Forward energy flow & forward jets in CMS

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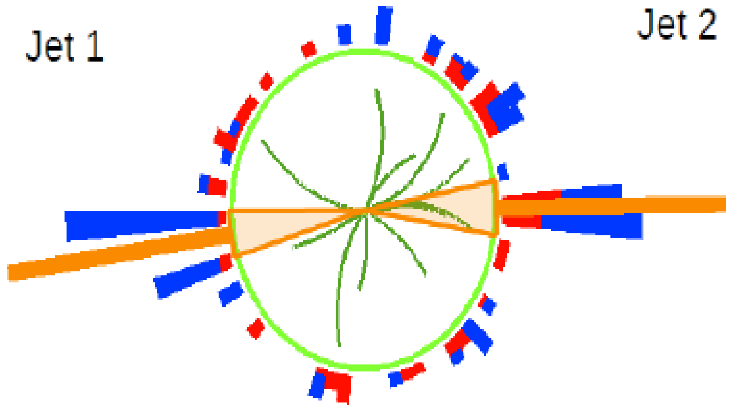
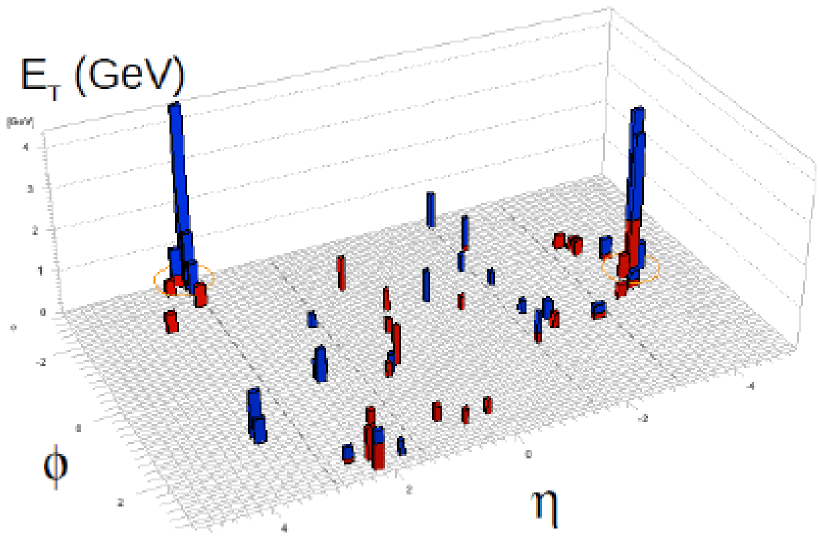
for the CMS collaboration

Low-x, 3-7 June 2011, Santiago de Compostela, Galicia (Spain)

Outline

- CMS detector
- Forward energy flow
  - Minimum bias & dijet datasets
- Forward jets
  - Inclusive forward jets cross section
  - Central + forward jets cross section
- Conclusions





Physics Analysis Summaries:

- FWD-10-003 (inclusive jets)
- FWD-10-006 (central/fwd jets)
- FWD-10-008 (fwd energy flow)
- FWD-10-011 (fwd energy flow)

see also **Soft and hard diffraction at CMS**, Juerg Eugster, Low-x, 6 June 2011

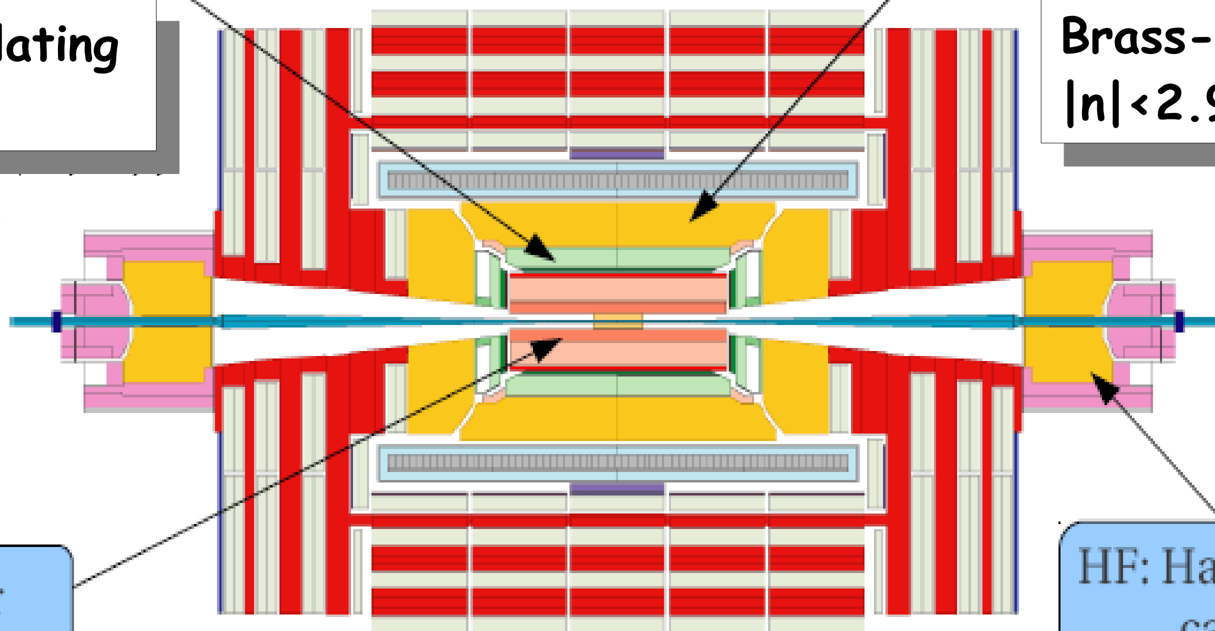
CMS detector

ECAL: Electromagnetic CALorimeter

PBWO4 scintillating crystals $|n|<3$

HCAL: Hadronic CALorimeter

Brass-scintillator $|n|<2.9$

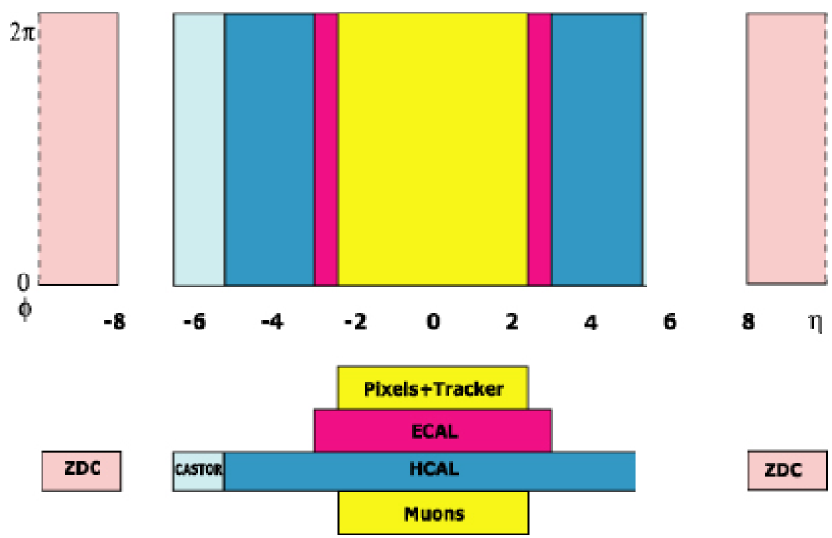


Tracker

Silicon pixel & silicon strip tracker $|n|<2.4$

HF: Hadronic Forward calorimeters

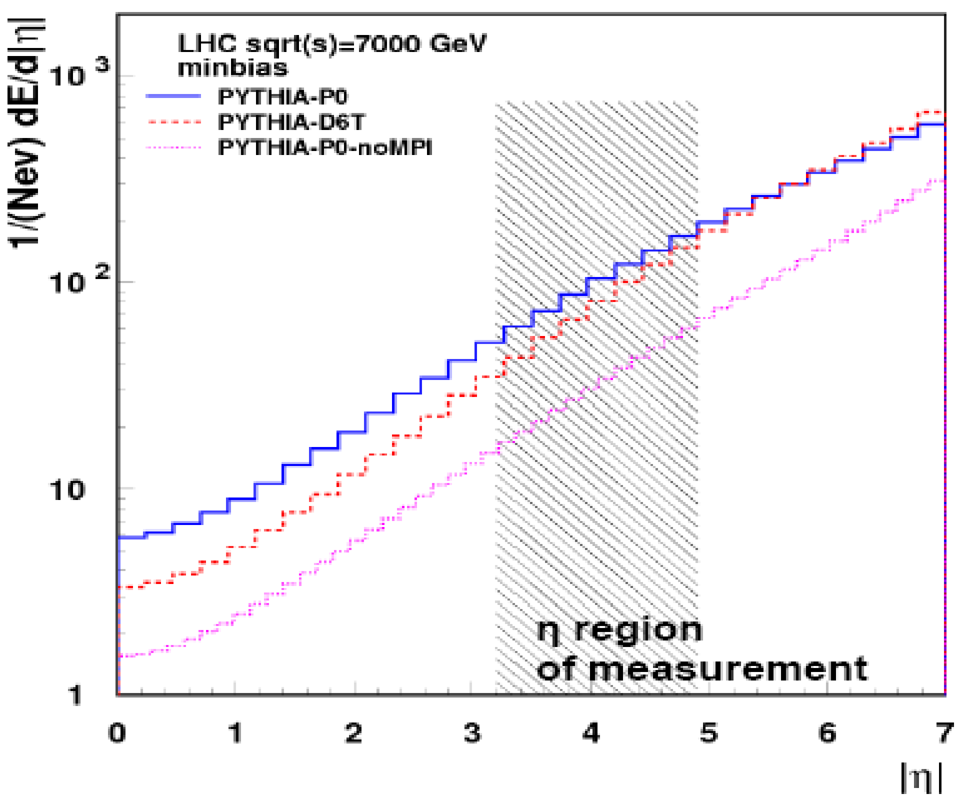
Steel-Quartz fiber Cherenkov calorimeter $\Delta n \times \Delta\varphi = 0.175 \times 0.35$ $2.9 < |n| < 5.2$

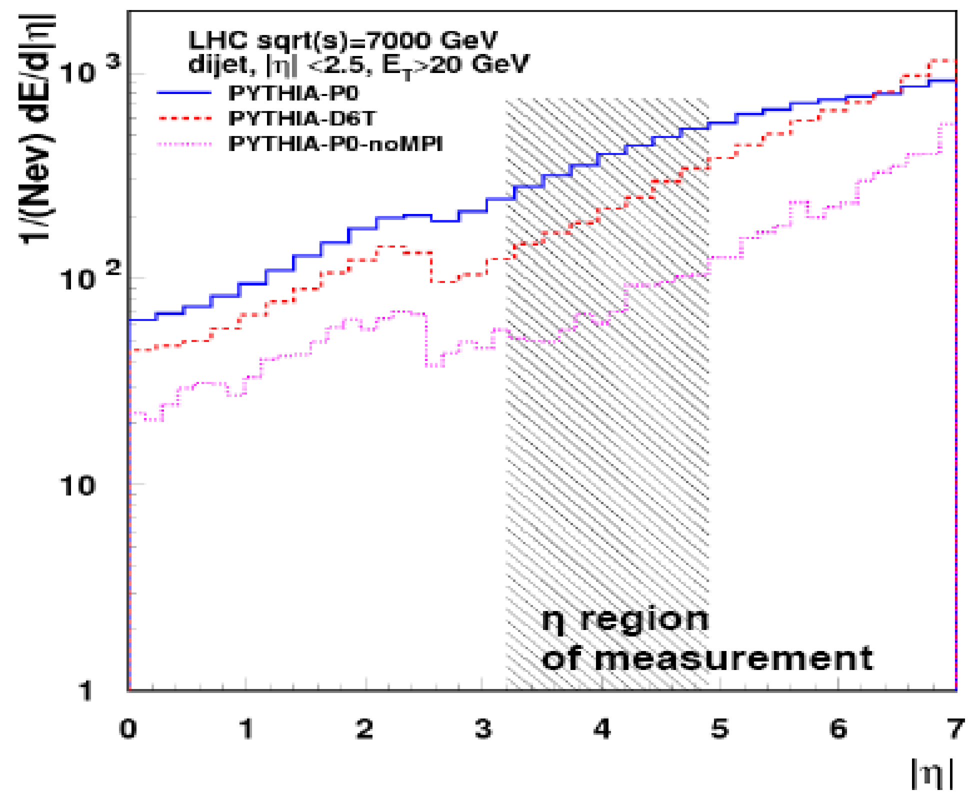


Forward energy flow

Motivation

- Large center-of-mass energies associated with low-x & large parton densities → high probability of multi-parton interactions (MPI)
- Forward region sensitive to the amount of parton radiation and MPI
- Different MPI schemes developed but tuned to measurements in central region; large uncertainty when extrapolating to |η|>3
- Discriminate between models, determine model parameters (tuning)





Analysis strategy

- Energy flow measured in p-p collisions at $\sqrt{s}$ = 0.9 and 7 TeV

$$\frac{1}{N_{events}}\frac{dE}{d\eta}[GeV]$$

- HF acceptance: $3.1 < |\eta| < 4.9$
- Two event classes: non-single diffractive minimum bias & events with a central di-jet system
- Data corrected to hadron level using a bin-by-bin method

Minimum bias selection

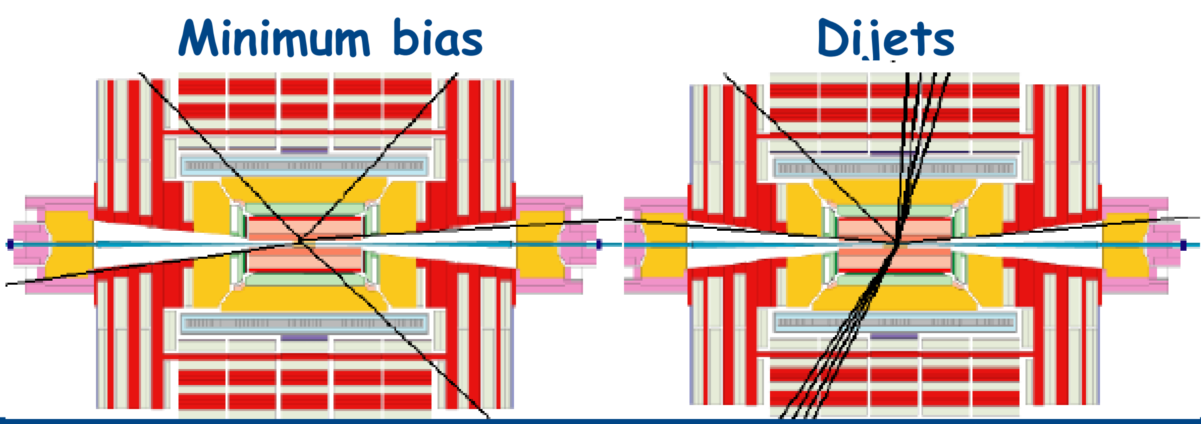
- BSC trigger on non-single diffractive events
- HF tower energy > 4 GeV (noise)

Dijet events selection

- Anti kT algorithm (R=0.5)
- Jets in $|\eta|<2.5$ and back-to-back $|\Delta\varphi - \pi| < 1$
- p_T > 8 (20) GeV, $\sqrt{s}$ = 0.9 (7) TeV

Hadron level definition

→ stable particles, excluding muons & neutrinos
→ at least one charged particle in forward AND backward region
→ hadron-level jets selected with same criteria as in data (p_T, η, $\delta\varphi$)



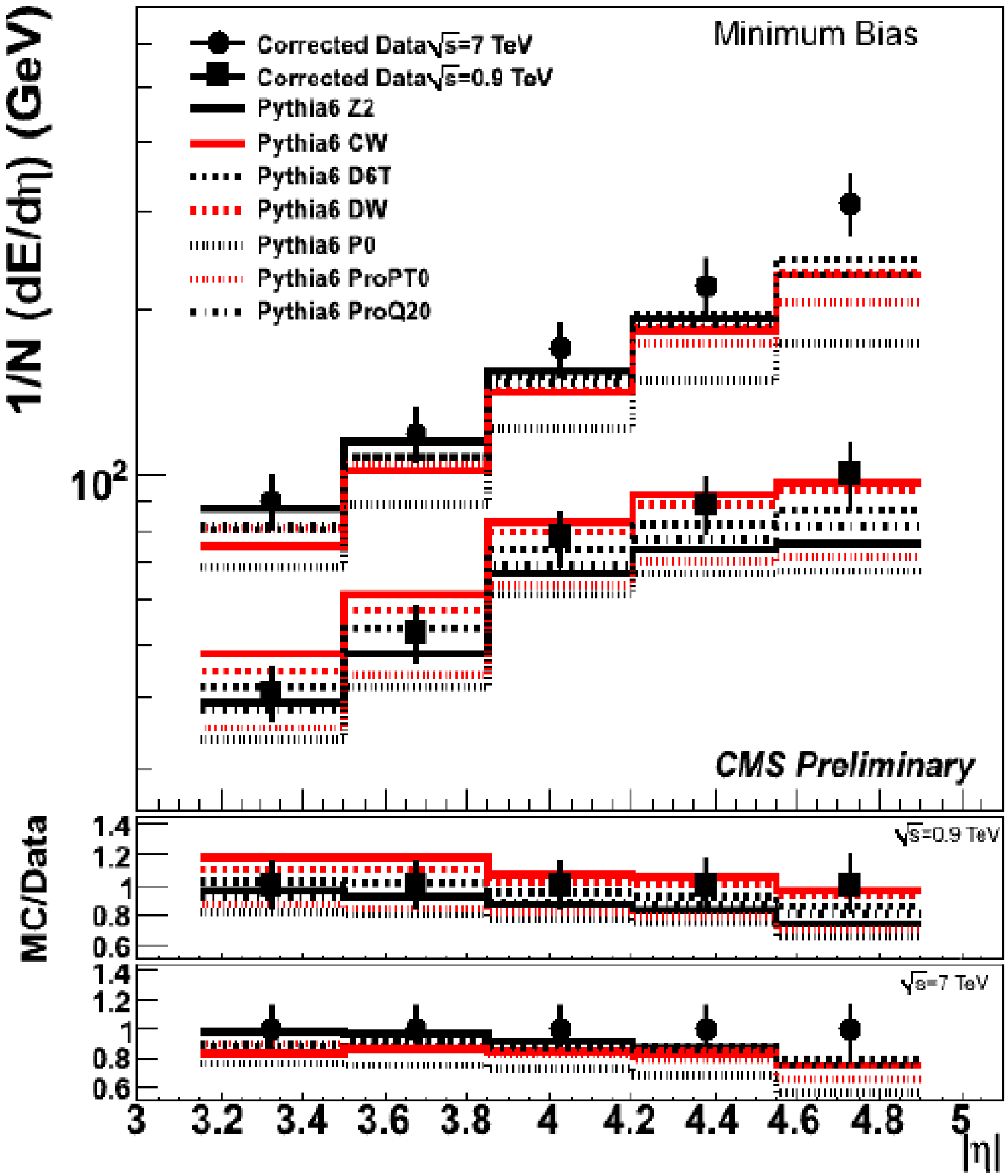
Systematic uncertainties

- **Energy scale uncertainty : 10%**
- **Model dependent uncertainties**
  - estimated by different Pythia 6 tunes used for the bin-by-bin corrections
  - minimum bias events : 3-9%
  - dijet events : 4-18%
- **Other uncertainties < 5%**
  - vertex position, HF calibration, noise cut, HF non-uniformity, jet energy scale, ...
- **Total systematic uncertainties**
  - minimum bias events : 11-14%
  - dijet events : 13-22%

Results – Minimum bias

Comparison to Pythia 6 tunes

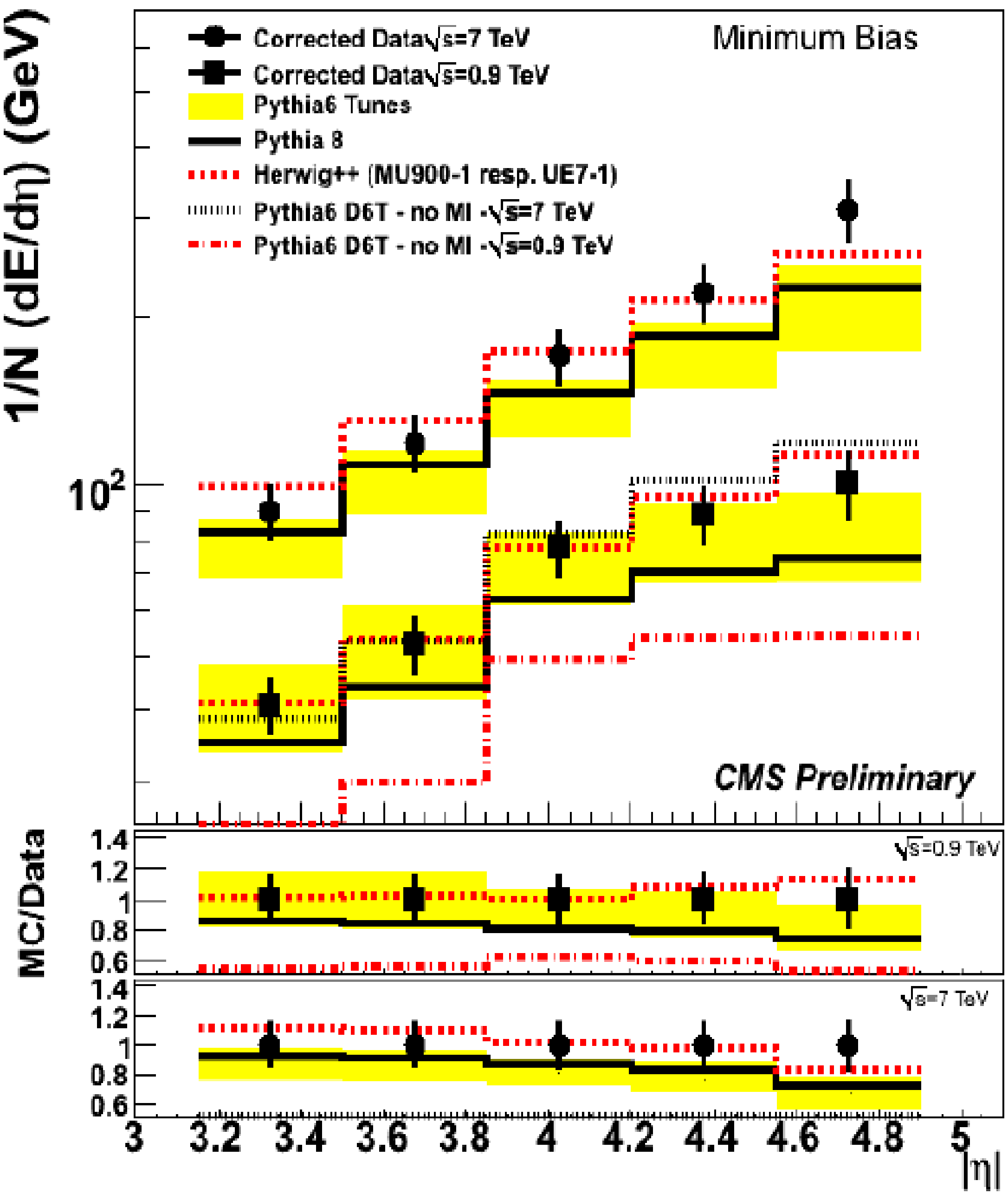
- Strong dependence on center-of-mass energy
- Predictions within large spread
- No systematic difference between tunes with p_T and Q^2 ordered showers
- ProQ20 provides the best description of the data
- P0 tune fails to describe the data



Results – Minimum bias

Comparison to different Monte Carlo generators

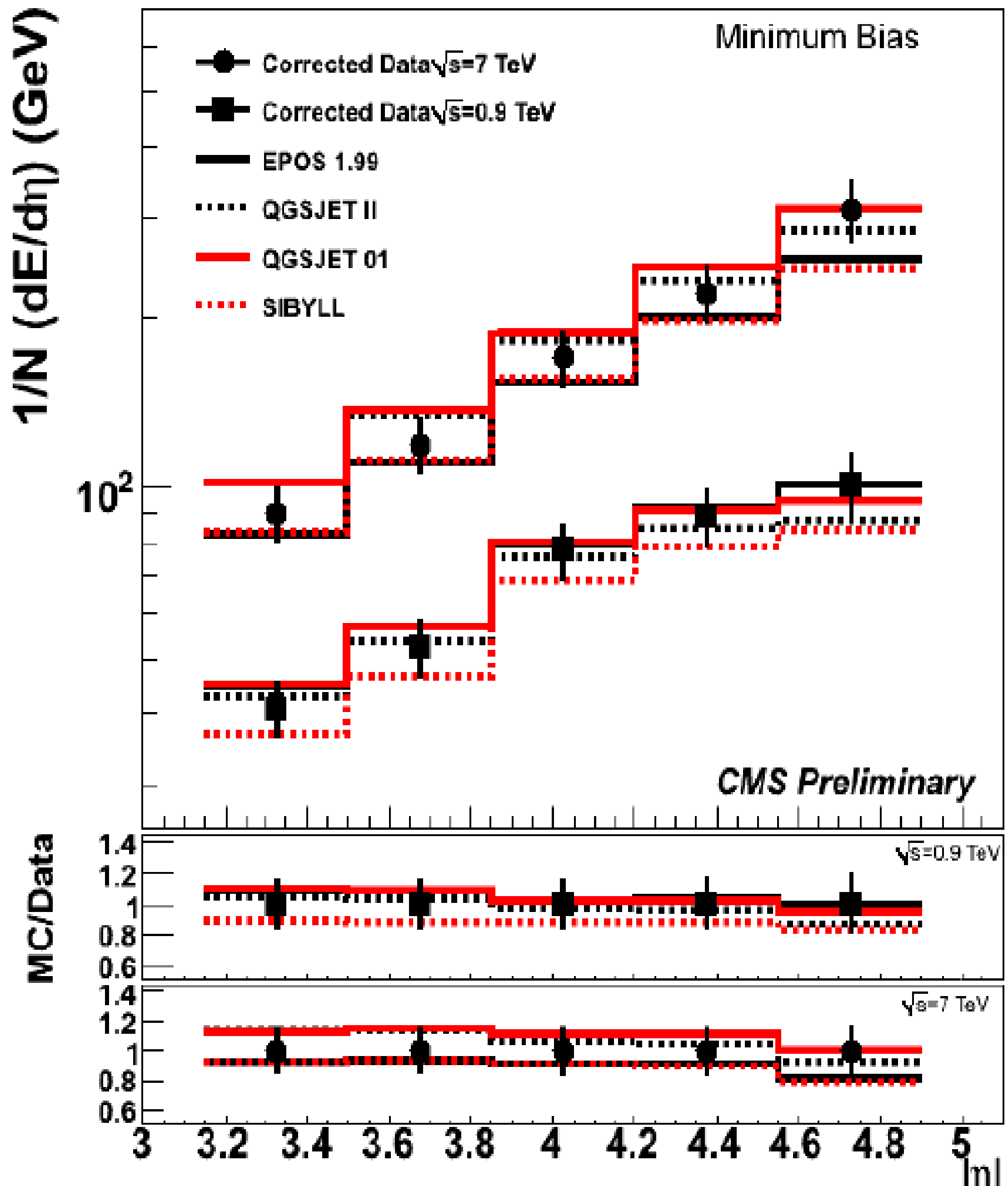
- Herwig++ using center-of-mass specific tunes describes the data well
- Pythia 8 fails to describe the data at the two highest |η| bins
- Significant contribution from multi-parton interactions; needed to describe the data



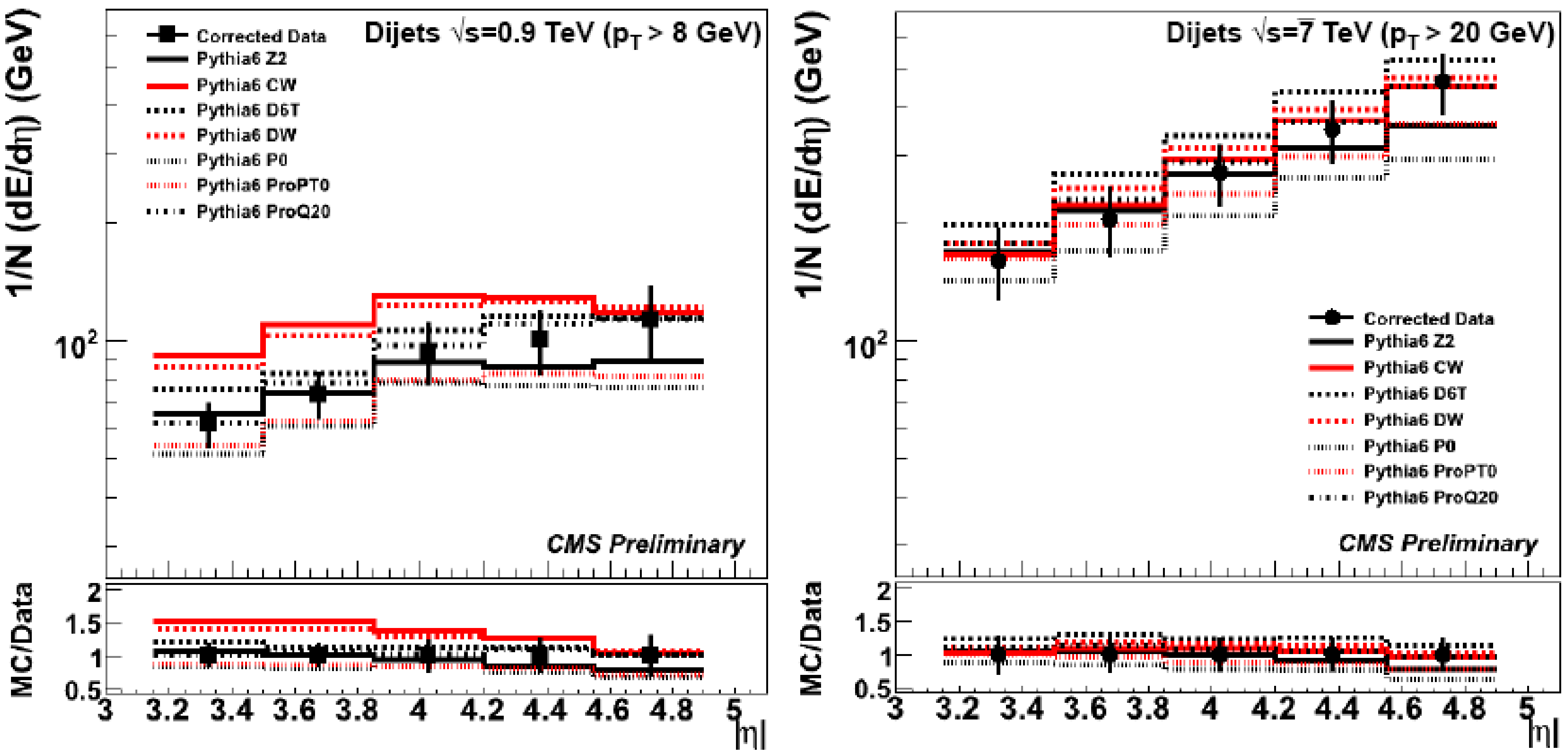
Results – Minimum bias

Comparison to cosmic-ray Monte Carlo generators

- Overall very good agreement with the data at both energies
- Small discrepancy only at the highest |η| bin
- Cosmic-ray MC developed to describe the forward region more accurately (RFT, multiple Pomeron exchange + DGLAP parton ladders)

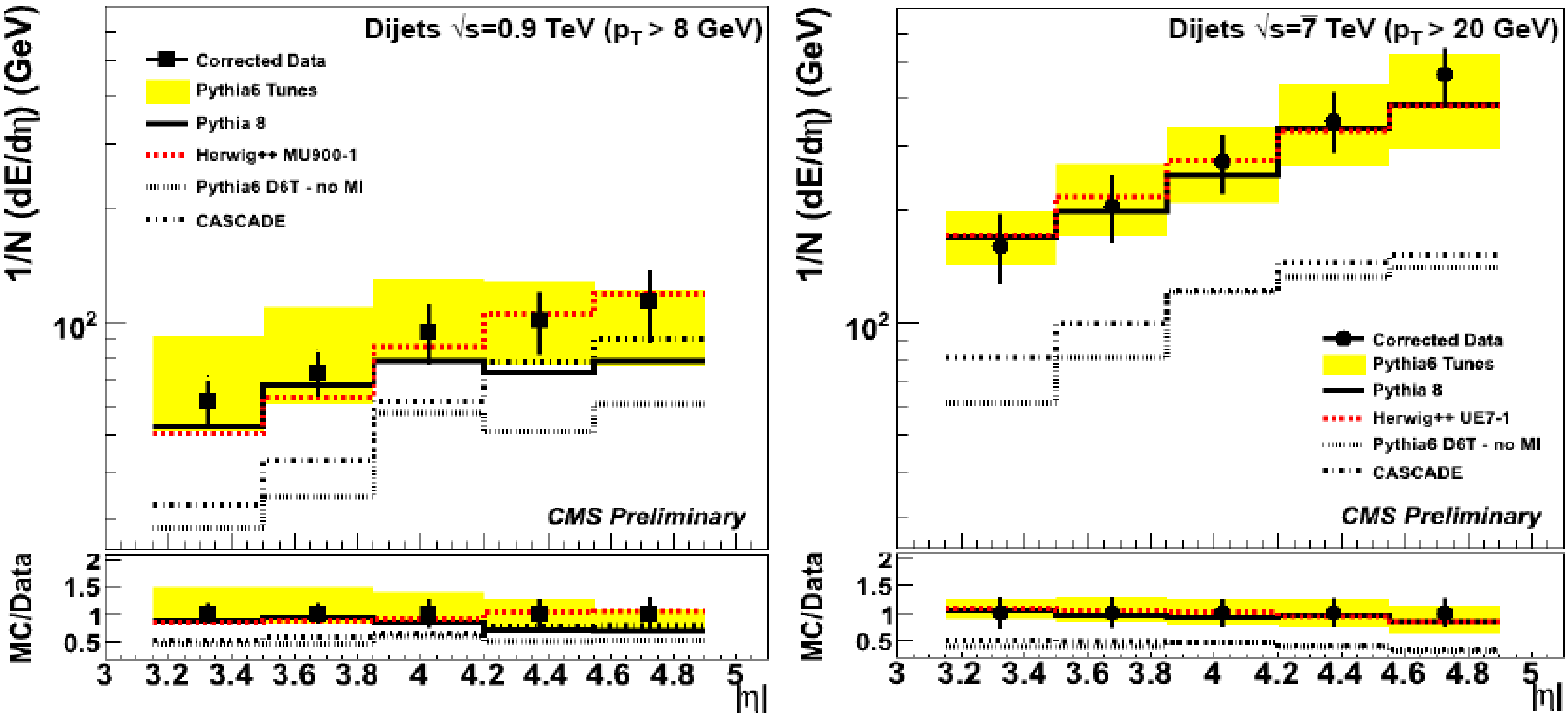


Results – Dijet events



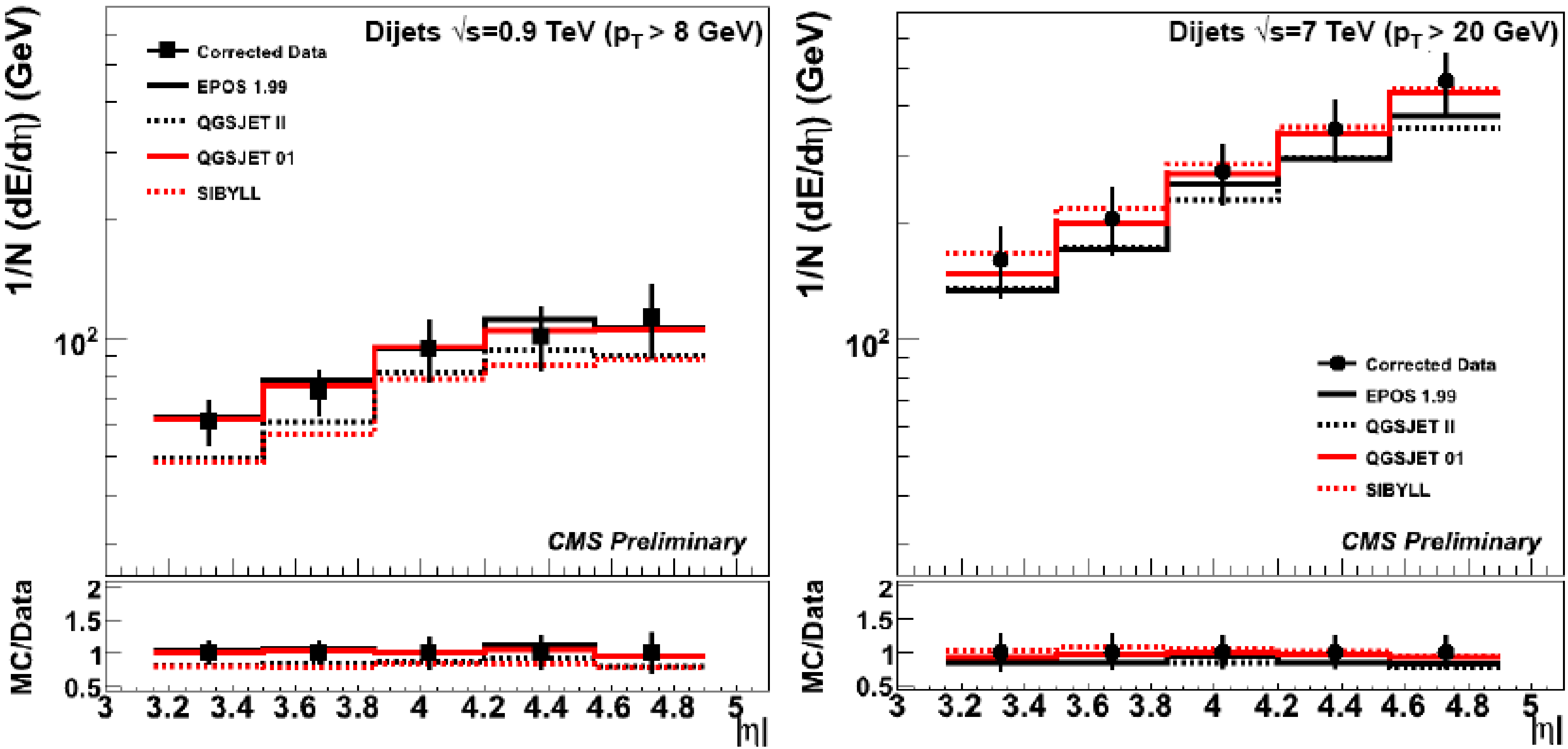
- Significantly higher forward energy flow in dijet events
- Pythia 6 tunes show larger spread in their predictions
- Only ProQ20 describes both 0.9 and 7 TeV data within errors

Results – Dijet events



- Pythia 6 band of predictions envelopes the data at both energies
- Pythia 8 describes the data better at 7 TeV than at 0.9 TeV
- Herwig++ tunes provide good description of the data
- Significant contribution from MPI as in minimum bias
- CASCADE gives higher energy flow than Pythia w/o MPI

Results – Dijet events

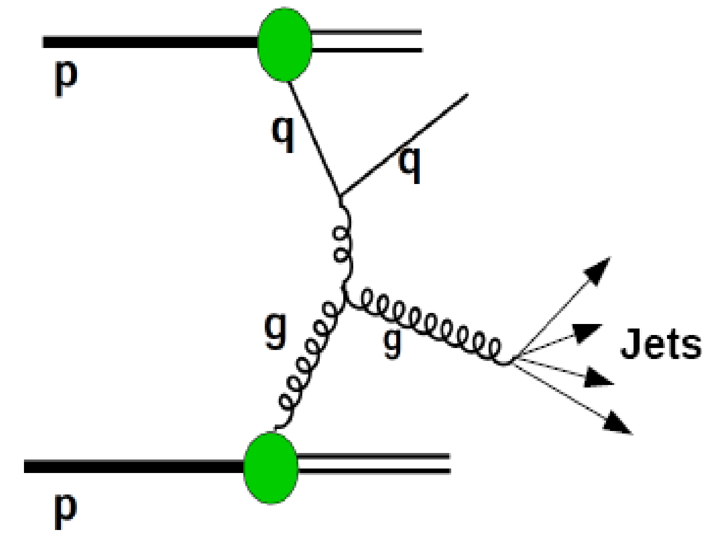


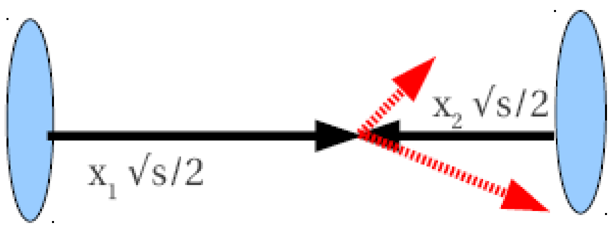
- Cosmic-ray Monte Carlo generators describe the forward energy flow in dijet events as well as for minimum bias
- QGSJET 01 is in best agreement with the data
- Smaller spread in the predictions compared to Pythia 6 tunes

Forward jets

Motivation

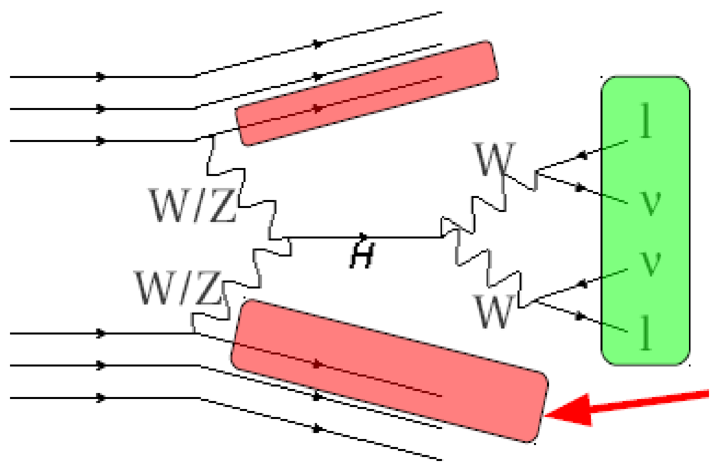
- Jet production in the forward region:
  - Test theory in a previously unexplored kinematic regime
  - QCD at very small-x
  - PDF less constrained by DIS data
  - Deviations beyond DGLAP evolution (e.g BFKL, CCFM or gluon saturation)
  - Beyond QCD: Higgs production via vector-boson-fusion process





$$x_2^{min} \sim \frac{p_T}{\sqrt{s}} \cdot e^{-y}$$

factor of 10 in x per 2 units of rapidity

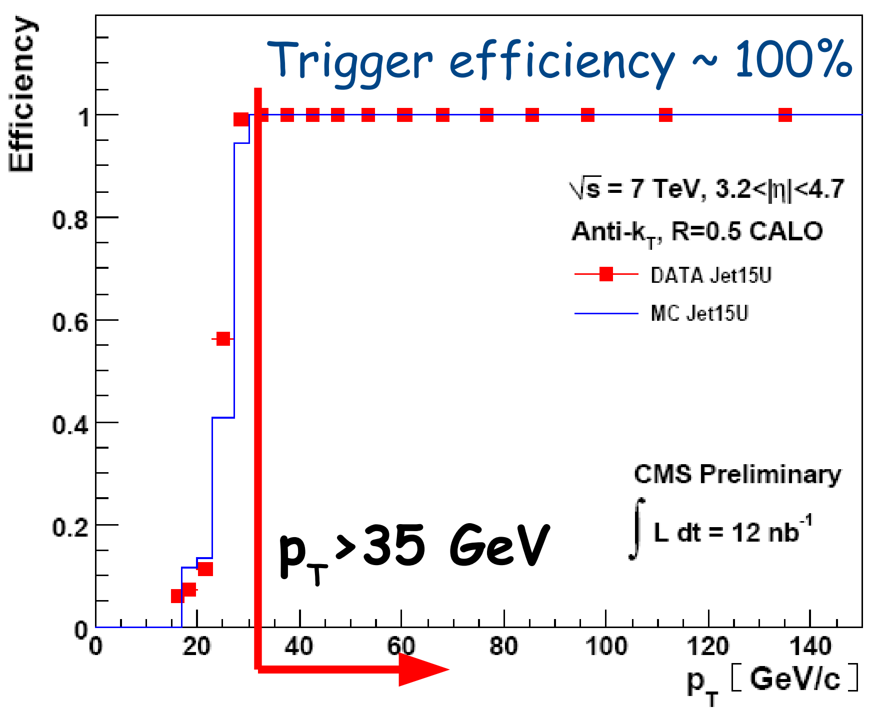


Analysis strategy

- Anti-k_T jet clustering (R=0.5)
- Single-jet triggers with uncorrected p_T > 15 GeV
- Jet quality criteria
- Good primary vertex
- acceptance: 3.2 < |η| < 4.7

$$\frac{d^2\sigma}{dp_T d\eta} = \frac{C_{unfold}}{L} \cdot \frac{N_{jets}}{\Delta p_T \Delta\eta}$$

- C_{unfold}: detector to hadron level correction accounting for bin-by-bin migrations due to resolution effects, trigger efficiency, etc.



Monte Carlo bin-by-bin method

$$C_{unfold} = \frac{N^{MC}(E^{MC}_{had} \in bin\ )i}{N^{MC}(E^{MC}_{det} \in bin\ )i}$$

Ansatz method

$$f(p_T) = N_0 \cdot p_T^{-\alpha}(1 - \frac{2cosh(y_{min}p_T}{\sqrt{s}})^{\beta} e^{-\gamma/p_T}$$

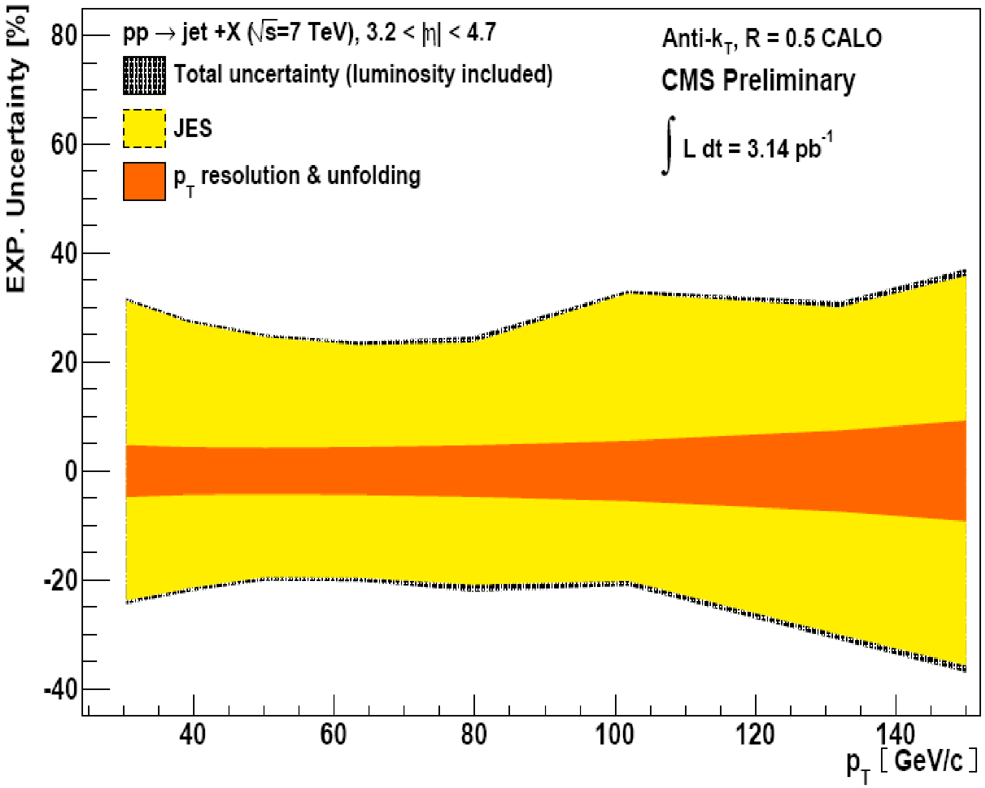
Systematics

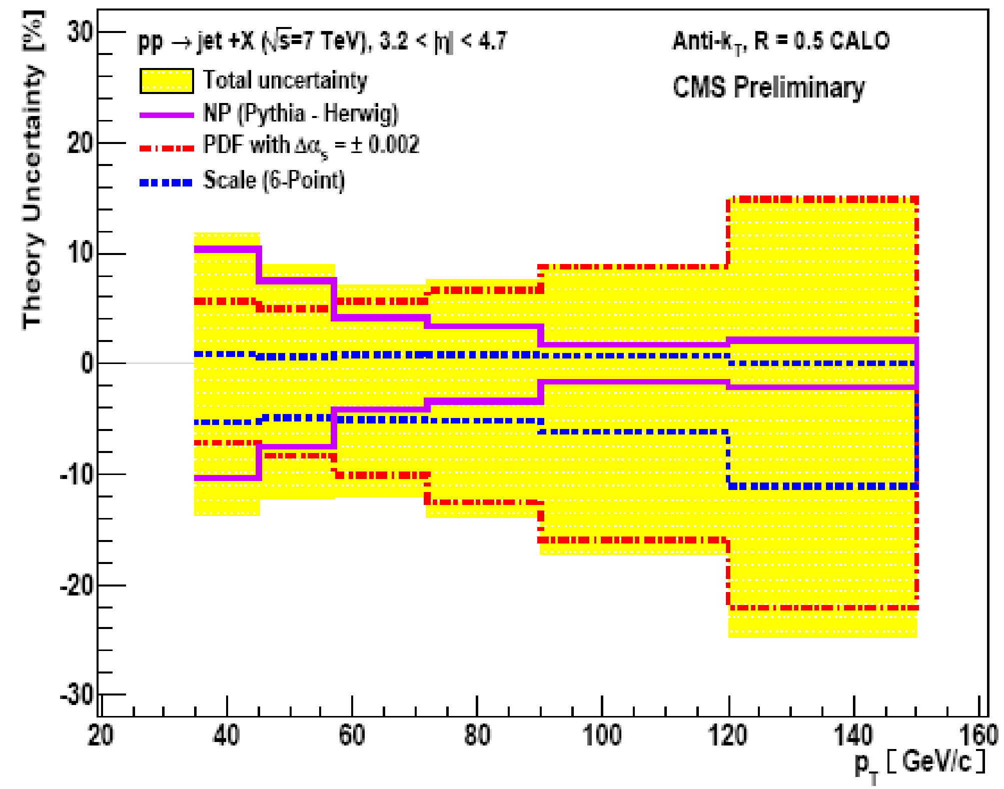
Experimental uncertainties:

- Jet energy scale ~ 30%
- p_T resolution ~ 6%
- Model dependence ~ 3%
- Luminosity ~ 4%

Theoretical uncertainties:

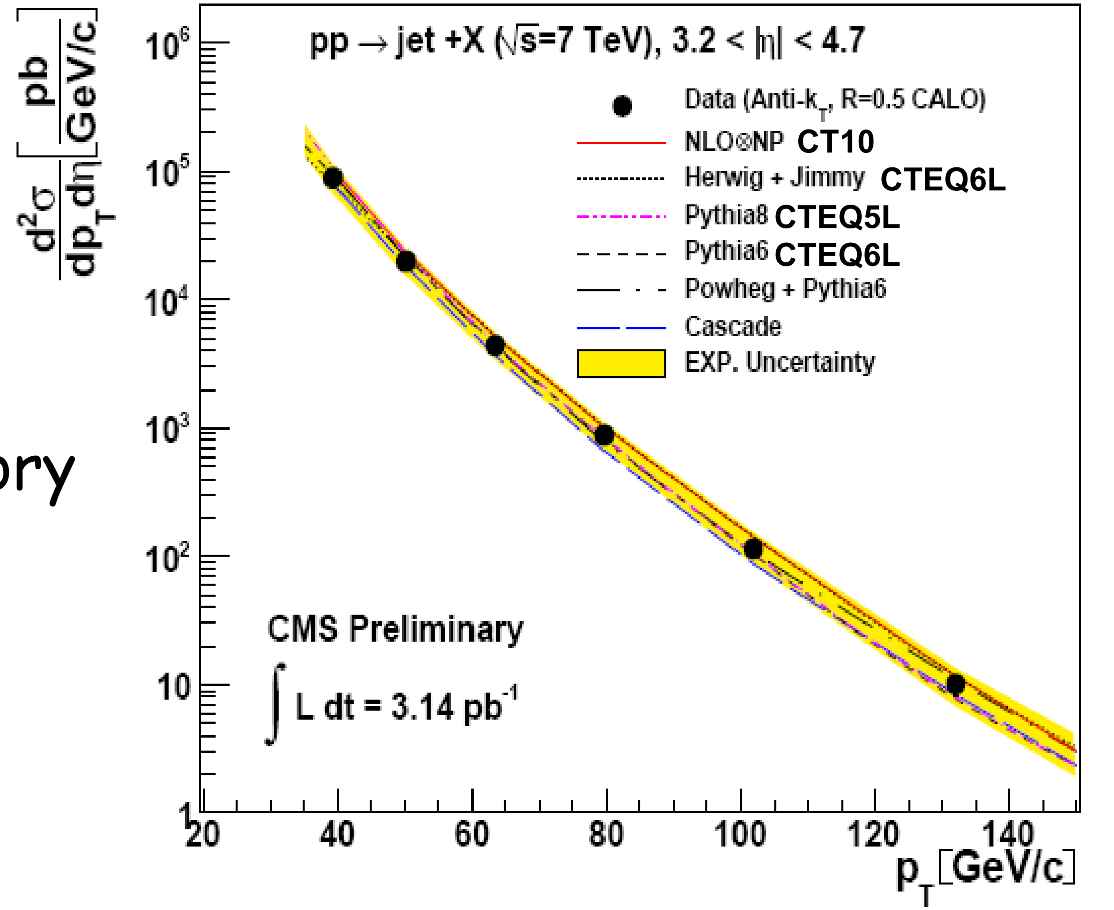
- Hadronization & UE (Pythia vs Herwig++)
- PDF uncertainty
- Renormalization & factorization scales

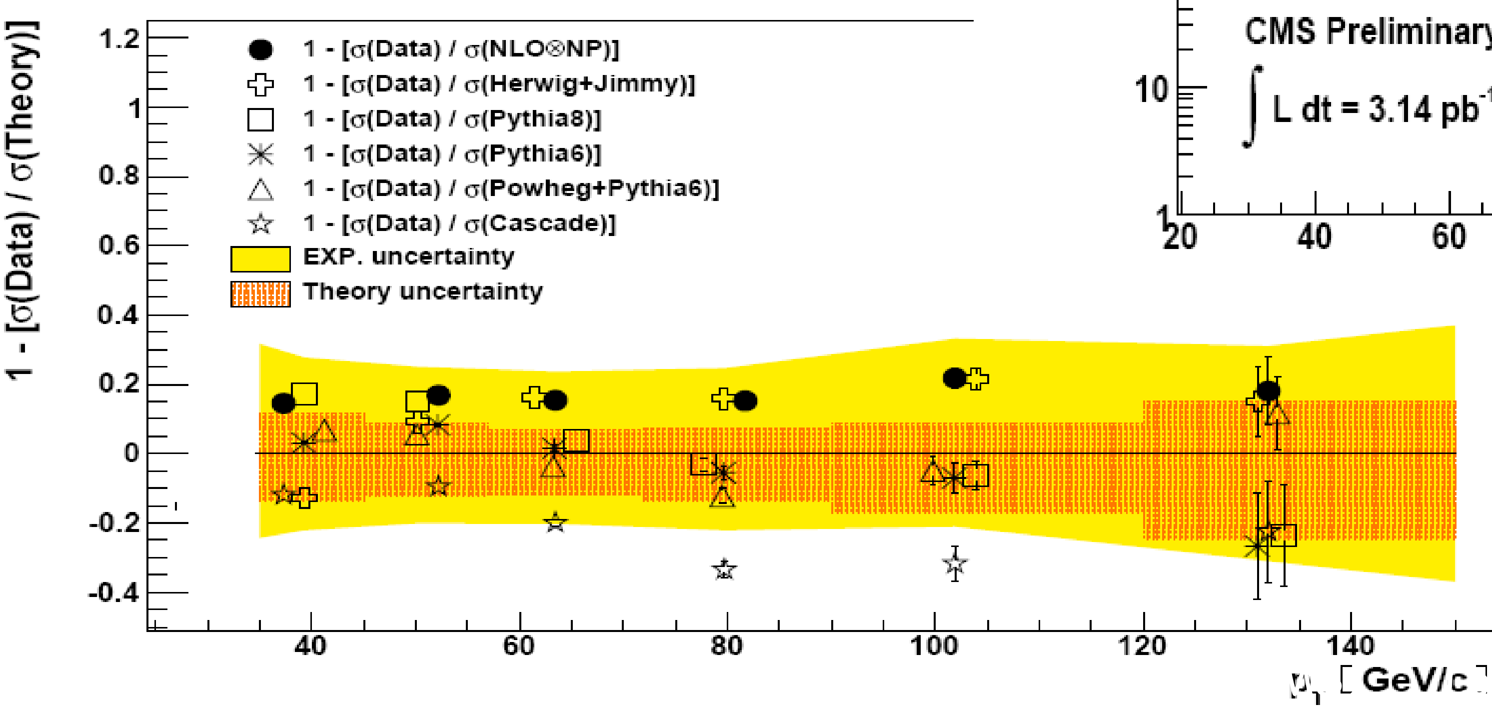




Inclusive fwd jets cross section

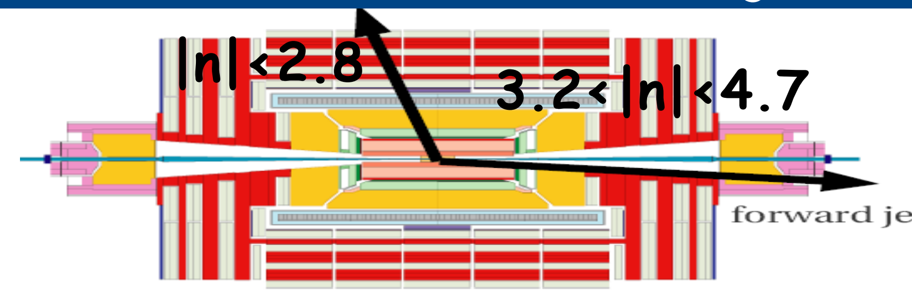
- Theoretical models agree reasonably with the measured cross section within errors
- Reduction of experimental uncertainties needed for more precise conclusions on data/theory

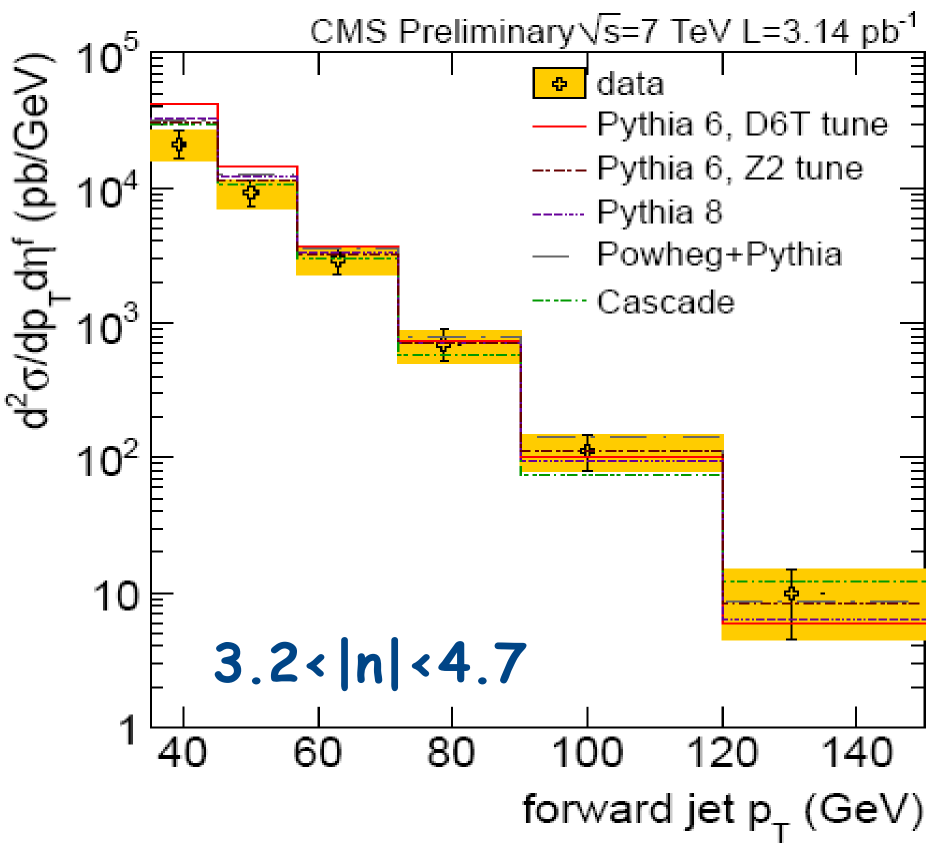


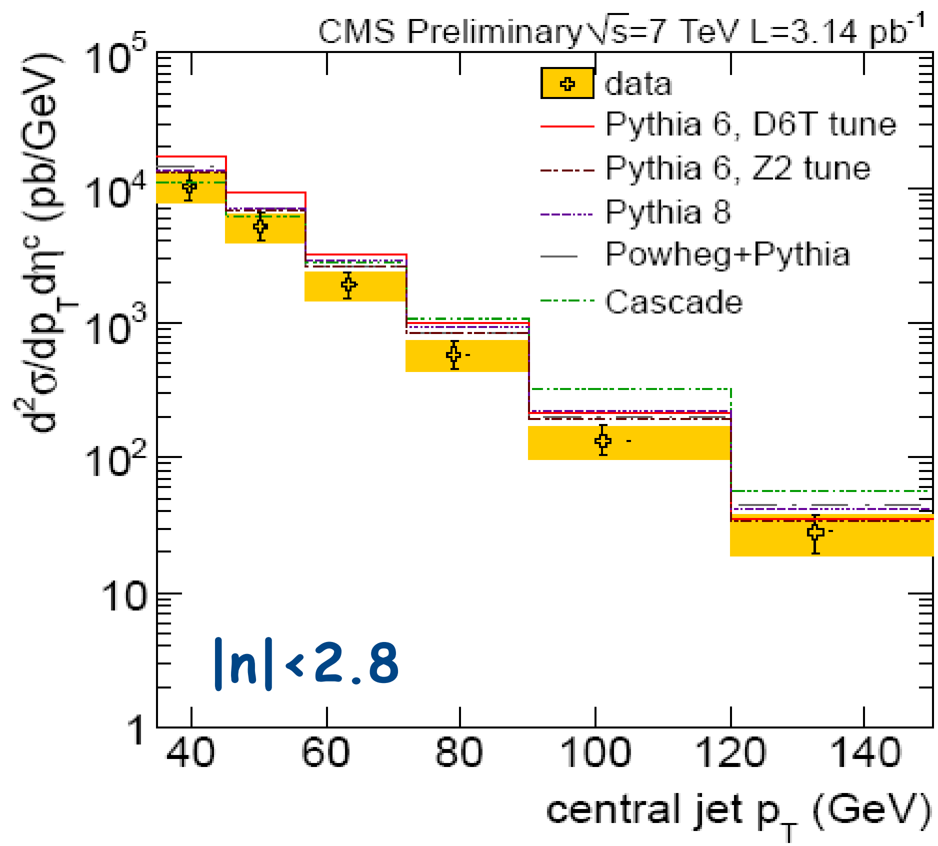


Simultaneous production of fwd+central jets

Events with presence of two jets:
at least 1 central + 1 forward jet

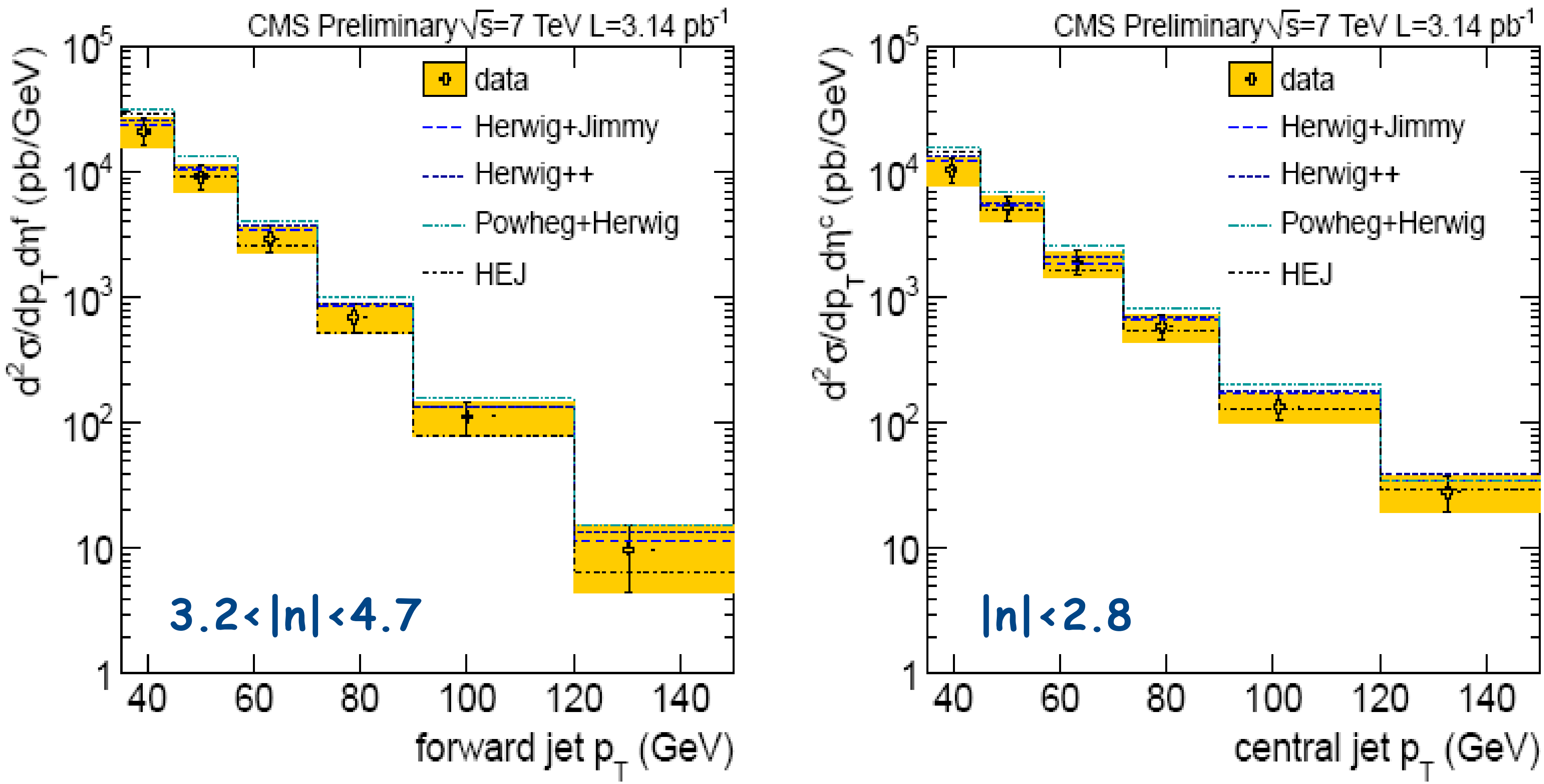






- Inclusive fwd jet spectrum x 4 at low p_T with presence of a central jet
- Pythia tunes generally overestimate the spectra (mainly for central jets)
- CASCADE does not reproduce the central jet spectrum

Simultaneous production of fwd+central jets



- HERWIG++ reproduces better the shape and absolute normalization
- NLO MC POWHEG matched with HERWIG parton shower describes the shape well but not the normalization
- HEJ with multijet topologies in good agreement

Summary

Forward energy flow

- First time measured in $3.1 < |\eta| < 4.9$ at $\sqrt{s}$ = 0.9 and 7 TeV in minimum bias events & events with a hard central dijet system
  - No Monte Carlo generator provides overall consistent description of the data; cosmic-ray generators are however in good agreement with all measurements
- Sensitive to models & tunes; use data for future MC tuning

Forward jets

- Inclusive forward jets cross section in $35 < p_T < 150$ GeV and $3.2 < |\eta| < 4.7$
  - Perturbative calculations globally reproduce the measurement
- Simultaneous production of central + forward jets
  - Observed some disagreements between models & data