Jet and Multijet Results from CMS

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Jet reconstruction and spectroscopy at hadron colliders
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Outline

- ✦ **Introduction**
- ✦ **Jet reconstruction**
- ✦ **Cross-section measurements**
  - inclusive jet production
  - dijet production
- ✦ **Dijet angular distributions**
- ✦ **Multijet properties**
  - dijet azimuthal decorrelation
  - hadronic event shapes
  - 3j/2j ratio
- ✦ **Summary**

Introduction: the Objectives

✦ **CMS has planned and prepared for a rich QCD program with jets:**
- cross-section measurements
- dijet & multijet properties

✦ **The 2010 program was defined according to:**
- the available integrated luminosity
- the level of understanding of the jet object
- the needs of the experiment
- the interest of the scientific community

✦ **Objectives:**
- confront the pQCD calculations in the new collision energy and in the unexplored kinematic region
- check the overall compatibility between data and theory predictions
- differentiate between the various QCD Monte Carlo generators and **provide feedback for their further tuning**
- provide feedback for the jet commissioning

Introduction: Kinematic Reach

- **Available integrated luminosity for QCD measurements: 36 pb^{-1}**
  - out of 47 pb^{-1} delivered and 43 pb^{-1} recorded
- **Jet p_T: 18 GeV → 1.1 TeV**
  - $5 \times 10^{-3} < x_T < 0.16$

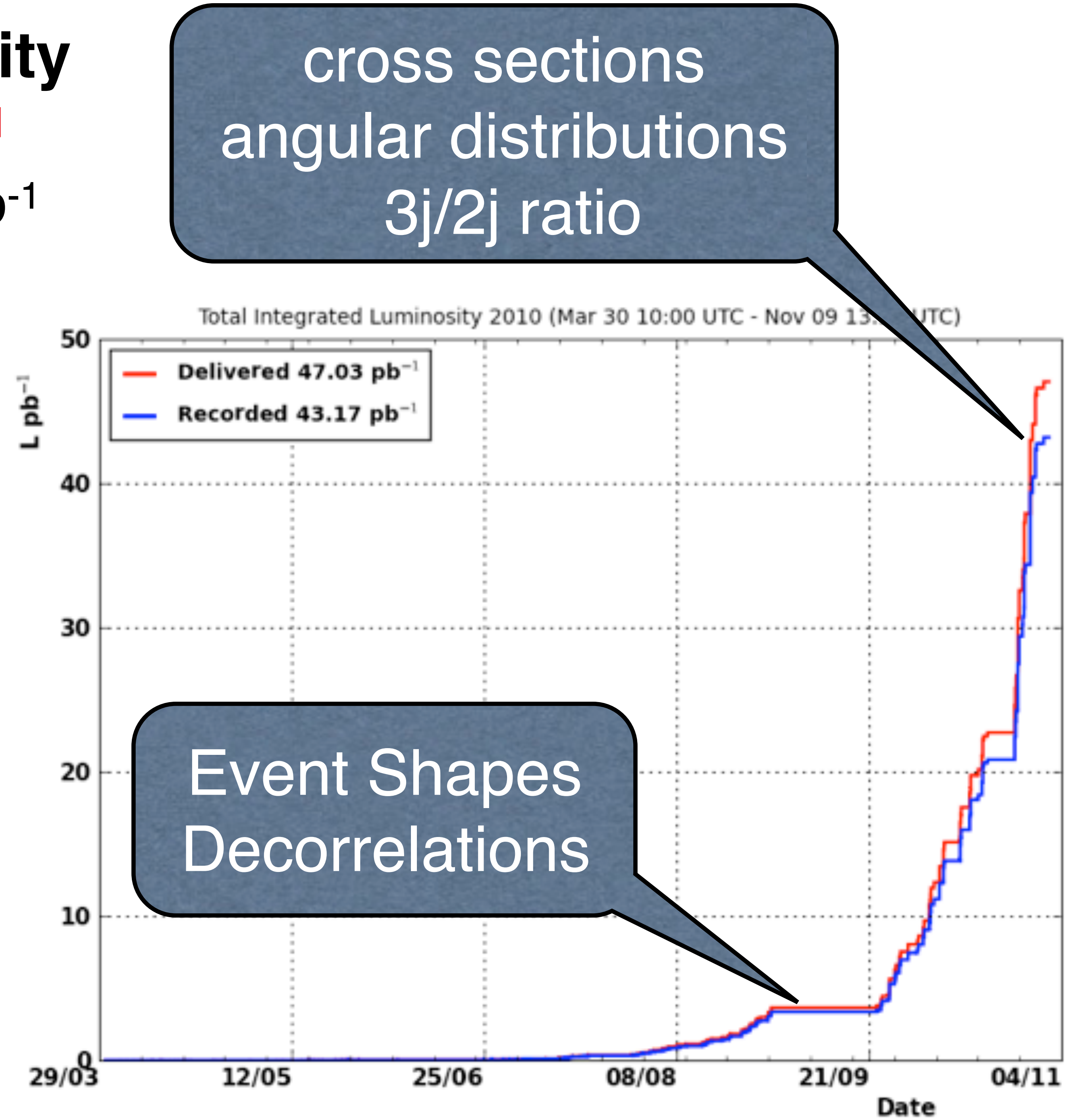
$$x_T = \frac{2p_T}{\sqrt{s}}$$

- **dijet mass: 0.16 → 3.5 TeV**
  - $5 \times 10^{-4} < x_1 \cdot x_2 < 0.25$

$$x_1 \cdot x_2 = \left(\frac{M_{\mathrm{JJ}}}{\sqrt{s}}\right)^2$$

- **H_T: 0.3 → 2.5 TeV**

$$H_T = \sum_{jets} p_T$$



Theory Predictions

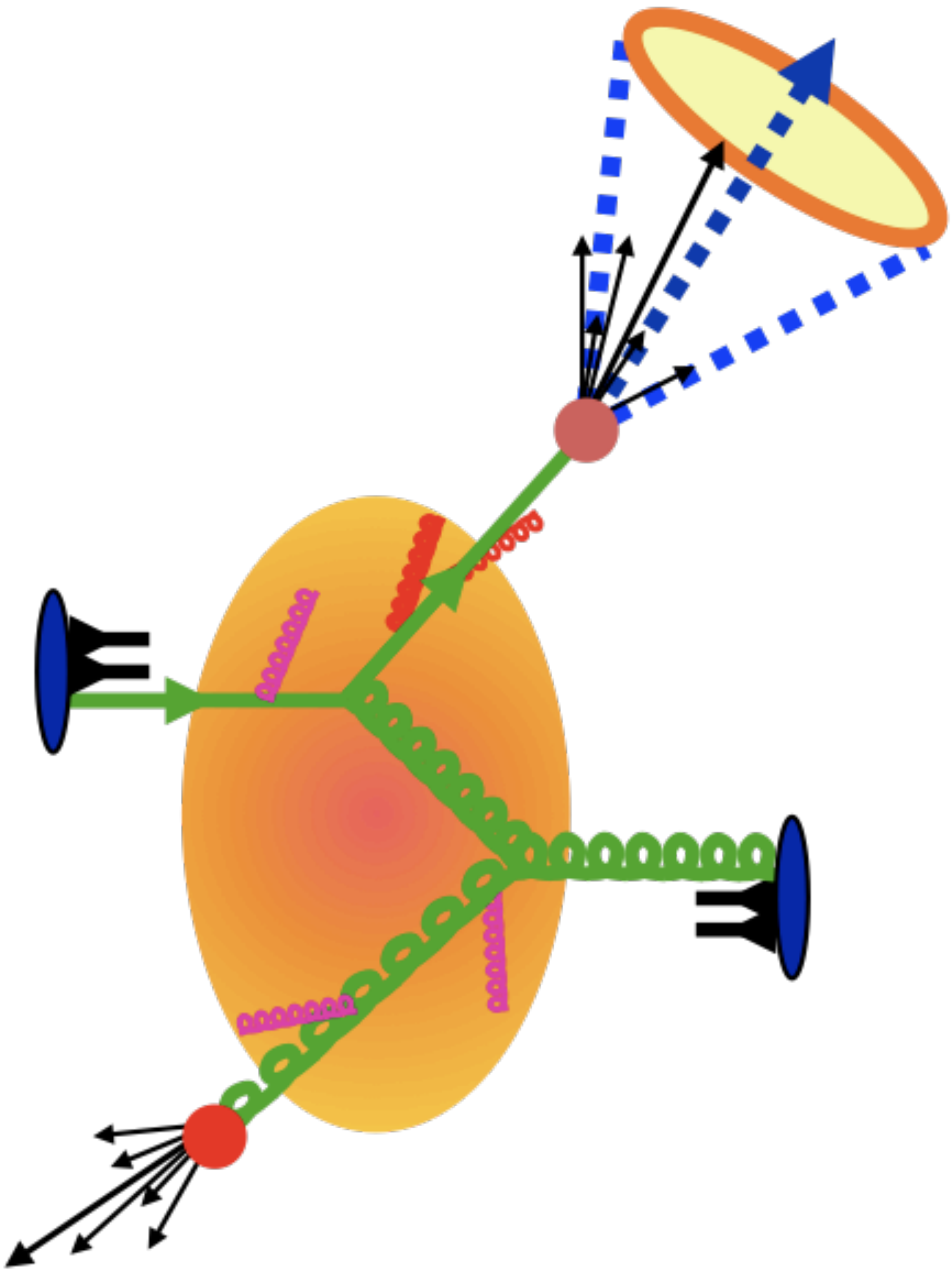
Ingredients of the Theory Predictions

✦ **Perturbative QCD calculations:**
- at next-to-leading order
- using the NLOJet++ program
- in the fastNLO package

✦ **Proton distribution functions (PDF):**
- CT10: $\alpha_S(M_Z) = 0.1180$
- MSTW2008: $\alpha_S(M_Z) = 0.1202$
- NNPDF2.0: $\alpha_S(M_Z) = 0.1190$

✦ **Non-perturbative corrections:**
- multi-parton interaction (MPI)
- hadronization

✦ **QCD Monte-Carlo generators:**
- PYTHIA6
- PYTHIA8
- HERWIG++
- ALPGEN
- MADGRAPH

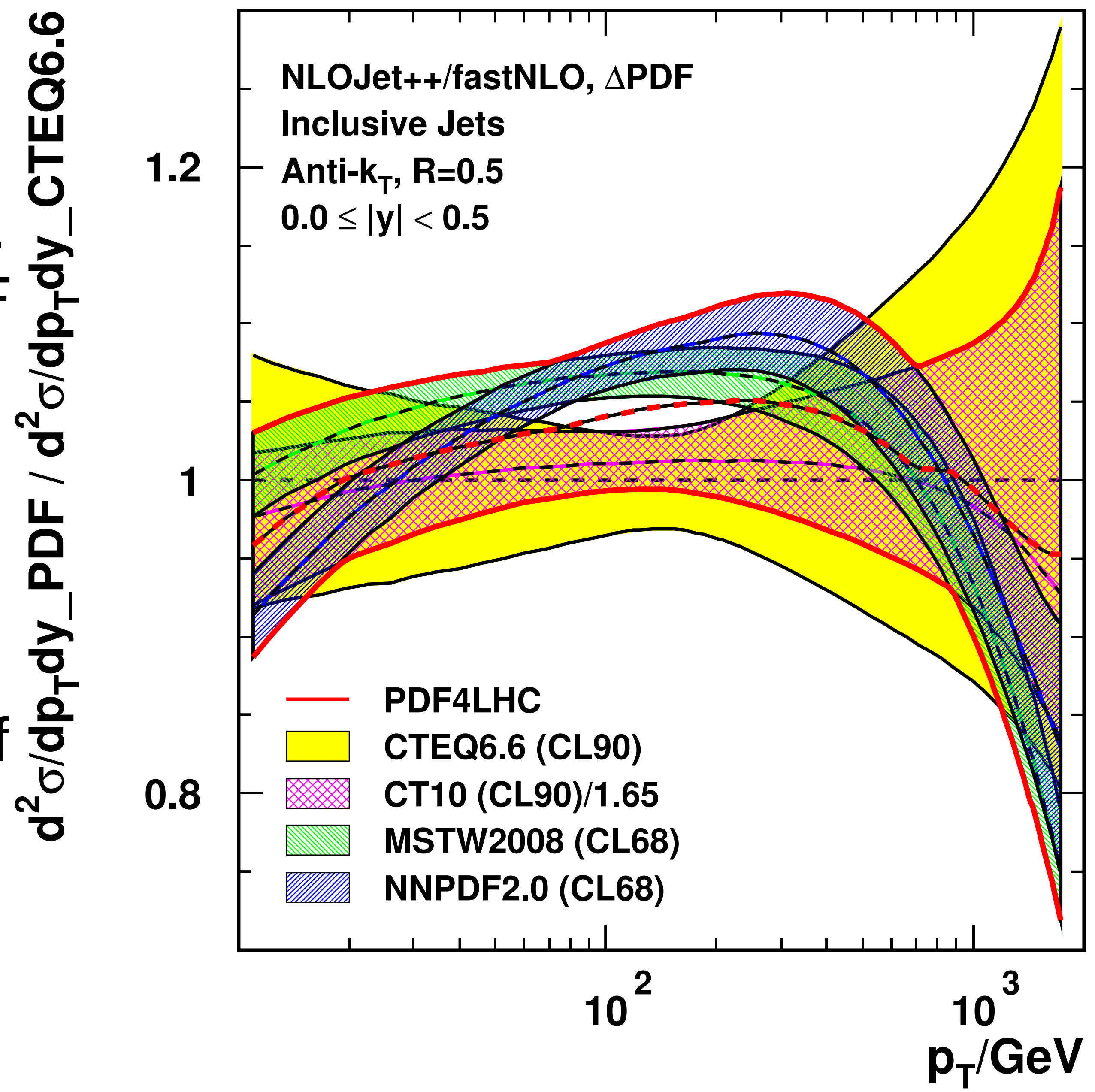


The PDF4LHC Prescription

✦ **The PDF4LHC prescription describes the way to combine the various PDFs:**

- compute the observable of interest (e.g. inclusive jet cross section) with each PDF set
- construct the 1-sigma (68% CL) band from each PDF set
- at every point, define the global envelope from the 1-sigma bands
- the PDF4LHC prediction is the center of the global envelope

✦ **The PDF4LHC prescription is meant for a check of the overall compatibility between data and theory predictions**

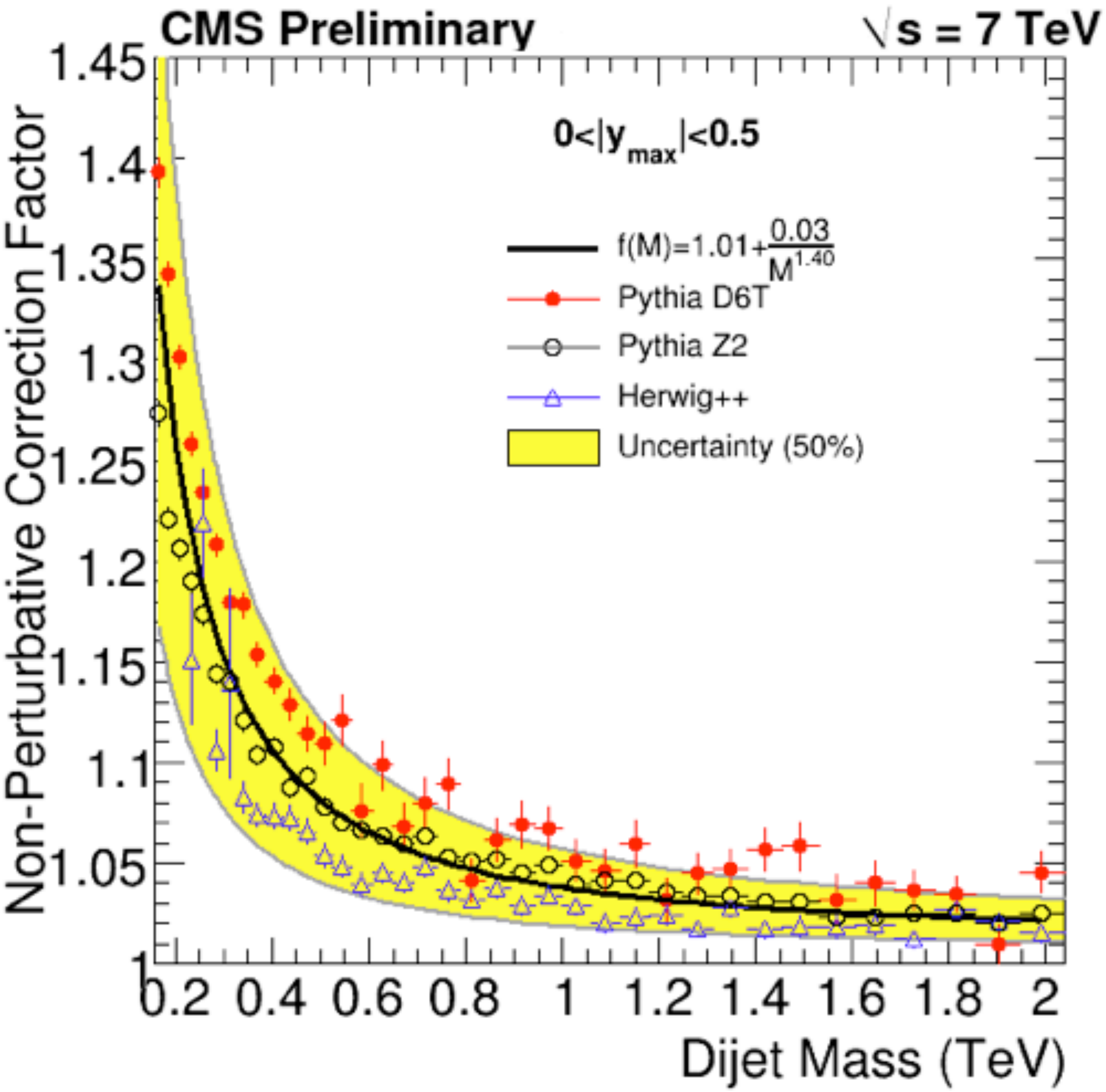


Non-Perturbative Corrections

✦ **A correction to pQCD is needed to "translate" the parton-level observables to the particle level**

✦ **Account for effects that cannot be calculated with pQCD**
- multi-parton interactions
- hadronization

✦ **The non-perturbative correction is estimated by using different MC generators**
- turn "on" and "off" the MPI and hadronization
- all measurements use the average between PYTHIA6 and Herwig++

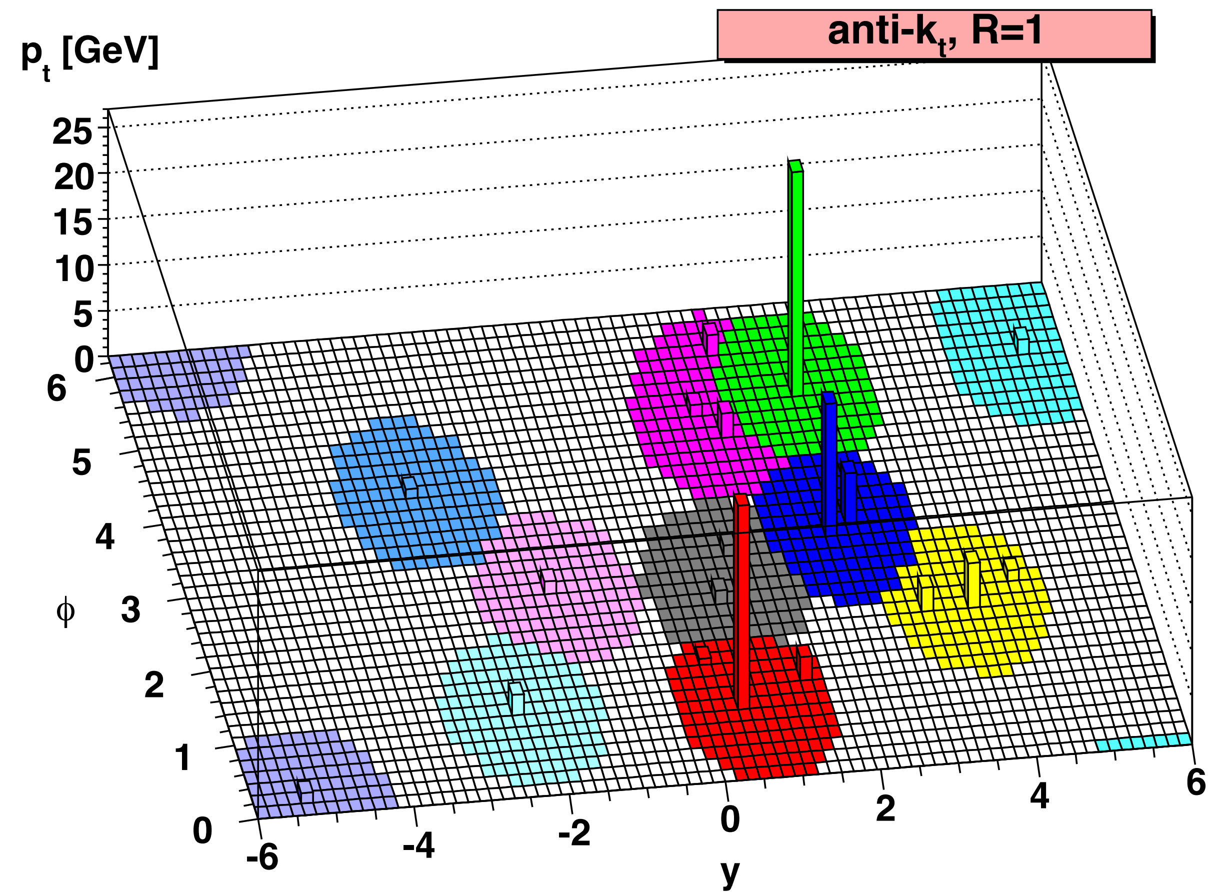


Jet Reconstruction

✦ **All measurements use the anti-k_T clustering algorithm:**
- sequential recombination (belongs to the k_T family)
- theoretically sound (infrared and collinear safe)
- geometrically well defined (circular shape in the y-ϕ plane)
- tends to cluster around the hard energy depositions
- distance parameter R

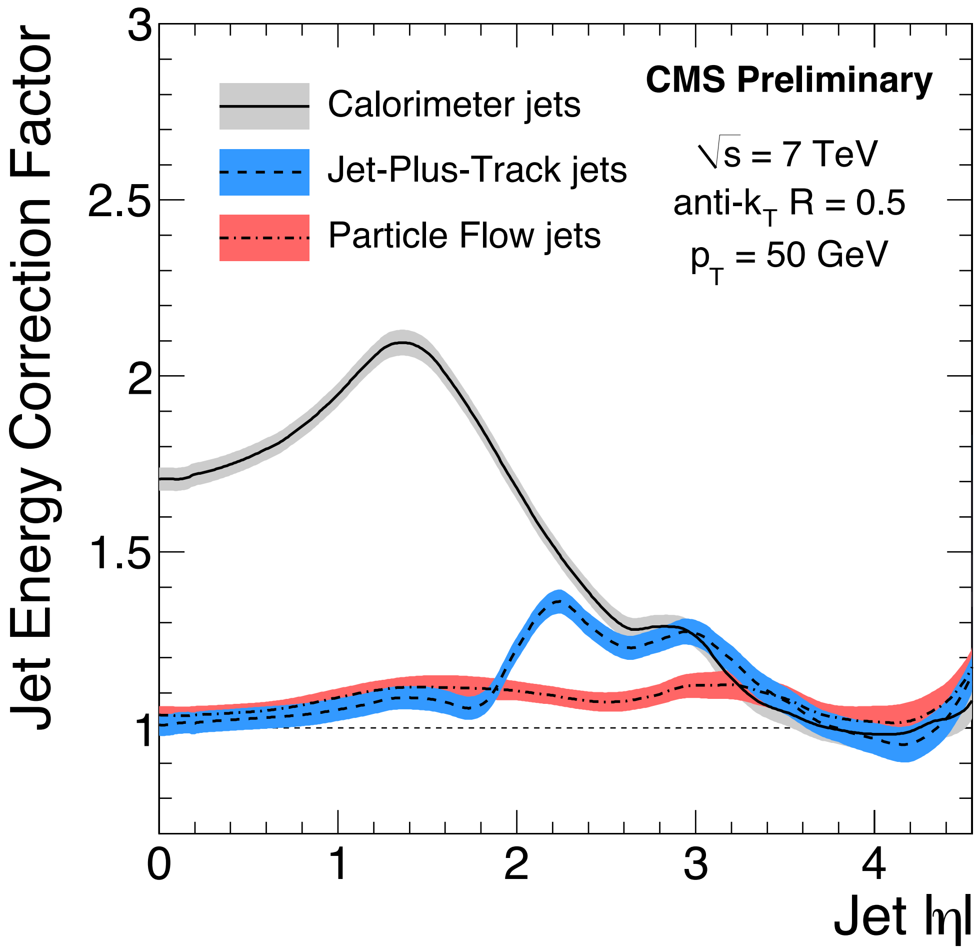
✦ **The jet reconstruction in CMS follows the *"E-scheme"***
- 4-momentum summation
- leads to massive jets

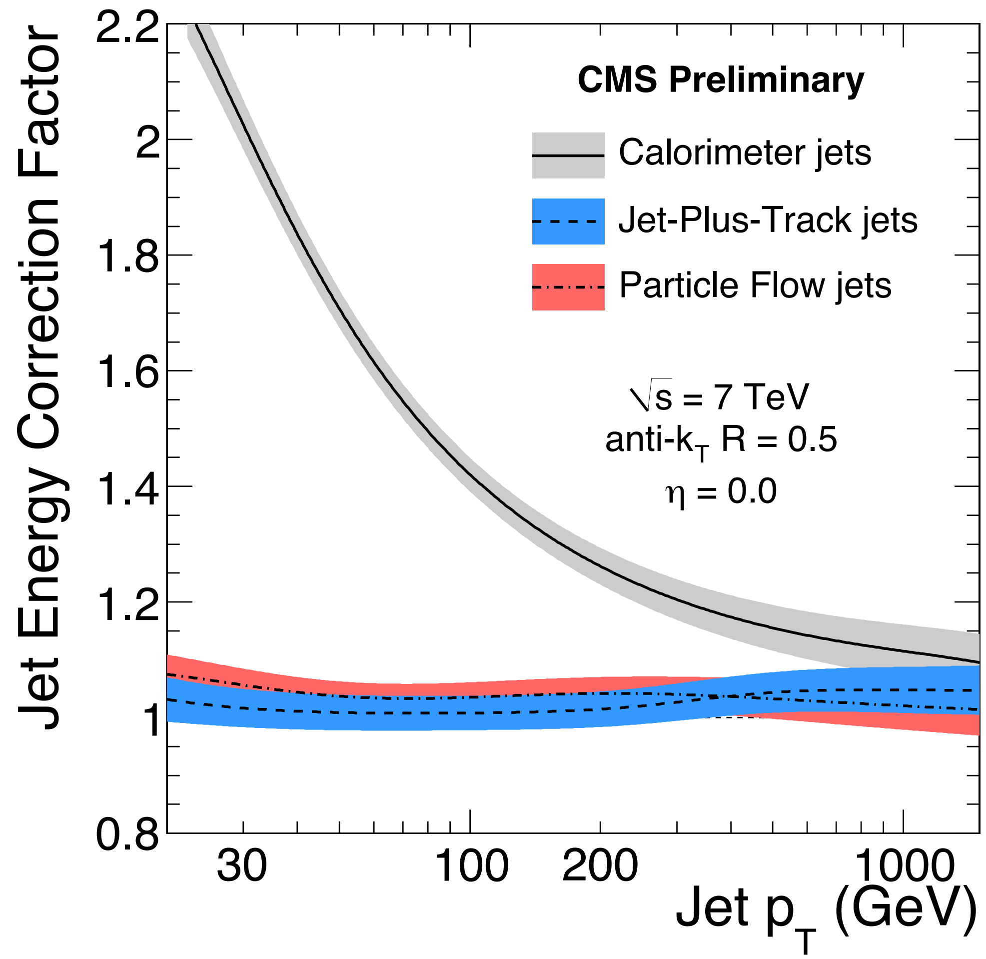
✦ **The inputs to the jet clustering algorithm are calorimeter towers or particle-flow candidates**



$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$
$$d_{iB} = p_{Ti}^{-2}$$
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

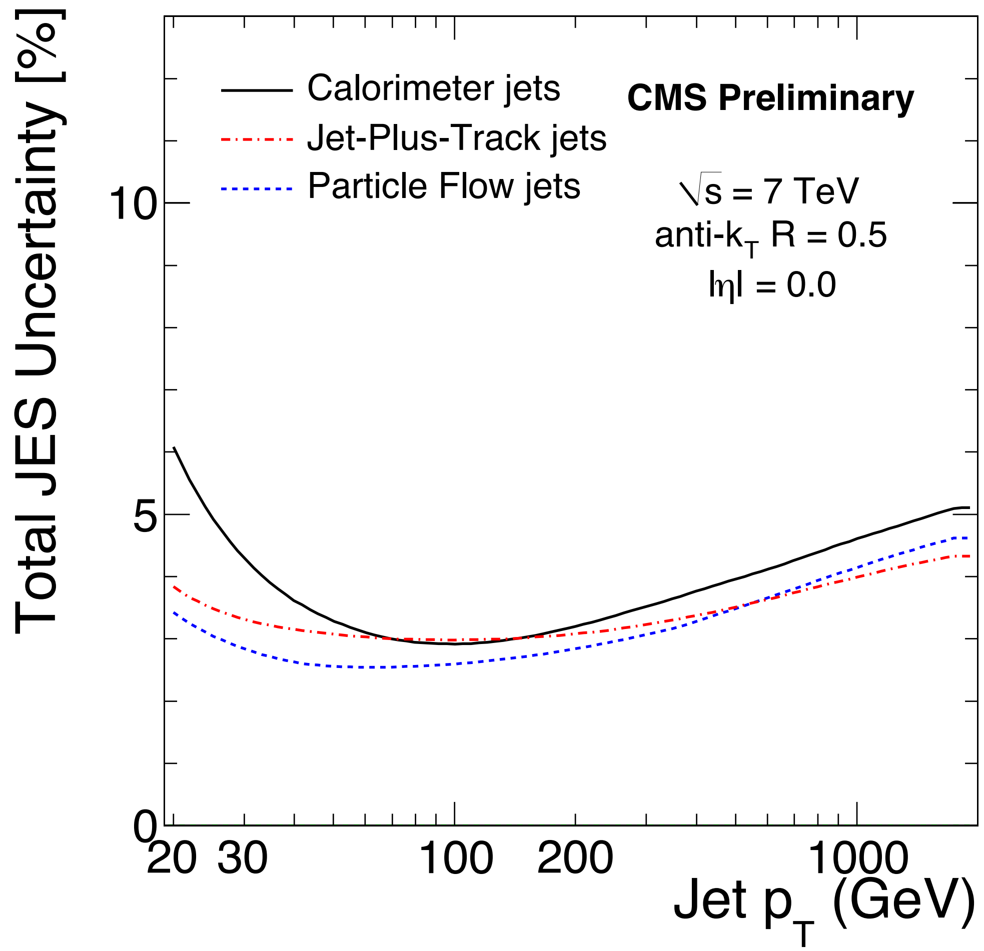
Jet Energy Calibration

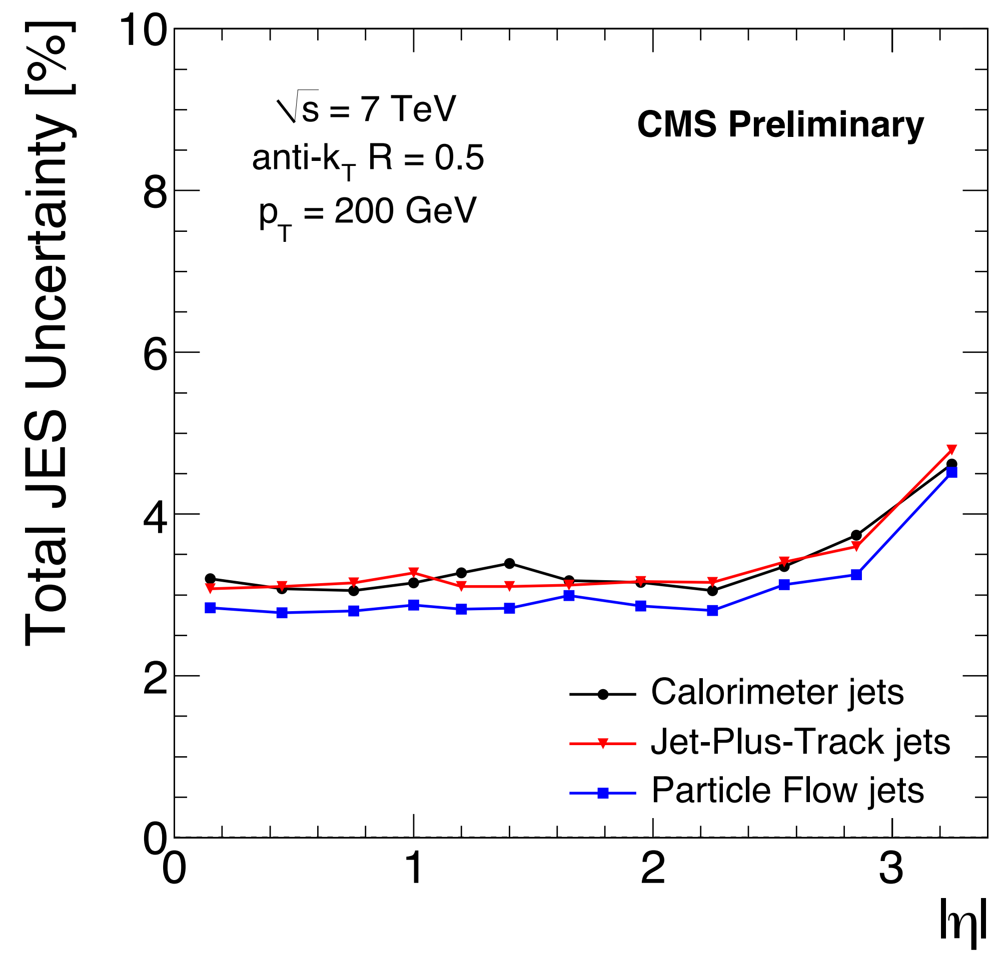




- **Correction applied as a scale factor to the full 4-momentum**
- **Hybrid jet energy calibration**
  - start with Monte Carlo truth and adjust according to dijet p_T balancing (η non-uniformity) and photon+jet p_T balancing (absolute scale)
- **Calorimeter jets require a large correction factor**
  - non-compensating hadron calorimeter
- **Particle-flow jets require a small correction factor (< 10%)**

Jet Energy Scale Uncertainty





- **Total jet energy scale uncertainty: 3-5% for all jet types**
  - estimated with the first 3 pb^{-1} of data
  - significantly improved (by a factor ~2) after using the entire sample (currently under review by CMS -- JINST paper to be submitted soon)
- **Uncertainty dominated by the high-p_T extrapolation**
  - beyond the p_T reach of the photon+jet sample

Measurements

Inclusive Jet Production (I)

$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{unsm}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{jets}}{\Delta p_T \Delta|y|}$$

✦ **Double-differential inclusive jet cross section vs jet p_T and y**

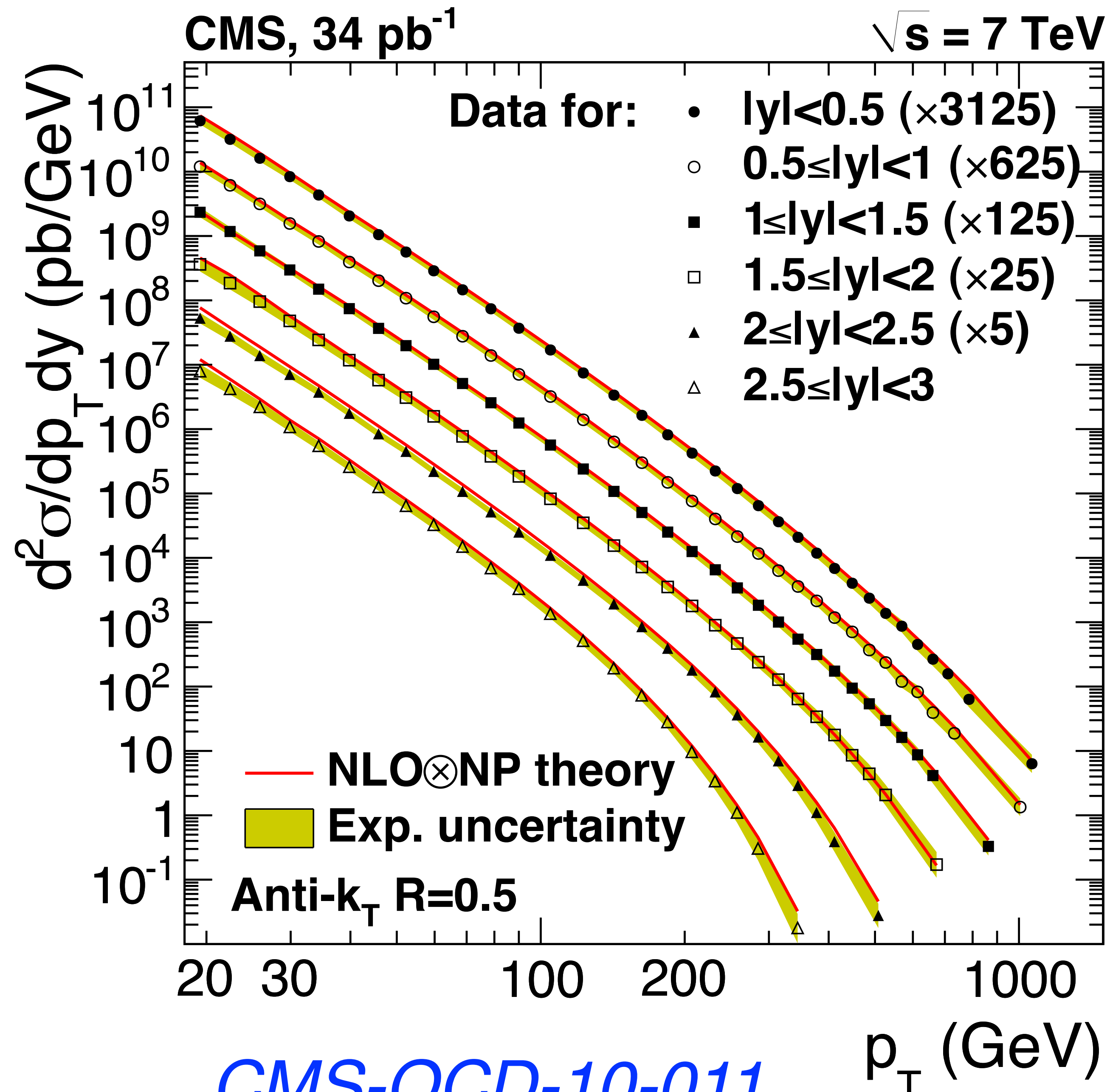
- using anti-k_T PF jets with R=0.5
- 34 pb^{-1}
- p_T range from 18 GeV to 1.1 TeV
- 6 rapidity bins, up to |y|=3.0 (the forward region 3.0 < |y| < 5.0 is covered by another, dedicated measurement)

✦ **Experimental Uncertainties**

- dominated by the JES

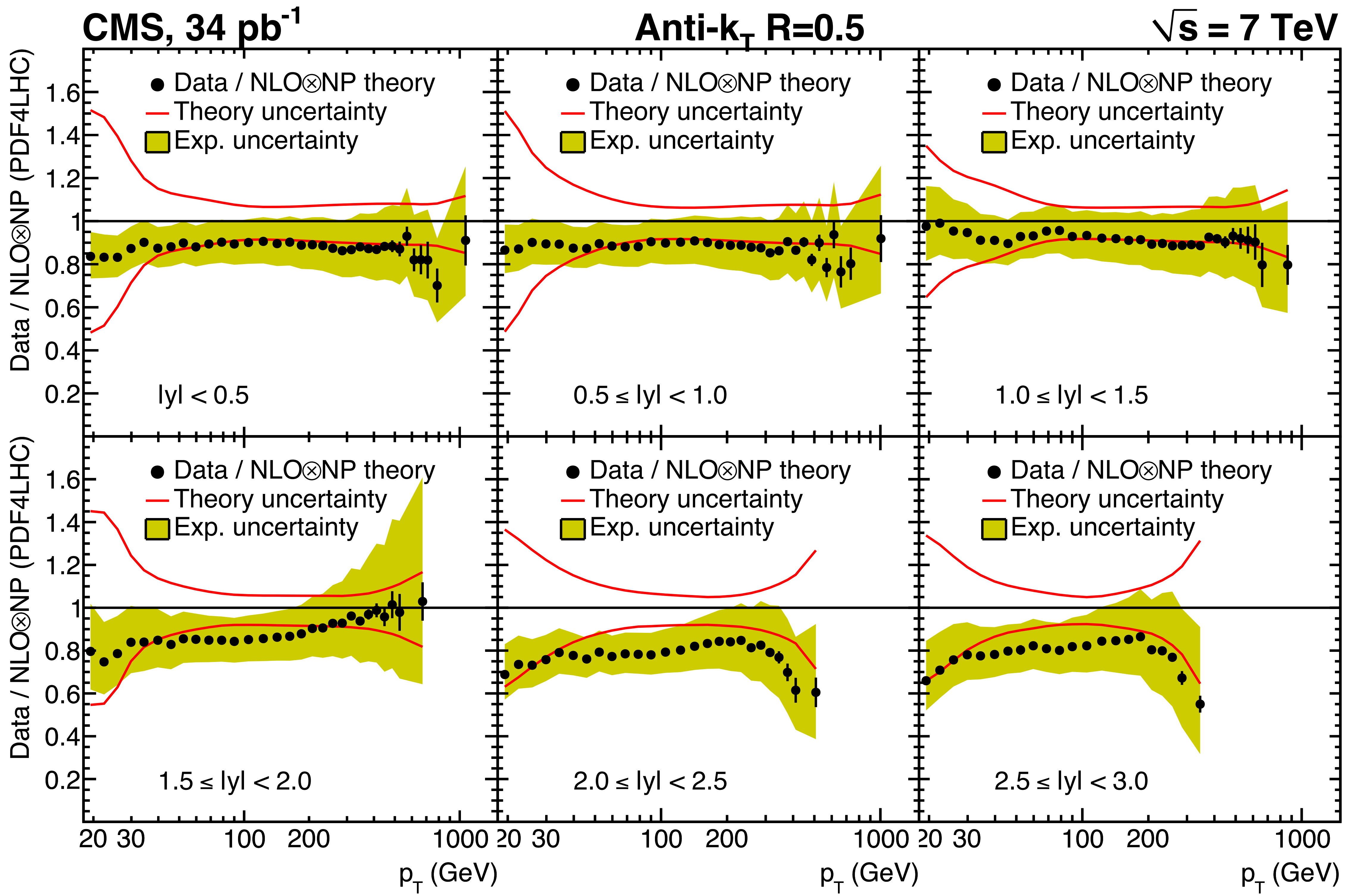
✦ **Theory Uncertainties**

- non-perturbative correction dominant at low p_T
- PDF dominant at high p_T
- small uncertainty due to scale variation and α_S



CMS-QCD-10-011

Inclusive Jet Production (II)



Data and theory are compatible in the entire phase-space of the measurement

Dijet Production (I)

$$\frac{d^2\sigma}{dM_{JJ}d|y|_{max}} = \frac{C_{unsm}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{ev}}{\Delta M_{JJ}\Delta|y|_{max}}$$

✦ **Double-differential inclusive dijet cross section vs dijet invariant mass and $|y|_{max}$**

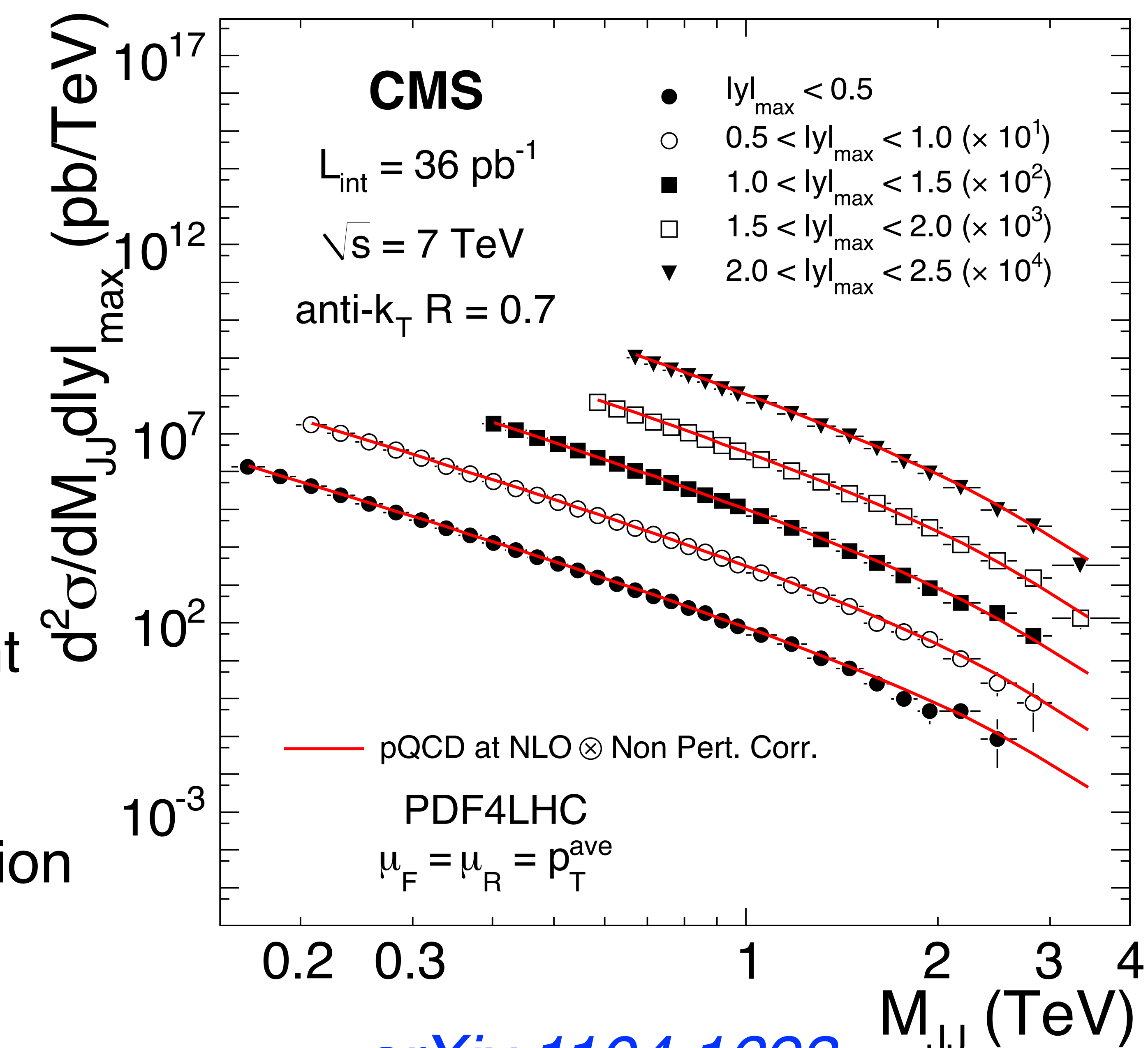
- using anti-k_T PF jets with R=0.7
- 36 pb^{-1}
- mass range from 0.16 to 3.5 TeV
- 5 bins of $|y|_{max}$, up to 2.5

✦ **Experimental uncertainties**

- dominated by the JES

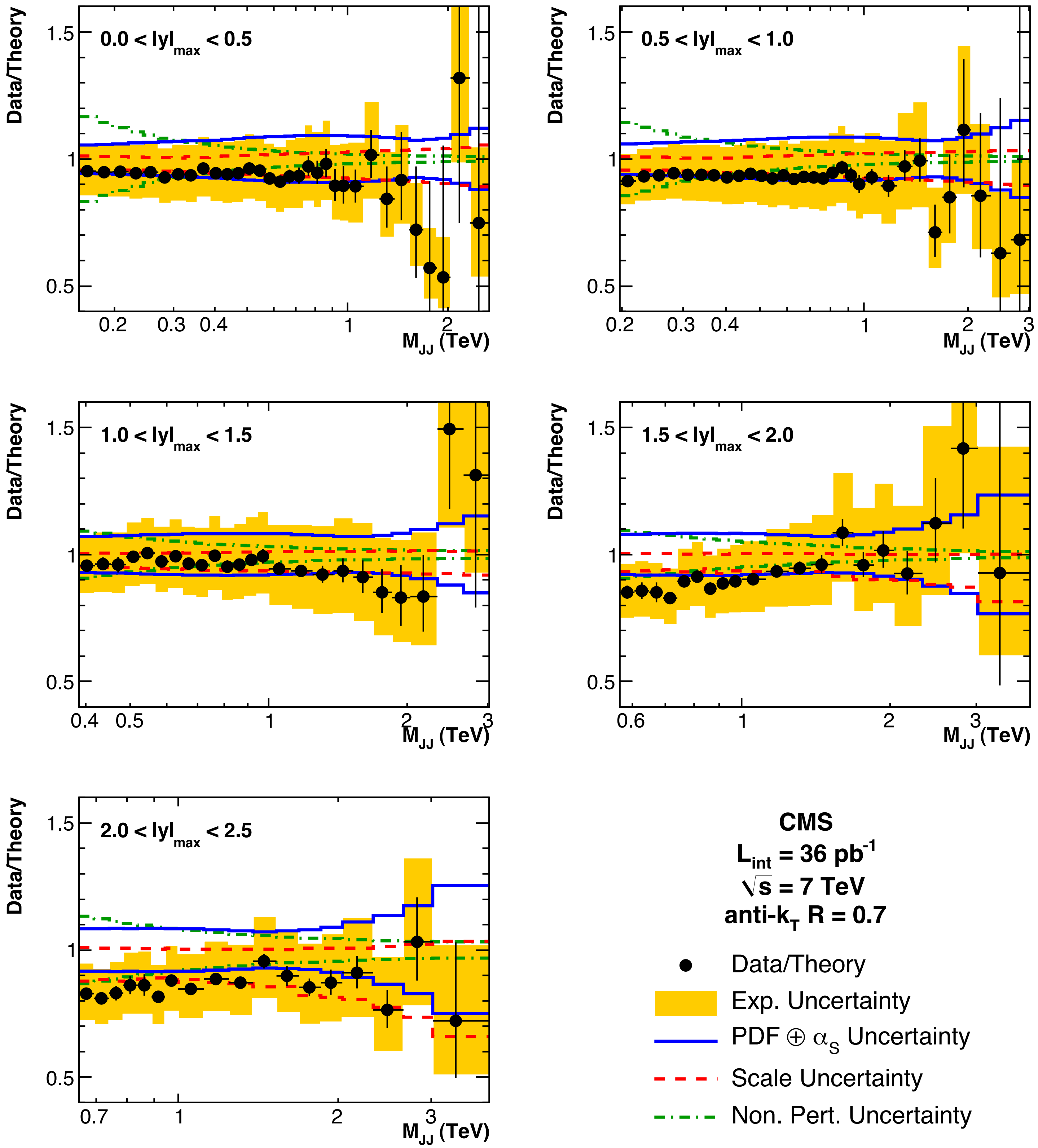
✦ **Theory uncertainties**

- non-perturbative correction dominant at low masses
- PDF dominant at high masses
- small uncertainty due to scale variation and α_S



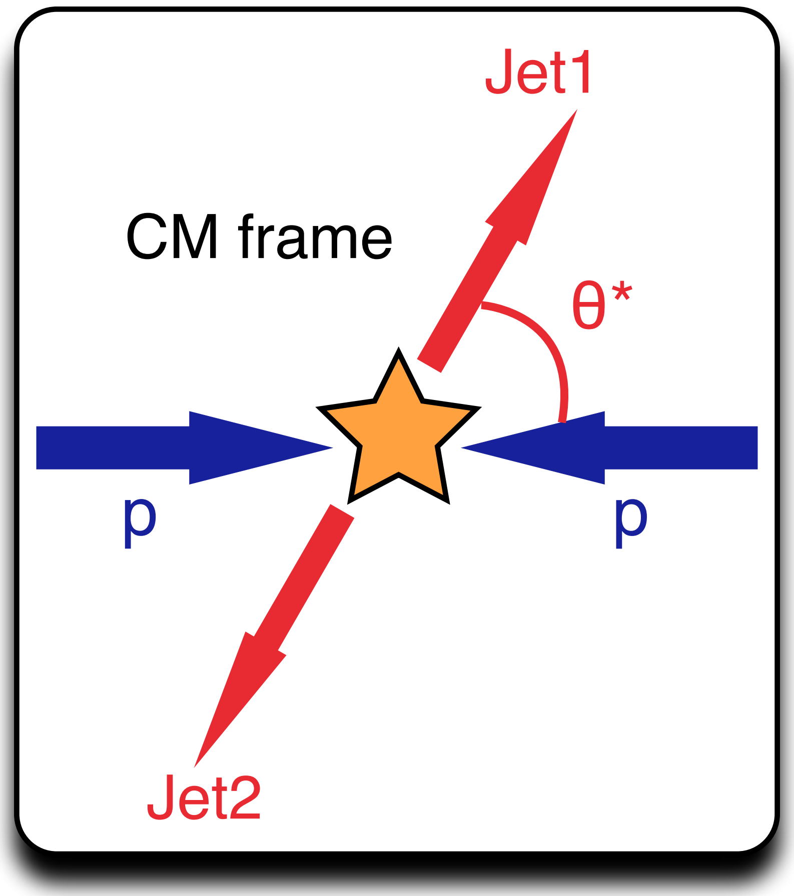
arXiv:1104.1693

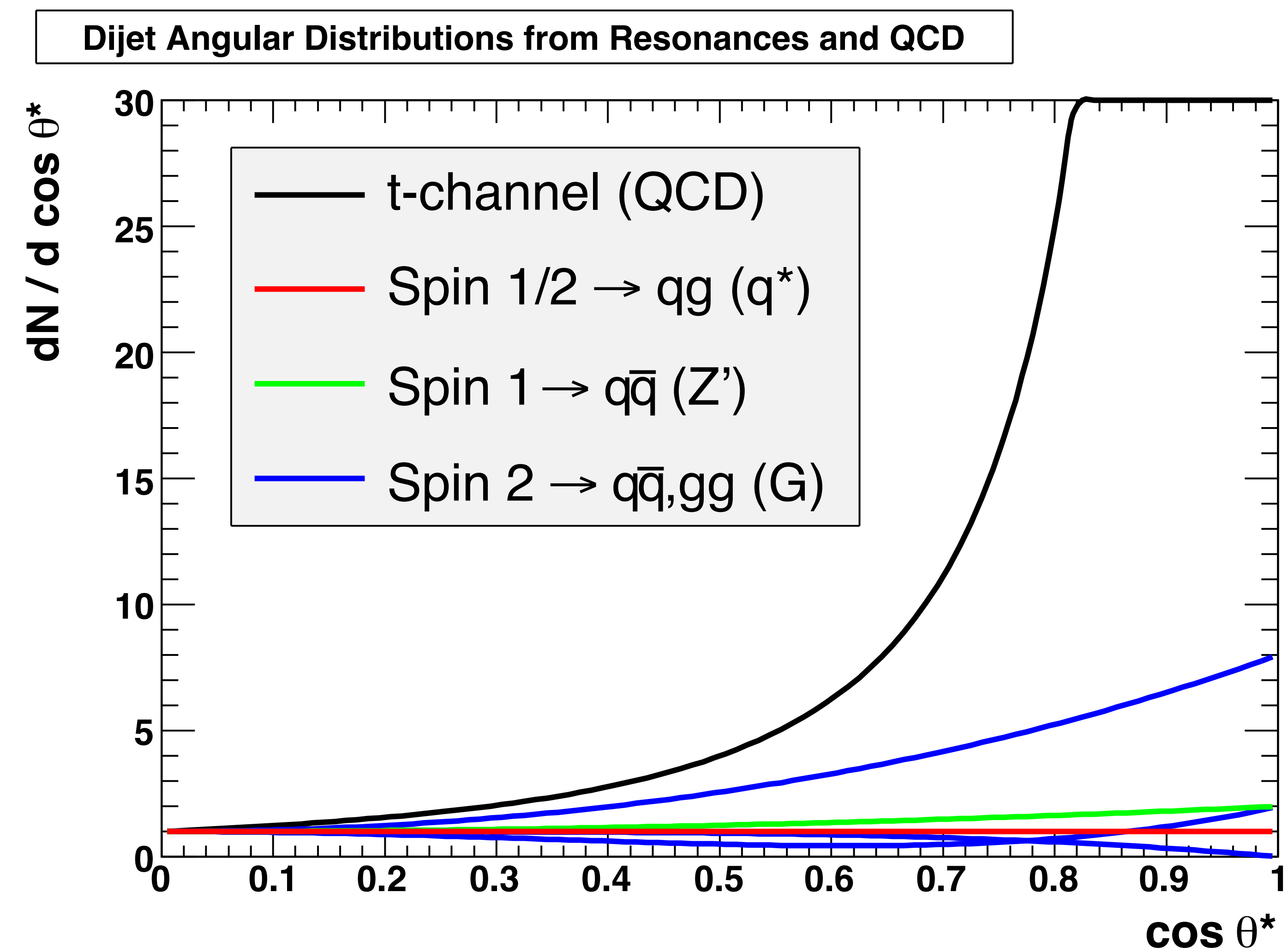
Dijet Production (II)



- ✦ **Data and theory are compatible in the entire phase-space of the measurement**
- ✦ **Similar trend with the inclusive jets**
  - but not directly comparable due to the different jet size

Dijet Angular Distributions (I)





✦ **The dijet angular distributions give additional insight to the QCD dynamics**

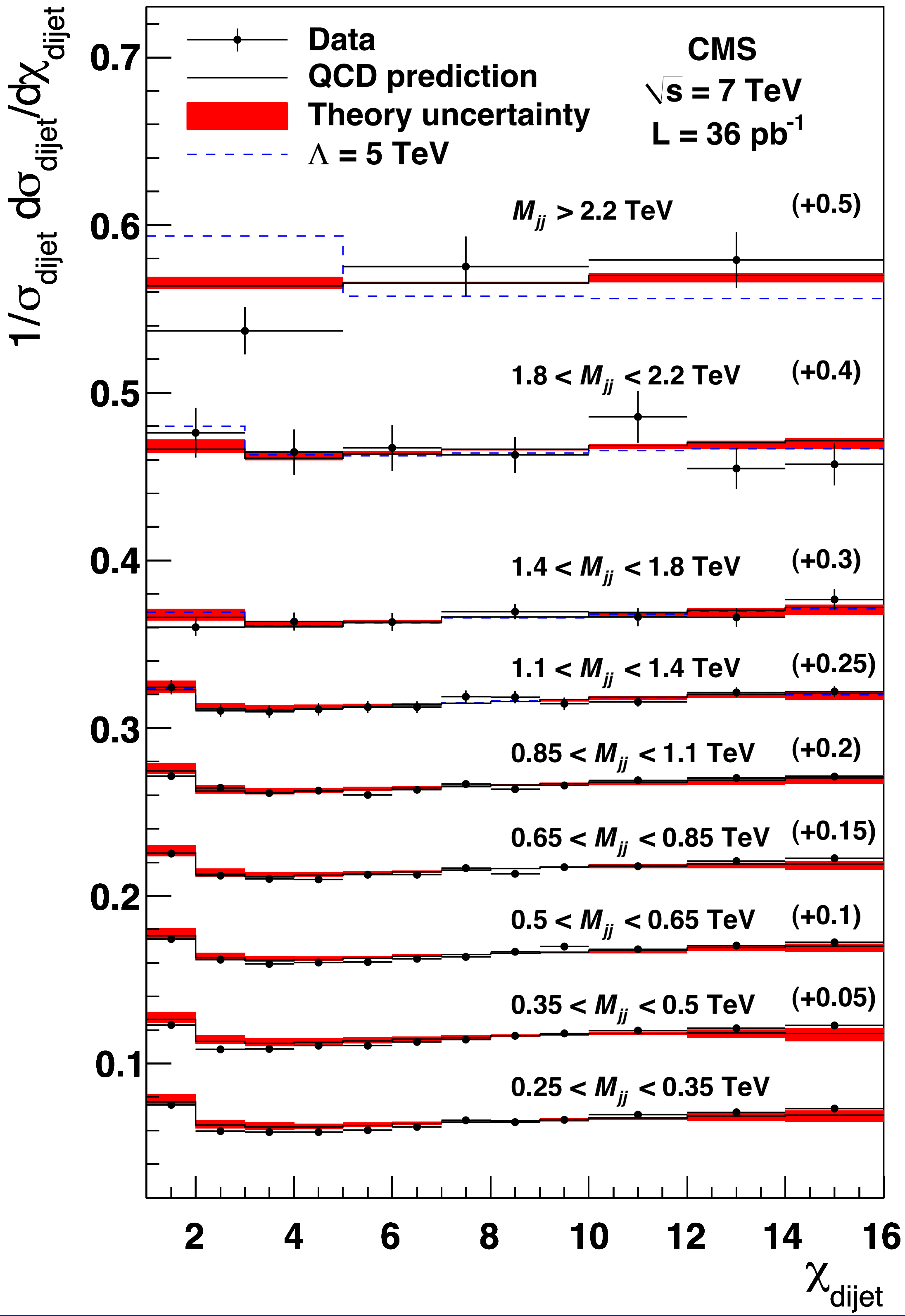
- parton-parton scattering in QCD is t-channel dominated (Rutherford scattering at small angles)

✦ **Stringent test of pQCD and sensitivity to New Physics**

- contact interactions or resonances would show deviation from QCD at large scattering angles

Dijet Angular Distributions (II)

arXiv:1102.2020v1

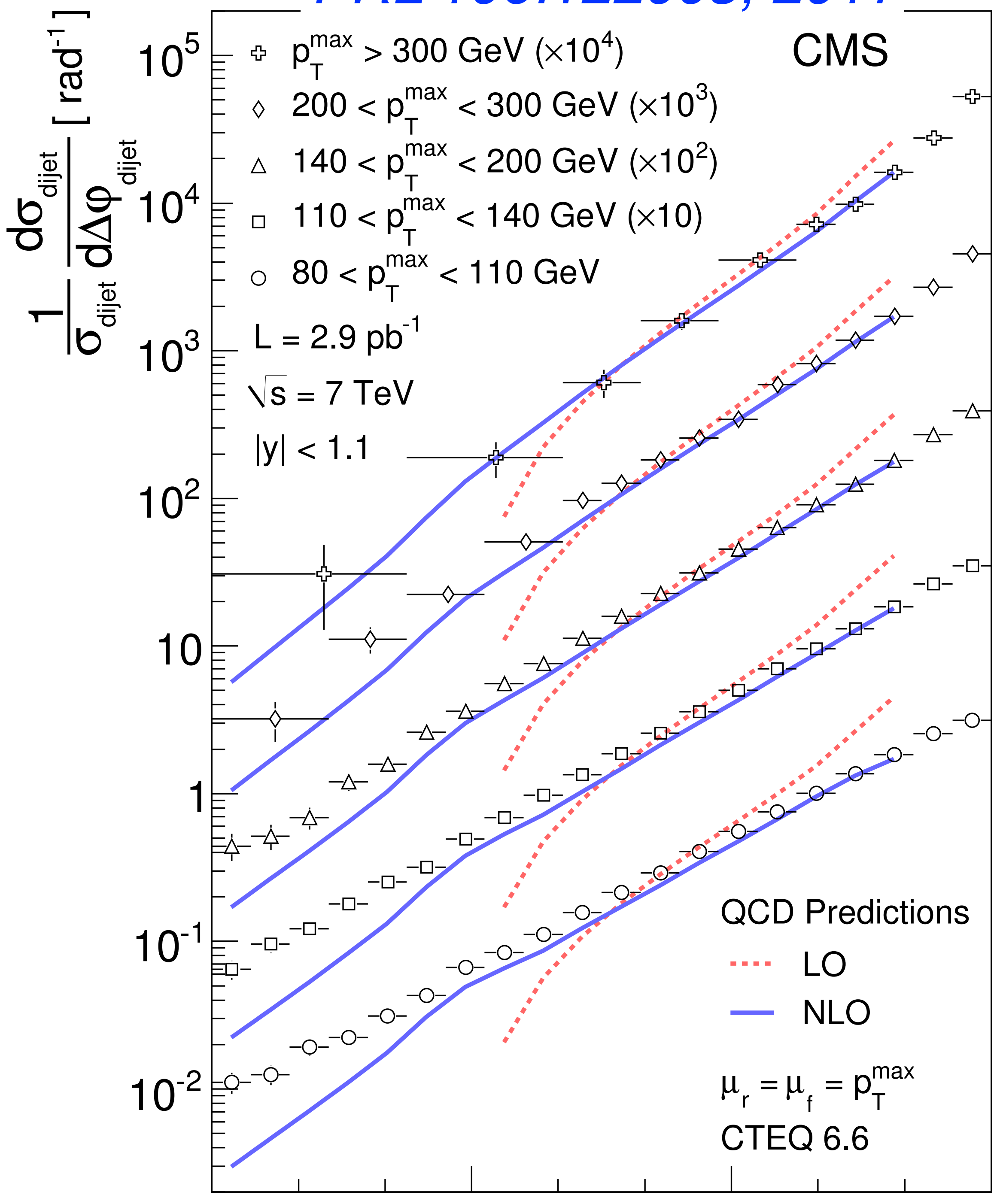


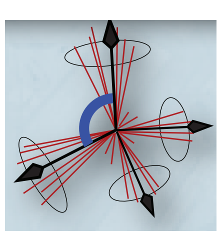
$$\chi = e^{|y_1 - y_2|} \approx \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$$

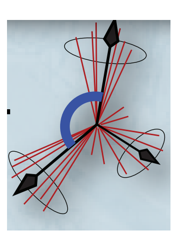
- ✦ **Normalized dijet cross section, as a function of χ, in mass bins**
  - χ is the preferred angular variable because QCD shape is relatively flat vs χ
  - using anti-k_T PF jets with R=0.5
  - 36 pb^{-1}
  - χ range: 1 < χ < 16
  - 9 dijet mass bins
- ✦ **Experimental uncertainties**
  - cancellation of many uncertainties (absolute JES, luminosity)
  - relative JES vs y, resolution
- ✦ **Theory uncertainties**
  - scale unc. dominates (5-9%)
  - non-perturbative correction unc. up to 4% at low masses
  - not sensitive to the PDFs

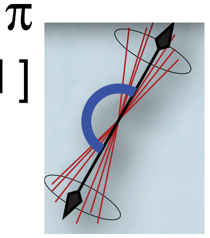
Dijet Azimuthal Decorrelations (I)

PRL 106:122003, 2011









✦ **Normalized dijet cross section, as a function of Δφ**

- indirect probe of multijet topologies, without explicitly measuring more than the two leading jets

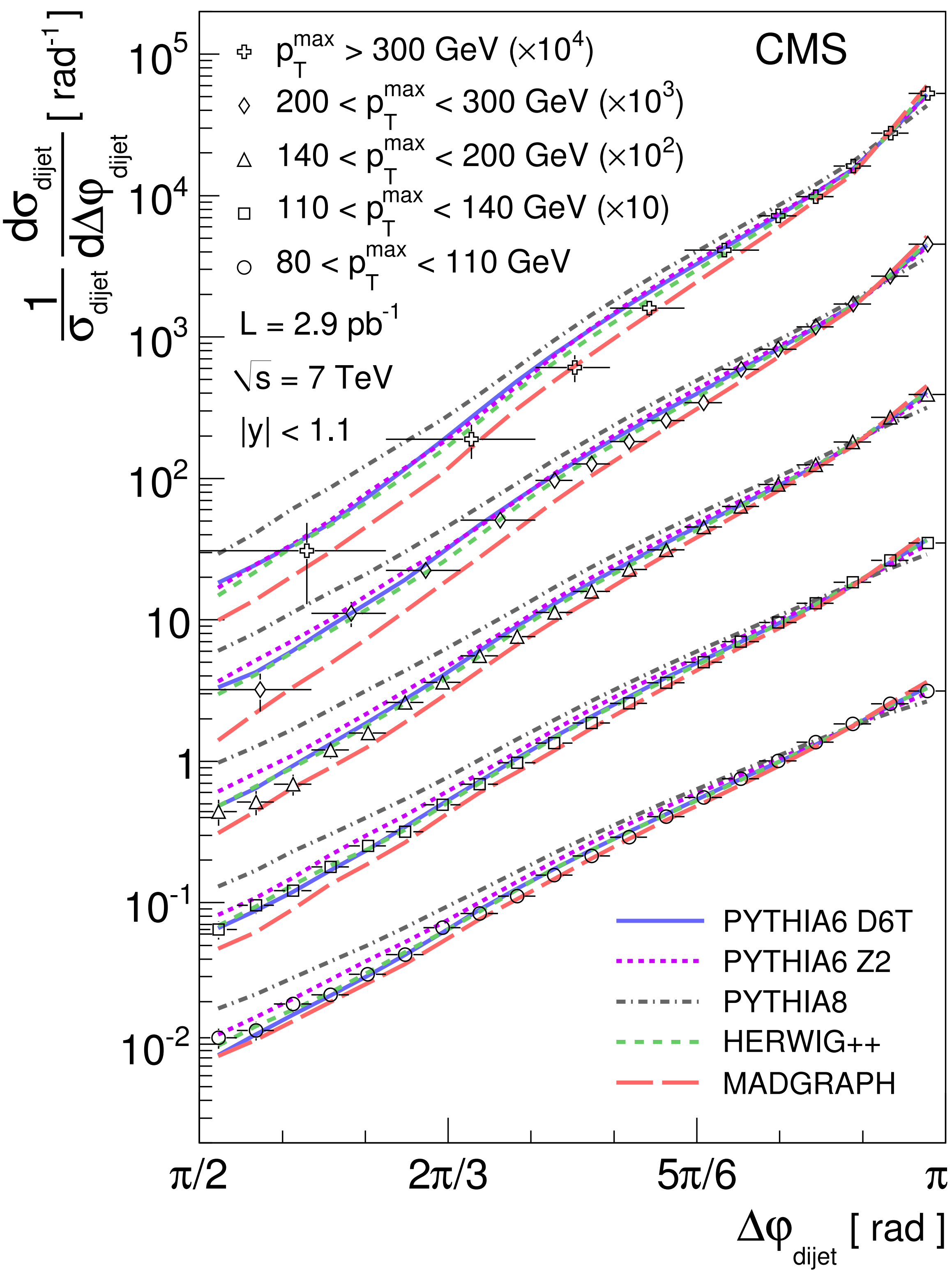
✦ **Experimental measurement**

- anti-k_T, R=0.5, PF Jets
- 5 bins of $p_{T,max}$
- 2.9 pb^{-1}
- cancellation of many jet unc.
- bin-by-bin unsmearing correction

✦ **Theory Prediction**

- NLO pQCD + non-perturbative corrections describe well the data for a Δφ > 120 deg (~ 3j topologies)
- the scale uncertainty dominates

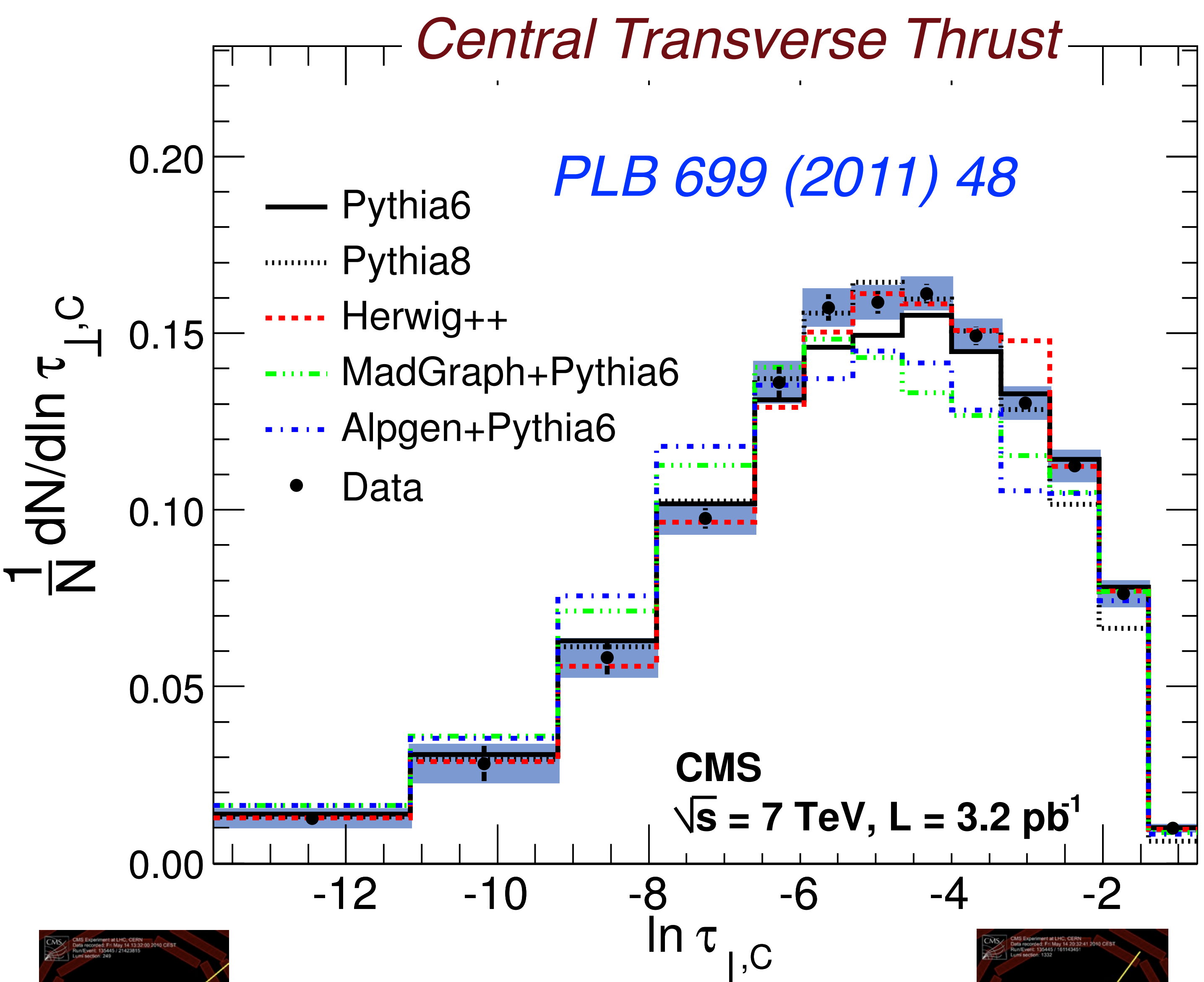
Dijet Azimuthal Decorrelations (II)

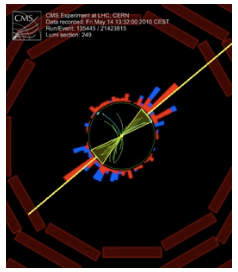


✦ Data vs MC comparison

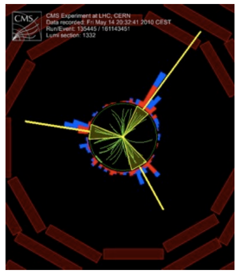
- Pythia6 and Herwig++ predictions are in good agreement with the data, in the entire phase space
- Pythia8 predicts more multijet-like events
- Madgraph predicts less multijet-like events

Hadronic Event Shapes (I)





$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_{\mathrm{T}}} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_{\mathrm{T}}|}{\sum_i p_{\perp,i}}$$



$$T_{m,\mathcal{C}} \equiv \frac{\sum_i |\vec{p}_{\perp,i} \times \hat{n}_{\mathrm{T},\mathcal{C}}|}{\sum_i p_{\perp,i}}$$

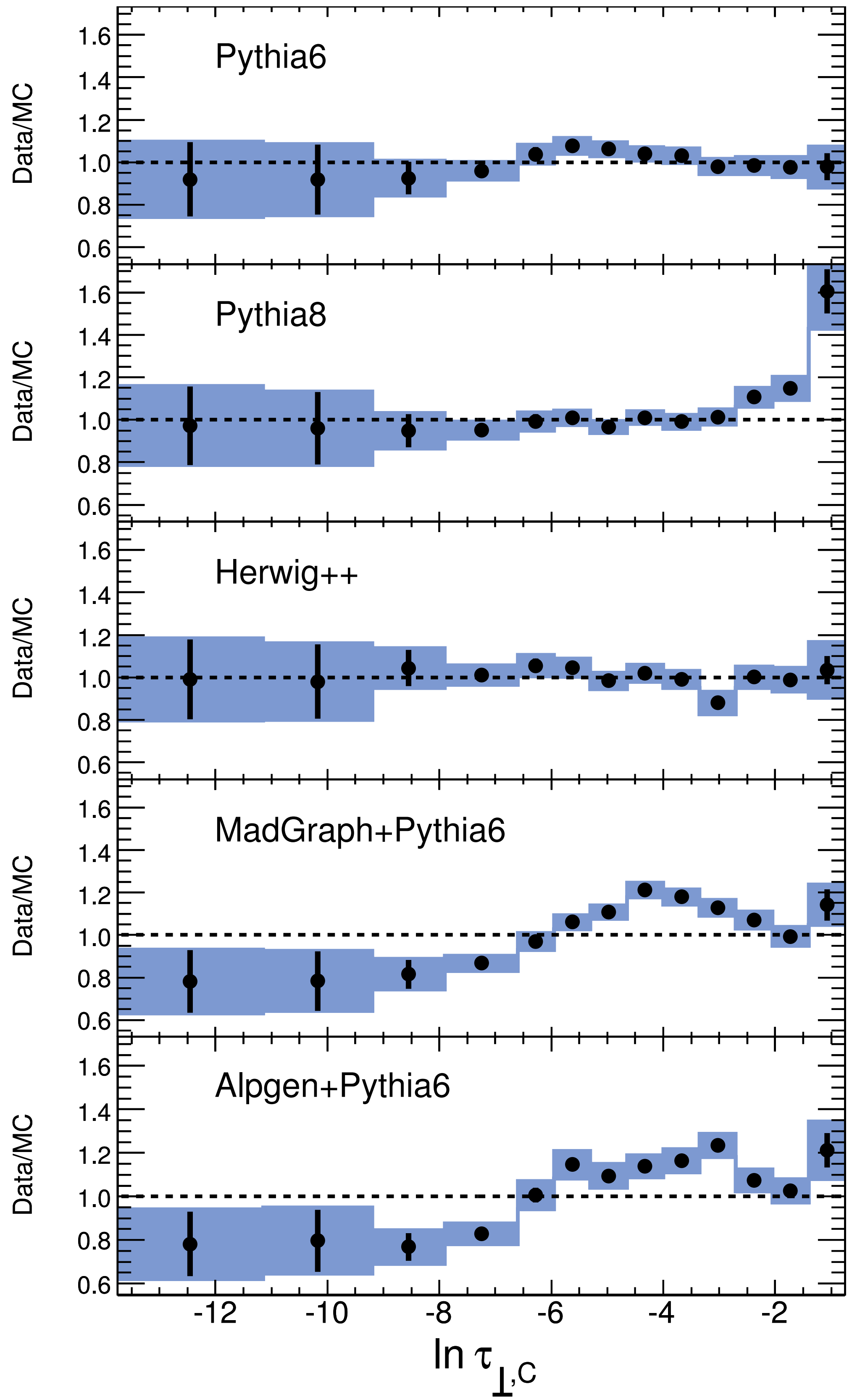
✦ Event-shape variables

- central transverse thrust and thrust minor
- probe different QCD radiative processes
- sensitive to the 2j and 3j topologies
- dijets events have small values

✦ Experimental measurement

- anti-k_T, R=0.5, PF Jets
- calculate the event shape variables from the central jets in 3 bins of $p_{T,max}$
- 3.2 pb^{-1}
- cancellation of many jet unc.
- full unfolding to the particle level using the SVD method

Hadronic Event Shapes (II)

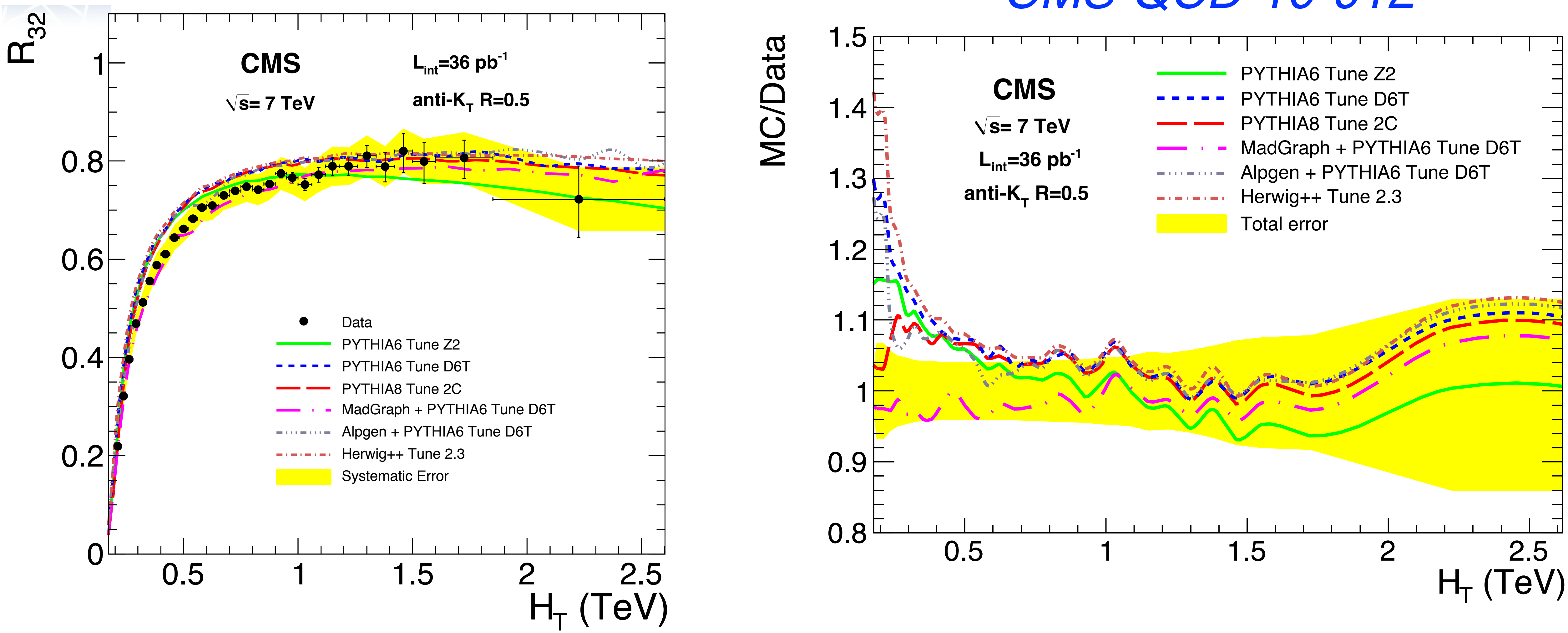


✦ Data vs MC comparison

- Pythia6 and Herwig++ predictions are in good agreement with the data, in the entire phase space
- Pythia8 agrees with the data in the 2 lowest bins, but shows a dijet deficit in the highest bin
- Madgraph and Alpgen show a similar discrepancy with the data (overestimate of dijet events)
  - further investigation revealed that the ME generators reproduce well the leading jet, but producer harder second jets

3j/2j Cross-Section Ratio

CMS-QCD-10-012



✦ Ratio of cross sections (3j/2j), vs H_T

- insensitive to experimental uncertainties
- the NLO calculation for the given setup is affected by large scale uncertainties
- can be used for the α_S measurement (in a different setup)

✦ Comparison to QCD MC generators

- all generators agree for $H_T > 0.7$ TeV with significant deviation at low values
- Madgraph is in excellent agreement with the data in the entire H_T range

Summary & Outlook

✦ CMS has completed successfully many QCD jet measurements with the 2010 data

- 2 papers published, 1 accepted, 1 submitted and 2 will be submitted shortly

✦ The advanced understanding of the jet reconstruction and energy calibration has allowed us to perform competing jet measurements

✦ **Overall, data and theory predictions are compatible**

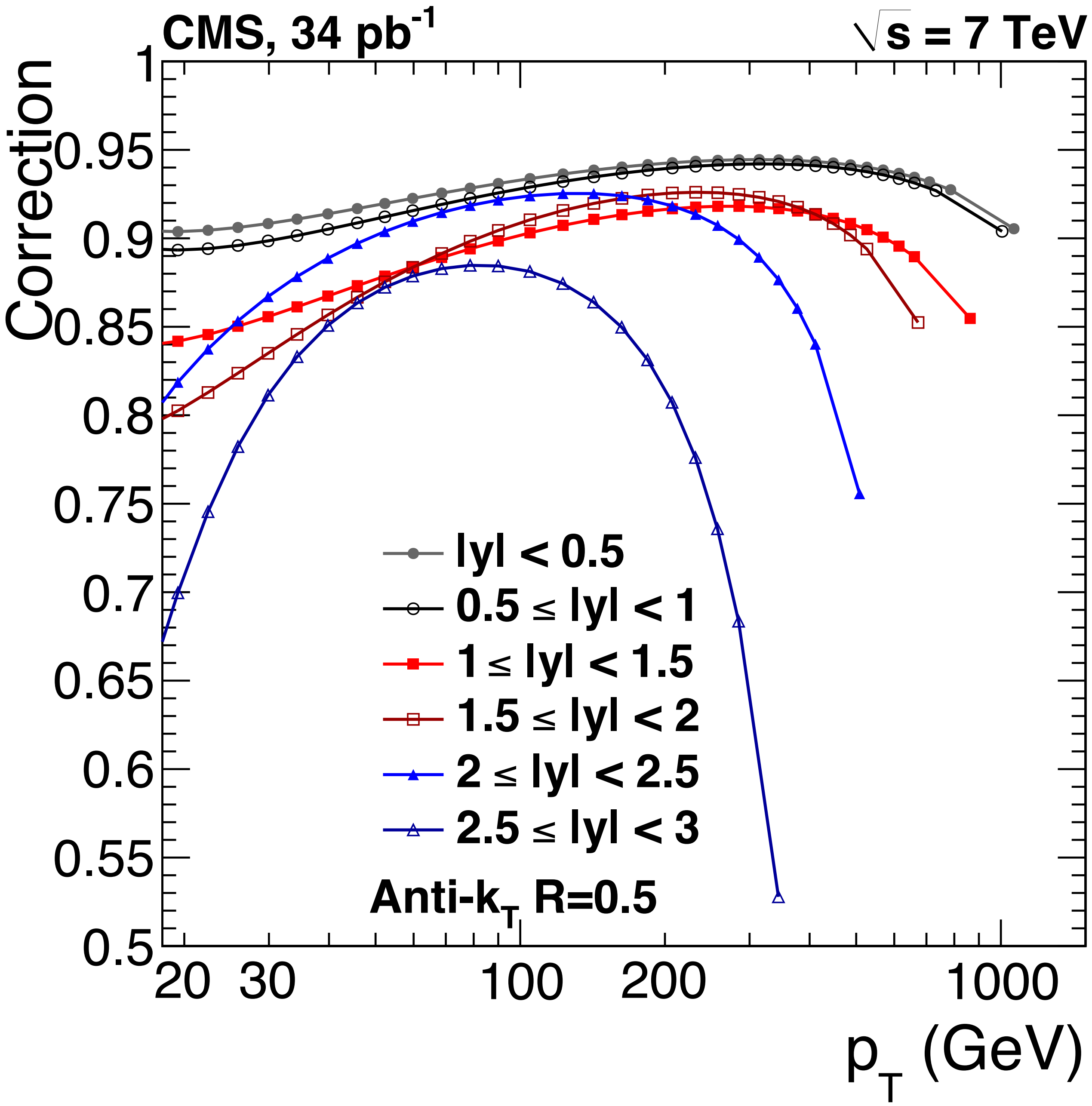
✦ Some small discrepancies have been observed in the QCD MC generators. The CMS measurements are available for further tuning of the MC generators

✦ With the 2011 data, CMS plans to perform precision studies (measurement of α_S, differentiate between the various PDFs) which will be documented in detailed, long papers

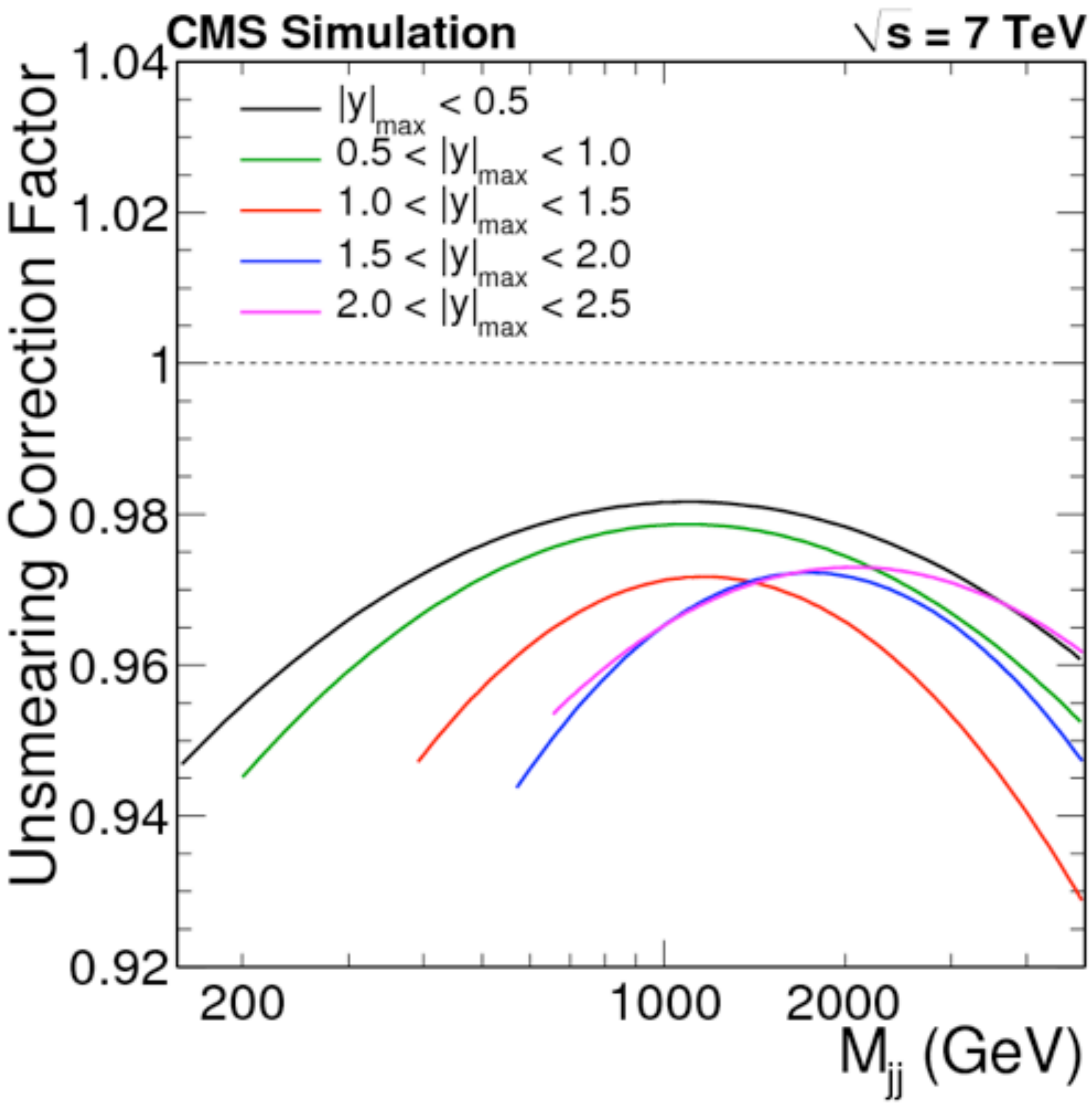
Backup

Cross-Section Unsmearing Factors

Inclusive Jets

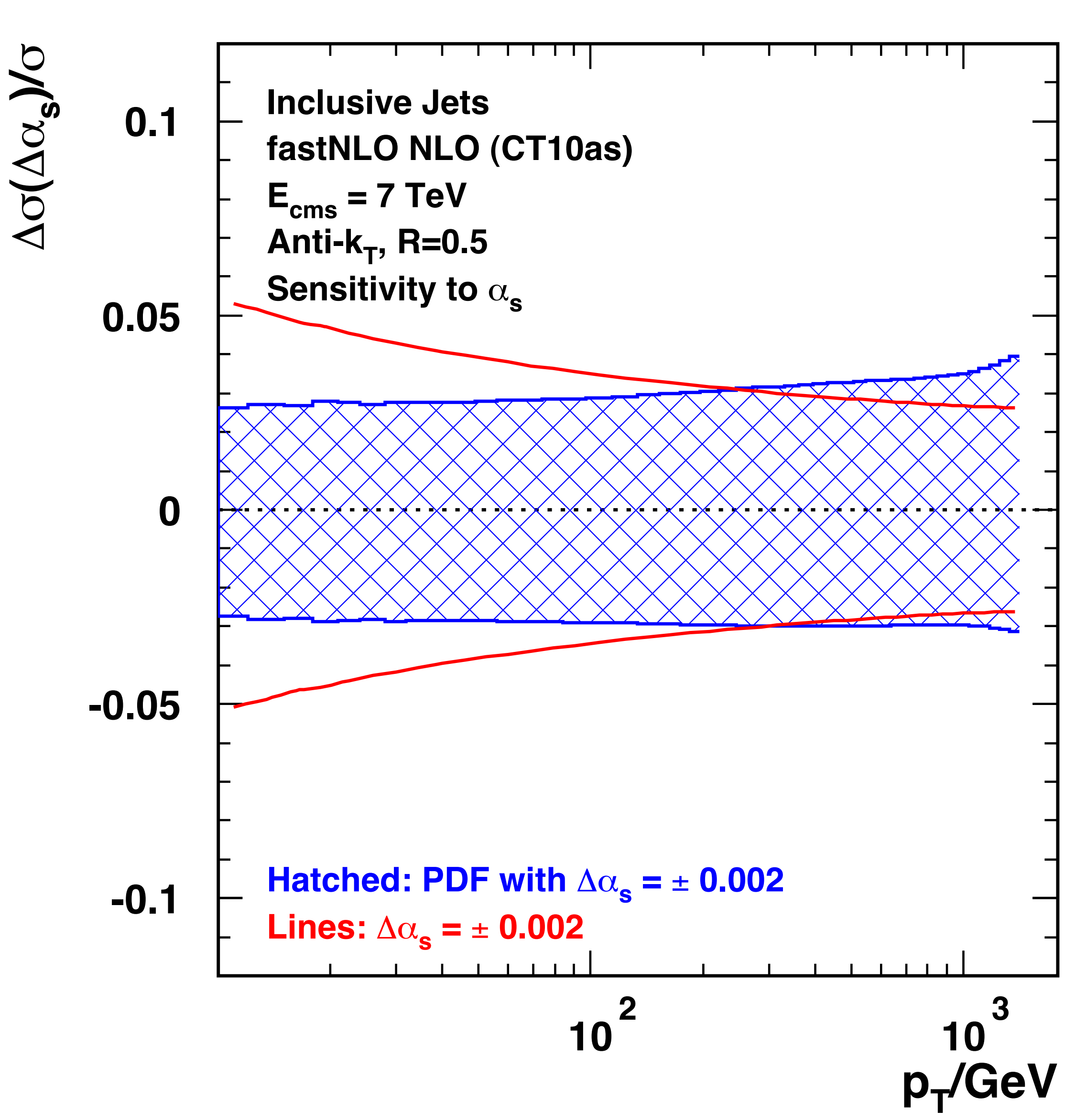


Dijet Mass

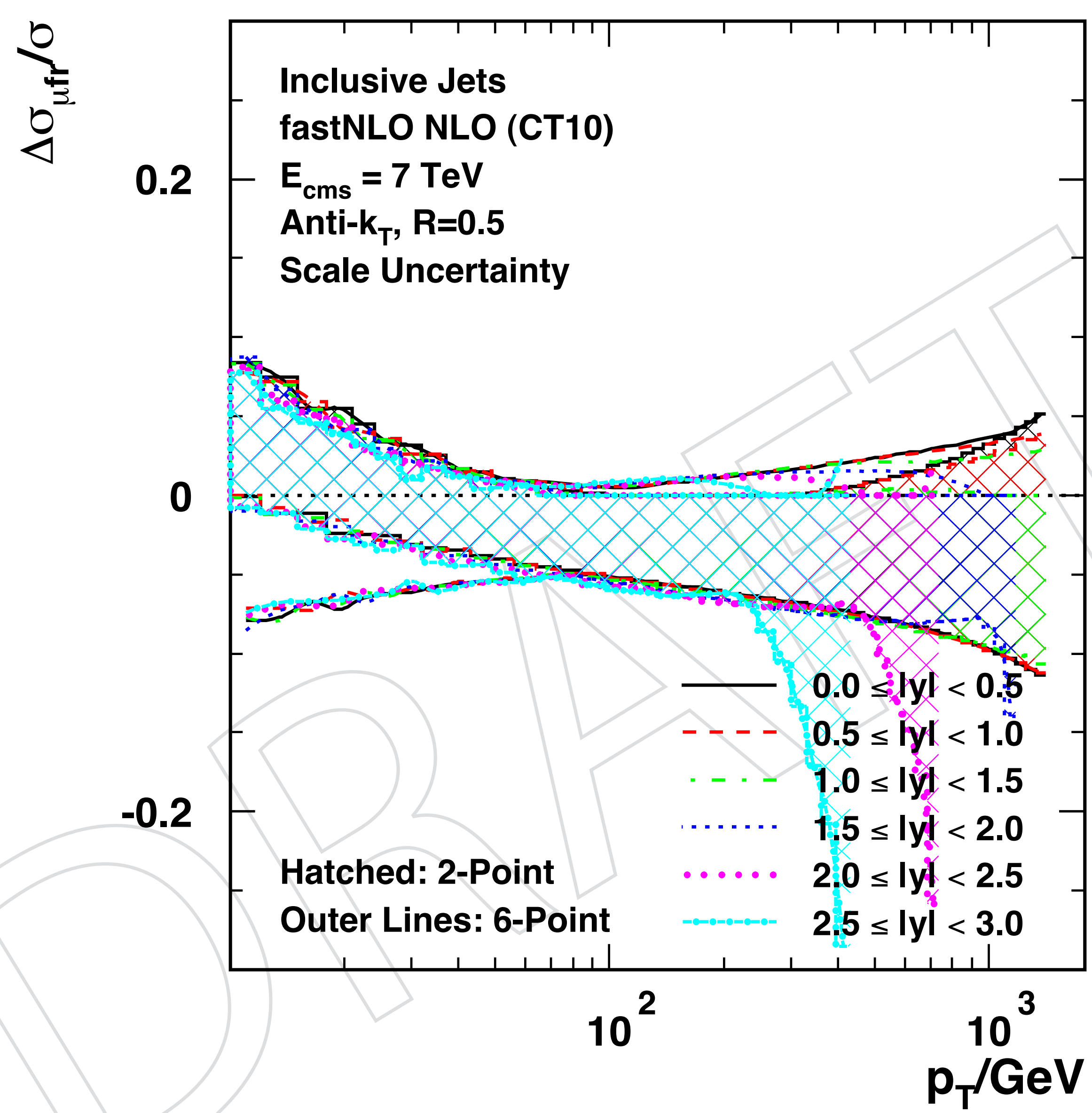


Cross-Section Theory Uncertainties

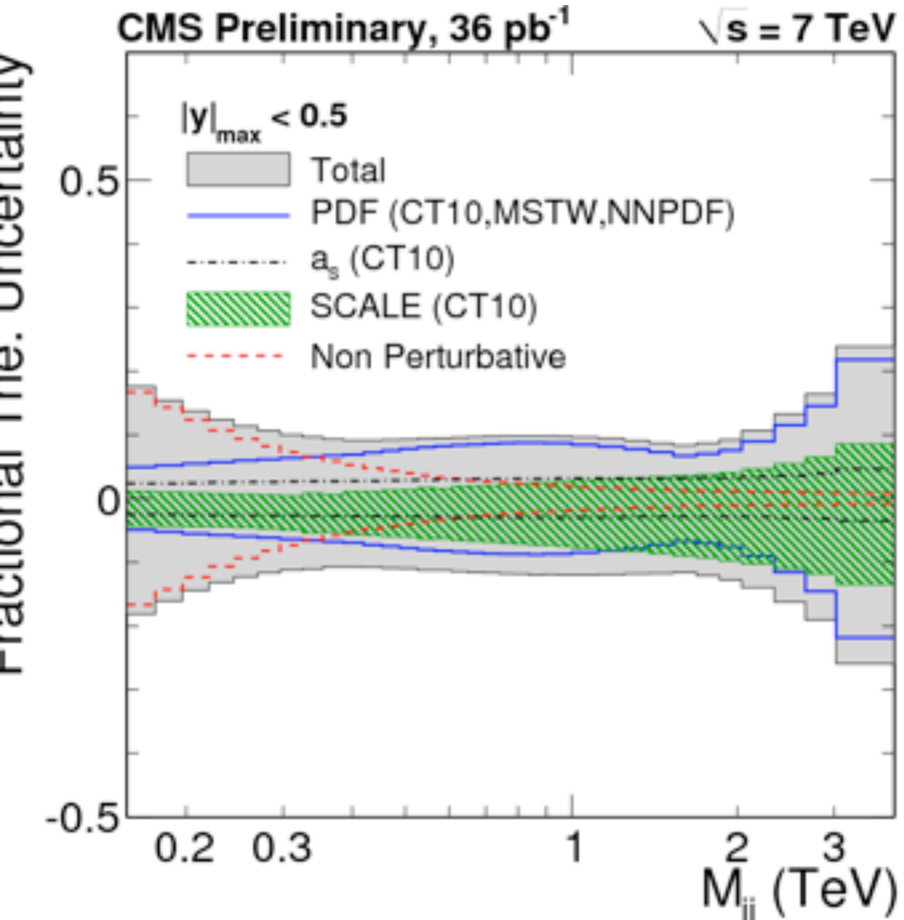
Strong coupling constant

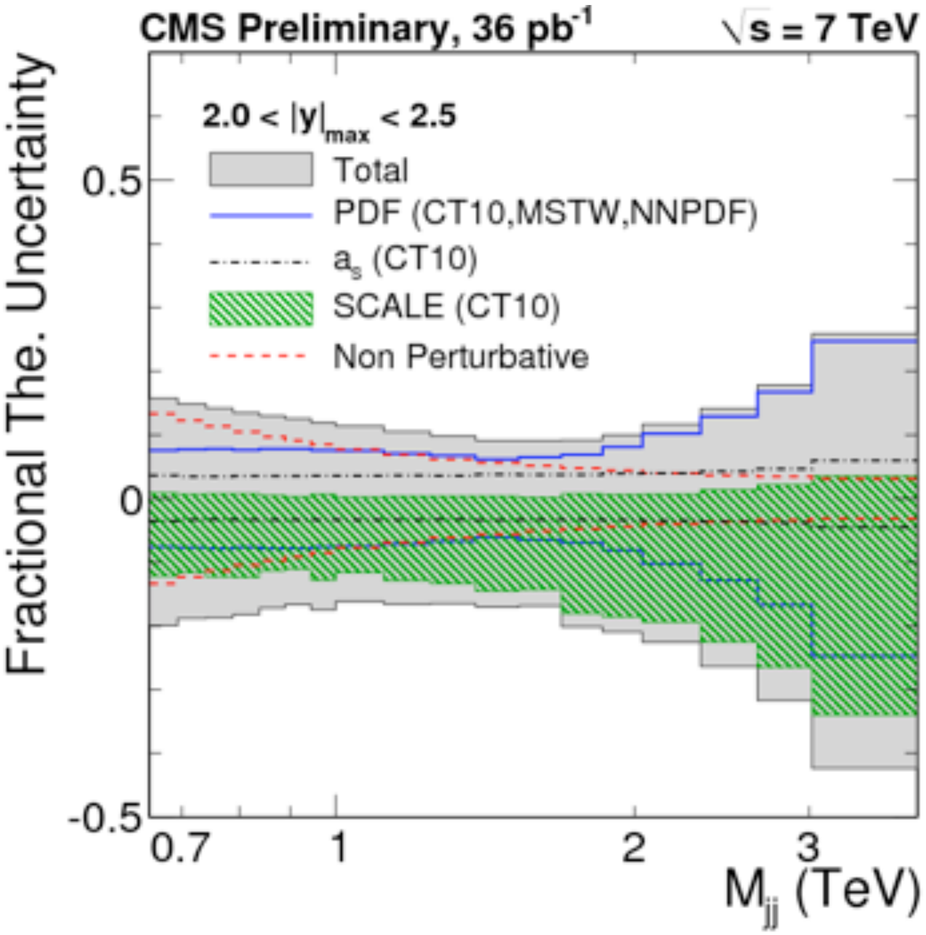


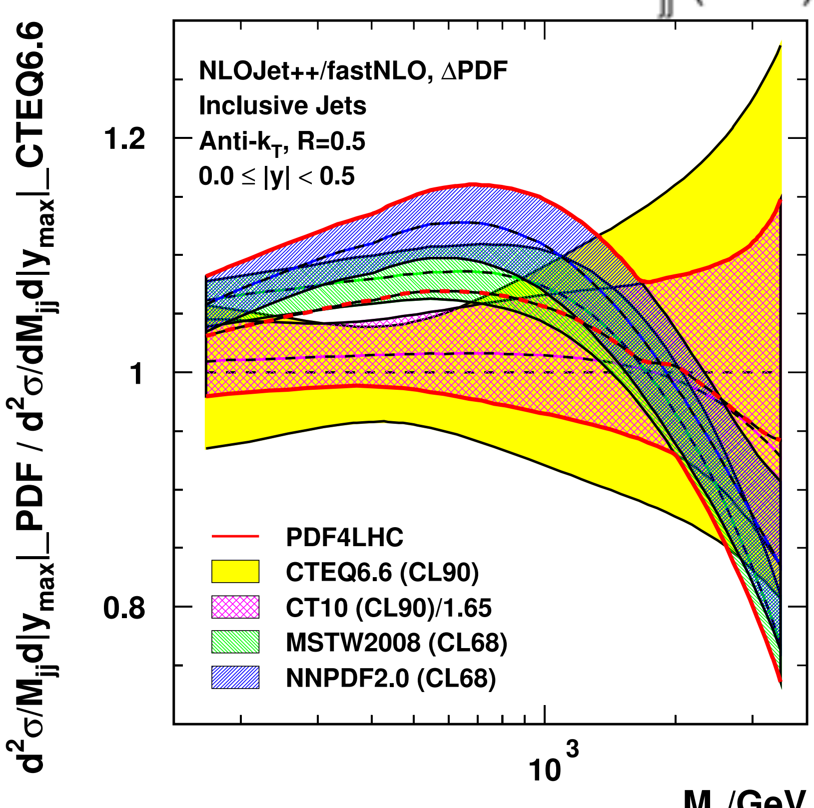
Scale

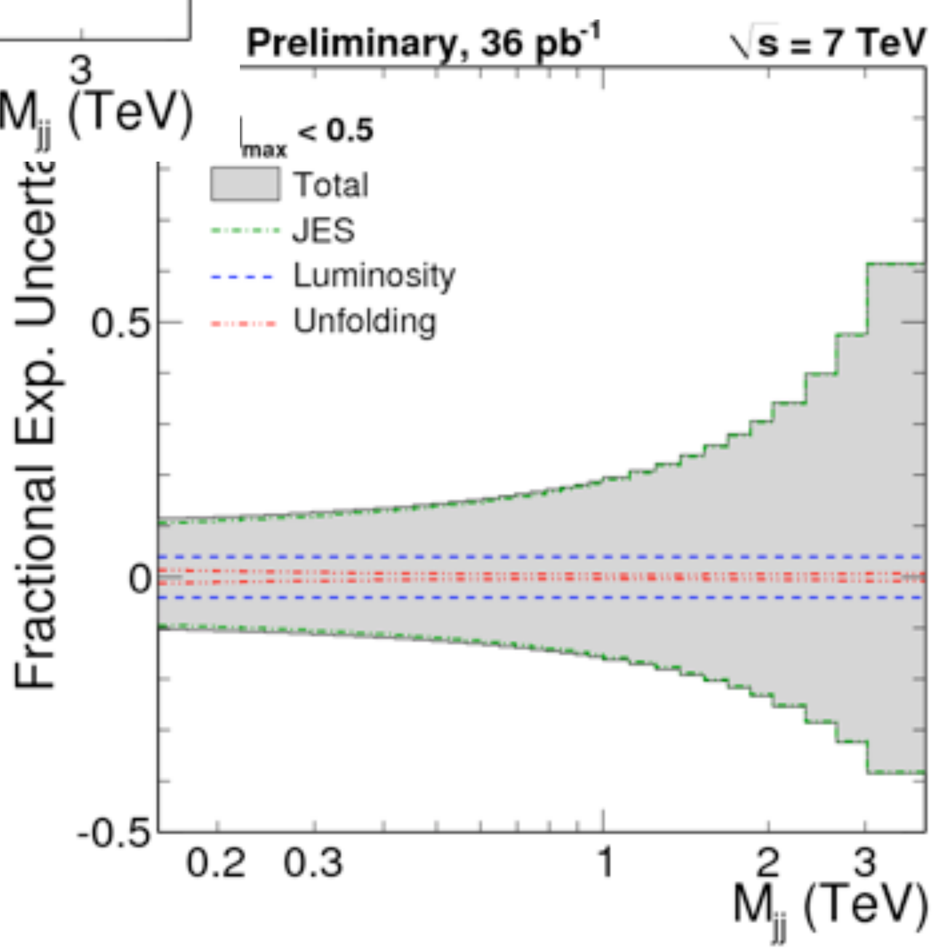


Dijet Cross-Section Uncertainties

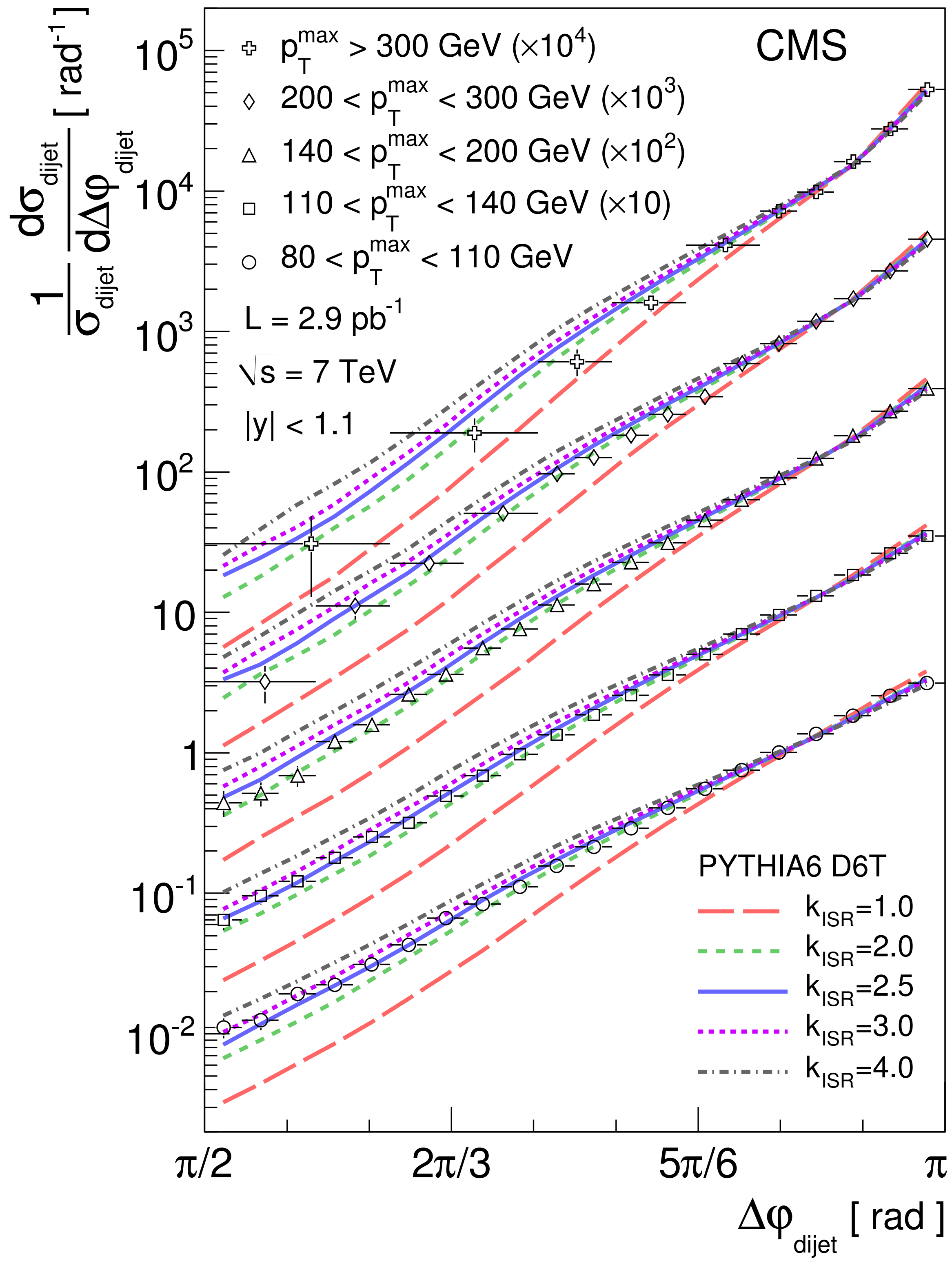








Dijet Azimuthal Decorrelations (ISR)



Hadronic Event Shapes

$90 < p_{T,max} < 125$ GeV | $125 < p_{T,max} < 200$ GeV | $p_{T,max} > 200$ GeV