University of Glasgow

MC Event Generators and Soft QCD at the LHC

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CERN

Science & Technology Facilities Council

Event Generators and Resummation
May 29 - June 1, 2012
DESY Hamburg

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DESY - Hamburg

Outline:

I. Introduction:

- MC generators for soft QCD: past & present

II. ("soft") QCD measurements:

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

III. Conclusions

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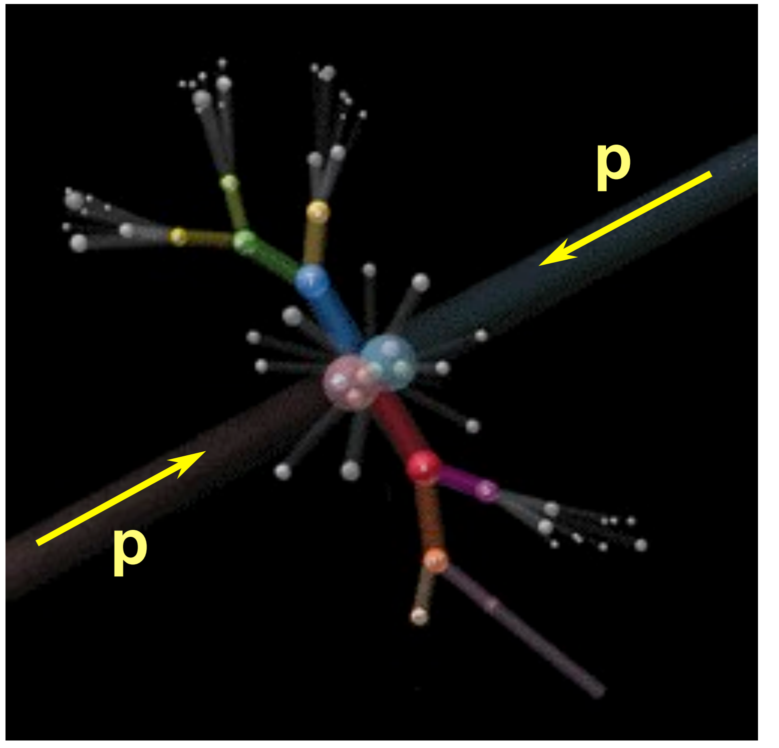
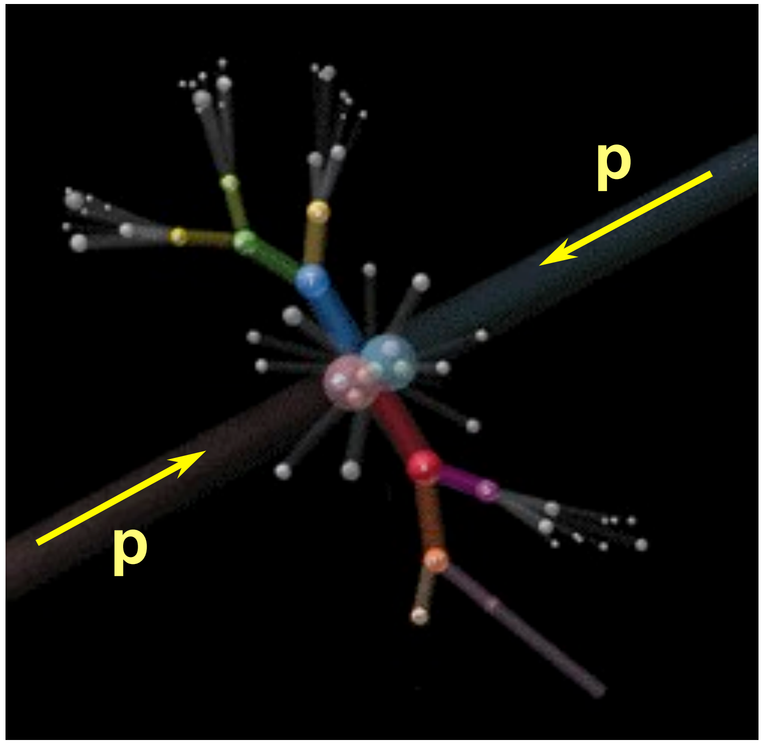
QCD at the LHC

- **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**



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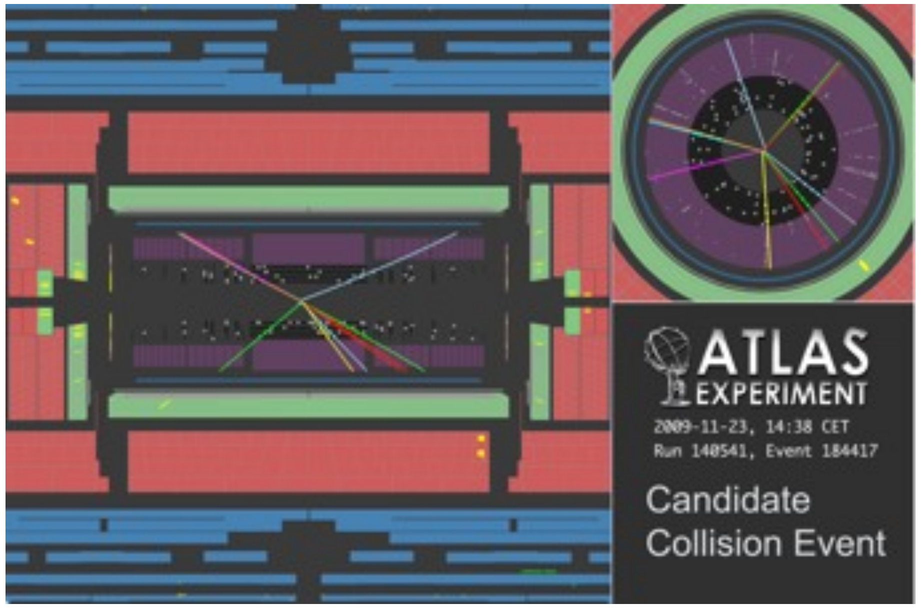
- Soft Interactions: Problems with strong coupling constant, $\alpha_s(Q^2)$, saturation effects,…
- Inelastic hadronic events are dominated by "soft" partonic interactions.
- On average, inelastic hadron-hadron collisions have low transverse energy, low multiplicity.
- Most pile-up events are (soft)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

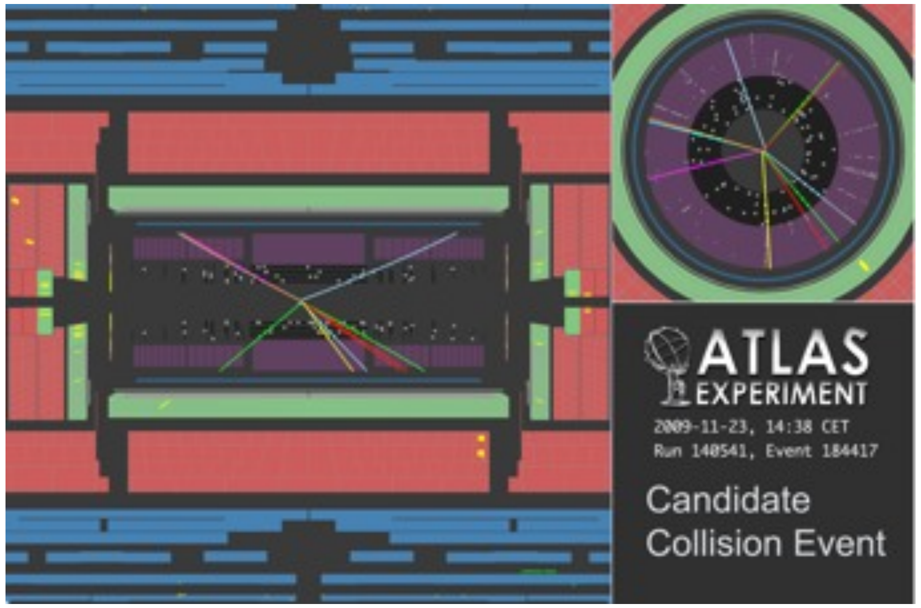
Pile-up events



2009

single vertex reconstructed!

Pile-up events



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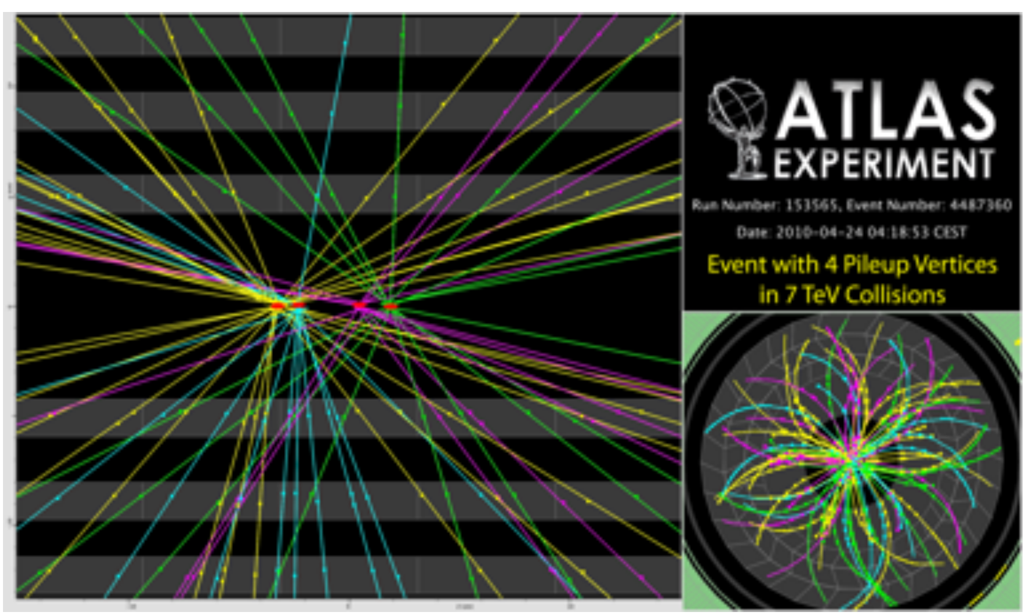
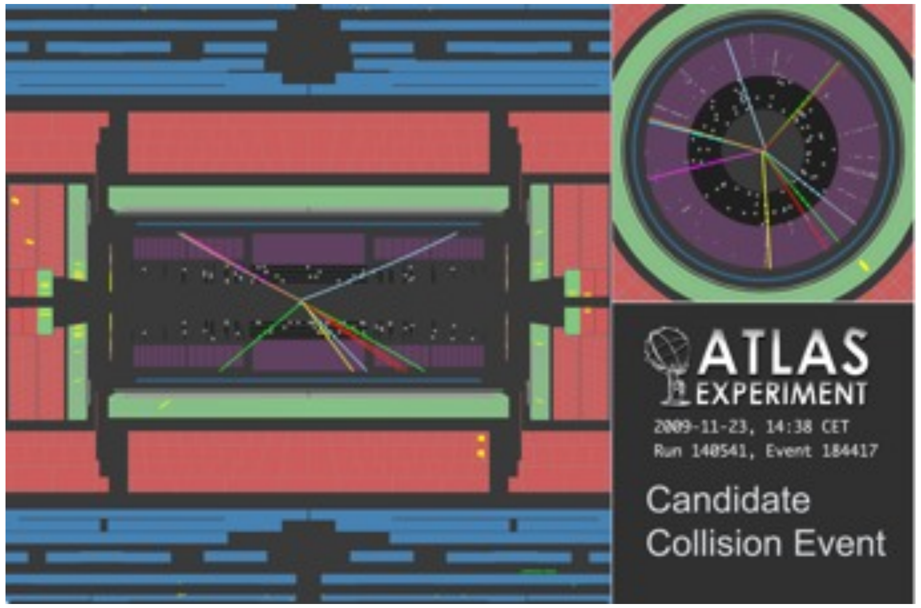


4 vertices

2010

Pile-up events



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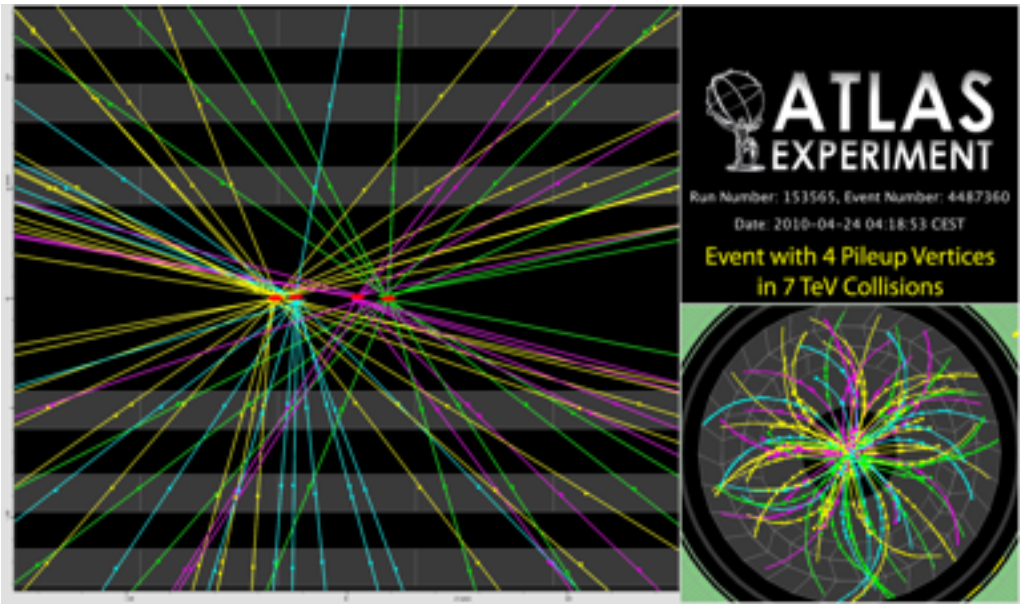
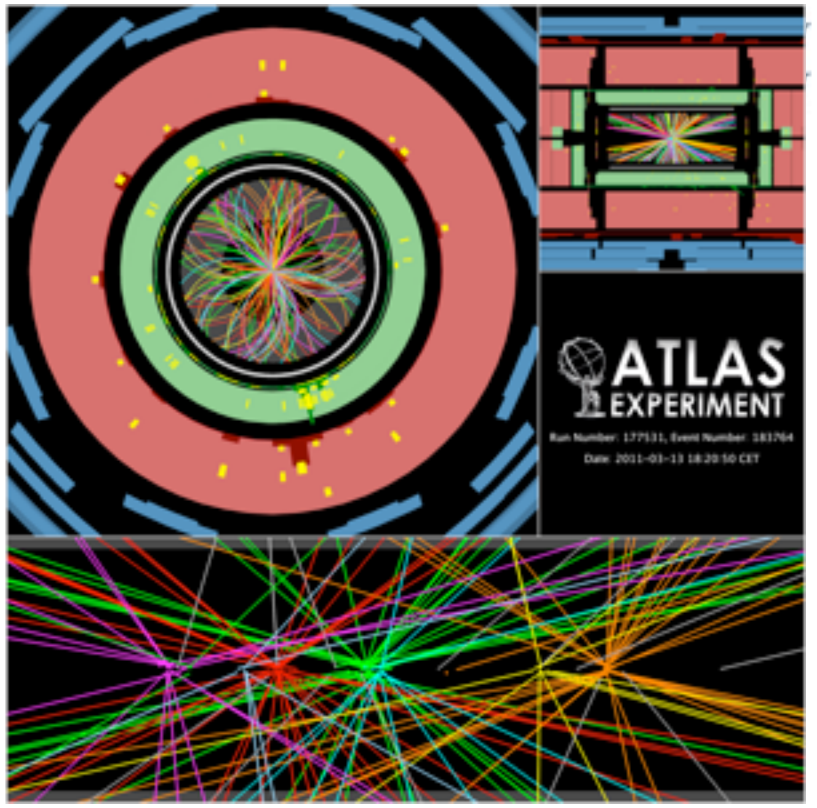


4 vertices

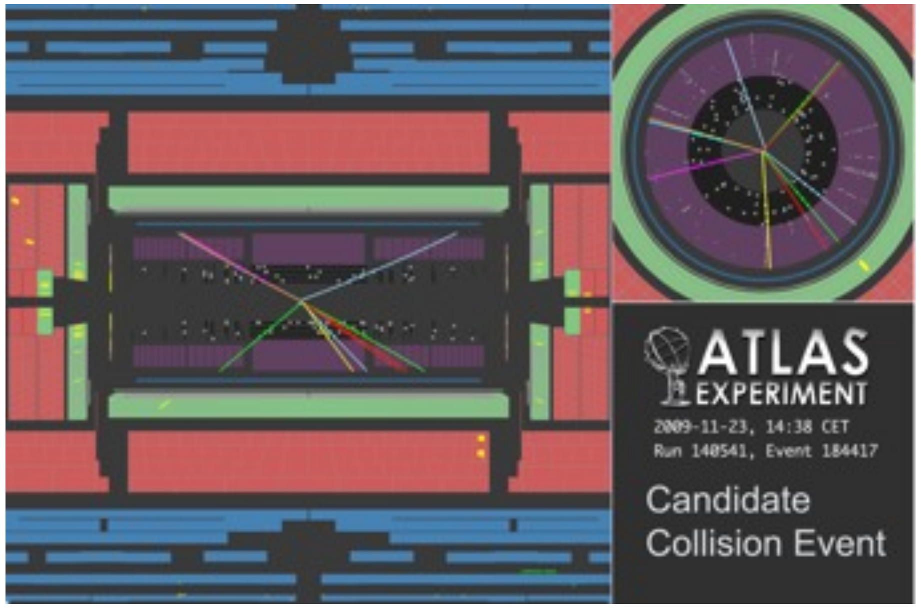
2010

7 vertices



2011

Pile-up events



2009

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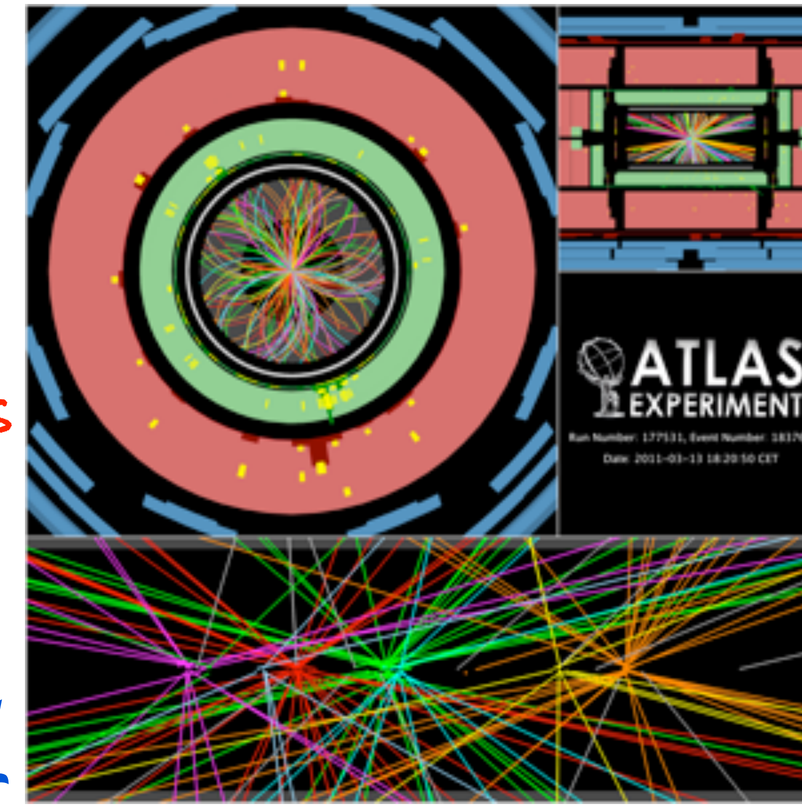
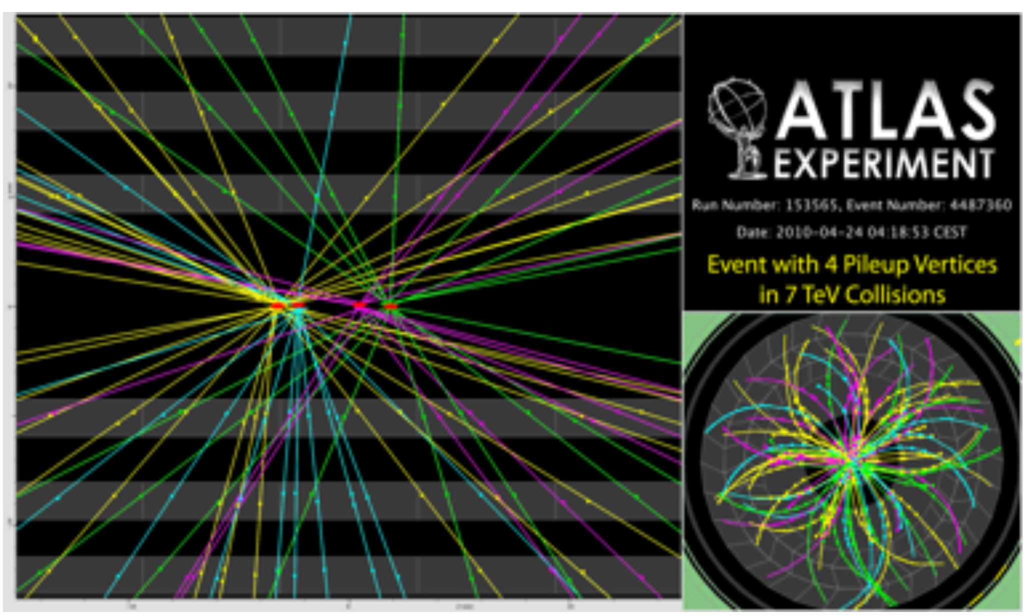


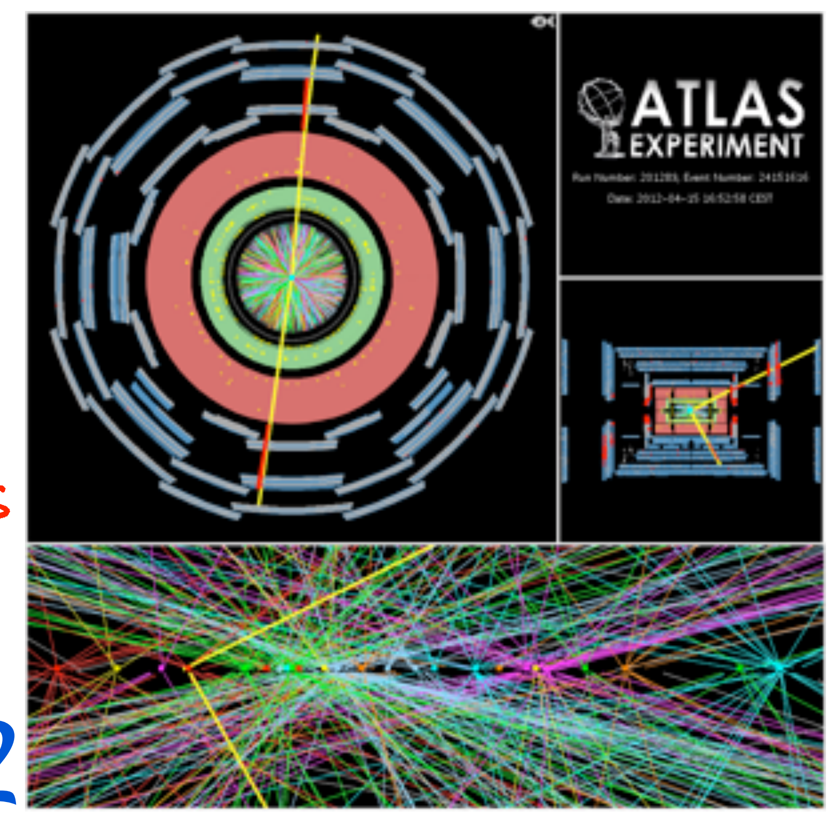
2011



4 vertices

2010

25 vertices

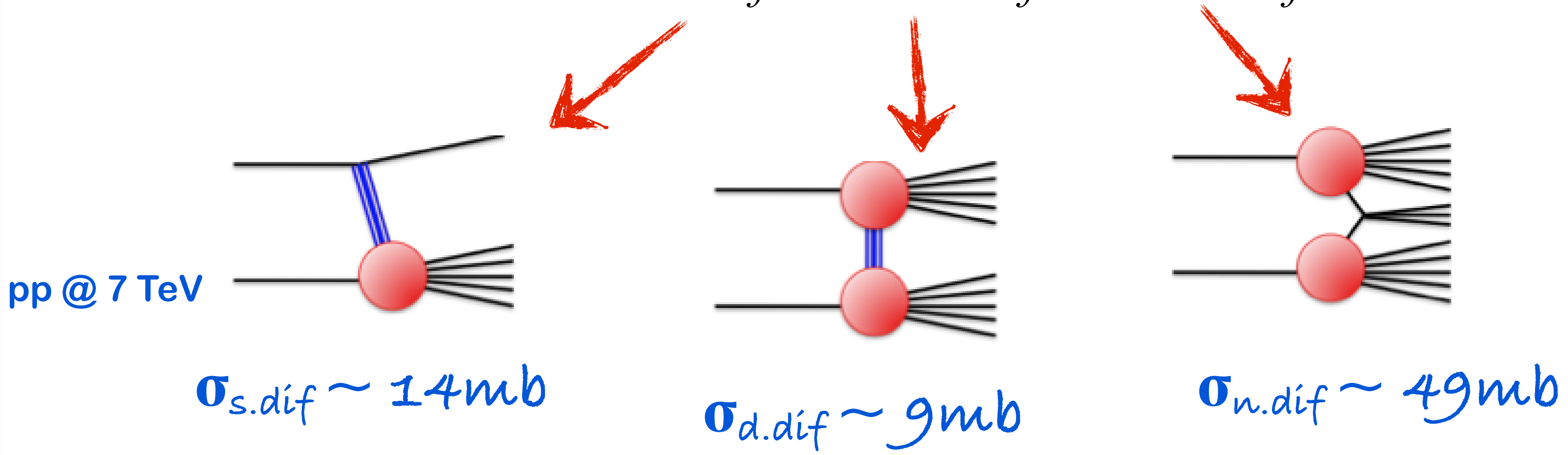


2012

Hadronic “soft” inelastic collisions

- *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).

Hadronic "soft" inelastic collisions

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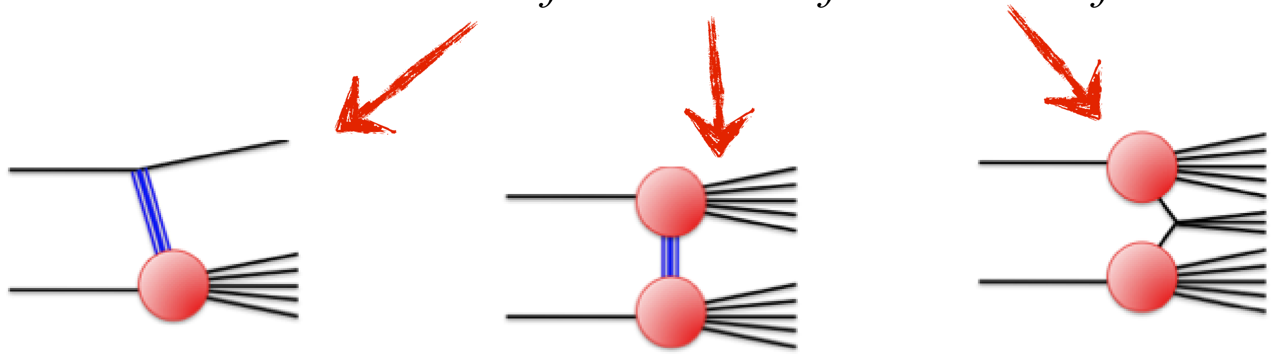
$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$

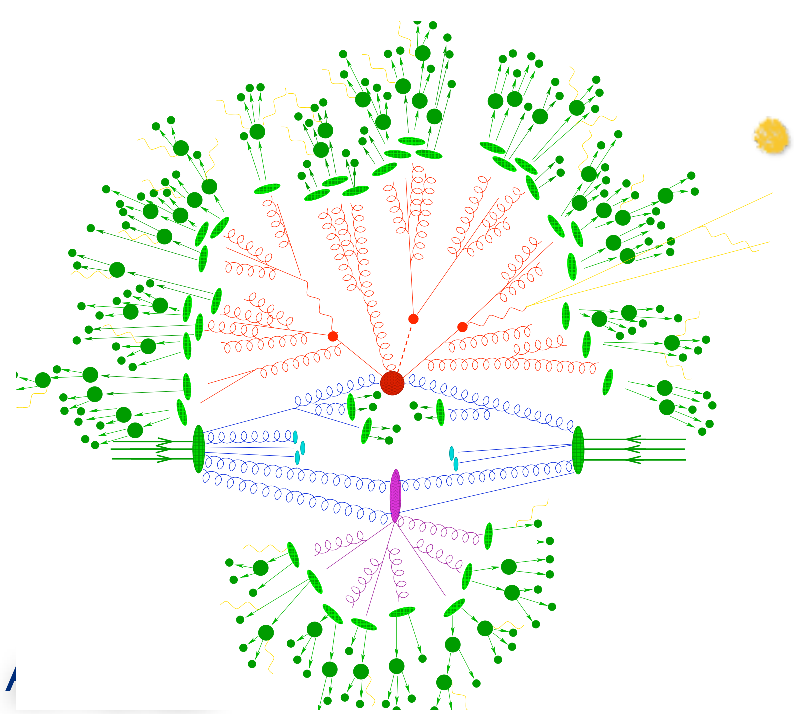
pp @ 7 TeV



$\sigma_{s.dif} \sim 14mb$ $\sigma_{d.dif} \sim 9mb$ $\sigma_{n.dif} \sim 49mb$

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

- **Modelling components:** (typical processes).



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

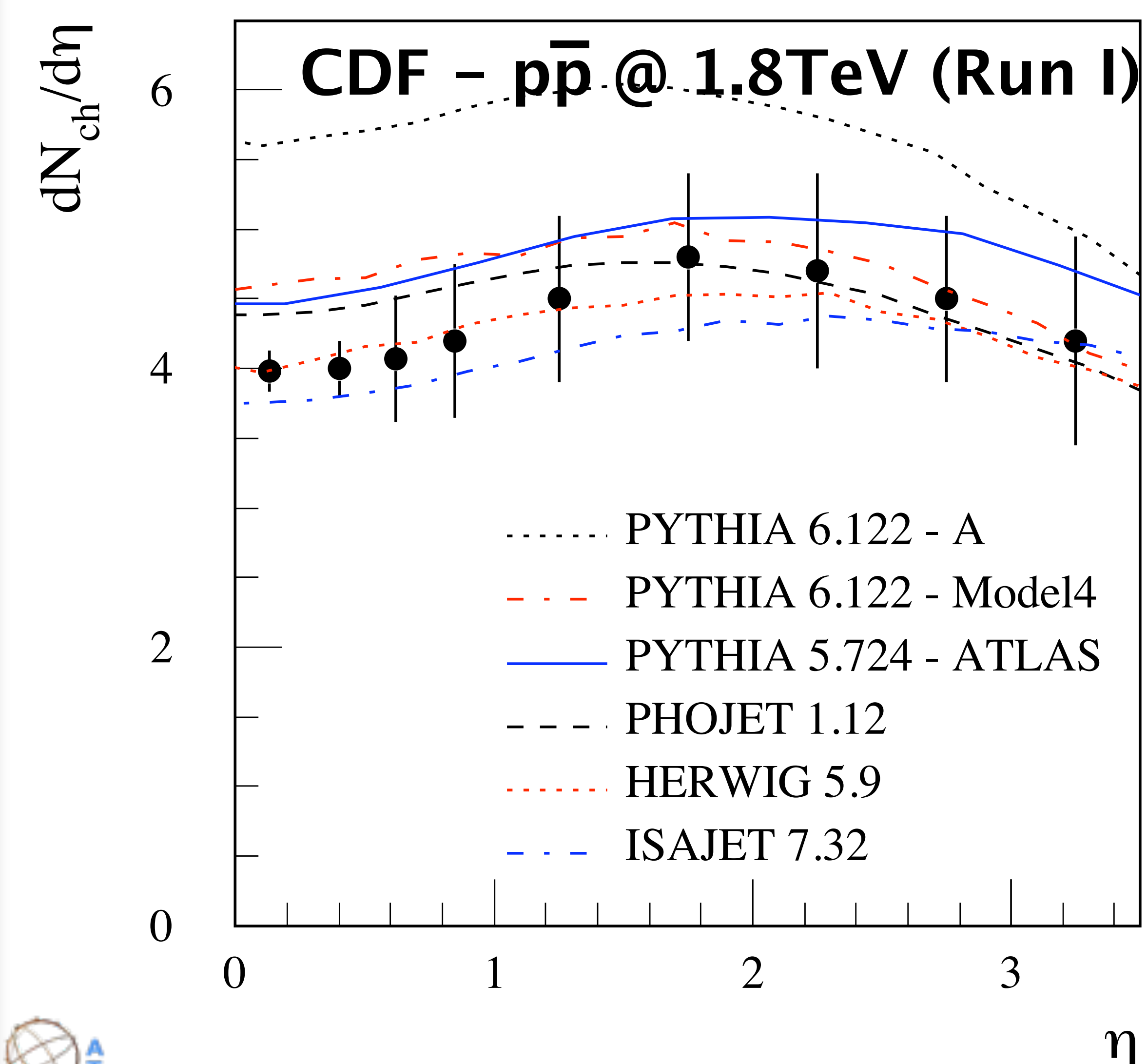
MC predictions for “soft” QCD: past & present

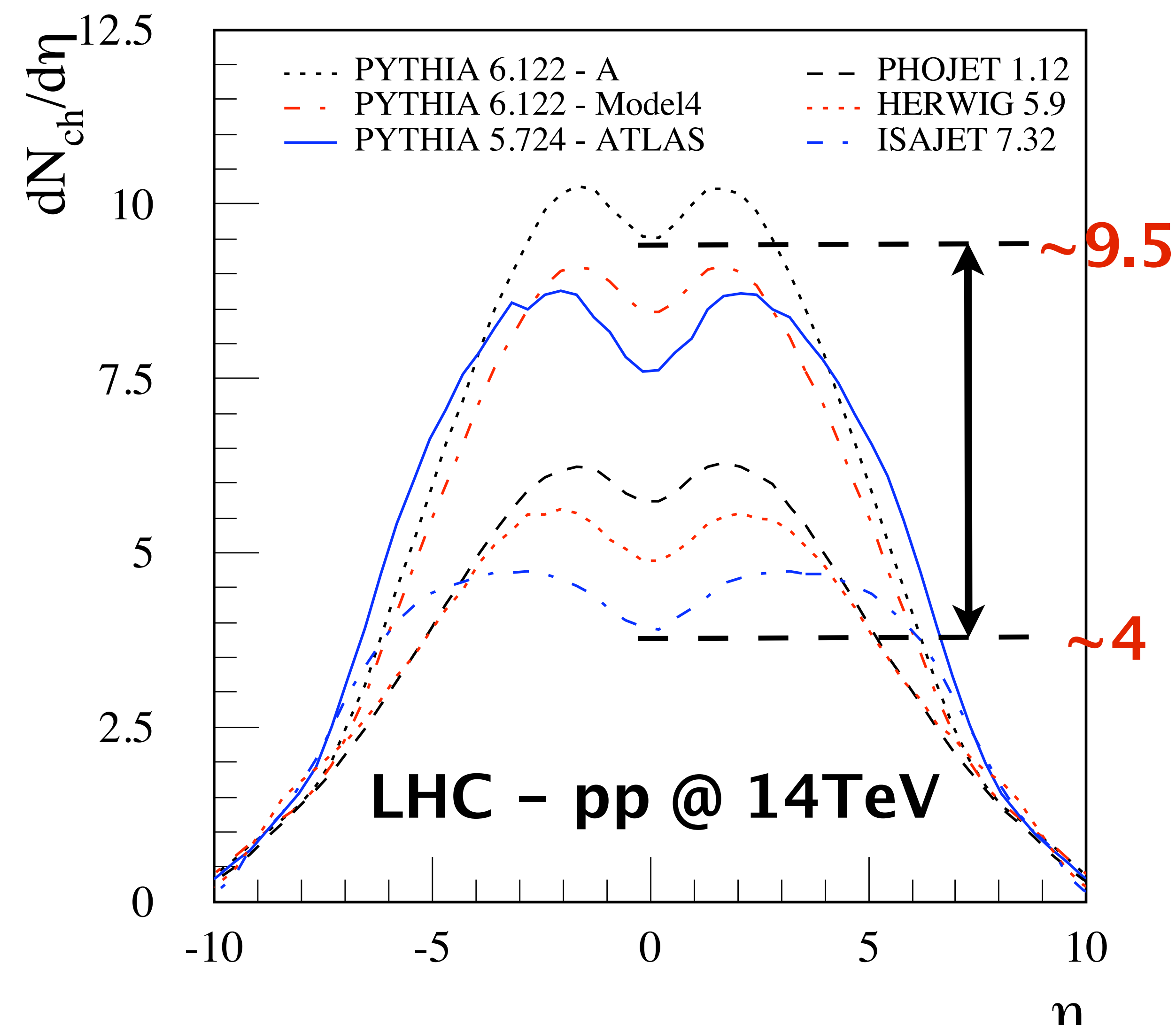
- **Tuning/calibration of MC models have evolved considerably from the time of the ATLAS Detector & Physics Performance TDR (*1999...*).**

MC predictions for "soft" QCD: past & present

- **Tuning/calibration of MC models have evolved considerably from the time of the ATLAS Detector & Physics Performance TDR (*1999…*).**
- **Factors of ~2 were "accepted" as reasonable. Nowadays we're ~10-20% in most distributions!**

Minimum bias distributions:





MC predictions for “soft” QCD: past & present

PYTHIA

HERWIG
(JIMMY, HERWIG++)

SHERPA

PHOJET

EPOS

...

MC predictions for "soft" QCD: past & present

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PYTHIA

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Note (I): there are simply too many variations of MC tunes and models to be covered in a single talk.

Note (II): Typical changes in MC tunes
- PDF set
- MPI model
- Low p_T cut-off
- ISR/FSR
- Colour reconnection
- Matter distribution profile
- ...

Details can be obtained from the relevant references.

MC predictions for "soft" QCD: past & present

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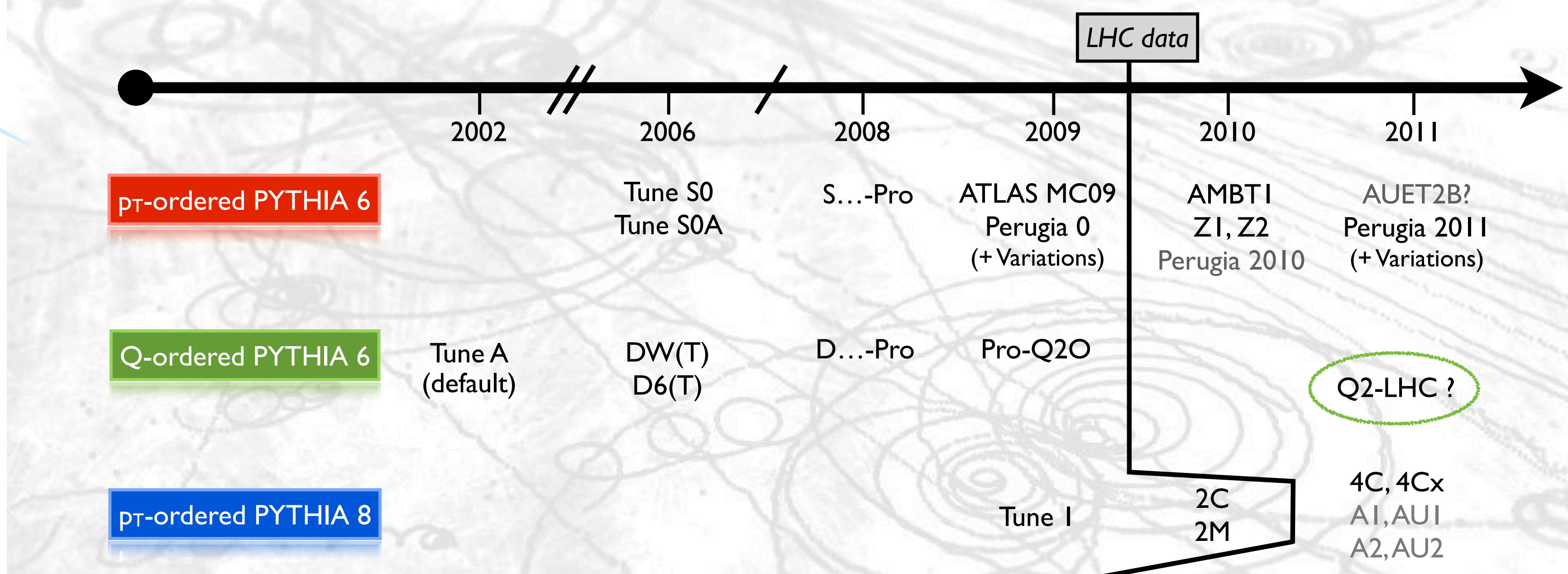

Main Data Sets included in each Tune (no guarantee that all subsets ok)

	A	DW, D6, ...	S0, S0A	MC09(c)	Pro-..., Perugia 0, Tune 1, 2C, 2M	AMBT1	Perugia 2010	Perugia 2011	Z1, Z2	4C, 4Cx	AUET2B, A2, AU2
LEP					✔		✔	✔		✔	✔
TeV MB			✔	✔	✔		✔	✔			?
TeV UE	✔	✔		✔	✔		✔	✔			✔?
TeV DY		✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
LHC MB						✔	✔	✔		✔	?
LHC UE								✔	✔		✔

(taken from P. Skands - MPI@LHC2011)

References to experimental results & MC predictions (and more...)

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LPCC
LHC Physics Centre at CERN

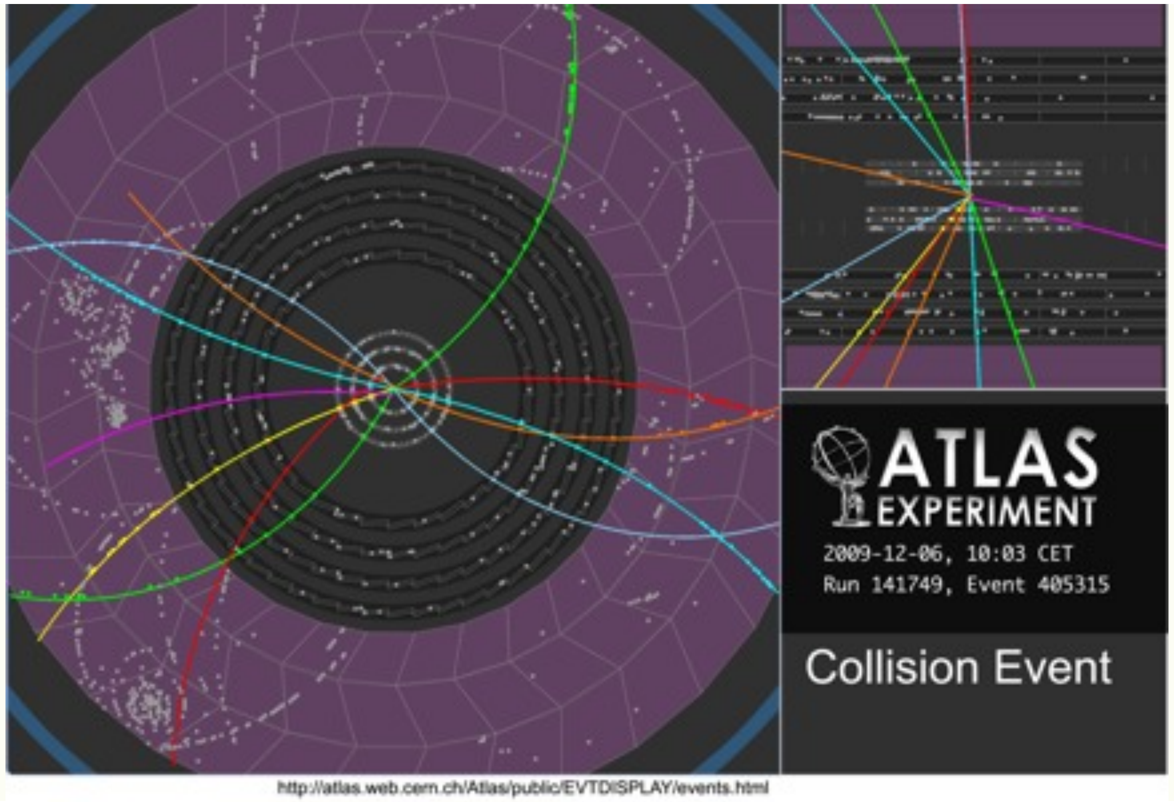
http://lpcc.web.cern.ch/LPCC/

- MC plots:

"CERN-based website for Monte Carlo comparisons, intended as a simple browsable repository of plots comparing HEP event generators to a wide variety of available experimental data, mainly based on the RIVET analysis tool."

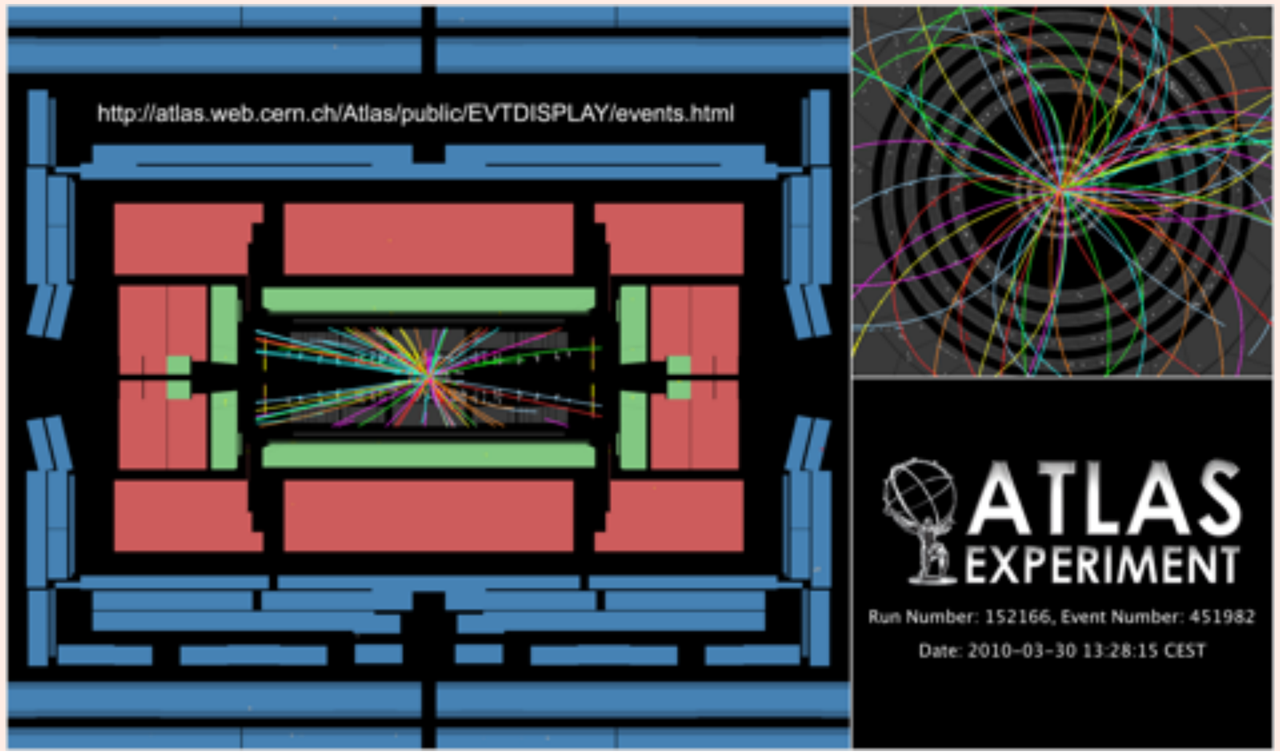
http://mcplots.cern.ch/

“Minimum bias” events:



- Event display: pp collision at $\sqrt{s}$=900GeV

- Event display: pp collision at $\sqrt{s}$=7 TeV



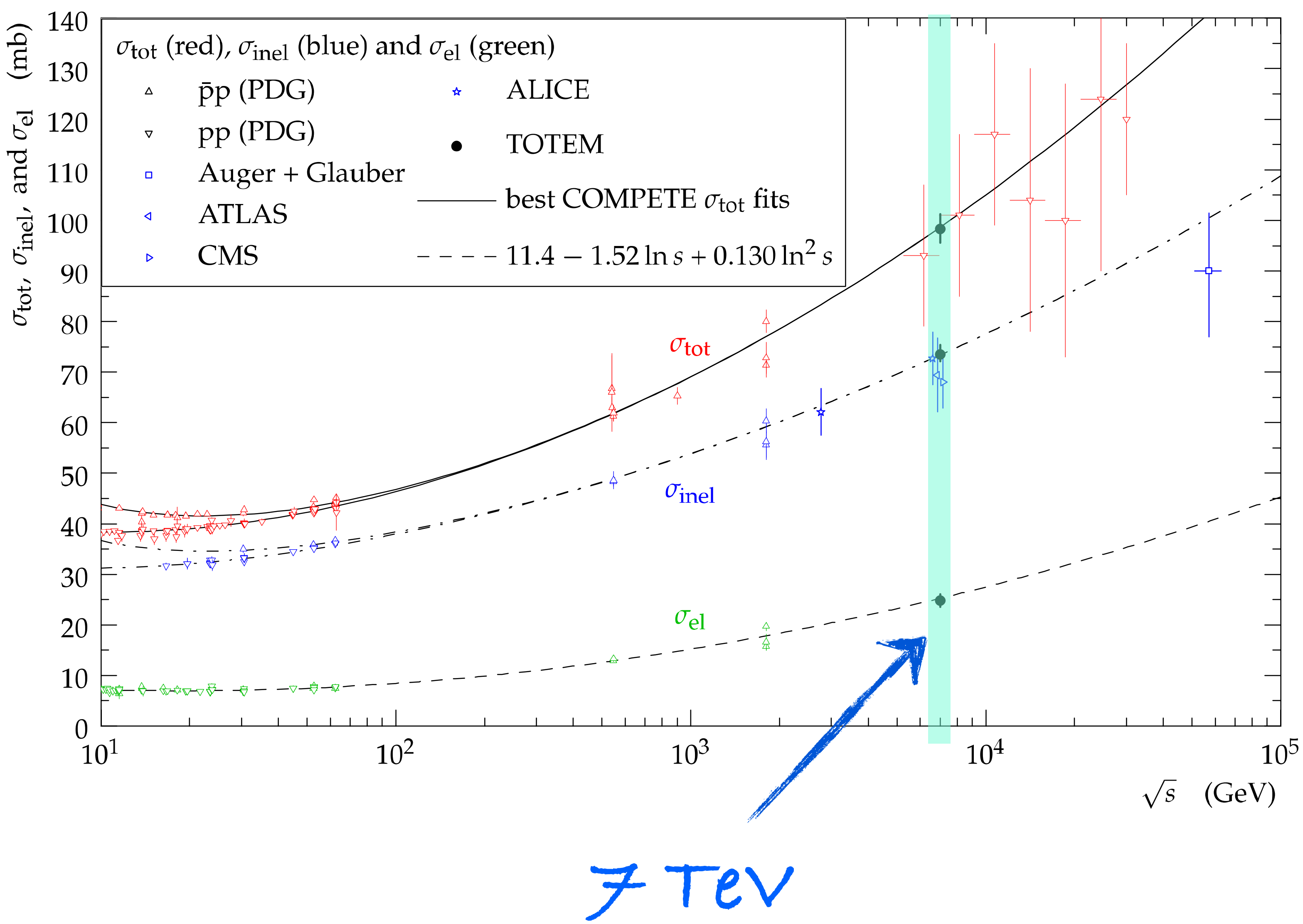
Elastic, Total and Inelastic cross-sections

TOTEM

$$\sigma_{tot} = 98.3 \pm 0.2^{(stat)} \pm 2.8^{(syst)}\ \text{mb}$$

$$\sigma_{ele} = 8.3\ \text{mb}^{(extrapol.)} + 16.5\ \text{mb}^{(measured)} = 24.8 \pm 0.2^{(stat)} \pm 1.2^{(syst)}\ \text{mb}$$

$$\sigma_{inel} = \sigma_{tot} - \sigma_{ele} = 73.5 \pm 0.6^{(stat)}\ {}^{+1.8}_{-1.3}\ {}^{(syst)}\ \text{mb}$$

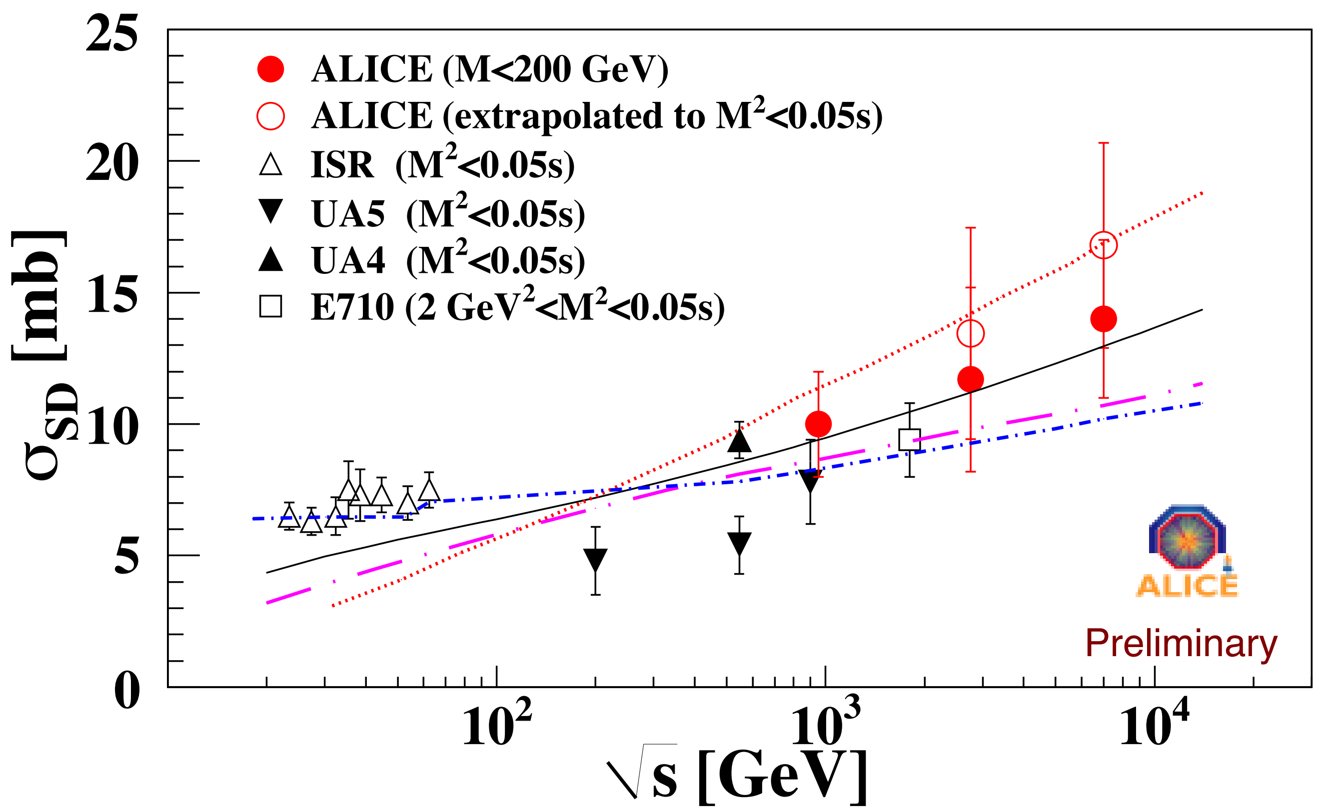


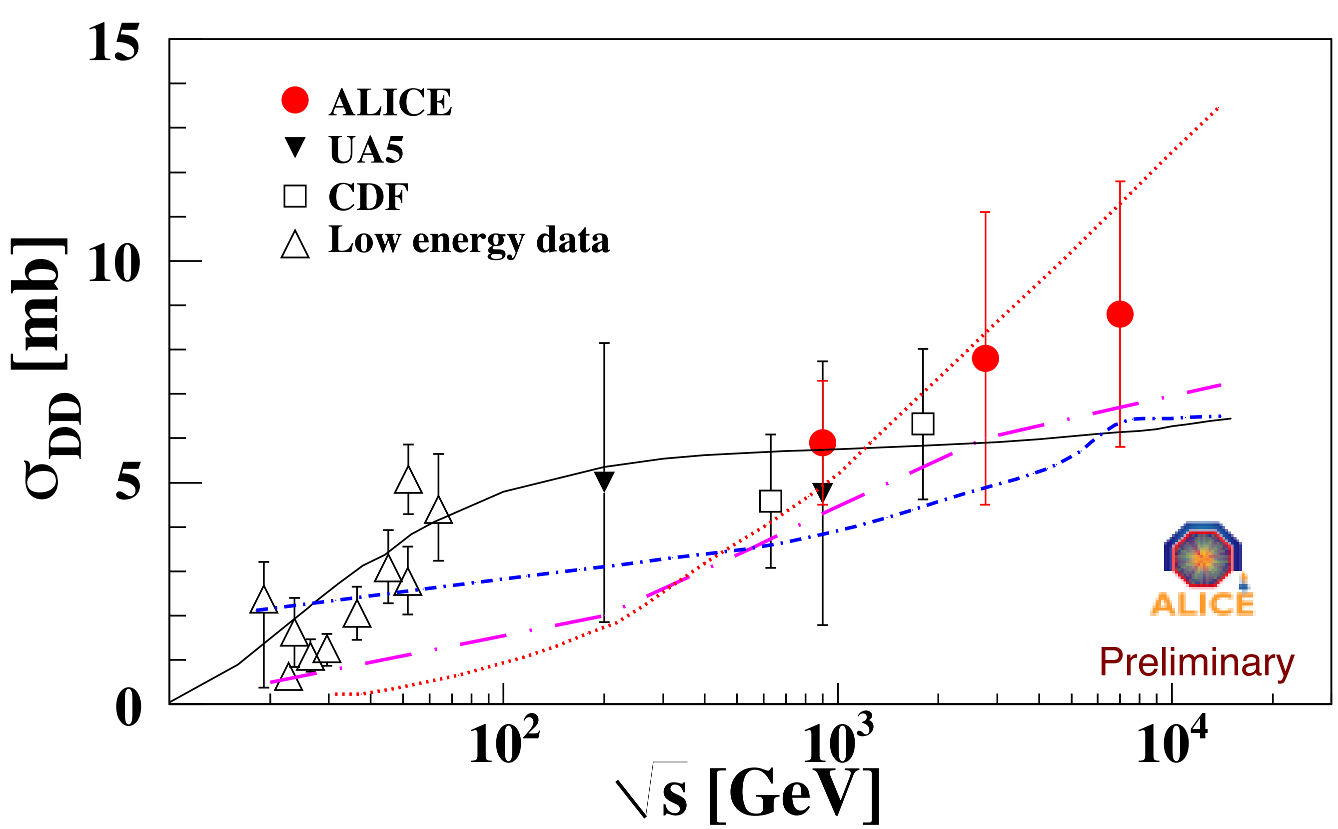
σ_{inel} (CMS) = $68.0 \pm 2.0^{(syst)} \pm 2.4^{(lumi)} \pm 4.0^{(extrap)}$ mb

σ_{inel} (ATLAS) = $69.4 \pm 2.4^{(exp)} \pm 6.9^{(extrap)}$ mb

σ_{inel} (ALICE) = $72.7 \pm 1.1^{(model)} \pm 5.1^{(lumi)}$ mb

Single and double diffractive cross-sections





Unfold integrated SD and DD cross sections at all three c.m. energies based on gap rates and topologies.

(implies some extrapolation into lowest ξ regions)

(1) Nature of inelastic collisions:

non-diffractive & diffractive interactions

- Challenges in measuring and modelling the different classes of interactions.

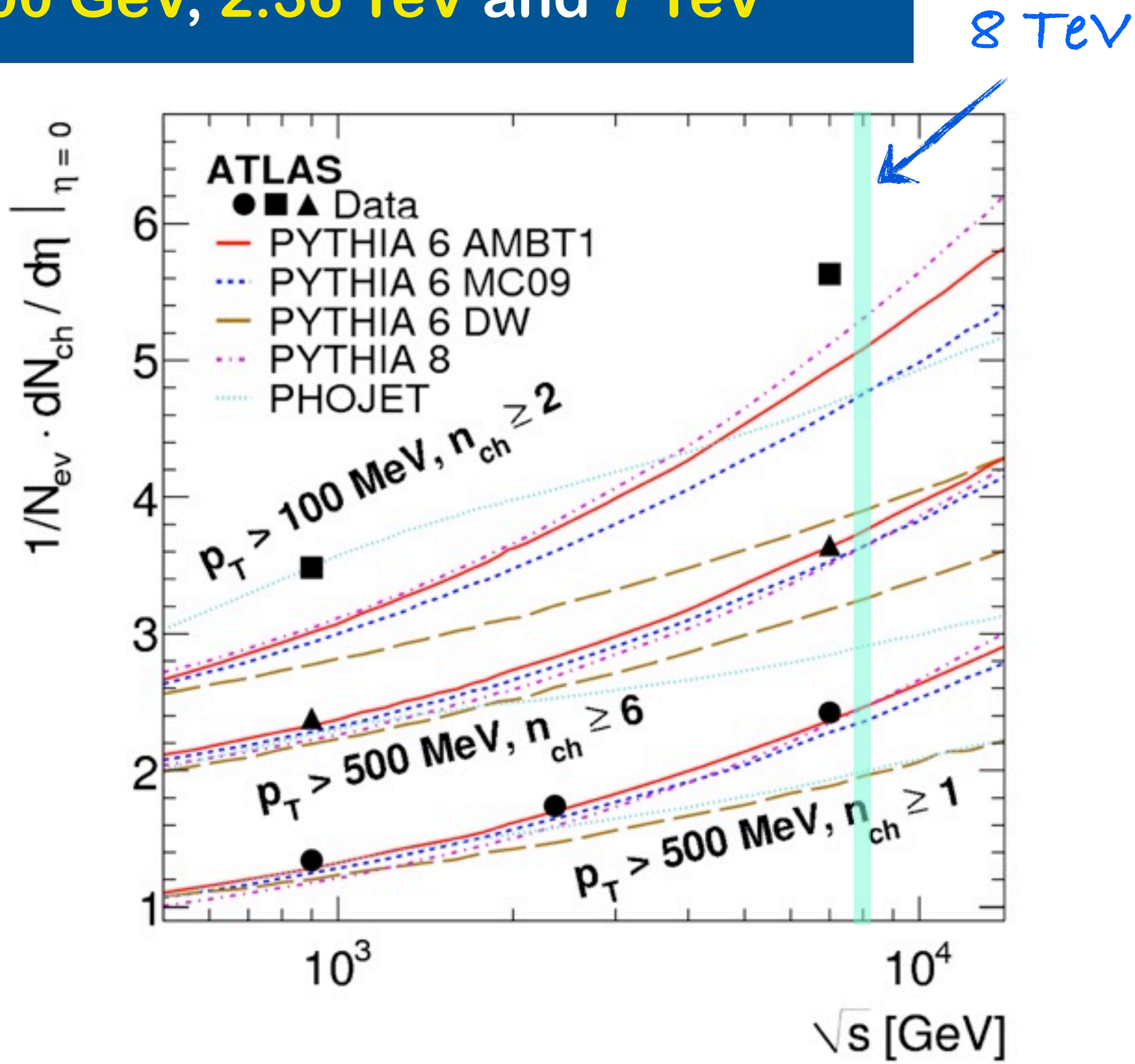
- Can be an issue in many measurements: affects trigger corrections.

- Contributes (significantly) to the uncertainty in measurements dominated by low multiplicity (low-p_T) event selection.

- Inelastic non-diffractive cross-section is used by some MC models as a parameter determining the MPI rate to be simulated.

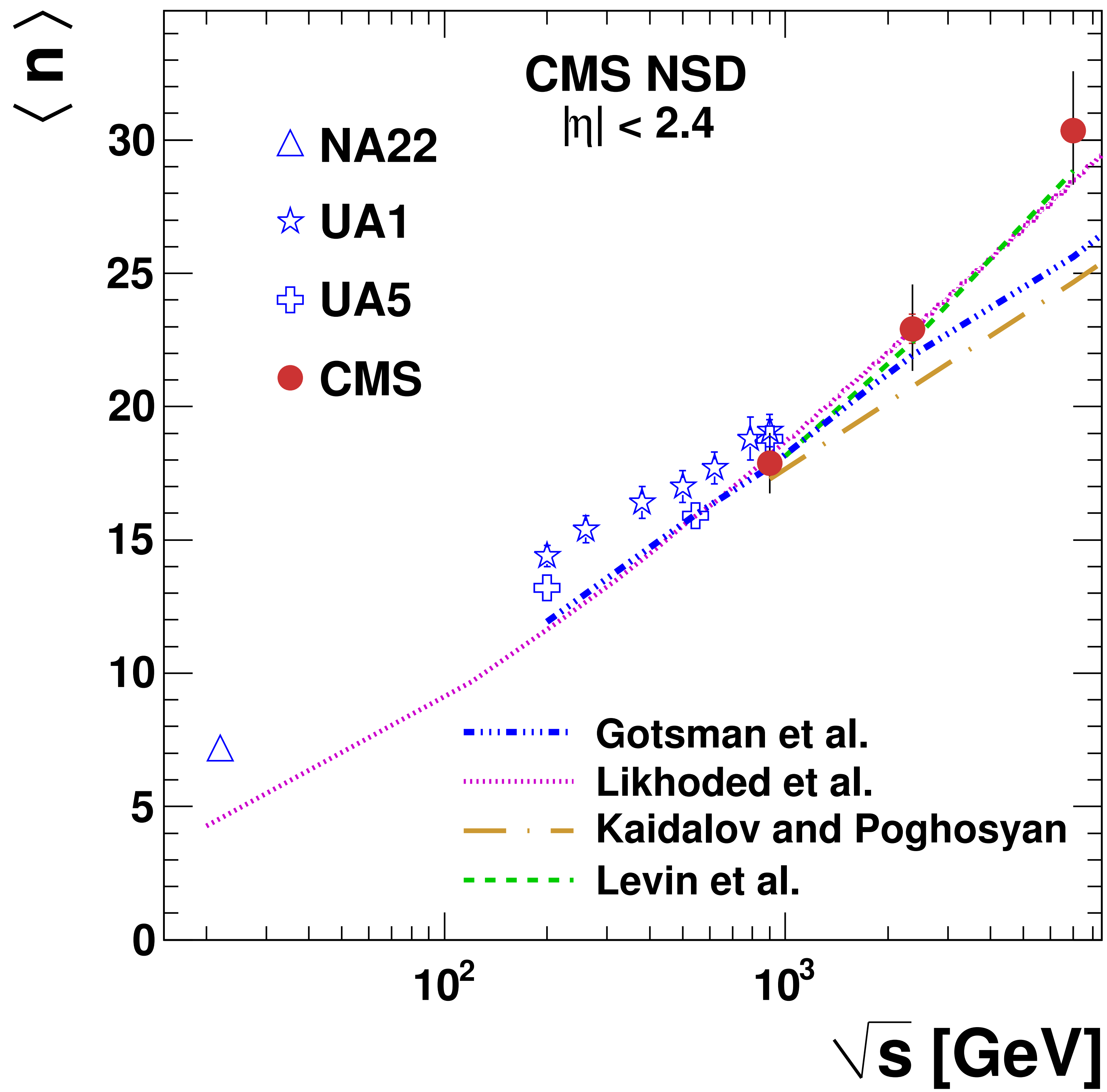
- Accurate description is necessary for pile-up simulation (luminosity is going to continue increasing! There's also the upgrade in the horizon...).

Charged particle density in η: $\sqrt{s}$=900 GeV, 2.36 TeV and 7 TeV

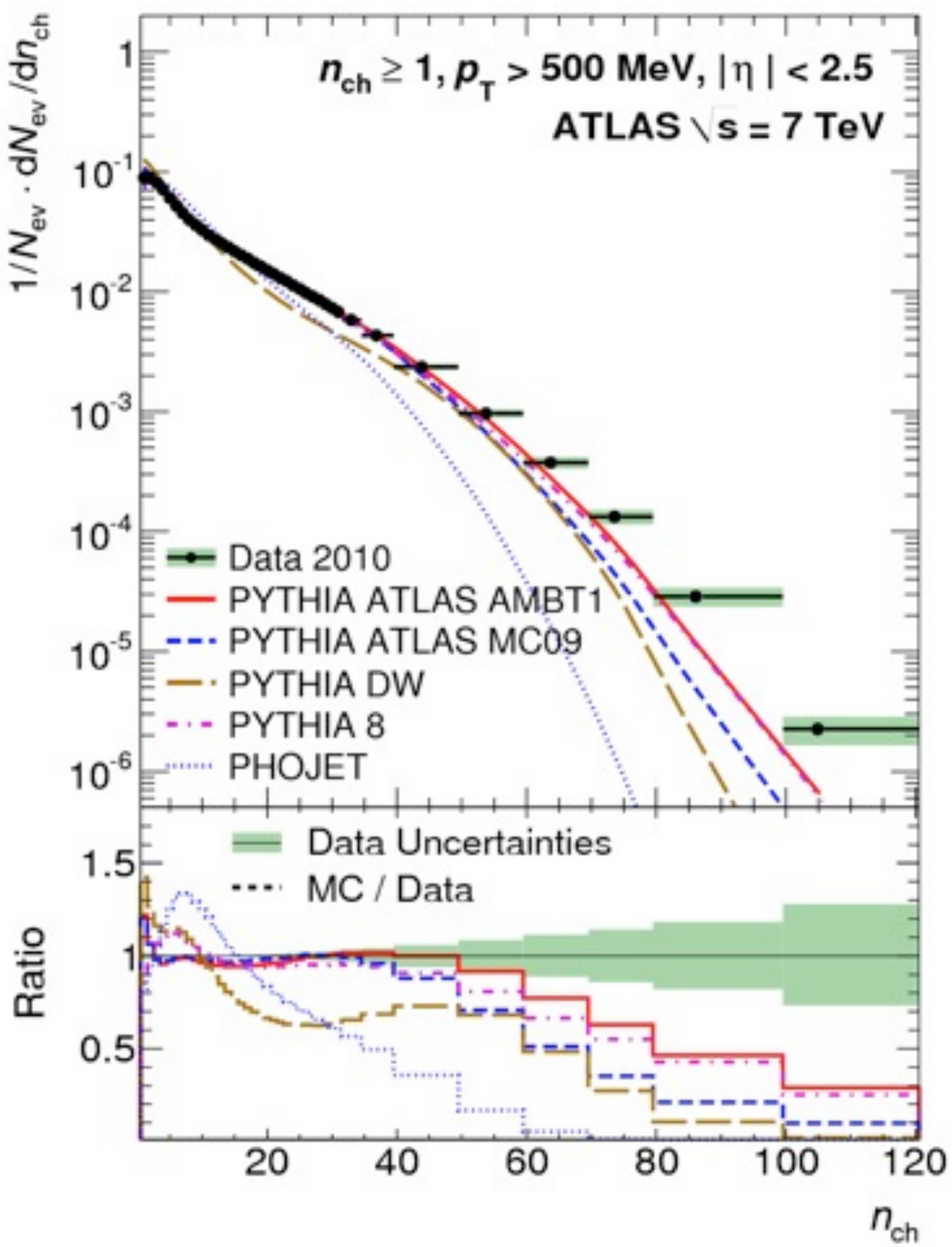


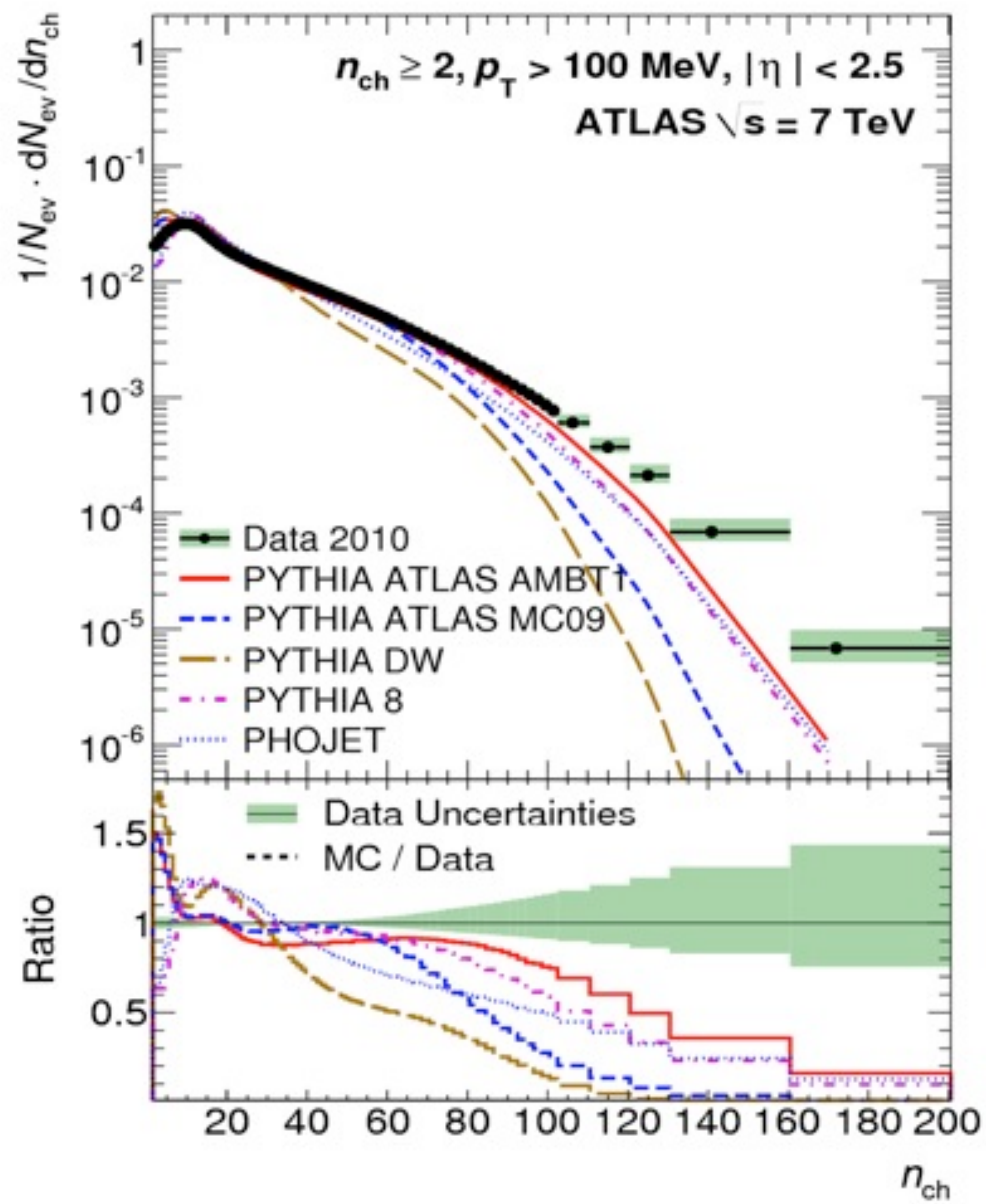
- **Measurements at different c.m. energies are crucial for an accurate understanding (prediction) of the evolution of inelastic hadronic processes.**

Charged particle multiplicity: √s=900 GeV, 2.36 TeV and 7 TeV



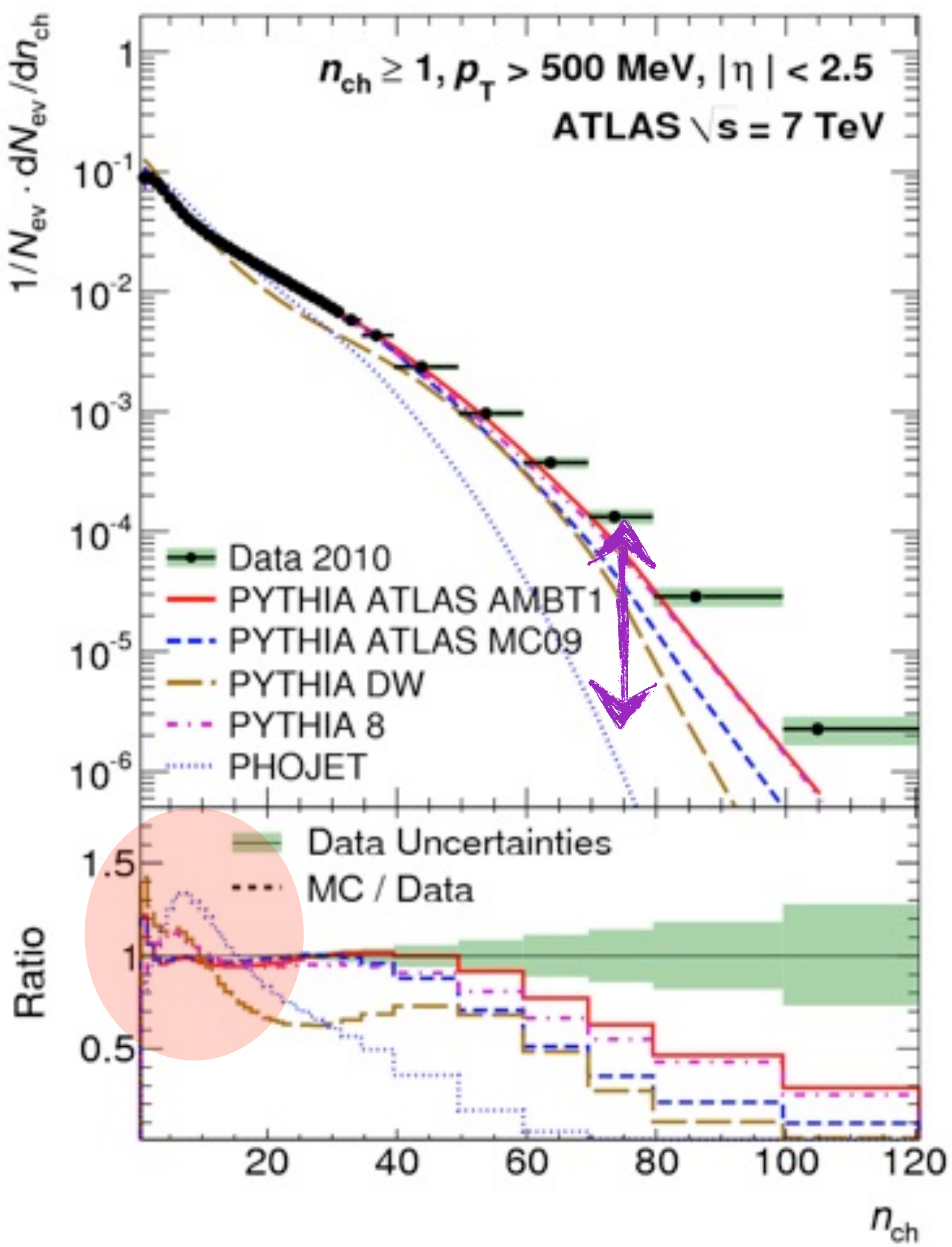
Charged particle multiplicity distributions

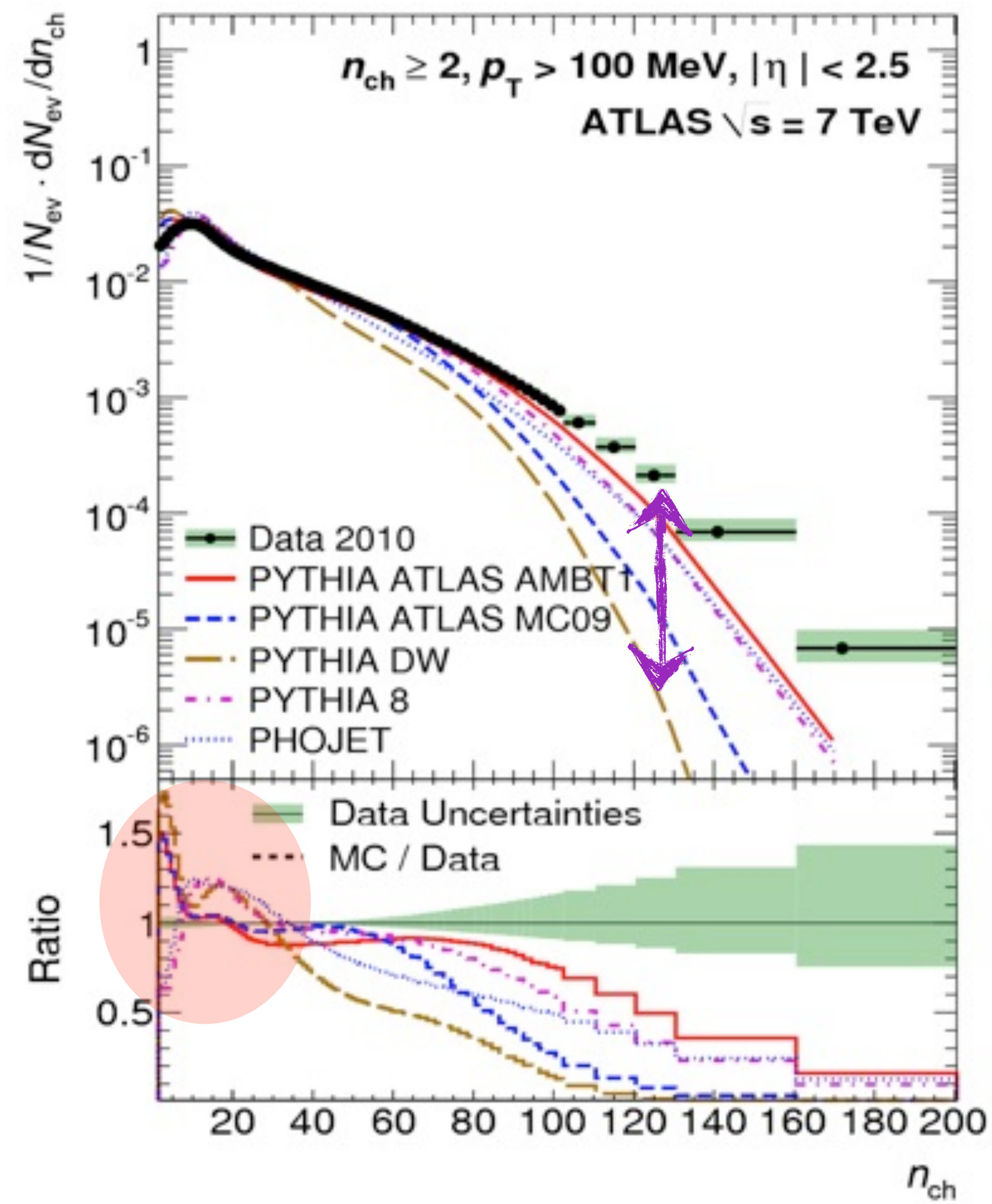




Charged particle multiplicity distributions: high n_{ch} tail not described by MC tunes! Problems also in low n_{ch} bins.

Charged particle multiplicity distributions





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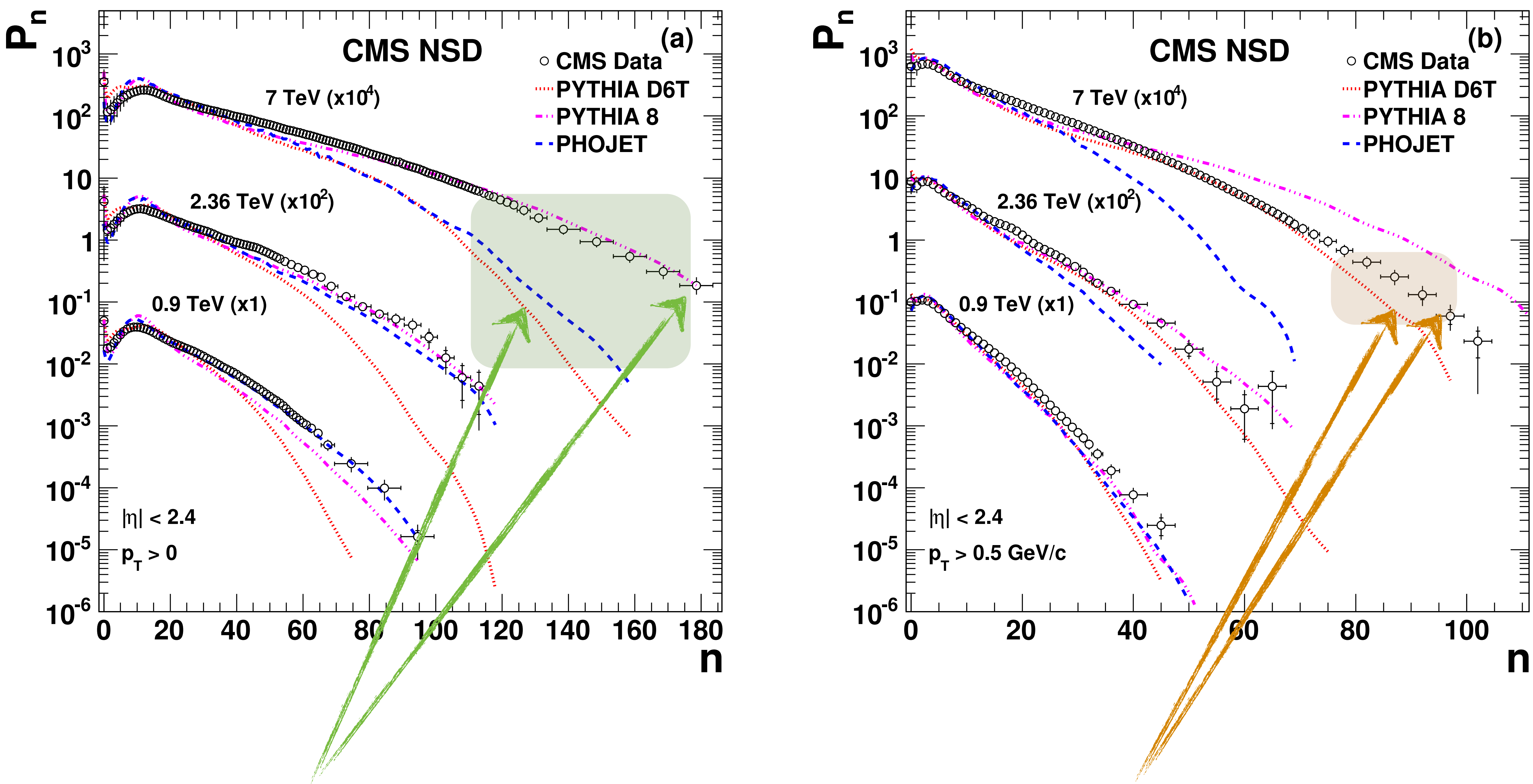
Charged particle multiplicity distributions



$p_T > 0$

$p_T > 0.5$ GeV

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

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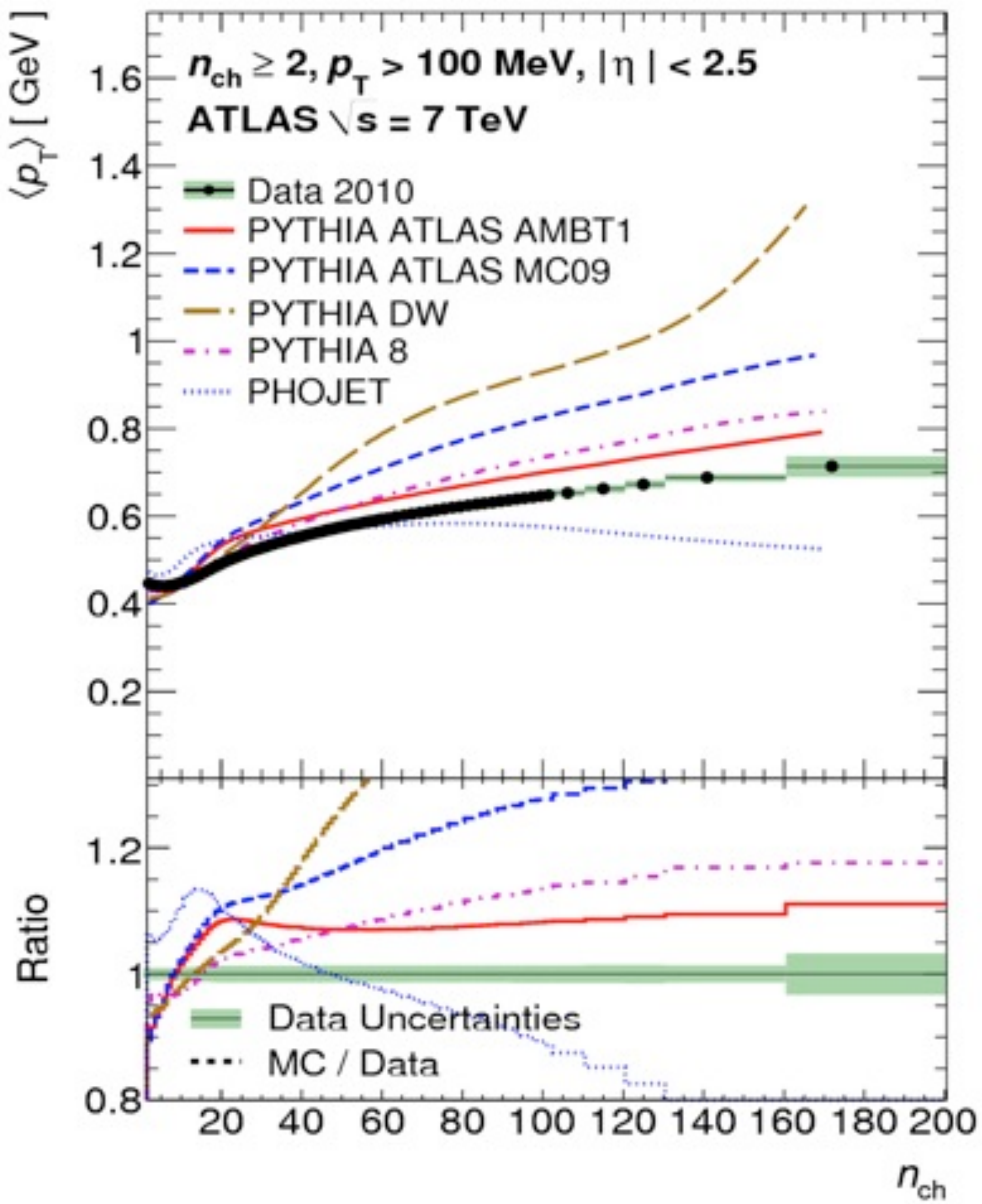
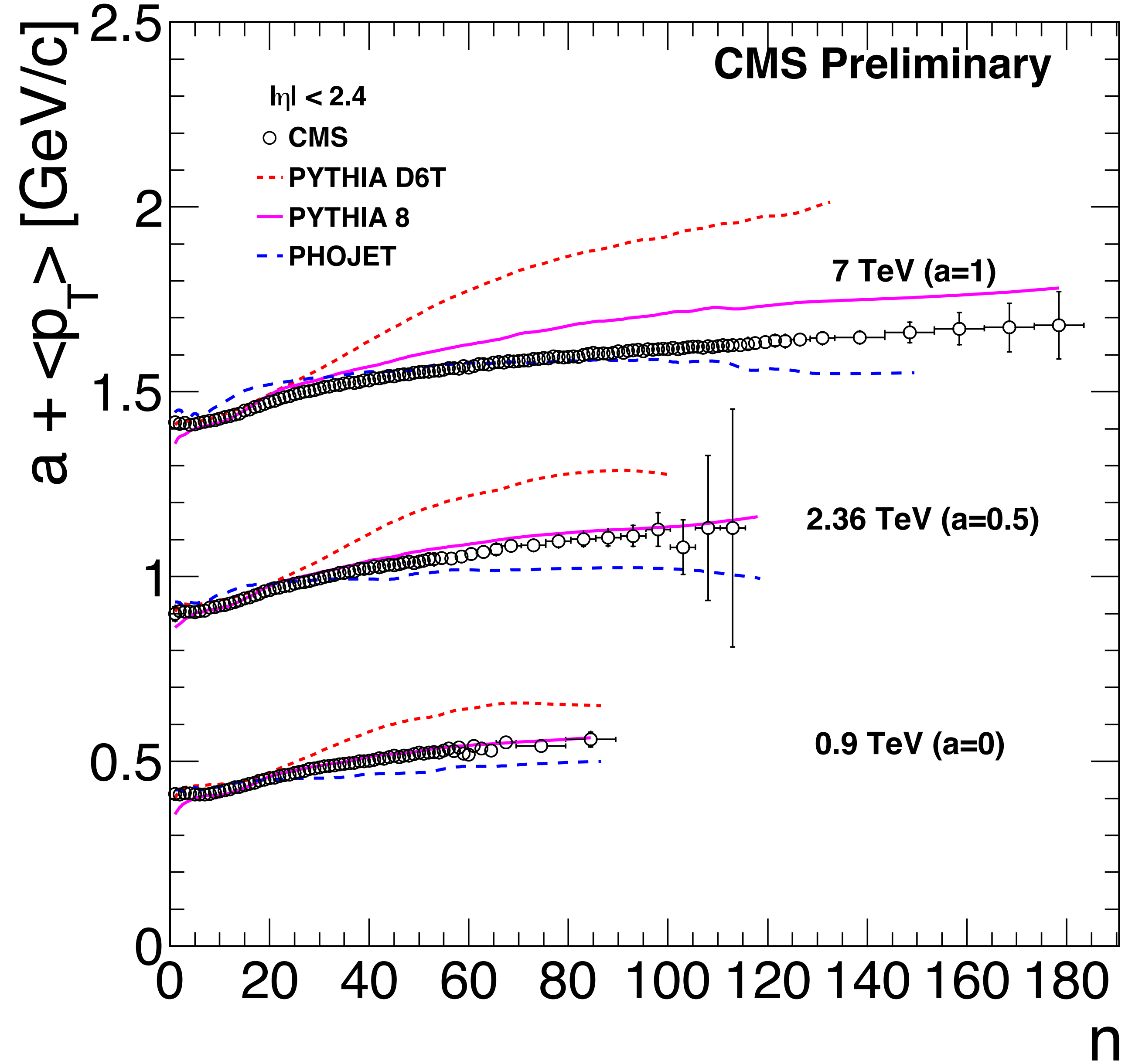




As low-p_T particles are added to the measurements, MC models no longer describes the data. Generated particles are, on average, harder than what we see in the data.

(2) Particle production as a function of $\sqrt{s}$:

Models can be tuned to measurements made at different $\sqrt{s}$ but predictive power is still to be proven.

(3) Low-p_T particle production:

Models tuned to measurements made with higher p_T particles fail to describe the low p_T data.

- Similar conclusions are obtained from comparisons between UE measurements and MC.

Forward-backward correlation

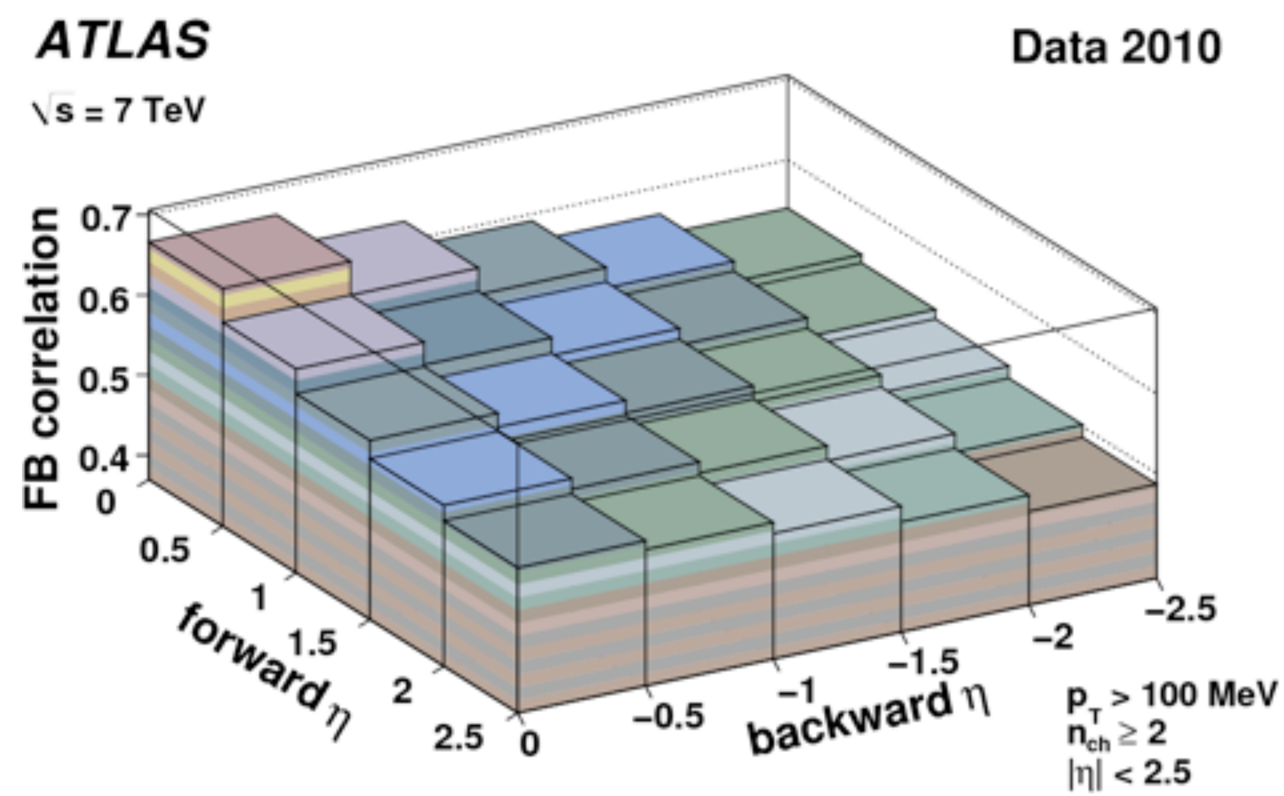
- Measurement of the correlation between charged particle multiplicities in the forward and backward regions of the ATLAS detector.

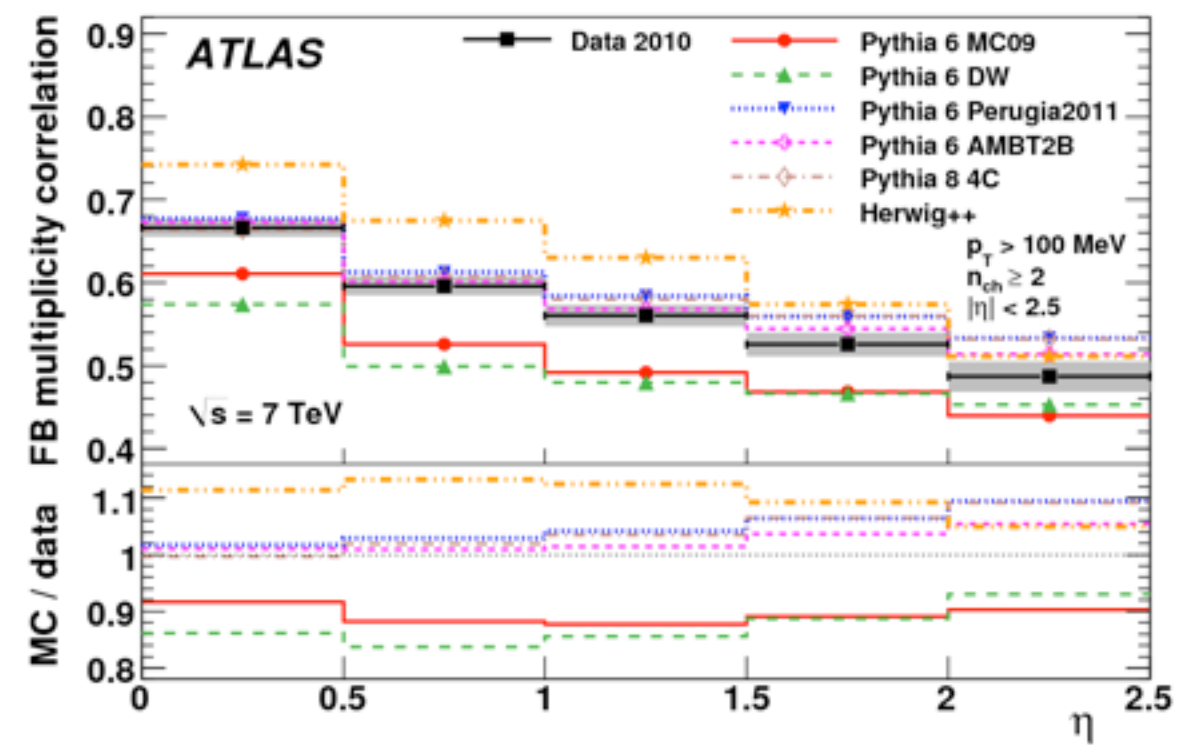
$$\rho^n_{fb} = \frac{\langle (n_f - \langle n_f \rangle)(n_b - \langle n_b \rangle)\rangle}{\sqrt{\langle (n_f - \langle n_f \rangle)^2 \rangle \langle (n_b - \langle n_b \rangle)^2 \rangle}}$$

- 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.

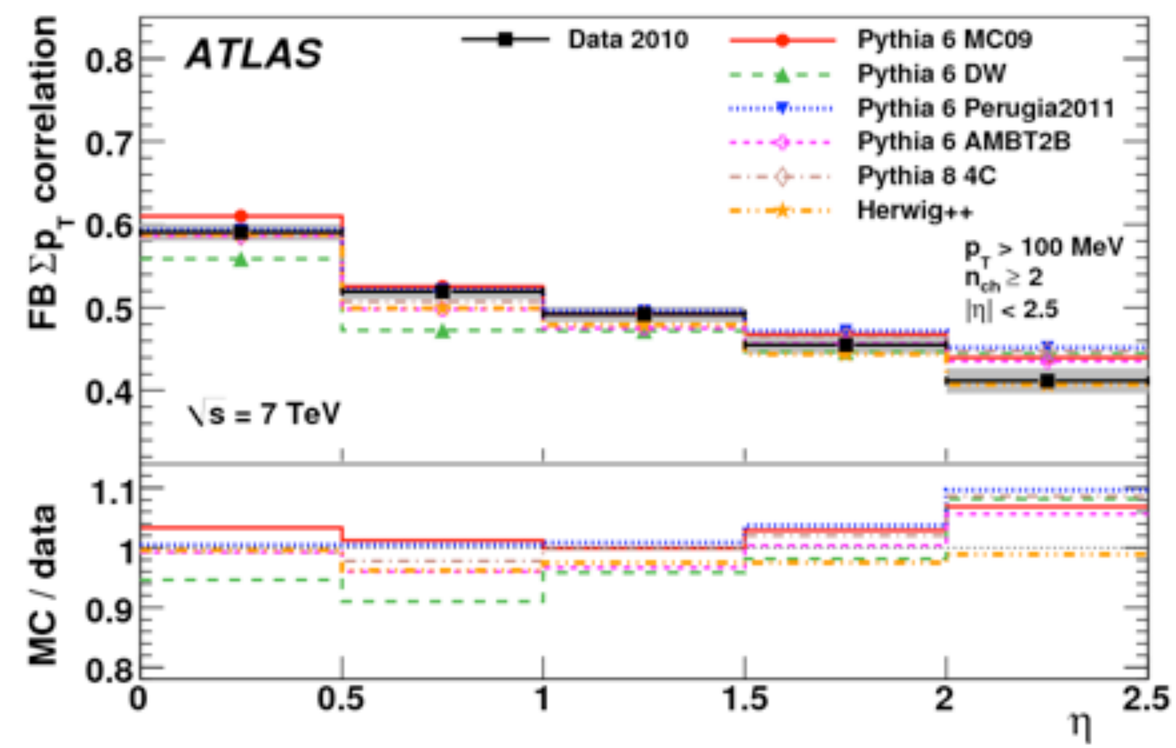




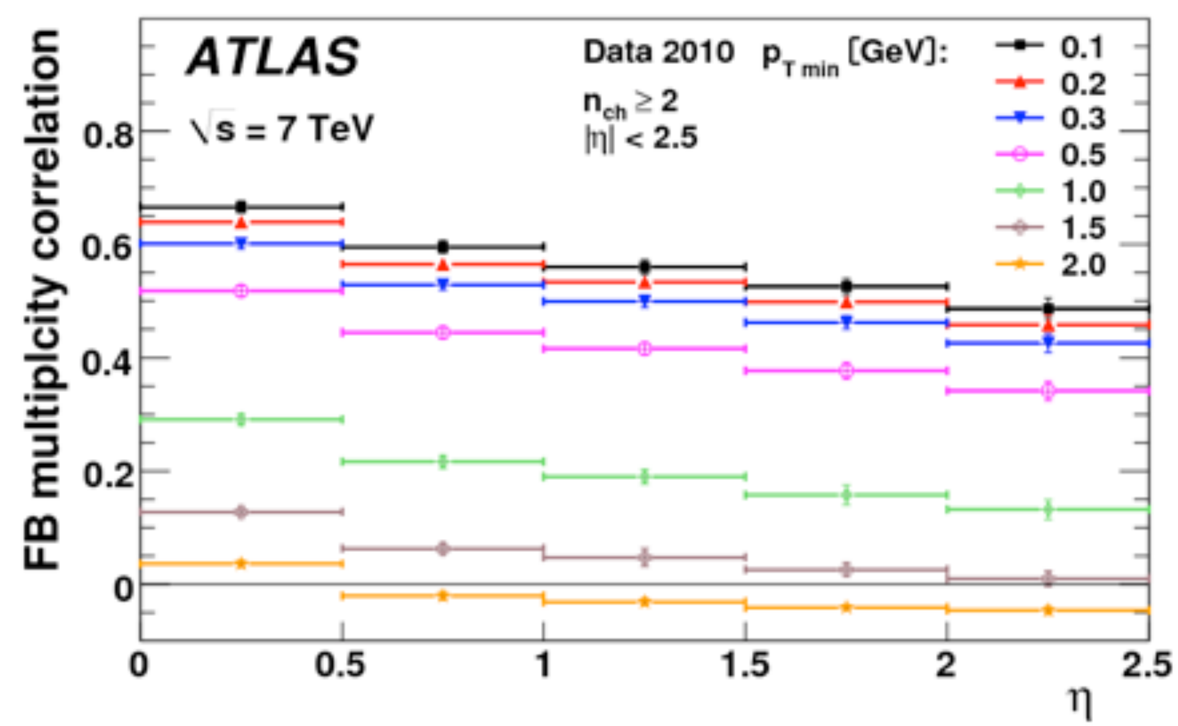
Forward-backward correlation

- FB momentum correlation (ρ^{p_T}): Correlation between forward and backward charged-particle summed transverse momentum.

$$\rho_{fb}^{p_T} = \frac{\langle(\sum p_T^f - \langle\sum p_T^f\rangle)(\sum p_T^b - \langle\sum p_T^b\rangle)\rangle}{\sqrt{\langle(\sum p_T^f - \langle\sum p_T^f\rangle)^2\rangle\langle(\sum p_T^b - \langle\sum p_T^b\rangle)^2\rangle}}$$



- The minimum value, p_{Tmin}, of the transverse momentum of the selected charged particles was varied for the 7 TeV data.
- As expected, the correlations fall rapidly as p_{Tmin} increases above a few hundred MeV, a feature also seen in the MC models (not shown).
  - Low p_{Tmin}: general tendency for a partonic string to fragment in a uniform way all along its length.
  - At higher p_{Tmin}: particles are more likely to be associated with jets, and there is no strong correlation between a given jet and another jet at any particular value of η.



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.

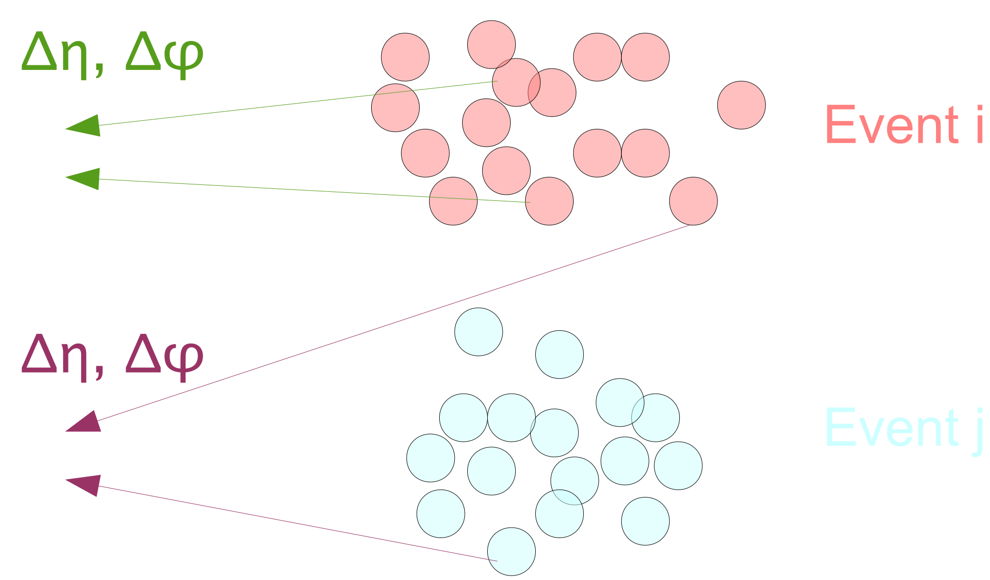
  - gives indication about multi-particle dynamics in heavy-ion collisions.

- **Two-particle angular correlation is defined as:**

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

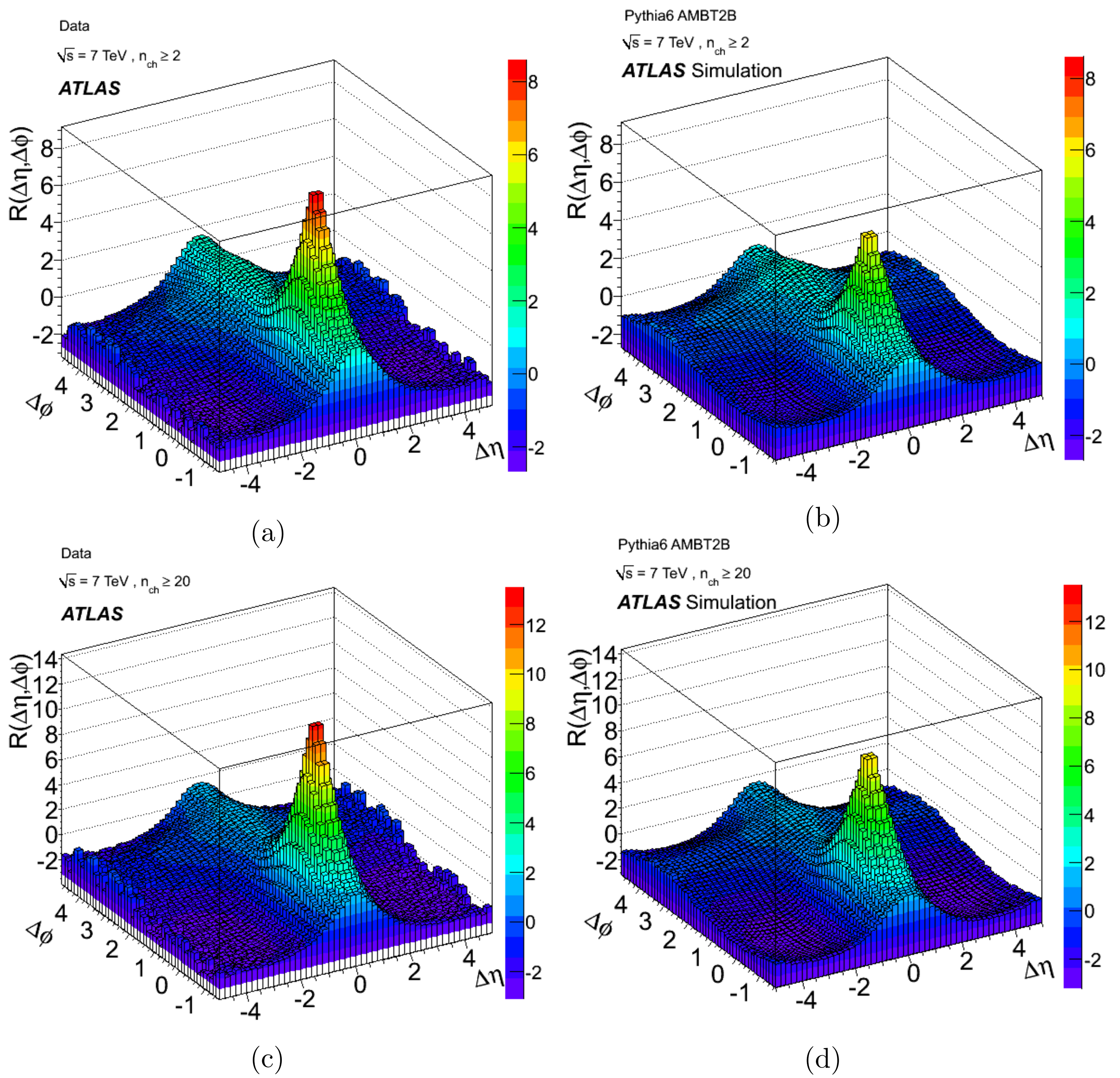
Foreground (F): all particle pairs in same event (correlated + uncorrelated pairs)

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



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

Two-particle angular correlation

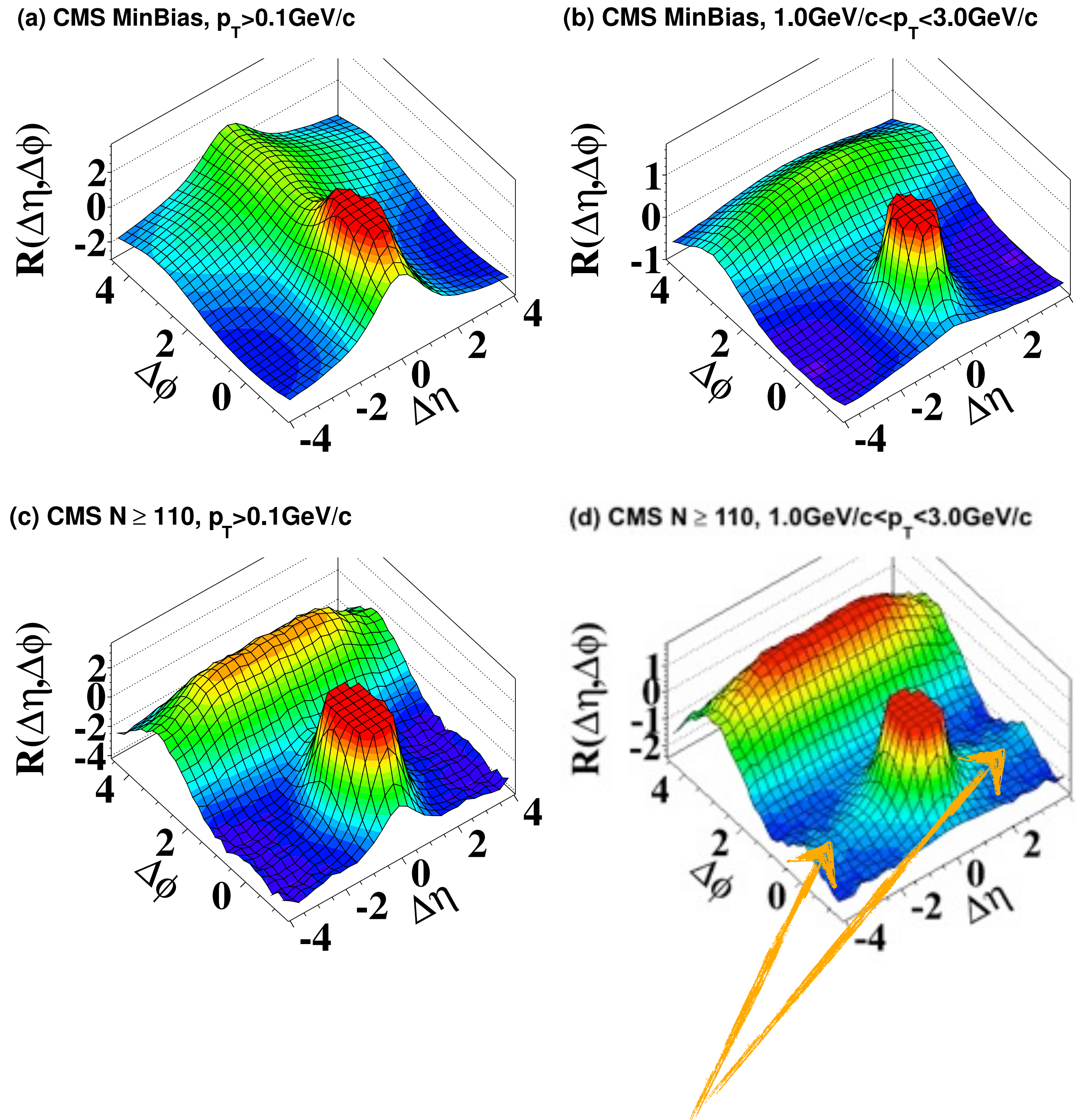


"Near-side" correlations: sharp peak at $(\Delta\eta, \Delta\varphi) \approx (0, 0)$ can be attributed to high-p_T processes.

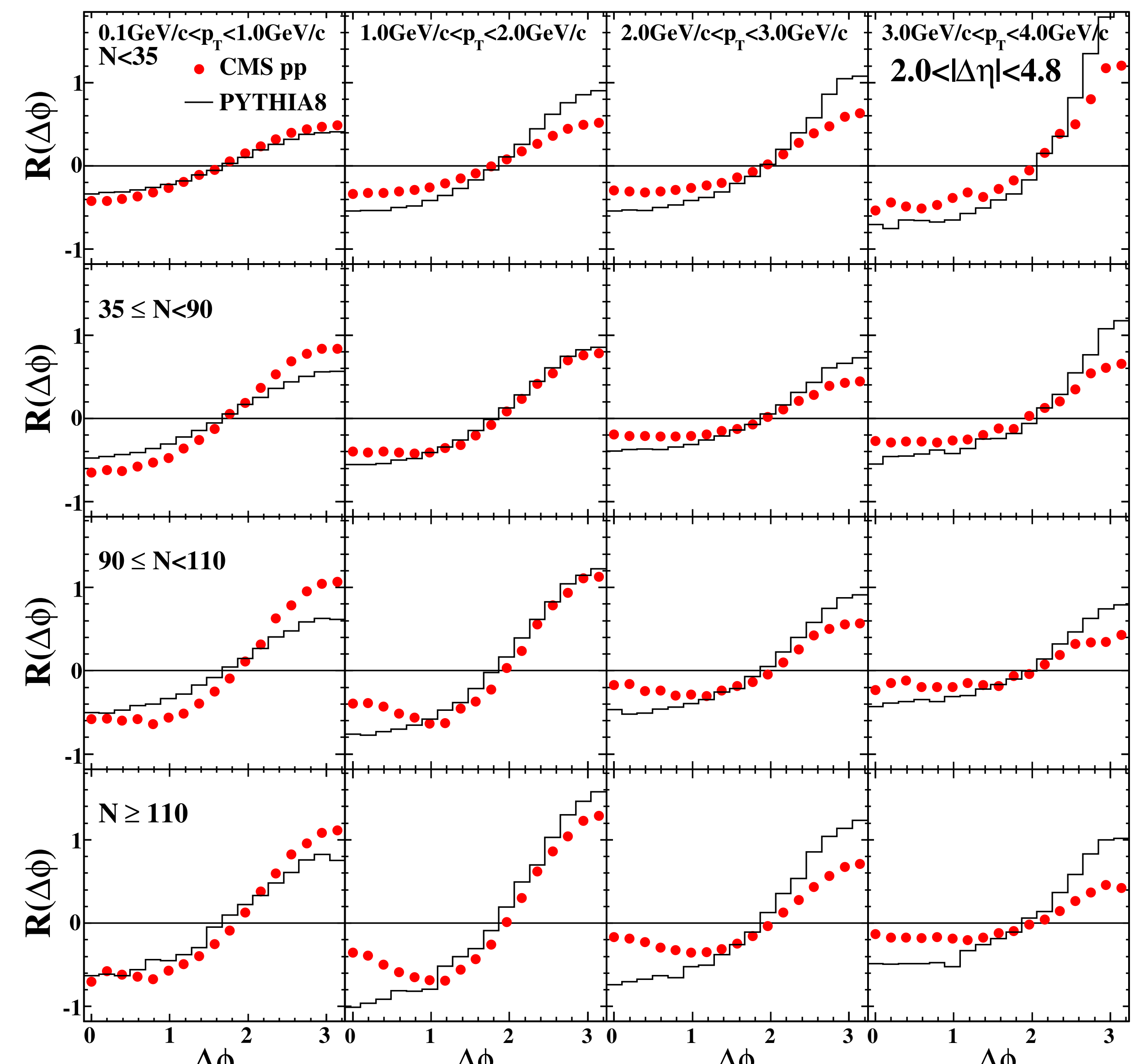
"Away-side" correlations: ridge at $\Delta\varphi \approx \pi$ can be attributed to momentum conservation.

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

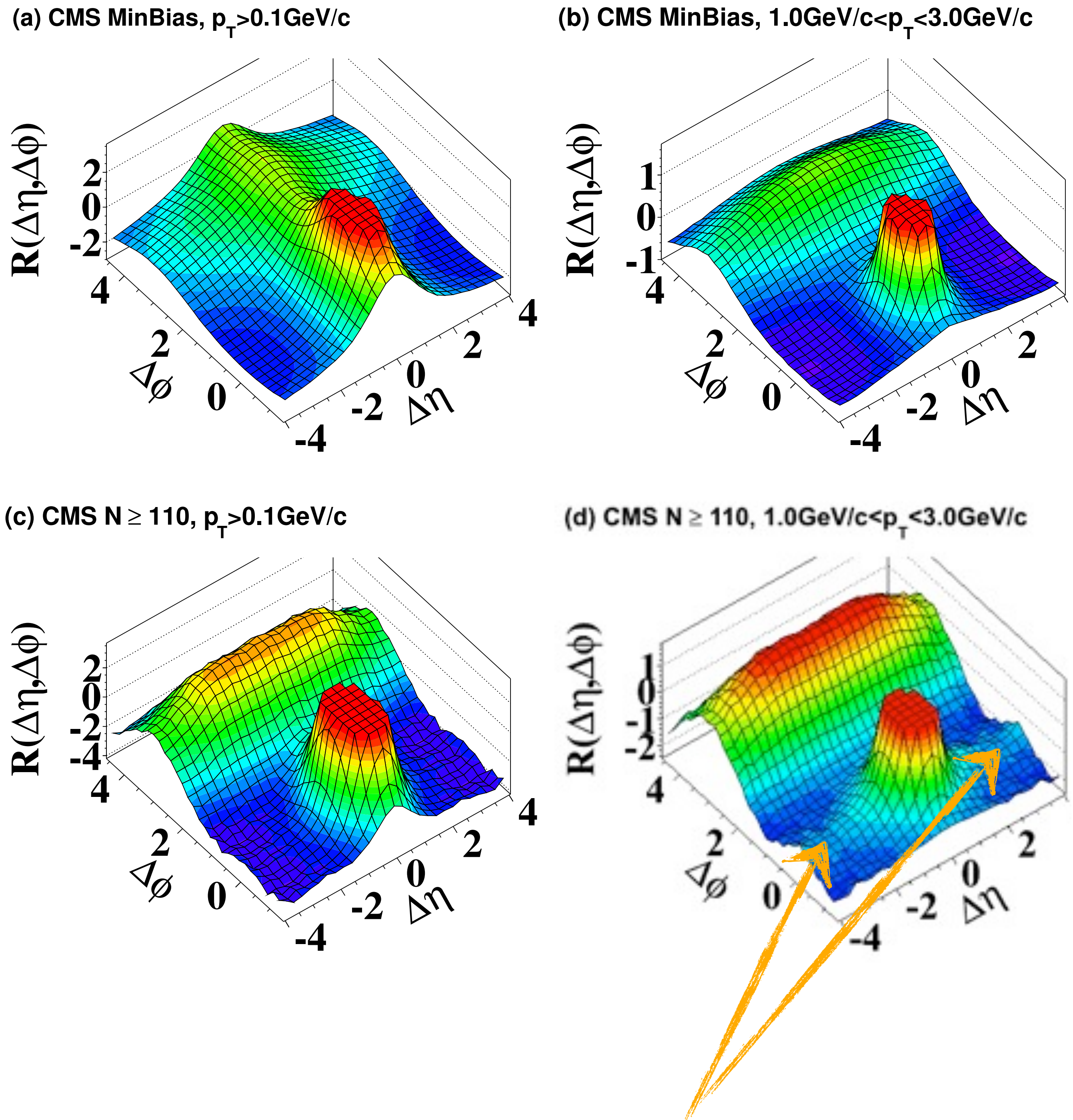
MC models are able to predict structure seen in data BUT fail to reproduce the strength of the correlations.



An identical analysis of high multiplicity events in PYTHIA8 results in correlation functions which do not exhibit the extended ridge at $\Delta\varphi \approx 0$, while all other structures of the correlation function are qualitatively reproduced.



The intermediate p_T range in high multiplicity events shows an unexpected effect: a clear and significant "ridge"-like structure emerges at $\Delta\varphi \approx 0$ extending to $|\Delta\eta|$ of at least 4 units. This is a novel feature of the data which has never been seen in two-particle correlation functions in pp or ppbar collisions.



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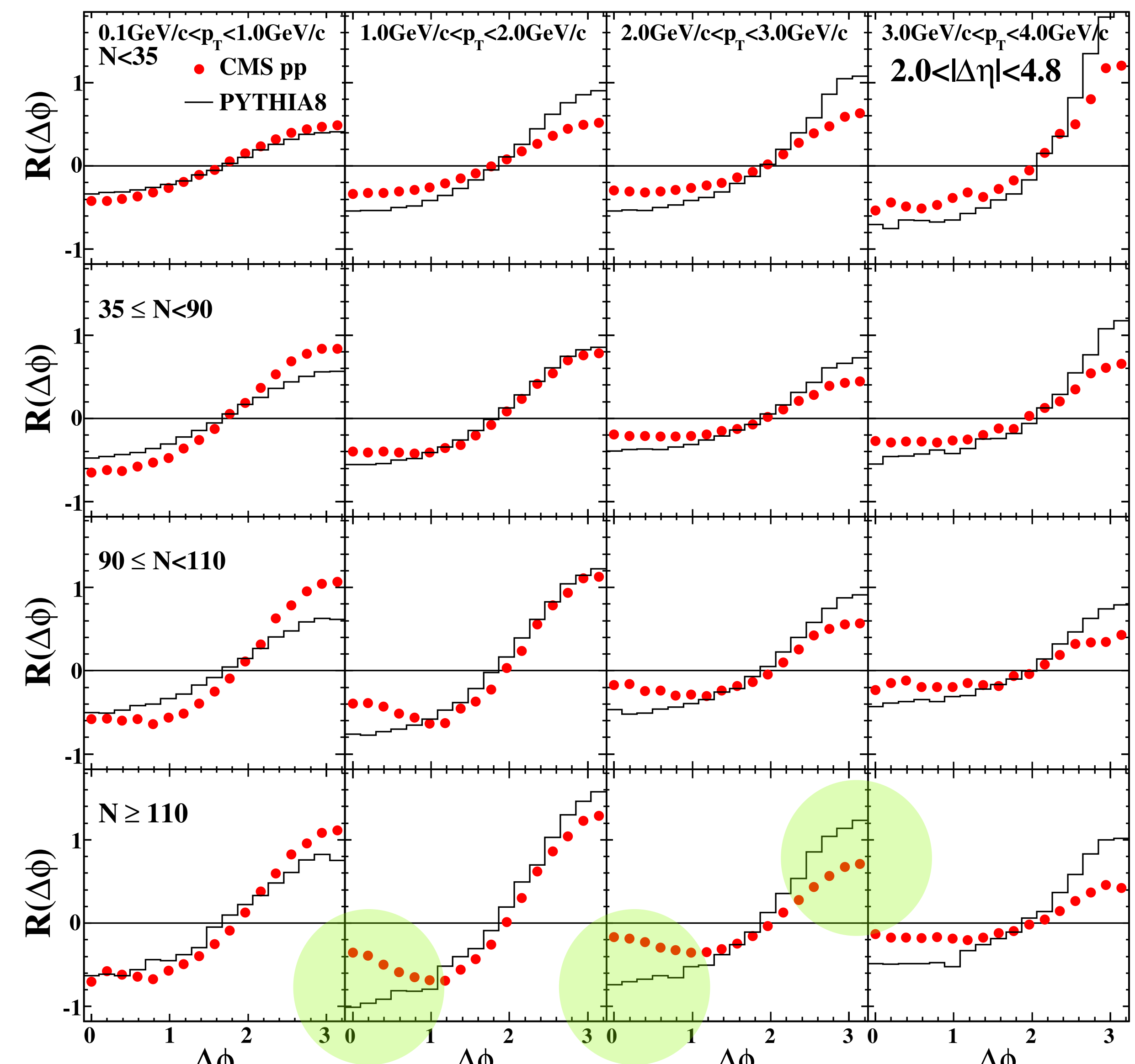

The intermediate p_T range in high multiplicity events shows an unexpected effect: a clear and significant **“ridge”-like structure** emerges at $\Delta\varphi \approx 0$ extending to $|\Delta\eta|$ of at least 4 units. This is a novel feature of the data which has never been seen in two-particle correlation functions in pp or ppbar collisions.

Azimuthal ordering of charged hadrons

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- **Charged particle measurements show limitations of phenomenological models**

  - Models cannot describe measured observables in all regions of the phase space.

  - Some discrepancy can be reduced by tuning, but

  - New formulation of certain components (e.g. fragmentation) is likely needed!

- **Two main hadronisation models used in multi-purpose MC generators:**

  - String (Lund) fragmentation model, e.g. PYTHIA, PHOJET

  - Cluster model, e.g. HERWIG

- **Azimuthal ordering of charged hadrons:**

  - Provides a test of hadronisation models.

  - Requires careful selection of the phase-space in order to test sensitivity to hadronisation effects.

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

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

Measure power spectra in the following samples:

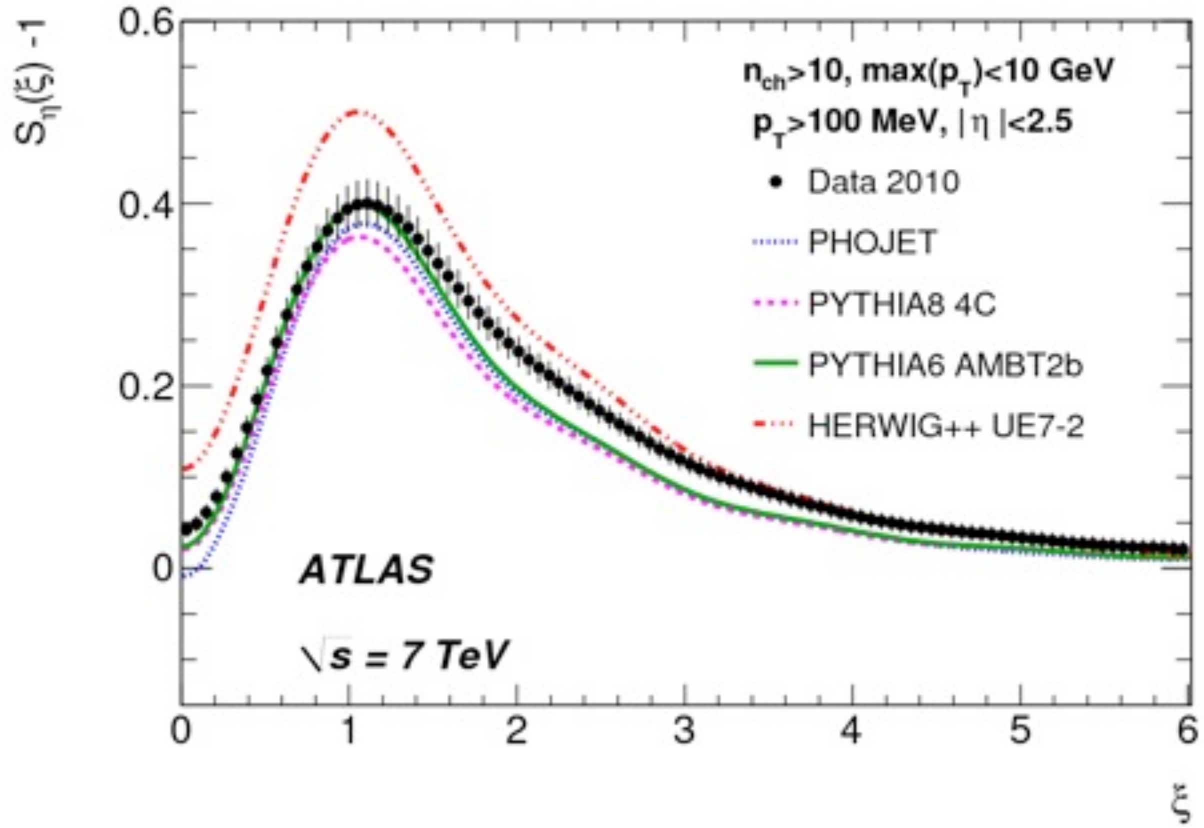
- "Inclusive": p_T > 100 MeV, veto events containing any track with p_T > 10 GeV.
- "Low-p_T enhanced": p_T > 100 MeV, veto events containing any track with p_T > 1 GeV.
- "Low-p_T depleted": p_T > 500 MeV, veto events containing any track with p_T > 10 GeV.

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

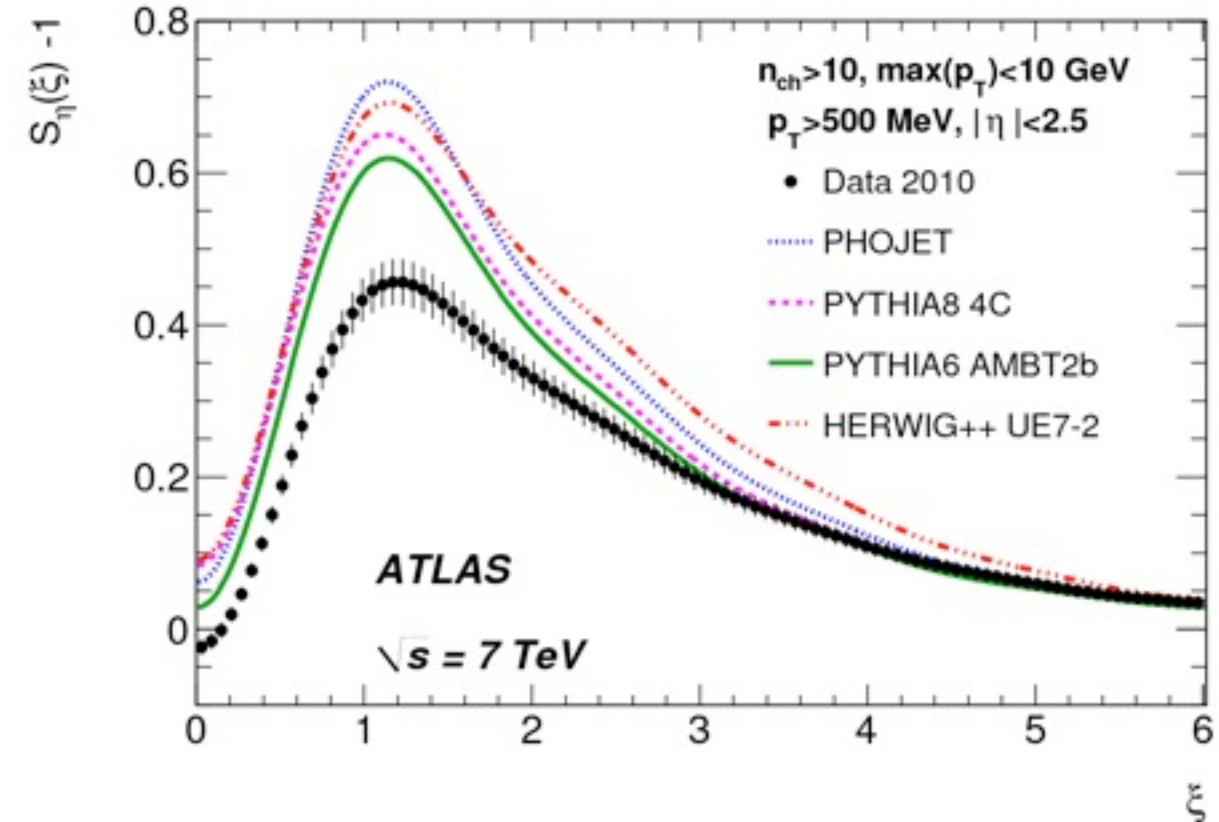
Azimuthal ordering of charged hadrons

University of Glasgow

Inclusive sample

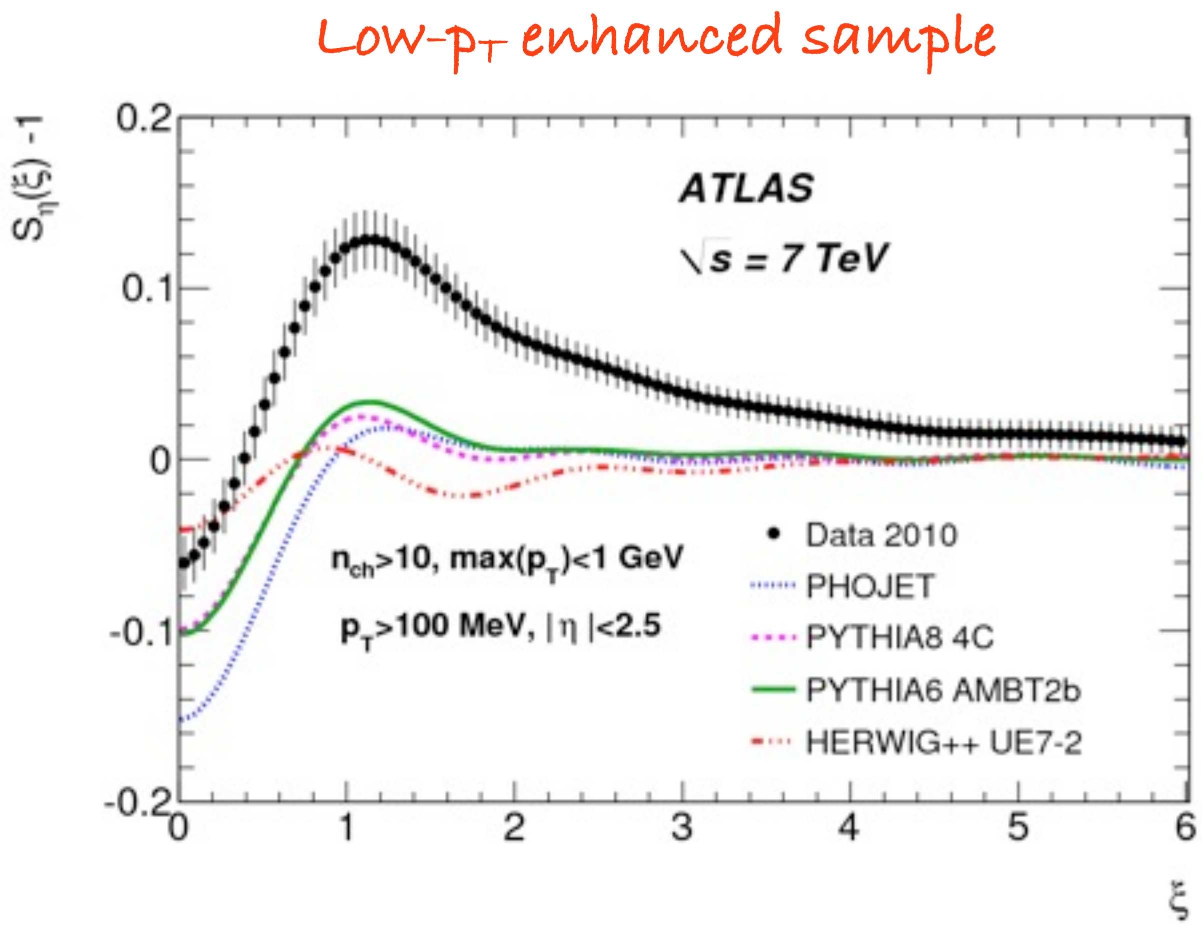


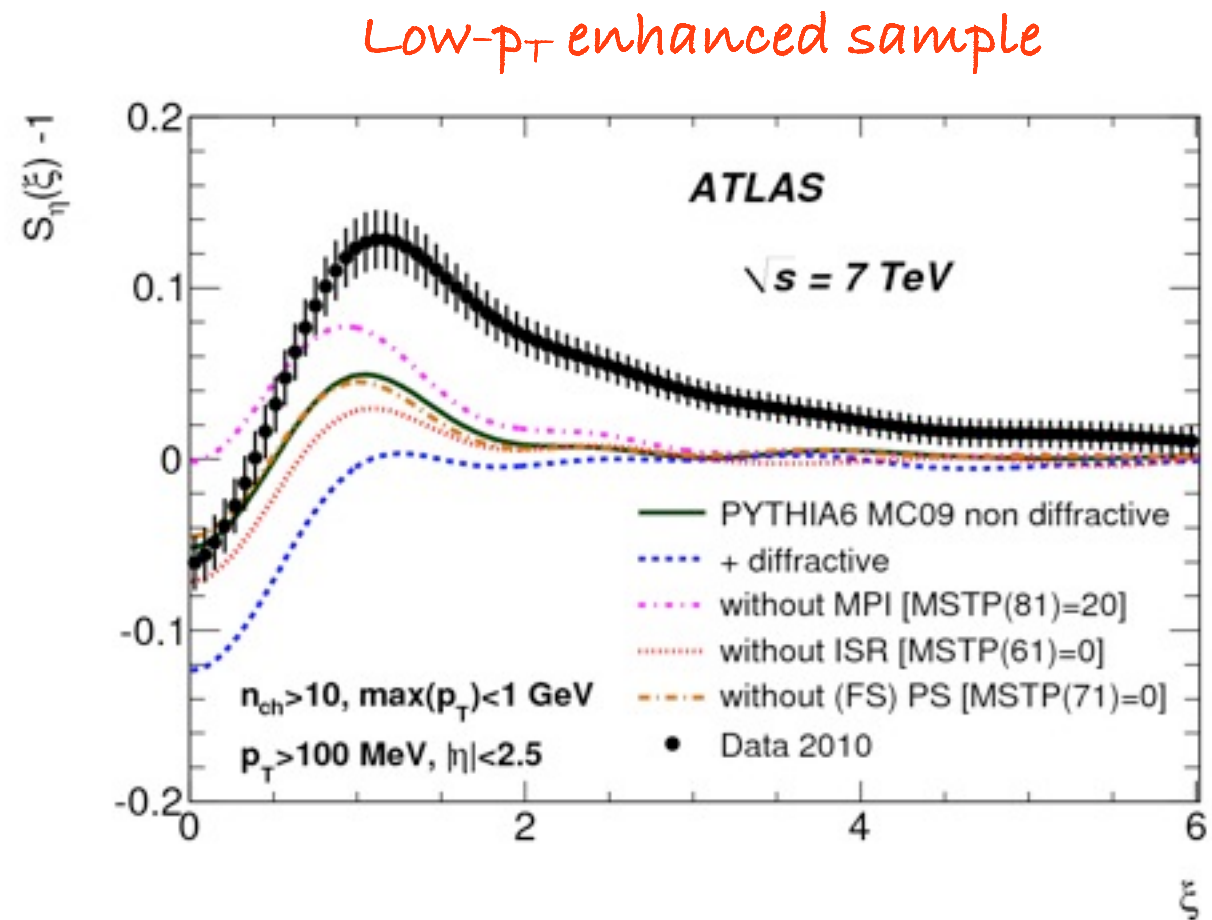
Low-p_T depleted sample



- **Too much correlation in typical MC, for high-p_T charged particles** (right plot), **but good description of inclusive sample** (left plot).

Azimuthal ordering of charged hadrons

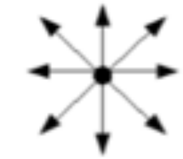


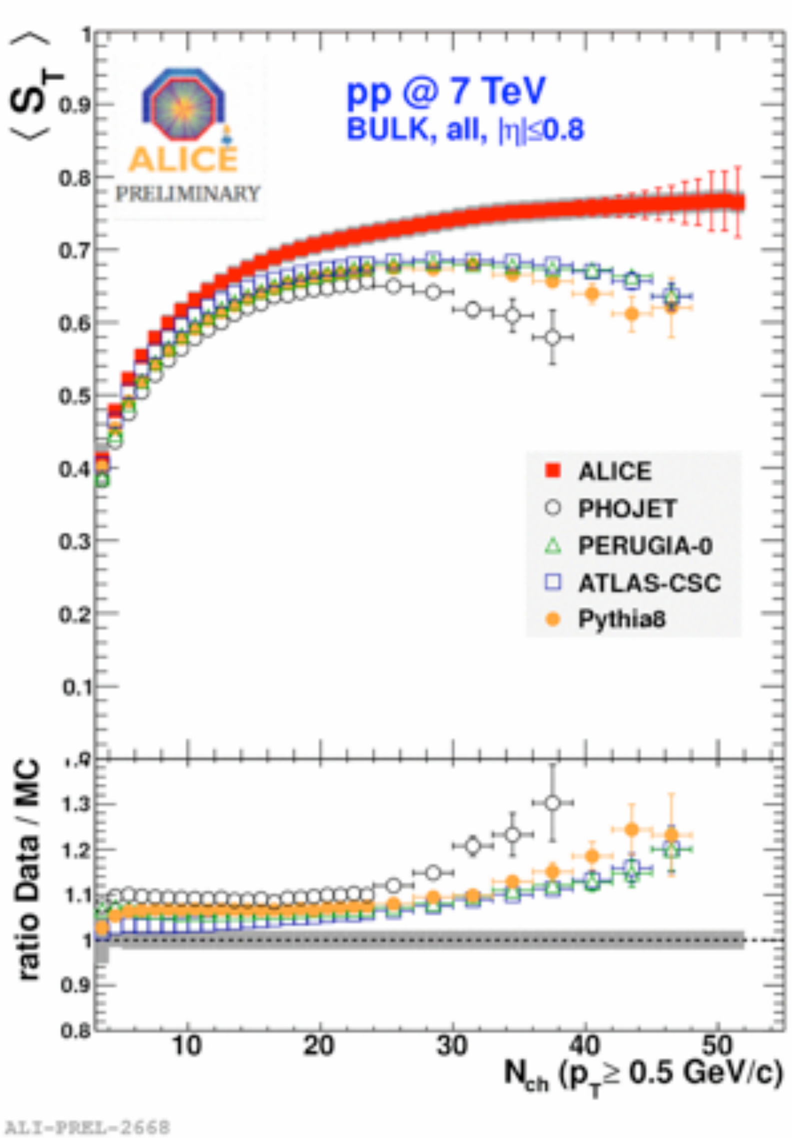


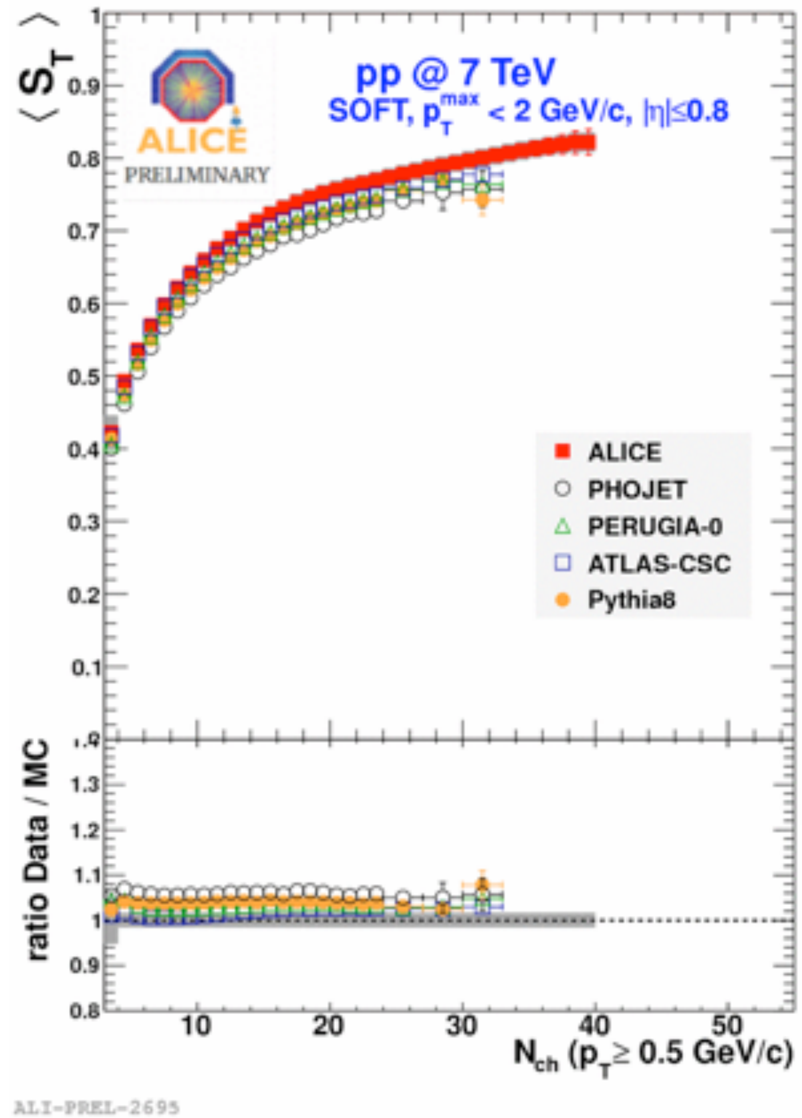
- Too little correlation for sample dominated by low-p_T charged particles (left plot).
- Modelling of diffractive events is a major source of discrepancy between data and models.
- Extreme variation of model parameters cannot provide reasonable description of data (right plot).

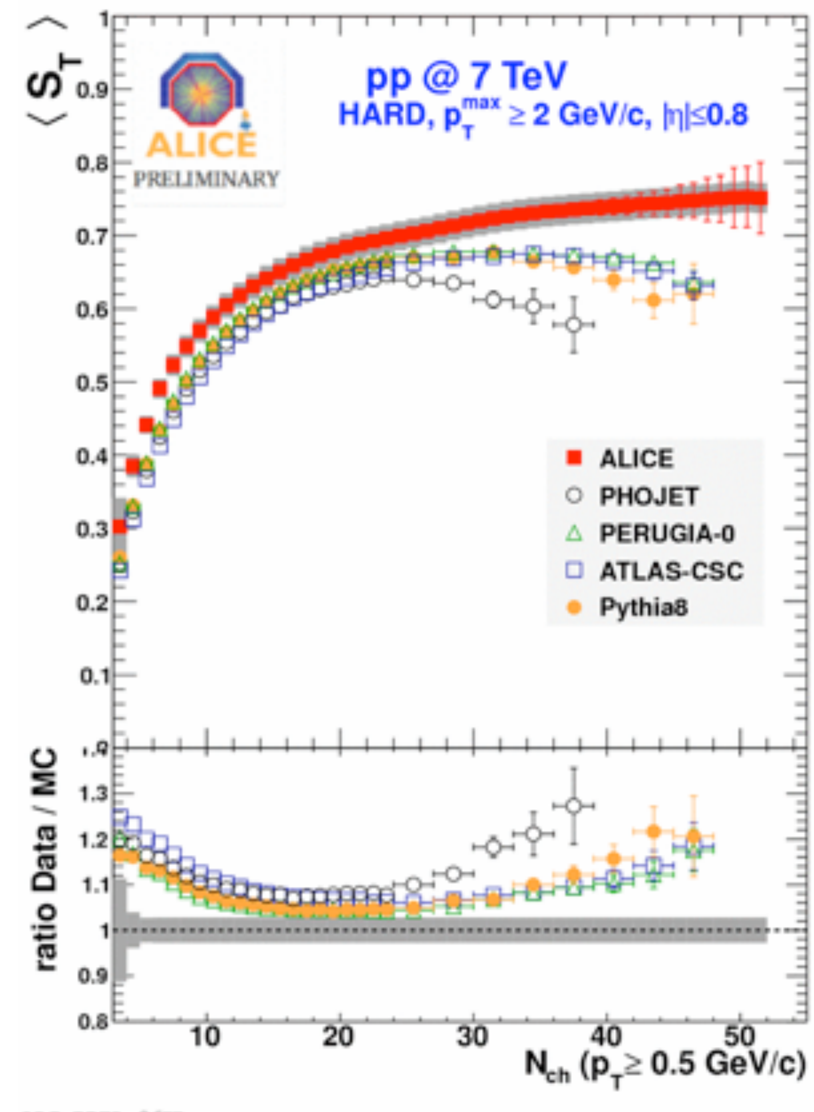
Transverse Sphericity: <S_T>

small S_T: 

large S_T: 



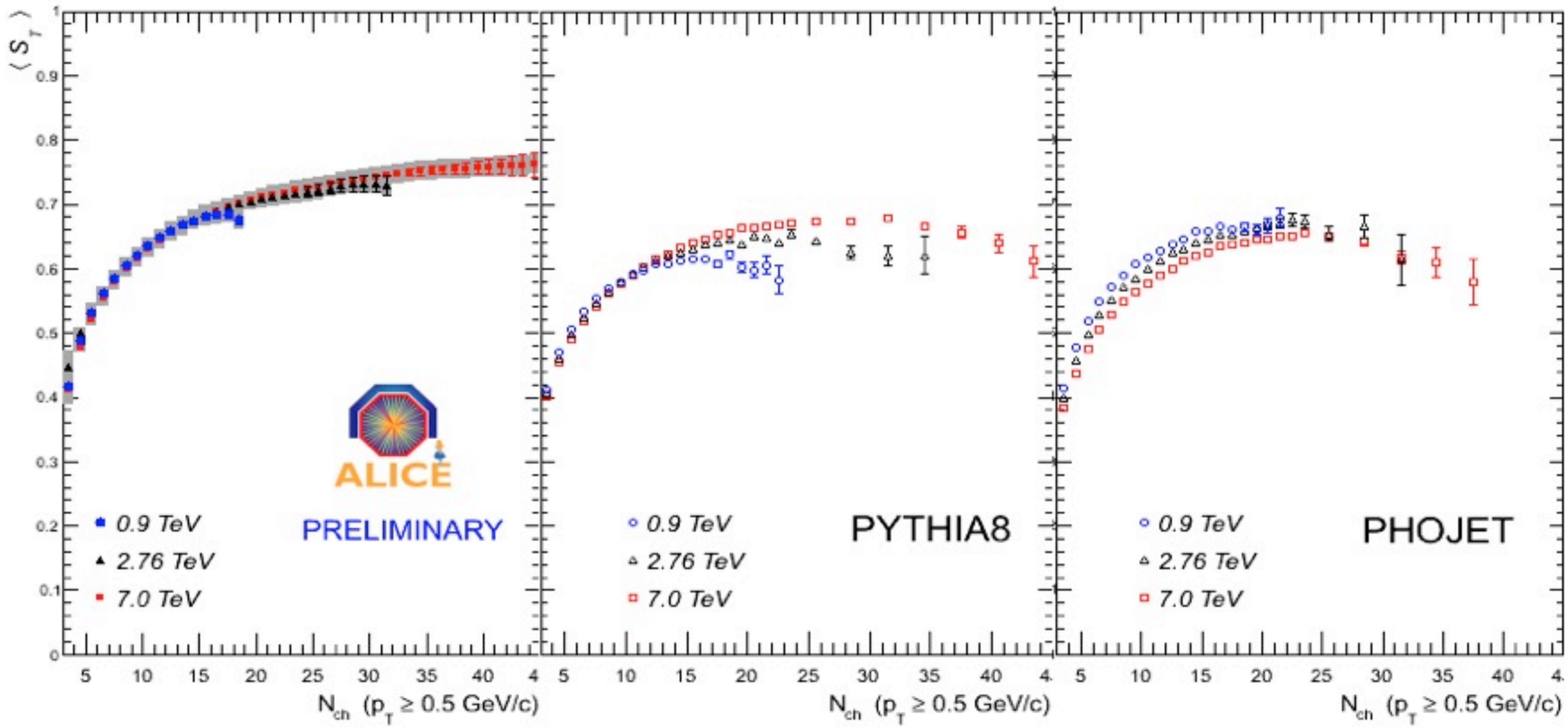




- **Analysis performed as function of multiplicity for soft and hard events**
  - Soft and hard events are defined by the leading track p_T
    - $p_{T,lead}$ < 2 GeV/c for soft events
    - $p_{T,lead}$ > 2 GeV/c for hard events

$\langle S_T \rangle$ vs $\sqrt{s}$

- **No significant difference between 0.9, 2.76 and 7 TeV**



(4) Correlations in high multiplicity events

- Long-range correlations which are still not well described by MC models (several interpretations & ideas though...)

- Transverse sphericity is not described for high multiplicity events either.

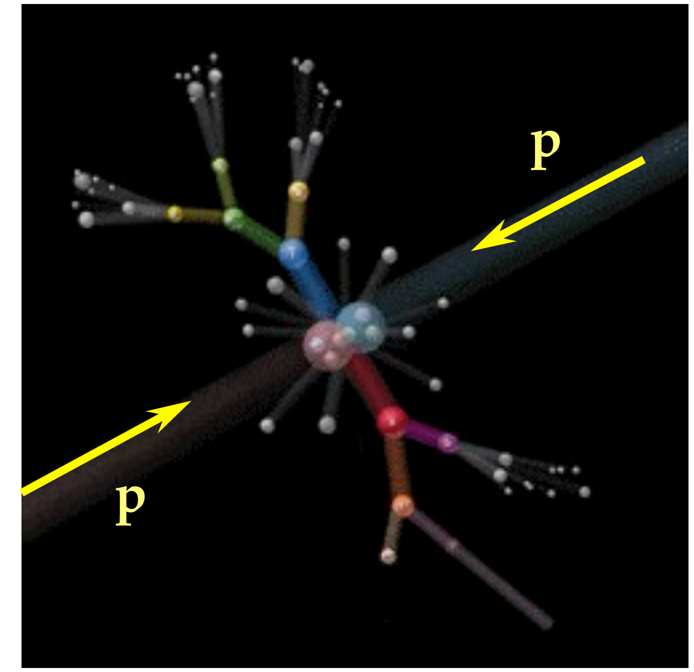
(5) Low-p_T particle azimuthal ordering:

Models cannot describe the fragmentation structure seen in data. Discrepancy appears to be “beyond tuning”!

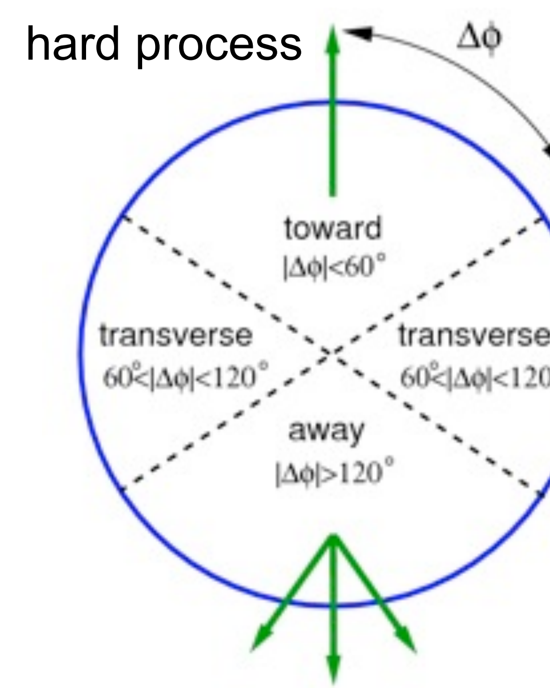
New hadronisation models?

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).



- UE characterised by activity in ϕ region transverse to the leading particle (= highest p_T track or cluster)
  - **Track-based measurement:**
    - charged particle component
  - **Cluster-based measurement:**
    - Use energy depositions in calorimeters associated to charged and neutral particles



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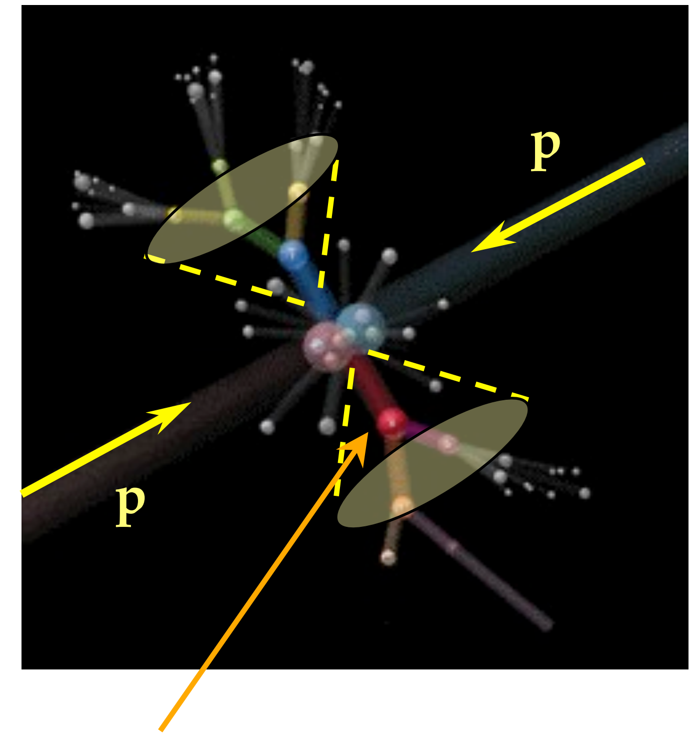

Process of interest (eg. high p_T jets, top-anti-top pair, Z boson)

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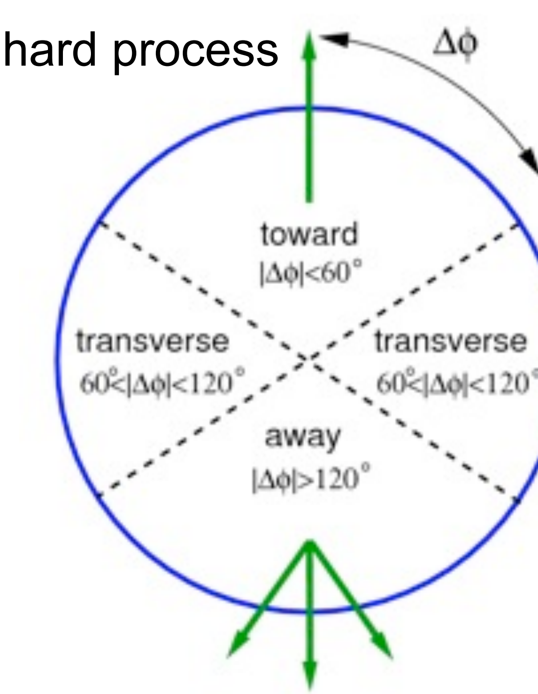

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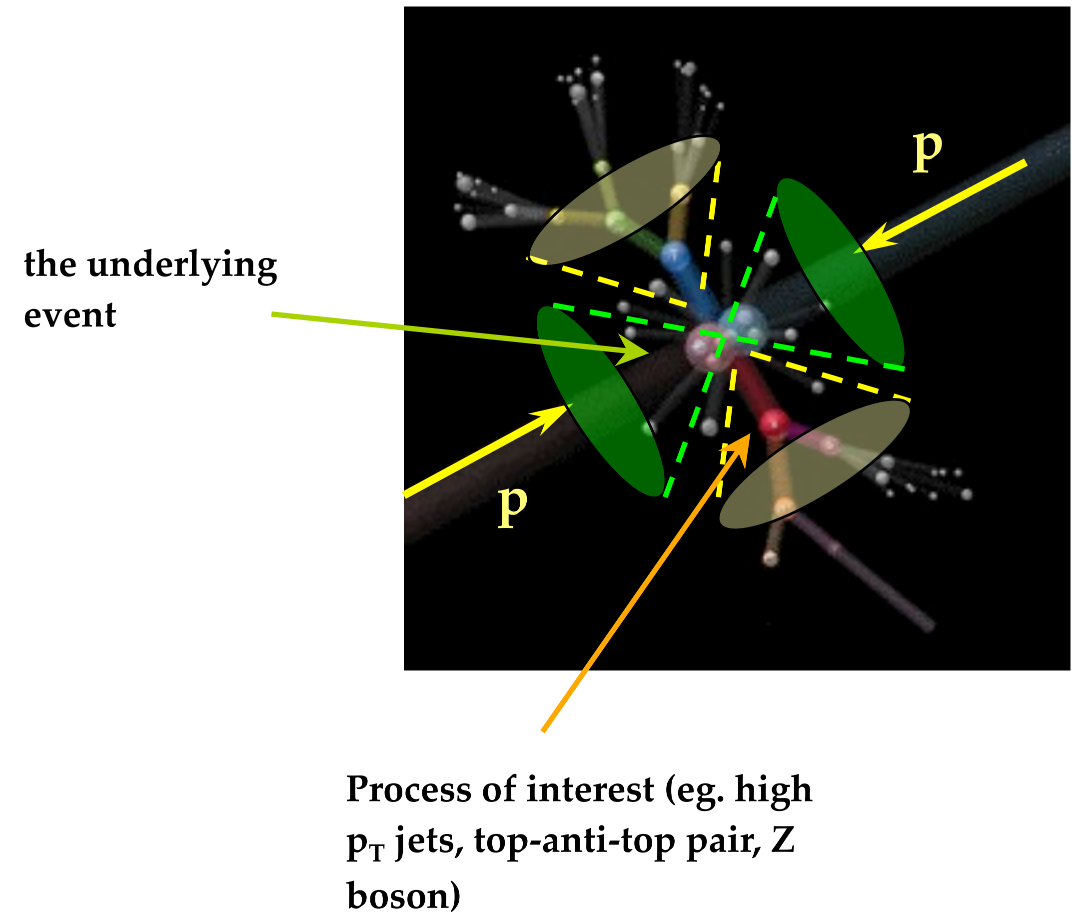

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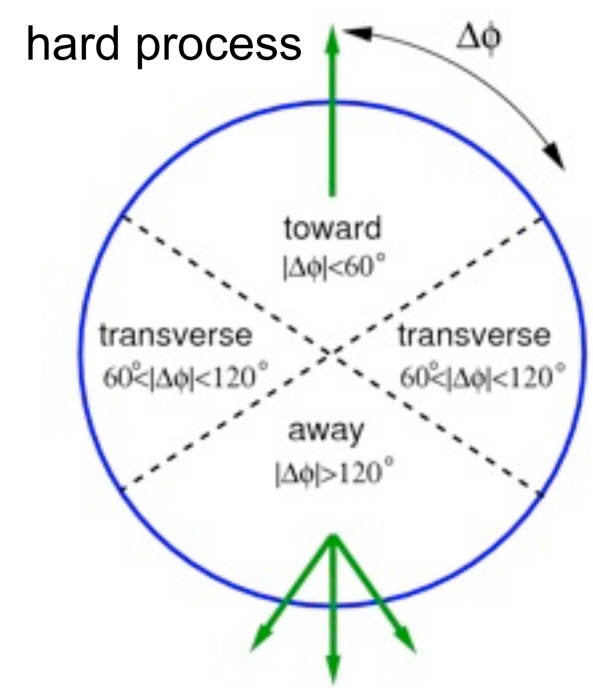
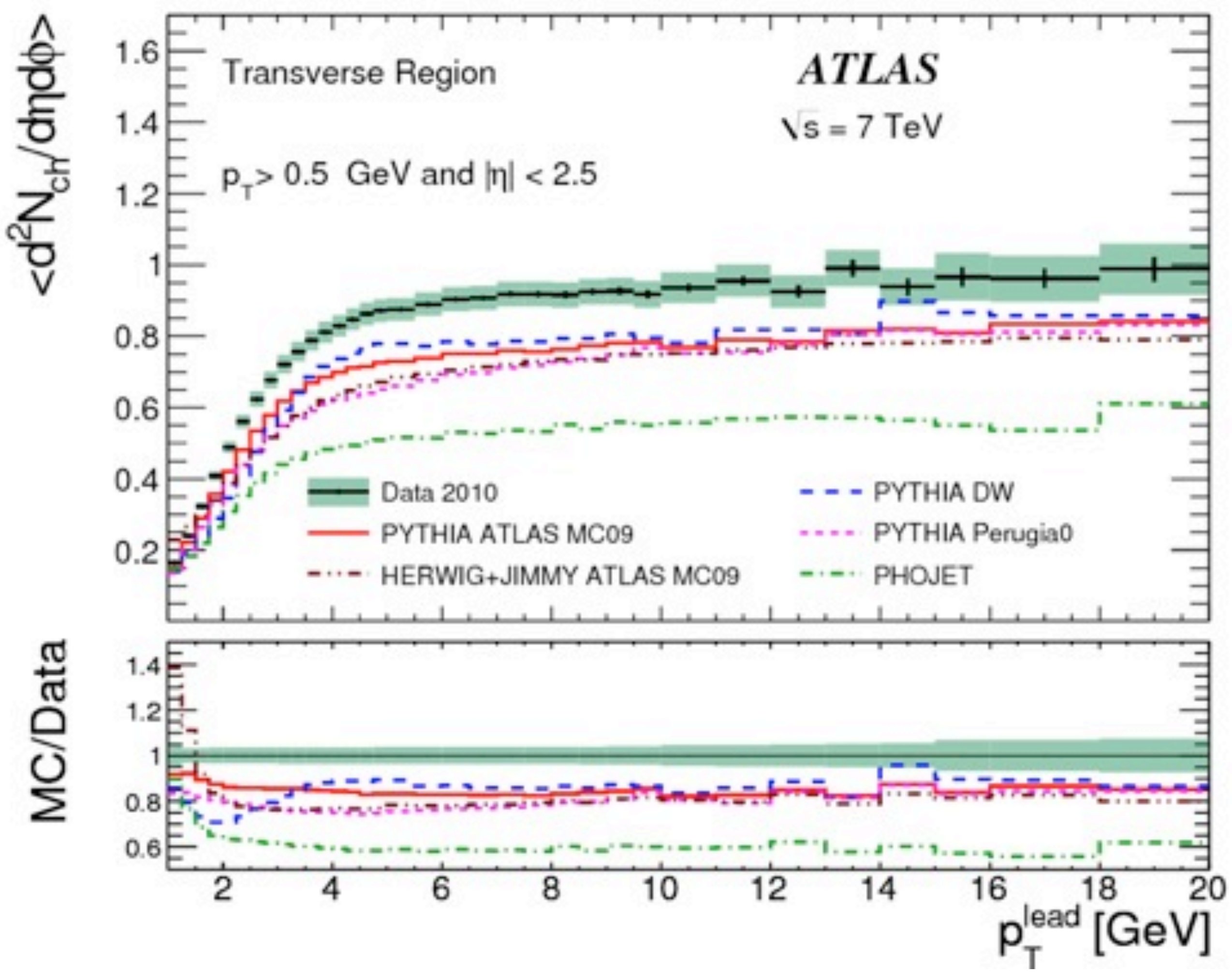
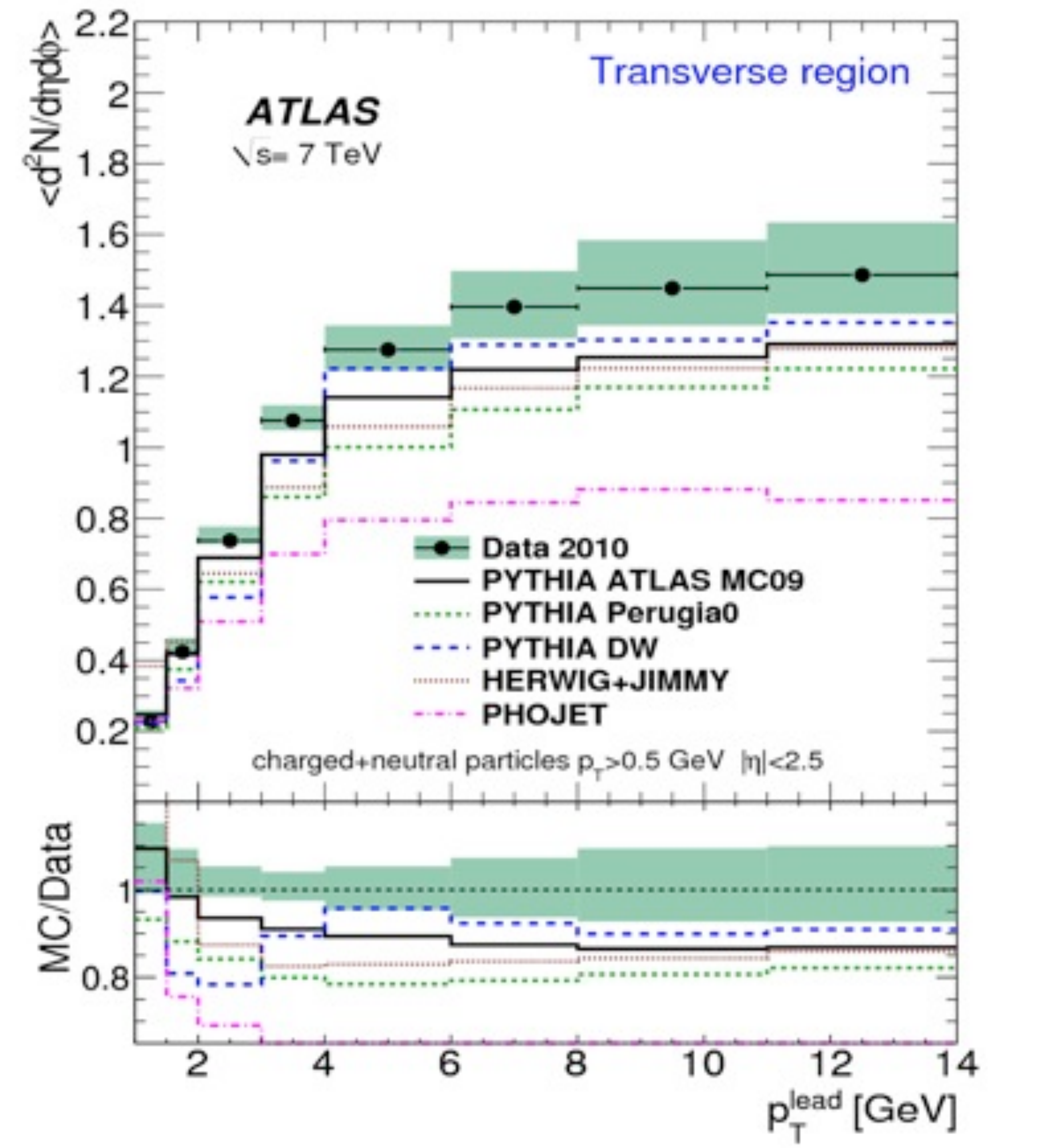


Leading Charged Particle: Transverse Number Density

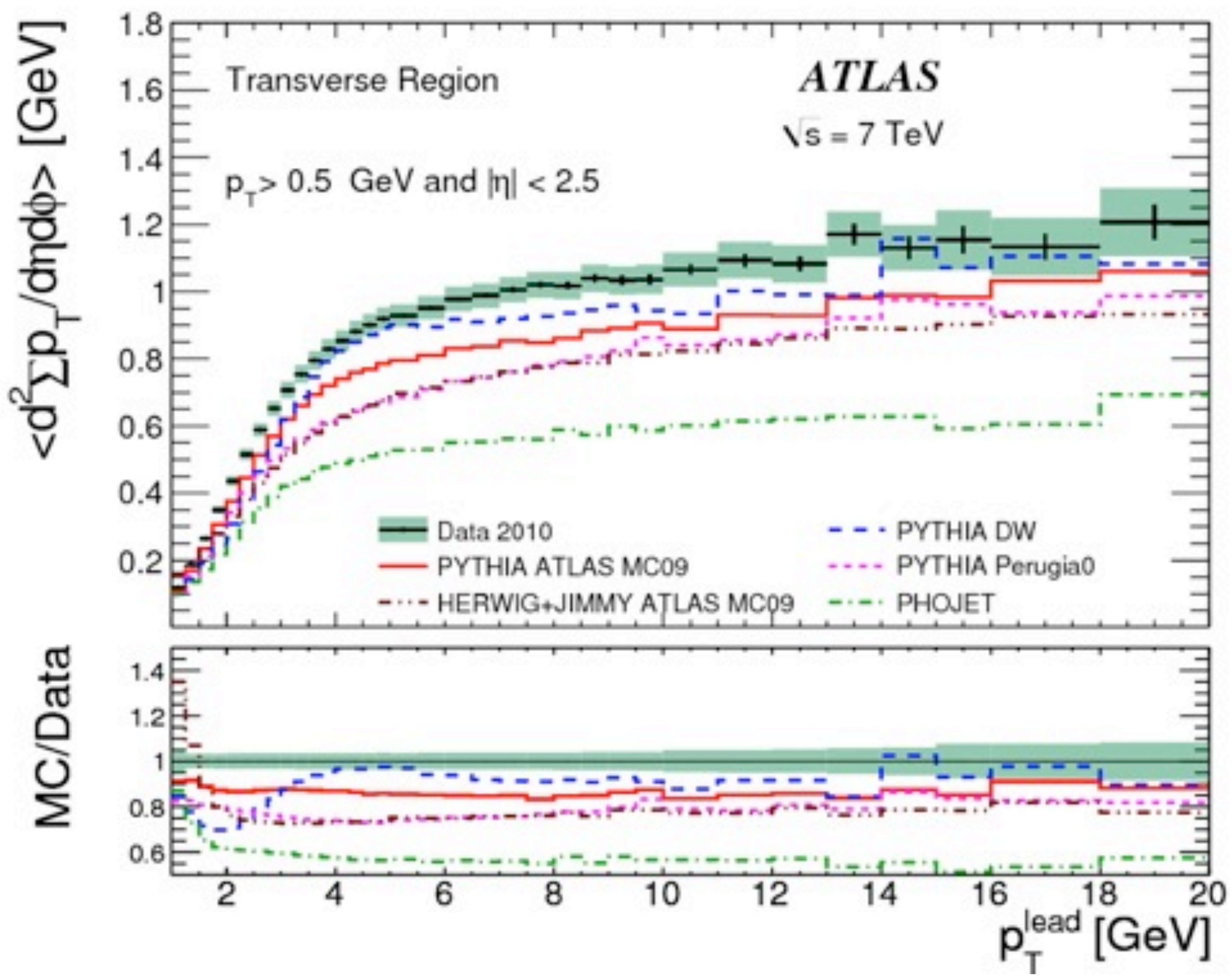


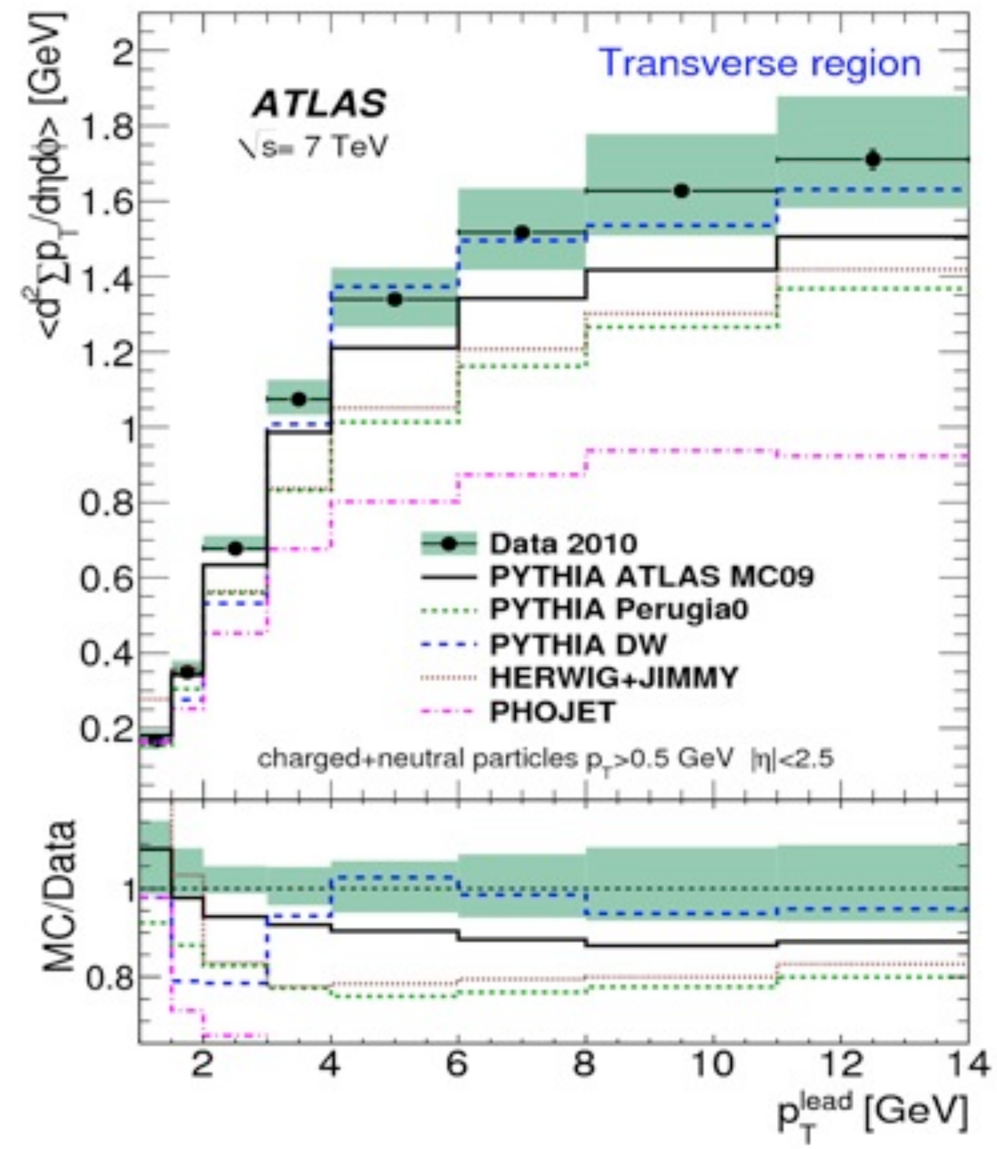


- The number density in data is higher than predicted by any of the MC tunes (also observed in comparisons to minimum bias densities).

- The difference is more significant at 7 TeV (energy extrapolation!). They get even **larger** as low p_T particles are added to the measurement.

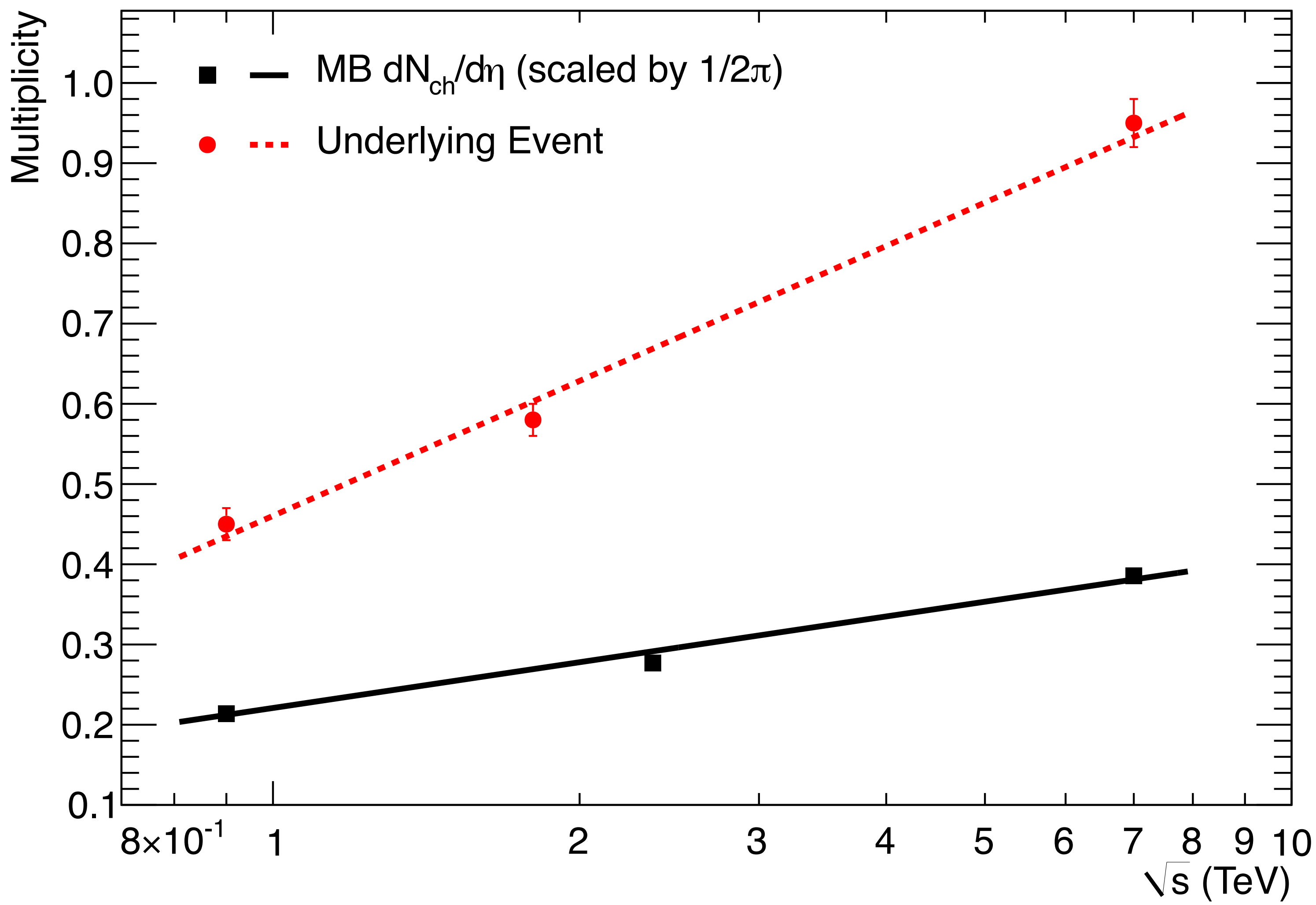
Leading Charged Particle: Transverse Sum p_T Density





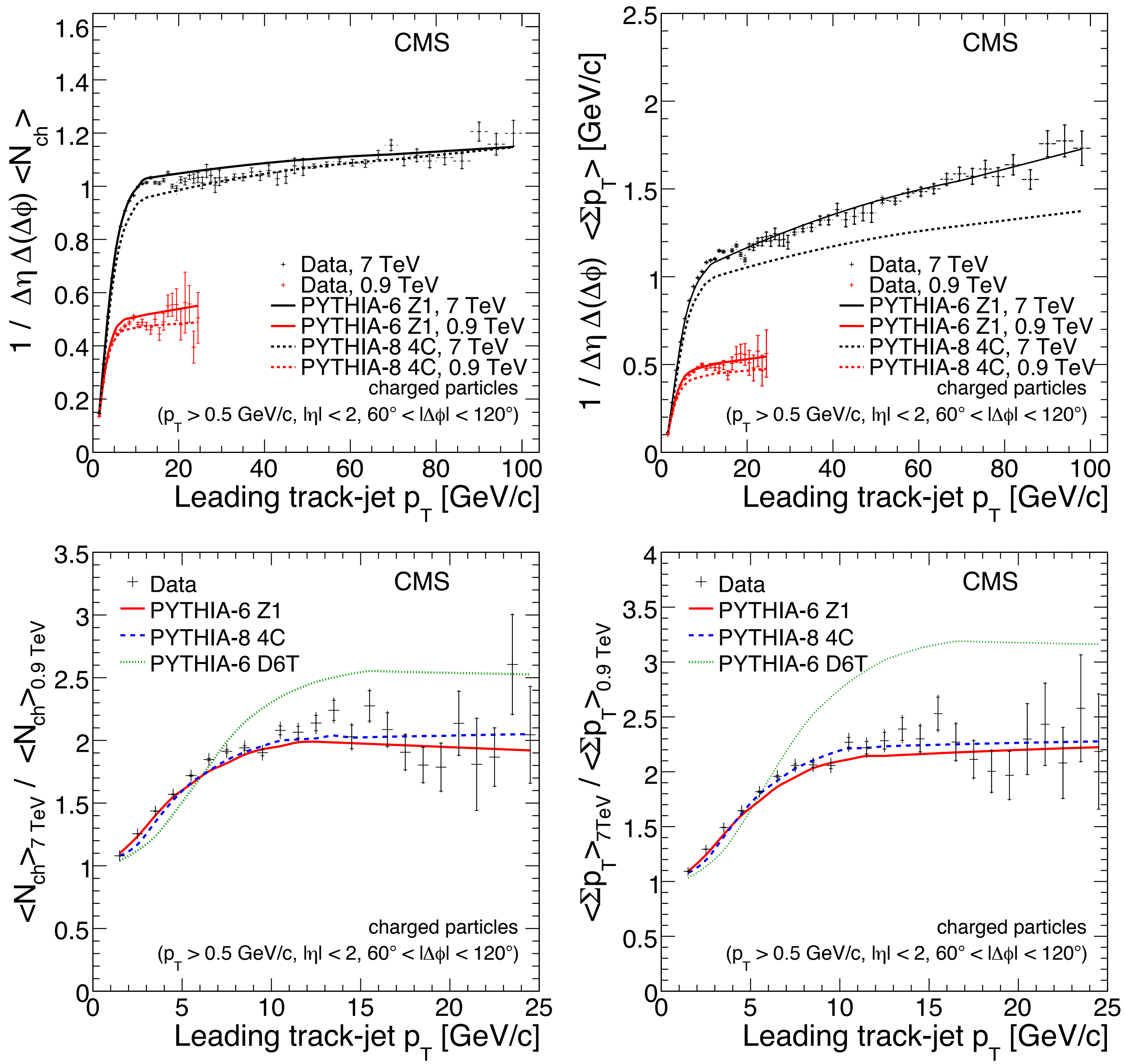
- The higher number density in data implies a higher p_T density as well.
- The summed charged particle p_T in the plateau characterises the mean contribution of the underlying event to jet energies.

Minimum bias vs. Underlying event



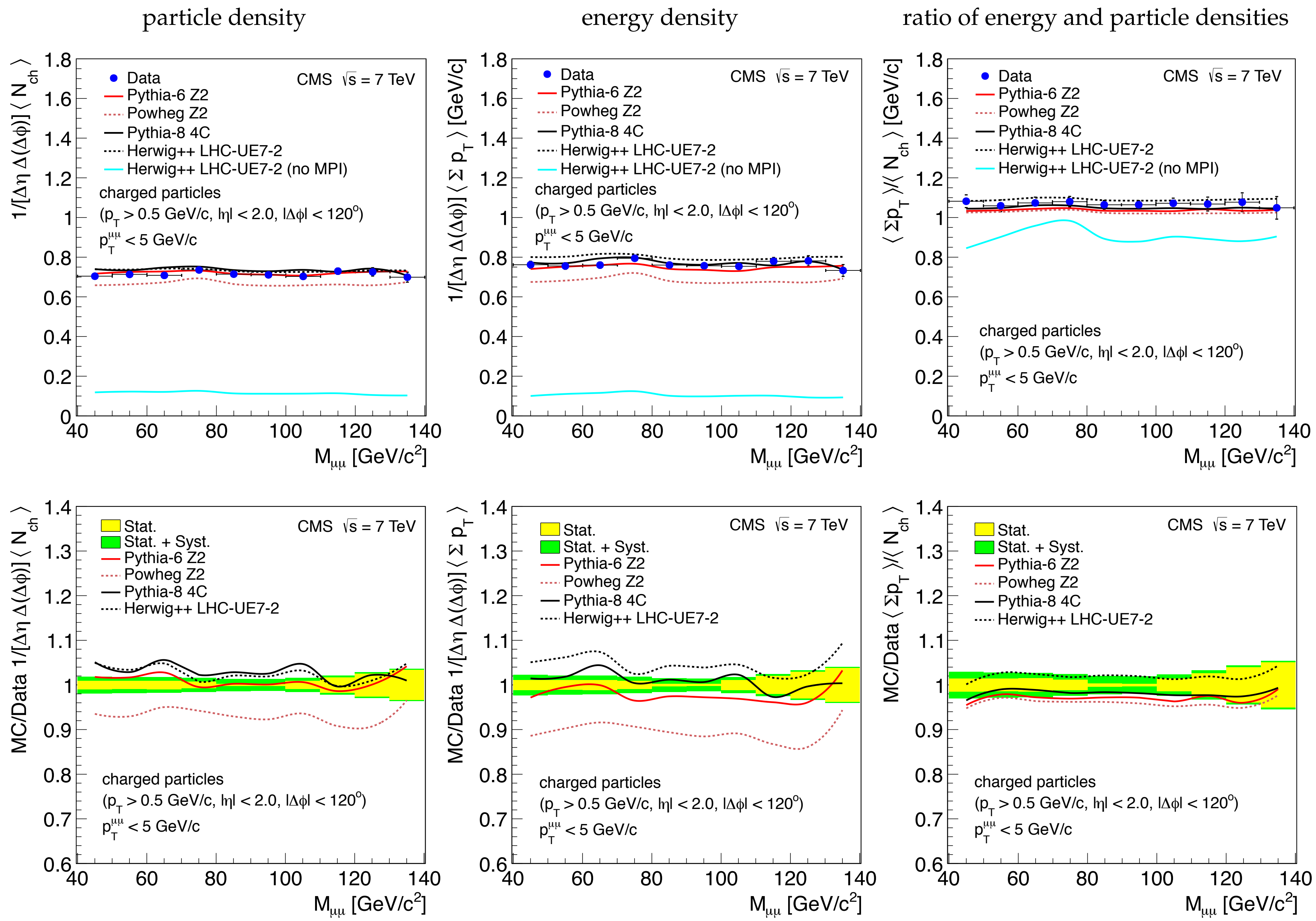
- **For illustration, this figure presents the number density in the plateau of the Transverse region for $p_T > 0.5$ GeV (CDF at 1.8TeV also included) compared with $dNch/d\eta$ at $\eta=0$ of charged particles with $p_T > 0.5$ GeV in minimum-bias events (scaled by $1/2\pi$).**
- **The UE activity in the plateau region is more than a factor 2 larger than the $dNch/d\eta$. Both can be fitted with a logarithmic dependence on s (a+b lns). The relative increase from 0.9 to 7TeV for the UE is larger than that for the $dNch/d\eta$: about 110% compared to about 80%, respectively.**

Leading track jet: Transverse Number Density



‣ Comparing number densities for 900 GeV and 7 TeV measurements: crucial information for a better understanding on how to model the energy extrapolation!

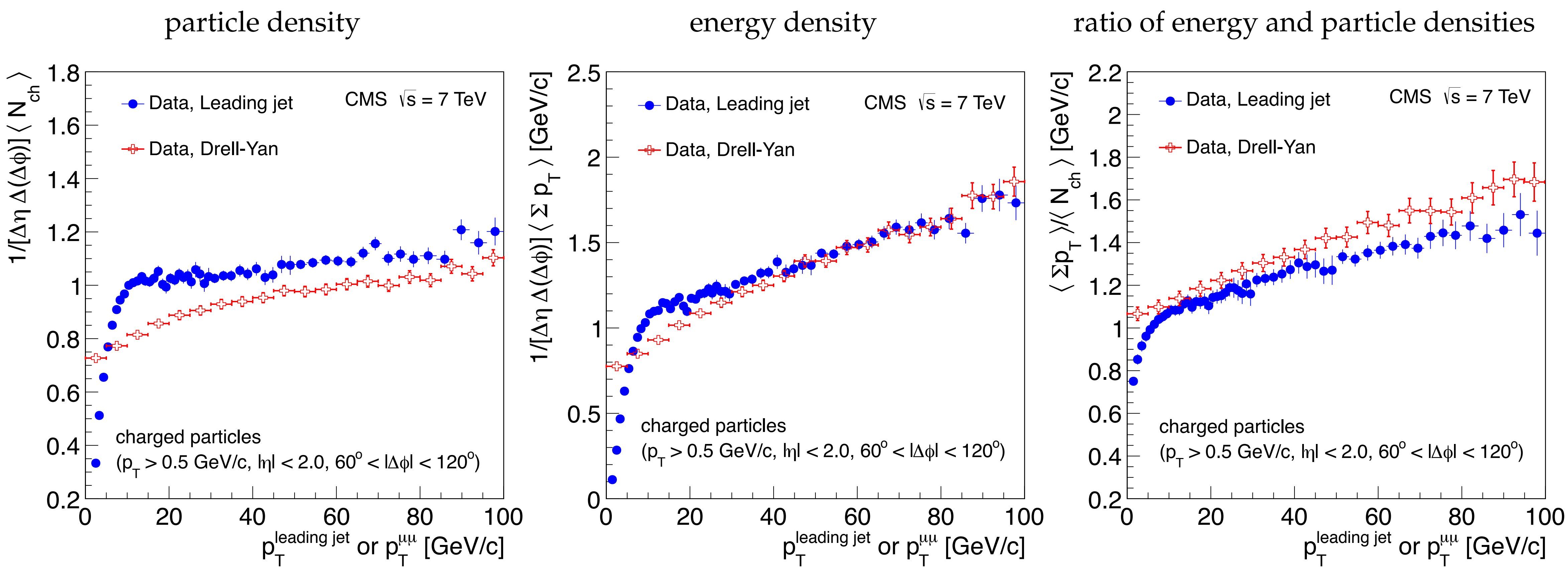
Drell-Yan UE measurements



- The UE activity as a function of the dimuon invariant mass ($M_{\mu\mu}$) for events with $p_T^{\mu\mu} < 5$GeV for charged particles having $\Delta\varphi < 120^\circ$.

- The dependence of the UE activity on the dimuon invariant mass is well described by PYTHIA and HERWIG++ tunes derived from the leading jet/track approach, illustrating the universality of the UE activity. The UE activity is observed to be independent of the dimuon invariant mass in the region above 40 GeV while a slow increase is observed with increasing transverse momentum of the dimuon system.

Drell-Yan UE measurements



- Comparison of the UE activity measured in the hadronic and the DY events (around the Z peak) in the transverse region as a function of $p_T^{leading\ jet}$ and $p_T^{\mu\mu}$ respectively.

- For $p_T^{\mu\mu}$ and $p_T^{leading\ jet}$ > 10 GeV, DY events have a smaller particle density with a harder p_T spectrum compared to the hadronic events. This distinction is due to the different nature of radiation in the hadronic and DY events. Drell–Yan events have only initial- state QCD radiation initiated by quarks, which fragment into a smaller number of hadrons carrying a larger fraction of the parent parton energy, whereas the hadronic events have both initial- and final-state QCD radiation predominantly initiated by gluons with a softer fragmentation into hadrons.

Summary

- **Minimum bias and underlying measurements have been measured by LHC experiments at different centre-of-mass energies.**
  - measurements are (typically) 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 LHC 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:**
  - non-perturbative dynamics still very challenging: MPI, colour reconnection, etc.

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- Diffraction: single and double diffractive interactions contribute to low n_{ch} regions.

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V. **Low-p_T particle azimuthal ordering:** Models cannot describe the hadronisation structure seen in data. Discrepancy appears to be "beyond tuning"!

Extra material…

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

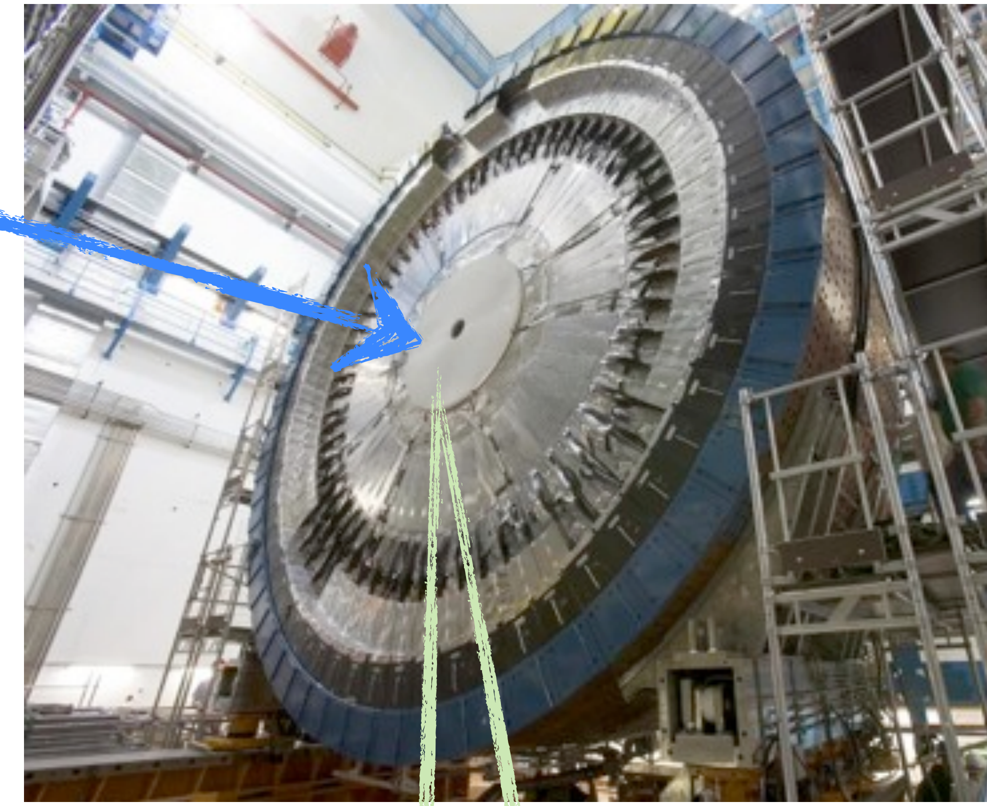
- **PYTHIA8**: new diffraction model with harder component.

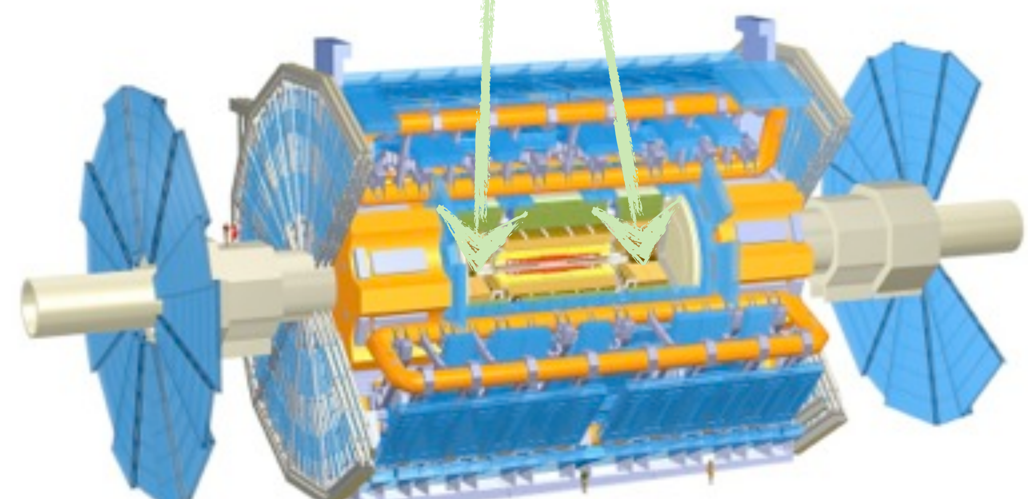
- **PHOJET**: alternative model to the PYTHIA based tunes. PHOJET is based on DPM.

Minimum Bias Trigger Scintilator

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.

- $2.1 < |\eta| < 3.8$

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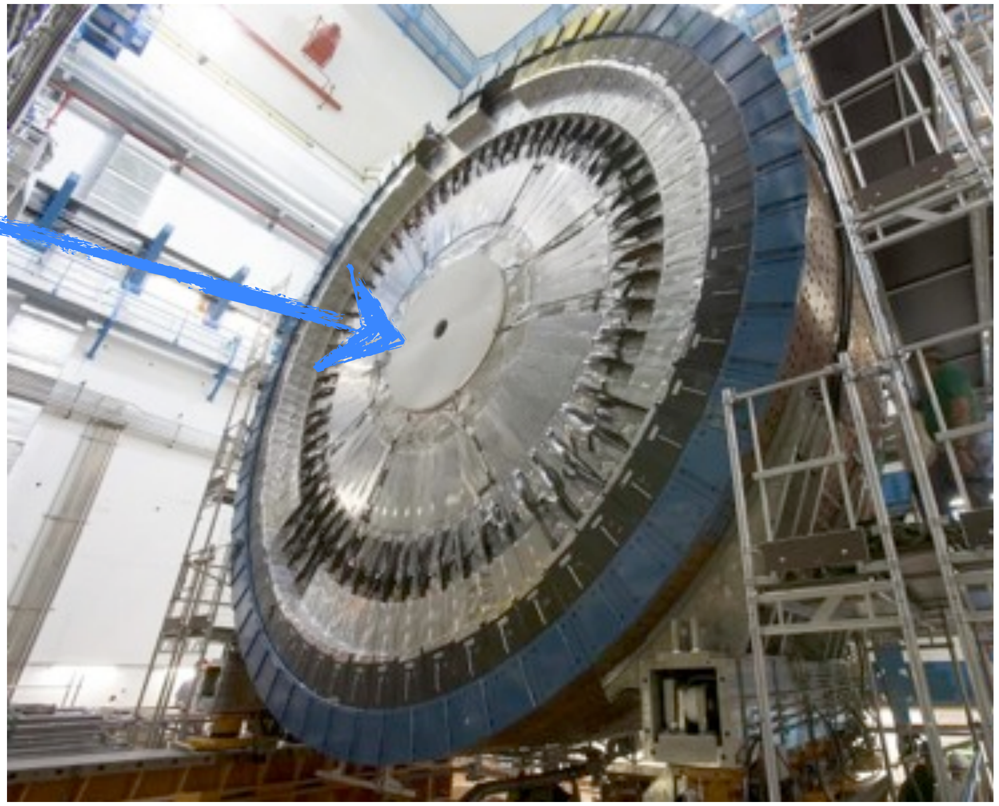

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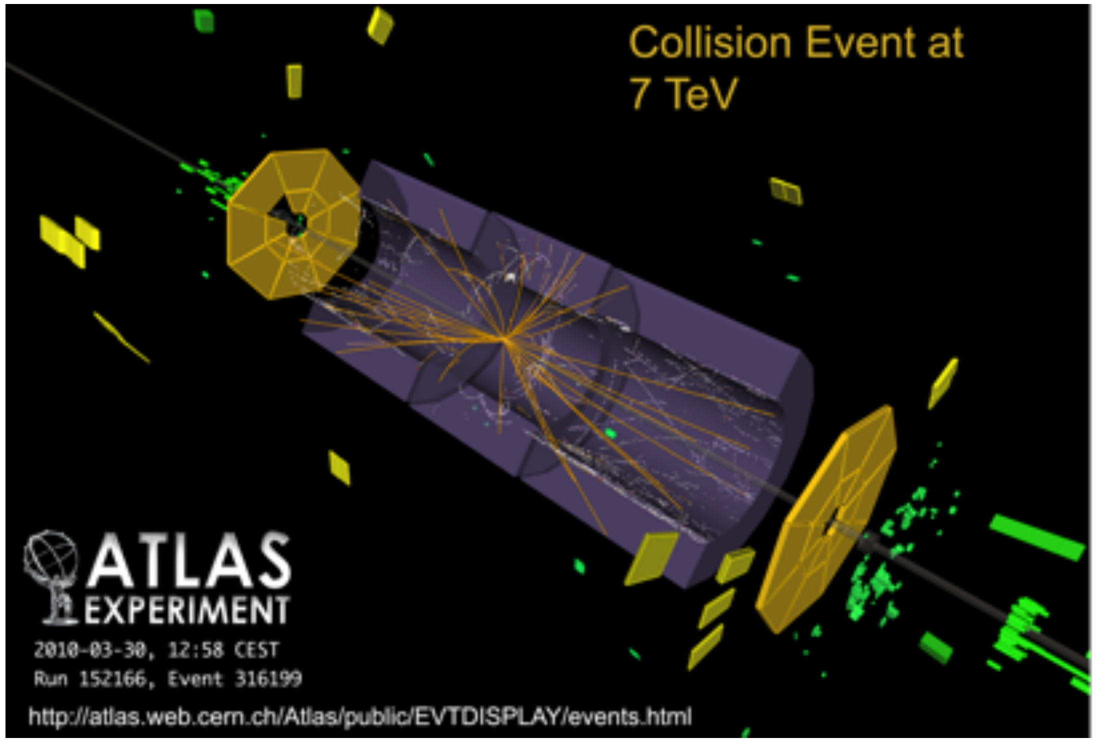
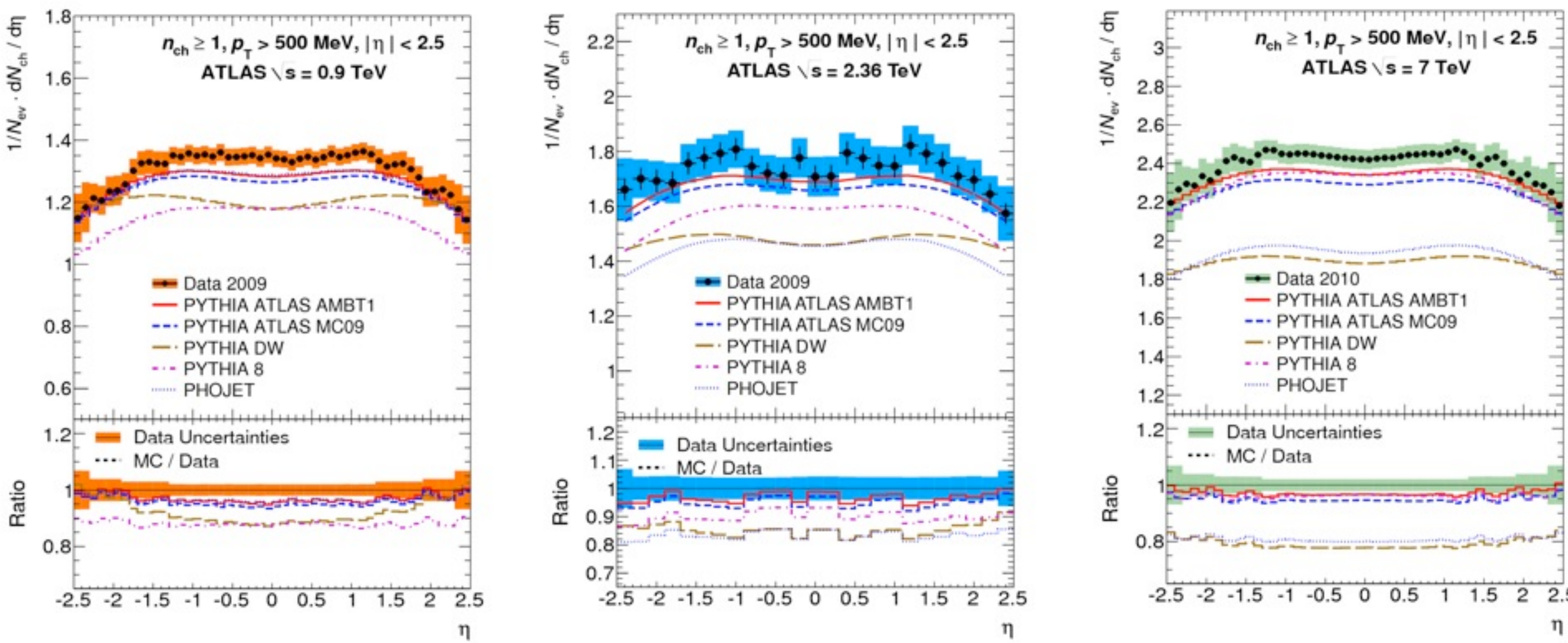
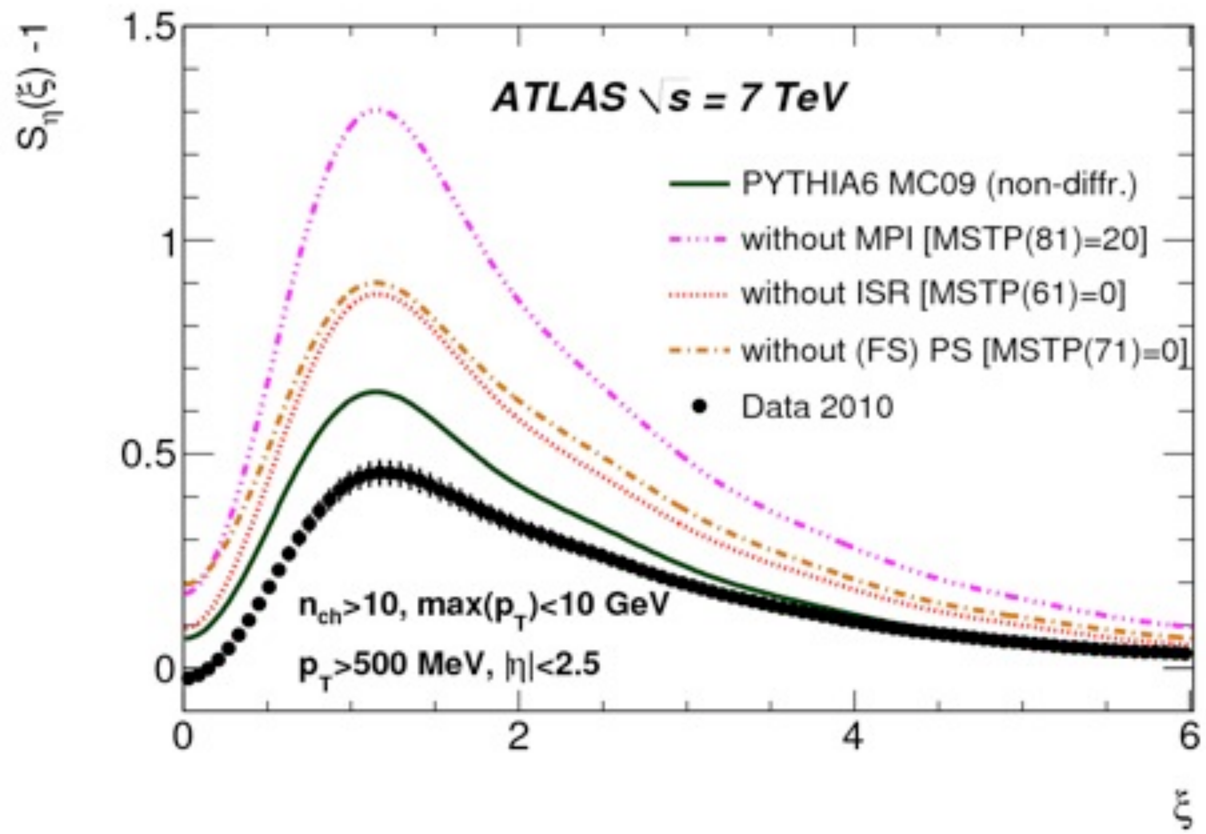


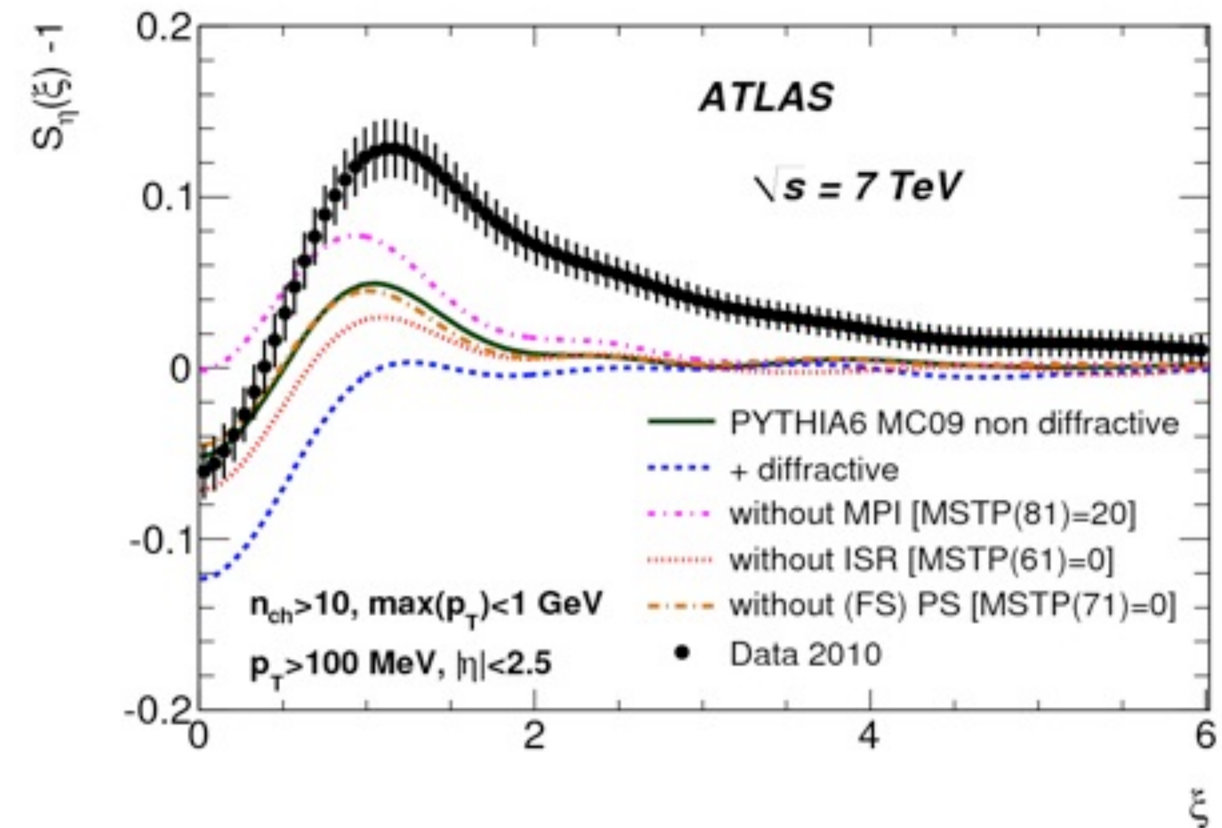
Charged particle density in η: √s=900 GeV, 2.36 TeV and 7 TeV



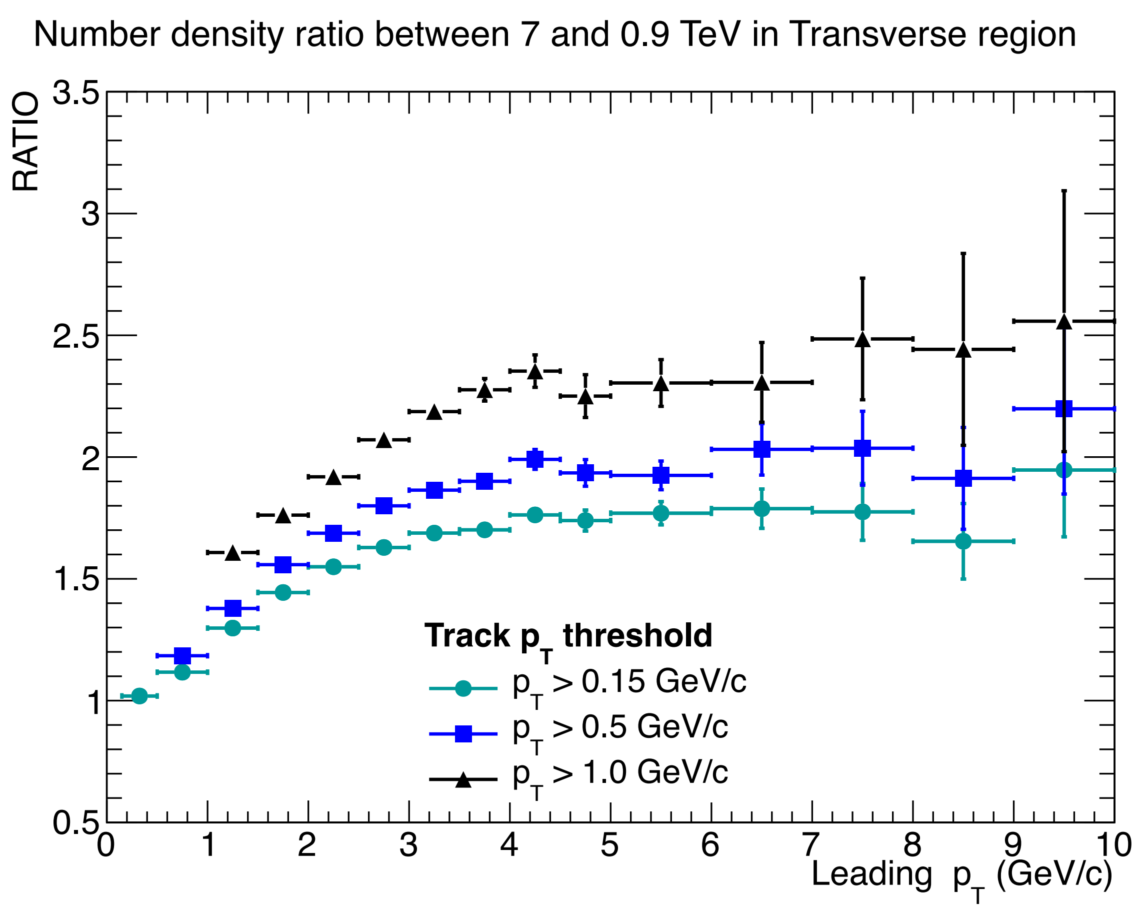
▸ **Measurements at different c.m. energies are crucial for an accurate understanding (prediction) of the evolution of inelastic hadronic processes.**

Azimuthal ordering of charged hadrons





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


Number density ratio between 7 and 0.9 TeV in Transverse region
RATIO
Leading p_T (GeV/c)
Track p_T threshold
p_T > 0.15 GeV/c
p_T > 0.5 GeV/c
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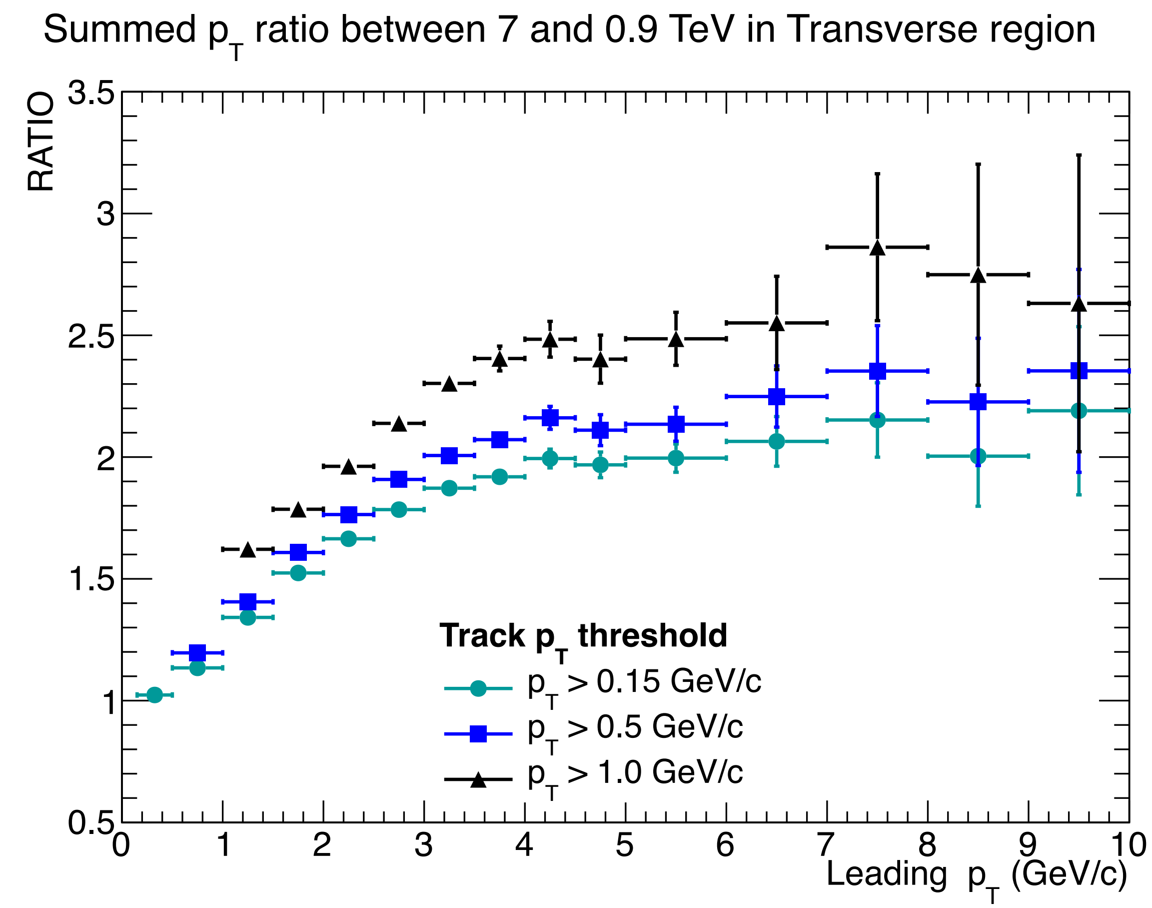
Summed p_T ratio between 7 and 0.9 TeV in Transverse region
RATIO
Leading p_T (GeV/c)
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