Jets and Missing E_T in ATLAS and CMS

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Filip Moortgat, Phil Harris, Francesco Pandolfi, Hartmut Stadie, Artur Apresyan (CMS)
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Introduction

Jets :
- experimental signature of quarks and gluons
- highly populate the events produced in an hadronic environment
- difficult to calibrate with high precision

MET :
- missing transverse energy in the event
- signature of neutrinos (analysis within the Standard Model)
- signature of all other non-interacting particles ! (search for New Physics)

These objects are widely used in physics analyses within ATLAS and CMS, and often an important source of systematics.
Their commissioning is crucial for the succes of the physics program !

Jet Reconstruction in ATLAS

Jets are reconstructed with the AntiKt [arXiv:0802.1189v2] algorithm for different ΔR parameters (0.4, 0.6, 1.0) and CA [hep-ph/9707323] (ΔR=1.2)

- ❑ **Truth-jets:**
  - reconstructed from simulated stable hadrons but muons and neutrinos;
- ❑ **Track-jets:**
  - input constituents are tracks from the inner detector ($|\eta|<2.5$) and reconstructed with a track pT threshold of 500 MeV;
  - Used mainly for systematic studies (jet-mass, b-JES, sub-jet JES).
- ❑ **Calorimeter-jets:**
  - Inputs are noise suppressed 3D topological clusters reconstructed from the calorimeter system ($|\eta|<4.9$).
  - These clusters are either :
    - used as input to the jet algorithm at EM-scale;
    - calibrated with the Local Cluster Weighting technique [**CERN-PH-EP-2011-191**].

Jet Reconstruction in CMS

Jets are reconstructed with the AntiKt algorithm (R 0.5, 0.7) and CA R 0.8 .

- ❑ **Truth-jets:**
  - reconstructed from simulated stable hadrons but neutrinos;
- ❑ **Calorimeter-jets:**
  - Inputs are EM and HAD calotowers
- ❑ **Jet-plus-Tracks-jets:**
  - CaloJets with applied energy and direction corrections extracted from tracks inside the jet cone
- ❑ **Particle Flow jets:**

• all subdetector information is combined into PF candidates
• choice of the PV as highest sum pT
• charged hadrons coming from other PVs are identified as PU and removed (Charged Hadron Subtraction)
• isolated objects (photons, leptons) are identified and PFcandidates removed from next step
• jets are clustered from PFcandidates

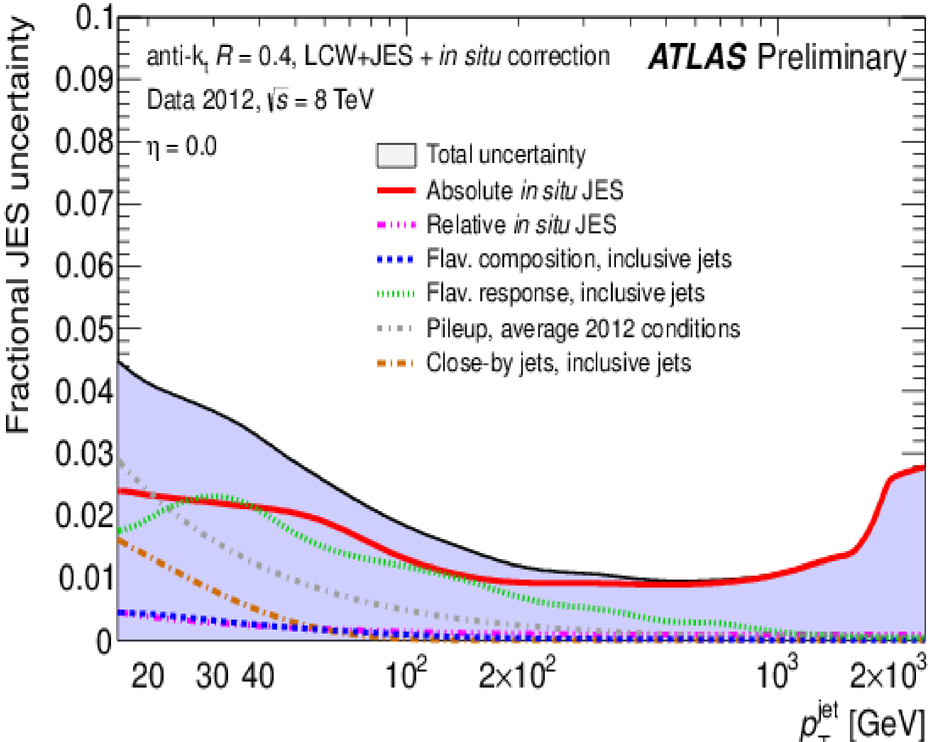
JEC Overview

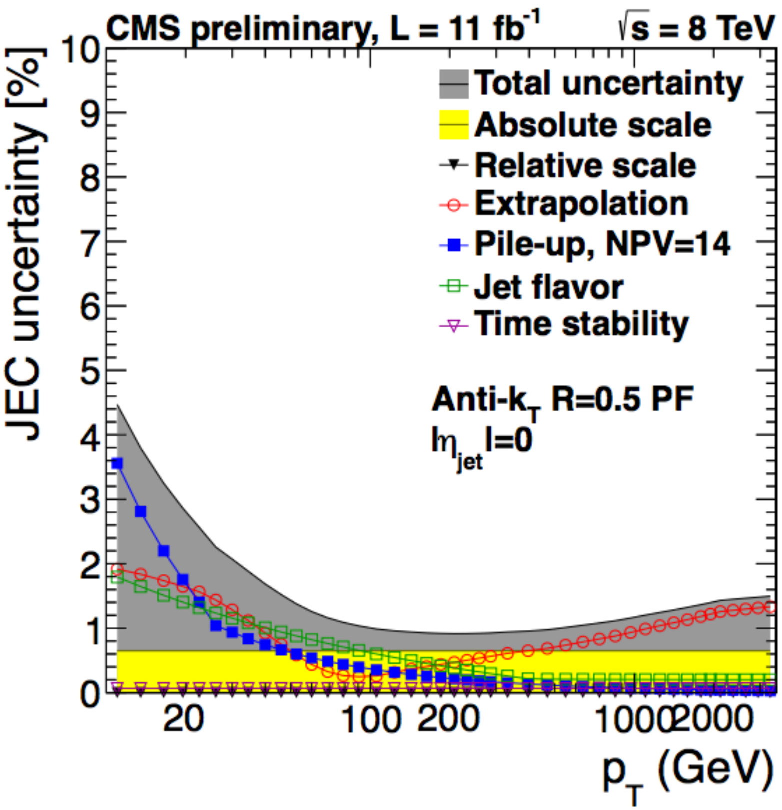
Jet energy calibration as recommended for 2012 analyses in ATLAS and CMS

Reconstructed jet | offset | MC truth (η and pT) | data residual (η and pT) | Calibrated jet

- ❑ Pileup offset correction
  - derived on MC with area method + residual correction for out-of-time, validated on data (ATLAS)
  - derived on data and MC with hybrid area method (CMS)
- ❑ MC truth correction
  - derived on Multijet MC (including PU)
  - restores the truth jet energy scale
- ❑ Residual data/MC corrections (η and p_T), applied only to data
  - derived on MC and data
  - dijet events for relative corrections in η
  - Z/γ+jet events for absolute corrections in p_T

JEC uncertainties overview





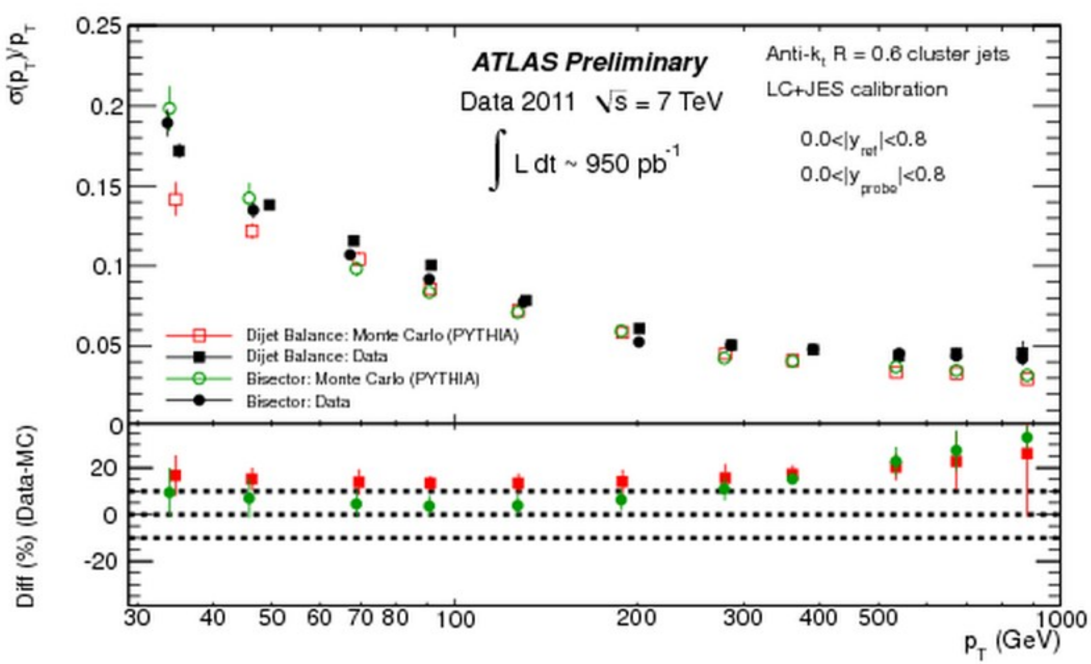
- JEC uncertainties dominated by :
  - PU at low p_T , flavor (ATLAS), absolute JES corrections extrapolation to high p_T
- ATLAS has one additional b-jets energy scale uncertainty term (not in this plot)
- Close-by uncertainty only present in ATLAS, seems not to affect CMS
- CMS time stability (forward region) is a temporary artifact of using prompt reco data, will be fixed in the reprocessed data

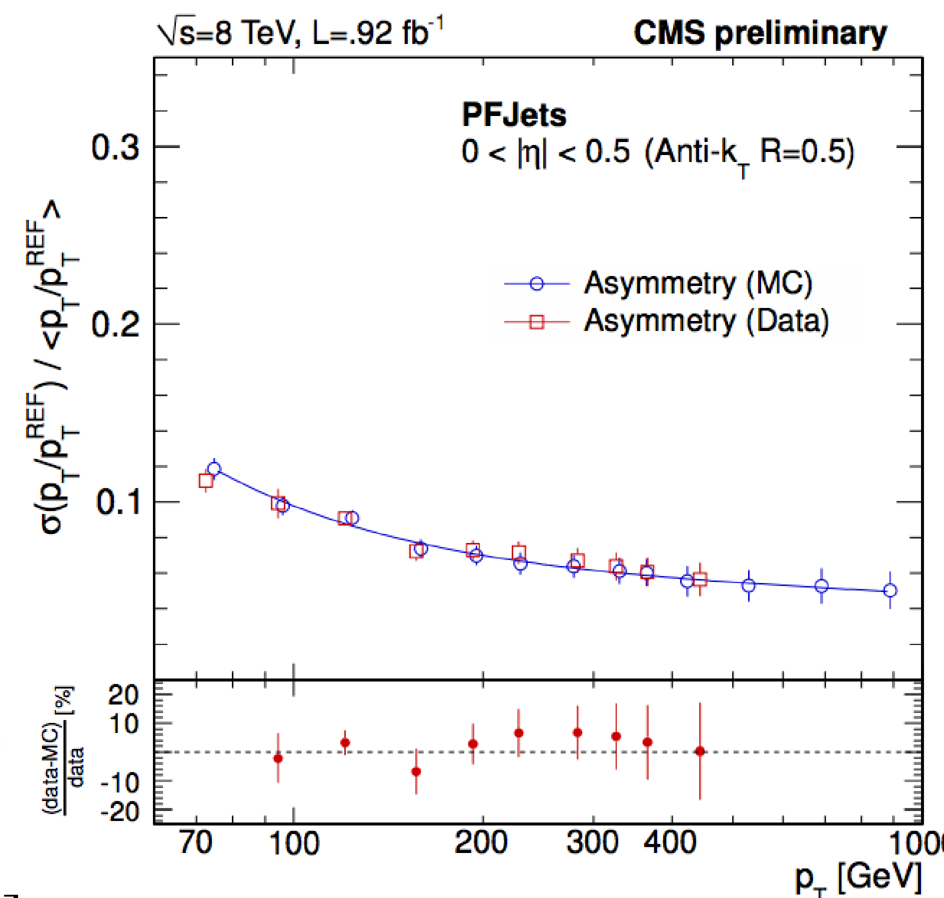
More in the backup slides !

Jet Energy Resolution

Jet energy resolution studied
- on simulated events (true resolution)
- on data dijet events, using asymmetry or bisector methods

Resolution gets to some percent at high pT





[ATLAS-CONF-2010-054, arXiv:1107.4277]

MET reconstruction

MET in ATLAS

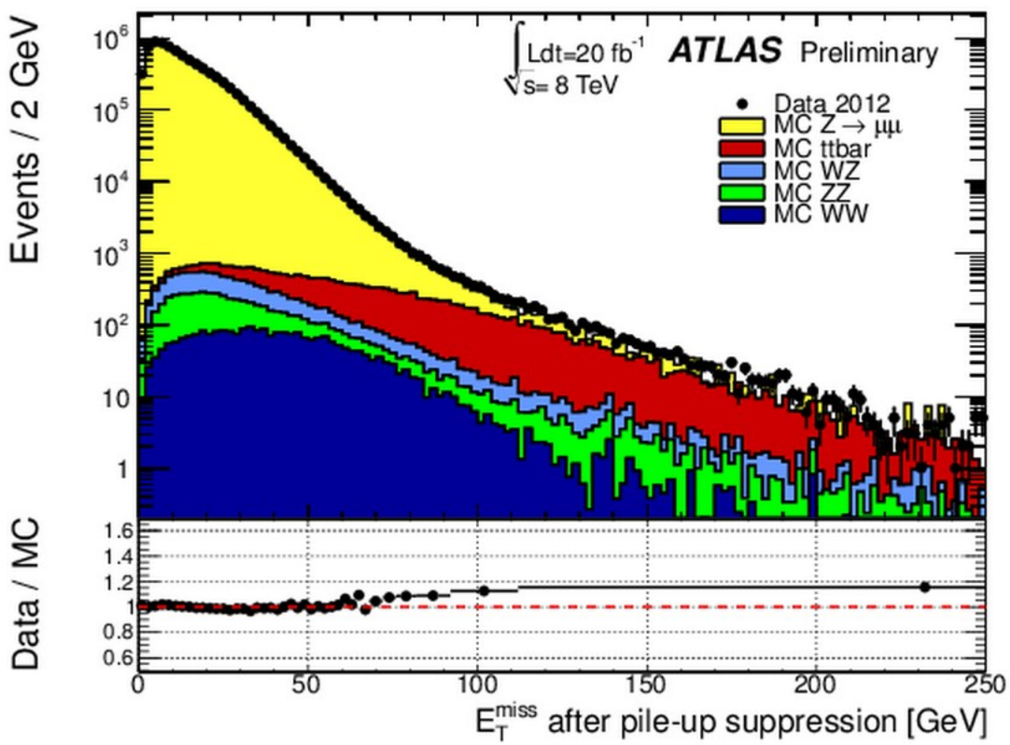
• Reconstructed from 3D topoclusters and from reconstructed muons
• Cells in clusters calibrated as the parent object
• Correction available to subtract PU

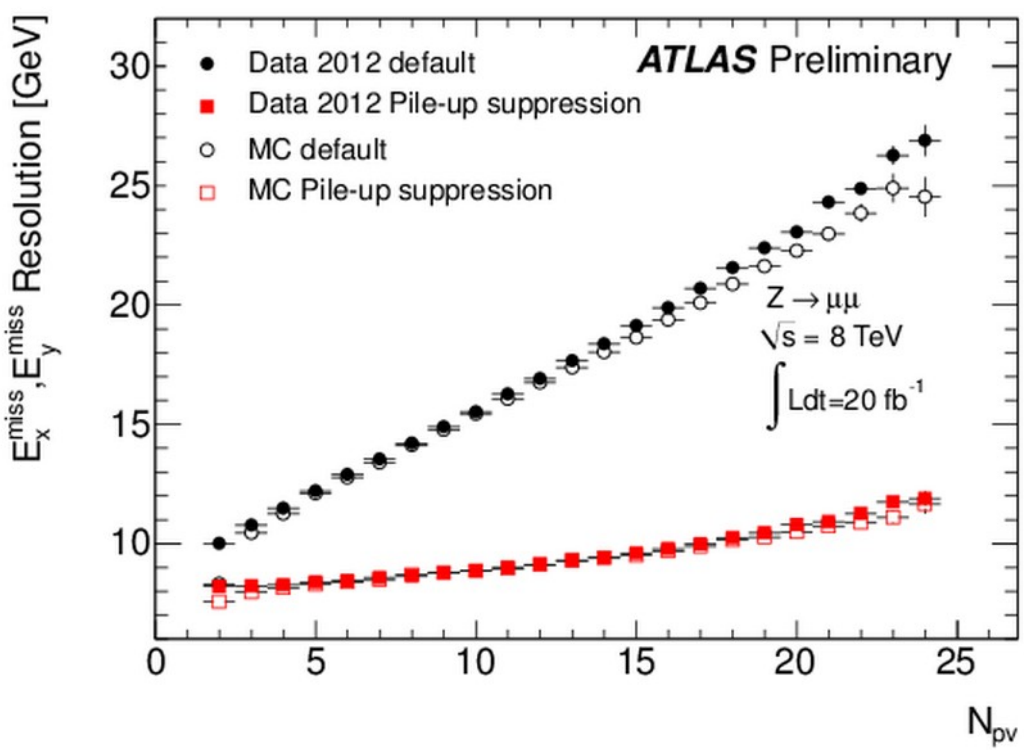
MET in CMS

• CaloMET : reconstructed from Calorimetric EM and Had deposits
• TcMET : CaloMET with corrections for charged particle responses from tracks information
PFMET : reconstructed from all PF candidates not associated to PU (Charged Hadron Subtraction)
• Additional correction to compensate the effect of Charged Hadron Subtraction
• Correction to propagate the effect of JEC to MET
• Corrections available to subtract PU and improve resolution (will show later the MVA)

• Uncertainties on individual components used to build MET are propagated to MET

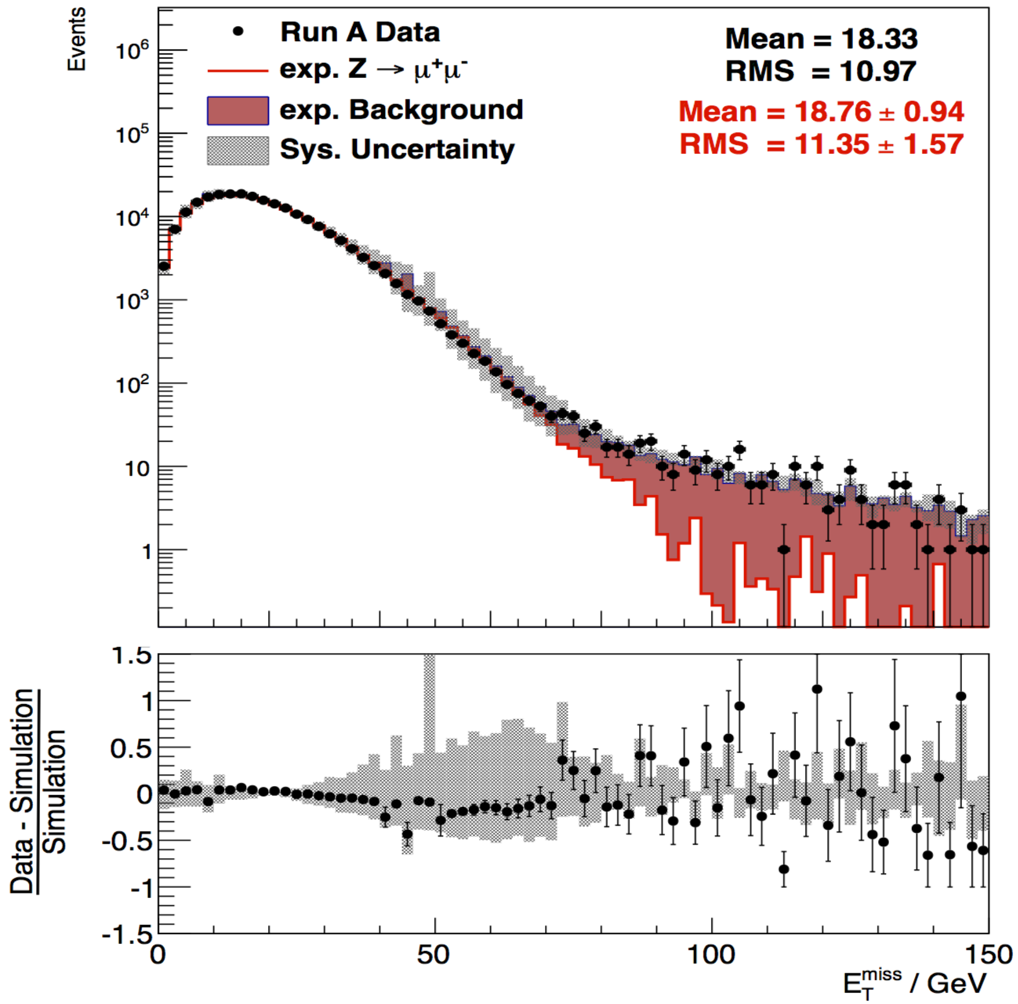
MET Performances (ATLAS)

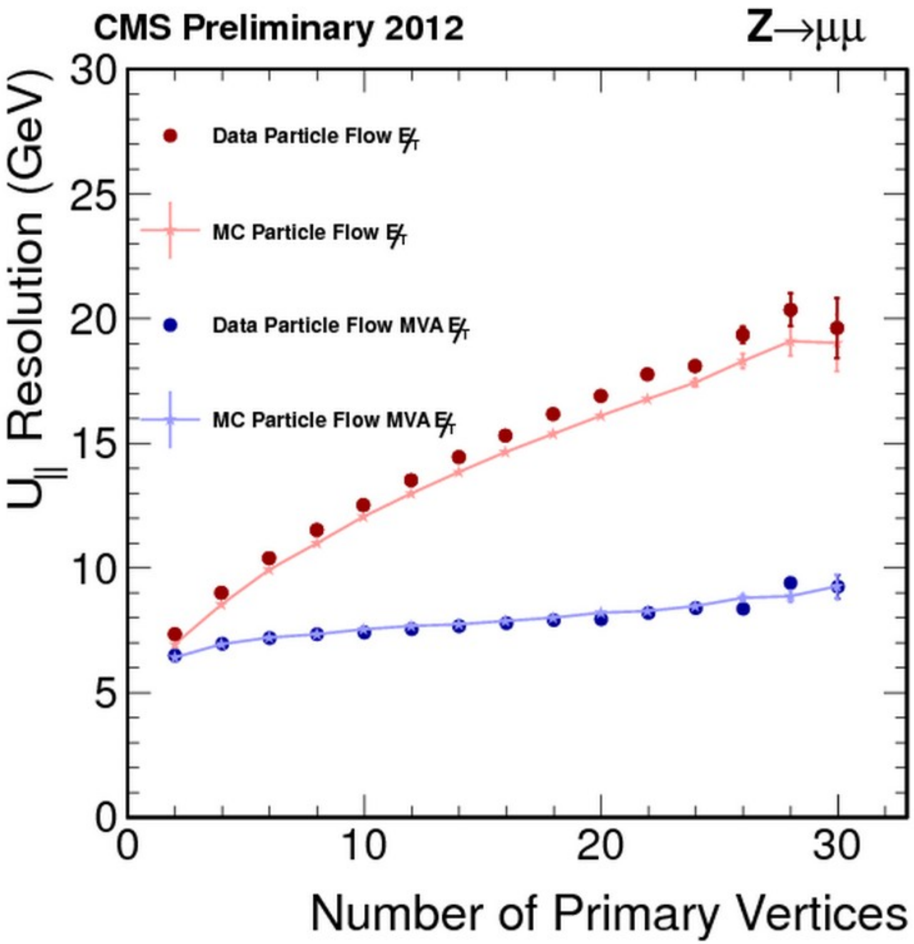




- ❑ Very good agreement with simulation and Data (at 7 and 8 TeV)
- ❑ Resolution worsens significantly with the increase of PU collisions
- ❑ SoftJets terms are scaled by the ratio of the tracks' sum pT associated to the main PV over all tracks.
  - → The resulting dependency in the number of PV becomes almost flat.

MET Performances (CMS)

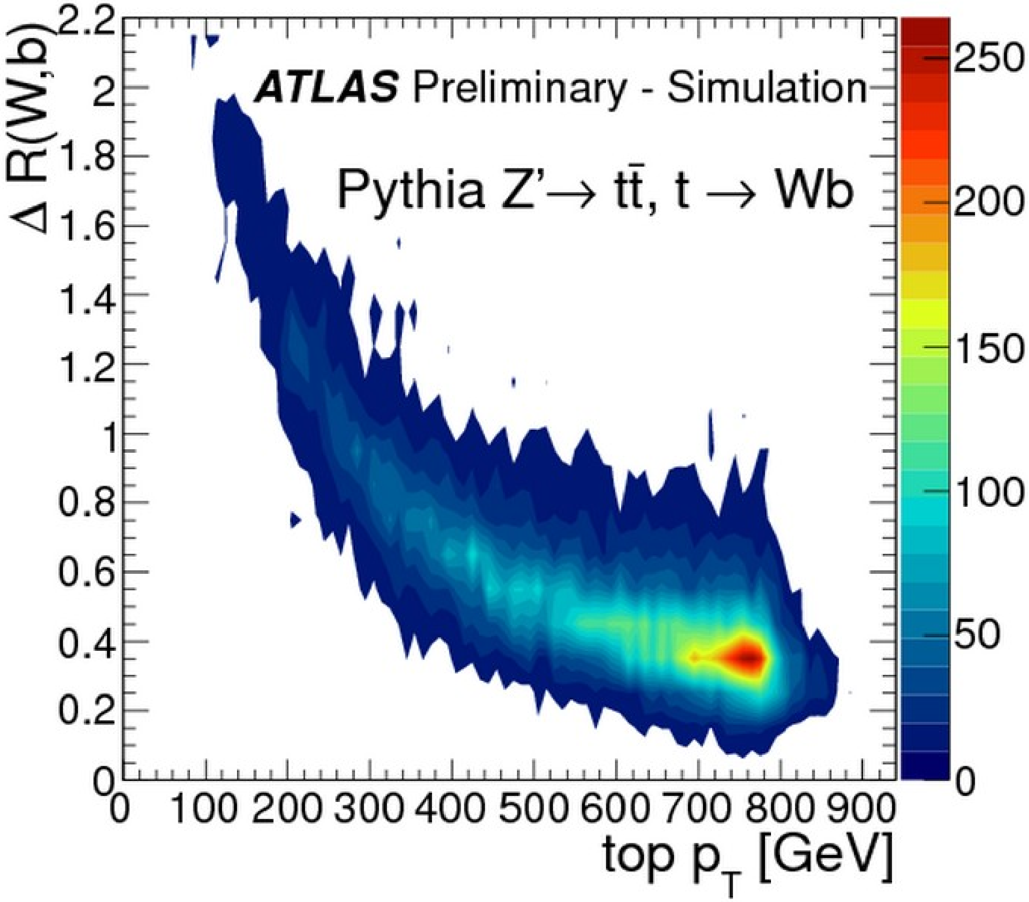




- Very good agreement with simulation and Data (at 7 and 8 TeV)
- MET resolution degradation with PU is recovered by correction
- PU dependence reduced in 2012 wrt 2011 from optimisation of data aquisition

Fat jets and substructure

Example of boosted tops (from a heavy resonance m=1.6TeV) decaying to bW. Plot at particle level.



Grooming algorithms :

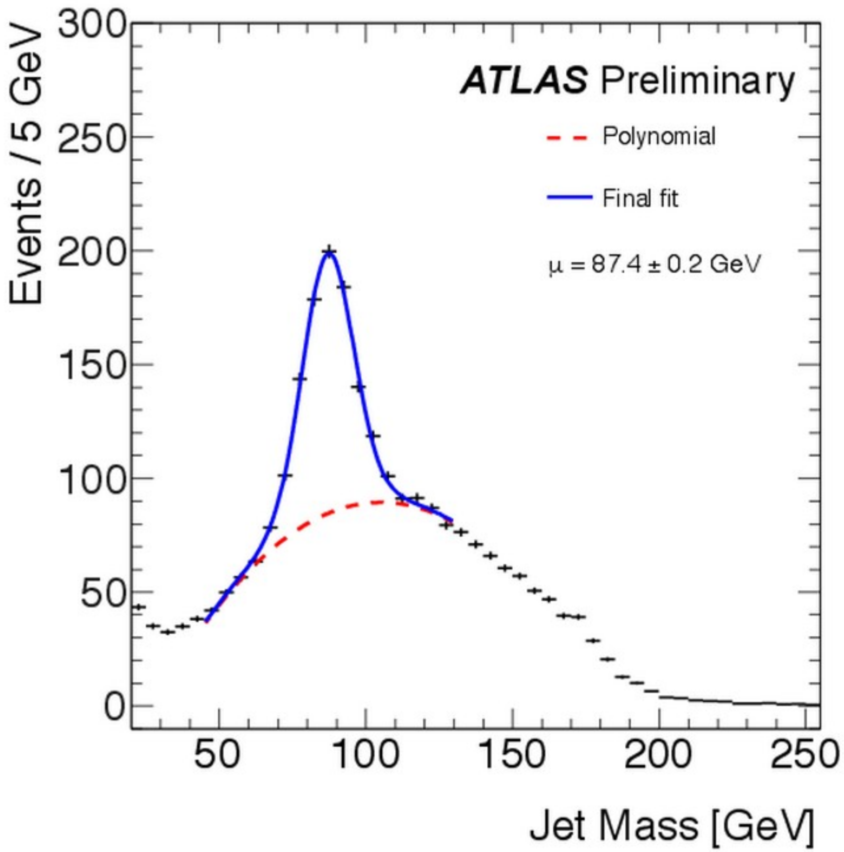
Trimming uses Kt algo to look for subjets and removes the soft ones (f=5%) [JHEP 1002:084 (2010)]

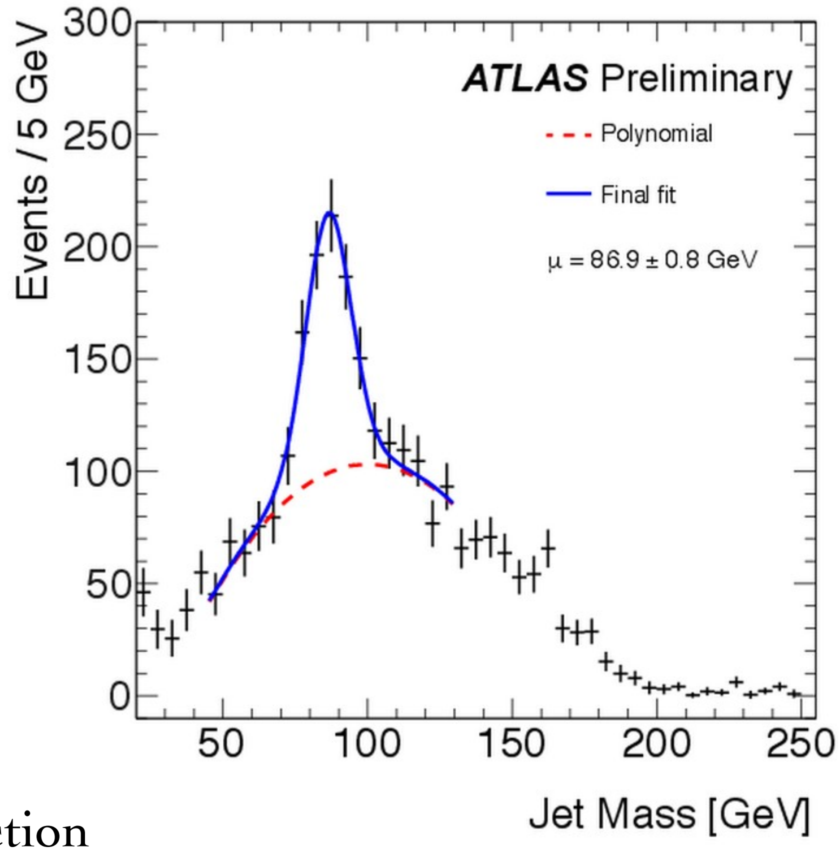
Pruning reclusters jet consituents (Kt or CA) vetoing wide angle soft constituents [arXiv:0912.0033, arXiv:0903.5081]

Mass drop/filtering (optimised for two-body hadronic decays on CA jets) : shrink jet radius until the jet splits into 2 subjets each with significant lower mass. Then keeps shrinking until 3 jets are found and filters away all the rest. [Phys.Rev.Lett.100:242001 (2008)]

Fat jets and substructure (ATLAS)

- Jet Energy corrections are derived centrally for fat jets (Antikt R=1, CA R=1.2)
- Additional jet mass calibration (to true jet mass in MC, after dedicated JEC)
- Validated on data





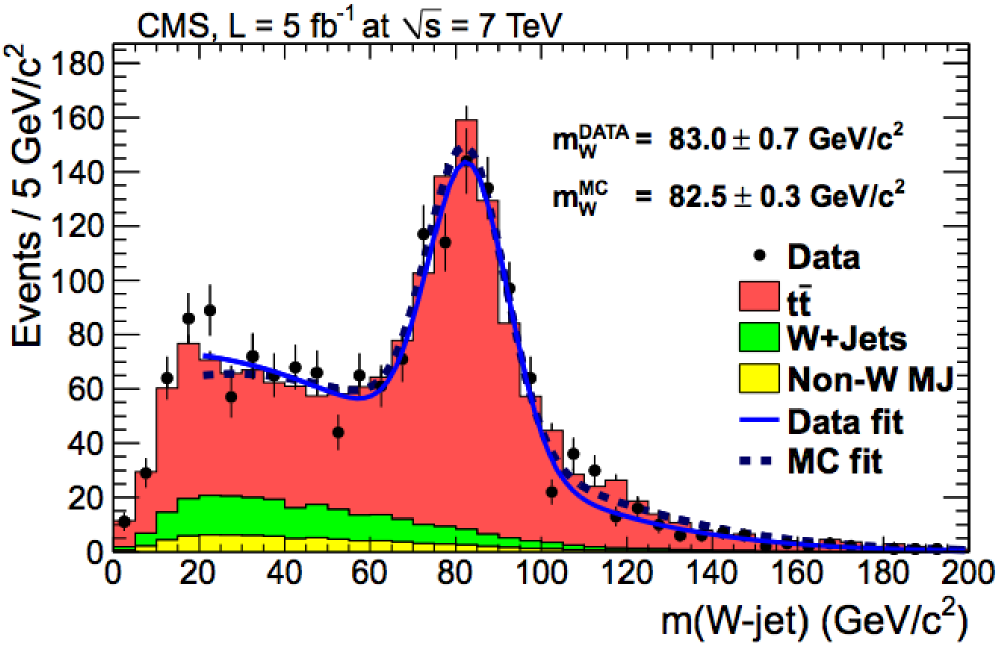
tt selection
Mass of the W candidate jet
Peak position (μ) consistent in data and MC

Fat jets and substructure (CMS)

Example here all-hadronic Z'→tt (CA R=0.8 jets)
• jet-pruning technique for W-tagging
• Top tagging (inverting the last steps of the CA algo) [arXiv:0806.0848]

• Standard (Antikt R=0.5) corrections applied (no specific corrections derived centrally)
• Additional 3% uncertainty from difference in absolute response for ak5 and pruned/top-tagged jets evaluated in dijet MC [arXiv:1204.2488]

• Subjet JES syst evaluated from data/MC ratio of jet (W) mass in a semimu control sample
• Subjet eff syst (mass drop cut) evalauted from data/MC efficiency differences for mW and mass drop cuts
• overall SF for ttbar events 0.94+-0.06

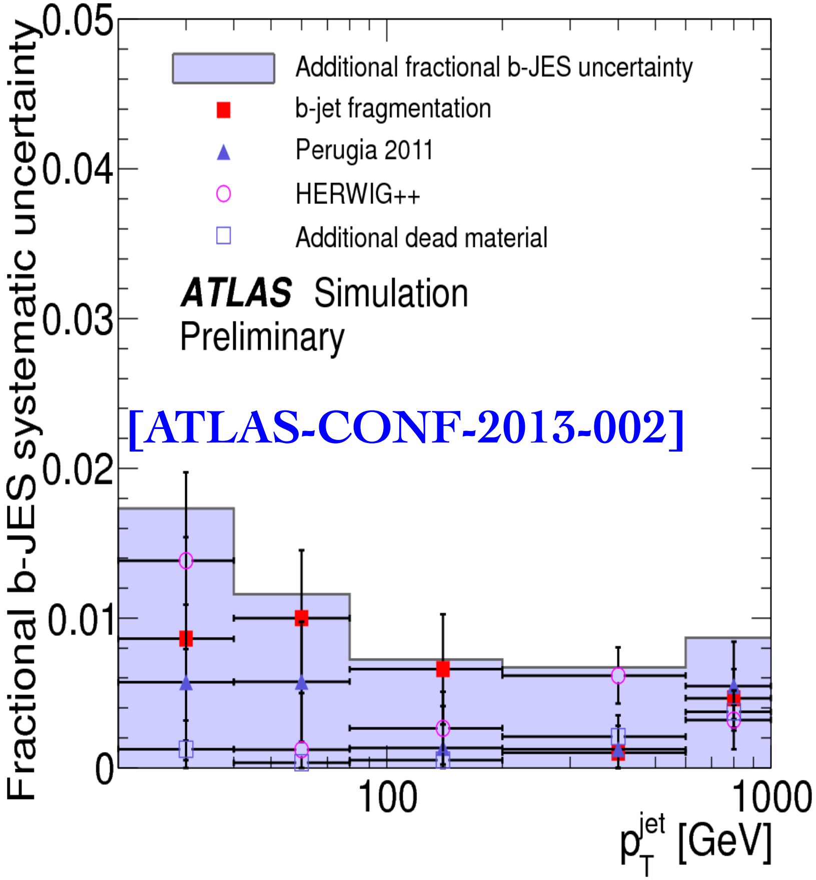


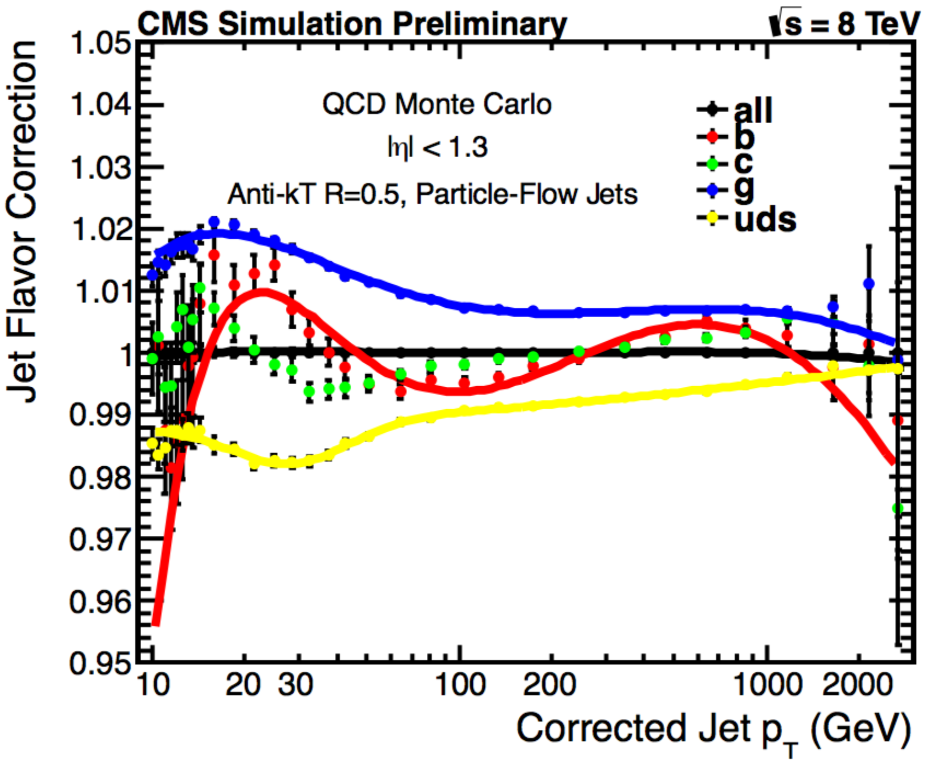
Conclusions

- Jets and MET are fundamental objects for physics analyses
- Often an important source of systematics (especially JES)
- A lot of effort in ATLAS and CMS to reconstruct/calibrate/commission these objects at best
- Getting ready for future challenges (PU increase, boosted objects)
- General strategies are very similar in concept in ATLAS and CMS, still, some differences here and there
- A centralised effort is on going towards a common set of jets and MET related systematics prescriptions for ATLAS and CMS within the TOPLHCWG

Backup

b-JES uncertainties





- Uncertainty: derived as the difference in response for different: specific b-jet fragmentations, Pythia Perugia 2011 tune, Shower model (Herwig++), Inactive material.
- Additional ~2% syst. applied to b-jets

- Only one overall flavor uncertainty
- based on Pythia6 Z2/Herwig++ 2.3 differences in quark-gluon responses (b and c in between)
- Applied to all jets

JEC references

ATLAS
Pile-up offset correction[ATLAS-CONF-2012-064]
MC based calibration [CERN-PH-EP-2011-191]
Residual calibration : [ATLAS-CONF-2013-003, ATLAS-CONF-2012-053, ATLAS-CONF-2012-063]

CMS
Methods described in :

1) **http://arxiv.org/pdf/1107.4277v1.pdf**

And recent results available at :

2) **https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME**

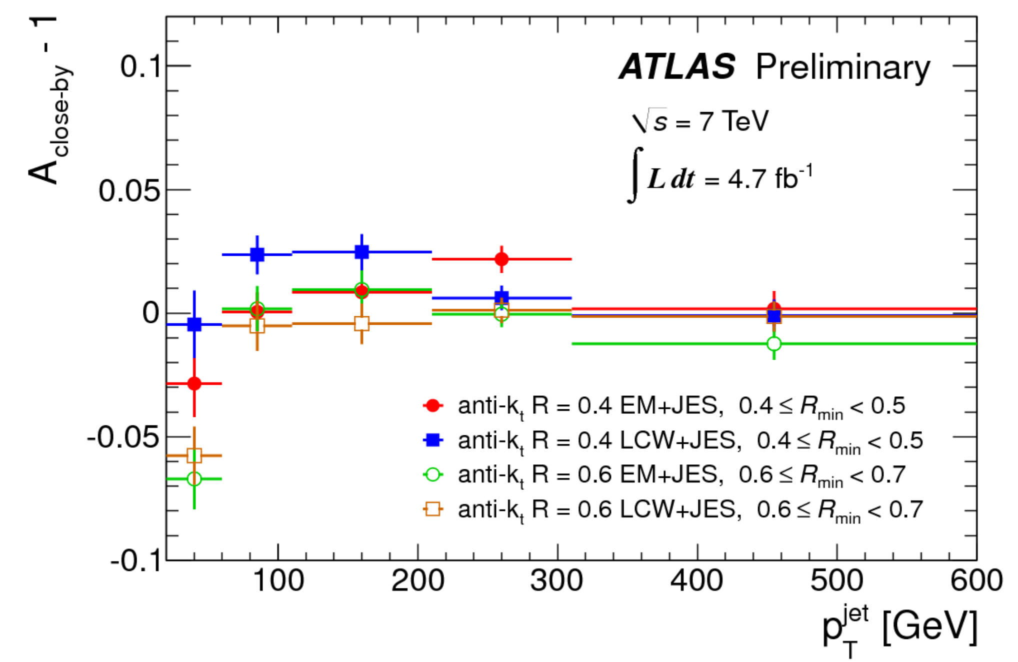
Close-by Uncertainty

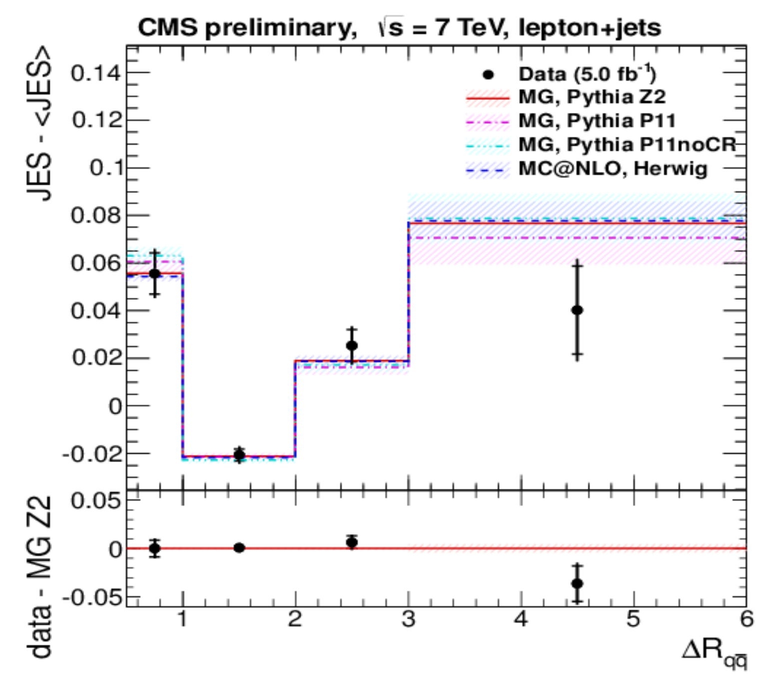
JES calibration is calculated for isolated jets. This can induce a potential mismodelling of close-by jet effects in calorimeter.

Close-by uncertainty is assessed at ATLAS separately using :

- track jets as a reference ;
- use double ratio of calorimeter/track jet response for isolated and non-isolated jets;
- evaluated in bins of distance from closest jet.

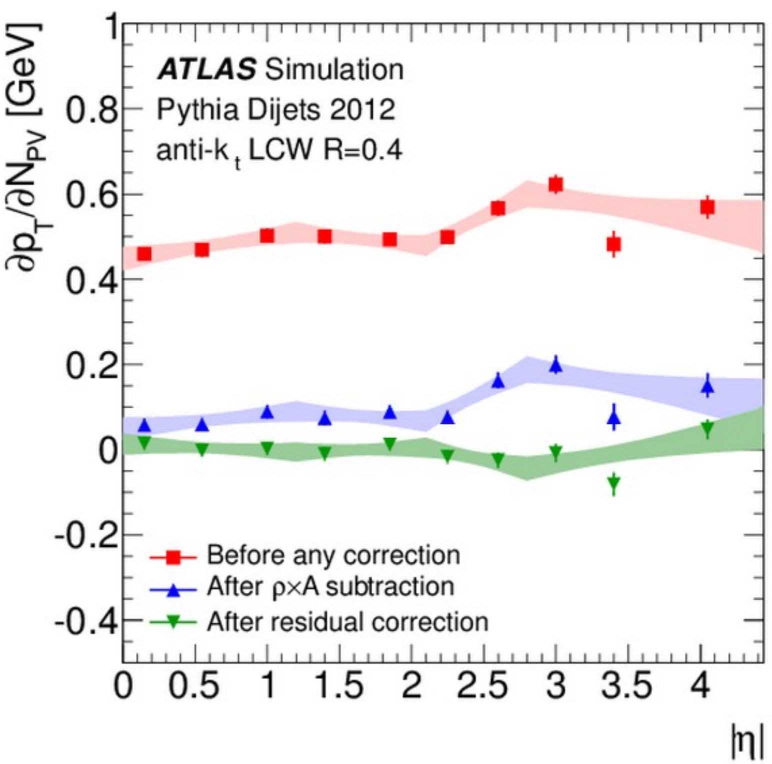
CMS : covered by current JES prescription and assessed analysis-by-analysis (expected to be less sensitive thanks to PF reconstruction)

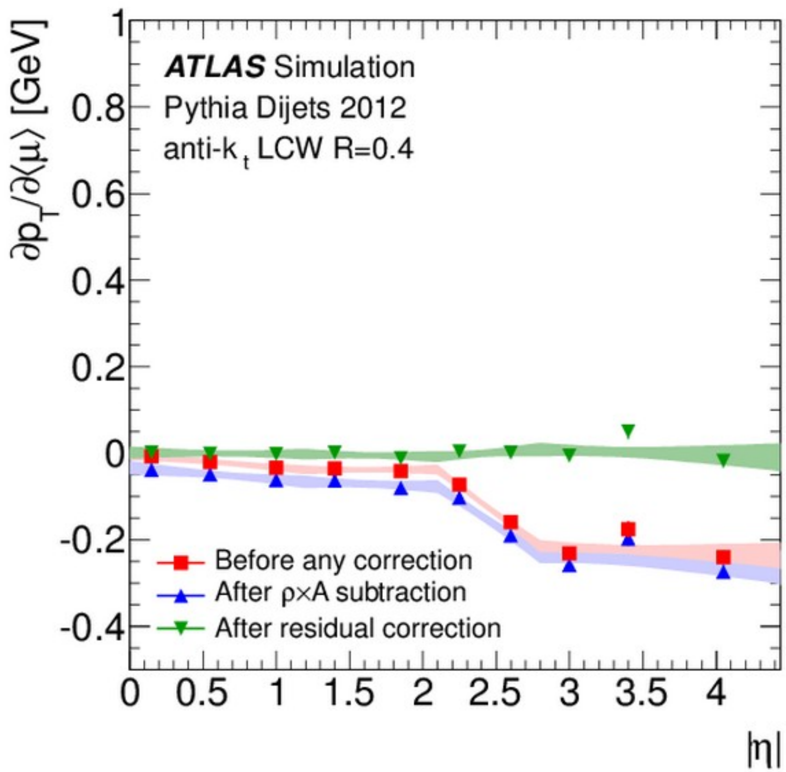




Pile-up Offset Correction (ATLAS)

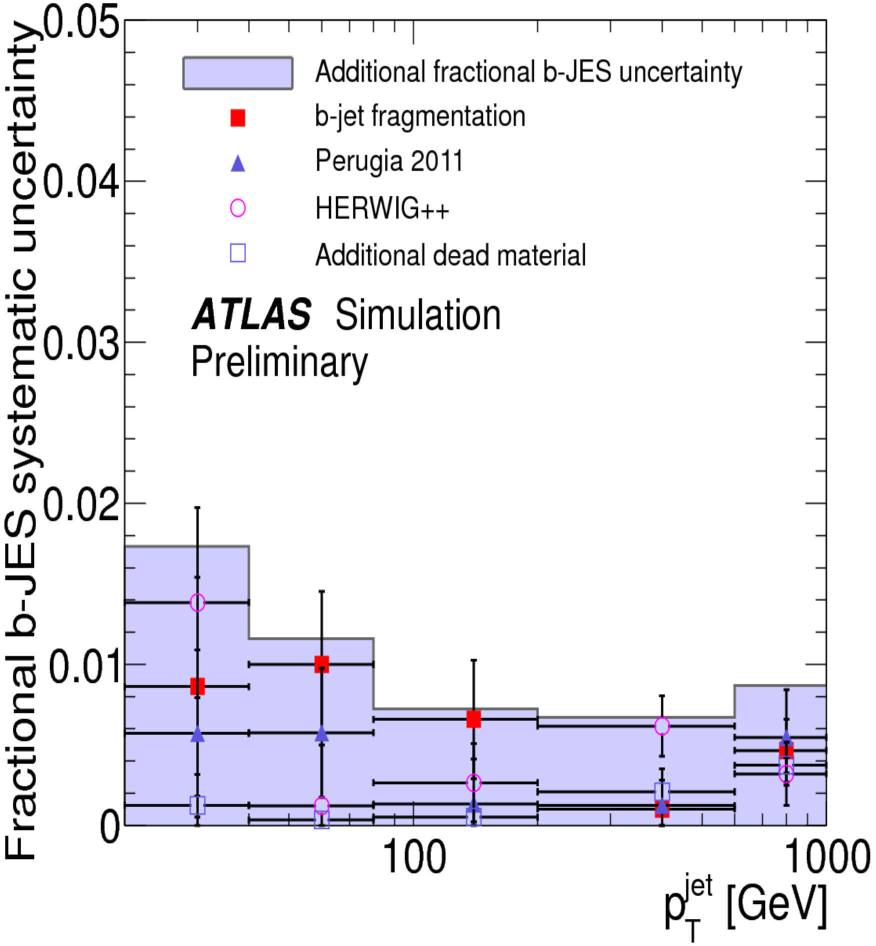
- dependence on **in-time PU** is corrected with jet area method
- residual correction (dependent on NPV and μ) to take into account the residual, mostly **out-of-time** PU contribution
- corrections extracted from MC (dijets) and validated on data (Z→μμ)





https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetEtmissApproved2013Pileup1

b-JES at ATLAS



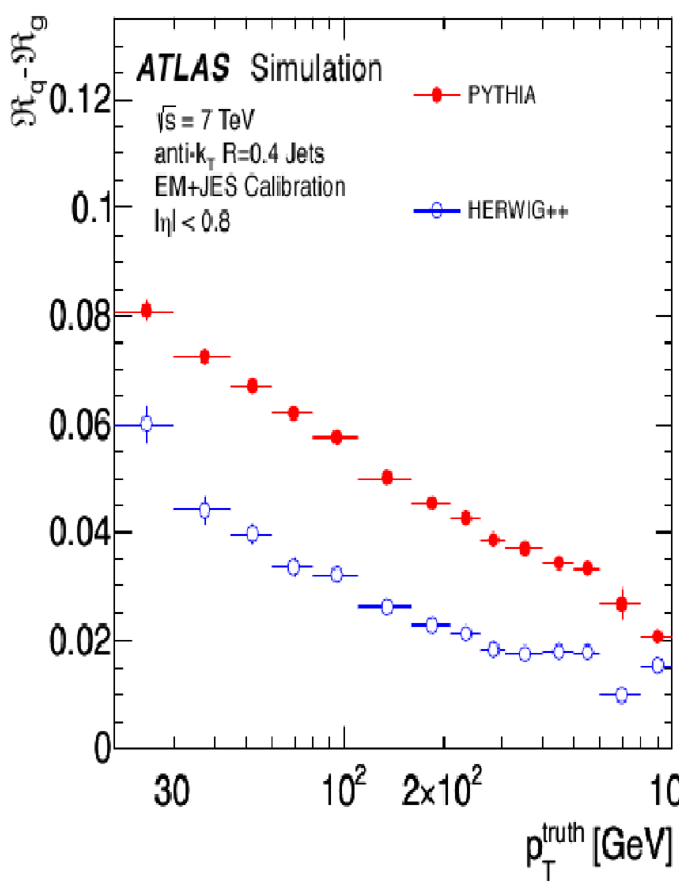
- ❑ **b-jets identification** :
  - MC: within $\Delta R<0.4$ to a true B hadron;
  - Data: Multivariate algorithm (MV1).
- ❑ **Fractional systematic uncertainty:** derived as the difference in response for different:
  - specific b-jet fragmentations;
  - Pythia Perugia 2011 tune ;
  - Shower model (Herwig++) ;
  - Inactive material.
- ❑ **Validation using track jets in data:**

[ATLAS-CONF-2013-002]

Additional systematics ~ 2 % at most applied to true b-jets.

Flavour Unc. in ATLAS

Two additional JES Uncertainty components **[ATLAS-CONF-2012-138]** :



- ❑ **Flavour Composition uncertainty**:
  - composition in quarks and gluons could differ in Data/MC and induce different jet response for specific analyses in Data and MC.

flavour composition uncertainty

$$\Delta f_g \times (\mathfrak{R}_q - \mathfrak{R}_g)$$

quark-gluon jet response difference

uncertainty on gluon fraction

→ Δf_g is either derived for each analysis or assumed by default to be 50 %

- ❑ **Flavour Response uncertainty:**
  - response for quarks and gluons could differ due to in-situ calibration based on quark-rich techniques.

  → data/MC comparisons for q/g-originated jets might be different.

flavour response uncertainty

$$f_g \times \Delta\mathfrak{R}_g$$

uncertainty on gluon jet response (from MC)

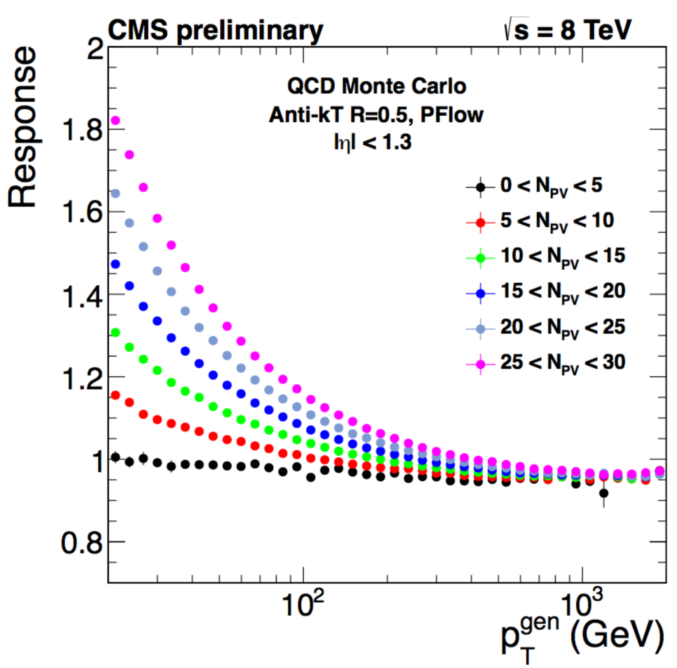
fraction of gluon jets in sample

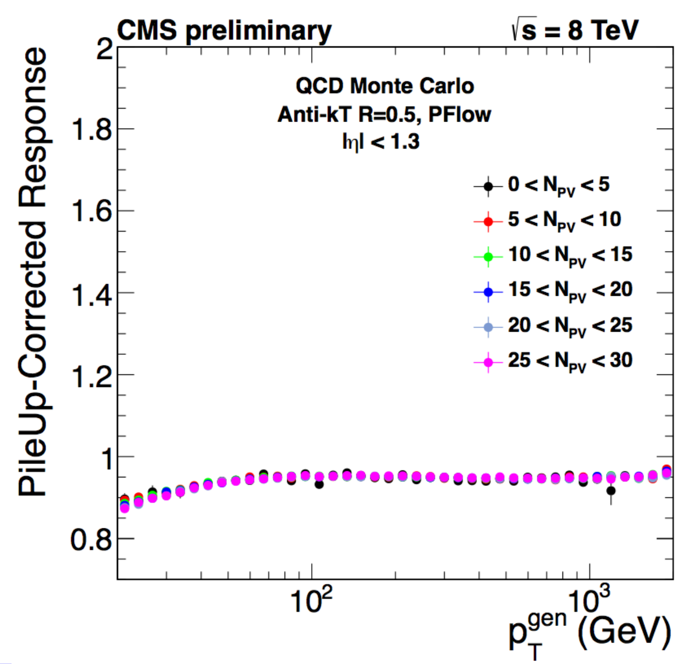
→ f_g is either derived for each analysis or assumed by default to be 50 %

Pile-up Offset Correction (CMS)

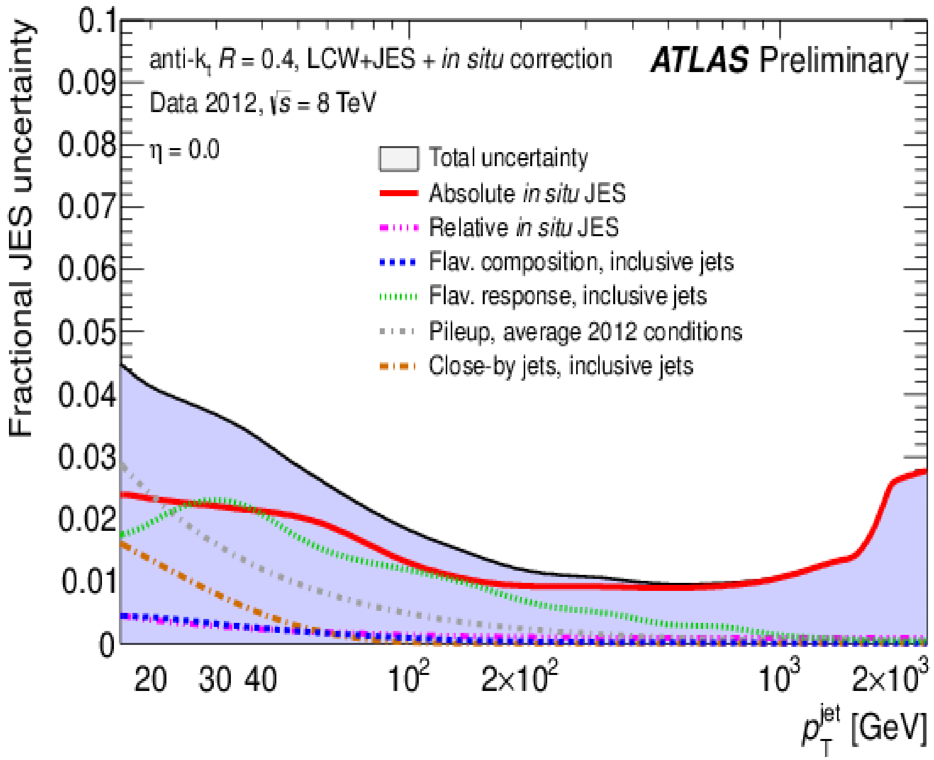
• correction calculated with **hybrid jet area method**
• One correction taking care of in-time and out-of-time PU (data aquisition optimised within 2011 and 2012 to minimize the impact of out-of-time PU)
• evaluated on data and MC Zero and MinBias events
Uncertainties from :

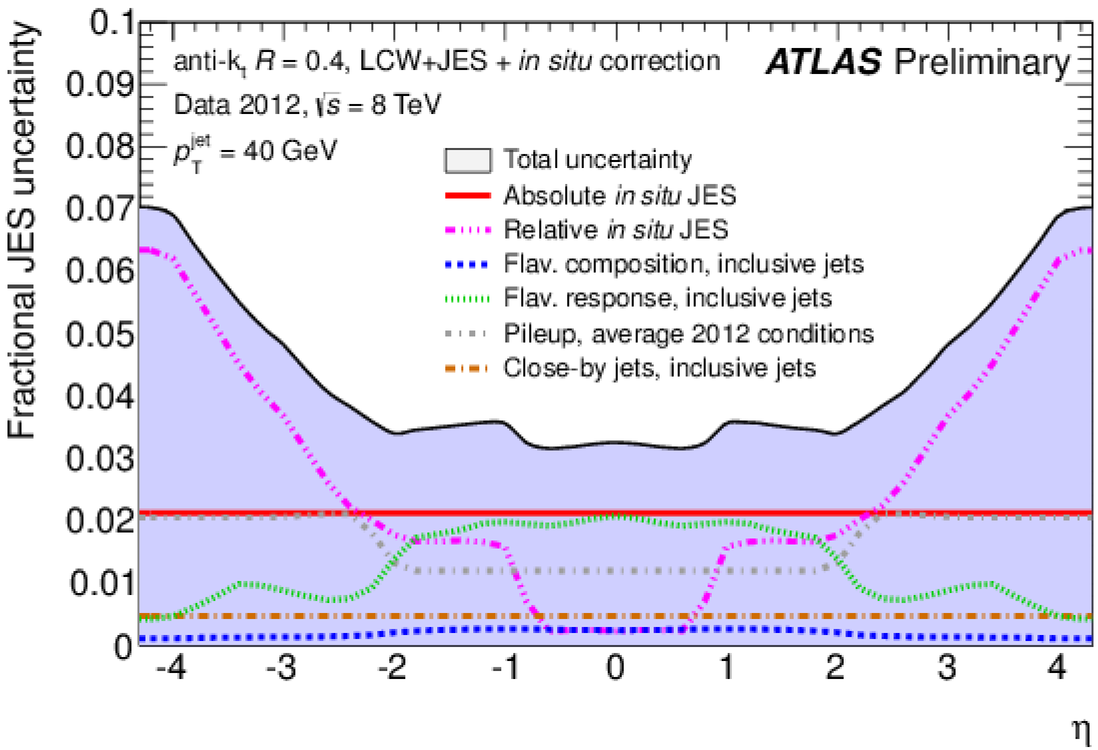
- jet pT dependence (parametrised as envelop covering the variations) ;
- PU Data/MC (from Random Cone method on ZeroBias data/MC) ;
- PU bias (non closure of Random Cone on Zero Bias method within true and measured offset on MC)





JEC uncertainties overview

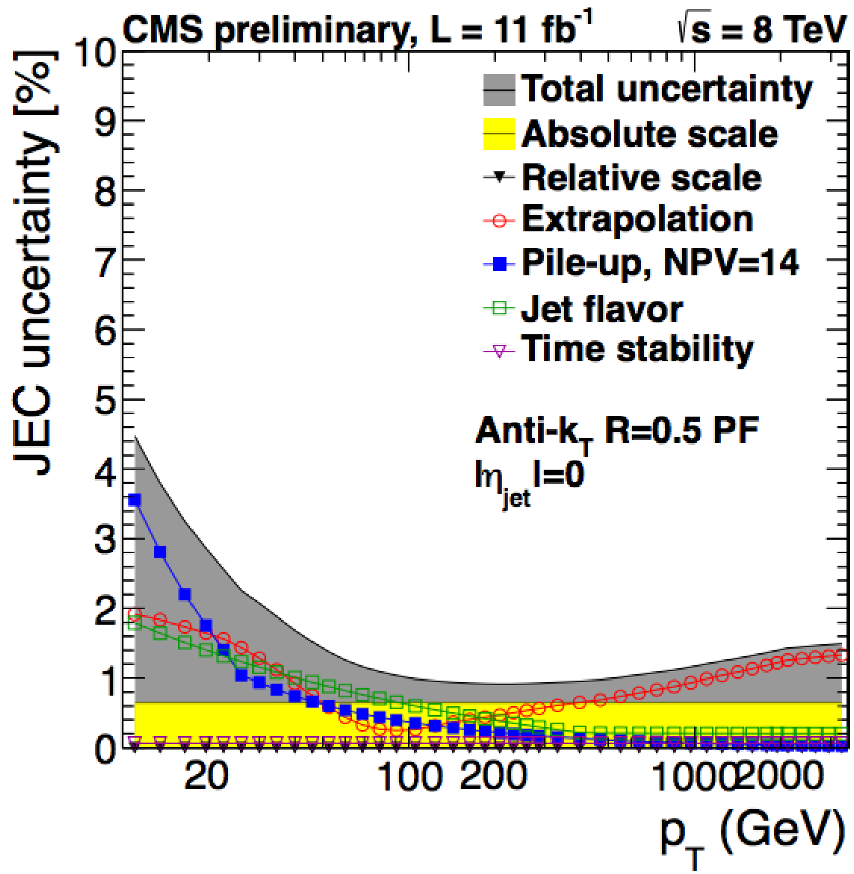


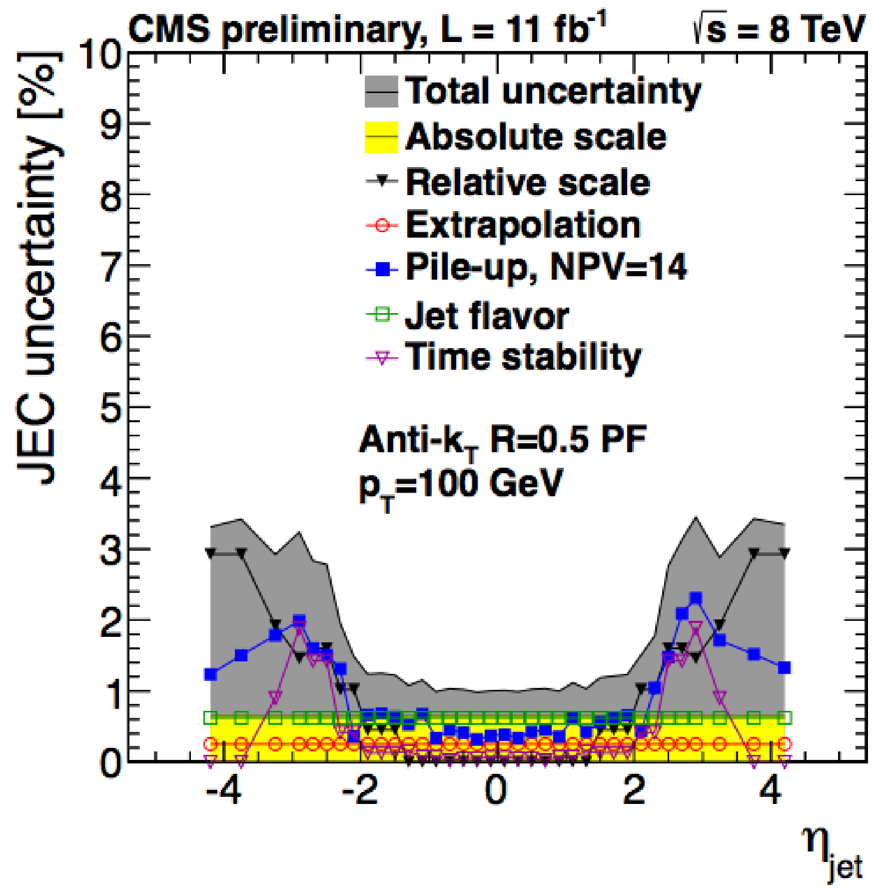


- ❑ JES uncertainties dominated by:
  - baseline/PU-uncertainties at low pT;
  - η-intercalibration modelling at high η.

- ❑ in addition to that JES total uncertainty, one needs to consider b-JES described later in this talk.

JEC uncertainties overview

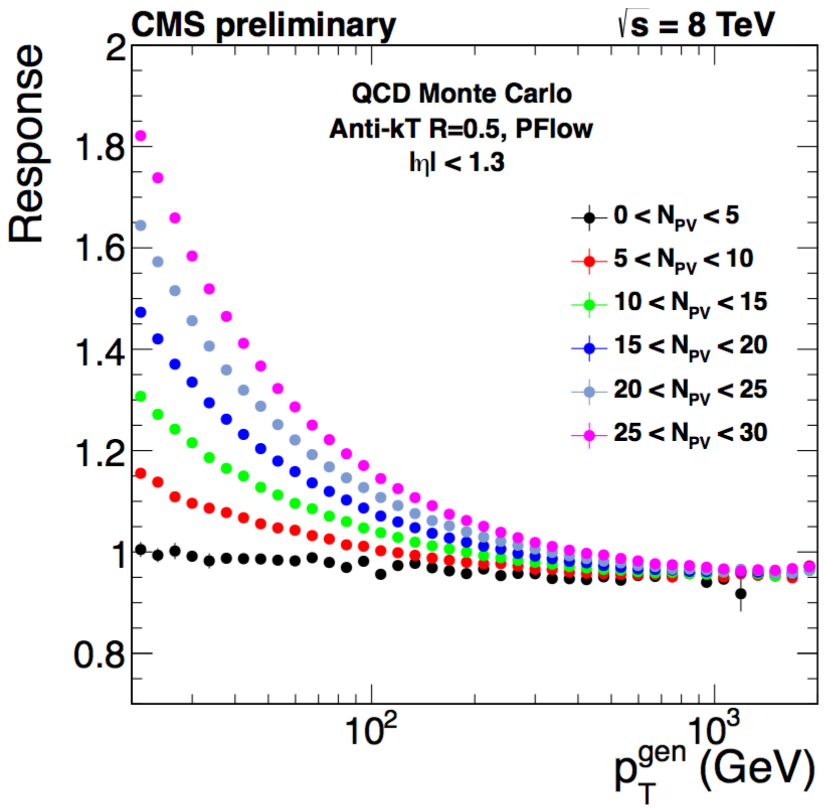


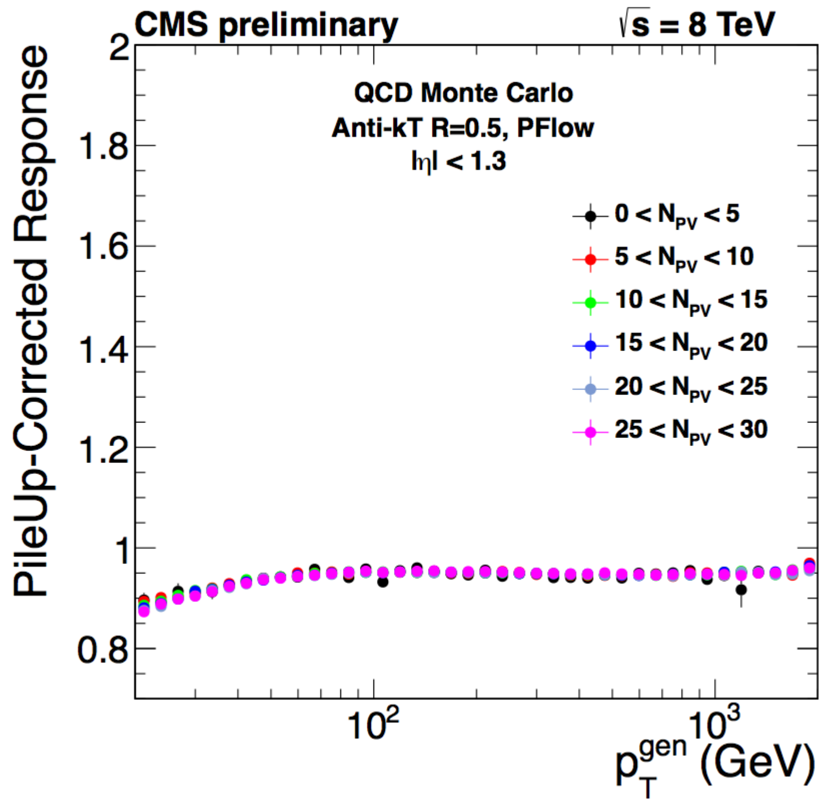


- ❑ JES uncertainties dominated by:
  - PU at low pT ;
  - extrapolation at high pT ;
  - relative scale at high η ;
- ❑ Time stability in the forward region is a temporary artifact of using prompt reco data, will be fixed in the reprocessed data

Pile-up Offset Correction (CMS)

- correction calculated with **hybrid jet area method**
- one correction taking care of **in-time** and **out-of-time** PU (data aquisition optimised within 2011 and 2012 to minimize the impact of out-of-time PU)
- evaluated on data and MC Zero and MinBias events

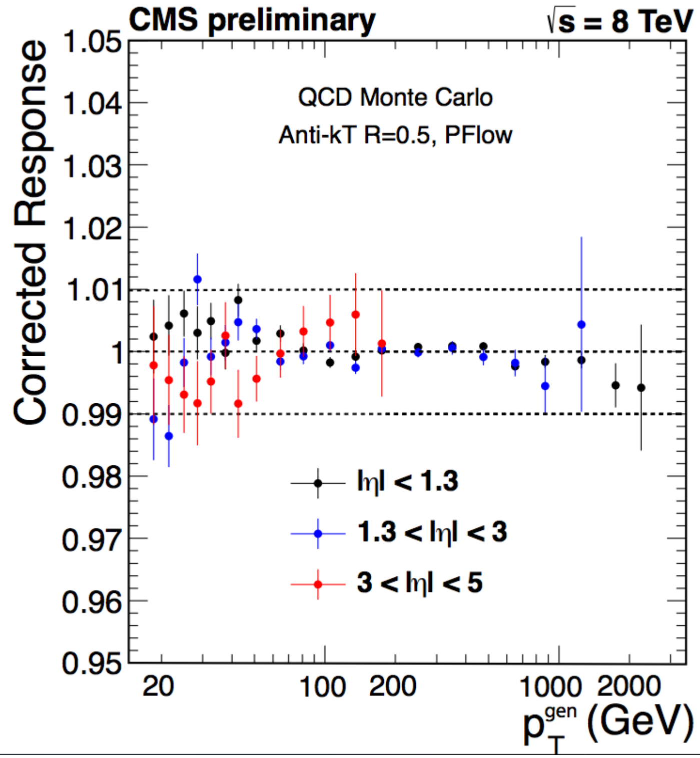


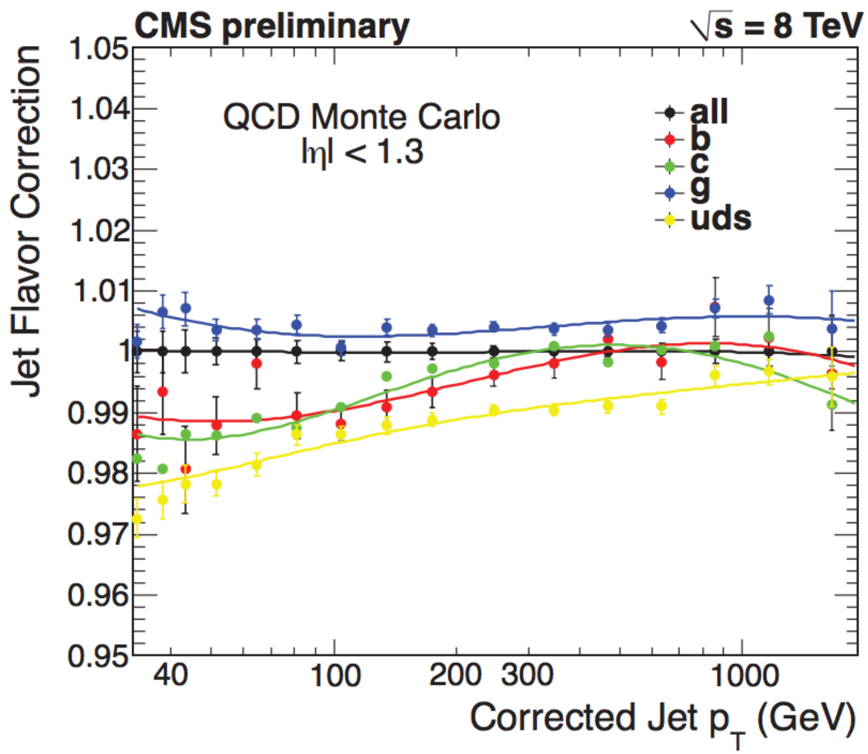


MC Truth Correction (η and pT)

Relative (η) and absolute (p_T) corrections are evaluated from a QCD MC sample :

- derived after PU correction (on a sample with PU generated and reweighted)
- good closure (<1%)
- Flavor uncertainty based on Pythia6 Z2/Herwig++ 2.3 differences in quark-gluon responses (b and c in between)

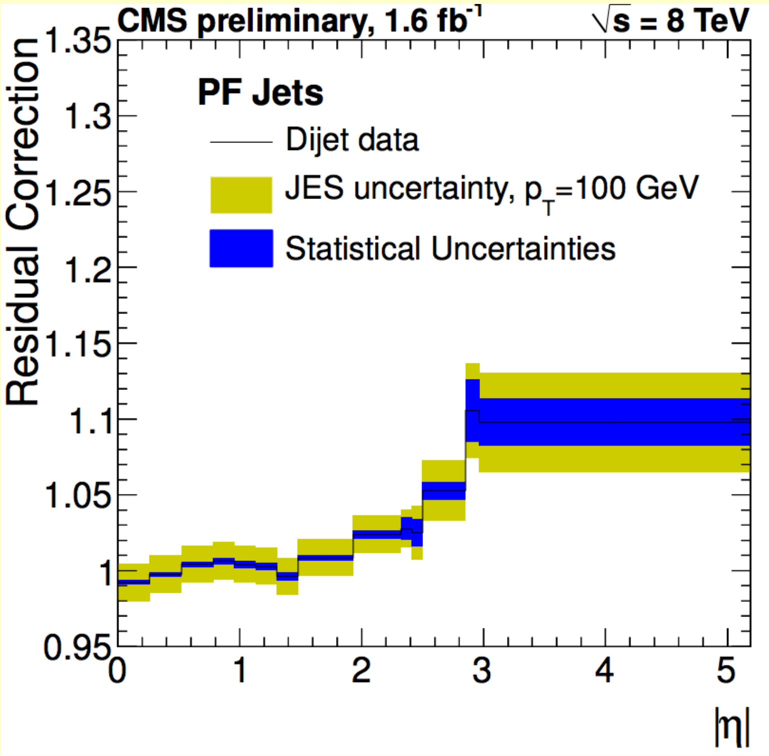




NB : dedicated MC based flavor corrections exist, but not really used in analyses, not discussed here

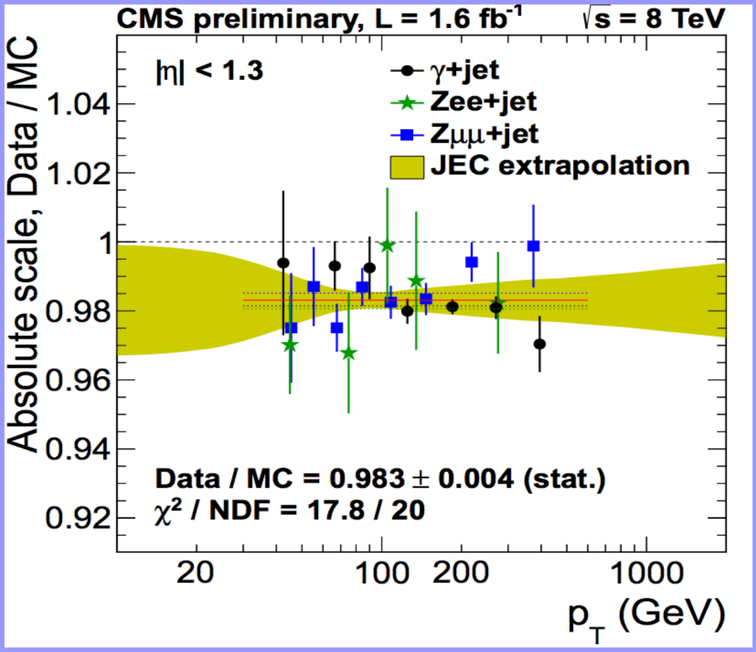
Corrections on data (η and pT)

Relative (η) dijet pT-balance technique : calibrate the response of a jet at a given η to the one for jets in $|\eta|<1.3$



- JER bias data/MC differences.
- Residual pT dependence
- Limited MC statistics (only important in endcap outside tracking and HF)

Absolute (p_T) : calibrate the jet to the Z/γ in Z/γ+jet events. No clear p_T dependece, correction parametrised as one constant.



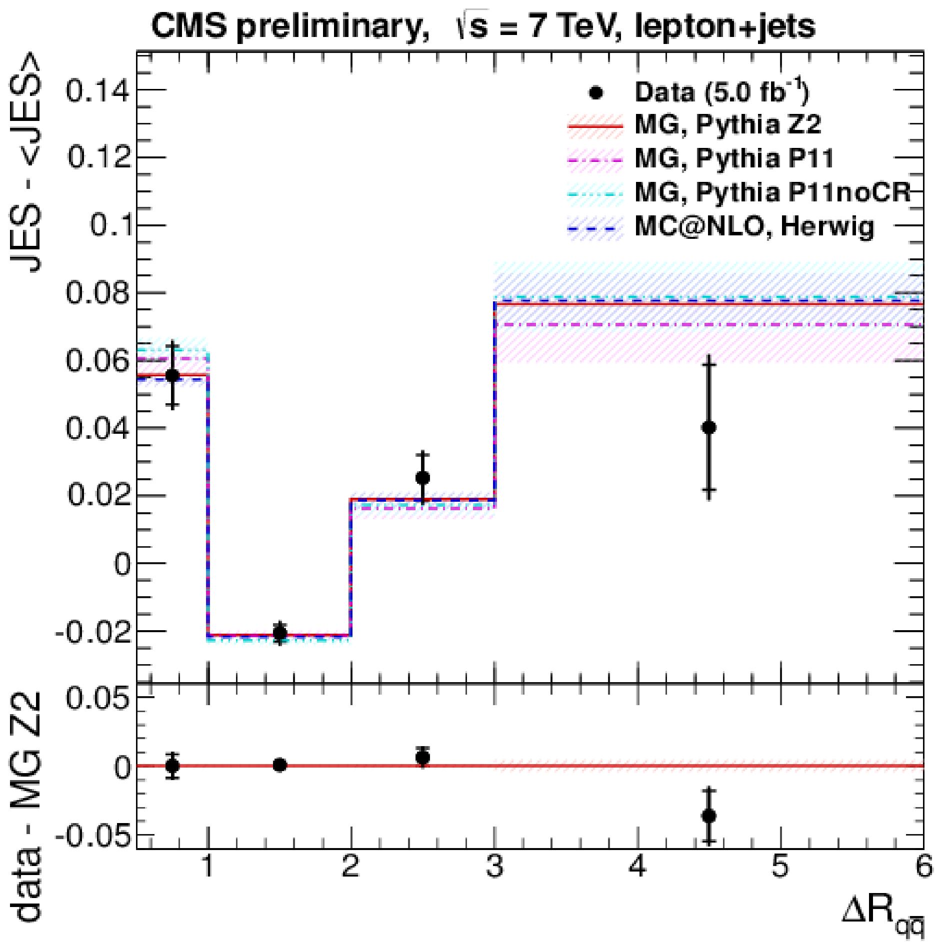
- radiation (presence of second jet)
- extrapolation to high pT region :
  - hadronisation (Pythia VS Herwig)
  - calorimeters single particle response (+-3% variation)

MET uncertainties

JEC are propagated to MET (for the energy clustered in jets) → type I corrected MET (recommended for analyses)
Uncertainties on individual components used to build MET are propagated to MET :

- Jets (JES, JER)
- Muons
- Electrons and photons (0.6% EB, 1.5% EE)
- Taus (3%)
- Unclustered energy (10%)

JEC in analyses



2-D fit of the JES and the top mass in different bins of for example the delta R between the two jets from the W-boson candidate.

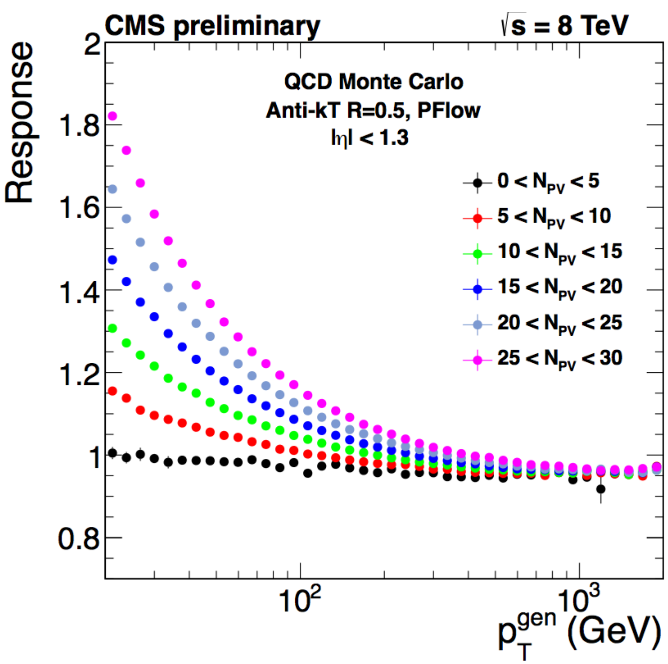
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP12029

- ==1 isolated lepton (e, mu) pT>30, |eta|<2.1
- >=4 Pfjets pT>30, |eta|<2.6
- ==2 btagged jets

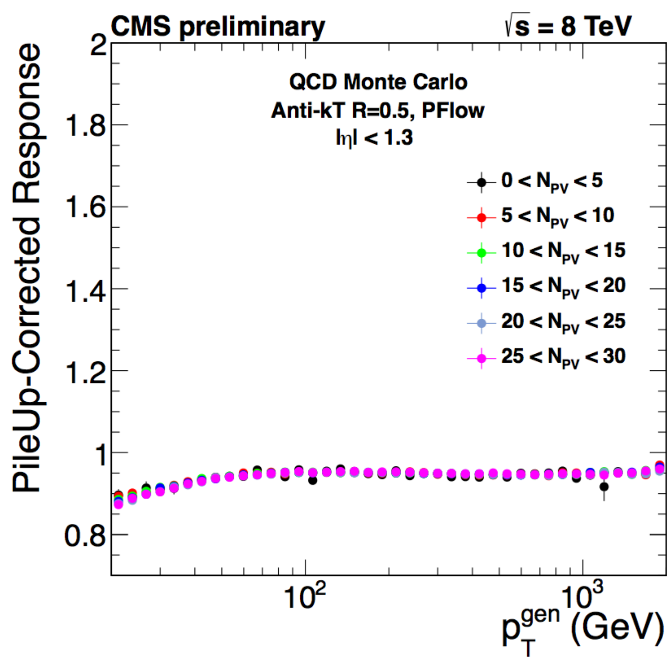
MC truth corrections

A look at PU dependance

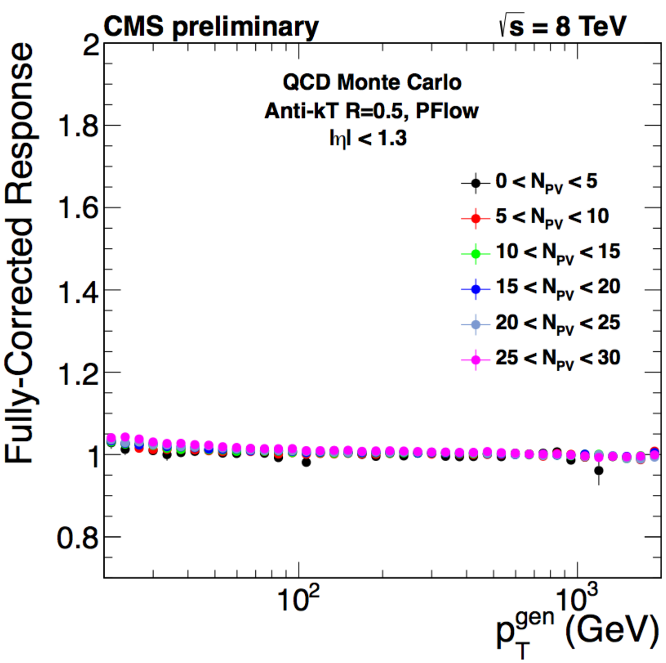
RAW jets



offset corrected



offset+MC truth



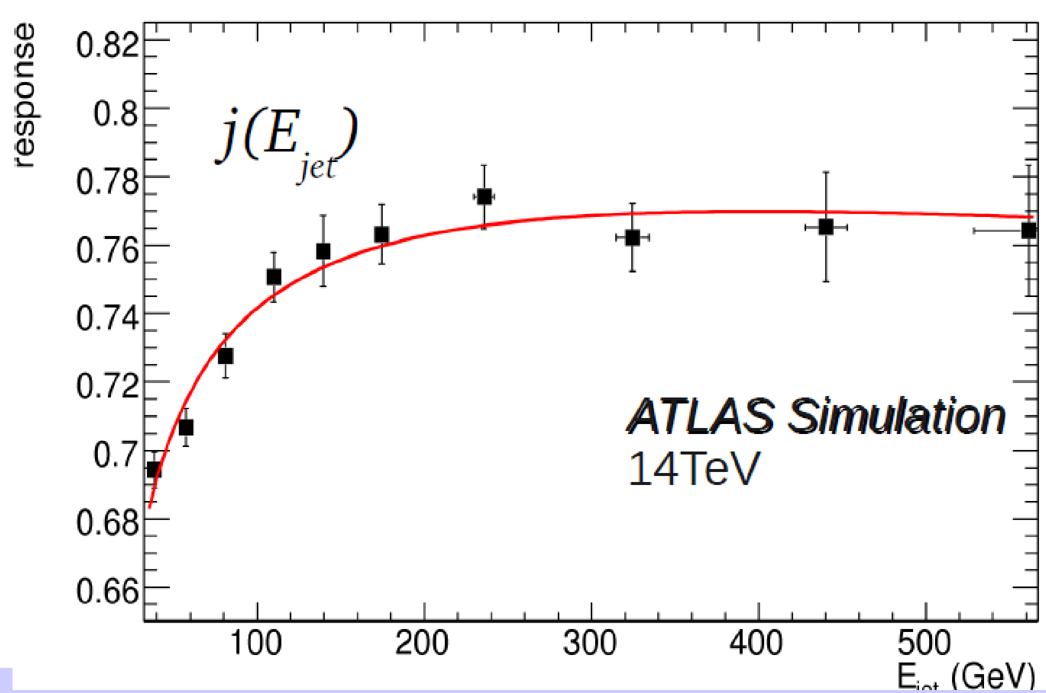
L1 removes response dependance on NPV, Mctruth L2L3 corrections bring the closure back to 1

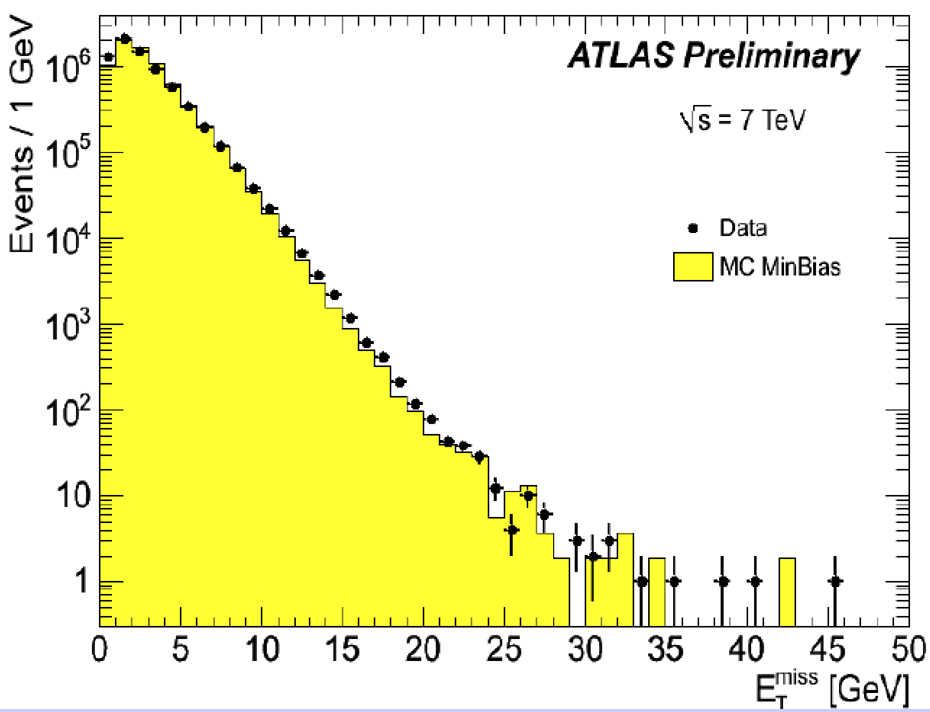
Strategy for Jet Calibration: in-situ Approaches

- Missing transverse energy Projection Fraction (MPF) balances the photon against the entire hadronic recoil to extract the jet response $j(E_{jet})$:

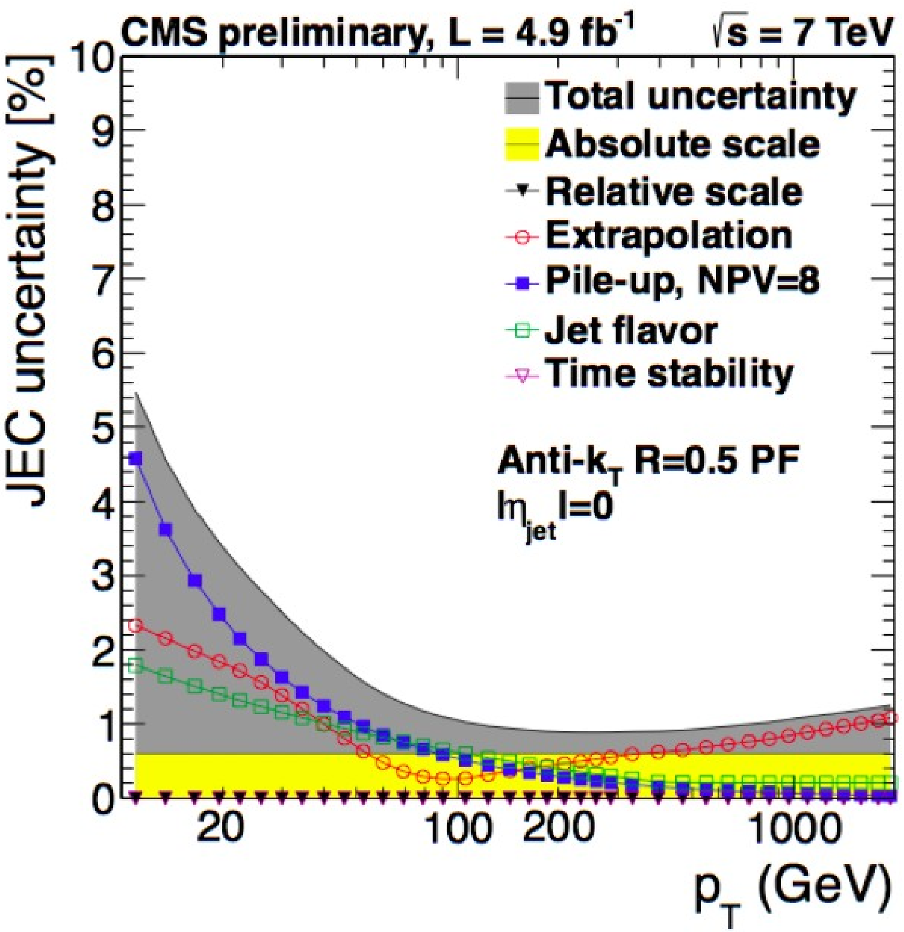
$$e\overrightarrow{E_T^{\gamma}} + j(E_{jet})\overrightarrow{E_T^{jet}} = -\overrightarrow{\not{E}_T} \quad \Longrightarrow \quad j(E_{jet}) = 1 + \frac{\overrightarrow{E_T^{\gamma}} \cdot \overrightarrow{\not{E}_T}}{(E_T^{\gamma})^2}$$

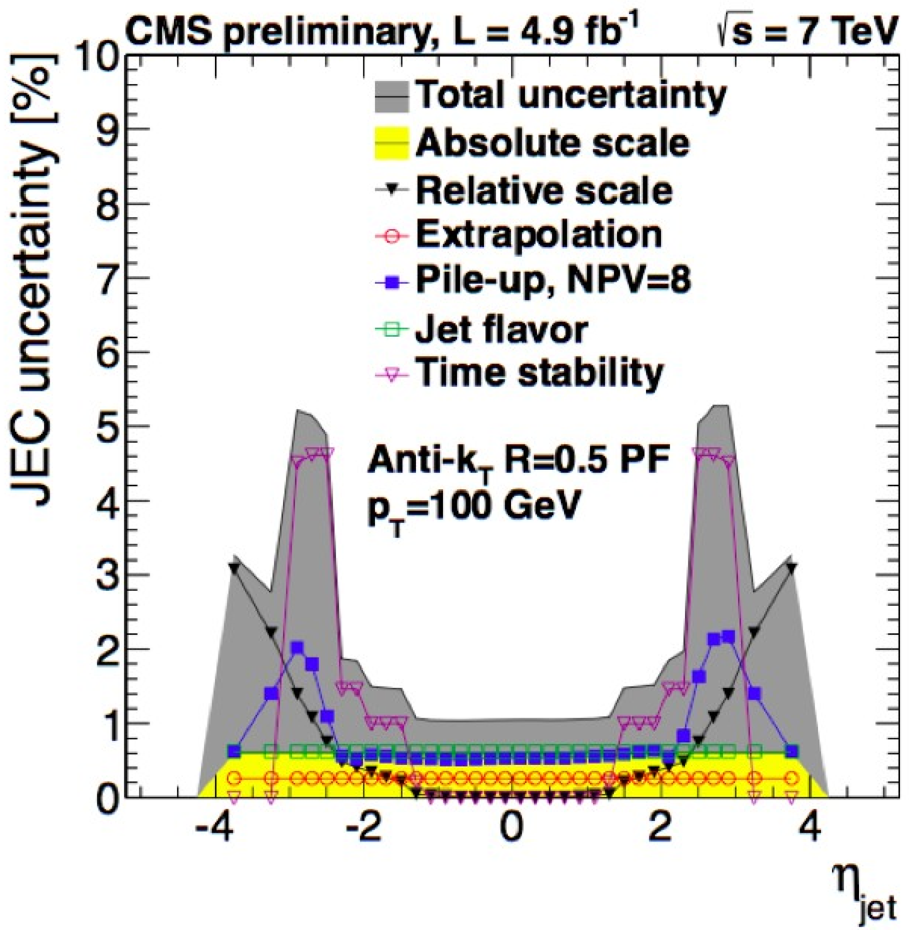
- Advantage: less dependent on the jet algorithm.
- Plots: **a)** MPF based response in bins of jet energy.
  b) Missing Et data /MC comparison at 7 TeV.





JEC uncertainties overview 2011



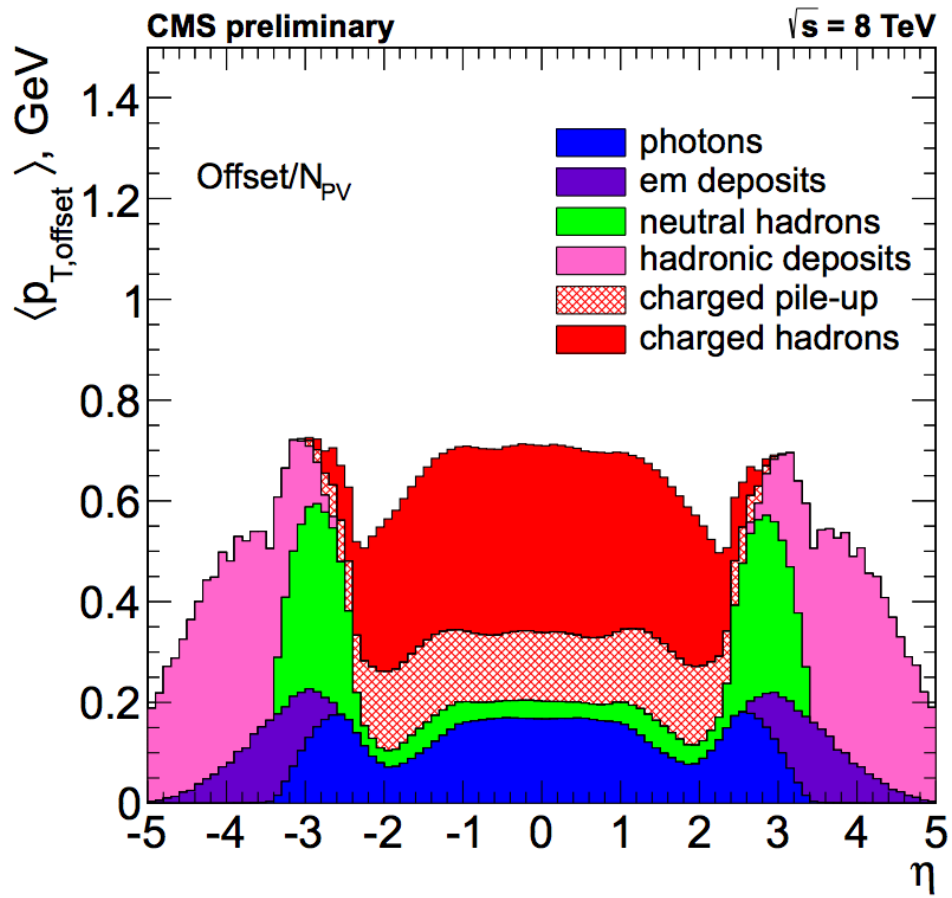


Dominated by PU at low p_T, extrapolation at high p_T, relative scale at high η

PU correction

Offset composition in terms of Pfcandidates (evaluated on Zero Bias data)

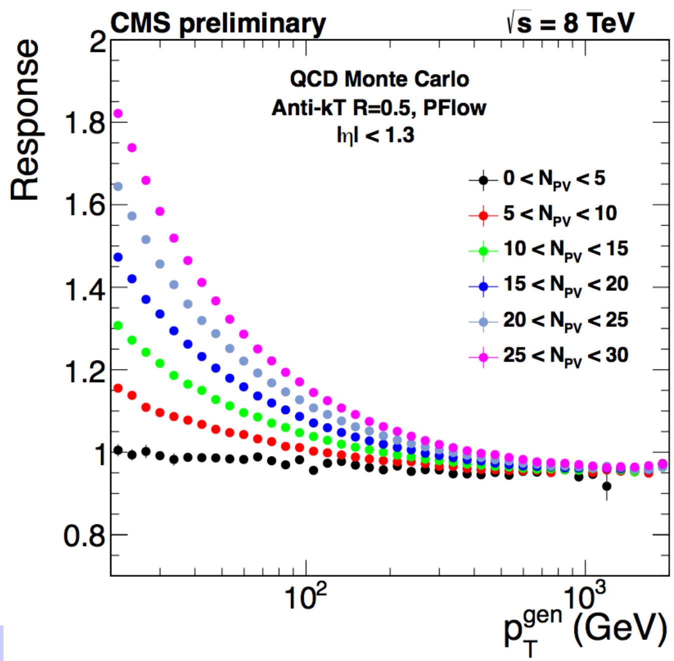
- charged hadrons : coming from PU vertices, can be removed (CHS)
- charged PU charged hadrons not associated to PV

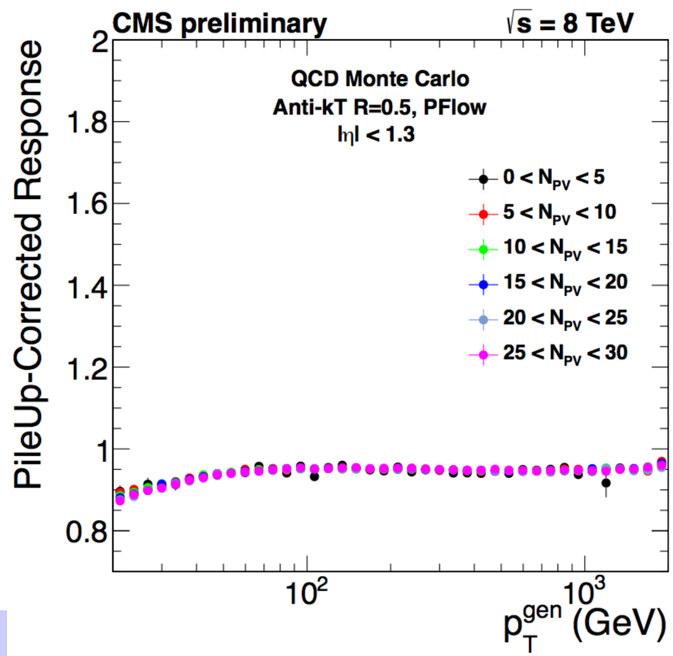


PU correction

Evaluated with the Hybrid jet area method : $C_{\text{hybrid}}(p_T^{raw}, \eta, A_j, \rho) = 1 - \frac{(\rho - \langle\rho_{\text{UE}}\rangle) \cdot \beta(\eta) \cdot A_j}{p_T^{raw}}$

- ρ : event average p_T-density
- ρ_{UE} : expected average p_T-density from UE and electronic noise (evaluated on data events with ==1PV)
- Aj : jet area (kt6, doi:10.1016/j.physletb.2007.09.077 and doi:10.1088/1126-6708/2008/04/005)
- $\beta(\eta)$: corrects for detector response non-uniformity (evaluated with offset method on MinBias events)

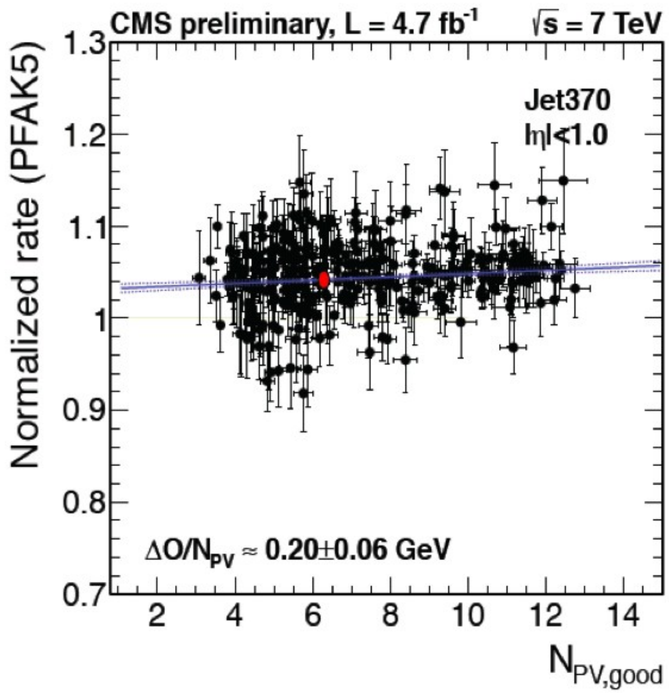




PU correction uncertainties

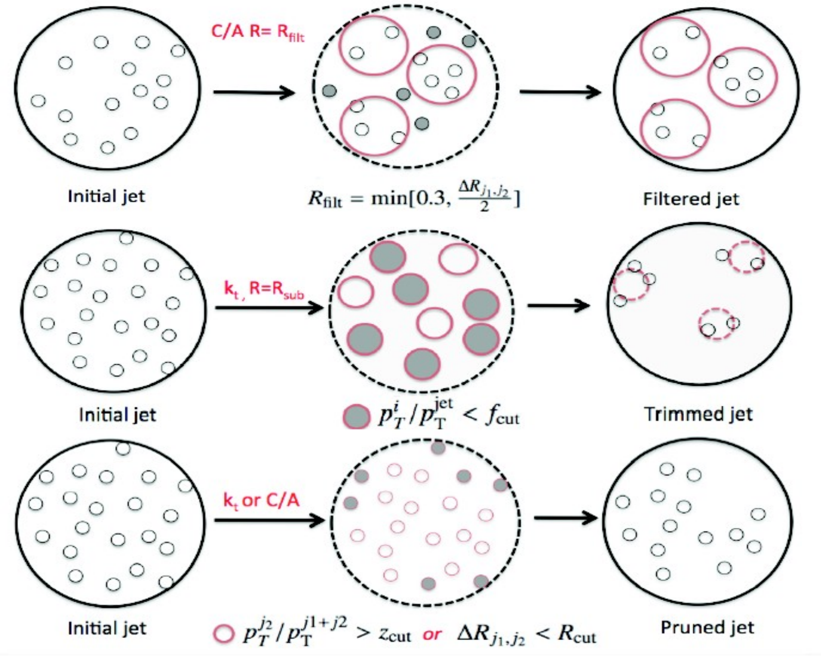
L1 correction uncertainties :

- ρ and ρ_{UE} varied independently, uncertainties added in quadrature
- jet pT dependence (parametrised as envelop covering the variations)
- PU Data/MC (from Random Cone method on ZeroBias data/MC)
- PU bias (bias of RCZB method on MC, non closure within true and measured offset)
- in 2011 OOT PU specific corrections (not an issue with 2TS reco)
- in 2011 PU jet rate uncertainty (affecting JER not JEC)



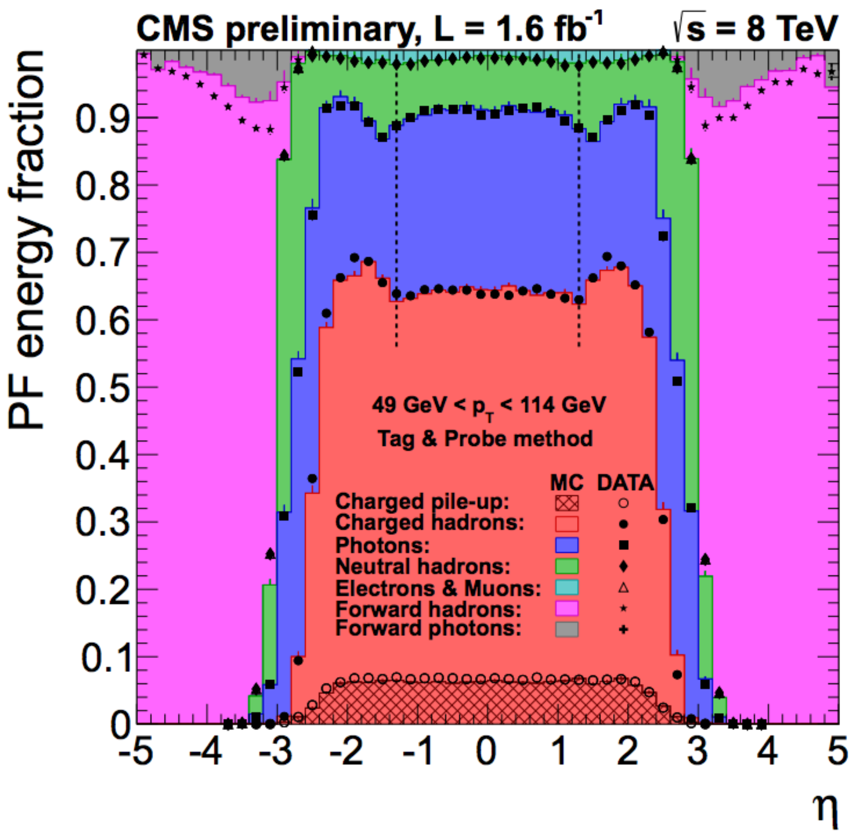
Jet Substructure

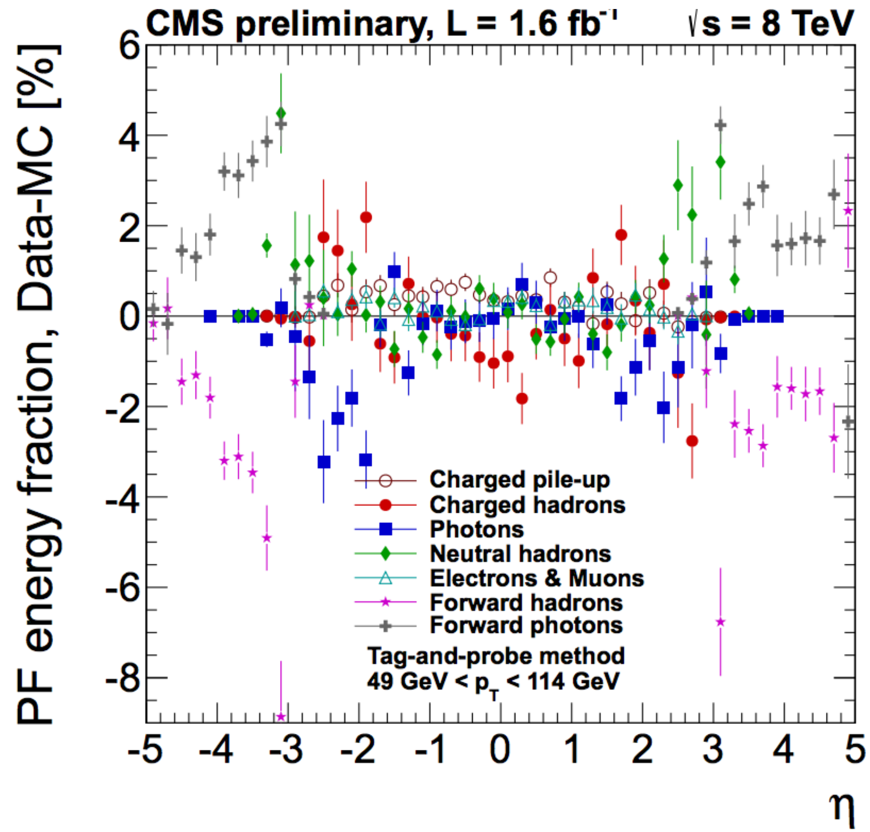
- allows to test internal structure of QCD jets.
- Measure non-perturbative jet properties
- Search for boosted objects (ongoing dedicated worskshops...)
- Remove soft radiation (pileup?) with the grooming techniques
- Three grooming algorithms called :Trimming, Filtering and Pruning



Pfjets composition

Pfjets composition well modeled by MC
Differences compatible with size of residual JEC



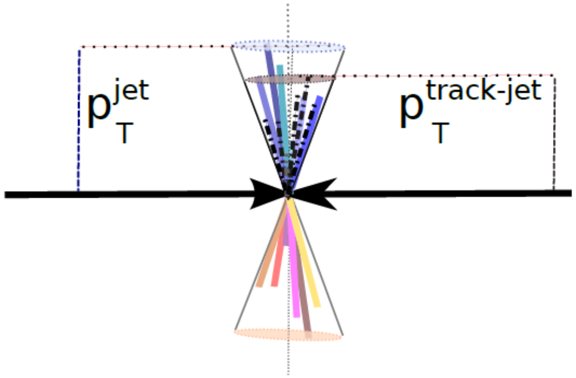


B-JES validation

Overview of validation procedure

1. Use tracks within ΔR <0.4 of the jet as reference object to probe calorimeter JES:

$$r_{trk} = \frac{\Sigma p_T^{trk}}{p_T^{jet}}$$



2. Compare r_{trk} in data and Monte Carlo

$$R_{r_{trk}} = \frac{\langle r_{trk}^{Data} \rangle}{\langle r_{trk}^{MC} \rangle}$$

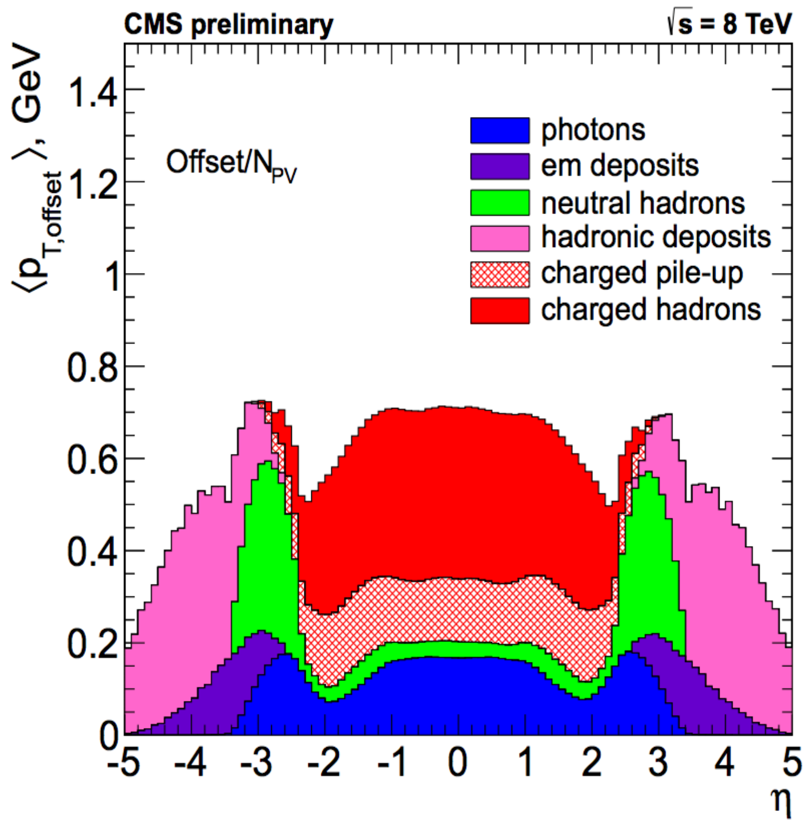
3. Probe differences between inclusive jets and b-jets, in inclusive and $t\bar{t}$ samples

$$R' = \frac{R_{r_{trk}, b-jets}}{R_{r_{trk}, inclusive\ jets}}$$

PF Jet Reconstruction in CMS

Particle Flow (PF) concept:
all subdetector information is combined into PF candidates:

- ❑ charged hadrons;
- ❑ neutral hadrons ;
- ❑ electrons;
- ❑ photons;
- ❑ muons.



Event reconstruction sequence:

- ❑ choice of the PV as highest sum pT;
- ❑ charged hadrons coming from other PVs are identified as PU and removed;
- ❑ Identified PF candidates are then assigned to objects and removed for the next steps:
  - isolated electrons ;
  - isolated muons ;
  - isolated photons ;
  - Jets (Akt R=0.5, Akt R=0.7) ;
  - Taus ;
- ❑ All PF candidates (except PU) are added back and MET is computed.

Systematics and discussions...

- Analyses are impacted by the uncertainty on the calibrated scale of the reconstructed Jets (JES).

- A typical example is the measurement at *7* TeV of the top-anti-top production cross section In the all-hadronic channel performed by ATLAS and CMS.

Source of uncertainty	Contribution (%)
Jet energy scale (JES)	$+20/-11$
b-tagging	$\pm$ 17
ISR, FSR	$\pm$ 17
Parton shower and Hadronisation	$\pm$ 13
Multi-jet trigger	$\pm$ 10
Generator	$\pm$ 7
PDF	$+7/-4$
Pile-up	$+5/-7$
Background model	$\pm$ 4
Luminosity	$\pm$ 4
Jet energy resolution	$\pm$ 3
Jet reconstruction efficiency	< 1
Total	$+36/-34$

Source	Relative uncertainty (%)
Jet energy scale	10.1
Background contribution	9.0
Tagging of b jets	6.0
Renormalisation and factorisation scale	5.8
Tune for underlying event	5.5
Trigger	5.0
Jet energy resolution	4.0
Matching matrix elements/parton showers	4.0
Mass of the top quark	2.1
Pileup	0.8
Total systematic	18.6
Total statistical	7.0
Luminosity	2.2
Total uncertainty	20.0