Measurements of the energy flow and UE behaviour at forward rapidities

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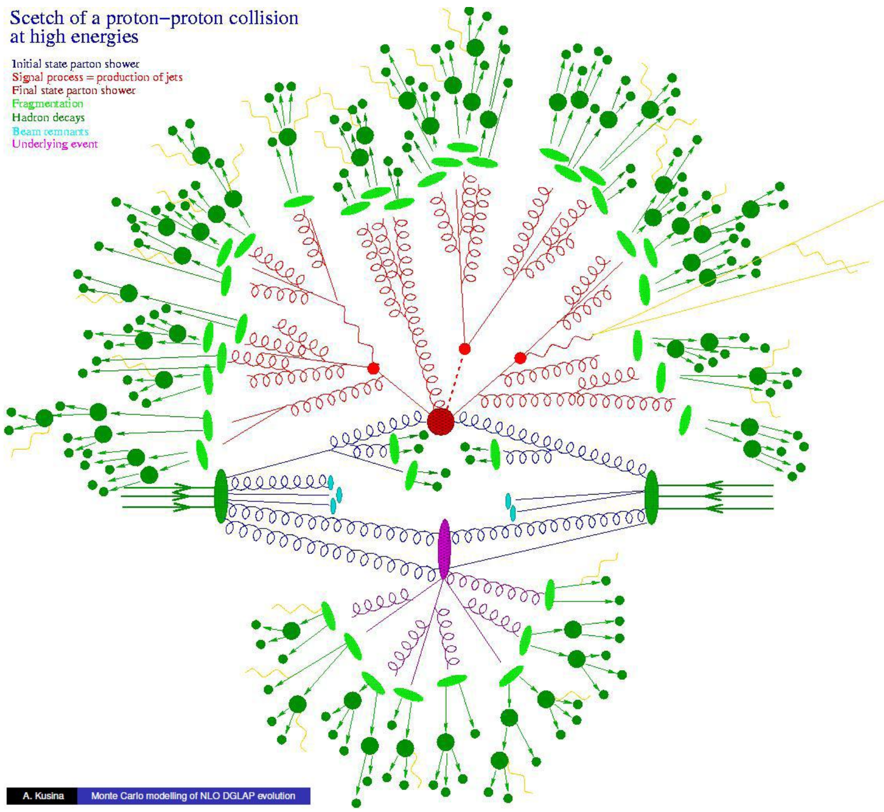
MPI@LHC 2012 Workshop – CERN,Geneva
Jets and UE properties session – December 3, 2012

Outline

- Introduction to Underlying Event physics
- Overview of foward energy flow measurements in $3.15 < |\eta| < 4.9$
- Presentation of novel UE studies at very forward rapidity: $-6.6 < \eta < -5.2$
- Summary

The underlying event in p-p collisions

- The underlying event (UE) is everything except the hard scattering:
  - ➔ Initial state radiation (ISR)
  - ➔ Final state radiation (FSR)
  - ➔ Multiple partonic interactions (MPI)
  - ➔ Beam remnants



- Its understanding is crucial for
  - ➔ precision measurements of the Standard Model processes
  - ➔ the search for new physics

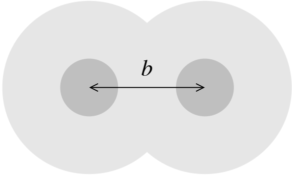
- But its dynamics are not well understood
  - ➔ soft & semi-hard interactions
  - ➔ can not be fully described with perturbative QCD
  - ➔ phenomenological models in MC involve parameters which **must be tuned using data**

- Use LHC data to constrain the existing UE models

Phenomenology of multi-parton interactions

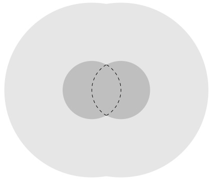
- The number of interactions depends on
  - ➔ the p_T scale of the event
  - ➔ the centre-of-mass energy: increase of particle densities

Minimum bias



Peripheral collision
few MPI

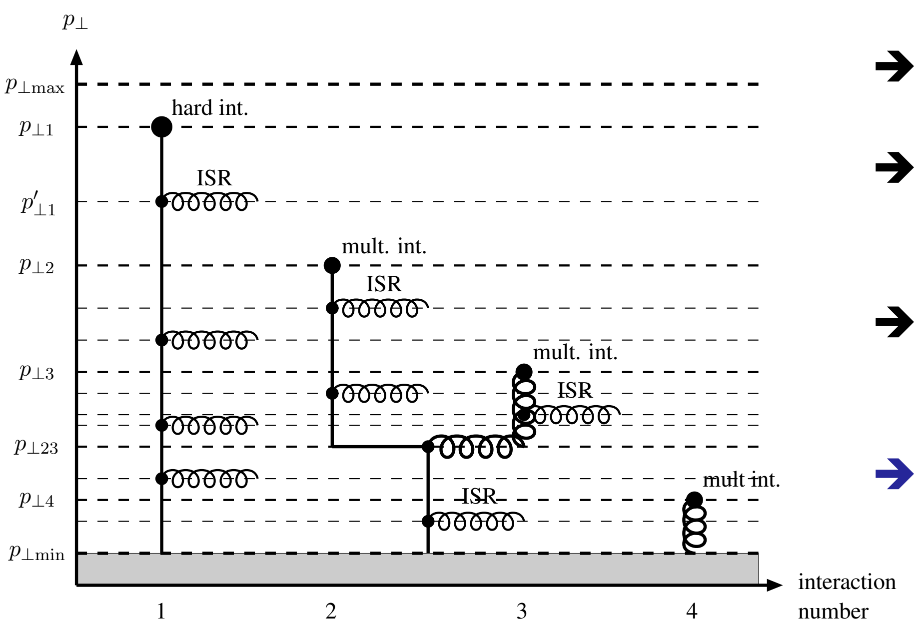
Hard scale $\hat{p}_T$



Central collision
many MPI

[Phys. Rev. D83 (2011) 054012]

- Introduce a MPI model to describe the soft interactions: extend hard scatter cross section to low p_T



[arXiv:hep-ph/0601012]

➔ But divergence: $1/\hat{p}_T^4$ if $\hat{p}_T \to 0$

➔ Introduce regularization:

$$1/\hat{p}_T^4 \to 1/(\hat{p}_T^2 + \hat{p}_{T,0}^2)^2$$

➔ Which is energy dependent:

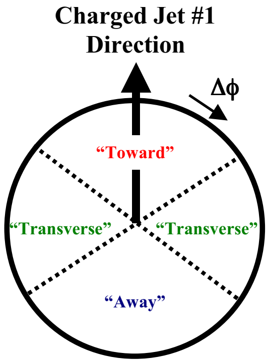
$$\hat{p}_{T,0}(\sqrt{s}) = \hat{p}_{T,0}(\sqrt{s_0}) \cdot (\sqrt{s} / \sqrt{s_0})^\varepsilon$$

➔ At a fixed √s, more MPI activity is predicted for smaller values of $\hat{p}_{T,0}$

Measurements of the UE

- Study the UE activity as a function of the hard scale of the event, and at different centre-of-mass energies

- Different possibilities
  ➔ <u>at central rapidities</u>



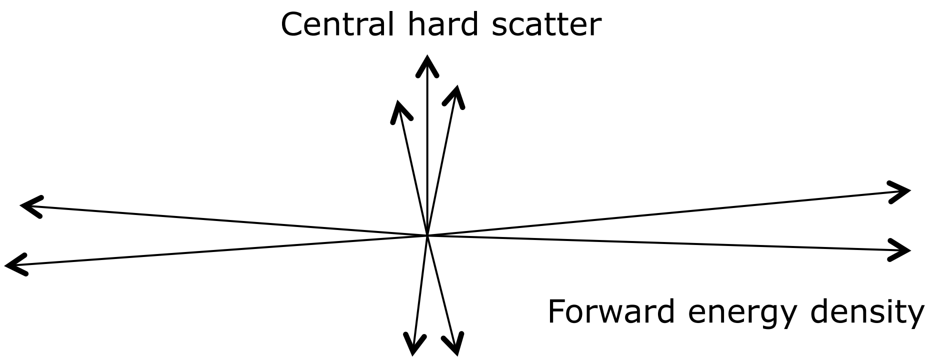
Hard scatter & UE are contained in same η range
➔ divide φ phase space to separate the UE from the hard scatter
➔ look at particle densities, energies in the transverse region
➔ As function of the hard scatter p_T scale
leading jets, Drell-Yan

[JHEP 09 (2011) 109]

➔ Use different observables: jet area/median
➔ no φ phase space division needed

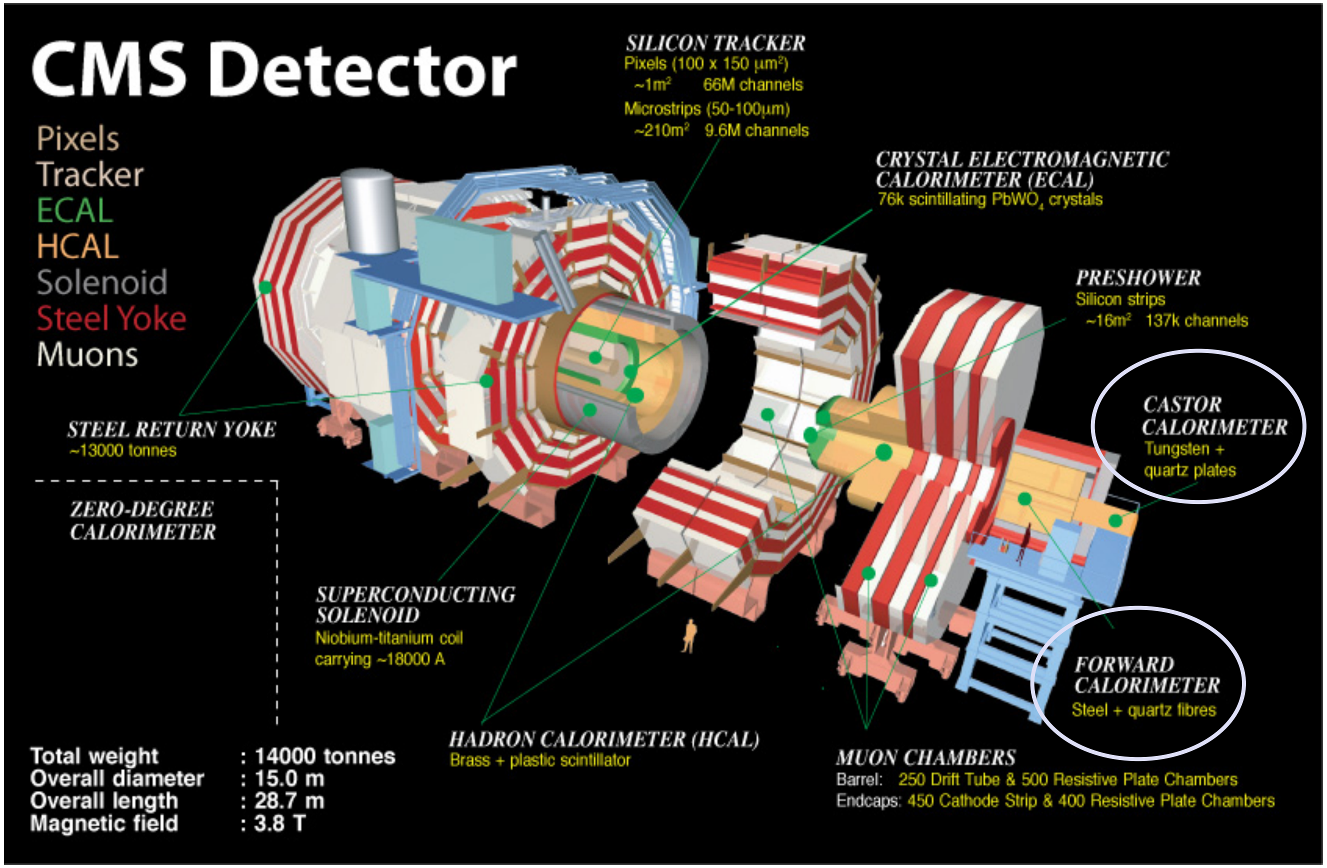
➔ **<u>at forward rapidities</u>**
UE observables separated with
large Δη from hard scatter
No division of φ phase space
Possible to study UE φ structure

➔ look at forward energy densities as a function of central leading jets



Measurements with CMS detector at LHC

- CMS has a very good pseudorapidity coverage: $-6.6 < \eta < 5.2$



HF calorimeter
* $2.9 < |\eta| < 5.2$
* 11m from IP
* iron/quartz fibres
* Čerenkov detector
* 13 η segmentations
* 36 φ segmentations
* EM/HAD shower measurement using long/short fibres

CASTOR calorimeter
* $-6.6 < \eta < -5.2$
* 14m from IP
* tungsten/quartz
* Čerenkov detector
* no η segmentation
* 16 φ segmentations
* 14 modules in z

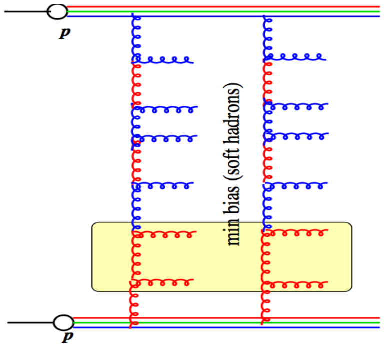
Forward energy flow measurement

- Measurement of energy flow in region: $3.15 < |\eta| < 4.9$ for centre-of-mass energies 900 GeV and 7 TeV

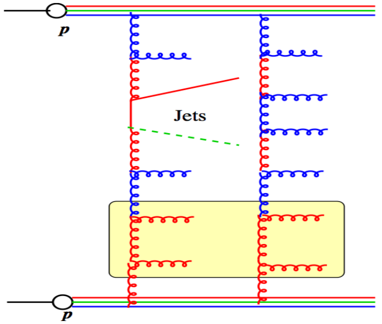
$$\frac{1}{N}\frac{dE}{d\eta}$$

- 2 classes of events:

Minimum Bias



Events with a hard scale
central dijets: $|\eta| < 2.5$
$p_T > 8(20)$ GeV at 900 GeV(7 TeV)



- Event selection:
  charged particles in region $3.23 < |\eta| < 4.65$
  further cleaning:
  good vertex conditions + removal of beam-induced background

- Data corrected to hadron level
  definition: unstable particles decay ($\tau < 10^{-12}$s), $3.15 < |\eta| < 4.9$, ν & μ excluded, diffractive events suppressed (at least 1 particle in $3.9 < |\eta| < 4.4$)

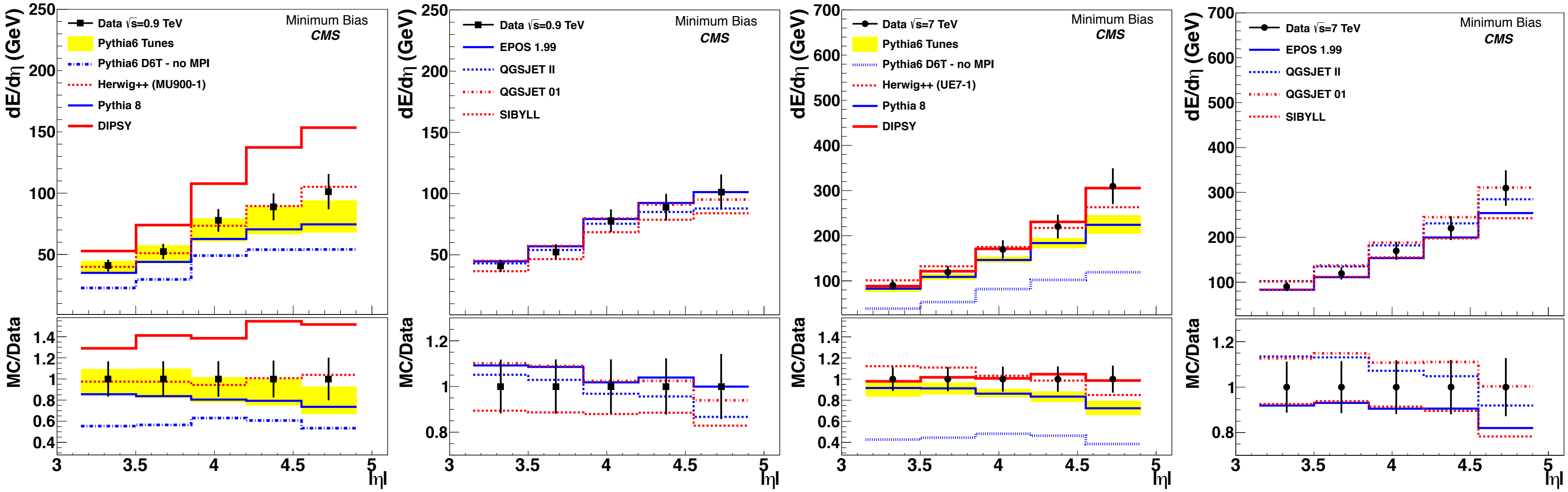
- Largest systematic uncertainties:
  Energy scale 10%
  HF simulation 3-9% (MB), 6-18% (dijet)
  Model uncertainty 1-3% (MB), 4-17% (dijet)

  Total: 11-15% (MB), 13-24% (dijet)

Forward energy flow: minimum bias

- Energy flow at 900 GeV (left) and 7 TeV (right):

10.1007/JHEP11(2011)148



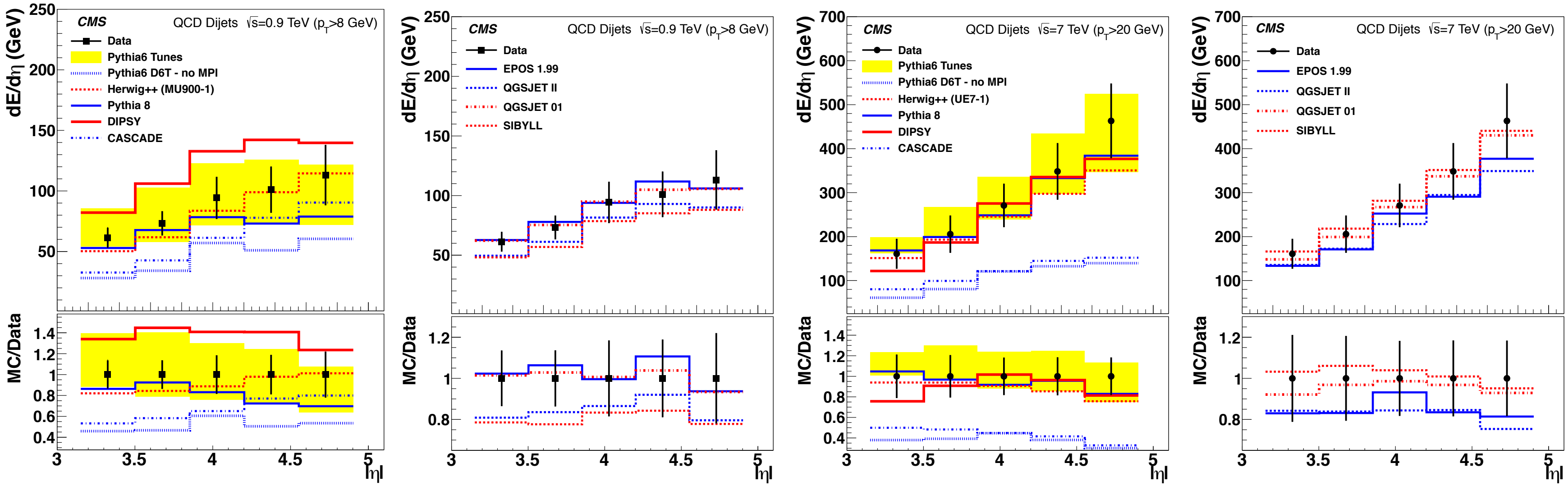
➔ We see a rise with η, corresponds to flat E_T flow
➔ Increase in E_T flow from 900 GeV to 7 TeV similar to increase in N_{ch}

➔ Predictions without MPI: too low
➔ HERWIG: tunes work
➔ DIPSY generator works at 7 TeV but overestimates at 900 GeV
➔ Pythia: large spread between different (LHC) tunes
➔ pp generators used in Cosmic Ray physics work quite well out of the box!

Forward energy flow: with dijet system

- Dijet energy flow at 900 GeV (left) and 7 TeV (right):

10.1007/JHEP11(2011)148



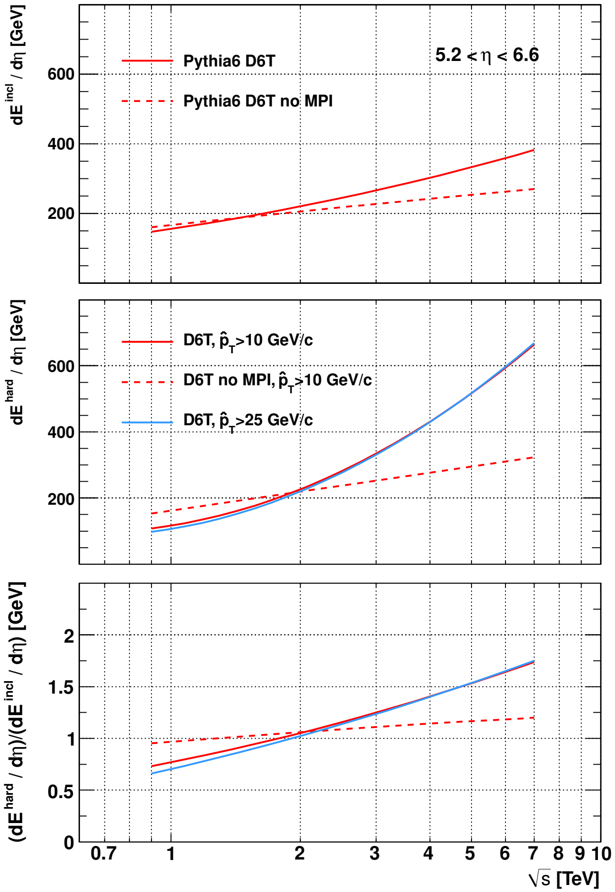
p_T > 8 GeV $\quad\quad$ p_T > 20 GeV

➔ Flatter η dependence corresponds to decreasing E_T flow

➔ Predictions without MPI: too low
➔ HERWIG and Pythia tunes cover the data
➔ CASCADE: increases faster
➔ DIPSY generator works at 7 TeV but overestimates at 900 GeV
➔ pp generators used in Cosmic Ray physics: describe data well

Study of UE activity at forward rapidity

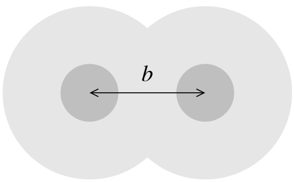
- Novel measurement of the Underlying Event activity by comparing energy density in CASTOR ($-6.6 < \eta < -5.2$) for minimum bias events w.r.t. events with a hard scale present



Minimum bias (inclusive events)

➔ energy density not much affected by MPI

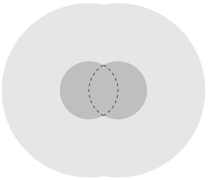
➔ non-diffractive dominated event sample



Hard scale $\hat{p}_T$

➔ energy flow strongly affected by MPI

➔ use the central leading charged jet with p_T > 1 GeV/c and $|\eta| < 2$



Compute ratio of energy densities

➔ able to factorize MPI contributions

➔ minimizes systematic uncertainties

Look at behavior of ratio as function of p_T scale and at relative energy flow as function of $\sqrt{s}$

CMS-PAS-FWD-11-003

Study of UE activity at forward rapidity (II)

- Trigger/event selection
  ➔ charged particles in region $3.23 < |\eta| < 4.65$
  ➔ exactly one primary vertex
  ➔ at least one HF tower with energy > 4 GeV in $3.23 < |\eta| < 4.65$
  ➔ at least one CASTOR tower with energy above 1.5 GeV

- Hard scale reconstructed by central leading track-jet
  ➔ anti-k_T with $R = 0.5$ & $p_T > 1$ GeV, $\eta < |2|$

- Energy density in CASTOR reconstructed by the total charge collected by the PMTs of the 5 front z-modules

- Data corrected to hadron level
  ➔ selection of dominantly nondiffractive sample using Lorentz invariant ξ

$$\xi_X = \frac{M_X^2}{s}, \qquad \xi_Y = \frac{M_Y^2}{s}, \qquad \xi_{DD} = \frac{M_X^2 M_Y^2}{m_p^2\, s}$$

$\sqrt{s}$ (TeV)	ξ_X^{min}	ξ_Y^{min}	ξ_{DD}^{min}
0.9	0.1	0.4	0.5
2.76	0.07	0.2	0.5
7	0.04	0.1	0.5

- Systematic uncertainties
  ➔ Total values range from 3.6% to 11%
  ➔ Main contributions: - uncertainty on CASTOR detector position
  (energy density at forward rapidity is very sensitive to small shifts)
  - model dependence on correction factors

CMS-PAS-FWD-11-003

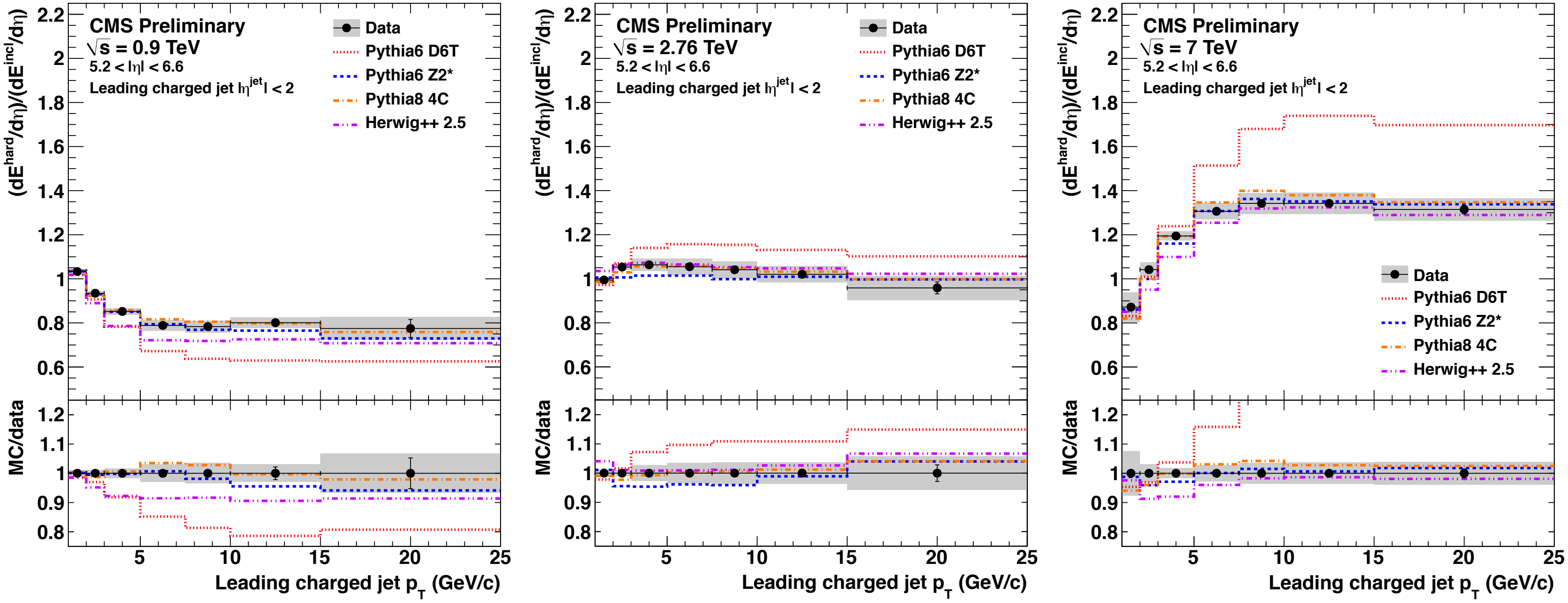
Study of UE activity at forward rapidity (III)

- Hard-to-inclusive ratio vs leading charged jet p_T at $\sqrt{s}$ = 0.9, 2.76, 7 TeV

At 0.9 TeV: ratio below 1
production of central hard jets accompanied with higher UE activity depletes energy of the proton remnant which fragments in CASTOR

At 7 TeV well known UE behaviour: fast increase at low p_T followed by a plateau above p_T=8 GeV/c

At 2.76 TeV the increase of the ratio is much reduced



➔ Pythia tunes fitted to LHC (Z2*, 4C) & Herwig 2.5 describe data well
➔ Older tune Pythia6 D6T predicts too much MPI

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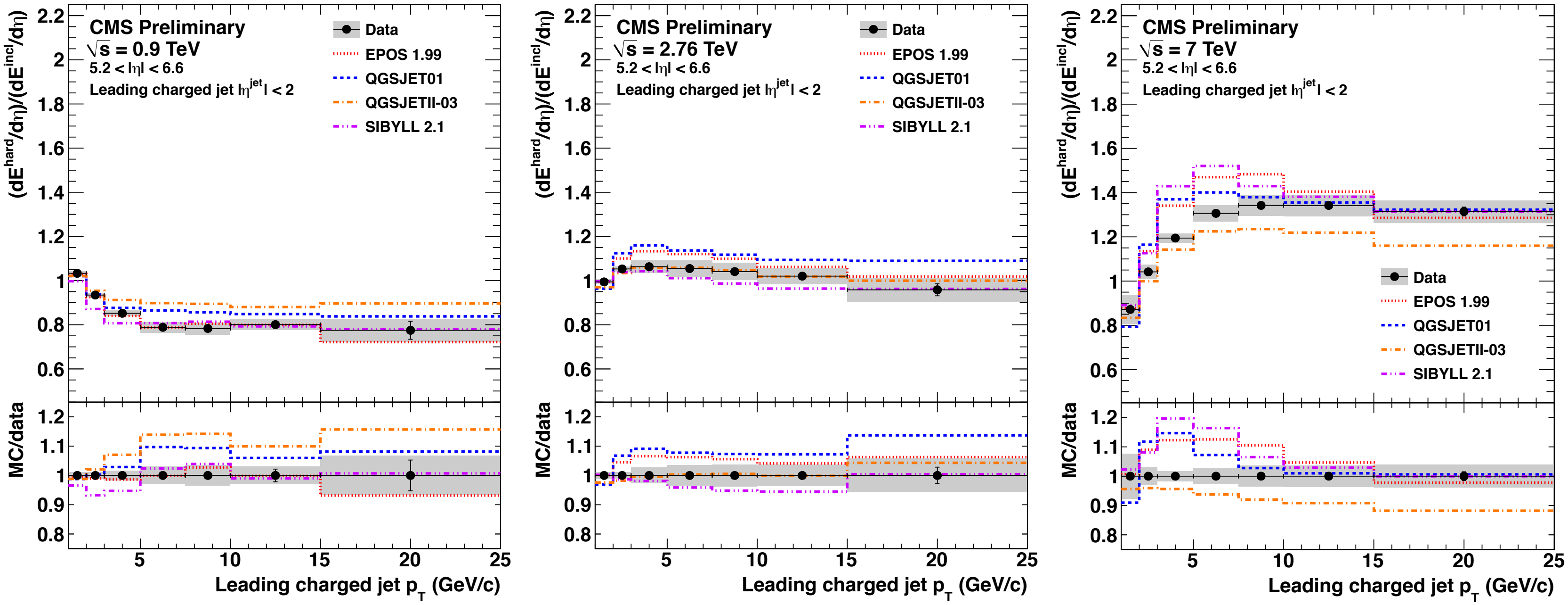
Study of UE activity at forward rapidity (IV)

- Hard-to-inclusive ratio vs leading charged jet p_T at $\sqrt{s}$ = 0.9, 2.76, 7 TeV

At 0.9 TeV: ratio below 1
production of central hard jets accompanied with higher UE activity depletes energy of the proton remnant which fragments in CASTOR

At 7 TeV well known UE behaviour: fast increase at low p_T followed by a plateau above p_T=8 GeV/c

At 2.76 TeV the increase of the ratio is much reduced



➔ Cosmic ray models are not tuned to LHC
➔ None of the tunes can fully describe the data

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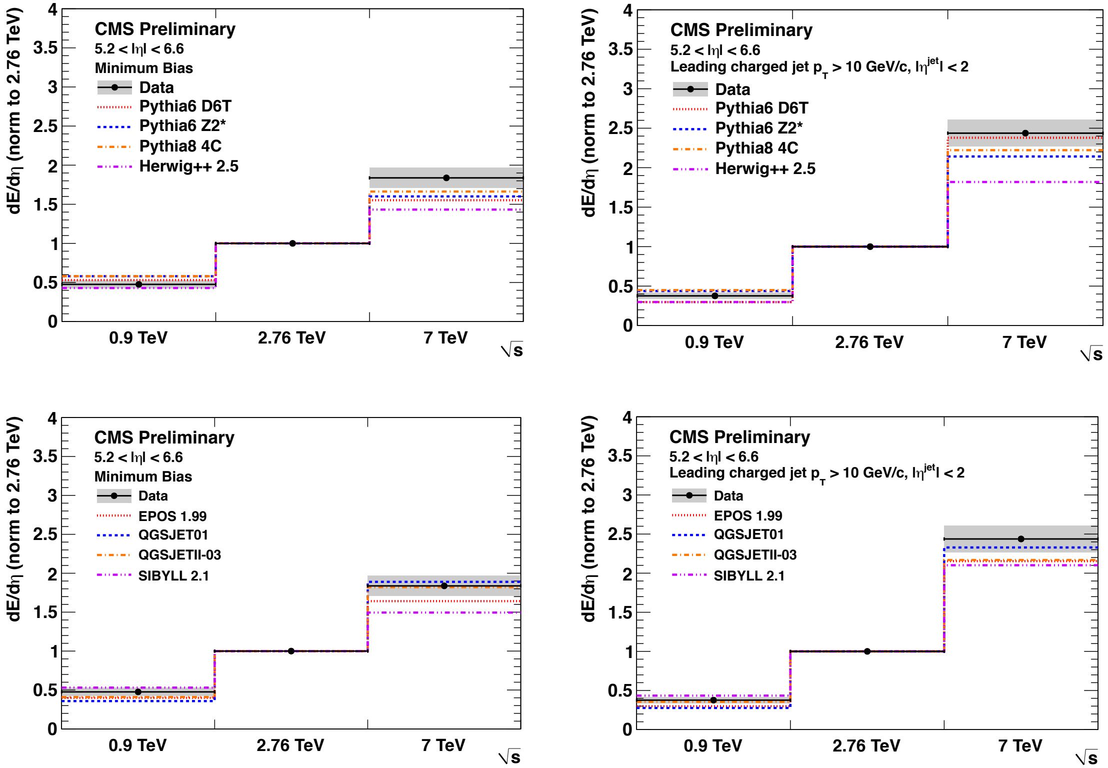
Study of UE activity at forward rapidity (V)

- Normalized energy density vs √s:
  - ➔ normalized to 2.76 TeV (minimize systematic uncertainties)
  - ➔ for both inclusive and hard scale (leading charged jet, p_T > 10 GeV/c, |η| < 2) events



Energy density increases much faster in events with a hard scale

Inclusive events:

- ➔ None of the Pythia & Herwig models can describe the relative increase at 7 TeV
- ➔ QGSJET describes data, other tunes underestimate

Hard scale:

- ➔ Pythia6 D6T & QGSJET01 close to the data, other tunes underestimate the increase

- Increase of the UE activity with centre-of-mass energy very challenging

CMS-PAS-FWD-11-003

Summary

- Measurements of the forward energy flow in CMS

  ➔ at rapidities $3.15 < |\eta| < 4.9$ for minimum bias events and events with a hard scale present (dijet system)
  ➔ at 2 different centre-of-mass energies: 0.9 and 7 TeV

- Novel study of the Underlying Event activity in CMS

  ➔ at rapidities $-6.6 < \eta < -5.2$ using leading jets to measure the relative energy densities
  ➔ at 3 different centre-of-mass energies: 0.9, 2.76 and 7 TeV

- Existing models can already describe many aspects of the UE

  ➔ clearly including MPI improves the description of data
  ➔ evolution of forward energy densities as function of the hard scale of the event (central leading jets)
  ➔ Cosmic Ray models work quite well

- Notable discrepancies

  ➔ None of the MC models can describe all energy flow measurements
  ➔ relative increase of forward energy density in inclusive and hard scale events

Backup slides