Multijet measurements with the CMS detector at 7TeV

P.Kokkas

University of Ioannina, Greece

On behalf of the CMS Collaboration

EPS-HEP 2001 : EPS High Energy Physics Conference

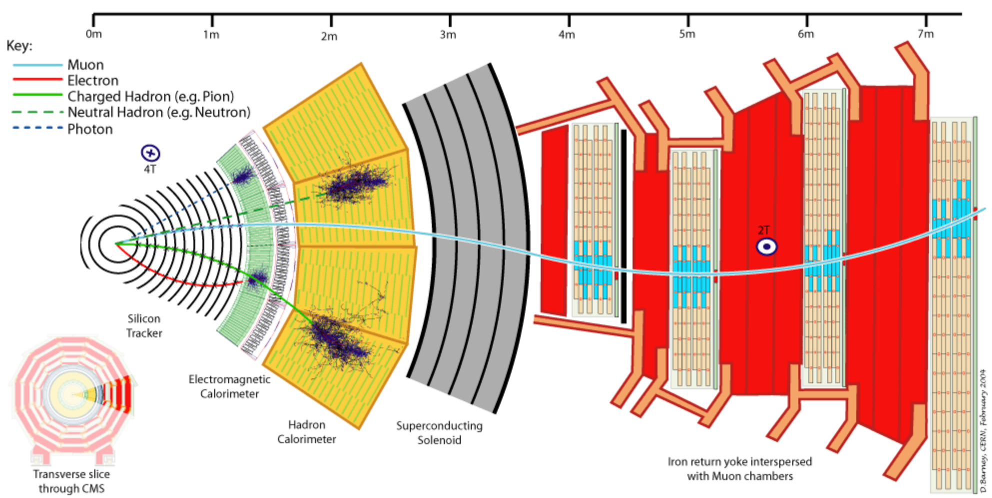
21-27 Jul 2011, Grenoble, Isere (France)

Outline

- Introduction & the CMS detector
- Jets reconstruction at CMS
- Jet energy scale calibration
- Measurements
  - Dijet Azimuthal Decorrelations
  - Hadronic Event Shapes
  - 3-jet to 2-jet cross section Ratio
- Conclusions

Introduction & the CMS detector

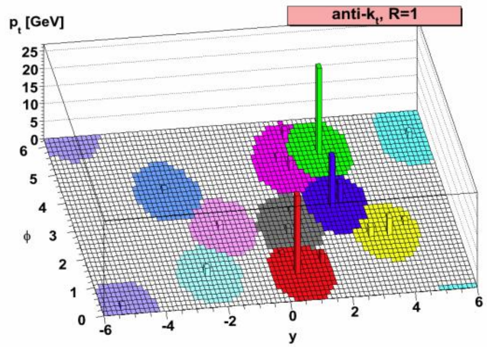
- Jet Measurements at LHC are very important:
  - They provide a test of pQCD in a previously unexplored energy region
  - Can be used to tune MC generators, to have a better description of the data
  - May be used to constrain PDFs and probe strong coupling constant α_s
  - Understanding of multijet production is of considerable interest because QCD induced processes constitute the dominant backgrounds for signals of new physics at the LHC (SUSY and BSM searches)



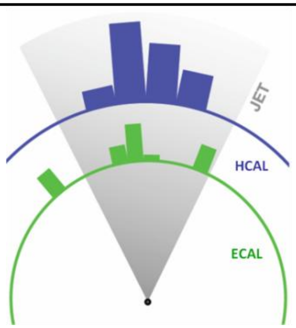
Tracking: $|\eta|<2.5$
Central Calorimetry: $|\eta|<3$
Forward Calorimetry: $3<|\eta|<5$

Jets reconstruction

- **Anti-k_T clustering algorithm** :
  - Infrared and collinear safe. Default for p-p collisions (Used by CMS and ATLAS). Used with parameter R=0.5

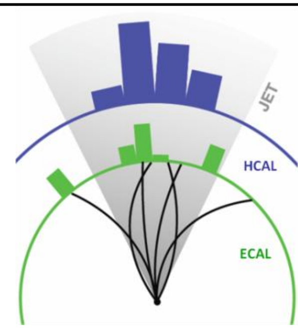


Calorimeter Jets (Calo Jets)



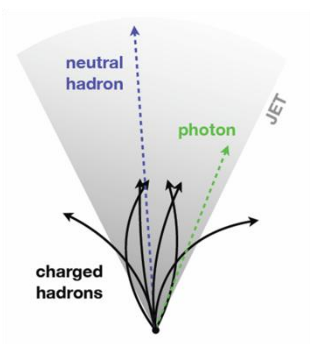
- Calo Jets are the output of the jet algorithm on clusters of calorimeter towers (ECAL & HCAL)

Jet Plus Tracks



- Calorimeter Jets corrected using the tracker info
- Improvement of the jet energy and direction measurement

Particle Flow Jets (PF Jets)



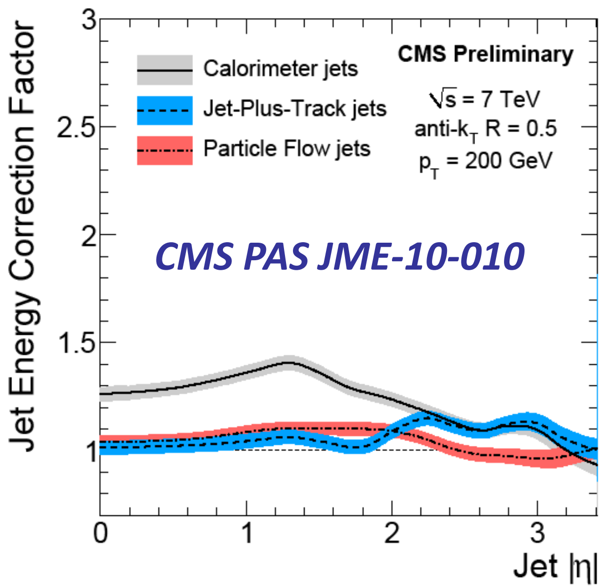
- The Particle Flow is an event reconstruction technique which attempts to reconstruct and identify all stable particles in the event, through the optimal combination of all CMS sub-detectors.
- PF Jets are the output of the jet algorithm on the reconstructed particles.
- Have the best resolution and used in most analysis

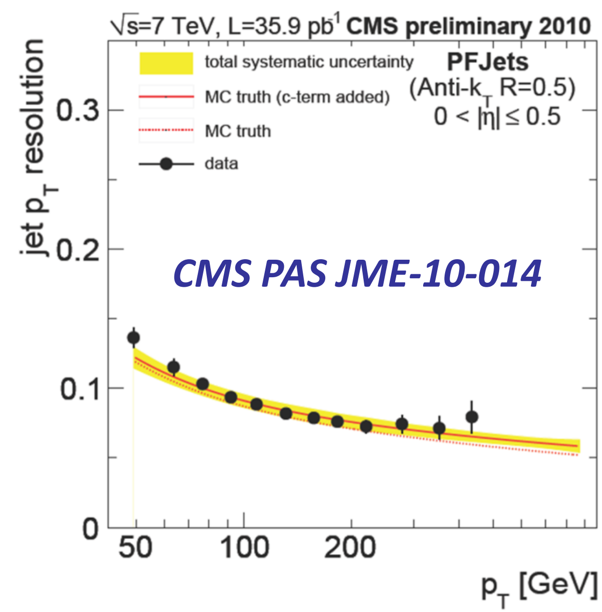
Jet Energy Scale Calibration

- The jet energy calibration is necessary
  - due to the non-linear and non-uniform response of the calorimeters
  - also pile-up events and electronics noise can lead to extra unwanted energy
- CMS adupted a Factorized approach.

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

  - **Offset** (removes the average energy due to pile-up and noise)
  - **Relative** (flattens jet response in pseudorapidity)
  - **Absolute** (flattens the jet response in p_T)
- Corrections derived using simulated events and in-situ measurements with dijet and photon+jet events.





Jet p_T resolution: ≈9% at 100 GeV

Dijet Azimuthal Decorrelations

- Dijets are produced back to back in the azimuthal angle:

  $$\Delta\varphi_{dijet}=|\varphi_{jet1}-\varphi_{jet2}|=\pi$$

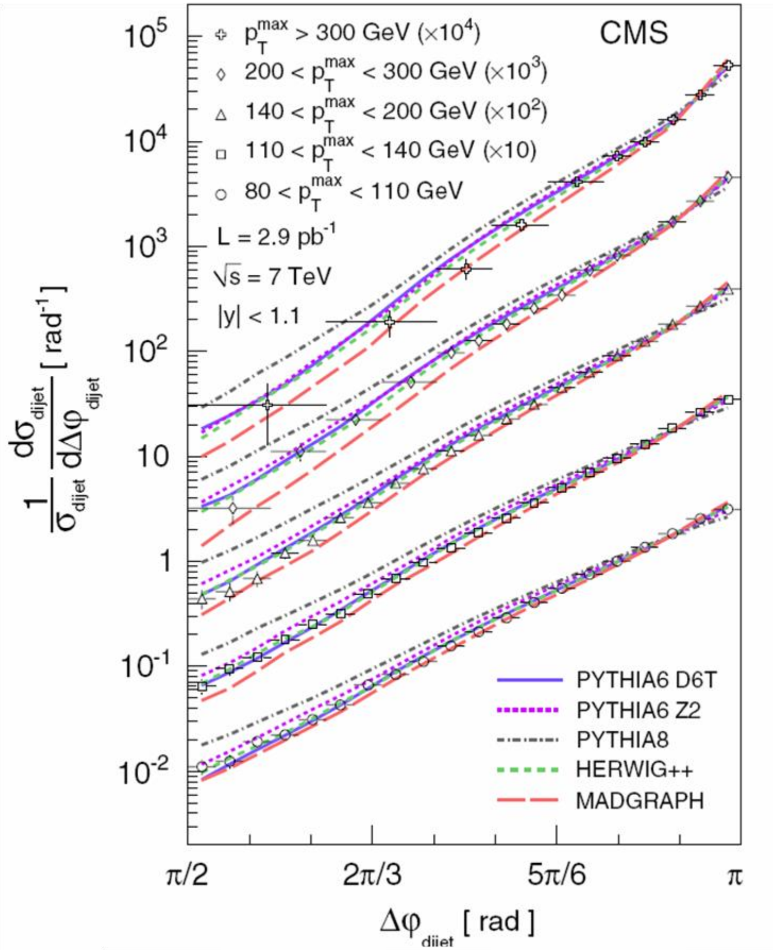
- Dijet azimuthal decorrelations (ie., the deviation of $\Delta\varphi_{dijet}$ from π) can be used to study QCD radiation effects over a wide range of jet multiplicities without the need to measure all the additional jets.

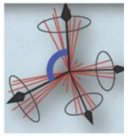
Observable : $$\frac{1}{\sigma_{dijet}}\frac{d\sigma_{dijet}}{d\Delta\varphi_{dijet}}$$

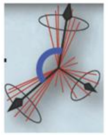
- The measurement is done using anti-k_T, R=0.5, PF Jets and L=2.9pb^{-1}
- Selection: Two leading jets with p_T>30 GeV and |y|<1.1
- Five $p_{T,max}$ bins : 80-110 GeV, 110-140 GeV, 140-200 GeV, 200-300 GeV, >300 GeV
- Systematics: JES & JER: 5% (≈π/2) to 1%(≈ π)
  unfolding : 8% (≈ π/2) to 1.5%(≈ π)

Dijet Azimuthal Decorrelations

PRL 106:122003 (2011)





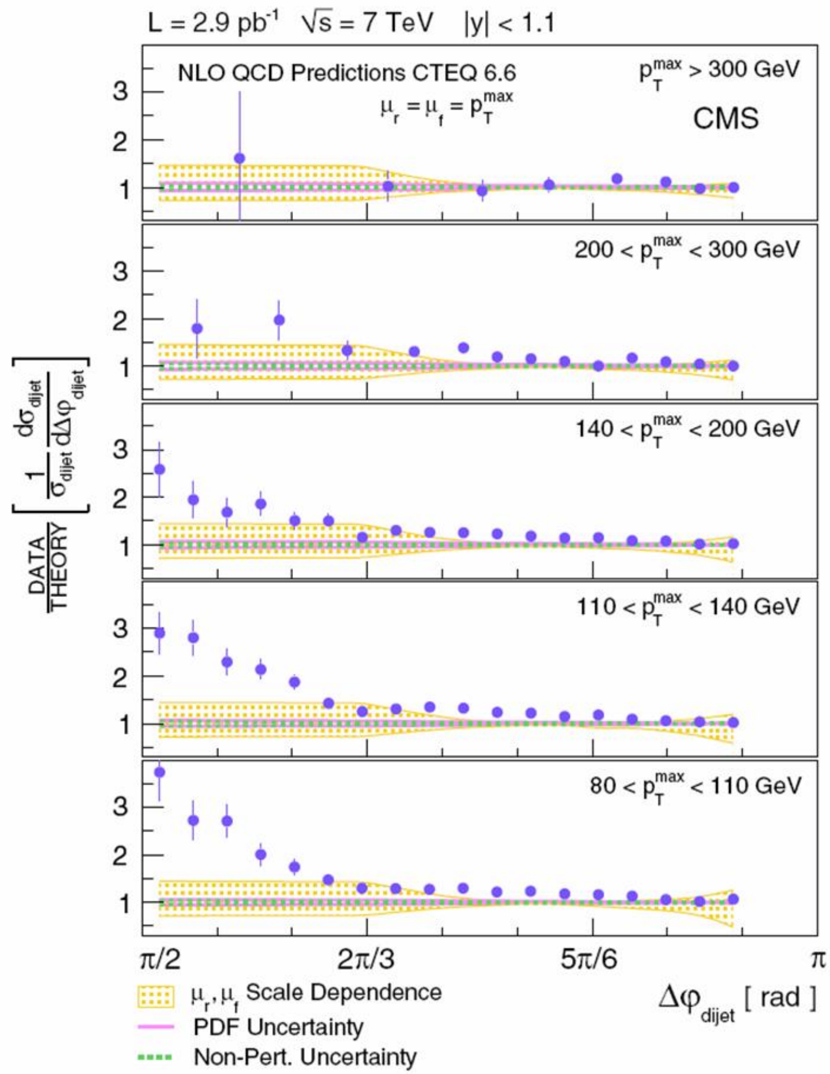


- The $\Delta\varphi_{dijet}$ distributions are strongly peaked at π and become steeper with increase $p_{T,max}$
  - π ≈ signifies a two jet event
  - π < $\Delta\varphi_{dijet}$ <2π/3 region is dominated by three jet topologies
  - <2π/3 ≈ is the multijet regime

- **Data vs MC prediction**
  - The predictions from Pythia6 and Herwig++ describes the shape of data distributions well, in the entire phase space.
  - MadGraph (Pythia8) predicts less (more) azimuthal decorrelation than is observed in the data.

Dijet Azimuthal Decorrelations

PRL 106:122003 (2011)

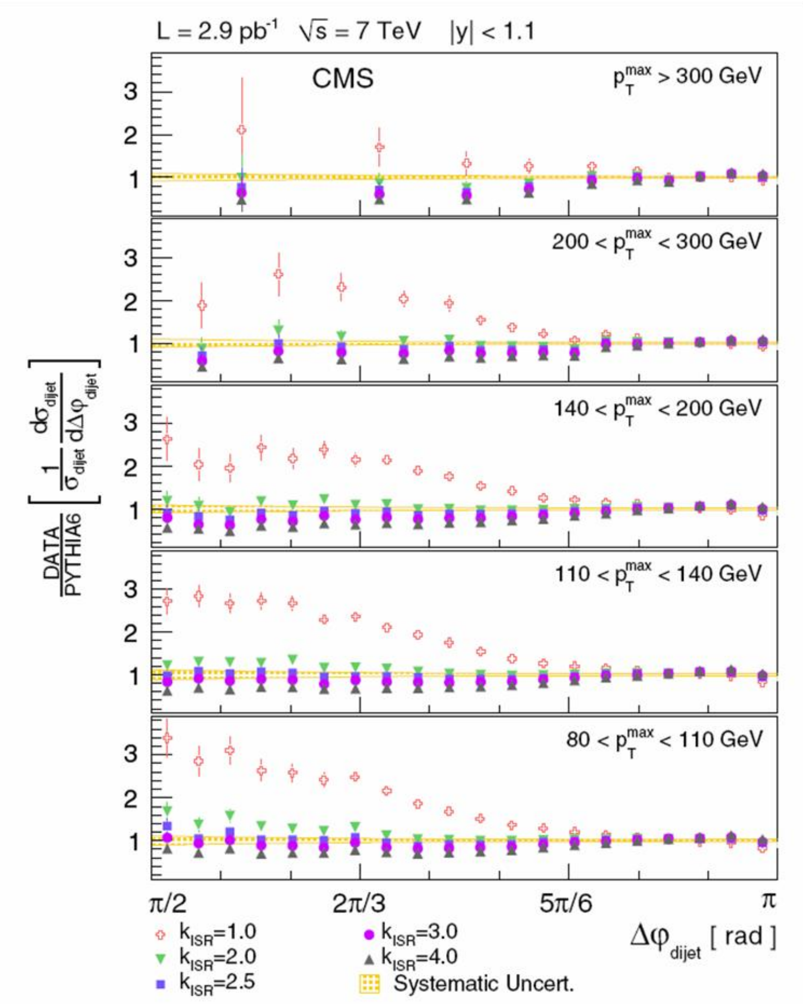


- Comparisons are also made to NLO predictions of pQCD (NLOJET++ within FASTNLO)

- **Data vs Theory prediction**
  - NLO pQCD + non-perturbative corrections describe well the data for $\Delta\varphi_{dijet} > 2\pi/3$ (≈ three jet topologies)
  - The reduced decorrelation in theoretical predictions at small $\Delta\varphi_{dijet}$ is attributed to the fact that the pQCD prediction in this region is effectively available only at leading order, since the contribution from tree-level four-parton final states dominates.

Dijet Azimuthal Decorrelations

PRL 106:122003 (2011)



- The sensitivity of the $\Delta\varphi_{dijet}$ distributions to initial-state parton shower radiation (ISR) is investigated by varying the input parameter k_{ISR} in Pythia6.
- The effects are more pronounced for smaller $\Delta\varphi_{dijet}$ angles, where multigluon radiation dominates.
- The $\Delta\varphi_{dijet}$ distributions are found to be sensitive to initial-state gluon radiation.
- Our results could be used to tune parameters in MC event generators that control radiative effects in the initial state.

Event shape variables

- **Event Shape variables**
  - Can probe different QCD radiative processes
  - The goal of this first measurement is to distinguish between different models of QCD jet production
  - The following two variables are mostly sensitive to the modeling of the two-and three- jet topologies.

Central Transverse Thrust

$$\tau_{\perp,C} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i \left|\vec{p}_{\perp,i} \cdot \hat{n}_T\right|}{\sum_i p_{\perp,i}}$$

Measure of the radiation along the transverse thrust axis

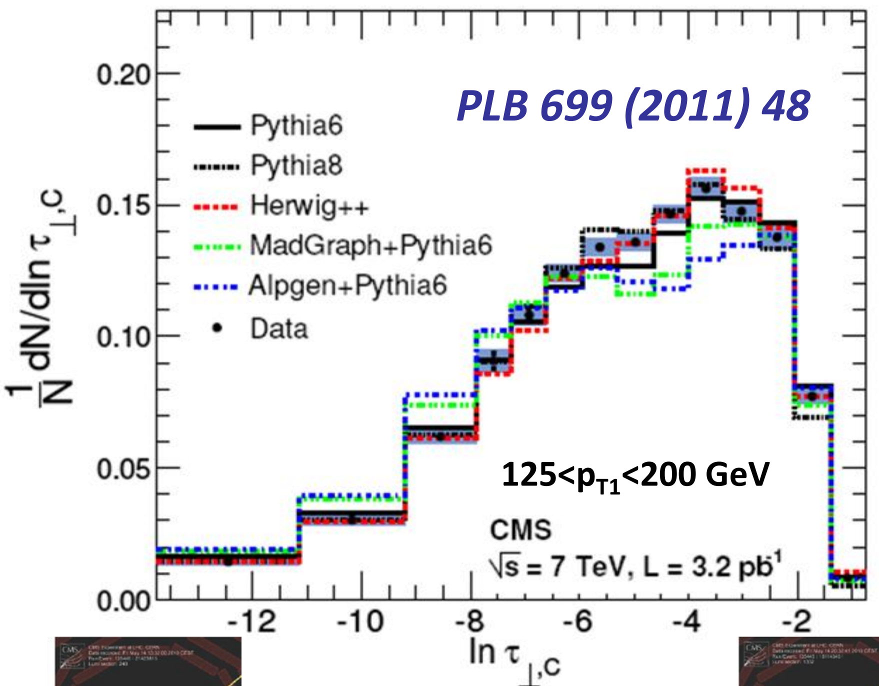
Central Thrust Minor

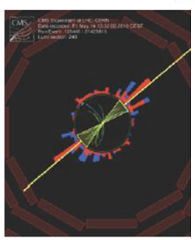
$$T_{m,C} \equiv \frac{\sum_i \left|\vec{p}_{\perp,i} \times \hat{n}_T\right|}{\sum_i p_{\perp,i}}$$

Measure of the radiation out of the plane defined by transverse thrust axis and the beam axis

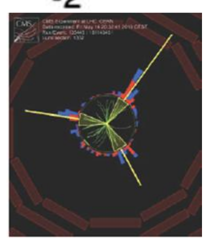
Banfi, Salam, Zanderighi, JHEP 0408 (2004) 62

Central Transverse Thrust





$$\tau_{\perp,C} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i \left|\vec{p}_{\perp,i} \cdot \hat{n}_T\right|}{\sum_i p_{\perp,i}}$$

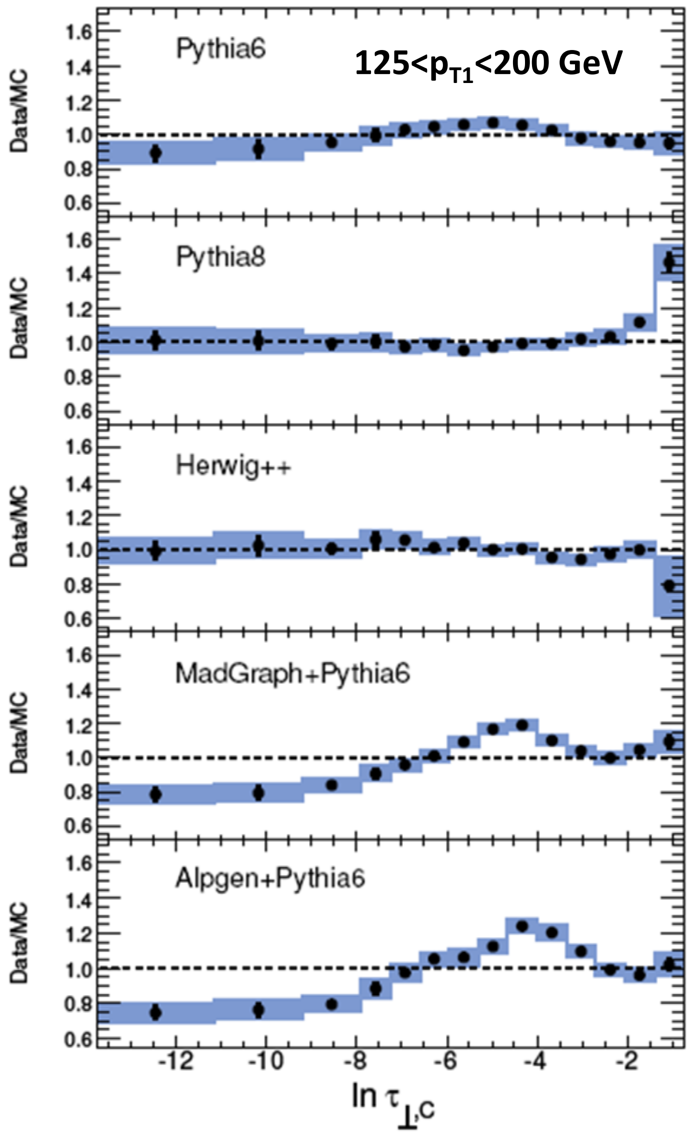


Experimental Measurement

- anti-k_T, R=0.5, PF Jets
- L=3.2pb^{-1}
- Selection: $|\eta|<1.3$ (central jets)
- Three p_{T1} bins : $90<p_{T1}<125$ GeV, $125<p_{T1}<200$ GeV and $p_{T1}>200$ GeV
- Systematics: JES 4%, JER<1%, unfolding<2%
- Two-jet events are well balanced and have low values of the observable variables, while isotopic multijet events have high values.

Hadronic Event Shapes

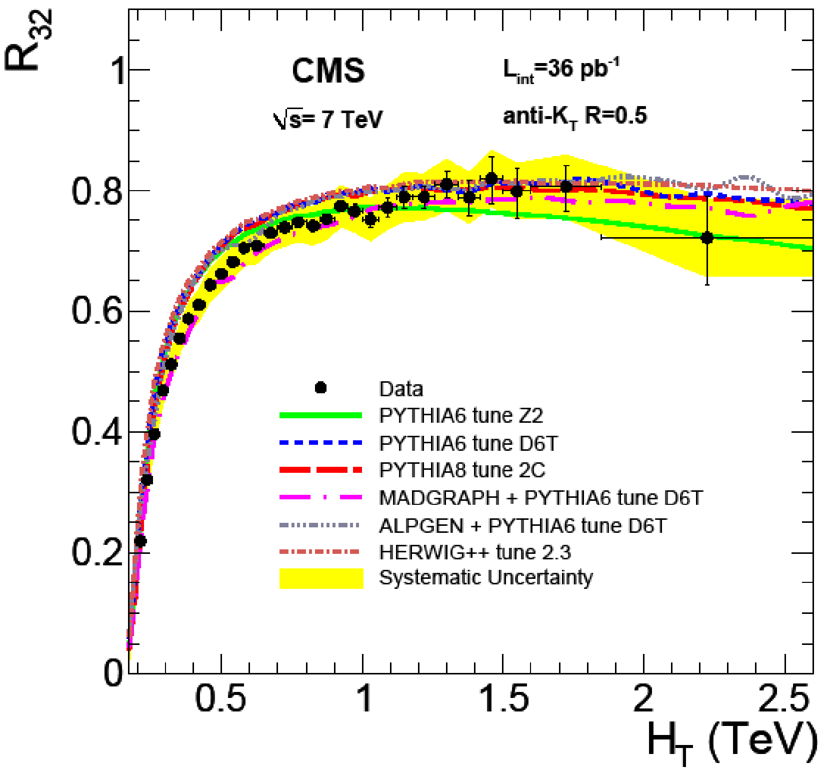
PLB 699 (2011) 48



Data vs MC comparison

- The Pythia 6 and Herwig++ predictions agree with the measurements, in the entire phase space.
- The Pythia8 predictions agree with measurements in all bins except in the highest one where it shows a dijet deficit (affects only 0.5% of all events)
- The Alpgen and MadGraph curves deviate from the data as a result of an over estimate of dijet events
  - Further studies indicate that MadGraph and Alpgen generators reproduce well the leading jet, but the second jet is harder.

arXiv:1106.0647



- **The measurement**

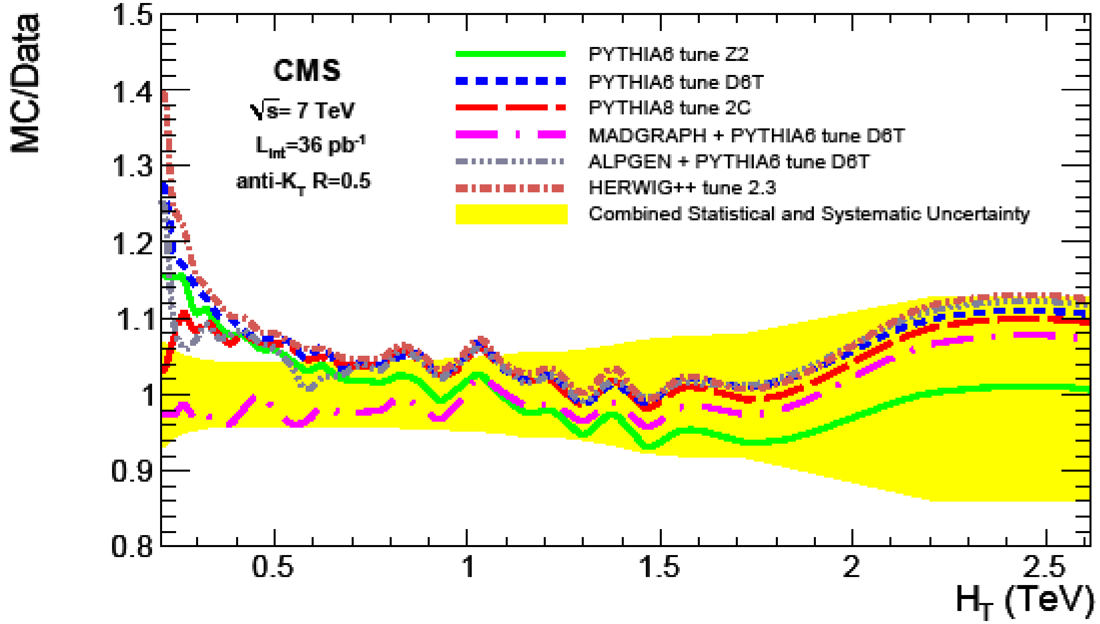
$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n \ \ \text{jets} + X;\ n \geq 3)}{\sigma(pp \to n \ \ \text{jets} + X;\ n \geq 2)}$$

$$\text{vs} \quad H_T = \sum p_T^{jet}$$

- anti-k_T, R=0.5, PF Jets and L=36 pb^{-1}
- Selection: at least two jets with p_T>50 GeV and |y|<2.5
- Systematics:
  - MC shape (3-5% for H_T<1 TeV, 7-8% at 2 TeV)
  - Jet energy scale, effect of pile-up, difference between caloJets and PFjets (≈1%)
- Measurement up to 2.5 TeV in H_T.

3-jet to 2-jet cross section ratio

arXiv:1106.0647

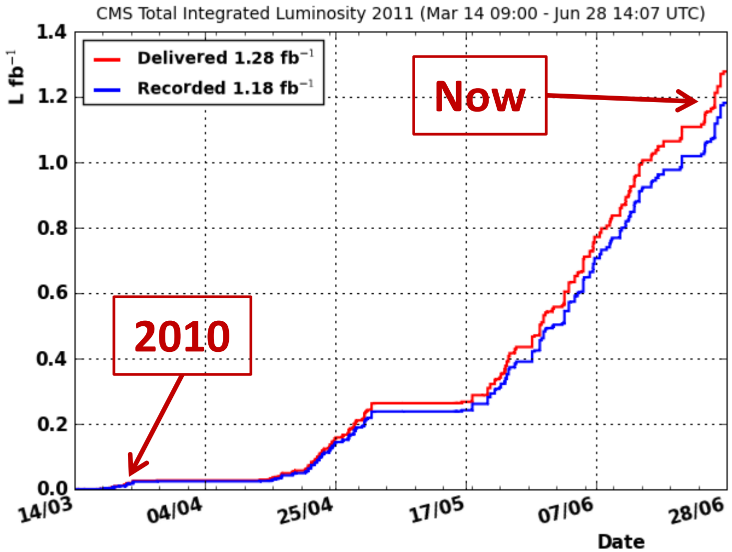


- **Data vs MC prediction**
  - All MC generators describe well the data above H_T > 0.5 TeV
  - MadGraph is in excellent agreement with the data in the entire H_T range.

Conclusions

- The advanced understanding of the jet reconstruction and energy calibration has allowed for precise jet measurements.
- The predictions of all QCD MC generators are in good agreement with data. Small discrepancies have been observed.
- The CMS measurements can be used for further tuning of these widely used QCD MC generators.

    - Using the 2011 data, CMS plans to perform precision studies (Detailed test of pQCD at NLO, constrain PDFs and α_s) .

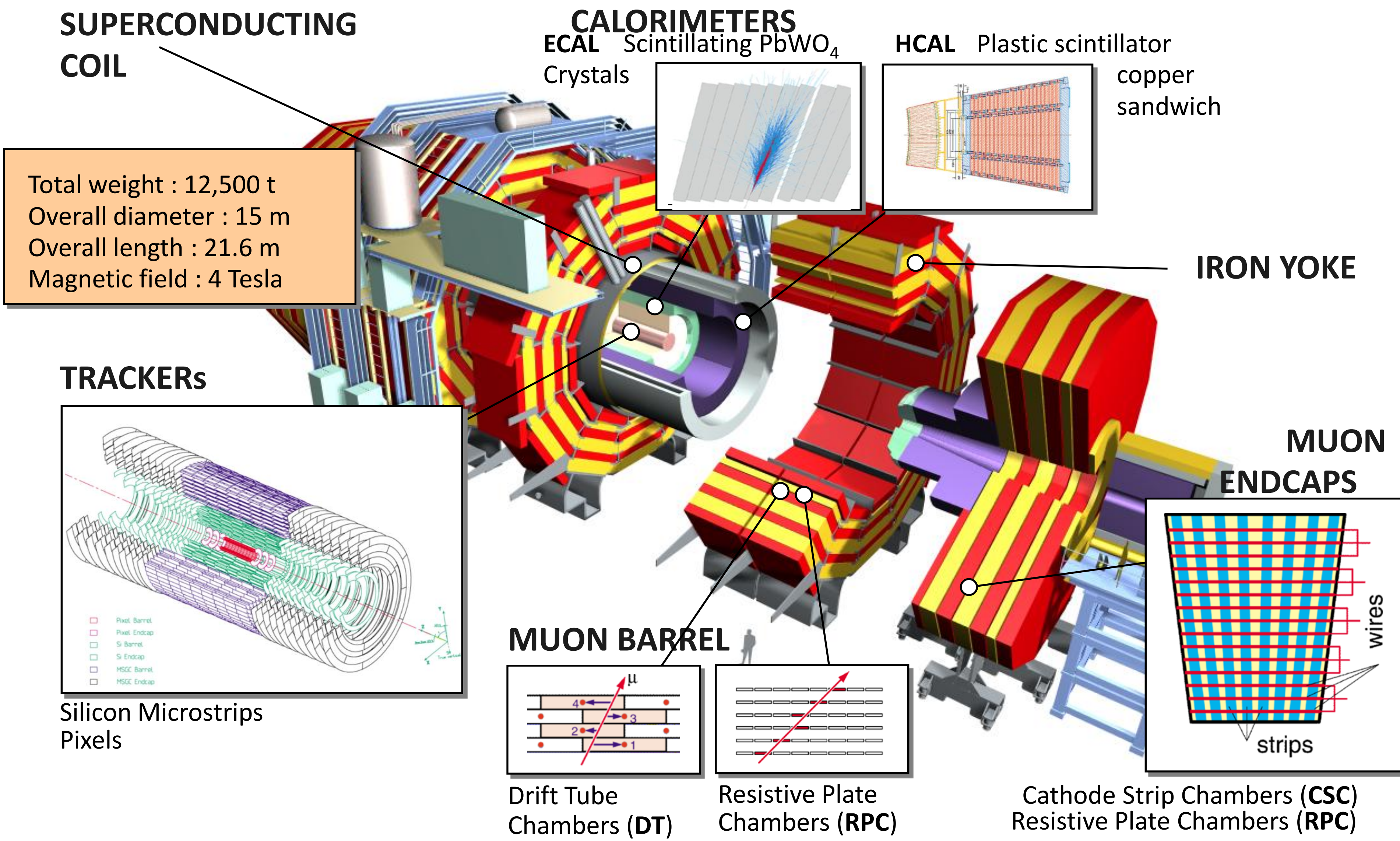


Spare

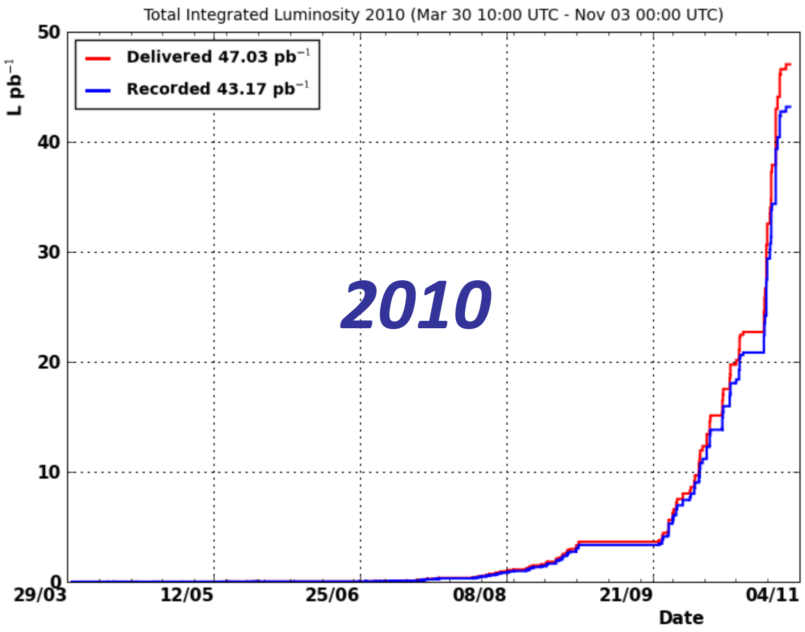
MC generators

MC Generator	Tune	Processes	PDF	PS ordered by	Hadronization	Jet-parton matching threshold
PYTHIA 6	D6T	2->2 : LO matrix elements Higher-order : PS model	CTEQ6L1	mass	Lund String Model	-
PYTHIA 6	Z2	2->2 : LO matrix elements Higher-order : PS model	CTEQ6L1	p_T	Lund String Model	-
PYTHIA 8	C2	2->2 : LO matrix elements Higher-order : PS model	CTEQ6L1	p_T	Lund String Model	-
Herwig++	2.3	LO matrix elements and simulates PS using coherent branching algorithm	MRST2001	angular ordering	Cluster model	-
MadGrraph	D6T	Tree level Higher-order : Pythia6	CTEQ6L1	mass	Lund String Model	30 GeV
Alpgen	D6T	Tree level Higher-order : Pythia6	CTEQ5	mass	Lund String Model	20 GeV

The CMS Detector



2010 data taking



- During the 2010 data taking
  - The total Integrated Luminosity delivered to CMS was 47 pb^{-1}
  - 43 pb^{-1} was recorded by the experiment.
  - ≈85% recorded with all sub-detectors in perfect operational conditions

k_T and anti-k_T : Sequential Recombination Algorithms

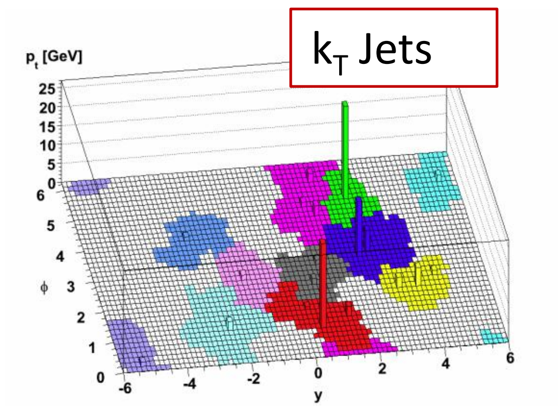
- The algorithm first defines for each protojet its beam distance: $d_{iB} = k_{ti}^{n}$
  and for each pair of protojets *i,j* their relative distance :

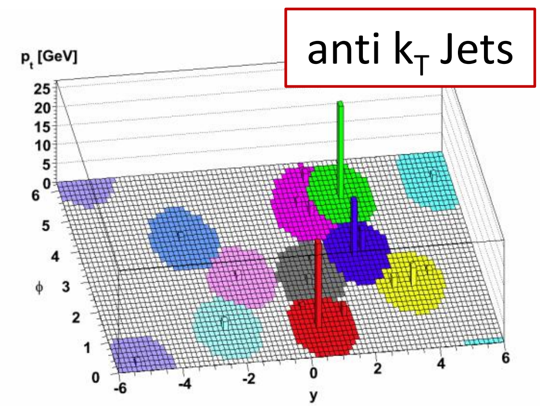
$$d_{ij} = \min\left(k_{ti}^{n}, k_{tj}^{n}\right)\frac{\Delta R_{ij}^{2}}{D^{2}} \quad \text{where} \quad \Delta R_{ij}^{2} = \left(y_i - y_j\right)^2 + \left(\varphi_i - \varphi_j\right)^2$$

  with D a jet radious resolution parameter being of the order of unity and k_{ti}, y_i and φ_i the transverse momentum, rapidity and azimuth of particle *i*, respectively.

- In a second step, if $d_{ij} \geq d_{iB}$ the protojet *i* is defined as a jet and removed from the list, otherwise the two protojets *i* and *j* combine into a single object.

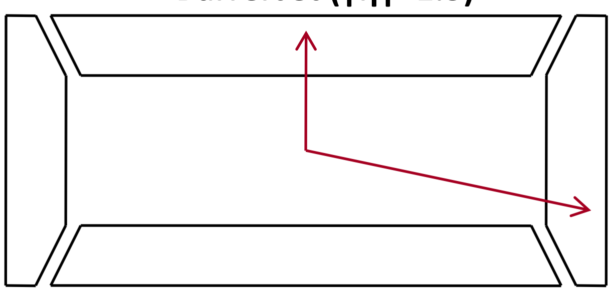
- **k_T algorithm** is defined for n=2 and favours clustering of low p_T protojets.
- **anti-k_T algorithm** is defined for n=-2 and favours clustering of high p_T protojets.
- Both algorithms are infrared and collinear safe.



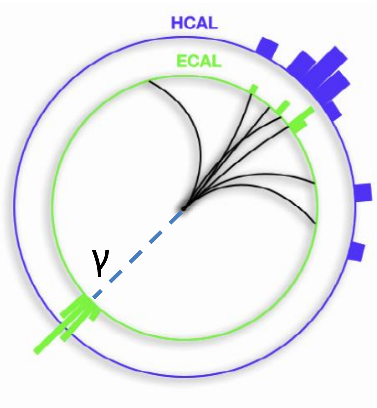


Jet Energy Scale Calibration

- Corrections derived using simulated events and in-situ measurements with dijet and photon+jet events.
- For **relative** corrections:
  - The di-jet p_T balance technique is employed taking the barrel jet ($|\eta|<1.3$) as reference and the other jet (probe jet) at any η.

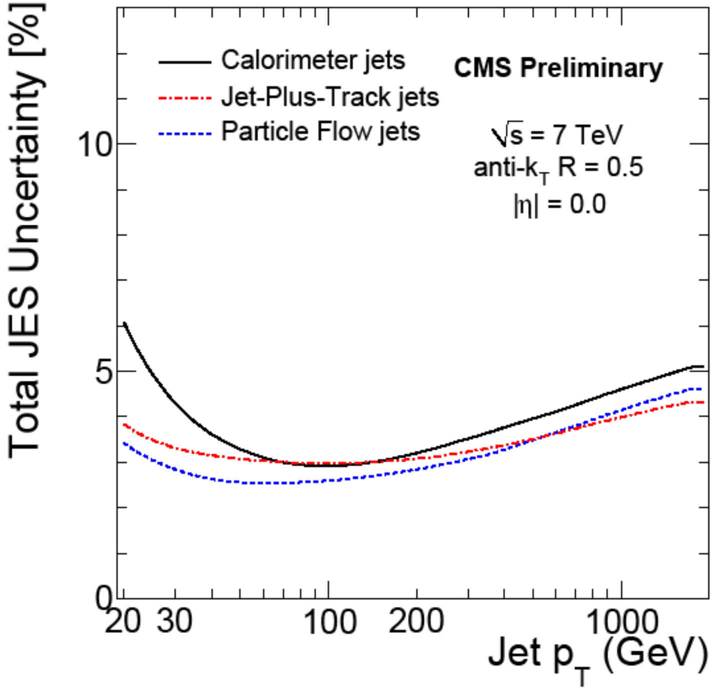


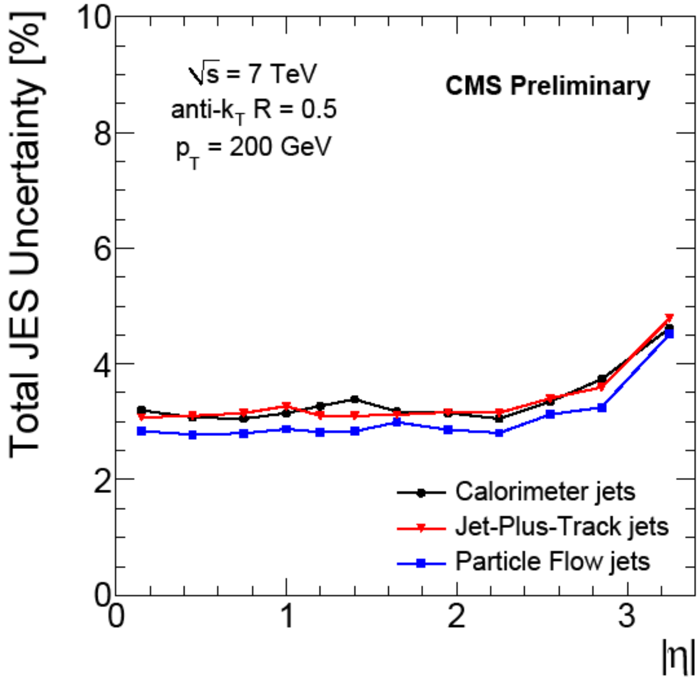
- The **absolute** jet energy response is measured using photons+jet events, with two different methods:
  - The MPF (missing E_T projection fraction)
  - And the p_T balance
- Both methods exploit the balance in the transverse plane between the photon and the recoiling jet.



Jet Calibration

CMS PAS JME-10-010

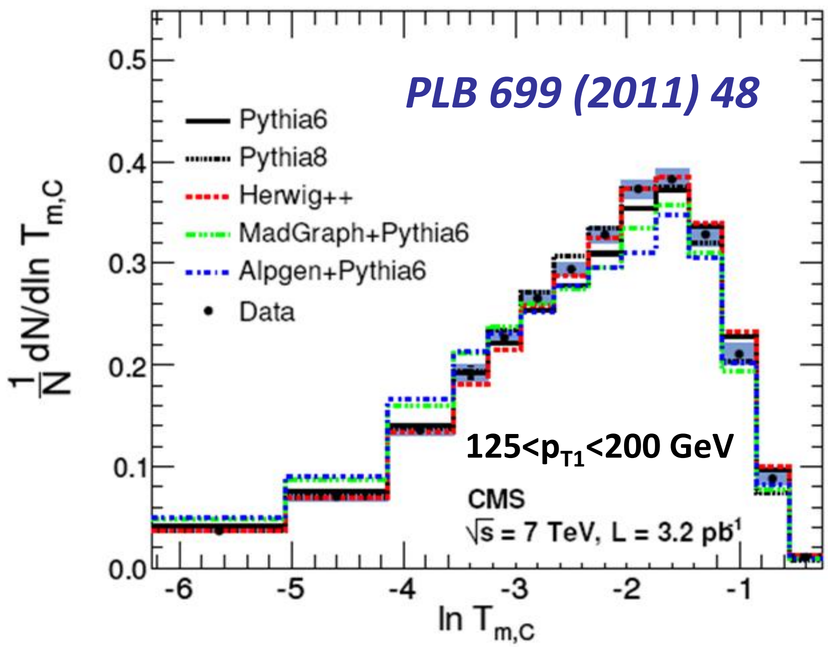




Detailed studies of the jet calibration precision yield a 3-6% uncertainty of the overall jet energy scale in a wide region of jet p_T from ≈20 GeV to 2 TeV.

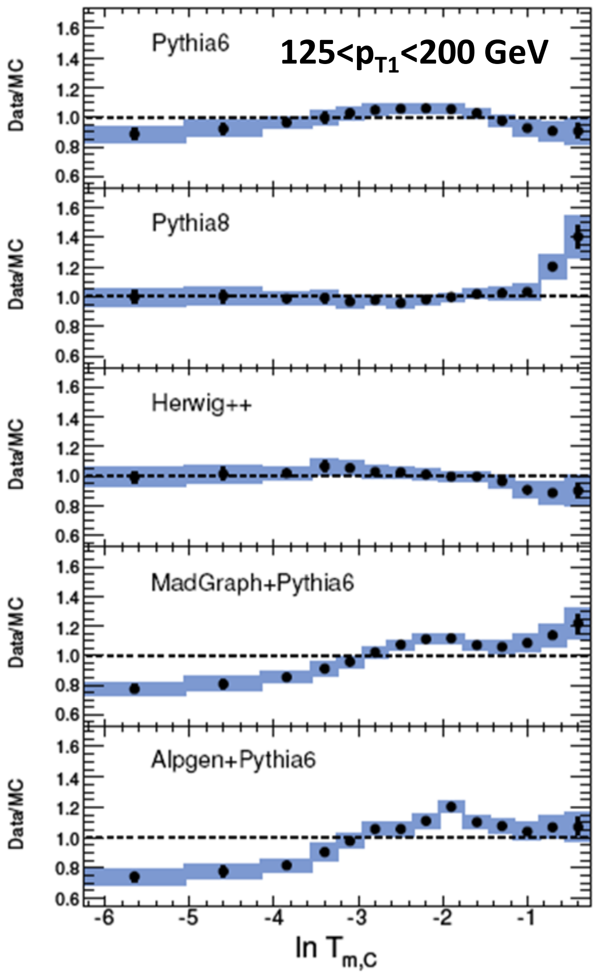
Hadronic Event Shapes

Central Thrust Minor



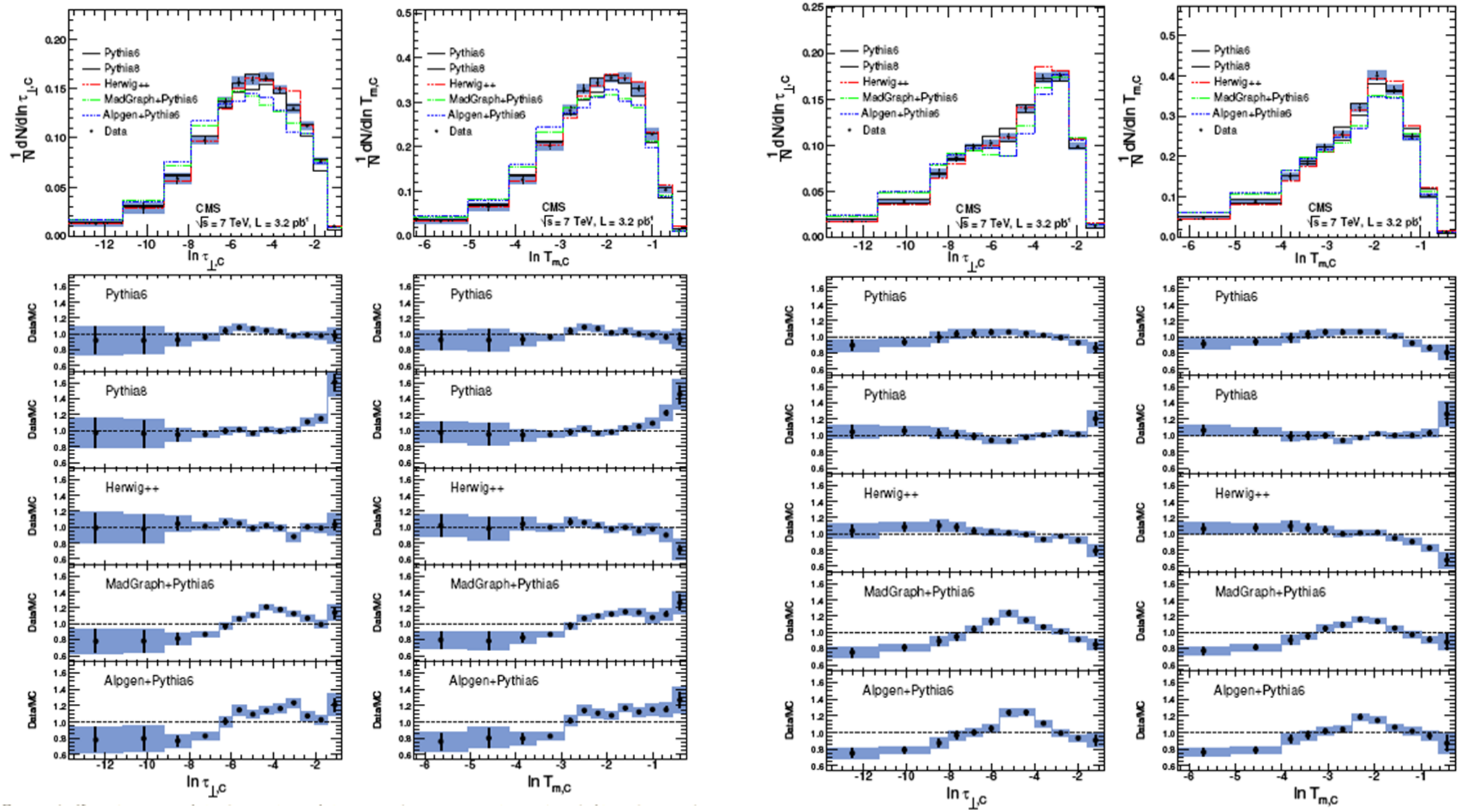
$$T_{m,C} \equiv \frac{\sum_i \left|\vec{p}_{\perp,i} \times \hat{n}_T\right|}{\sum_i p_{\perp,i}}$$

PLB 699 (2011) 48



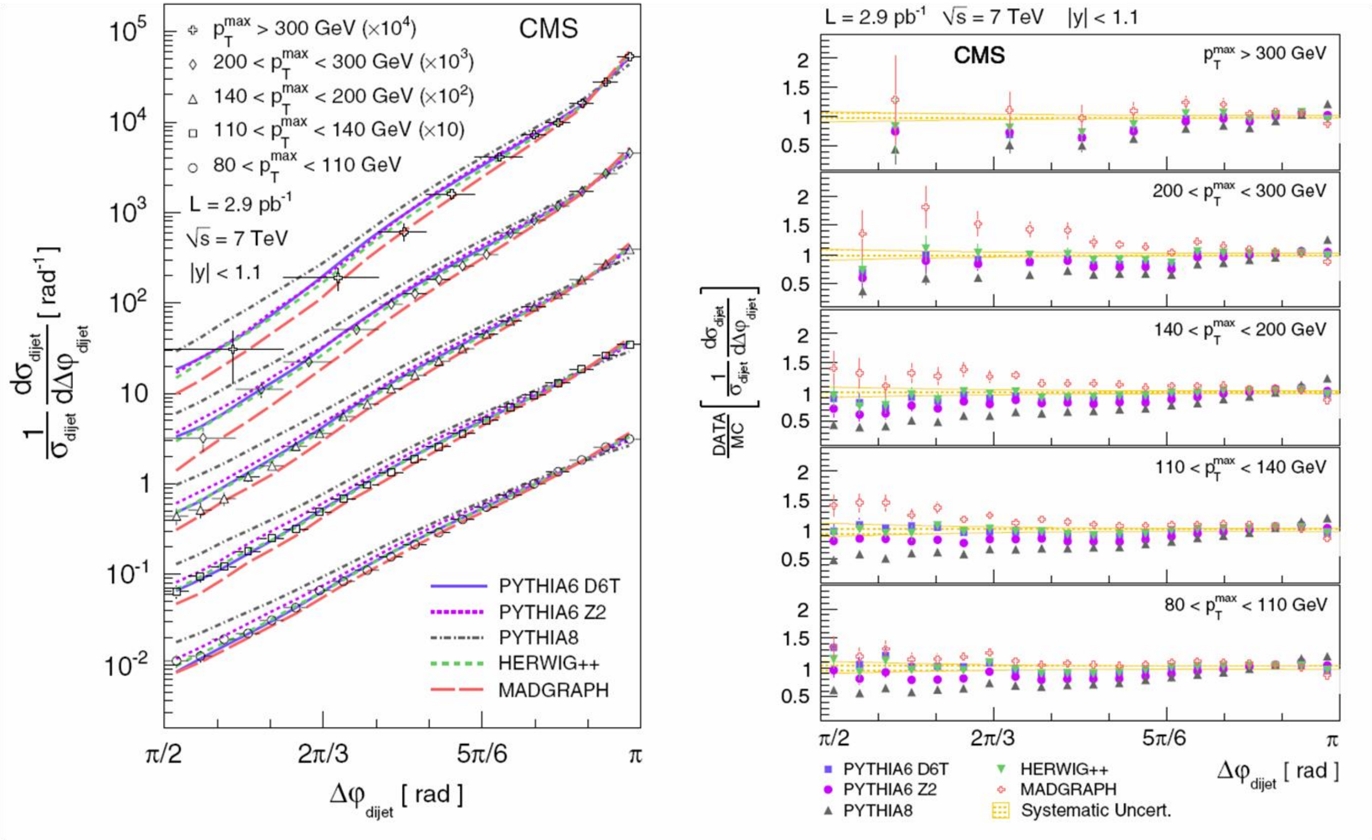
Hadronic Event Shapes: $90<p_{T1}<120$ & $p_{T1}>200$ GeV

$90<p_{T1}<120$ GeV *PLB 699 (2011) 48* **$p_{T1}>200$ GeV**



Dijet Azimuthal Decorrelations

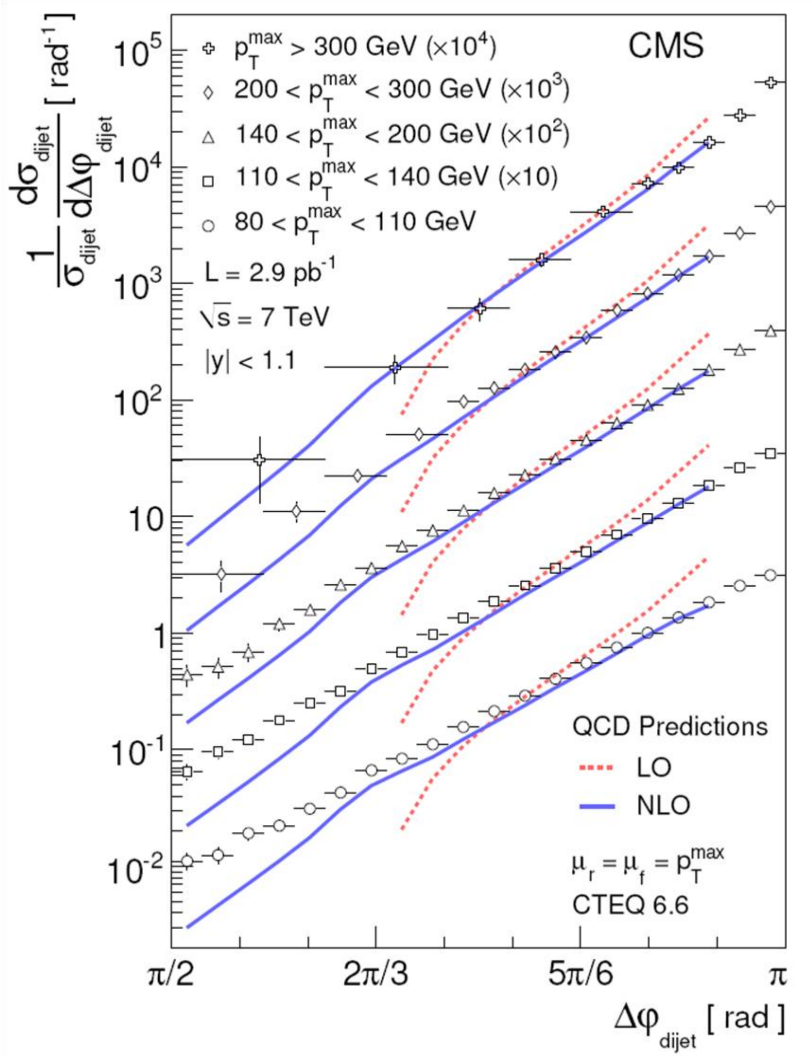
PRL 106:122003 (2011)

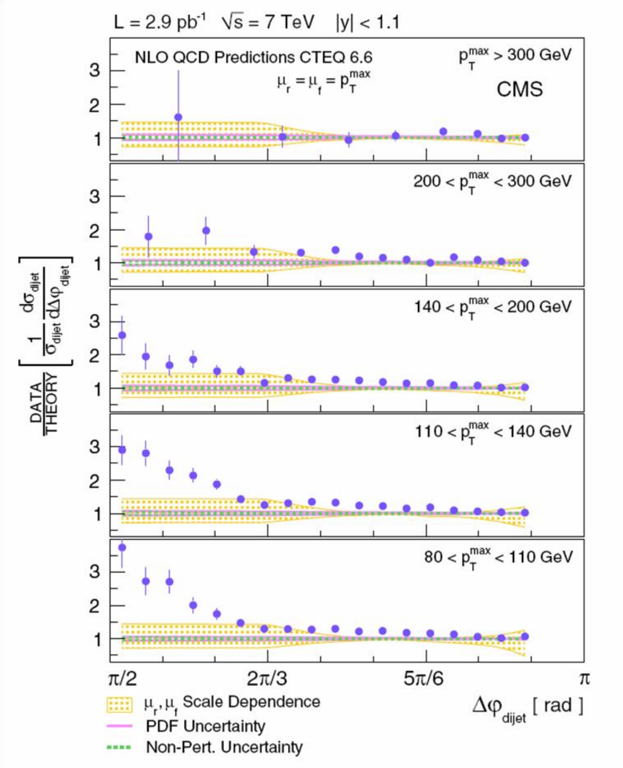


- **Data vs MC prediction**
  - The predictions from Pythia6 and Herwig++ describes the shape of data distributions well, in the entire phase space.
  - MadGraph (Pythia8) predicts less (more) azimouthal decorrelation than is observed in the data

Dijet Azimuthal Decorrelations

PRL 106:122003 (2011)





- **Theory prediction**
  - NLO pQCD + non-perturbative corrections describe well the data for $\Delta\varphi_{dijet} > 2\pi/3$ (≈ three jet topologies)
  - Scale uncertainty dominates