Forward Jets, Forward-central Di-jets and Di-jets with Large Rapidity Separations

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on behalf of CMS Collaboration

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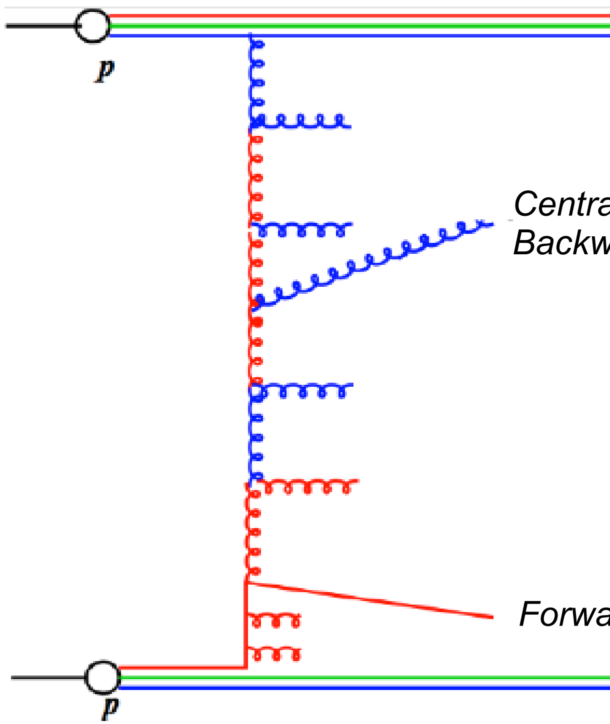
Outline

- Introduction
- Measurements
  - Forward and central jet cross-sections
  - Ratios in di-jet events
  - Azimuthal correlations of jets widely separated in η New!
- Summary / Conclusions

Physics Motivation

- **Forward Jets:**
  Classic final state for studies of higher order QCD, parton dynamics beyond DGLAP, BFKL effects.



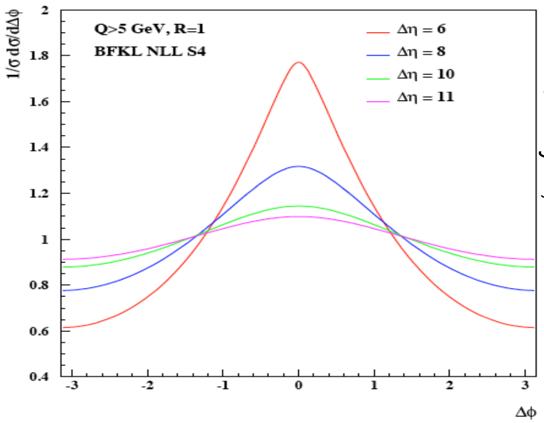
- **Azimuthal de-correlations between di-jets:**
  At LO: Δφ =180

  Higher order reactions: Δφ < 180
  In DGLAP the momentum balance between the two jets is expected to be more conserved, while H.O BFKL emissions expects to give a flatter Δφ distribution.

  Additional effects from using unintegrated gluon densities.
  Input k_t from gluon PDF > 0 → Δφ < 180 already at LO

- **Jets with large rapidity separation:**
  Large rapidity range between jets to further open up phase space for more emissions.

  Larger separation between jets → more decorrelation in Δφ.



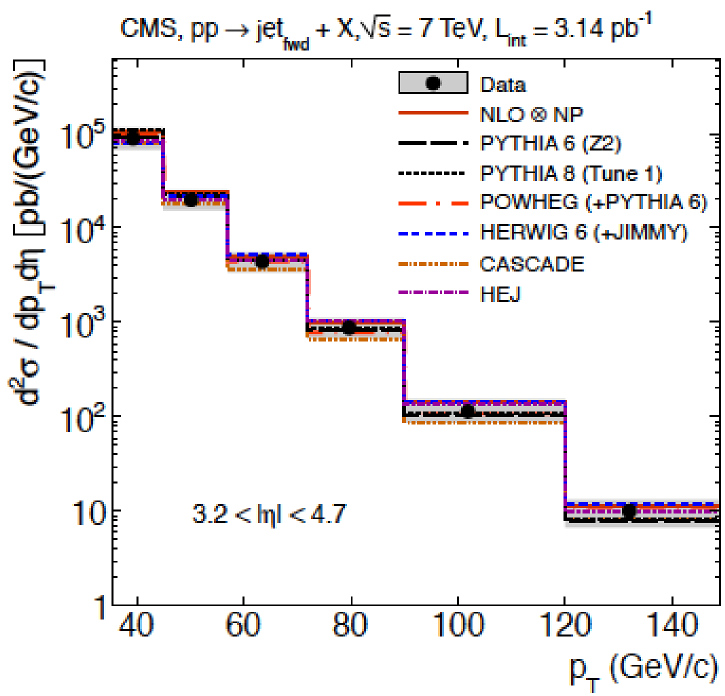
C. Royon, DIS2007

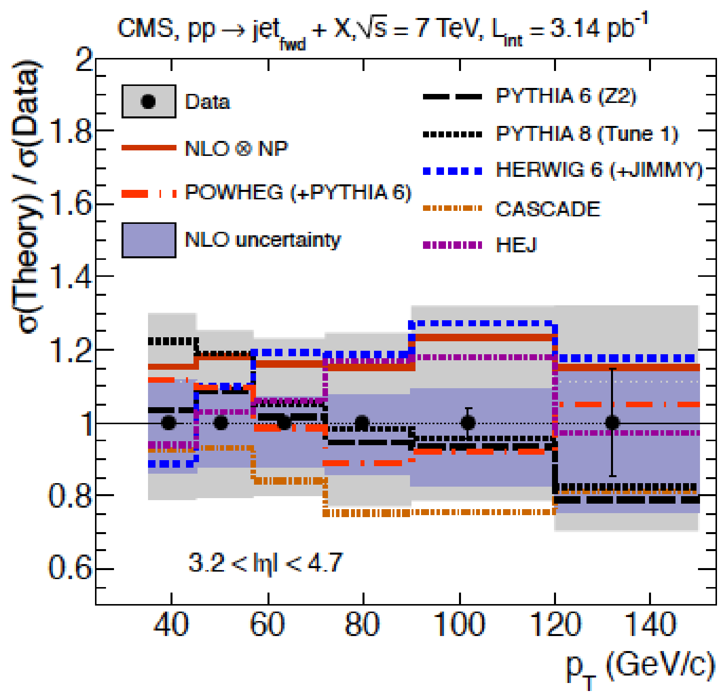
→ **Presented CMS measurements make benefit of all topics.**

Forward and Forward+Central Jet Cross sections

Forward Jet Measurement

Events with at least one jet with 3.5<|η|<4.7 and $p_{t,jet}$>35 GeV





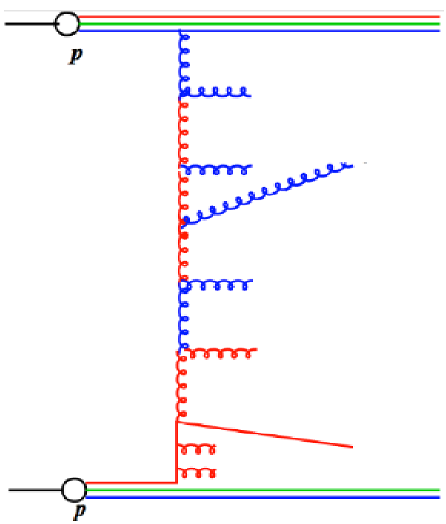
- **All predictions describe the data within the uncertainties.**
- **NLO prediction (NLOJET++) too high, but agrees with the data within the large theoretical and experimental uncertainties.**
- **NLO+PS (POWHEG+PYTHIA6) best.**

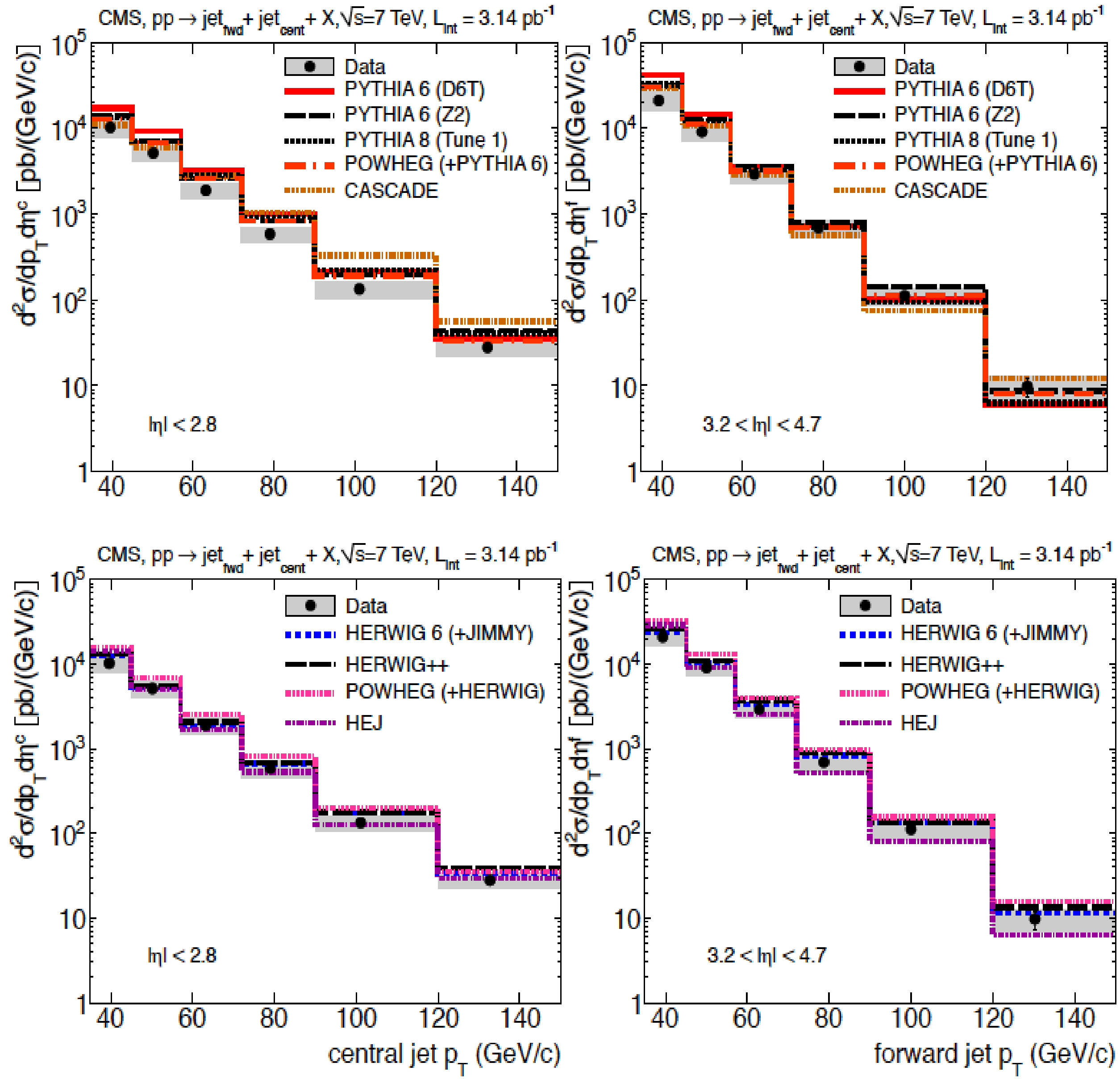
JHEP 1206 (2012) 036
arXiv:1202.0704

Forward+Central Jets

Events with at least one jet with
- $3.5<|\eta|<4.7$
- $p_{t,jet}>35$ GeV

and one central jet with
- $|\eta|<2.8$
- $p_{t,jet}>35$ GeV

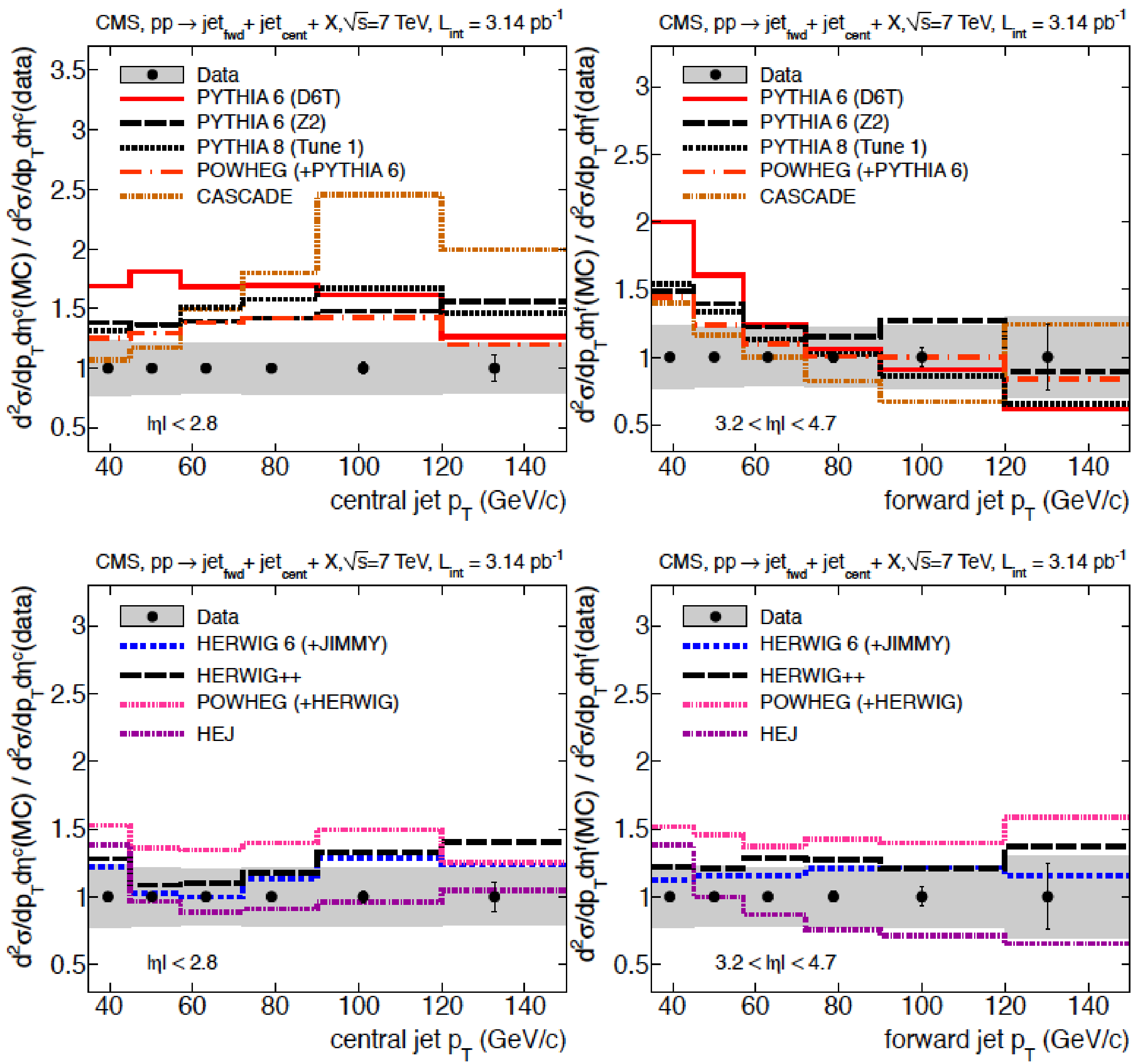




- **Forward jet cross-section somewhat steeper than central jet cross-section.**
- **Comparison to several generators. (ratios on next slide)**

JHEP 1206 (2012) 036
arXiv:1202.0704

- **Difference in MC description of data between the forward and the central jet.**
- **Largest shape difference for forward jet.**
- **Pythia6 and Pythia8, as well as CCFM based CASCADE problem with normalization of the central jet and shape of the forward jet.**
- **Herwig6, Herwig++, and the BFKL inspired MC HEJ describe the data best.**



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Ratios of Dijet Production

Inclusive over Exclusive Di-jet Cross-section

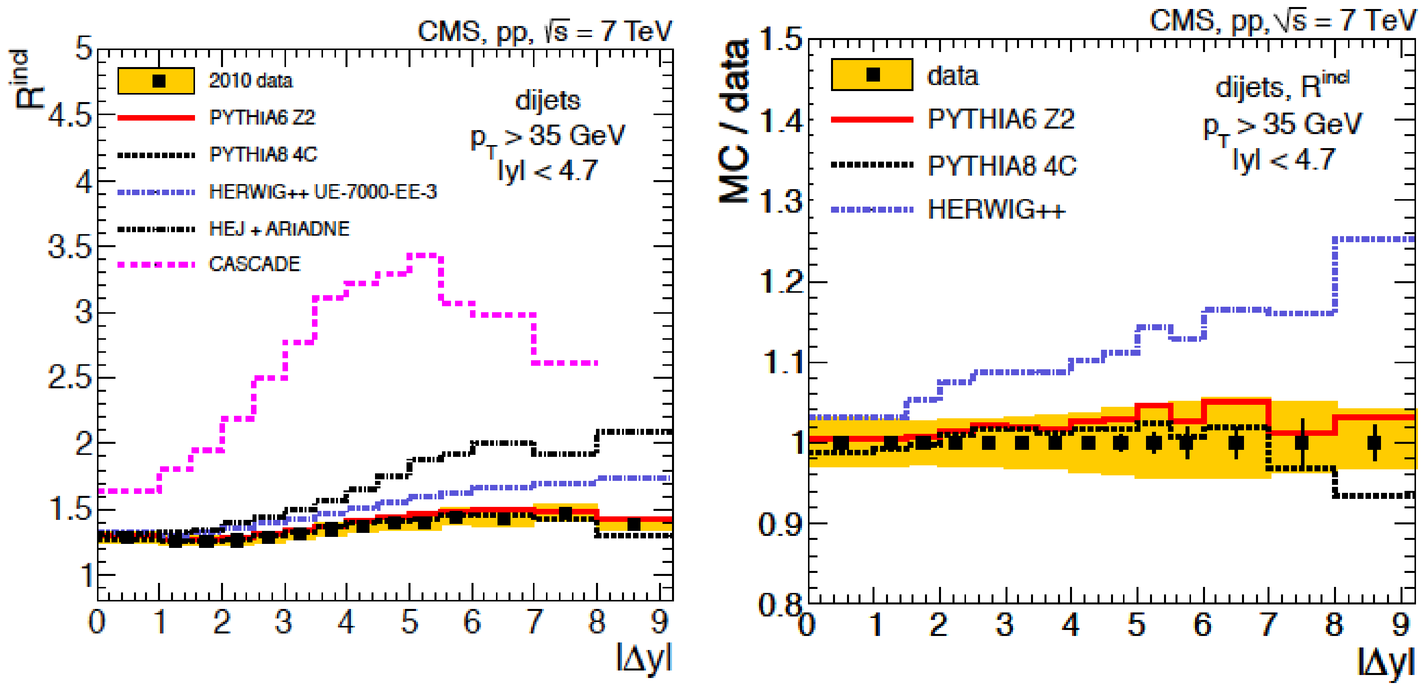
Jets reconstructed with the anti-kT algorithm (R=0.5)
$p_{t,jet}$>35 GeV and $|\eta_{jet}|$<4.7

Observable: Rapidity difference between jets, Δy

Inclusive jets: **All jet pairs in the events considered**
Exclusive jets: **Events with exactly two jets above the threshold**
Mueller-Navelet jets: **Most forward and backward jet in the inclusive sample**

$$R = \frac{\sigma_{dijet}(\text{inclusive})}{\sigma_{dijet}(\text{exclusive})}$$

$$R = \frac{\sigma_{dijet}(\text{MN})}{\sigma_{dijet}(\text{exclusive})}$$



- Increasing Δy → Larger phase space for radiation
- Pythia6 (Z2) and Pythia8 (4C) agrees well with data
- Herwig++ (EE3) and HEJ+Ariadne too high at high Δy
- Small effect from MPI (not shown)
- Cascade off

MN over Exclusive Di-jet Cross-section

Eur.Phys.J.C72(2012)2216
arXiv:1204.0696

Jets reconstructed with the anti-kT algorithm (R=0.5)
$p_{t,jet}$>35 GeV and $|\eta_{jet}|$<4.7

Observable: Rapidity difference between jets, Δy

Inclusive jets: **All jet pairs in the events considered**
Exclusive jets: **Events with exactly two jets above the threshold**
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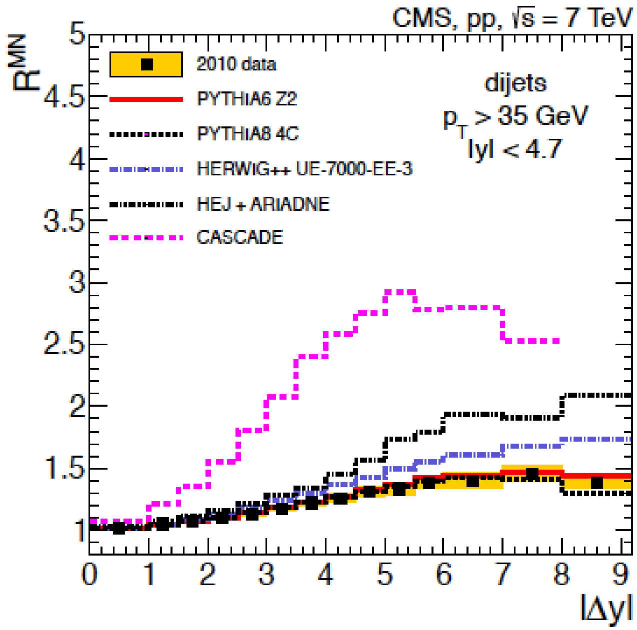
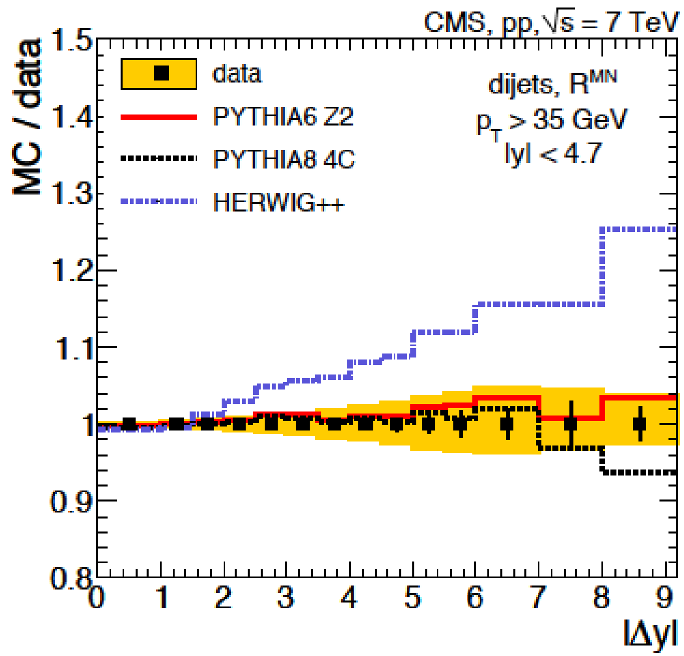
$$R = \frac{\sigma_{dijet}(\text{inclusive})}{\sigma_{dijet}(\text{exclusive})}$$

$$R = \frac{\sigma_{dijet}(\text{MN})}{\sigma_{dijet}(\text{exclusive})}$$





- Low Δy: Ratio(MN/exclusive) per definition *smaller* than Ratio(inclusive/exclusive)
- High Δy: Ratio(MN/exclusive) per definition *same* than Ratio(inclusive/exclusive)
- MC data comparison: same conclusion as on previous slide

General conclusion: No visible effects beyond collinear factorization + LL parton-showers

Azimuthal decorrelations of jet widely separated in η

Measurement

CMS-FSQ-12-002

- $\sqrt{s}$ = 7 TeV, Luminosity ≈ 5 pb^{-1}
- Inclusive single jet trigger, and dedicated forward+backward jet trigger.
- Calorimeter jets - anti-kt algorithm with R=0.5.
- Events with at least two jets with $p_{t,jet}$>35 GeV and $|\eta|$<4.7.
  The two jets with largest rapidity separation selected.
- Measurement corrected to stable particle level
- Observables:

  - Azimuthal angle between the two jets with largest rapidity separation: : $\Delta\varphi$

  - Fourier coefficients, C_n : $d\sigma/d(\Delta\varphi) \sim \sum C_n \cos(\pi - \Delta\varphi)$

    $C_1 = \langle\cos(\pi - \Delta\varphi)\rangle$

    $C_2 = \langle\cos(2^*(\pi - \Delta\varphi))\rangle$

    $C_3 = \langle\cos(3^*(\pi - \Delta\varphi))\rangle$

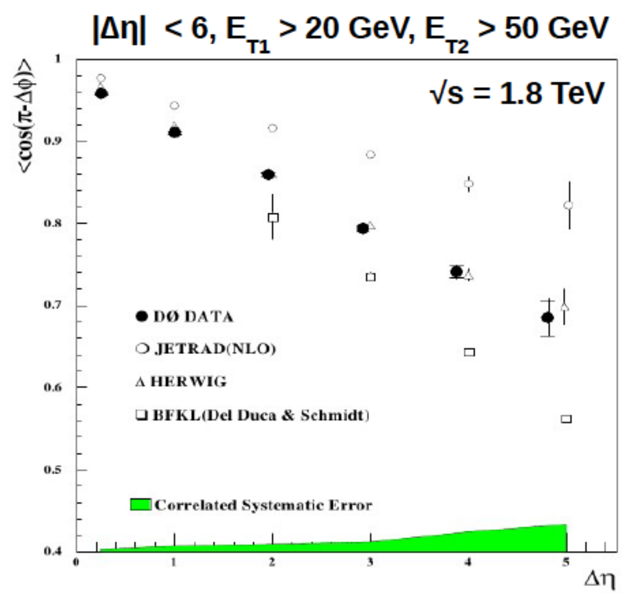
  - Ratios C_2/C_1 and C_3/C_2

  These quantities are measurement in 3 bins of rapidity separation between the jets: $0 < \Delta y < 3$

  $3 < \Delta y < 6$

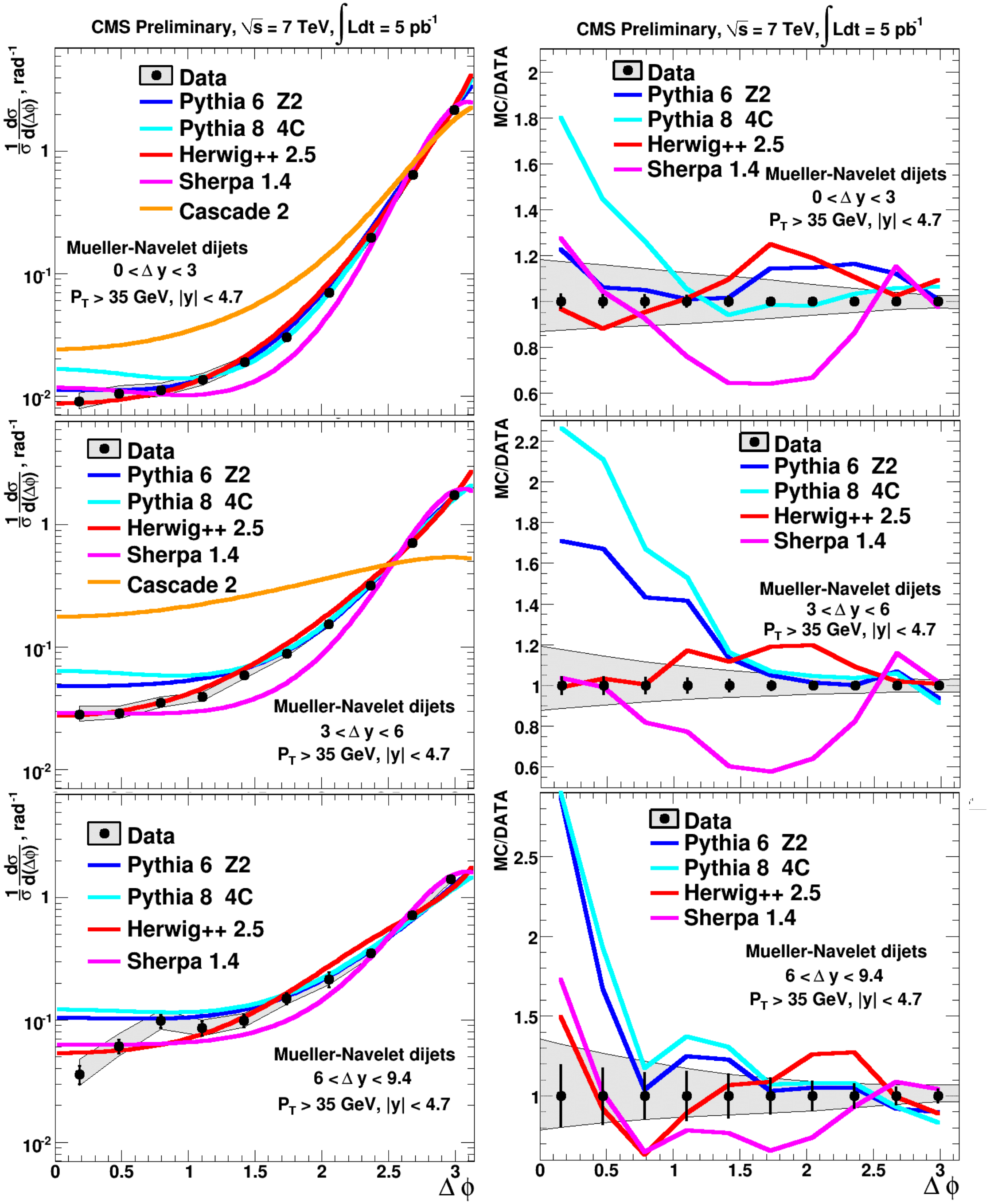
  $6 < \Delta y < 9.4$

Previously measured up to $\Delta y <$ 6.0.



Azimuthal decorrelations – Δφ

CMS-FSQ-12-002



Events with at least two hard jets with $|\eta|<4.7$ and $p_{t,jet}>35$ GeV

Measure azimuthal difference between the two jets with largest rapidity separation selected.

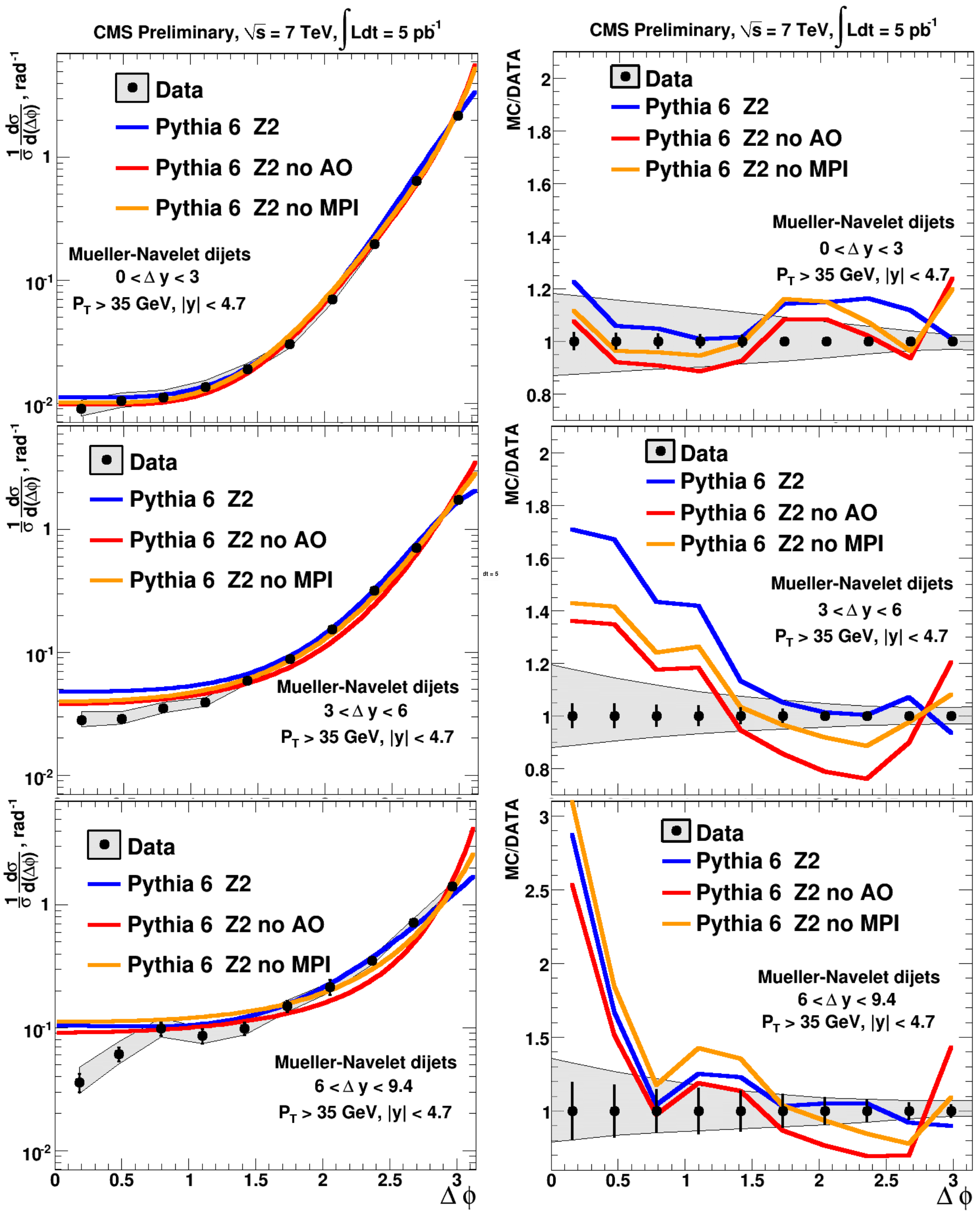
- **Larger azimuthal decorrelation with increasing Δy**
- **Herwig++ provides the best description of data**
- **Pythia6/8 too large decorrelation**

  → Overall description is opposite to what we see in the di-jet ratios

- **Sherpa with 4 final state partons – too much correlation**
- **CASCADE – k_t-factorization based (CCFM) – too strong decorrelations**

Azimuthal decorrelations – AO and MPI

CMS-FSQ-12-002

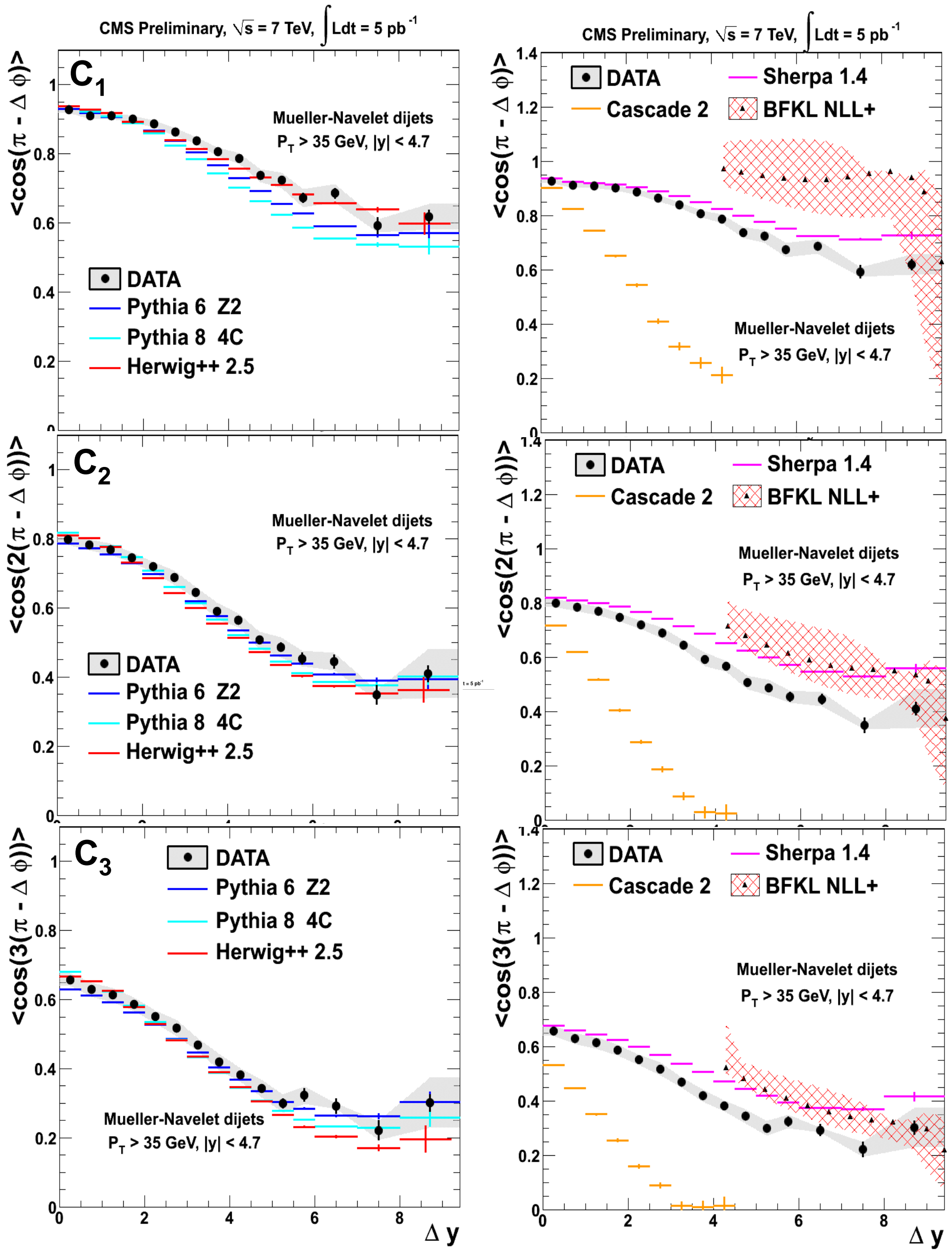


Pythia with and w/o angular ordering (AO) or MPI.

- **Switching off angular ordering or MPI**
  - **approximately the same correlation at small Δy**
  - **stronger correlation at medium and large Δy**

$C_N = < \cos (N (\pi - \Delta\varphi)) >$

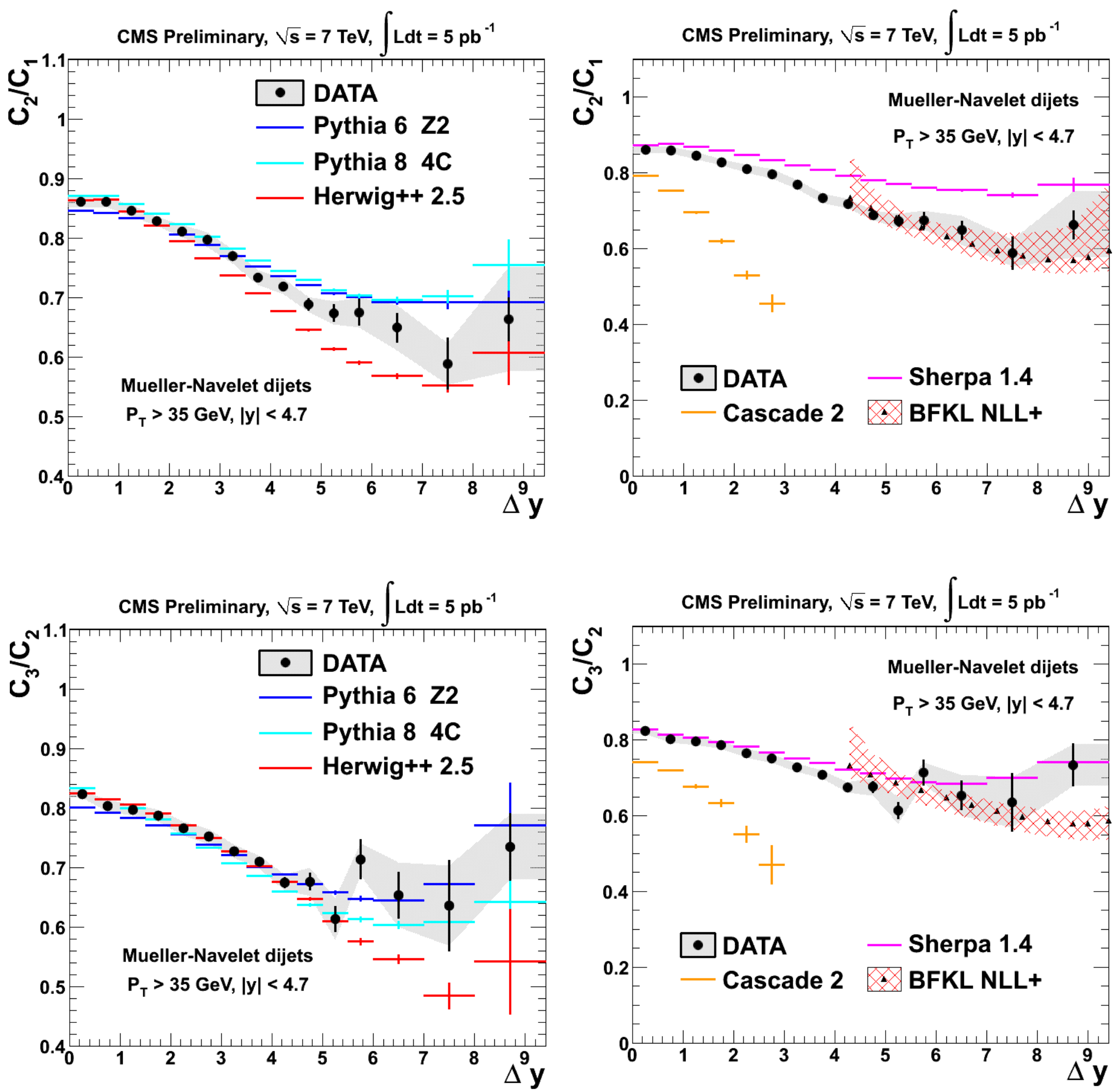
CMS-FSQ-12-002



- **Fourier coefficients, C_n, expected to be sensitive to properties of non-collinear dynamics**
  - **$C_1 = <\cos(\pi - \Delta\varphi)>$**
  - **$C_2 = <\cos(2*(\pi - \Delta\varphi))>$**
  - **$C_3 = <\cos(3*(\pi - \Delta\varphi))>$**
- **Herwig++ and Pythia6/8 qualitatively describe $C_N = < \cos (N (\pi - \Delta\varphi)) >$**
- **Sherpa overestimates the data**
- **CCFM based CASCADE predicts too weak angular correlation**
- **BFKL NLL calculations**
  (arXiv:1302.7012 [Ducloue et al])
  - **only valid for $\Delta y > 4$**
  - **parton level predictions. However, small effect from hadronization compared to systematic uncertainty**
  - **Too strong angular correlation compared to data**

C_2/C_1 and C_3/C_2

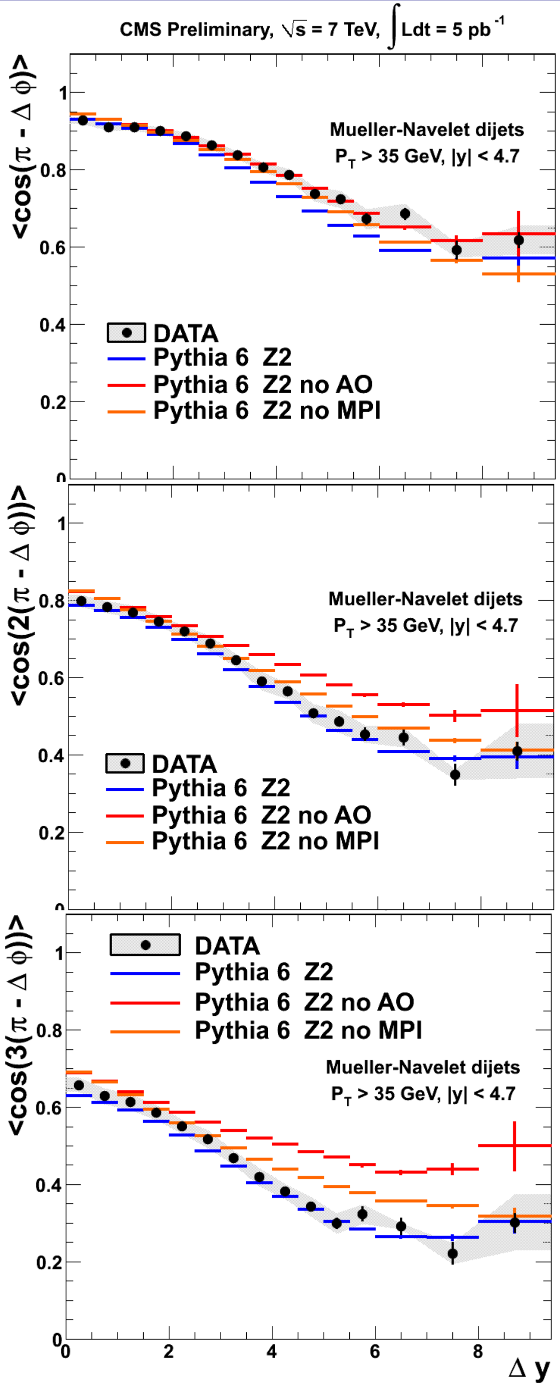
CMS-FSQ-12-002



- DGLAP contributions are expected to partly cancel in the C_{n+1}/C_n – ratios.
- C_{n+1}/C_n described by LL DGLAP based generators towards low Δy
- Pythia8, Pythia6 Z2 overestimate C_2/C_1
- Herwig++ underestimate C_2/C_1
- Sherpa overestimates data
- CCFM based CASCADE predicts too small C_{n+1}/C_n
- At Δy > 4 theoretical BFKL NLL describe in particular C_2/C_1 within uncertainties

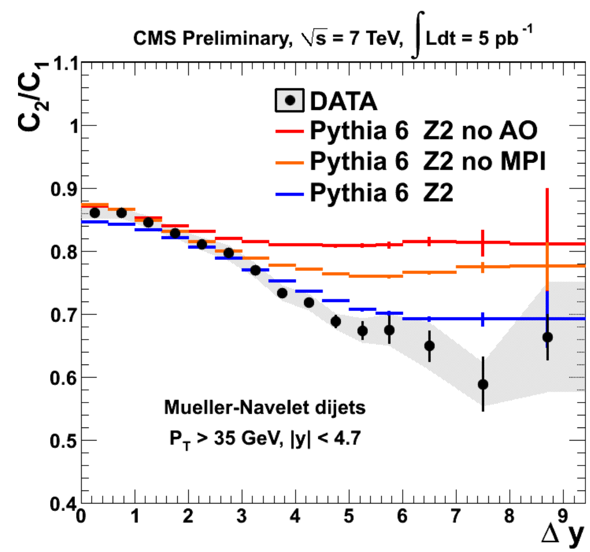
C_N and C_{N+1}/C_N – AO and MPI

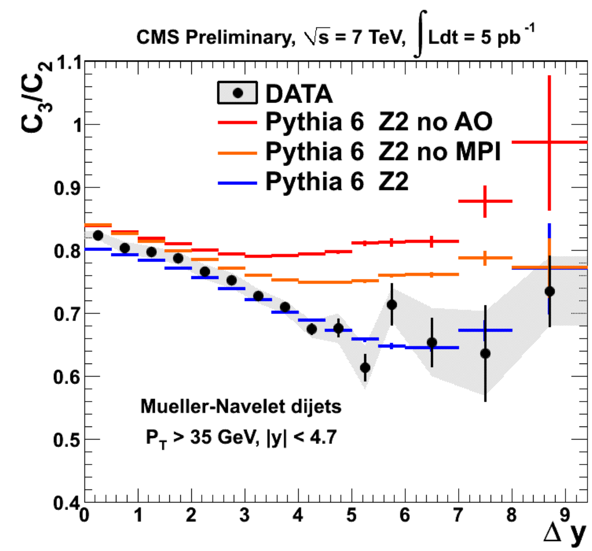
CMS-FSQ-12-002



Pythia with and w/o angular ordering or MPI.

- **AO and MPI improve the description of the data, In particular at high Deltay**
- **C_2/C_1 and C_3/C_2 are more sensitive to AO and MPI conditions**





Summary of MN measurement

- **Azimuthal decorrelations of MN dijets as a function of rapidity separation are measured for the first time up to $\Delta y = 9.4$ at $\sqrt{s} = 7$ TeV**
- **Measurements are sensitive to details of QCD radiation**
- **Herwig++ provides overall the best description of the data**
- **Pythia6/8 predicts a too weak correlation specially for increasingly larger rapidity separations**
- **NLL DGLAP based Sherpa predicts smaller decorrelations than seen in data**
- **kt-factorization based MC generator CASCADE predicts too strong decorrelations**
- **Comparison with BFKL NLL (arXiv:1302.7012), $\Delta y > 4$:**
  - **$\langle \cos(\pi - \Delta\varphi) \rangle$: The predictions agree with the data within the fairly large theoretical and experimental uncertainties**
  - **Satisfactory description of C2/C1 and C3/C2**

Summary / Conclusions

Summary and Conclusions

CMS results on forward and forward-central jets presented:

- **Forward + Central Jets**
  - **Data does not prefer a certain model, but Herwig and HEJ best.**

- **Ratios of Dijet Production up to Δy < 9.4**
  - **Well described by Pythia6 and Pythia8. Herwig fails.**

- ***Azimuthal correlations of jets with large rapidity separation***
  For the first time the azimuthal correlations have been measured up to Δy < 9.4.
  - **Herwig best. Pythia too decorrelated.**

→ **Different DGLAP based generators describe the data differently.
Collinear factorization ~ OK, but not in a consistent way. No MC describes all data.**

→ **No deviations beyond collinear-factorization+parton-shower (LL emissions) in regions of phase-space where BFKL effects are expected to be enhanced.**

→ **Deviation between data and MC can not be interpreted as due to non-DGLAP dynamics**

→ **Failure of MC models is not only a matter of tuning**

**“Beyond DGLAP”-situation is still a bit inconclusive.
No evidence for or against non-collinear dynamics.**

Back up

The CMS Detector