Hard QCD Results from CMS

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Physics at LHC 2011
5 - 11 June 2011, Perugia, Italy

Outline

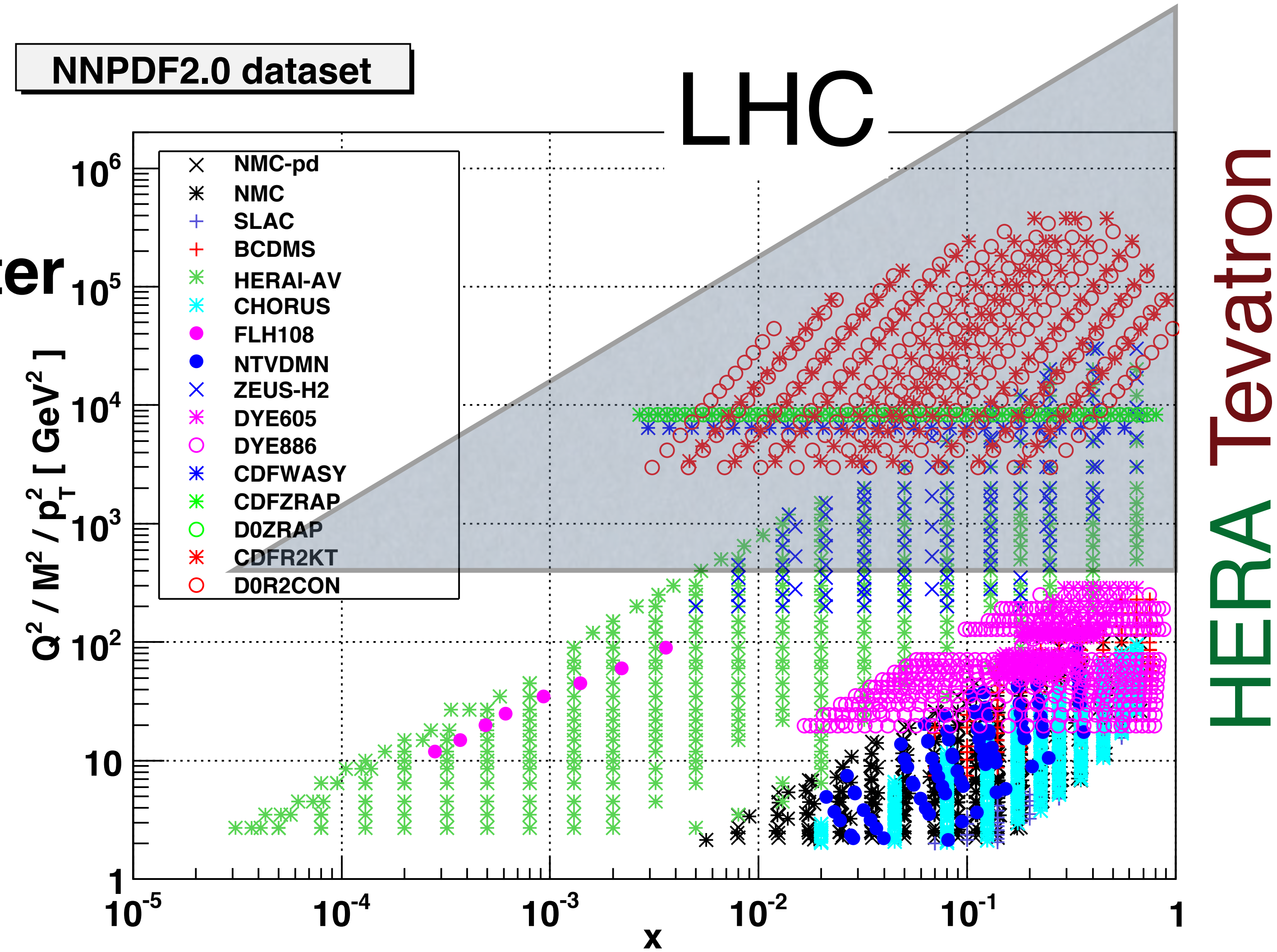
- ✦ **Motivation & Introduction**
- ✦ **Cross-section measurements**
  - inclusive jet production
  - dijet production
  - inclusive isolated photon production
- ✦ **Dijet angular distributions**
- ✦ **Multijet properties**
  - dijet azimuthal decorrelations
  - hadronic event shapes
  - 3j/2j ratio
- ✦ **Summary**

Hard QCD at LHC: Motivation

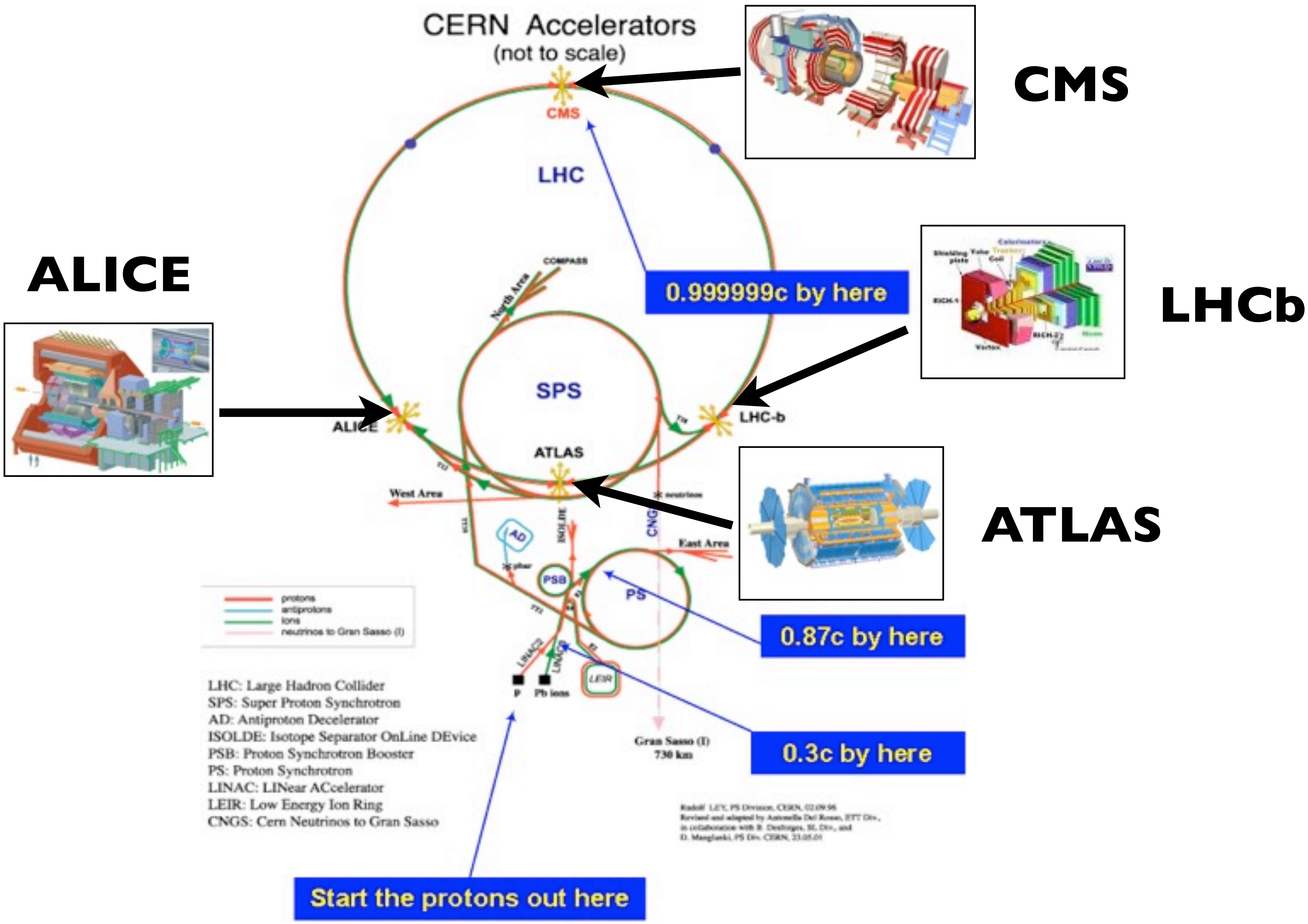
✦ **QCD is dominant at LHC**
- it affects all measurements, either as signal or as background
- needs to be understood

✦ **LHC pp collisions @ 7 TeV (and later @ 14 TeV) give access to unexplored phase space**
- at lower x and higher Q
- pQCD in the multi-TeV region

✦ **The precise knowledge of QCD is important for new-physics searches**
- PDF uncertainties are important for the Higgs hunt
- multijet production is relevant for SUSY-like searches



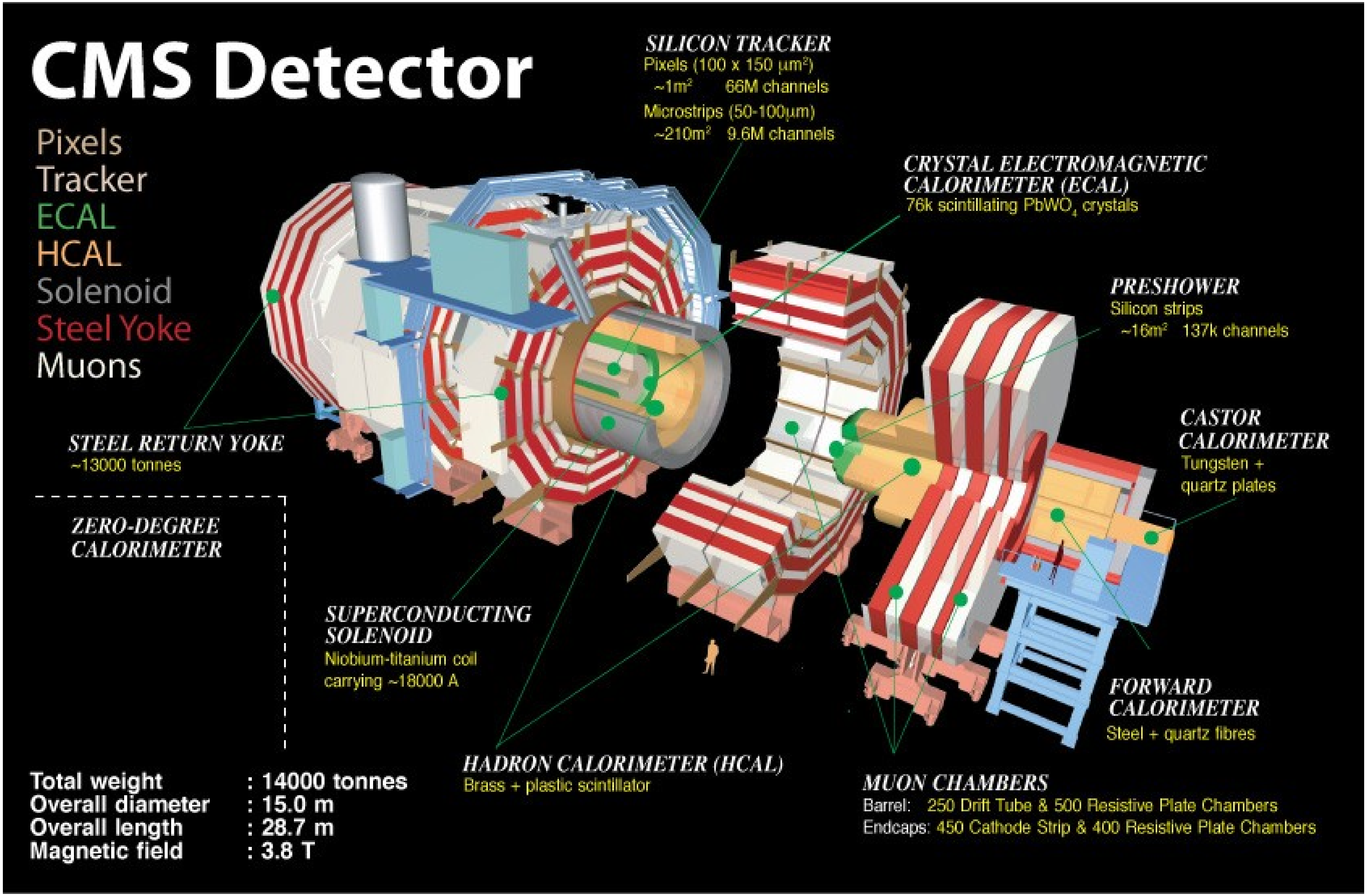
The LHC Complex



2010: proton-proton collisions @ 7TeV

Congratulations to the machine people for the remarkable LHC performance

The CMS Detector



Introduction: the 2010 Objectives

✦ **CMS has completed a rich QCD program with jets & photons during the first year of the LHC operation:**

- cross-section measurements
- dijet & multijet properties

✦ **The 2010 program was defined according to:**

- the available integrated luminosity
- the level of understanding of the jet & photon objects
- the needs of the experiment
- the interest of the scientific community

✦ **Objectives:**

- confront the pQCD calculations at 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**

Introduction: 2010 Kinematic Reach

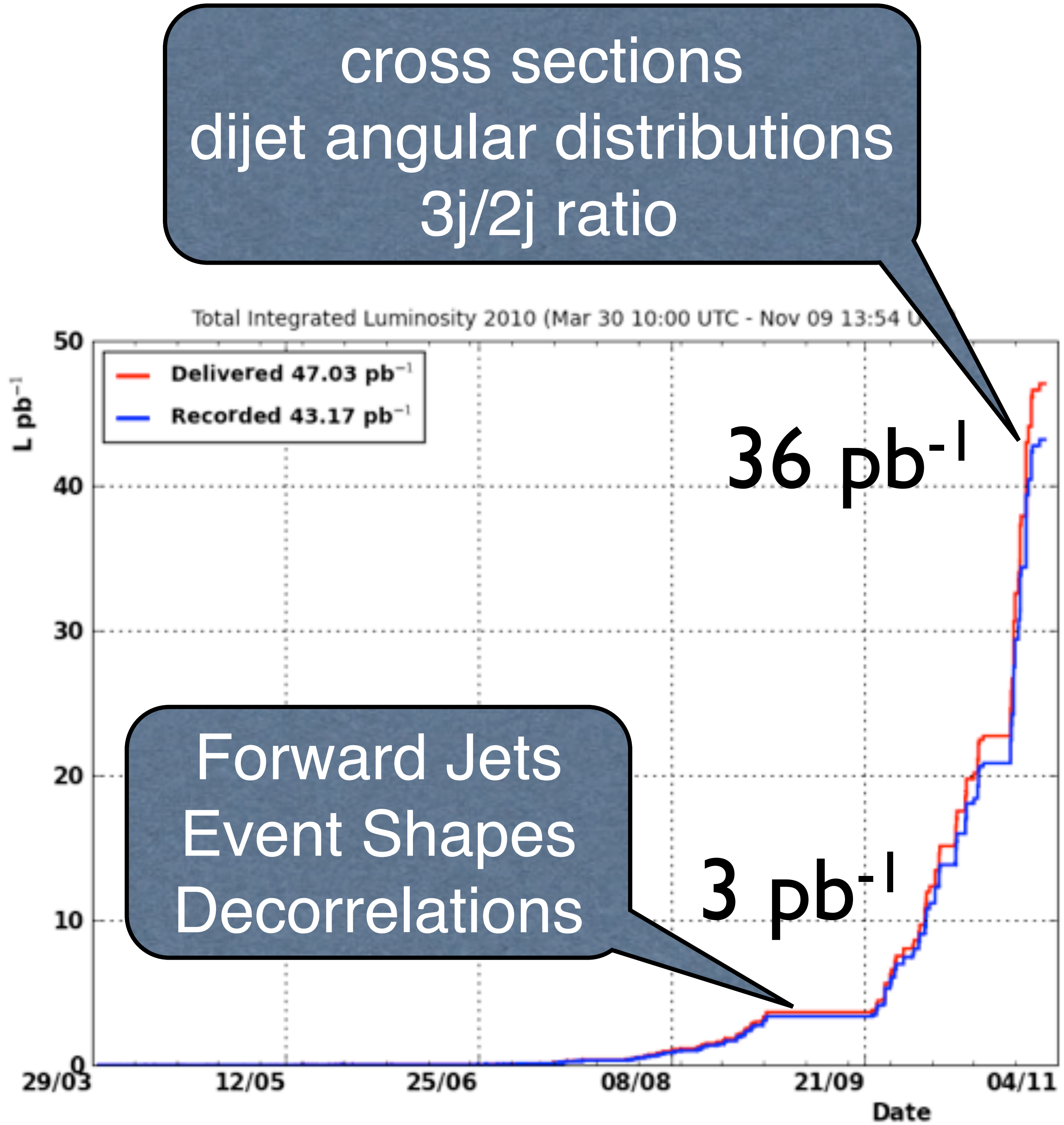
✦ **Available integrated luminosity for QCD measurements: 36 pb^{-1}**
- out of 47 pb^{-1} delivered and 43 pb^{-1} recorded

✦ **Jet p_T (|y| < 4.7)**
- central jets: **18 GeV → 1.1 TeV**
- forward jets: **35 GeV → 150 GeV**

✦ **Photon E_T (|η| < 2.5)**
- central photons: **20 GeV → 400 GeV**

✦ **Dijet invariant mass (|y| < 2.5)**
- **0.16 → 3.5 TeV**

✦ **Multijet H_T**
- **0.3 → 2.5 TeV**



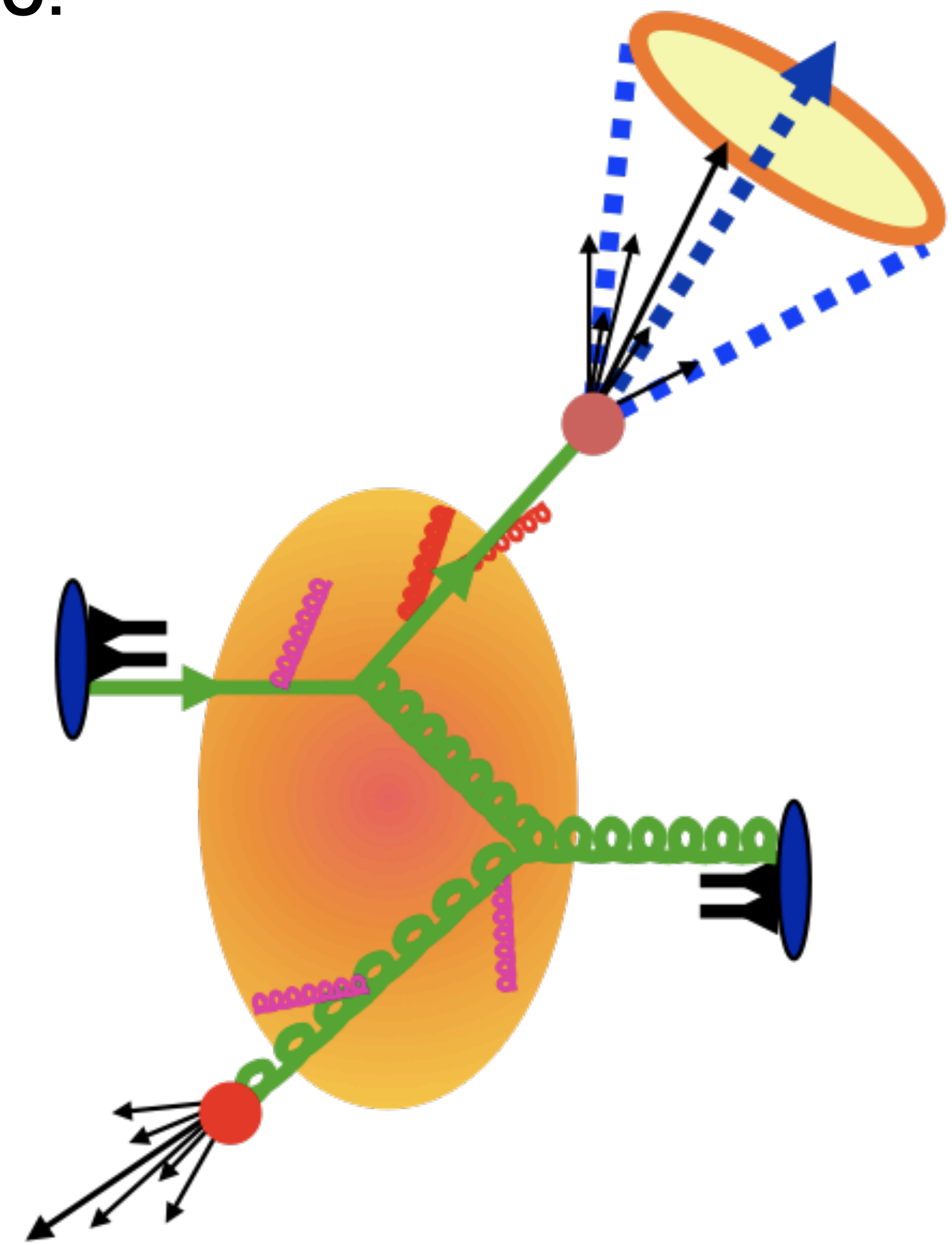
Ingredients of the Theory Predictions

✦ **Perturbative QCD calculations @ NLO:**
- using NLOJet++/JETPHOX
- extensive use of *fastNLO* package

✦ **Parton distribution functions (PDF):**
- CT10
- MSTW2008
- NNPDF2.0
- HERAPDF1.0
- ABKM09

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

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



Non-Perturbative Corrections

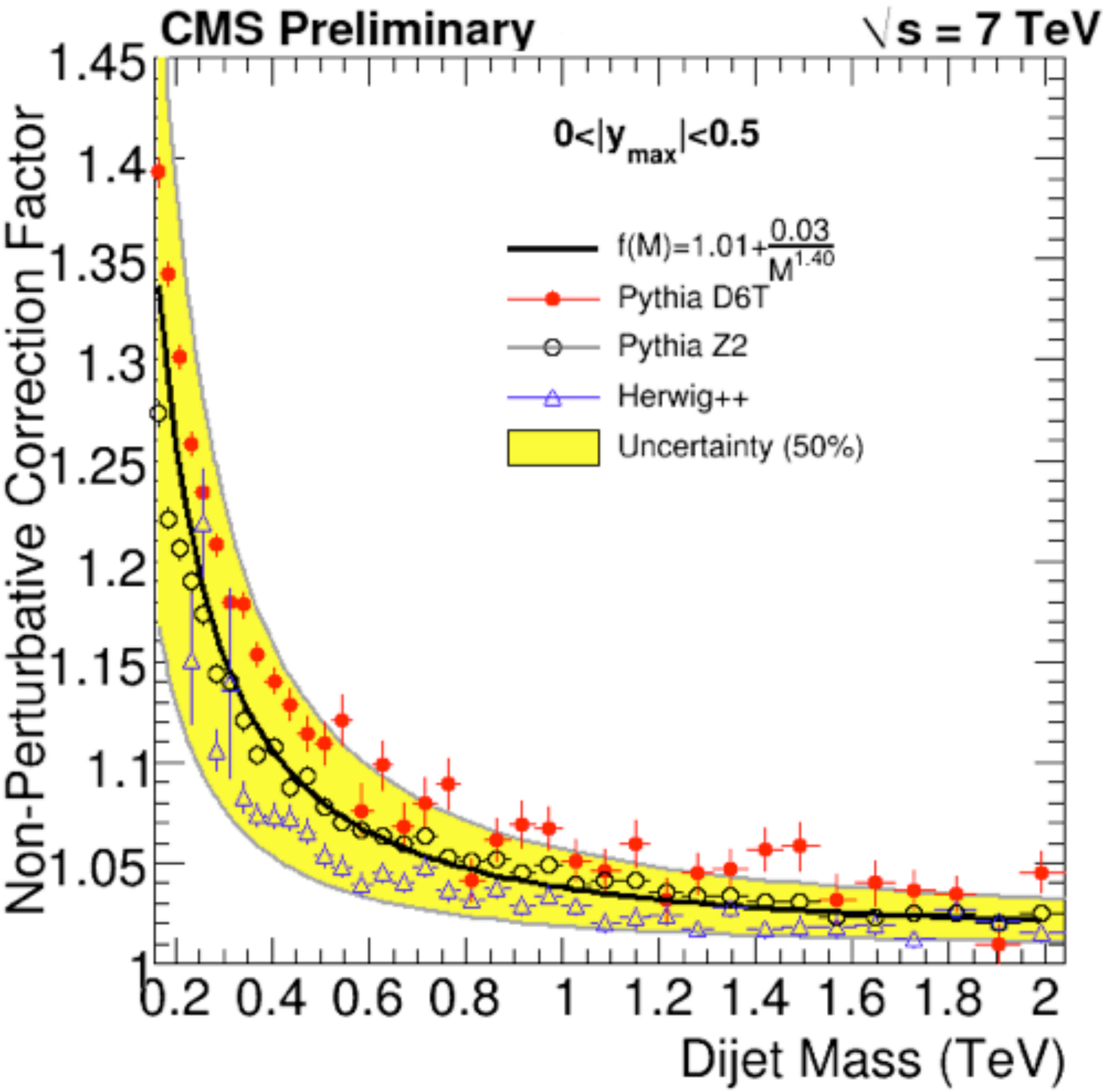
✦ **A correction to pQCD is needed to "translate" the parton-level observables to the particle level**

✦ **Account for effects that cannot be calculated with pQCD**

- multi-parton interactions
- hadronization

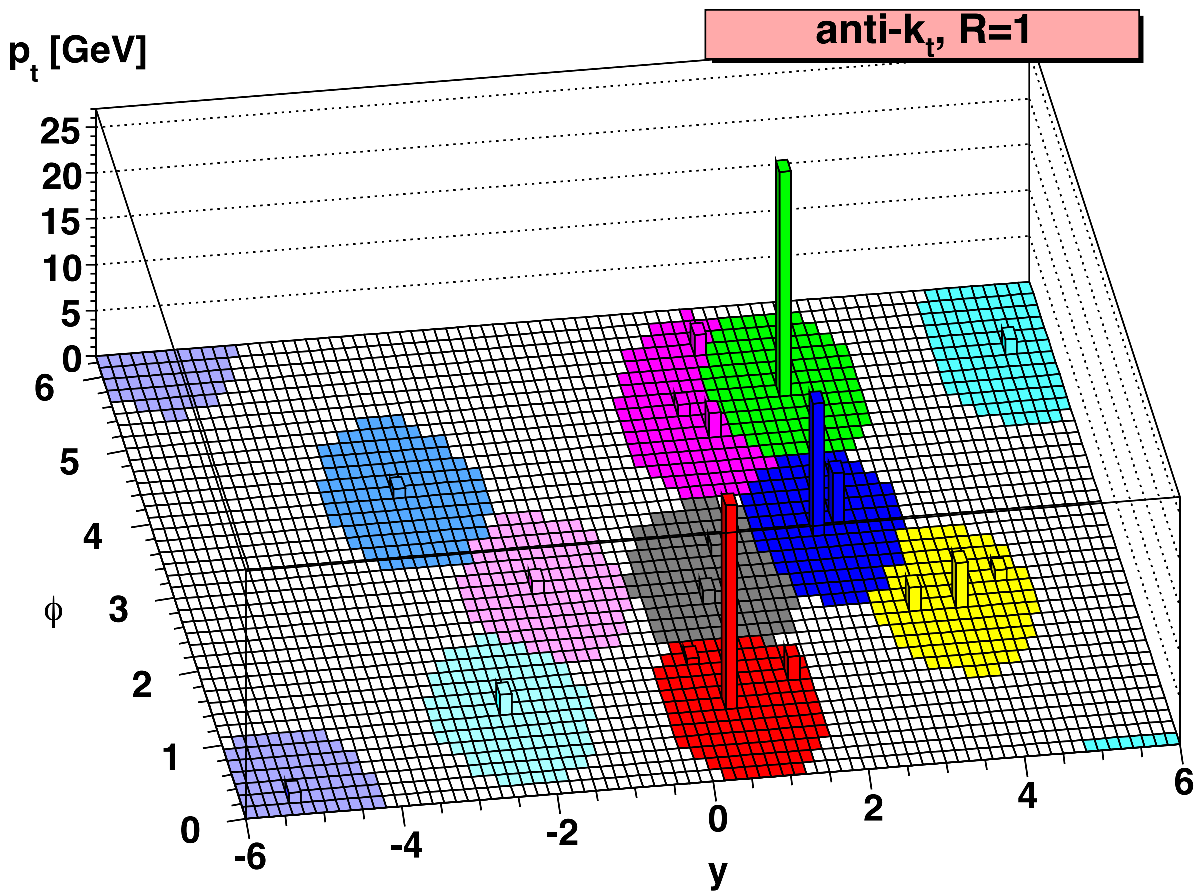
✦ **The non-perturbative correction is estimated by using different MC generators**

- turn "on" and "off" the MPI and hadronization
- most measurements use the average between PYTHIA6 and Herwig++



Jet Clustering

✦ **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

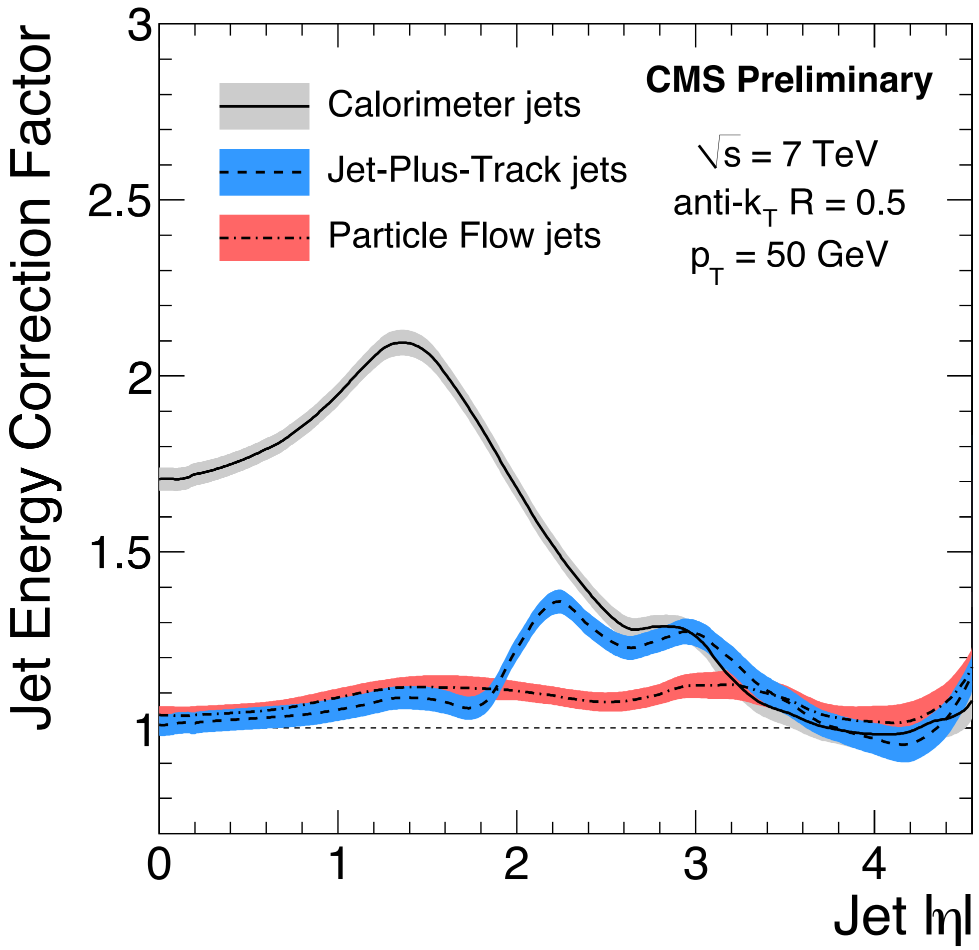


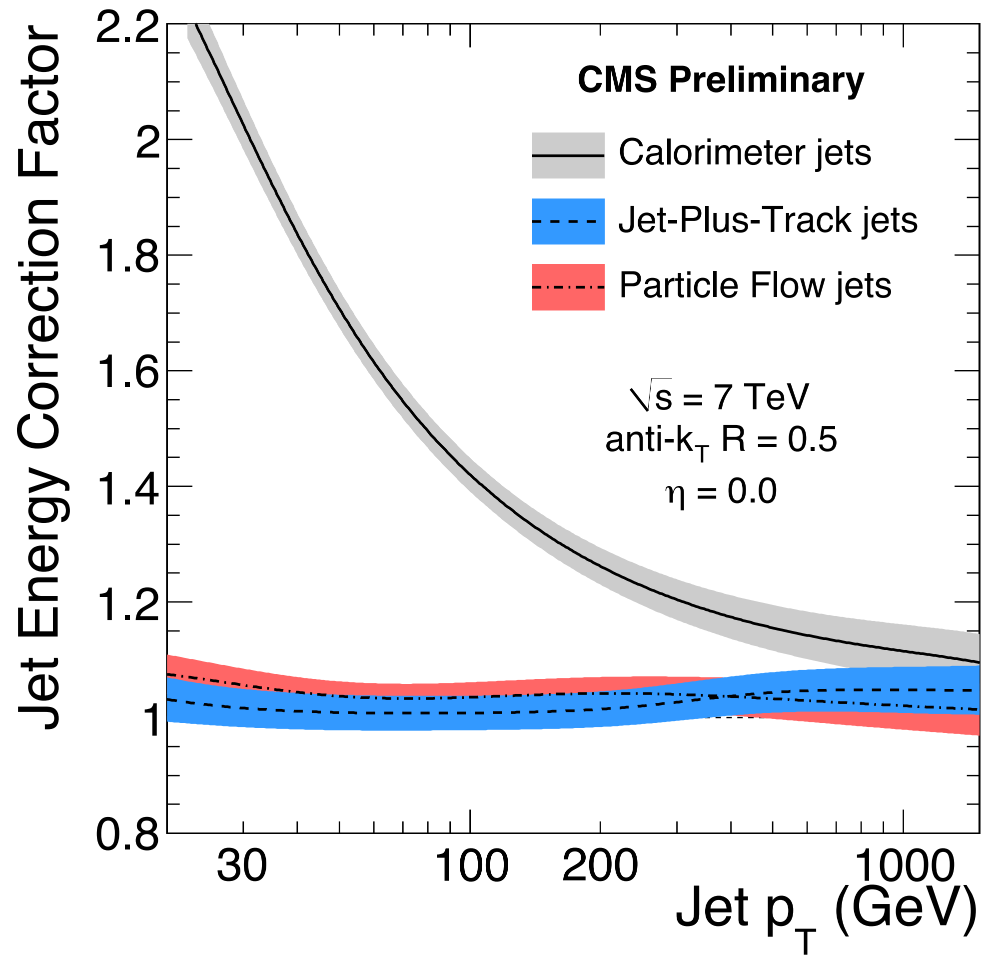
$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right) \frac{\Delta R_{ij}^2}{R^2}$$
$$d_{iB} = p_{Ti}^{-2}$$
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

✦ **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**

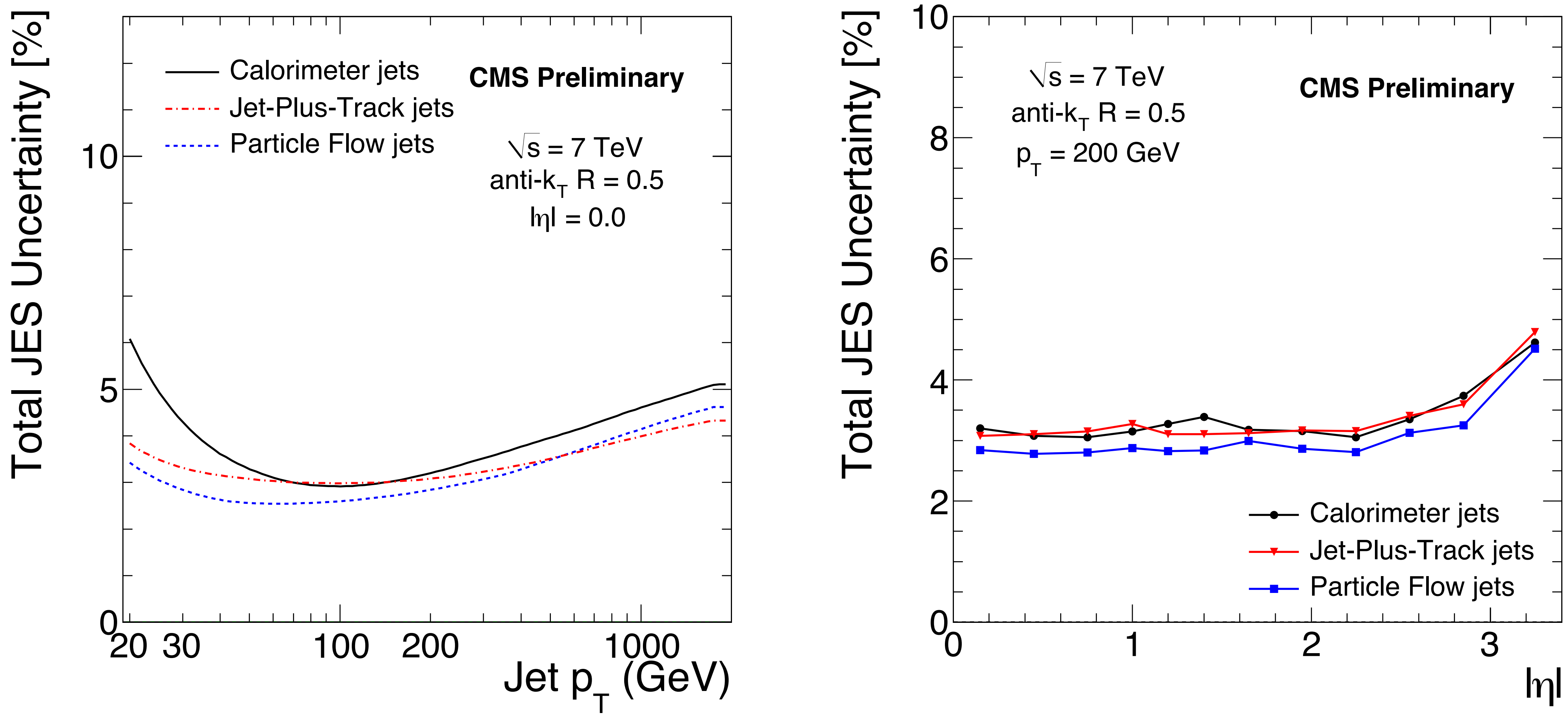
Jet Energy Calibration





- ✦ **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 calorimetric system
- ✦ **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**

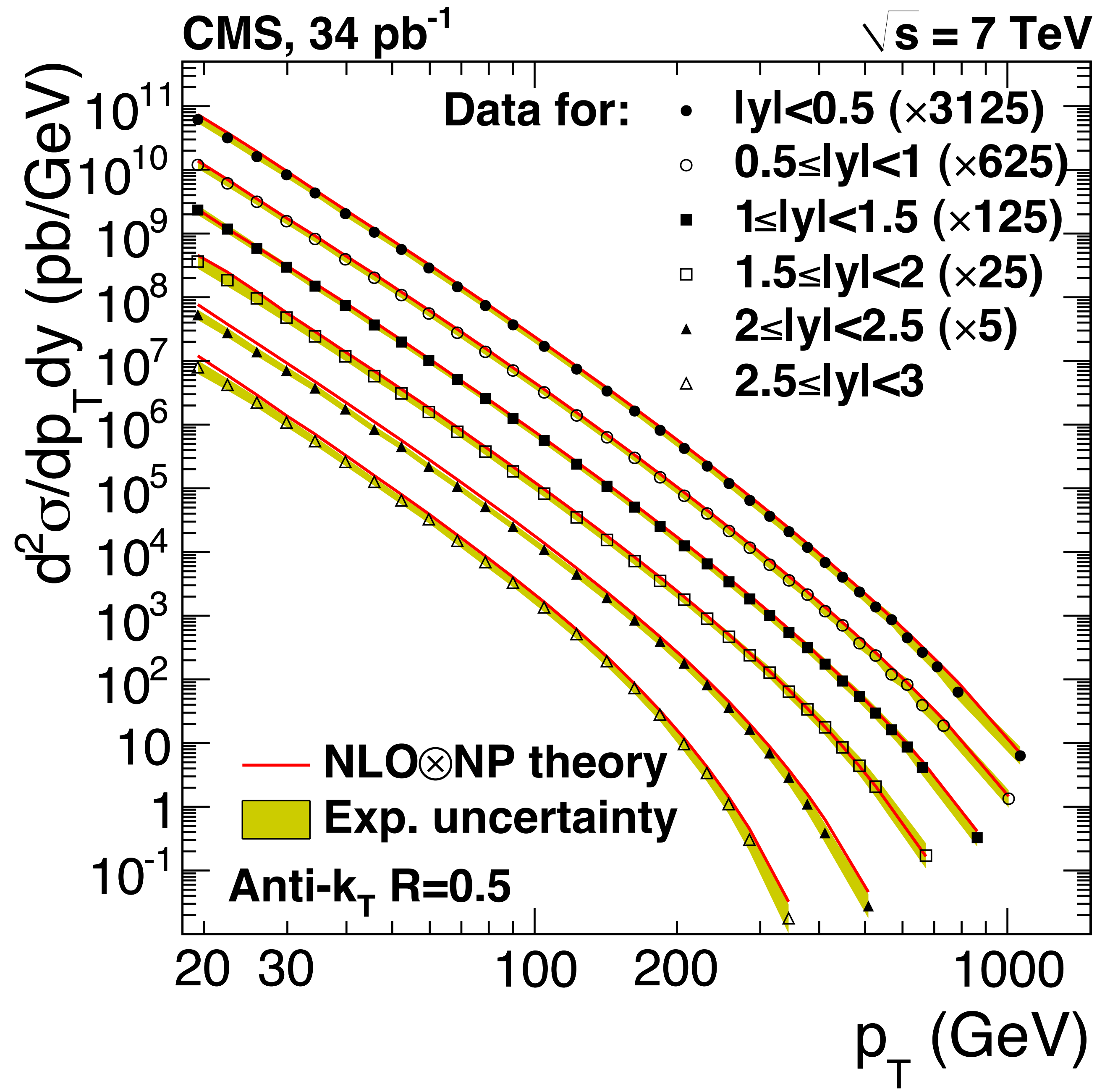
- using anti-k_T PF jets with R=0.5
- 34 pb^{-1}
- p_T range from 18 GeV to 1.1 TeV
- 6 rapidity bins, up to |y|=3.0 (the forward region 3.0 < |y| < 5.0 is covered by another, dedicated measurement)

✦ **Experimental Uncertainties**

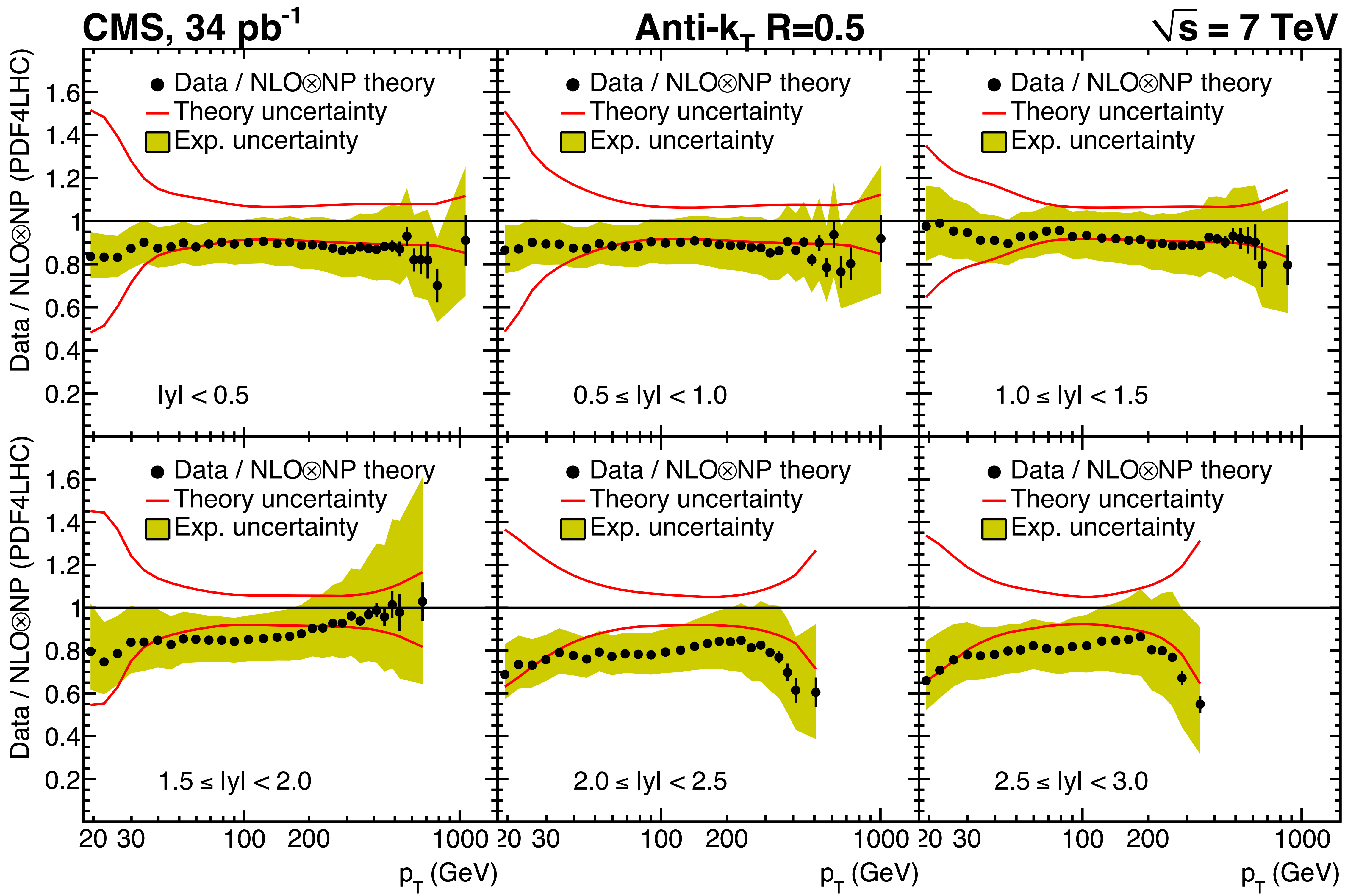
- dominated by the JES

✦ **Theoretical Uncertainties**

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

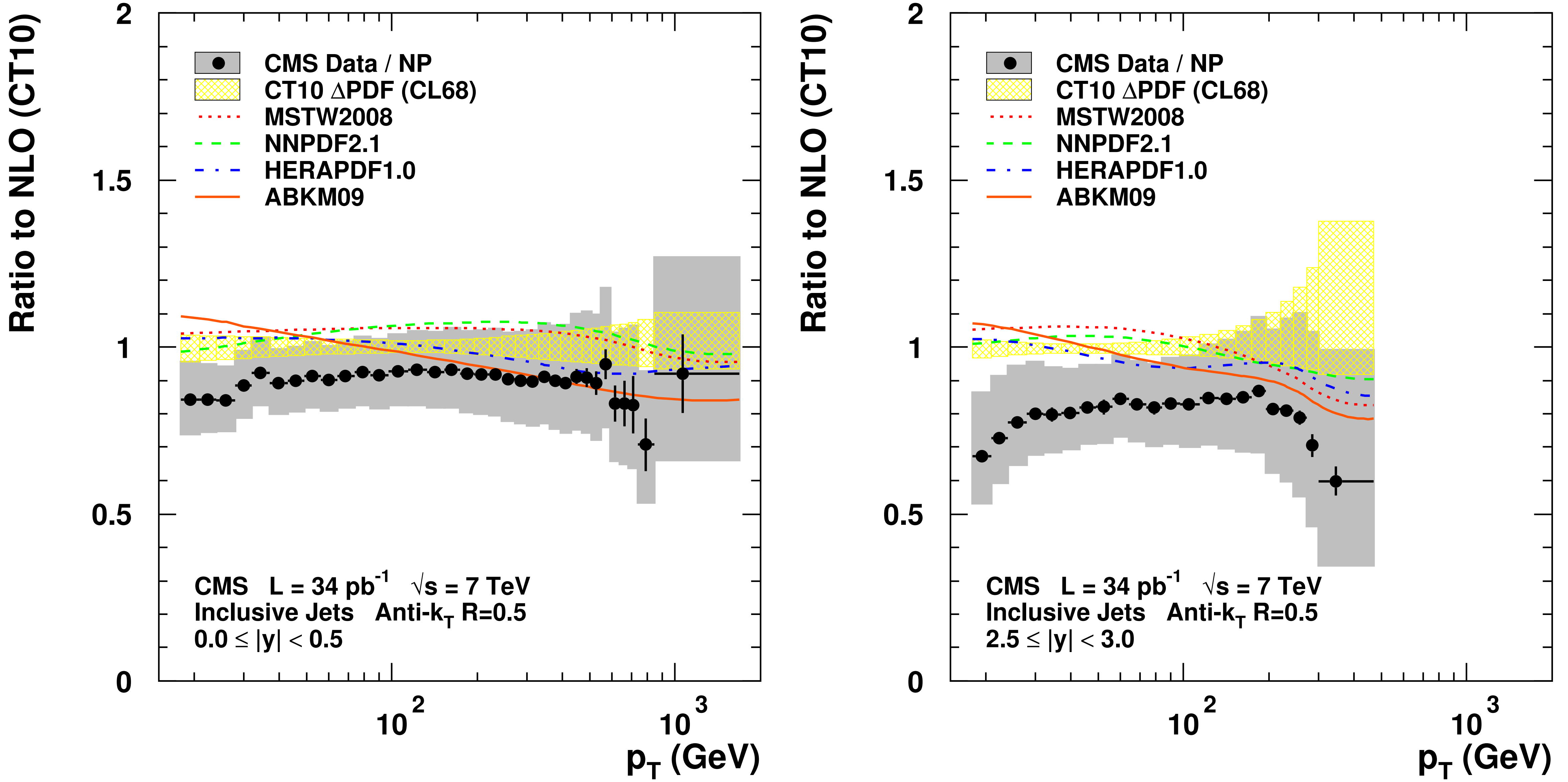


Inclusive Jet Production (II)



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

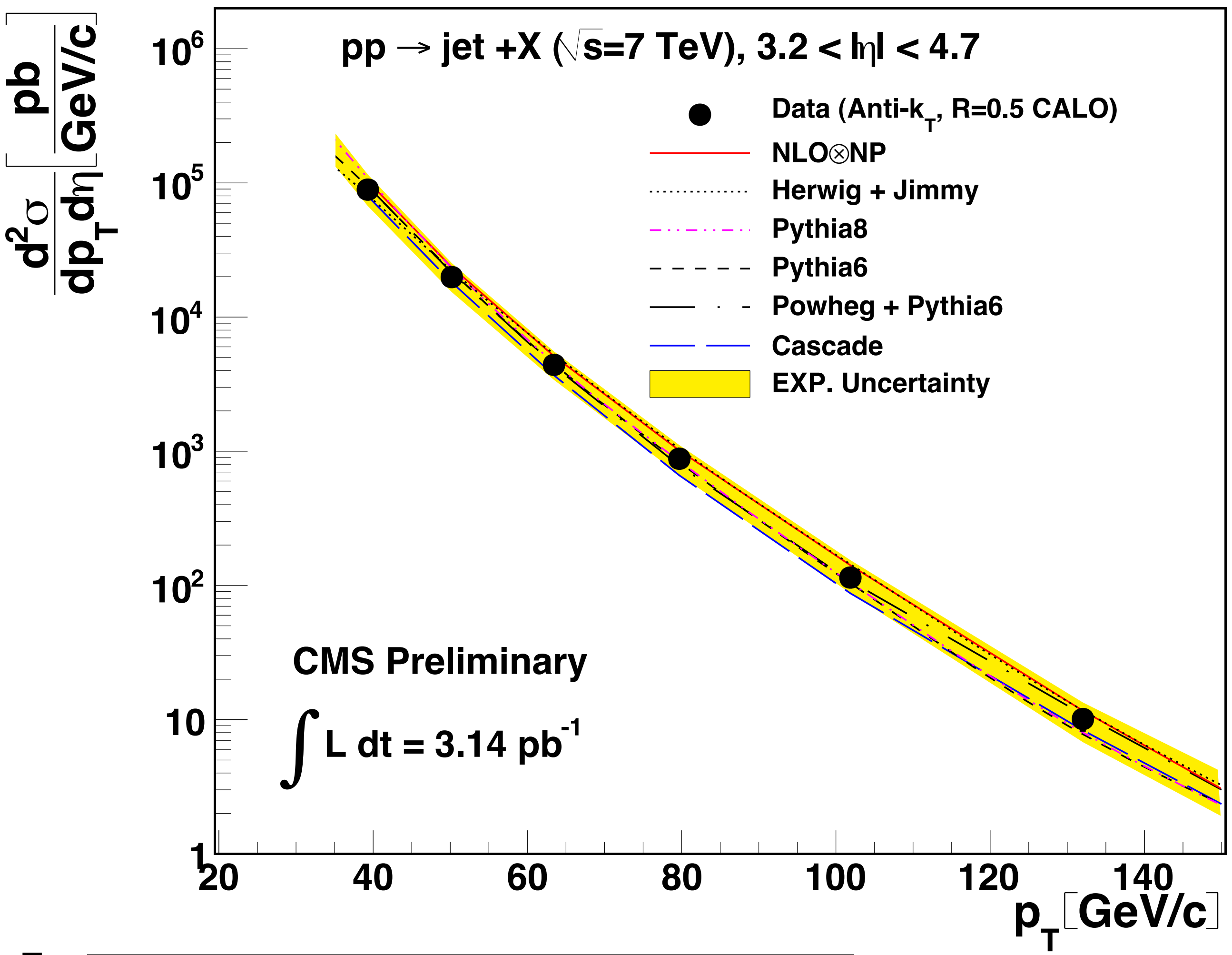
Inclusive Jet Production (PDF Comparison)

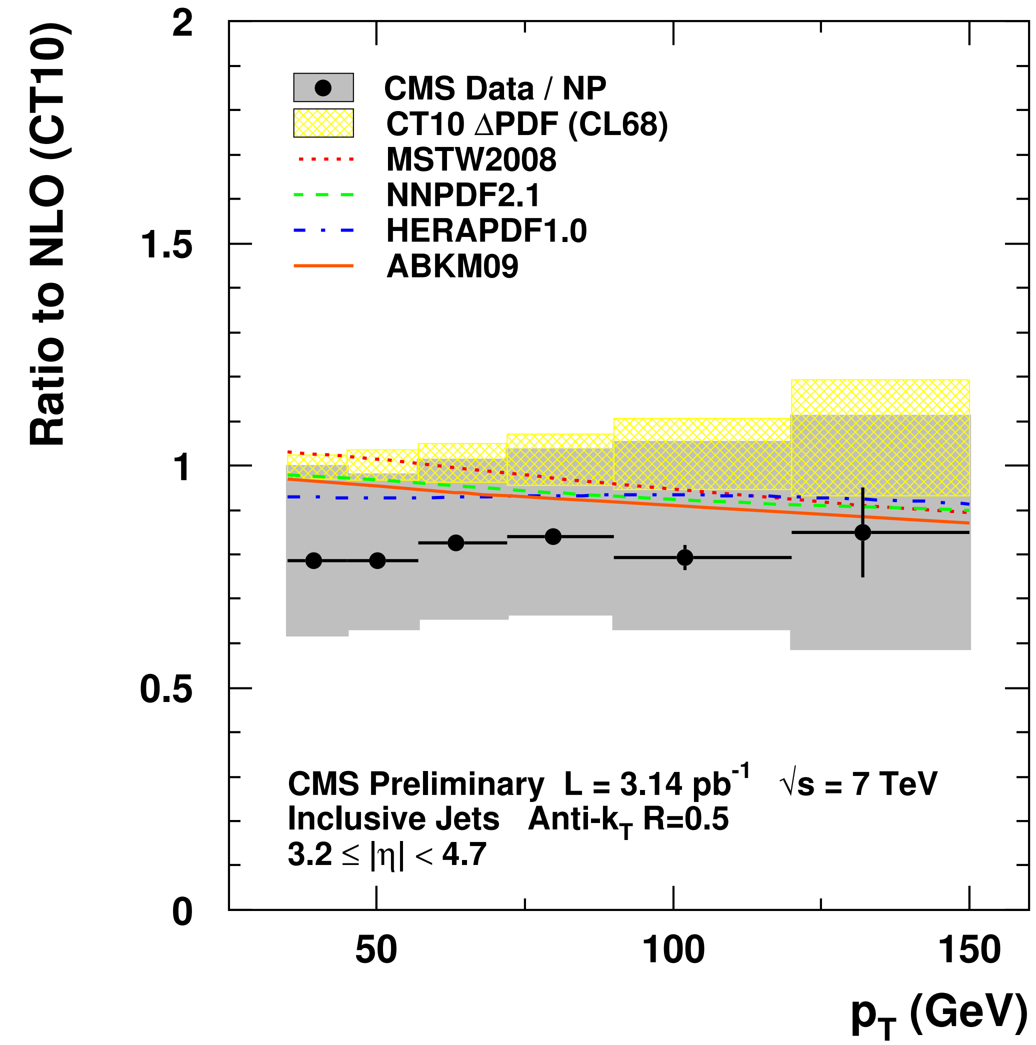


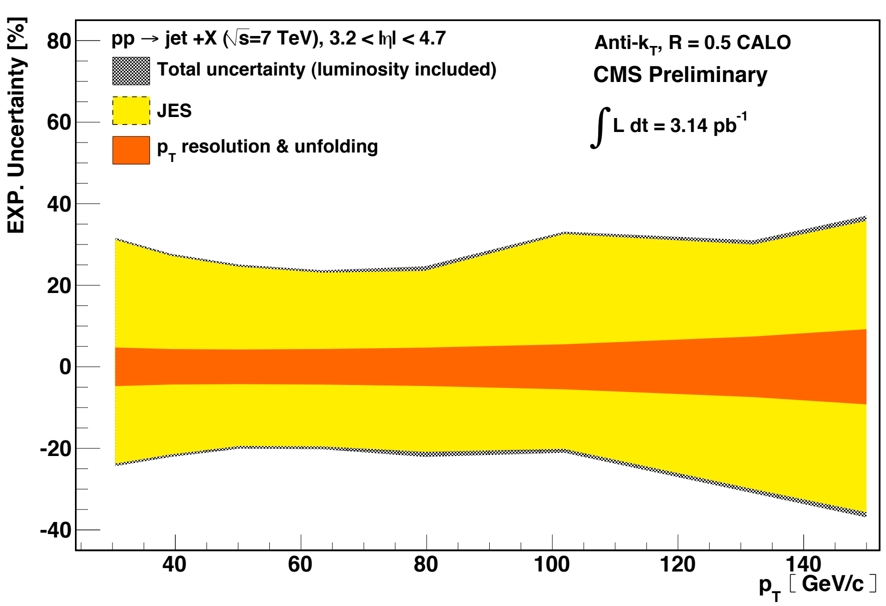
✦ **comparison to various PDF sets**

- compatibility with all PDFs in the central rapidity bins
- better agreement at higher jet p_T (> 100 GeV) but NP correction uncertainties large at low p_T
- the agreement slightly worsens in the outer rapidity bins

Forward Jet Production







✦ **inclusive forward-jet production cross section**

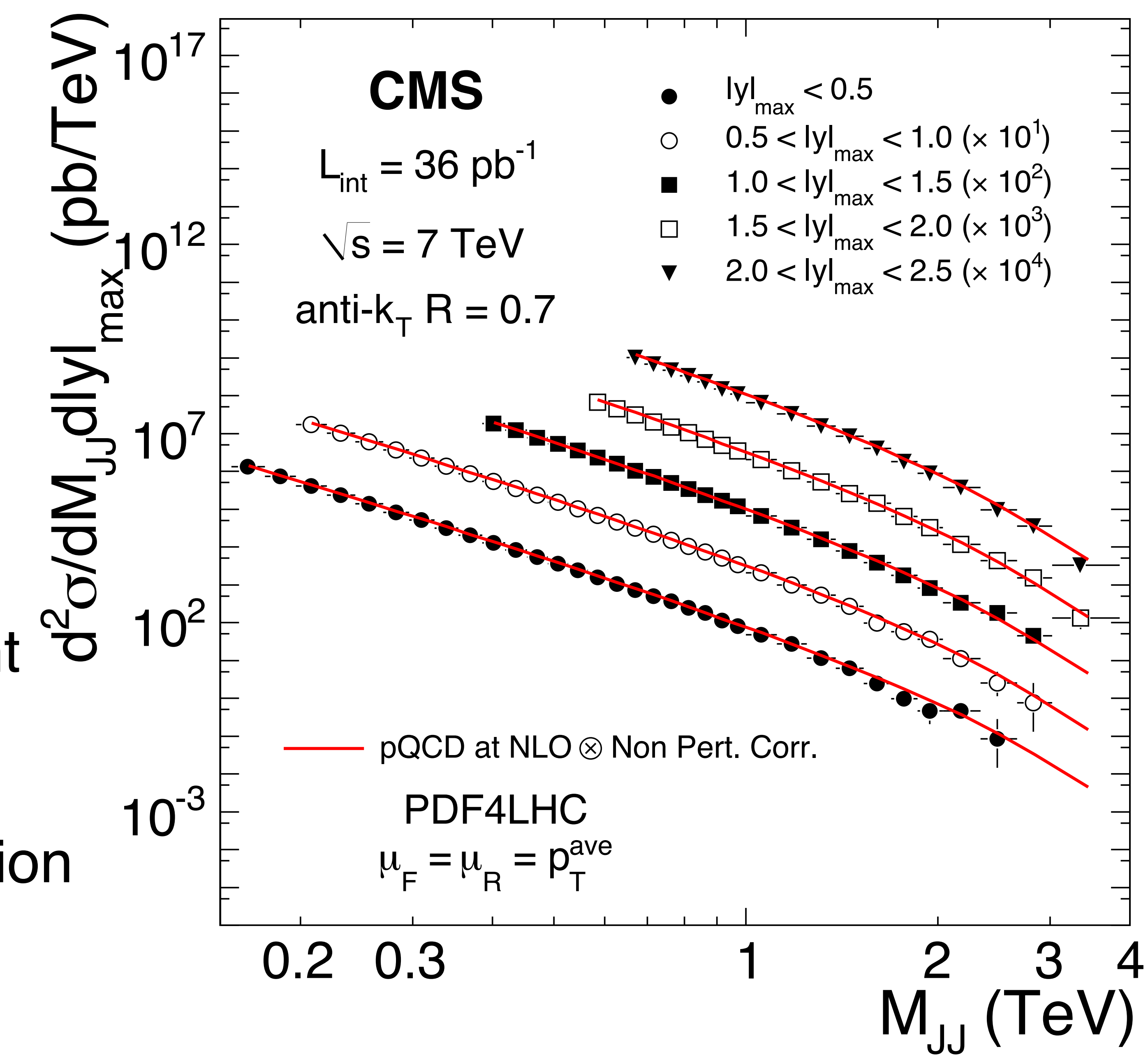
- using calorimeter jets
- measurement dominated by the JES uncertainty
- good agreement with the MC predictions
- compatible with the NLO prediction

Details in the talk by A. Flossdorf (*"Measurements of forward energy flow and forward jet production with CMS"*)

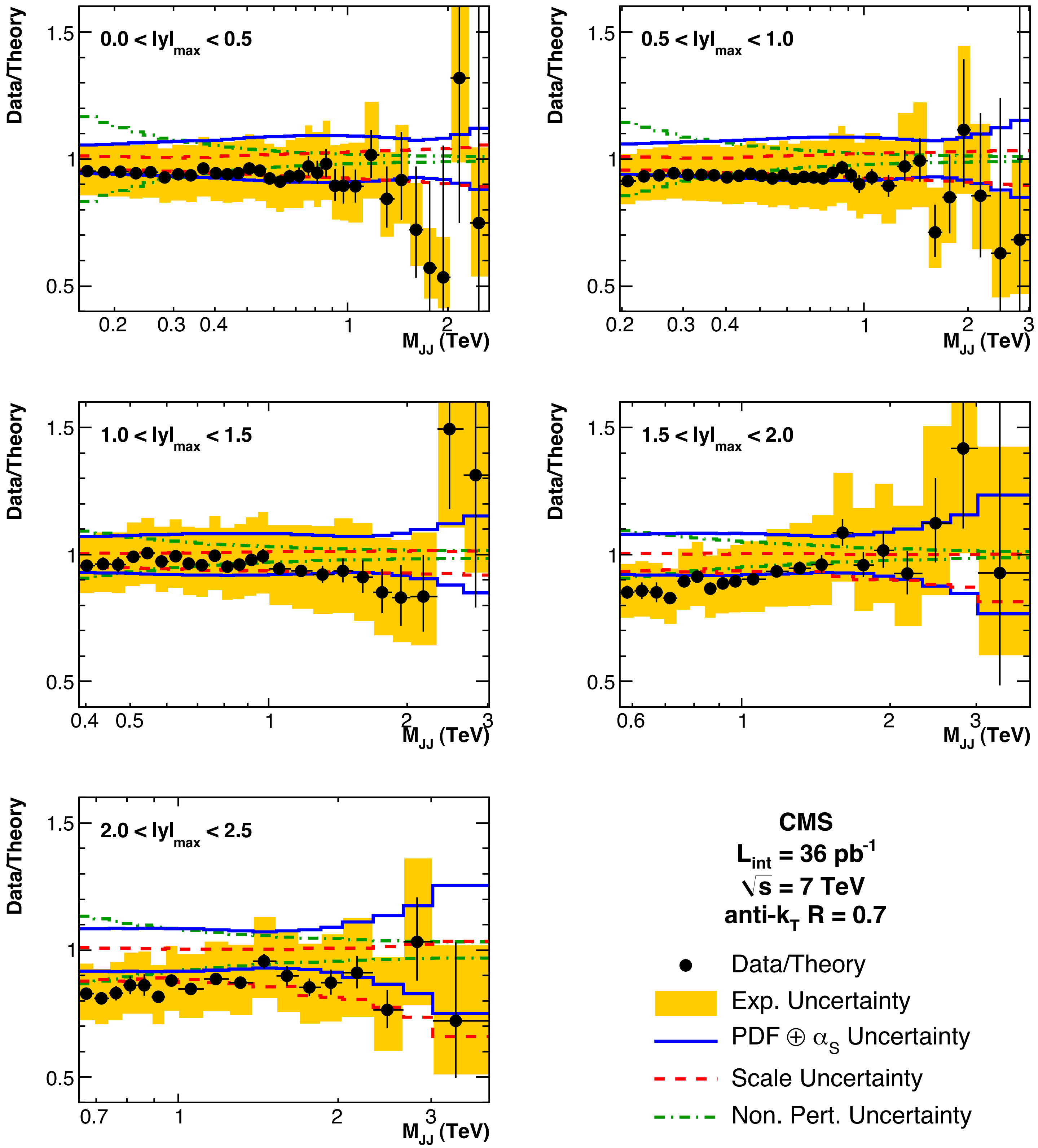
Dijet Production (I)

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

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



Dijet Production (II)

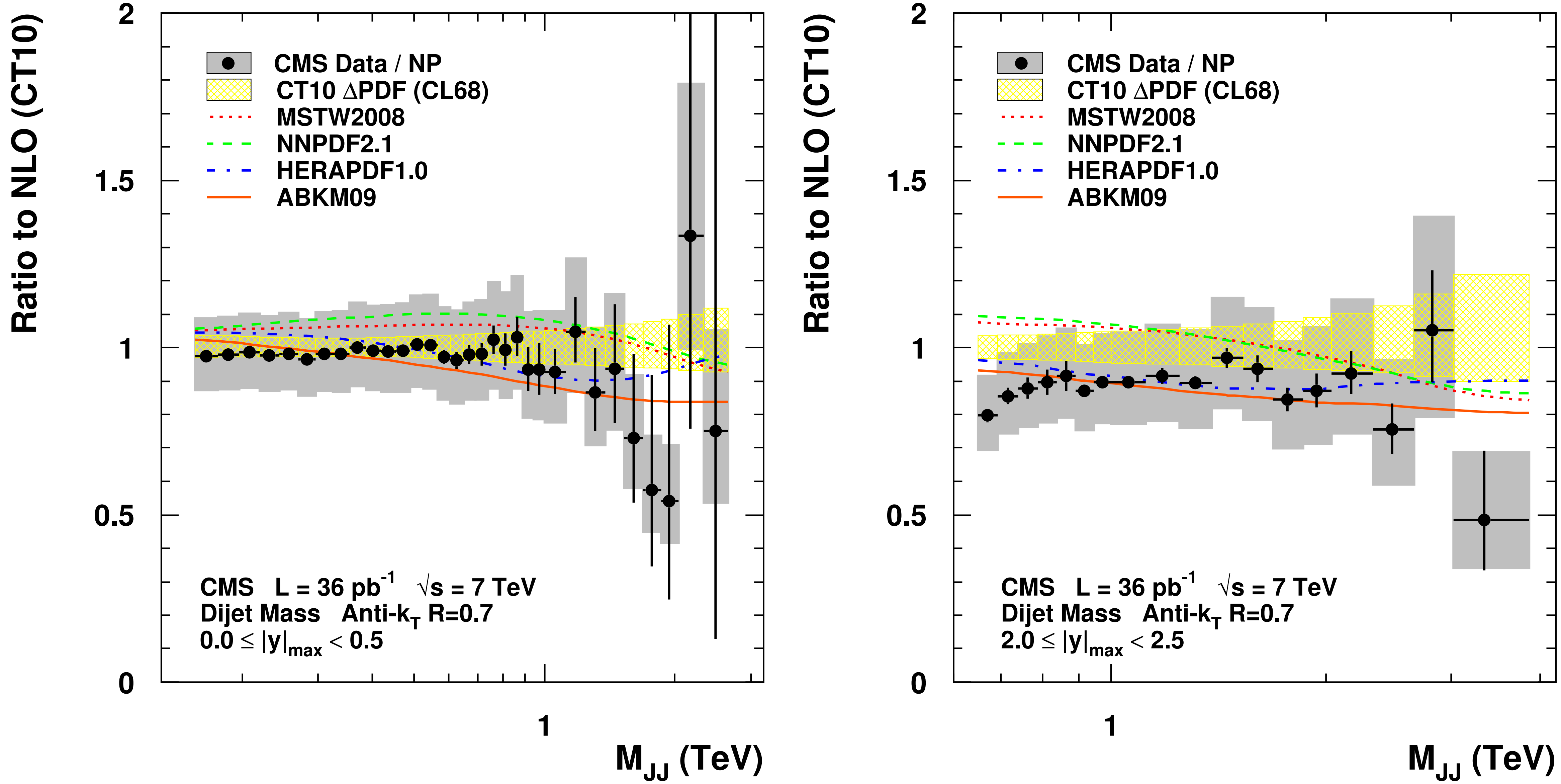


✦ **Data and theory are compatible in the entire phase-space of the measurement**

✦ **Similar trend with the inclusive jets**

- but not directly comparable due to the different jet size

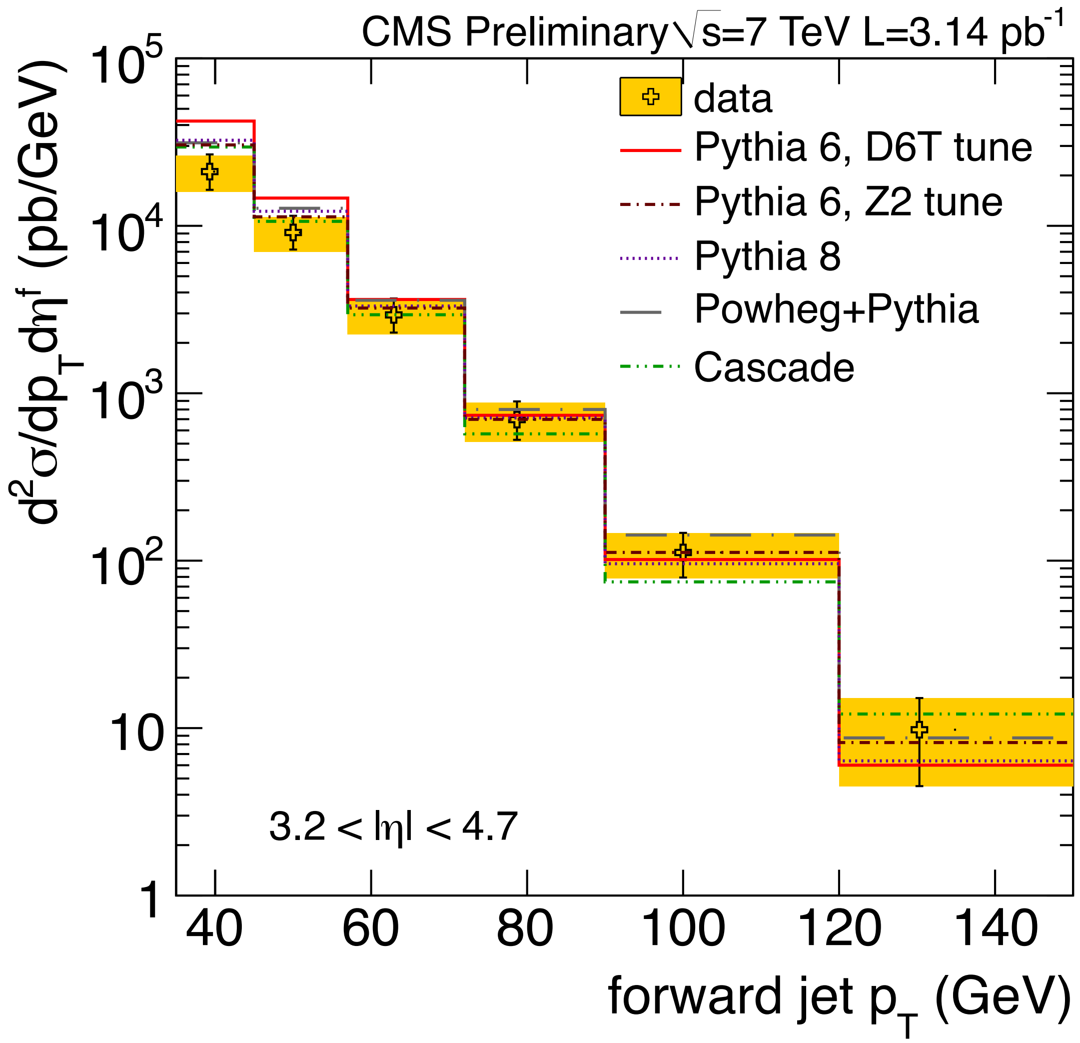
Dijet Production (PDF Comparison)

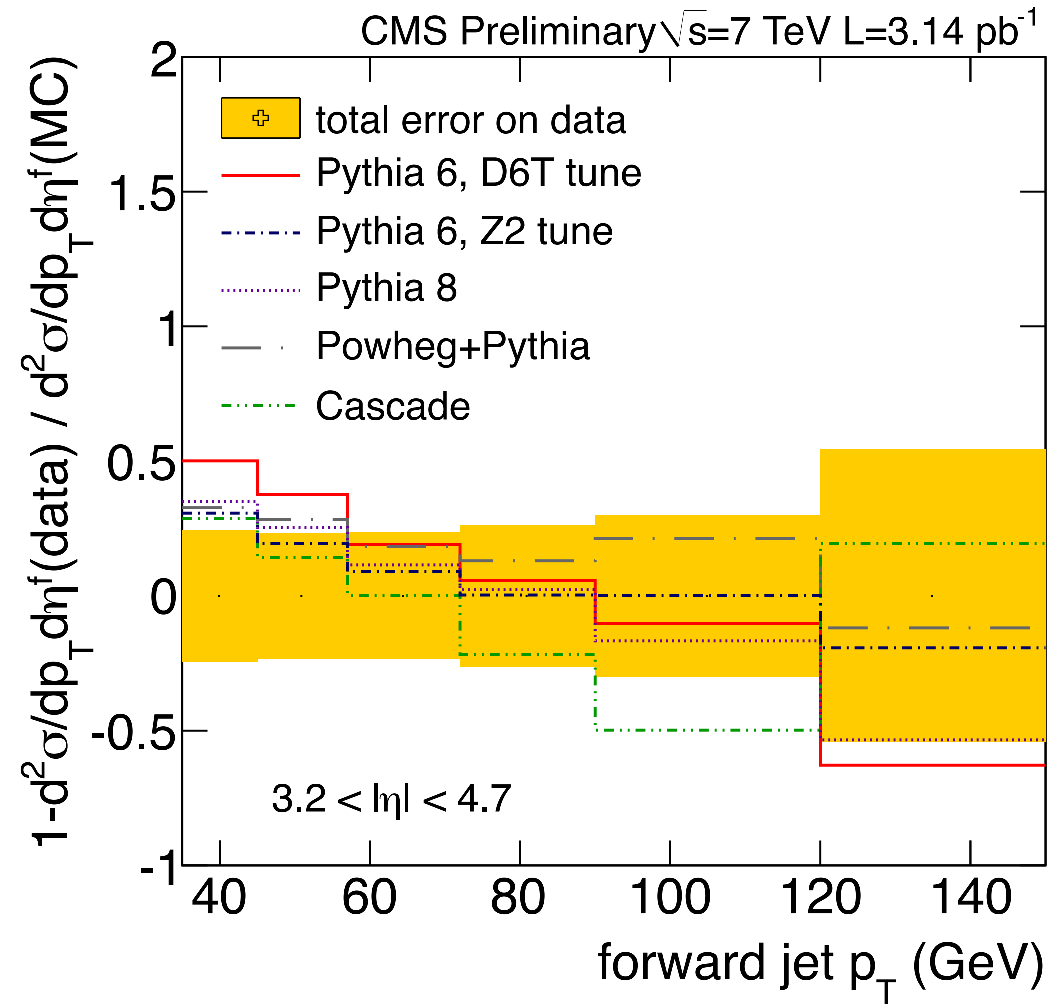


✦ **comparison to various PDF sets**

- good agreement with all PDFs in the central rapidity bins
- agreement with CT10, MSTW2008, NNPDF2.1 worsens in the outer rapidity bins but improves for HERAPDF1.0 and ABKM09

Dijet Production (Central-Forward)

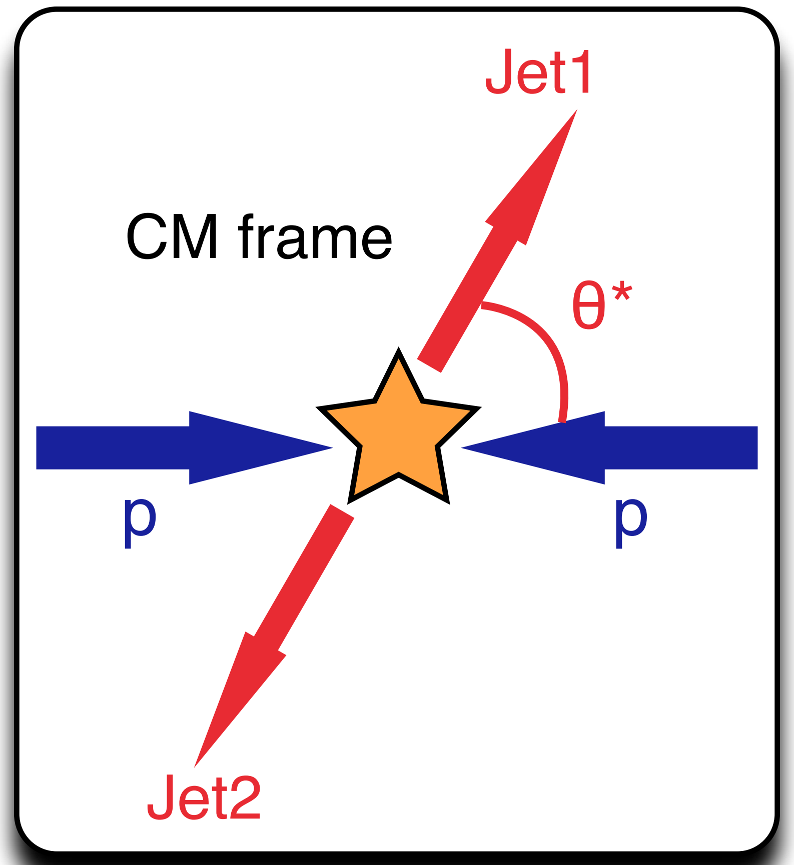


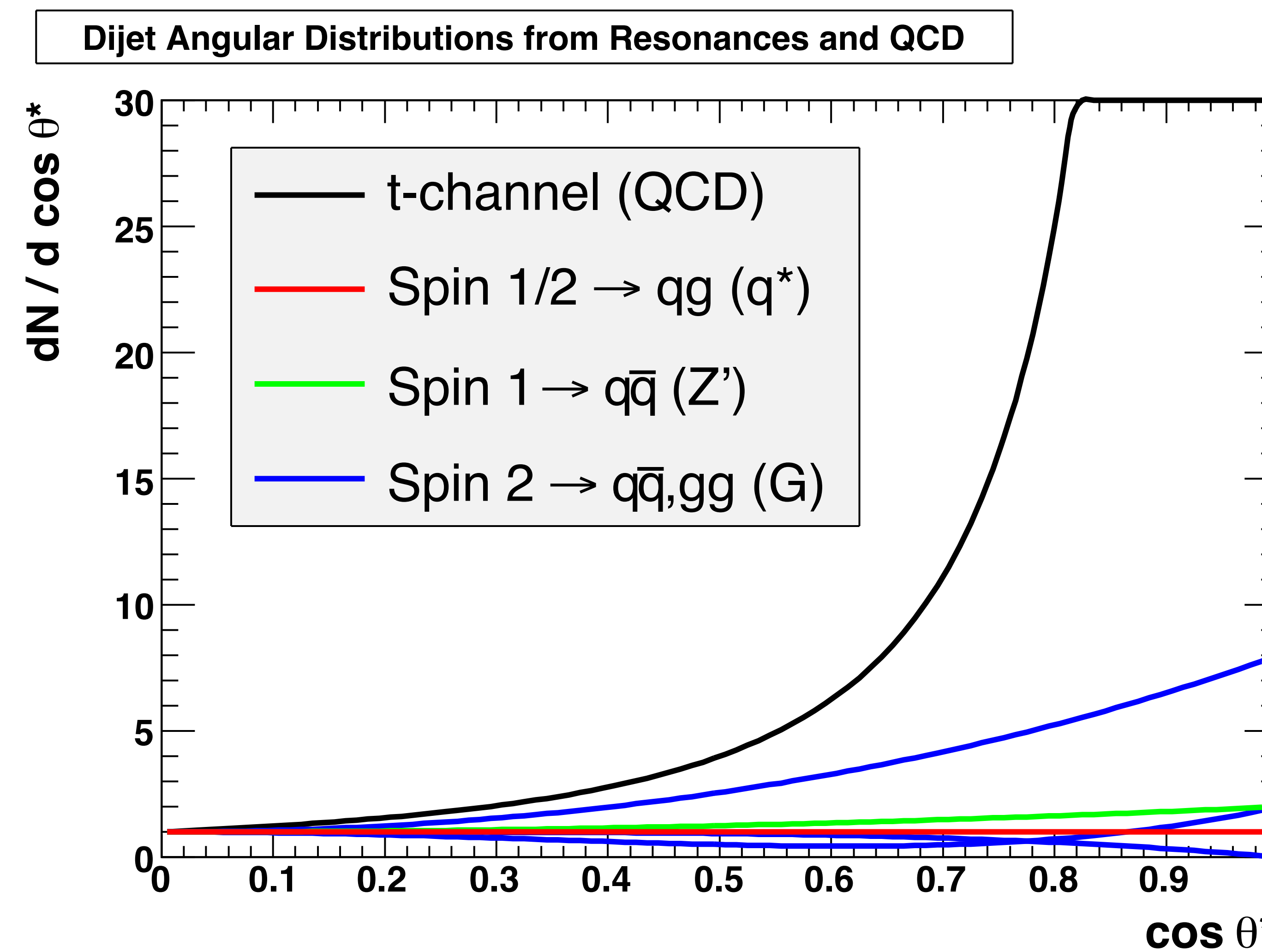


- **dijet cross section with one central ($|\eta|<2.8$) and one forward ($3.2<|\eta|<4.7$) jet**
  - forward jet production essential for understanding the VBF Higgs backgrounds
  - important ingredient for vector-boson scattering
- **experimental uncertainty dominated by JES**
- **comparisons to various MC models**
  - discrepancies observed, either in the shape, or the overall normalization
  - no model describes the data fully
  - room for improvement

Details in the talk by A. Flossdorf (*"Measurements of forward energy flow and forward jet production with CMS"*)

Dijet Angular Distributions (I)





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

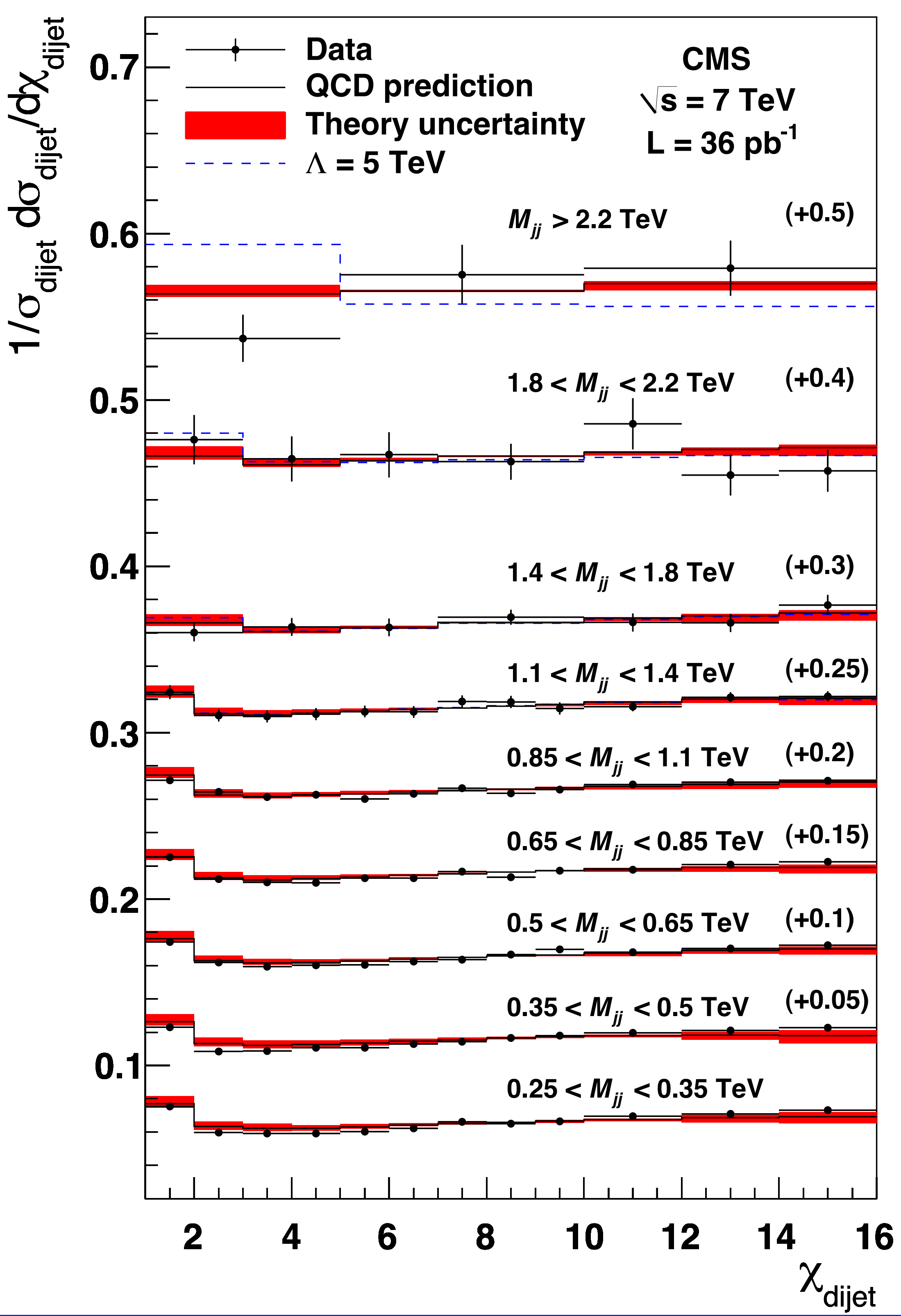
- parton-parton scattering in QCD is *t-channel* dominated (Rutherford scattering at small angles)

✦ **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)

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



✦ **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

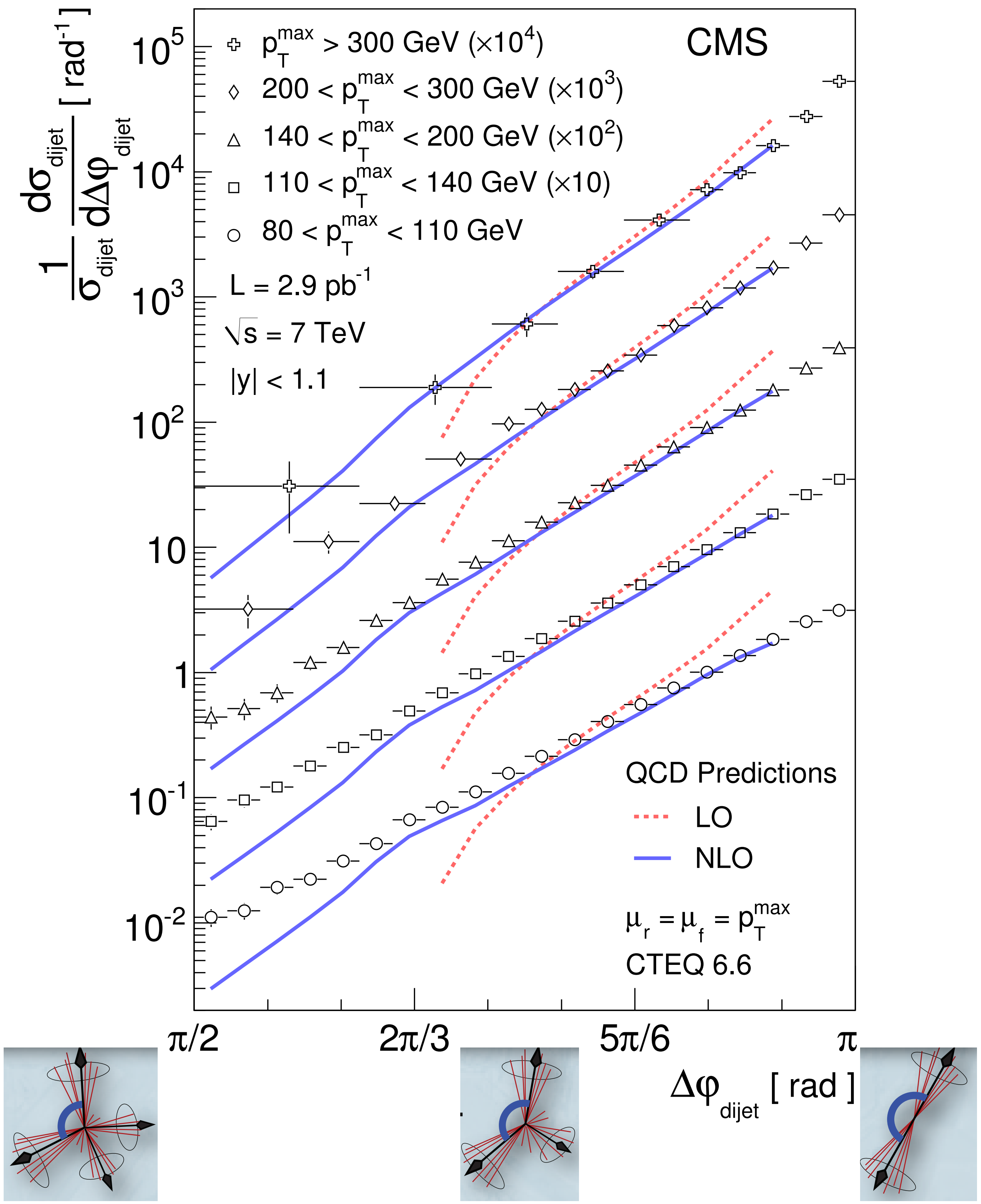
✦ **Experimental uncertainties**

- cancellation of many uncertainties (absolute JES, luminosity)
- relative JES vs y, resolution

✦ **Theoretical 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)



✦ **Normalized dijet cross section, as a function of $\Delta\phi$**

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

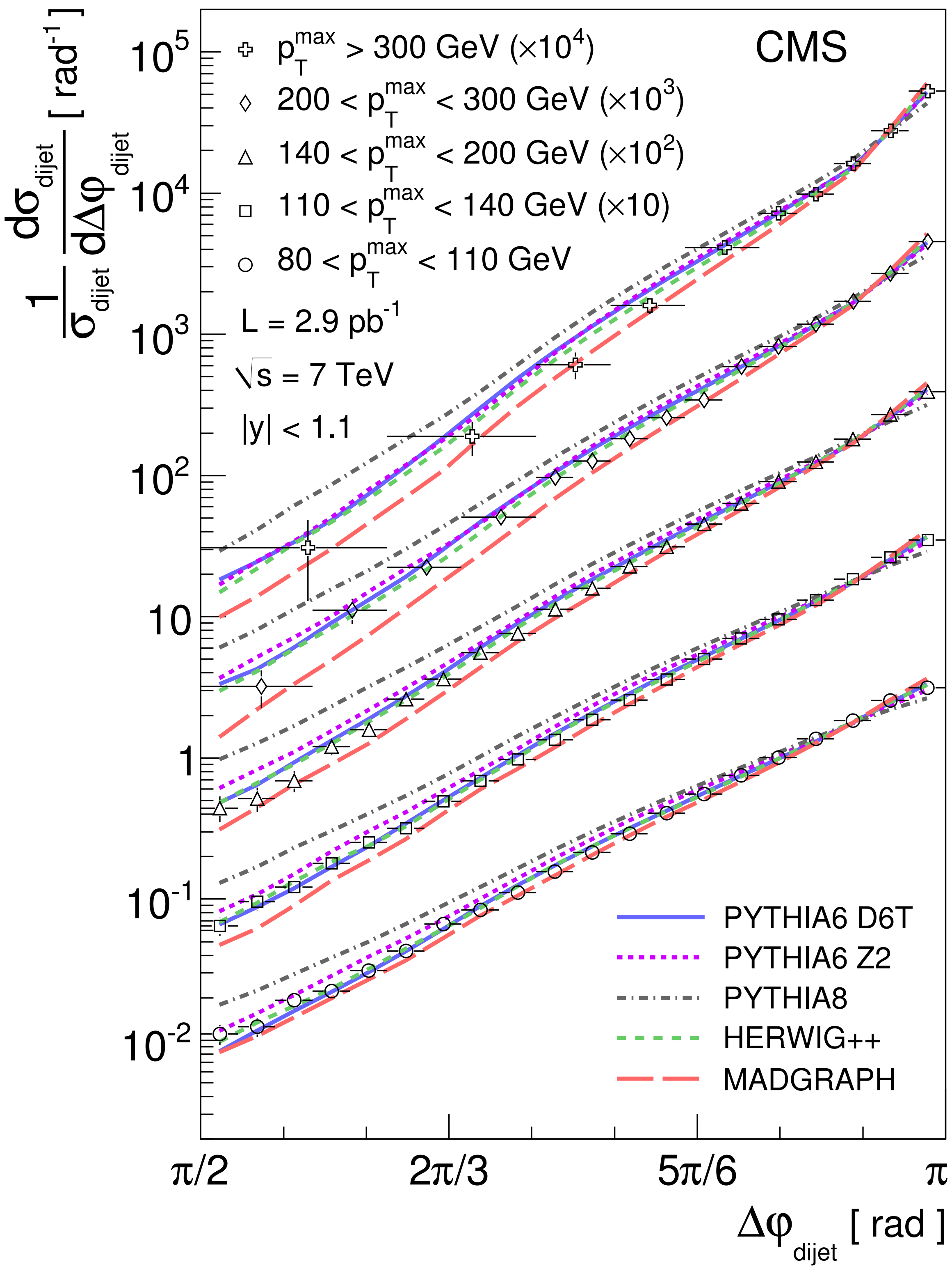
✦ **Experimental measurement**

- 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 $\Delta\phi$ > 120 deg (~ 3j topologies)
- the scale uncertainty dominates

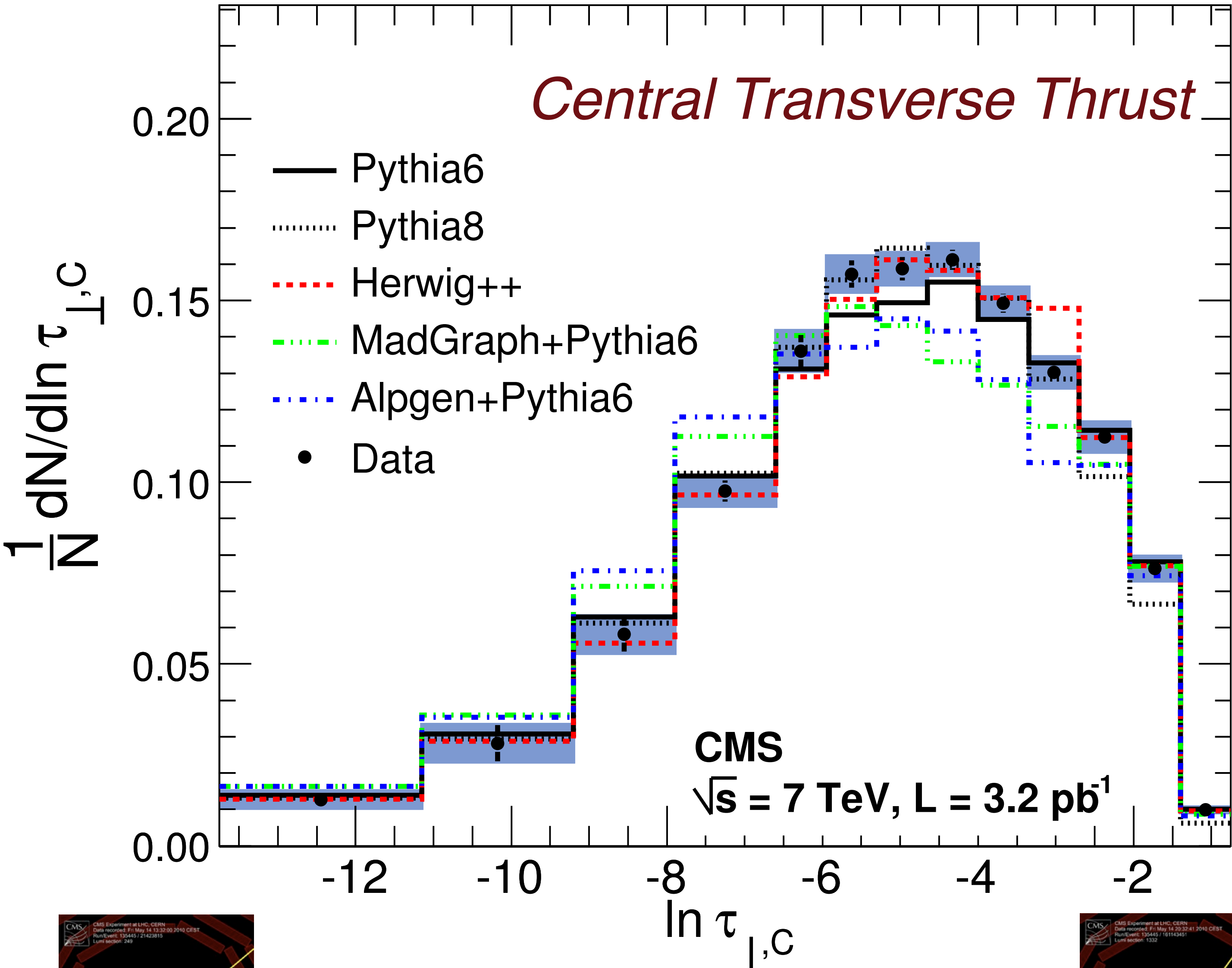
Dijet Azimuthal Decorrelations (II)

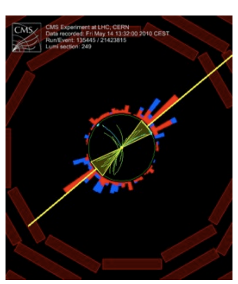


✦ **Data vs MC comparison**

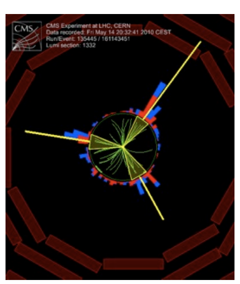
- Pythia6 and Herwig++ predictions are in good agreement with the data, in the entire phase space
- Pythia8 predicts more multijet-like events
- Madgraph predicts less multijet-like events

Hadronic Event Shapes (I)





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



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

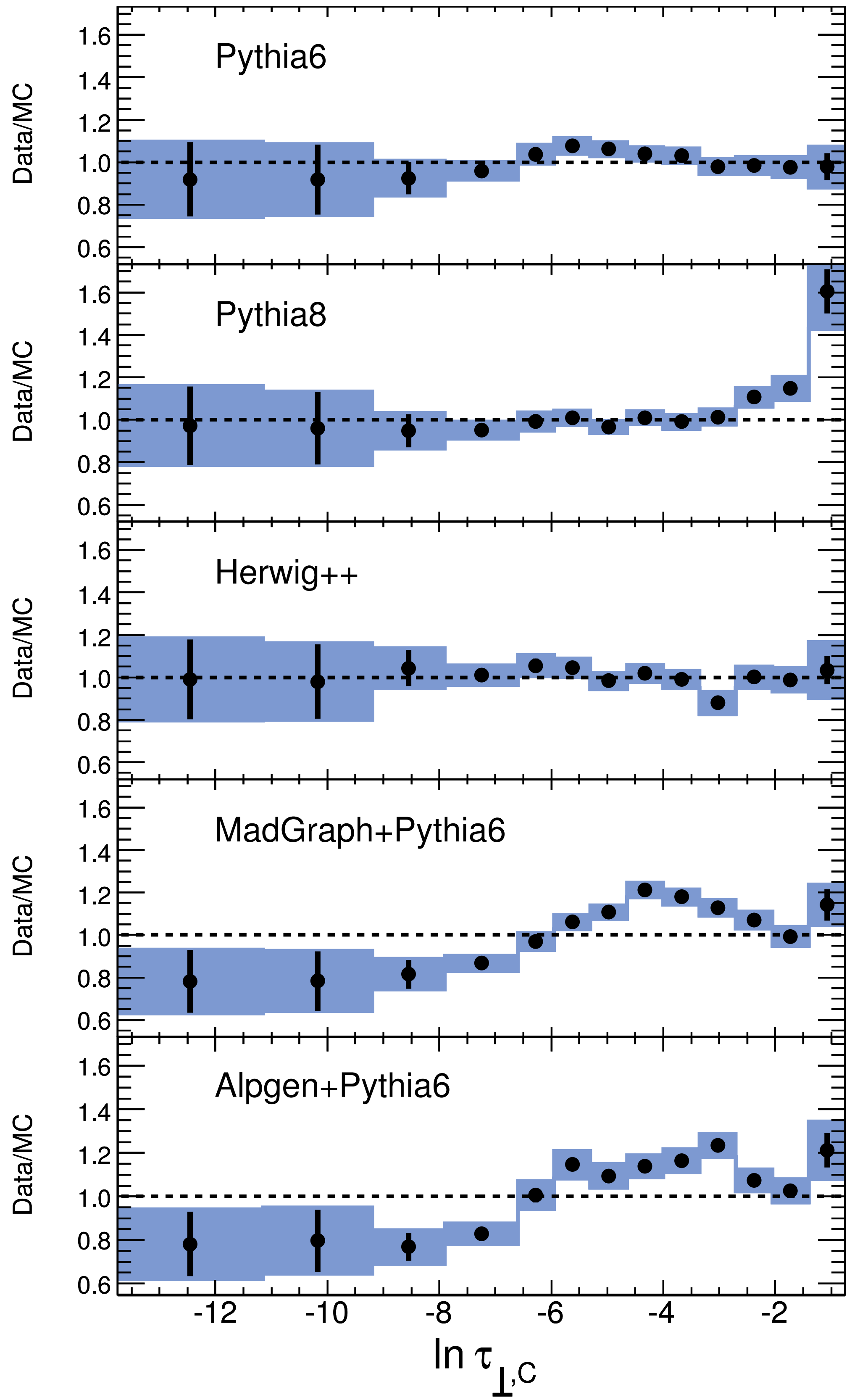
✦ Event-shape variables

- 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)

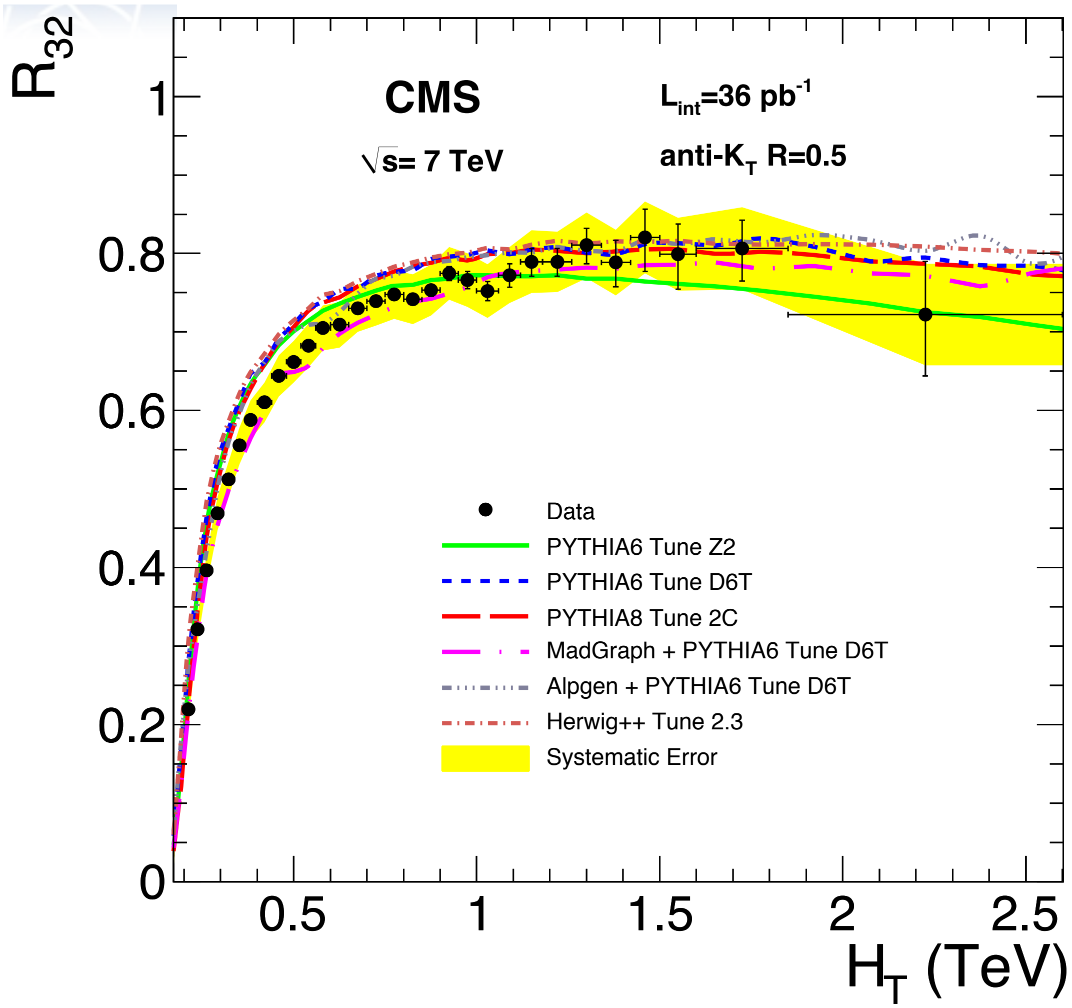


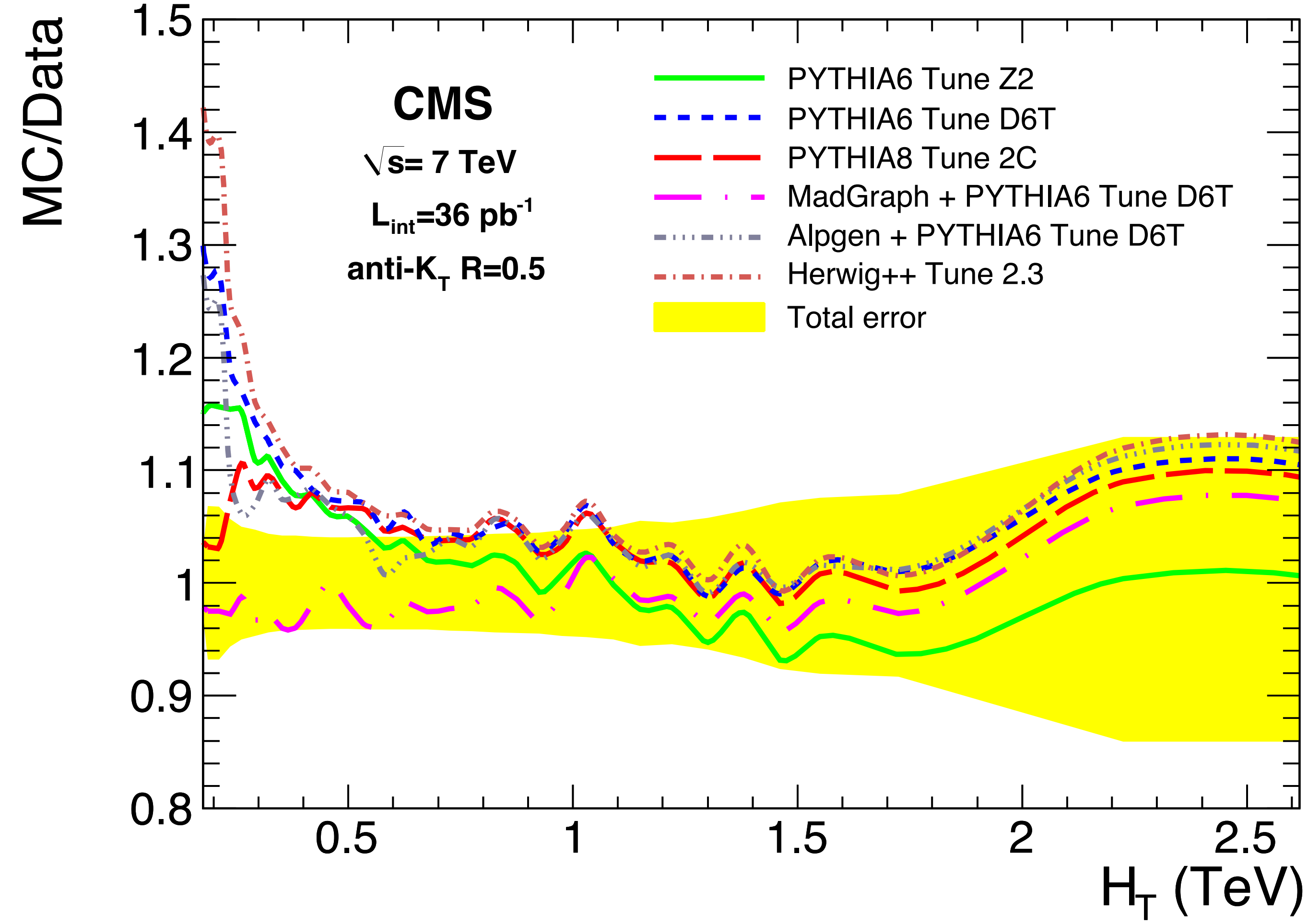
✦ Data vs MC comparison

- 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 p_T spectrum, but produce harder second jets*

3j/2j Cross-Section Ratio





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

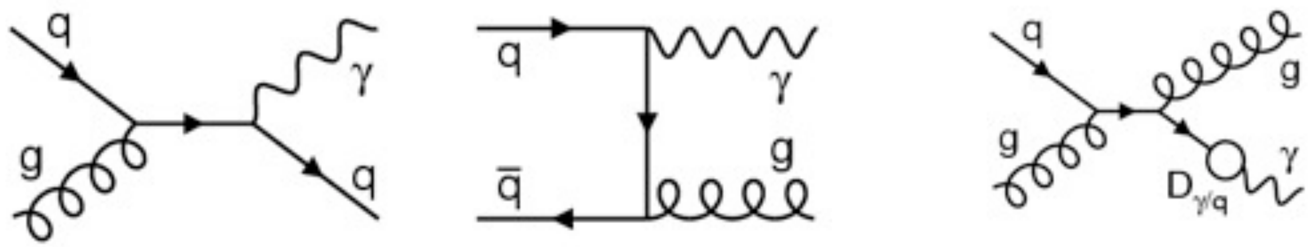
- insensitive to many experimental uncertainties
- the NLO calculation for the given setup is affected by large scale uncertainties
- can be used for the α_S measurement (in a different setup)

✦ Comparison to QCD MC generators

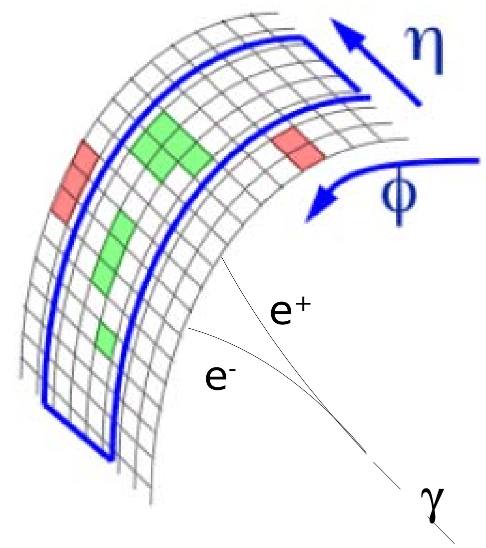
- all generators agree for $H_T > 0.7$ TeV with some deviation at low values
- Madgraph is in excellent agreement with the data in the entire H_T range

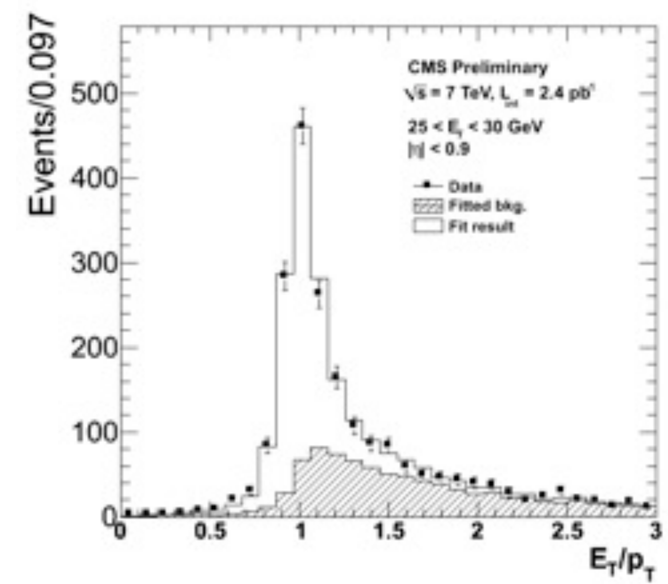
Direct Photon Production (I)

Compton Annihilation Fragmentation



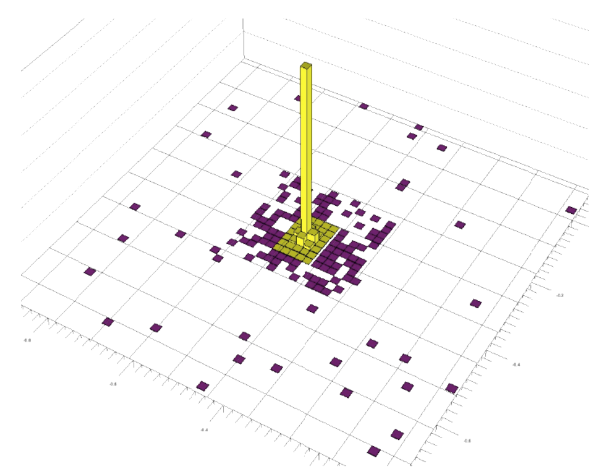
Conversion

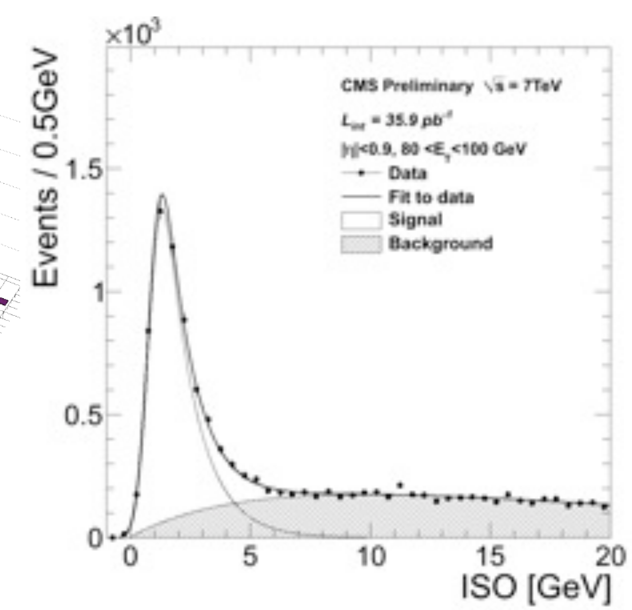




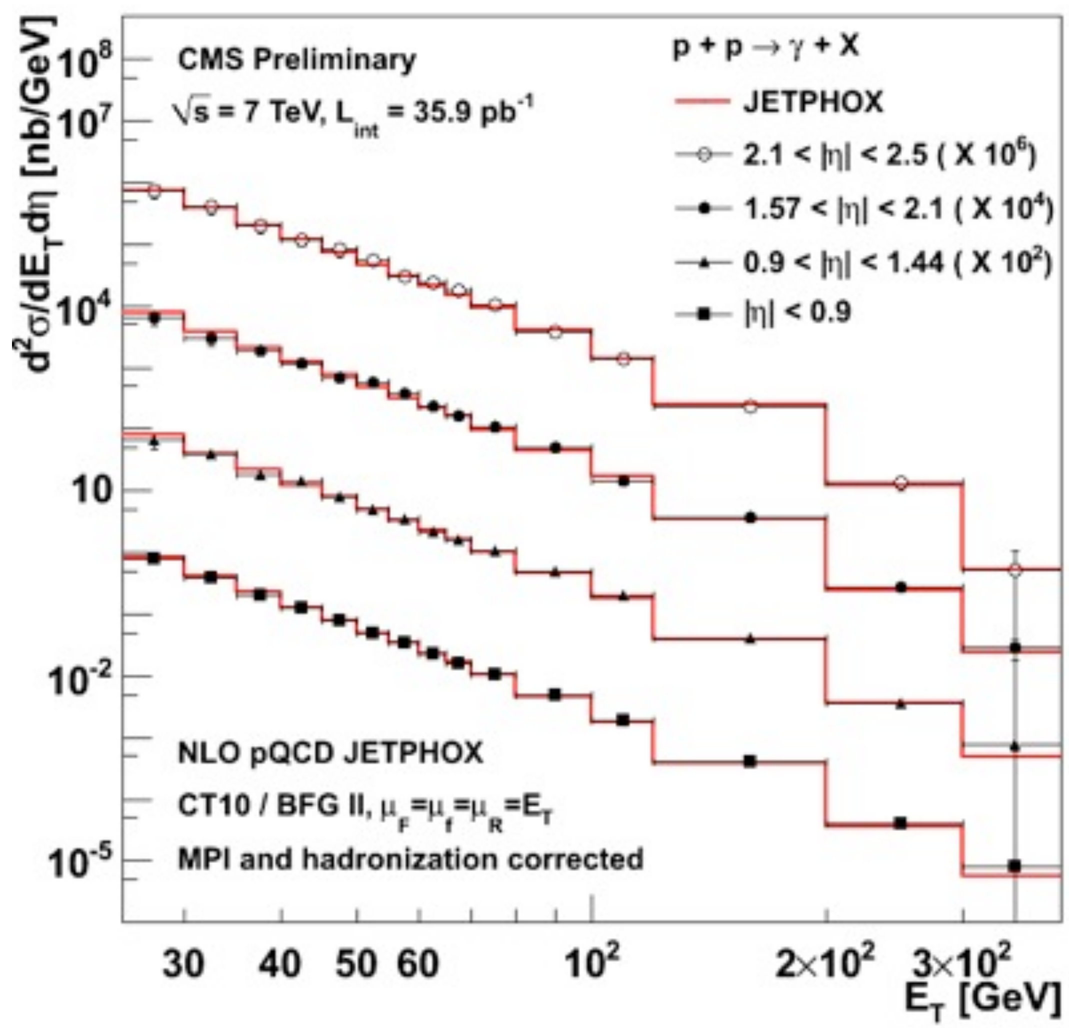
- ✦ **production mechanisms**
  - quark-gluon Compton scattering
  - quark-antiquark annihilation
  - fragmentation of colored partons (greatly suppressed by isolation requirements)
- ✦ **test of pQCD**
  - direct probe of gluon PDF
- ✦ **photon reconstruction**
  - conversion (powerful at low E_T)
  - isolation template (powerful at high E_T)
  - photon candidates contaminated by decays of energetic neutral mesons
  - signal extracted statistically

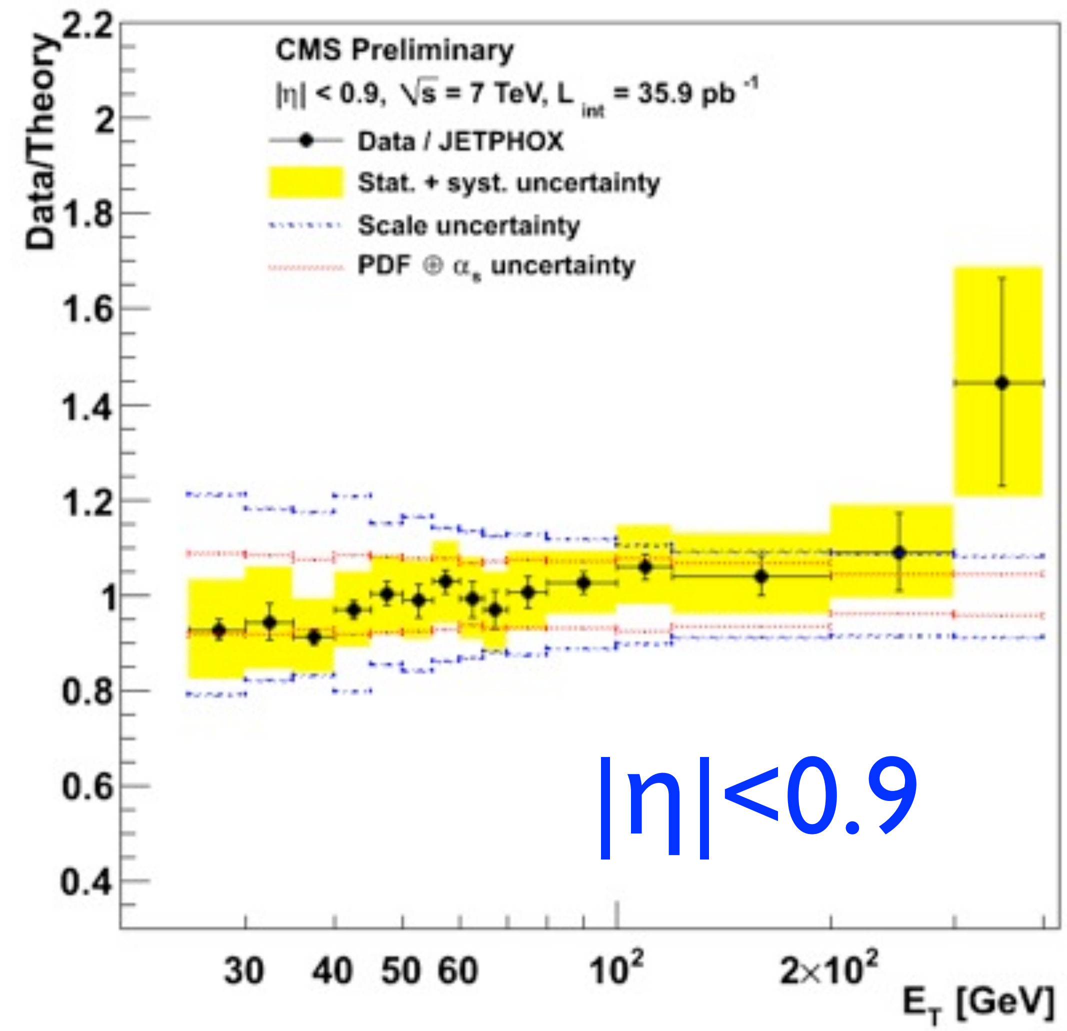
Isolation Template





Direct Photon Production (II)





- ✦ **differential inclusive direct photon cross section**
  - combination of conversions and isolation template methods
  - measurement ranging from 25 GeV to 400 GeV in E_T and up to |η| = 2.5
- ✦ **good agreement with the theory**
  - scale uncertainty dominates the theoretical prediction

Details in the talk by **P. Gras** (*"QCD studies with photons in CMS"*)

Summary

✦ The precise understanding of hard QCD is of great importance for the LHC physics program.

✦ CMS has completed a reach program of QCD measurements with the 2010 data, in an unexplored kinematic region.

✦ The advanced understanding of the jet & photon reconstruction in CMS allowed for competing measurements.

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

- not yet able to differentiate between the various PDF sets due to the size of the experimental systematic uncertainties.

✦ The QCD MC generators do not fully reproduce the data: the CMS measurements are available for their further tuning.

✦ Further QCD precision studies are being pursued with the 2011 data

References

(1) *Measurement of the differential dijet production cross section in proton-proton collisions at 7 TeV*, Phys. Lett. B 700 (2011) 187–206

(2) *Measurement of Dijet Angular Distributions and Search for Quark Compositeness in pp Collisions at 7 TeV*, Phys.Rev.Lett.106:201804,2011

(3) *First Measurement of Hadronic Event Shapes in pp Collisions at 7 TeV*, Phys. Lett. B 699 (2011) 48-67

(4) *Dijet Azimuthal Decorrelations in pp Collisions at 7 TeV*, Phys.Rev.Lett. 106:122003,2011

(5) *Measurement of forward jets in proton--proton collisions at 7 TeV*, CMS-FWD-10-003

(6) *Cross section measurement for simultaneous production of a central and a forward jet in proton-proton collisions at 7 TeV*, CMS-FWD-10-006

(7) *Measurement of the Inclusive Jet Cross Section in pp Collisions at 7 TeV*, arXiv:1106.0208

(8) *Measurement of the 3-jet to 2-jet Cross Section Ratio in pp Collisions at 7 TeV*, arXiv:1106.0647

(9) *Measurement of the Isolated Prompt Photon Production Cross Section in pp Collisions at 7 TeV*, Phys. Rev. Lett. 106 (2011) 082001

(10) *Measurement of the Differential Isolated Prompt Photon Production Cross Section in pp Collisions at 7 TeV*, CMS-QCD-10-037

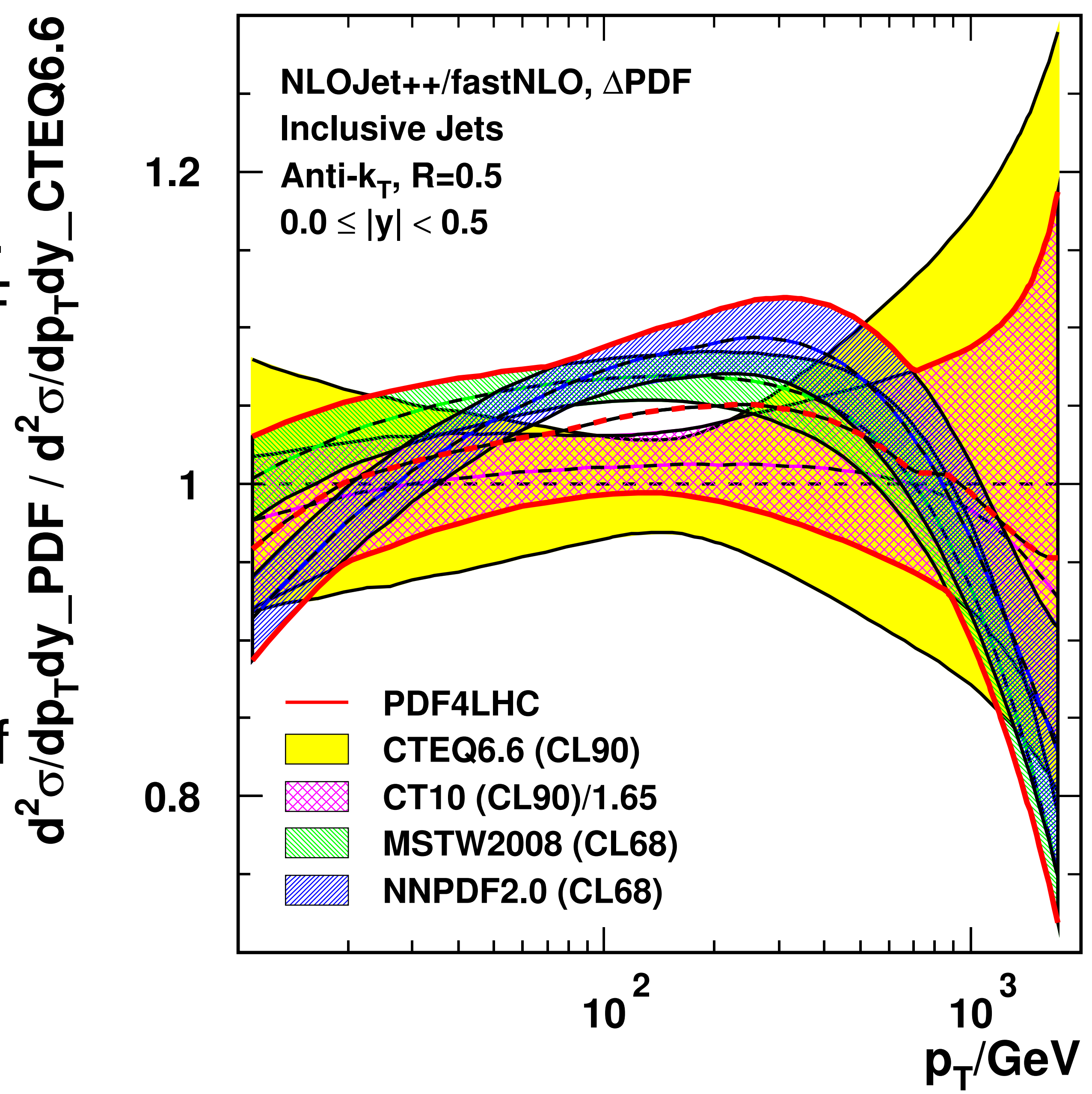
Backup

The PDF4LHC Prescription

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

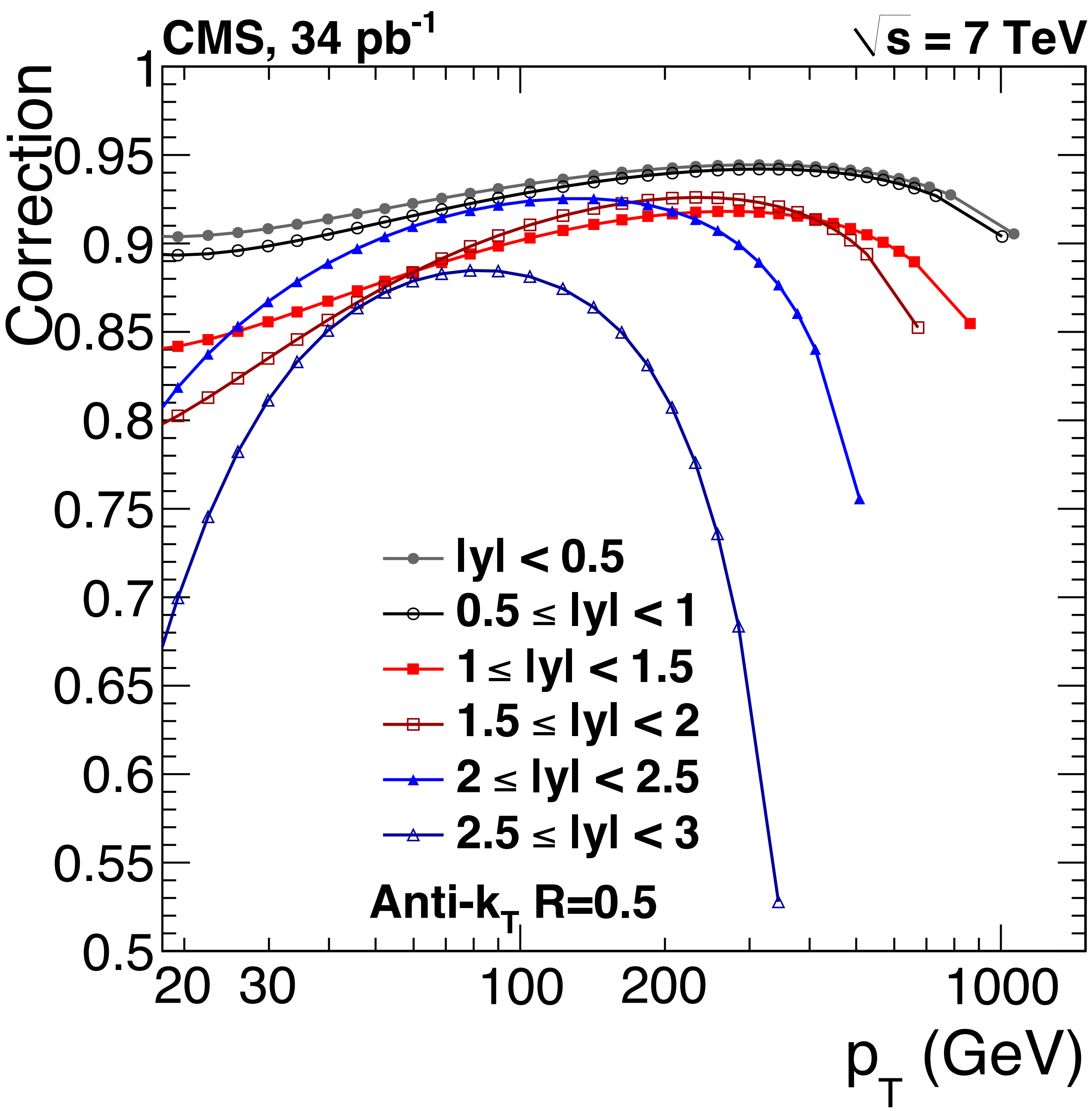
- compute the observable of interest (e.g. inclusive jet cross section) with each PDF set
- construct the 1-sigma (68% CL) band from each PDF set
- at every point, define the global envelope from the 1-sigma bands
- the PDF4LHC prediction is the center of the global envelope

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

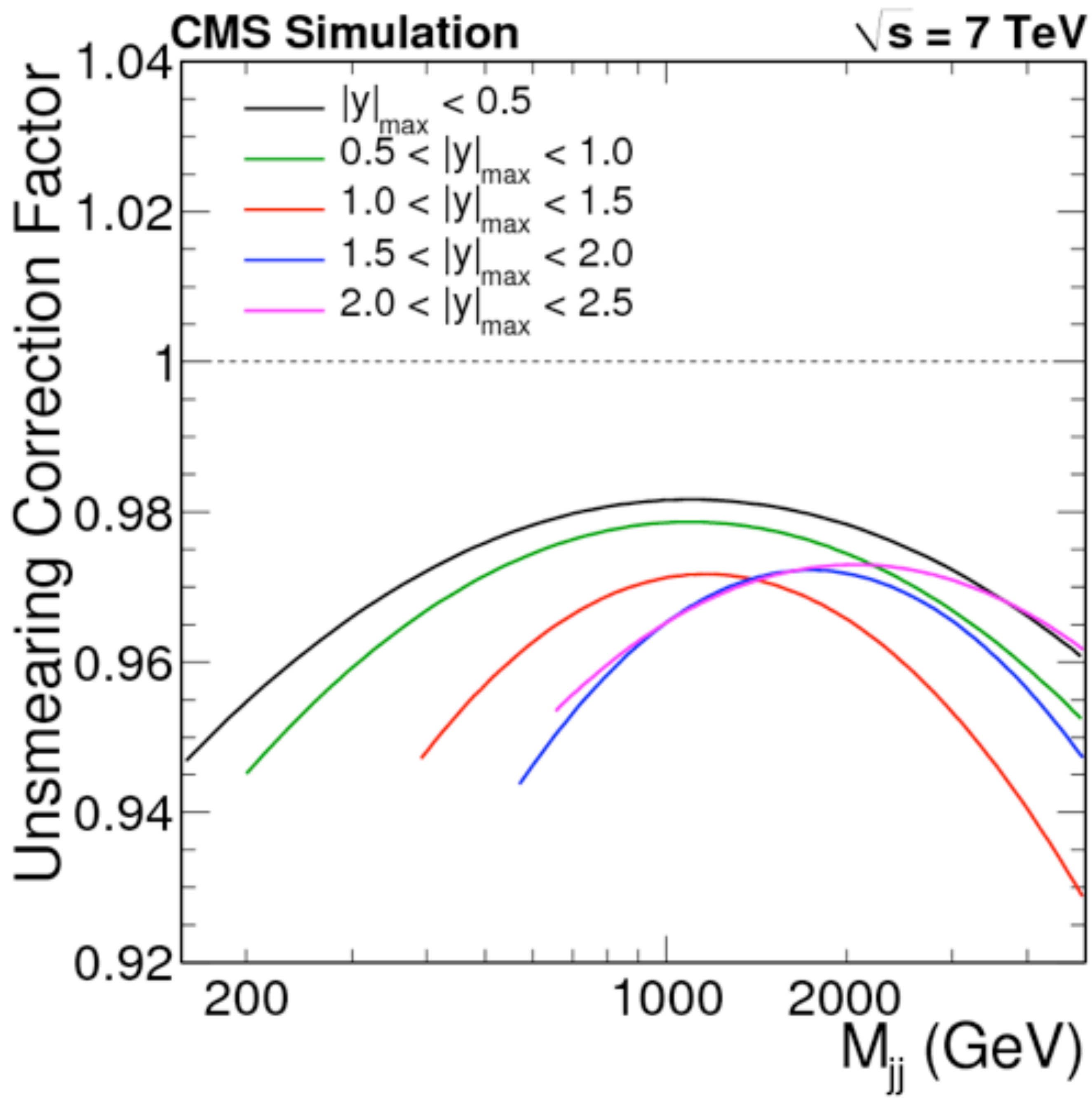


Cross-Section Unsmearing Factors

Inclusive Jets

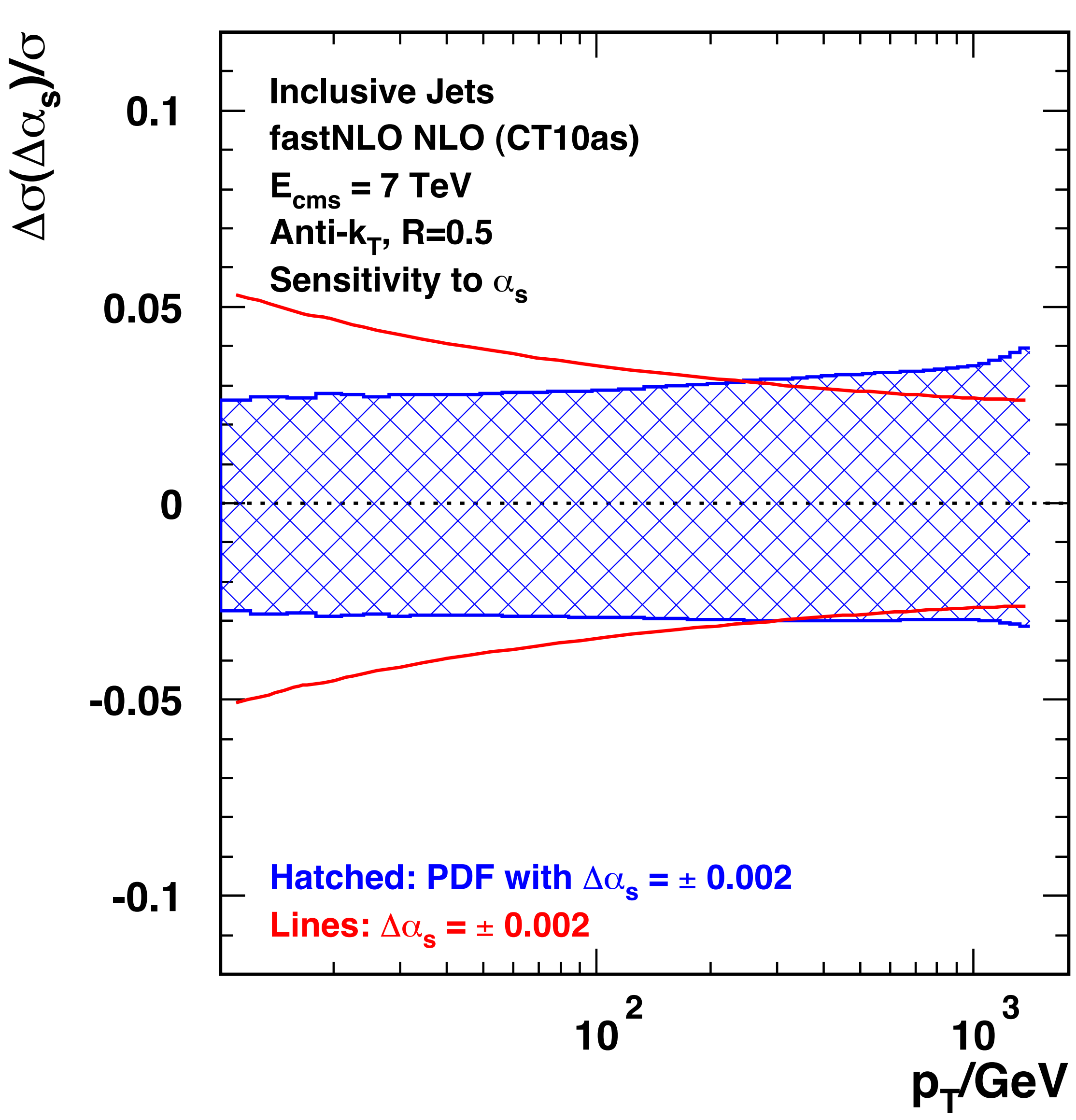


Dijet Mass

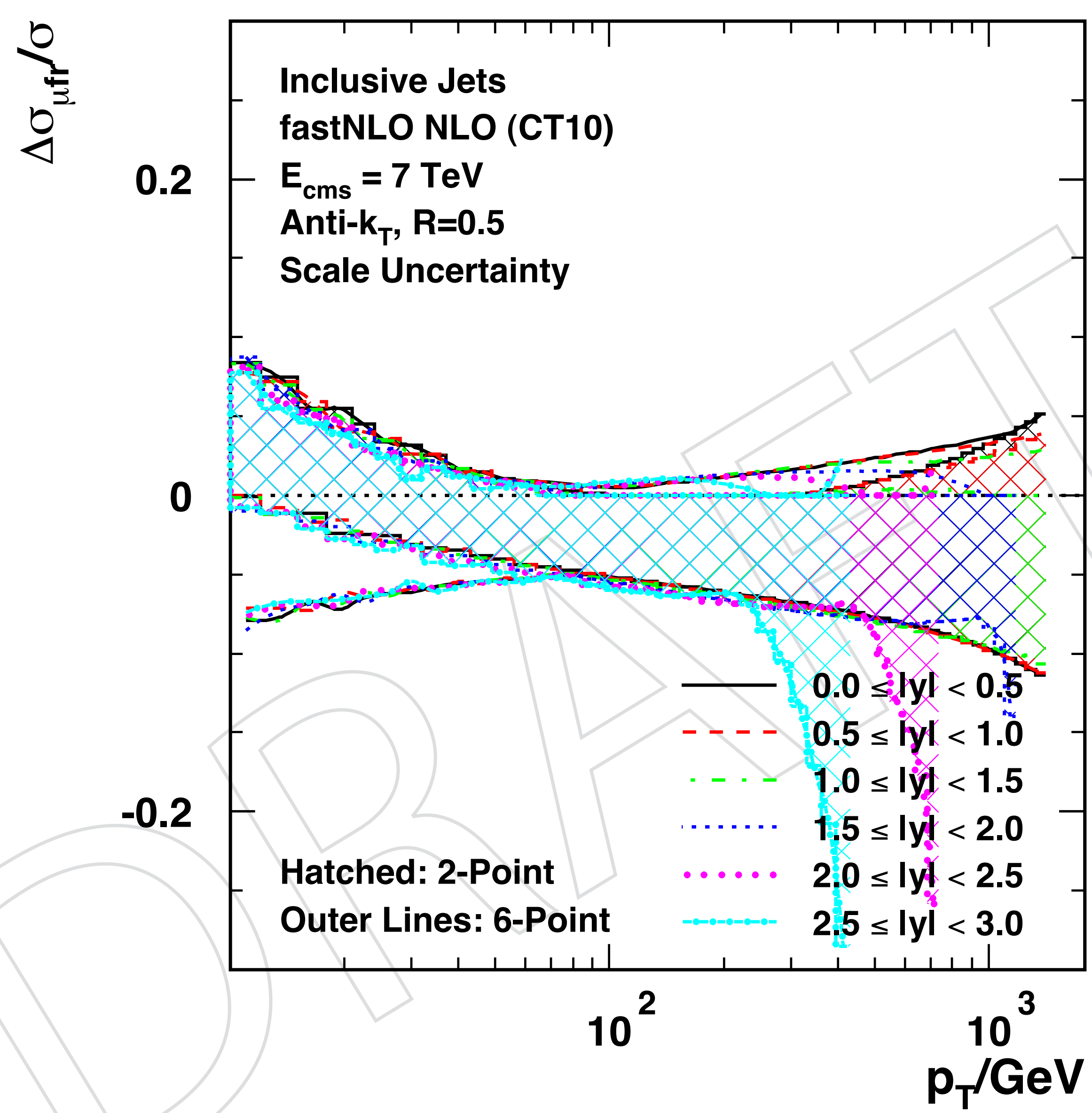


Cross-Section Theory Uncertainties

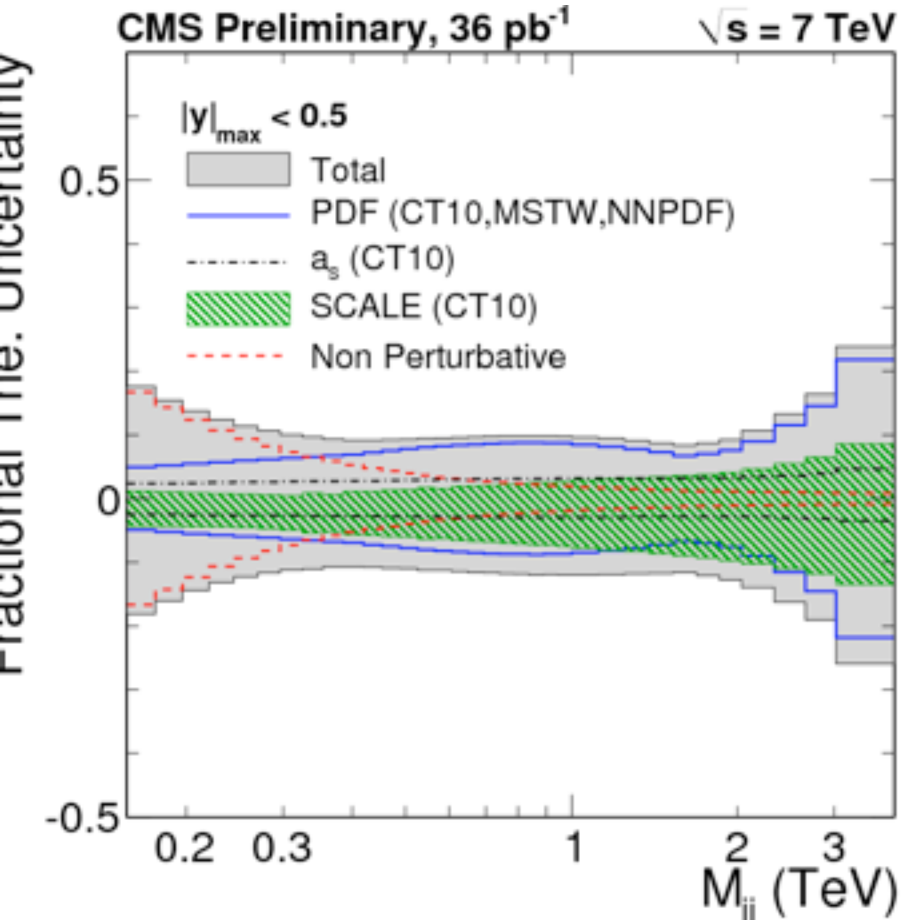
Strong coupling constant

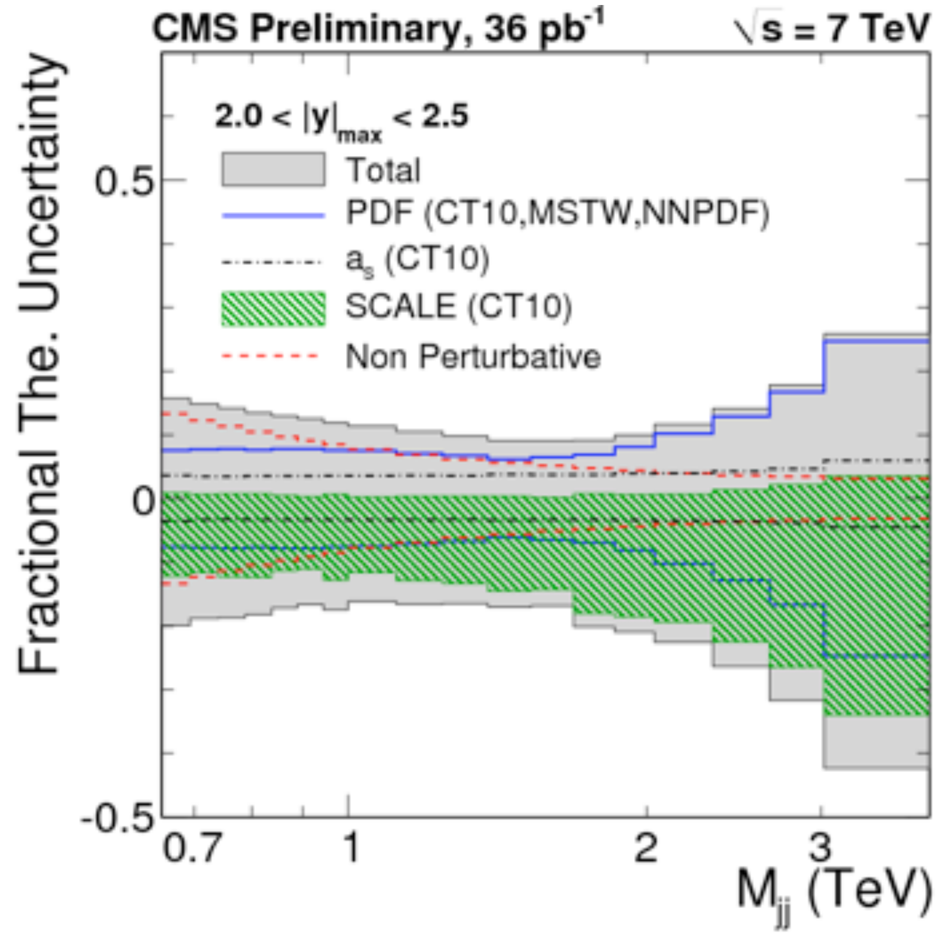


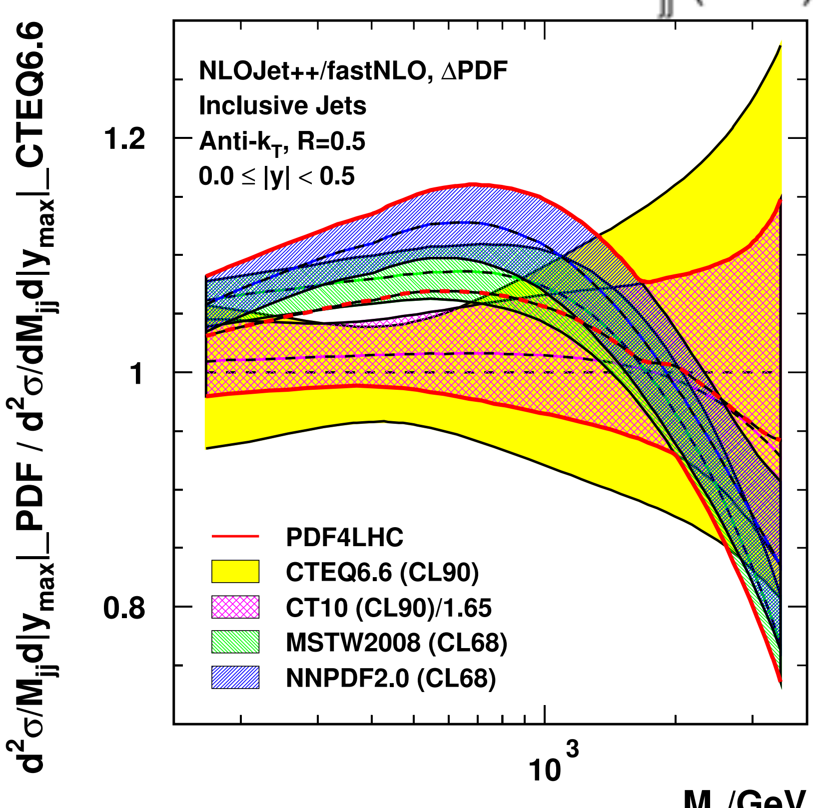
Scale

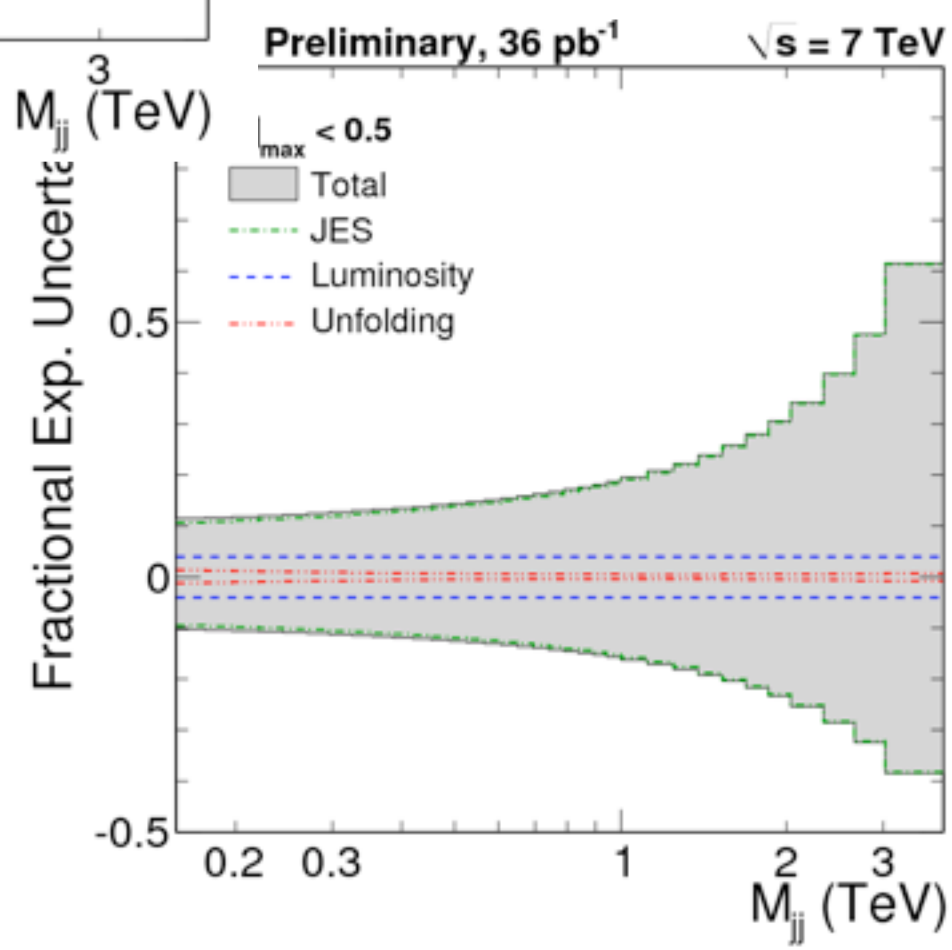


Dijet Cross-Section Uncertainties

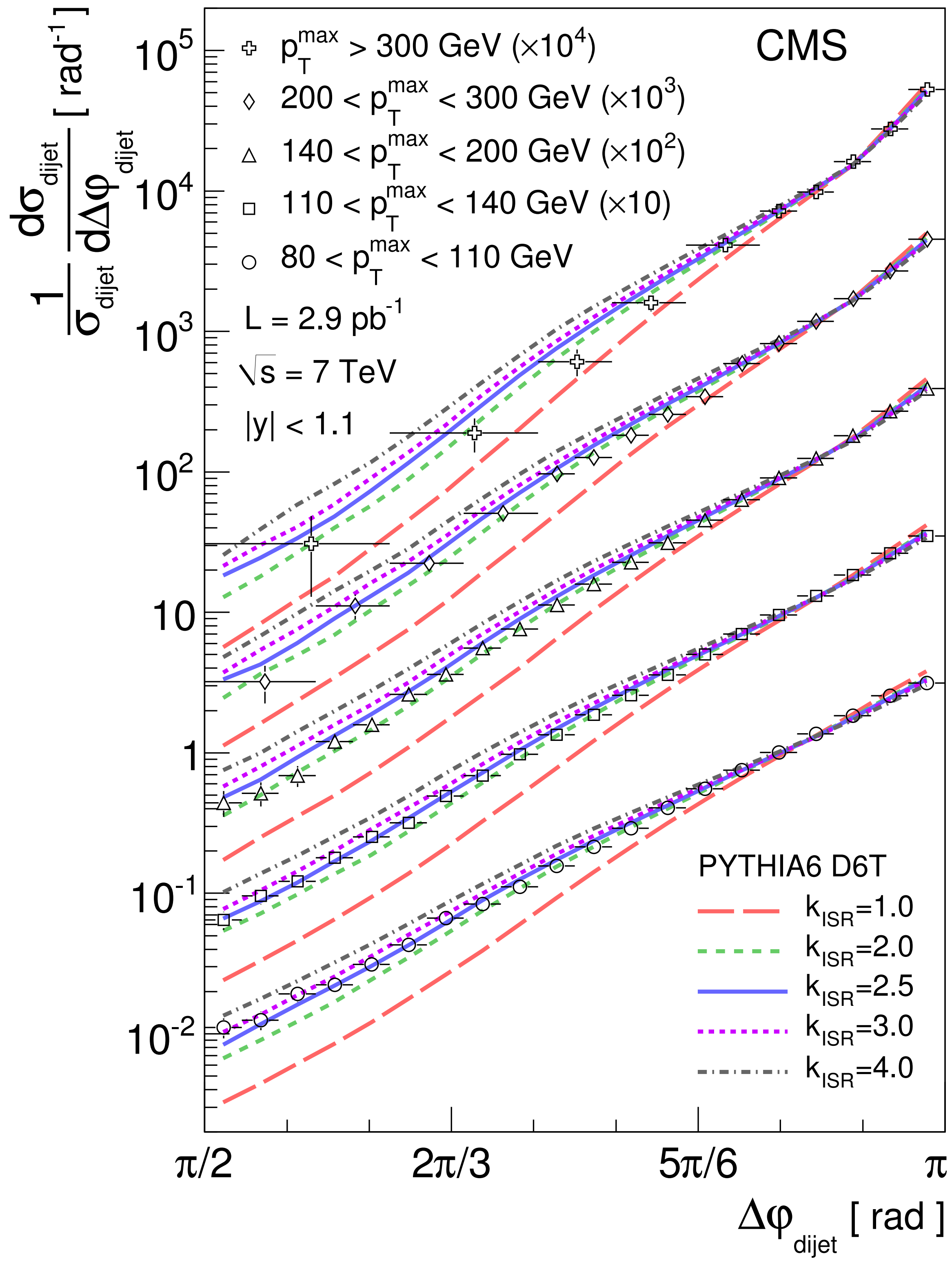








Dijet Azimuthal Decorrelations (ISR)



Hadronic Event Shapes

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