MPI and small-x QCD in CMS

A. Knutsson (Universiteit Antwerpen)
on behalf of CMS Collaboration

MPI@LHC
Krakow, 3 – 7 November, 2014

- Leading tracks and track-jets at very low p_T New
- Azimuthal correlations of jets widely separated in η
- Forward-Central Jet Correlations

CMS-PAS-FSQ-12-026, CMS-PAS-FSQ-12-032 - http://cds.cern.ch/record/1546365
CMS-PAS-FSQ-12-002 - http://cds.cern.ch/record/1547075
CMS-PAS-FSQ-12-008 - http://cds.cern.ch/record/1643105

Normalized integrated event cross-sections of leading tracks and track-jets at very low p_T

Analyses motivated by:

Jet production and the inelastic *pp* cross section at the LHC

A. Grebenyuk[a], F. Hautmann[b], H. Jung[a,c], P. Katsas[a] and A. Knutsson[a]

Abstract

We suggest that, if current measurements of inclusive jet production for central rapidities at the LHC are extended to lower transverse momenta, one could define a visible cross section sensitive to the unitarity bound set by the recent determination of the inelastic proton-proton cross section.

arXiv:1209.6265v1 [hep-ph] 27 Sept 2012

Phys.Rev. D86 (2012) 117501

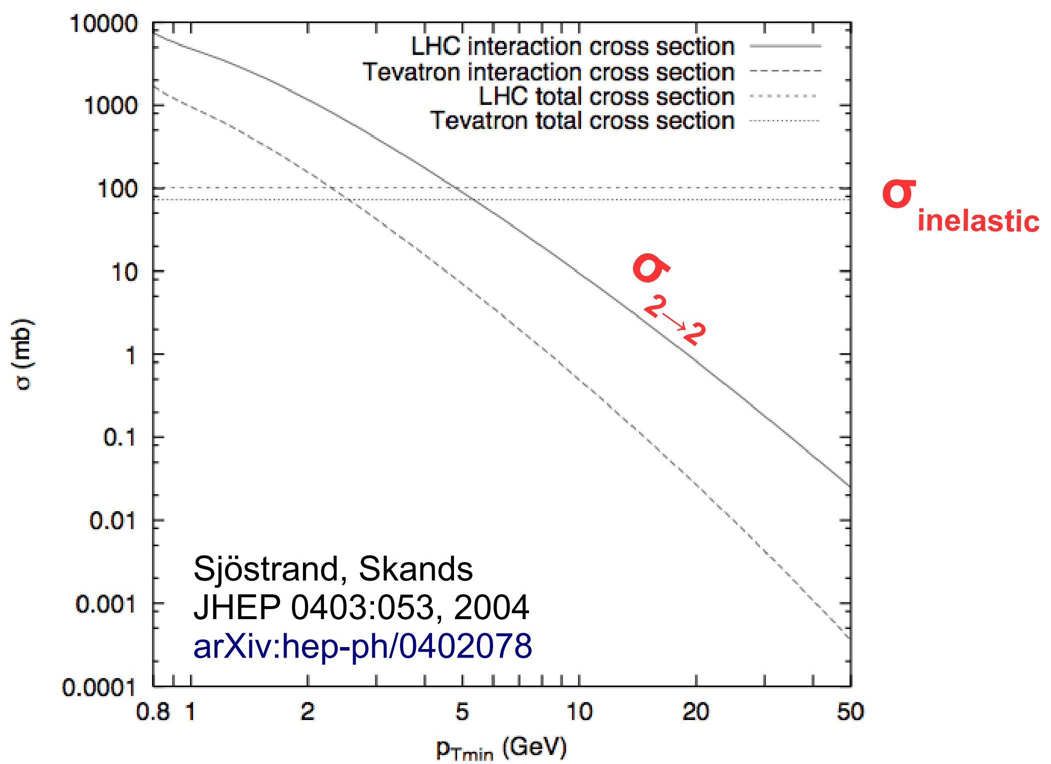
Introduction

- **Total cross-section for 2→2 process given by**

$$\sigma(p_{T\ min}) = \int_{p_{T\ min}} dp_T^2 \int_{-\infty}^{\infty} dy \frac{d^2\sigma}{dp_T^2\, dy}$$

- **Divergent towards low $p_{T,min}$ and eventually the total 2→2 cross-section becomes larger than the total inelastic cross-section.**

- **At LHC this happens around ~5 GeV at LHC.**



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- Thus, in theory, the cross-section needs to be tamed.

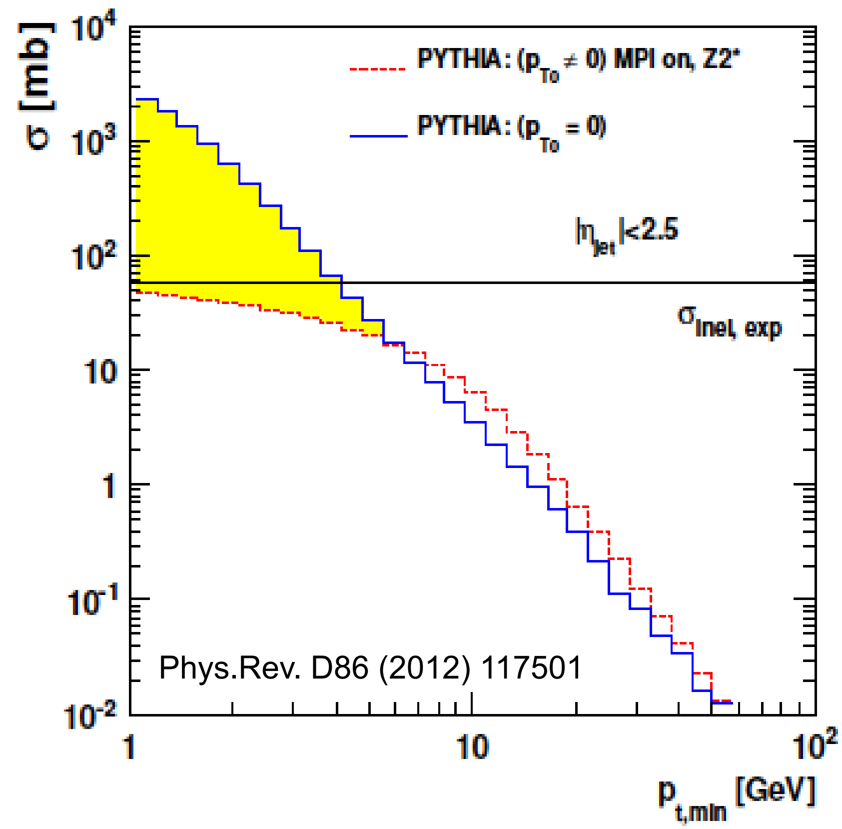
For example, in Pythia, the rise of the 2→2 cross-section is "tamed" by

1. Regularization factor for the cross-section

$$\sigma \to \sigma \times \frac{\alpha_s(p_t + p_{t0})}{\alpha_s(p_t)} \frac{p_t^4}{(p_t^2 + p_{t0}^2)^2}$$

where p_{T0} is determined by tuning to data.

2. MPI: $\langle n_{MPI} \rangle = \sigma_{2\to 2}/\sigma_{Total}$



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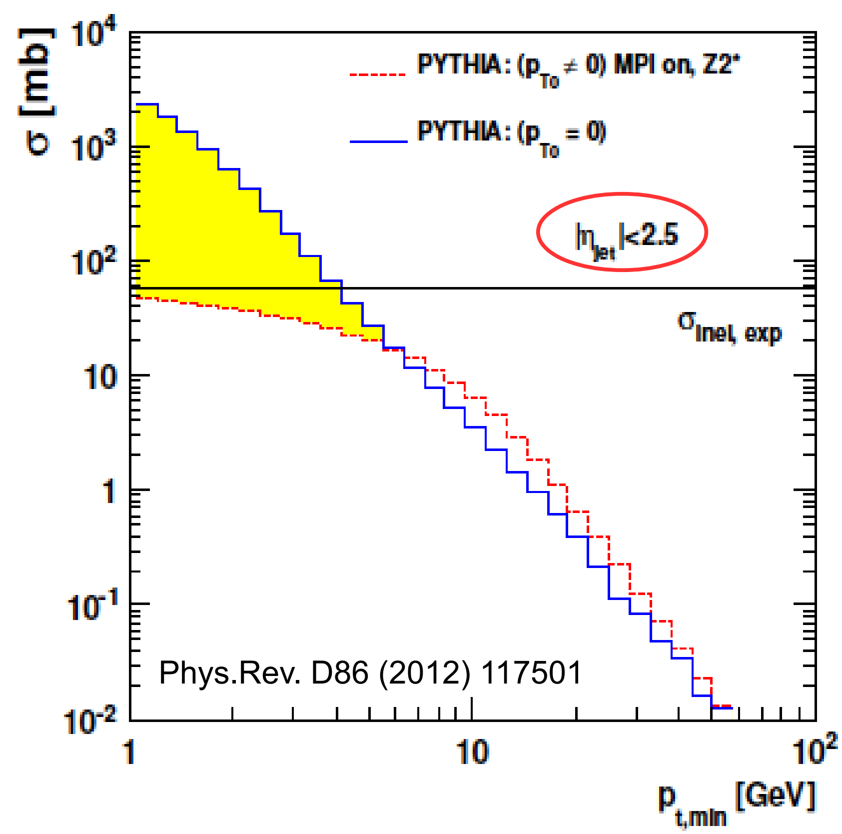
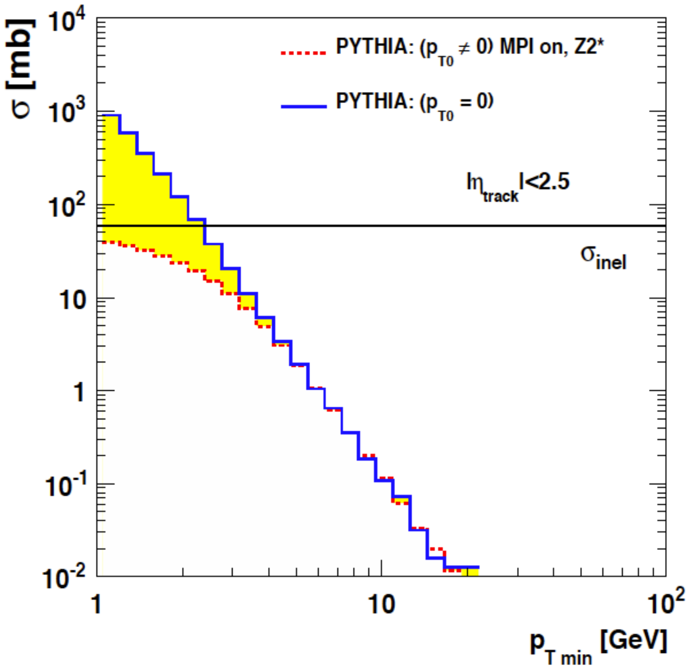
Can be studied in a range accessible by the experiments.



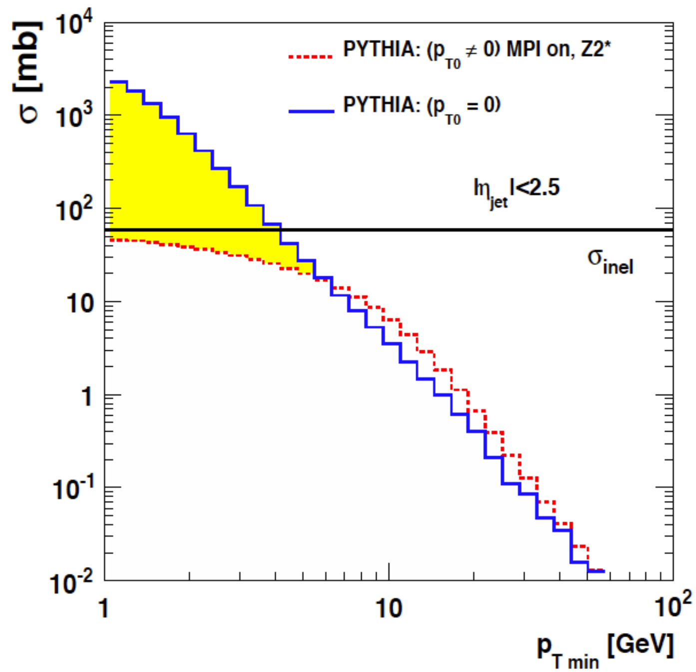
Tracks vs Jets

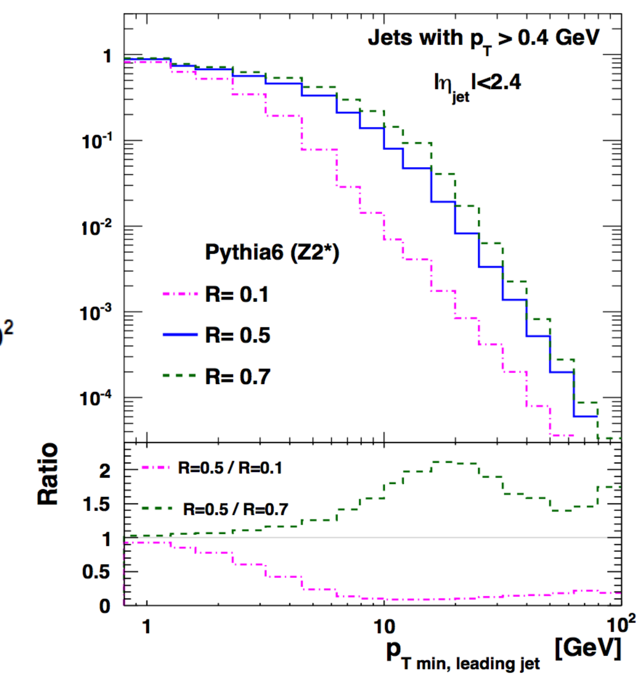
- Measurement possible to do with tracks and track jets.

Leading charged particles



Leading charged particle jets

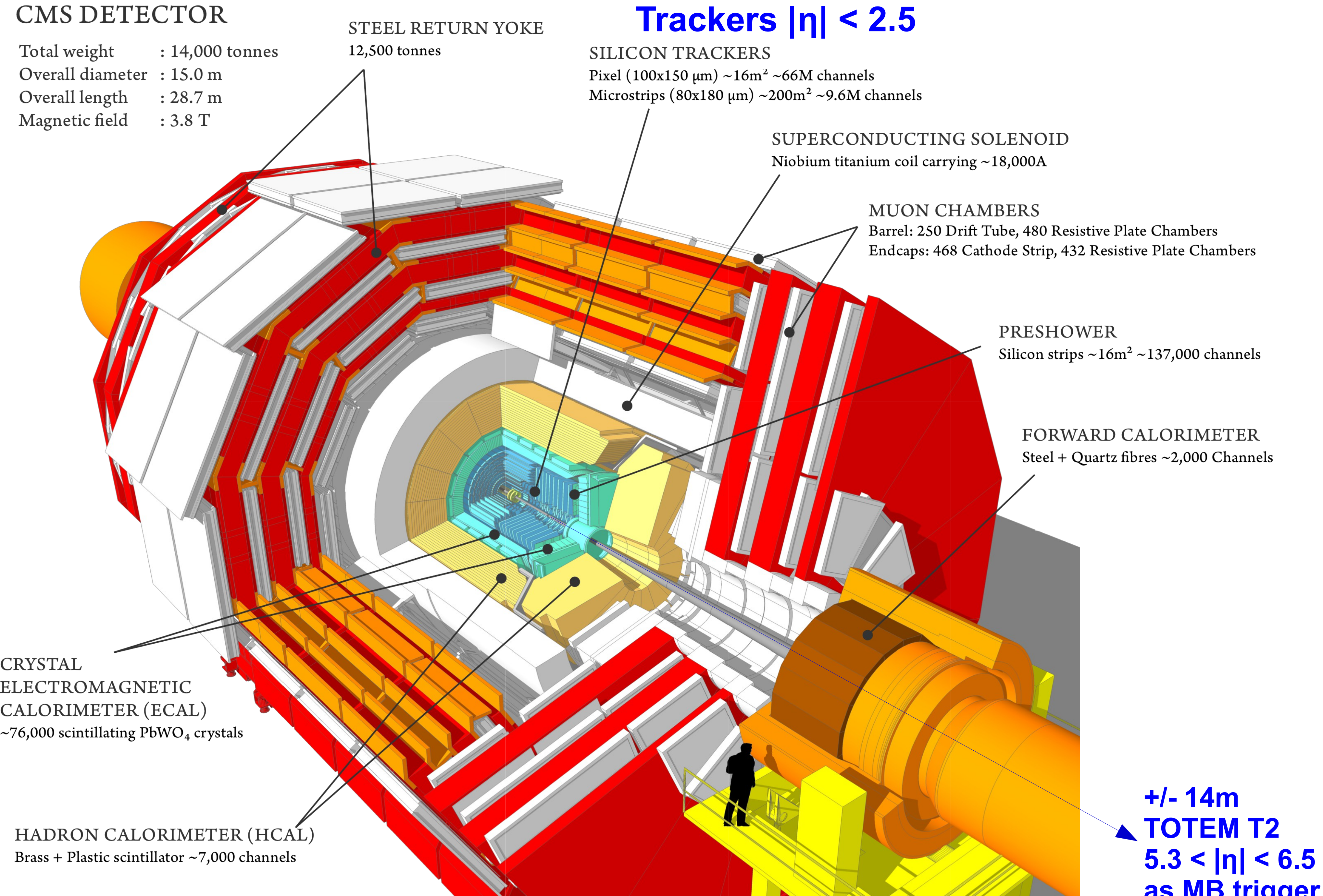




- Different shapes of the cross-sections. The jet events are shifted towards higher values. More than just the leading particle clustered in the jet. UE important for the jets.

- When radius parameter in the jet algorithm is decreased the shape of the jet cross-section approaches the leading track cross-section.

CMS and T2 Detectors



Trackers $|\eta| < 2.5$

+/- 14m
TOTEM T2
$5.3 < |\eta| < 6.5$
as MB trigger

Data and selections

- Common CMS+TOTEM data taking. Run with very low pile-up at $\sqrt{s}$ = 8 TeV (2012). (Non standard high β^* = 90m optics configuration.)

- MB events triggered by TOTEM T2:
  At least one track with p_t > 40 MeV in $5.3 < |\eta| < 6.5$

- Track selection:
  $|\eta| < 2.4$, $p_t > 0.4$ GeV

  → Measurement of the **normalized integrated *leading track* cross-section.**

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- Track-jets:
  Anti-k_t algorithm. R = 0.5.
  Input: Tracks with $|\eta| < 2.4$ and $p_t > 0.4$ GeV.
  Jet selection: The leading jet in $|\eta| < 1.9$ with $p_t > 1$ GeV.

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  → Measurement of the **normalized integrated *leading track-jet* cross-section.**

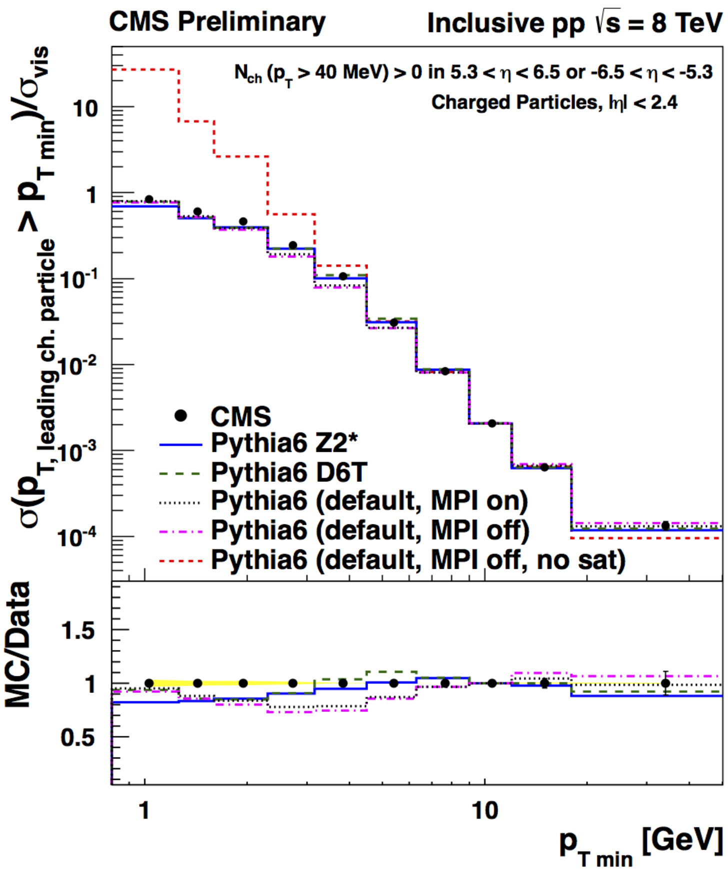
- *Measurement corrected to stable particle level defined by cuts as above (but with no p_t or η restriction on the charged particles entering the jet algorithm)*

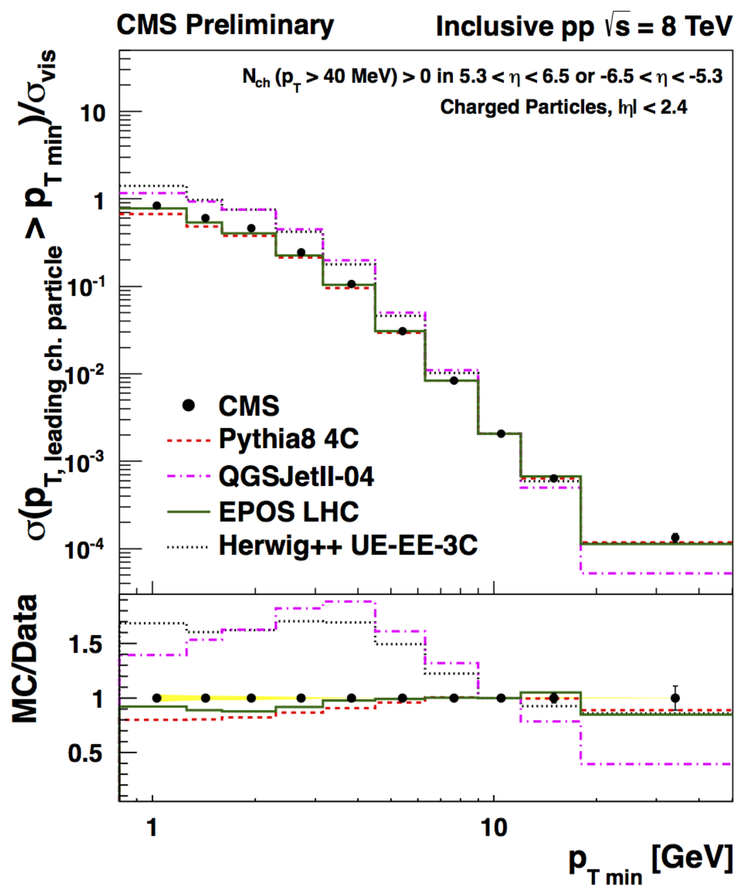
Measurement

- **Normalized integrated** charged-particle or charged particle jet **event cross-section** as a function of $p_{T,min}$ for events with a leading charged particle (jet) with $p_T > p_{T,min}$.

$$D(p_{\mathrm{T,min}}) = \frac{1}{N_{\mathrm{events}}} \sum_{p_{\mathrm{T,leading}} > p_{\mathrm{T,min}}} \Delta p_{\mathrm{T,\,leading}} \left(\frac{dN_{\mathrm{ch}}}{dp_{\mathrm{T,leading}}} \right)$$

- Measurement to normalized to events (N_{events}) with a leading charged particle with $|\eta|<2.4$ and $p_T > 0.4$ GeV

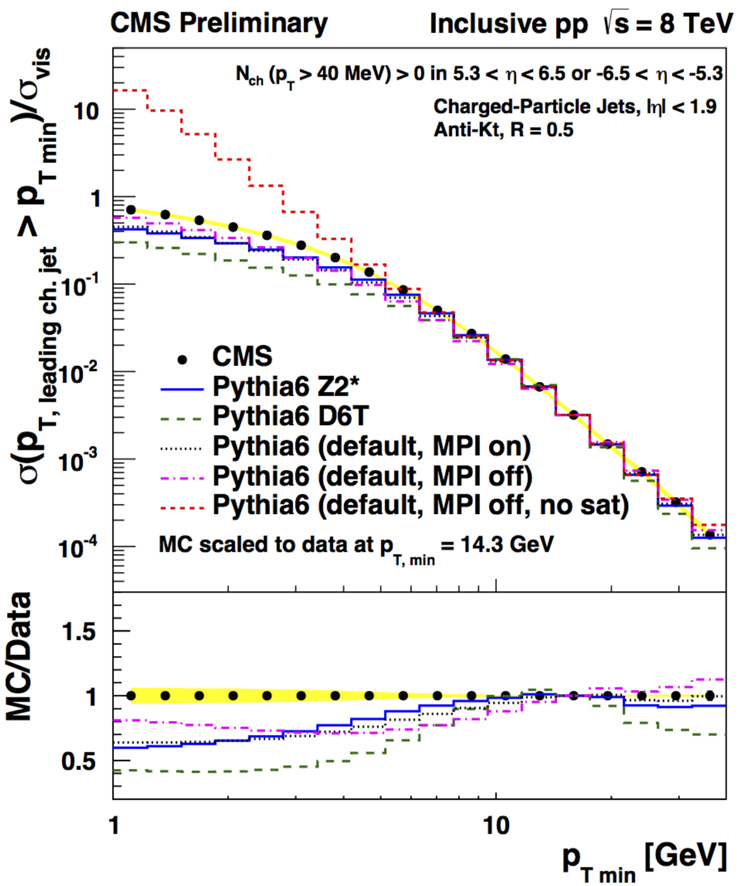


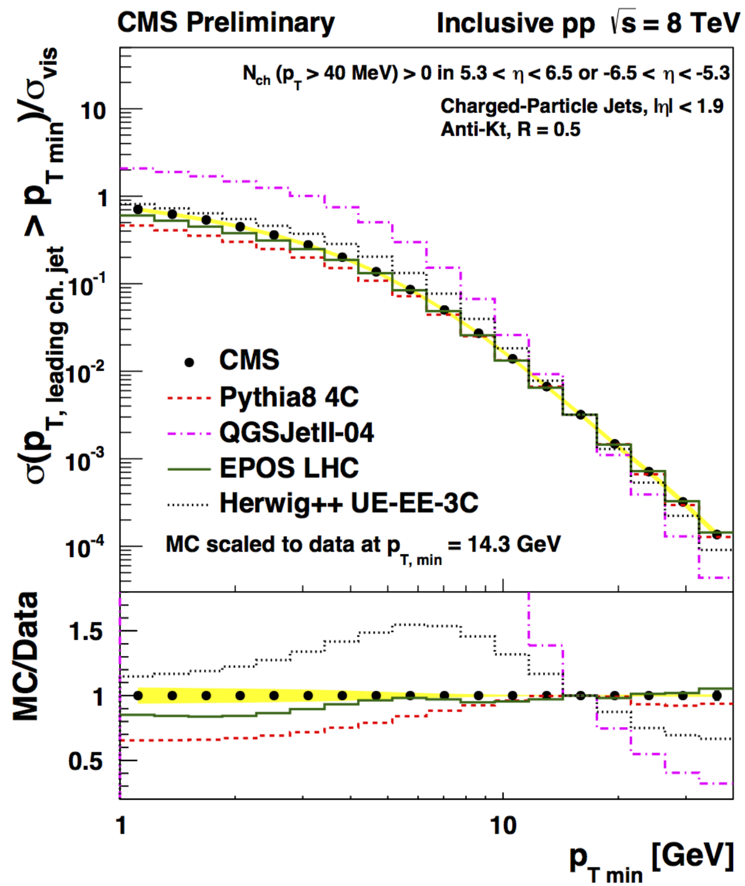


Normalized cross-sections for events with a central leading charged particle with $p_T > p_{T,min}$ as a function $p_{T,min}$.

- Normalized event cross-sections.
  - → No sensitivity to particle multiplicities in events.
  - → Distribution converges to one by construction.
    Looking for effects at low p_T - MC scaled to data at $p_{T,min}$ = 9 GeV.
- Large difference between models. Tune sensitivity.
- Pythia and Herwig do not describe the data. (*)
- Cosmic Ray Monte Carlos: EPOS good. QGSJET fails.

Normalized Leading Charged Particle Jet Cross-sections





Normalized cross-sections for events with a central leading charged particle with $p_T > p_{T,min}$ as a function $p_{T,min}$.

- Normalized event cross-sections.
  - → No sensitivity to jet multiplicities in events.
  - → Distribution converges to one by construction.

    Looking for effects at low p_T - MC scaled to data at $p_{T,min}$ = 14 GeV.

- Larger difference between models. Tune sensitivity.

- Pythia and Herwig do not describe the data. (*)

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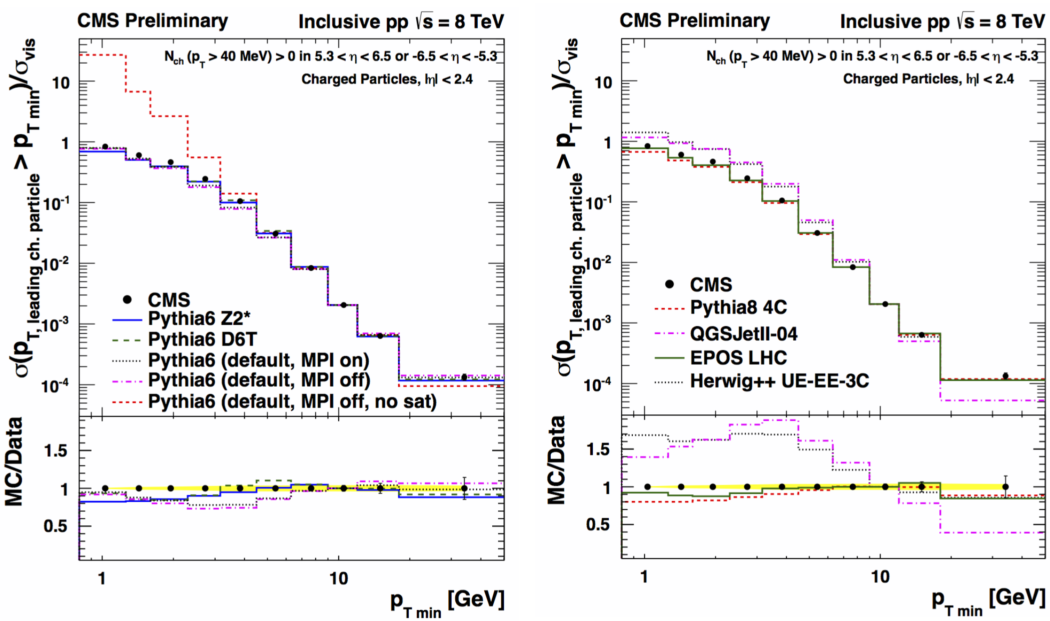
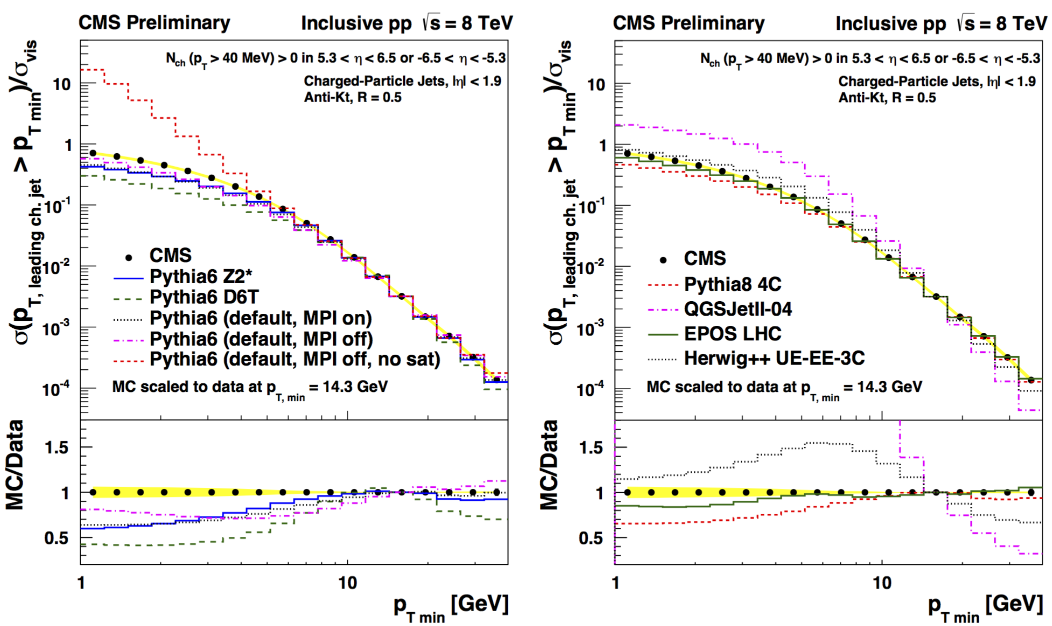
Comparison Track vs Jet measurement

Leading charged particles



Leading charged particle jets



- Different shapes for leading jets and leading charged particles.
- More activity than just the leading track clustered in the jet. Thus, UE important for the jets.

→ The p_t is shifted towards higher value in jets compared to leading charged particles.

→ Larger spread between different MC predictions in the jet measurement.

→ Larger deviation between MC and data for the jets compared to the charged particles.

→ MC somewhat better description of the charge particle measurement.

Azimuthal decorrelations of jets widely separated in η

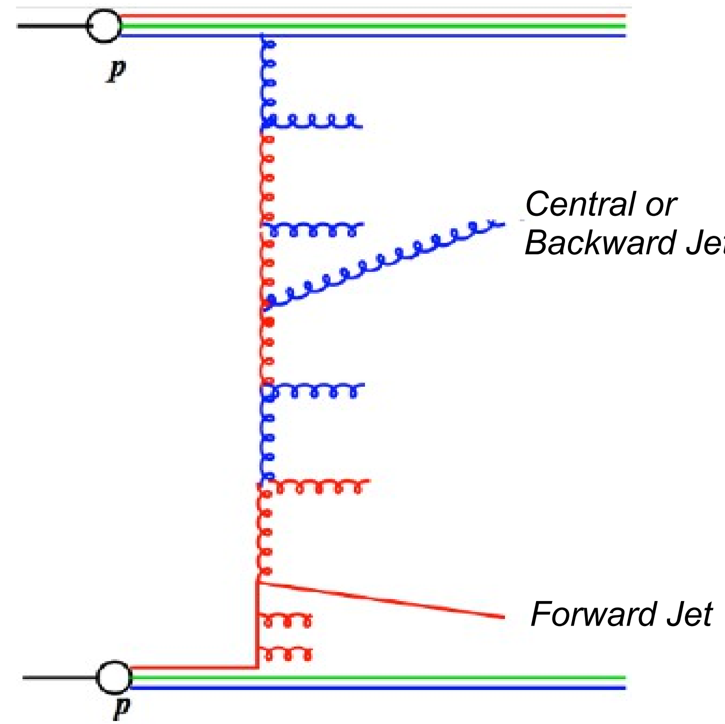
Physics Motivation

- **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

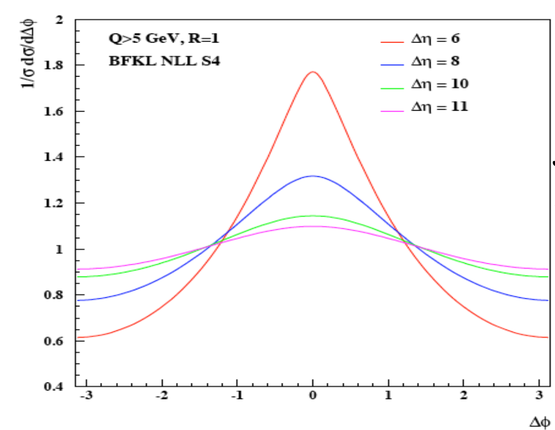
  Higher order reactions: Δφ < 180
  In DGLAP the momentum balance between the two jets is expected to be more conserved, while H.O BFKL emissions expects to give a flatter Δφ distribution.

  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

Measurement

CMS-FSQ-12-002

- $\sqrt{s}$ = 7 TeV, Luminosity ≈ 5 pb^{-1}
- Calorimeter jets - anti-kt algorithm with R=0.5.
- Events with at least two jets with $p_{t,jet}$>35 GeV and |η|<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: : Δφ

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

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

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

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

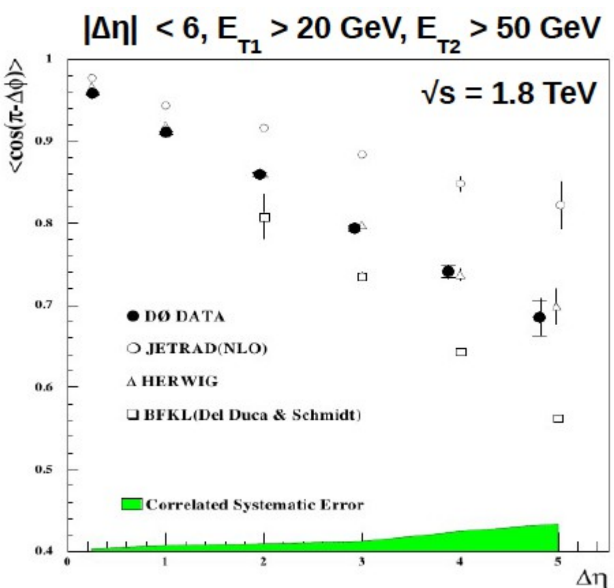
  - Ratios C_2/C_1 and C_3/C_2

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

  $3 < \Delta y < 6$

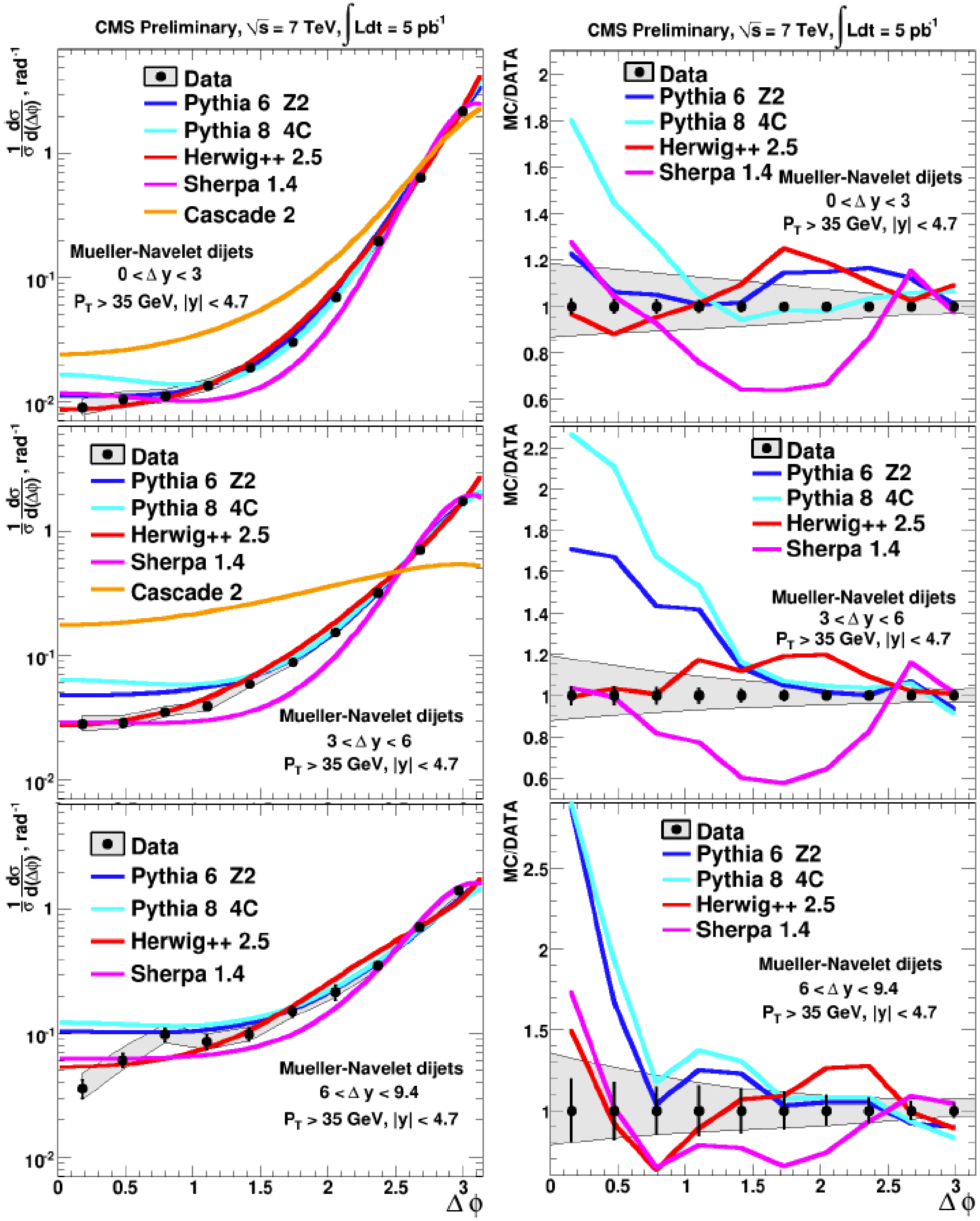
  $6 < \Delta y < 9.4$

Previously measured up to Δy < 6.0.



Azimuthal decorrelations – Δφ

CMS-FSQ-12-002

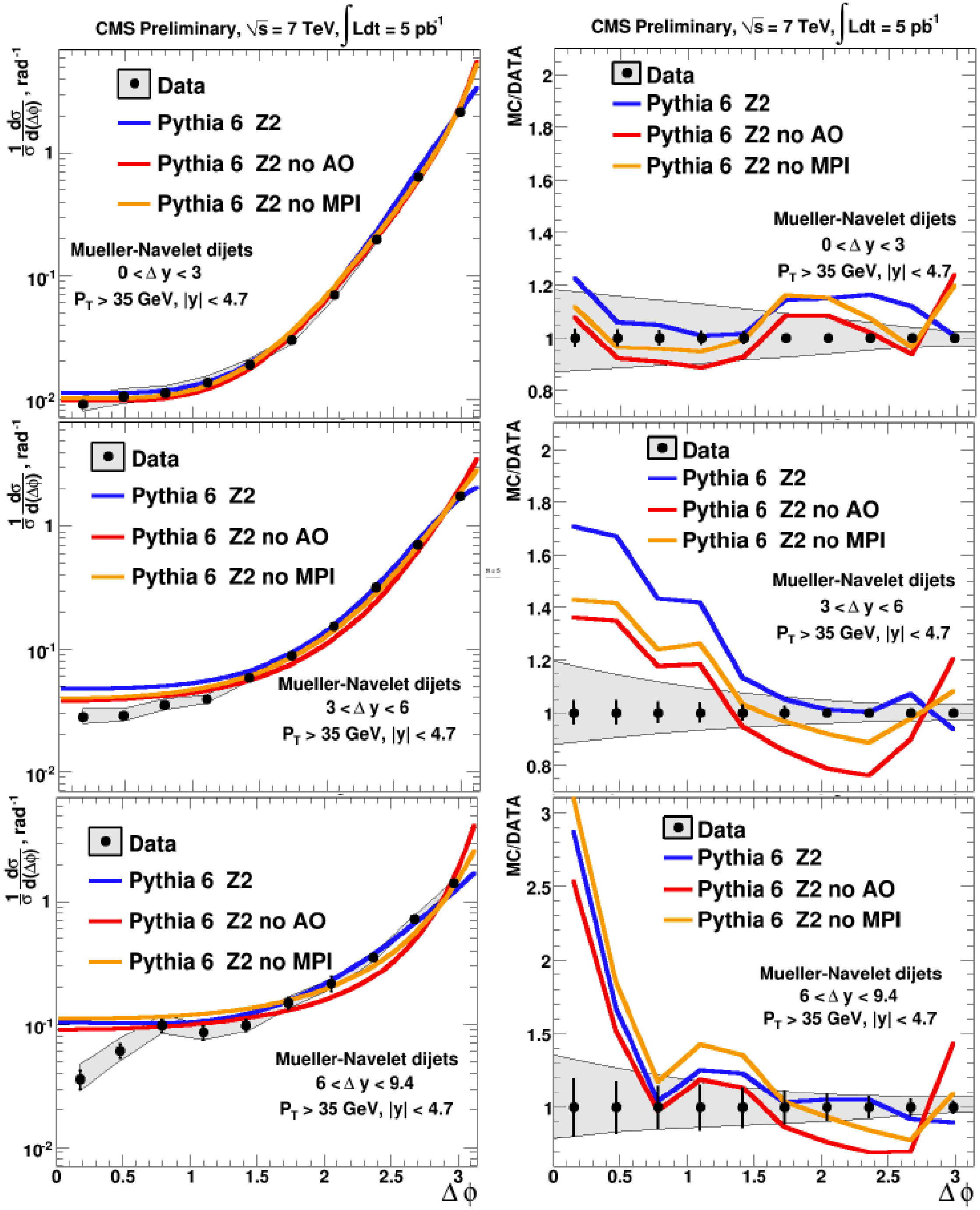


Events with at least two hard jets with $|\eta|<4.7$ and $p_{t,jet}>35$ GeV

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

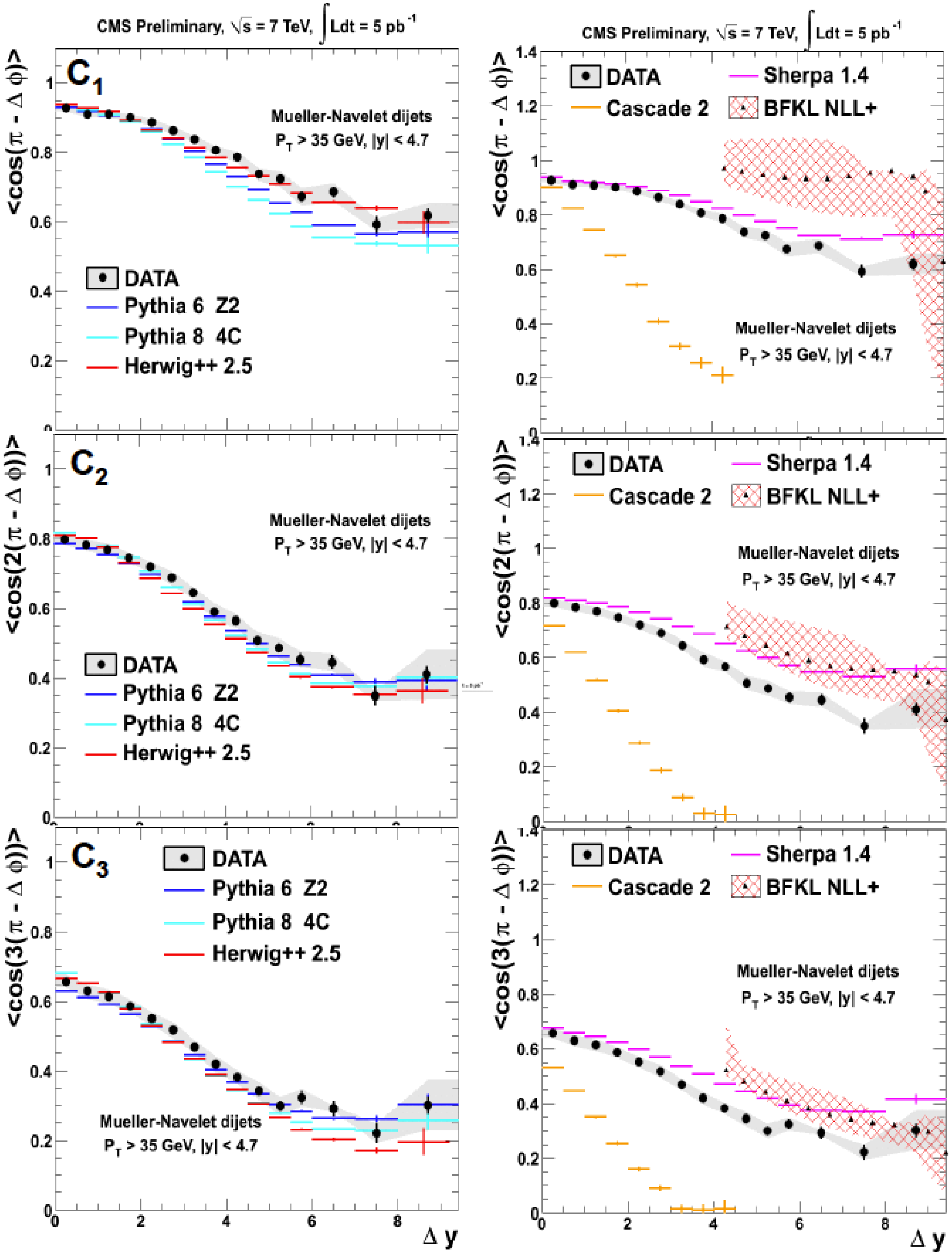
Azimuthal decorrelations – AO and MPI



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**

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



- **Fourier coefficients, C_n, expected to be sensitive to properties of non-collinear dynamics**
  - **$C_1 = <\cos(\pi - \Delta\varphi)>$**
  - **$C_2 = <\cos(2*(\pi - \Delta\varphi))>$**
  - **$C_3 = <\cos(3*(\pi - \Delta\varphi))>$**

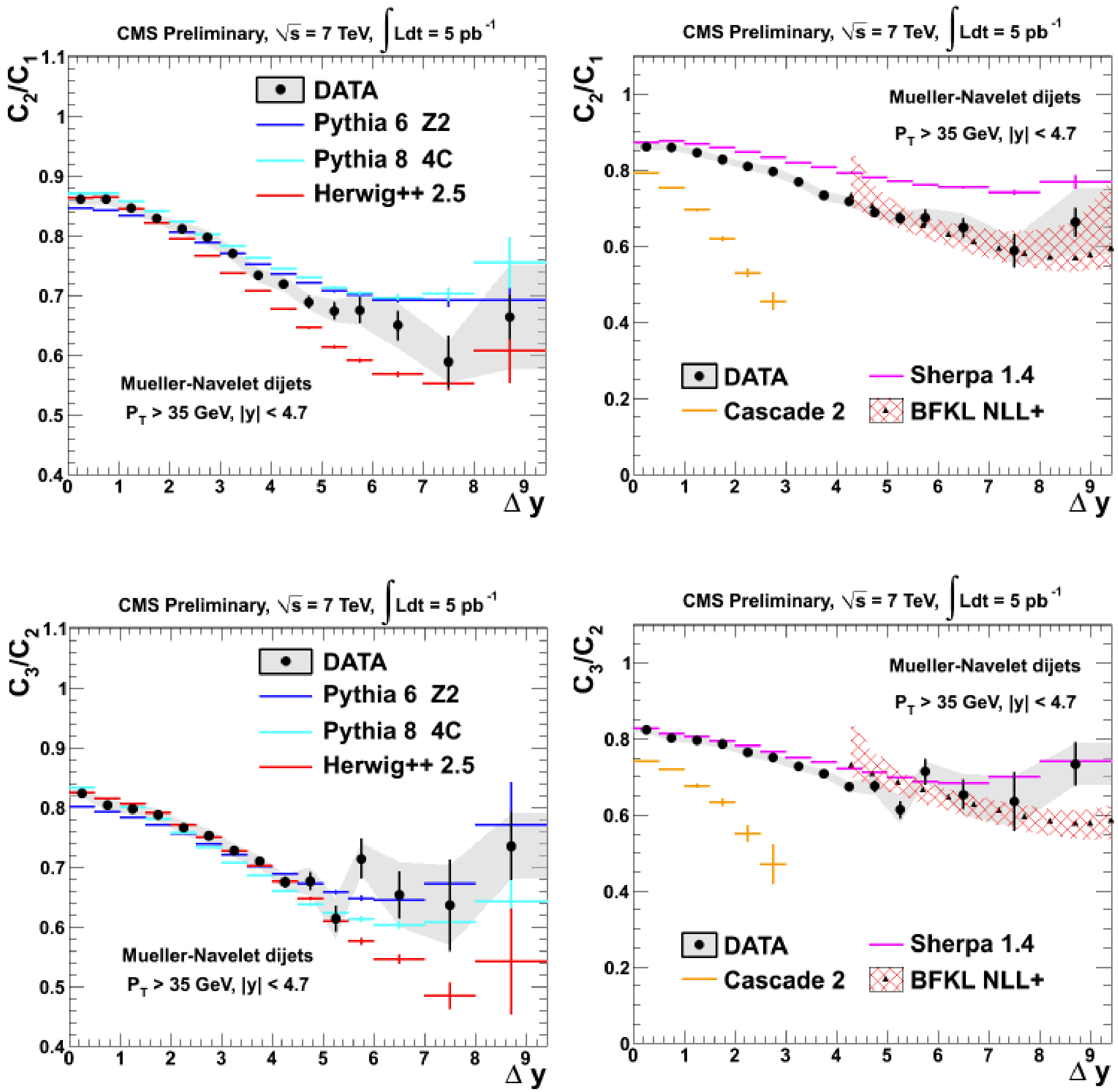
- **Herwig++ and Pythia6/8 qualitatively describe $C_N = < \cos(N(\pi - \Delta\varphi)) >$**

- **Sherpa overestimates the data**

- **CCFM based CASCADE predicts too weak angular correlation**

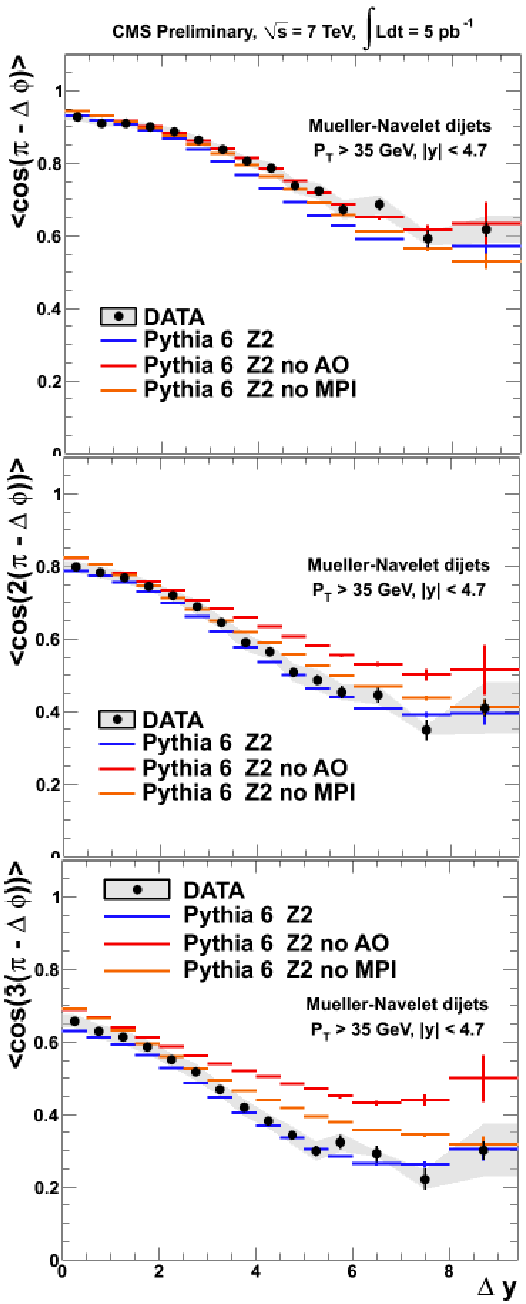
- **BFKL NLL calculations** (arXiv:1302.7012 [Ducloue et al])
  - **- only valid for $\Delta y > 4$**
  - **- parton level predictions. However, small effect from hadronization compared to systematic uncertainty**
  - **- Too strong angular correlation compared to data**

C_2/C_1 and C_3/C_2



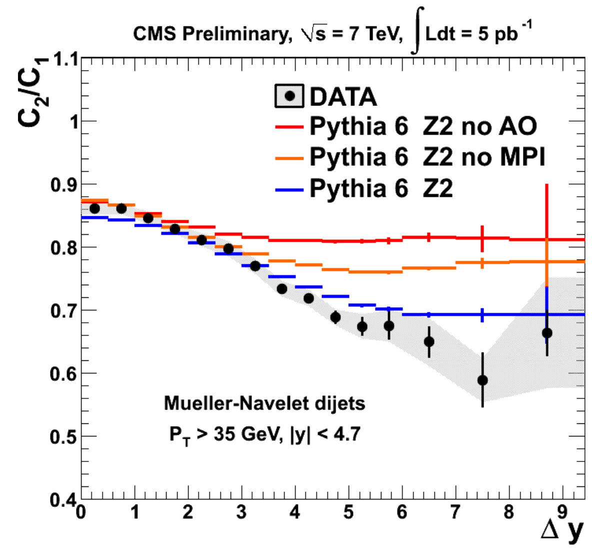
- **DGLAP contributions are expected to partly cancel in the C_{n+1}/C_n – ratios.**
- **C_{n+1}/C_n described by LL DGLAP based generators towards low Δy**
- **Pythia8, Pythia6 Z2 overestimate C_2/C_1**
- **Herwig++ underestimate C_2/C_1**
- **Sherpa overestimates data**
- **CCFM based CASCADE predicts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

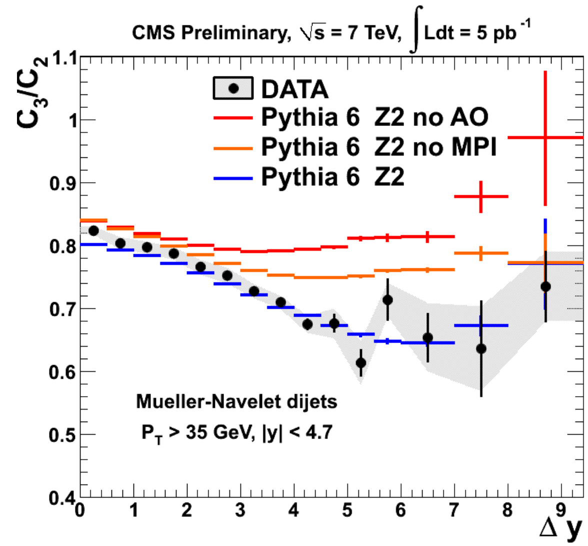
C_N and C_{N+1}/C_N – AO and MPI



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**





Forward-Central Jet Correlations

Forward-Central Jet Decorrelations

Data

3.2 pb^{-1} from 2010 low pile-up *pp* collisions at $\sqrt{s} = 7$ TeV

Physics selection

Events with at least one forward ($3.2 < |\eta| < 4.7$) and at least one central ($|\eta| < 2.8$) jet with $p_T > 35$ GeV

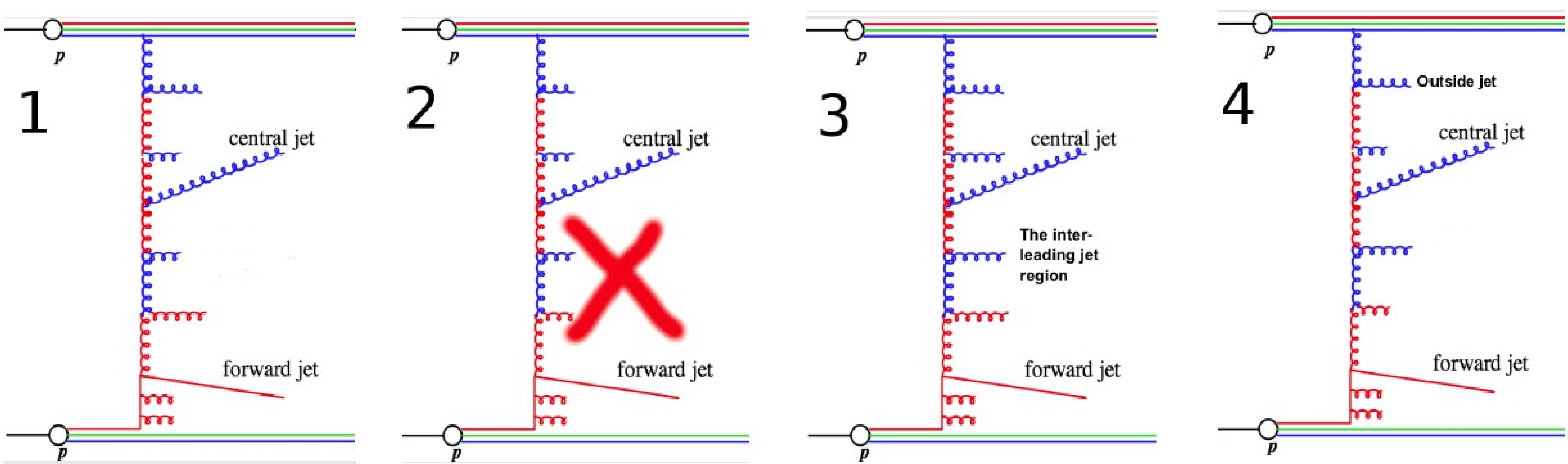
Different scenarios

1) Inclusive fwd+cntrl jets

2) Inside jet veto ($p_{T,\text{inside jet}} < 20$ GeV)

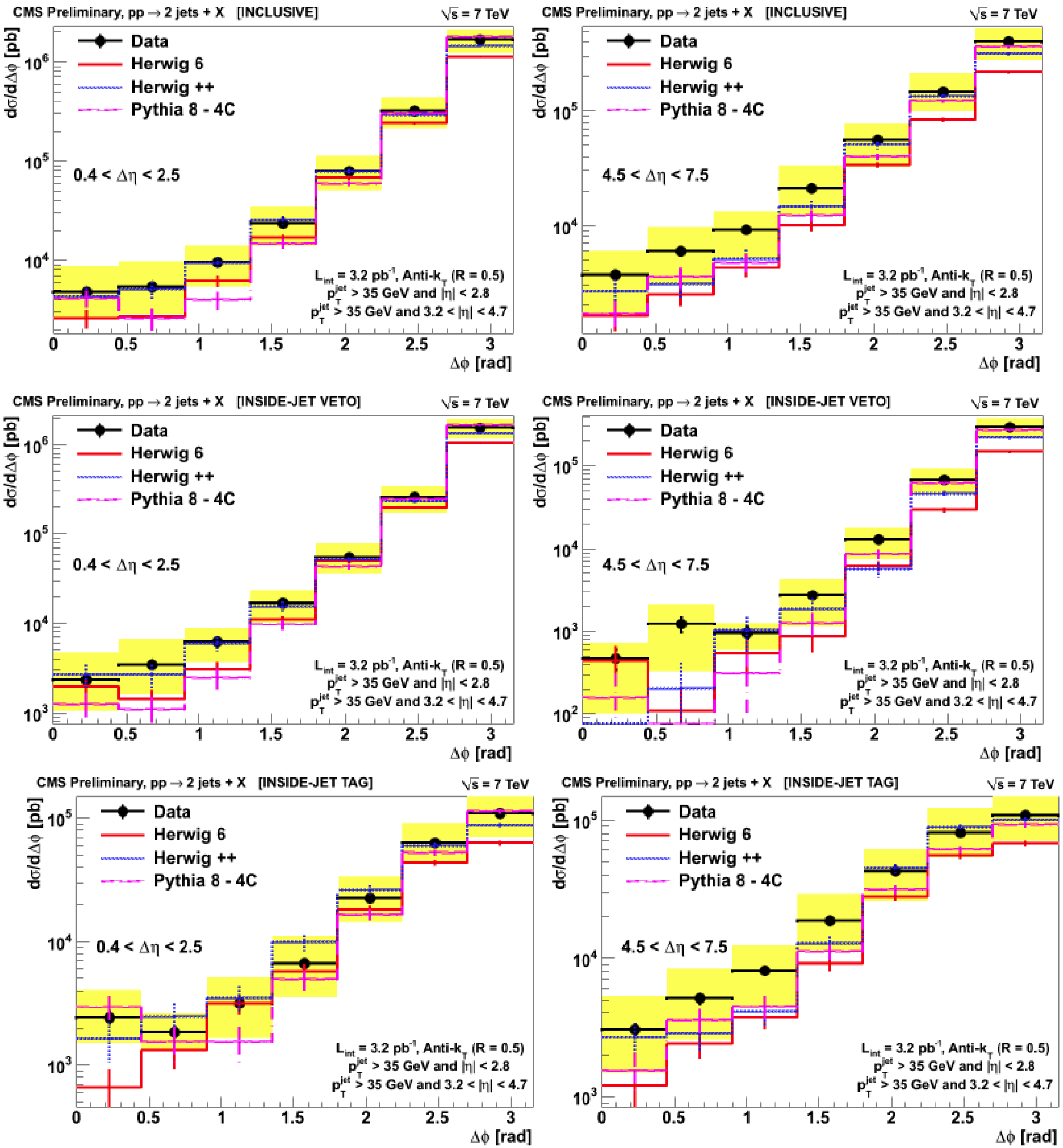
3) Inside jet tag ($p_{T,\text{inside jet}} > 20$ GeV)

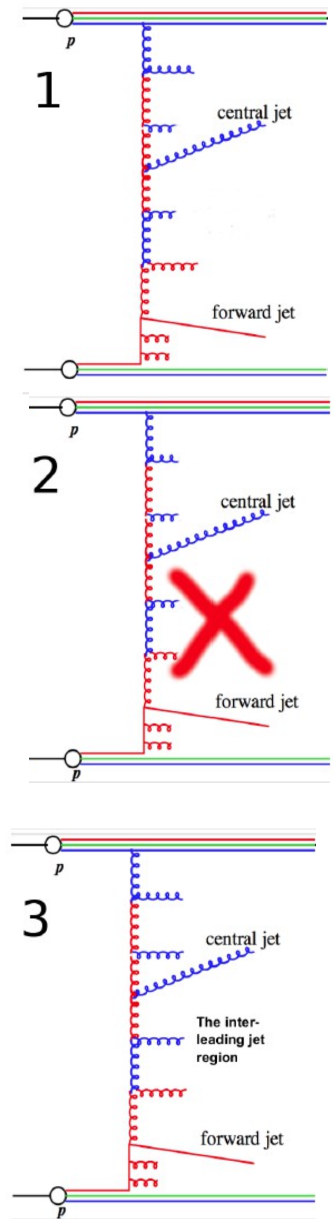
4) Outside jet tag ($p_{T,\text{outside jet}} > 20$ GeV)



Δφ in bins of Δη for different scenarious

$0.4 < \Delta\eta < 2.5$ **$4.5 < \Delta\eta < 7.5$**



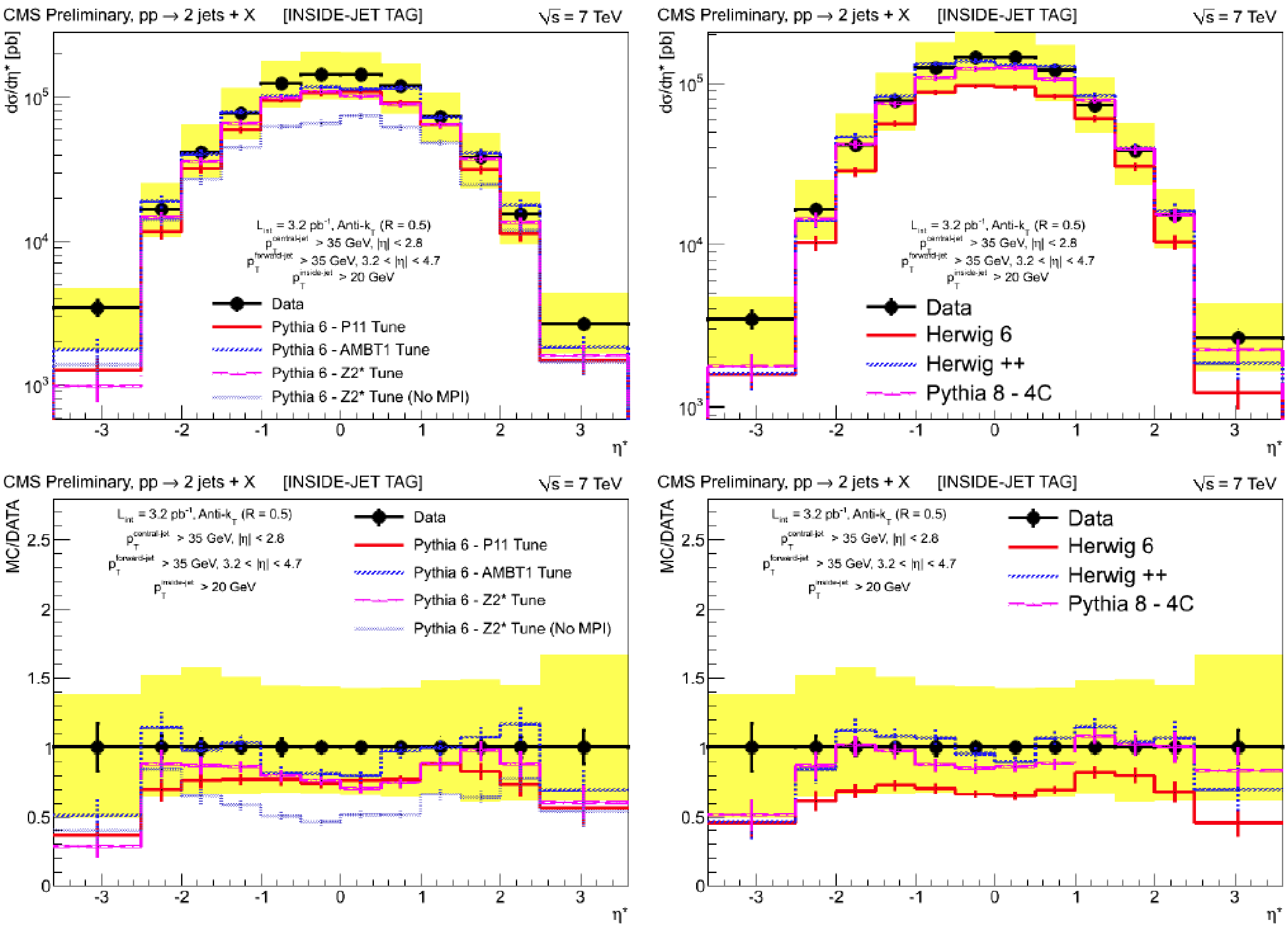


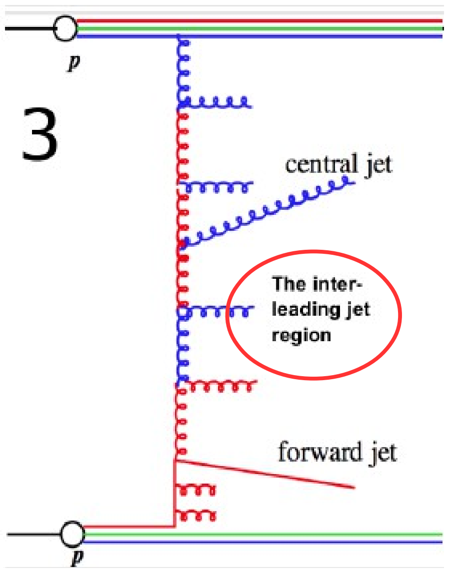
- **All MCs describe the data, considering the fairly large experimental uncertainty**

Position of inside jet

$$\eta* = \eta_{inside-jet} - (\eta_{central-jet} + \eta_{forward-jet})/2$$

Position of inside jet expected to give additional sensitivity to PS algorithms and color coherence effects.



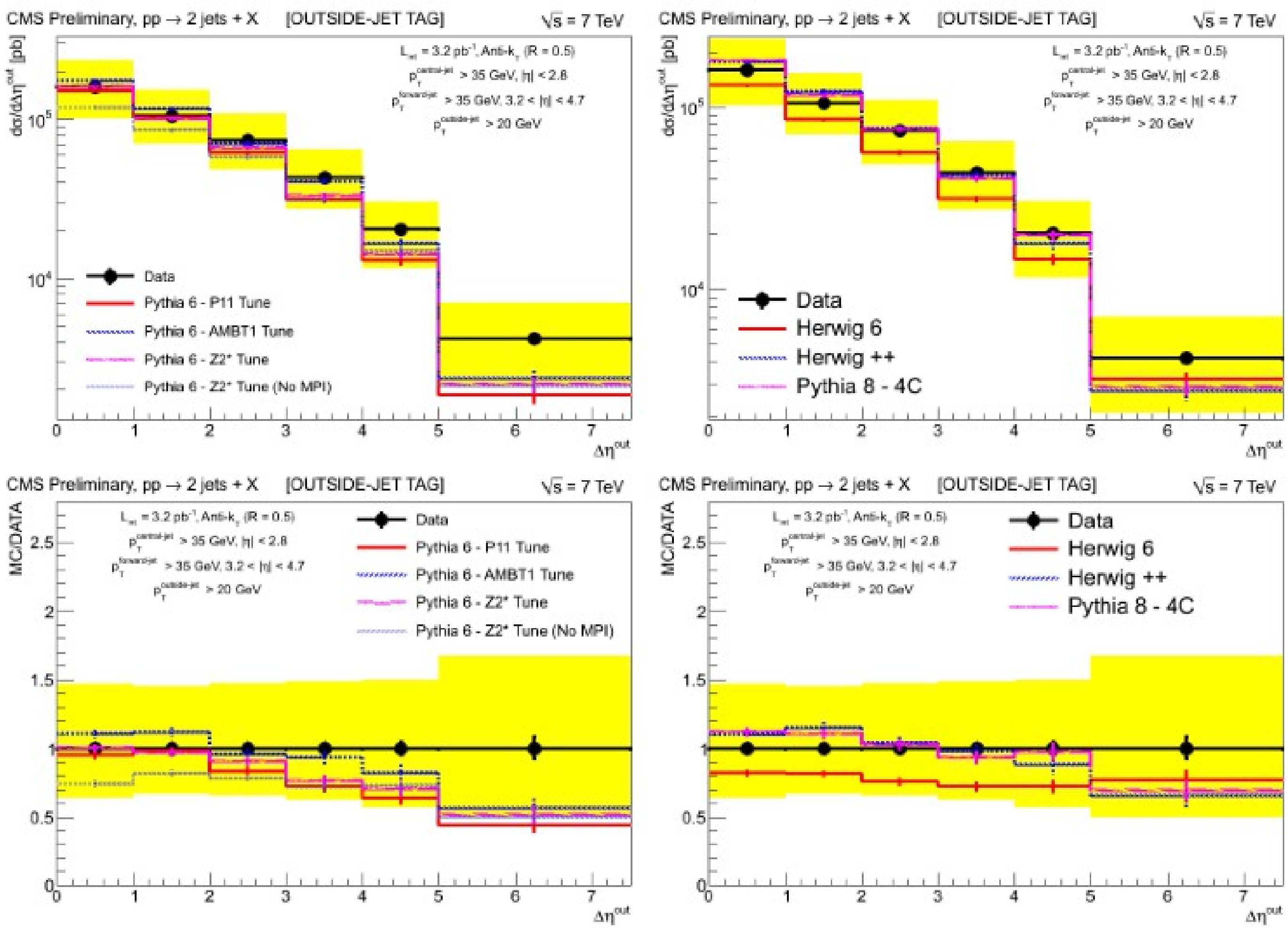


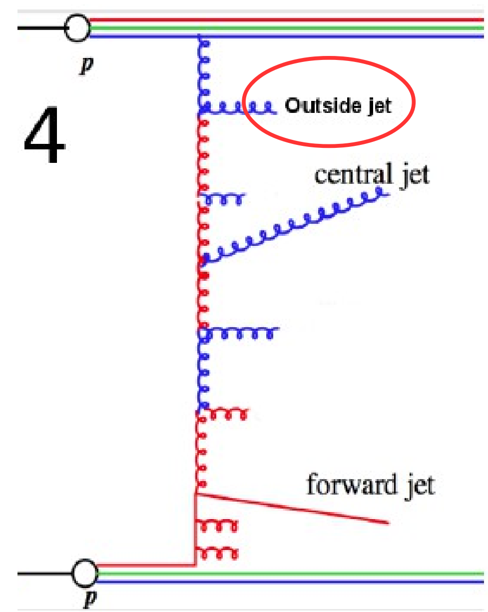
- MPI largest at central η*.
- Again, large exp. uncert – MC not separable

Position of outside jet

$$\Delta\eta^{out} = \min(|\eta_{outside-jet} - \eta_{central-jet}|, |\eta_{outside-jet} - \eta_{forward-jet}|)$$

Expected to give additional sensitivity to PS algorithms and color coherence effects.





Monte Carlo describes the data.

Summary / Conclusions

Summary and Conclusions

- **Leading track and leading track-jet event cross-sections at very low Pt**

  - Probe the transition from the pertubative to the non-pertubative regions, and are sensitive to the "taming of the cross-section".

  - Difficult to describe by MC models. Cosmic Ray MC EPOS best.

  - Difference between the charge particle and the charge particle jet measurement. Jets larger sensitivity to MPI and UE – larger separation between tunes and models.

- **Azimuthal correlations of jets with large rapidity separation**

  - Azimuthal correlations measured up to $\Delta y < 9.4$.

  - Herwig best. Pythia too decorrelated.

  - Largest contribution from MPI at small $\Delta\varphi$ and large Δy

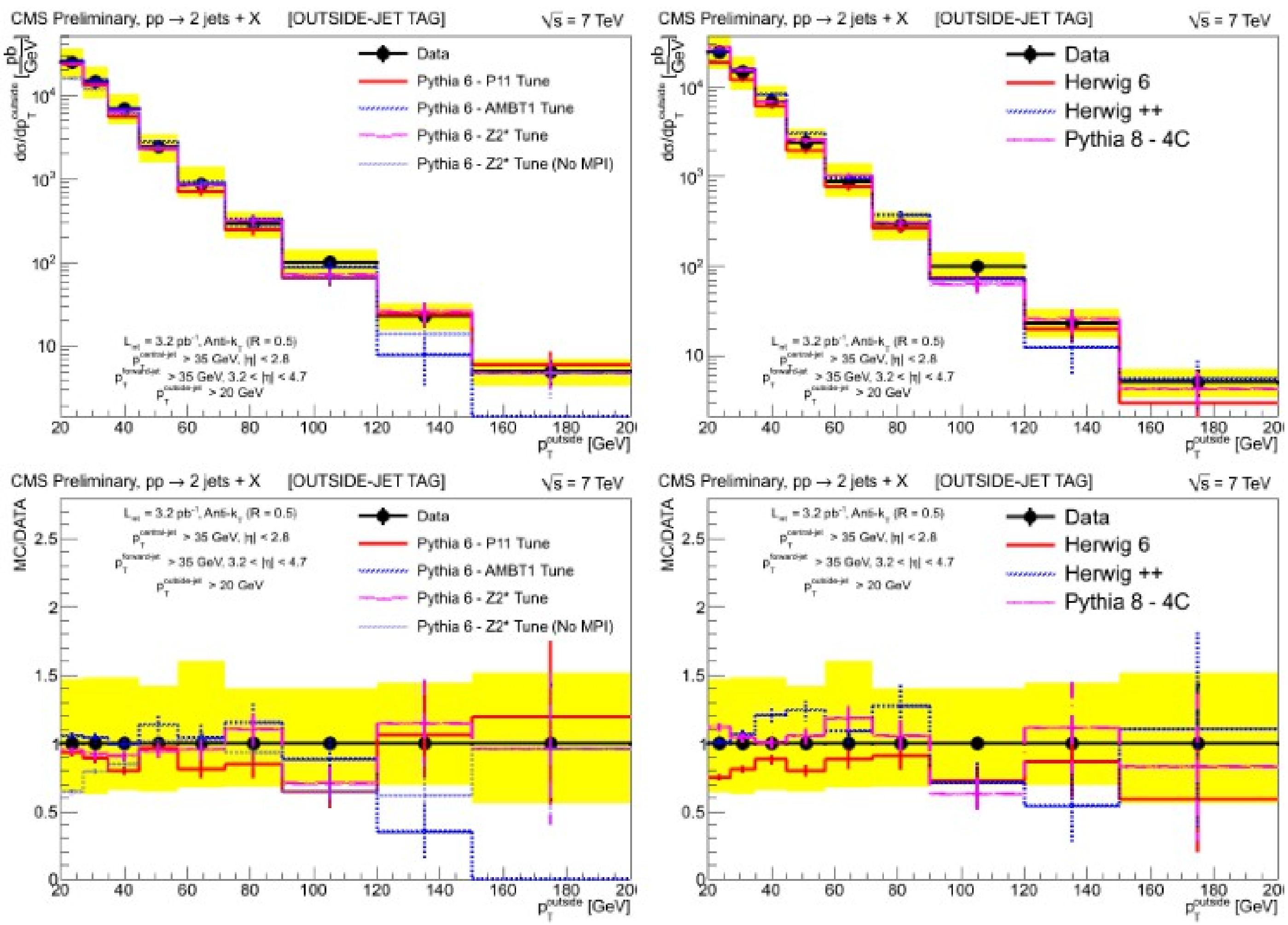
- **Central-Forward Jet Correlations in different scenarios**

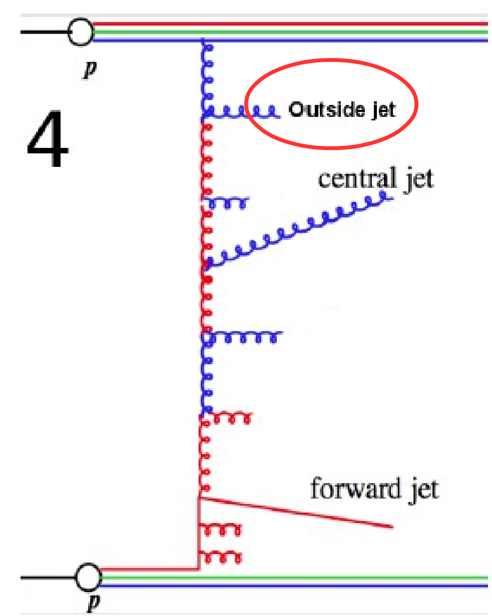
  - Also properties of additional jets measured

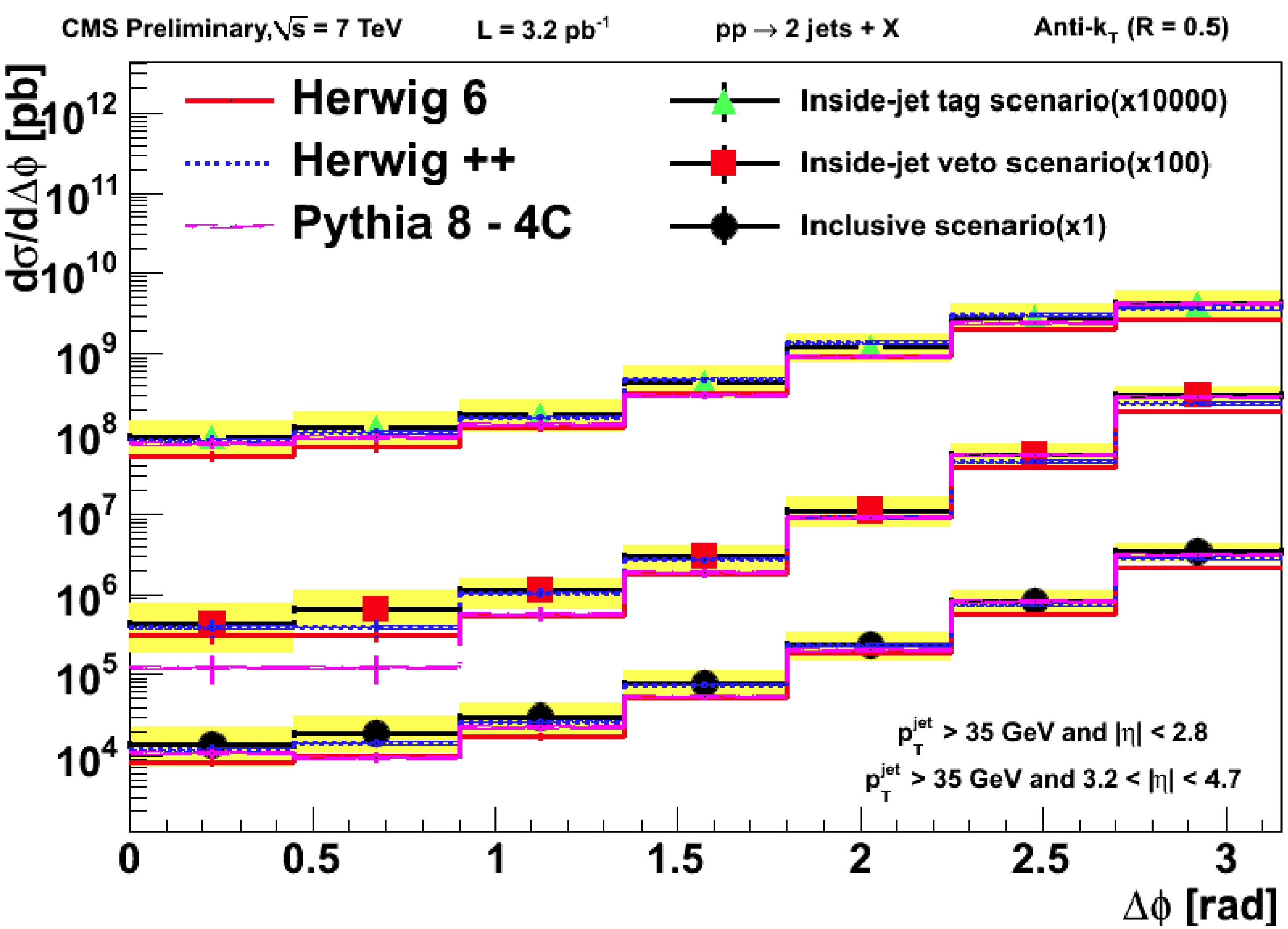
  - MPI contribution largest at central η^* (position of inter-leading jet)

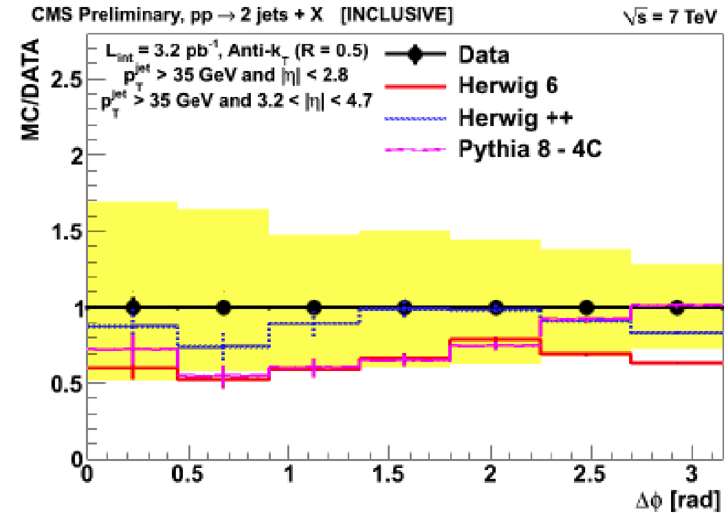
  - MC describes the data within large exp. uncertainty

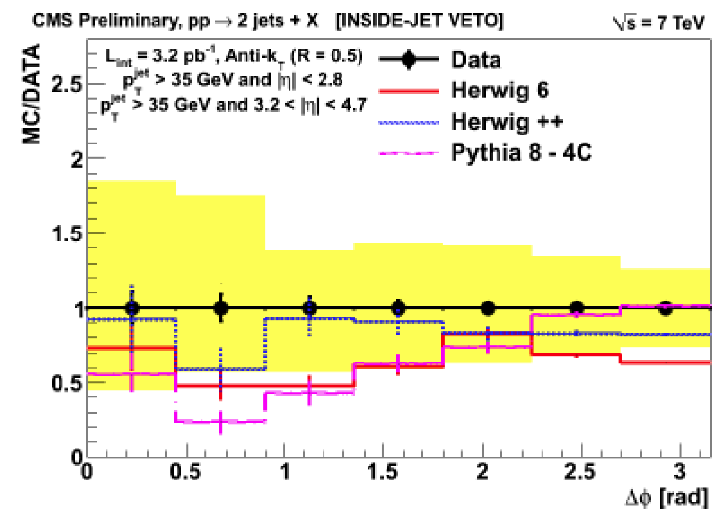
BACKUP

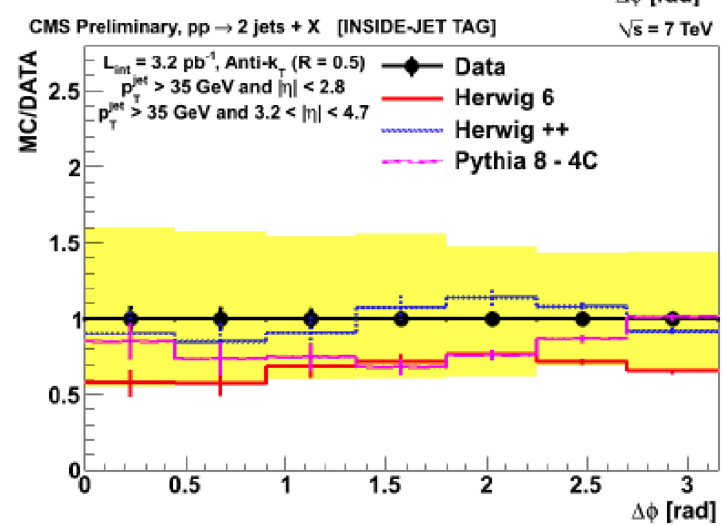

CMS Preliminary, pp → 2 jets + X [OUTSIDE-JET TAG] √s = 7 TeV
Data
Pythia 6 - P11 Tune
Pythia 6 - AMBT1 Tune
Pythia 6 - Z2* Tune
Pythia 6 - Z2* Tune (No MPI)
Herwig 6
Herwig ++
Pythia 8 - 4C
MC/DATA
[GeV]


4
p
Outside jet
central jet
forward jet
p









- **All tested MCs describe the data, considering the fairly large experimental uncertainty**

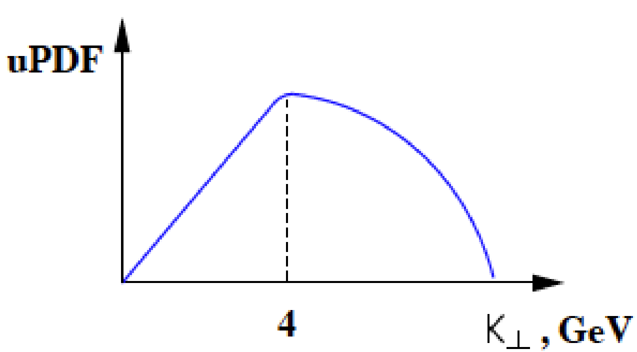
Saturated uPDF

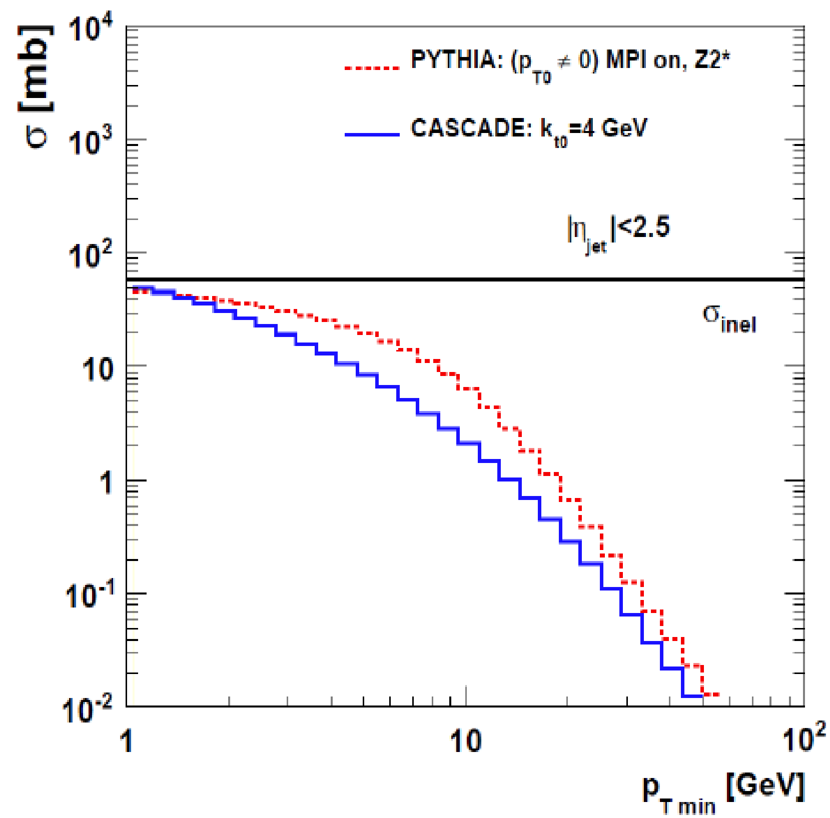
- Tame the divergence by using saturated PDFs.

- CASCADE. KT-factorization based MC generator.
  Low-pT behavior from:
  - ME dependence (low-p_T rise from $k_T << p_T$, slower rise for k_T)
  - unintegrated PDF $f(x,k_T,\mu)$ - suppression of uPDF at low k_T

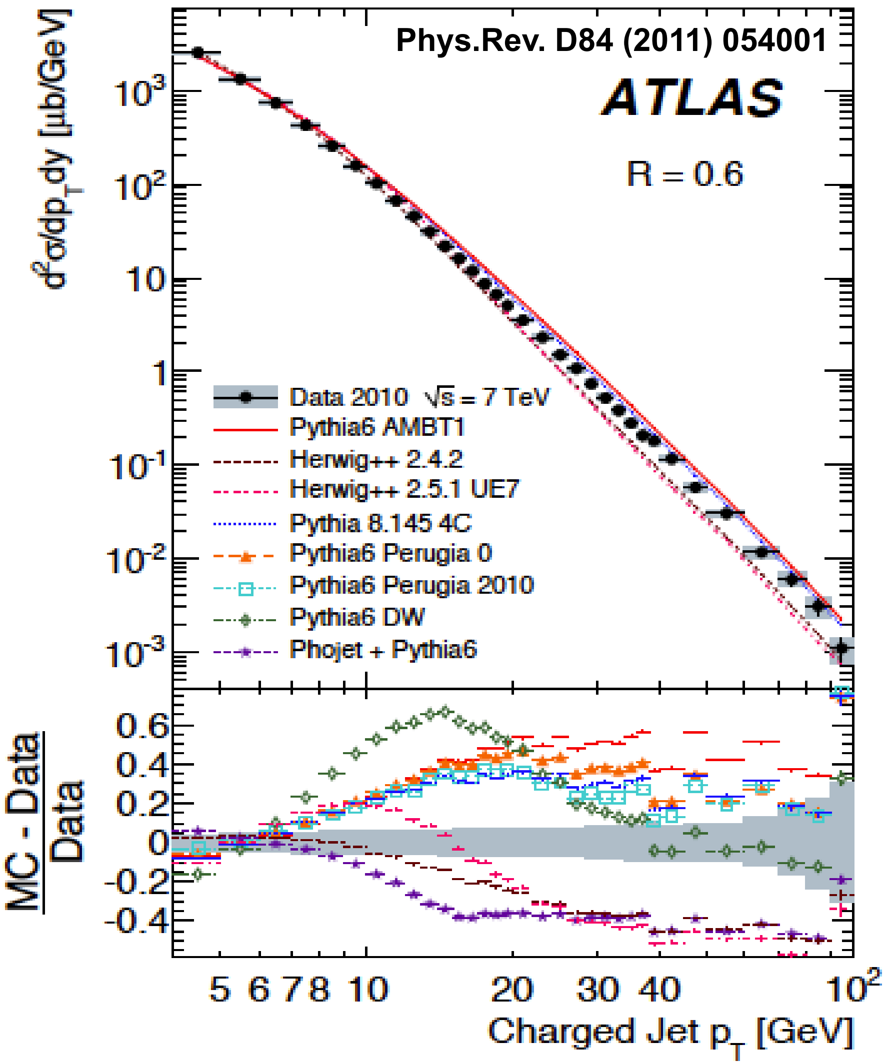
Modification of uPDF such that it goes to 0 for kT → 0.

for $k_T \to 0$:





Normalization discuss ?



(b) $R = 0.6$

Cross-section of jets with
$4 < p_T < 100$ GeV
$|\eta| < 1.9$

MC area normalised to data.

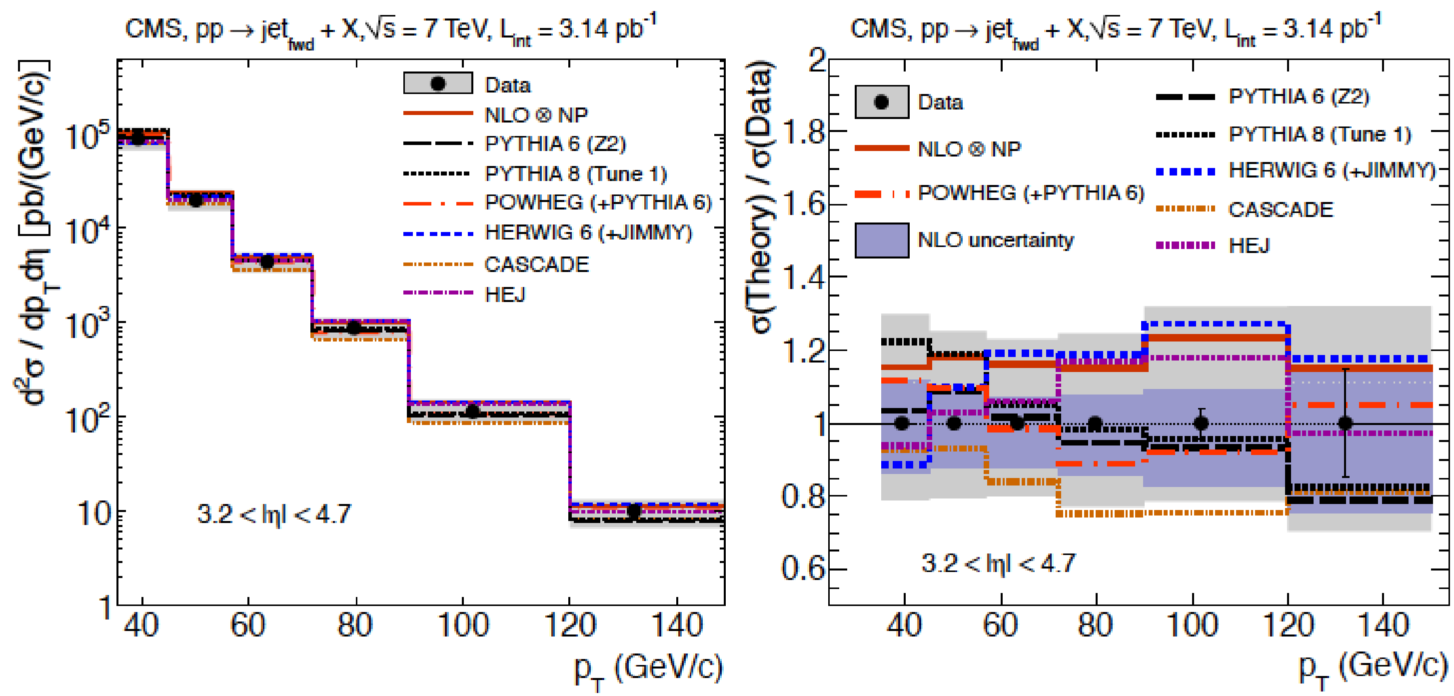
→

Data well described at low pt.
MC fails at high pt.

Older measurements from CMS

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.**

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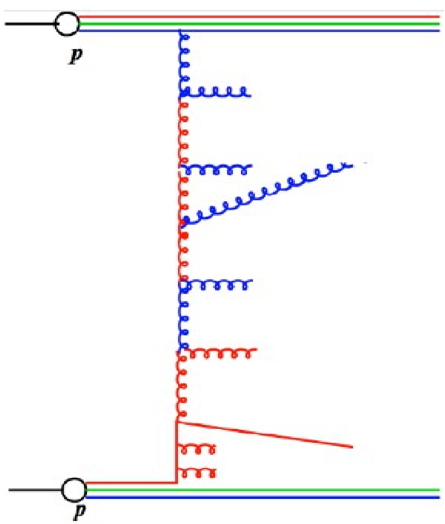
`arXiv:1202.0704`

Forward+Central Jets

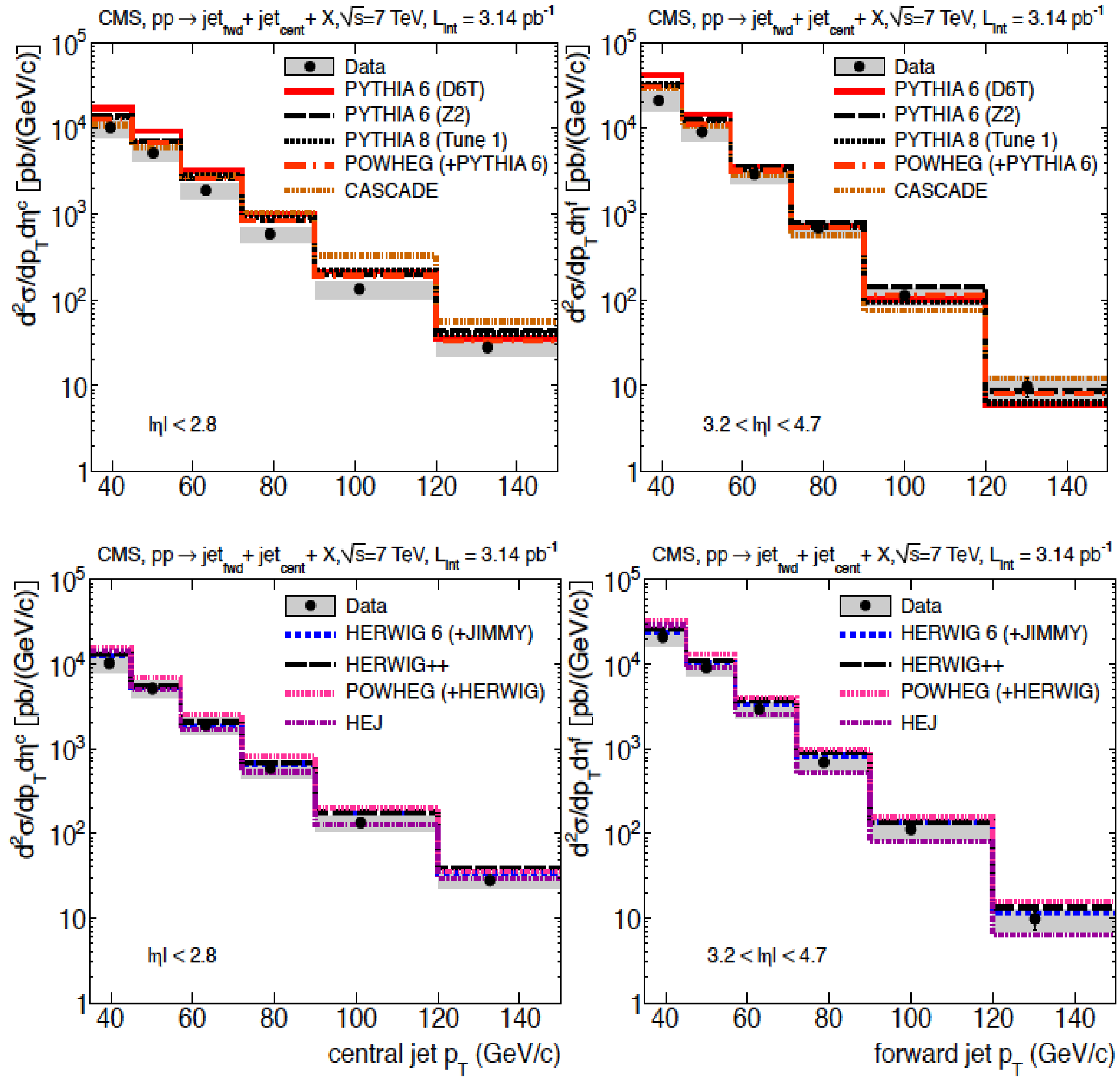
Events with at least one jet with
- **$3.5<|\eta|<4.7$**
- **$p_{t,jet}>35$ GeV**

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)**



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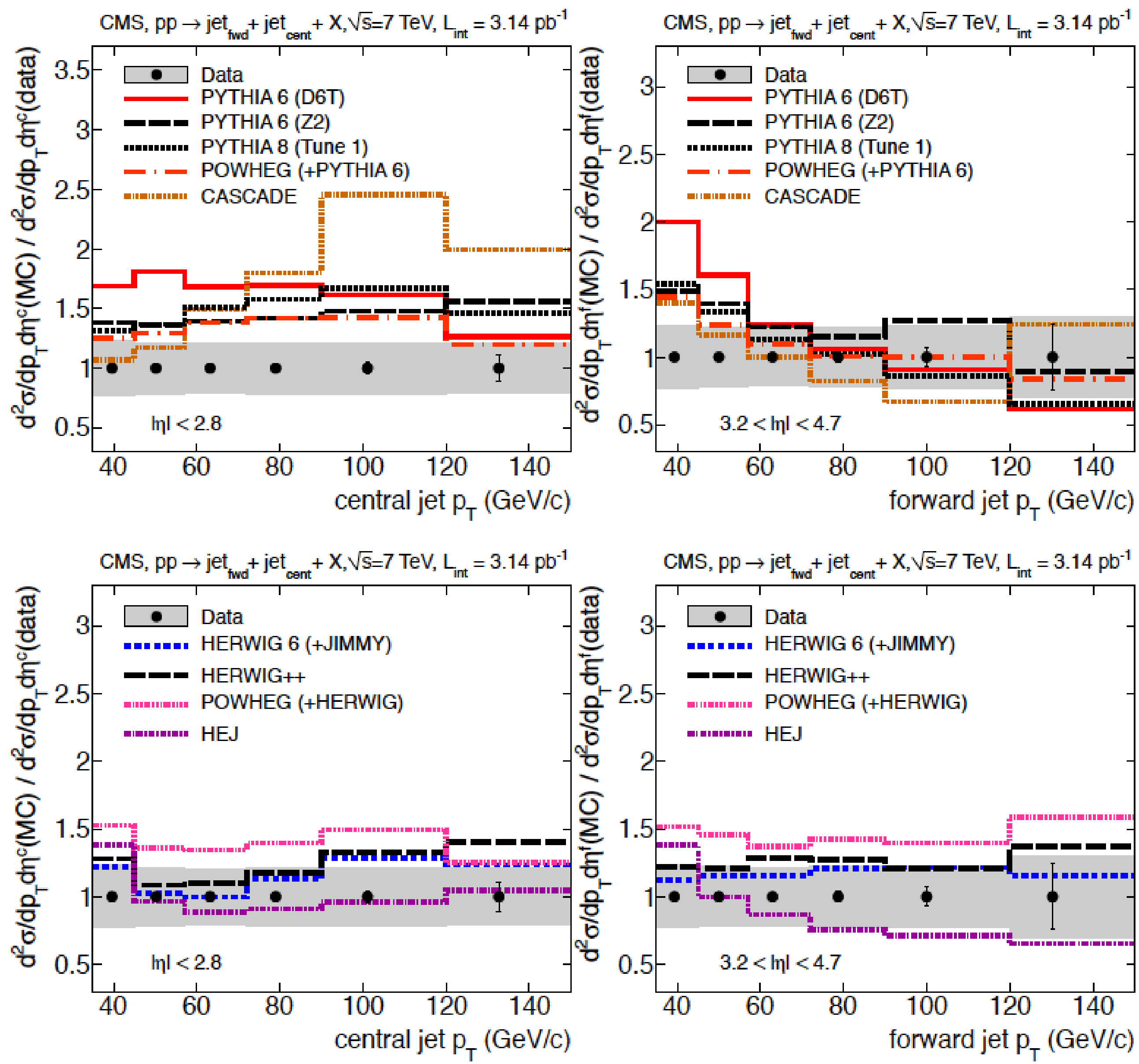
Forward+Central Jets

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

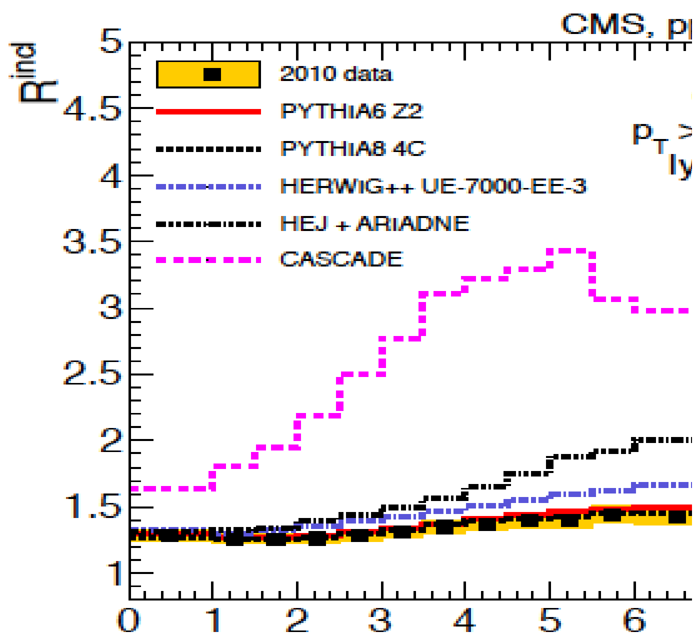
Jets reconstructed with the anti-kT algorithm (R=0.5)
$p_{t,jet}$>35 GeV and $|\eta_{jet}|$<4.7

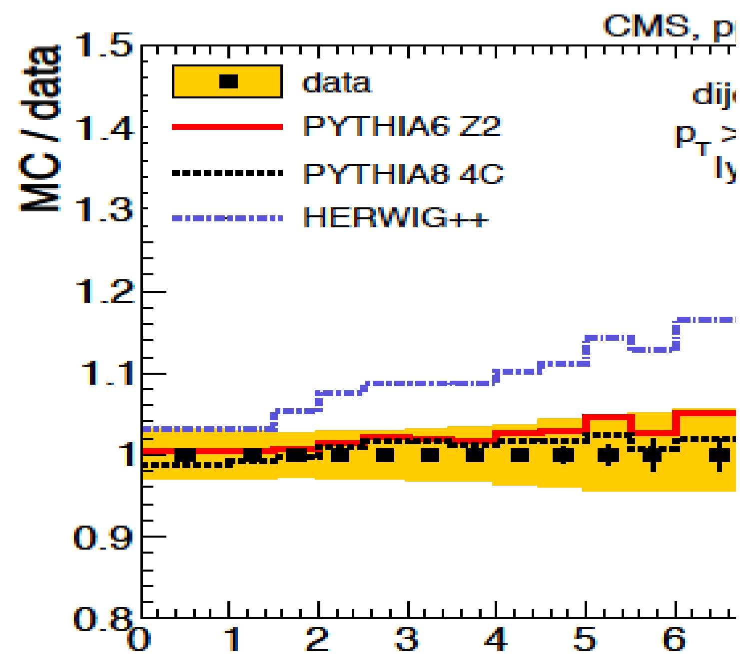
Observable: Rapidity difference between jets, Δy

Inclusive jets: **All jet pairs in the events considered**
Exclusive jets: **Events with exactly two jets above the threshold**
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

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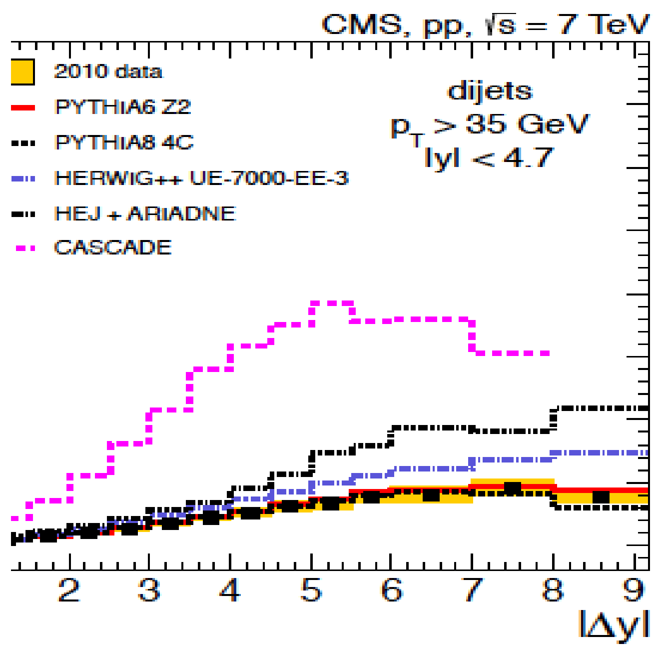
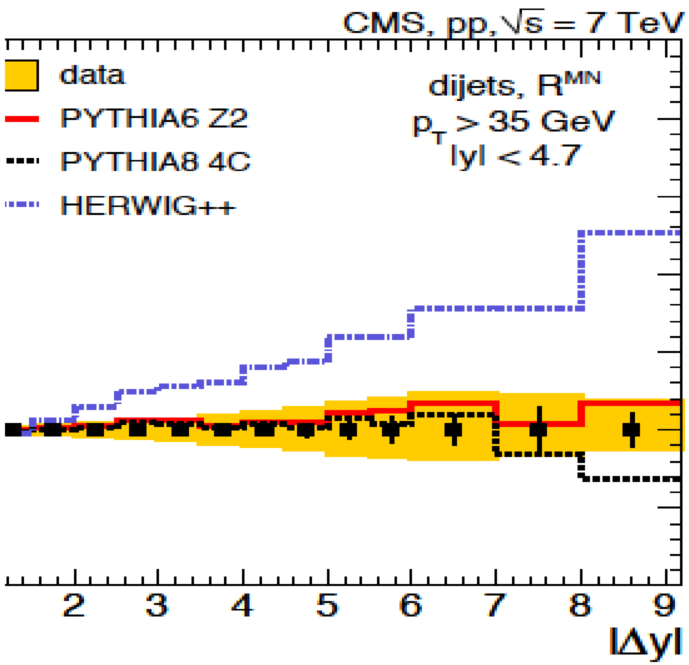
$$R = \frac{\sigma_{dijet}(\text{MN})}{\sigma_{dijet}(\text{exclusive})}$$





- 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