Double Parton Scattering & Multiple Parton Interactions in ATLAS+CMS

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(on behalf of CMS & ATLAS Collaboration)

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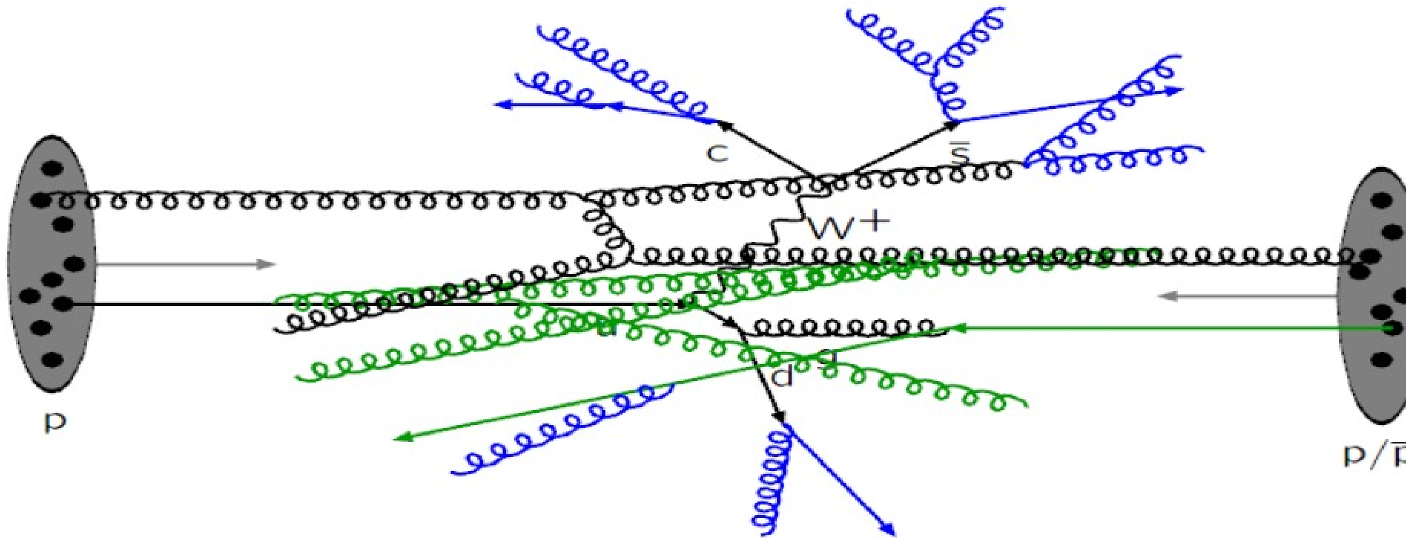
Multi-parton Interactions



Lecture by Torbjörn Sjöstrand, April 2005

A hard p-p collision at LHC can be interpreted as a hard scattering between partons accompained by Underlying Event(UE) consisting of:

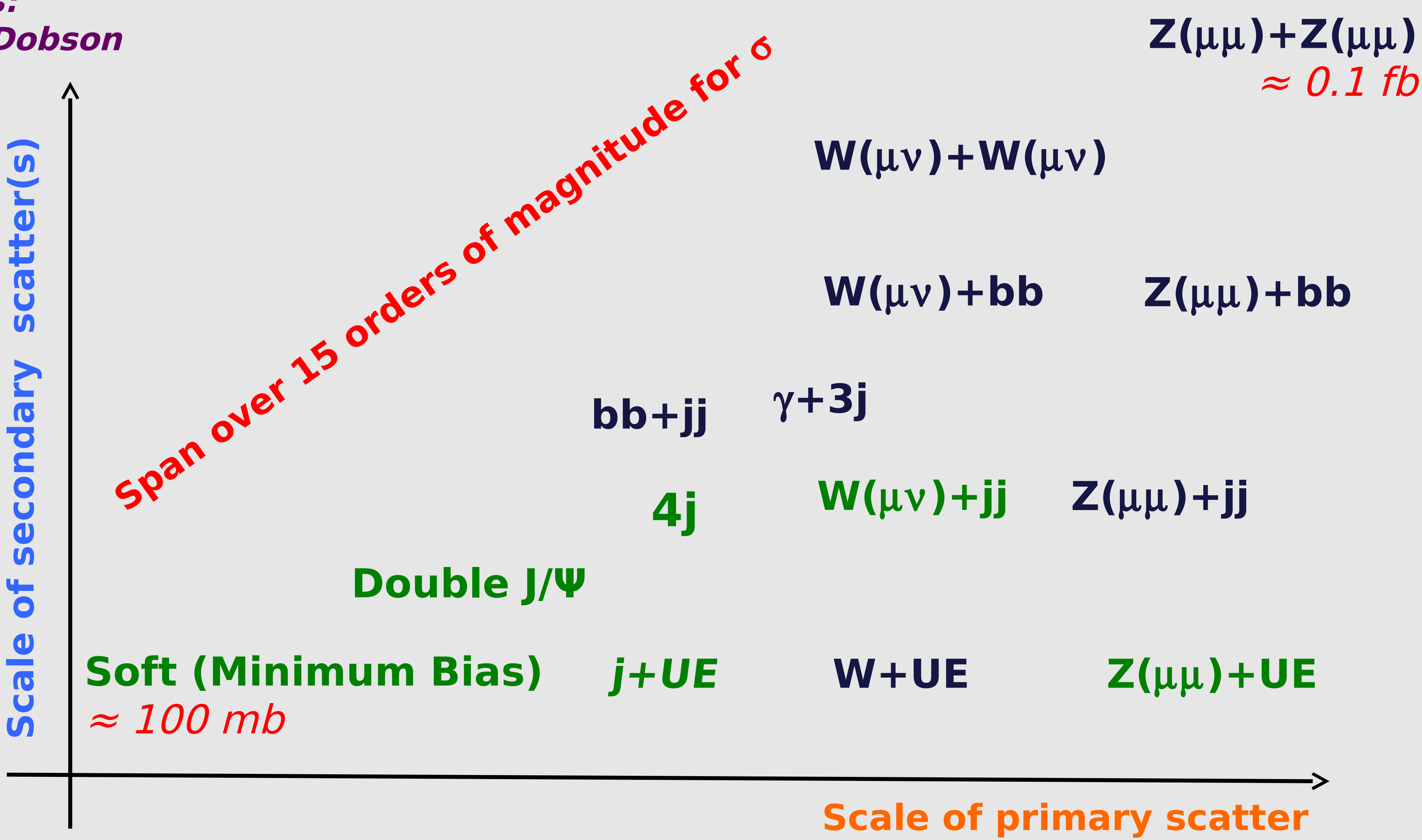
- Intial state radiation (ISR) & final state radiation (FSR)
- Multi-parton interactions (MPI)
- Beam Remnants (BR)

In general, UE is a softer contribution, but... SOME MPI's can be hard.

► **Double Parton Scattering**

Where can we see Multiple Parton Interactions?

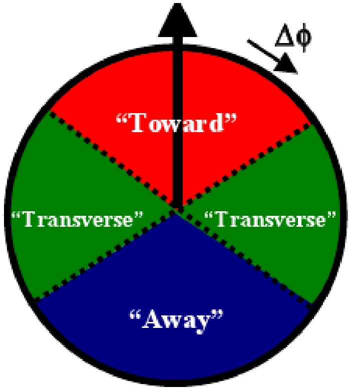
Credits:
- Ellie Dobson



LHC measurements available
LHC measurements not yet available

Complement with p-A and A-A

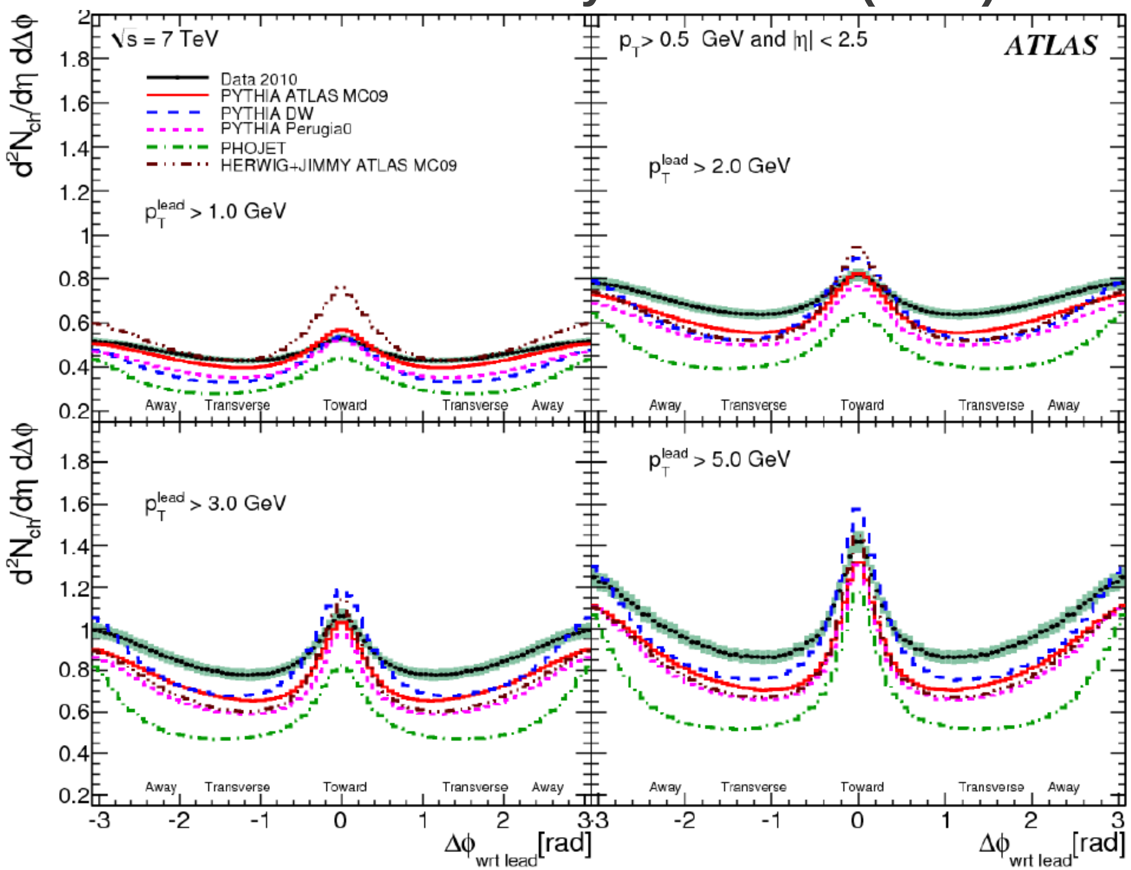
UE Measurements

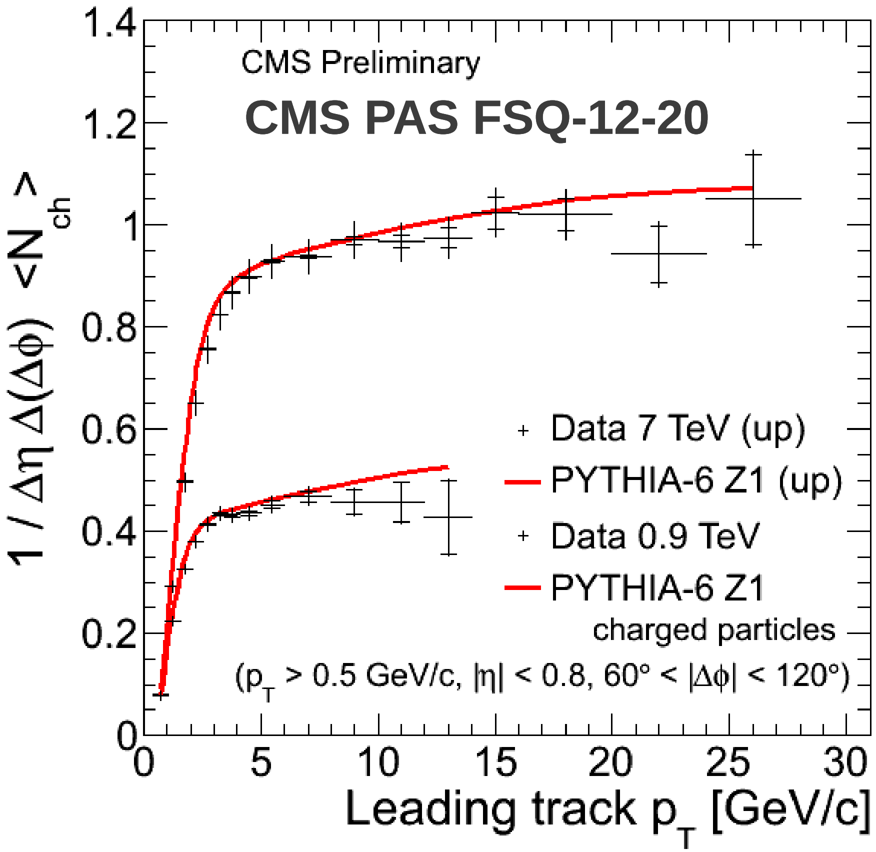


- Transverse region (Most appropriate for UE)
- For a hard scatter in the event, UE is likely to have more MPI than MB.

- Rapid rise in lower bins: increase of MPI activity. Corresponds to more central collisions.
- Increase of UE activity with √s.

Phys. Rev.D83 (2011) 112001





Strange-particle Production in UE

arXiv:1305.6016

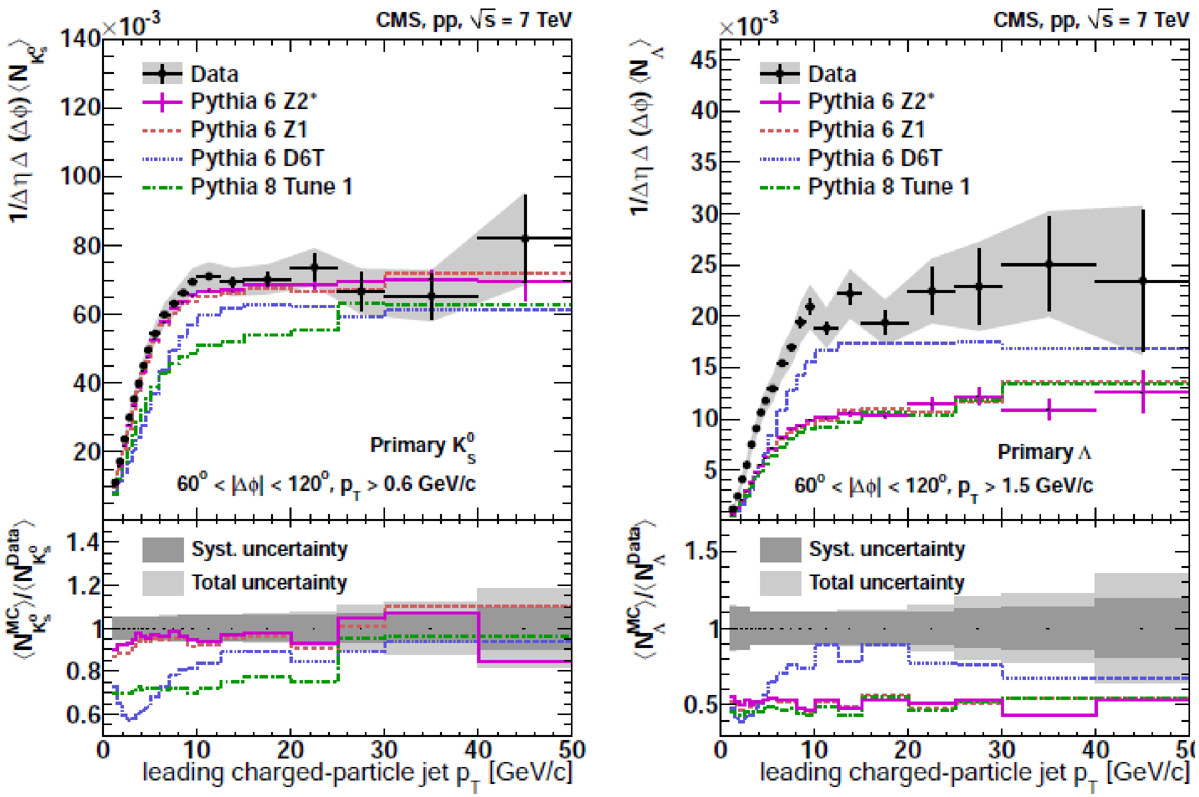
- Measurement of production of K^0_S, Λ, $\overline{\Lambda}$ in UE (1 > p_T >50 GeV/c).

- Transverse Region

  (Most appropriate for MPI)

- Growth in avg. multiplicity and avg. scalar sum p_T of K^0_{S} and $\Lambda + \overline{\Lambda}$ with $p_T(K^0_S)$ > 0.6GeV/c and $p_T(\Lambda, \overline{\Lambda})$ > 1.5 GeV/c within $|\eta|$ < 2.

- Followed by saturation at large scale.



Pythia simulations underestimate the activity by

15-30% for K^0_S mesons and 50% for $(\Lambda, \overline{\Lambda})$

UE activity in Drell-Yan

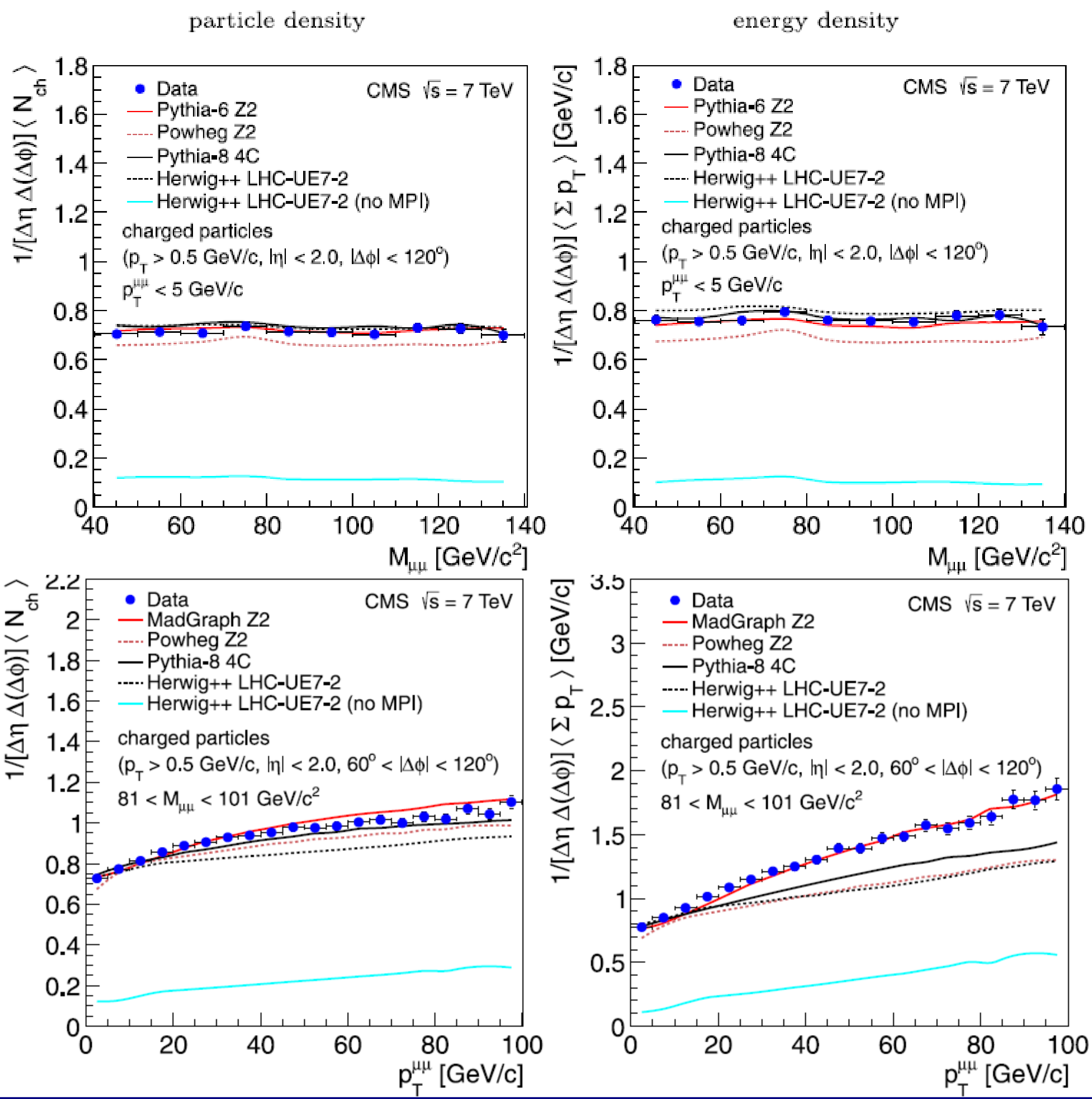
Eur. Phys. J. C 72 (2012) 2080

- UE independent of di-muon mass above 40 GeV/c^2, after requiring small recoil activity confirming MPI saturation at this scale.

- UE activity in DY events with no hard ISR is well described by Z2 tune for different generators, Pythia6 and MadGraph using PDF. But, it differs from POWHEG.

- Pythia8 (4C tune) describes well energy dependance of UE

- Results from models with no-MPI are inconsistant with data.

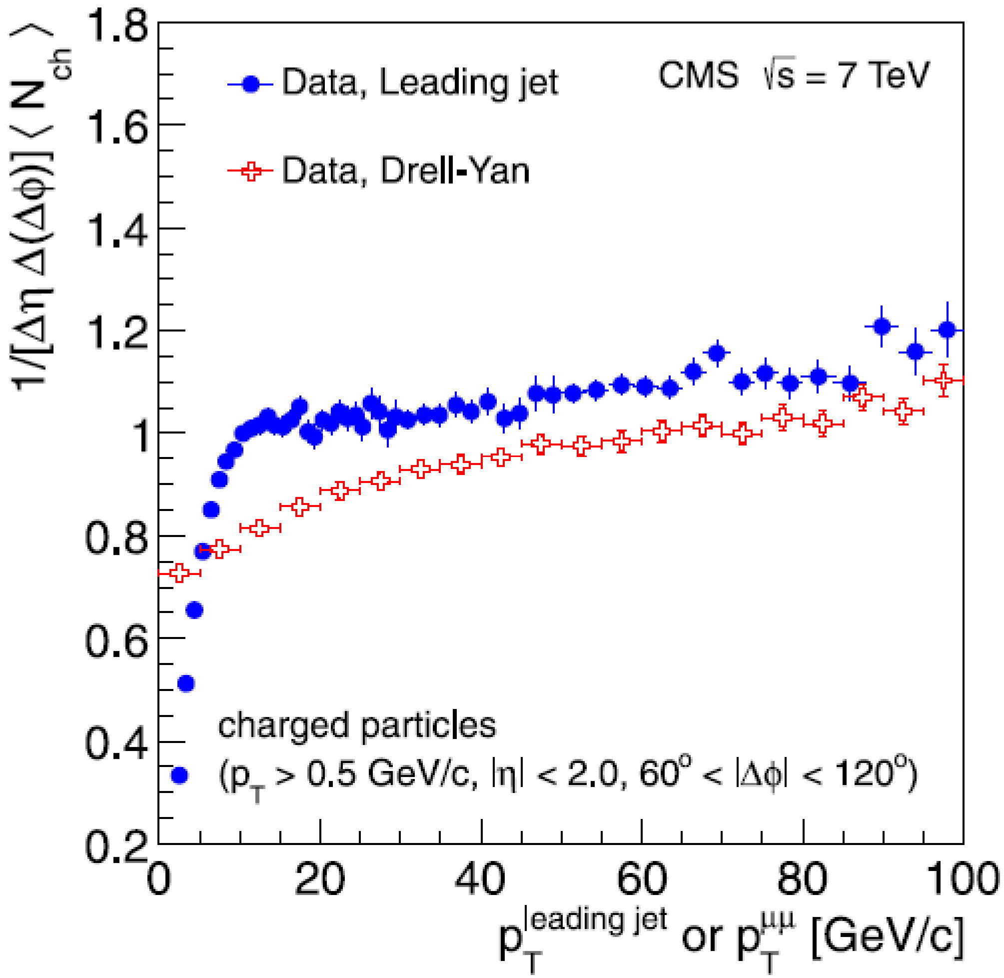


UE activity in Drell-Yan

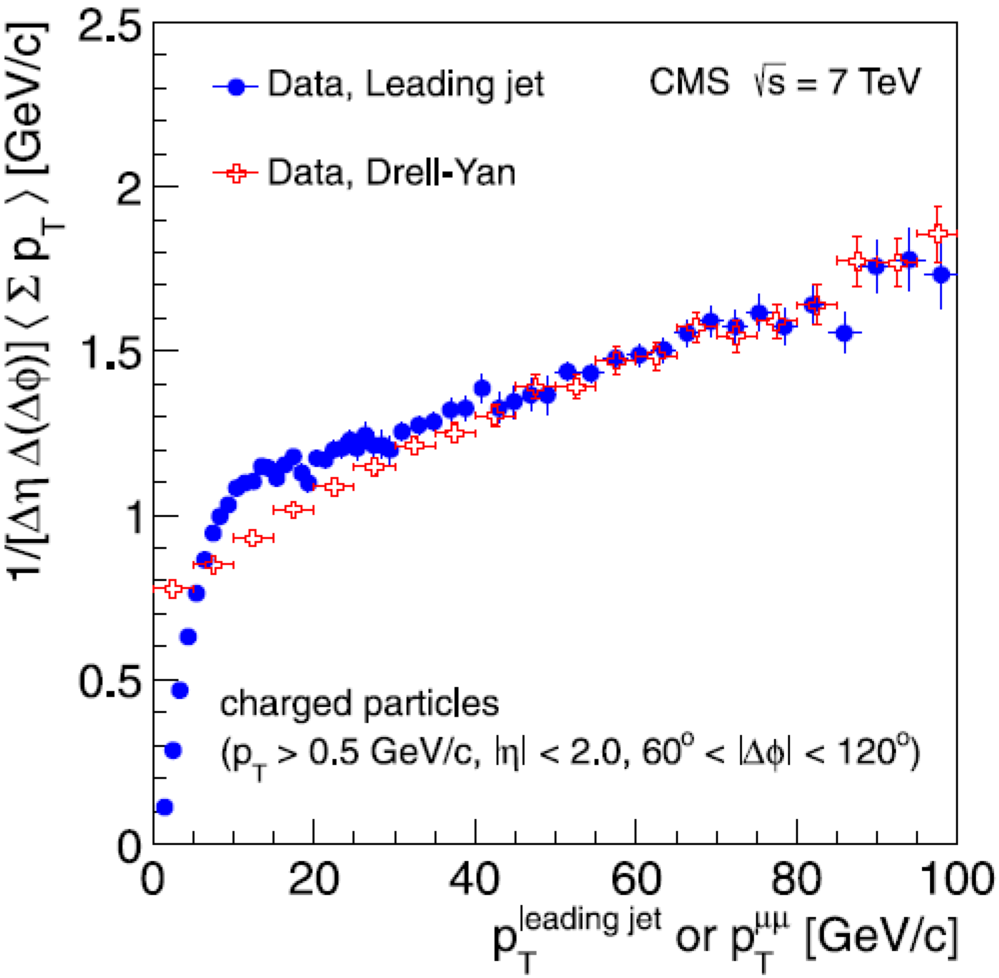
Eur. Phys. J. C 72 (2012) 2080

- Dependance of UE on energy scale is well described by tunes derived from fitting of UE measurement with leading track and leading jet events. (universality of UE)

particle density



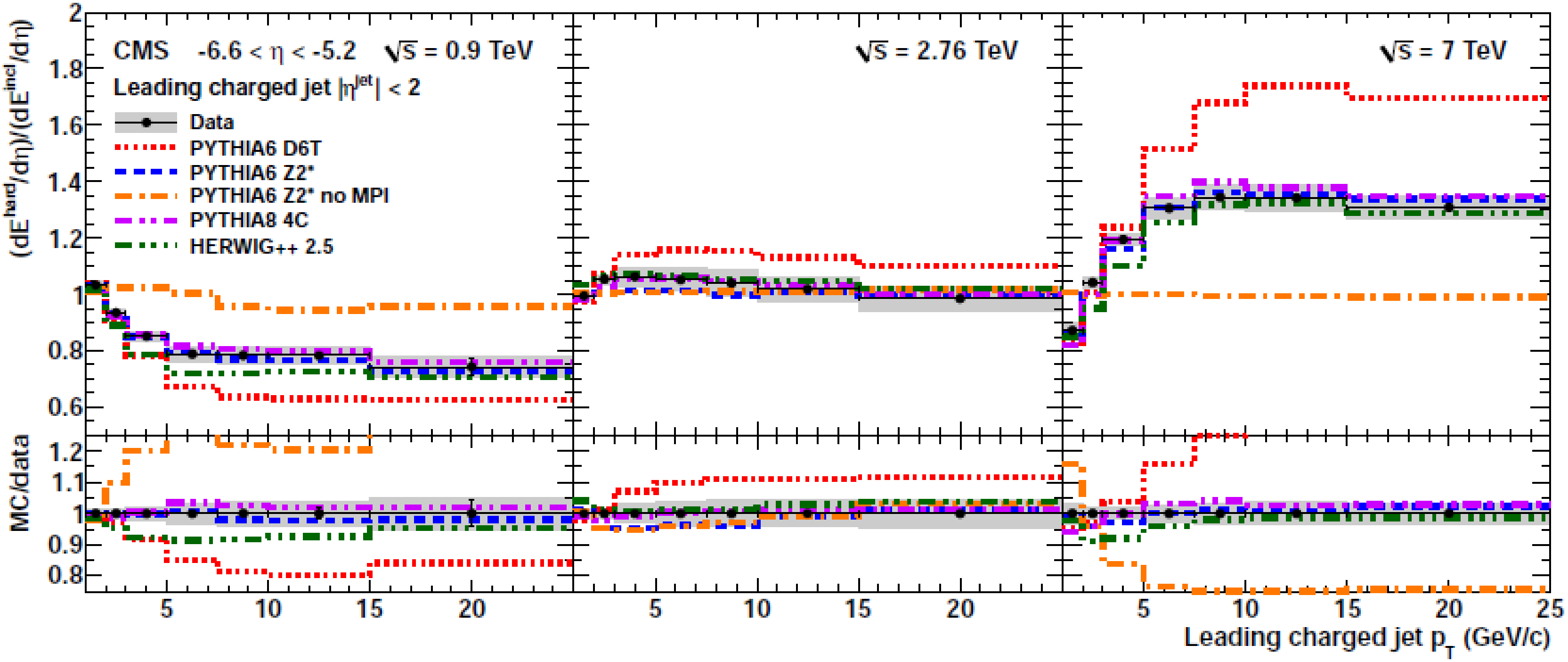
energy density



Underlying Activity in Forward Rapidity Region

arXiv:1302.2394v2

Hard-to-inclusive forward energy ratio vs leading jet p_T



At 0.9 TeV: ratio < 1
Production of central hard jets accompanied with higher UE
Depletes energy of proton remnant fragmenting in castor.

2.76 TeV the ratio is almost 1

7 TeV: fast increase in low pT,
Followed by plateau

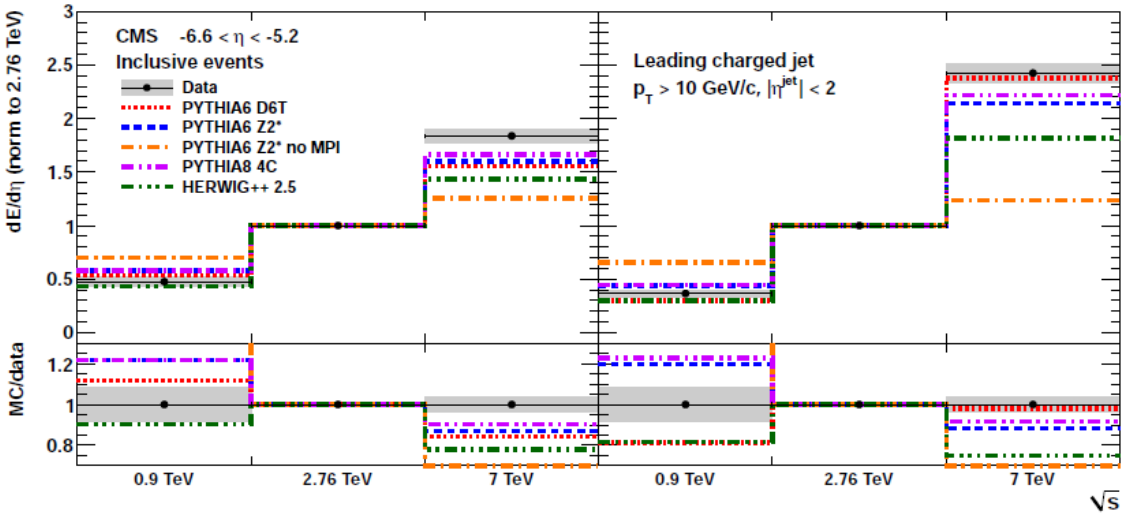
Discriminating tunes: Pythia6, with D6T tunes fails to describe data
Pythia tunes Z2*, 4C and herwig 2.5 describe data well

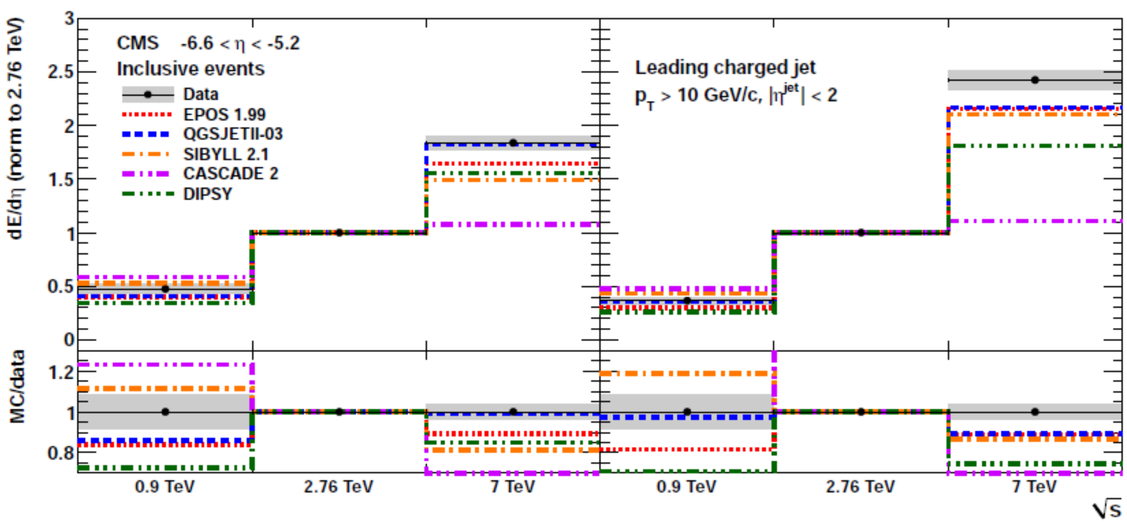
Relative increase as of energy density as a function of centre-of-mass energy

Underlying Activity in Forward Rapidity Region

Normalized energy density as a function of √s :

arXiv:1302.2394v2





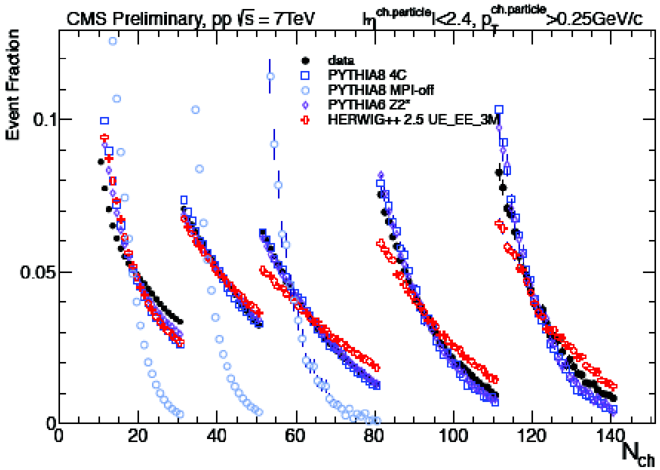
- Energy density increases at a faster rate for events with a hard scale.

- Inclusive events: Pythia or Herwig fails to describe the increase at 7 TeV

- QGSJET describes data well

- Hard scale: QGSJET01 Describe data better.

Jet and UE properties vs Particle Multiplicites



CMS PAS FSQ-12-022

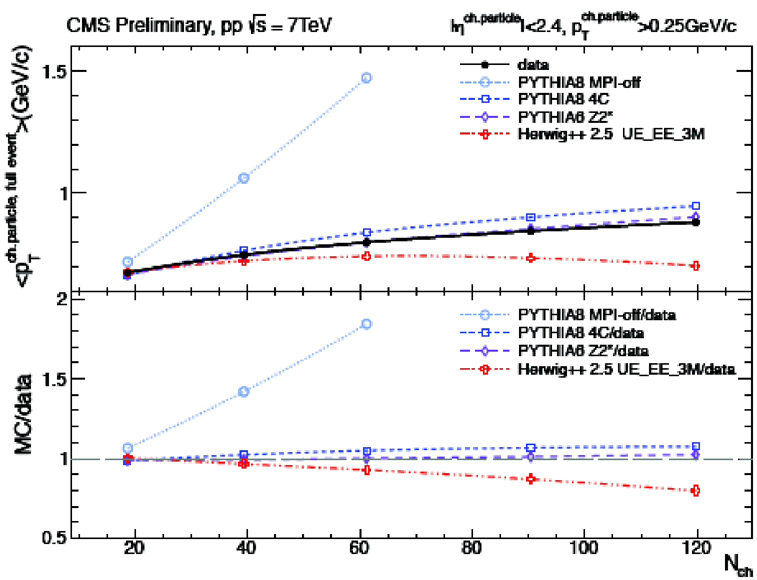
- Study mechanisms of multi-particle production in different multiplicity domains.

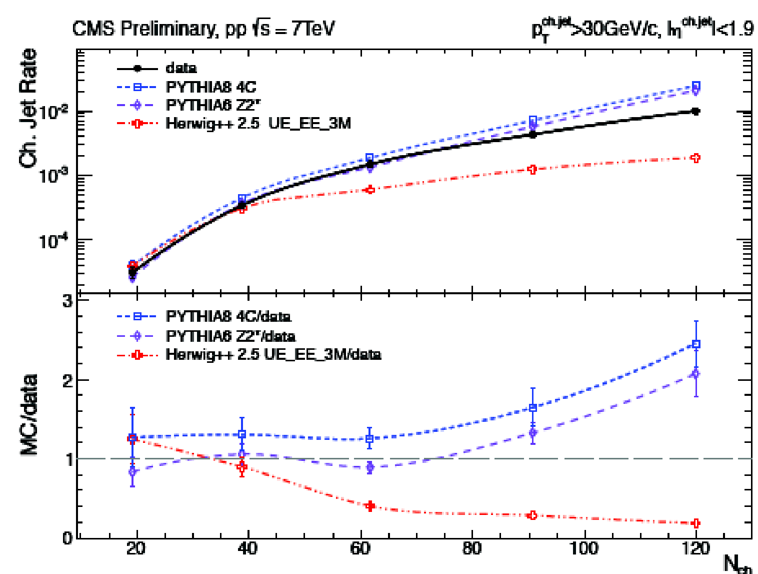
- High parton densities associated with collective mult-parton effects (e.g. ridge effect)

- Methodology:
  Classify events in different multiplicity domains.
  Identify intra-jet particles within track-jet cones.
  Particles not within a jet cone are associated with UE.
  Observables as a function of particle multiplicity.

$<p_T^{ch\ ptc}|>$ log-dependent on muliplicity.

$<p_T^{jet}>$ and <jet- rate> not described at high N^{ch}

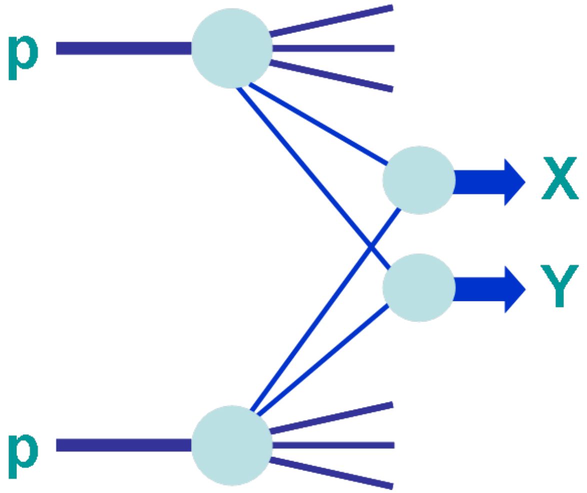




•Results from models with no-MPI are inconsistant with data.

Double Parton Scattering: Soft to Hard Scale

The cross-section for a generic process that involves DPS can be written as:



$$\sigma_{XY} = m \cdot \frac{\sigma_X \cdot \sigma_Y}{\sigma_{eff}}$$

where, m = 1/2 for identical interactions and 1 otherwise.

"Effective area parameter for double-parton interactions"

σ_{eff}, regarded as most natural link to the theories.

- Process independent, scale independent, √s independent. [D. Treleani et. al]
- 3→4 processes give significant contributions rising with xBjorken [Y. Dokshitzer at. al]

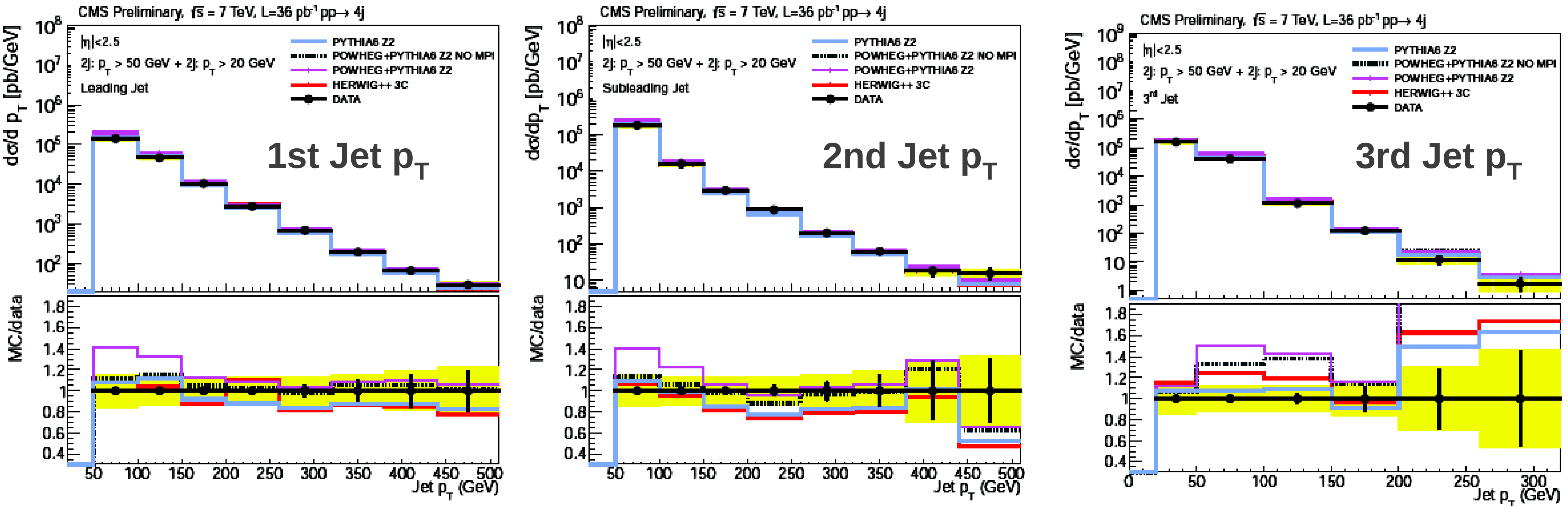
From experimental point of view these possibilties should be tested.

DPS via 4-jets

A 4-jet final state may arise from the one of the two chains:
- Parton shower (PS)
- 2nd hard scattering

2010 CMS collision data
Integrated Luminosity is 36 pb^{-1}

|η| (jets) < 2.5
Hard pair of jets: p_T > 50 GeV/c
Soft pair of jets: p_T > 20 GeV/c



- A NLO calculation does not perform necessarily well with best tune at LO.
- LO Generators perform well even for softer jets.

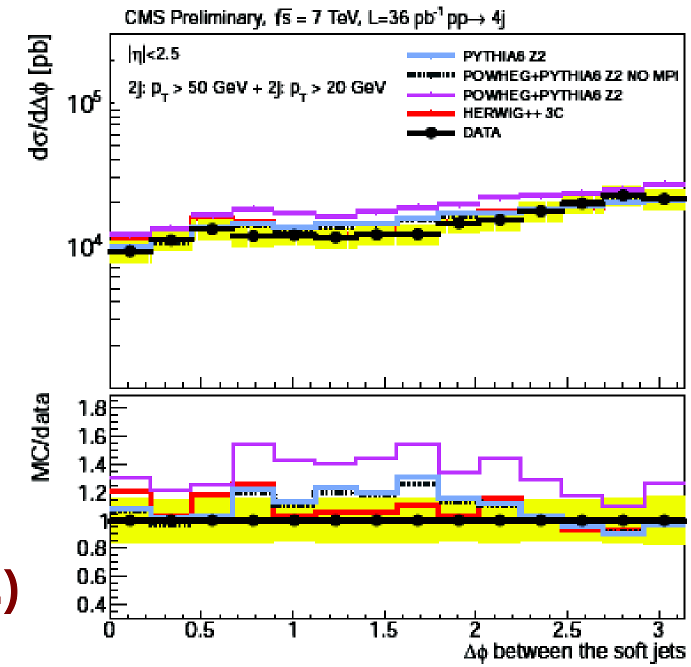
DPS via 4-jets

DPS Observables

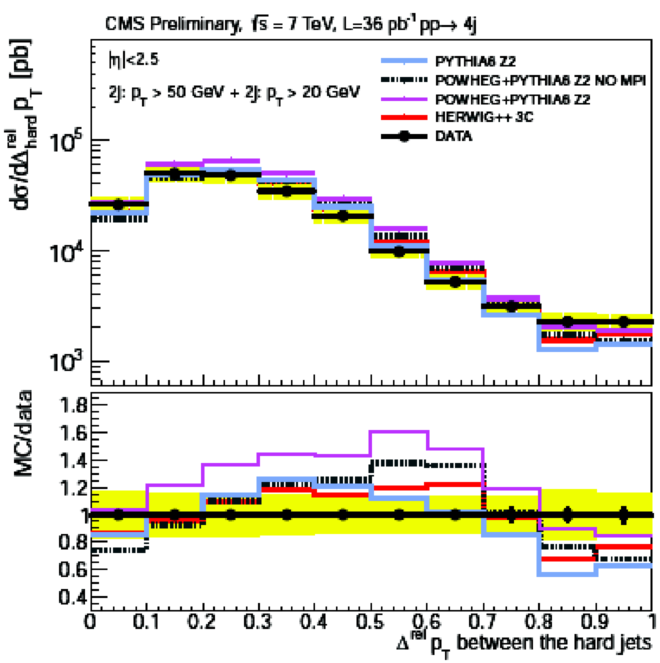
$$\Delta\phi_{soft} = \phi_{soft_1} - \phi_{soft_2}$$
$$\Delta\phi_{hard} = \phi_{hard_1} - \phi_{hard_2}$$
$$\Delta\eta_{hard} = \eta_{hard_1} - \eta_{hard_2}$$
$$\Delta\eta_{soft} = \eta_{soft_1} - \eta_{soft_2}$$

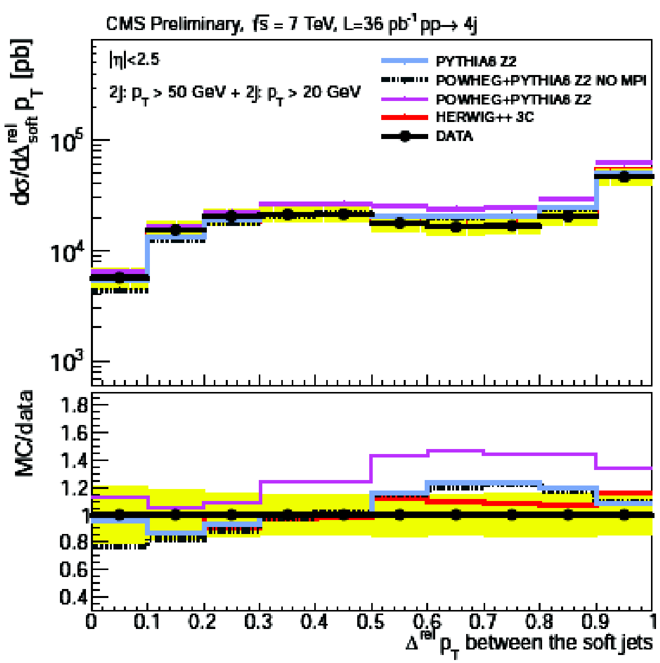
$$\Delta^{rel}_{soft} p_T = \frac{|\vec{p}_T^{\,soft_1} + \vec{p}_T^{\,soft_2}|}{|p_T^{soft_1}| + |p_T^{soft_2}|}$$

$$\Delta^{rel}_{hard} p_T = \frac{|\vec{p}_T^{\,hard_1} + \vec{p}_T^{\,hard_2}|}{|p_T^{hard_1}| + |p_T^{hard_2}|}$$



Final state cross-section, σ(4 jets) = 201 ± 3 (stat.) ± 34 (syst.)



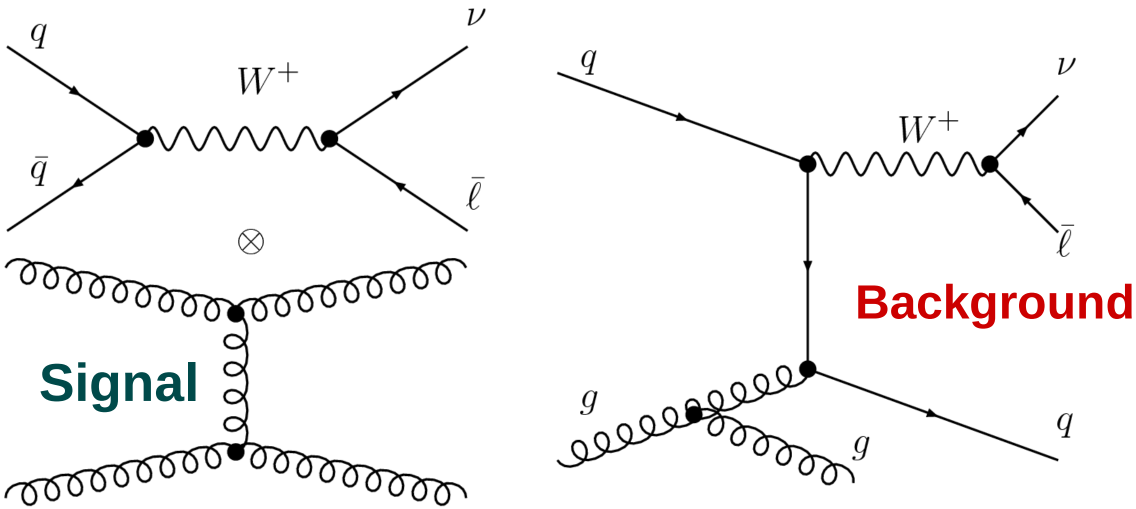


- POWHEG interfaced with Pythia6 overshoots the data by 30-40 %. (263.83 nb)
- Improvement in agreement, if MPI is switched off. (213.54 nb)
- HERWIG++ (212.23 nb) and Pythia6 with Z2* tune(216.72 nb) describes the data very well.

DPS via W+ 2-jets

Signal: W from 1st hard parton-parton interaction, two jets from second one.

Background: W + 2 jets from single parton interaction



Selection Criteria

pT(μ) > 35 GeV, |η| < 2.1
MET > 30 GeV
Transverse Mass(W) > 50
Jets with p_T > 20 GeV & |η| < 2.0

- **Δϕ(j1,j2), azimuthal separation between two jets**

$$\Delta\varphi(j1, j2) = |\varphi(j1) - \varphi(j2)|$$

- **transverse momentum imbalance b/w two jets**

$$\Delta^{rel}_{p_T}(j1, j2) = \left(\frac{\vec{p}_T(j1) + \vec{p}_T(j2)}{|p_T(j1)| + |p_T(j2)|}\right)$$

- **ΔS, angle between W(μν) and dijet vector**

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\mu, MET) \circ \vec{p}_T(dijet)}{|p_T(\mu, MET)| . |p_T(dijet)|}\right)$$

DPS via W+ 2-jets

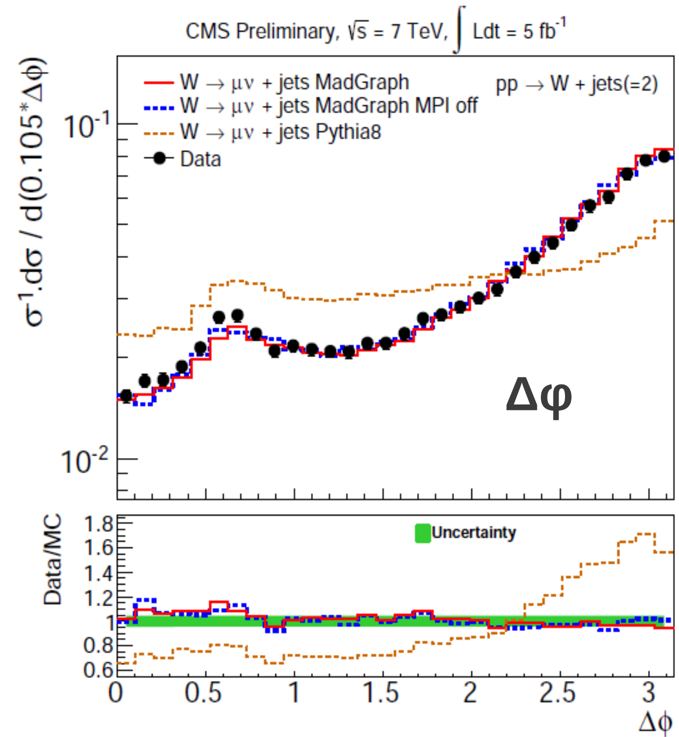
Event Class : Exclusive two jet

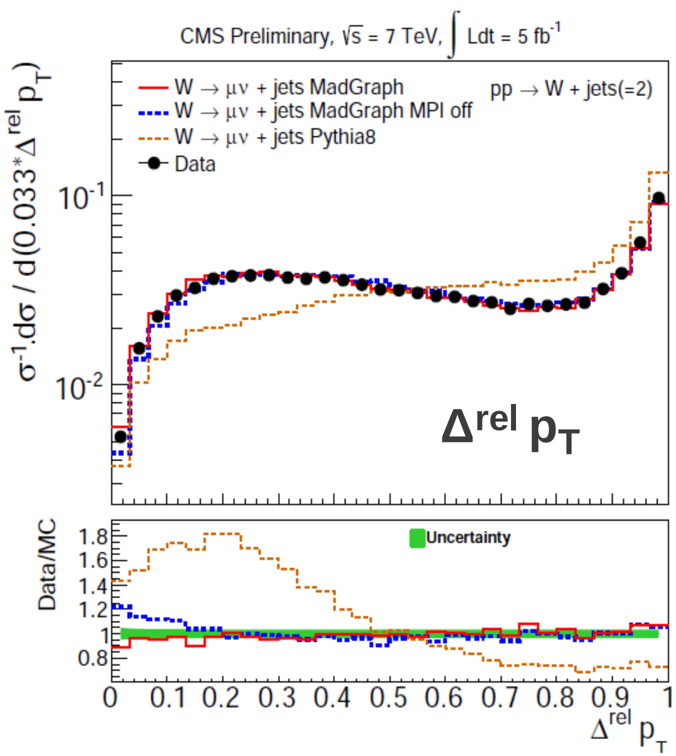
Integrated cross section = 60.6 ± 6.1 pb for data

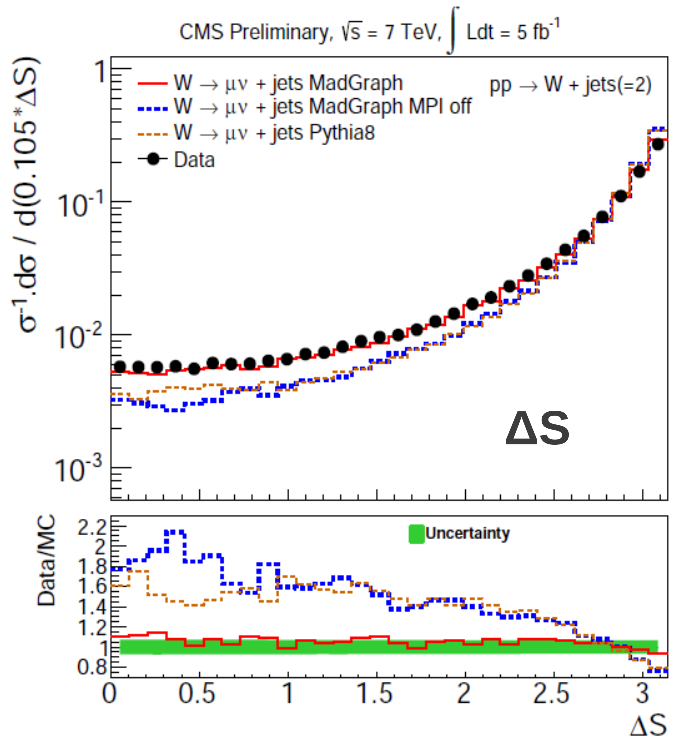
Nice agreement of corrected data with MadGraph MPI on.

MadGraph without MPI underestimates data by 18%.

Pythia8 underestimates by a factor of 1-2 in DPS sensitive region due to missing higher order processes.







Different Observables show different sensitivity in DPS region.

ΔS distributions show a better discrimination between MadGraph with MPI and without MPI.

DPS via W+2-jets

New J. Phys. 15 (2013) 033038

ATLAS Collaboration

Events from pp collisons at 7TeV:
Collected by ATLAS detector.

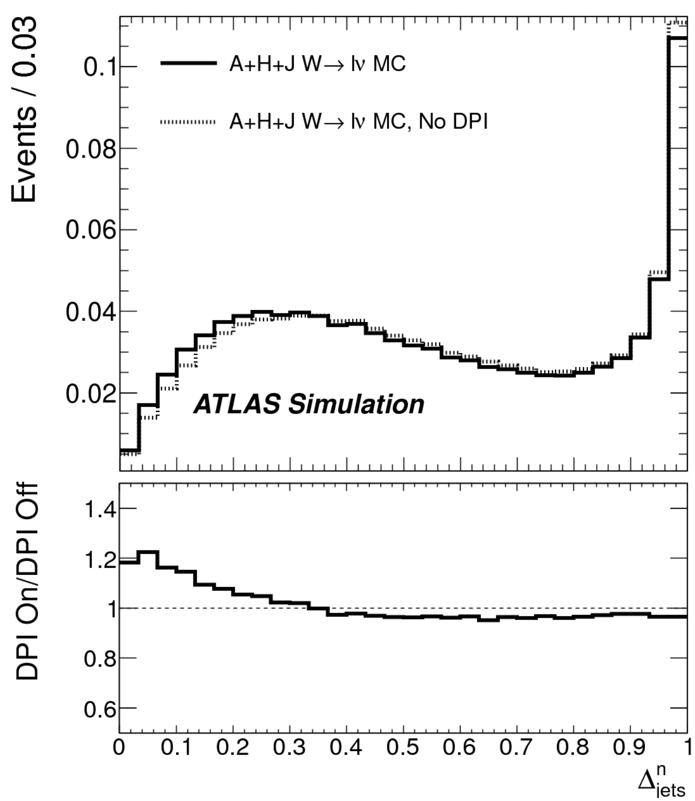
- 36 pb[-1] (2010 data)
- with W boson & exactly two jets
  $p_T > 20$ GeV & $|y| < 2.8$

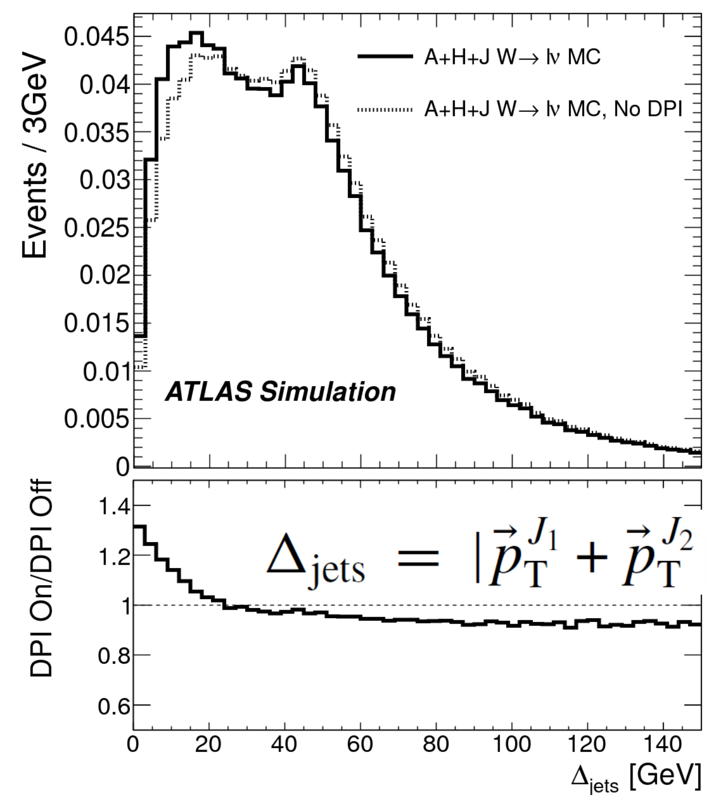
$$\sigma_{\text{eff}} = \frac{N_{W_{0j}}\, N_{2j}}{f_{\text{DP}}^{(\text{D})} \cdot N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j}} \cdot \frac{1}{\mathscr{L}_{2j}}$$

$$f_{\text{DP}}^{(\text{D})} = \frac{N_{W_{0j}+2j_{\text{DPI}}}}{N_{W+2j}} = \frac{N_{W_{0j}+2j_{\text{DPI}}}}{N_{W_{2j}} + N_{W_{0j}+2j_{\text{DPI}}}}$$

Observable sensitive to DPS: Important for DPS fraction extraction

$$\Delta^{\text{n}}_{\text{jets}} = \frac{|\vec{p}_{\text{T}}^{\,J_1} + \vec{p}_{\text{T}}^{\,J_2}|}{|\vec{p}_{\text{T}}^{\,J_1}| + |\vec{p}_{\text{T}}^{\,J_2}|}$$





$$\Delta_{\text{jets}} = |\vec{p}_{\text{T}}^{\,J_1} + \vec{p}_{\text{T}}^{\,J_2}|$$

DPS via W+2-jets

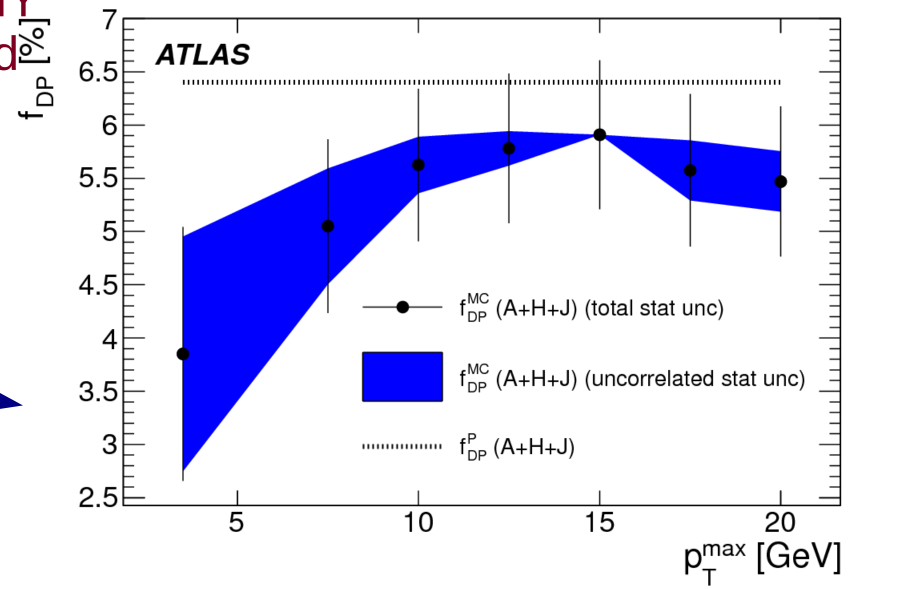
New J. Phys. 15 (2013) 033038

ATLAS Collaboration

Template A "DPI-off": ALPGEN + HERWIG + JIMMY
Remove events with hard MPI partons above defined cut-off scale(p_T^{max}), optimization needed

Template B "DPI only": di-jet events from Data

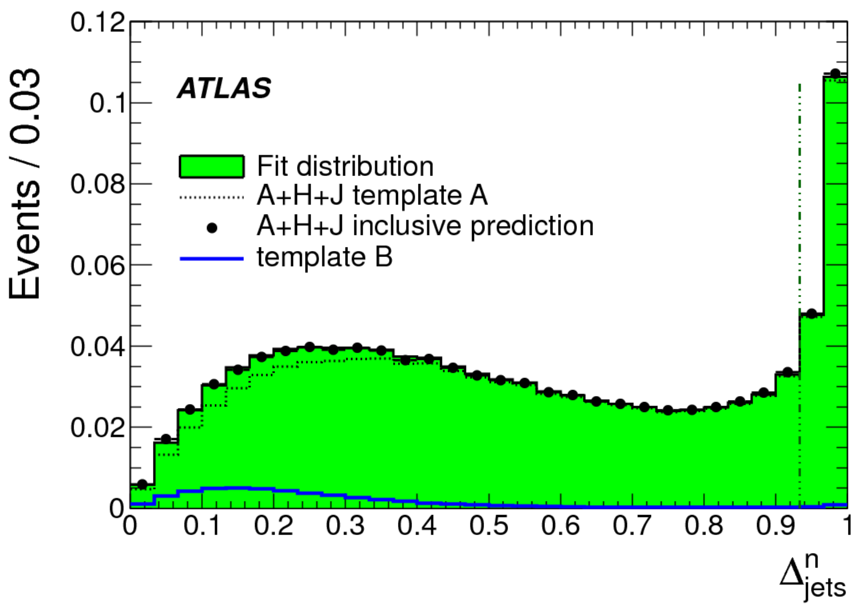
$f_{DP}^{(MC)}$ as a function of the p_T^{max} cut imposed on the scattered partons.

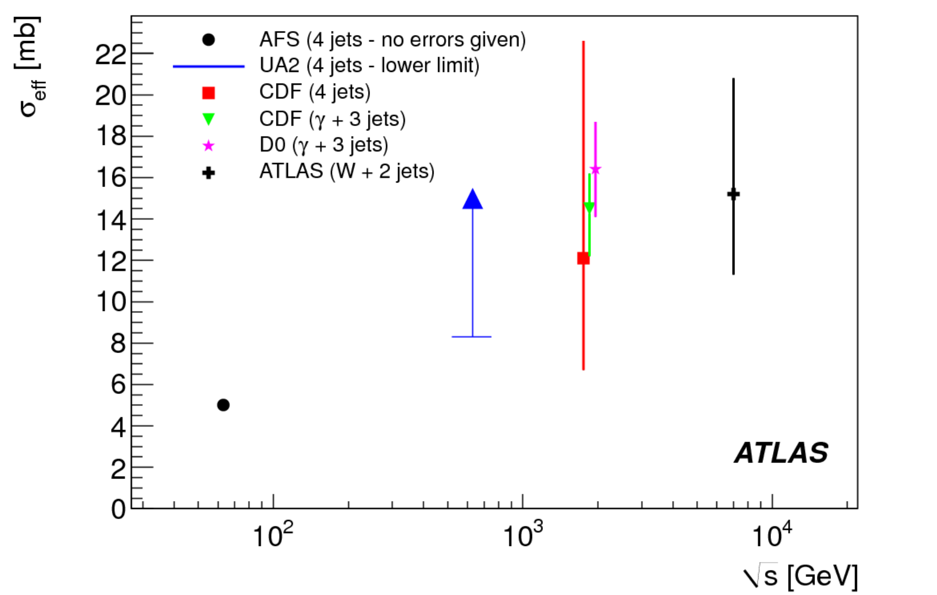


Fit Result with $\Delta^{n\ jets}$ distribution in the background-subtracted data.

$$f_{DP}^{(D)} = 0.08 \pm 0.01\ (\text{stat.}) \pm 0.02\ (\text{sys.})$$

$$\sigma_{\text{eff}}(7\ \text{TeV}) = 15 \pm 3\ (\text{stat.})\ ^{+5}_{-3}\ (\text{sys.})\ \text{mb}$$





Summary

• LHC experiments have a rich MPI research program. Both ATLAS and CMS experiments studied in detail minimum bias as well as Underlying Event activities at LHC energies.

• At high scale of interaction, MPI gets saturated. Measurements are reasonably well described by recent tunes derived from UE activities in fully hadronic final states.

• Current emphasis of the LHC experiments in MPI studies is on understanding of double parton scatterings (DPS).

• Effective cross-section is considered as the most effiecient link to the theories.

• Observables senstive to DPS processes are defined and data distributions corrected to particle level are provided by CMS, are compared with different MC events.

• ATLAS provides estimation of effective cross-section in W + 2 jets process, which is in close agreement with previous measuremets from Tevatron.

$$\sigma_{\mathrm{eff}}(7\ \mathrm{TeV}) = 15 \pm 3\ (\mathrm{stat.})\ ^{+5}_{-3}\ (\mathrm{sys.})\ \mathrm{mb}$$

Thanks for kind attention... :)

Central Region (Tracks)

QCD-10-001: "First Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 0.9 TeV". Eur. Phys. J. C 70 (2010) 555-572.

QCD-10-010: "Measurement of the Underlying Event Activity at the LHC with $\sqrt{s}$ = 7 TeV and Comparison with $\sqrt{s}$ = 0.9 TeV". JHEP 1109, 109 (2011).

QCD-10-021: "Measurement of the Underlying Event Activity with the Jet Area/Median Approach at 7 TeV and comparison to 0.9 TeV". CERN-PH-EP-2012-152, arXiv (2012), 1207.2392, submitted to JHEP.

QCD-11-012: "Measurement of the Underlying Event Activity in the Drell-Yan process in proton-proton collisions at $\sqrt{s}$ = 7 TeV". CERN-PH-EP-2012-085, arXiv:1204.1411v1, submitted to Eur. Phys. J. C.

Forward Region (E-Flow)

FWD-10-008: "Forward Energy Flow, Central Charged-Particle Multiplicities, and Pseudorapidity Gaps in W and Z Boson Events from pp Collisions at 7 TeV. ". Eur.Phys.J. C72 (2012) 1839.

FWD-10-011: "Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s}$ = 0.9 and 7 TeV". JHEP 1111 (2011) 148, Erratum-ibid. 1202 (2012) 055.

FWD-11-003: "Study of the Underlying Event at Forward Rapidity in Proton-Proton Collisions at the LHC". CDS Record: 1434458.