# Hard QCD @ CMS

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QCD@LHC 2011

# Outline

- Overview of the QCD physics program at the LHC
- CMS detector
    - Detection techniques for jets
- CMS has produced a large amount of QCD measurements on the 2010 data sample
    - Jet inclusive spectra
    - Di-jet mass, angular correlations
    - Event shapes
    - Forward jets
    - Inclusive photon production differential spectra
    - W/Z + jets, Z+ heavy flavor

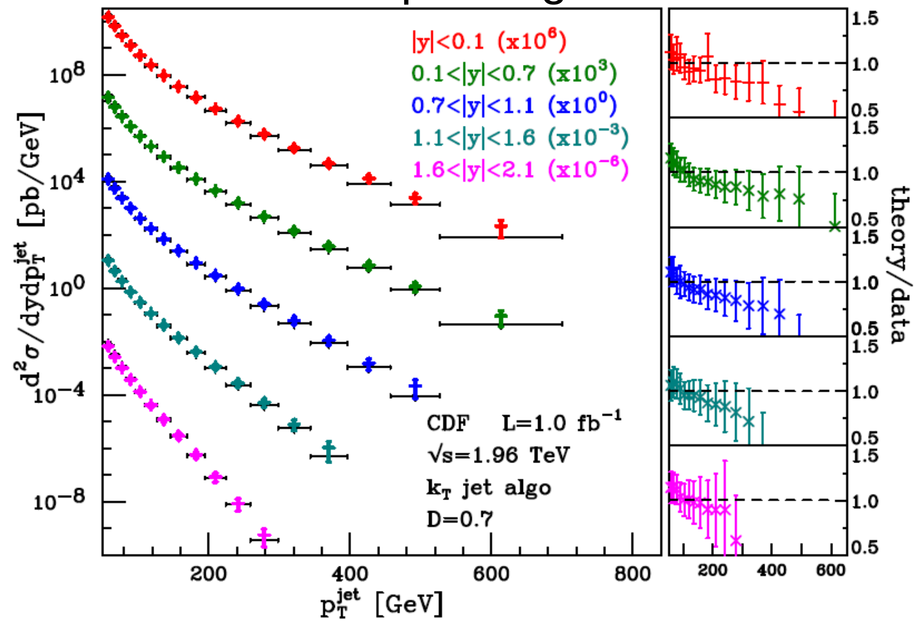
# Hard QCD at LHC

- Hard QCD processes are important for two broad classes of reasons
  - They represent a ubiquitous source of background for virtually any signal (both SM and searches) at a hadron collider
  - They provide a tool to test the predictions of perturbative QCD
    - The current understanding of our detectors allows both ATLAS and CMS collaborations to do <u>precision</u> QCD measurements

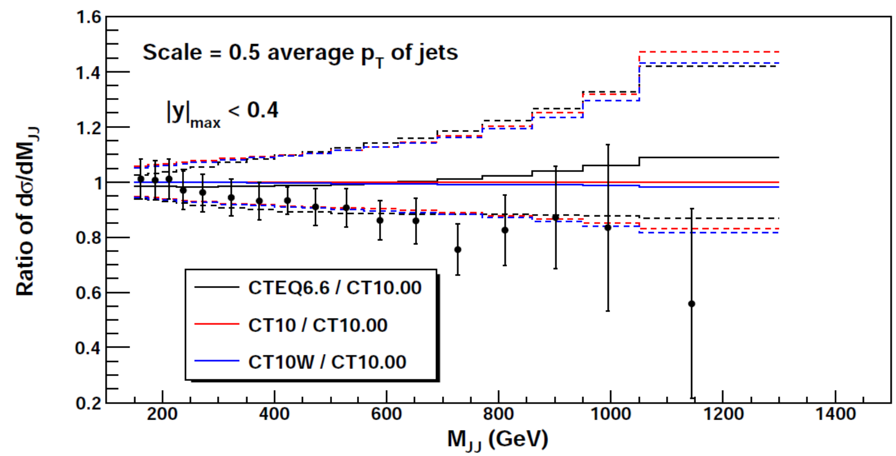
# Available predictions

- Accurate predictions for dijet production, W/Z/gamma + jets production at the LHC are available
  - Monte Carlo event generators
    - NLO + parton shower (MC@NLO, POWHEG)
    - LO (many legs) + parton shower (Alpgen, MadGraph, Sherpa)
  - Parton level codes for distributions at NLO
- Modern parton distribution functions

powheg

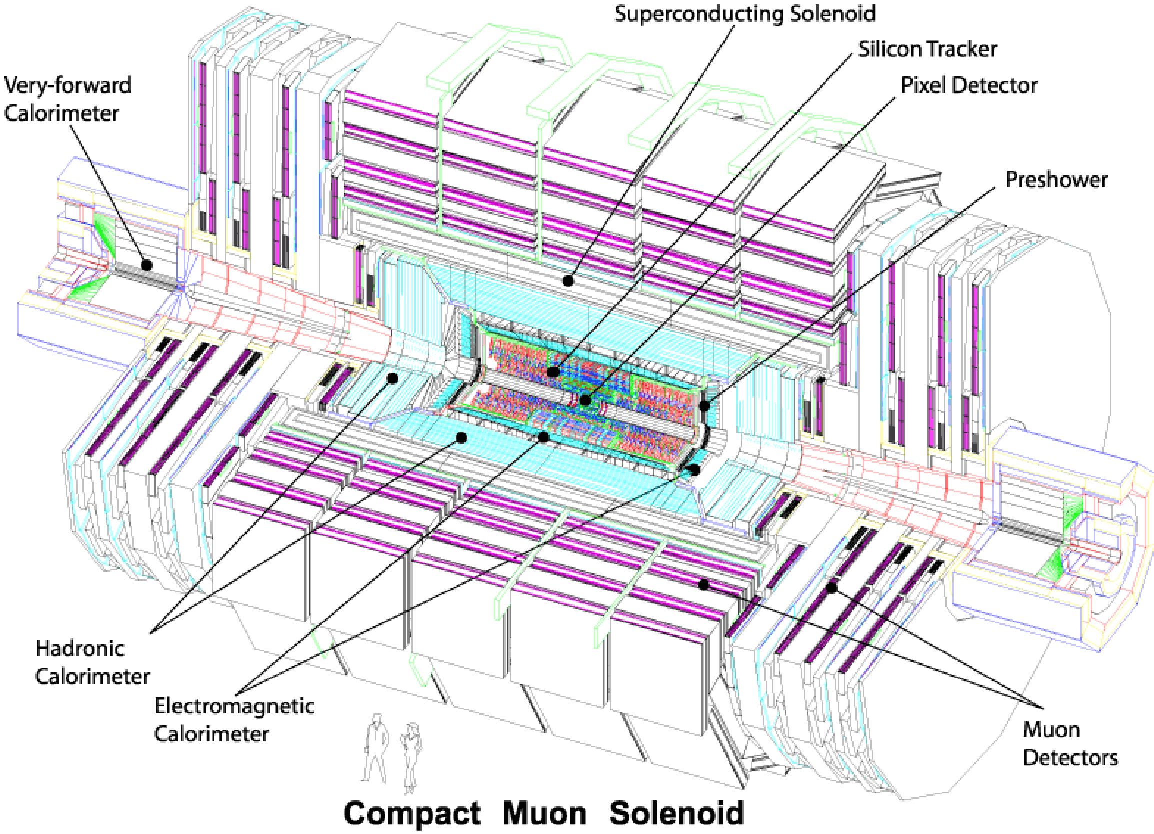



Modern PDFs



# CMS detector

- 4 T solenoid
- Pixel + SiStrip tracker
- Scintillating crystals ($PbWO_4$) electromagnetic calorimeter
- Brass/plastic hadron calorimeter (non-compensating)
- Muon spectrometer in the magnet iron return yoke



# Jet reconstruction

- Jets are reconstructed with the anti-kt algorithm, with radius of 0.5 or 0.7
- 3 available algorithms for jet reconstruction
  - Calo-Jets: use only the calorimeter towers
  - Jet-Plus-Track Jets: improve the calorimeter jets using the tracks in the jet cone
  - Particle-Flow jets: uses particle flow candidates as input to the clustering algorithm
    - Particle flow reconstruction:
      - global event reconstruction
      - Identifies muons, electrons, taus, photons, charged hadron, neutral hadrons
      - Combines the information from all detectors

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# Jet energy scale

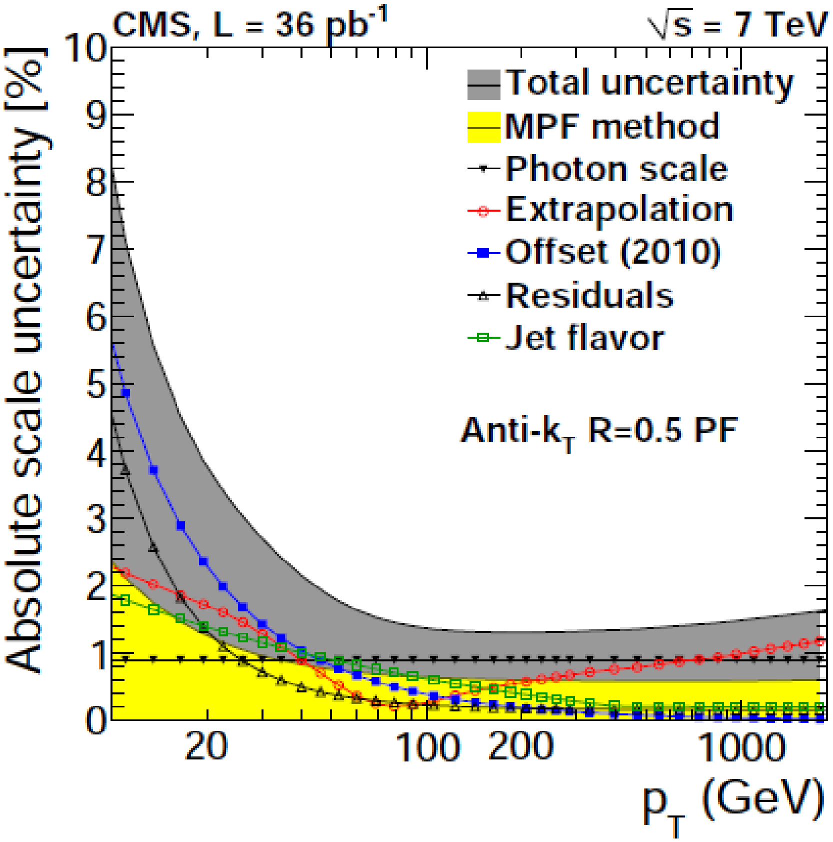
- We use a multi-step procedure to correct the energy of our jets

$$p_{\mu}^{cor} = \mathcal{C} \cdot p_{\mu}^{raw}. \qquad \mathcal{C} = C_{\text{offset}}(p_T^{raw}) \cdot C_{\text{MC}}(p_T', \eta) \cdot C_{\text{rel}}(\eta) \cdot C_{\text{abs}}(p_T'')$$

  - $C_{offset}$ accounts for detector noise and pile-up
  - The method uses correction factors extracted from the full simulation of CMS, $C_{MC}$
  - Residual differences with respect to data are accounted for as further scaling factors
    - $C_{rel}$ accounts for non-uniformity in eta. It is obtained applying on data and MC the di-jet balance method
    - $C_{abs}$ accounts for residual absolute scale differences between data and MC. It is obtained applying on data and MC the γ+jet and Z +jet pT balancing
  - In this MC + residual method effects like the presence of additional radiation spoiling dijet or γ+jet and Z +jet balancing enter only at second order

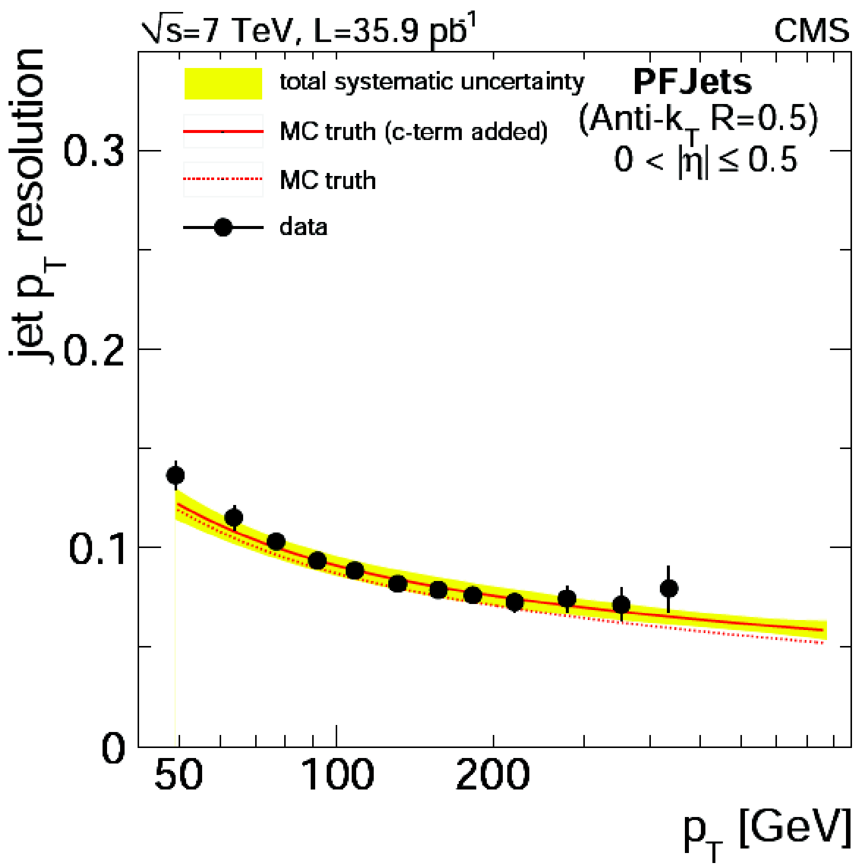
# Jet energy scale

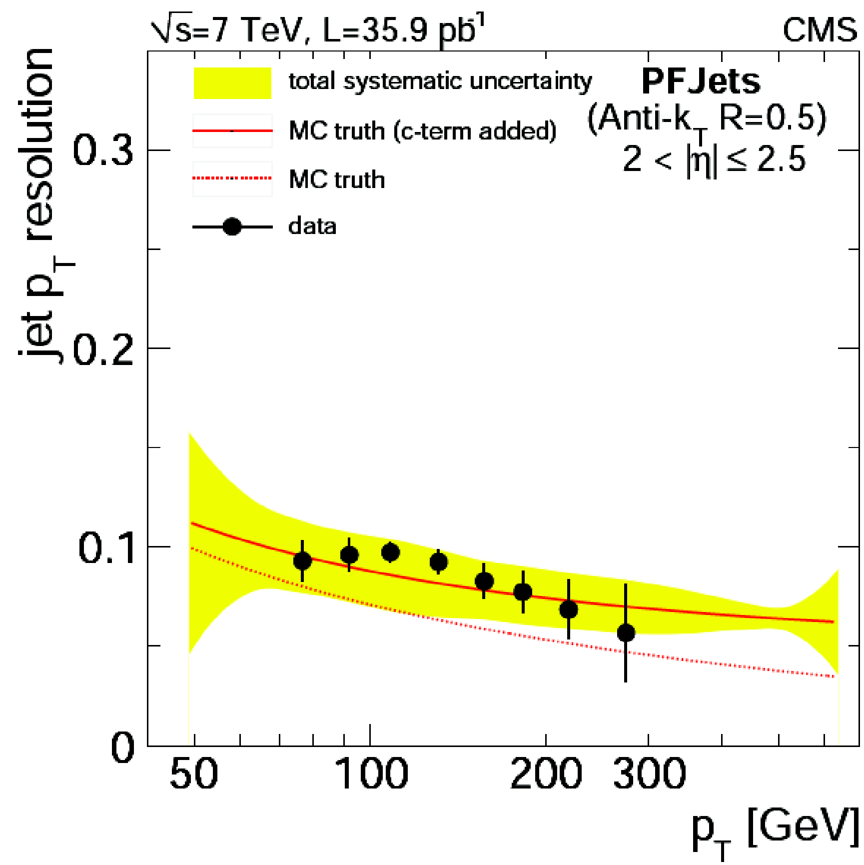
- Total systematic uncertainty on the energy scale for particle-flow jets
- The main sources of uncertainty are:
  - The photon energy scale, known at 1%
  - The relative response across detector regions
  - Pile-up effects
  - Extrapolations down to 0 for the additional activity in the balance methods
  - Dependency on jet flavor in the MC used



# Jet energy resolution

- Determined with di-jet and γ+jet pT balance
  - Plots show two example regions in η
  - Resolution is of the order of 10% around 50 GeV

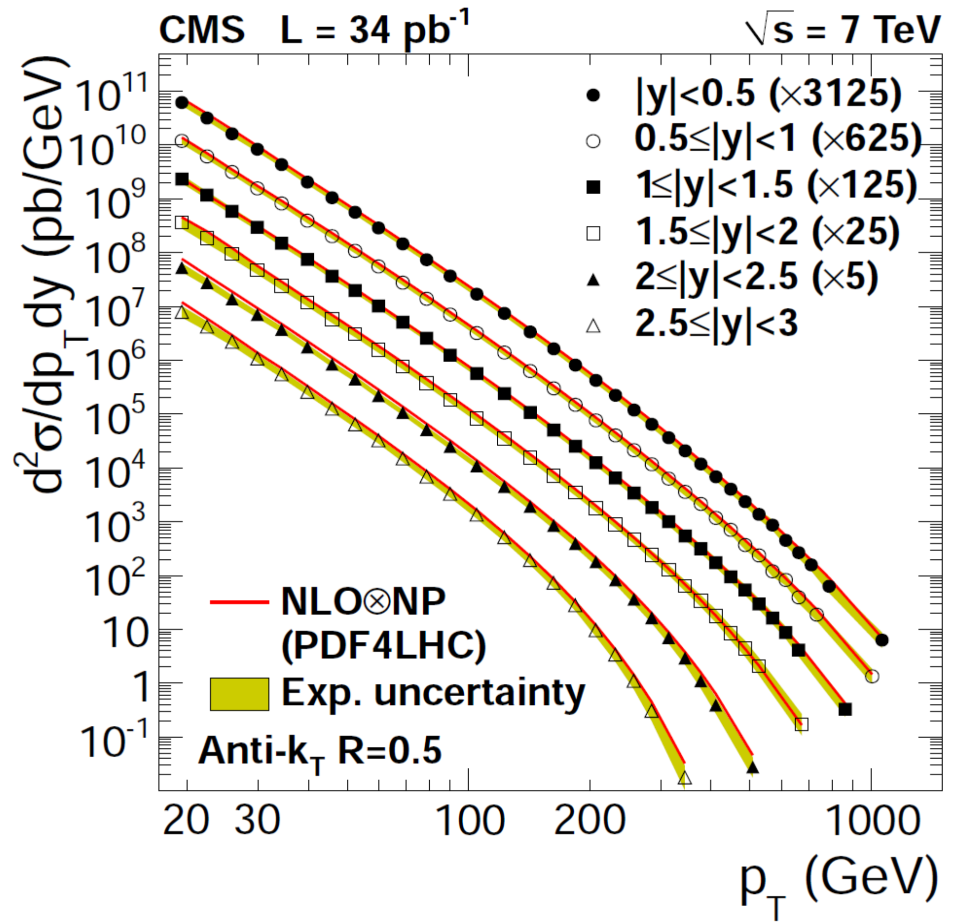


# Inclusive jets

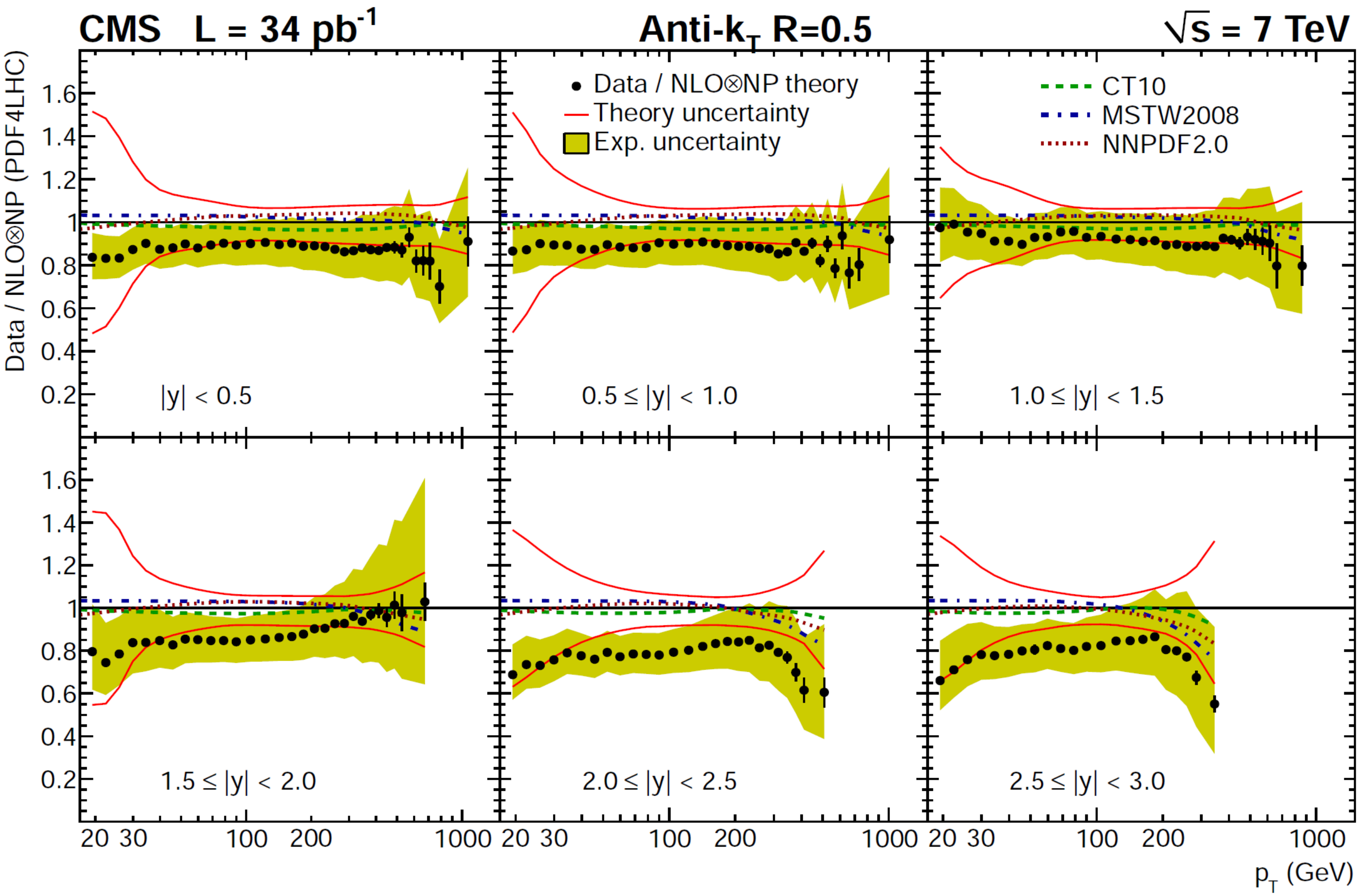
CERN-PH-EP-2011-053

- Jet pT spectra are measured in the 18-1100 GeV range
- In 6 rapidity intervals, up to 3
- Resolution effect are unfolded
- Main systematic: jet energy scale
- Data are compared with the predictions at NLO, including non-perturbative (NP) corrections obtained with a shower MC



# Inclusive jets

- Data/theory ratios for the 6 rapidity bins
  - Experimental uncertainty represented by shaded area
  - Theoretical uncertainty as solid lines
    - The envelope of predictions from CT10, MSTW08 and NNPDF2.0 is used
    - The central values for the three PDF sets are also shown

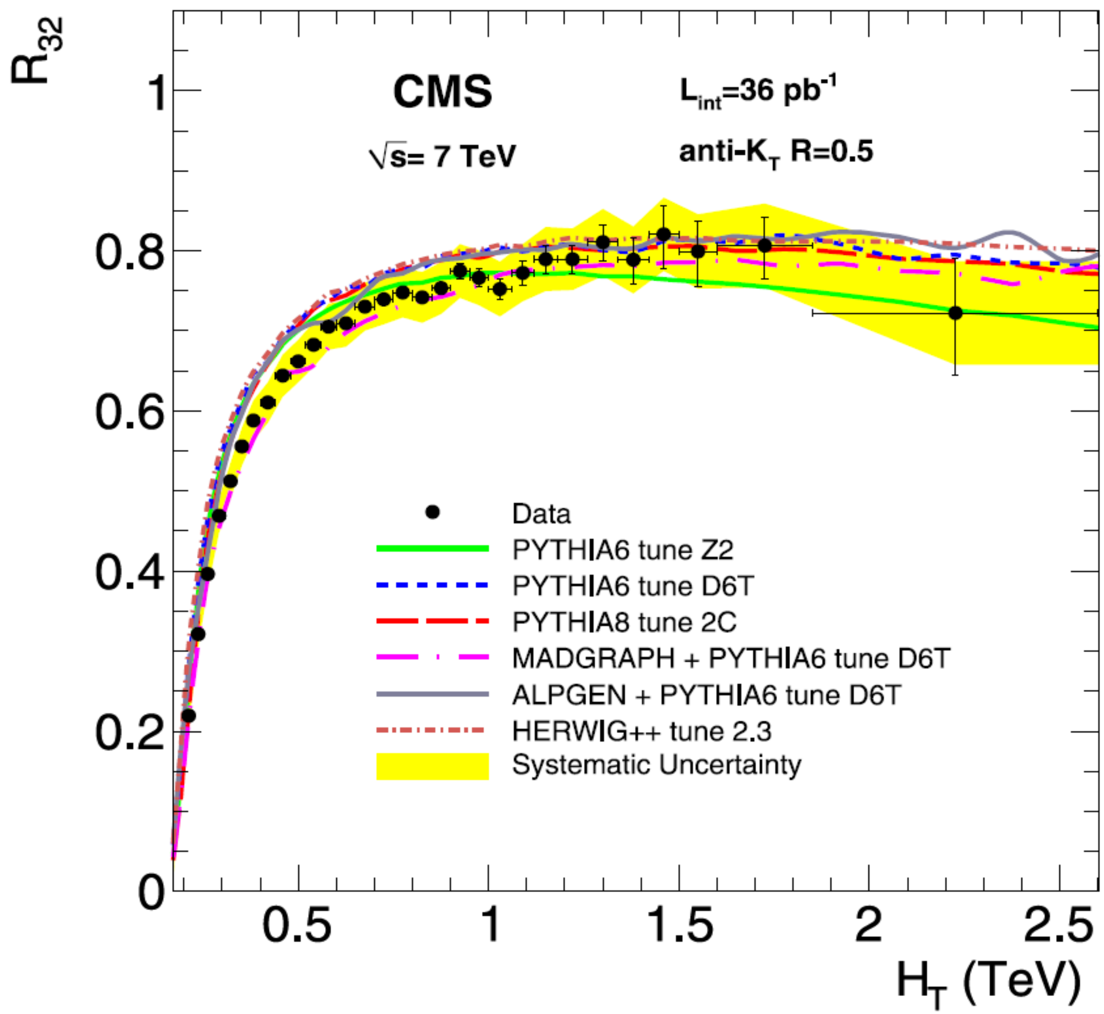



- Data and theory agree within systematic uncertainty
- Predictions are systematically above data
- Shapes of data and of theory central predictions are similar

# 3-jets over 2-jets ratio

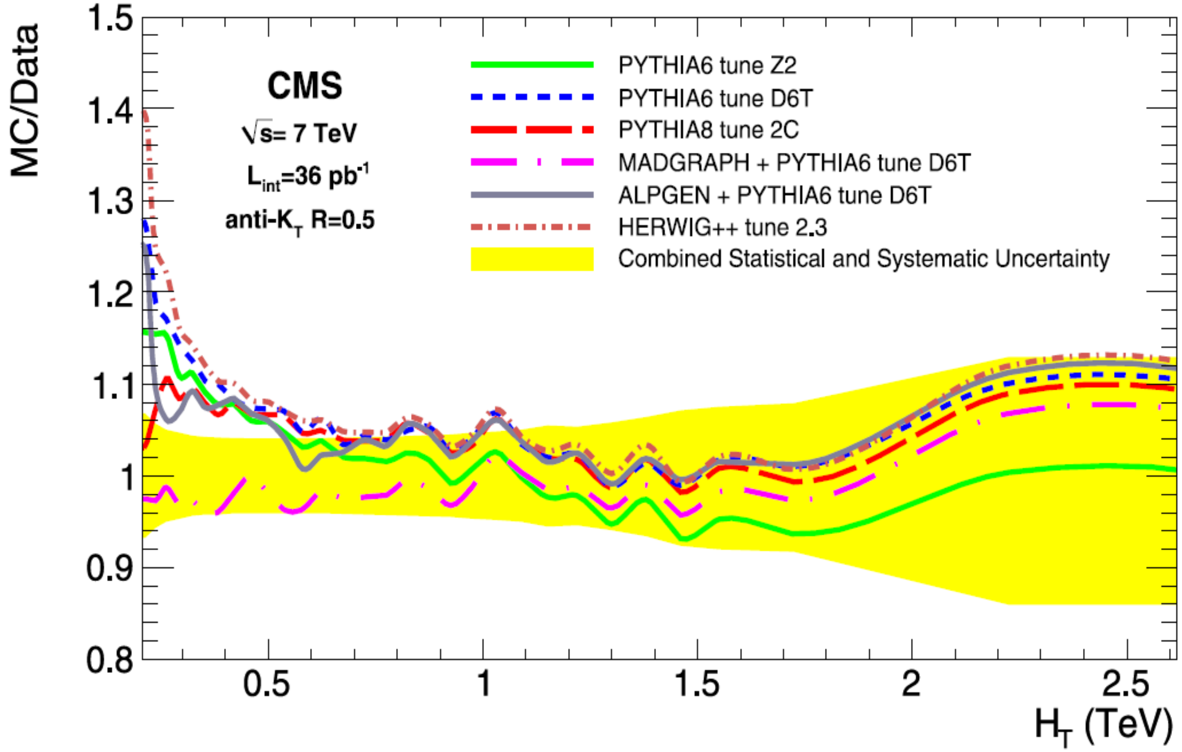
Phys. Lett. B 702 (2011) 336

- Measurement of the ratio of events with 3 or more jets over events with 2 or more jets, as a function of $H_T$ (scalar sum of jets' pT)
  - Jets: pT > 50 GeV, |y|<2.5
- Provides a stringent test of hard gluon radiation and higher order effects
- Several systematic effects cancel (largely or completely)
  - Luminosity
  - Jet energy scale



# 3-jets over 2-jets ratio

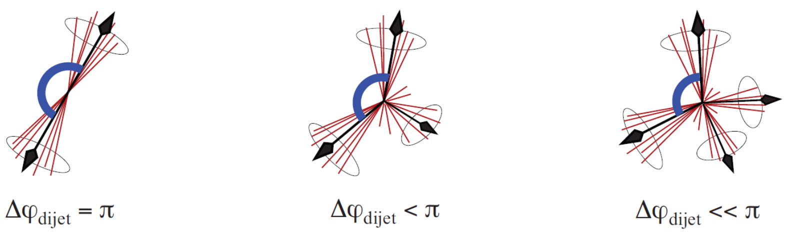
- Data fully corrected for detector effects with bin-by-bin corrections
- Main systematics:
  - Jet energy scale, unfolding uncertainties
- Comparison to several MC models:
  - Madgraph is the closest to data
    - Matched sample with up to 4 partons
- Alpgen doesn't do quite as good
    - Why? Could the difference between Madgraph and alpgen be regarded as an estimate of the theory uncertainty?
- Pure shower models overestimate the ratio for $H_T$<0.5 TeV



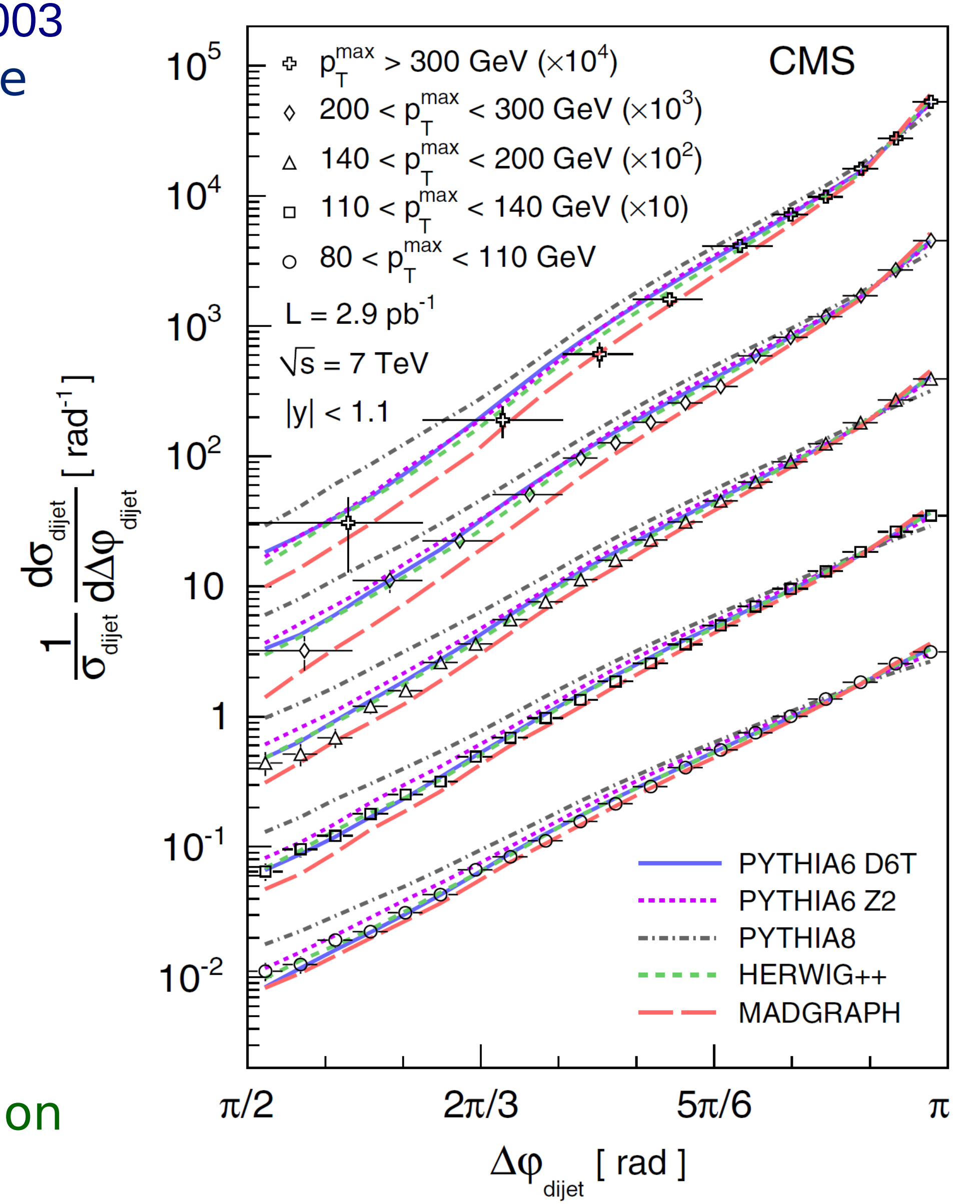
# Azimuthal decorrelation

Phys. Rev. Lett. 106 (2011) 122003

- Δφ between the two leading jets in the event
  - It is very sensitive to additional radiation effects (hence to higher order corrections) but also to MPI and hadronization

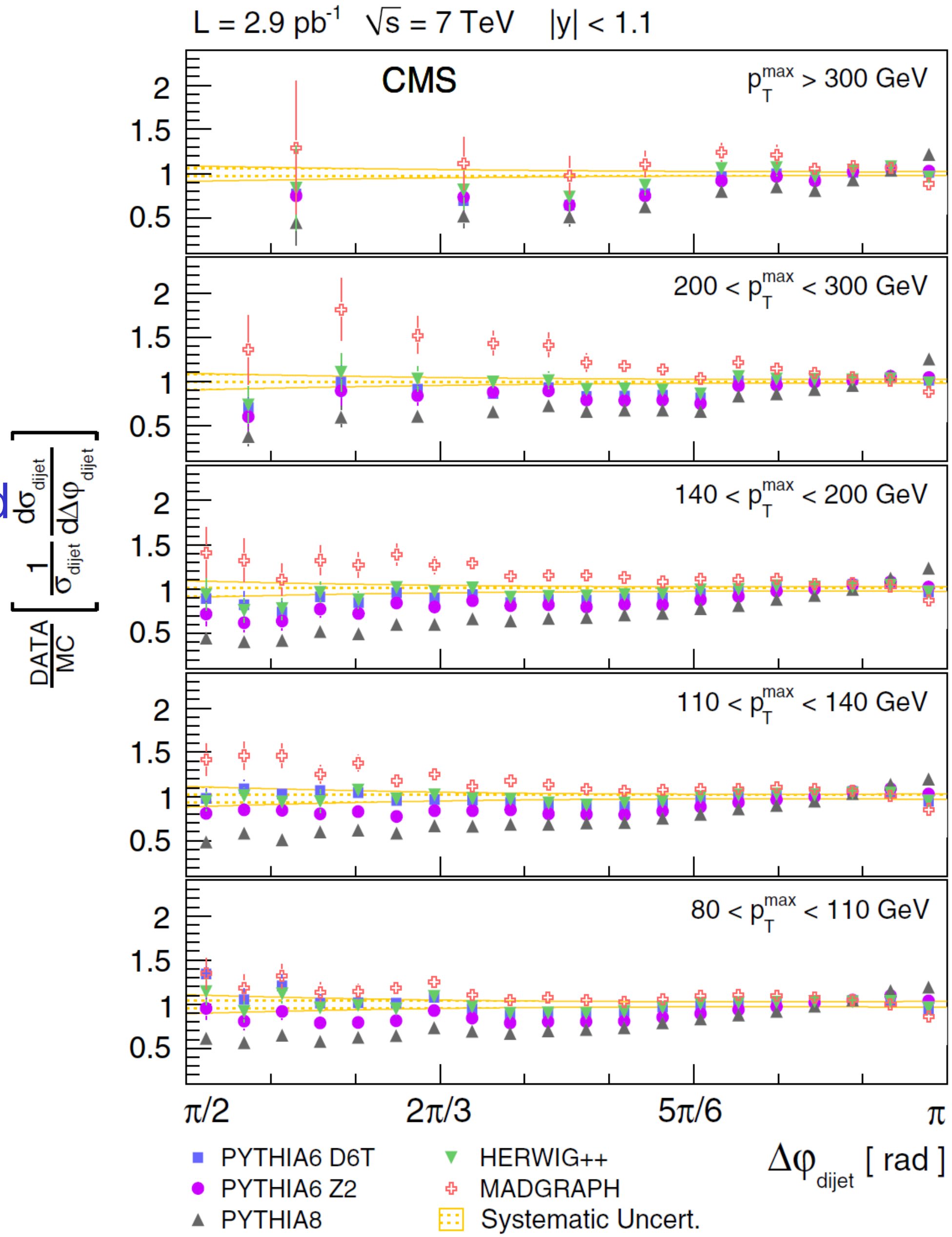



  - Anti-kt (0.5) jets are required to have pT>30 GeV and |y|<1.1
  - Five bins of leading jet pT
  - Data corrected to hadron level
  - Main sources of systematics
    - Jet energy scale
    - Transverse momentum resolution
    - Unfolding



# Azimuthal decorrelation

- Comparison to several MC models
  - Pythia6 and Herwig++ provide the best description of data
  - Madgraph (Pythia8) predict less (more) decorrelation
  - Surprisingly, the matched calculation implemented in Madgraph doesn't provide a good description of data
    - Might be due to interplay between higher order corrections and tuning aspects
      - Might learn something about tuning
      - It would be useful to compare to other ME + PS models



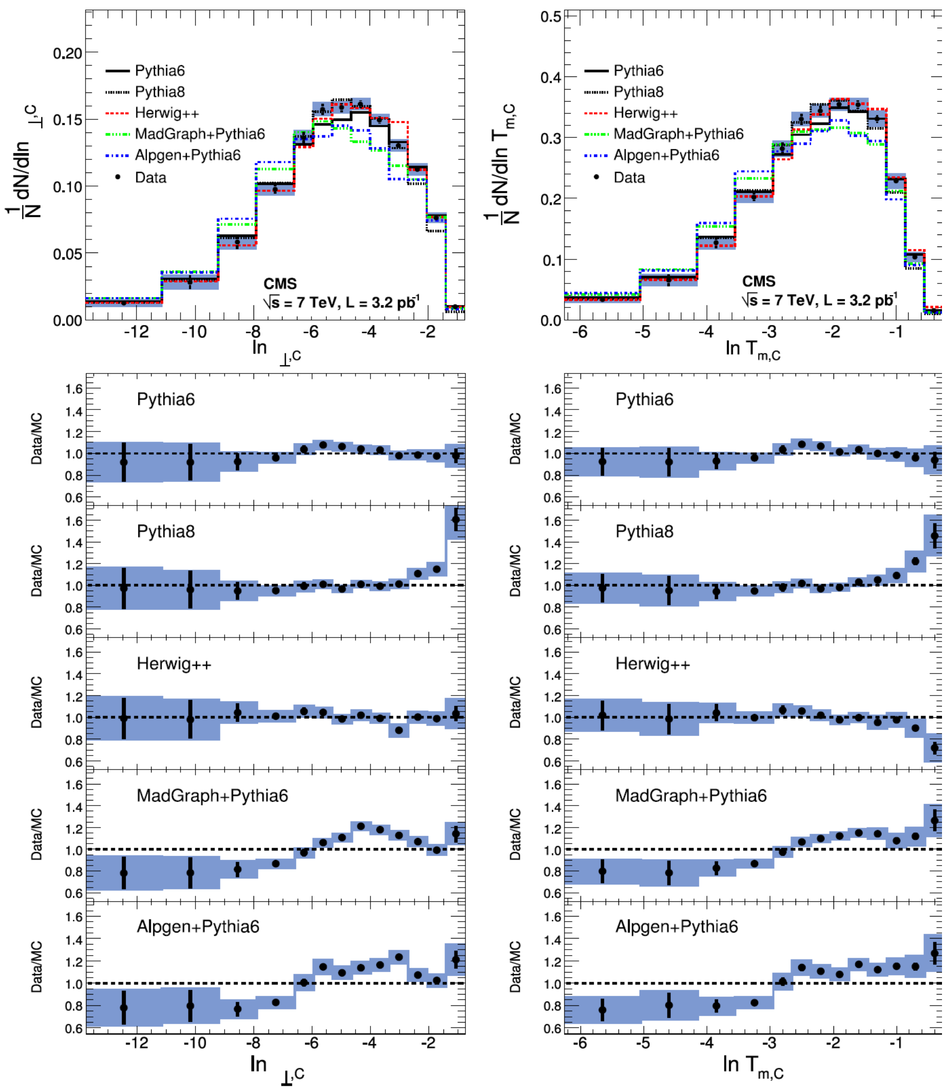
# Event shapes

Phys. Lett. B 699 (2011) 48

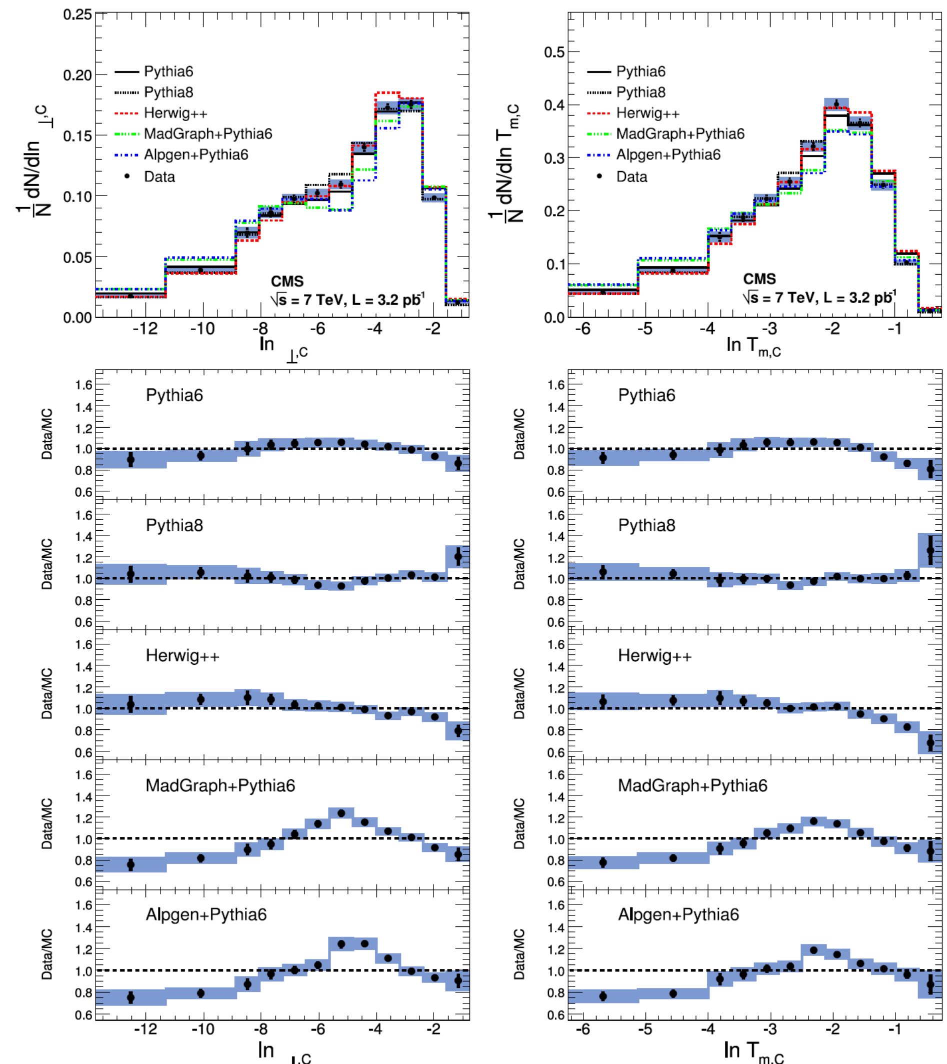
- Distributions of central transverse thrust and thrust minor, using central (|η|<1.3) jets as input, in the transverse plane
- $$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$
  - Is a measurement of radiation along the thrust axis
  - A dijet event has small values of central transverse thrust, while an isotropic multi jet has large values
- $$T_{m,\mathcal{C}} \equiv \frac{\sum_i |\vec{p}_{\perp,i} \times \hat{n}_{T,\mathcal{C}}|}{\sum_i p_{\perp,i}}$$
  - Is a measurement of the radiation out of the plane defined by the thrust axis and the beams
  - A dijet event has small values of central thrust minor, while an isotropic multi jet has large values
- Jets are reconstructed with the anti-kt algorithm
  - pT > 30 GeV
  - 3 bins of leading jet pT

# Event shapes

- 90 GeV <pT(leading) < 125 GeV




- pT(leading) > 200 GeV



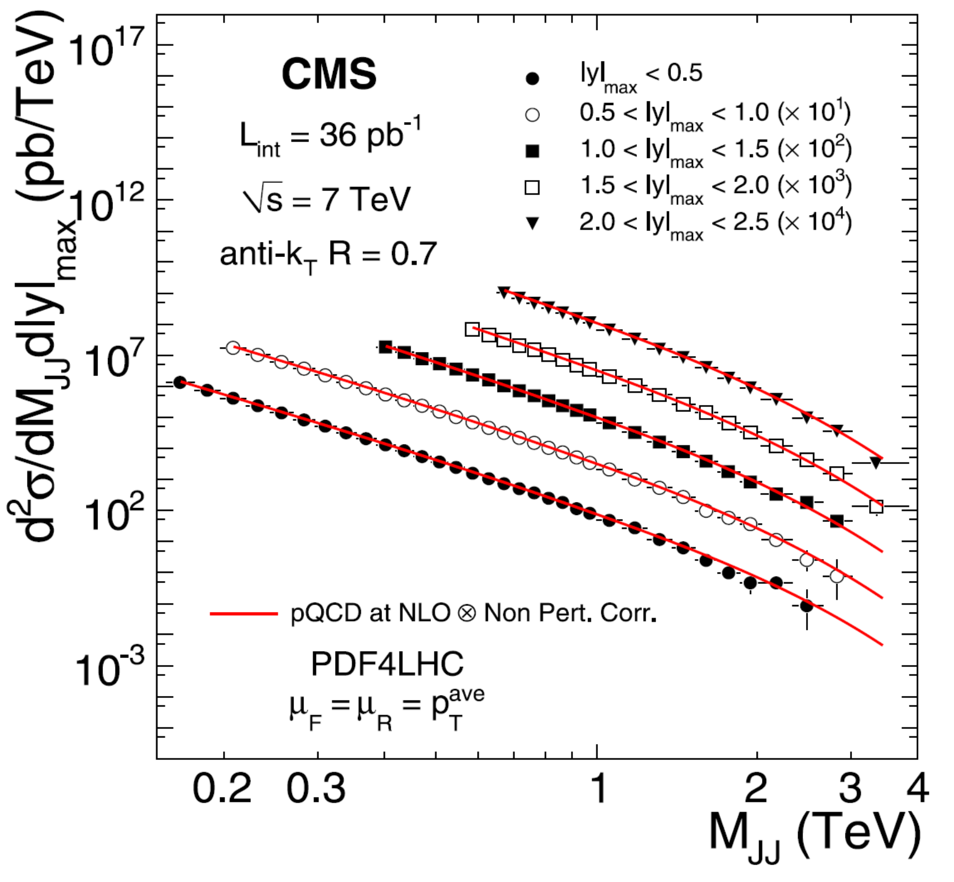
# Event shapes

- Pythia6 and Herwig++ do a good job in all bins
- Pythia8 tends to underestimate high values, i.e. very busy multi-jet events
- Both Alpgen and Madgraph are worse than the pure shower models
  - Why?
  - A pattern seems to emerge: it looks like ME+Shower are in general good at describing rates, but not as good at describing angles
  - Does tuning play a role here?
  - Checks with other tools are needed

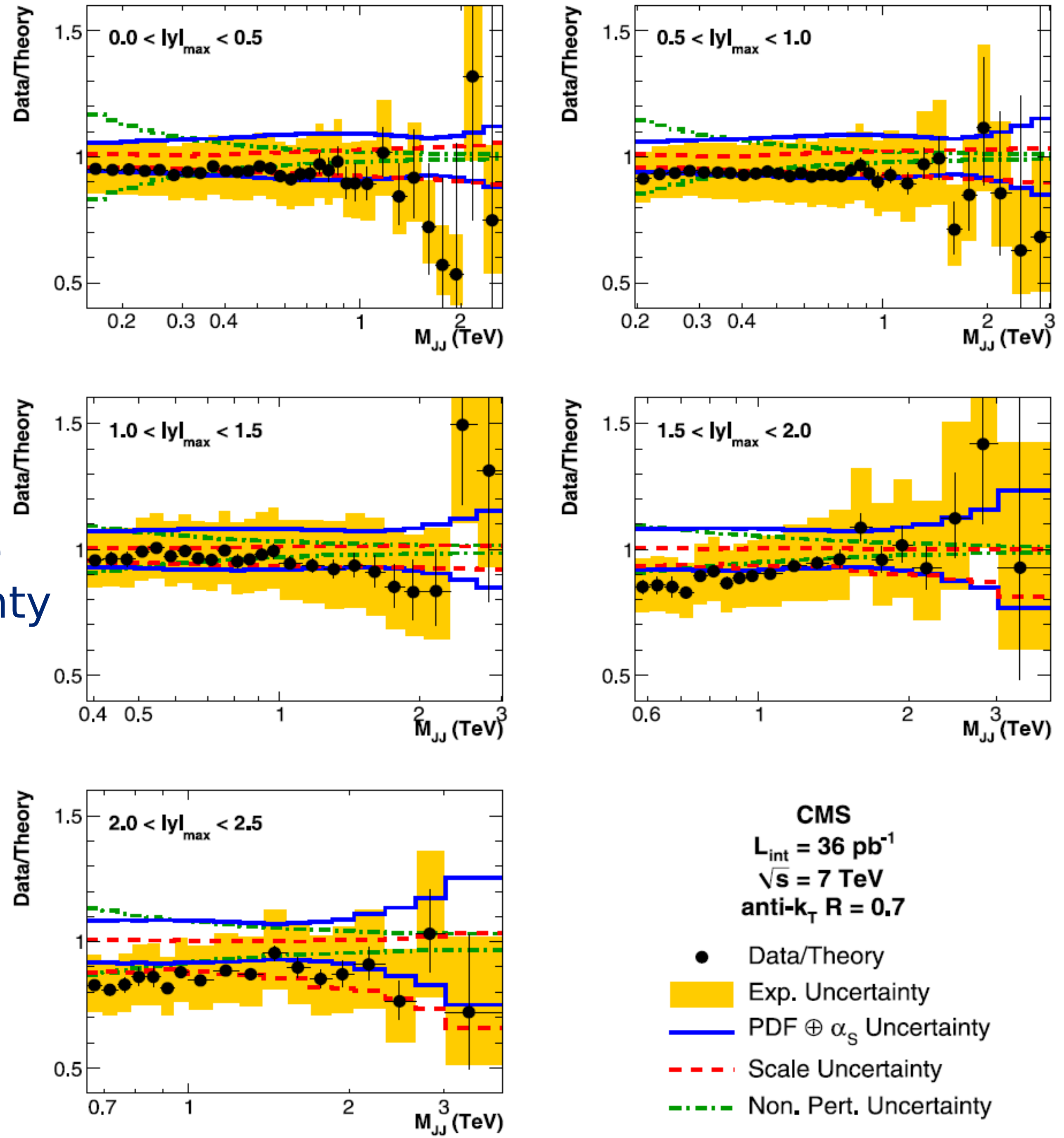
# Di-jet mass

Phys. Lett. B 700 (2011) 187

- A measurement of the di-jet mass in 5 bins of leading jet rapidity, ranging from 0.2 to 2.5 TeV
- Anti-kt 0.7 jets, |y|<2.5
- Experimental resolution unfolded to hadron level with MC correction factors
- Comparison with pure NLO + non perturbative corrections
  - Theory prediction with CT10, MSTW2008, NNPDF2.0, folded according to PDF4LHC prescription
- Main systematic is the Jet energy scale
  - Experimental error comparable to theory uncertainty
  - With improved energy scale systematic it will be possible to constrain PDFs



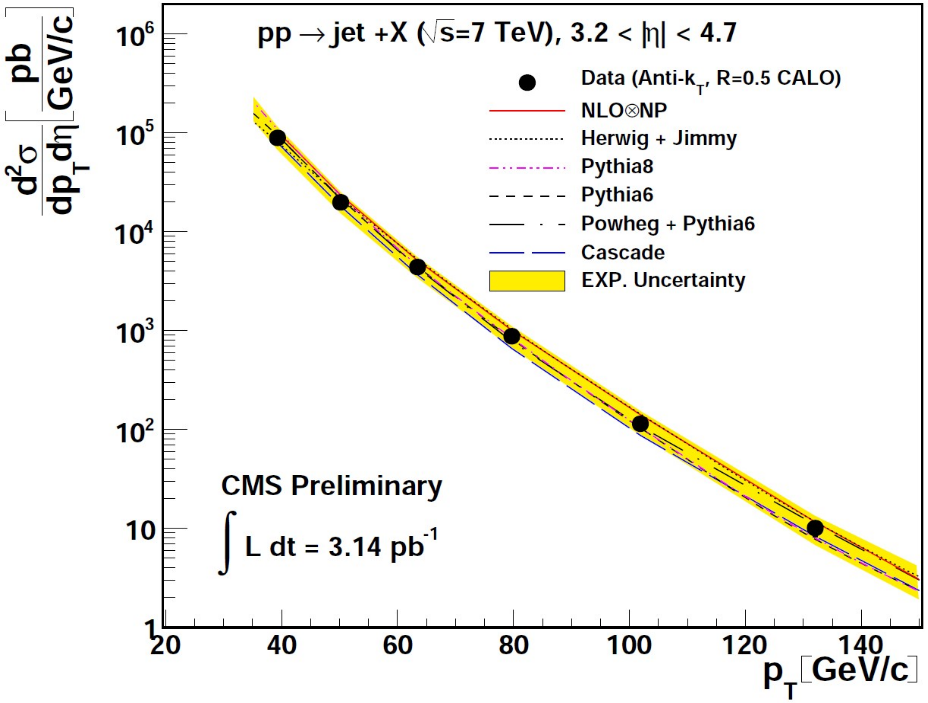
- Data show good agreement with predictions in all rapidity bins
- The experimental uncertainty is comparable with the theoretical uncertainty
- Data can be used to constrain PDFs



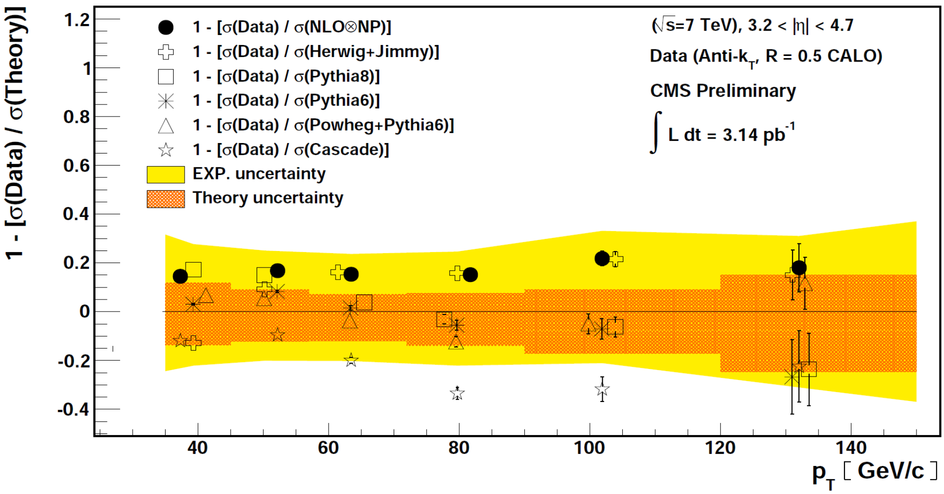
# Inclusive forward jets

CMS-PAS-FWD-10-003

- Inclusive measurement of the rate of jets in the forward region 3.2 < |η| < 4.7
- Sensitive to PDFs
- Also sensitive to tuning aspects



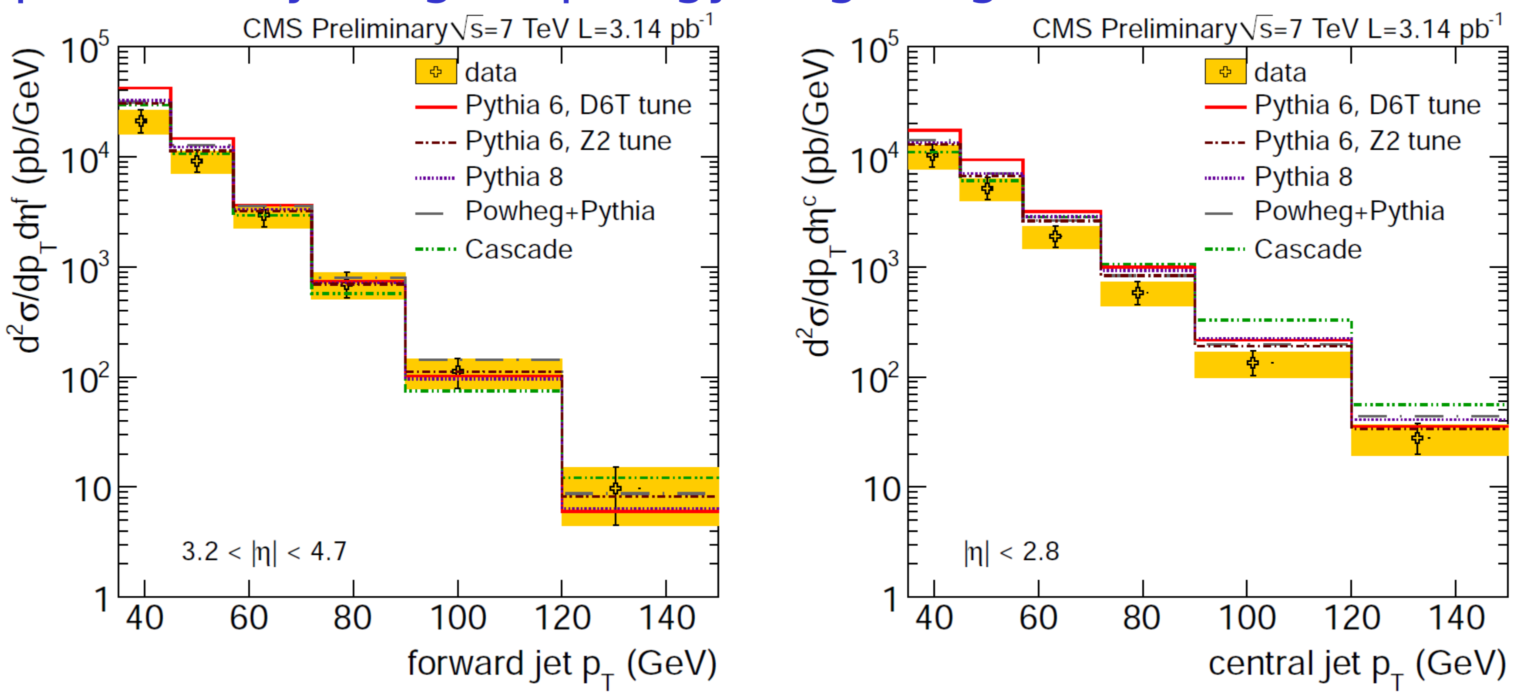

- With more statistics and improved JES we will become more and more sensitive to PDFs



# Forward-central jets

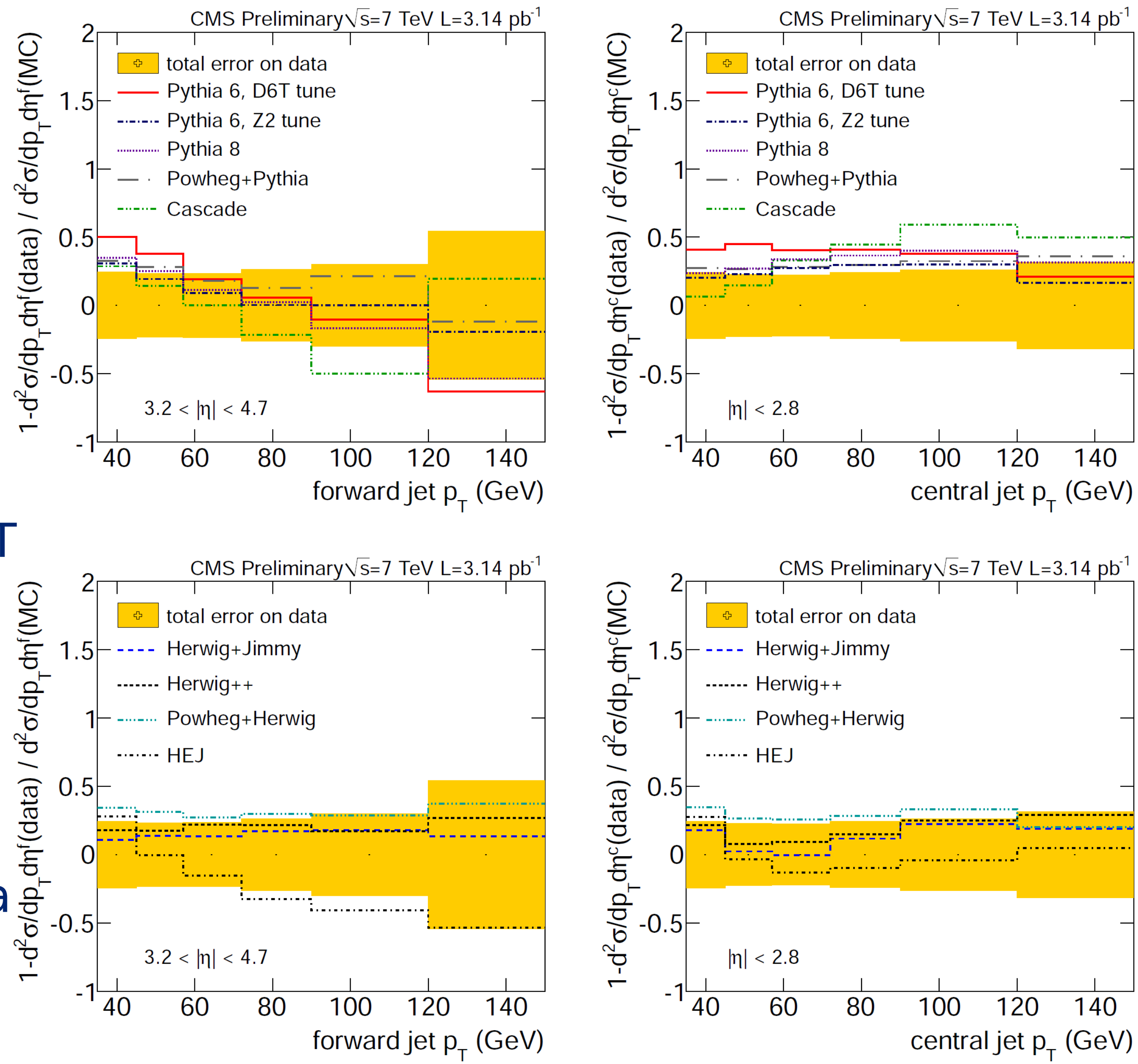
CMS-PAS-FWD-10-006

- An even more complicated topology:
  - One central jet (|η| < 2.8) and one forward jet (3.2 < |η| < 4.7)
  - PT > 35 GeV
- It is sensitive to the details of the UE model and on the details of the shower
- Several MC generators were compared to the data
  - A particularly tough topology to get right



# Forward-central jets

- All models overestimate the total rate
- Herwig seems to be best at describing both spectra
- Pythia8 and Pythia6 tune Z2 describe data better than D6T
- Powheg + Herwig is ok in shape but doesn't get the normalization right
- HEJ (pure parton level) describes data reasonably well



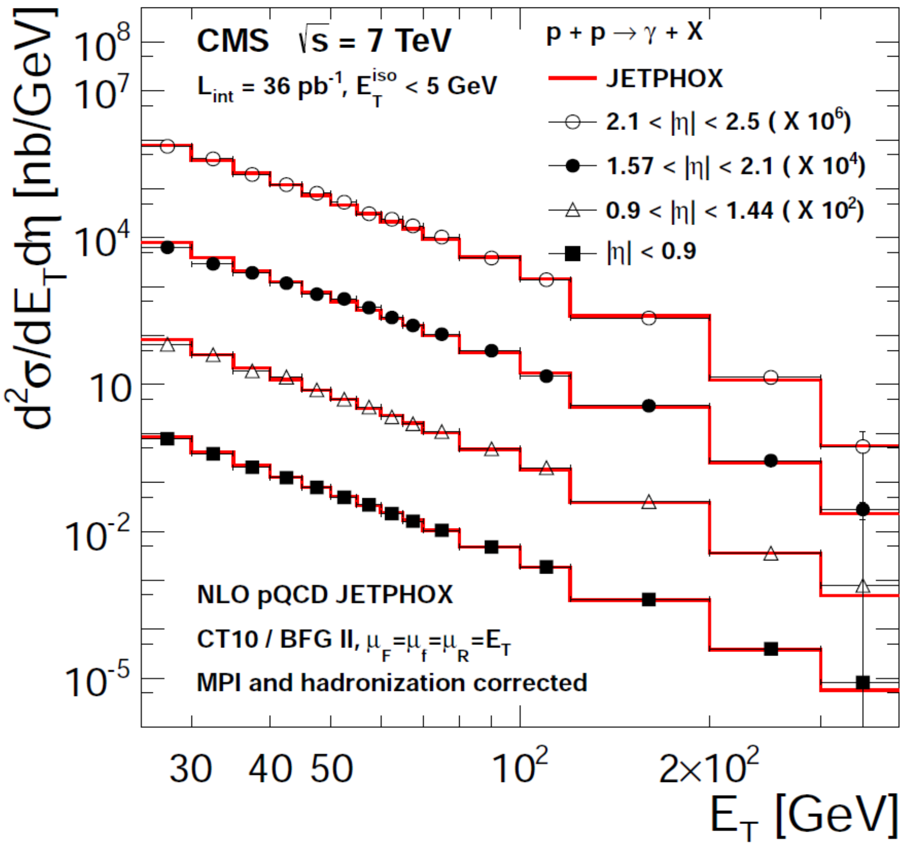
# Inclusive photon production

Phys. Rev. Lett. 106 (2011) 082001

- Prompt photon production is a stringent test of pQCD
- Measurement of differential production rate as a function of pT in bins of η
- The prompt photon signal is defined at particle level through an isolation cut of 5 GeV on the scalar sum of charged and neutral particles in a cone of 0.4 around the photon
- Analysis strategy:
  - Fit of the isolation distributions (non converted component)
  - Fit of the ratio Et in calorimeters to pT of the electrons from conversions (converted component)
- Main systematics:
  - Signal and background modeling in fits
  - Photon identification efficiency

# Inclusive photon production

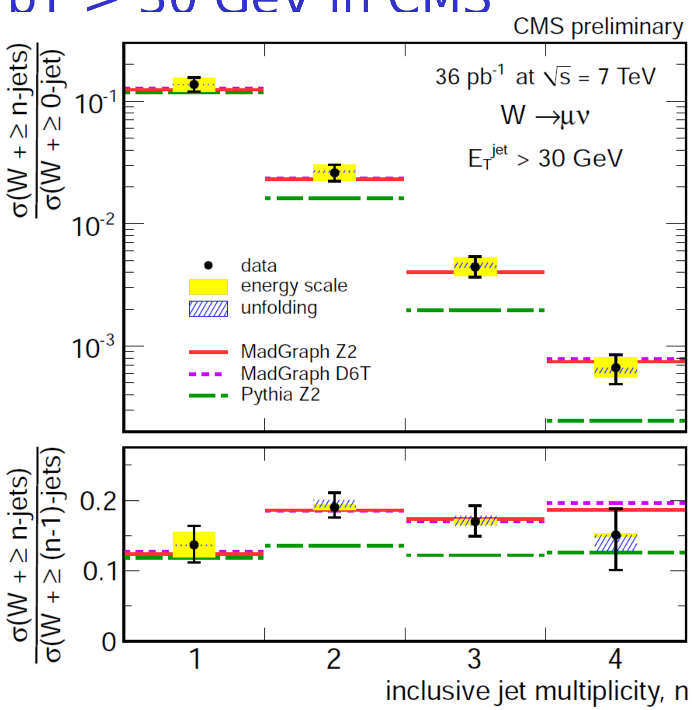
- The measurement has been performed in 4 photon rapidity bins, for transverse energies between 25 and 400 GeV
- Good agreement with NLO predictions from JETPHOX
  - Predictions are corrected for non-perturbative effects
  - MC predictions show a slight tendency to overshoot the data at low pT

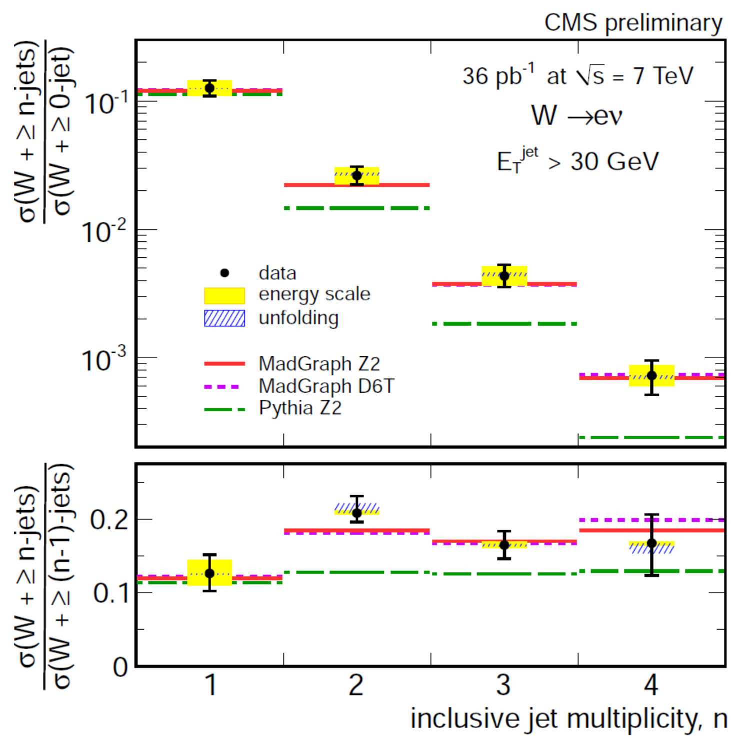


# W/Z+jets

CMS-PAS-EWK-10-012

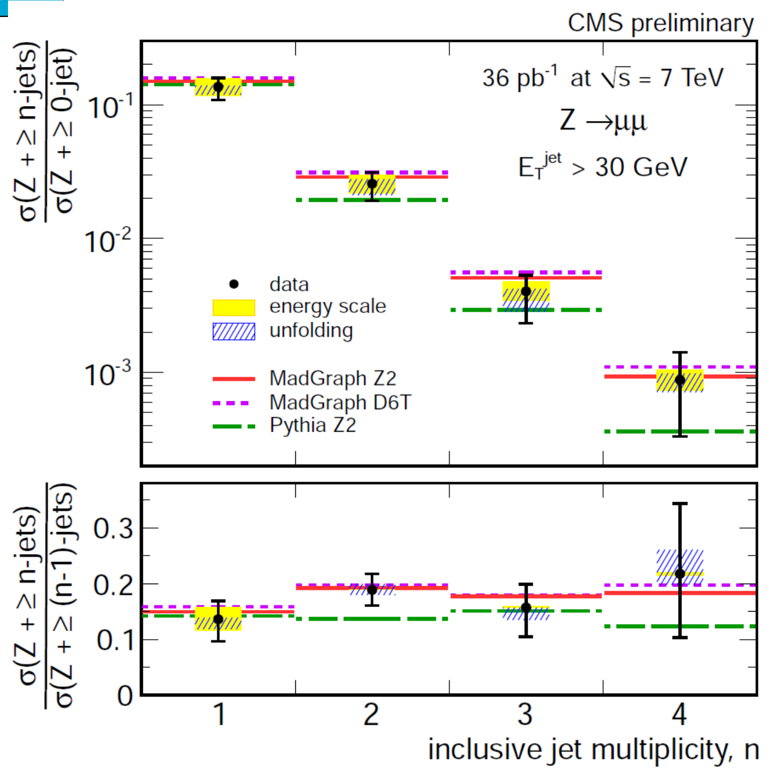
- Important as background for searches and as testing ground for higher order corrections in pQCD
- Detector's jet energy scale is the main systematic effect.
- CMS measured rates of events with jets accompanying the vector boson
  - Results are given within the kinematic acceptance for leptons, unfolding detector effects
  - Jets are reconstructed with the anti-kT algorithm, with a radius of 0.5, pT > 30 GeV in CMS

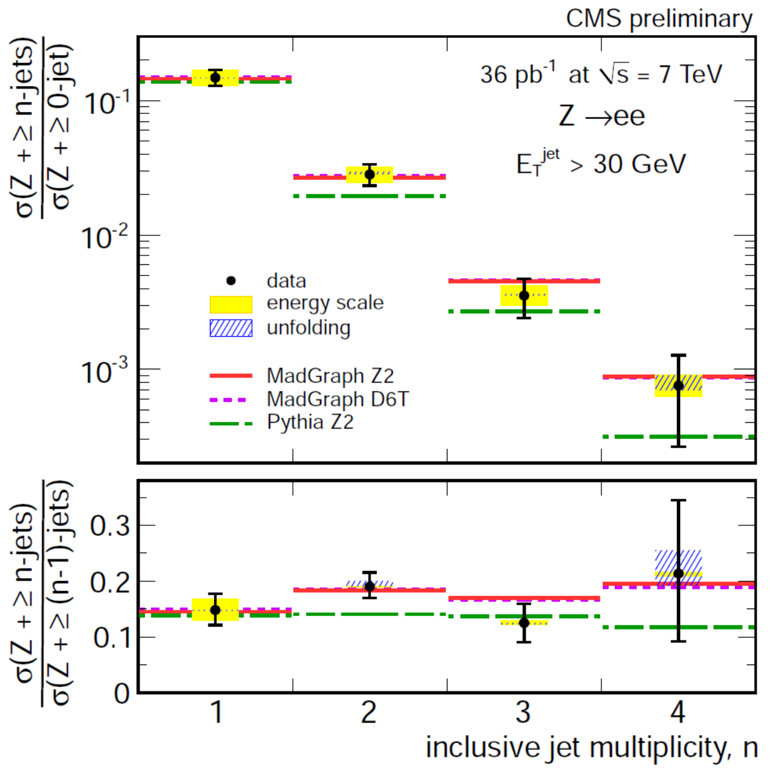



CMS-PAS-EWK-10-012

# W/Z+jets



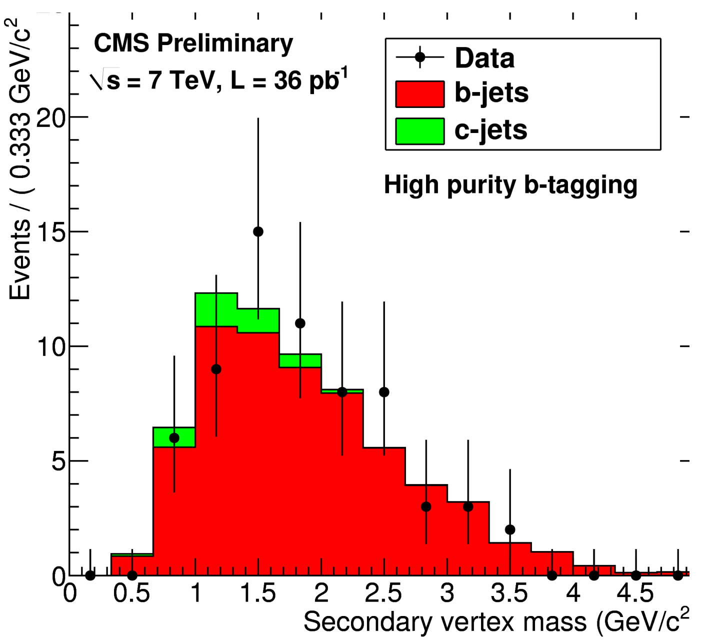




- Pure parton shower (Pythia) is not able to describe multi jet rates
- Several Matrix Element + shower predictions compared to data
  - General agreement with these predictions is found

# W/Z+jets

CMS-PAS-EWK-10-015

- CMS measured the associated production of Z + b-jets
  - Z selection plus high purity b-tagging
  - Main systematics: JES, b-tagging efficiency and mis-tag rate
  - The ratio between the Z+ b jets and Z + any jet has been measured for both electron and muon decay channels

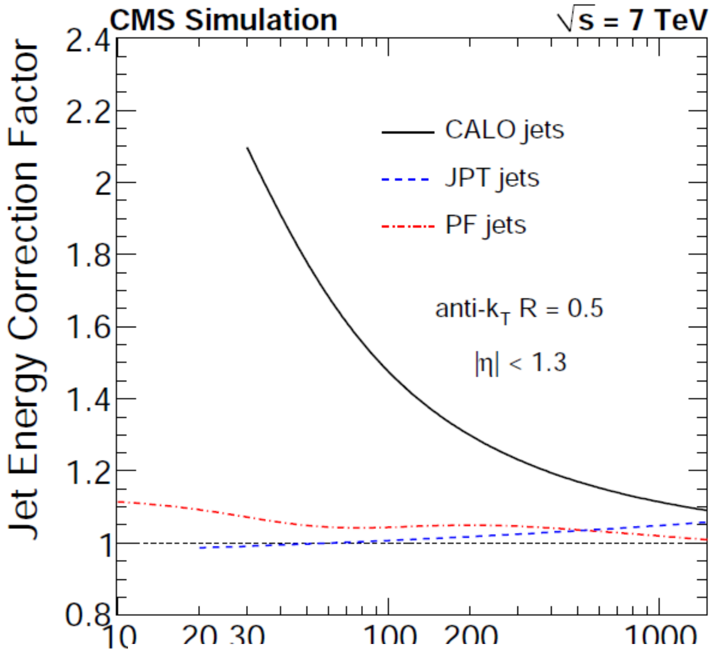


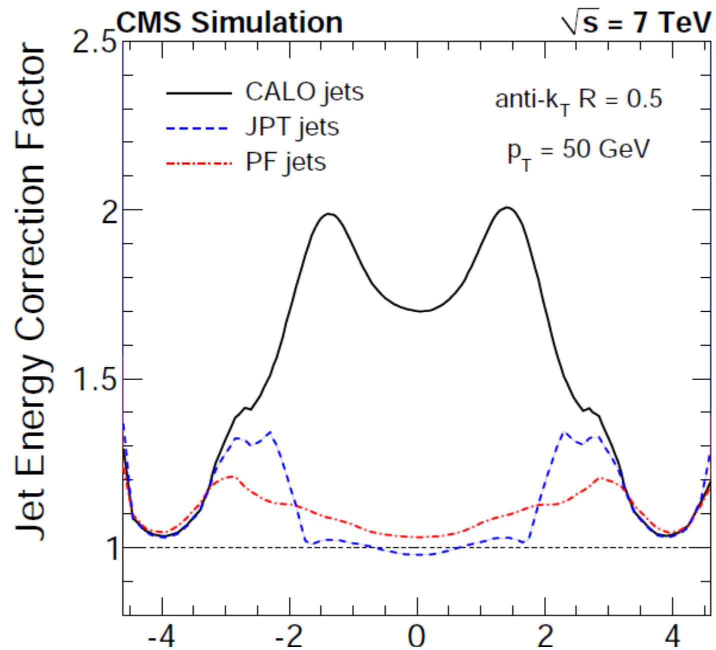

| Sample | $\mathcal{R}(Z \to ee)$ (%), $p_T^e > 25$ GeV, $\lvert\eta^e\rvert < 2.5$ | $\mathcal{R}(Z \to \mu\mu)$ (%), $p_T^\mu > 20$ GeV, $\lvert\eta^\mu\rvert < 2.1$ |
|---|---|---|
| Data HE | $4.3 \pm 0.6(stat) \pm 1.1(syst)$ | $5.1 \pm 0.6(stat) \pm 1.3(syst)$ |
| Data HP | $5.4 \pm 1.0(stat) \pm 1.2(syst)$ | $4.6 \pm 0.8(stat) \pm 1.1(syst)$ |
| MADGRAPH | $5.1 \pm 0.2(stat) \pm 0.2(syst) \pm 0.6(theory)$ | $5.3 \pm 0.1(stat) \pm 0.2(syst) \pm 0.6(theory)$ |
| MCFM | $4.3 \pm 0.5(theory)$ | $4.7 \pm 0.5(theory)$ |

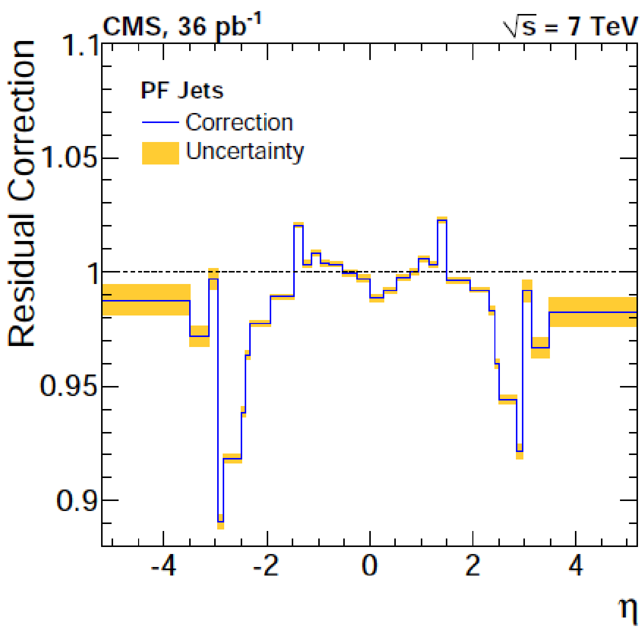
# Conclusion

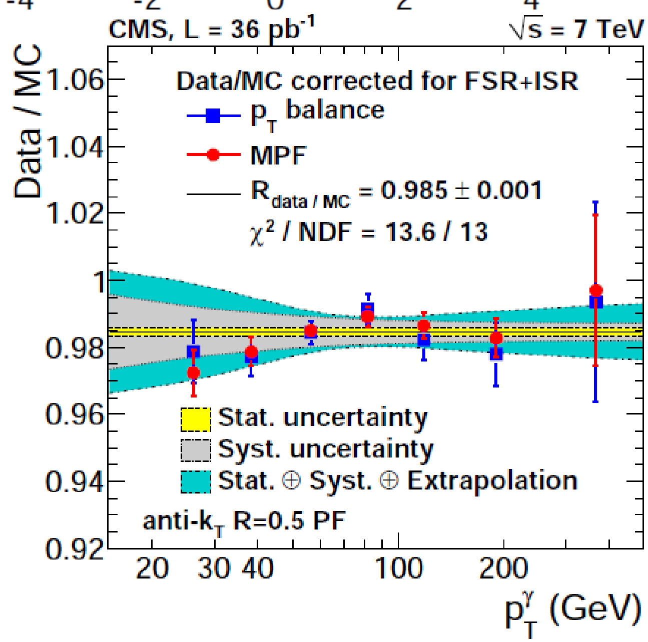
- The CMS QCD program is progressing very well!
- CMS produced an large number of results with 2010 data
  - Cross sections
  - Differential distributions
  - Associated production of vector boson with jets (and b-jets)
  - Forward jet measurements
- Plenty of data to test different codes and different models
- And more results are coming from the 2011 data!

# Backup


CMS Simulation
$\sqrt{s}$ = 7 TeV
Jet Energy Correction Factor
CALO jets
JPT jets
PF jets
anti-$k_T$ R = 0.5
$|\eta|$ < 1.3
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
10
20 30
100
200
1000


CMS Simulation
$\sqrt{s}$ = 7 TeV
Jet Energy Correction Factor
CALO jets
JPT jets
PF jets
anti-$k_T$ R = 0.5
$p_T$ = 50 GeV
2.5
2
1.5
1
-4
-2
0
2
4


CMS, 36 $pb^{-1}$
$\sqrt{s}$ = 7 TeV
Residual Correction
PF Jets
Correction
Uncertainty
1.1
1.05
1
0.95
0.9
-4
-2
0
2
4
$\eta$

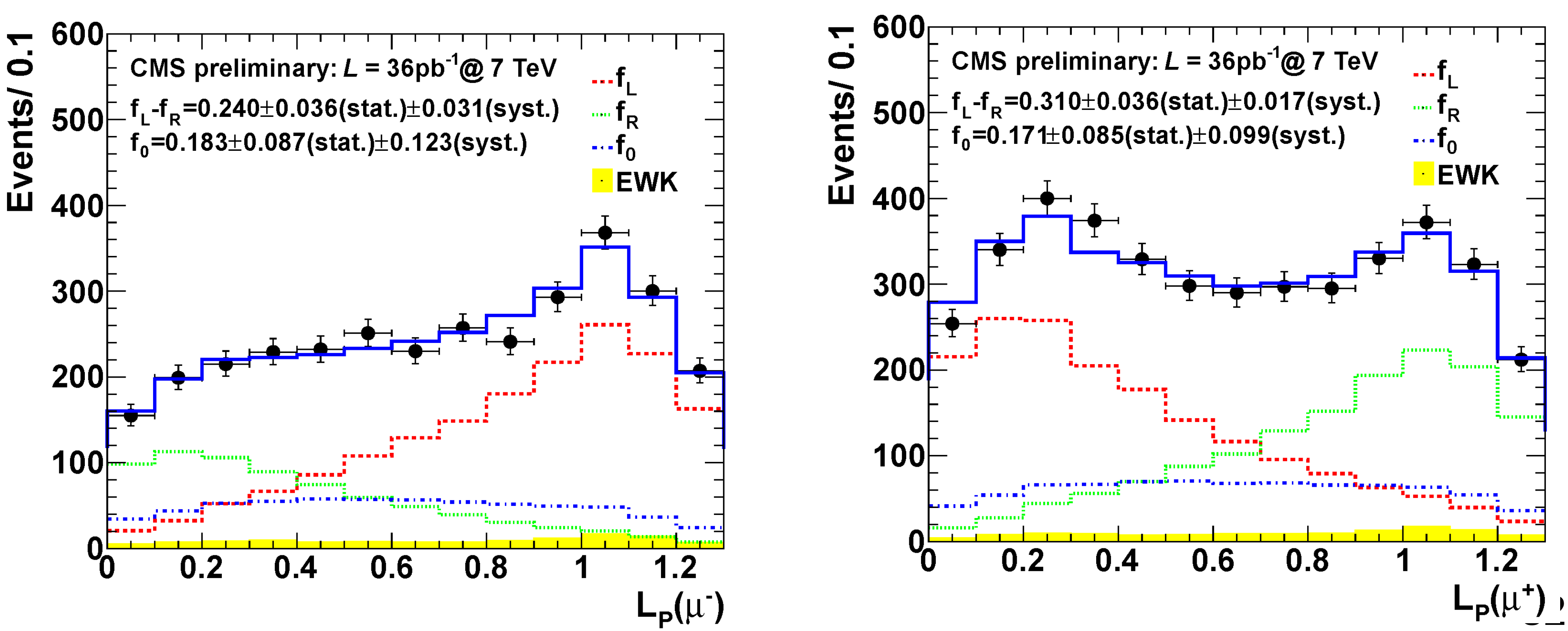

CMS, L = 36 $pb^{-1}$
$\sqrt{s}$ = 7 TeV
Data / MC
Data/MC corrected for FSR+ISR
$p_T$ balance
MPF
$R_{data / MC}$ = 0.985 $\pm$ 0.001
$\chi^2$ / NDF = 13.6 / 13
Stat. uncertainty
Syst. uncertainty
Stat. $\oplus$ Syst. $\oplus$ Extrapolation
anti-$k_T$ R=0.5 PF
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
20
30
40
100
200
$p_T^\gamma$ (GeV)

# W polarization

arXiv:1104.3829

- W polarization for large transverse momentum
  - Effect unique to pp collisions!
  - CMS measured the effect for pT > 50 GeV and found that Ws are predominantly left-handed in pp collisions, as predicted by the SM
  - Since the kinematic is not closed, the lepton-projection (LP) variable was used and fitted to data

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(\mathrm{W})}{|\vec{p}_T(\mathrm{W})|^2}$$



# Inclusive photon production

- Data to theory ratios in the four rapidity bins
- Shaded area is the data uncertainty
- PDF and scale uncertainties on the predictions are also shown