Minimum bias and the underlying event measurements with ATLAS

Arthur M. Moraes

University of Glasgow

(on behalf of the ATLAS Collaboration)

Outline:

I. Introduction:

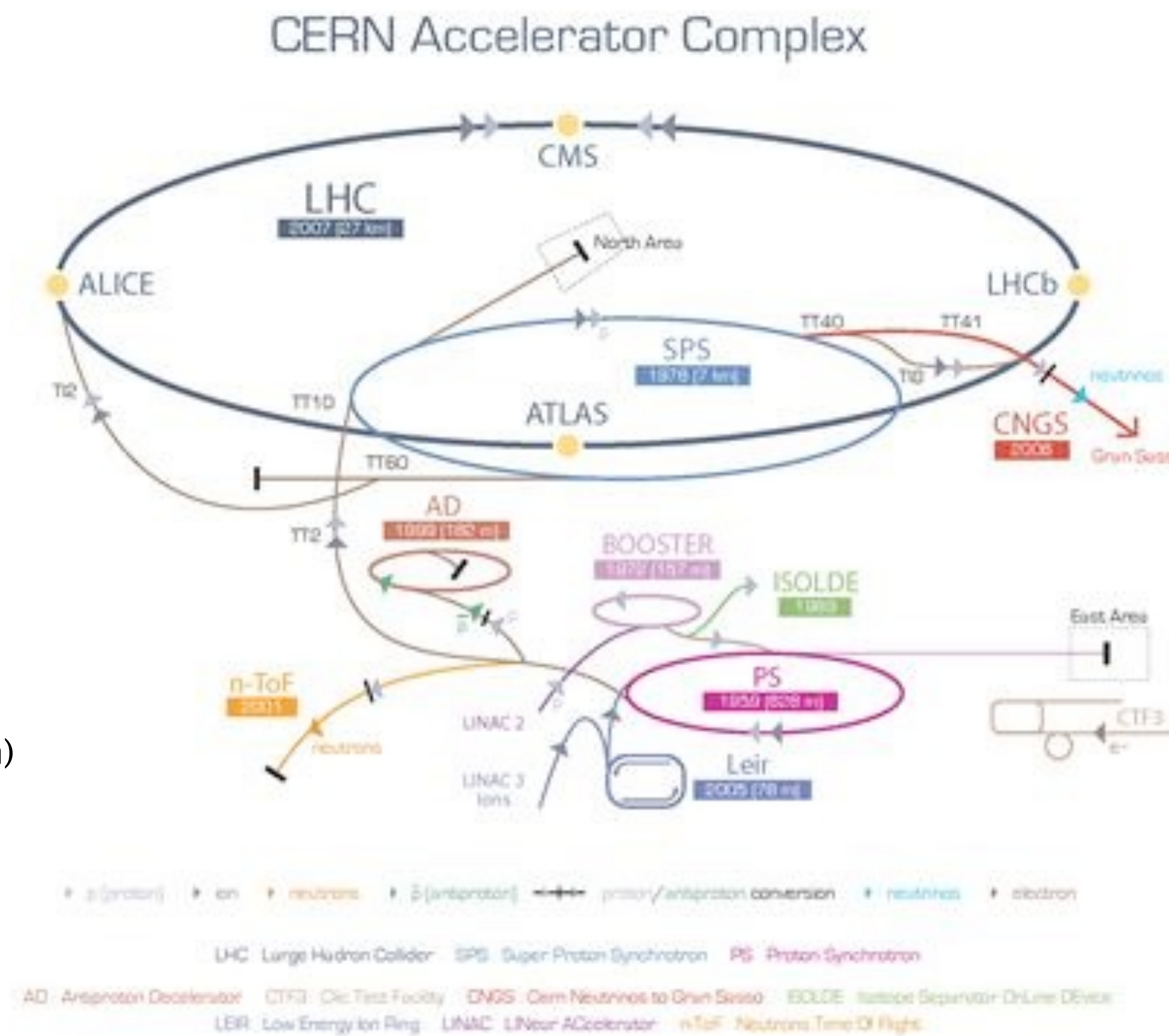
- The Large Hadron Collider - LHC
- ATLAS

II. QCD measurements with early data:

- Minimum bias events
  - $\sqrt{s}$=900GeV, 2.36TeV and 7TeV
- Track-based underlying event
  - $\sqrt{s}$=900GeV and 7TeV

III. Summary

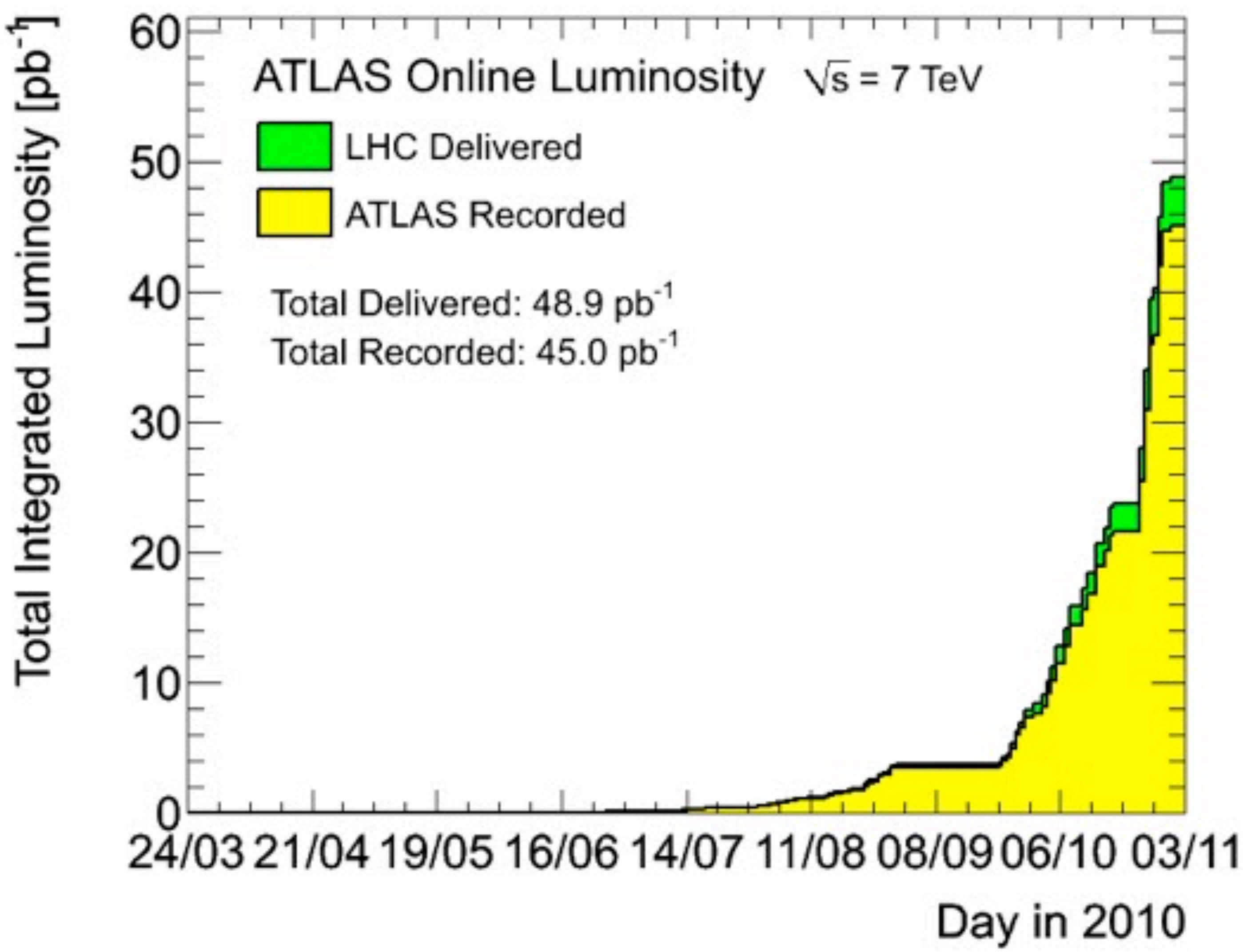
The Large Hadron Collider



- Design specifications:
  - p-p collisions at $\sqrt{s}$=14TeV (x7 wrt Tevatron)
  - design luminosity 10^{34} $cm^{-2}s^{-1}$ (x100 wrt Tevatron)
  - bunch crossing every 25 ns (**40 MHz**)
- **Current operation:**
  - Re-started p-p collisions in November 2009: pp collisions at $\sqrt{s}$=0.9 (2.36)TeV
  - **it has been running for the past few months on "physics mode" at $\sqrt{s}$=7TeV**
    - **expect to collect hundreds of pb^{-1}, before "long" shutdown for upgrades.**
    - **moderate pile-up early on.**

The Large Hadron Collider

Total number of collisions at 7 TeV (31/10/2010)**: ~3.2 trillion** (ATLAS)



- Ramping-up the luminosity:
  - beam set-up is continuously being improved allowing steep rise in data accumulation.
- Recent configuration for collisions:
  - 295 colliding bunches in ATLAS;
  - $>10^{11}$ protons per bunch;
  - peak luminosity ~ 10^{32} cm^{-2} s^{-1}
- **Plans for 2010-11 run:**
  - **peak luminosity ~ 10^{32} cm^{-2} s^{-1}**
  - **up to 800 bunches per beam**
  - **record ~1fb^{-1} of integrated luminosity.**

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

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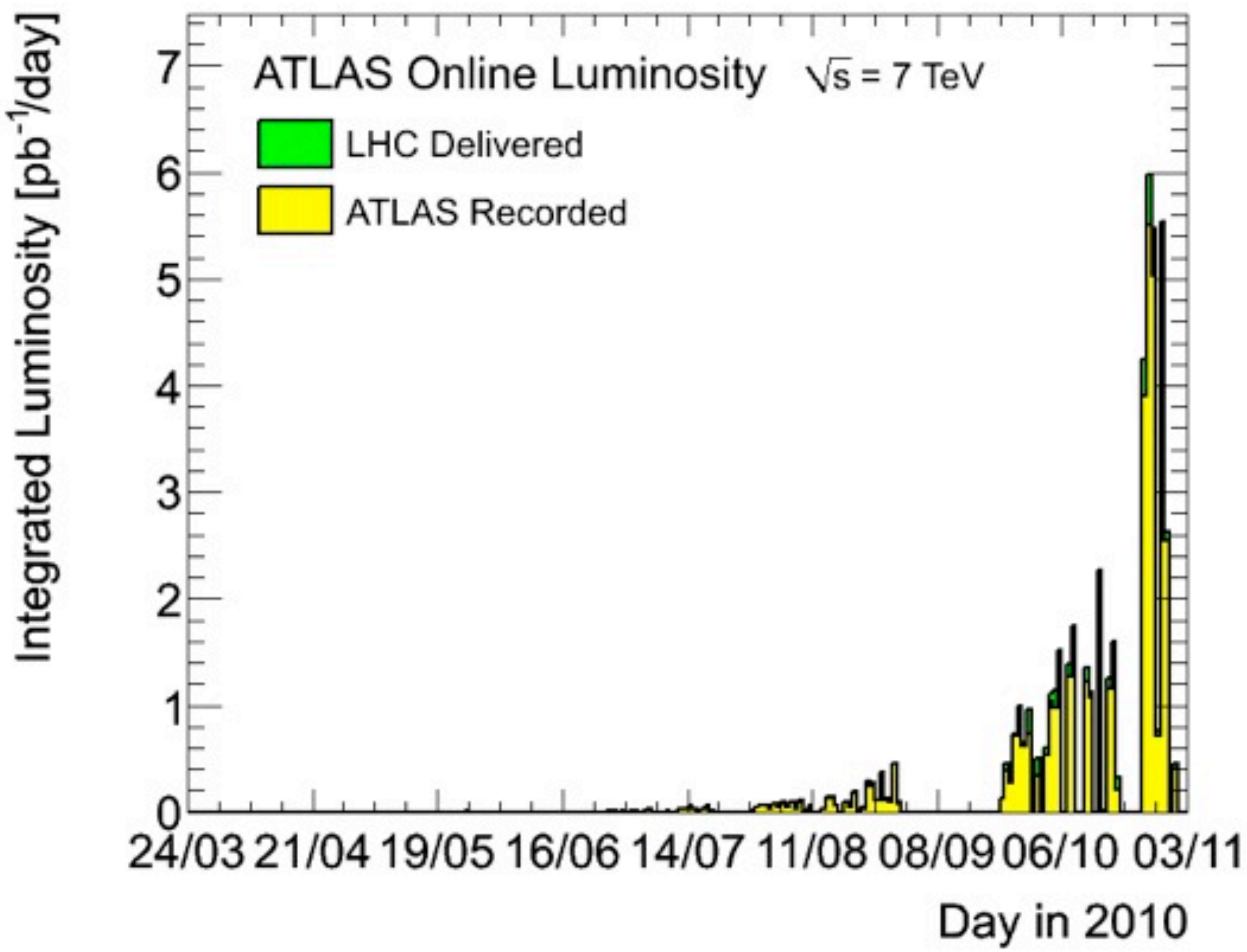

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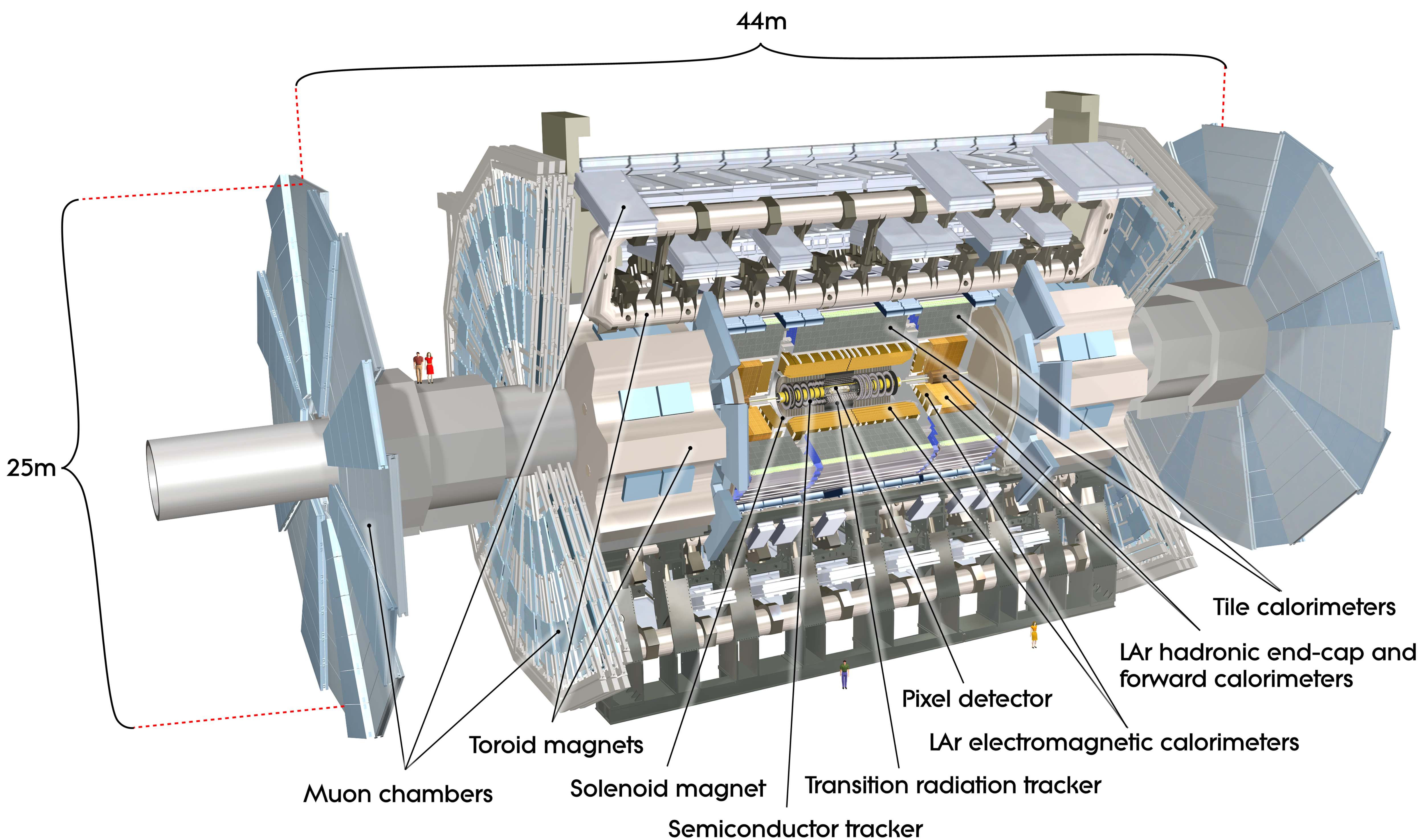
ATLAS: A Toroidal LHC ApparatuS



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

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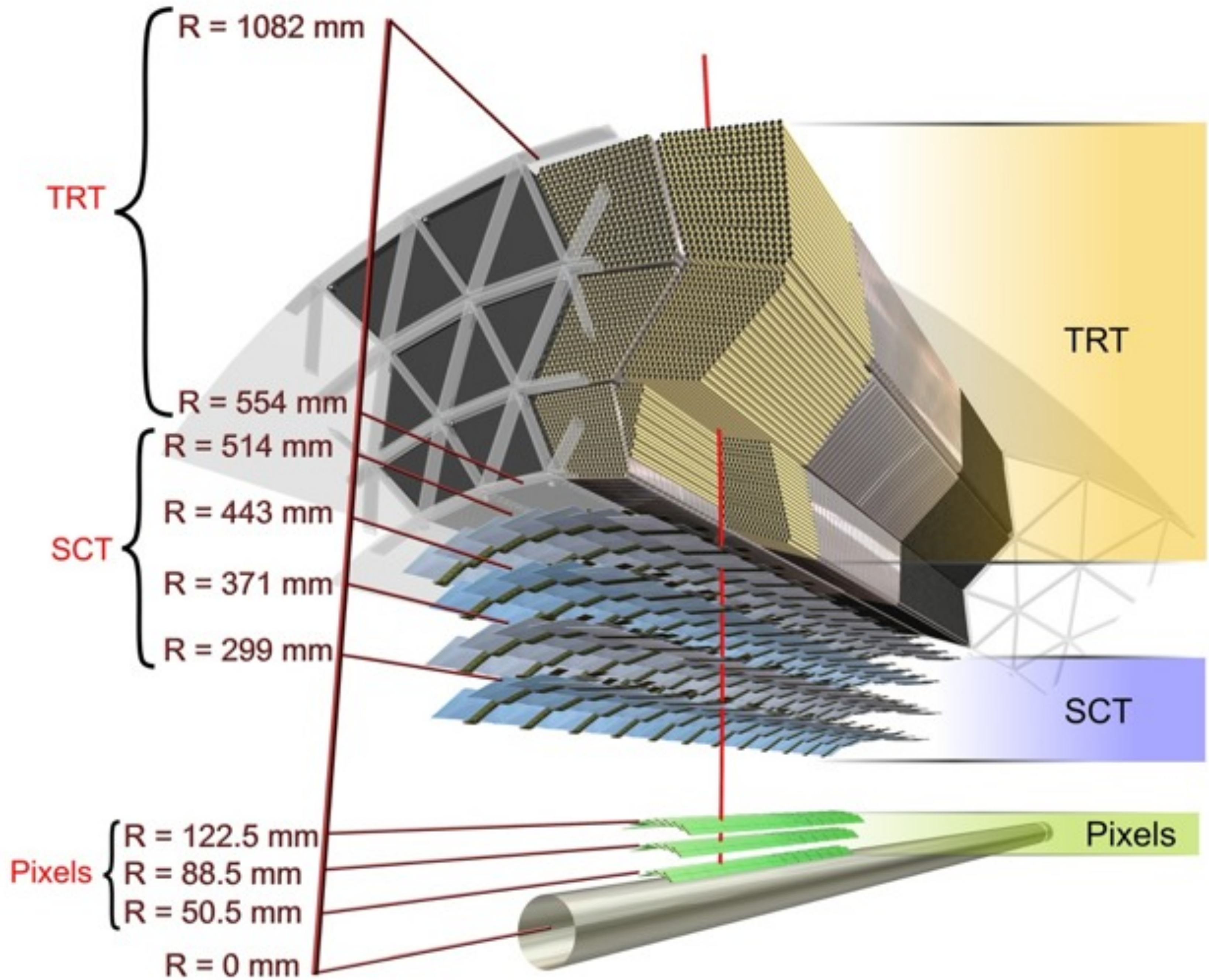
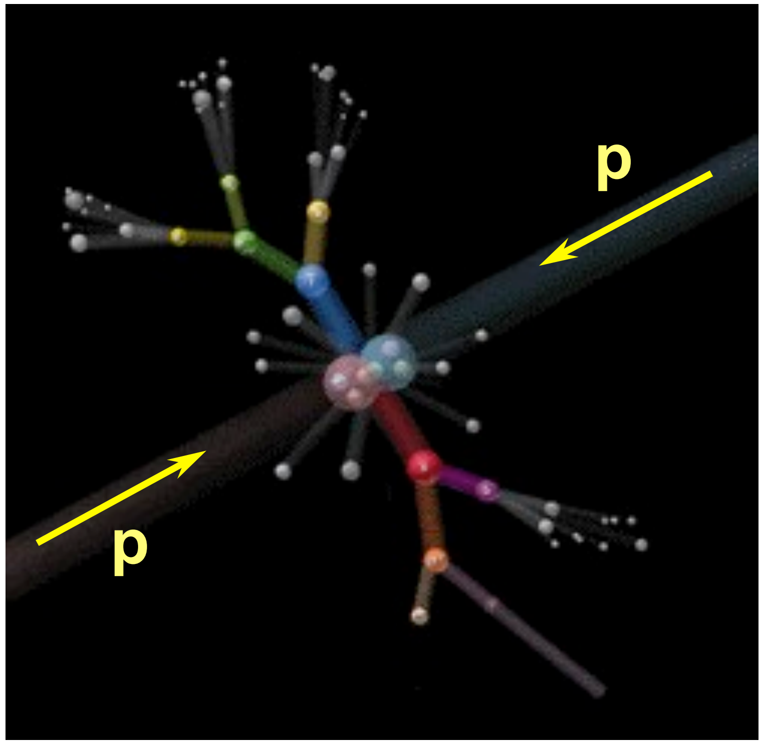


Hadron-hadron collisions

- 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



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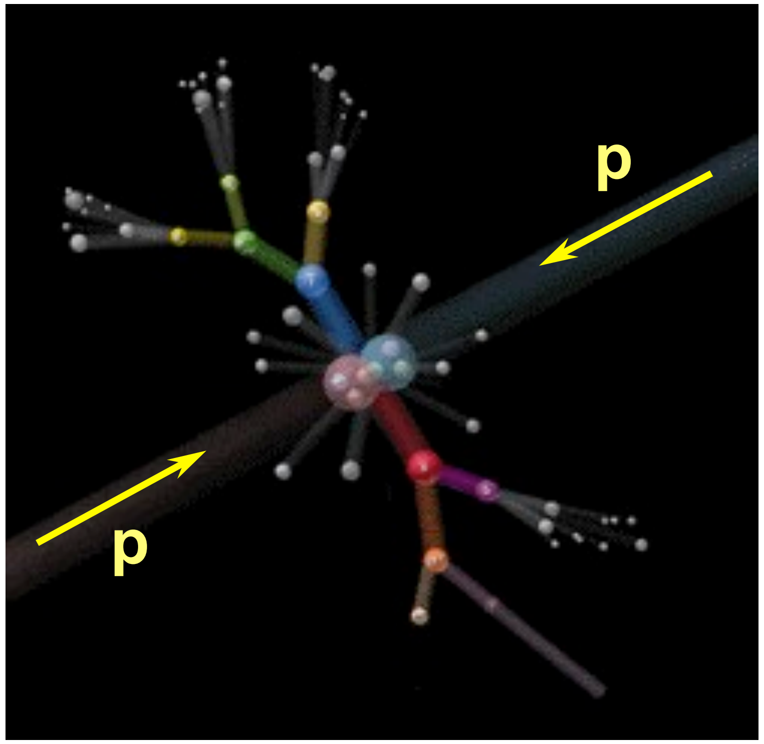
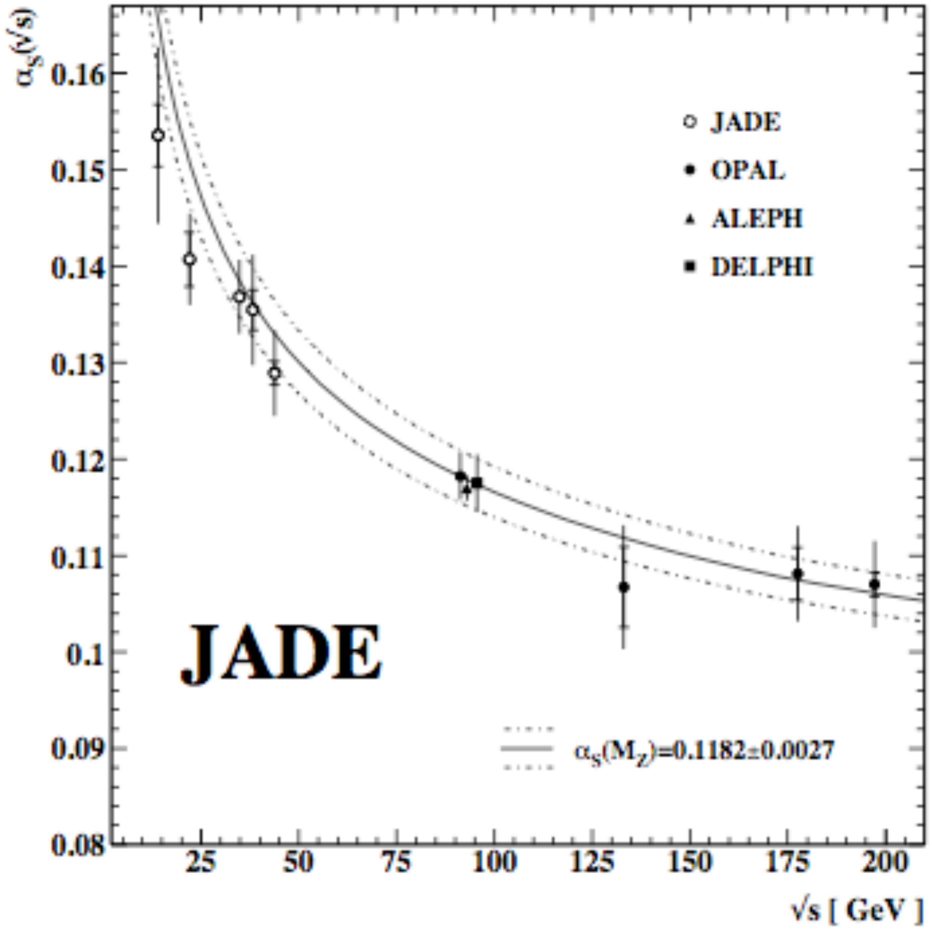




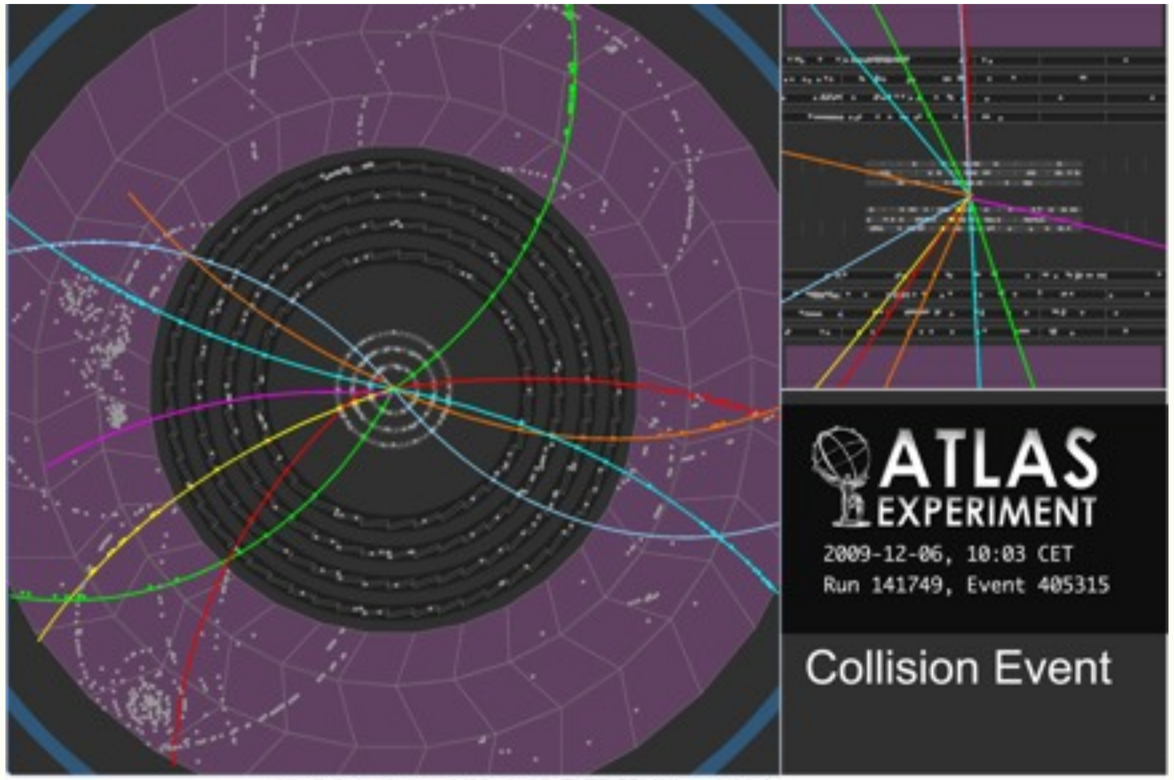
arXiv:hep-ex/0610013v1

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.

Measuring "minimum bias" events at ATLAS



http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

- ATLAS: pp collision at $\sqrt{s}$=900GeV
- First physics publication with ATLAS measurements: Phys Lett B **688**, Issue 1, 21-42 (March 2010)

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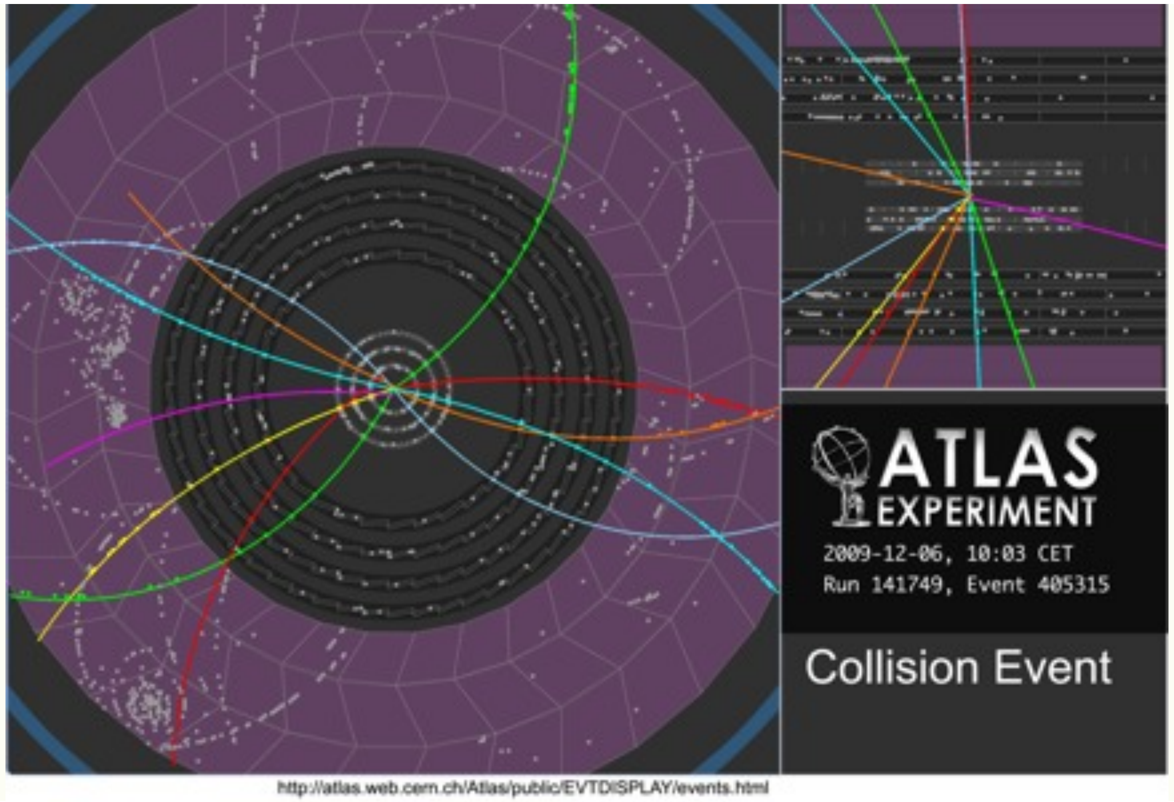
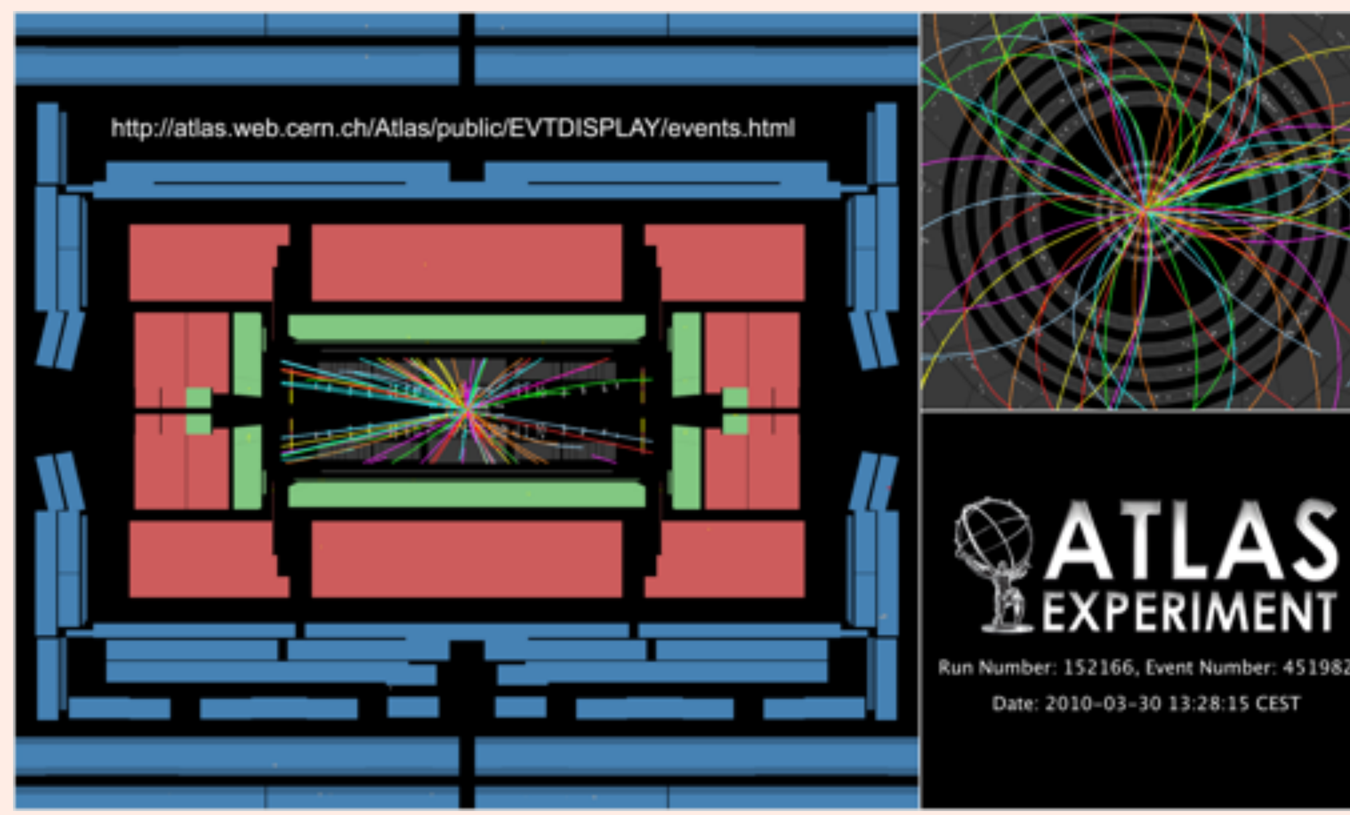


- ATLAS: pp collision at $\sqrt{s}$=900GeV
- First physics publication with ATLAS measurements: [Phys Lett B **688**, Issue 1, 21-42](#) (March 2010)

- ATLAS: pp collision at $\sqrt{s}$=7 TeV
- Results have been shown in conferences (paper under preparation):

ATLAS-CONF-2010-024 (April 2010)

ATLAS-CONF-2010-046 (July 2010)

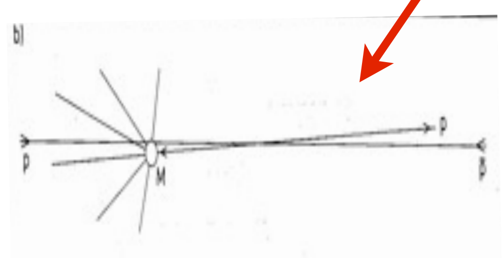


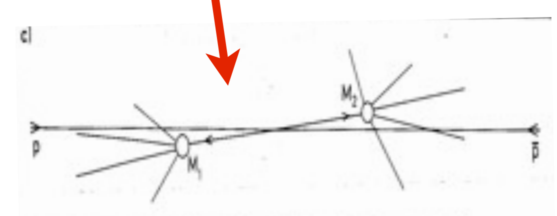
Measuring "minimum bias" events

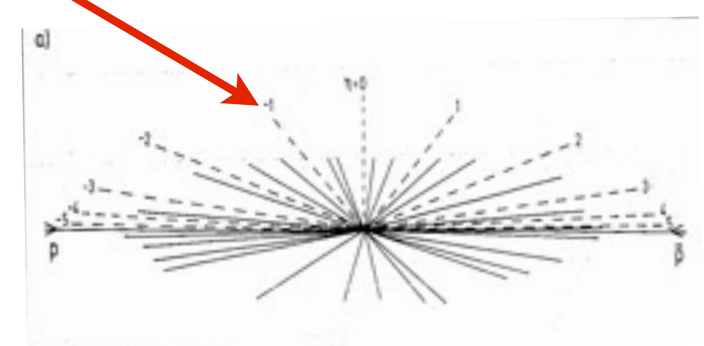
What do we want in our final minimum bias sample?

- **most of the inelastic events** (with as little or "minimum" bias as possible).

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







(beam-halo)

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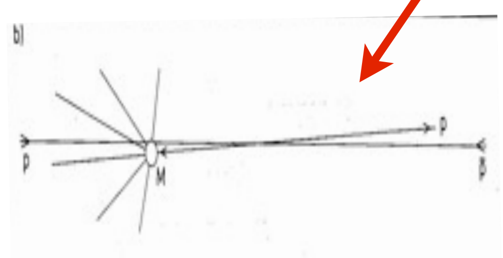
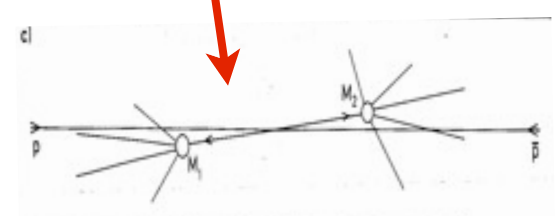
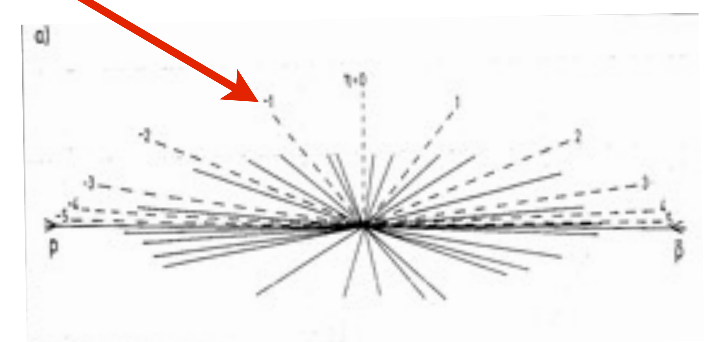
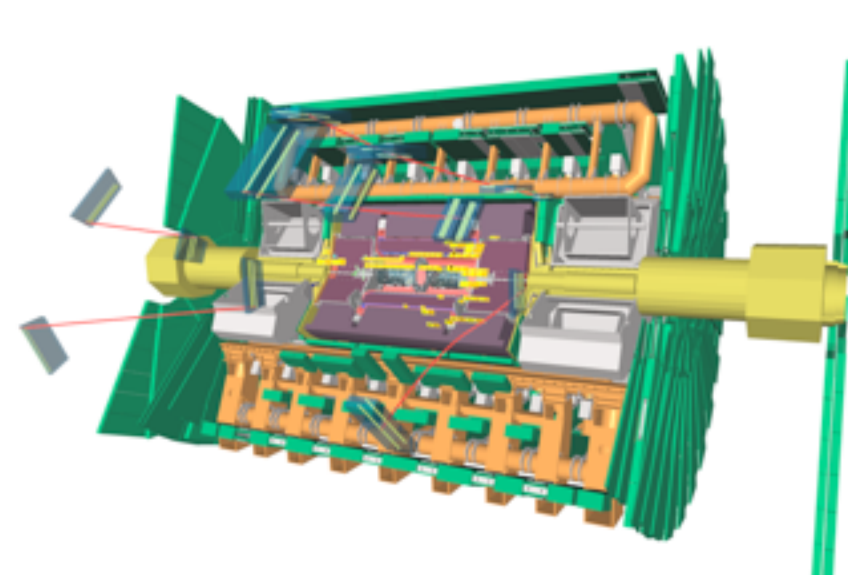






What do we need to separate?

- **Empty events** (for initial runs at very low luminosity, large proportion of bunch crossings were empty)**;**
- **Beam-gas;**
- **Beam-halo;**
- **Pile-up** (not so much of a big issue early on, but is becoming important as luminosity is increased).

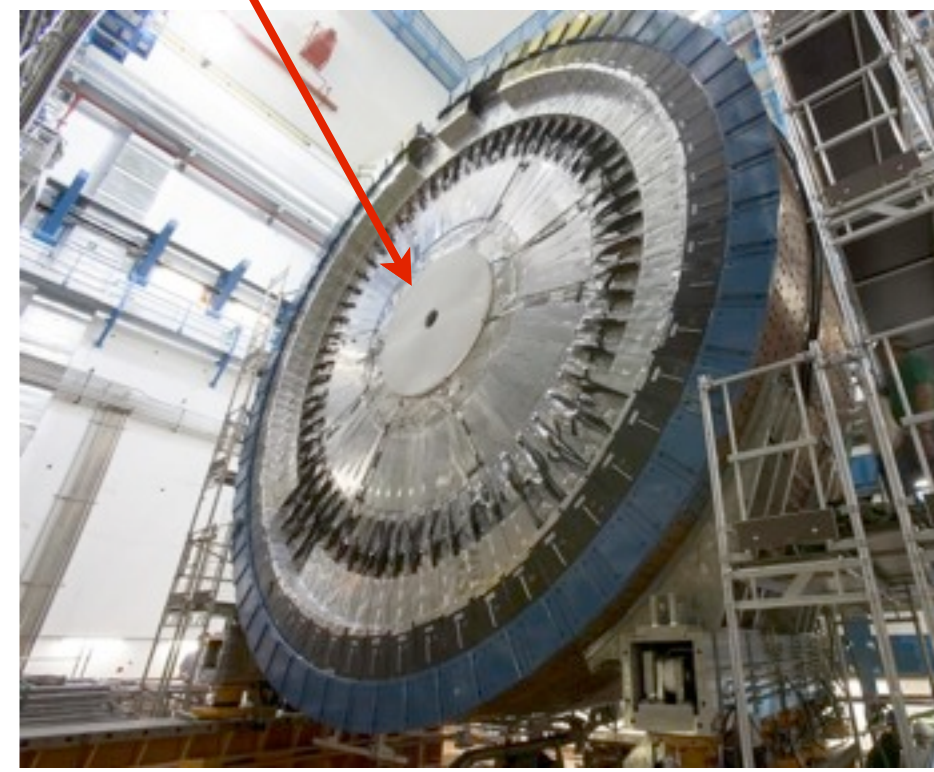


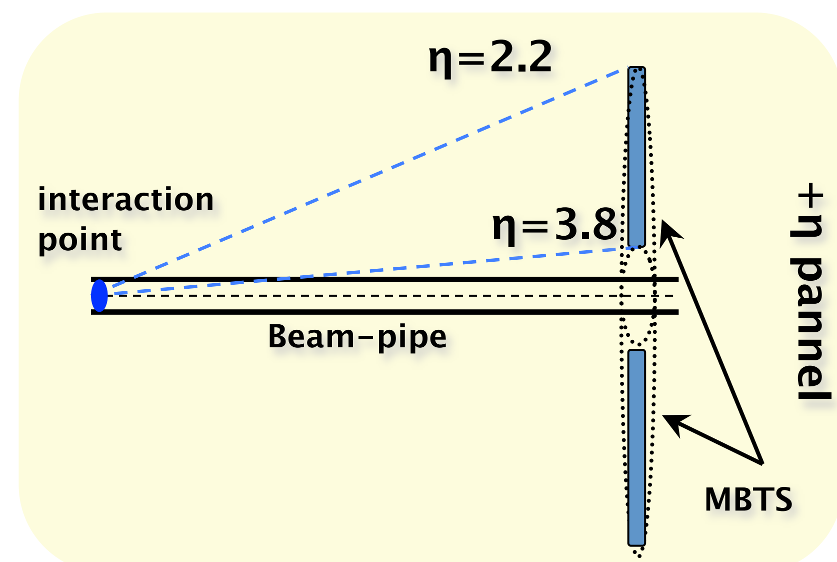
(beam-halo)

Measuring "minimum bias" events at ATLAS

- Data:
  - 900 GeV sample: ~455K events (PLB March'10)
  - 7 TeV sample: ~370K (ATLAS-CONF-2010-024) & ~10M (ATLAS-CONF-2010-046) events
- Event selection:
  - Single-arm trigger: require ≥ 1 MBTS counter to fire on either side
  - At least one primary vertex reconstructed
  - No additional primary vertices
  - Require: ≥1 track, p_T>500MeV (ATLAS-CONF-2010-024) or ≥2 tracks, p_T>100MeV (ATLAS-CONF-2010-046), $|\eta|<2.5$

Minimum Bias Trigger Scintilators (MBTS)





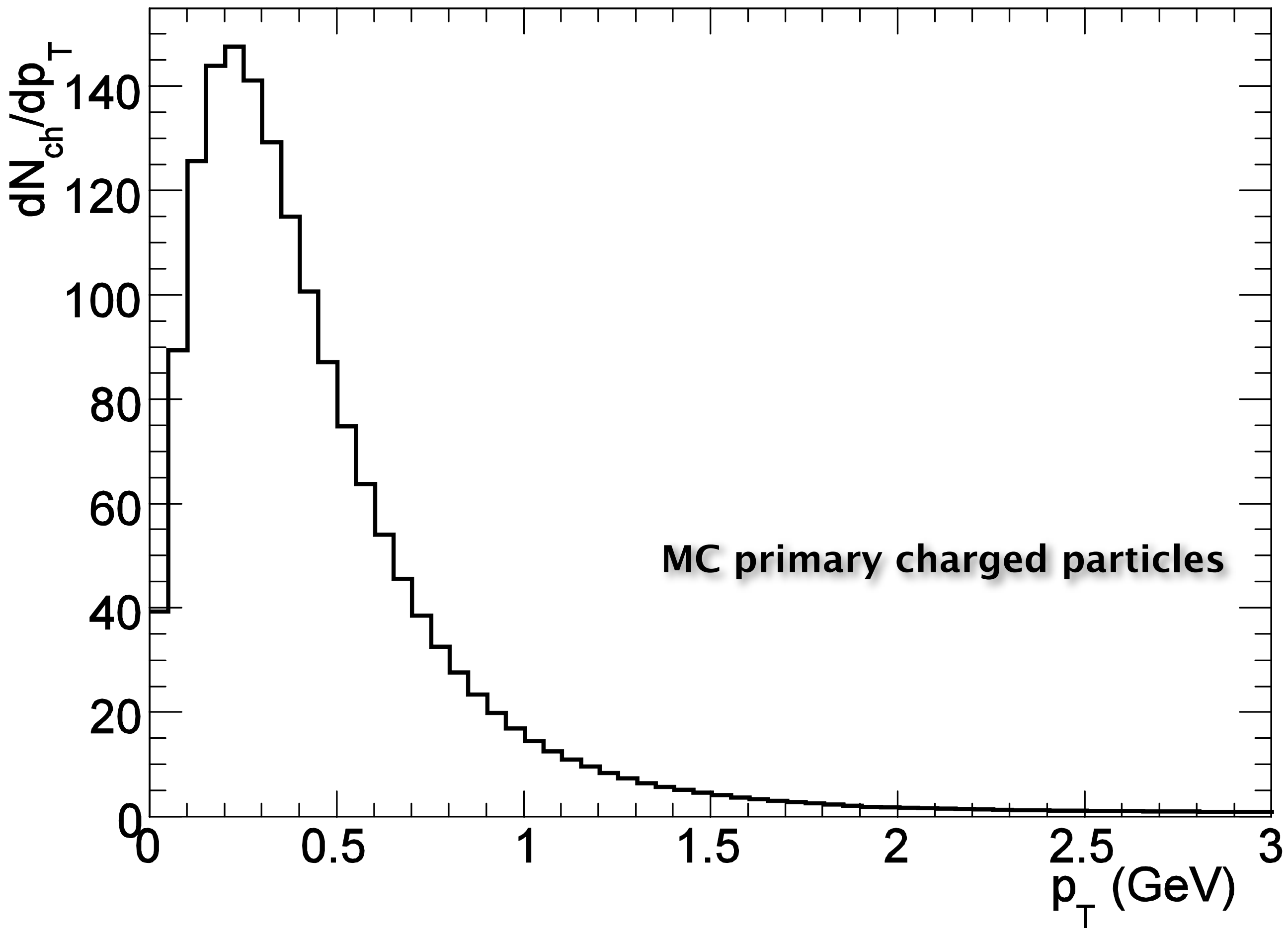
Trigger efficiency ~99% (slightly lower for low-p_T analysis)

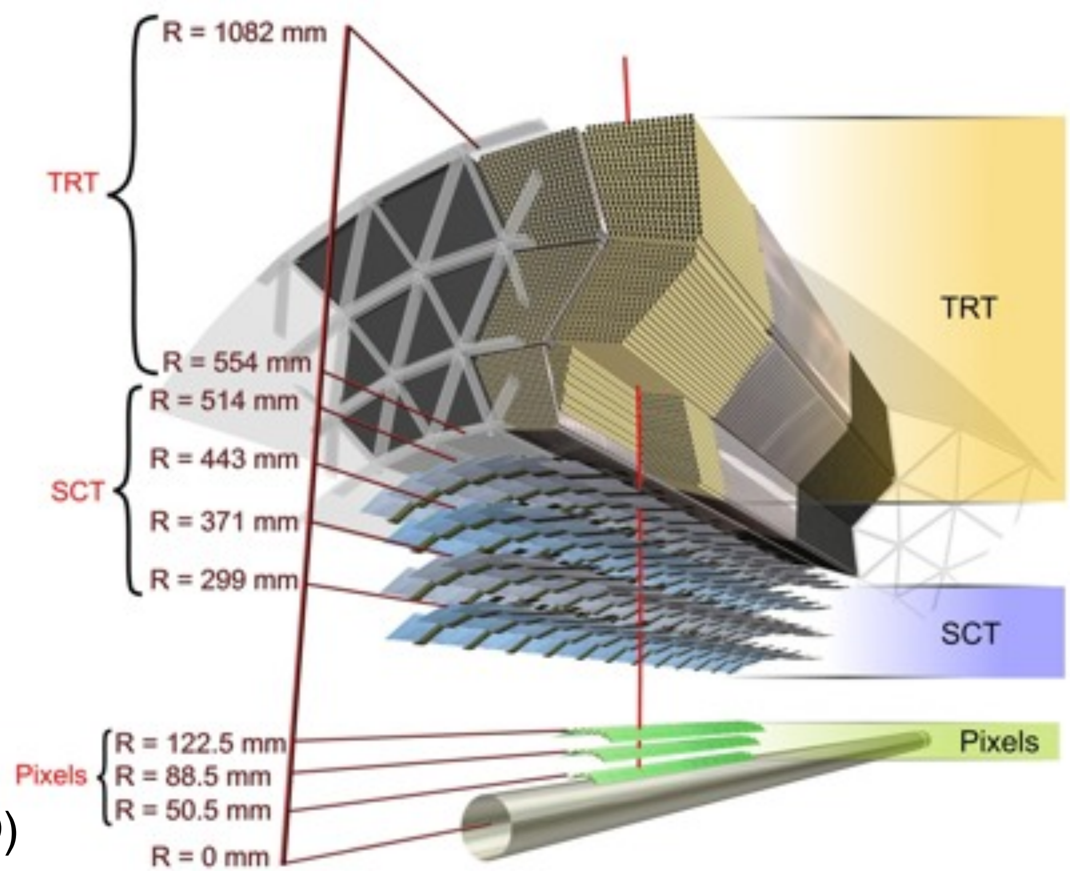
Cosmic ray background < 10^{-6} and beam backgrounds <0.1%

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

Reconstructing minimum bias events

- The goal is to reconstruct the event and recover all charged particles;
  - main limitation: soft track reconstruction!
  - at start-up, “typical” reconstruction: low p_T cut set to 500MeV;





(schematic view of the ATLAS ID)

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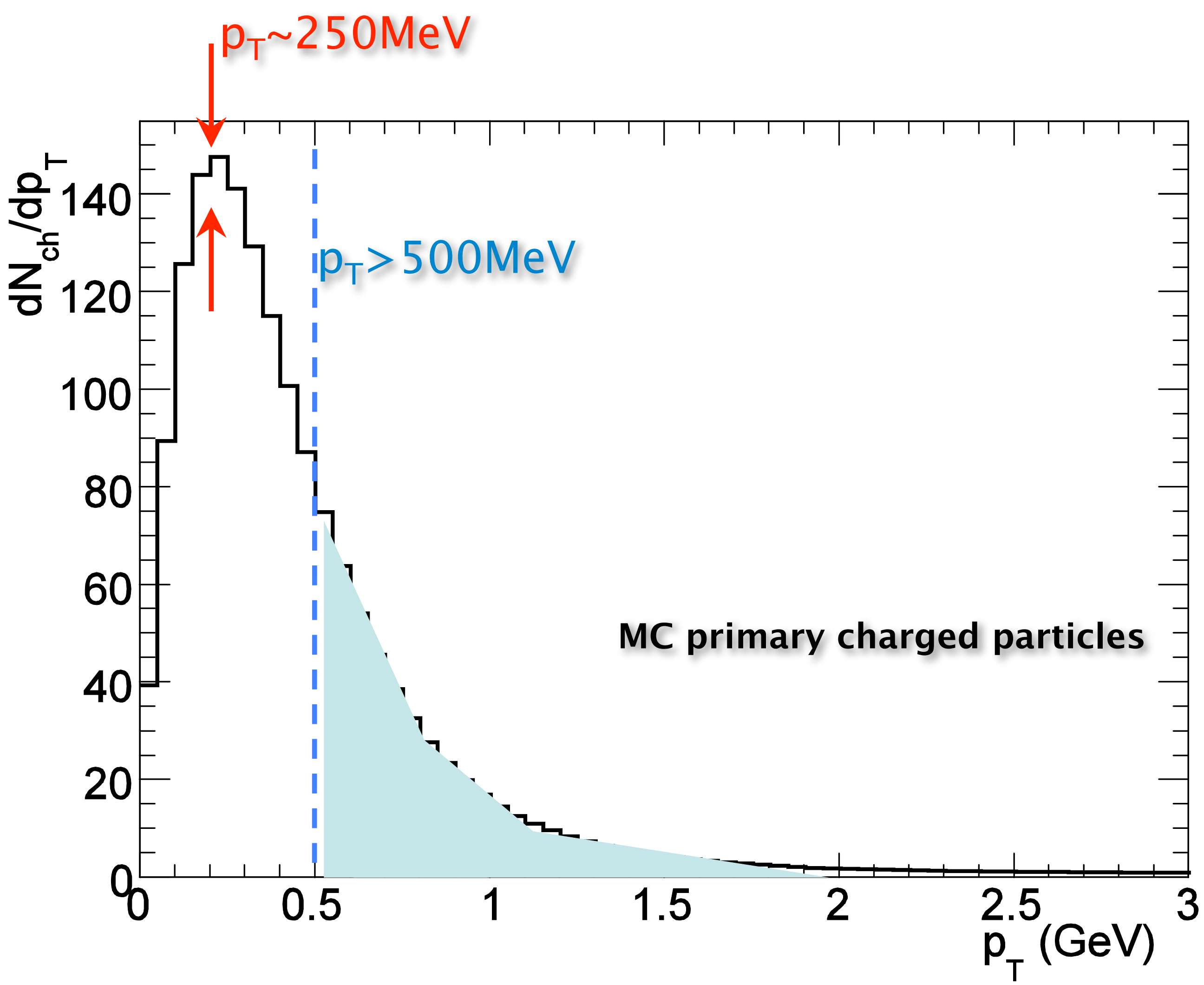
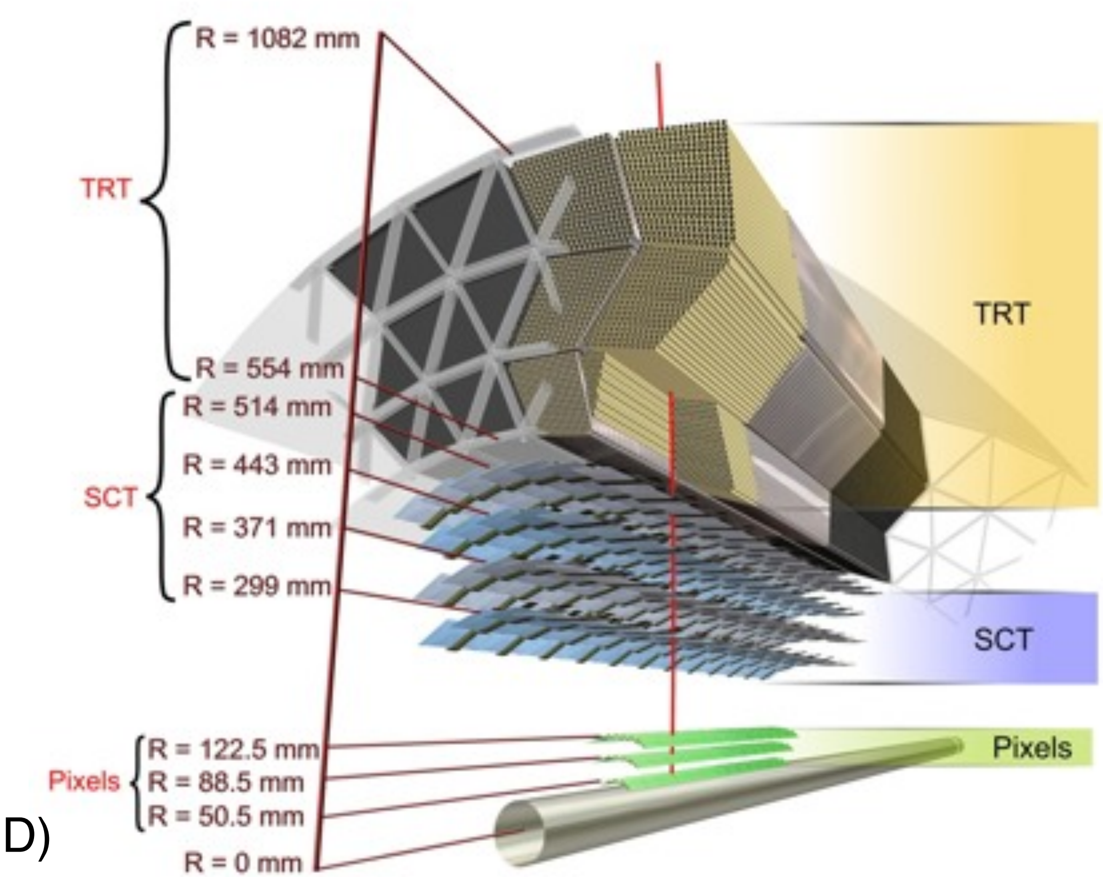


- Several strategies already available to push this limit to p_T ~ 100 MeV;
- Avoid large extrapolation factors for measurements such as $dN_{ch}/d\eta$.



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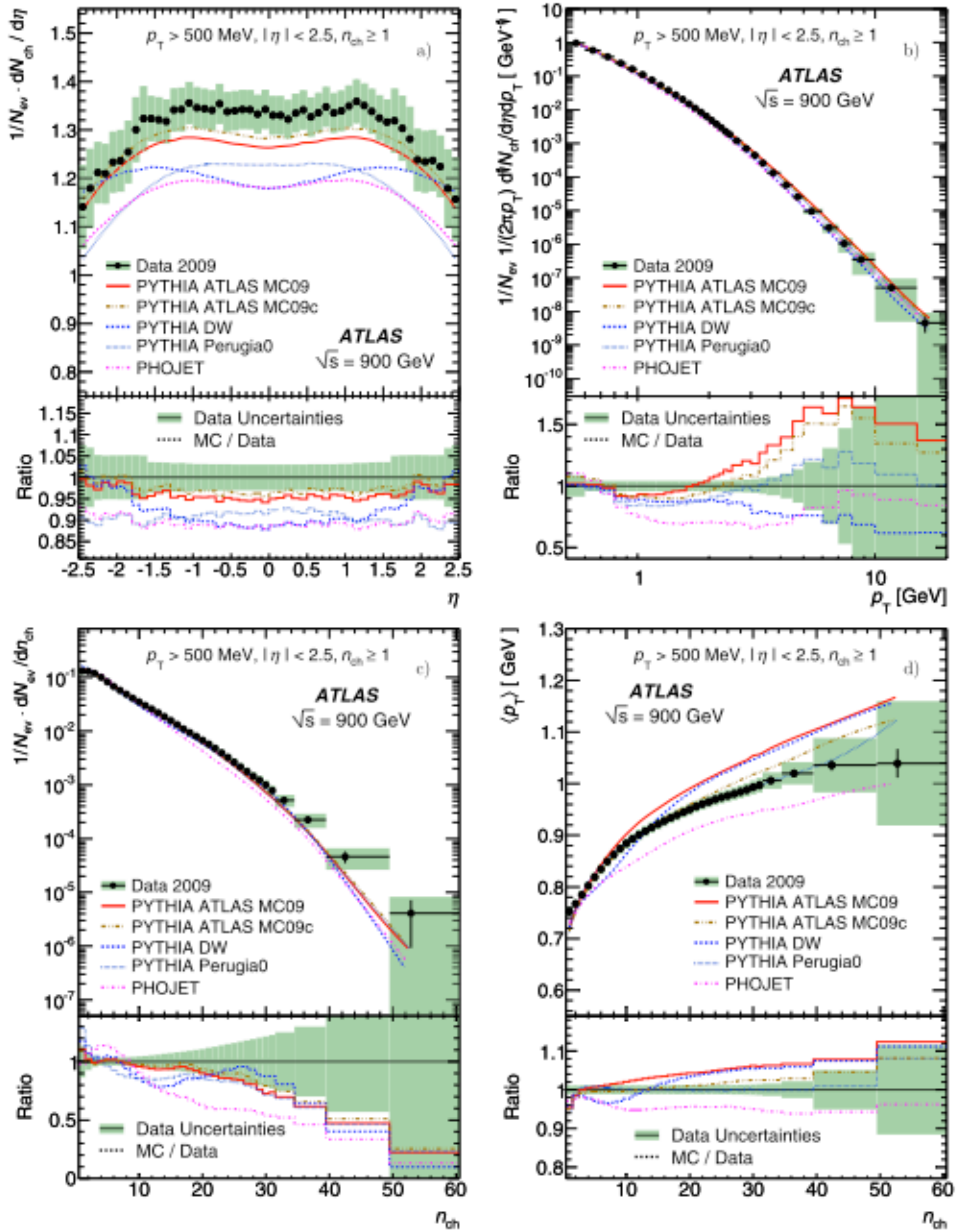
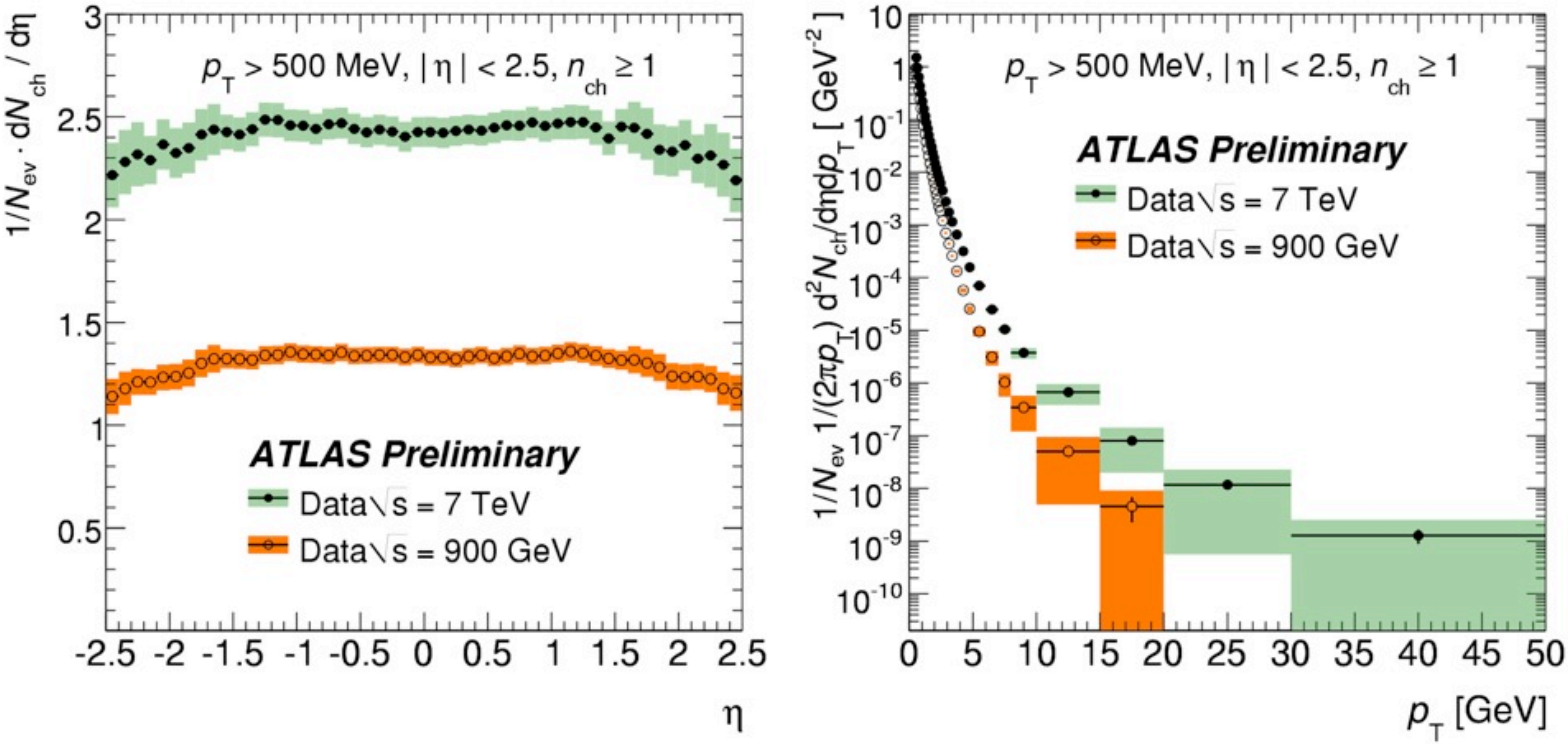
Minimum Bias measurements at √s=900 GeV

- **900 GeV data.**
- ATLAS presented measurements for an inclusive inelastic sample (avoiding model-dependent corrections).
  - Require ≥ 1 track (p_T>500MeV, |η|<2.5)
- **Data corrected to particle level!**
- Results are **NOT** directly comparable to ALICE, CMS and previous experiments (which are usually corrected to NSD).
- The charged particle densities in η and p_T are not "perfectly" described by any of the MC tunes.
- [Phys. Lett. B **688** (2010) 21-42](#)



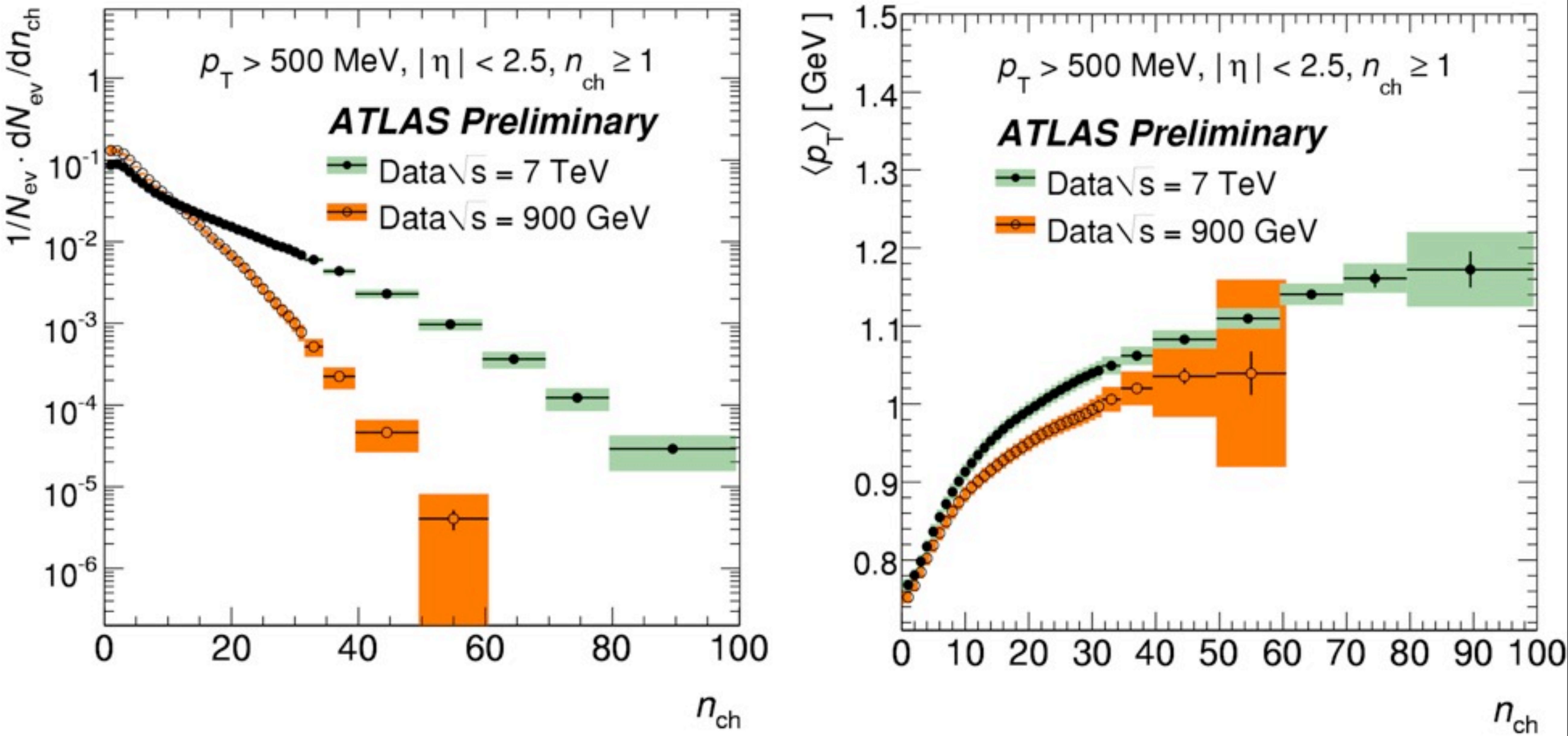
Charged particle distributions: √s=900 GeV vs √s=7 TeV



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

ATLAS-CONF-2010-024

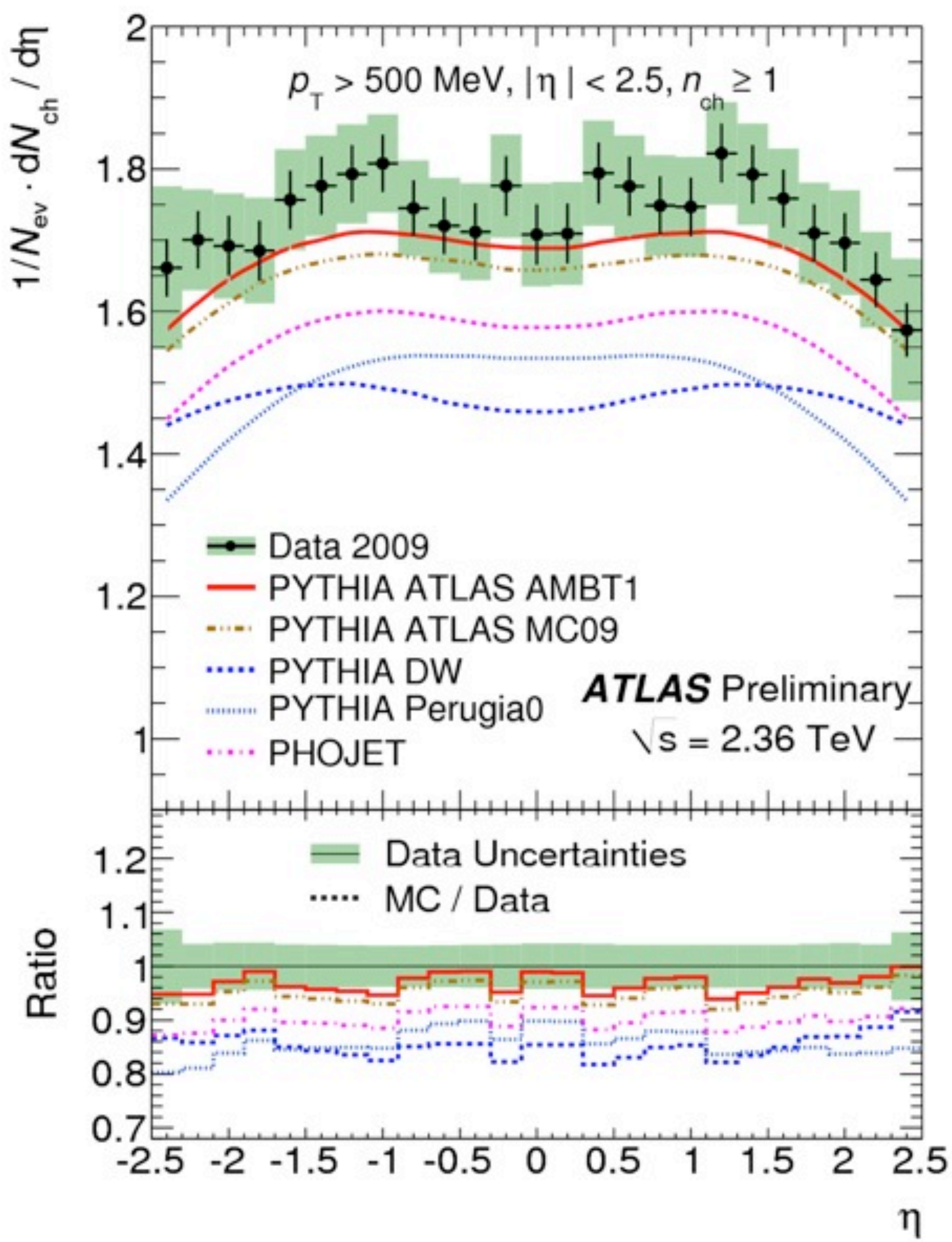
Charged particle distributions: $\sqrt{s}$=900 GeV vs $\sqrt{s}$=7 TeV



▸ Repeated these measurements for a diffractive limited phase-space sample (ie. requirement of higher multiplicity). Used to re-tune MC generators **(AMBT1)** benefiting from information on the energy dependence.

- For more details: ATLAS-CONF-2010-031

Charged particle distributions: √s=2.36 TeV (limited detector operation)



- pp collisions at √s=2.36TeV: stable beam conditions were not declared!
- 8151 events triggered MBTS.
- SCT operated at “standby” mode (ie. lower voltage, lower efficiency).
- Two complementary methods used to reconstruct tracks: pixel track & ID track
- New PYTHIA-ATLAS tune to 900GeV and 7TeV data (AMBT1) gives a good description of 2.36TeV measurements.

- For more details: ATLAS-CONF-2010-047

Charged particle distributions: $\sqrt{s}$=2.36 TeV (limited detector operation)

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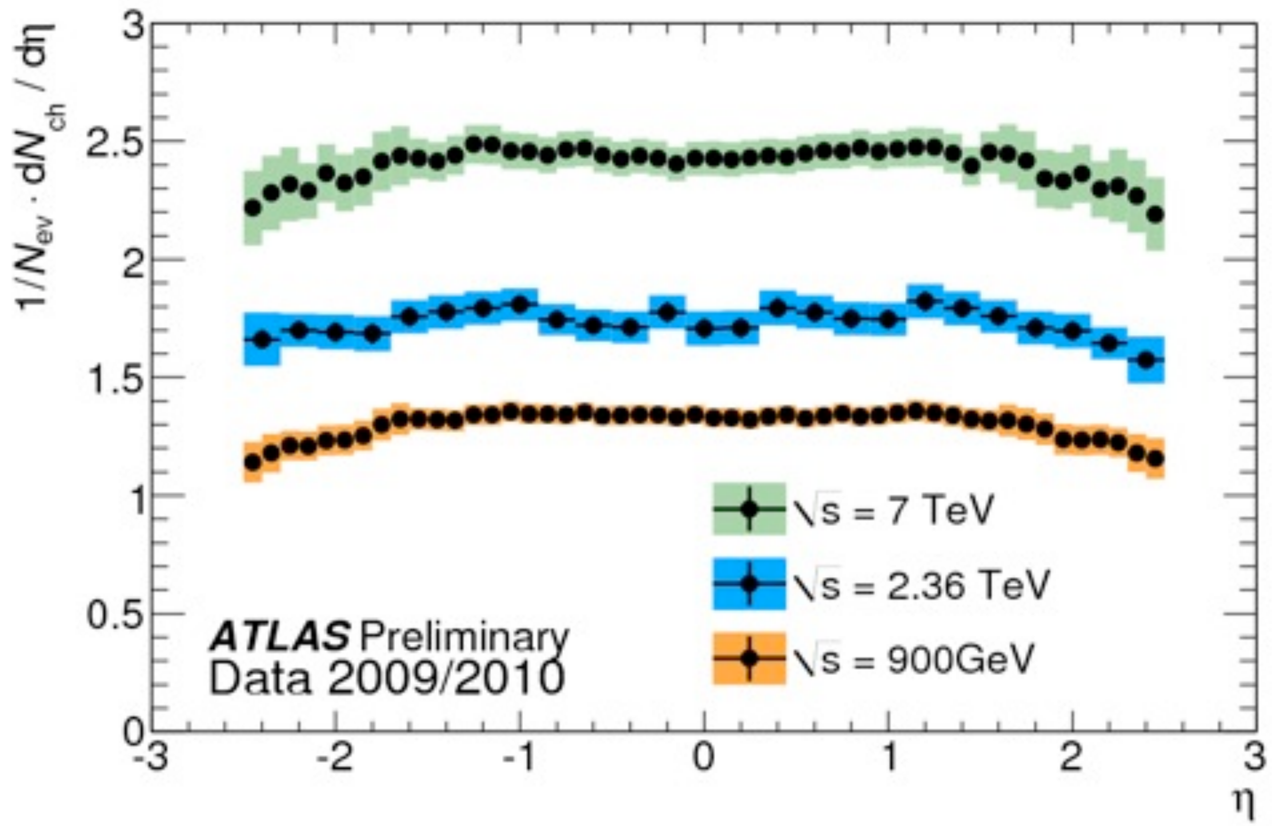

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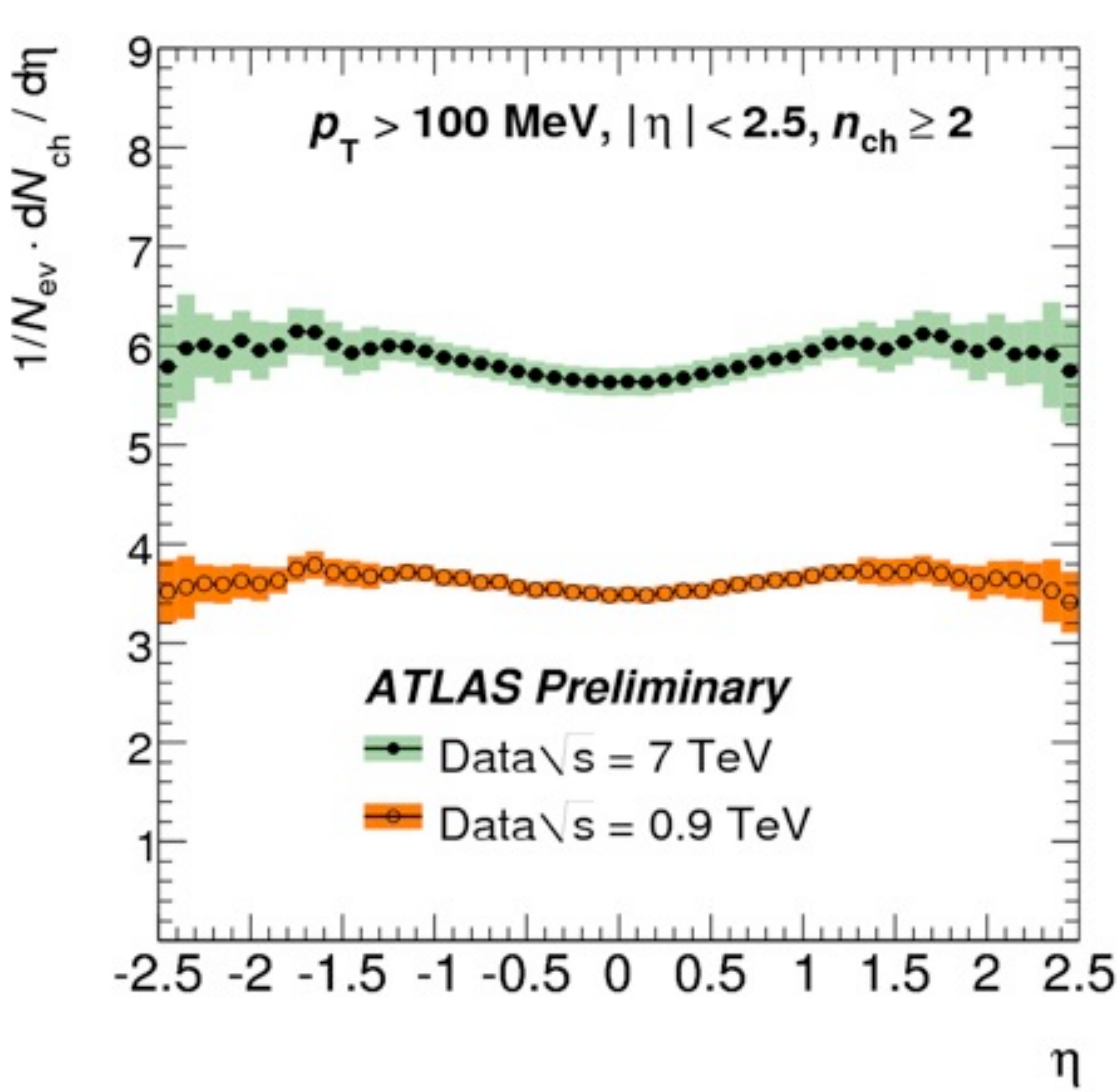
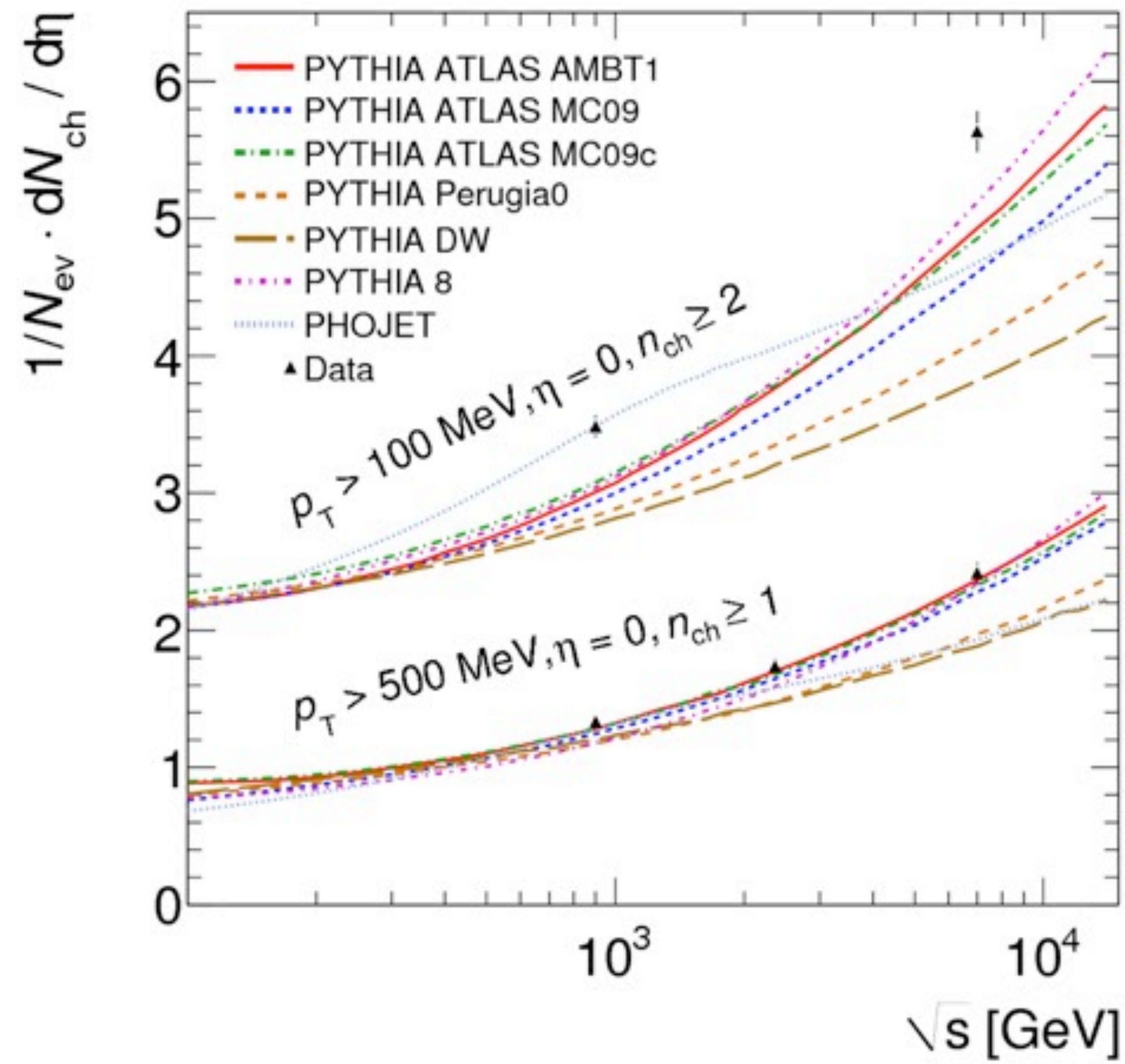
For more details: ATLAS-CONF-2010-047

ATLAS: Charged particle distributions for tracks with $p_T > 100\,\text{MeV}$

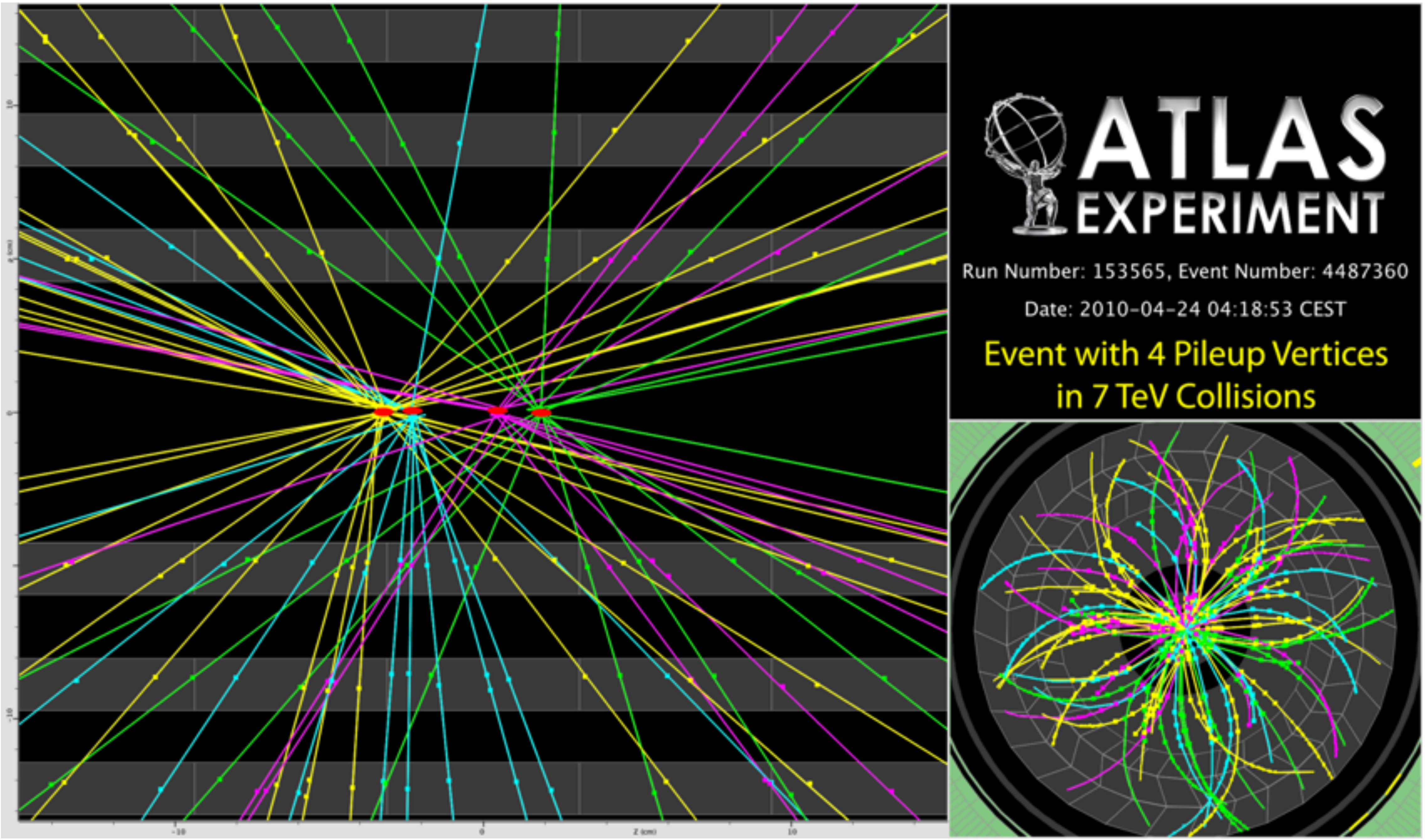




- Major improvement: track p_T threshold reduced from **500MeV** to **100MeV** (probing softer particle production). Measurements at 7TeV were made over a much larger sample (~10M events) than in the previous analysis.

- **ATLAS-CONF-2010-046**

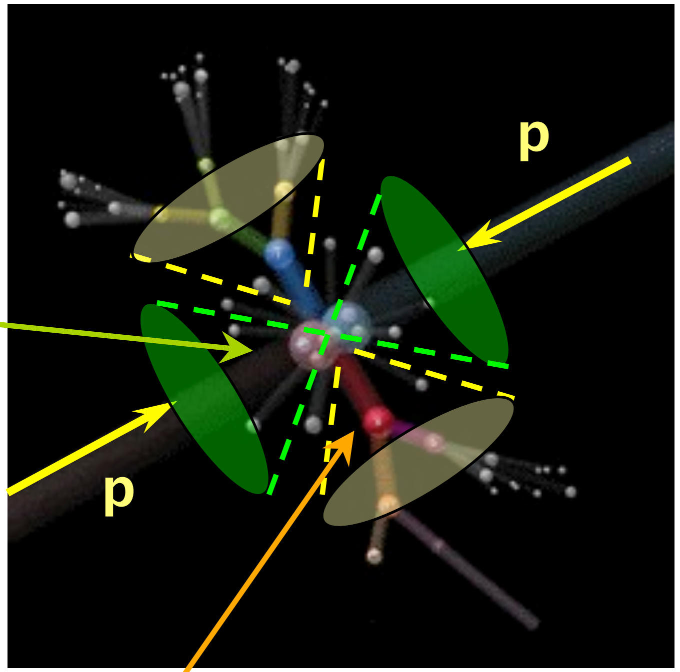
ATLAS event with 4 pile-up vertices in 7 TeV collisions



Measuring the Underlying Event

- **The underlying event:** All particles from a single particle collision except the process of interest.
  - Sometimes, the underlying event can also be defined as everything in the collision except the hard process (high-Q^2).

the underlying event



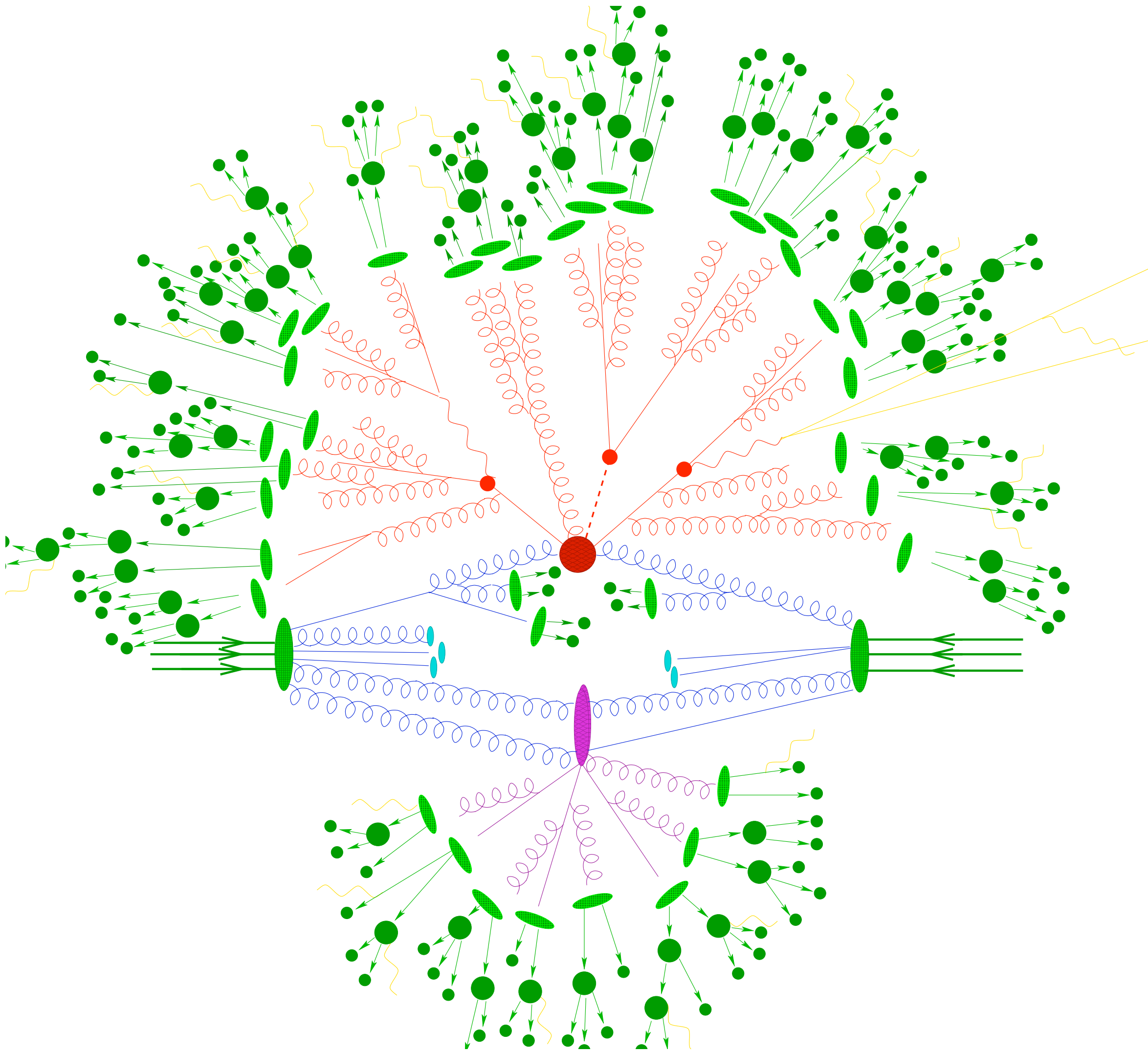
Process of interest (eg. high p_T jets, top-anti-top pair, Z boson)

- **Common mis-conception**: in the pre-Tevatron era, the activity in the underlying event (particle multiplicity, p_T^{sum}, ...) was assumed to be **"approximately"** the activity measured in minimum bias events.

- The underlying event studies allow us to take advantage of the **structure of hadron-hadron collision events**.

The CDF collaboration: Phys. Rev. D65, 092002 (2002).

More detailed look into the underlying event...



* Influenced by contributions from:
  - parton showers (ISR/FSR)
  - multiparton interactions

    (cross-section raises faster than originally thought!)
  - beam remnants
  - colour field connecting hard-scatter to beam remnants

    (this appears to be essential to get correlation $\langle p_T \rangle$ – n_{chg} correctly described)

Experimental challenge: define observables that allow us to "isolate" individual components of the underlying event!

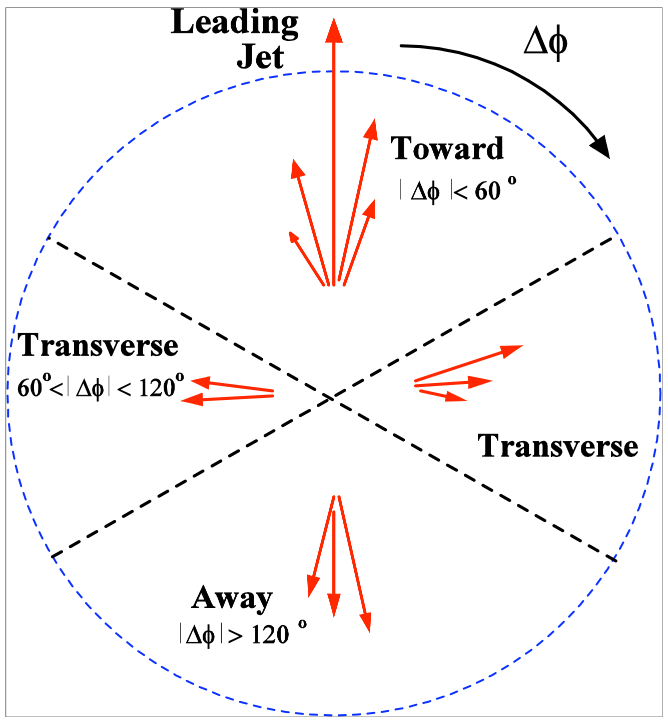
Modelling challenge: vary model parameters consistently so most (if not all) observables can be properly described

The underlying event in pp collisions at √s = 14 TeV (simulation)

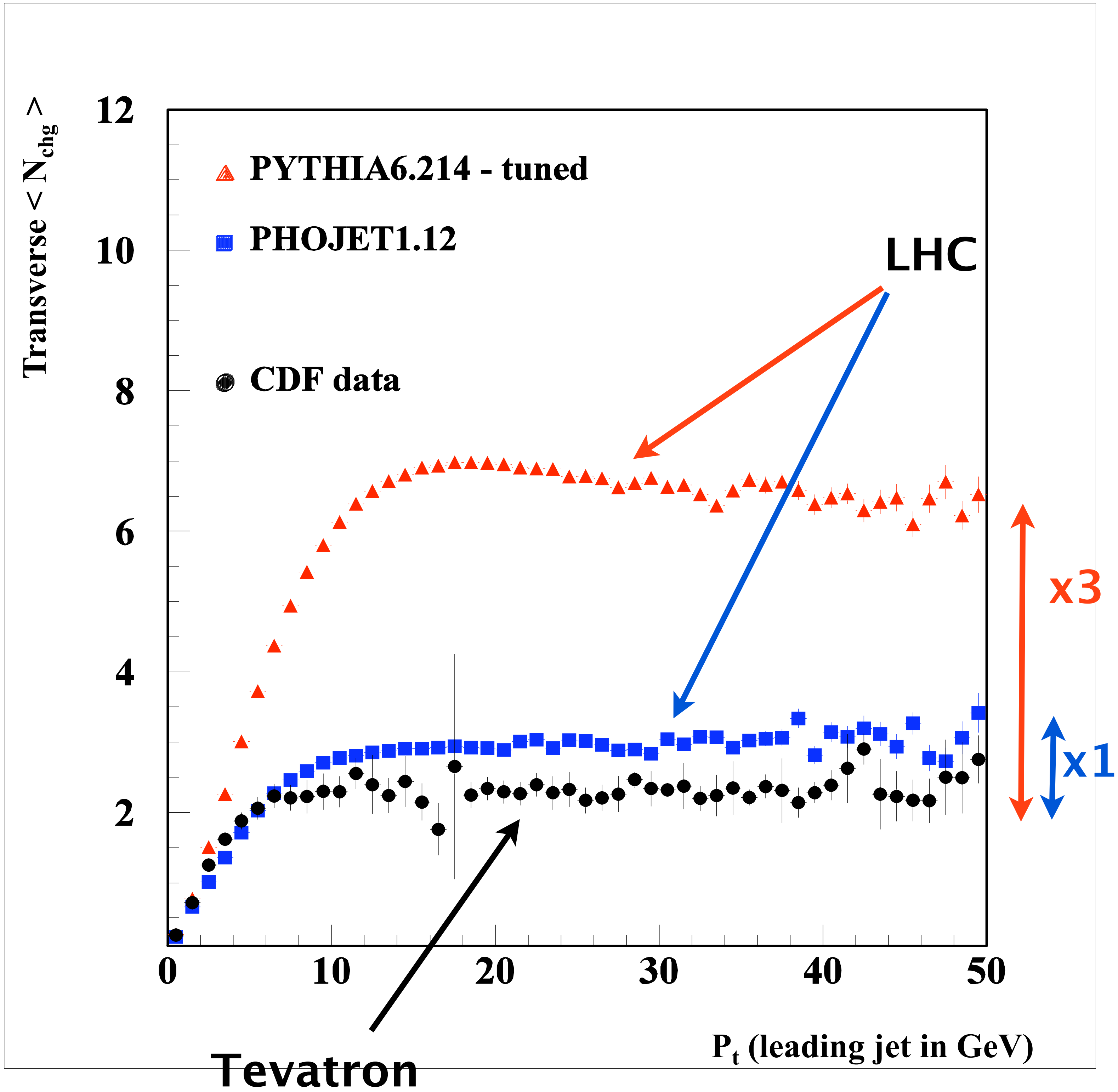
CDF - Run I "Style"

Charged particles:
p_t>0.5 GeV and |η|<1

Cone jet finder: R=0.7

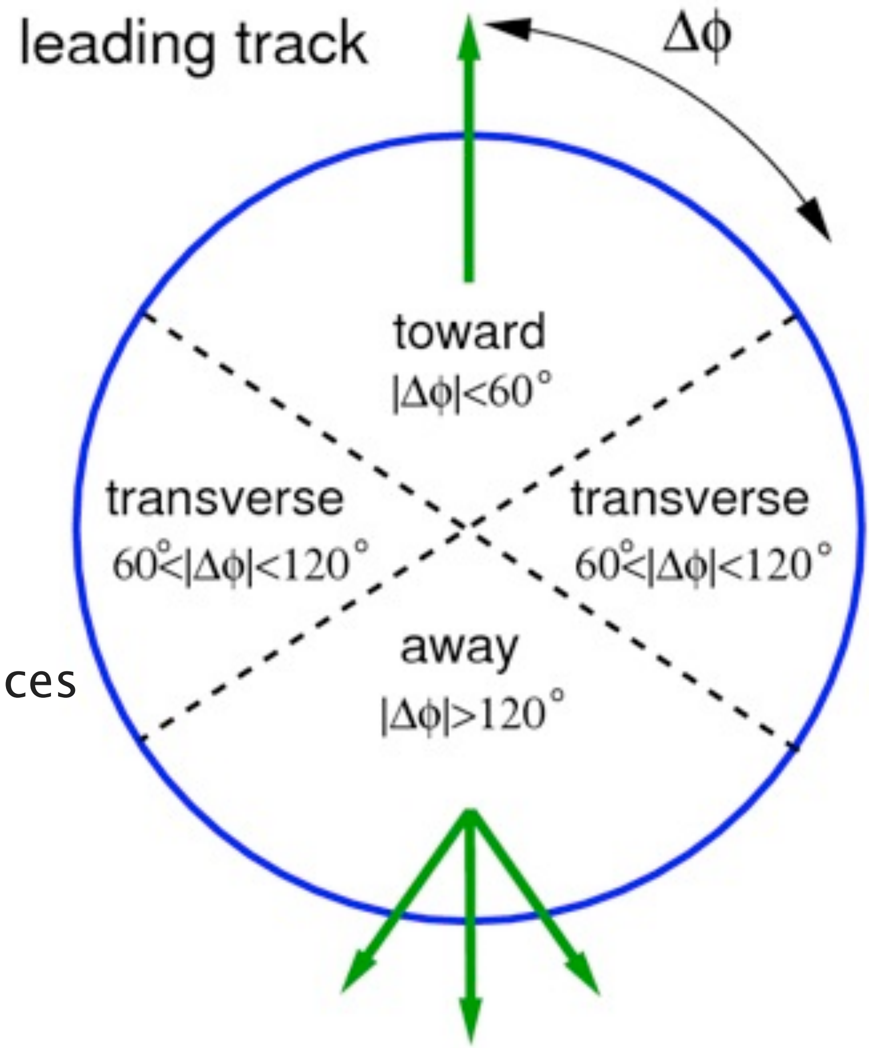


UE particles come from region transverse to the leading jet.



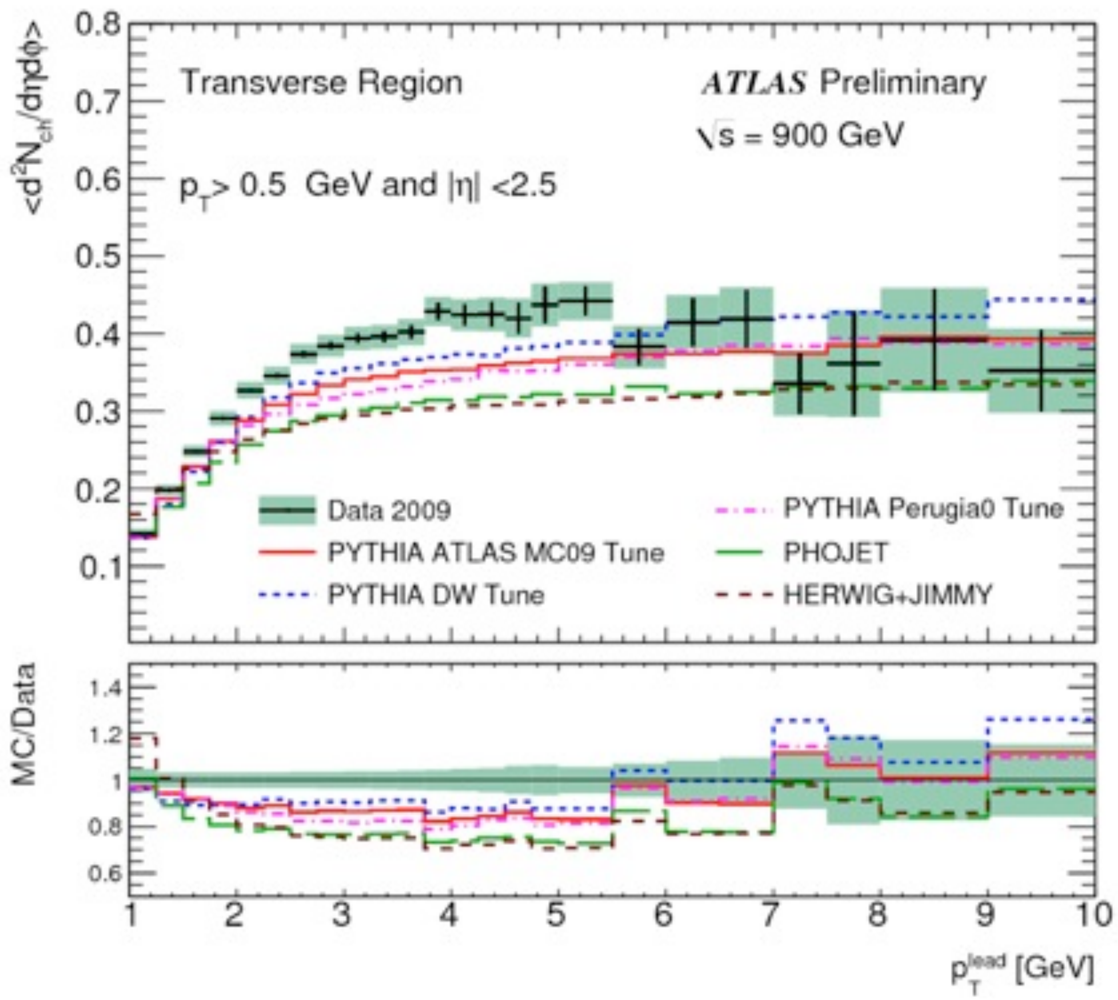
The underlying event: ATLAS measurement

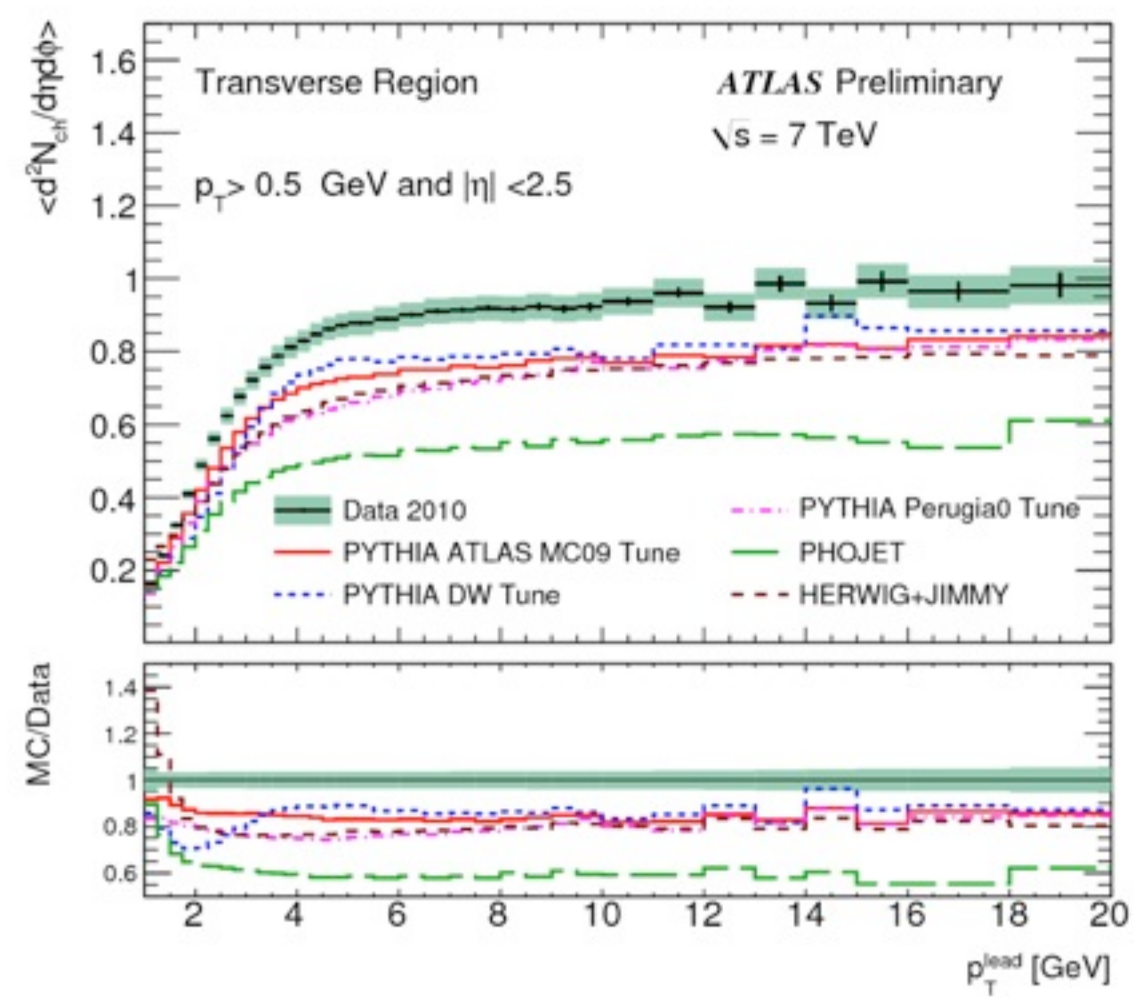
- Event selection:
  - stable beams, MBTS and ID at nominal conditions
  - full 900GeV sample (same as used for Minimum Bias measurements)
  - 7 TeV: collected between March – April 2010
  - L1_MBTS_1 ≥ 1 hit
  - At least one primary vertex reconstructed
  - No additional primary vertices with 4 or more associated vertex tracks
  - At least one selected track with $p_T > 1.0$ GeV (this reduces diffraction significantly,ie. <1% of tracks originate from diffraction!)
- Track selection:
  - 1 Pixel & 6 SCT hits
  - Require $p_T > 500$ MeV & $|\eta| < 2.5$
  - $|d_0| < 1.5$ mm
  - $|z_0|\sin\theta < 1.5$ mm



ATLAS-CONF-2010-081

Transverse Number Density
(charged particles)

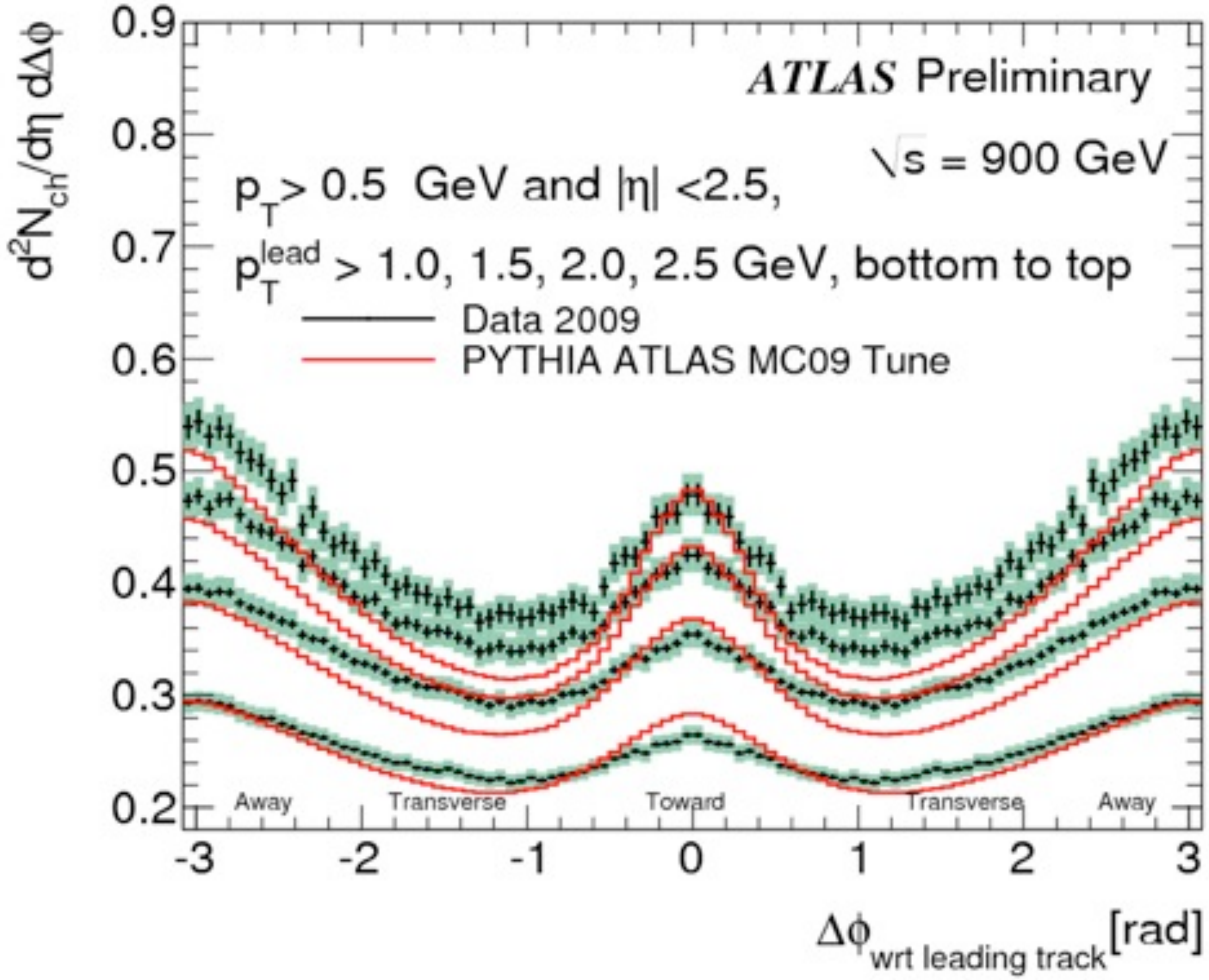


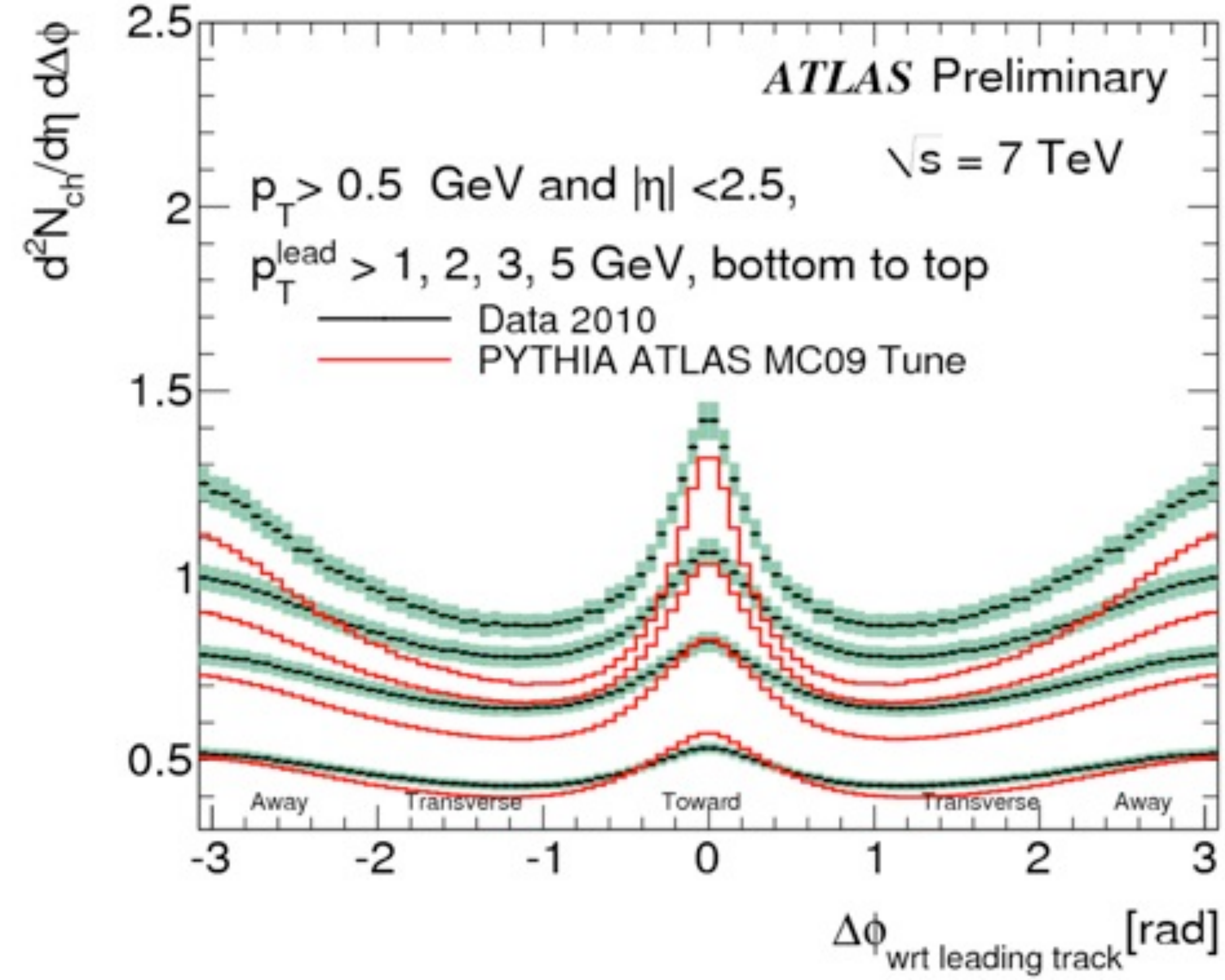


- Data corrected to particle level: a) Event level (trigger, vertex and lead. track); b) Tracking (p_T–η bins); c) Unfolding (bin-by-bin migration and event reorientation).
- The number density in data is higher than predicted by any of the MC tunes (also observed in comparisons to minimum bias densities).
- The difference is more significant at 7 TeV (energy extrapolation!).

ATLAS-CONF-2010-081

Angular Distributions
(charged particles)

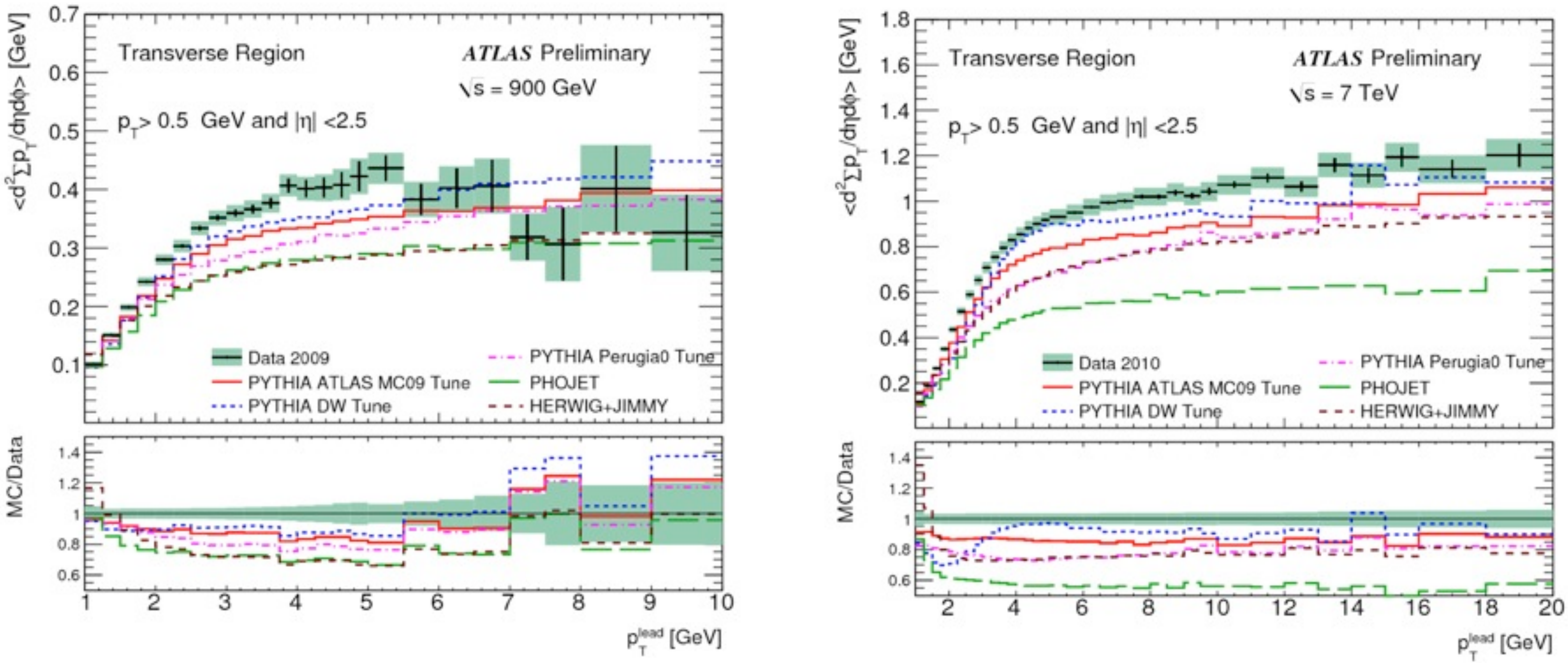




- Charged particle density as a function of ΔΦ w.r.t. the leading particle (which is excluded from these plots). Data corrected to the particle level.
- As the p_T of the leading particle increases, the development of “jet-like” region of higher number density is observed adjacent to and opposite the leading particle.
- The number density is both higher and has a different angular distribution than is predicted by the ATLAS MC09 tune.

ATLAS-CONF-2010-081

Transverse Sum p_T Density
(charged particles)



- 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.

ATLAS-CONF-2010-081

$\langle p_T \rangle$ vs. multiplicity
(charged particles)

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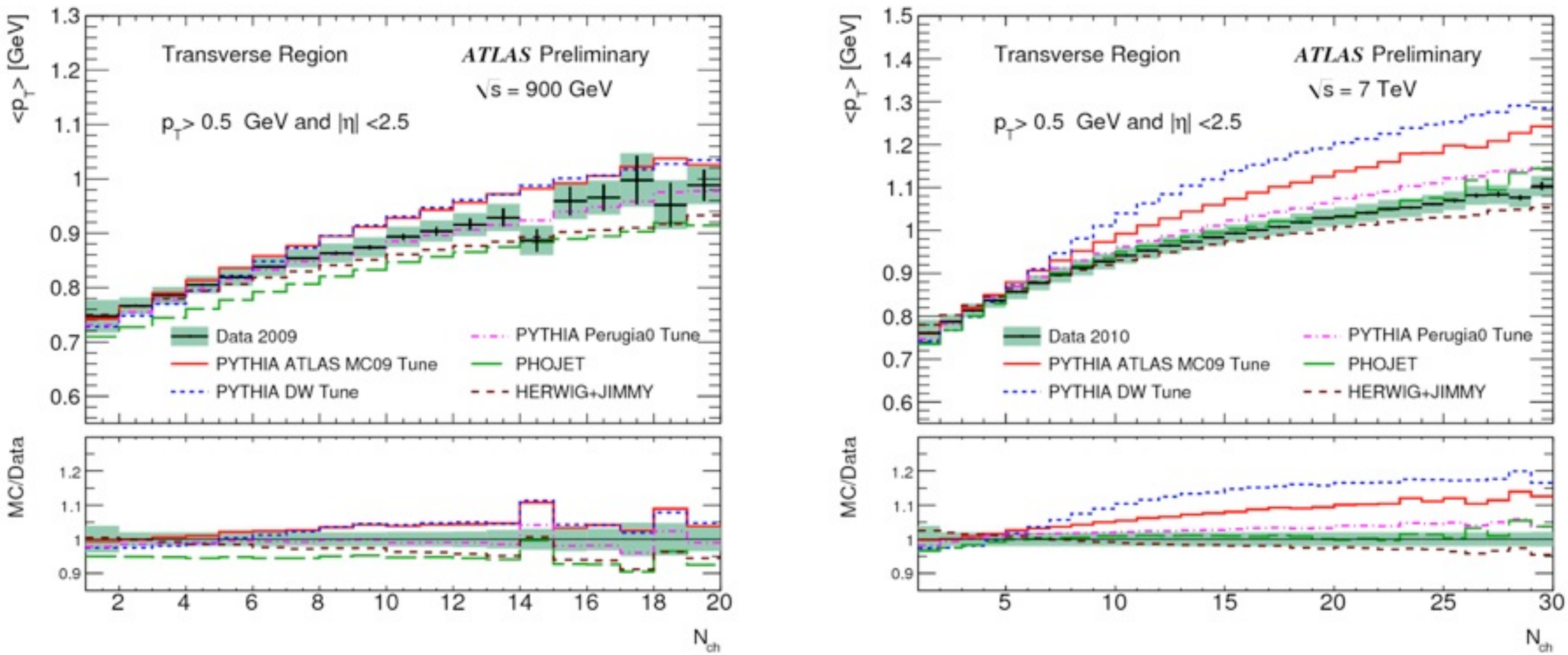
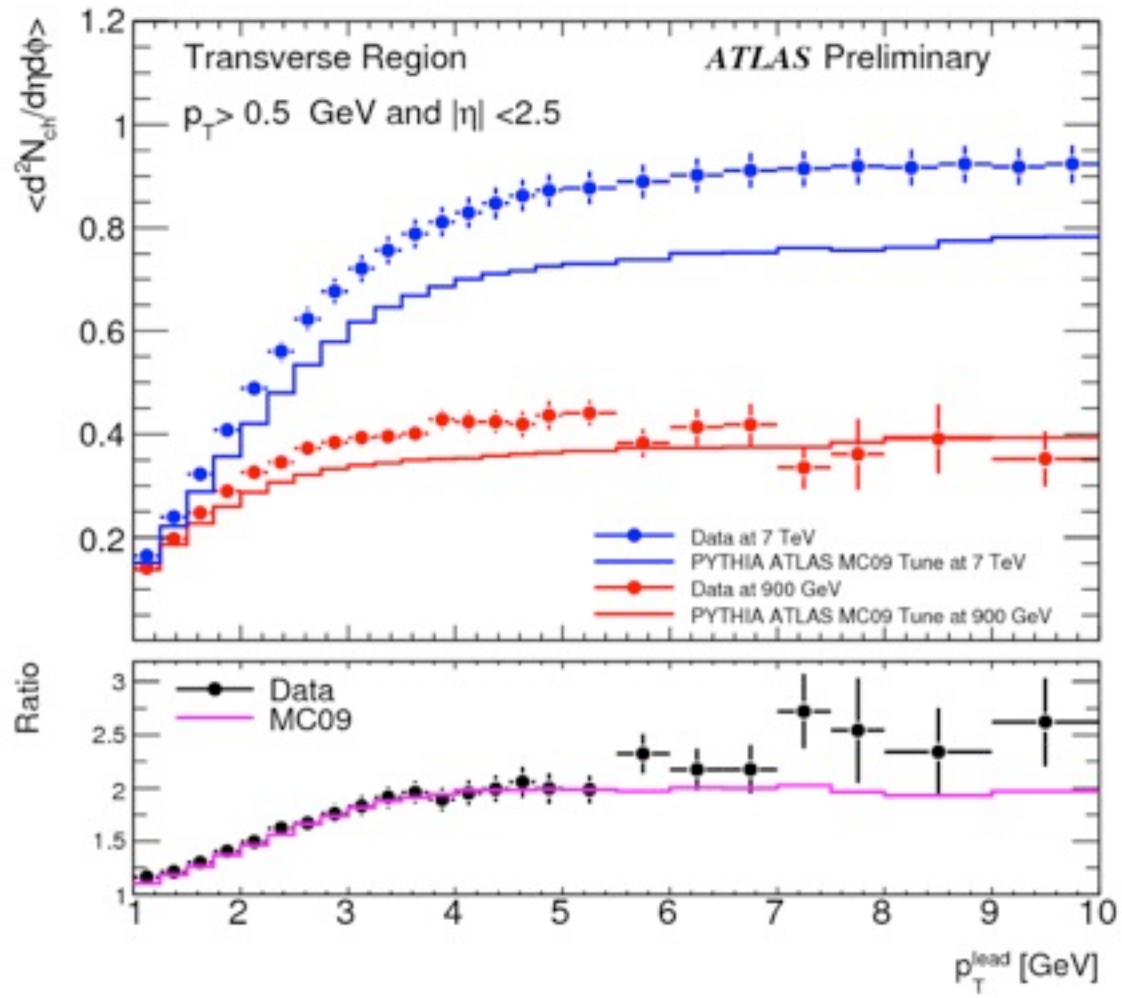
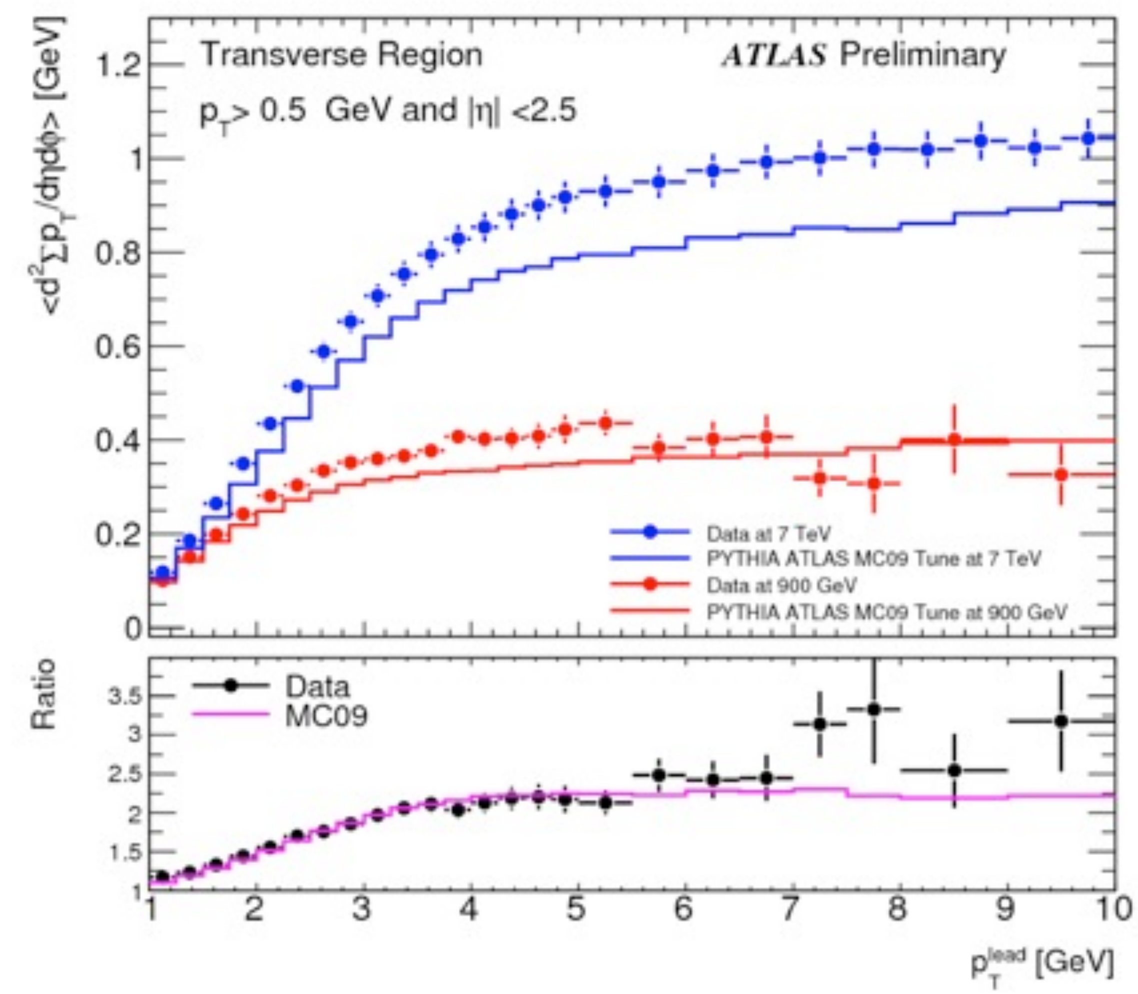


- $\langle p_T \rangle$ of charged particles against the charged multiplicity with $p_T > 0.5$ GeV and $|\eta| < 2.5$ as a function of the leading track p_T, for the transverse region.
- If only beam-beam remnant contributed to the UE, $\langle p_T \rangle$ would not depend on the multiplicity.
- Rising trend of $\langle p_T \rangle$ indicates that (semi-) hard processes contribute to the UE in addition to beam-beam remnants.

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

University of Glasgow





- Comparing number and sum p_T densities for 900GeV 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 HERWIG/JIMMY **(AUET1)** benefiting from information on the energy dependence.
  - more details on AUET1: **ATLAS-PHYS-PUB-2010-014**

Summary

- **The search for "New Physics" at the LHC has begun with studies aimed at understanding the detector and the hadronic environment in LHC collisions.**

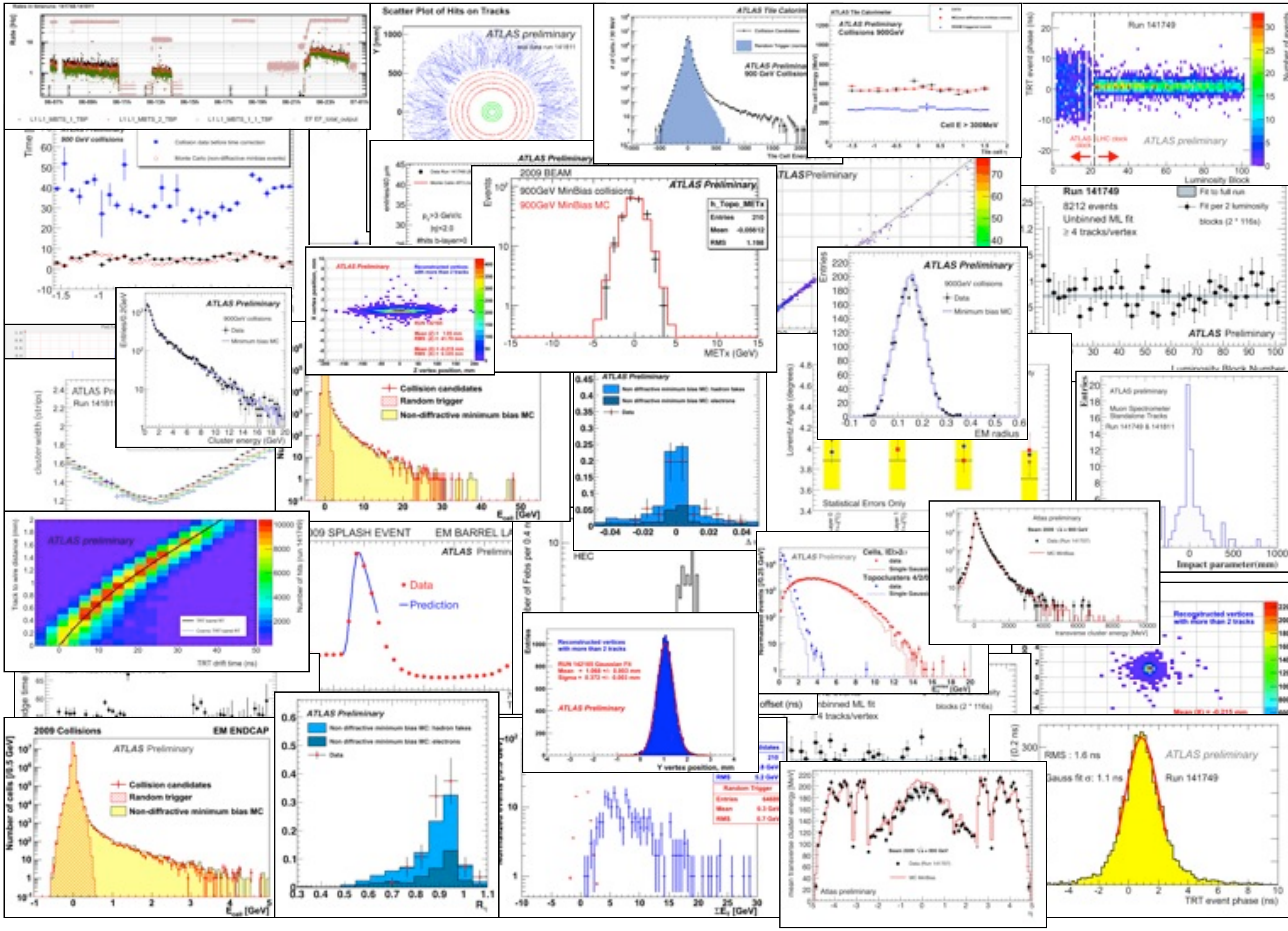
- **Data – MC comparisons show there is a need to continue improving models/ MC tunings.**
  - new MC tunes using ATLAS data have already been produced: AMBT1 & AUET1

- **"Early" measurements ≠ "Easy" measurements!** Remember: brand new physics environment & new technologies.
  - Performance of trigger systems and detectors have been the focus of this early round of data taking / analysis.
  - Early characterisation of minimum bias events with track measurements has been successfully performed for both $\sqrt{s}$=900 GeV (2.36 TeV) and 7 TeV.
  - First measurements of the underlying event have also been made. Other event topologies currently being studied.
  - The definitive papers on MB and UE for these data samples are being reviewed by the collaboration (should appear later this year).
  - Very promising start of a new era of collider physics...discoveries are "just" in the horizon!

Backup

...some examples of (preliminary) detector performance results

University of Glasgow



The ATLAS Collaboration,
G. Aad *et al.*, Performance of the ATLAS Detector using First Collision Data, JHEP09 (2010) 056

Systematic uncertainties: Minimum bias

Systematic uncertainty on the number of events, N_{ev}		
	$\sqrt{s}$ = 0.9 TeV	$\sqrt{s}$ = 7 TeV
Trigger efficiency	0.2%	0.2%
Vertex-reconstruction efficiency	< 0.1%	< 0.1%
Track-reconstruction efficiency	1.0%	0.7%
Different Monte Carlo tunes	0.4%	0.4%
Total uncertainty on N_{ev}	1.1%	0.8%
Systematic uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$		
Track-reconstruction efficiency	3.1%	3.1%
Trigger and vertex efficiency	< 0.1%	< 0.1%
Secondary fraction	0.4%	0.4%
Total uncertainty on N_{ev}	−1.1%	−0.8%
Total uncertainty on $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$	2.1%	2.3%

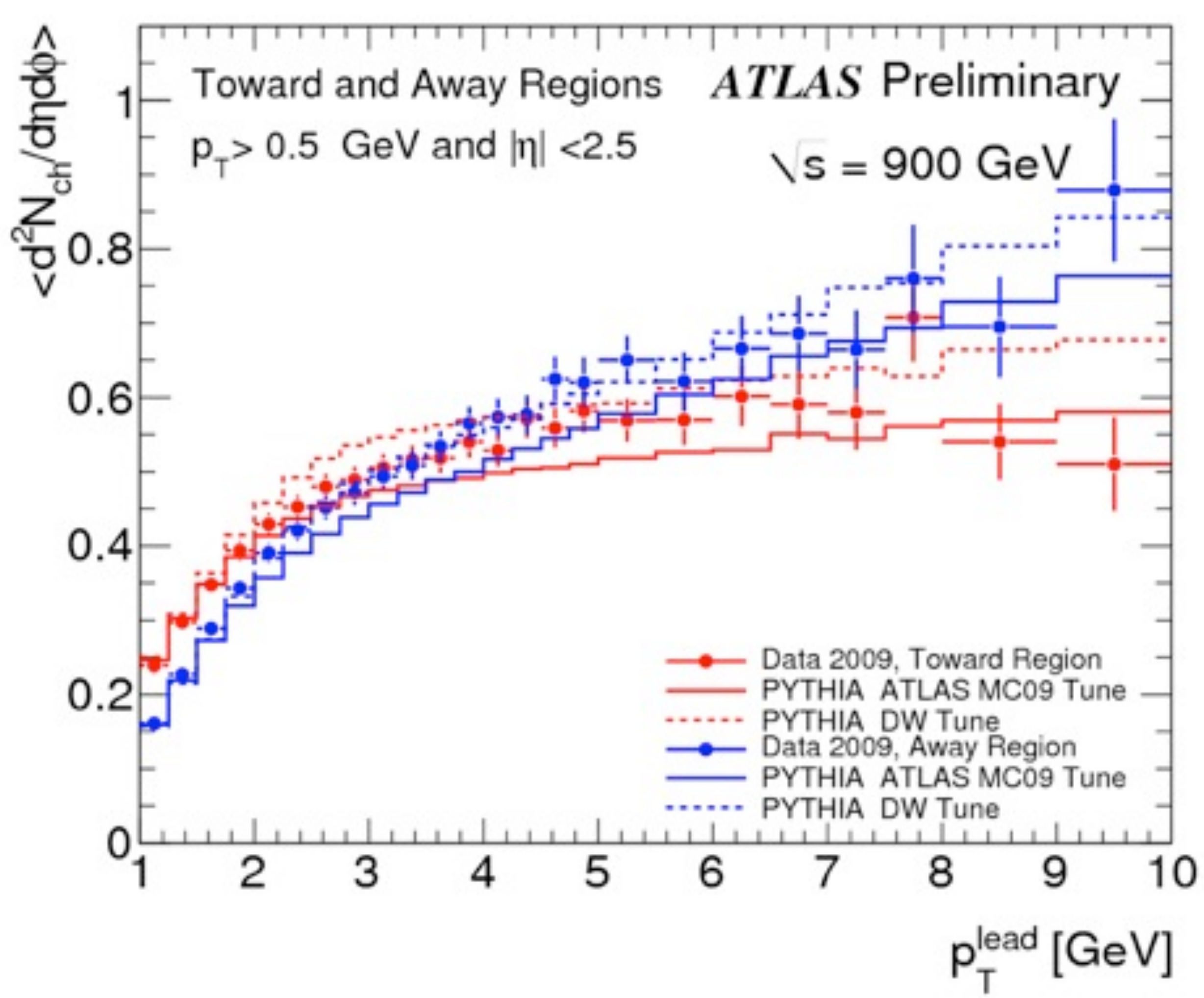
Summary of systematic uncertainties on the number of events, N_{ev}, and on the charged-particle density $(1/N_{ev})\cdot(dN_{ch}/d\eta)$ at $\eta = 0$. All sources of uncertainty are assumed to be uncorrelated.

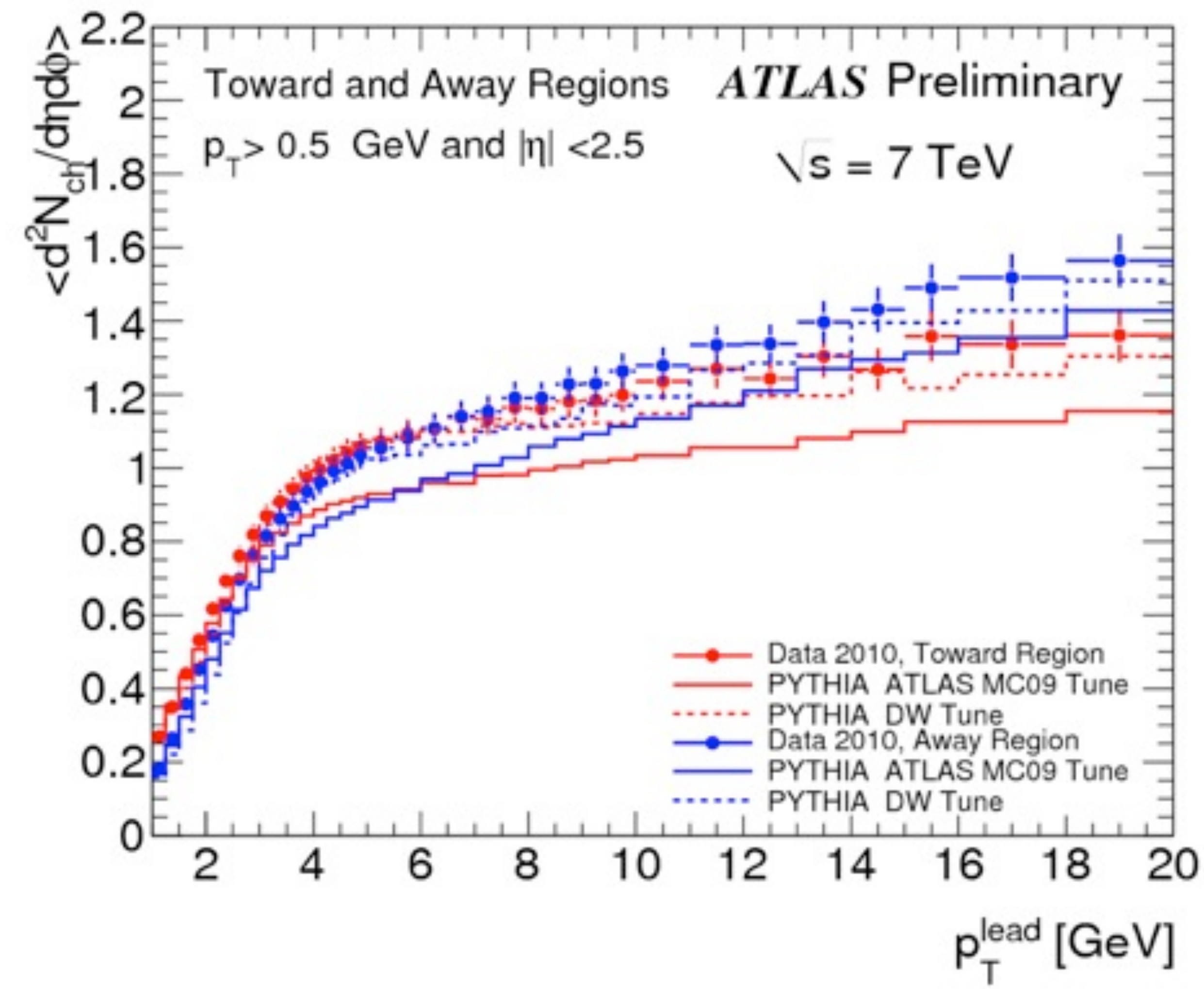
Systematic uncertainties: UE

Summary of systematic uncertainties, shown in the lowest, intermediate and highest p_T bins. For the analysis with 7 TeV (900 GeV) center of mass energy data, the lowest p_T bin refers to $p_T^{lead} = 1.0 - 1.5$ GeV, the intermediate p_T bin refers to $p_T^{lead} = 9 - 10$ GeV ($4 - 5$ GeV), and the highest p_T bin refers to $p_T^{lead} = 18 - 20$ GeV ($9 - 10$ GeV). The uncertainties are calculated from an example distribution, the transverse region charged $\sum p_T$ plot, and all the other profiles are estimated to have comparable or less systematic uncertainty. Each uncertainty is given relative to the profile value at that stage in the correction sequence. In the cases where the uncertainties are different for 900 GeV and 7 TeV analysis, the 900 GeV value is shown in the parenthesis.

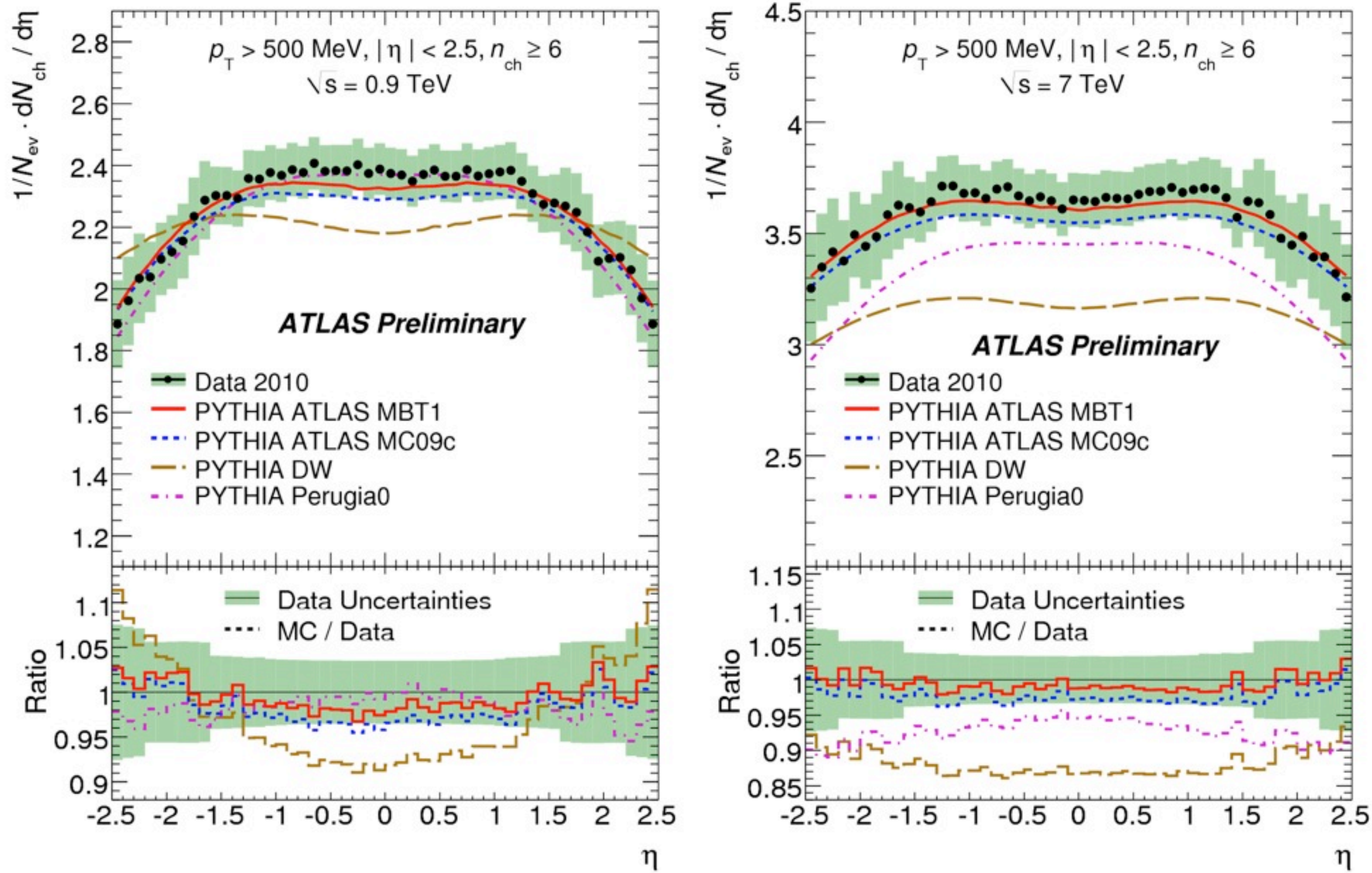
	Lowest p_T bin	Intermediate p_T bin	Highest p_T bin
Systematic uncertainty on unfolding			
Difference between PYTHIA and PHOJET	4%	2%	2%
Statistical uncertainty on PYTHIA unfolding	< 0.1%	1% (2%)	4% (5%)
Systematic uncertainties from efficiency corrections			
Track reconstruction	3%	4%	4%
Leading track requirement	1%	< 0.1%	< 0.1%
Trigger and vertex efficiency	— —	< 0.1% (everywhere)	— —
Total from efficiency corrections	2.5%	4%	4%
Total systematic uncertainty	4.5%	4.5% (5%)	6% (6.5%)

Charged Particle Densities: toward and away regions



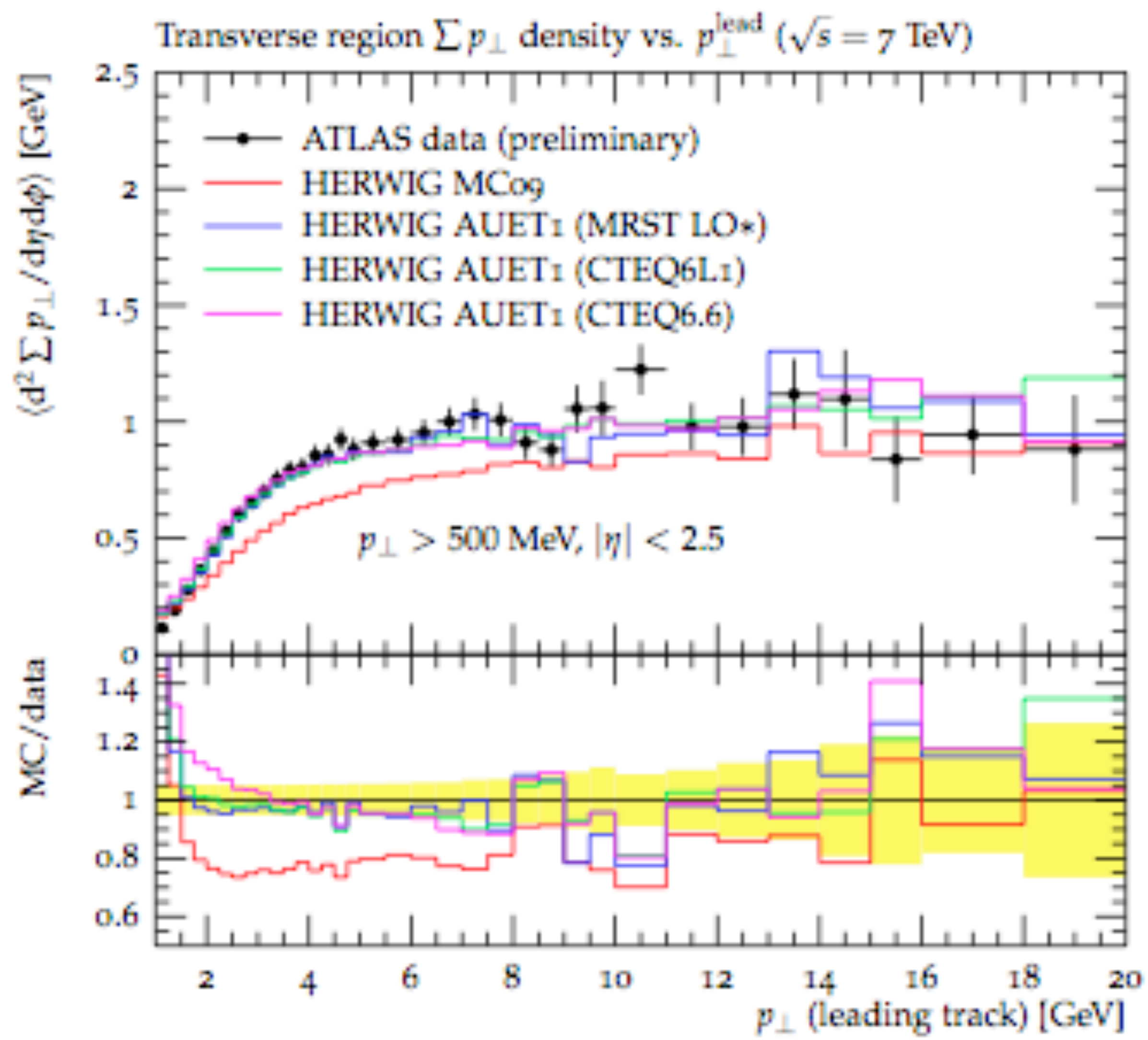


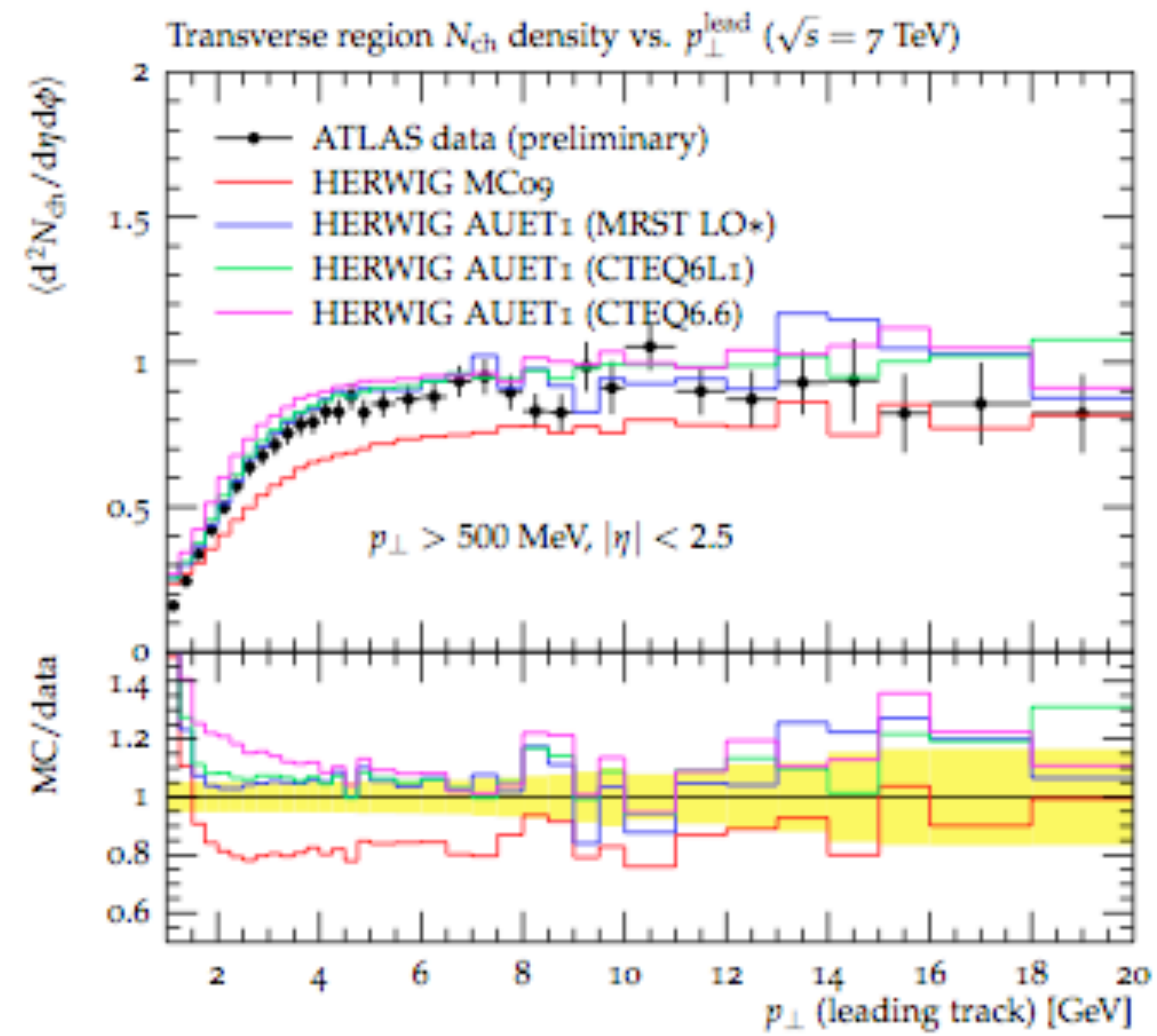
AMBT1: comparison to MB data



- For more details: ATLAS-CONF-2010-031

AUET1: comparison to UE data





- more details on AUET1: ATLAS-PHYS-PUB-2010-014

Charged Particle Sum p_T Densities: toward and away regions