CMS results on multi-jet correlations

Grigory Safronov
(ITEP, Moscow)

for the CMS Collaboration

Outline

- **Introduction**
- **CMS detector**
- **Datasets**
- **Measurements**
  - Integrated mini-jet cross-section
  - Inclusive jet production
  - Production of jets with large rapidity separation
- **Summary**

Physics overview

Integrated mini-jet cross-section

Low p_T (> 1 GeV); probe for pQCD to NP QCD transition as implemented in MC models

Inclusive forward jet cross-section

pQCD benchmark measurement covering large phase space; an access to $x_1 \ll x_2$

Jets with large rapidity separation

Probes for effects beyond the DGLAP resummation, BFKL

Forward-central dijet production cross-section

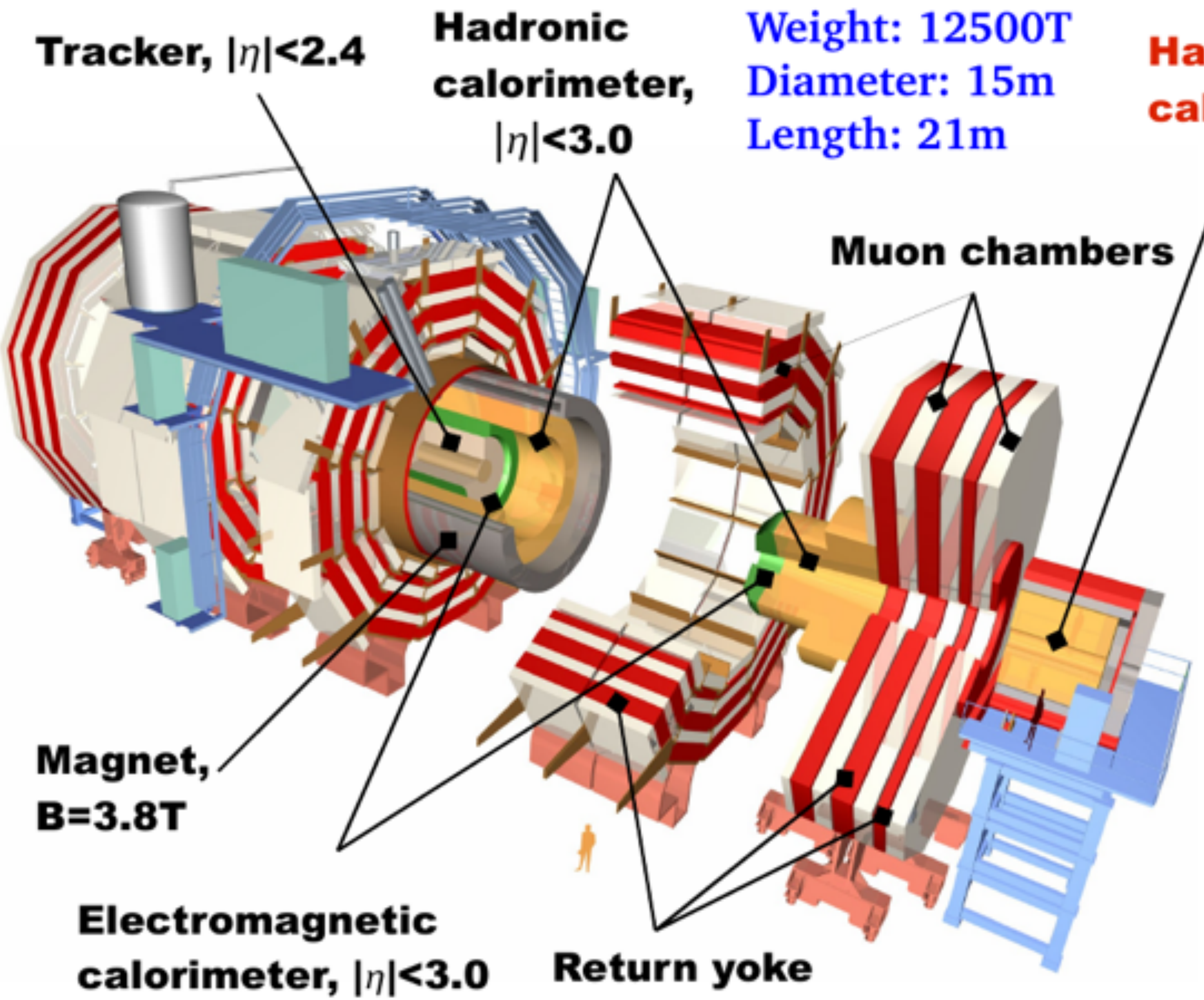
Sensitivity to $x_1 \ll x_2$, small-x PDFs

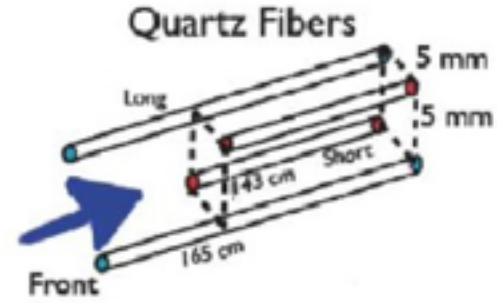
Mueller-Navelet dijet decorrelations

Higher order pQCD contributions at large rapidity intervals

CMS detector

Weight: 12500T
Diameter: 15m
Length: 21m





- Steel absorber
- Radiation-hard quartz fibers, Cherenkov light detection
- "Long" and "short" segments allow to distinguish between EM and HAD components of hadronic jet

Datasets

LHC pp runs: ~30 fb^{-1} collected in 2010 - 2013

- High luminosity was provided by huge bunch intensity
- Huge pileup (PU): up to 20

Pileup is a problem for forward jet or low-p_T measurements

- Jet primary vertex tagging is not possible in forward region

Analyses presented here use 2010 and 2012 data taken at low pileup

- **7 TeV 2010: <PU> ~ 2.2, l = 44.2pb^{-1}**
- **8 TeV, summer 2012: 2 runs <PU> ~ 4, l = 5.8 pb^{-1}**
- **8 TeV, summer 2012: common CMS + TOTEM run, <PU> = 0.054, l = 45 μb^{-1}**

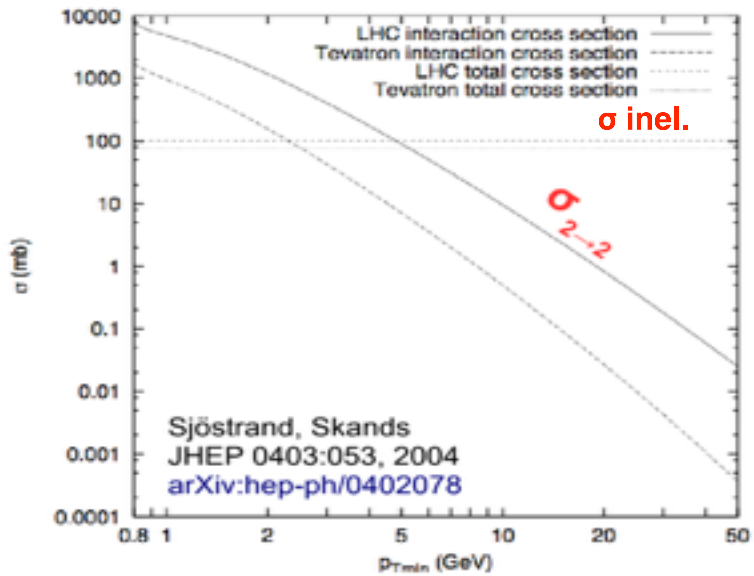
Measurements

Mini-jet cross-section (I)

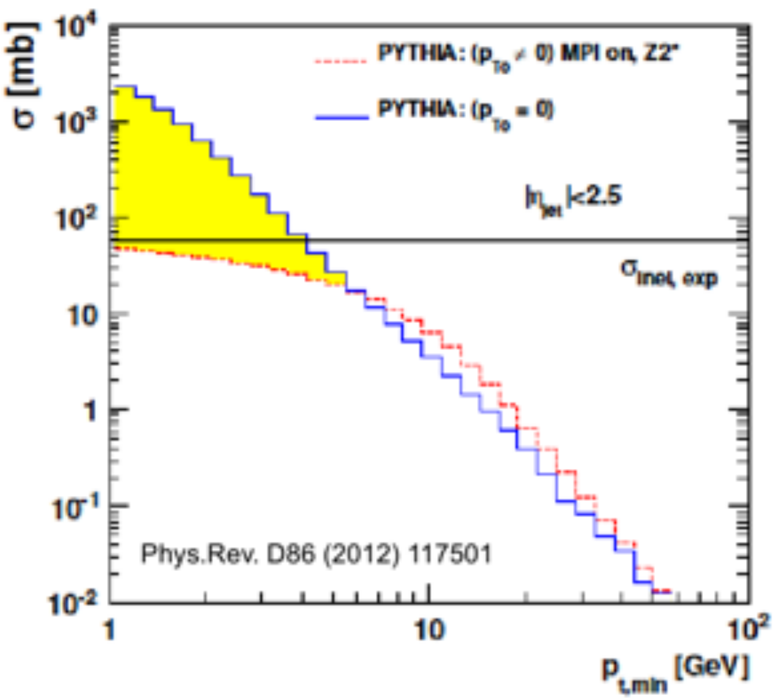
Based on Phys. Rev. D86(2012) 117501
(A. Grebenyuk, F. Hautmann, H.Jung, P. Katsas, A. Knutsson)

Total 2→2 cross-section is divergent towards low $p_{T,min}$ (integration threshold, $p_T > p_{T,min}$) and eventually becomes larger than total inelastic cross-section

At LHC this happens around $p_{T,min} \sim 5$ GeV



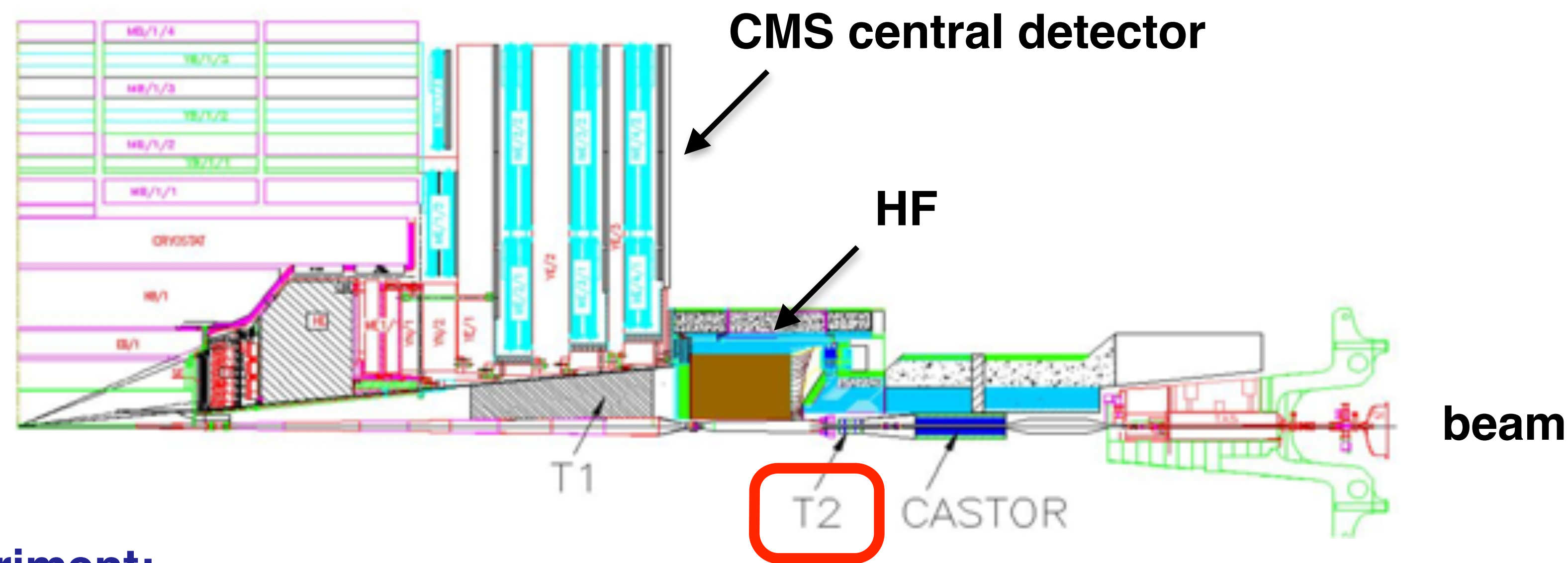
CMS-PAS-FSQ-12-032



In theory 2→2 cross-section needs to be tamed

Pythia, phenomenological parameters:

- Regularisation factor for the cross-section
- Multi-parton interactions



CMS-PAS-FSQ-12-032

TOTEM experiment:

T2 telescope

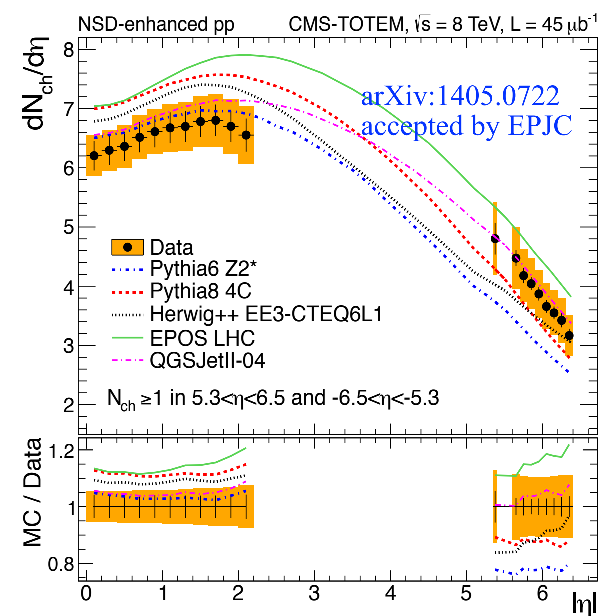
- tracking in the region $5.3 < |\eta| < 6.5$

Common trigger with the CMS - at least one track in **T2**

- 91-96 (%) of total pp inelastic x-sec captured

Common CMS + TOTEM data-taking

- **Run with very low pileup at $\sqrt{s}$ = 8 TeV (2012), <PU>=0.054, l=45 μb^{-1}**



Mini-jet cross-section (III)

Events are triggered by TOTEM T2:

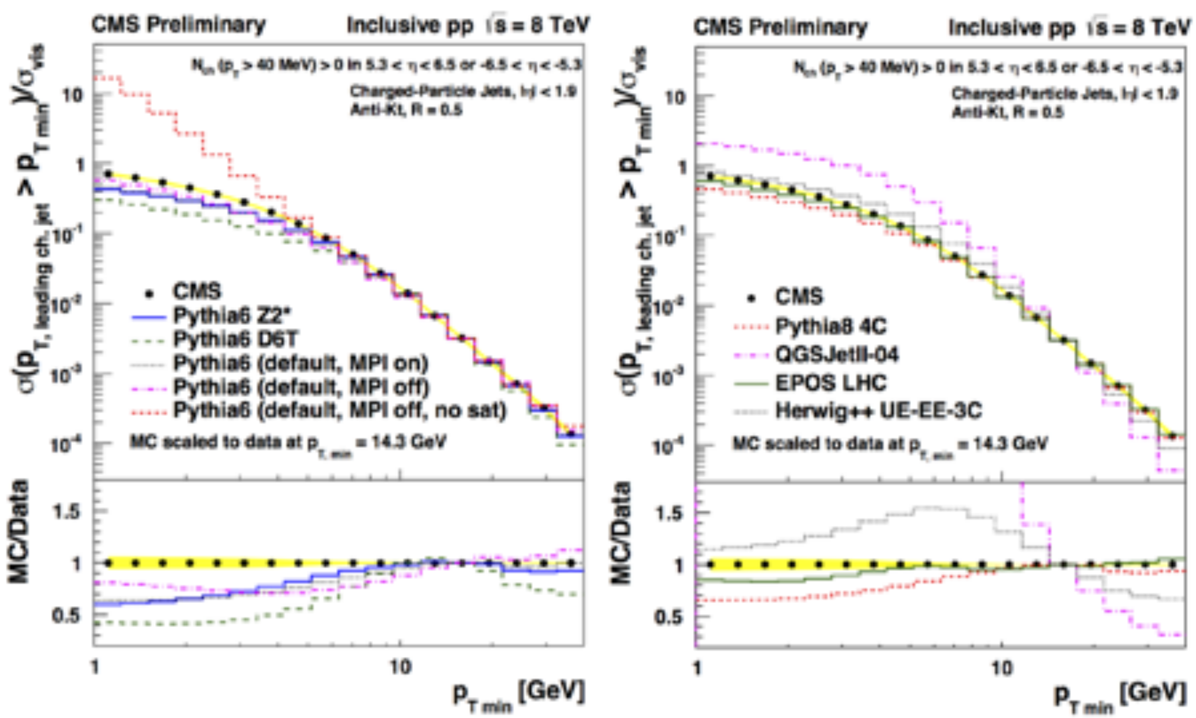
- At least one track p_T > 40 MeV, 5.3 < |η| < 6.5

Track-jet selection:

- Charged component, anti-k_T R=0.5, p_T > 1 GeV, |η| < 1.9

Event yield as a function of integration threshold pT,min is measured

- And divided by the total number of events



Observations:

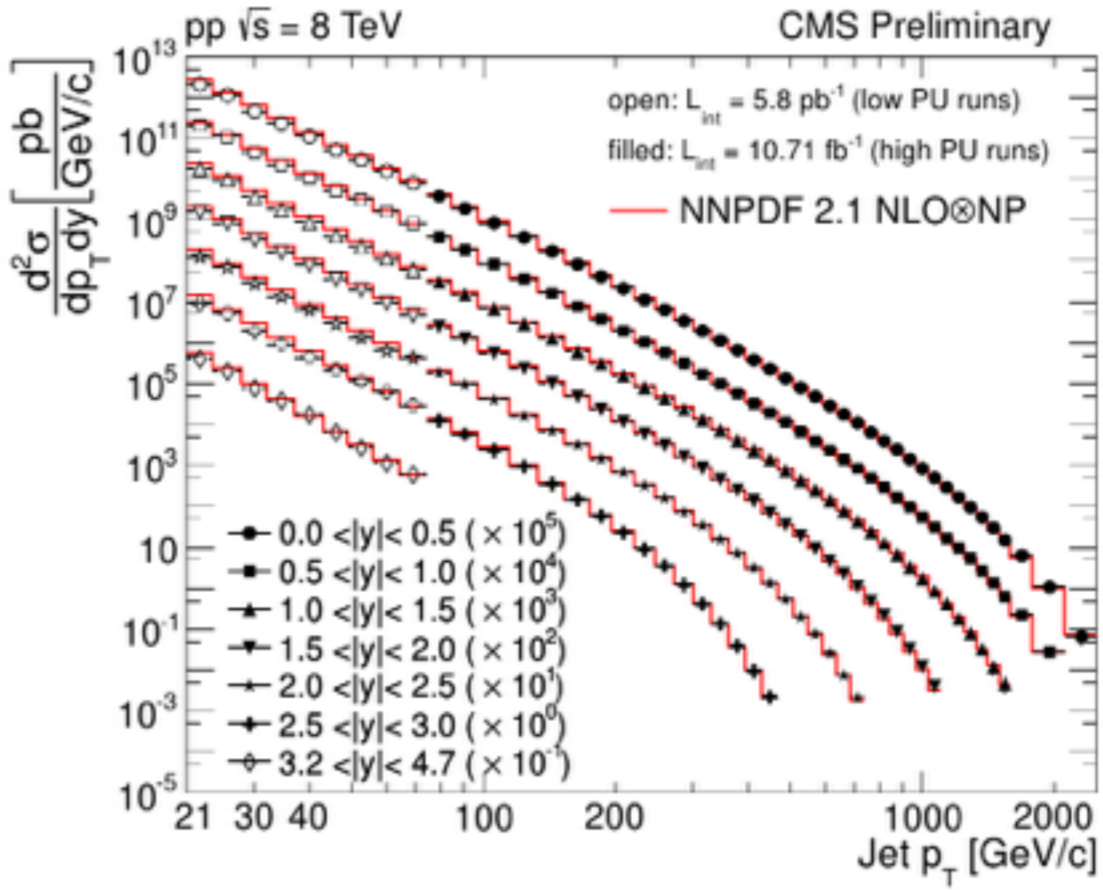
- Taming of the cross-section is visible
- Large difference between the models
- Tune sensitivity
- Pythia and Herwig do not describe the data
- Cosmic ray models: **EPOS gives the best desription**; QGSJet fails

CMS-PAS-FSQ-12-032

Inclusive jet cross-section

CMS measurements are performed within 20 ≲ p_T ≲ 2000 (GeV) and |y| < 4.7

- Combined low-PU runs (Summer 12, <PU> ~ 4, l = 5.8 pb^{-1}) and full 2012 dataset (l = 10.7 fb^{-1})



CMS-PAS-FSQ-12-031 [comb. CMS-PAS-SMP-12-012]

Data is well-described by NLO calculations with NP corrections

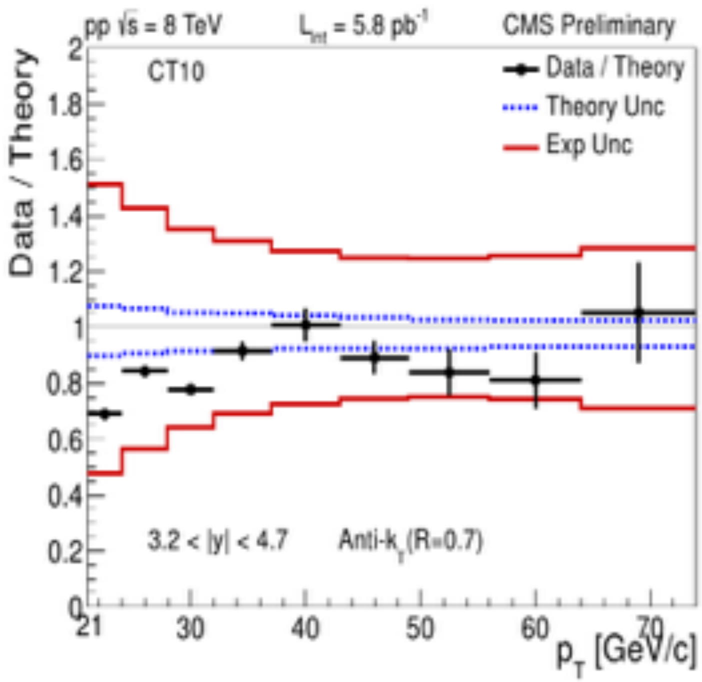
Forward jet cross-section

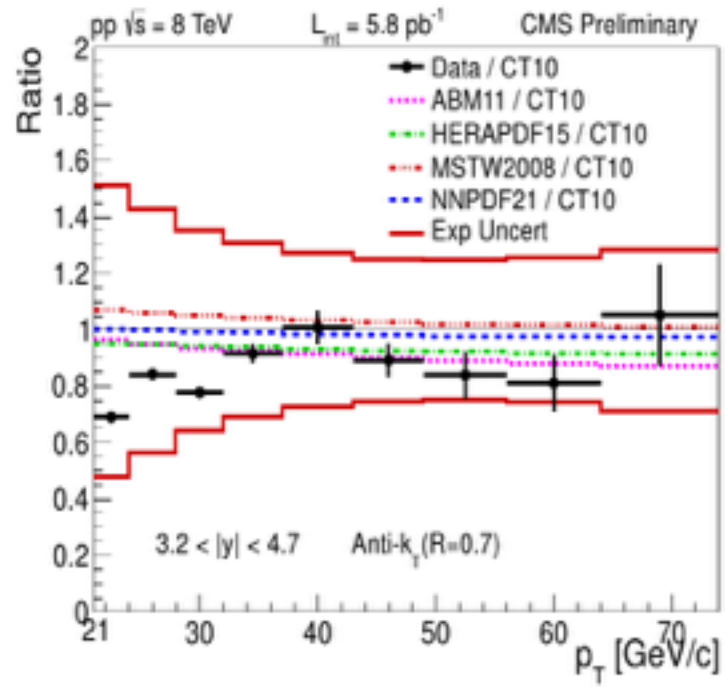
Closer look at forward jets:

- **3.2 < |η| < 4.7**
- **21 < p_T < 80 (GeV)**

Experimental uncertainties:

- Jet energy scale (JES): < 45%
- Unfolding: 3-6%
- Luminosity: 4%





CMS-PAS-FSQ-12-031

All predictions agree with data within the uncertainties

Inclusive jet production is well-described by NLO⊗NP predictions over the wide range of p_T and rapidity

Jets with large rapidity separation

pQCD resummation → parton showers (PS)

DGLAP PS regime:

$\sqrt{s} \sim p_T > \Lambda_{QCD}$

Strong ordering of emissions in pT

Measure high-p_T leading jets

BFKL PS regime (QCD high energy limit):

$\sqrt{s} \gg p_T > \Lambda_{QCD}$

Strong ordering of emissions in y

Random walk of emissions in p_T

Measure low-p_T jets with large rapidity span (Δy) → approach BFKL limit and open the phase space for multiple emissions with similar p_T

BFKL prediction: $$\hat{\sigma} \sim \hat{s}^A \sim e^{A\Delta y}, A > 1$$

Search for beyond-DGLAP effects in low-p_T PS with large rapidity span

"low-p_T" means as low as allowed by the trigger and reconstruction techniques (~ 30 GeV)

Forward-Central jet production (I)

2010 pp runs (low PU), 3.2 pb^{-1}

Measure simultaneous production of forward and central jets

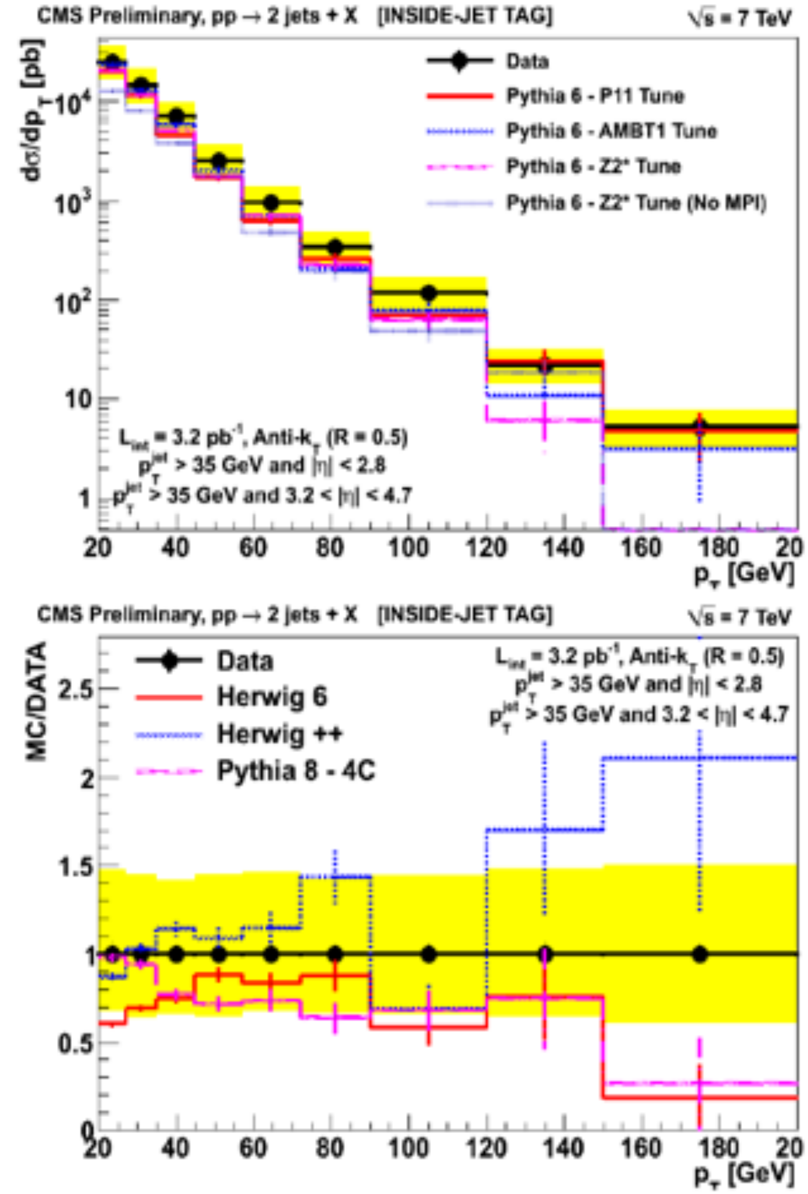
- p_T > 35 GeV
- central : $|\eta| < 2.8$
- forward: $3.2 < |\eta| < 4.7$
- p_T - ordering of jets in each region

Absolute differential cross-section

- Leading exp. uncertainty: JES - up to 50%

Cross-section in p_T bins for intermediate jets

- Good agreement of MC predictions with data



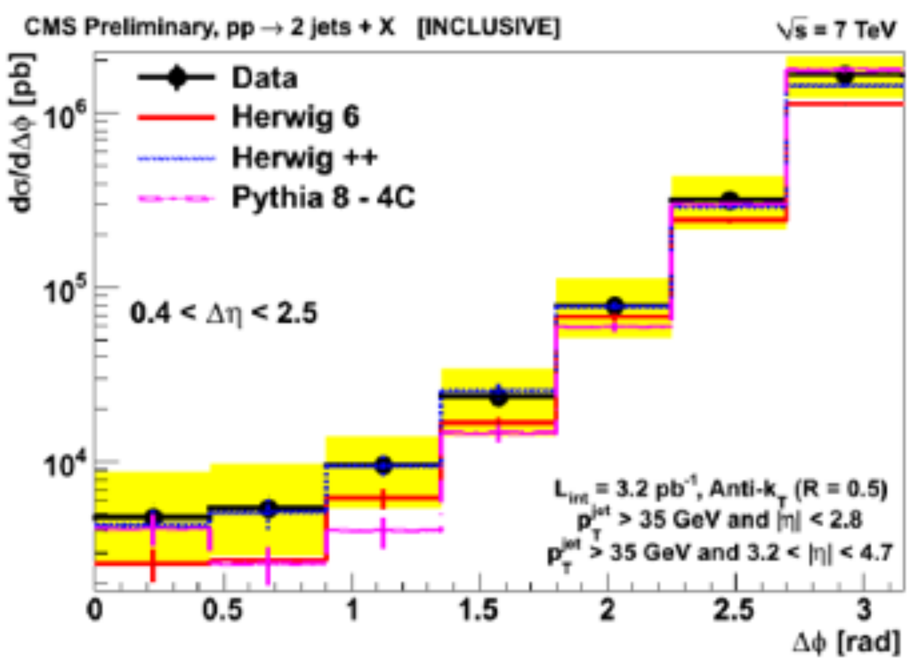
CMS-PAS-FSQ-12-008

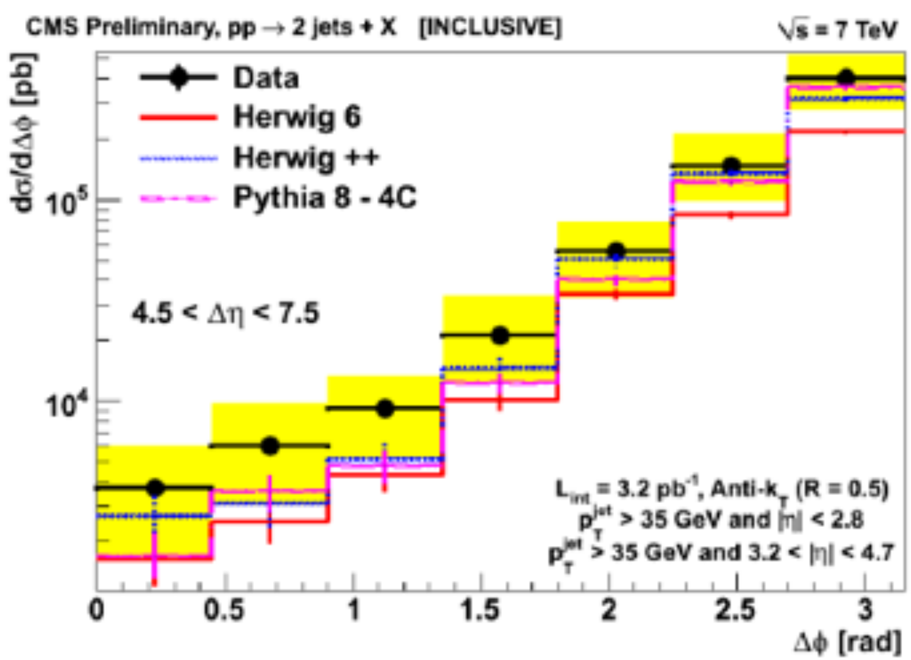
Forward-Central jet production (II)

CMS-PAS-FSQ-12-008

Cross-section differential in forward-central azimuthal angle difference, $\Delta\phi$
- In bins of rapidity separation

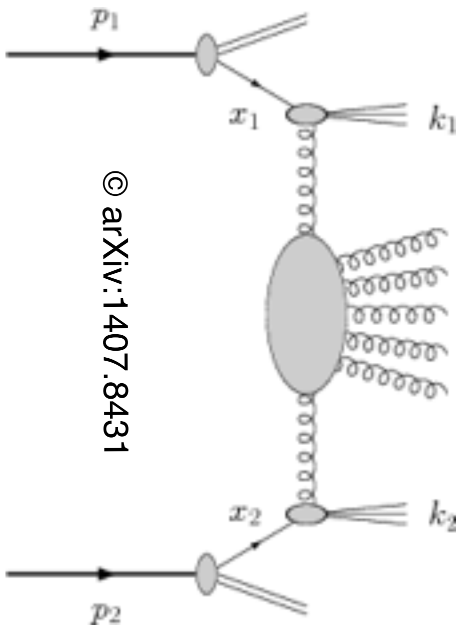
Herwig and Pythia predictions agree with data within the uncertainty





Mueller-Navelet jet production

Mueller-Navelet (MN) jets – jet pair with similar p_T ($k_1 \sim k_2$) and large rapidity separation



2010 data (low PU), 5 pb^{-1}

Selections:

- Require single primary vertex (~1/3 of 2010 data)
- Calorimeter **jet p_T > 35 GeV, $|\eta|$ < 4.7**
- Rapidity separation coverage of the measurement: **Δy < 9.4**
  - Combination of inclusive and forward-backward jet triggers

Systematic uncertainties:

- Dominated by JES and unfolding uncertainties, small compared to absolute cross-section measurements
- Pileup influence is reduced (or even removed) by single vertex requirement

Dijet production ratio

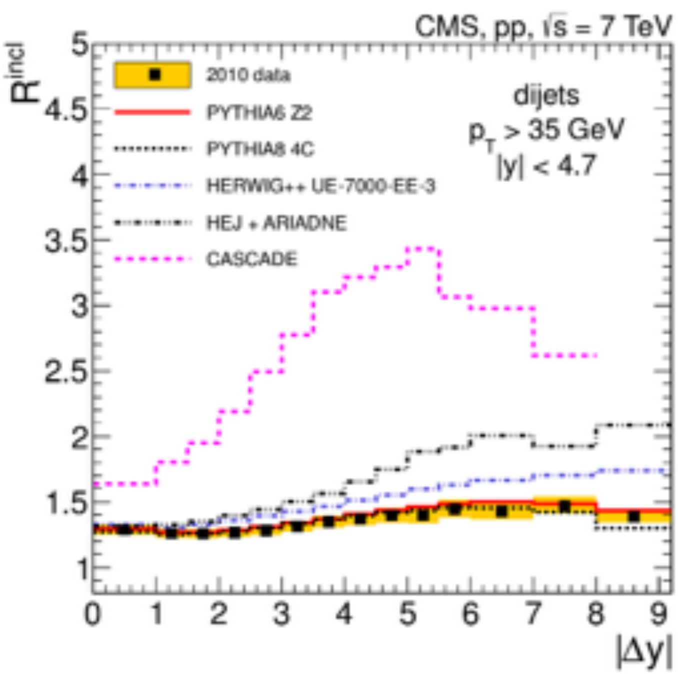
Direct probe for higher order radiation:

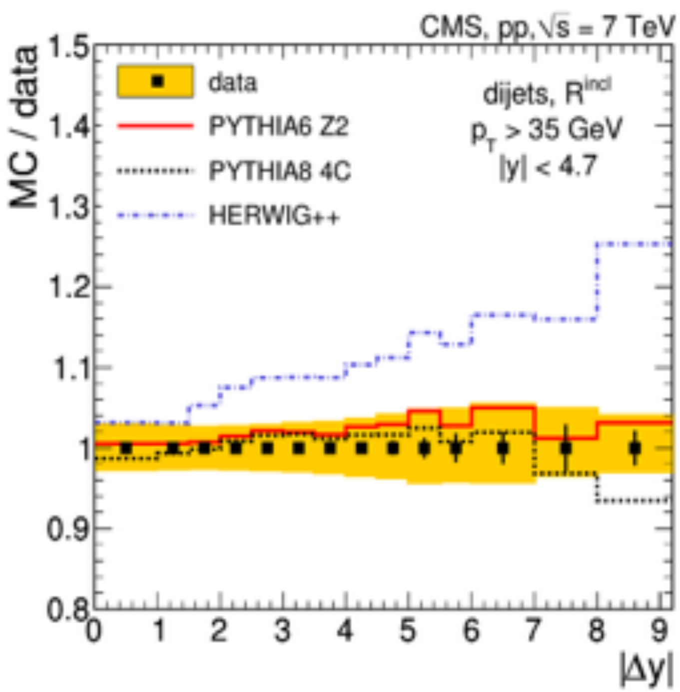
$$R^{\text{incl}} = \sigma^{\text{incl}} / \sigma^{\text{excl}}$$

"exclusive" - events with exactly two jets above the threshold

Significant spread between models:

- **Best description of the ratio is given by PYTHIA6 and PYTHIA8**
- **Herwig++ shows larger growth with increase of rapidity separation**
- **BFKL - inspired models CASCADE and HEJ overestimate the data**





CMS-PAS-FWD-10-014 10.1140/epjc/s10052-012-2216-6

MN azimuthal decorrelations

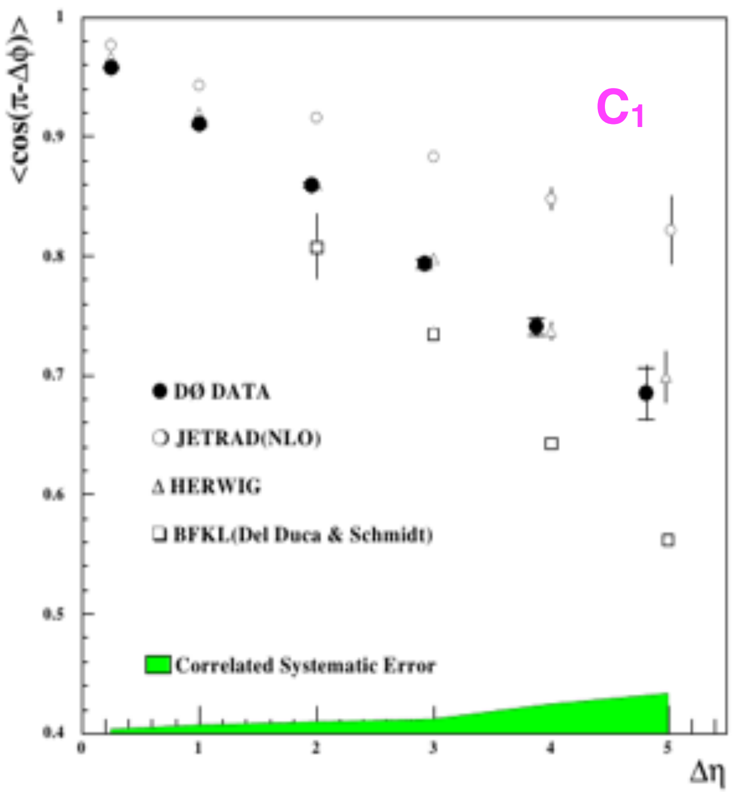
Measurement at D0 in 1996

[10.1103/PhysRevLett.77.595]

$\Delta\eta < 6.0$, $E_T > 50$ (20) GeV

LL BFKL overestimates decorrelation

HERWIG6 gives the best description



CMS measurement

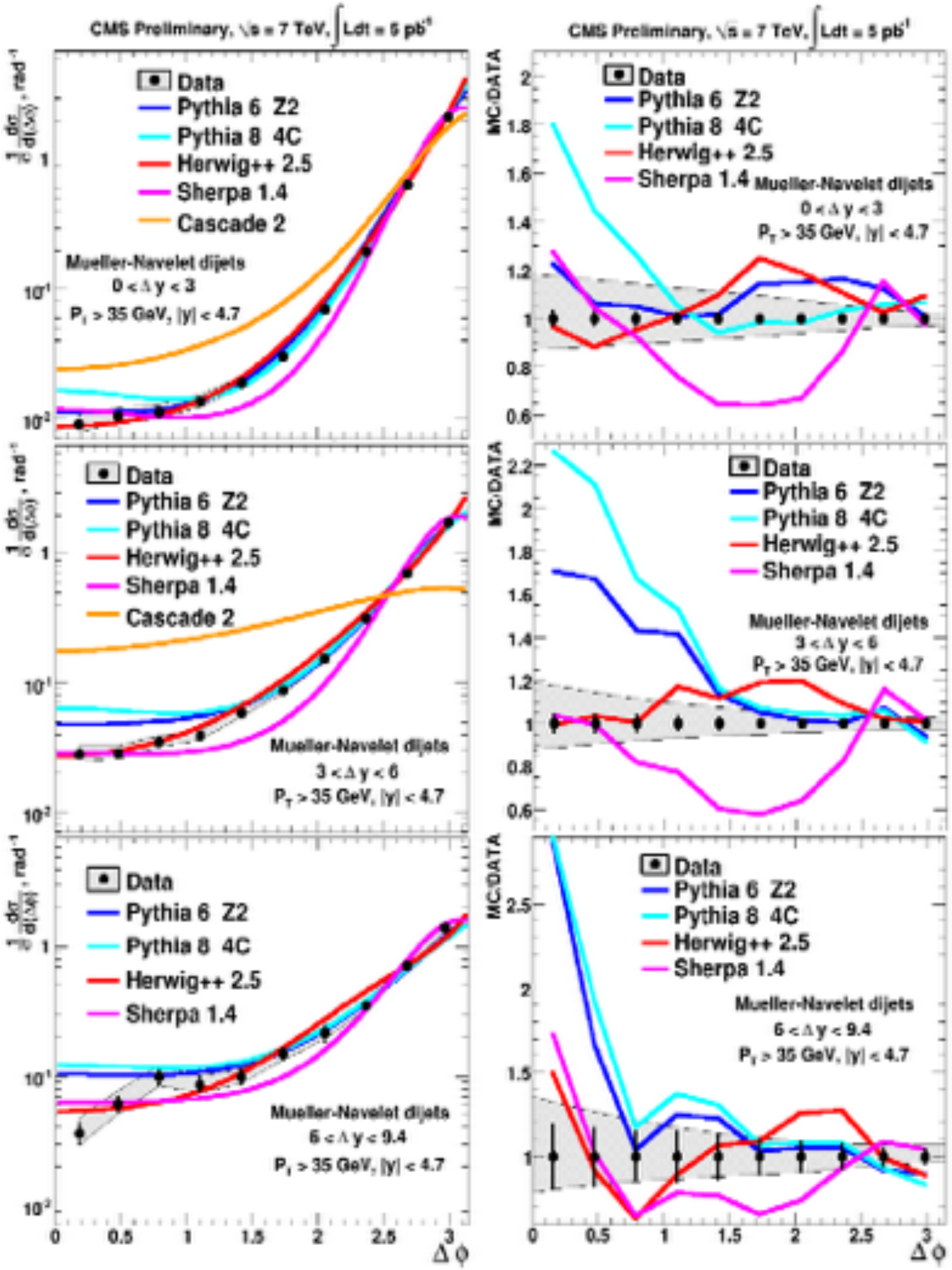
Extends to **$\Delta y < 9.4$**

Symmetric **$p_T > 35$ GeV**

Observables:

- **Azimuthal angle separation $\Delta\phi$ in Δy bins**
- **Average cosines C_1, C_2, C_3 as a function of Δy**
- **Ratios C_2/C_1, C_3/C_2**

Δφ shapes



In 2 → 2 scattering jets are back-to-back and $\Delta\phi = \pi$

Decorrelation is due to higher order radiation

PYTHIA6 and PYTHIA8 show too strong decorrelation

SHERPA underestimates decorrelation

HERWIG++ gives the best description

CMS-PAS-FSQ-12-002

Average cosines (I)

First 3 coefficients of Fourrier transform of Δϕ distribution

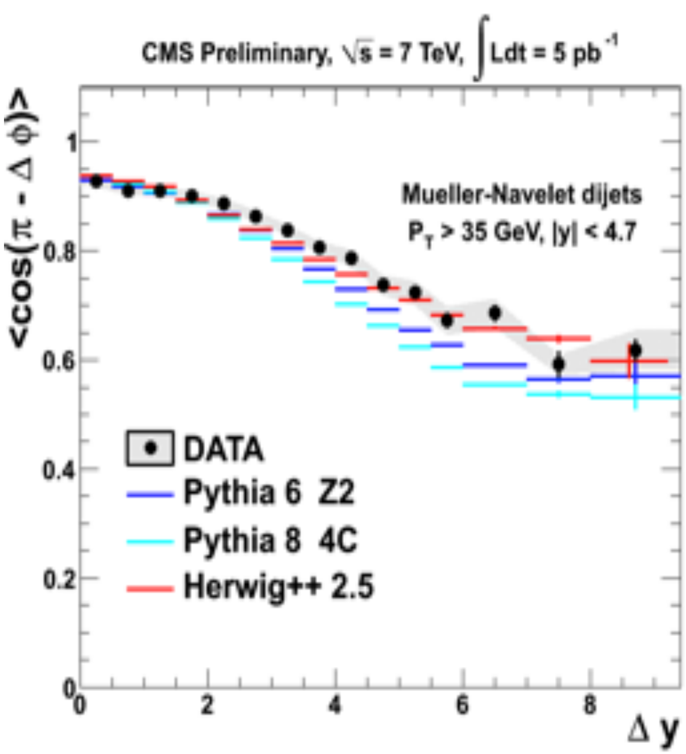
Equal to average cosines: $C_n = \langle \cos(n(\pi - \Delta\phi)) \rangle$

BFKL NLL predictions at parton level provided by:

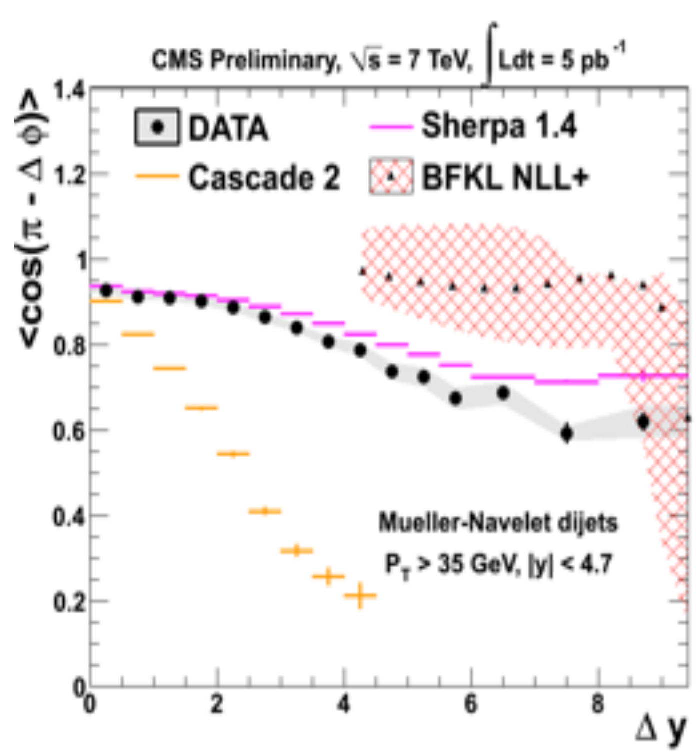
B. Ducloué, L. Szymanowski, S. Wallon, **[10.1007/JHEP05(2013)096]**

- Later calculation is available which shows better agreement (arXiv:1309.3229)

CMS-PAS-FSQ-12-002

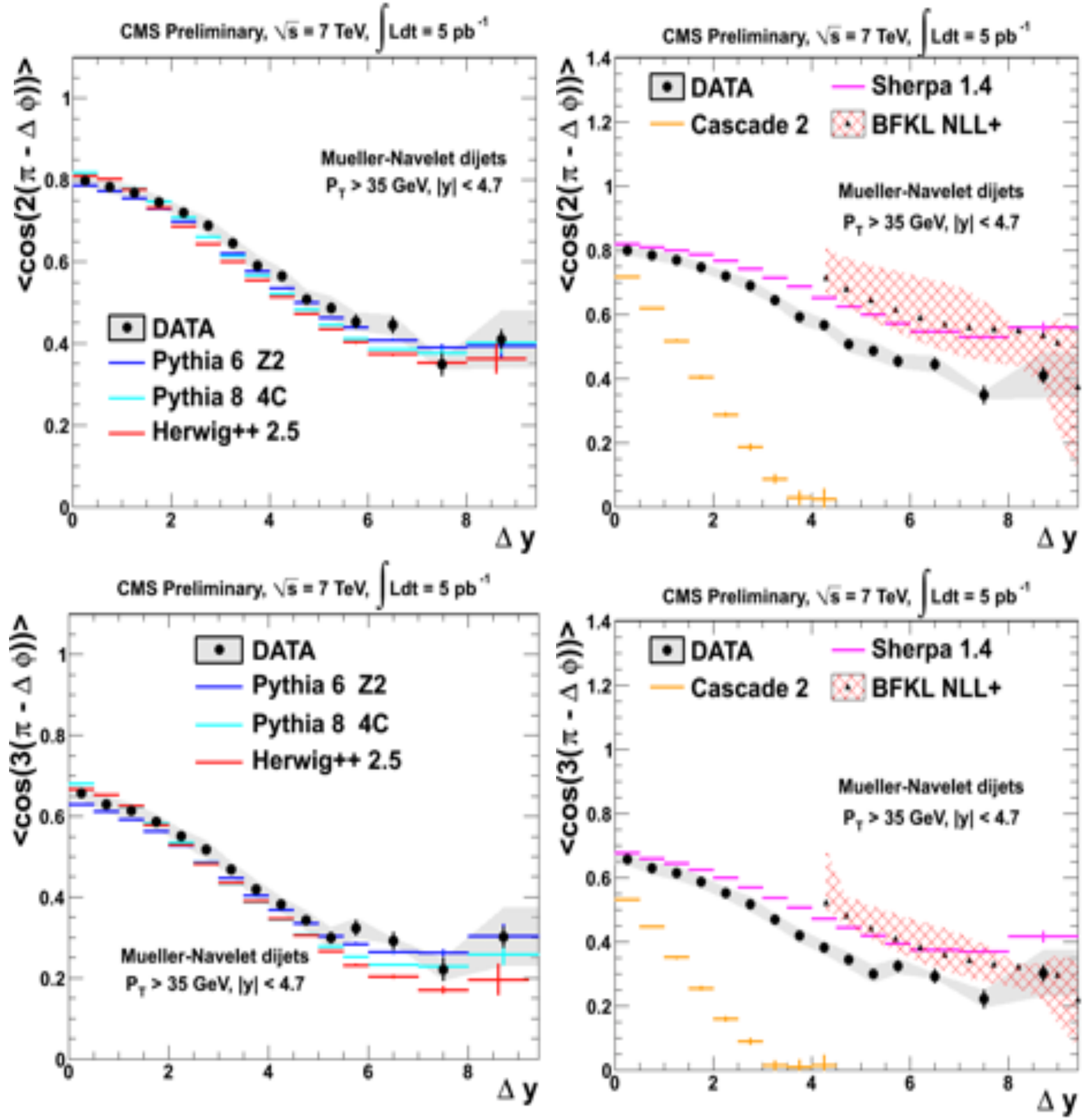


C1



Average cosines (II)

C2



Correlation in SHERPA is stronger than in data

PYTHIA and HERWIG describe the data well

C3

CMS-PAS-FSQ-12-002

Ratios of cosines as proposed in
10.1016/j.nuclphysb.2007.03.050
(A. Sabio Vera, F. Schwennsen)

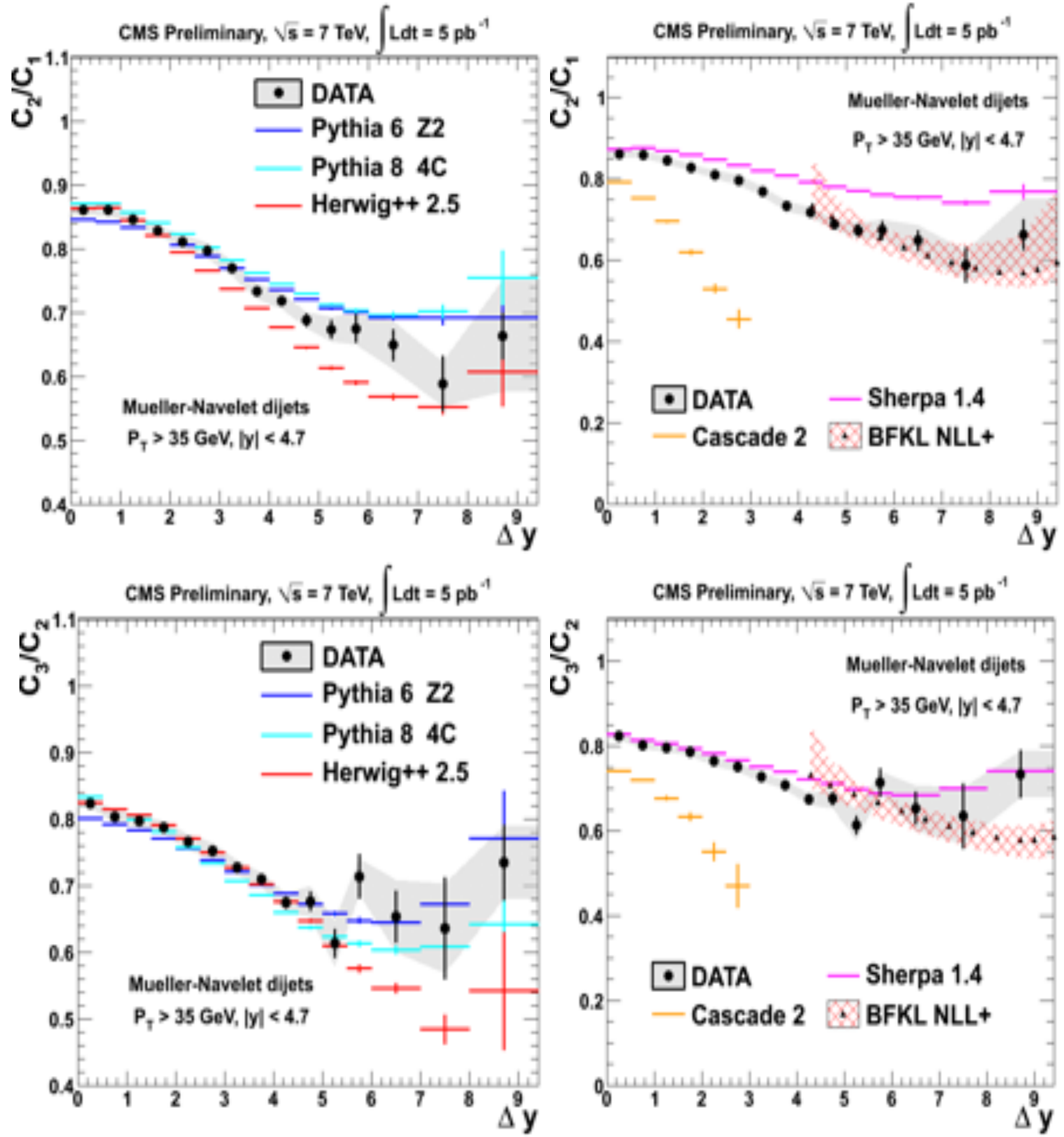
- C_2/C_1, C_3/C_2

Not conclusive for PYTHIA6, 8 and HERWIG++

SHERPA overestimates C_2/C_1,
Consistent with C_3/C_2

NLL BFKL is consistent with ratios

CMS-PAS-FSQ-12-002

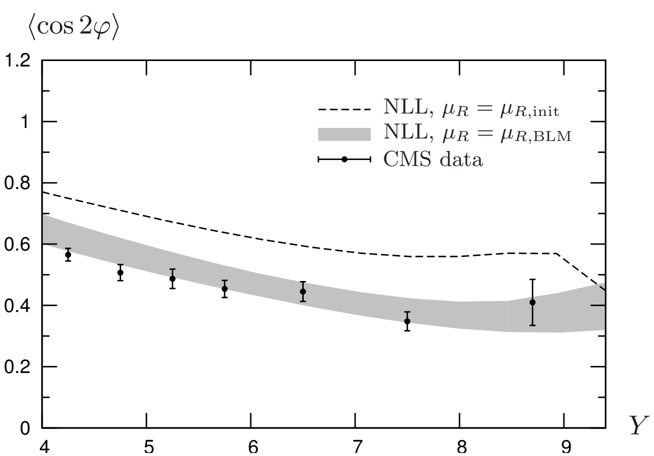


MN azimuthal decorrelations, summary

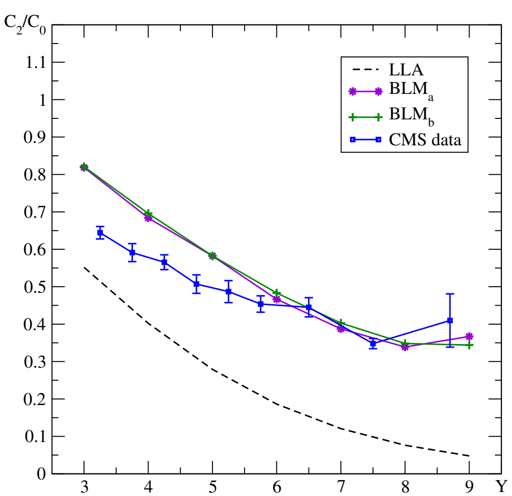
- MN azimuthal decorrelations were measured up to $\Delta y = 9.4$
- Diversity in MC predictions:
  - None of MC models describe all observables
  - Best combined description among MC is given by HERWIG++
  - PYTHIA6, PYTHIA8 and SHERPA show worse agreement
- Analytic predictions: Data is well-described by NLL BFKL calculations from two groups of authors (not on CMS plots yet)

CMS-PAS-FSQ-12-002

10.1103/PhysRevLett.112.082003,
arxiv:1309.3229
(B.Ducloe, L. Szymanowski, S. Wallon)



arXiv:1407:8431
(F. Caporale, D.Yu. Ivanov, B. Murdaca, A. Papa)



SUMMARY

Minijet cross-section

Most of MC fail to describe the data. Best description is given by cosmic ray model EPOS

Inclusive jet production

Data is well described by NLO⊗NP over the wide p_T and rapidity range

Forward-central jets

PYTHIA and HERWIG provide good description of the data

Mueller-Navelet jets

Inclusive to exclusive dijet production ratios

- PYTHIA6 and PYTHIA8 predictions are within the experimental uncertainties
- HERWIG++, HEJ, CASCADE predict too strong parton radiation

Mueller-Navelet jets angular decorrelations

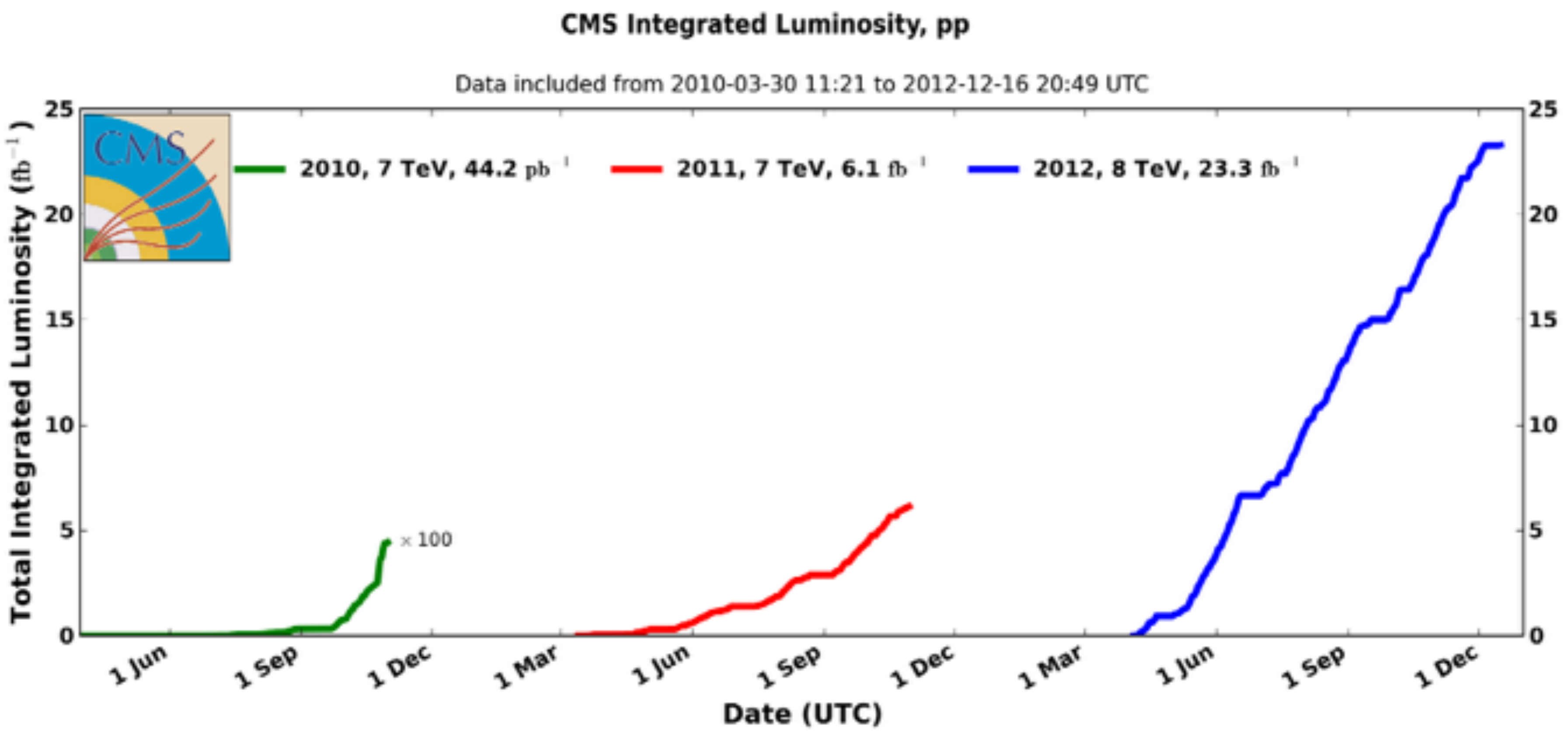
- No DGLAP-based MC prediction describing all observables
- Analytic NLL BFKL predictions provide better description of the data

BACKUP

Datasets (I)

LHC pp runs: ~30 fb^{-1} collected in 2010 - 2013

pp data at 7, 8 and 2.76 TeV



Jet reconstruction

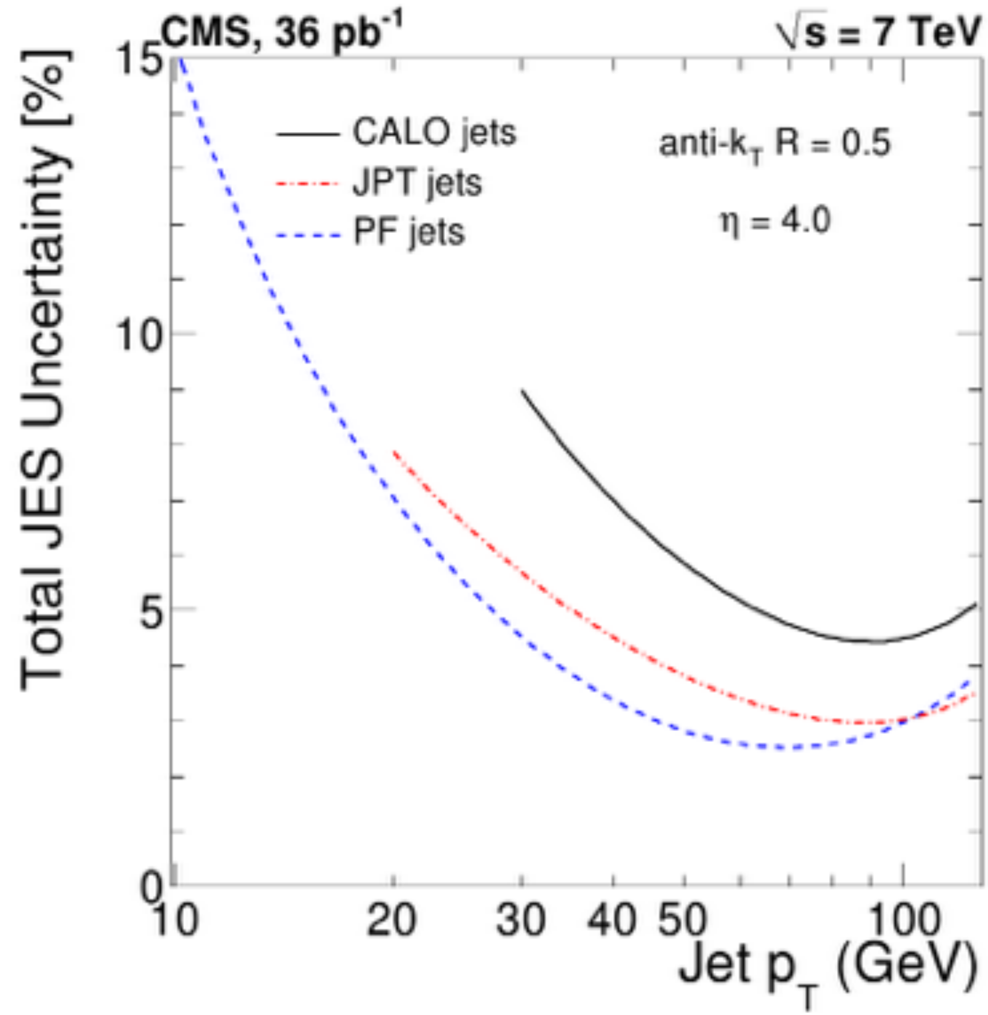
Several jet reconstruction techniques

- Calorimeter jets
- "Jet Plus Track" jets
- Particle Flow jets

Anti-k_T, R=0.5 or 0.7 clustering algorithm

MC- and data-driven Jet Energy Scale (JES) calibration techniques

- Uncertainty of calibration < 5% for high-p jets
- Uncertainty for low-$_{pT}$ jets can be as high as 10%



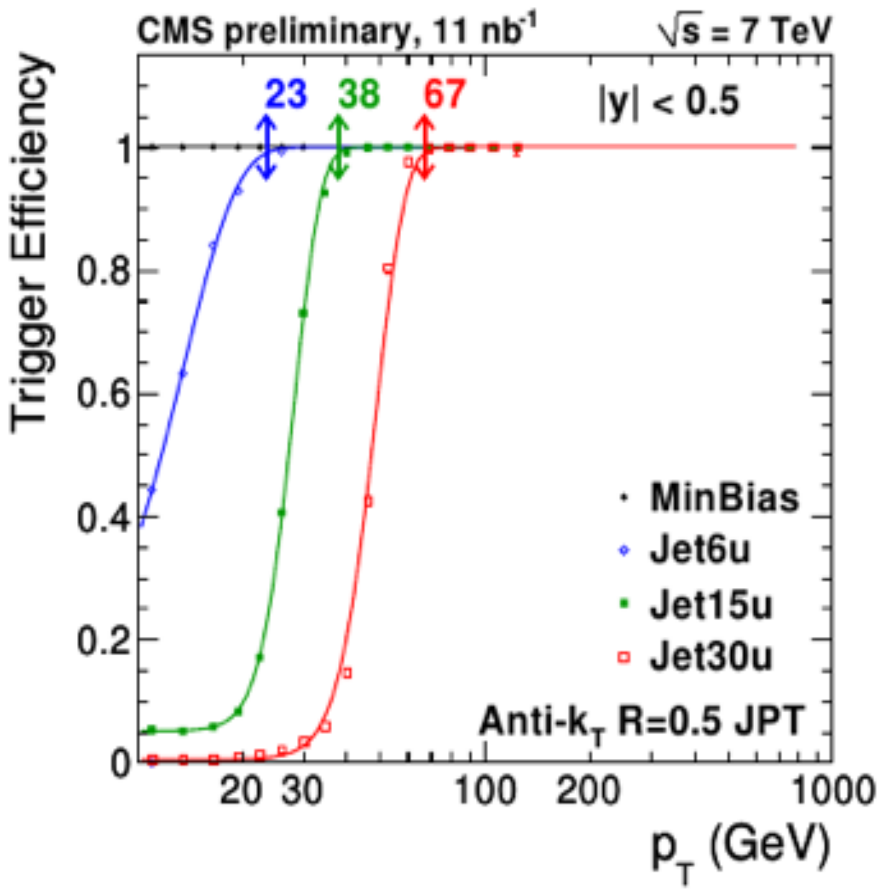
JES uncertainty – leading source of experimental uncertainty

Jet triggers

Jet triggers are based on uncorrected calorimeter energy deposits

Lowest available trigger threshold pT > 15 GeV

- Turn-on point depends on η and type of the jet
- **99% efficiency in full acceptance for calojets with pT > 35 GeV**



Presented analyses use triggers requiring one or two jets with uncorrected ET > 15 GeV

Dijet production ratios

Measurement of dijet production cross-section ratios as a function of rapidity separation

$$R^{\mathrm{incl}} = \sigma^{\mathrm{incl}}/\sigma^{\mathrm{excl}}$$

σ^{excl} - veto on additional jets above the threshold in the event

σ^{incl} - inclusive selection, all pairwise combinations

Properties of observables:

- ✓ **Ratio emphasizes higher orders enhanced by $(\alpha_S \Delta y)^n$ in the BFKL limit**
- ✓ **Remove PDF contributions**
- ✓ **Experimental systematic uncertainties are decreased**

CMS-PAS-FWD-10-014 10.1140/epjc/s10052-012-2216-6