CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

University of Ioannina

Measurements of dijet azimuthal decorrelation at 8 TeV from CMS

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On behalf of the CMS Collaboration

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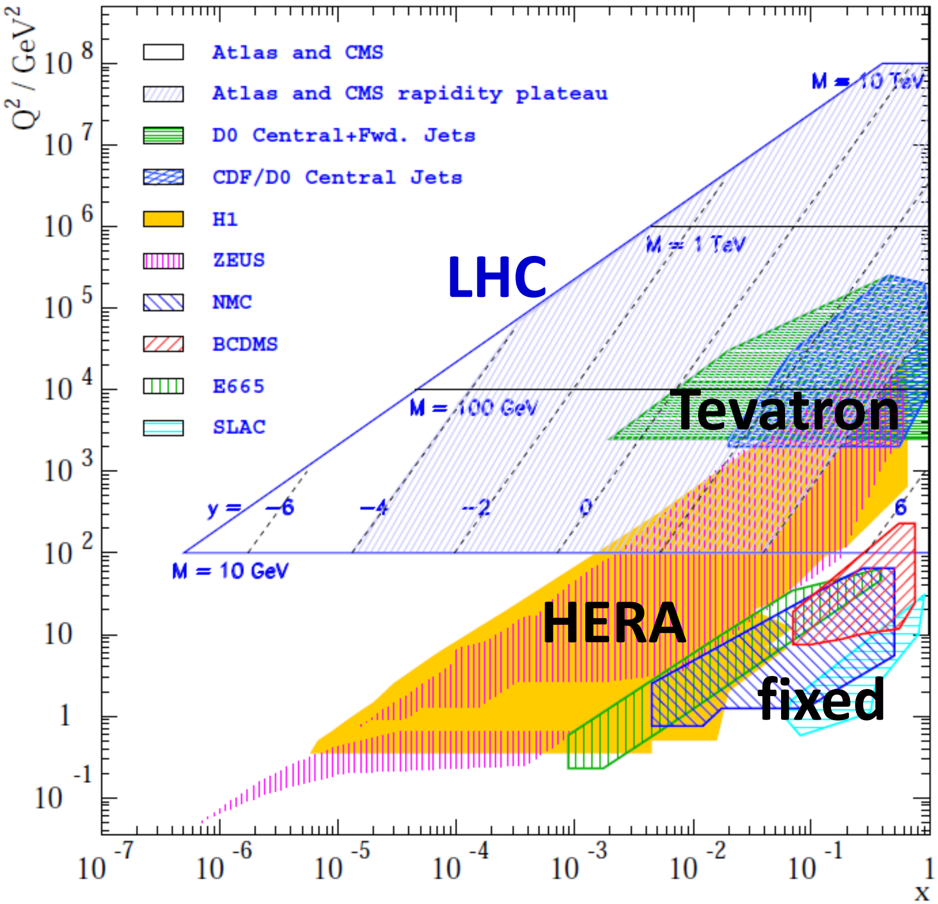
Outline

- Introduction
- Jet Reconstruction
- Jet Energy Scale Calibration at 8 TeV
- Measurements of dijet azimuthal decorrelation at 8 TeV
  - Description of the measurement
  - Comparison to fixed-orer NLO calculations in pQCD
  - Comparison to MC generators matched to parton shower simulations
- Summary

Introduction

- QCD processes are dominant at LHC. **LHC is a jet factory**.
- Jet measurements @ LHC
  - provide a test of pQCD in a previously unexplored energy region.
  - Check SM predictions at high energy scales.
  - Measure and understand the main background to many new physics searches.
  - Provide constraints on PDF's and probe the highest energy transfers at which to determine α_S.
  - Excellent place to study multi-jet production.

Kinematic plane of process Q^2 vs x



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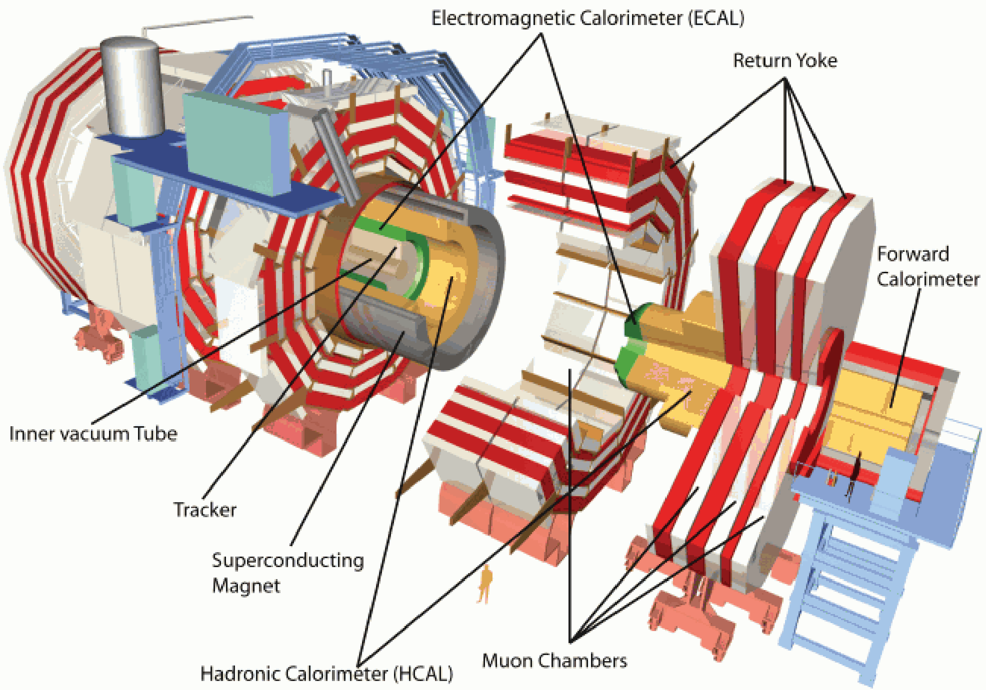
CMS detector and Integrated Luminosity

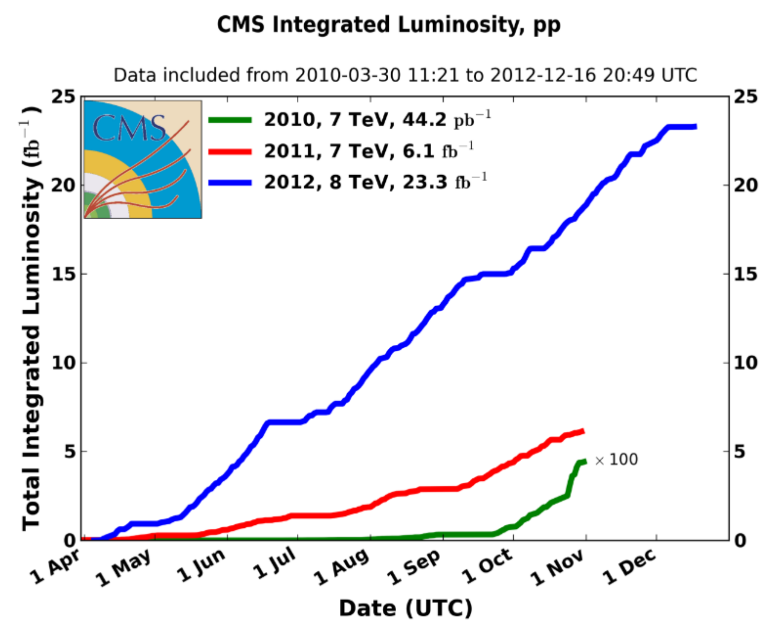


CMS detector pseudorapidity coverage:

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

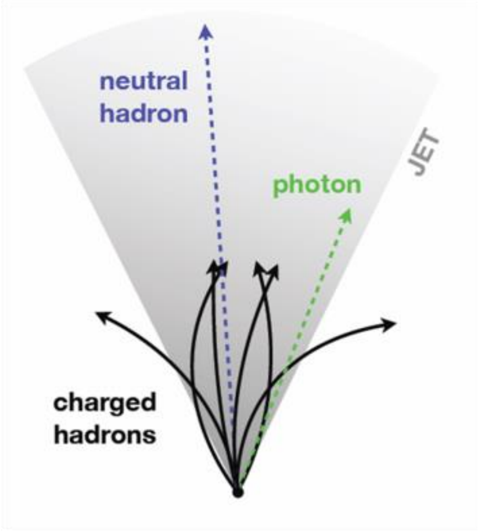
Very successful LHC operation and CMS data recording during Run 1 :

- 7 TeV (2010 & 2011)
- 8 TeV (2012)

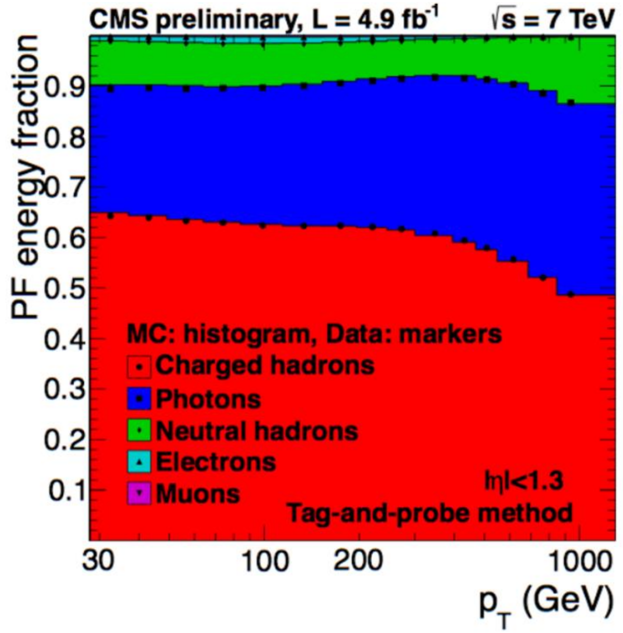


Jet Reconstruction

- **Anti-k_t clustering algorithm** : Infrared and collinear safe. Used with R=0.5 and 0.7 (for LHC Run 1).
- **CMS** Particle Flow Jets (PF Jets) : Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.



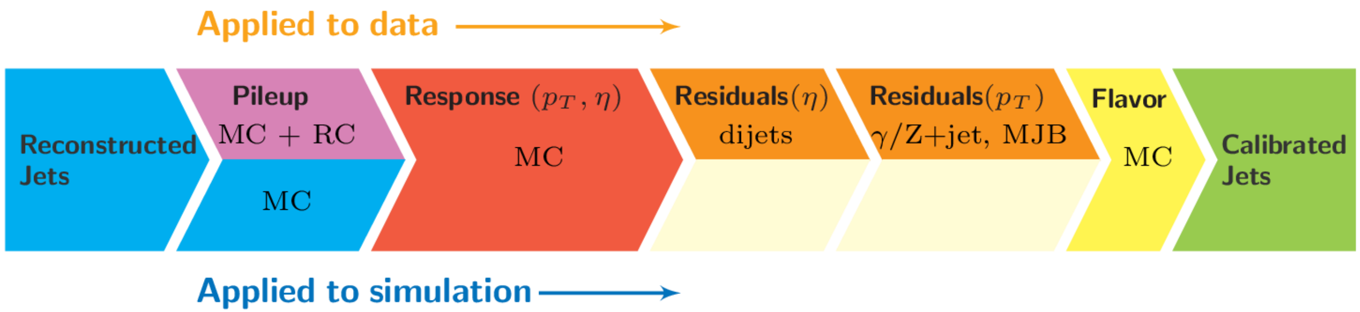
CMS DP-2015-044



- PF Jet composition
  - Charged hadrons ≈ 60%
  - Photons ≈ 30%
  - Neutral hadrons ≈ 10%
  - Leptons ≈ 2%

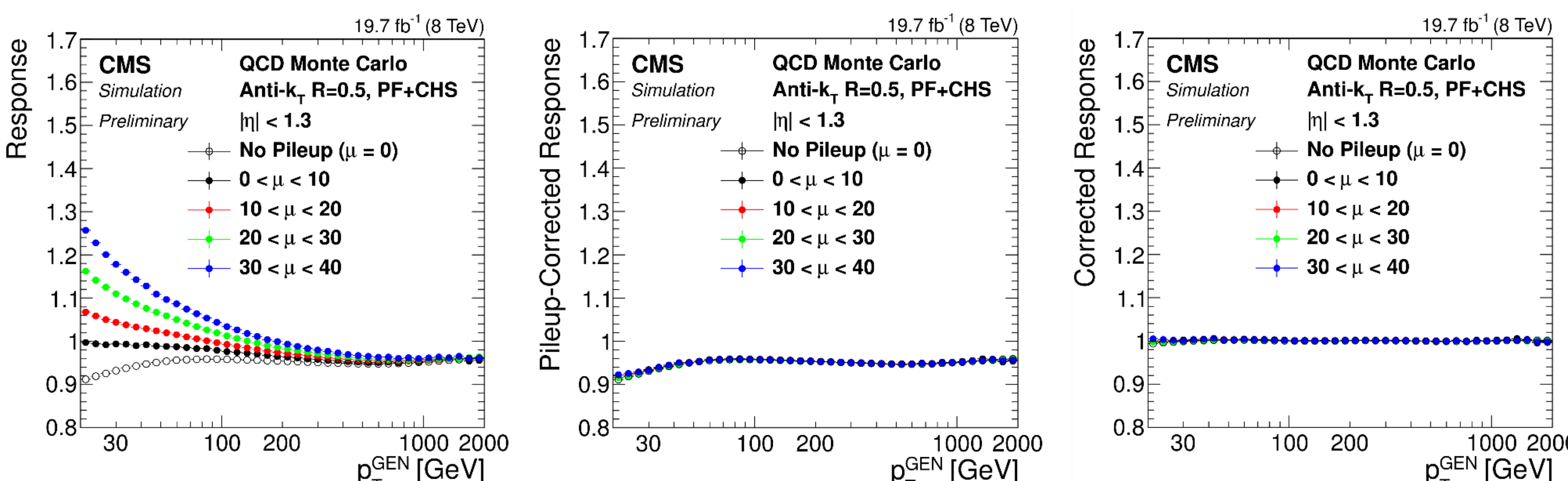
Jet Energy Scale Calibration at 8 TeV

- For the jet energy scale calibration CMS adopted a Factorized approach.

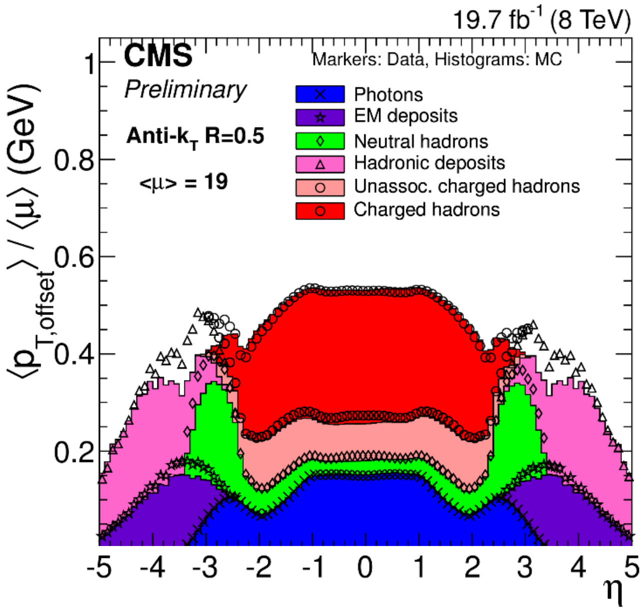


- **Pileup** → corrects for "offset" energy
- **Response** → Make jet response flat on η and p_T
- **Data/MC residuals** → residual differences between data and MC
- **Flavor (optional)** → corrects dependence on jet flavor

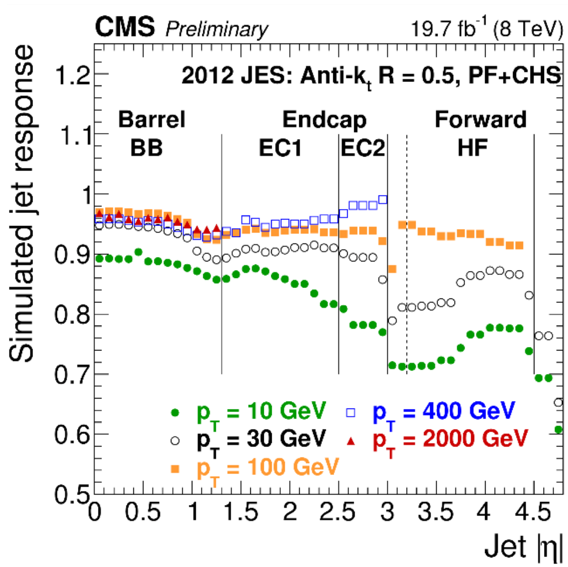
CMS DP-2015-044

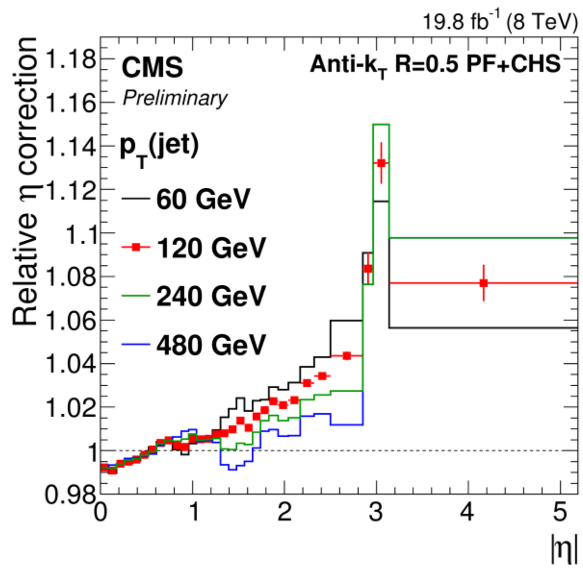


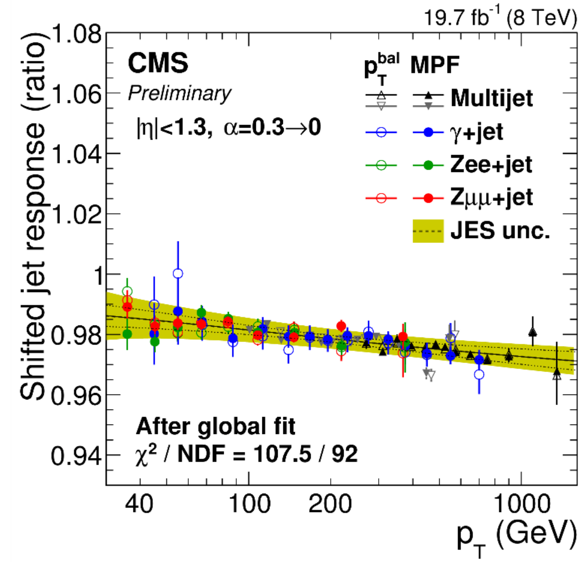
Jet Energy Scale Calibration



- **Pileup** : subtracts offset energy from multiple pp collisions $P_{T,reco}(\text{WithPU}) \rightarrow P_{T,reco}(\text{NoPU})$
- **Simulated Response** : Flattens jet response vs η and p_T $P_{T,reco}(\text{MC}) \rightarrow P_{T,ptcl}(\text{MC})$
- **Residuals** : Data/MC differences $P_{T,reco}(\text{data}) \rightarrow P_{T,reco}(\text{MC})$
  - Relative (η) : derived from dijet balance
  - Absolute (p_T) : derived from $\gamma, Z + jet$ and multijets







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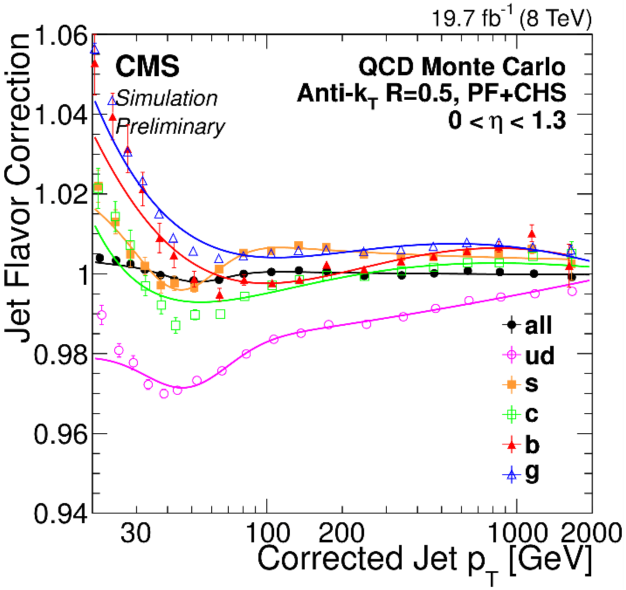
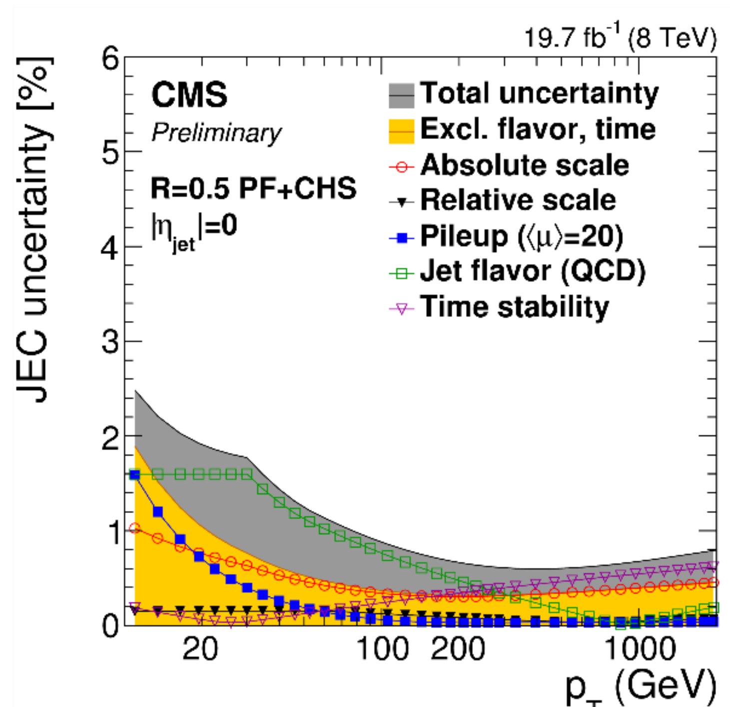
Jet Energy Scale Calibration



- **Flavor (optional)** : corrects dependense on jet flavor p_T(ud,s,c,b,g) →p_T(QCD mixture)
  - ud have the highest response
  - g the lowest (larger number of soft particles)
  - cbs response in between

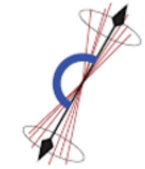
- **In the important parts of the phase space JEC uncertainties are of the order of 1%.**



CMS DP-2015-044

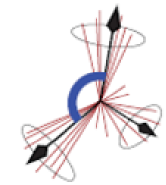
Measurements of dijet azimuthal decorrelation at 8 TeV

- At LO in pQCD the two final-state partons are produced back-to-back in transverse plane.



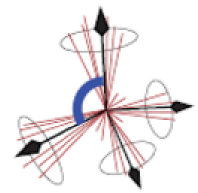
$\Delta\varphi_{\mathrm{dijet}} = \pi$

- The production of a third jet leads to a decorrelation in azimuthal angle.



$2\pi/3 \leq \Delta\varphi_{\mathrm{dijet}} < \pi$

- If more than three jets are produced, the azimuthal angle between the two leading jets can approach zero.



$0 < \Delta\varphi_{\mathrm{dijet}} \ll \pi$

- The dijet azimuthal angular decorrelation probes the multijet production processes without measuring jets beyond the leading two.

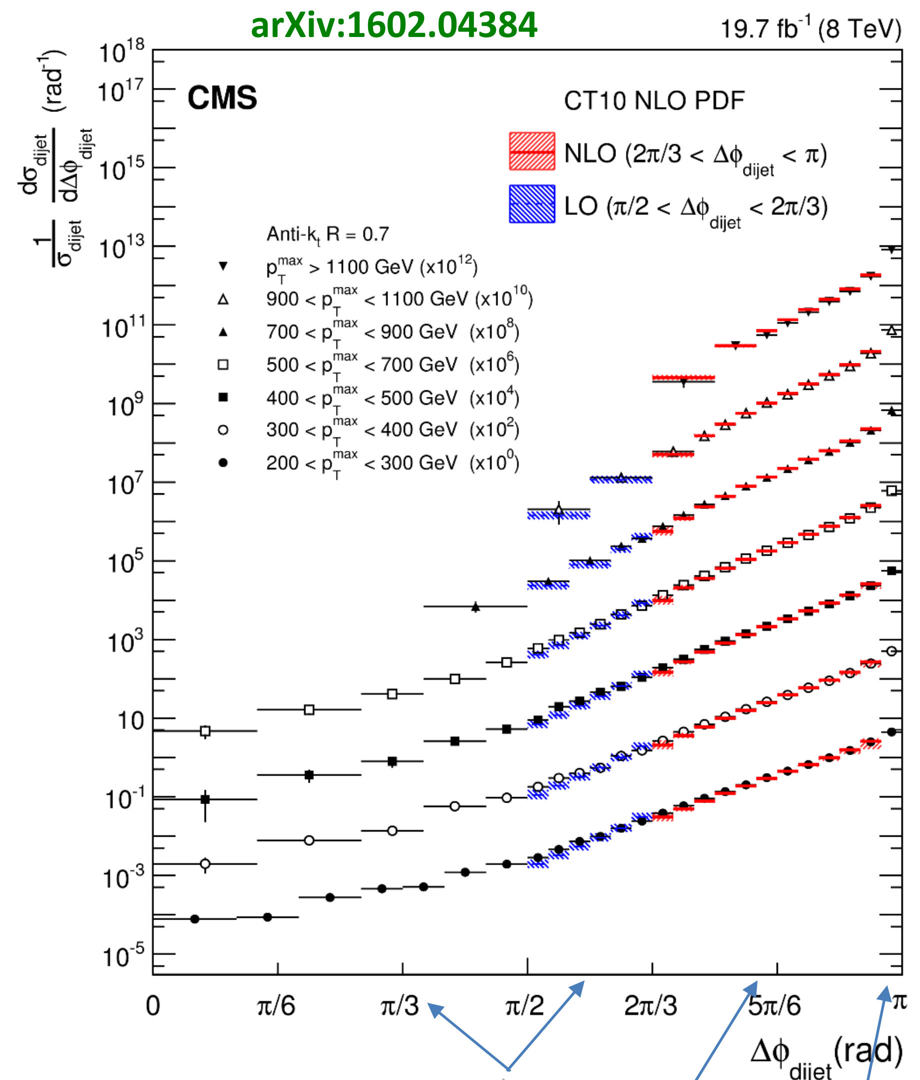
The Measurement

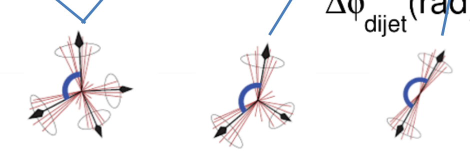
- The observable:

$$\frac{1}{\sigma_{\mathrm{dijet}}}\frac{d\sigma_{\mathrm{dijet}}}{d\Delta\varphi_{\mathrm{dijet}}}$$

- Jet $p_T > 100\mathrm{GeV},\ |y| < 2.5$
- Measured for seven regions of the leading jet p_T^{max}
- Systematics
  - Jet Energy Scale : 7% - 1%
  - Jet Energy Resolution : 5% - 0.5%
  - Unfolding 1%

- The $\Delta\varphi_{\mathrm{dijet}}$ distributions are strongly peaked at π and become steeper with increasing p_T^{max} .





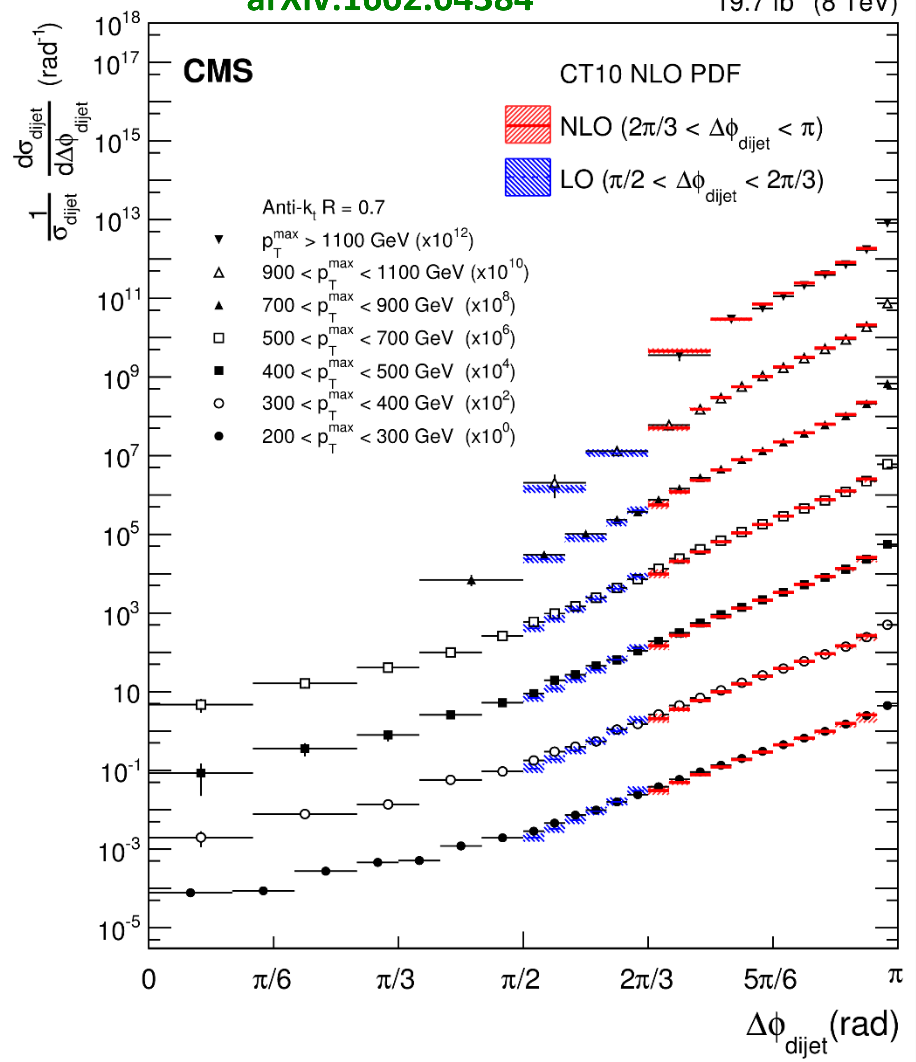
Comparison to fixed-order NLO calculations in pQCD

- Calculations performed with NLOJET++ & FASTNLO.
- 3-jet NLO calculation (3-4 partons):
  - NLO precision : $2\pi/3 \leq \Delta\varphi_{\mathbf{dijet}} < \pi$
  - LO precision : $\pi/2 \leq \Delta\varphi_{\mathbf{dijet}} < 2\pi/3$
- Normalization to dijet cross section:
  - NLO : $2\pi/3 \leq \Delta\varphi_{\mathbf{dijet}} < \pi$
  - LO : $\pi/2 \leq \Delta\varphi_{\mathbf{dijet}} < 2\pi/3$
- Scale choice : $\mu_r = \mu_f = \mathrm{p}_{\mathrm{T}}^{\max}$

PDFs

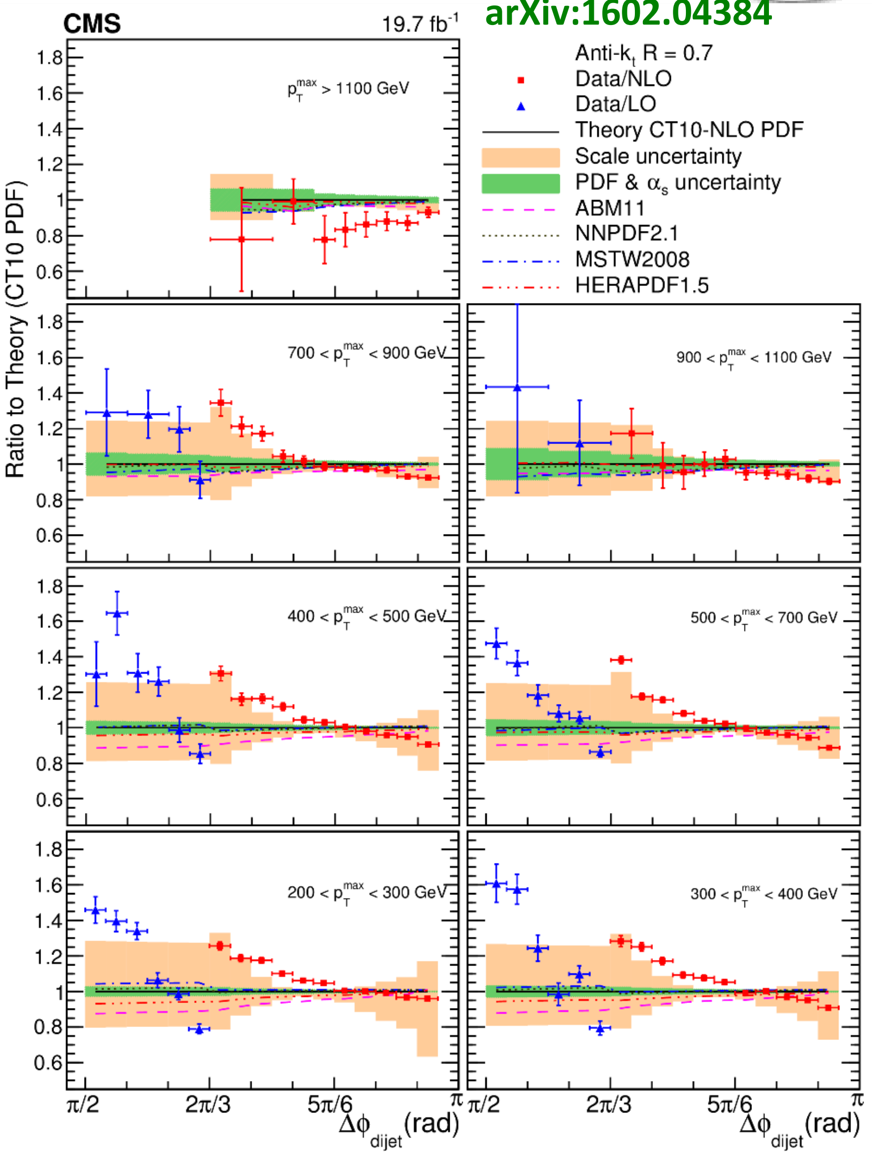
Base set	Refs.	N_f	$\alpha_S(M_Z)$
ABM11	[30]	5	0.1180
CT10	[31]	≤5	0.1180
HERAPDF1.5	[32]	≤5	0.1176
MSTW2008	[33]	≤5	0.1202
NNPDF21	[34]	≤6	0.1190

arXiv:1602.04384



Comparison to fixed-order NLO calculations in pQCD

arXiv:1602.04384



- **Scale uncertainty** : varying independently μ_r/Q and μ_f/Q from ½ to 2, and get maximal deviation.
- **PDF uncertainty** : following prescriptions of CT10 set, varying eigenvectors up and down.
- **α_S uncertainty** : vary $\alpha_S(M_Z)$ by ±0.001.

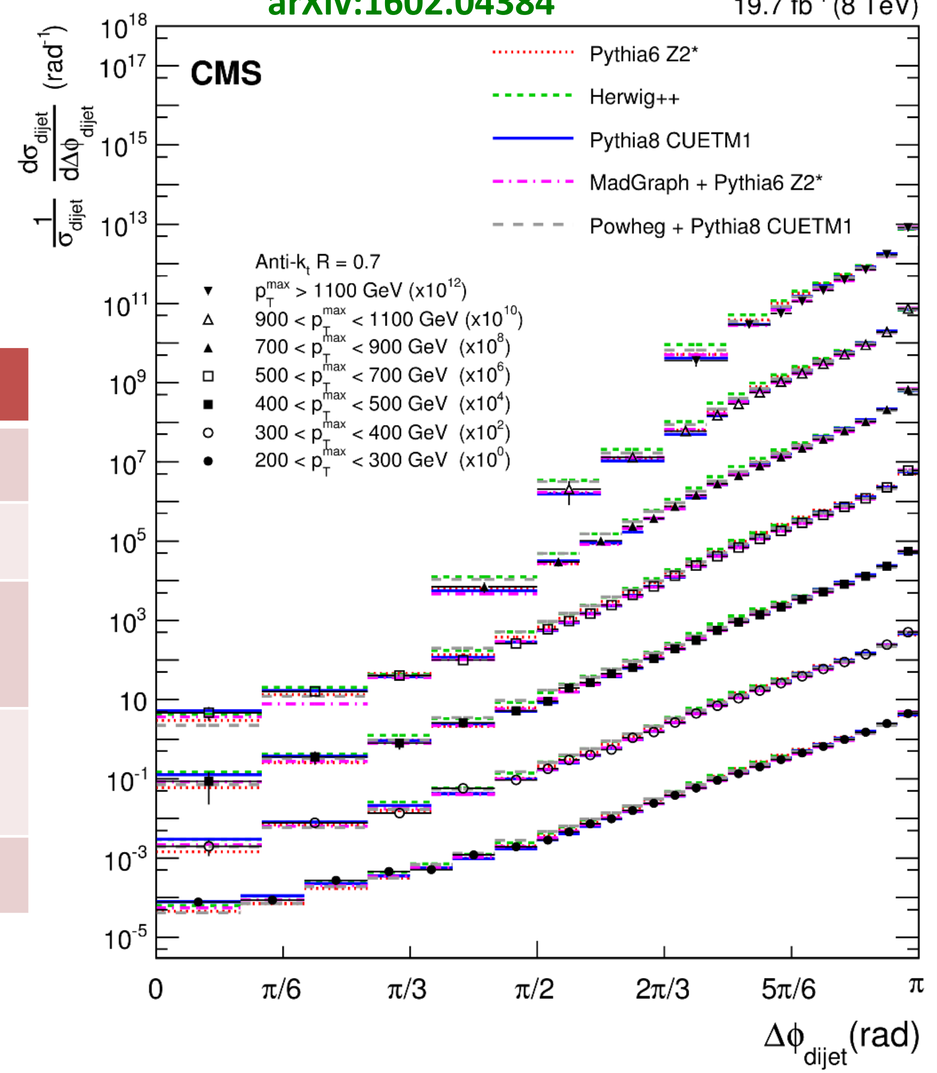
- Nice agreement for $\mathbf{\Delta\varphi_{dijet}} > \frac{5\pi}{6}$, except for the highest p_T^{max} region.
- For $\frac{2\pi}{3} \leq \mathbf{\Delta\varphi_{dijet}} < \frac{5\pi}{6}$ systematic discre-pancies are exhibited that diminish with increasing p_T^{max}
- For $\frac{\pi}{2} \leq \mathbf{\Delta\varphi_{dijet}} < \frac{2\pi}{3}$ same pattern but with less significance.

Comparison to MC generators

- MC generators used:

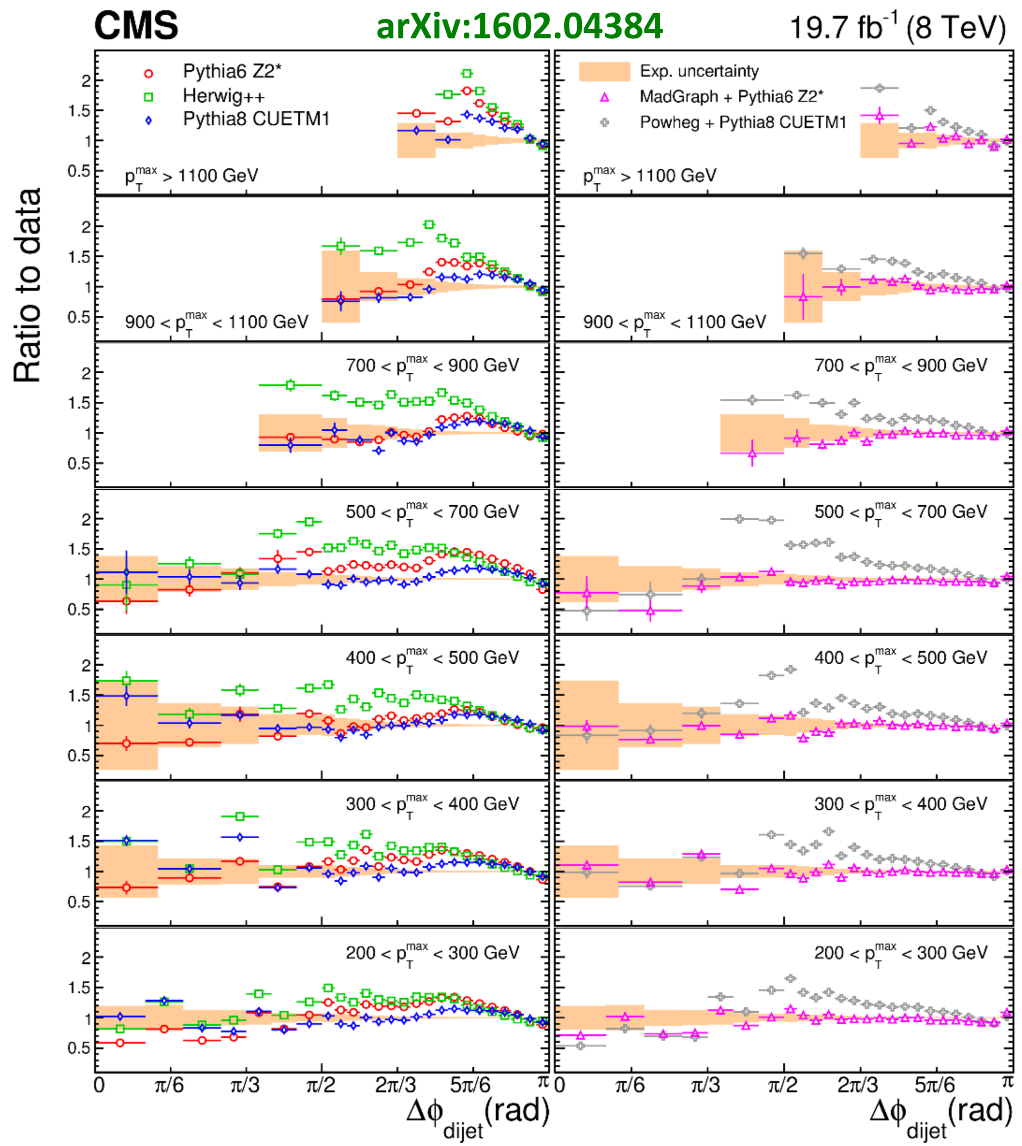
Generator	Calculation	PS	Tune
Pythia6	LO dijet	pT-ordering	Z2*
Pythia8	LO dijet	pT-ordering	CUETM1
Herwig++	LO dijet	angular ordering	EE3C
MadGraph	LO 2 to 4 partons	Pythia6	Z2*
Powheg	NLO dijet	Pythia8	CUETM1

arXiv:1602.04384



Comparison to MC generators

- LO dijet event generators Pythia6, Pythia8 and Herwig++ shows deviations from data.
- Similar behaviour for the NLO dijet generator Powheg matched to Pythia8.
- Best description by the tree-level multiparton event generator MADGRAPH interfaced with PYTHIA6.



Summary

- **CMS** has an **excellent understanding** of the **jet reconstruction** and **energy calibration** and together with the **high data quality** make jet measurements **PRECISION PHYSICS**.
  - In the important parts of the phase space JEC uncertainties are of the order of 1%.

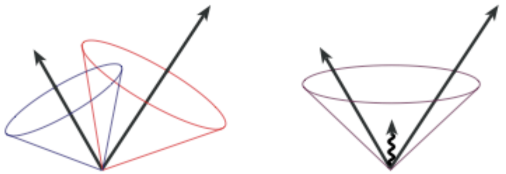
- The measurements of **dijet azimuthal decorrelation** at **8 TeV** is presented
  - Presented for the first time in the whole phase space : $\mathbf{0 \leq \Delta\varphi_{dijet} < \pi}$
  - Comparison to fixed order NLO calculations show an overall agreement to data (some systematic discrepancies are exhibited)
  - Best description of data by the tree-level multiparton event generator **MADGRAPH**
  - The observations emphasizes the need to improve predictions for multijet production.

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-14-015/index.html

SPARE SLIDES

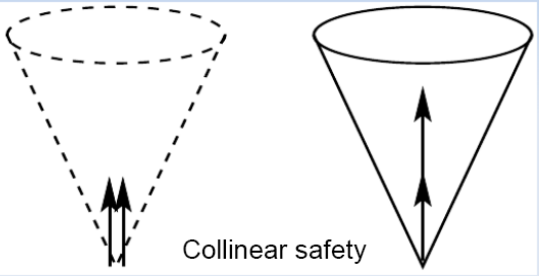
Jet reconstruction algorithm requirements

- Infrared safety
  - A jet algorithm is infrared safe if, for any n-parton configuration, adding an infinitely soft parton does not affect the result at all.



soft radiation may cause merging of 2 jets

- Collinear safety
  - A jet algorithm is collinear safe if, for any n-parton configuration, replacing any massless parton by an exactly collinear pair of massless partons does not affect the result at all.



- Same jet algorithms for data and theoretical predictions.
  - so that perturbative calculations can be compared to experiments.
- Detector independence.
- Not too sensitive to underlying event and pile up.

k_T and anti-k_T : Sequential Recombination Algorithms

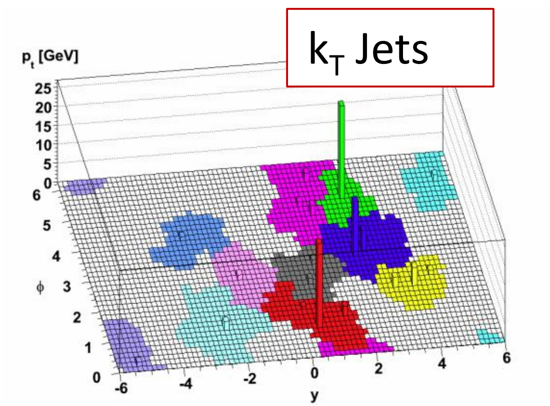
- The algorithm first defines for each protojet its beam distance: $d_{iB} = k_{ti}^{n}$
  and for each pair of protojets *i,j* their relative distance :

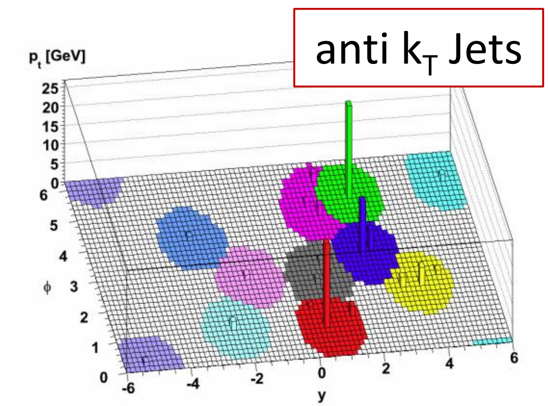
$$d_{ij} = \min\left(k_{ti}^{n}, k_{tj}^{n}\right)\frac{\Delta R_{ij}^{2}}{D^{2}} \qquad \text{where} \qquad \Delta R_{ij}^{2} = \left(y_i - y_j\right)^2 + \left(\varphi_i - \varphi_j\right)^2$$

  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.

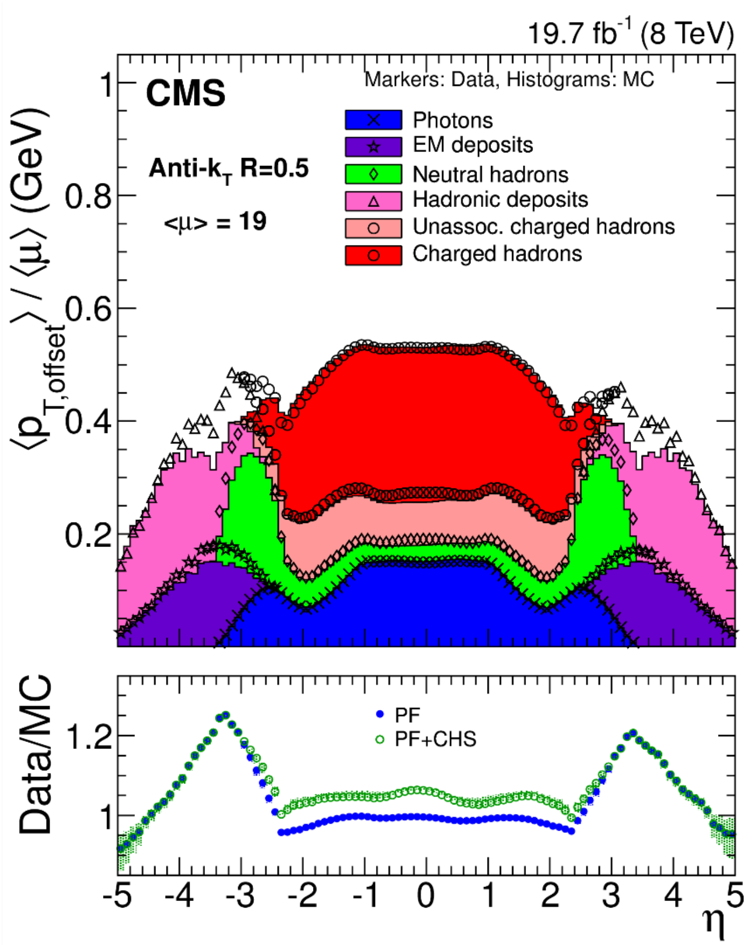
- In a second step, if $d_{ij} \geq d_{iB}$ the protojet *i* is defined as a jet and removed from the list, otherwise the two protojets *i* and *j* combine into a single object.

- **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.



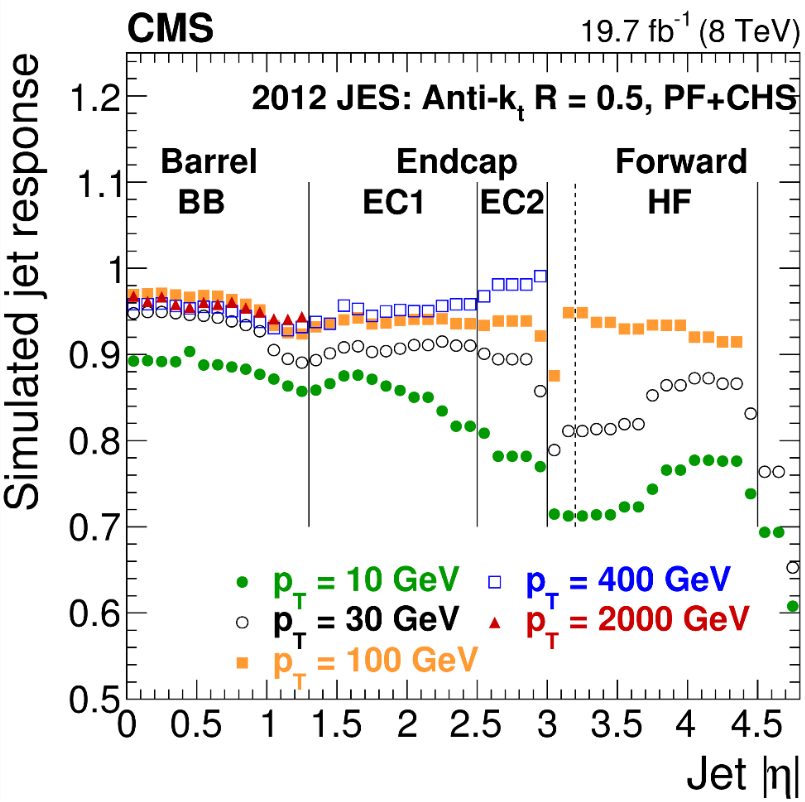


Pilup offset corrections



- The Pileup offset corrections:
  - determined from simulation (QCD) with and without pileup
- Parametrized vs:
  - The offset energy density ρ
  - The jet area A
  - The jet η
  - The jet p_T
- Residual differences between data-MC vs η
  - Determined using the Random Cone (RC) method on minimum bias events
- PFchs jets :
  - Charged Hadron Substruction (CHS) method remove tracks originated from pileup vertices.

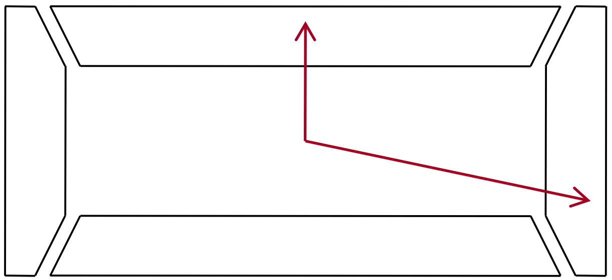
Simulated jet Response

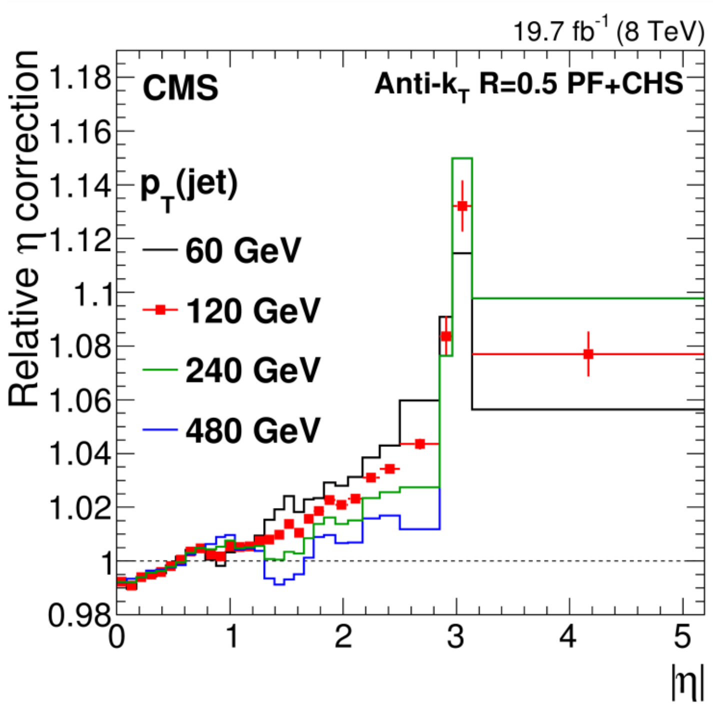


- Simulated jet response corrections:
  - Determined from Pythia6 Z2*
  - Detector simulation with GEANT4
- Corrections have:
  - Stable response in barrel
  - Lower response in endcaps
  - HF performance similar to endcap
- Uncertainties:
  - Modelling jet fragmentation (comparison to Herwig++ EE3C)
  - From detector simulation using the CMA fast simulation

Residual η (Relative) corrections

- Residual Relative corrections:
  - Determined by dijet events.
  - The dijet p_T balance technique is employed taking the barrel jet (|η|<1.3) as reference and the other jet (probe jet) at any η.



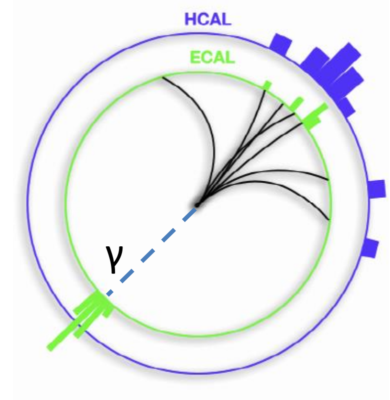


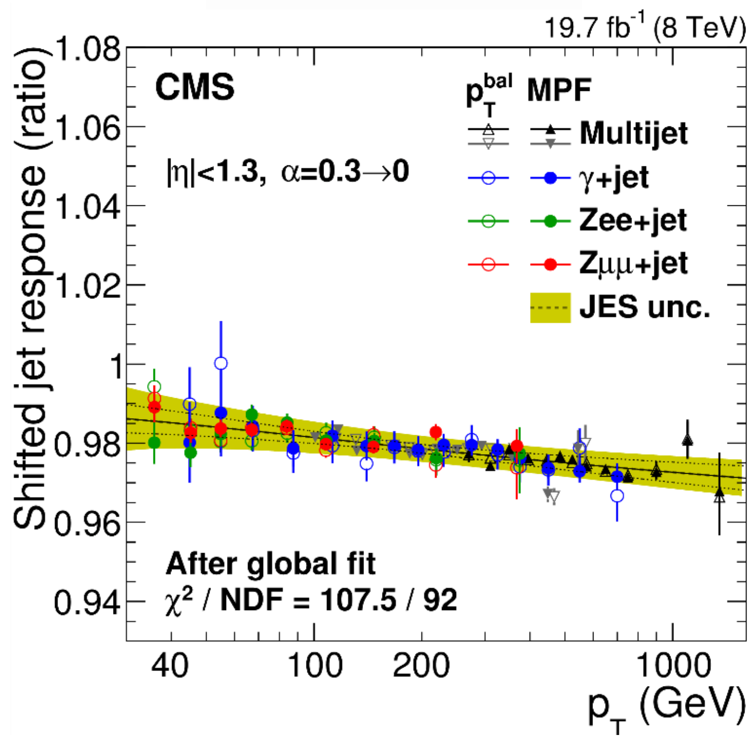
- Residual Relative corrections:
  - Increases at low p_T in endcaps.
  - Large 10% residual in HF

Residual Absolute Scale Correction

- Residual absolute corrections:
  - Using $\gamma, Z + jet$ (30<p_T<800 GeV)
  - Using multijets (p_T>800 GeV)
- Methods
  - The MPF (missing E_T projection fraction)
  - And the p_T balance
  - Both methods exploit the balance in the transverse plane between the γ, Z and the recoiling jet

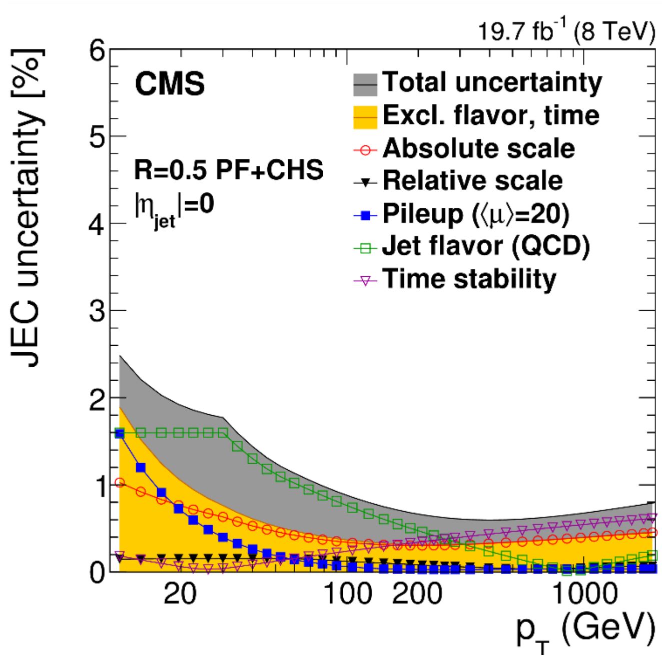
- Final result from a global fit to $\gamma, Z + jet$ and multijet data.

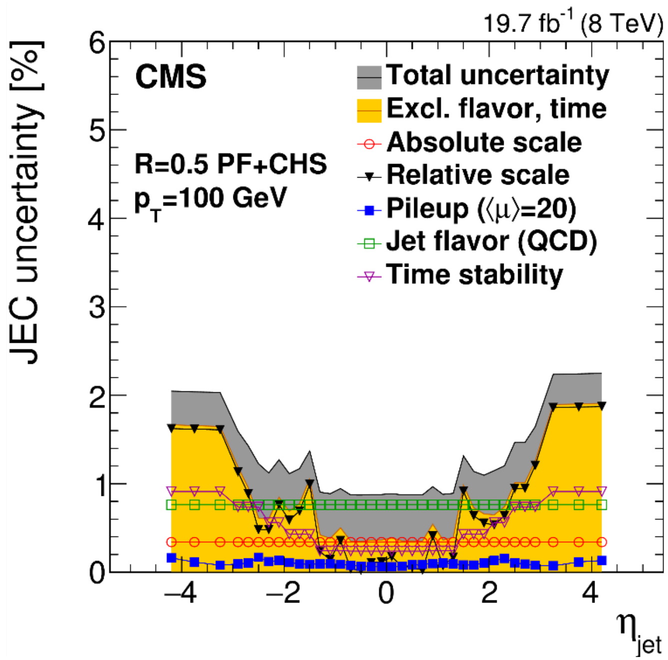




Total JEC uncertainties

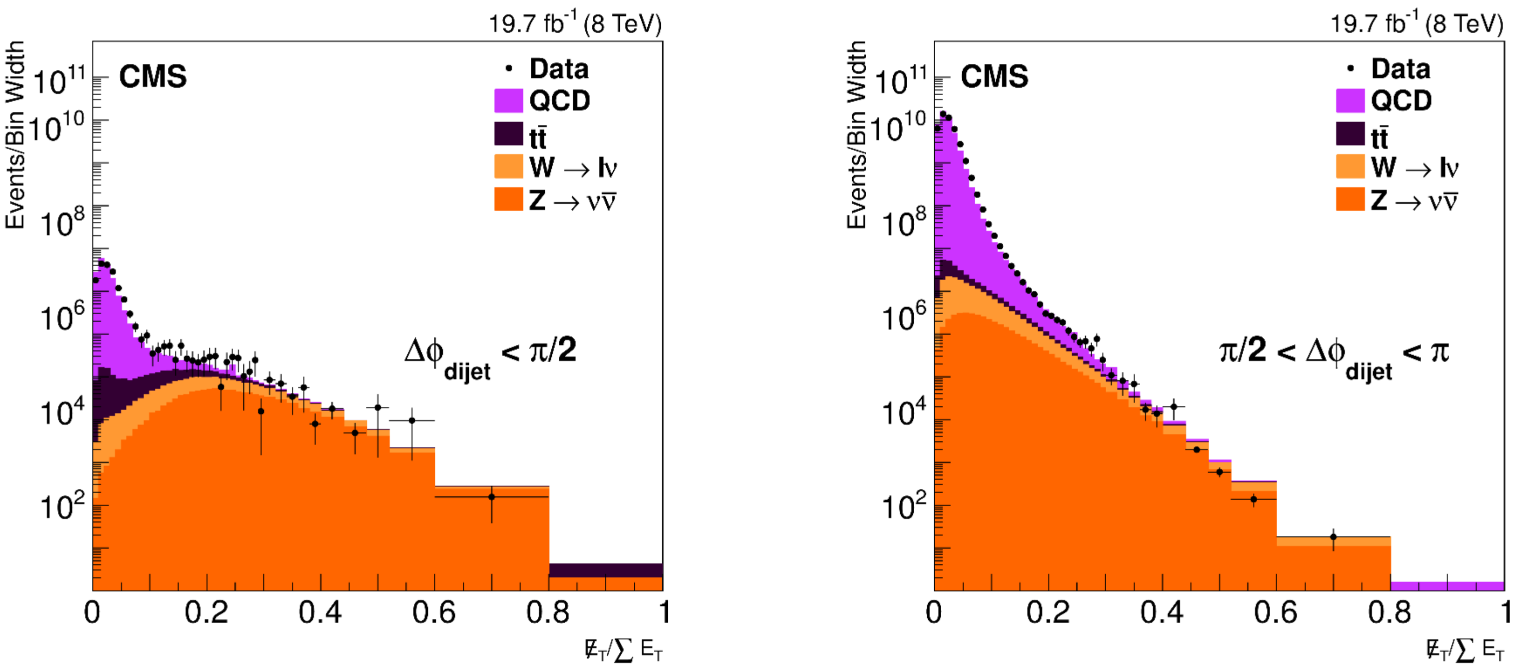
- **JetFlavorQCD** is the dominant JEC for inclusive jets
- **Time stability** dominant at high p_T (excluded if whole 8TeV sample is used)
- **Pileup** uncertainty is small due to absorption into residual η+p_T corrections
- Other main uncertainties are **absolute** and relative **scale**
  - Minimum of **0.32%** at **p_T=200 GeV** and **|η|=0** (excluding flavour and time)
  - Minimum of **0.60%** at **p_T=400 GeV** and **|η|=0** (all uncertainties)





MET/SumET selection cut

- Optimization of background in small $\Delta\varphi_{\mathrm{dijet}}$



Comparison to fixed-order NLO calculations in pQCD

- 3-jet NLO calculation (α_S^4, 3-4 partons):
  - NLO precision : $2\pi/3 \leq \Delta\varphi_{\text{dijet}} < \pi$
  - LO precision : $\pi/2 \leq \Delta\varphi_{\text{dijet}} < 2\pi/3$
- Normalization to dijet cross section:
  - NLO : $2\pi/3 \leq \Delta\varphi_{\text{dijet}} < \pi$
  - LO : $\pi/2 \leq \Delta\varphi_{\text{dijet}} < 2\pi/3$
- Improved description of data at $\pi/2 \leq \Delta\varphi_{\text{dijet}} < 2\pi/3$ by normalizing with LO dijet cross section. Avoids artificially increased scale uncertainties see:
  - JHEP 12(2015) 024
  - Nucl.Phys. B 513 (1998) 269

arXiv:1602.04384