Multi-jet measurements at CMS

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Introduction

QCD is complex:

Fixed order perturbative calculations:

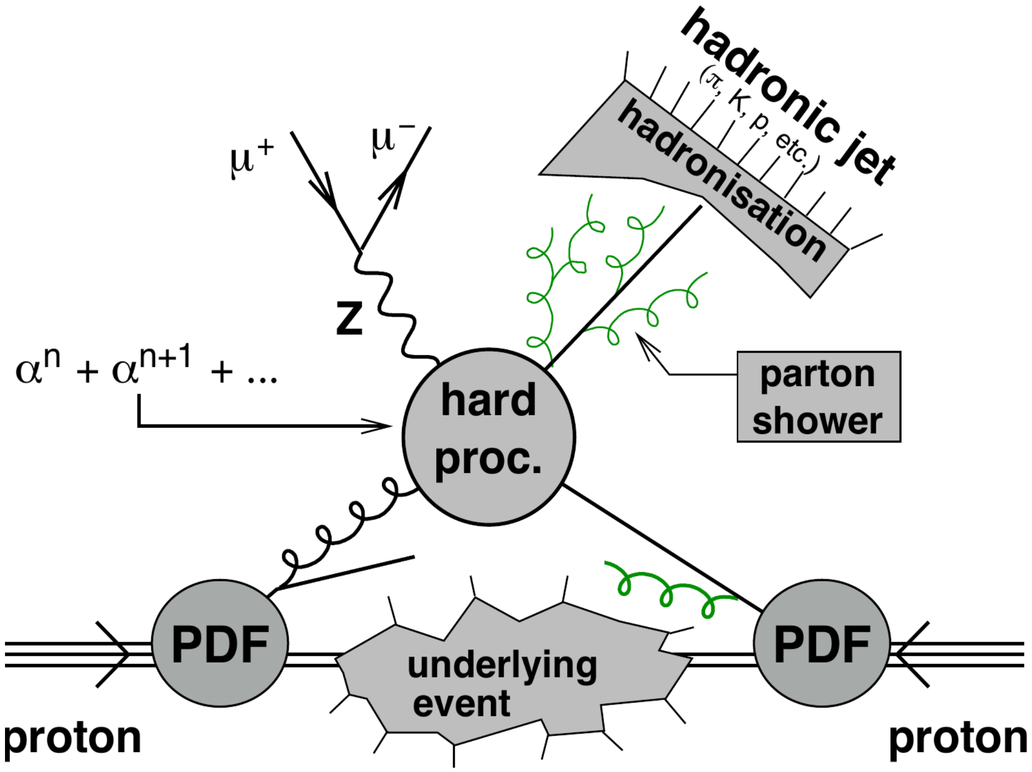
- Hard scattering

Perturbative series resummation (DGLAP, BFKL):

- Parton shower (PS)
- Parton density function (PDF) evolution

Non-perturbative (NP):

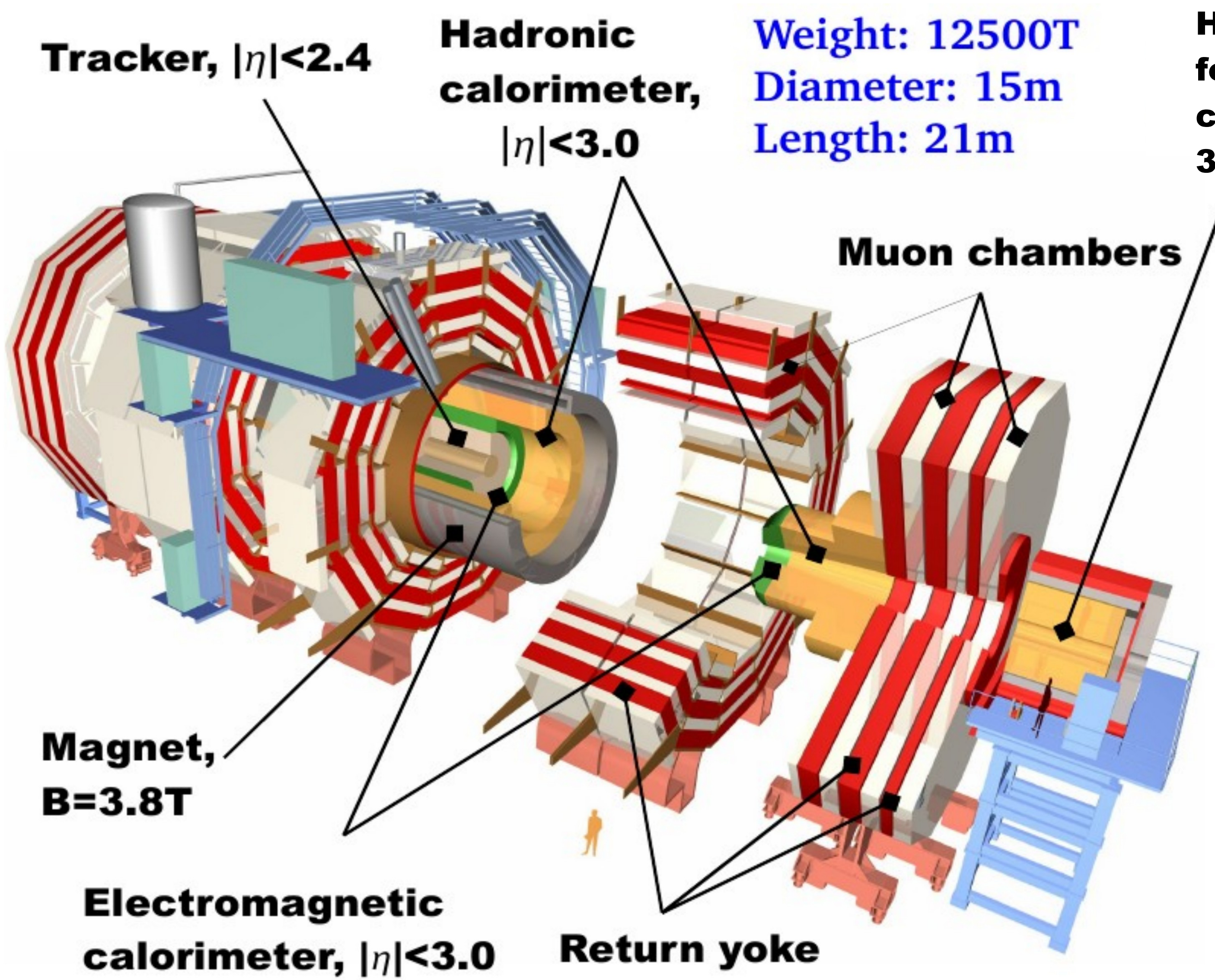
- PDF values
- Underlying event
- Hadronisation
- Multi-parton interactions



Hadronic jets carry information about partons produced in the interaction

- Focus on their use for PDF and α_s extraction, studies of PS
- Selection of analyses

Detector and datasets



CMS Run I pp datasets:

2010: 7 TeV, 44.2 pb^{-1}

2011: 7 TeV, 6.1 fb^{-1}

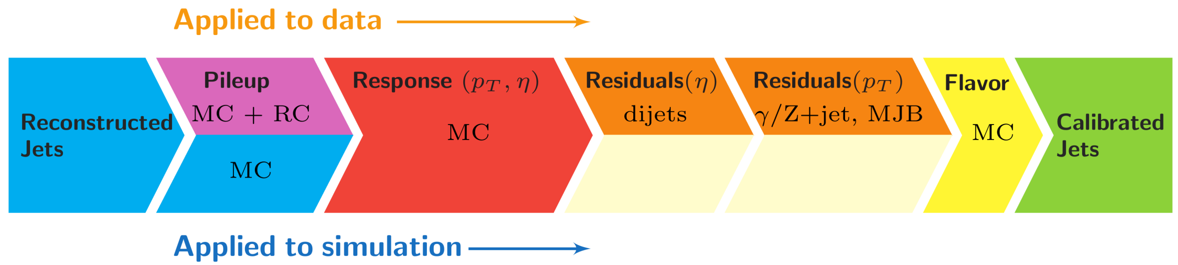
2012: 8 TeV, 23.3 fb^{-1}

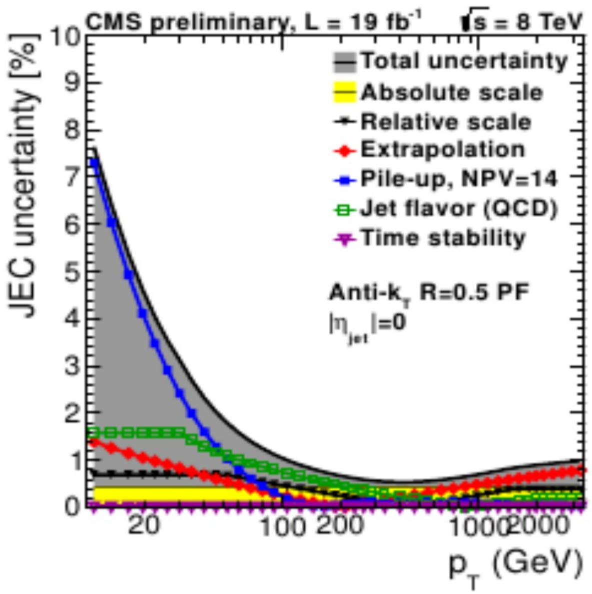
2013: 2.76 TeV, 5.0 pb^{-1}

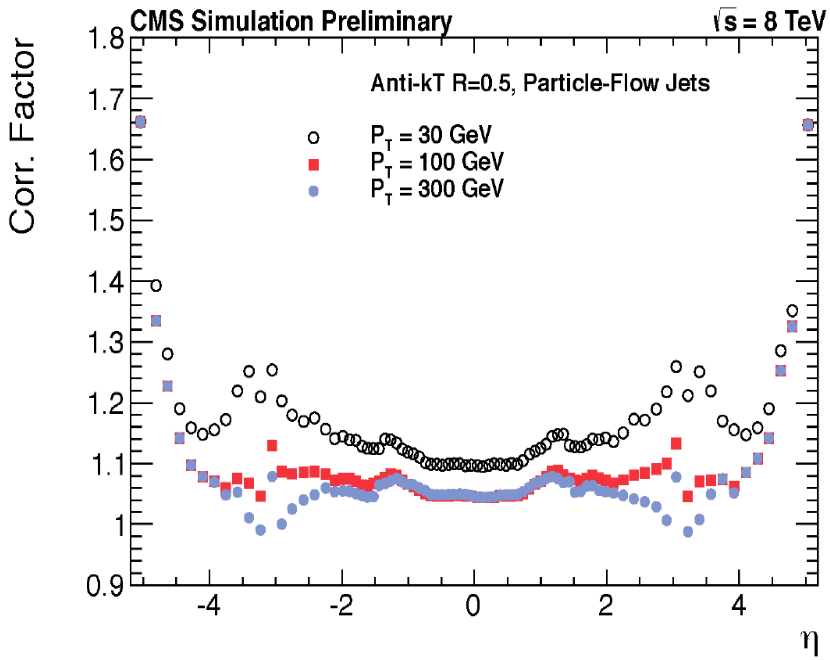
Jet reconstruction at CMS

Anti-kT algorithm:
Input from particle flow or calorimeter energy deposits

Factorized jet energy correction scheme:



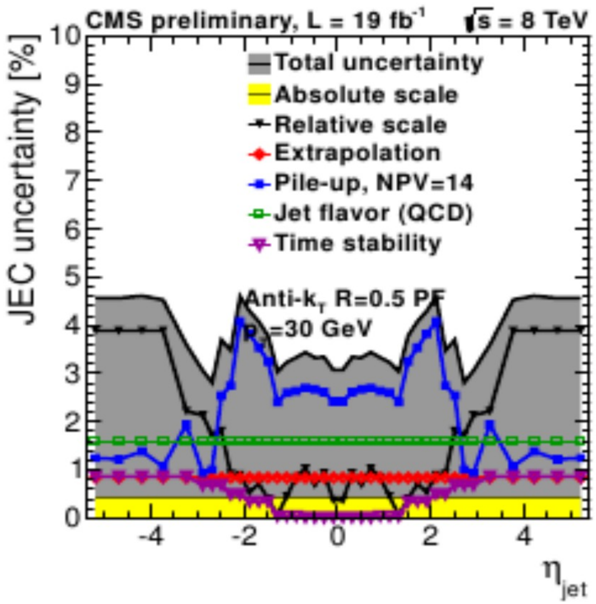




Bulk of the correction due to non-linear and non-uniform calorimeter response is derived in MC

Residual correction is based on the data

CMS-DP-2013/033



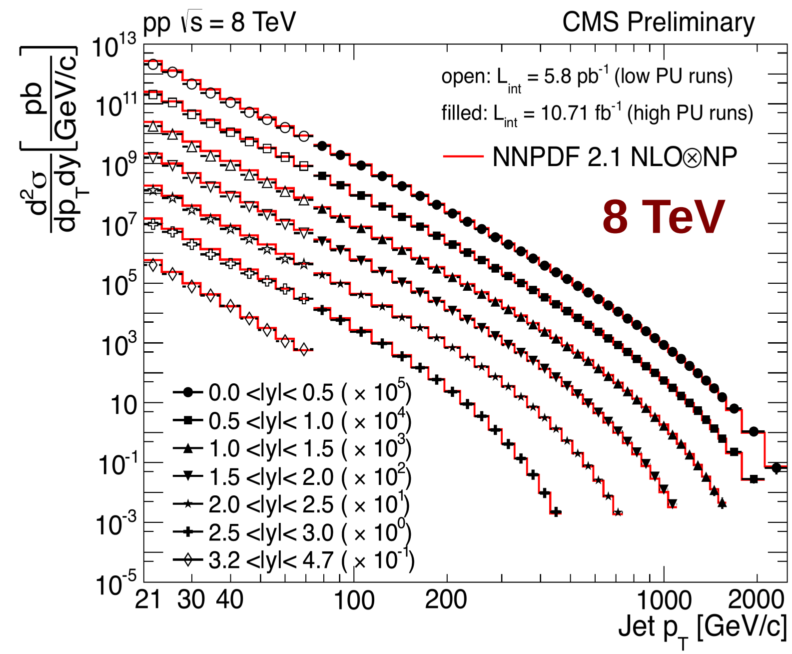
Inclusive jet production

Inclusive jet production cross-section measurement:

> Probe for basic pQCD calculation components – fixed order matrix elements and PDFs

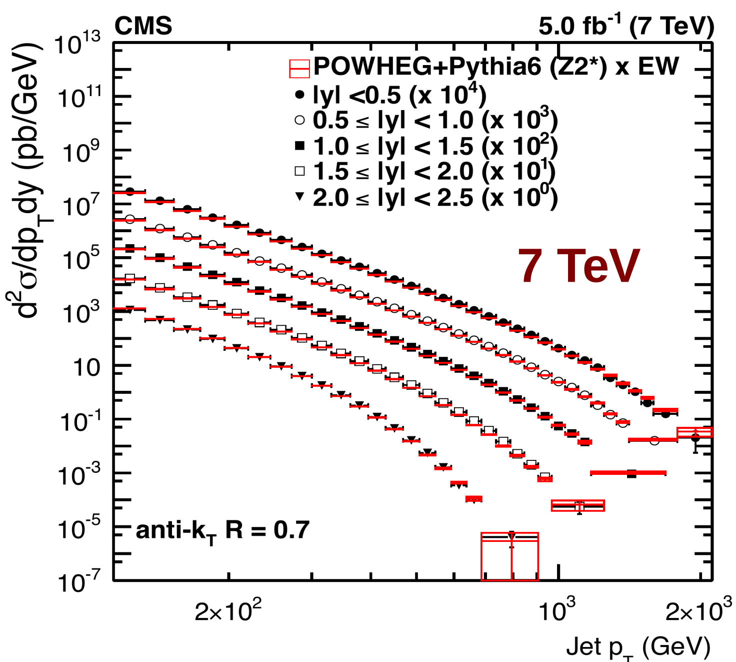
CMS has measurements at all energues available from RunI: 7 TeV, 8 TeV, 2.76 TeV

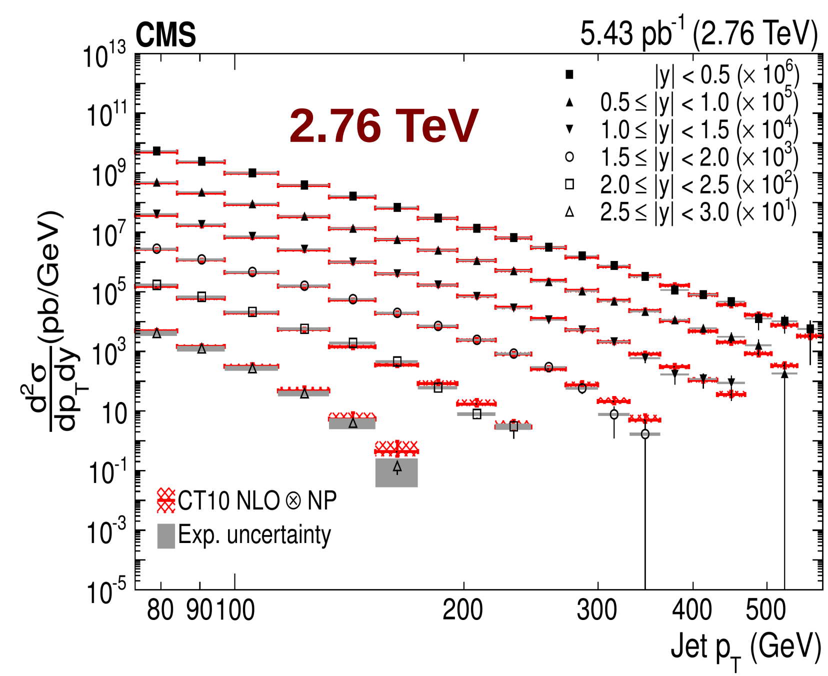
NLO calculations corrected for non-perturbative (NP) effects describe the data well



CMS-PAS-SMP-12-012, CMS-PAS-FSQ-12-031

Phys.Rev. D 87, 112002





CMS-PAS-SMP-14-017 public in 2015

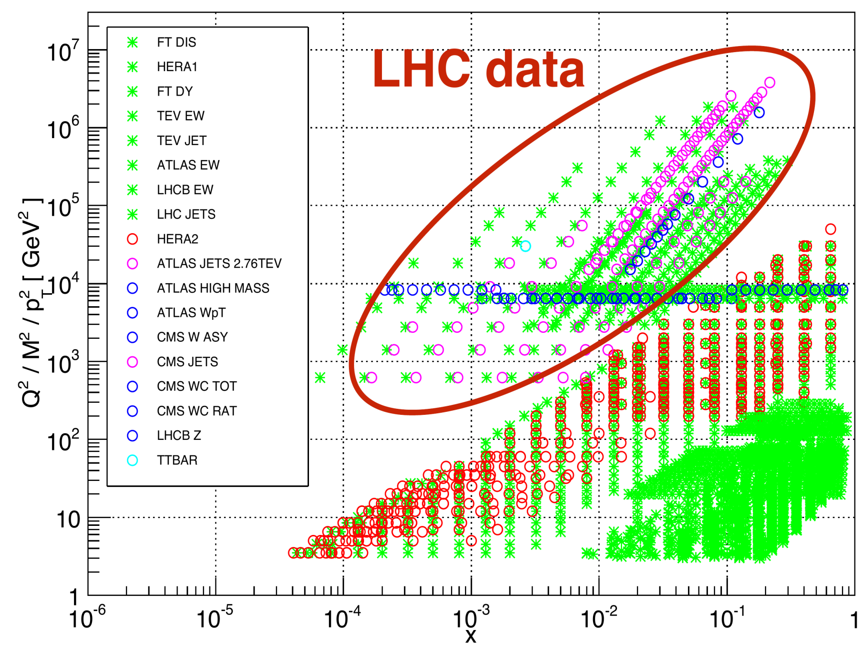
Jet data and PDF fits

Jet data is very important for PDF fits based on LHC RunI data:

- An access to widest rage of x at high Q^2 values

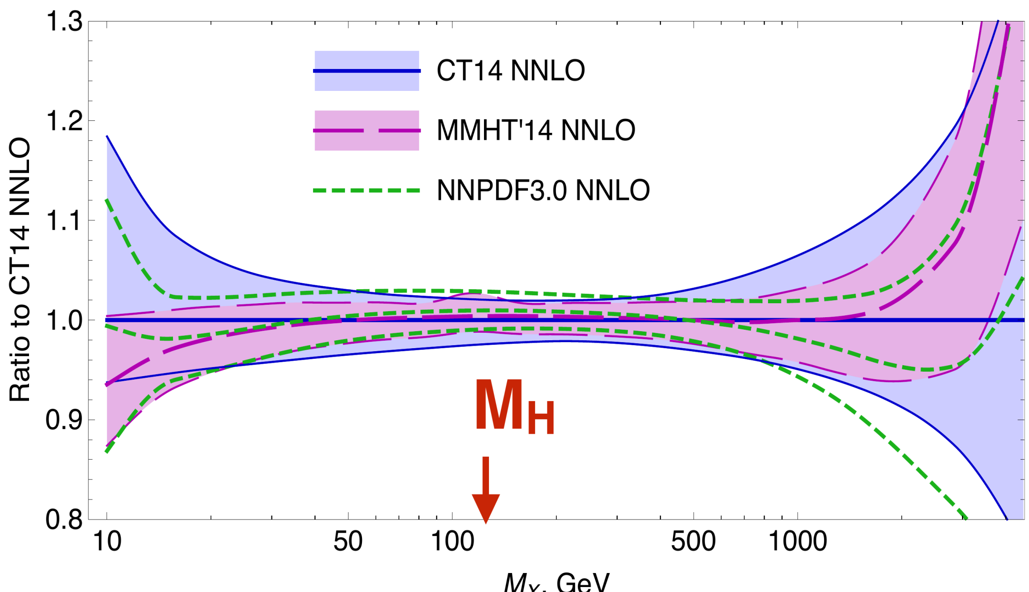
Results from CTEQ and NNPDF collaborations are shown here

NNPDF collaboration, arXiv:1410.8849



S. Dulat, et al. (CTEQ): arXiv: 1504.07443

Gluon–gluon luminosity, $\sqrt{s}$=13 TeV, 68% c.l.



Inclusive jet cross-section (next slide)

Inclusive jet cross-section ratios at different energies

- Cancellation of uncertaintites (CMS-PAS-SMP-14-017)

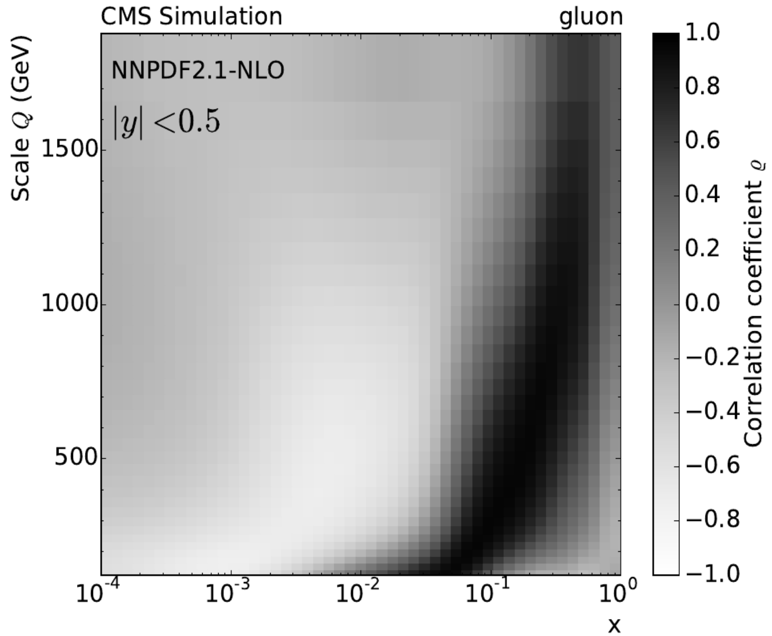
PDF extraction from inclusive jet data

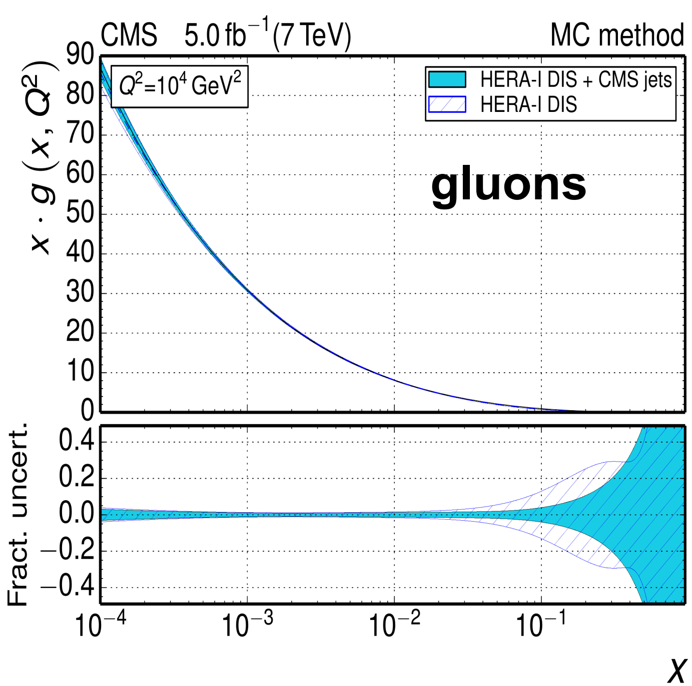
7 TeV, 5fb^{-1} inclusive jets

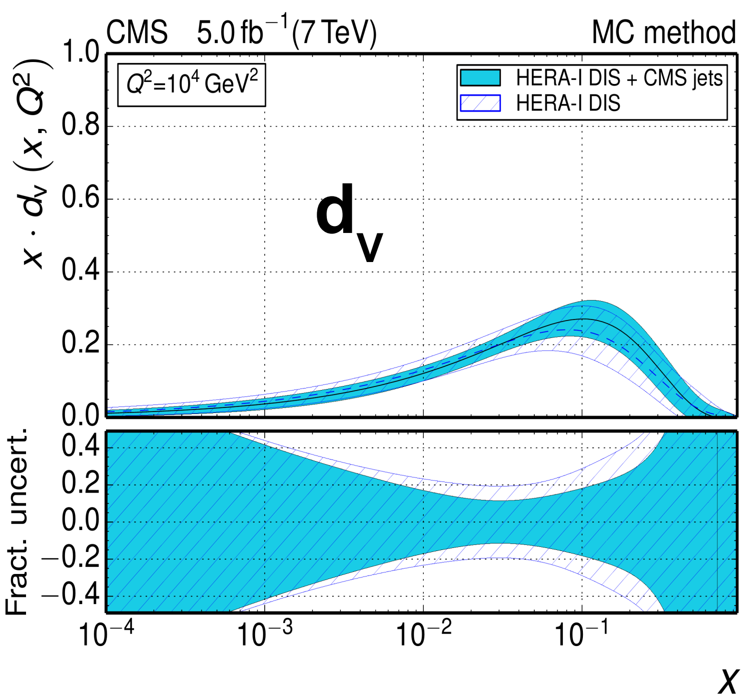
Inclusive jet cross-section is particularly sensitive to gluon PDF

NLO PDF fit
- Combined with HERA I inclusive DIS cross-sections
- HERAfitter framework

Improvement in high-x region







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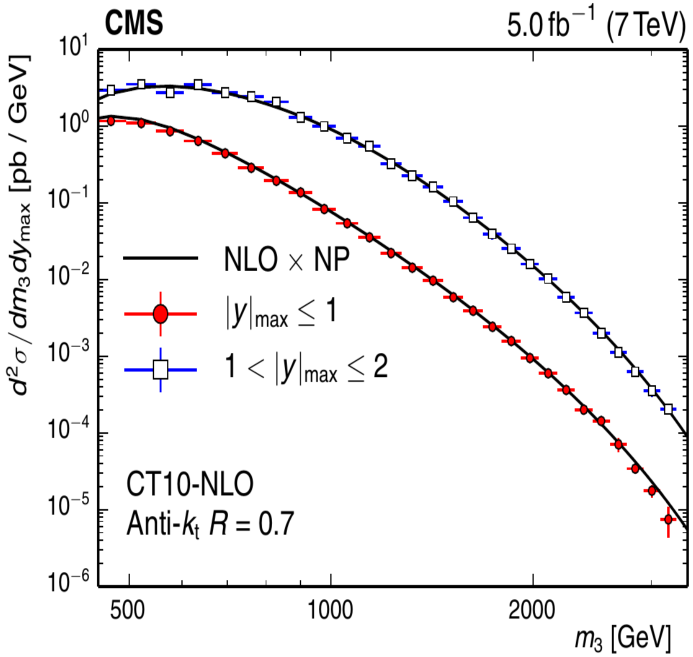
3-jet production



Leading order is proportional to $\alpha_S^{\,3}$

Very sensitive to variations of α_s → intresting to study constraining power

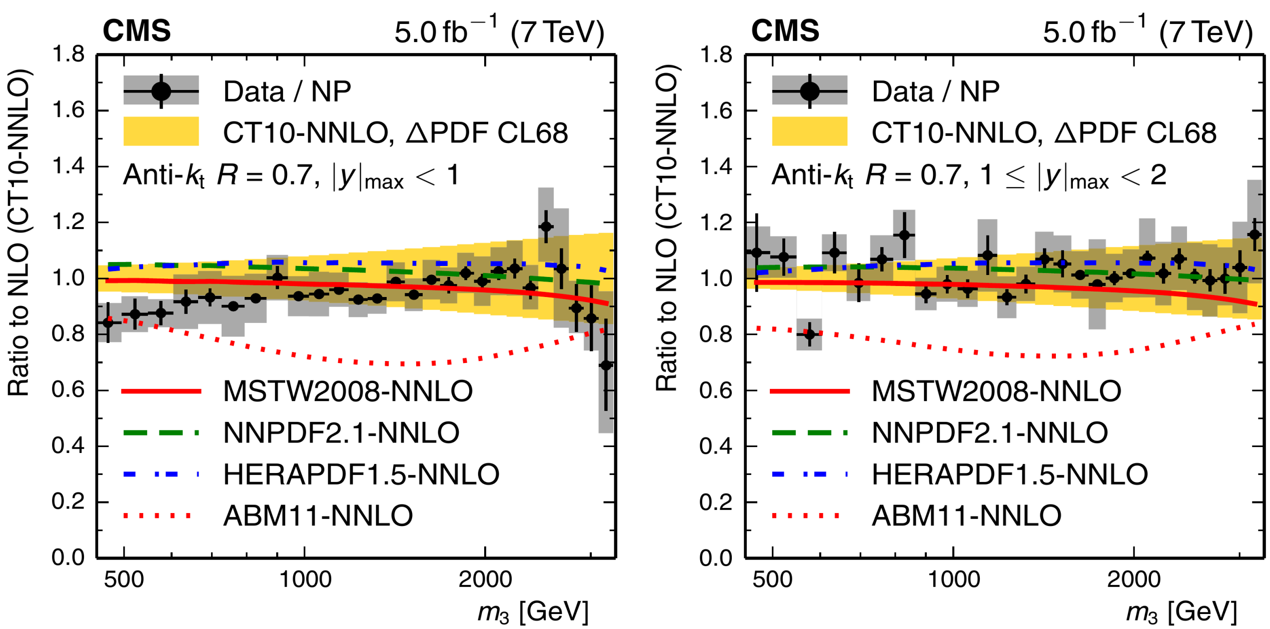
Double differential 3-jet cross-section:

- Three leading jets with |y|<2, p_T > 100 GeV
- Two bins of y_{max}=sgn(max(y_1,y_2,y_3))
- Function of m_3

NLO calculations of the process are available:

- Data is compared to NLO*NP calculations with NLO or NNLO pdf sets
- Goog agreement with data, except for AMB11 pdf set

Eur. Phys.J C 75 (2015) 186
published in 2015



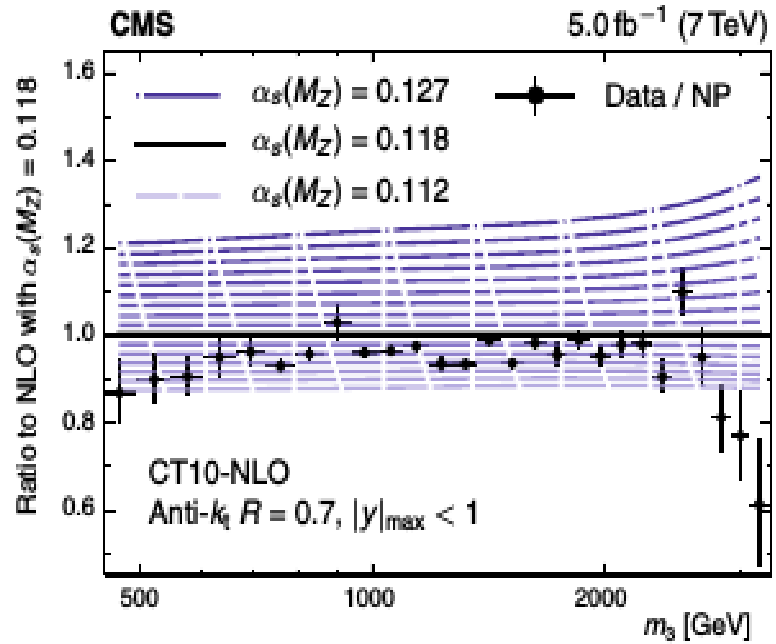
3-jet: extraction of α_s

CT10-NLO pdf set is used

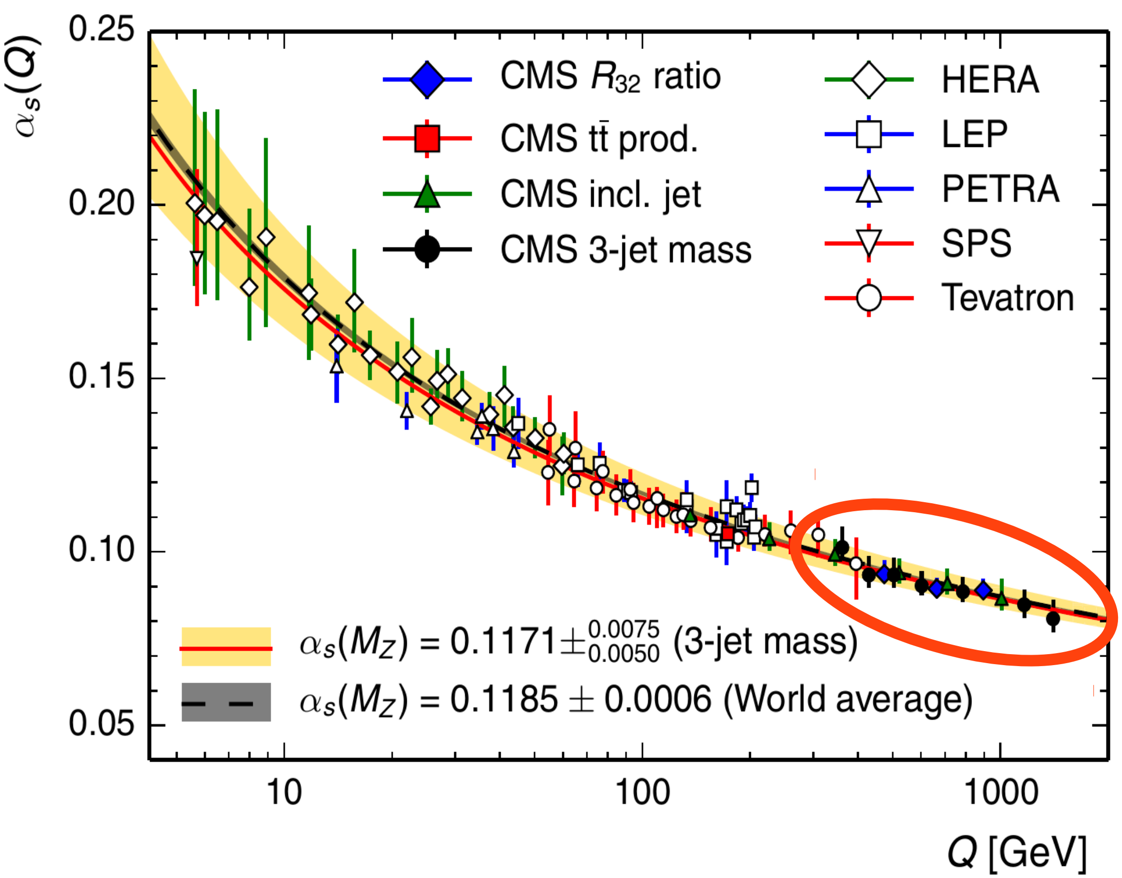
- Large spread of α_s
- Central value close to combined fit result

Minimisation of χ^2 wrt. data points is performed:

$$\chi^2 = \sum_{ij}^{N} (D_i - T_i)\, C_{ij}^{-1} \left(D_j - T_j\right)$$



Range of Q is extended to 1.4 TeV



Results are in agreement with other CMS measurements

- Fit to inclusive jets at 7 TeV
- Ratio of 3 to 2 jet cross-section

Eur. Phys.J C 75 (2015) 186
(published in 2015)

Dijet azimuthal decorrelations

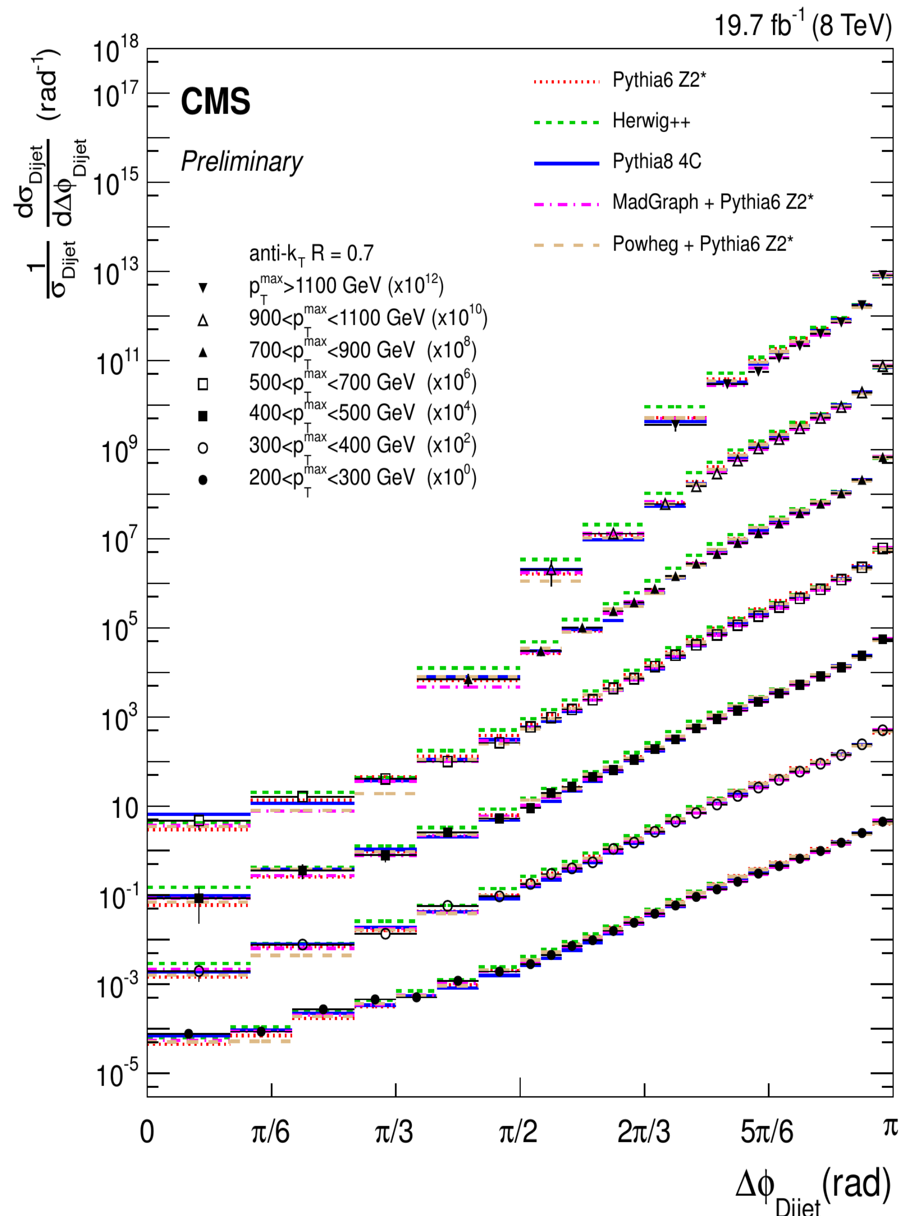
Probing parton showers with just two jets:
- At LO jets are back-to-back
- Higher-order high-p_T parton emissions decrease angle between jets
- Azimuthal decorrelation – probe for parton shower dynamics

Full 8 TeV dataset: 19.7 fb^{-1}

Normalised cross-section differential in azimuthal distance between **two leading jets**

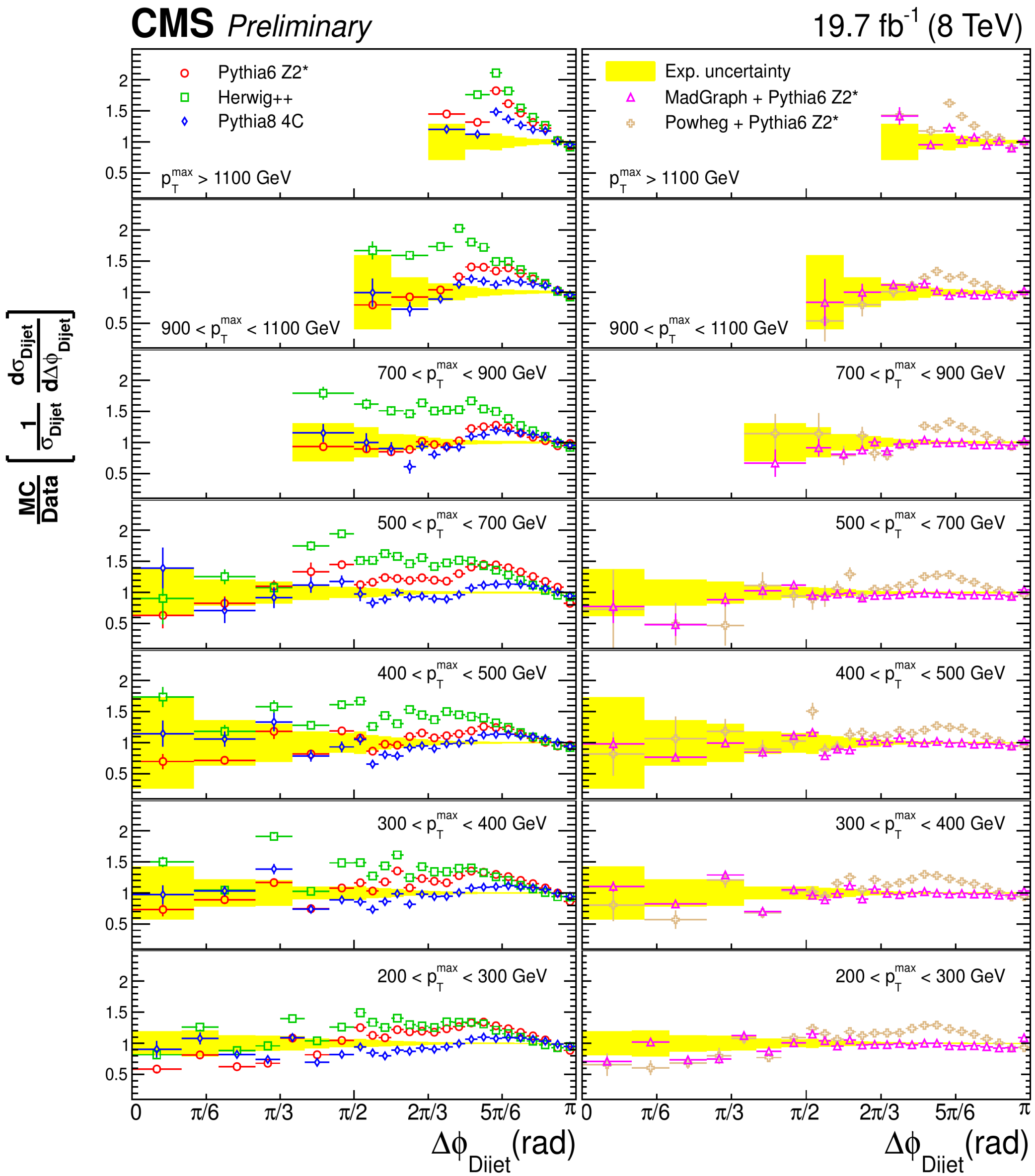
$200\ \mathrm{GeV} < p_T < 1100\ \mathrm{GeV}$

$|y| < 2.5$



CMS-PAS-SMP-14-015
public in 2015

Dijet azimuthal decorrelation II



CMS-PAS-SMP-14-015
public in 2015

It is natural to compare observable to various parton shower models and use-cases

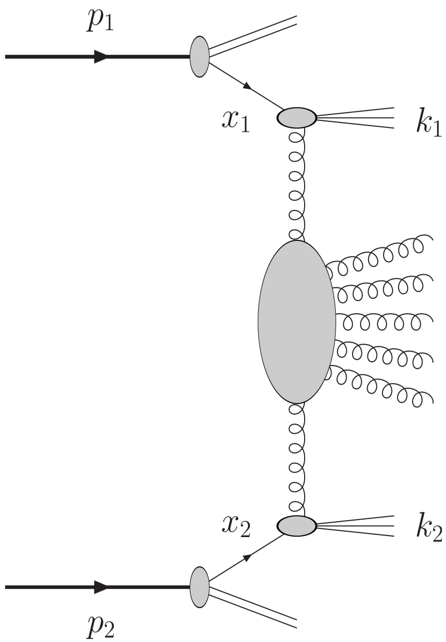
LO + PS Monte Carlo: Pythia, Herwig
- Some disagreement in high-$\Delta\varphi$ region
- Within exp. uncertainty for small-angle radiation
- Best agreement: Pythia8

NLO matched to PS: Powheg+Pythia 6 Z2*
- Some disagreement in high $\Delta\varphi$

Multileg matched to PS: MadGraph + Pythia6 Z2*
- Perfect agreement with data

Mueller-Navelet jet production

DGLAP: $\sqrt{s} \sim p_T \gg \Lambda_{QCD}$; strong ordering of emissions in pT
BFKL: $\sqrt{s} \gg p_T \gg \Lambda_{QCD}$ – high energy limit; emissions are ordered in y



Previous observable belonged to DGLAP kinematics domain

Mueller – Navelet jets: jets above threshold with largest rapidity separation in the event

- no p_T ordering
- lower p_T allows to approach high energy limit

Full NLL BFKL calculations of the process are available
Phys.Rev.Lett. 112 (2013) 082003
Eur.Phys.J. C 74 (2014) 3084

Observables:

- $\Delta\varphi$ distribution between MN jets
- Average cosines of $n*\Delta\varphi$ between MN jets as a function of Δy
- Ratio of cosines C_{n+1}/C_n as a function of Δy

Azimuthal decorrelation of MN jets I

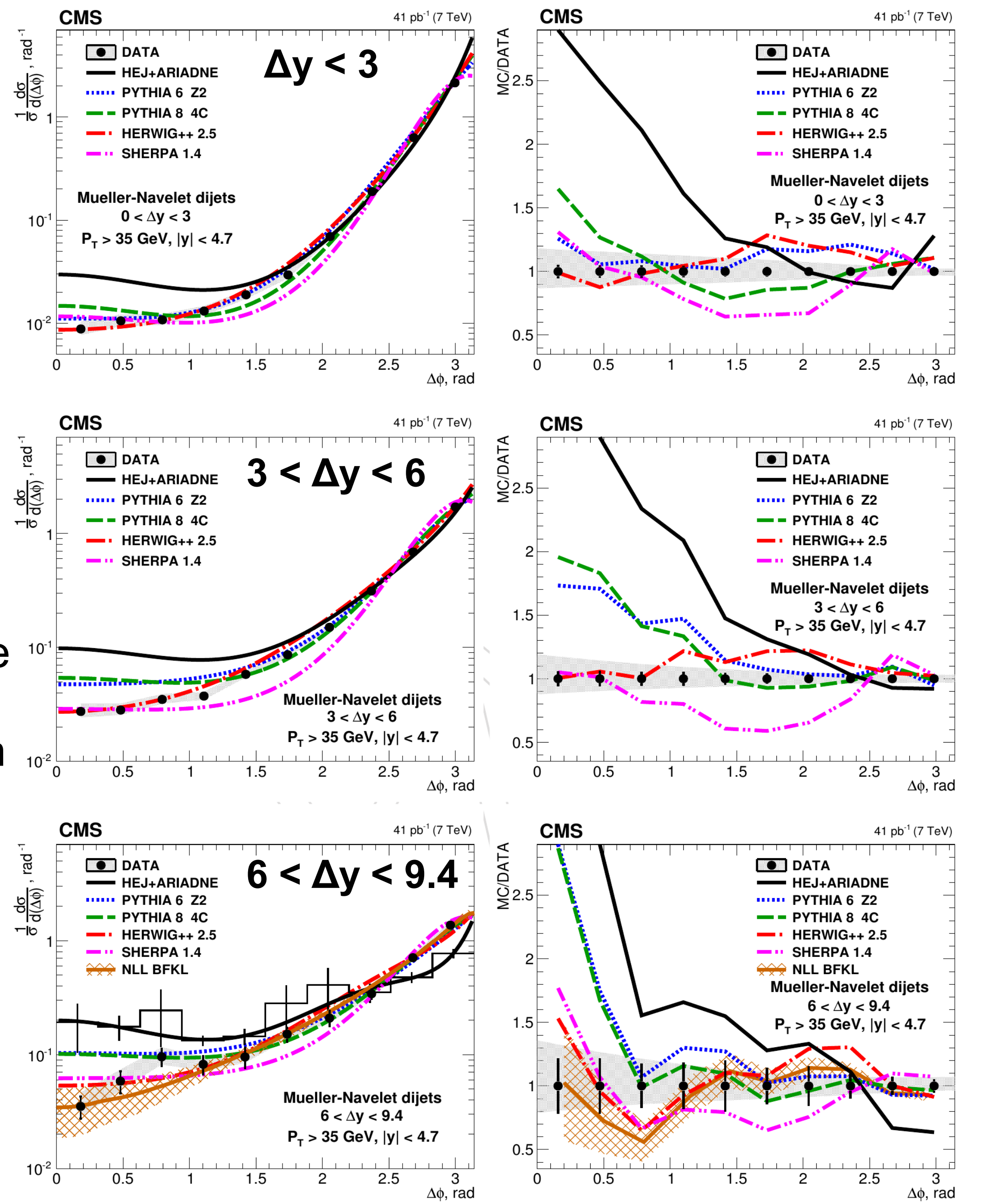
7 TeV, 2010 dataset: 41 pb^{-1}

Select soft jets: pT > 35, |y| < 4.7

Normalised differential cross-section in bins of Δy

Worse agreement with data and larger spread of predictions than in DGLAP scenario:

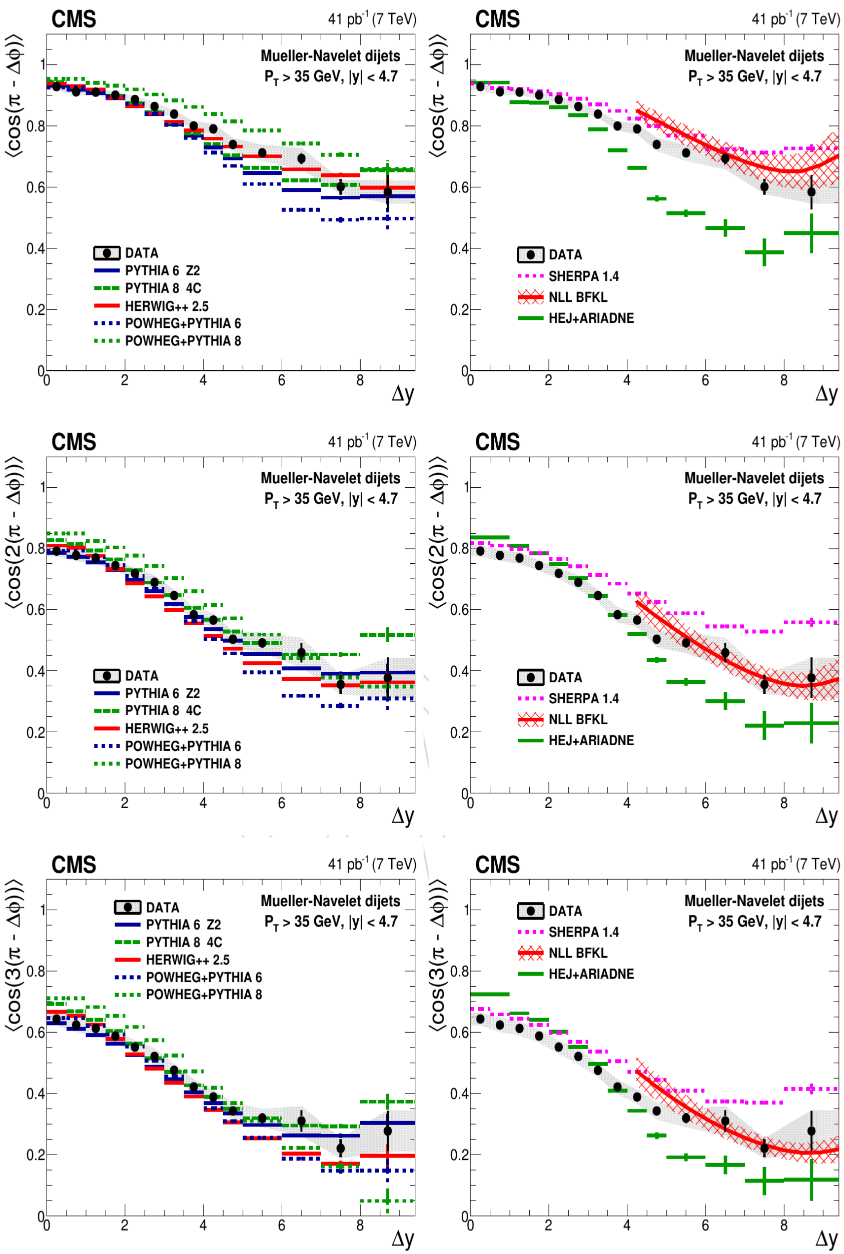
- Pythia predicts less peaked at $\Delta\varphi=\pi$ distribution
- HEJ + ARIADNE largely overestimate the parton radiation
- Sherpa is more peaked at $\Delta\varphi=\pi$ than data
- Herwig shows best agreement with data
- NLL BFKL calculations agree well (B. Ducloe, L Szymanowski, S. Wallon, Phys. Rev. Lett 112 (2013), 082003)



CMS-PAS-FSQ-12-002

UPDATED

Azimuthal decorrelation of MN jets II



First three coefficients of Fourrier transform of $\Delta\varphi$ distribution equal to C_n=<cos(π-Δφ)>

Considerable spread of predictions

None of MC describe the data well

NLL BFKL predictions describe the data within theoretical and experimental uncertainty

CMS-PAS-FSQ-12-002
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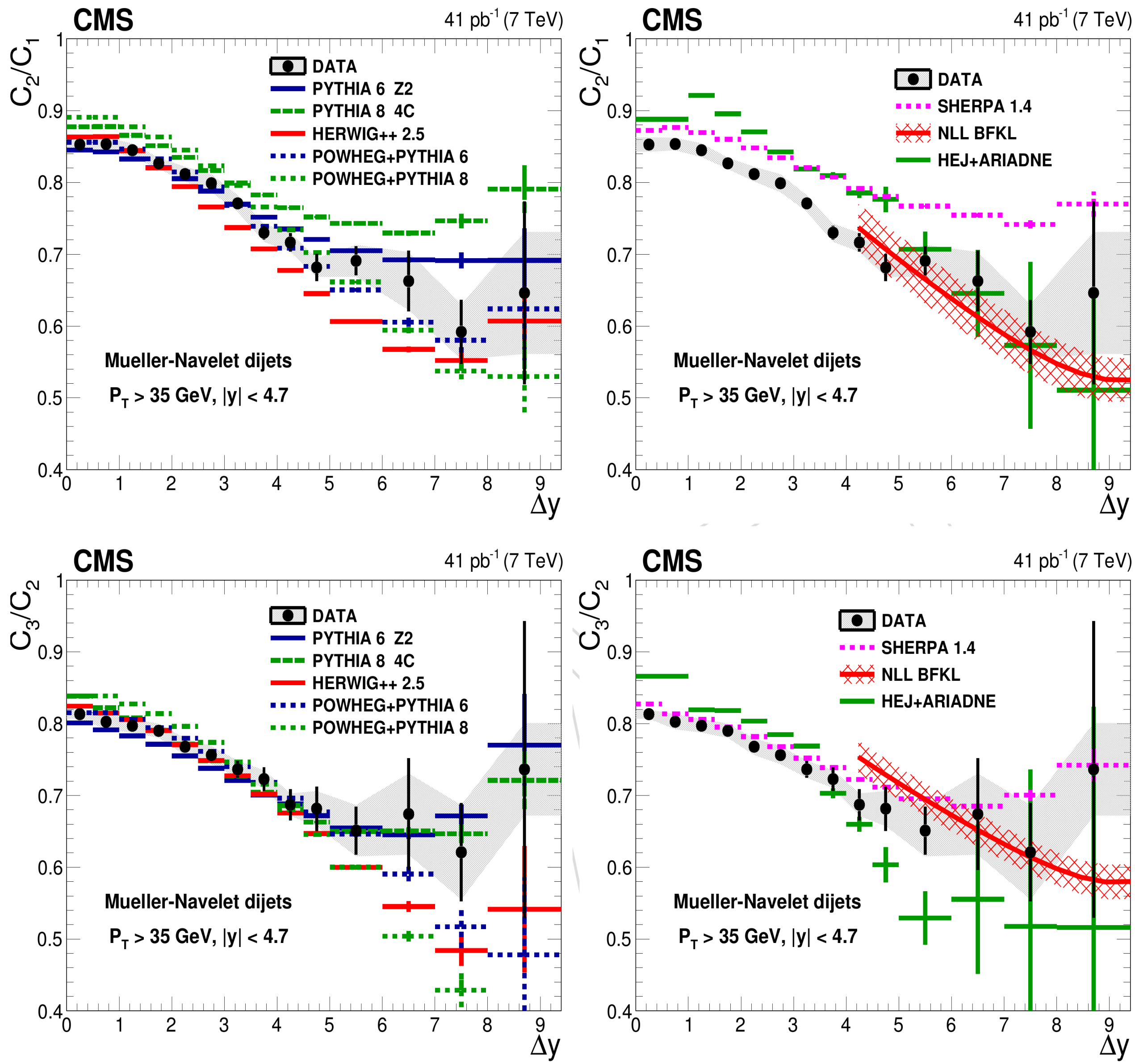
Azimuthal decorrelation of MN jets III

Ratio of cosines, C_{n+1}/C_n – cancellation of theoretical uncertainties

Best description – NLL BFKL calculations



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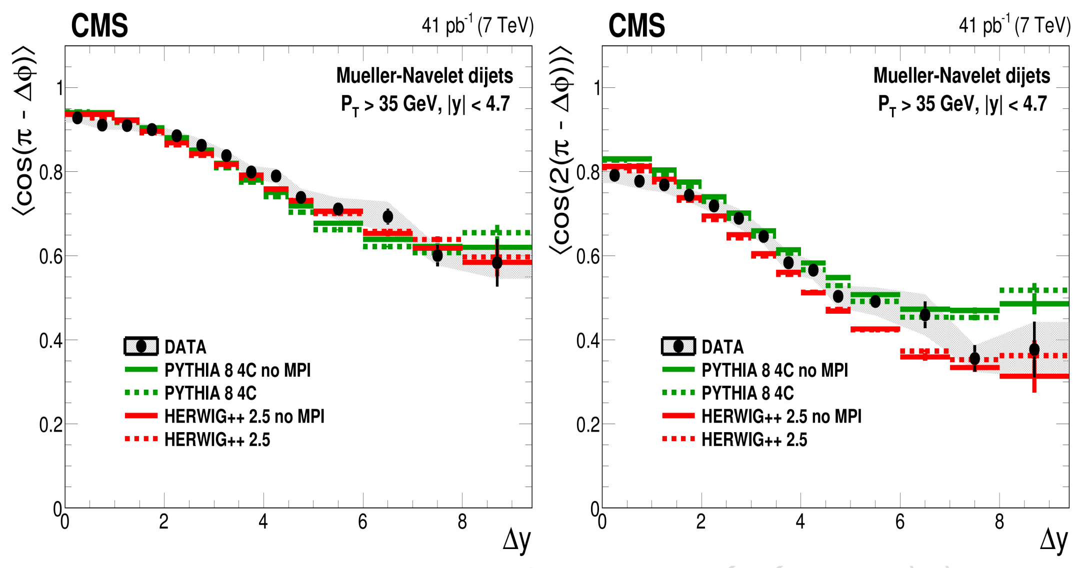
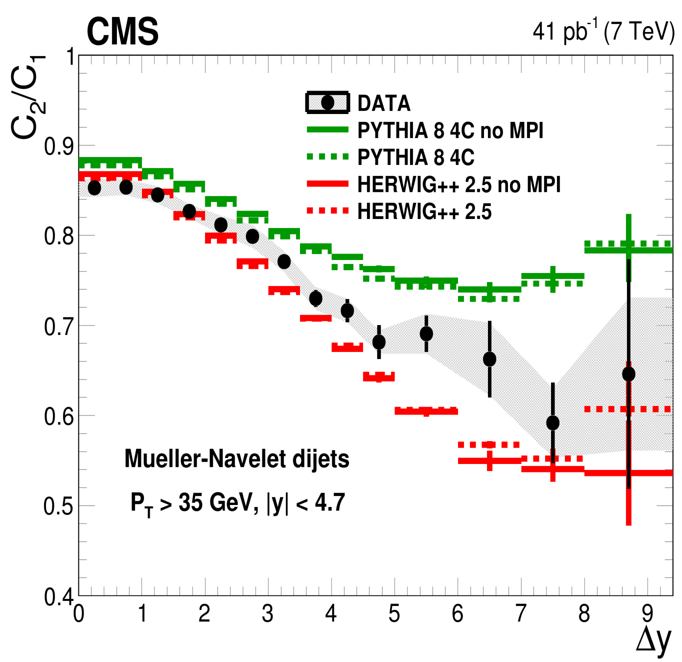
Azimuthal decorrelation of MN jets: MPI

An effect of MPI was studied:
Turn MPI on and off in
Pythia 8 and Herwig++



Very small or no effect was found
However the effect can
increase when p_T is lowered
or energy is inreased



This justifies the use of this observable for tests of perturbative QCD calculations or models of parton showers

CMS-PAS-FSQ-12-002
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Summary

Inclusive jet production cross-section data has been used in PDF fits based on LHC Run I data: input for the LHC Run II analyses

- Significant impact on gluon PDF in wide range of x

Extraction of α_s from 3-jet double differential mass measurement

- Extend Q range to 1.4 TeV

Azimuthal decorrelation of jets at 7 TeV

- High-p_T leading jets: best description is given by multileg + parton shower MC (madgraph + pythia6 Z2*)
- Mueller-Navelet jets: best description is given by NLL BFKL calculations (Ducloe, Szymanowski, Wallon: Phys.Rev.Lett. 112 (2013) 082003)

BACKUP

Dijet azimuthal decorrelation: NLO