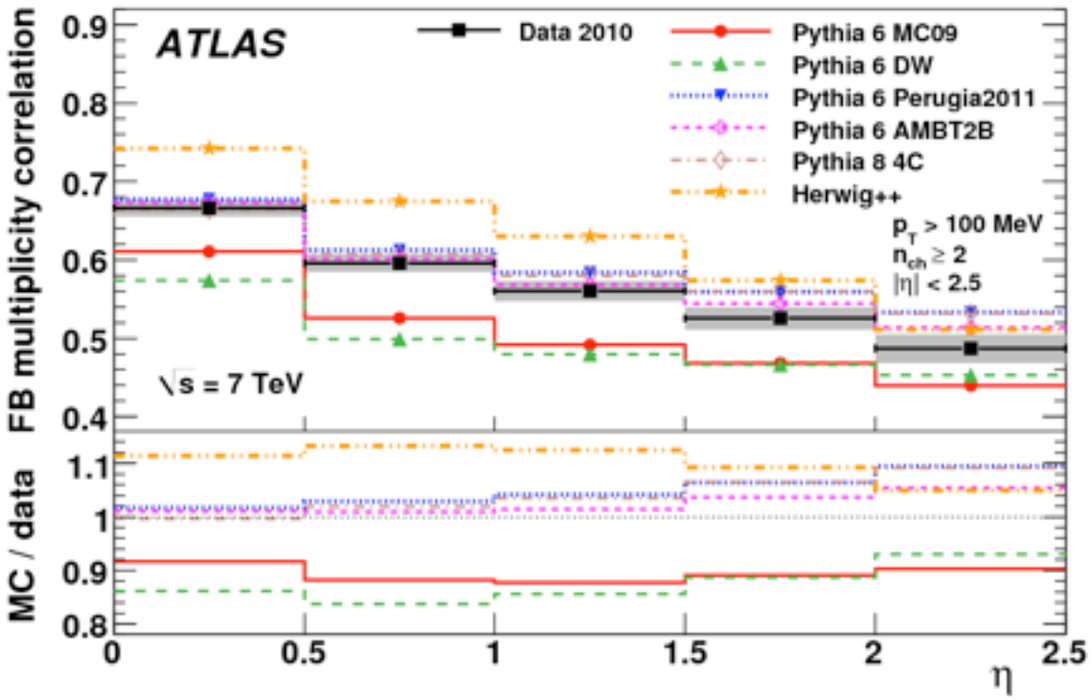
$$\rho_{fb}^{n} = \frac{\langle (n_f - \langle n_f \rangle)(n_b - \langle n_b \rangle) \rangle}{\sqrt{\langle (n_f - \langle n_f \rangle)^2 \rangle \langle (n_b - \langle n_b \rangle)^2 \rangle}}$$



- n_f and n_b are the multiplicity (per event) in a forward and backward pseudorapidity intervals.

- The data is corrected for detector-related effects that would reduce the correlation.

- Latest MC tunes adequately capture the correlations observed in the data.



Two-particle angular correlation

- Measurement of two-particle angular correlations in pseudorapidity (η) and azimuthal angle (φ) for charged particles.

- Observable is sensitive to the underlying mechanisms of soft particle production.

  - correlations between final states can indicate a common origin of production.

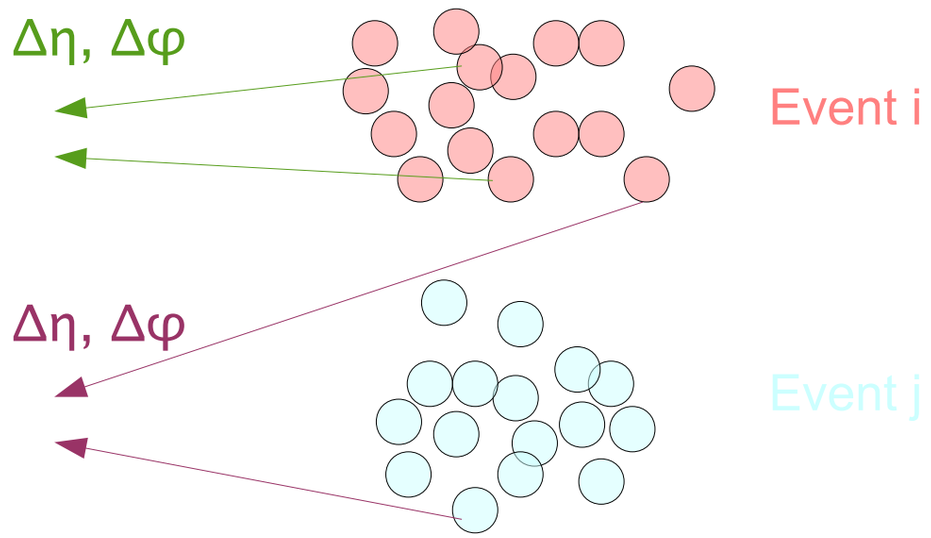
  - gives indication about multi-particle dynamics in heavy-ion collisions.

- Two-particle angular correlation is defined as:

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

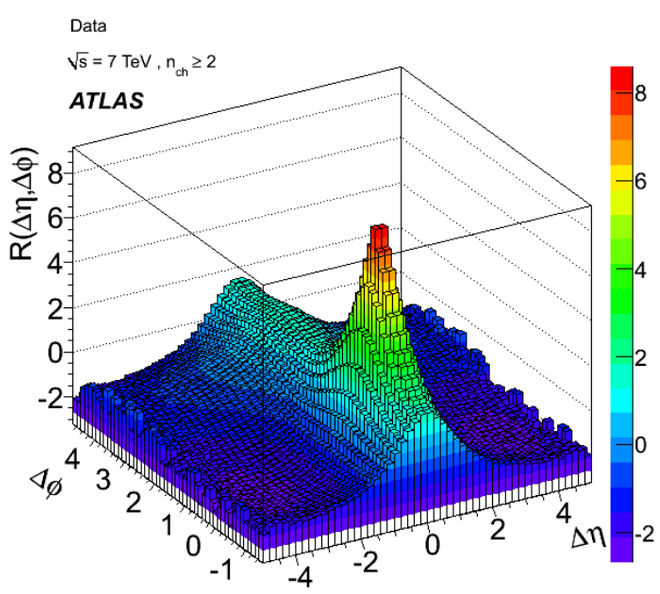
Foreground (F): all particle pairs in same event (correlated + uncorrelated pairs)

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

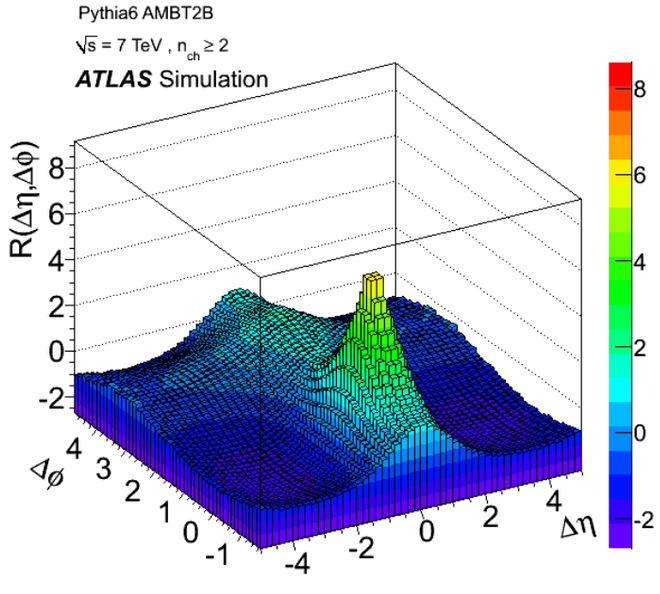


arXiv:1203.3549 [hep-ex] (submitted to JHEP)

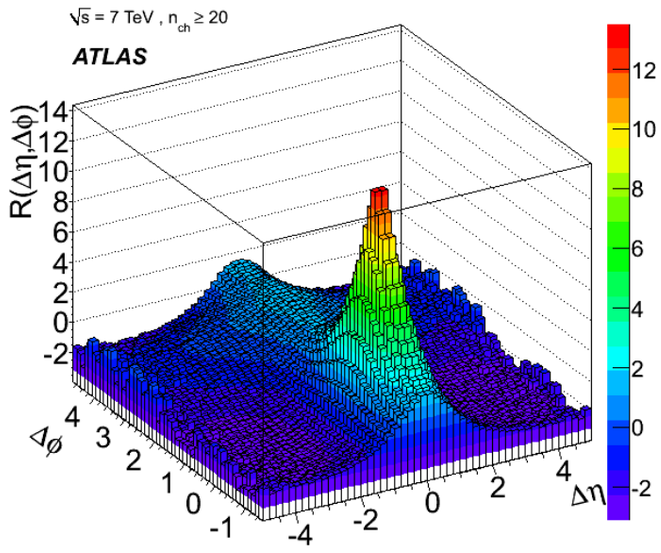
Two-particle angular correlation



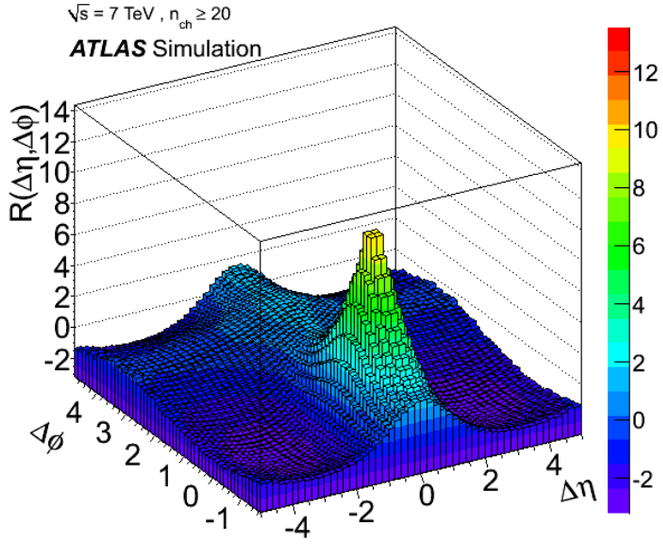
(a)



(b)



(c)



(d)

"Near-side" correlations: sharp peak at $(\Delta\eta, \Delta\varphi) \approx (0, 0)$ can be attributed to high-p_T processes.

"Away-side" correlations: ridge at $\Delta\varphi \approx \pi$ can be attributed to momentum conservation.

Gaussian ridge: $\Delta\eta \approx 0$ decay of particles with low-p_T (decays of resonances, strings or cluster fragmentation).

MC models are able to predict structure seen in data BUT fail to reproduce the strength of the correlations.

arXiv:1203.3549 [hep-ex] (submitted to JHEP)

Azimuthal ordering of charged hadrons

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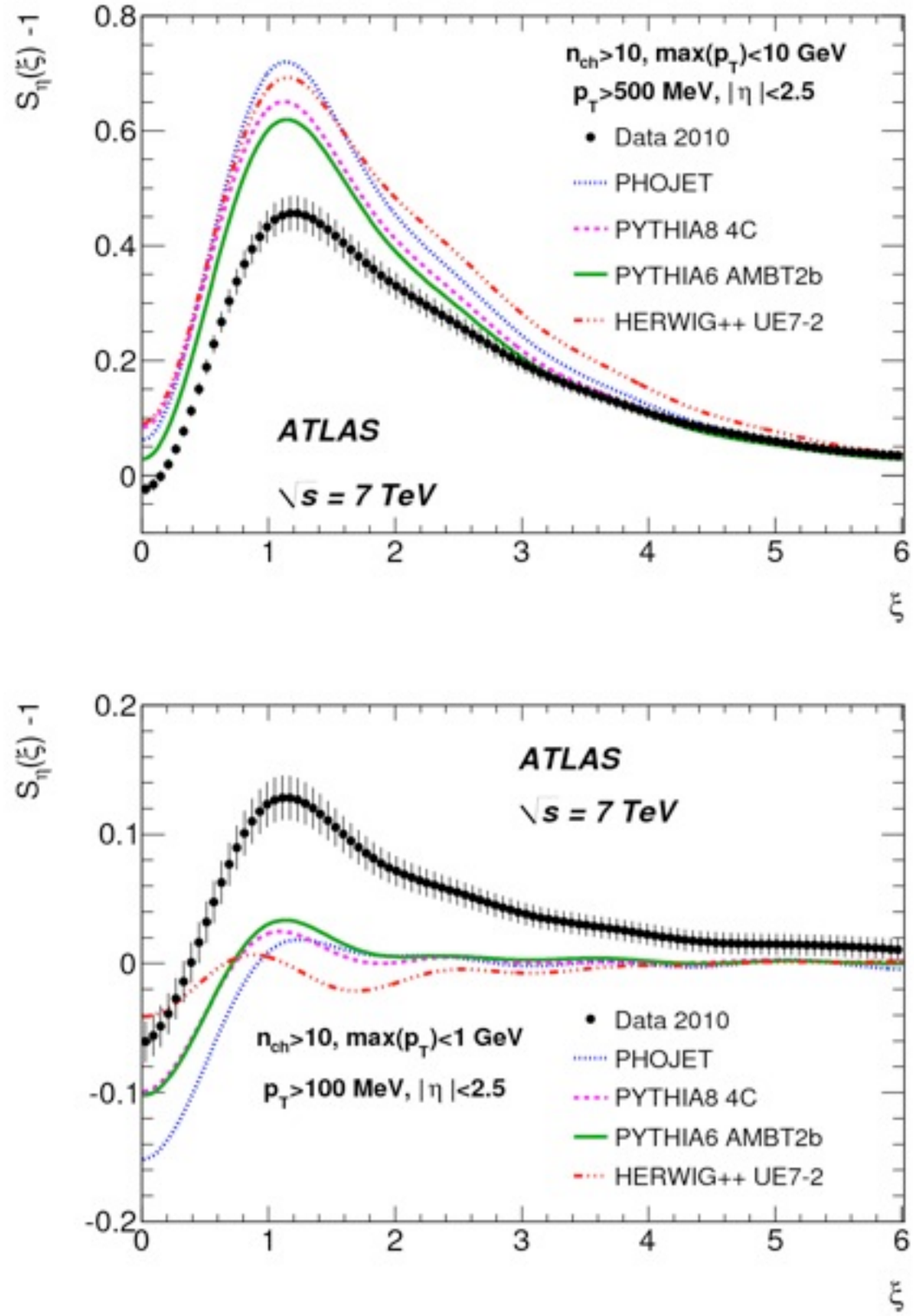
- Spectral analysis of correlations between the longitudinal and transverse components of charged hadrons

$$S_\eta(\xi) = \frac{1}{N_{\text{ev}}} \sum_{\text{event}} \frac{1}{n_{\text{ch}}} \left| \sum_{\text{j}}^{n_{\text{ch}}} \exp(i(\xi \eta_{\text{j}} - \phi_{\text{j}})) \right|^2$$

- Data corrected for detector inefficiencies and the measurement is presented at particle level.

- Too much correlation in typical MC, for high-p_T charged particles (top plot), but too little correlation for low-pT charged particles (bottom plot).



arXiv:1203.0419 [hep-ex] (submitted to PRD)

The underlying event

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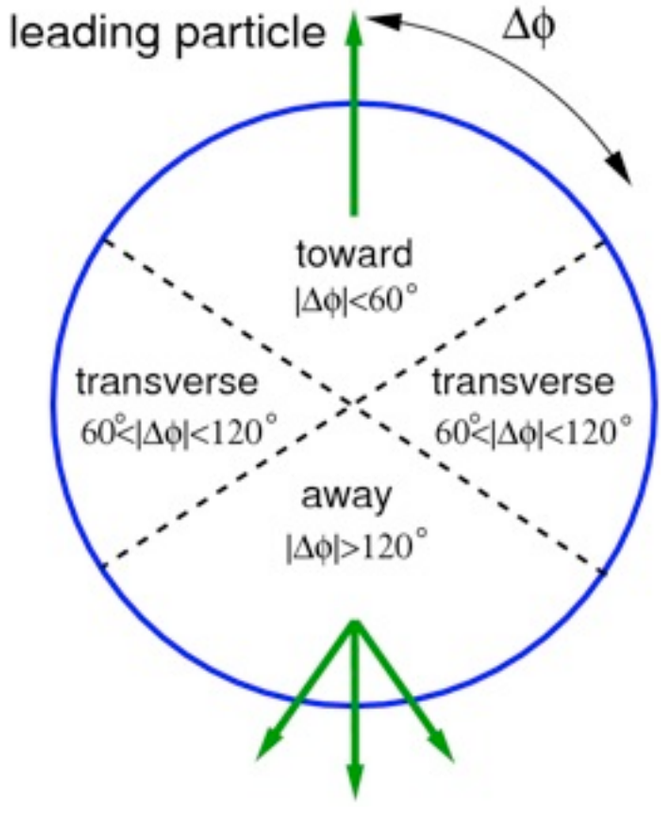
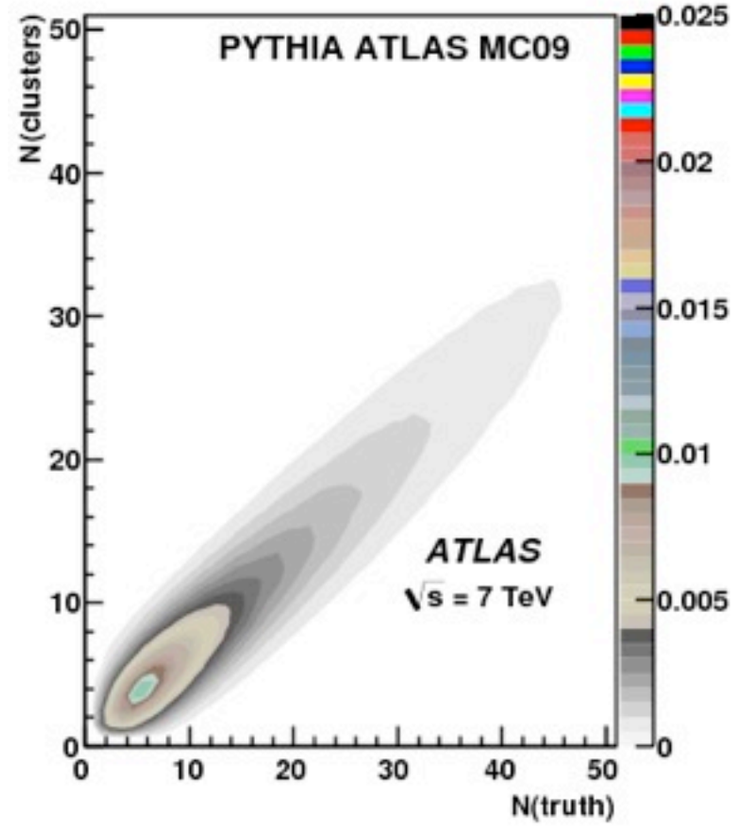
- **UE characterised by activity in ϕ region transverse to the leading particle (= highest p_T track or cluster)**
  - At least one selected track or cluster with $p_T > 1.0$ GeV
    (this reduces diffraction significantly,ie. <1%)

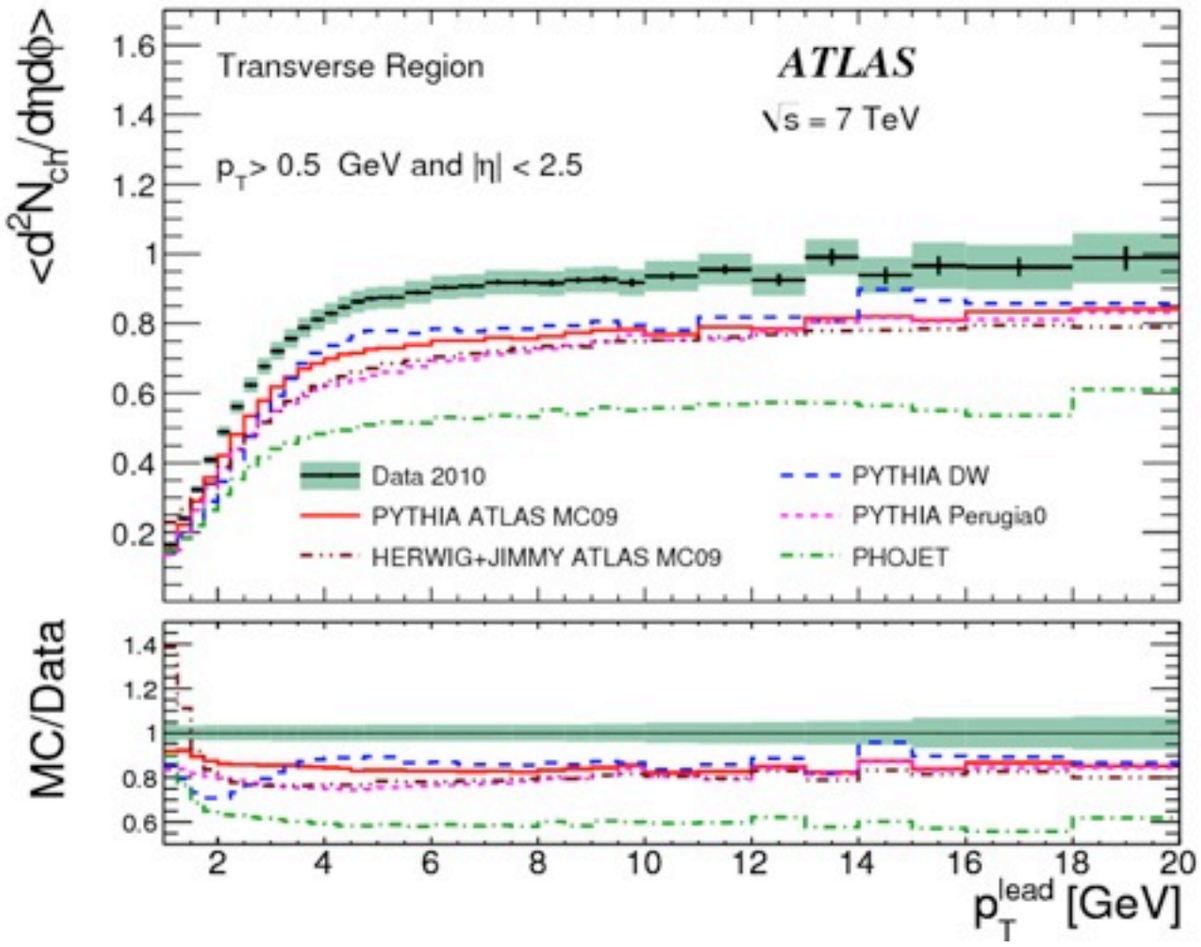


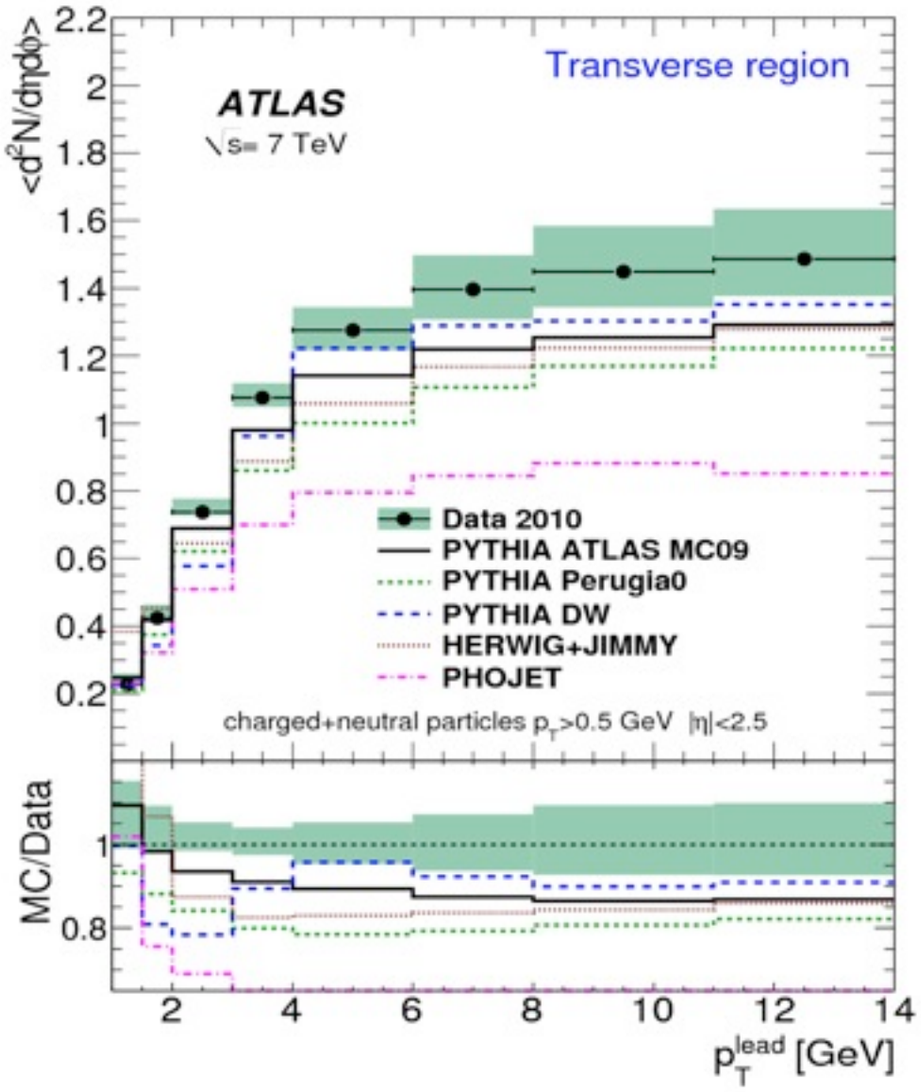
- **Track-based measurement:**
  - **Reconstruct ID tracks of charged particles**
  - **Corrections for vertex, trigger and tracking efficiency similar as for minimum bias studies**

- **Cluster-based measurement:**
  - **Use energy depositions in calorimeters associated to charged and neutral particles**
  - **Correct cluster distributions to stable-particle level using correction factor derived from MC**
  - **Cross-check using data/simulation comparison of N(clusters) vs. N(tracks)**



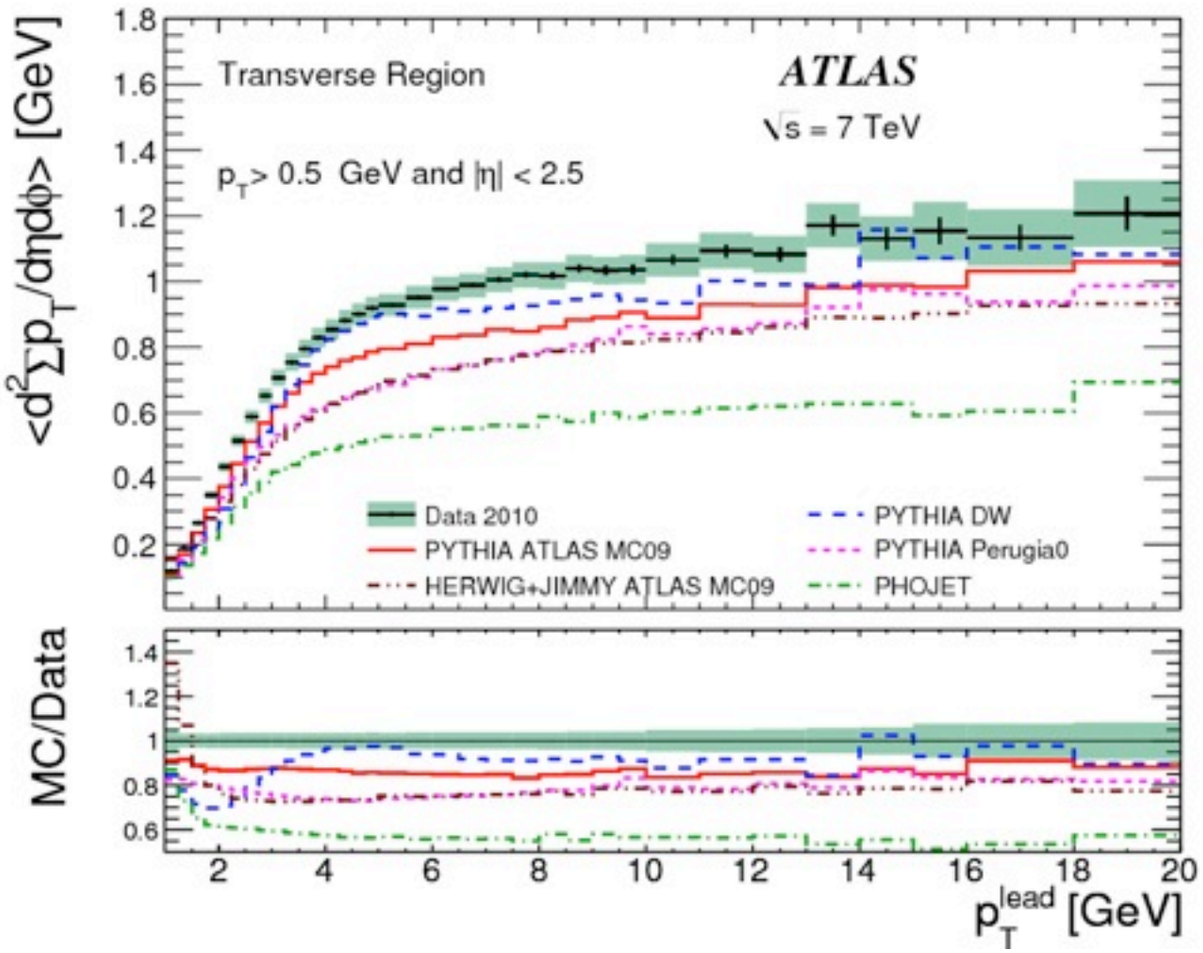
Transverse Number Density

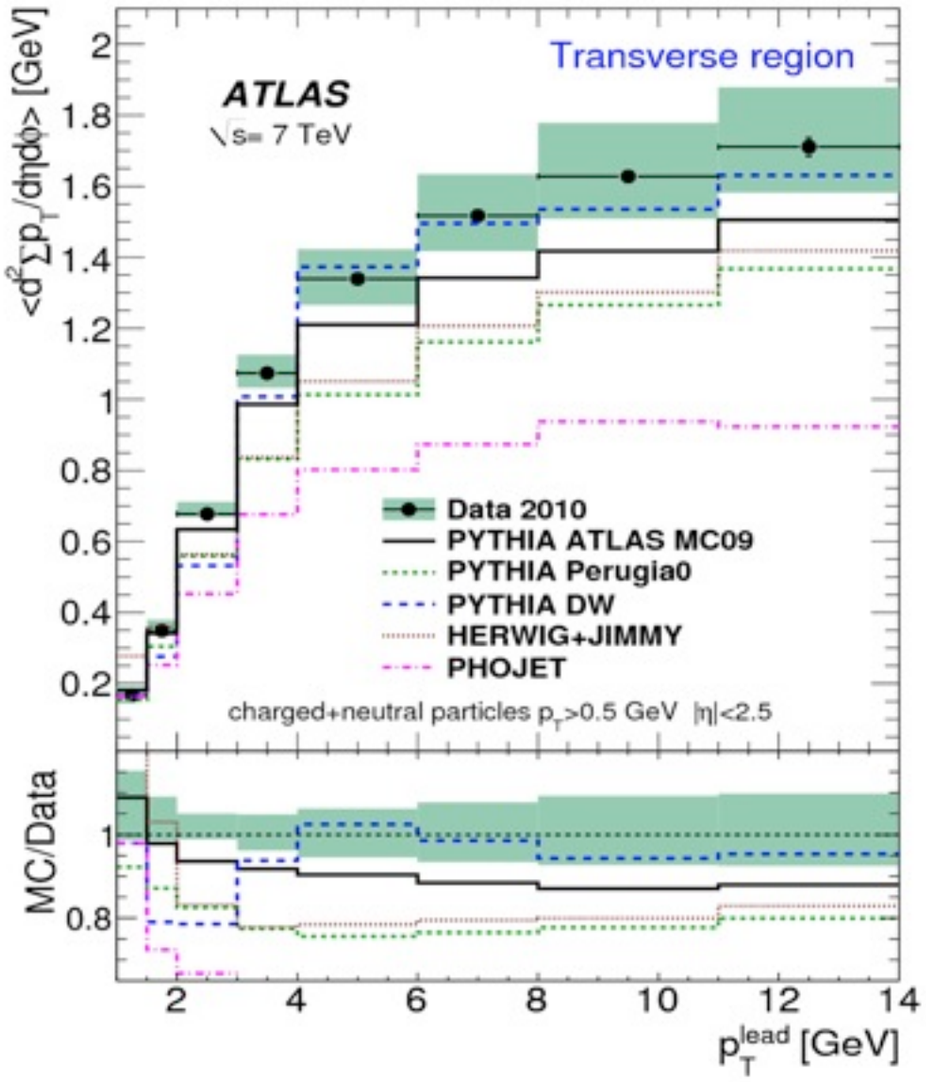




- The number density in data is higher than predicted by any of the MC tunes (also observed in comparisons to minimum bias densities).
- The difference is more significant at 7 TeV (energy extrapolation!). They get even larger as low p_T particles are added to the measurement.

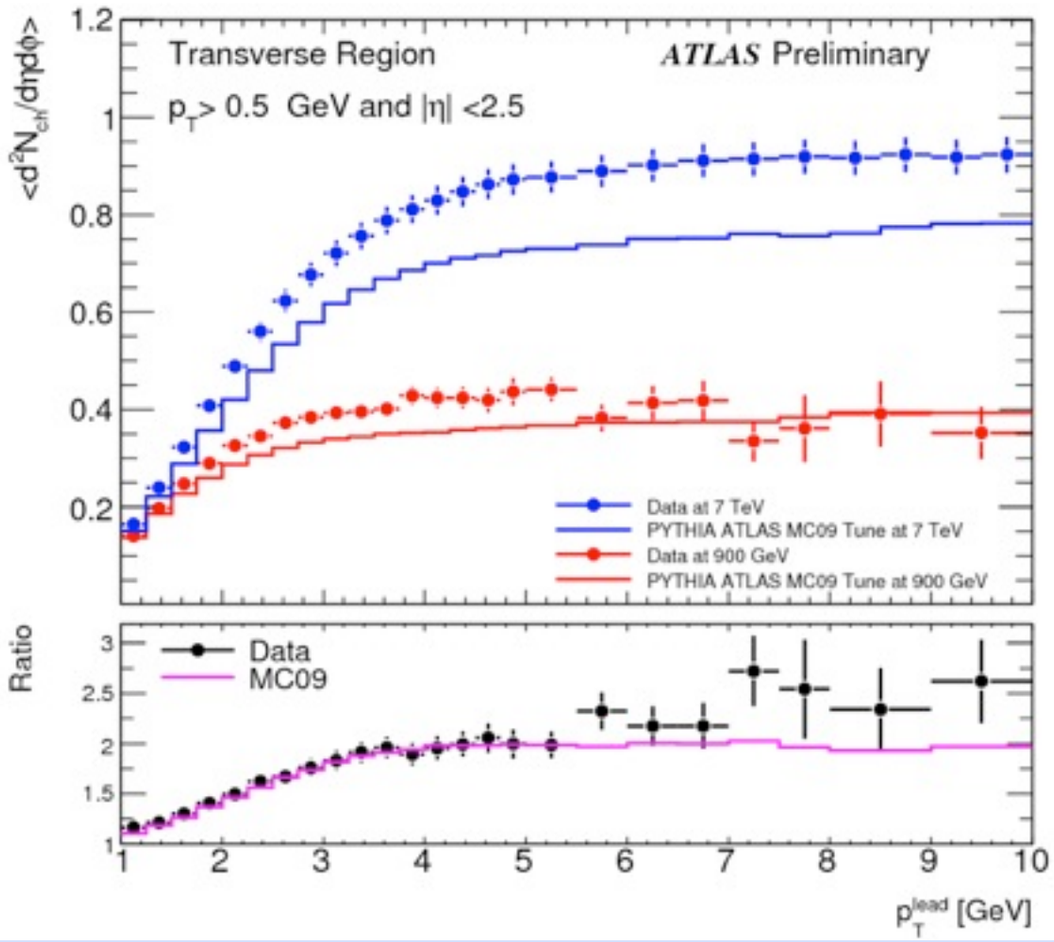
Transverse Sum p_T Density

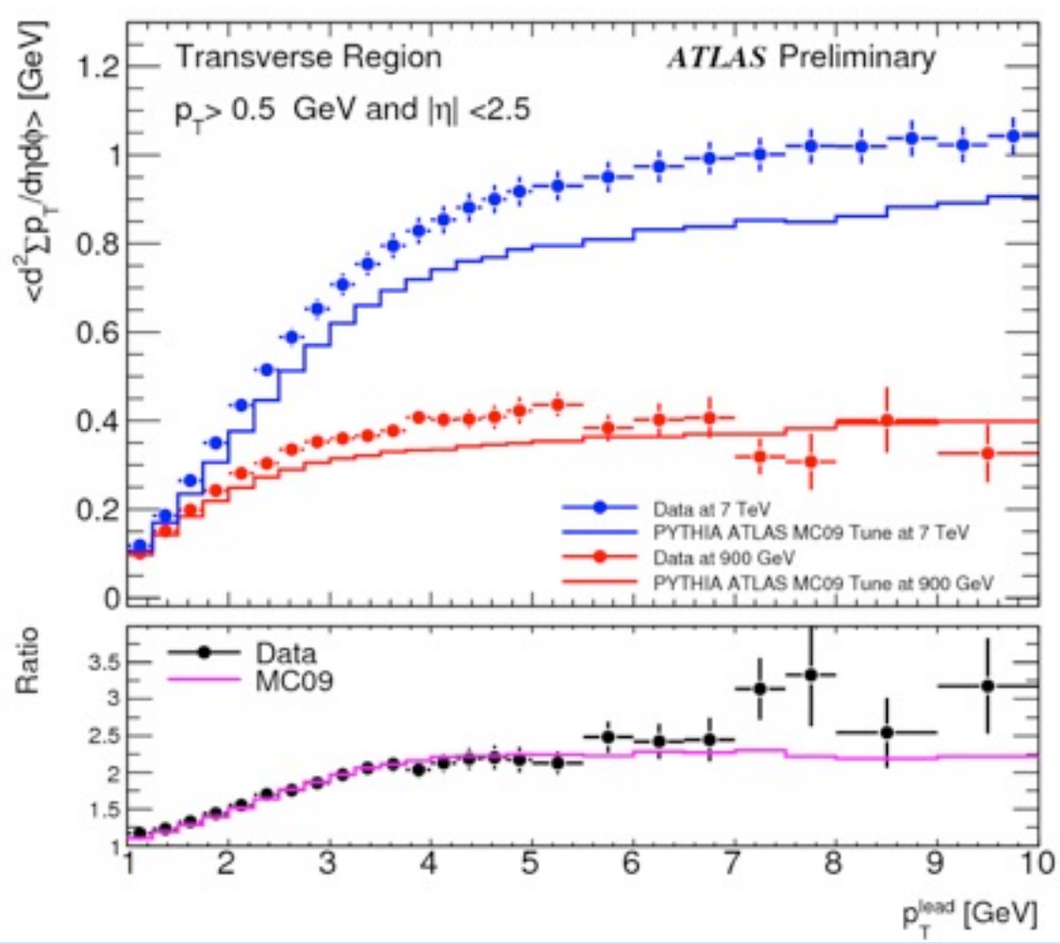




- The higher number density in data implies a higher p_T density as well.
- The summed charged particle p_T in the plateau characterises the mean contribution of the underlying event to jet energies.

Transverse Number and Sum p_T Density: 900 GeV vs 7 TeV





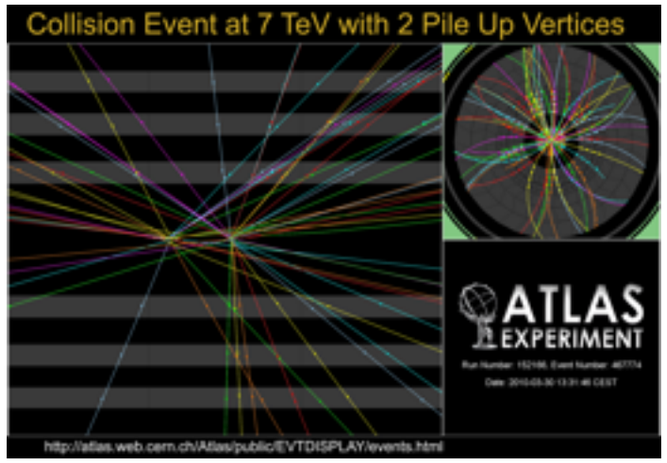
- Comparing number and sum p_T densities for 900 GeV and 7 TeV measurements: crucial information for a better understanding on how to model the energy extrapolation!
- Charged particle density in the UE (plateau) compared to minimum bias (p_T>500MeV):
  - 900 GeV: 2.5 (UE) vs 1.3 (MB) chg. particles per unit η
  - 7 TeV: 5 (UE) vs 2.4 (MB) chg. particles per unit η
- UE measurements used to re-tune MC **(e.g. AUET1 & AUET2)** benefiting from information on the energy dependence.

Conclusions

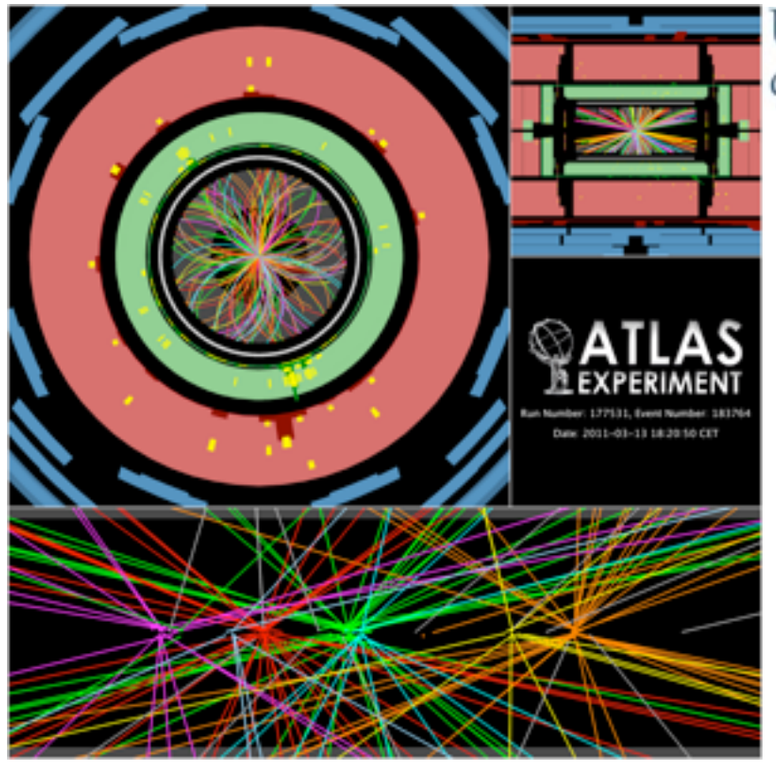
- **Minimum bias and underlying measurements have been measured by ATLAS at different centre-of-mass energies.**
  - measurements are presented with well defined phase-space selection & corrected back to "particle level" (i.e. directly comparable to MC predictions)
  - new results on particle correlations expose strengths and weaknesses of MC models
- **Data - MC comparisons show there is a need to continue improving models/MC tunings.**
  - new MC tunes using ATLAS data have already been produced. This benefits from several observables as well as multiple points at different $\sqrt{s}$.
  - very useful for preparations for 2012 data taking (8 TeV).
- **Challenges presented by the data:**
  - Diffraction: single and double diffractive interactions contribute to low n_{ch} regions.
  - Low-p_T particle production. Models tuned to measurements made with higher p_T particles fail to describe the low p_T data.
  - non-perturbative dynamics still very challenging: MPI, colour reconnection, etc.

Extra material...

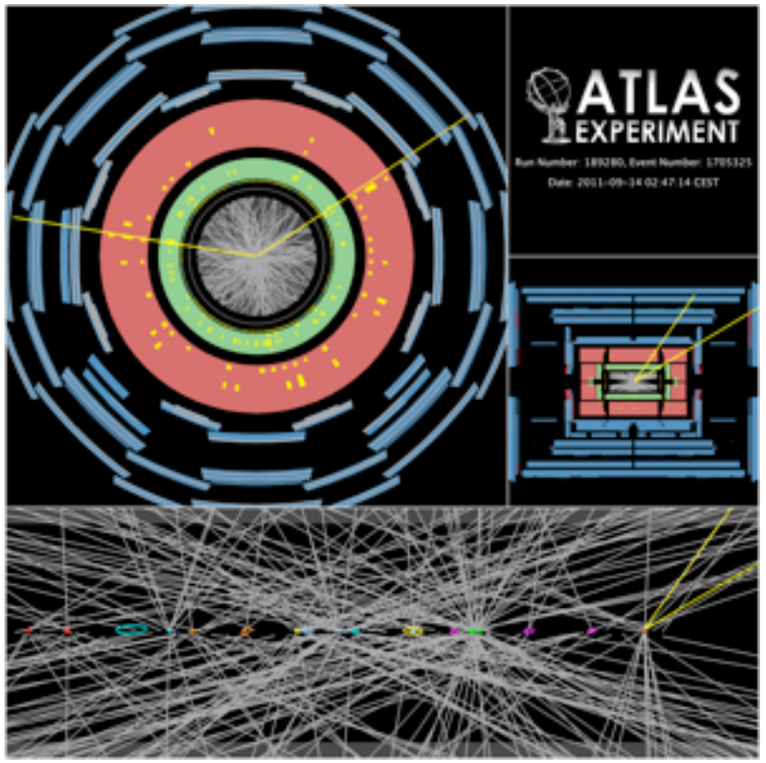
Pile-up events



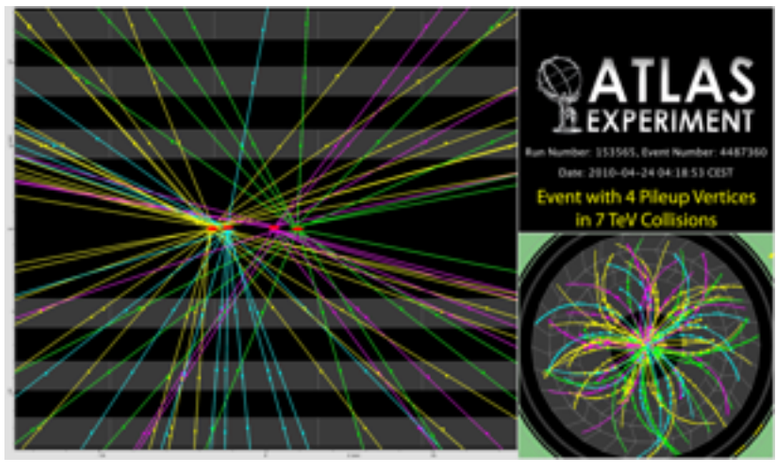
2 vertices reconstructed!



7 vertices



20 vertices



4 vertices

2010

2011

Minimum Bias Trigger Scintilator

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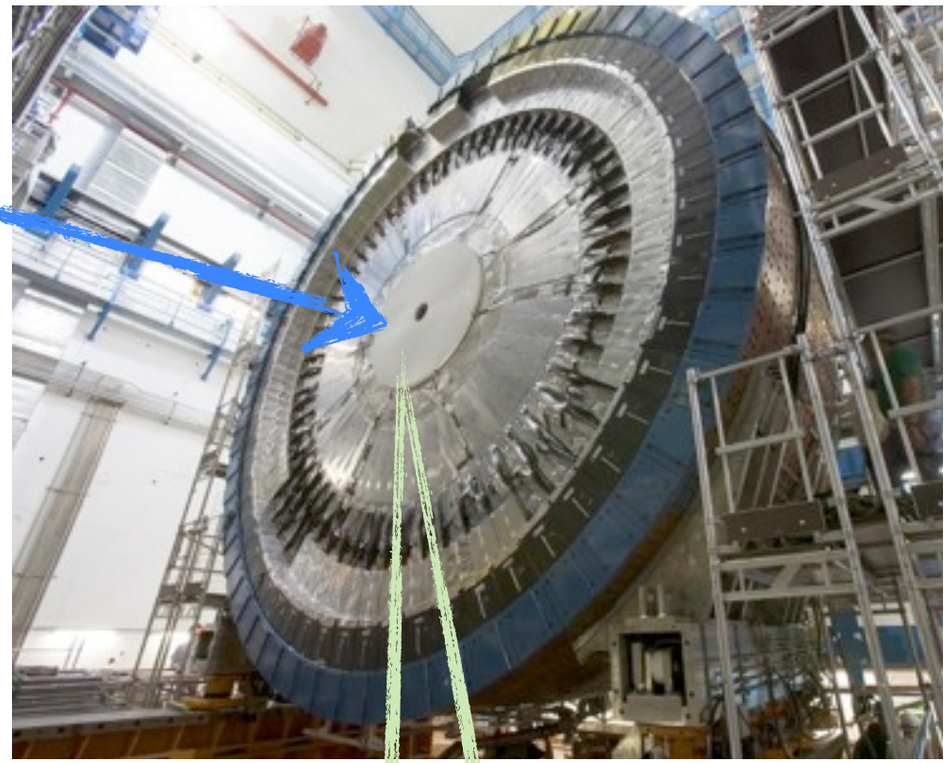
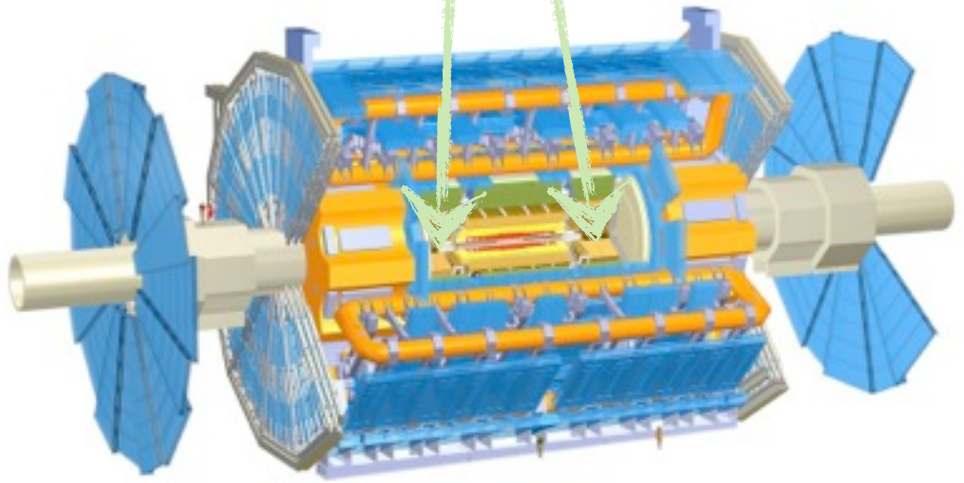
MBTS

Segmented into 16 counters on each side.





Plastic scintillator planes connected to photomultiplier tubes.

Highly efficient trigger on charged particles.

MBTS is the primary Minimum Bias trigger.

- $2.1 < |\eta| < 3.8$

Minimum Bias Trigger Scintilator

University of Glasgow

MBTS

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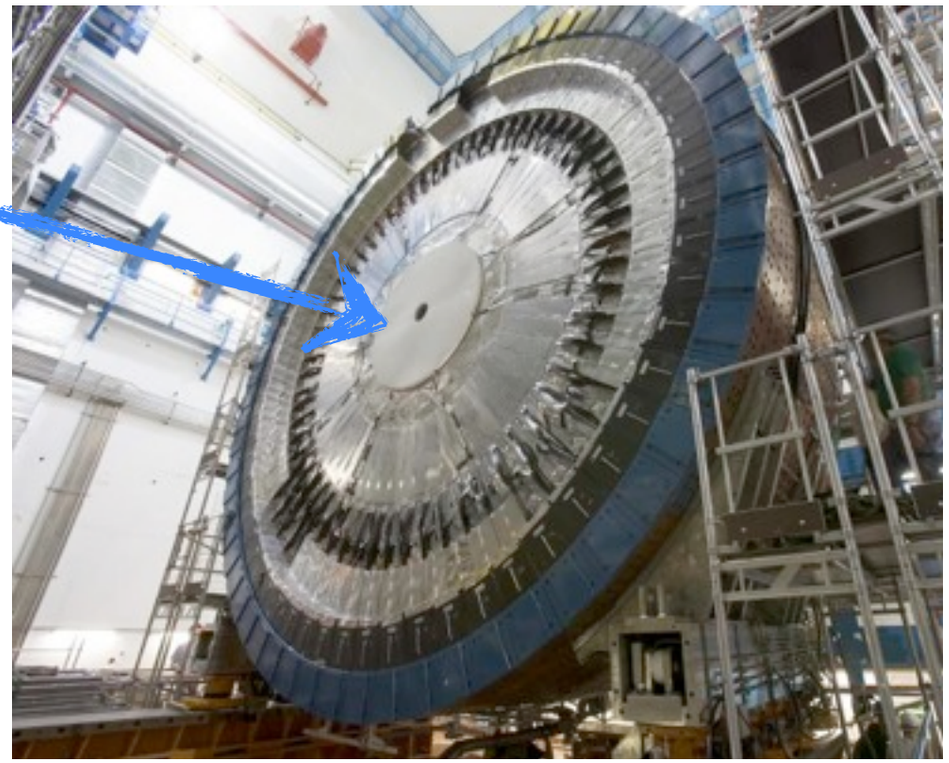

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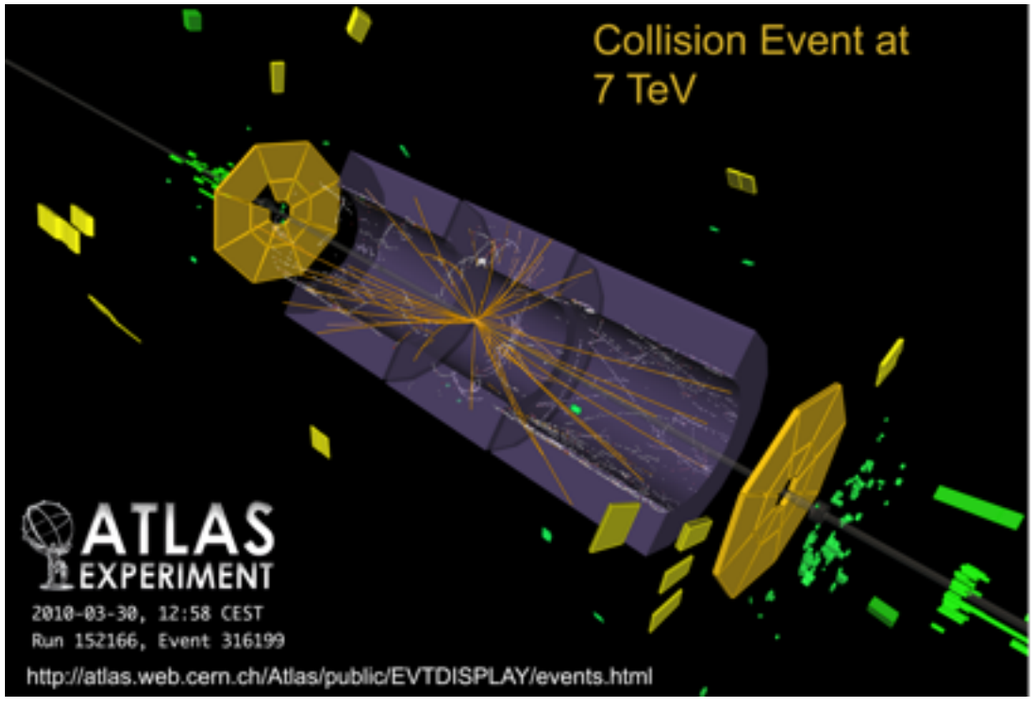

Charged particle density in η: √s=900 GeV, 2.36 TeV and 7 TeV

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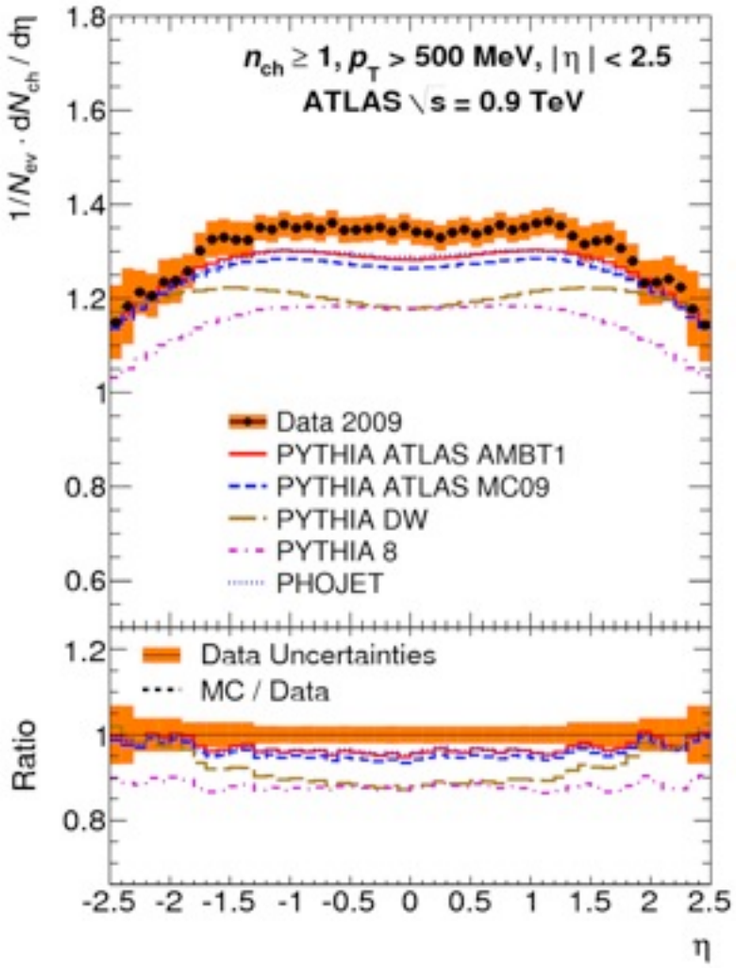
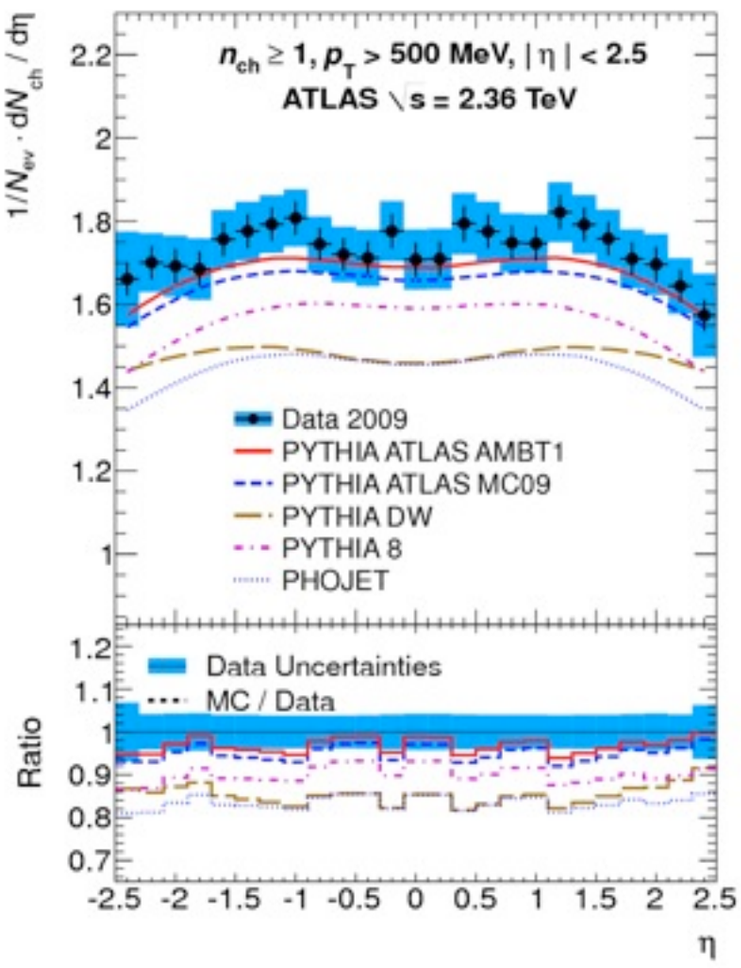
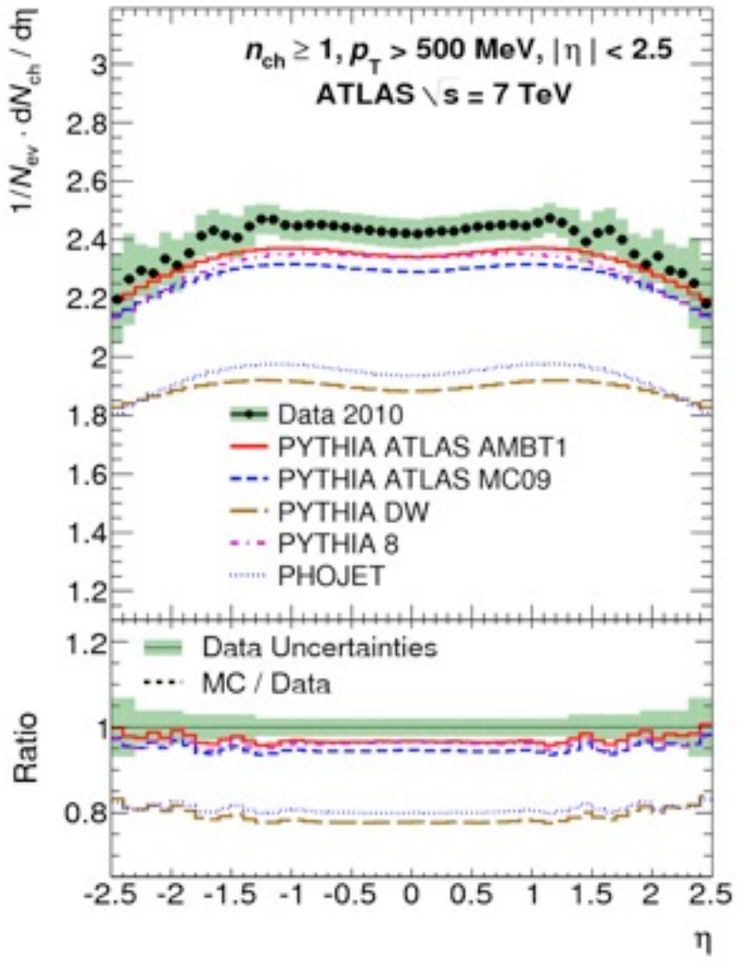
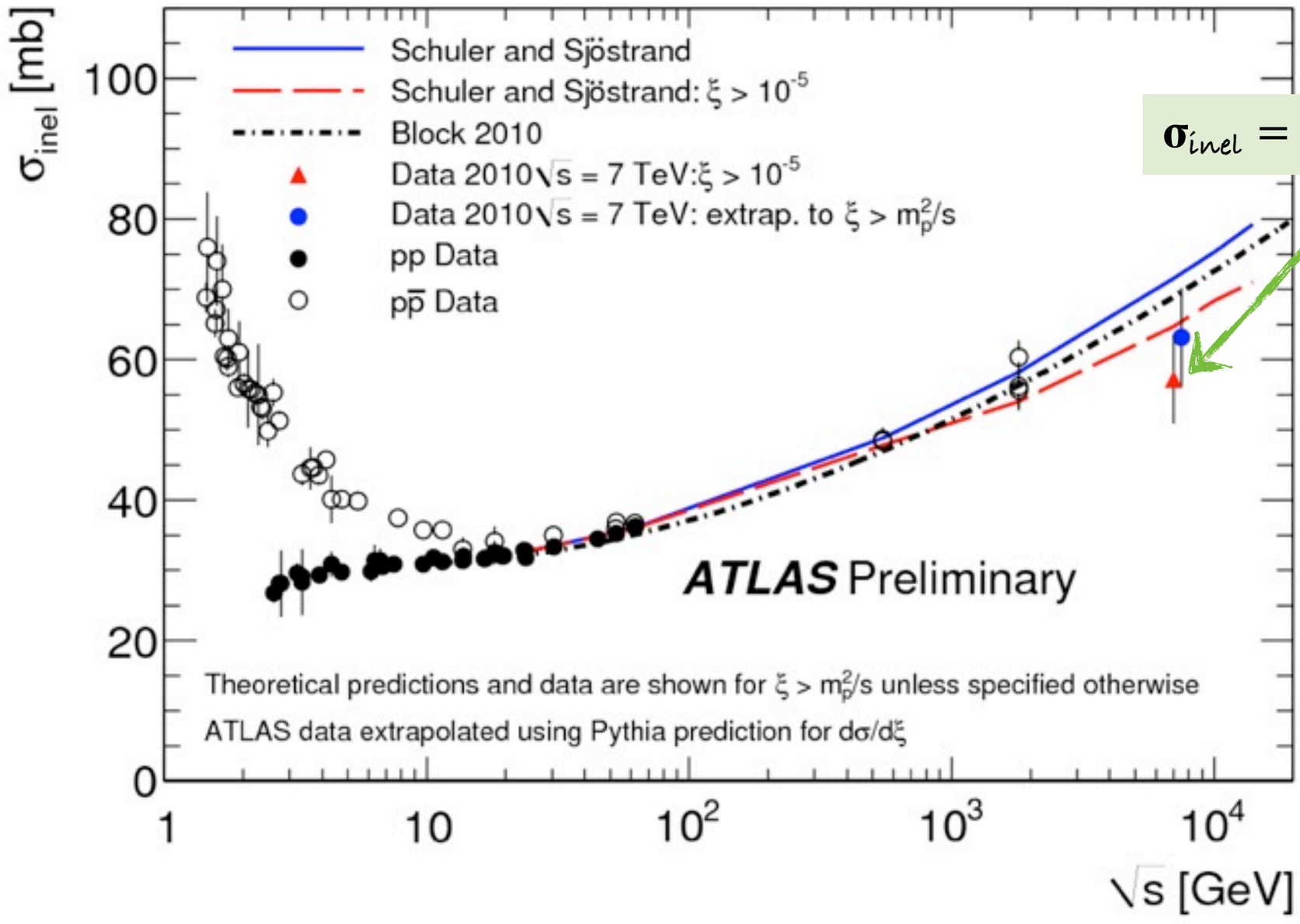






- **Measurements at different c.m. energies are crucial for an accurate understanding (prediction) of the evolution of inelastic hadronic processes.**

Measuring the inelastic cross-section at $\sqrt{s}$ = 7 TeV with ATLAS



$\sigma_{inel} = 57.2 \pm 6.3$ mb.

- Measurement made with data from first stable fill in 2010 (~21μb^{-1}) using the MBTS to select inelastic collisions. Extrapolation done using MC models for diffraction.

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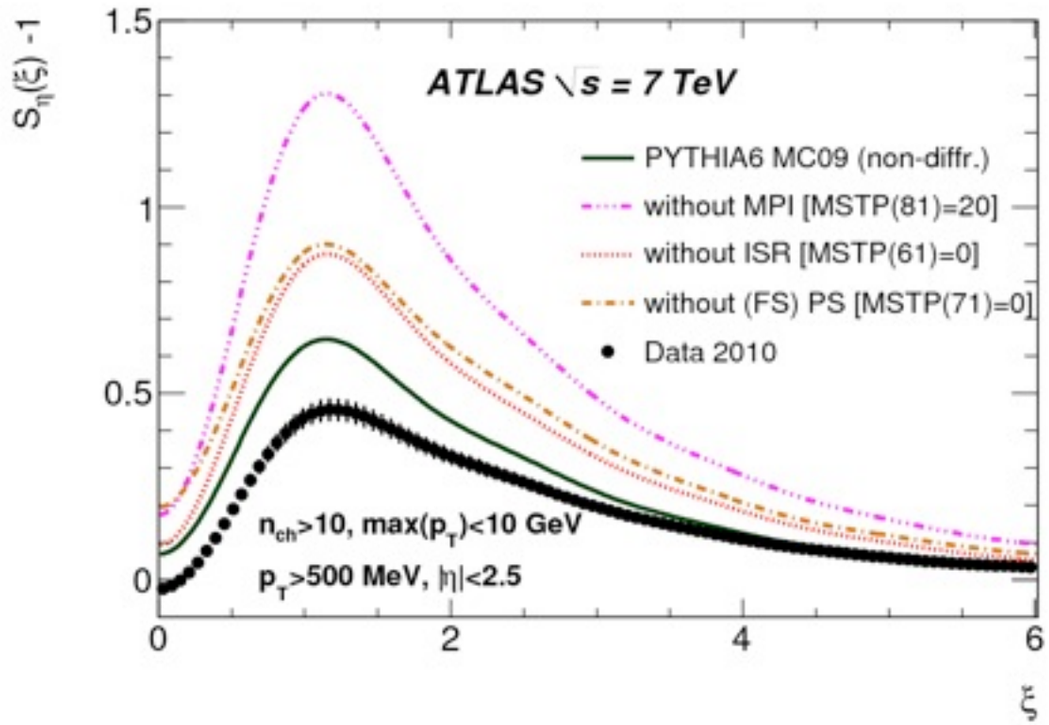
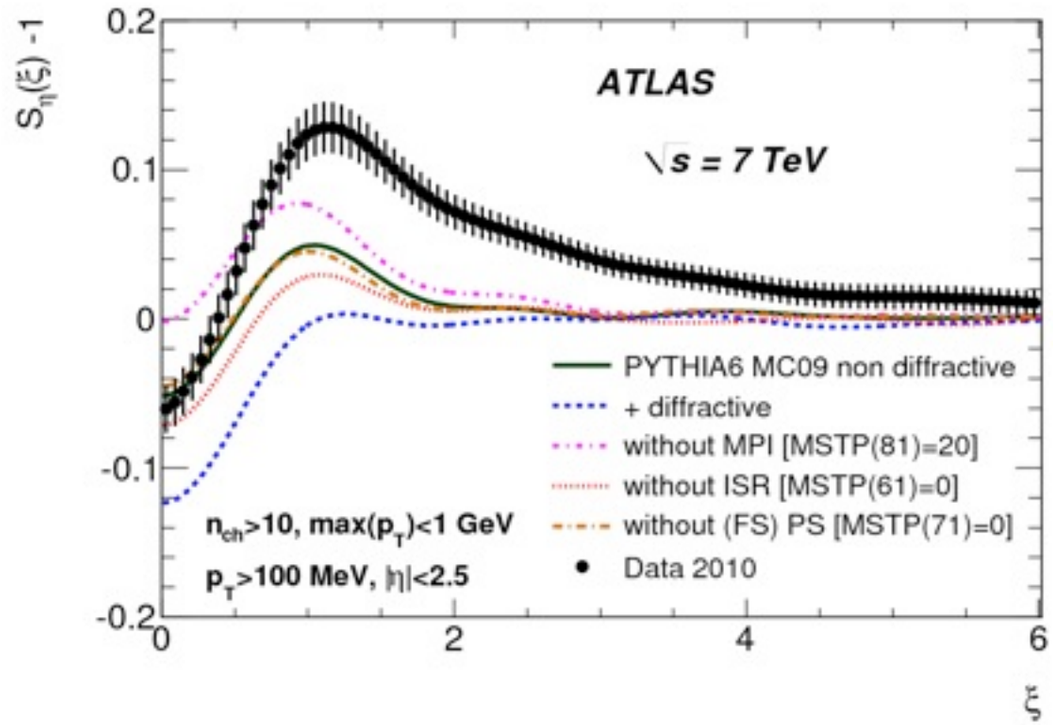
Azimuthal ordering of charged hadrons





arXiv:1203.0419 [hep-ex] (submitted to PRD)

Measuring “minimum bias” events at ATLAS

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- Data:
  - 900 GeV sample: ~455K events / ~7 μb^{-1} (PLB March’10)
  - 2.36 TeV sample: 8,151 events / ~0.1 μb^{-1} (arXiv:1012.5104v2 [hep-ex])
  - 7 TeV sample: ~10M events / ~190 μb^{-1} (arXiv:1012.5104v2 [hep-ex])
- Event selection:
  - Single-arm trigger: require ≥ 1 MBTS counter to fire on either side
  - At least one primary vertex reconstructed (constrained by the beam-spot)
  - No additional primary vertices
  - Phase space:

N_{chg}	$\|\eta\|$	p_T
> 1	2.5	> 500 MeV
> 2	2.5	> 100 MeV
> 6	2.5	> 500 MeV

(most inclusive)

Measuring “minimum bias” events at ATLAS

University of Glasgow

- Number of events & tracks in the three phase-space regions:

Phase space		$\sqrt{s}$ = 900 GeV Full tracks		$\sqrt{s}$ = 7 TeV Full tracks		$\sqrt{s}$ = 2.36 TeV ID Tracks	
N_{chg}	min p_T (MeV)	Events	Tracks	Events	Tracks	Events	Tracks
> 2	100	357K	4.5M	10M	209M	-	-
> 1	500	334K	1.9M	9.6M	97M	5.9K	39K
> 6	500	125K	1.3M	5.4M	86M	-	-

Trigger efficiency ~99% (slightly lower for low-p_T analysis)

Cosmic ray background < 10^{-6} and beam backgrounds <0.1%

Pile-up removal ~0.2%, residual rate from pile-up ~0.01%

“Peak” luminosity for the 7 TeV data in this analysis: 1.9 x 10^{27} $cm^{-2}s^{-1}$

Brief comment on MC tunes…

- **MC09**: ATLAS reference tune for PYTHIA6 tune ("new" MPI model: pT ordered). "Pre-LHC" tune!

- **AMBT1, AMBT2**: PYTHIA6 tune ("new" MPI model: pT ordered) developed by ATLAS. Focus on minimum bias results for both 900GeV and 7 TeV.

- **AUET1, AUET2**: PYTHIA6 (from AUET2 and newer) and HERWIG+JIMMY tunes developed by ATLAS. Focus on underlying event results for both 900GeV and 7 TeV.

- **DW**: PYTHIA6 tune ("old" MPI model: virtuality ordered) developed by CDF. Drell-Yan CDF measurements

- **PYTHIA8**: new diffraction model with harder component.

- **PHOJET**: alternative model to the PYTHIA based tunes. PHOJET is based on DPM.