LHC MPI and underlying event results

Marianna Testa (ATLAS)
for the ALICE, ATLAS, CMS & LHCb collaborations

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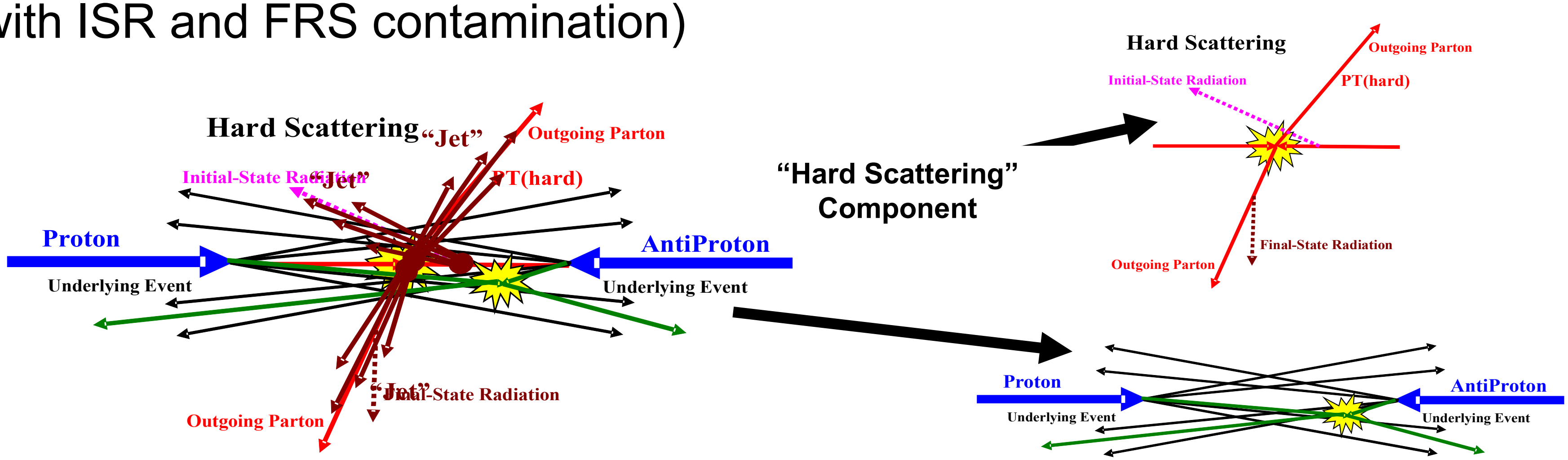
The Underlying Event

Everything in hadron collisions apart from the hard parton interaction is called the Underlying Event (UE)
UE = Multiple parton interactions+beam-beam remnants
(with ISR and FRS contamination)



"Underlying Event"

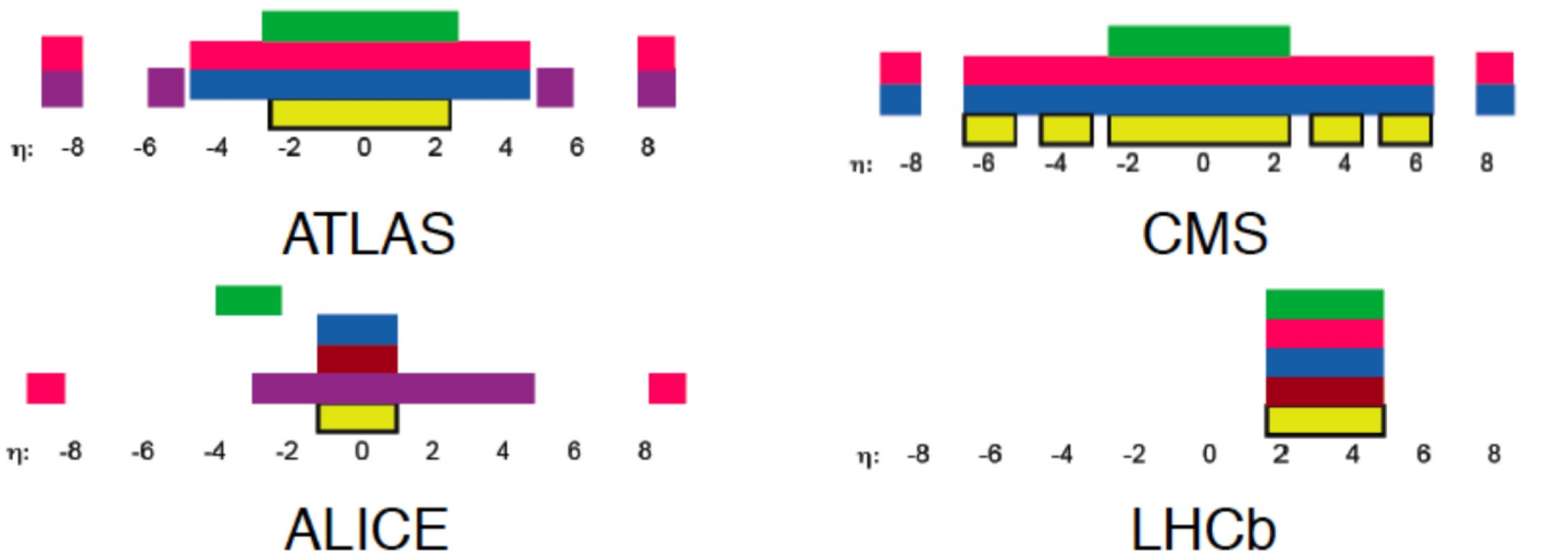
- UE definition is intrinsically model dependent

- UE is sensitive to the connection between soft QCD collective behaviors and hard interaction

- It is an irreducible background for high-p_T analyses
Affect E_T^{miss} resolution, jets reconstruction, isolations cones

- Best possible description in MC is crucial
MC generators for soft QCD rely on phenomenological model→need to tune

LHC detectors



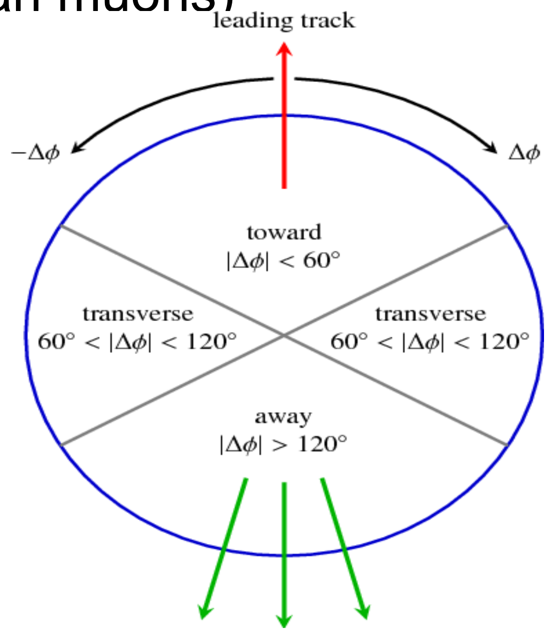
tracking, ECAL, HCAL, counters lumi, muon, hadron PID

- ATLAS and CMS are general-purpose, fully 4π detectors.
- ALICE has a central tracker comparable in η range to ATLAS and CMS.
- LHCb is an entirely forward, one-sided detector, with a forward-facing tracker geometry.

Underlying event measurements

Transverse method

- Consistent separation of UE and hard contributions by geometrically slicing the event
- Select suitable event topologies(e.g. di-jet events, Drell-Yan muons)
- Identify leading object in event (tracks,clusters, track-jets)
- Leading object defines event scale
- Examine transverse region
- Typical observables include $< p_T >$, $\sum p_T$ and nTracks/nClusters in transverse region
- Very well suited for MC tuning



Other Approaches

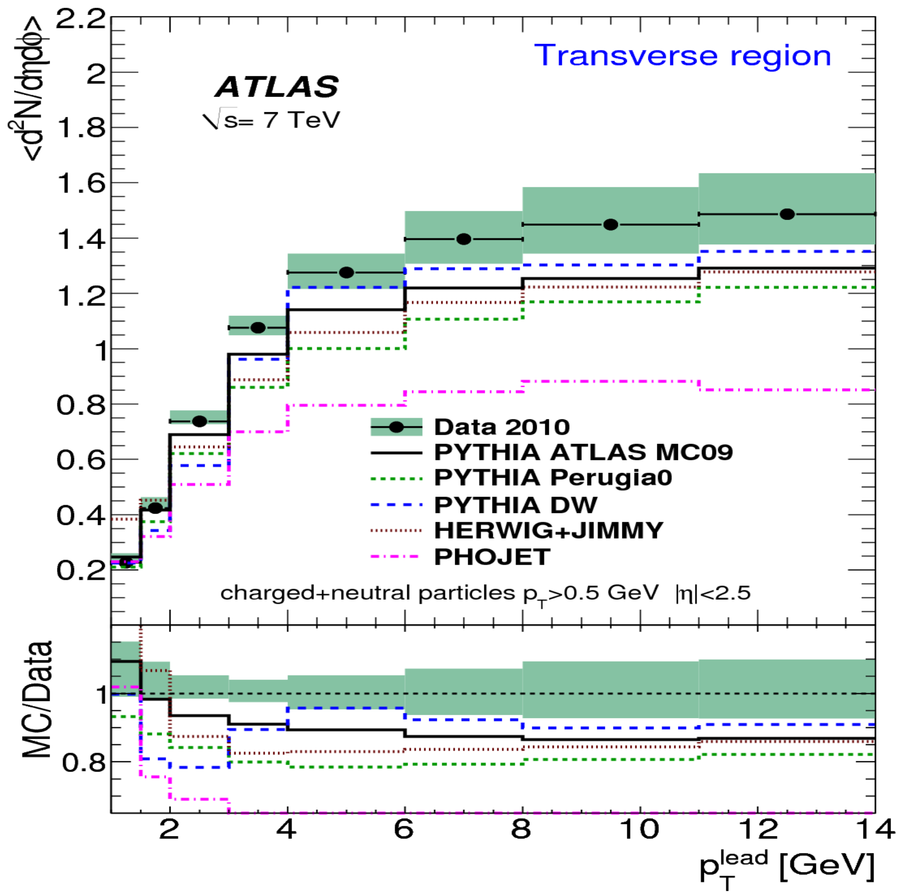
Several additional measurements are closely connected to the UE

Range goes from jet substructure to forward activity and particle correlation

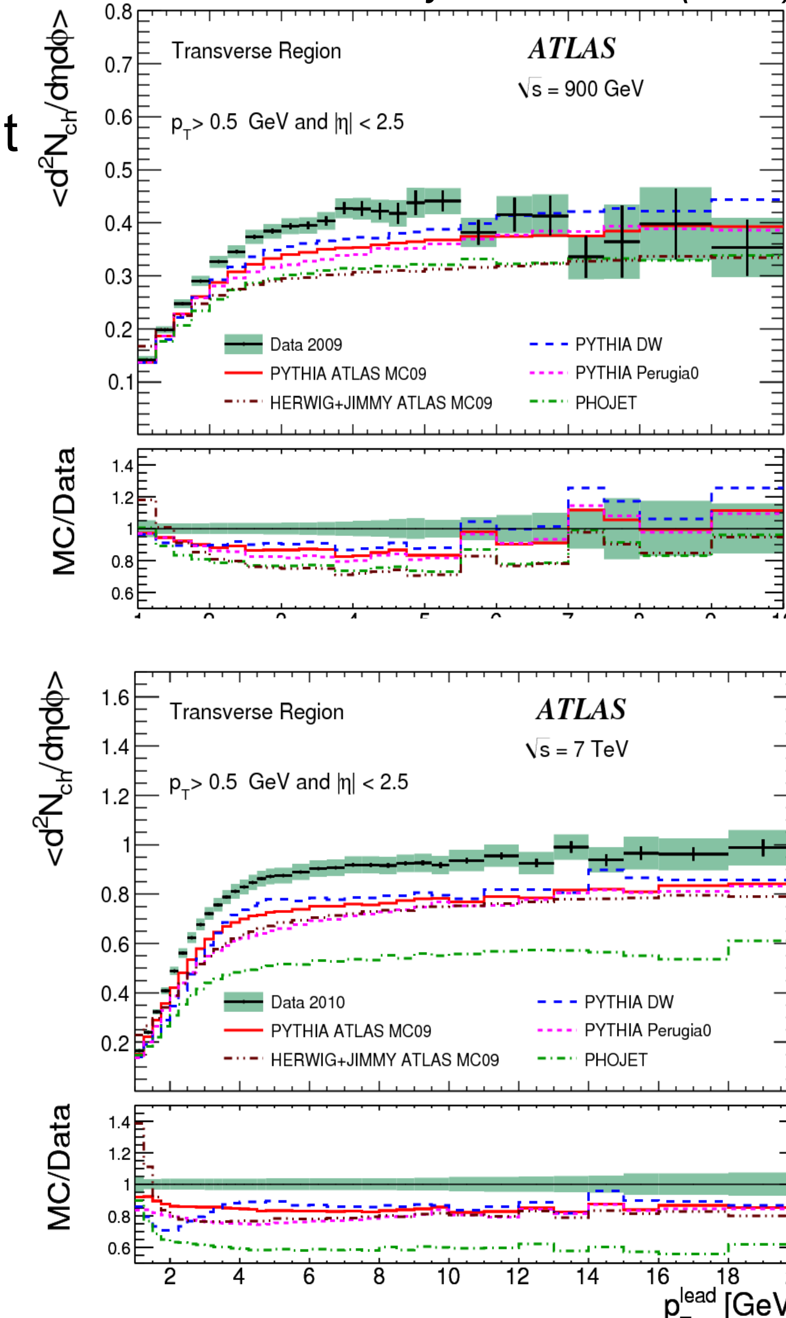
ATLAS underlying event results

- Track-based and Cluster-based measurement
- Minimum bias data at 0.9 and 7 TeV
- The particle number density in data is higher than predicted by any of the MC tunes

Cluster method *Eur.Phys.J. C71 (2011) 1636*



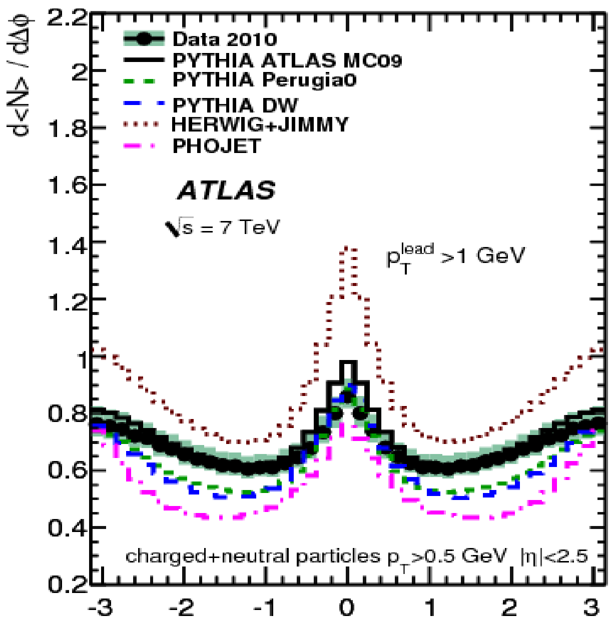
Track method *Phys. Rev. D83 (2011) 112001*



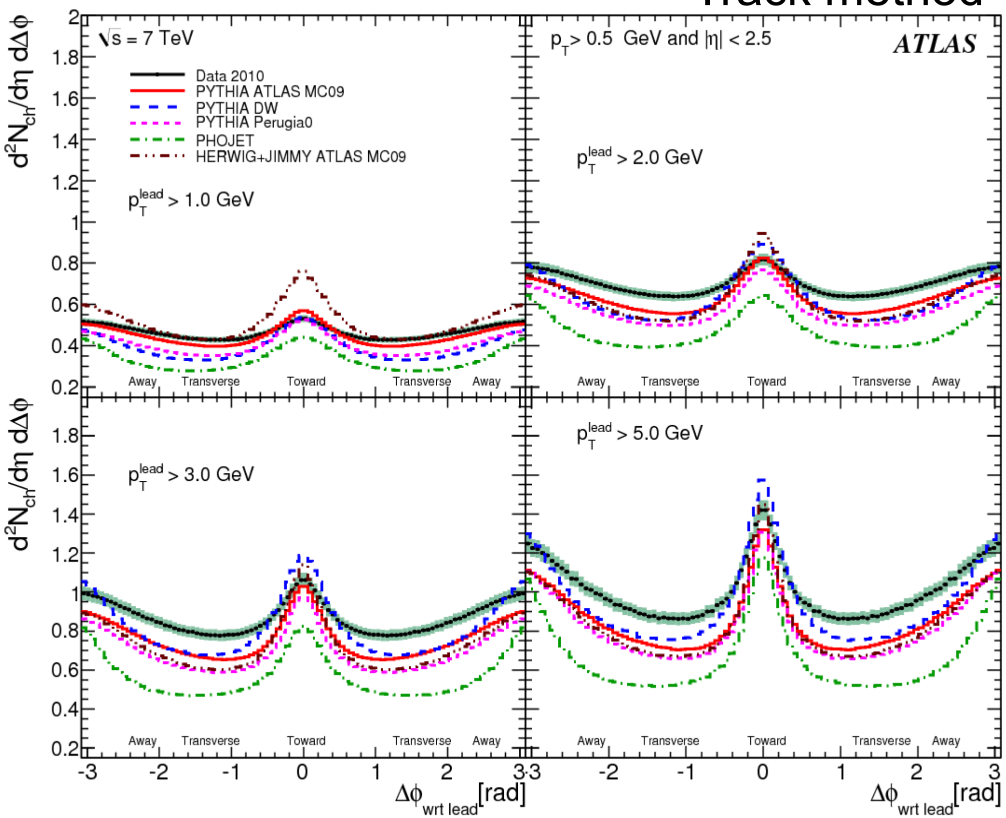
ATLAS underlying event results

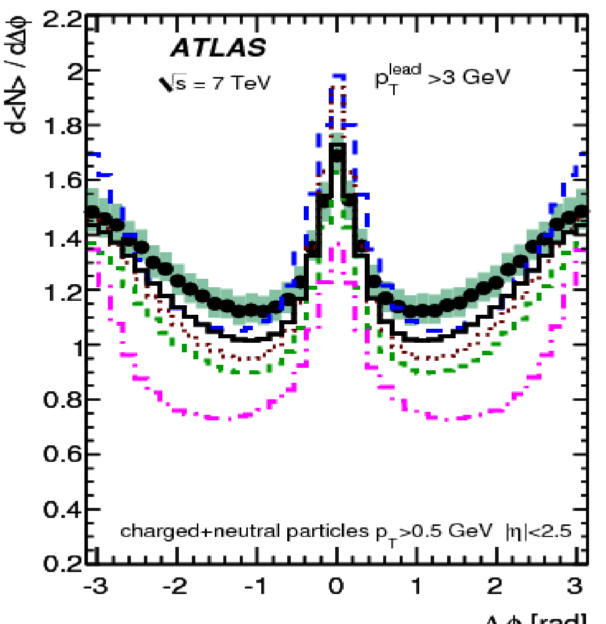
- Particle density vs phi
- Development of 'jet-like' region of higher density as p_T of leading track/particle increases (toward,away)
- Particle density is higher and has a different angular distribution than predicted by MC

Cluster method



Track method

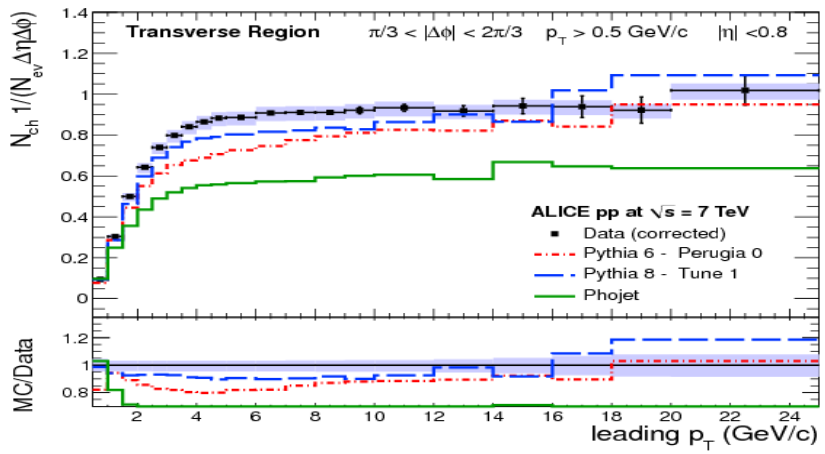


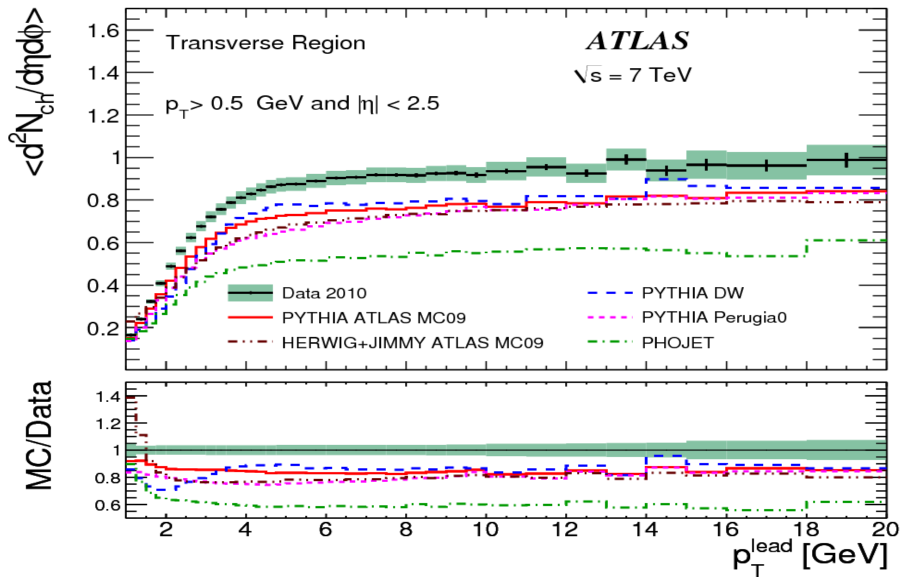


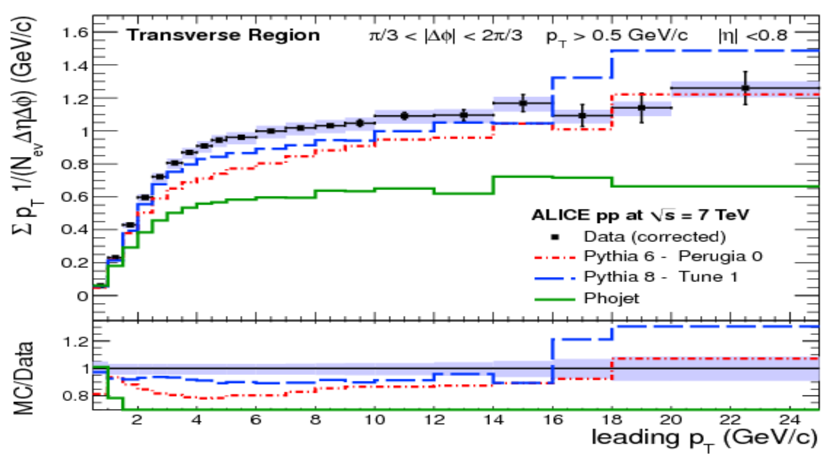
Alice underlying events results

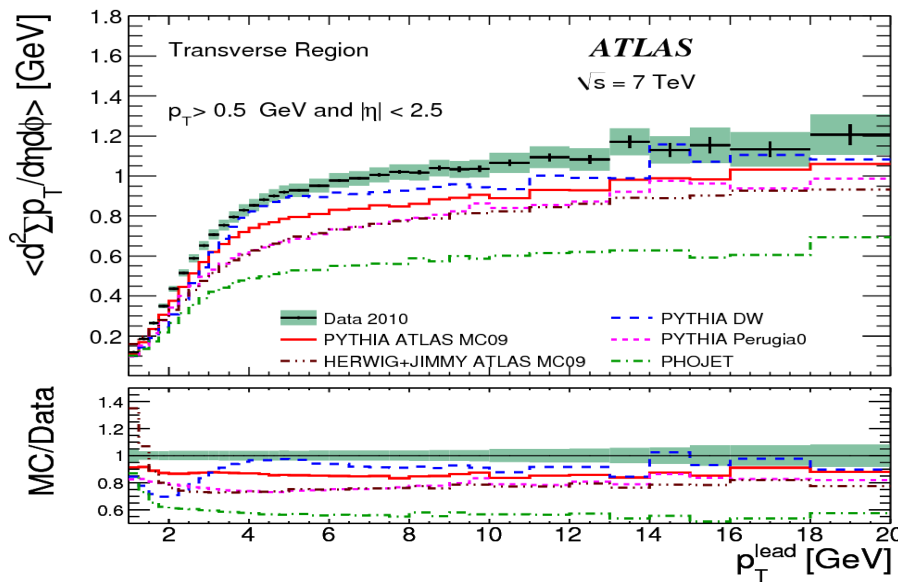
arXiv:1112.2082v2

- Track-based analysis
- pp collisions and minimum bias data at 0.9 and 7 TeV
- Multiplicity and $\sum p_T$ density in the transverse region in good agreement with ATLAS





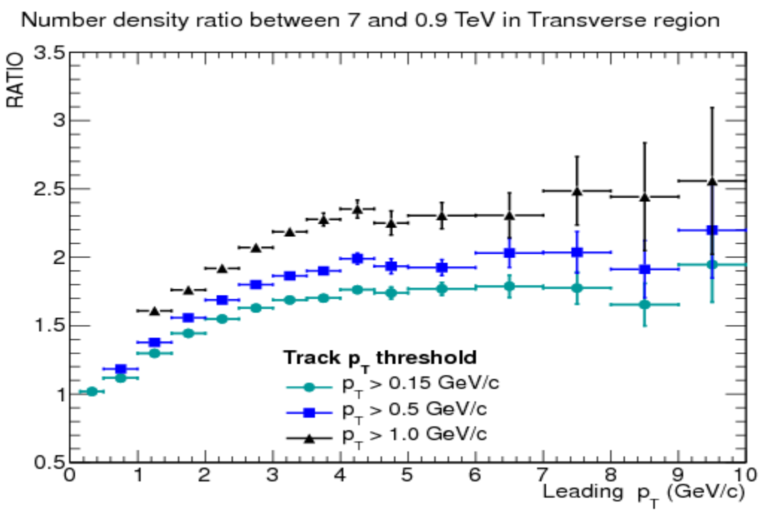


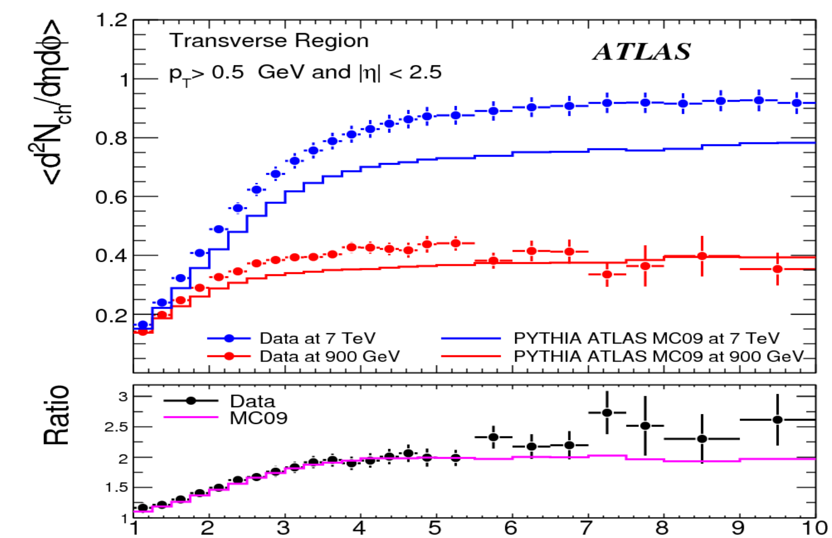


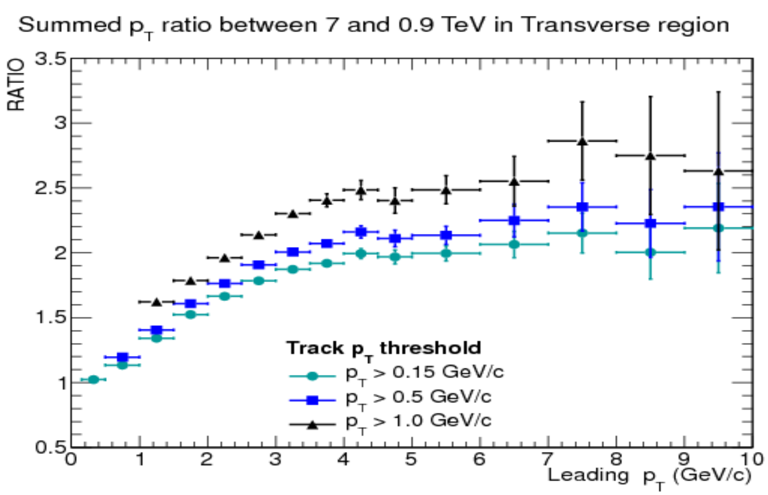
Alice underlying events results

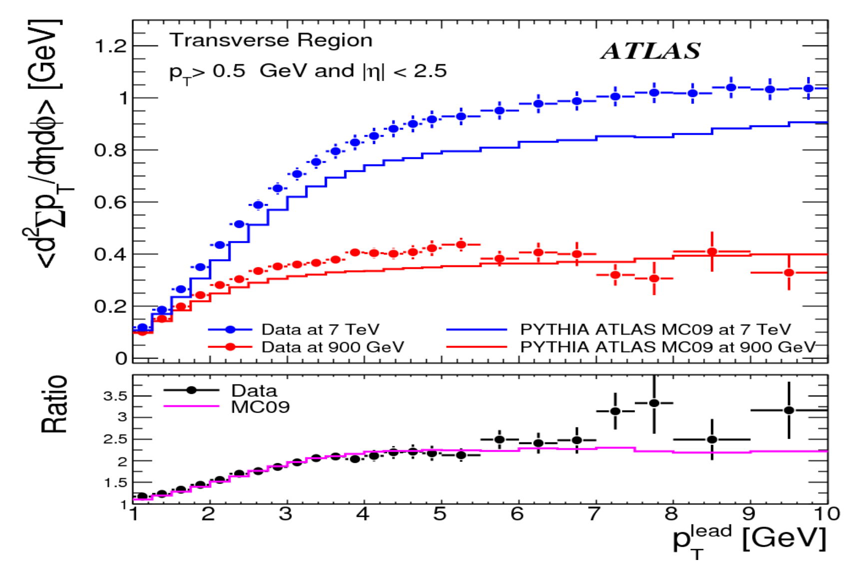
arXiv:1112.2082v2

Scaling with center of mass energy is in agreement with ATLAS and CMS results





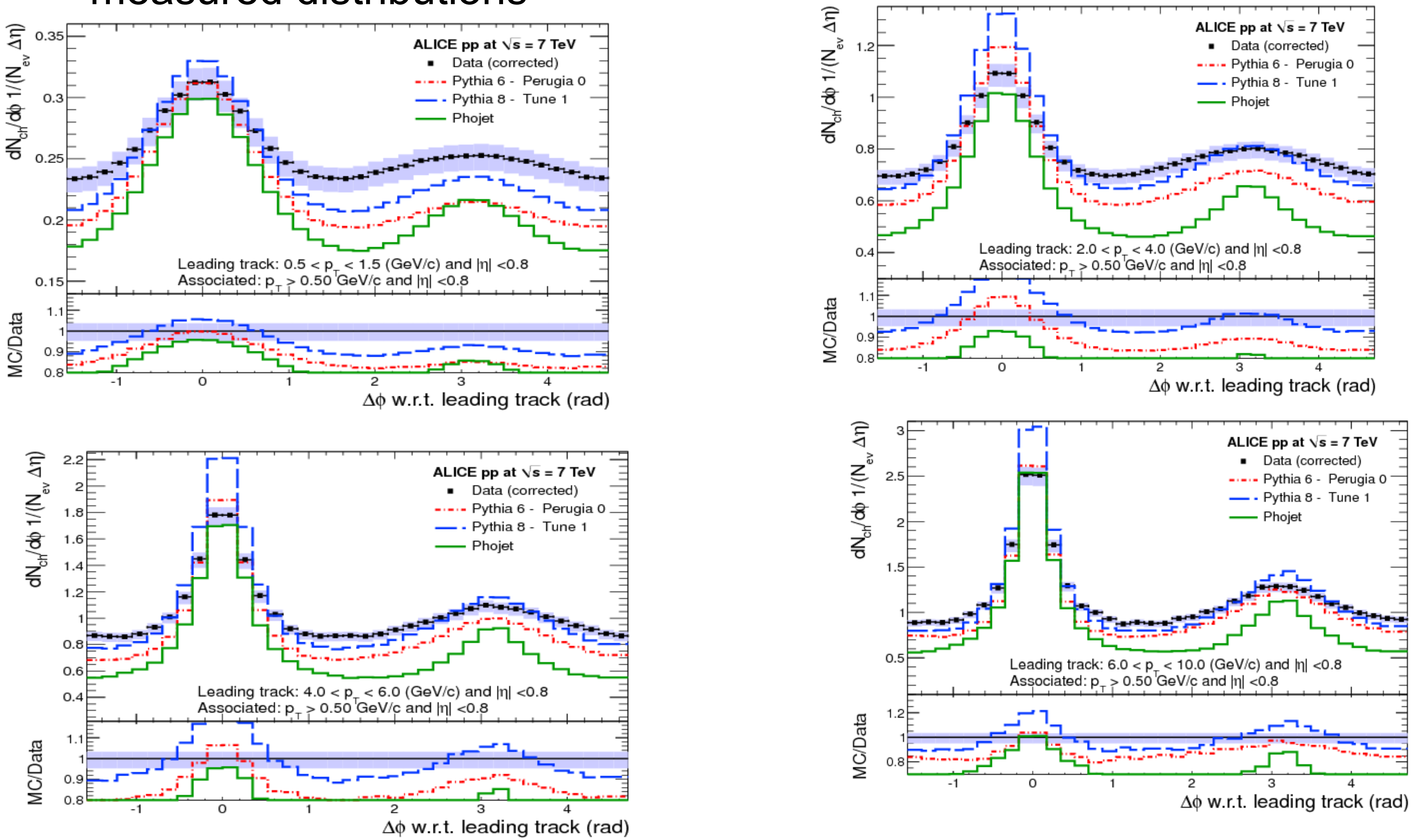




Alice underlying events results

arXiv:1112.2082v2

- Particle density vs phi
- The regions $-1/3\pi < \Delta\phi < 1/3\pi$ (Toward) and $2/3\pi < |\Delta\phi| < \pi$ (Away) collect the fragmentation products of the leading and sub-leading jets.
- Monte Carlo simulations considered fail to reproduce the shape of the measured distributions

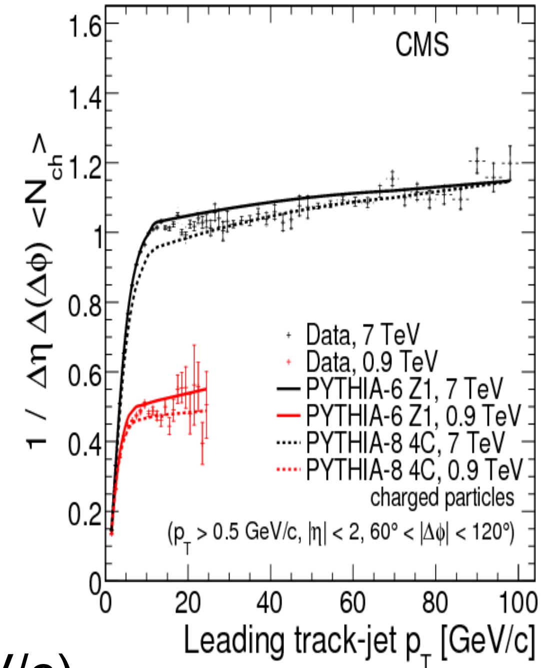


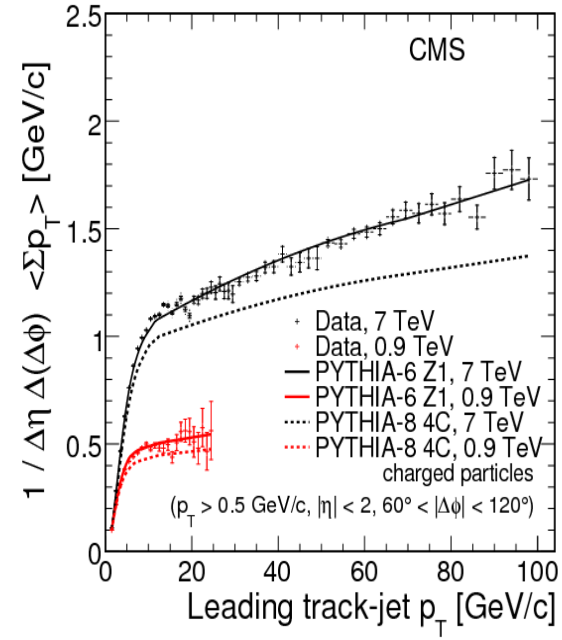
CMS underlying events results

JHEP 09 (2011) 109

- Track based analysis:
Use track-jet: Extending event scale far into plateau region

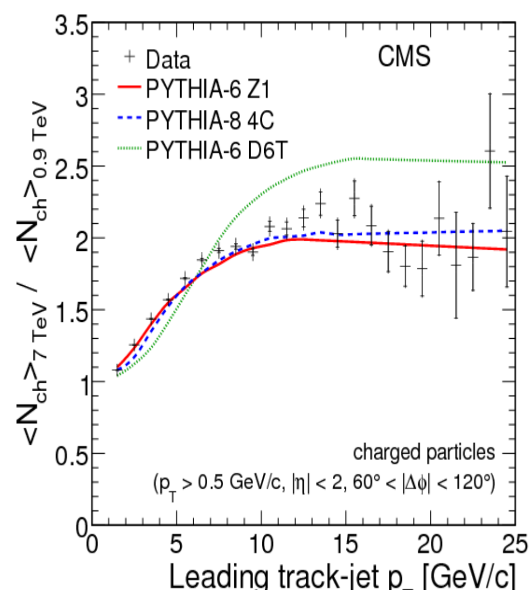
- Minimum bias and jet stream data at 0.9 and 7 TeV

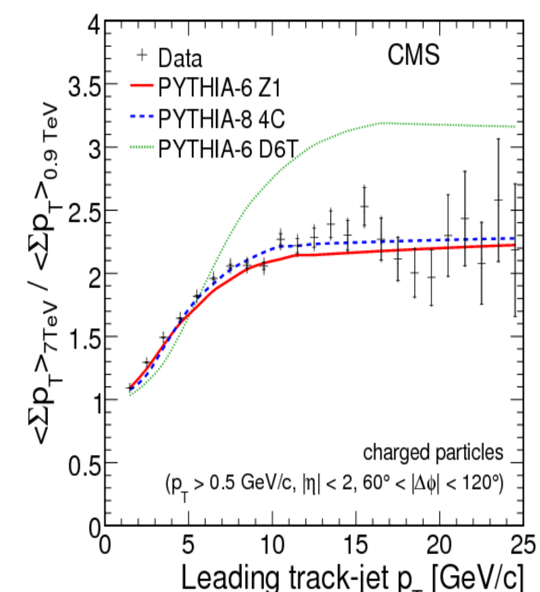




- Fast rise for p_T < 8 GeV/c (4 GeV/c), due to increase of MPI activity

- Dedicated tunes Z1 and 4C perform very well for both 0.9 and 7 TeV.
MPI growth with √s well described by Z1 and 4C





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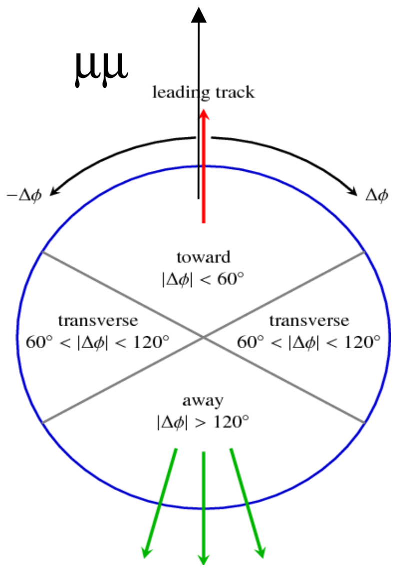
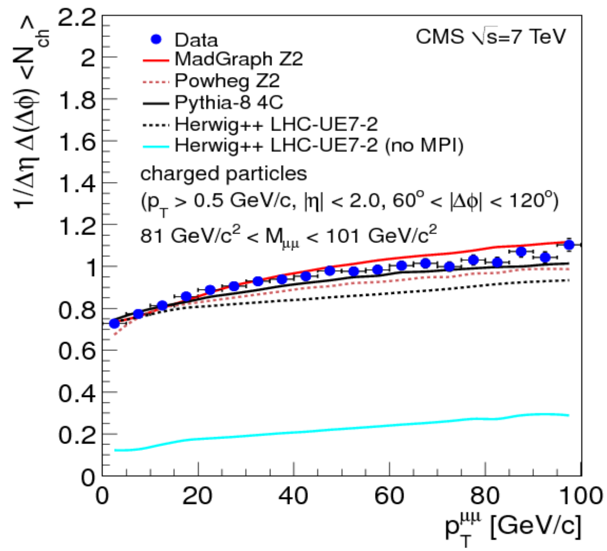
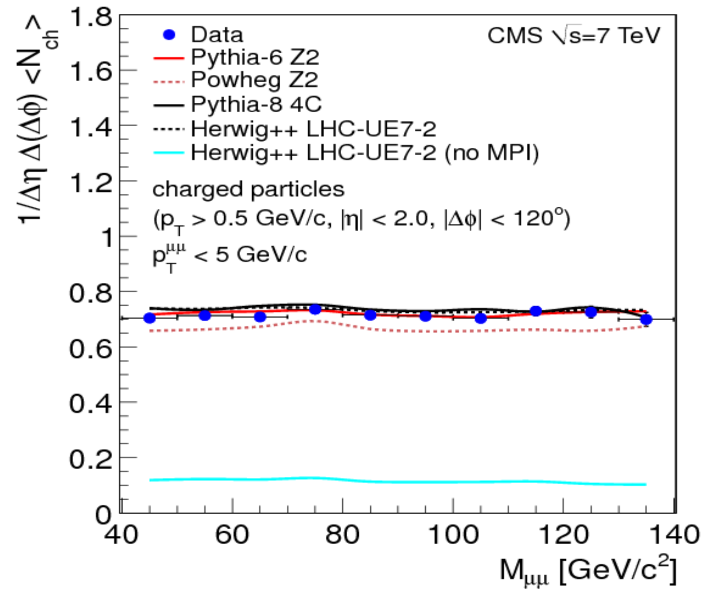
CMS underlying events results in the DrellYan processes

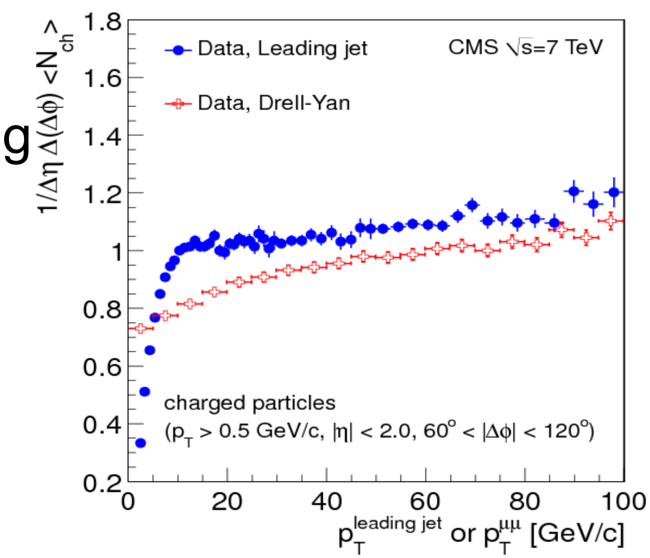


CMS-PAS-QCD-10-040





- No hadronic activity from hard interaction, no interplay of production mechanisms expected
- A slow growth of the activity is observed with increasing $p^{\mu\mu}_T$ which can be attributed to the increase in radiation
- N_{ch} (and p_T) densities being independent of the muon pair $\Rightarrow$ the already saturated MPI in the selected event scale.



Other approaches for underlying event measurements: particle correlations and forward activity

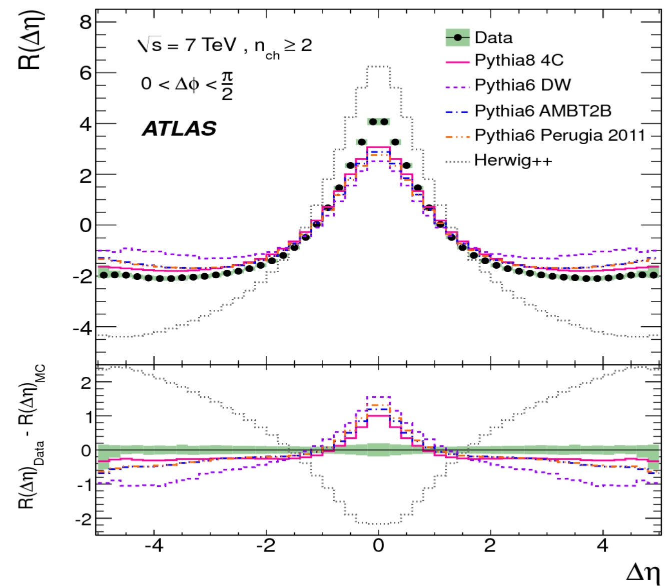
Two particle correlation at ATLAS

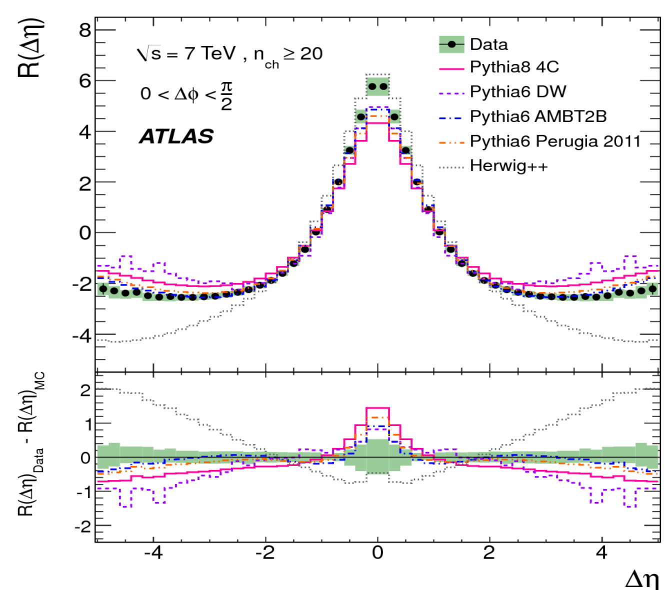
Two-particle angular correlation function:

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

Foreground (F): all particle pairs in same event (correlated + uncorrelated pairs)
Background (B): particle pairs from different events (uncorrelated pairs)

ATLAS-CONF-2011-055





- Minimum bias data at 0.9 and 7 TeV (N_{ch}>2 and N_{ch}>20)
- All MC show a similar complex structure in Δη and Δφ but fail to reproduce the strength of the correlations seen in data.

Azimuthal ordering of hadrons (ATLAS)

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

$$S_\eta(\zeta)=\frac{1}{N_{ev}}\sum_{event}\frac{1}{n_{ch}}\left|\sum_{g}^{n_{ch}}\exp\left(i\left(\zeta\eta_j-\phi_j\right)\right)\right|^2$$

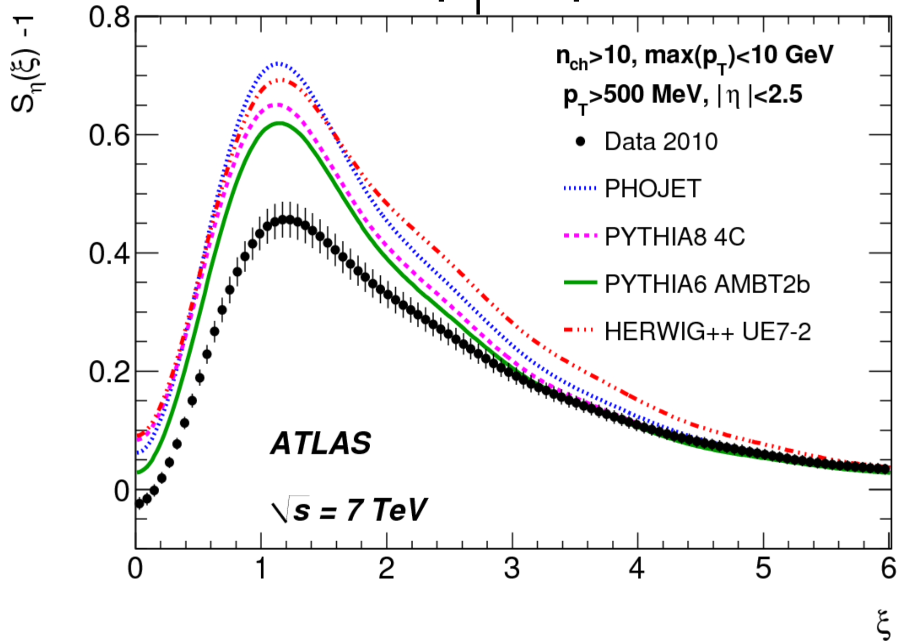
- Sensitive to new formulation of certain components of models (e.g. fragmentation)

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

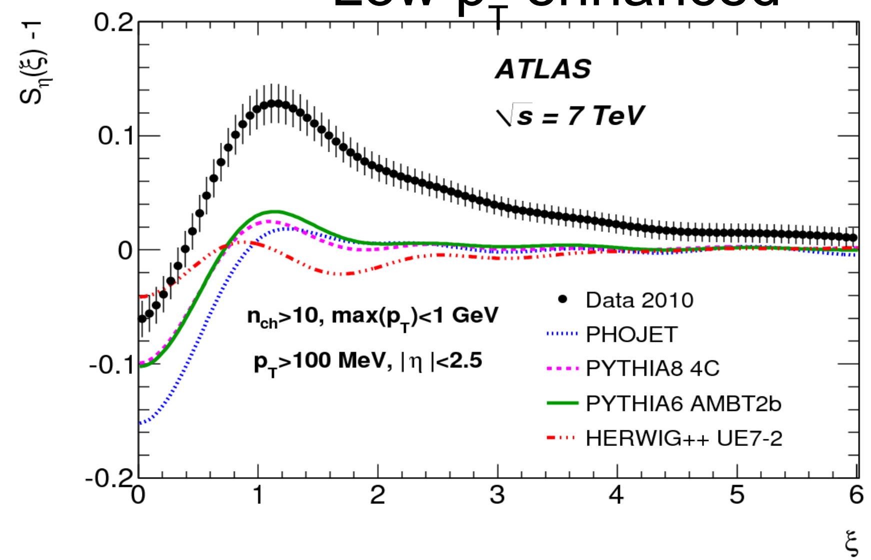
- Too much correlation in typical MCs, for high-p_T charged particles (top), but too little correlation for low-pT charge particles.

arXiv:1203.0419

Low p_T depleted



Low p_T enhanced

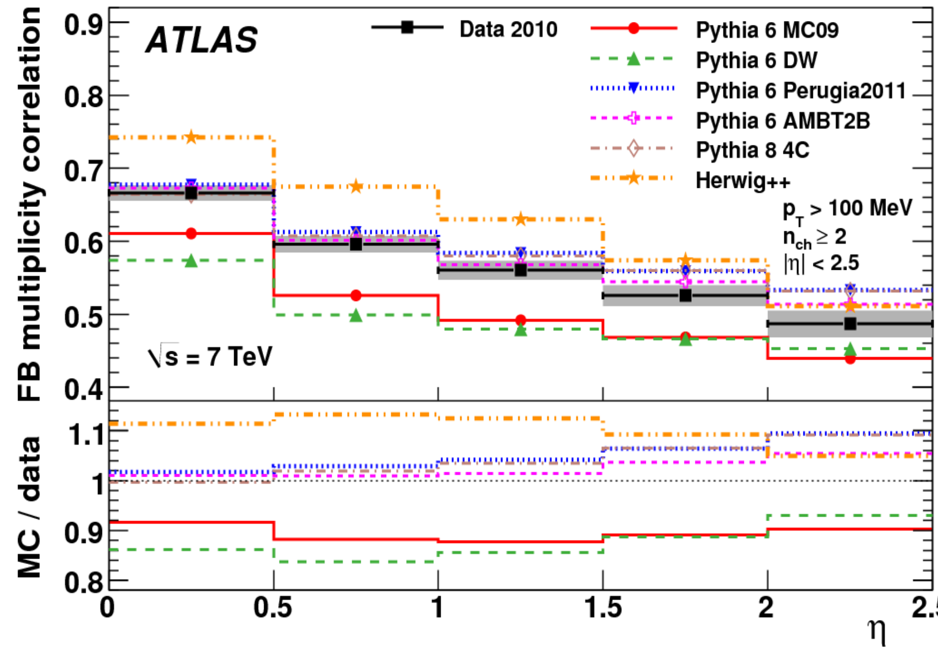


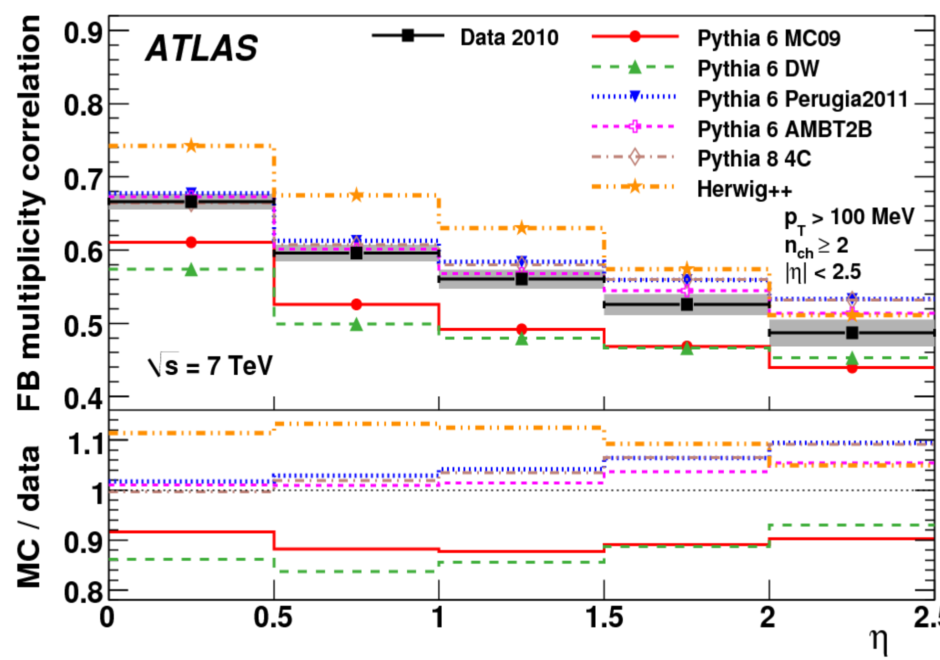
Forward-backwards correlations (ATLAS)

Measurement of the correlation between charged particle multiplicities and $\sum p_T$ in the forward and backward regions

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

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





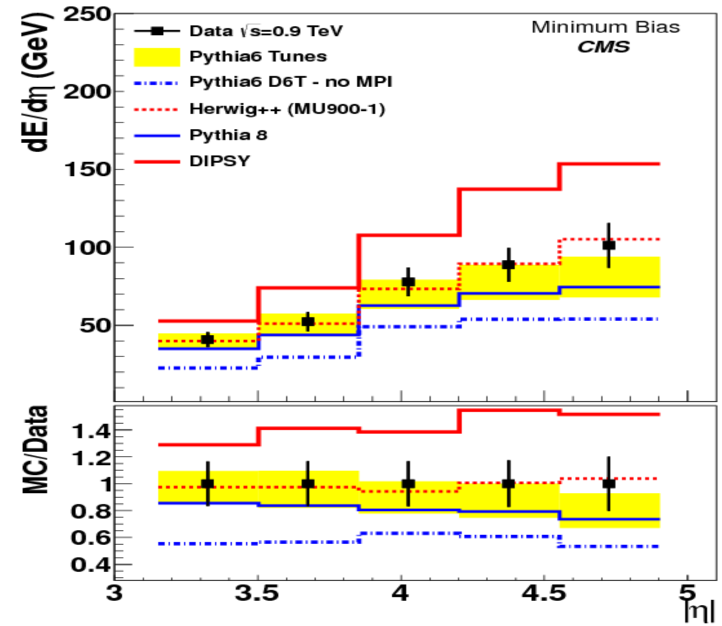
Latest MC tunes adequately describe the correlations observed in the data.

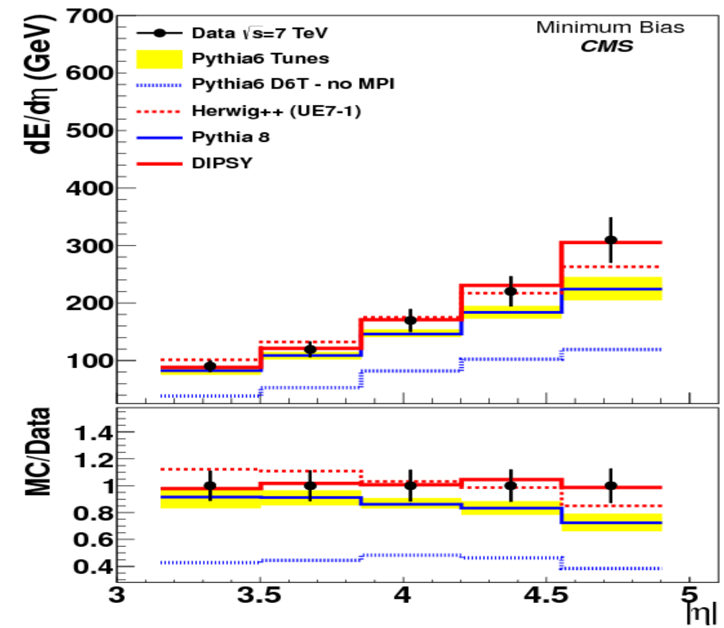
arXiv:1203.3100

Forward Energy flow (CMS)

CMS PAS FWD-10-011

- Investigates geometrical space inaccessible to tracking based analyses
- Minimum bias and di-jet events at 0.9 and 7 TeV
- Strong dependence on center of mass energy
- Significant contribution from multiple parton interactions.
- Pythia 8 and Pythia 6 tunes fail at high eta
- Herwig++ describes the data using center-of-mass specific tunes.

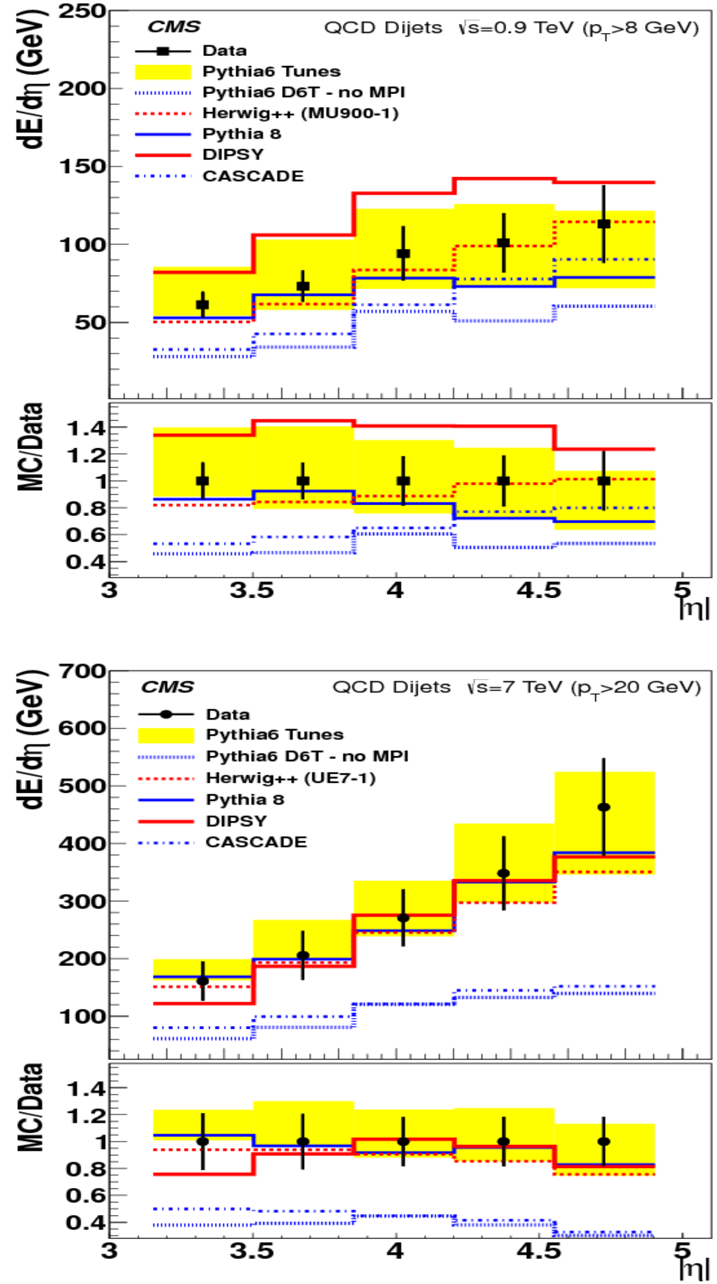




Forward Energy flow (CMS)

CMS PAS FWD-10-011

- Investigates geometrical space inaccessible to tracking based analyses
- Minimum bias and di-jet events at 0.9 and 7 TeV
- Significantly higher forward energy flow in di-jet events than in minimum bias
- Pythia 8 describes the data at $\sqrt{s}$=7 TeV
- Herwig++ good, when using c.o.m. specific tunes
- Large contribution from multiple parton interactions

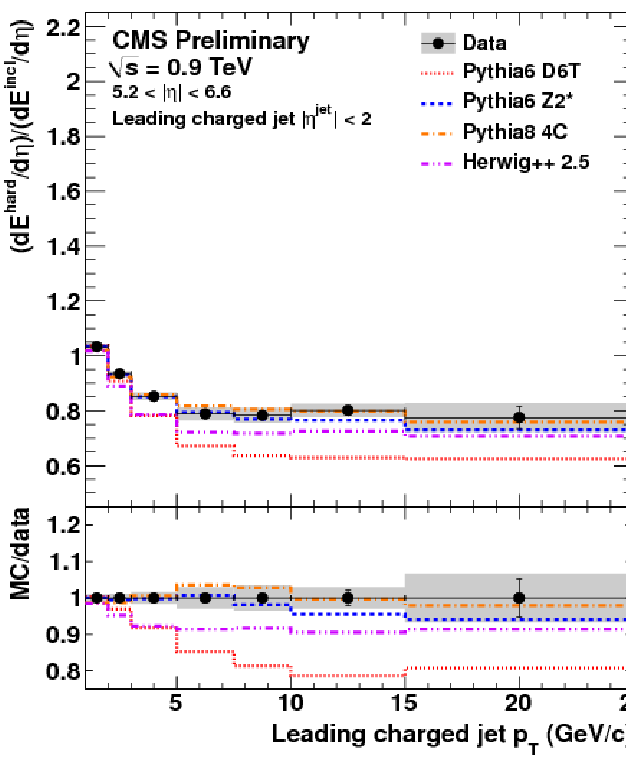


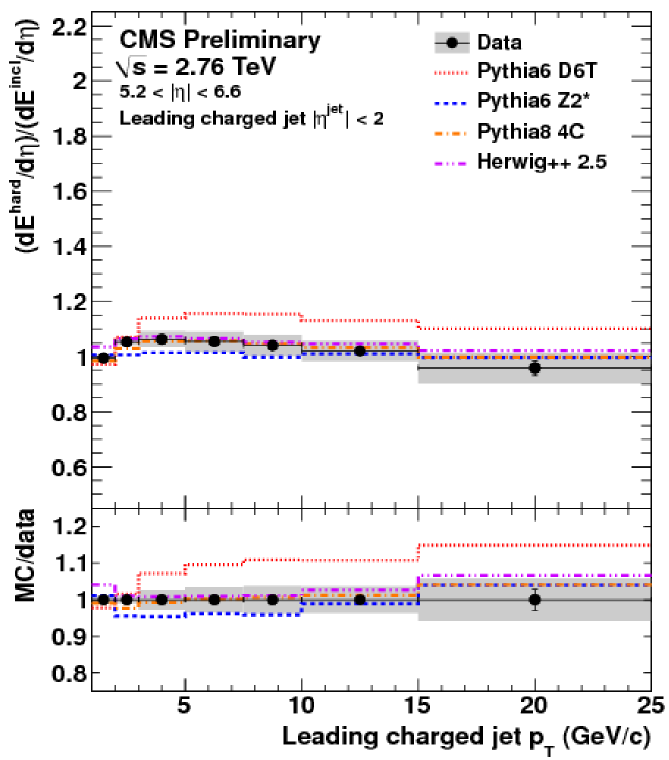
UE activity at forward rapidity (CMS)

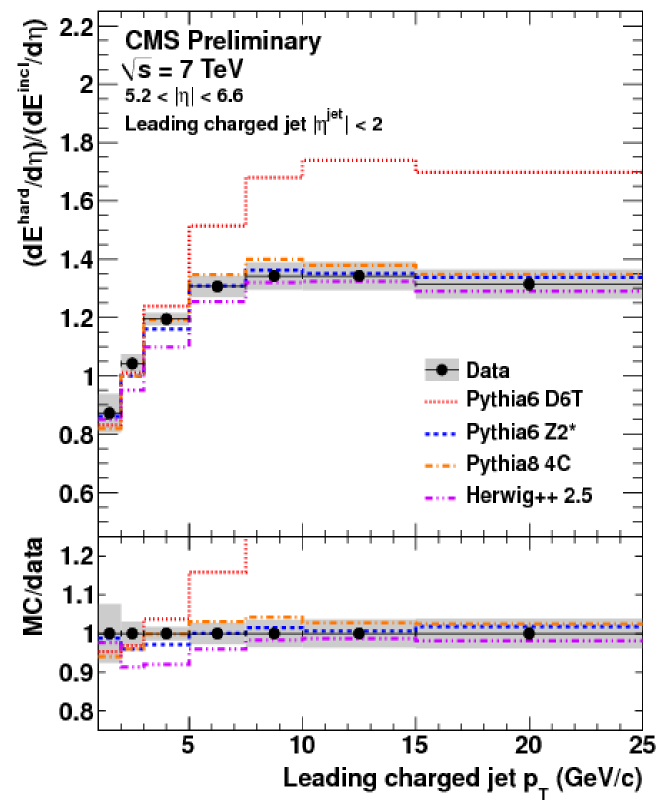
Compare energy density in forward calorimeter ($-6.6 < \eta < -5.2$) for events with a central leading charged jet (p_T>1 GeV and $|\eta|<2$) w.r.t. minimum bias events at $\sqrt{s}$ =0.9, 2.76 and 7 TeV ⇒ sensitivity to MPI contributions

At 0.9TeV Central jets with high UE activity depletes energy of the proton remnant

At 2.76 and 7 TeV well know UE behavior : fast increase at low p_T followed by a plateau





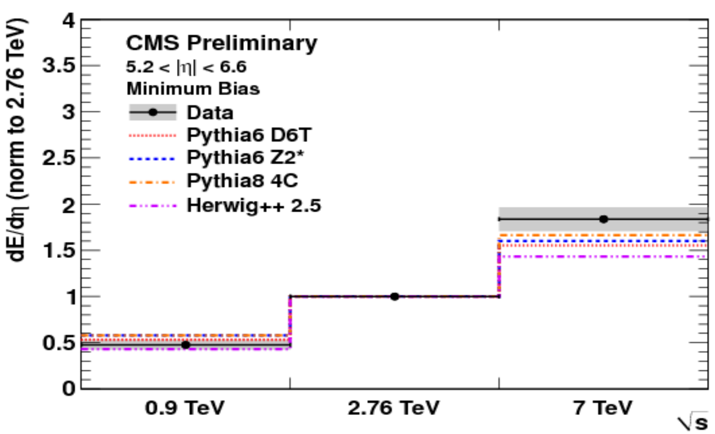


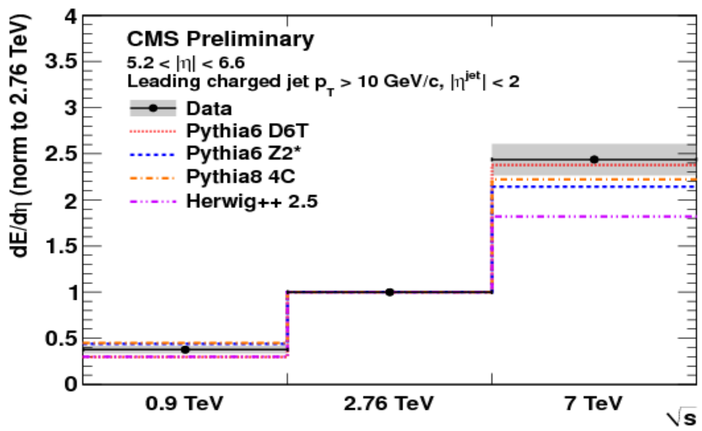
Most of the tunes (except an older tune of Pythia) describe well data

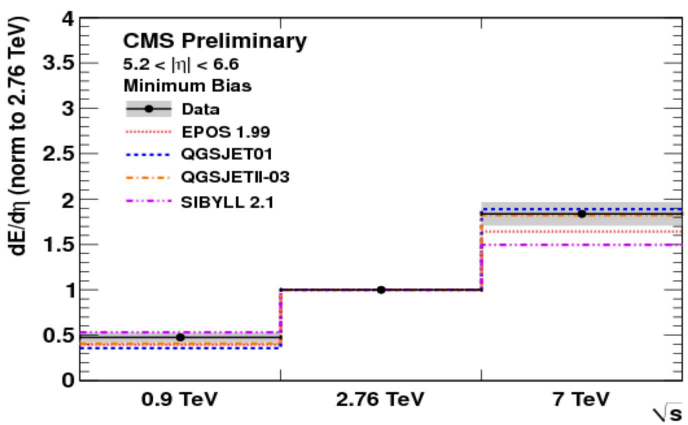
UE activity at forward rapidity (CMS)

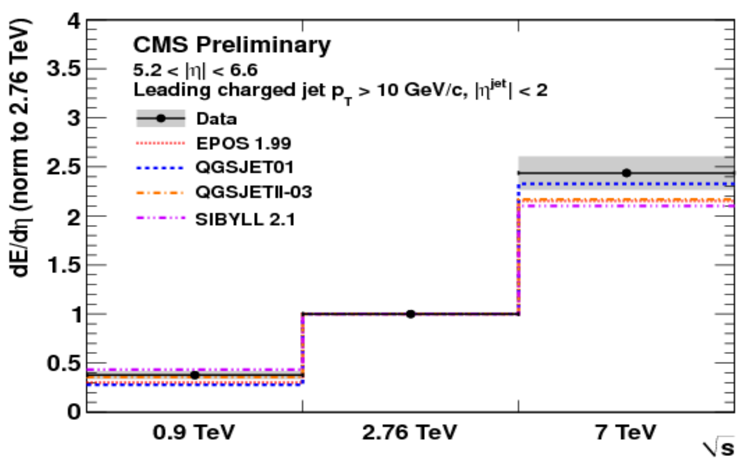
Energy densities vs $\sqrt{s}$ normalized at $\sqrt{s}$ = 2.76 TeV

- Minimum bias events: Most of the MC (except QGSJET cosmic ray model) underestimate the relative increase at $\sqrt{s}$= 7 TeV
- Events with leading jet: Pythia6 D6T and QGSJET cosmic ray model describe data, other tunes underestimate the increase







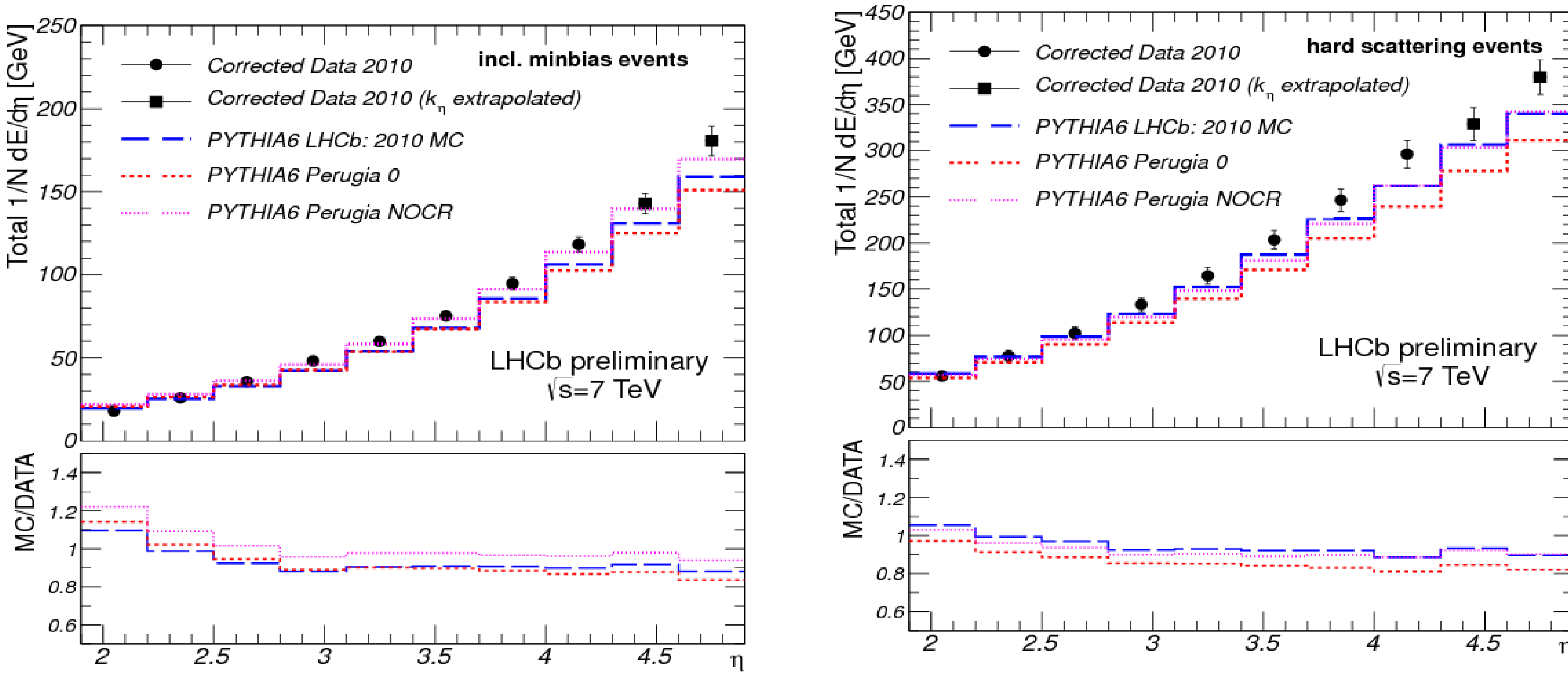


Forward Energy Flow (LHCb)

LHCb-CONF-2012-012

- Study energy flow in 1.9 <η < 4.9
- 4 topologies to test complementary aspects of MPI:
  - Minim bias data,
  - Hard scattering processes, at least 1 long track in 1.9<η<4.9 with pT>3 GeV/c
  - Diffractive enriched events no backward tracks reconstructed in –3.5<η<–1.5
  - Diffractive enriched at least 1 backward track in –3.5<η<–1.5

PYTHIA-based models underestimate energy flow at large η



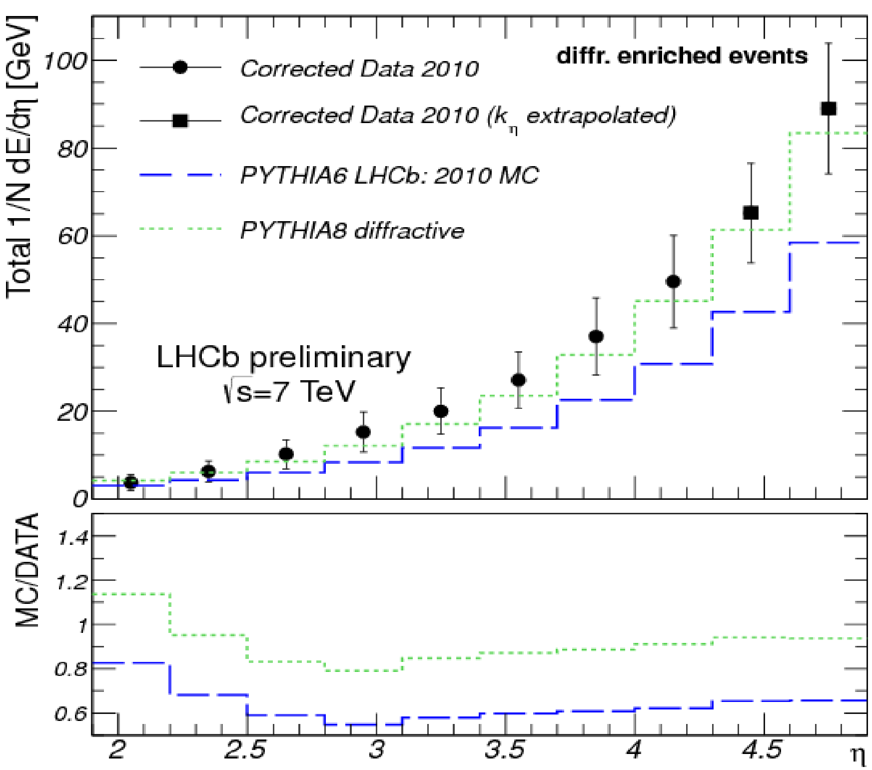
Forward Energy Flow (LHCb)

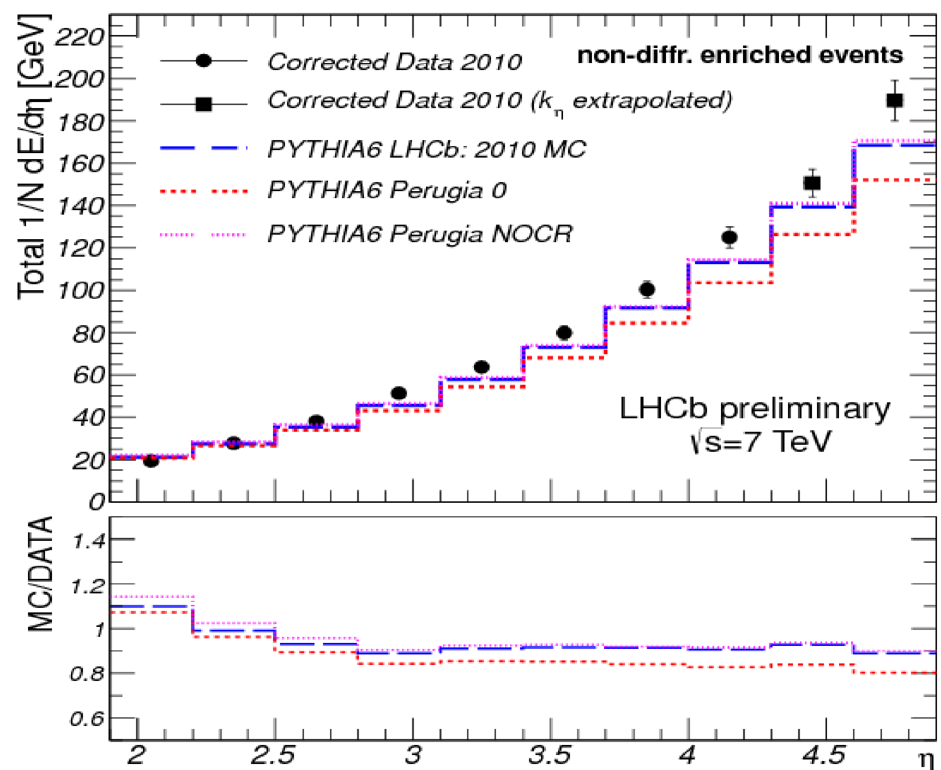
- Study energy flow in $1.9 < \eta < 4.9$

LHCb-CONF-2012-012

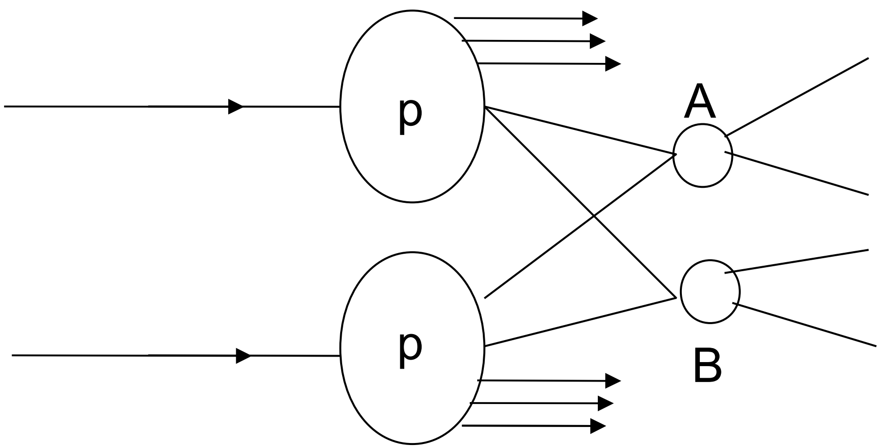
- 4 topologies to test complementary aspects of MPI:
  - Minim bias data,
  - Hard scattering processes, at least 1 long track in $1.9<\eta<4.9$ with pT>3 GeV/c
  - Diffractive enriched events no backward tracks reconstructed in $-3.5<\eta<-1.5$
  - Diffractive enriched at least 1 backward track in $-3.5<\eta<-1.5$

- PYTHIA8 describes the diffractive energy flow much better than all other models
- non-diffractive and diffractive EF are underestimated by the PYTHIA-based models





Multiple Parton Interaction at high p_T



● Multiple parton interactions play an important role in hadron collisions at high energies and are one of the most common, yet poorly understood phenomenon at the LHC

● Assume factorization of A and B:
Factorization of longitudinal & transverse components and two parton distributions =>

$$\sigma^{AB}_{DPS} = \frac{m}{2} \frac{\sigma^{A}_{SPS} \sigma^{B}_{SPS}}{\sigma_{eff}}$$

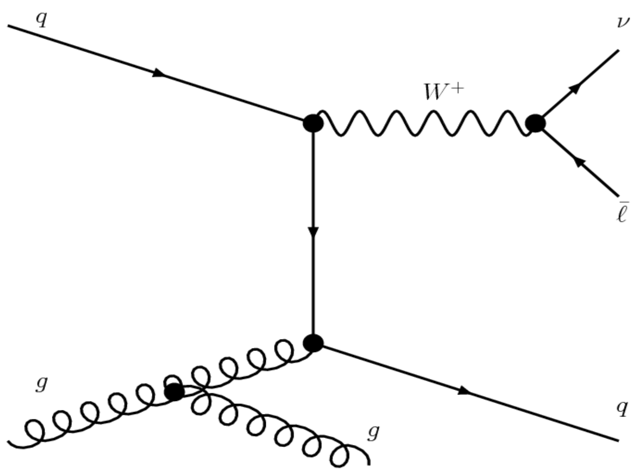
σ^{A}_{SPS} = inclusive cross section of single hard scattering
σ_{eff} = non-perturbative quantity related to transverse size of hadrons

● correlations between parton distributions may change this simple relation of σ_{DPS}

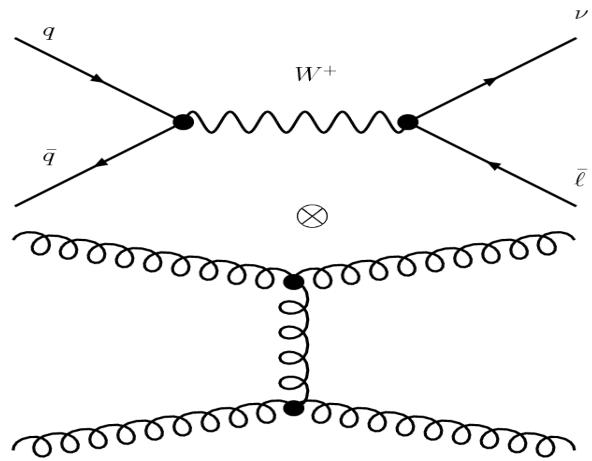
Direct measurement of double parton interaction in ATLAS

- Production of W bosons in association with two jets

direct



Double parton interaction



- Cross section for W+2jet production

$$d\sigma_{W+2j}^{tot}(s) = d\sigma_{W+2j}^{dir}(s) + \frac{d\sigma_W(s) \times d\sigma_{2j}(s)}{\sigma_{eff}}$$

- W selection
  Single lepton trigger
  1 lepton (e, μ) $p_T > 20$ GeV, $|\eta| < 2.5$
  MET > 25 GeV, $m_T > 40$ GeV
  2 jets, $p_T > 20$ GeV, $|y| < 2.8$

- Jet selection
  Minimum bias trigger
  2 jets, pT > 20 GeV, $|y| < 2.8$

Direct measurement of double parton interaction in ATLAS

- Measure fraction of W_0 + $2j_{DPI}$ in the W+2jet sample

$$f_{DP}^{R} = \frac{N_{W^0+2jDPI}}{N_{W0+2J}}$$

- Exploiting p_T-balance of jets:

  Jets from second scatter will be more balanced in p_T

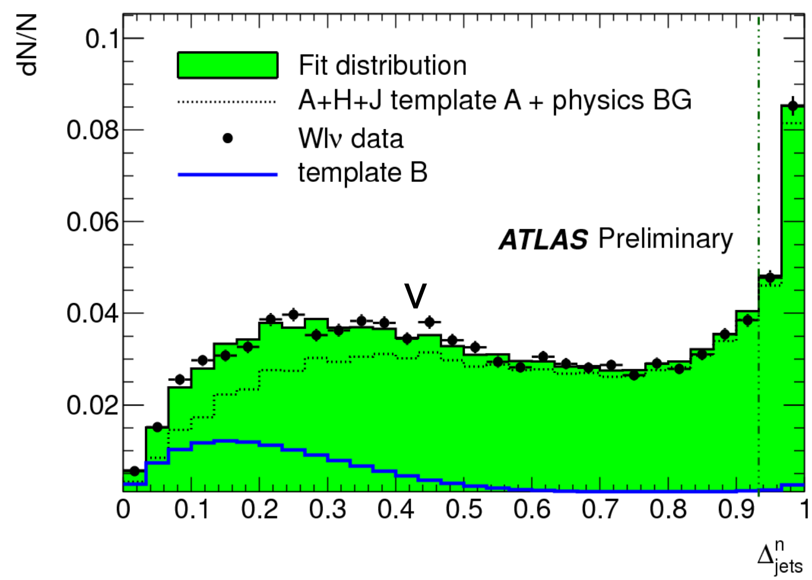
$$\Delta_{jets}^{n} = \frac{|\vec{p}_{T,1} + \vec{p}_{T,2}|}{|\vec{p}_{T,1}| + |\vec{p}_{T,2}|}$$

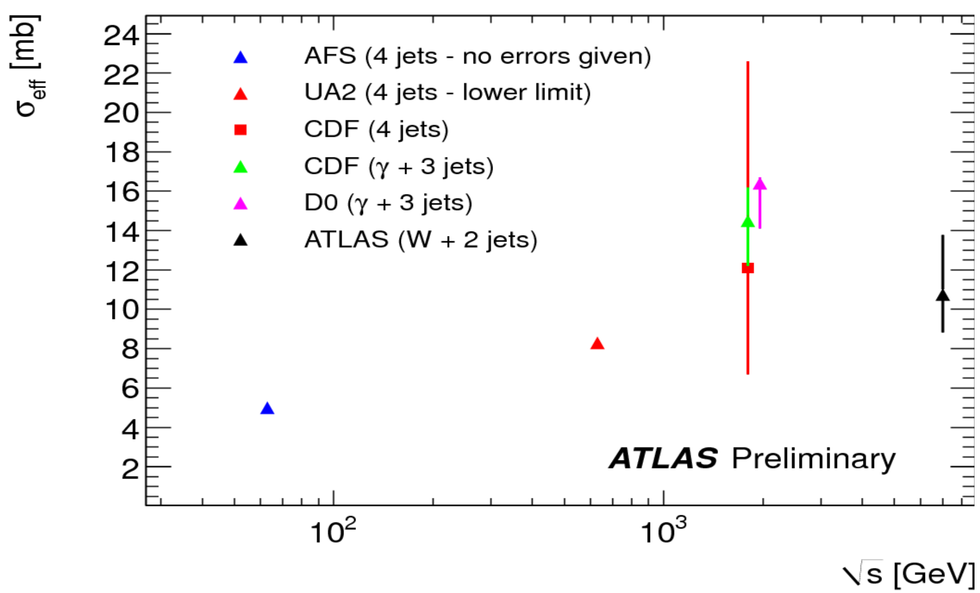
- Relate with σ_{eff}

$$\sigma_{eff} = \frac{1.}{f_{DP}^{R}} \cdot \frac{N_{W0} N_{2j}}{N_{W+2j}} \cdot \frac{1}{\epsilon_{2j} L_{2j}}$$

- σ_{eff} consistent with Tevatron results
- s-dependence not excluded

ATLAS-CONF-2011-160





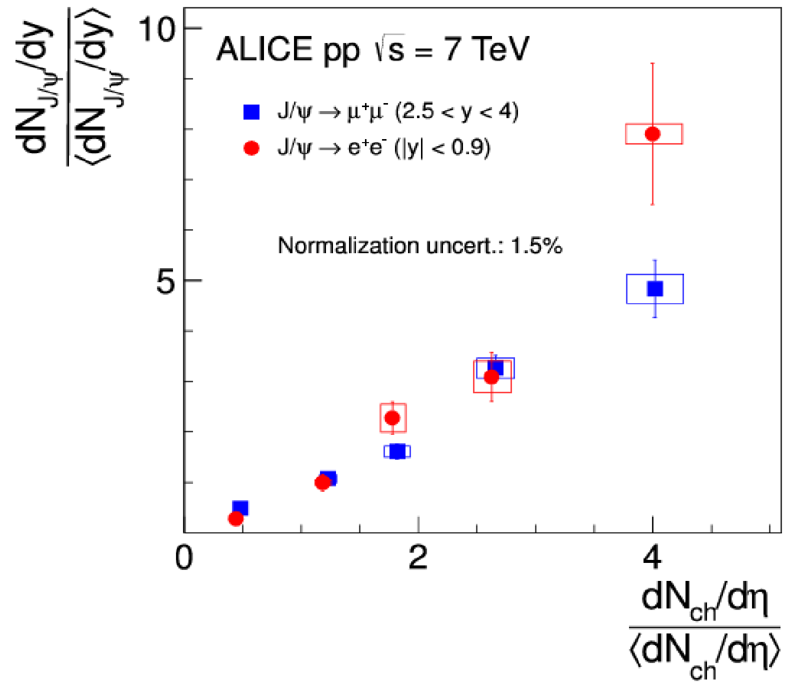
J/ψ production vs charged particle multiplicity in pp collisions at 7 TeV in ALICE

arXiv:1202.2816

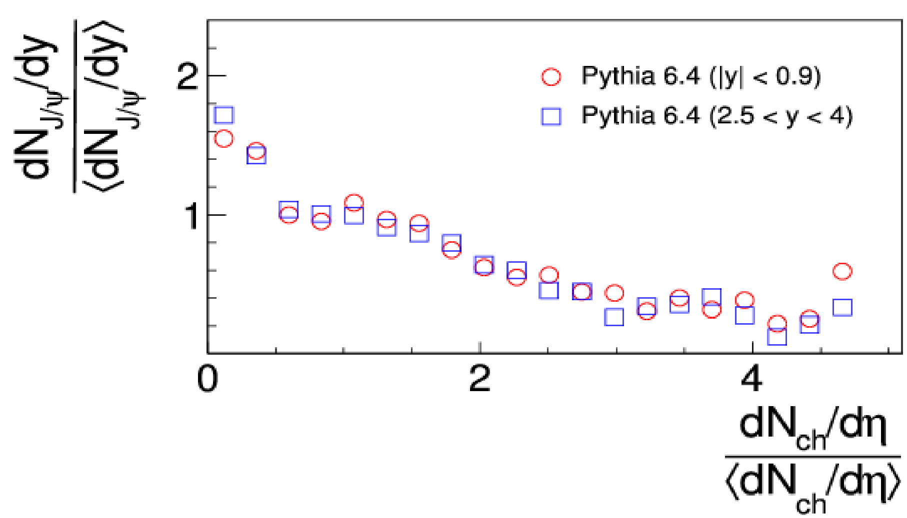
- Linear increase as a function of multiplicity

- J/ψ mesons are detected at mid-rapidity (|y | < 0.9) and forward rapidity (2.5 < y < 4), while dNch /dη is determined at mid-rapidity (|η | < 1).

- Same trend in the two rapidity regions



- Comparison with PYTHIA 6.4.25 in the PERUGIA 2011 tunes where J/ψ yields originated from the first hard interaction decreases as a function of relative multiplicity do not follow the same trend as seen in the data



Double charm production and Double Parton Scattering (LHCb)

- Measurement of Double J/ψ, J/ψ with open charm (C) and double open charm (CC)

- First measurement of charmonia pairs at LHC by LHCb Collaboration
  $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0\ (\text{stat}) \pm 1.1\ (\text{syst})$ nb Phys. Lett. B 707 (2012)
  in agreement with pQCD calculation $\sigma_{pQCD} = 4.1 \pm 1.2$ nb

- Recently measured J/ψ with open charm and double open charm in pp collision at 7 TeV (paper in preparation)

- Important to test Double Parton scattering(DPS)

$$\sigma_{DPS}^{A,B} = \frac{m}{2} \frac{\sigma_{SPS}^{A} \sigma_{SPS}^{B}}{\sigma_{eff}^{DPS}}, m = 1(2) \, for\, A = B (\neq B)$$

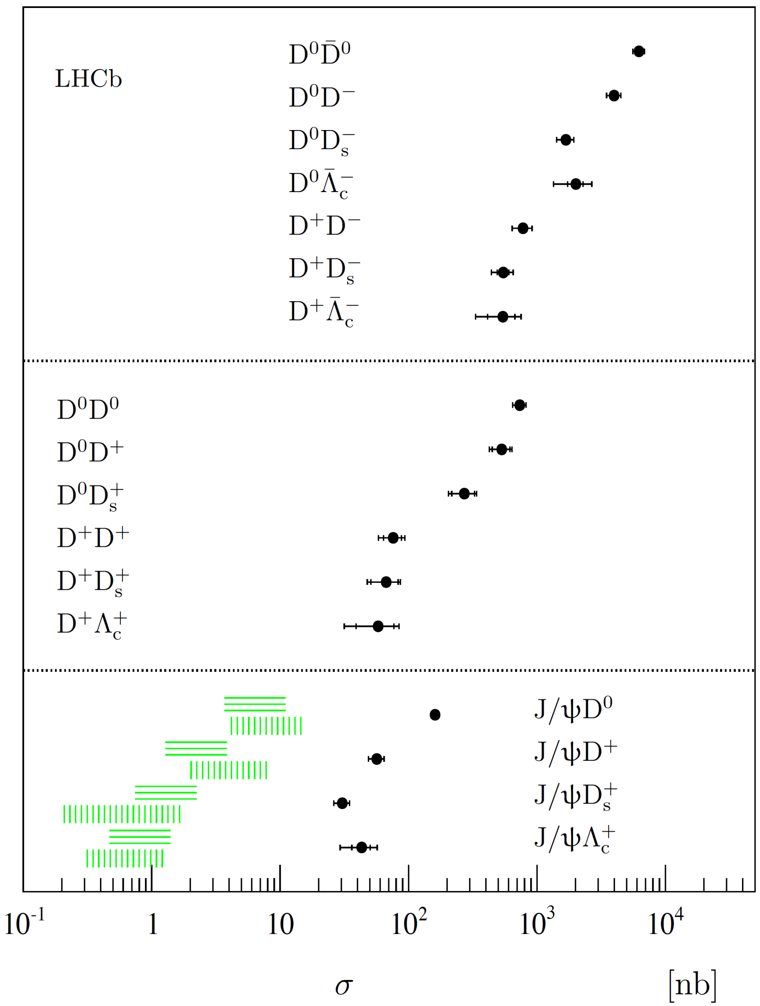
$\sigma^{DPS}_{eff} = 14.5 \pm 1.7$ mb
Measured by CDF PDR 56 3811 (1997)

- Predictions for the production cross-sections of the $J/\psi C$ and CC modes

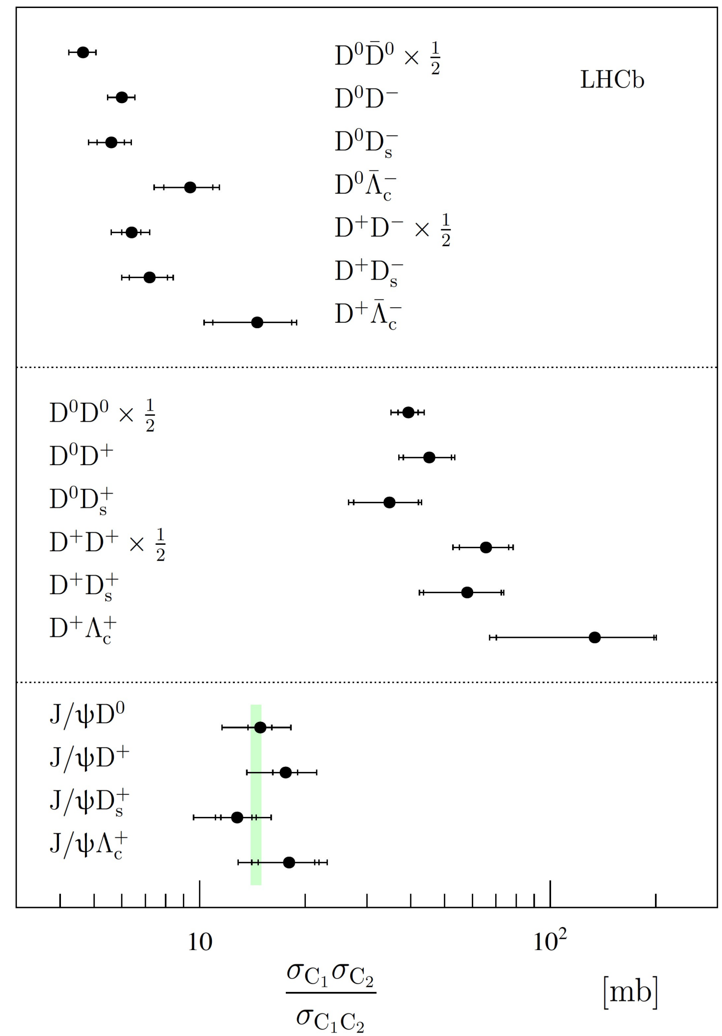
Mode	σ_{gg} [12, 13]	σ_{gg} [17]	σ_{DPS}	σ_{IC}
		[nb]		
$J/\psi D^0$	10 ± 6	7.4 ± 3.7	146 ± 39	220
$J/\psi D^+$	5 ± 3	2.6 ± 1.3	60 ± 17	100
$J/\psi D_s^+$	1.0 ± 0.8	1.5 ± 0.7	24 ± 7	30
$J/\psi \Lambda_c^+$	0.8 ± 0.5	0.9 ± 0.5	56 ± 22	—

Double charm production and Double Parton Scattering (LHCb)

Cross sections measurements:
The expectations from gg fusion processes significantly below the measurements for J/ψ C modes



Extraction of σ_{eff} :
For J/ψ C modes good agreement with CDF
For CC modes higher by a factor of 2-3



Conclusions

Underlying Event:

- Several studies investigating the Underlying Event have been presented from ATLAS,CMS and ALICE
- Different approaches, physical objects and detector components have been used to produce a complete picture of UE contributions at the LHC
- New tunes have been produced by both experiments based on these analyses that are already widely in use

Multiple Parton Interactions:

- ATLAS results on σ_{eff} from $W \rightarrow l\upsilon$ + 2 jets consistent with results obtained in different channels at the Tevatron
- New result on double charm production from LHCb
- First experimental measurement of J/ψ production as a function of charged particle multiplicity in pp collisions at $\sqrt{s}$= 7 TeV with the ALICE experiment