QCD Results with Jets and Photons

On Behalf of the CMS Collaboration

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Outline

- Introduction
- Jet reconstruction
- Jet Energy Scale and Resolution
- QCD with Jets:
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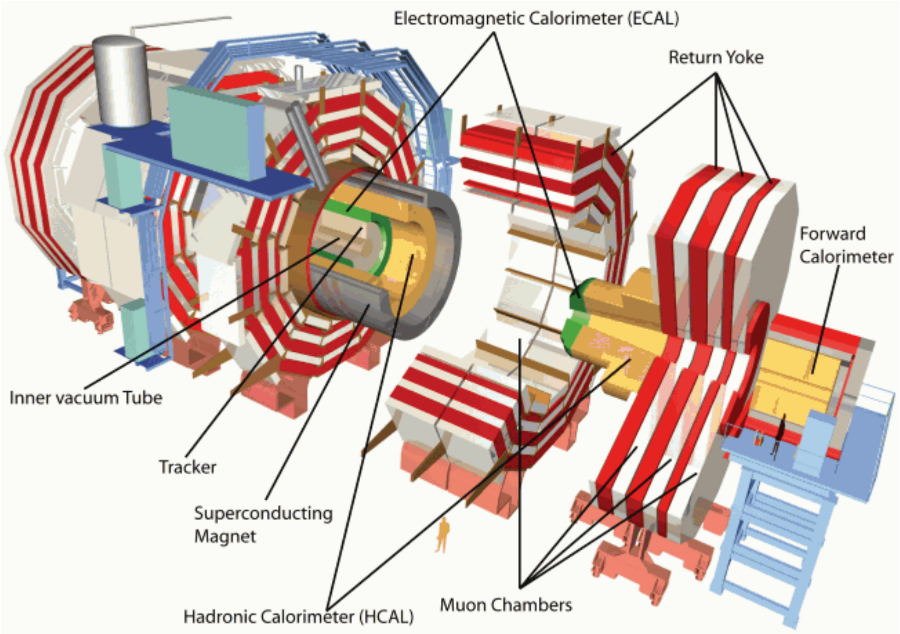
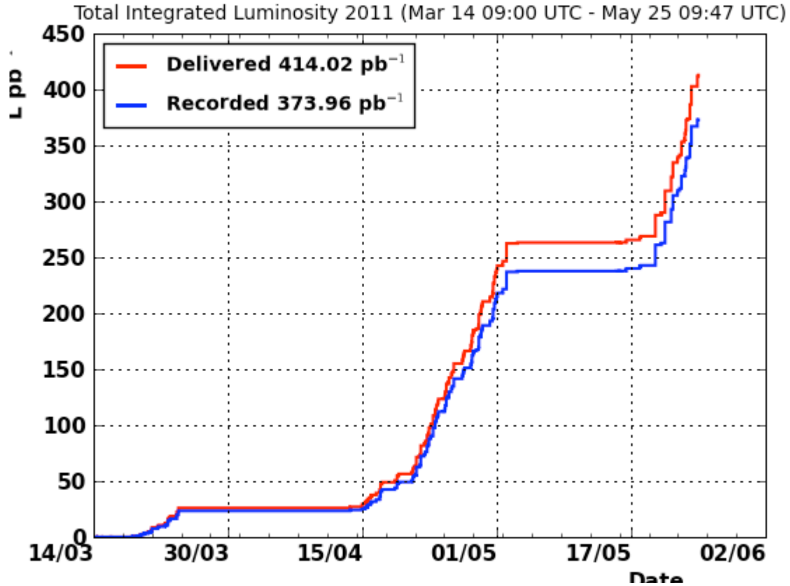
  - Di-Jet Cross Section
  - Di-Jet Azimuthal Decorrelations
  - Di-Jet Angular Distributions
- Photon reconstruction and Identification
- QCD with Photons:
  - Inclusive Photon Cross Section
- Summary Conclusions

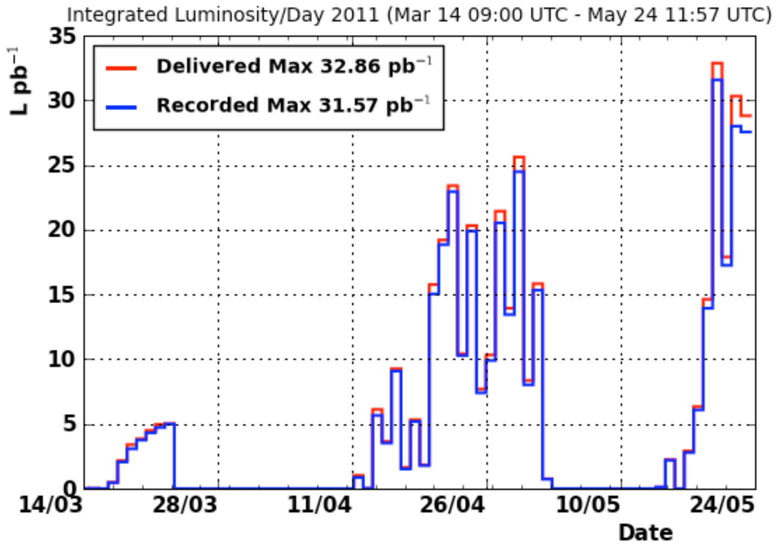
Introduction

- QCD measurements with Jets and Photons are of great important in order to:
  - **Test pQCD in a new energy regime, in a totally unexplored kinematic region.**
  - **Tune Monte Carlo generators in order to better describe the data.**
  - **Commission and understand basic physics objects (photons and jets) used in all analysis looking for New Physics (NP)**
  - **Measure and understand the main background to most NP physics searches, or get a chance to have a first glimpse of something new and unexpected.**

CMS Experiment

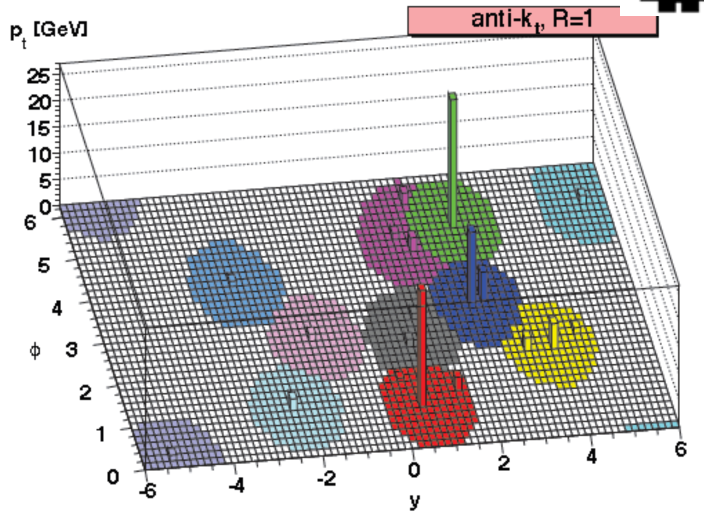






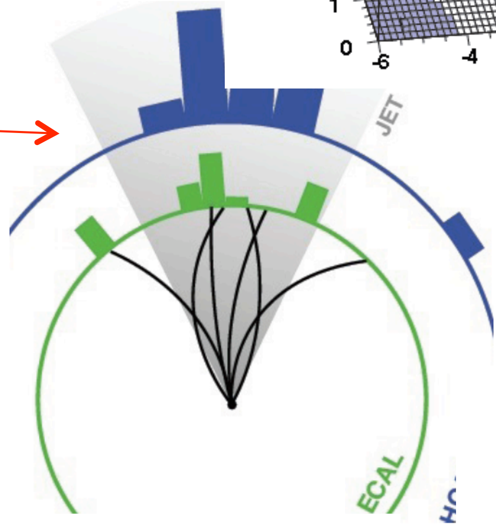
Results presented here make use of the 2010 Data Run with a total integrated luminosity of 36 pb^{-1} out of the 47 pb^{-1} delivered and 43 pb^{-1} recorded.

Jet Reconstruction

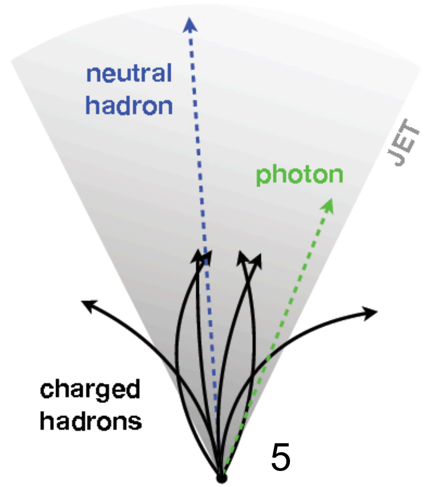


- **Anti-kt clustering algorithm :** with a cone R = 0.5, which is infrared and collinear safe, geometrically well defined, and tends to cluster around the hard energy deposits.

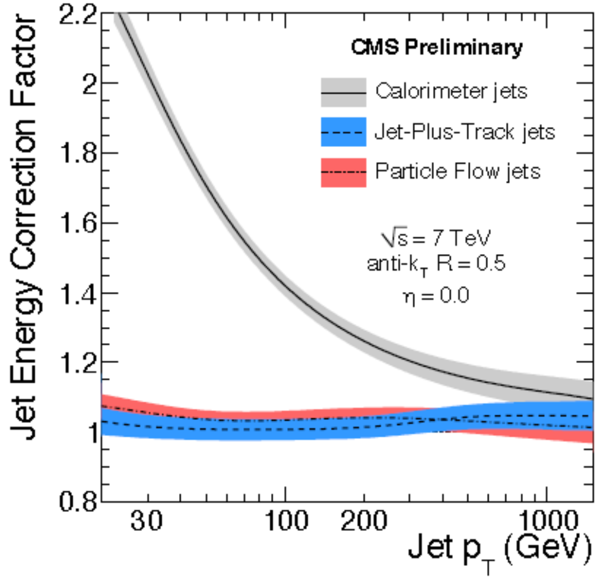
- **Calorimeter Jets :** Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits

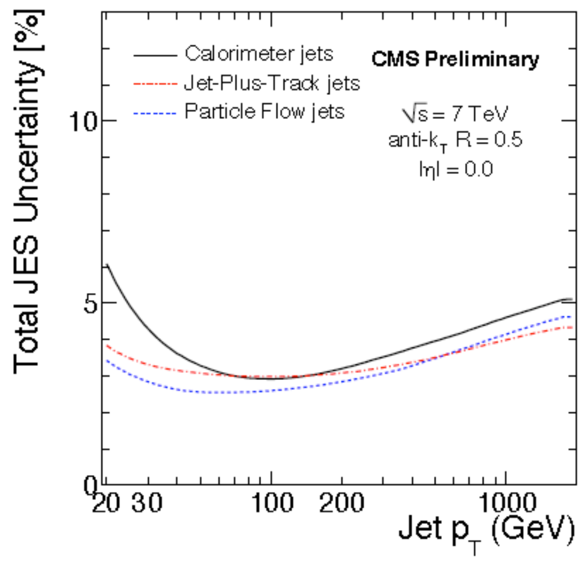


- **Particle Flow Jets :** Clustering of Particle Flow candidates constructed combining information from all sub-detector systems.



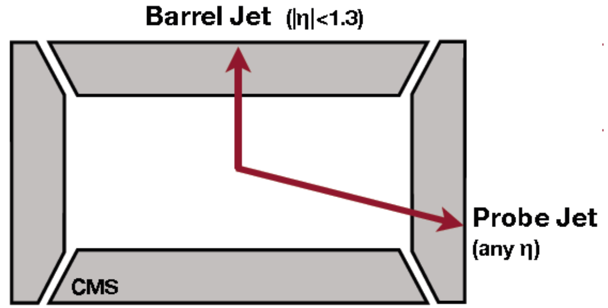
Jet Energy Scale and Resolution

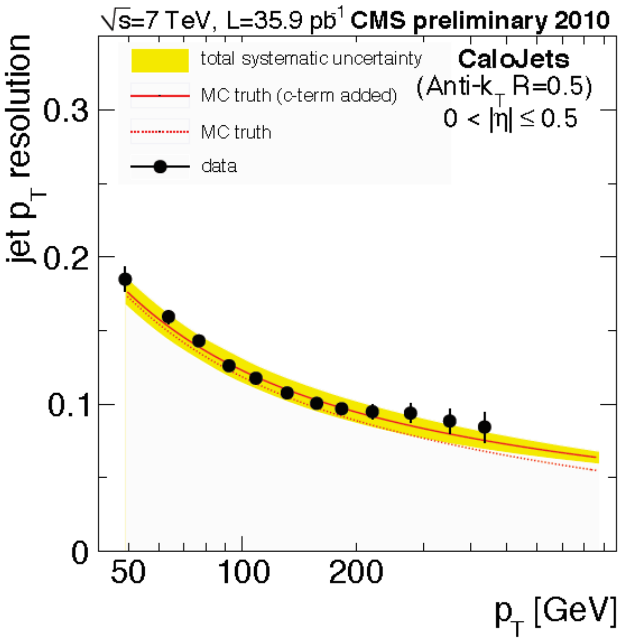


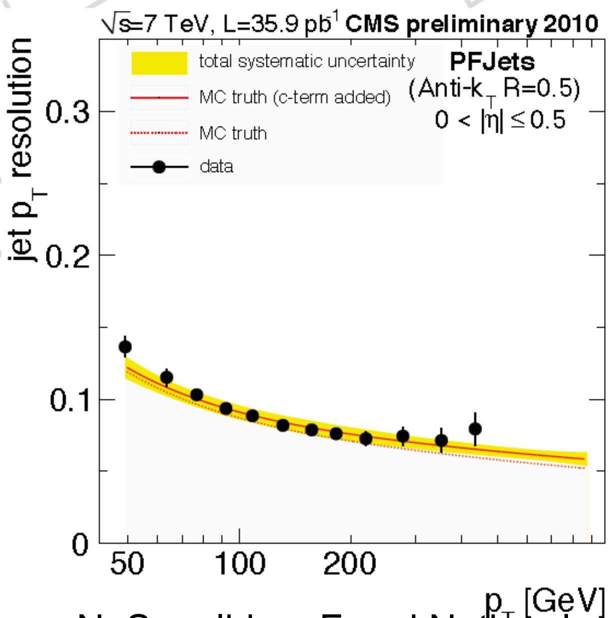


Data driven methods used

- Dijet Asymmetry

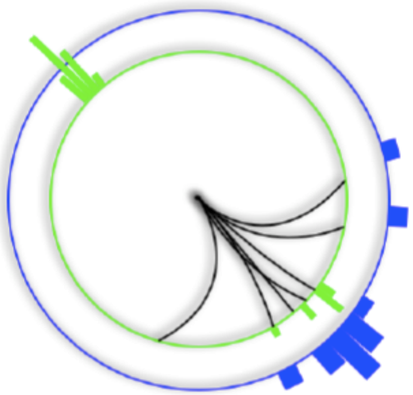






- Photon plus Jet Balance

γ+Jet events:

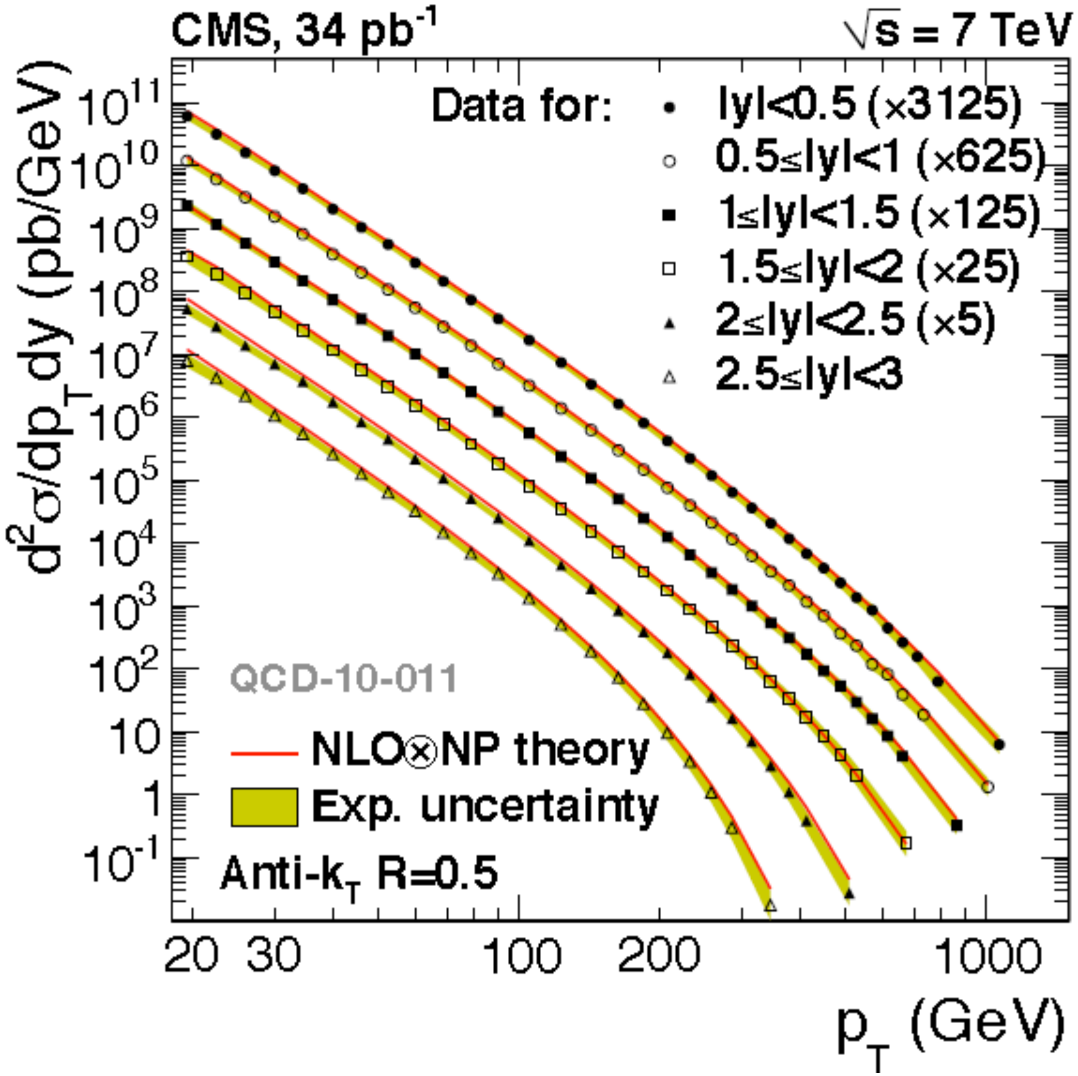


Inclusive Jet Cross Section

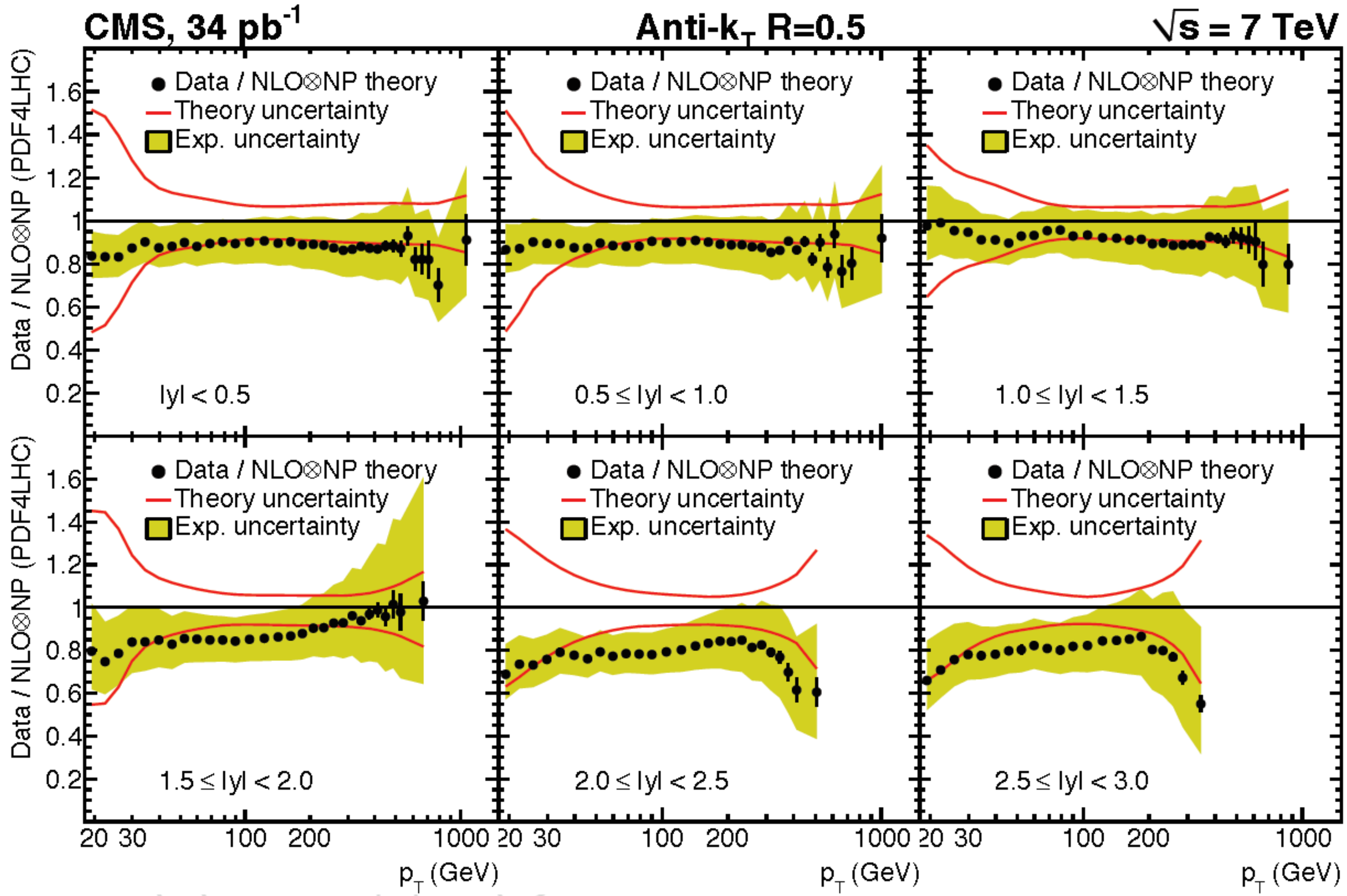
$$\frac{d^2\sigma}{dp_T d|y|} = \frac{C_{\rm unsm}}{\epsilon \cdot \mathcal{L}} \cdot \frac{N_{\rm jets}}{\Delta p_T \Delta|y|}$$

CMS-QCD-10-011

- Experimental uncertainties dominated by JES.
- Theoretical uncertainties dominated by non perturbative corrections at low pT, and PDFs at high pT.
- **Good agreement between data and theory.**



Inclusive Jet Cross Section



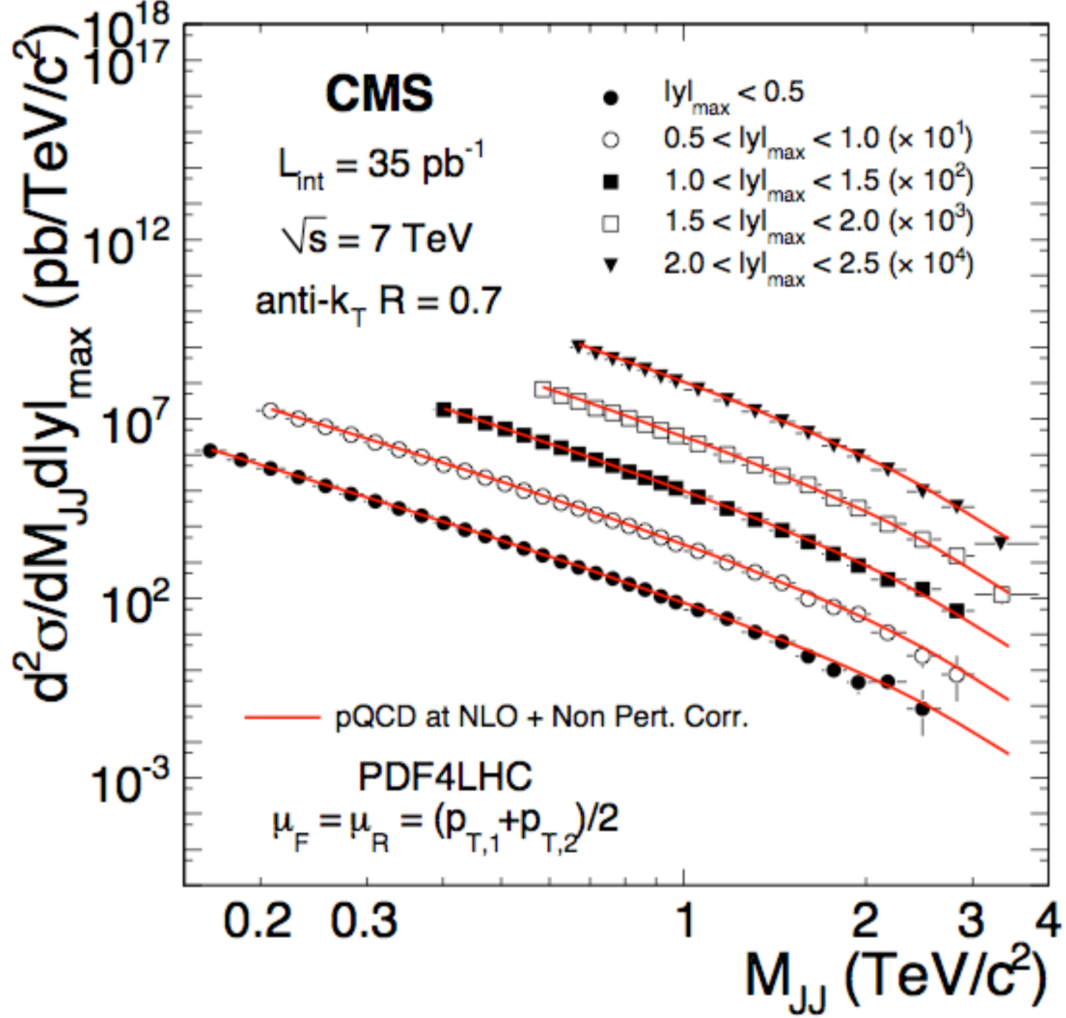
- **Good agreement between data and theory.**

Dijet Cross Section

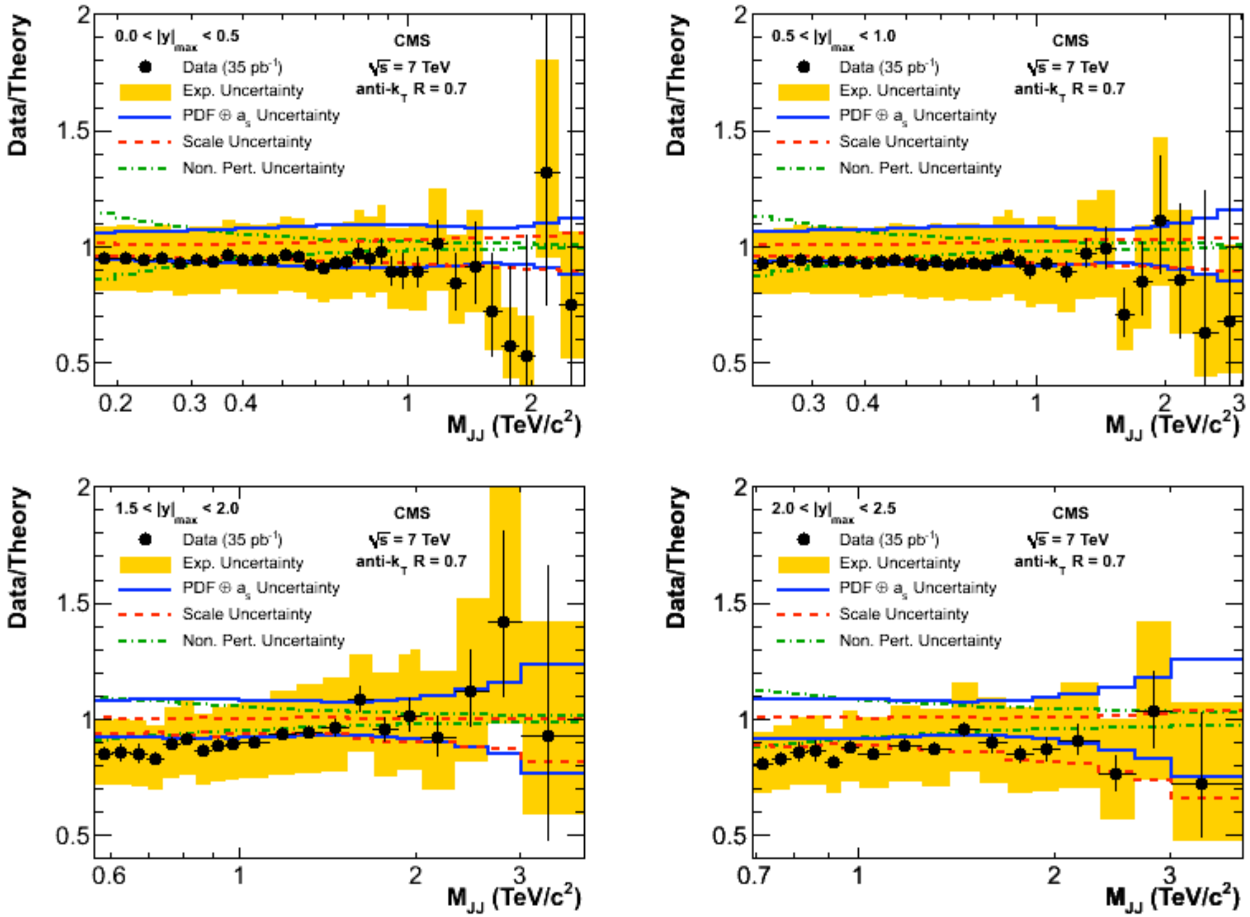
$$\frac{d^2\sigma}{dM_{JJ}d|y|_{max}} = \frac{\mathcal{C}}{\epsilon \cdot \mathcal{L}_{\text{equiv}}} \cdot \frac{N}{\Delta M_{JJ}\Delta|y|_{max}}$$

Arxiv1104.1693
Accepted in PLB

- Experimental uncertainties dominated by JES.
- Theoretical uncertainties dominated by non perturbative corrections at low masses, and PDFs at high masses.
- **Good agreement between data and theory.**



Dijet Cross Section



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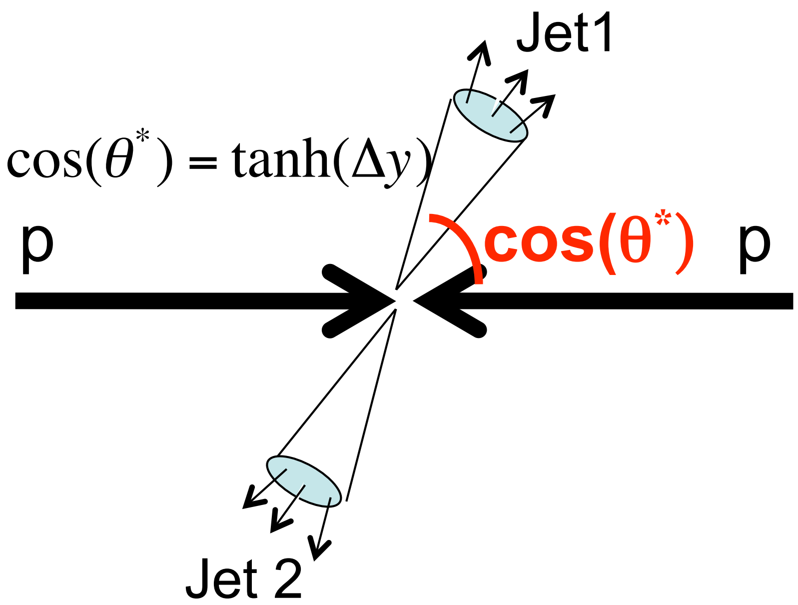
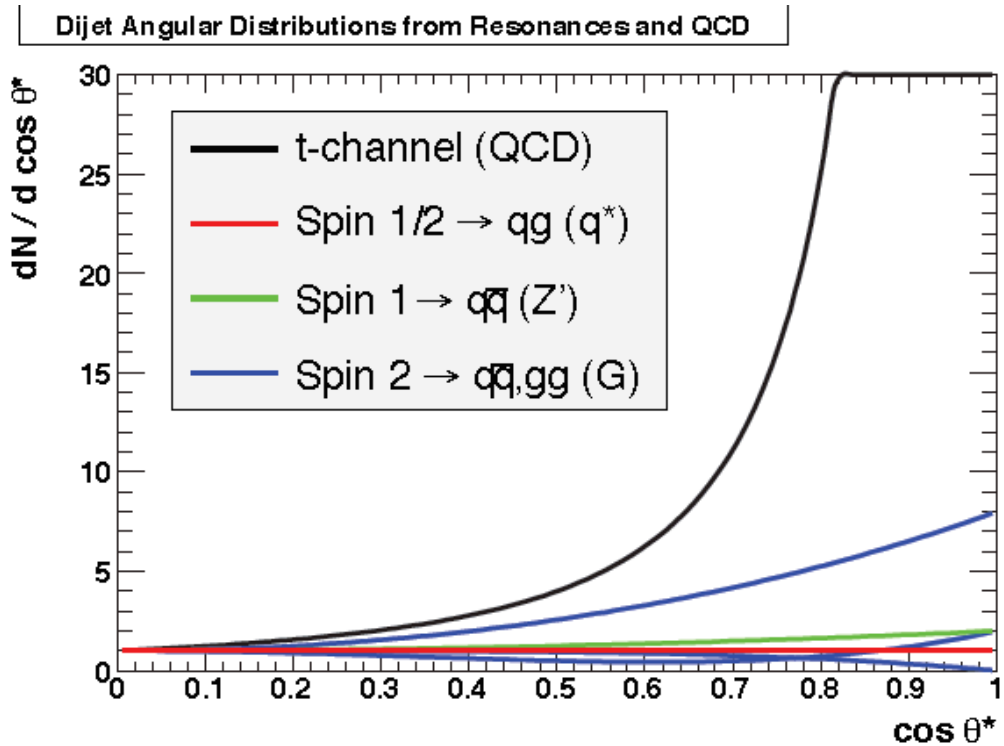
Accepted in PLB

Good agreement between pQCD@NLO and Data.

Dijet Angular Distributions





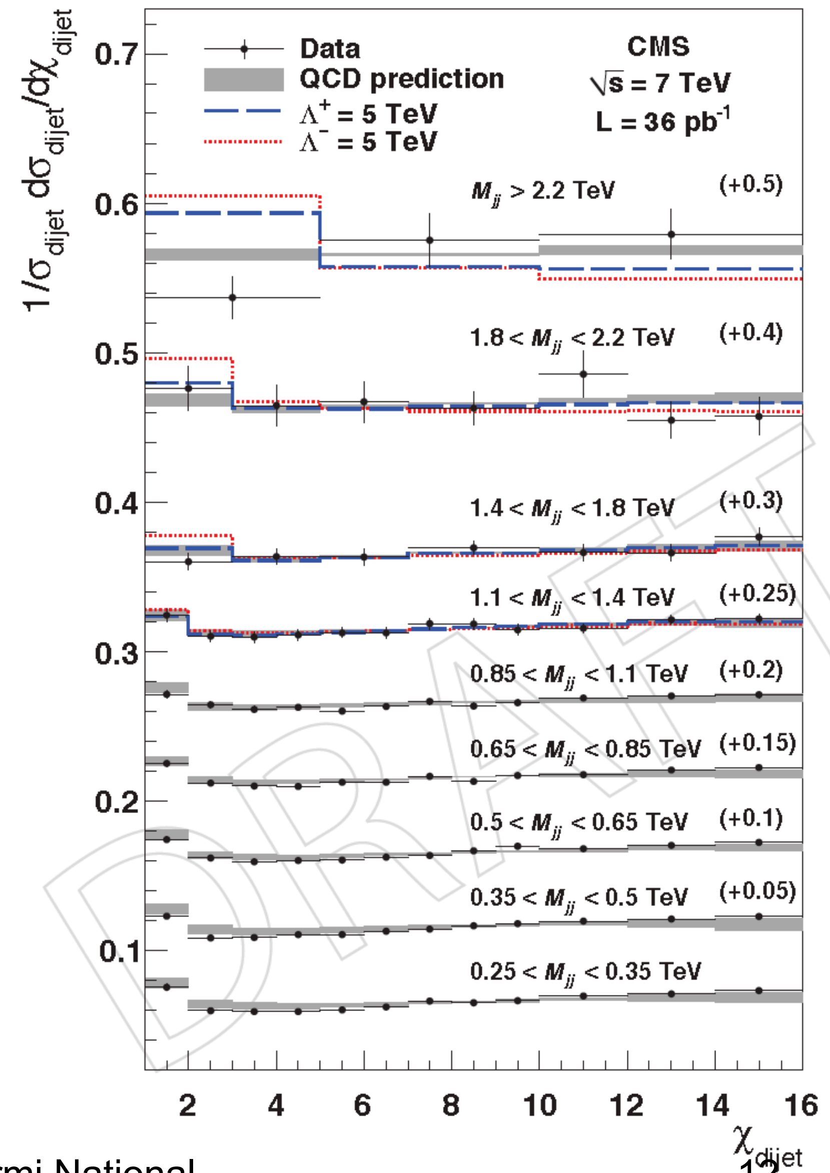
- Parton-parton scattering in QCD is t-channel dominated.
- Stringent test of pQCD with no dependence on PDFs.
- New physics would show deviations from expectation at large scattering angles.

Dijet Angular Distributions

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

Phys.Rev.Lett.106:201804,2011

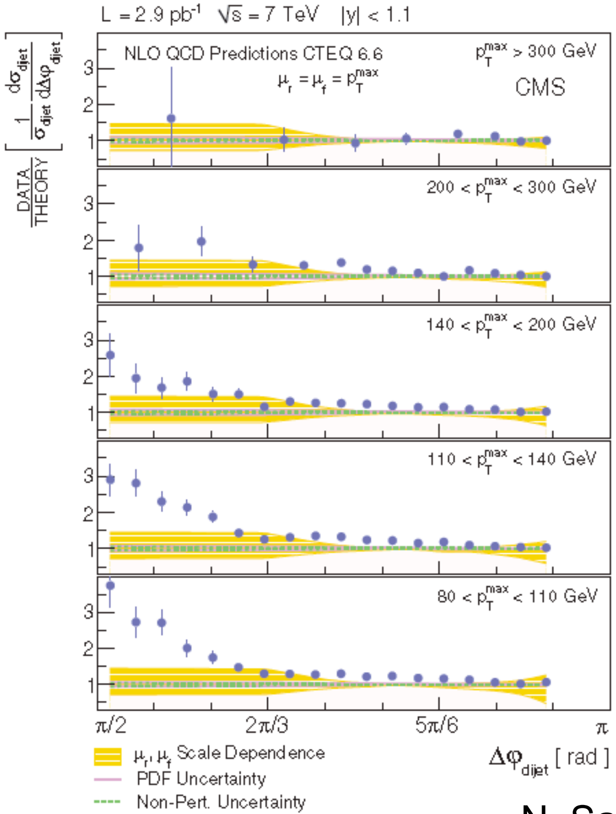
- X chosen since QCD flat as a function of x.
- Experimental uncertainties dominated by jet resolution and relative (vs η) JES (absolute cancels)
- Theoretical uncertainties dominated by non perturbative corrections and renormalization scale.
- **Good agreement between data and theory. Highest mass bins sensitive to contact interactions.**

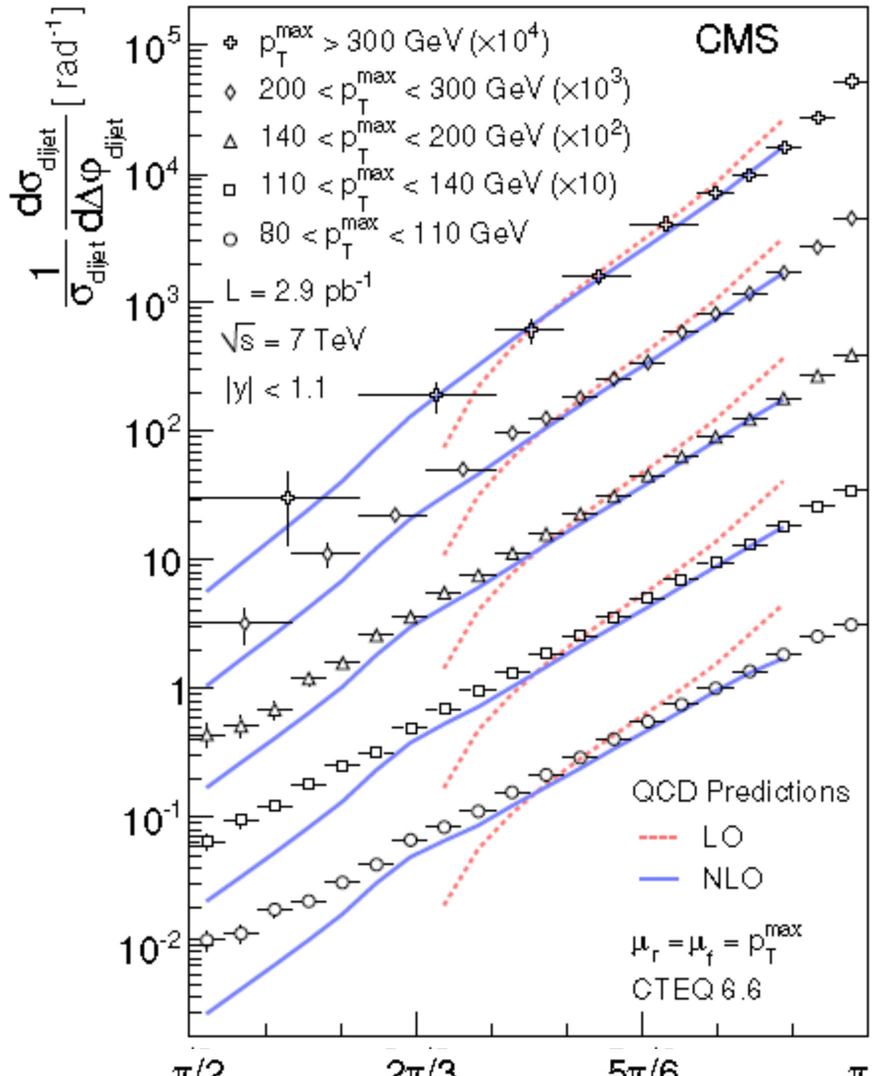


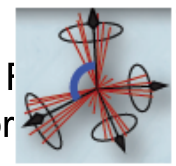
Dijet Azimuthal Decorrelations

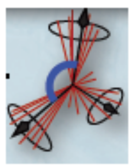
Phys.Rev.Lett.106:122003,2011.

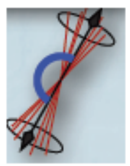
- Normalized Dijet cross section as a function of $\Delta\phi$ and indirect probe of multijet topologies
- NLO pQCD describes the data well up to ~$2\pi/3$, NNLO needed for higher jet multiplicities





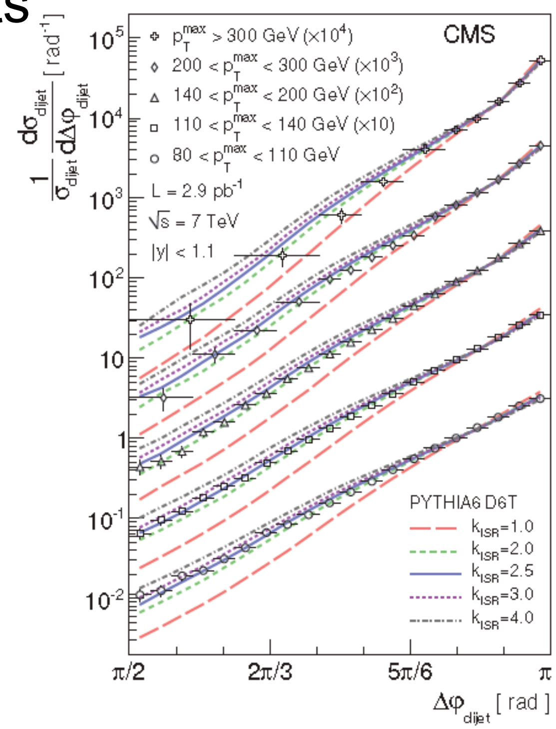




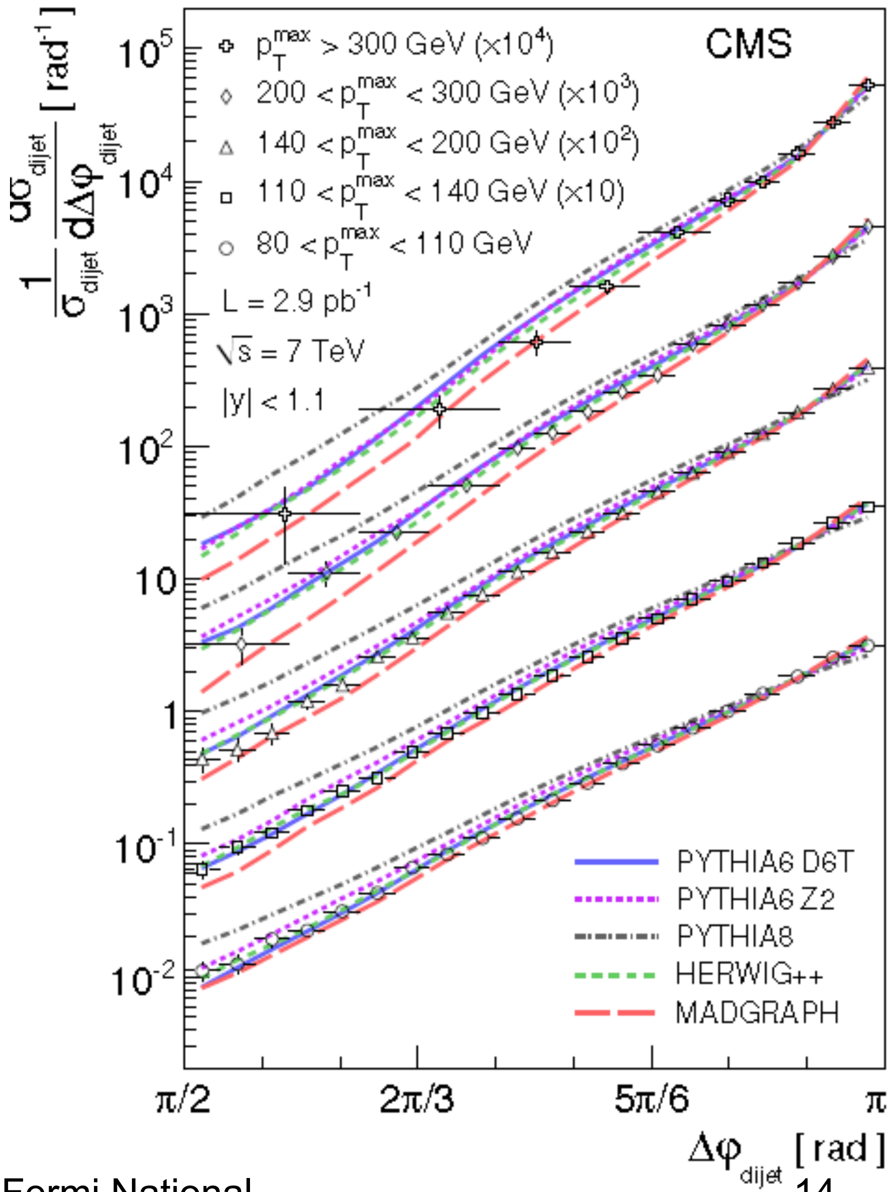


Dijet Azimuthal Decorrelations

- **Pythia6 and Herwig++ in good agreement with the Data**
- **Madgraph predicts less multijet events and Pythia8 more.**
- Results are sensitive to ISR effects



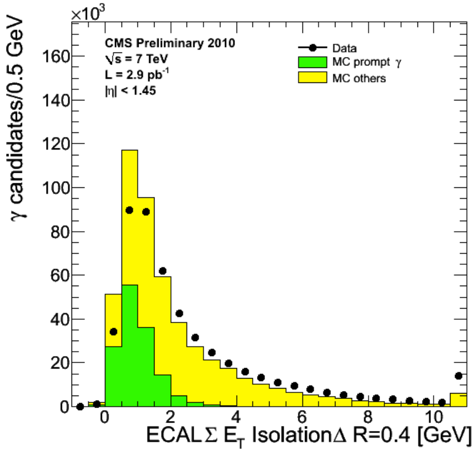
Phys.Rev.Lett.106:122003,2011.

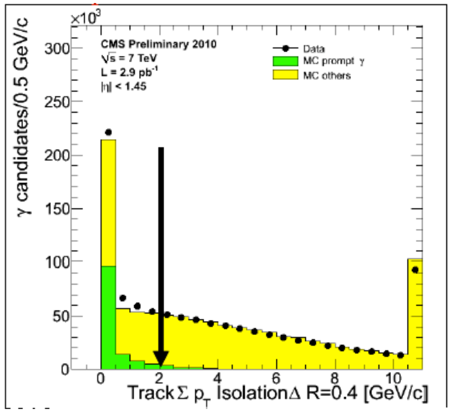


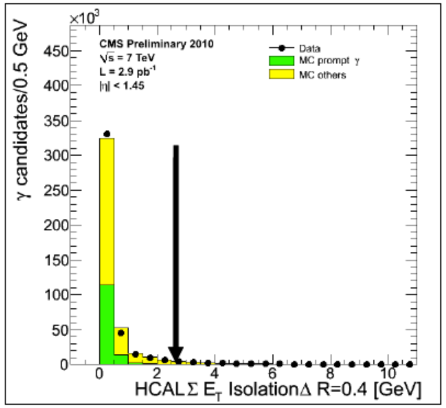
Photon Reconstruction

Photons are key objects for both calibration and major discoveries.
(H->γγ and BMS searches)

- Photons are isolated energy deposits in the ECAL, with no charged track pointing to them, and with a shape compatible with a photon electromagnetic Shower.





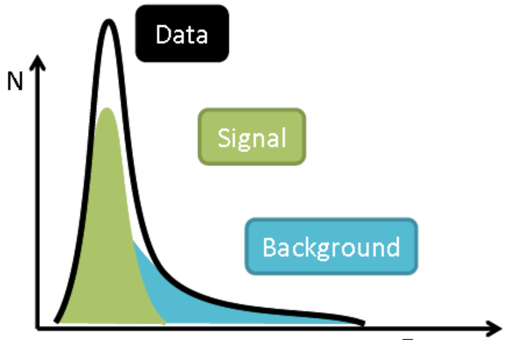


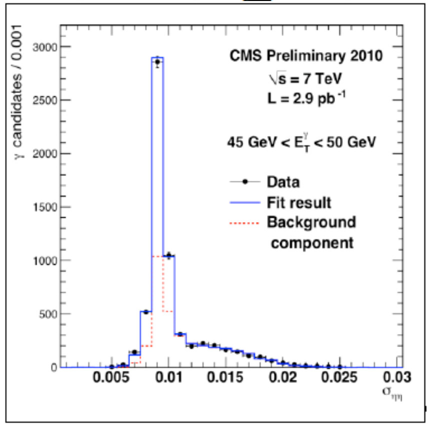
$$\mathcal{L} = -\ln L = -(N_S + N_B) + \sum^{n} N_i \ln(N_S \mathcal{S}_i + N_B \mathcal{B}_i)$$

Shower shape definition

$$\sigma_{i\eta i\eta}^{2} = \frac{\sum (\eta_i - \bar{\eta})^2 w_i}{w_i}, \quad \bar{\eta} = \frac{\sum \eta_i w_i}{\sum w_i}$$

$$w_i = \max(0, 4.7 + \log(E_i / E_{5x5}))$$



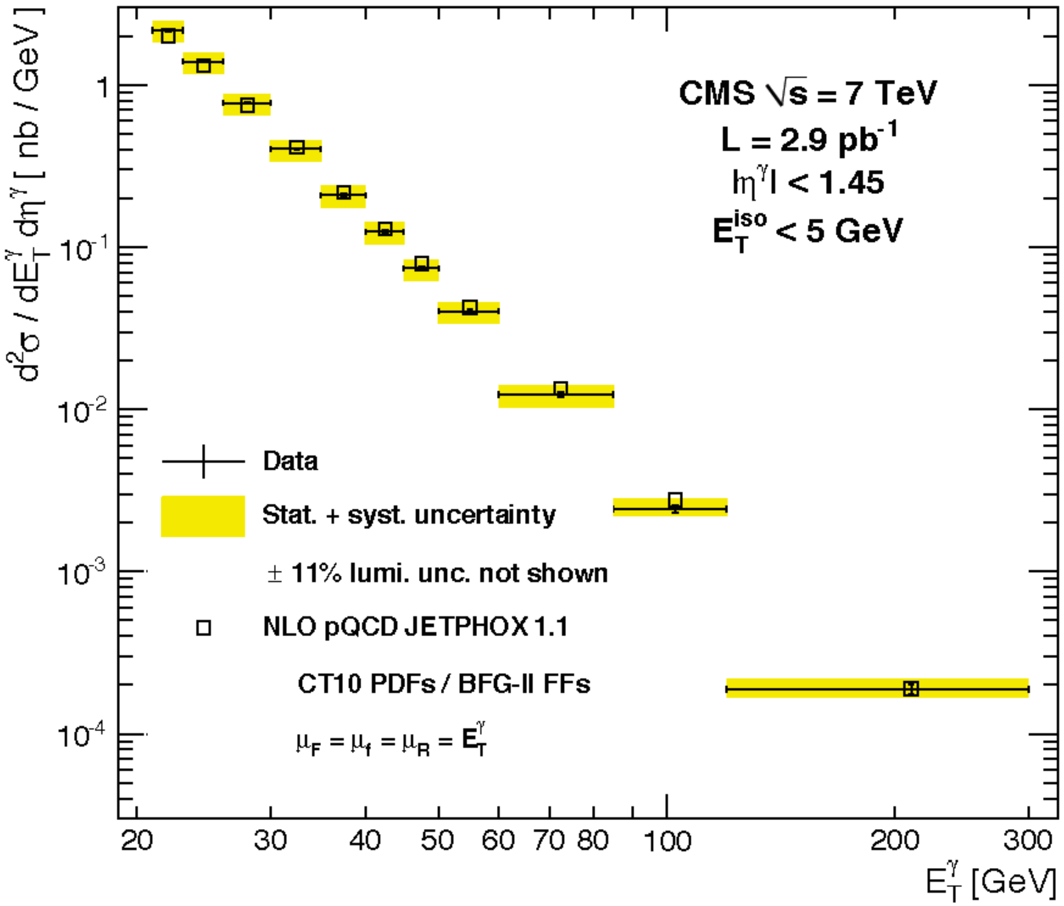


Inclusive Photon Cross Section

$$d^2\sigma/dE_T^\gamma d\eta^\gamma = N^\gamma/(L \cdot \mathcal{U} \cdot \epsilon \cdot \Delta E_T^\gamma \cdot \Delta\eta^\gamma)$$

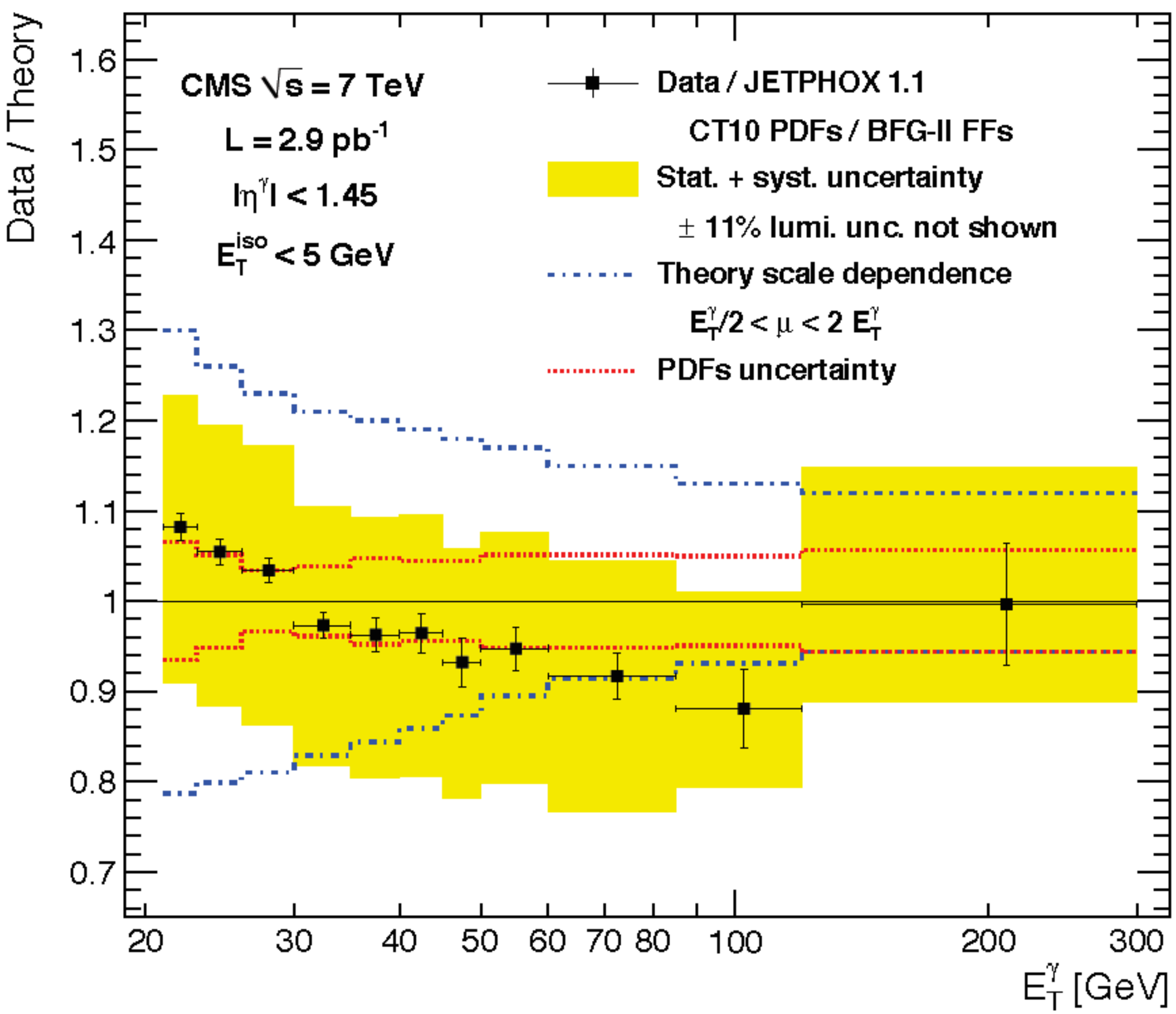
Phys.Rev.Lett.106:082001,2011.

- Good agreement with NLO prediction.
- Experimental systematic uncertainty varies from 10% to 16% with the dominant source being from the background template shape.
- Dominant theoretical systematic uncertainty is the scale dependence.



Inclusive Photon Cross Section

Phys.Rev.Lett.106:082001,2011.



Good agreement of data with pQCD at NLO

Summary - Conclusions

- CMS has very good understanding of jet reconstruction and calibration as well as photon reconstruction and identification.
- Using these physics objects many important as well as challenging QCD measurements have been performed and published.
- The agreement between data and pQCD at NLO has been surprisingly good.
- With the 2011 data, CMS plans to perform precision studies and differentiate between the various PDFs , and perhaps gets a glimpse of the "unexpected".

BACKUP

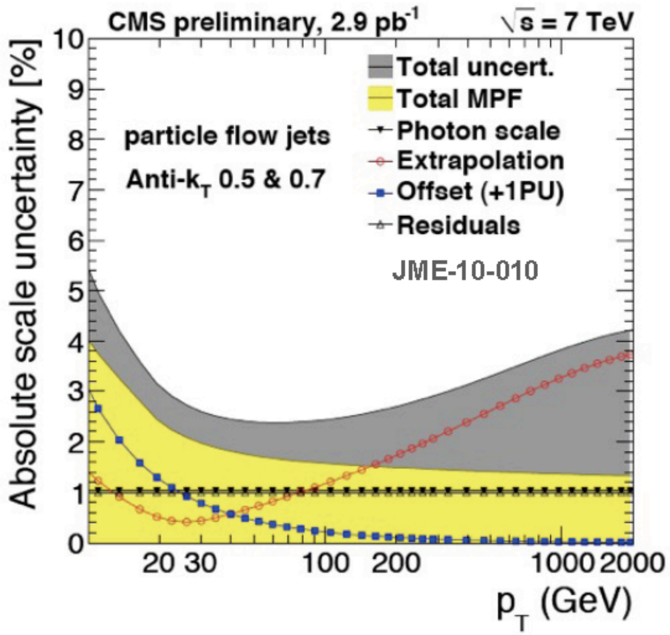
Jet Calibration

Physics Object

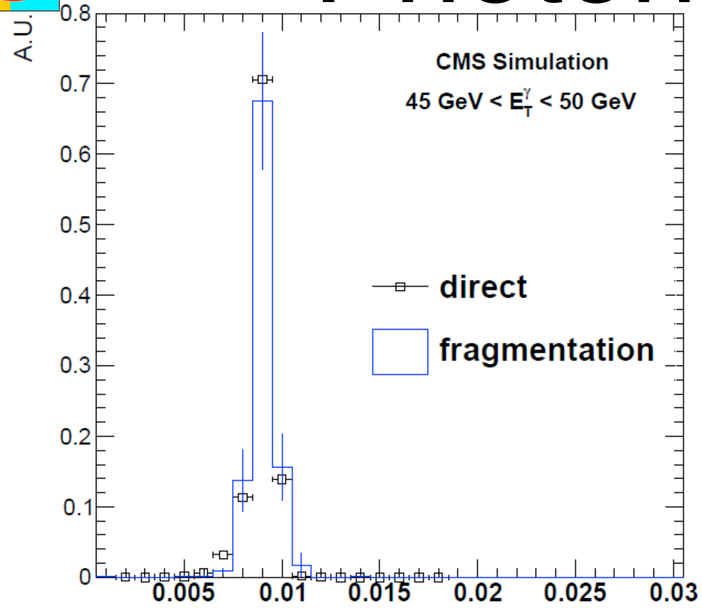
- Dijet asymmetry

Raw Jet × Offset Correction (pile up) × Relative Response (vs. η) × Absolute Response (vs. p_T) = Calibrated Jet

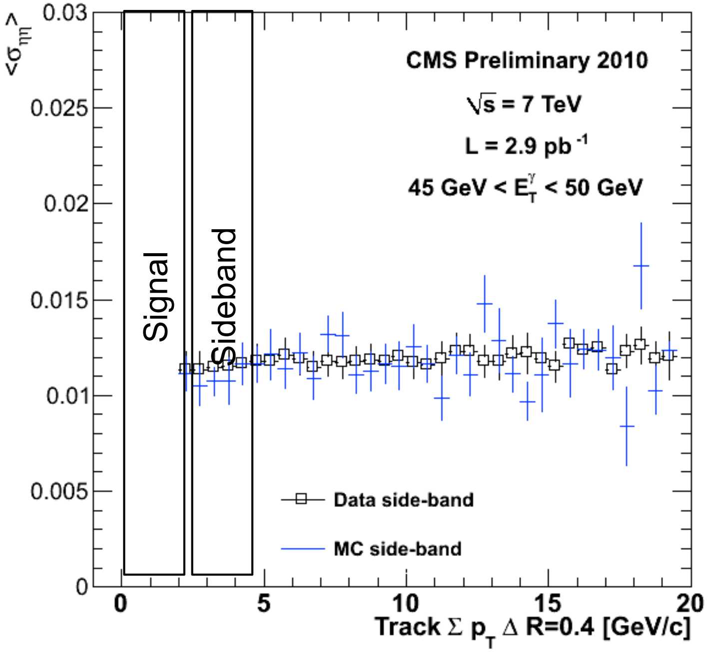
- Photon+Jet Balance



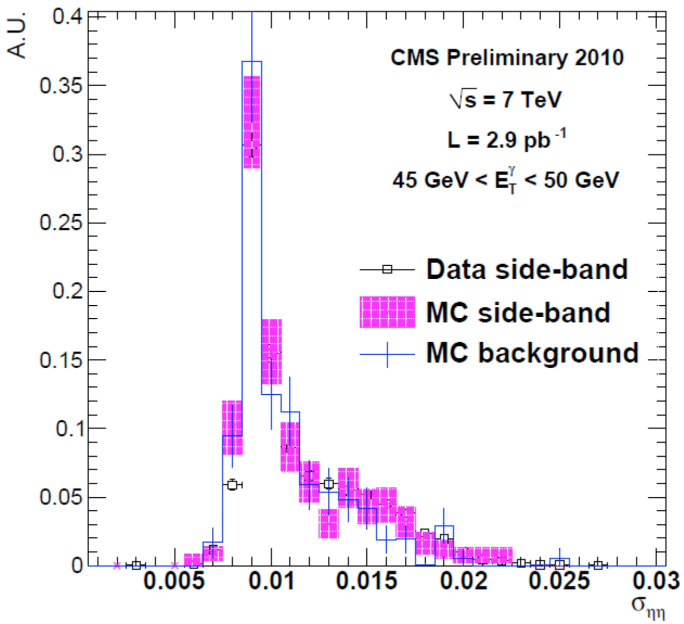
Photon Shower Shape



Signal shape : Pythia MC



Background Shape: Track Isolation Sideband



Theory Predictions

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

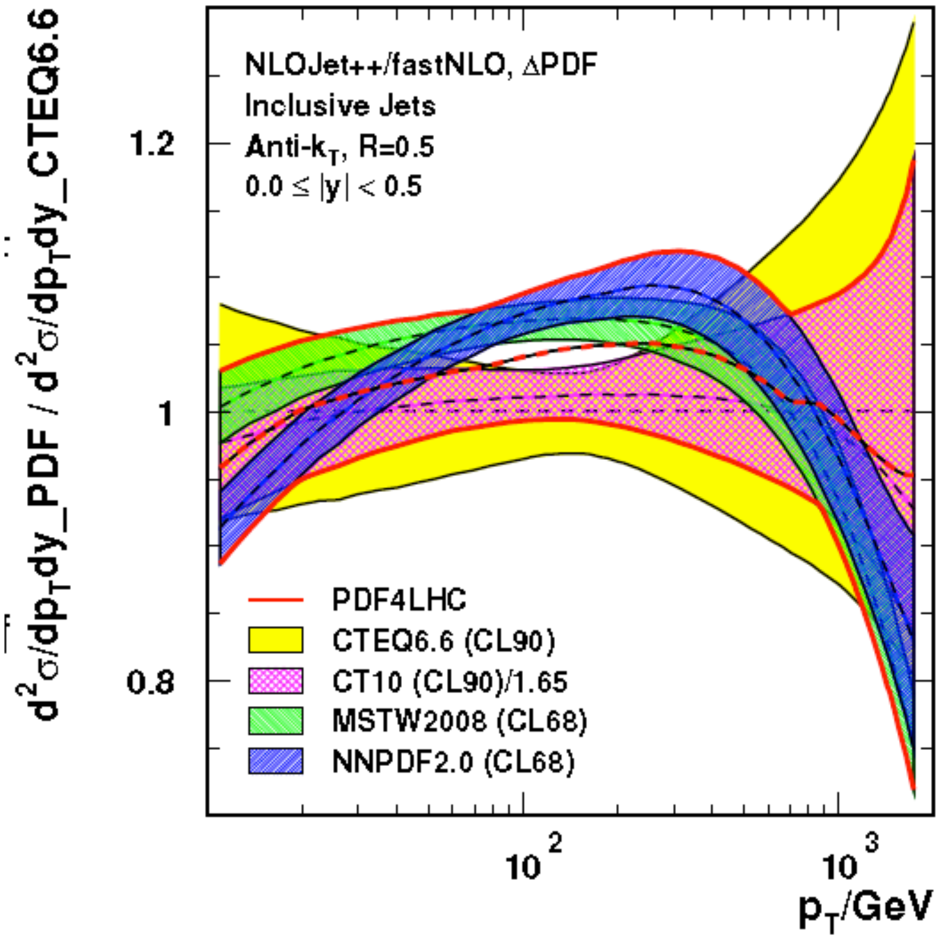
- **Proton PDFs**
  - CT10: αS(MZ) = 0.1180
  - MSTW2008: αS(MZ) = 0.1202
  - NNPDF2.0: αS(MZ) = 0.1190

- **Perturbative QCD Calculations**
  - Next to leading order using NLOJet++ program at the fastNLO package

- **Non Perturbative Corrections**
  - MPI
  - Hadronization

PDF4LHC

- **The PDF4LHC prescription describes the way to combine the various PDFs:**
  - compute the observable of interest 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

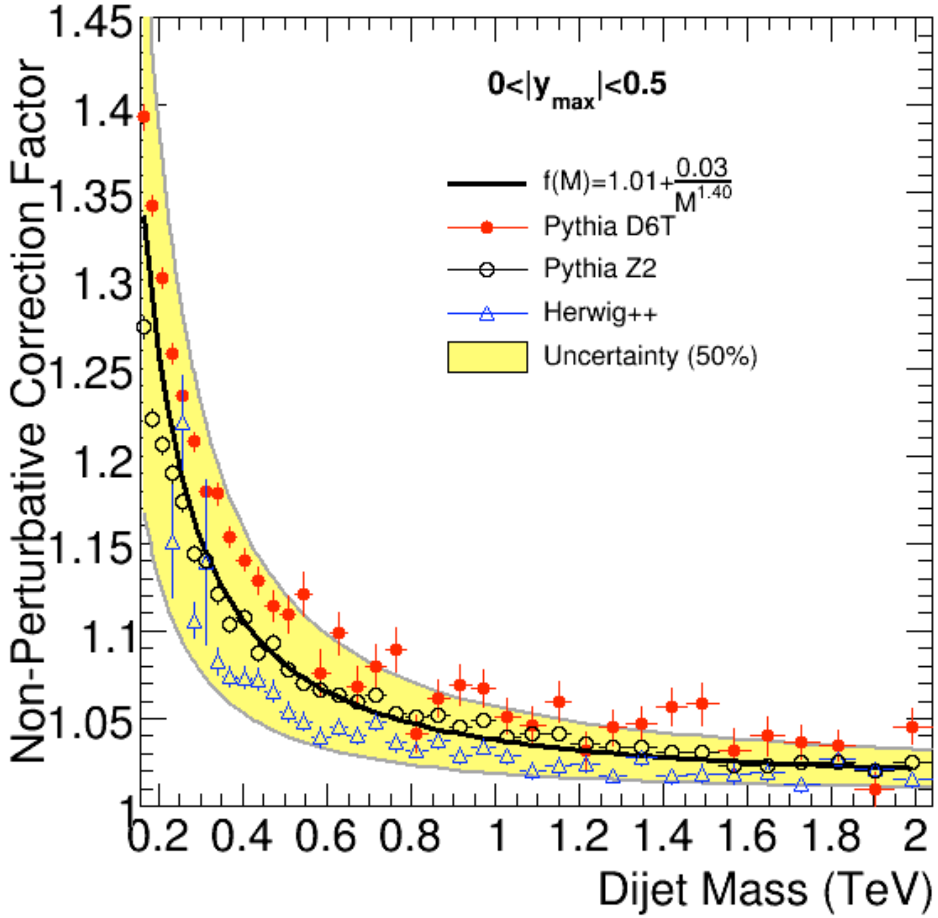


Non perturbative corrections

- Non perturbative corrections needed to go from parton to particle level, and hence be able to compare theory with data.

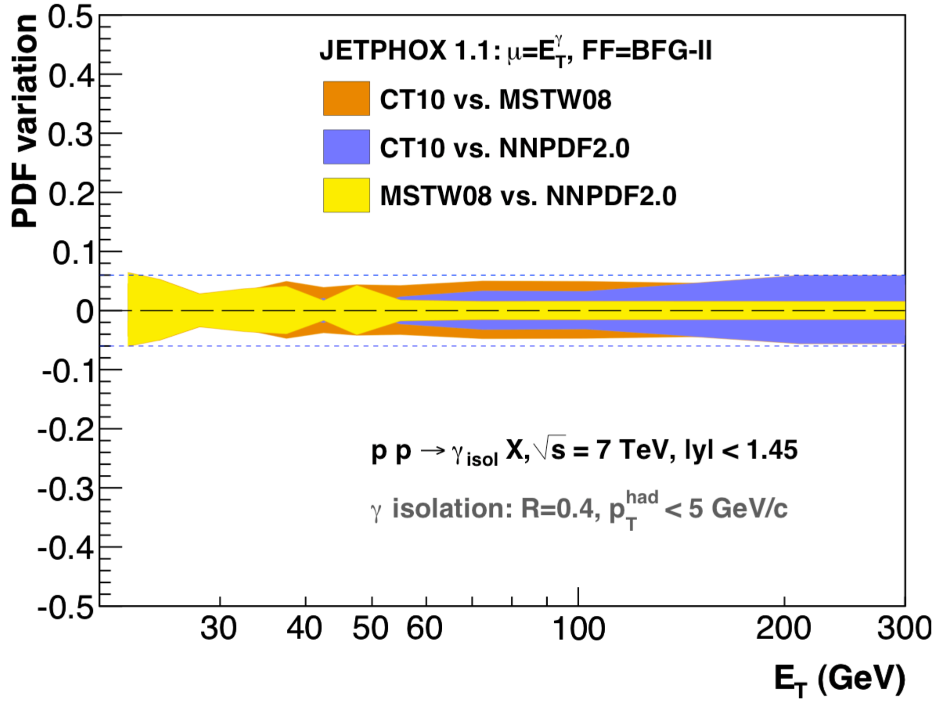
- Non perturbative corrections account for :
  - Multi-parton interactions
  - Hadronization effects

- Use different MC generators to estimate, and take spread as systematic uncertainty.



JetPhox Predictions

- NLO pQCD
  - JETPHOX1.1,CT10 PDFs, BFG II FF
  - Renormalization, fragmentation, and factorization scales set to ET
  - Require “isolated” definition: ΣET<5 GeV within R<0.4
- Scale uncertainty
  - 30 to 11% with ET, change all scales to ET/2 and 2ET
- PDF uncertainty
  - 6% over full ET range
- Envelope of CT10, MSTW08 and NNPDF2.0 (PDF4LHC recommendation)
- CTEQ6M instead of CT10: 3%
- BFG I instead of BFG II: <1%

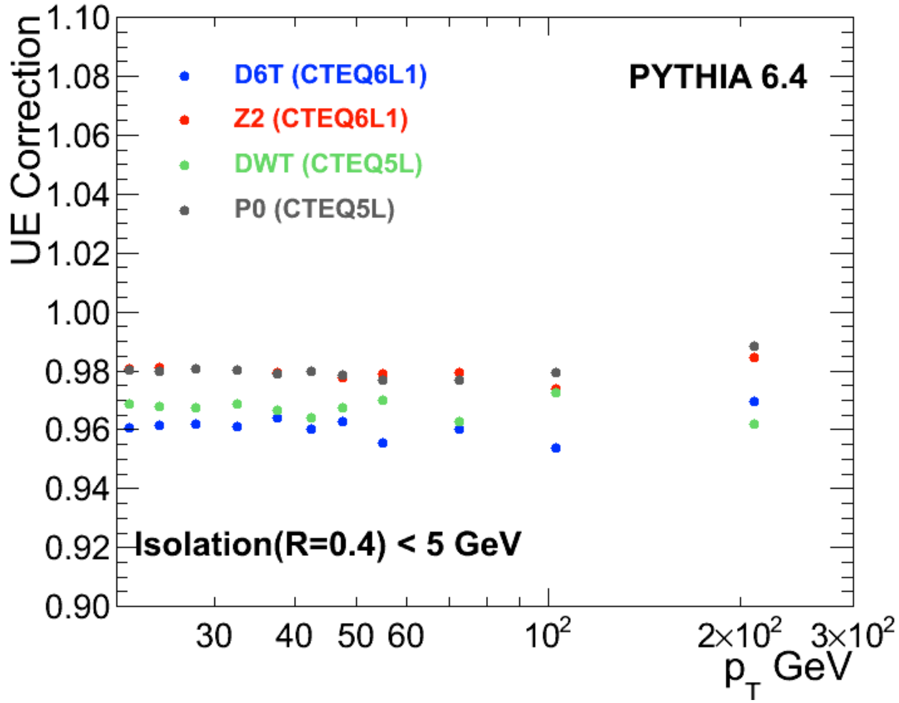


Non Perturbative Corrections

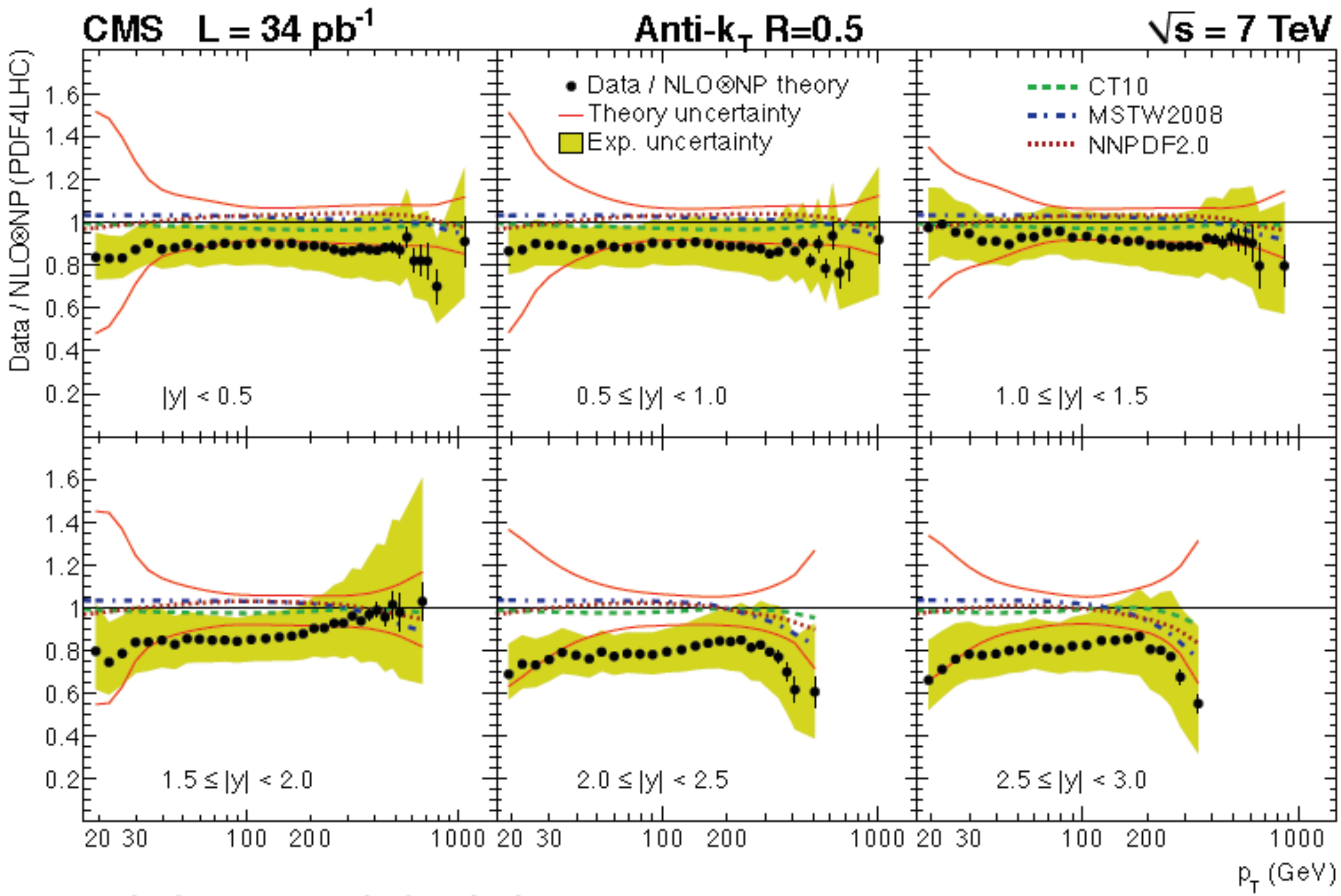
- Non-perturbative effects increase energy in isolation cone

- Correction is obtained by comparing the efficiency of isolation cut of 5GeV in a cone of radius 0.4 with and without:
  - Multi-parton interaction
  - Hadronization

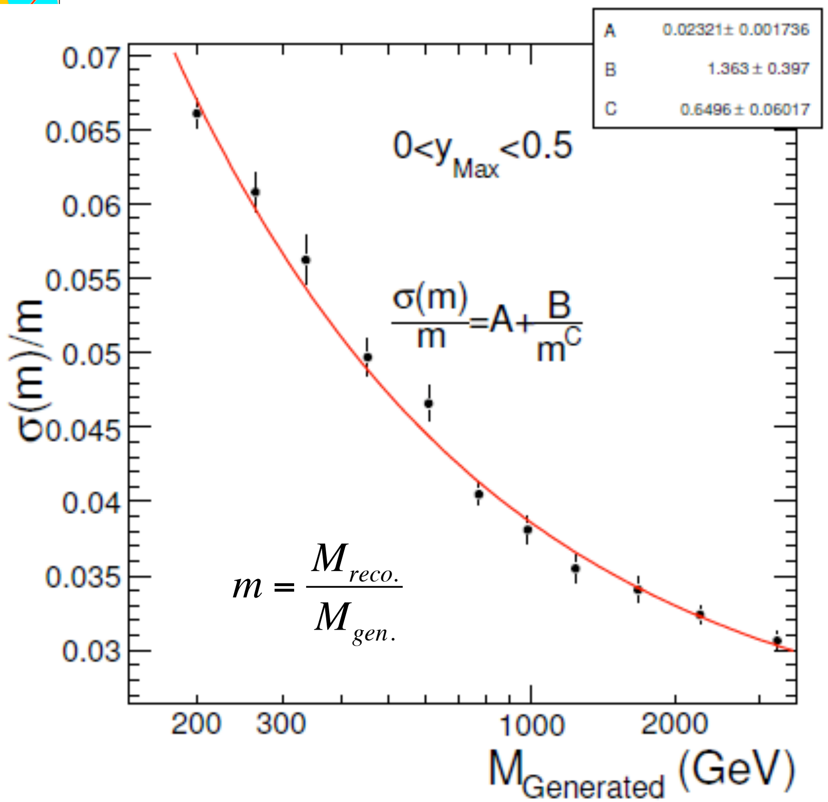
- Final correction is the mean of the four different tunes considered
  - D6T
  - Z2
  - DWT
  - P0

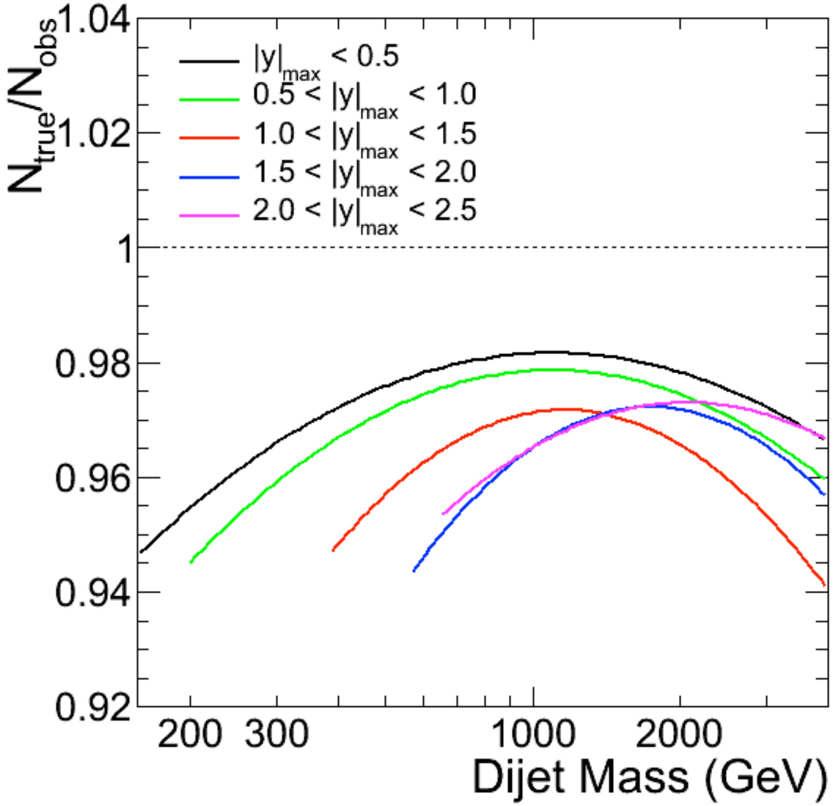


- ~3% overall correction applied to the NLO calculation


CMS L = 34 pb-1
Anti-kT R=0.5
√s = 7 TeV
Data / NLO⊗NP (PDF4LHC)
Data / NLO⊗NP theory
Theory uncertainty
Exp. uncertainty
CT10
MSTW2008
NNPDF2.0
|y| < 0.5
0.5 ≤ |y| < 1.0
1.0 ≤ |y| < 1.5
1.5 ≤ |y| < 2.0
2.0 ≤ |y| < 2.5
2.5 ≤ |y| < 3.0
pT (GeV)

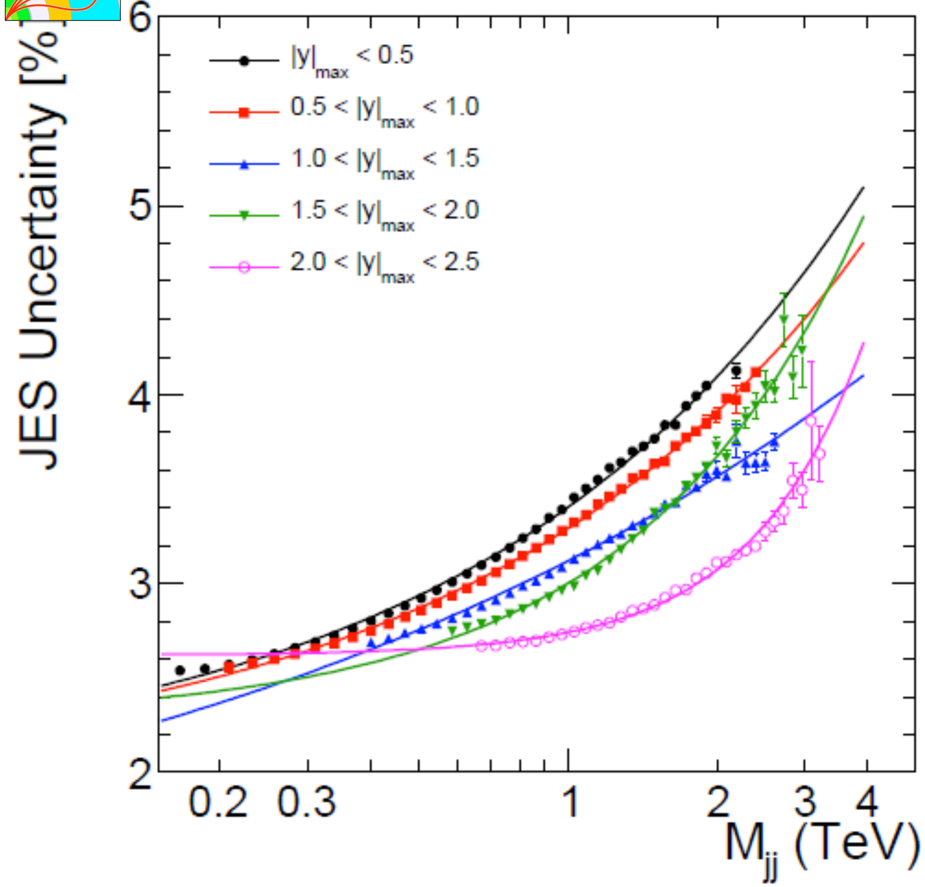
Smearing Correction

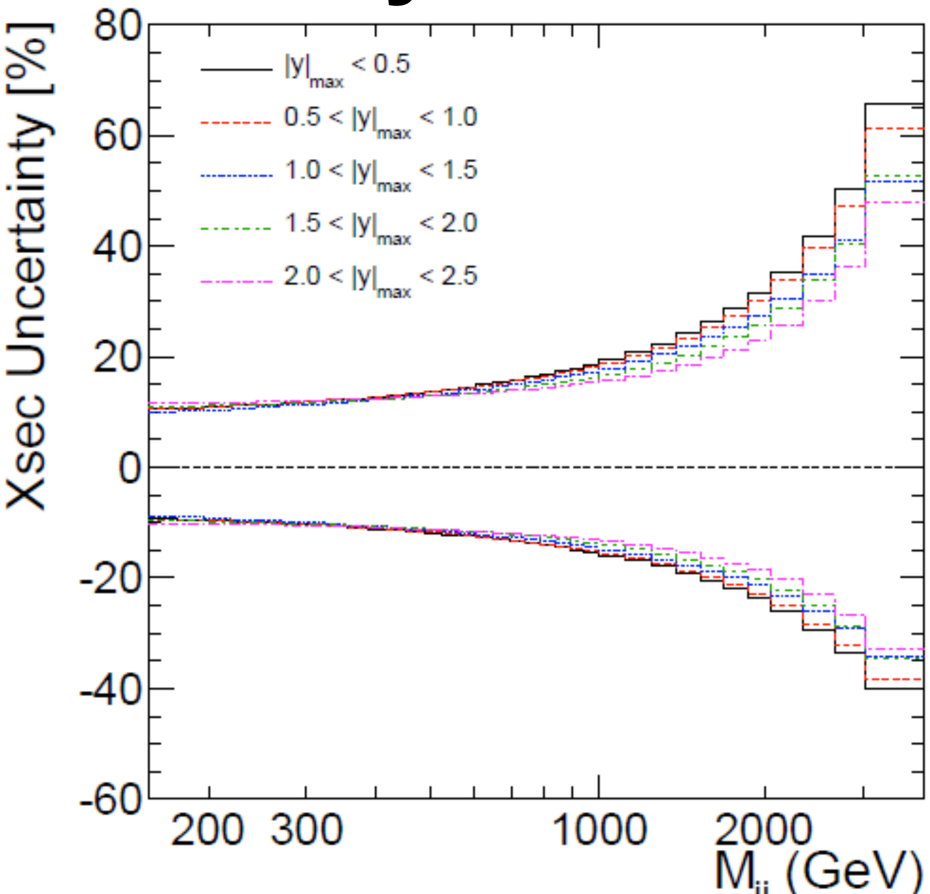




- Unfolding correction through forward smearing : Generate true jet mass according to the NLO spectrum and smear using the MC mass resolution (bin by bin correction)
- Straightforward to study the systematics by varying the spectrum slope and the Dijet mass resolution
- The result agrees with the more advanced SVD and Bayes Unfolding methods
- The unfolding correction is small (between 0.94 and 0.98) for all rapidity bins

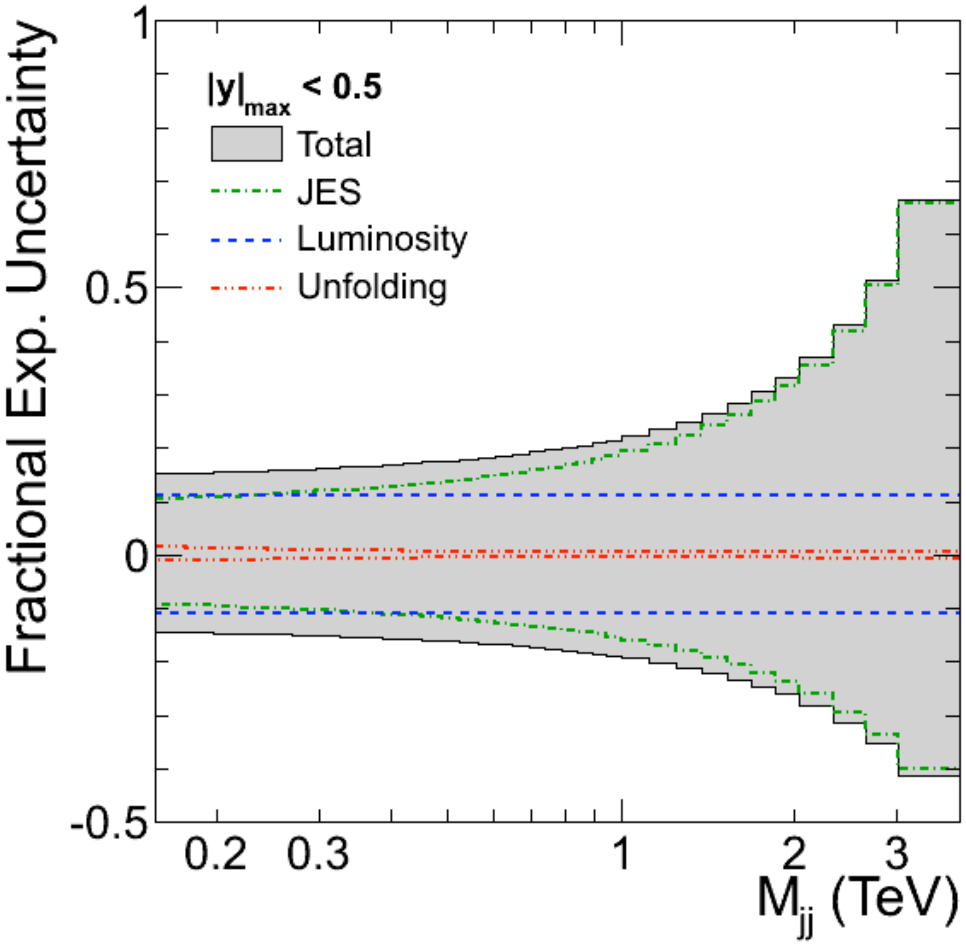
JES Uncertainty





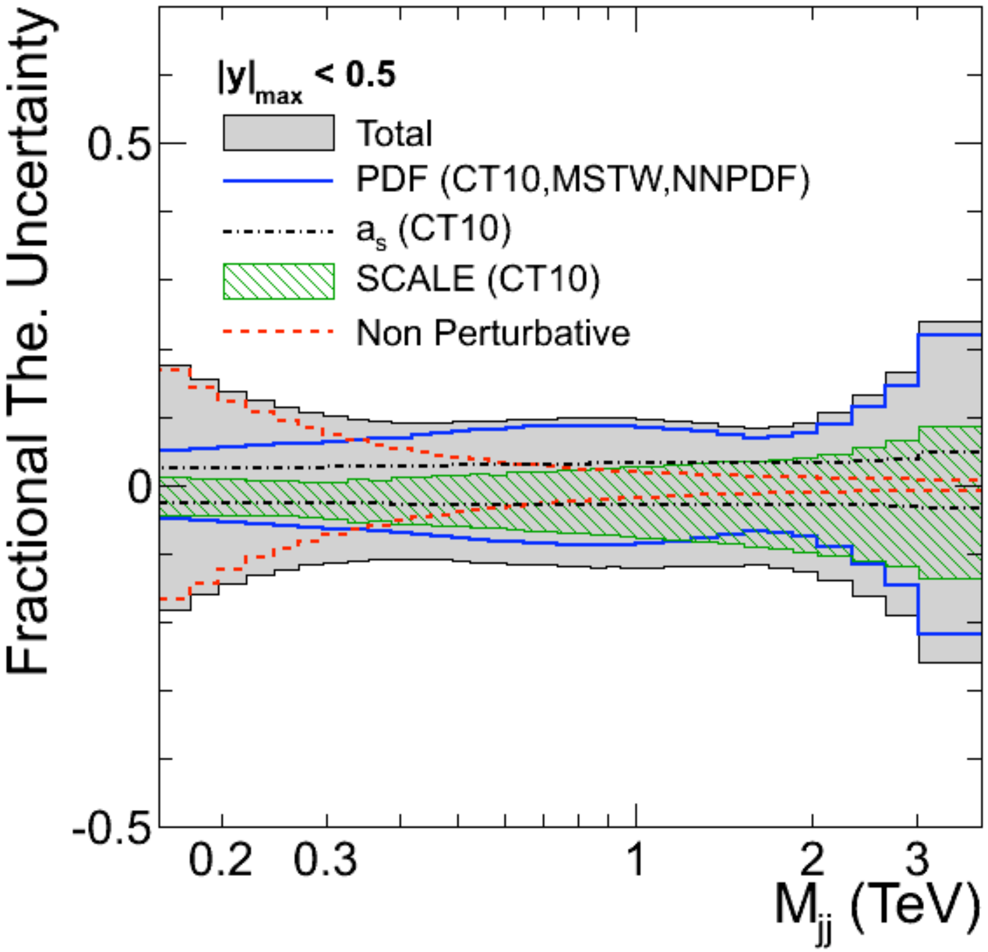
- The JES uncertainty is mapped on the dijet mass variable through “jet-by-jet” shifting and taking the average over all jets in each rapidity bin.
- For outer rapidity bins, the mass scale uncertainty is lower because it probes smaller jet p_T.

Experimental Uncertainties



- The total experimental uncertainty ranges from ~15% at low mass values to ~60% at high mass values.
- This is almost the same for all rapidity bins
- The major contribution to the total experimental uncertainty comes from the JES uncertainty
- The unsmearing uncertainty is of order ~2 -3%

Theoretical Uncertainties



- The PDF uncertainty is estimated according to the PDF4LHC prescription through the variation of the PDF sets.

- Maximal deviation of the six point variation is used to estimate the renormalization and factorization scale uncertainties (μ_R/pT_{ave} , μ_F/pT_{ave})=(1/2, 1/2), (2, 2), (1, 1/2), (1, 2), (1/2, 1), (2, 1)

- The non-perturbation correction uncertainty is estimated as half of the NP correction deviation from unity