Jet Energy Calibration

Konstantinos Kousouris
Fermilab

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Outline

- **Basic principles**
  - showering, fragmentation & hadronization, composition of jets
  - calorimeter response to hadrons
  - calorimeter response to jets
- **Calibration after jet clustering (“*top-down*”)**
  - average jet calibration
    - Monte Carlo truth
    - in situ measurements of energy scale and resolution
  - jet-by-jet Calibration
    - the ATLAS’s global sequential calibration (GS) and the track based improvement
    - the CMS’s jet plus track algorithm
- **Calibration before jet clustering (“*bottom-up*”)**
  - the ATLAS’s global cell weighting (CSW) and local cluster weighting (LCW)
  - the CMS’s particle flow
- **Summary**

Motivation

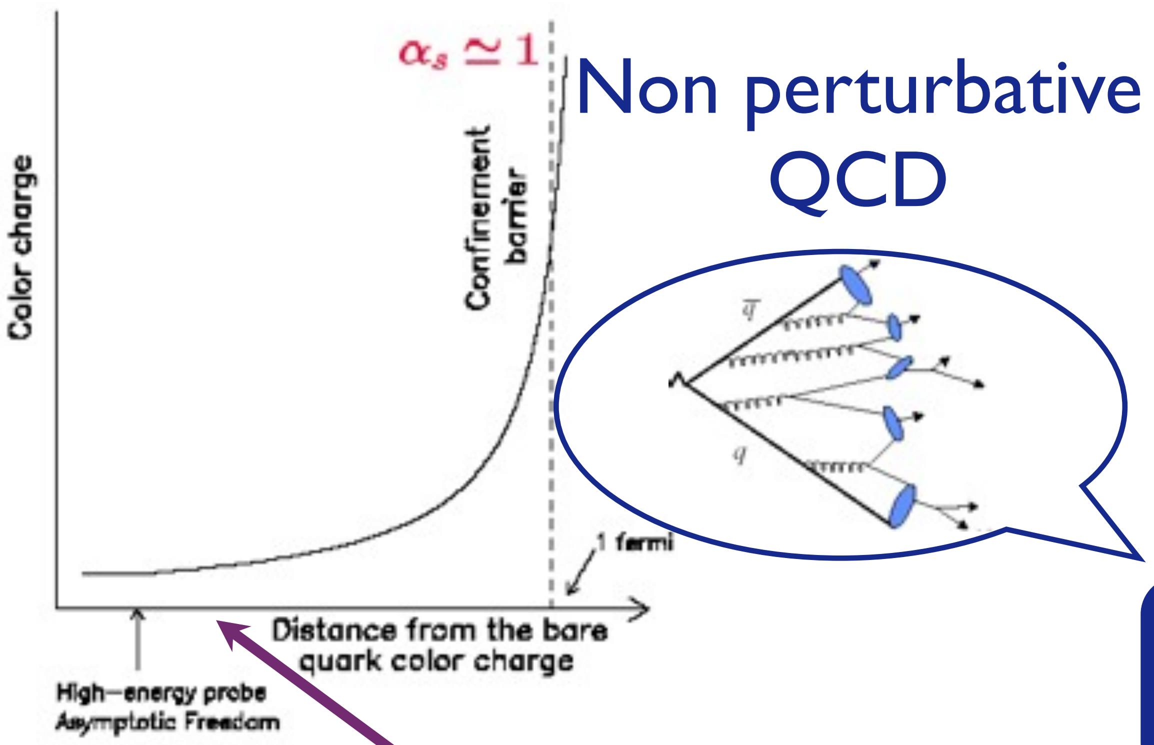
- ☑ present the jet energy calibration strategies employed by CMS and ATLAS
- ☑ describe the data-driven measurement techniques
- ☑ bring to the surface the complexity and ambiguity of the jet object

Disclaimer

this presentation does not intend to compare the performance of ATLAS and CMS experiments

(I) Basic Principles

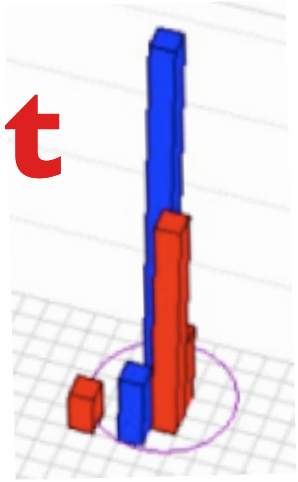
The Jet Object

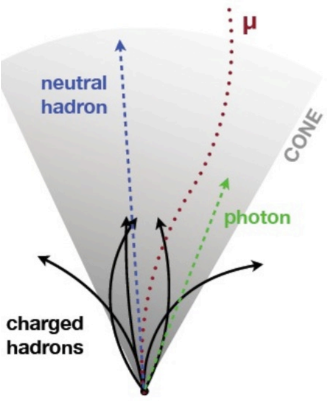


Non perturbative QCD

Detector

Jet

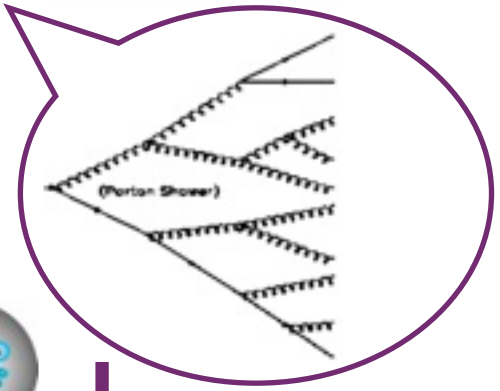




Hadronization

A jet is the experimental signature of quarks and gluons

Parton showering

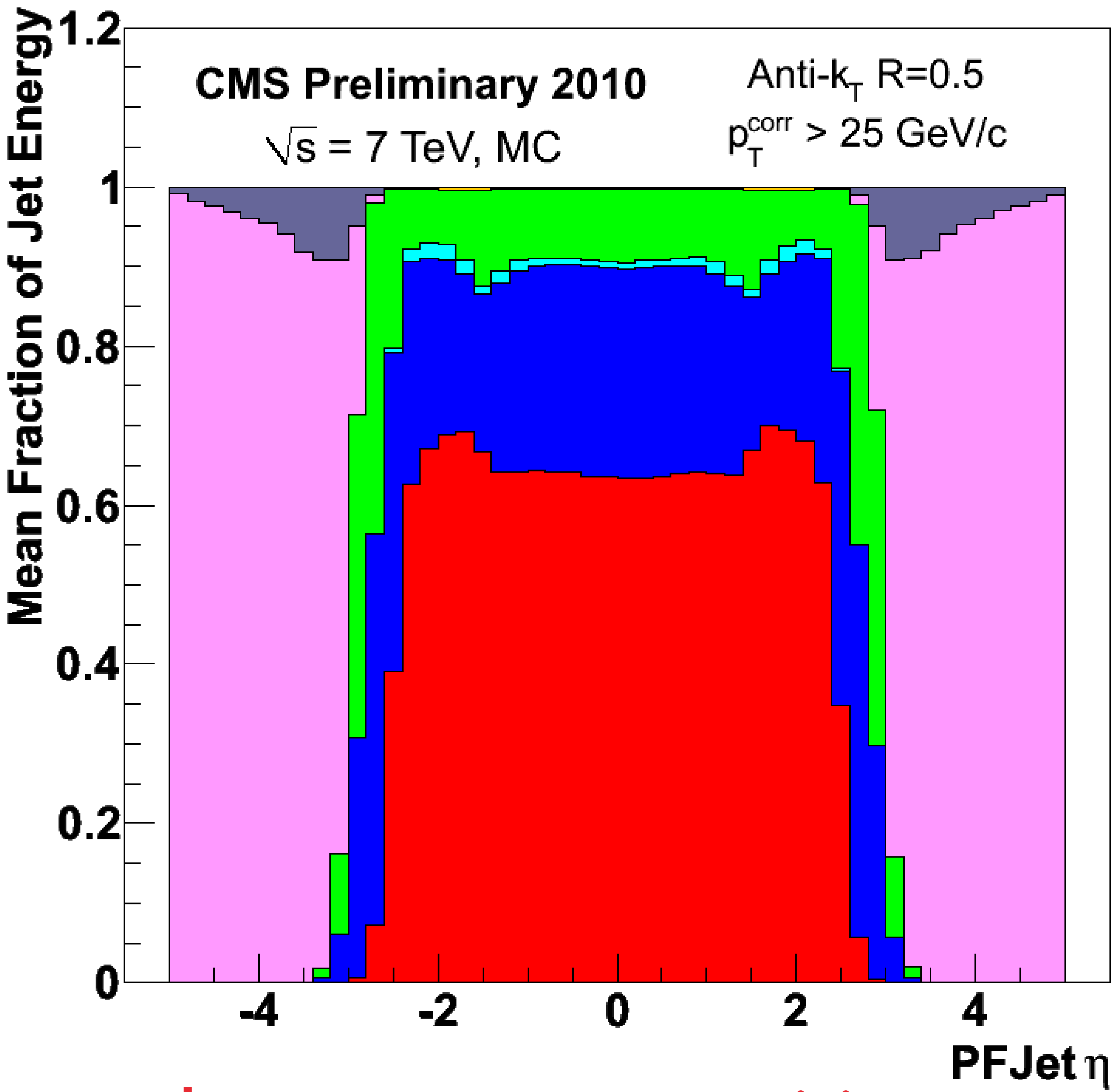


Perturbative QCD

$q, \bar{q}, g$

Hard parton scattering
(determined by matrix QCD element
and proton PDF)

Jet Composition

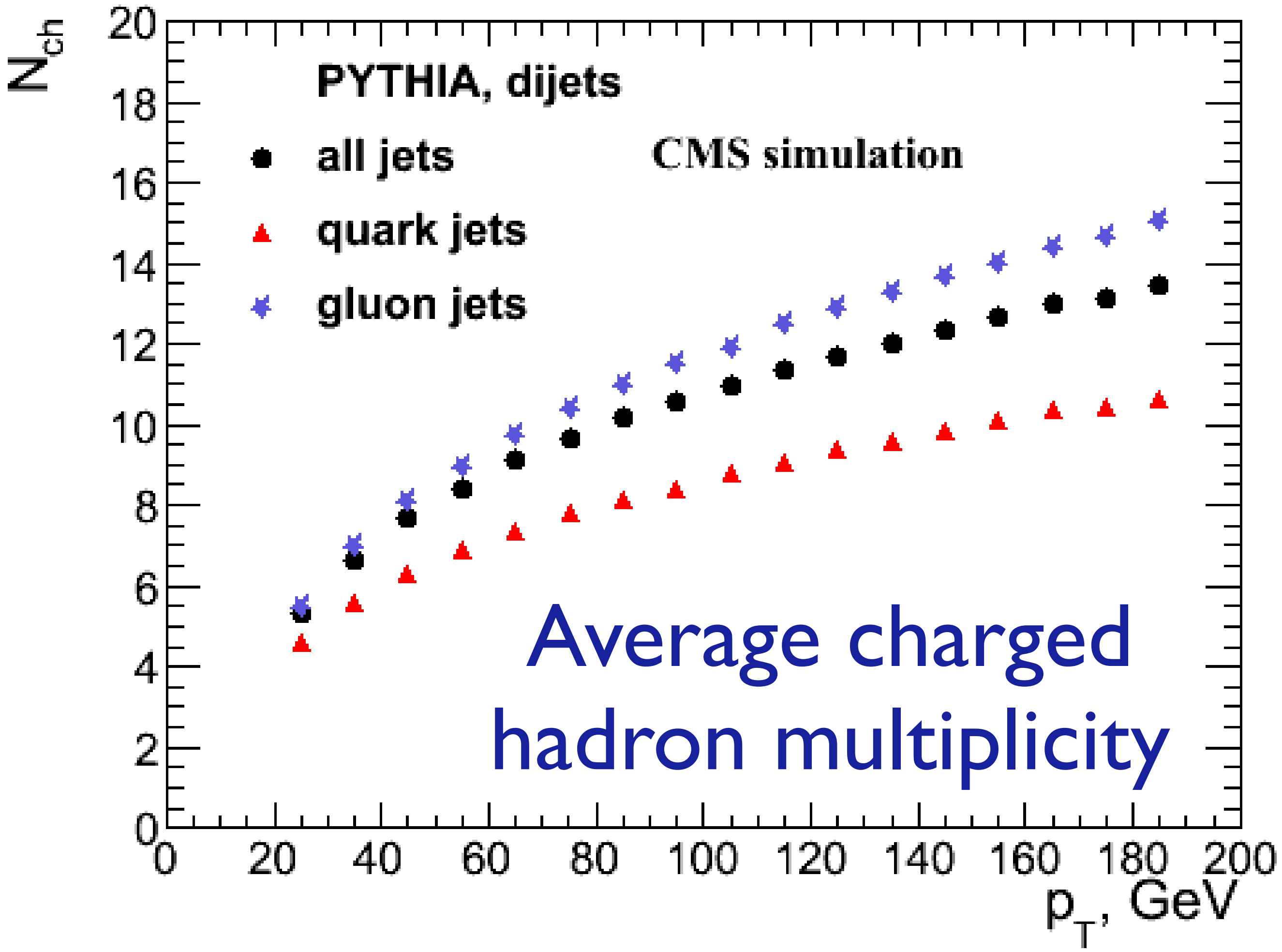


Jet energy composition, reconstructed with the particle flow algorithm

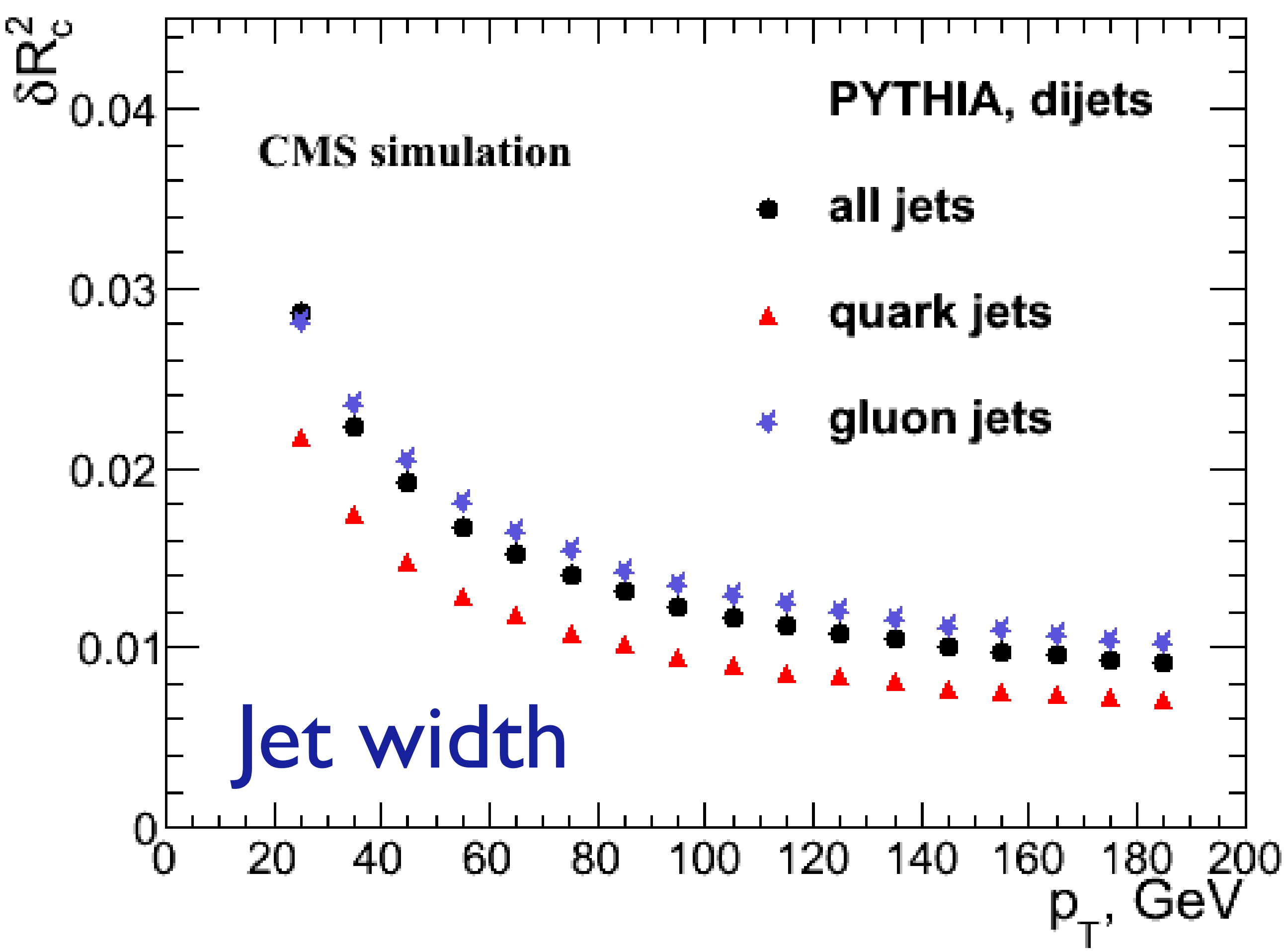
✦ the jet composition determines the jet energy response

- ~65% of the jet energy is carried by charged hadrons
- ~25% of the jet energy is carried by photons
- ~10% of the jet energy is carried by neutral hadrons

Gluon vs Quark Jets



Average charged hadron multiplicity



Jet width

✦ gluon jets are different than quark jets. The differences emerge during the showering and fragmentation, mainly due to the larger color factor of the gluon Feynman diagrams.

- gluon jets contain more particles
- gluon jets contain softer particles
- gluon jets are wider

Calorimeter Response to Hadrons

intrinsic calorimetric property

$$\frac{e}{\pi} = \frac{\boxed{e/h}}{1-(1-e/h)\boxed{\langle f_{em}\rangle}}$$

fraction of neutral hadrons
~ln(E) dependence

✦The hadronic shower is composed of a purely electromagnetic component and a purely hadronic one.

✦The calorimeter response to hadrons is usually expressed through the "e/π" ratio (ratio of response to the electromagnetic energy deposition over the response to the hadronic component). It equals the response ratio to electrons and pions of the same energy.

✦The ratio "e/h" is the ratio of the electromagnetic over the the hadronic energy detection efficiency. This is an intrinsic property of the calorimeter.

✦ Calorimeters with e/h ~ 1 are called "compensating".

✦The finite energy resolution is caused by the largely fluctuating number of neutral hadrons in the shower.

Calorimeter Response to Jets

$z=E_h/E_J$

$$R_J = 1 - (1 - h/e)\left(\frac{E_J}{E_o}\right)^{m-1} \int z^m \boxed{D(z)}\, d\boxed{z}$$

fragmentation function

✦ The calorimeter response to jets is the integral of the single hadron response over the jet distribution.

✦ In a real experiment, the jet energy response depends on several factors:

- jet composition
- calorimeter response to hadrons
- noise suppression thresholds
- dead material in front of the calorimeter
- track bending magnetic field (does not allow soft tracks to reach the calorimeter)

Jet Energy Calibration Strategies

- **"*Top-down*" approach**

  (1) first reconstruct jets from various detector inputs (calorimeter towers, tracks, clusters, particles, etc)
  (2) then derive average jet energy calibration factors (p_T and η dependent)
  (3) finally apply jet-by-jet corrections to improve the resolution, based on individual jet characteristics (charged fraction, width, associated tracks, etc)

- **"*Bottom-up*" approach**

  (1) first calibrate separately each detector input (particle flow candidates, clusters, etc)
  (2) then reconstruct the jets from the calibrated inputs
  (3) apply small residual (average) calibration if needed

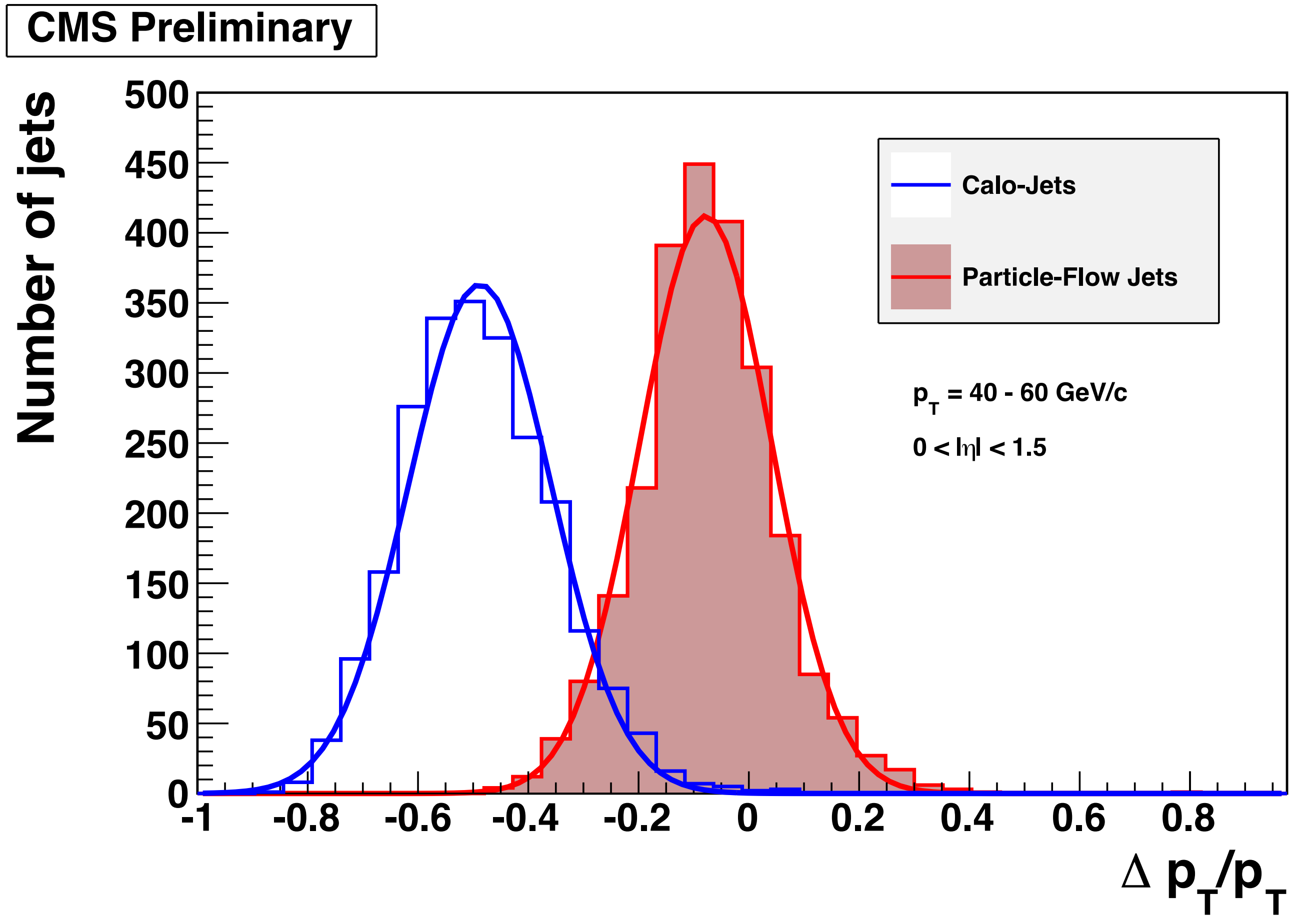
Challenges of the Jet Energy Calibration

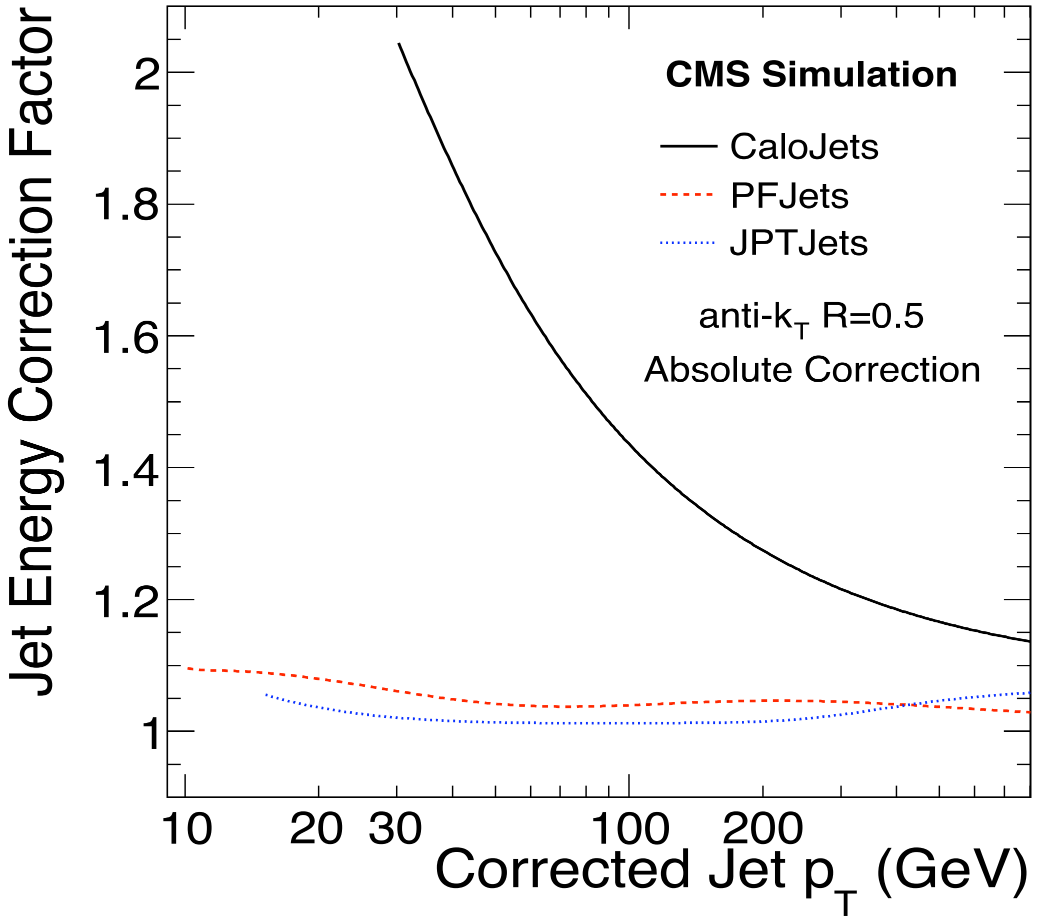
the calibration of the jet energy scale is a particularly challenging task:

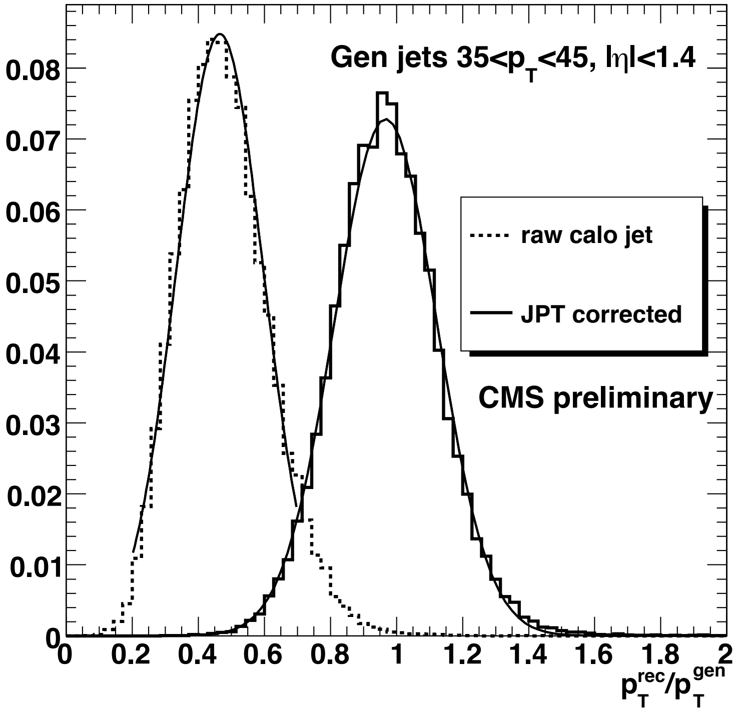
- **because of the jet nature**
  - jets are complicated composite objects, unlike the other particles which are elementary (electrons, muons, photons)
- **because of the hadrons interaction with matter**
  - hadronic showers have electromagnetic, hadronic and invisible components
- **because of the gluon/quark jet differences**
  - each physics sample is a unique mixture
- **because of the inherent jet definition ambiguity**
  - particle level vs parton level
  - dependence on the jet clustering algorithm
- **because of the significant biases of the in-situ measurements**
  - steeply falling jet spectra
  - finite resolution (much worse than other particles)

(II) "*Top-down*" Calibration

Monte Carlo Truth

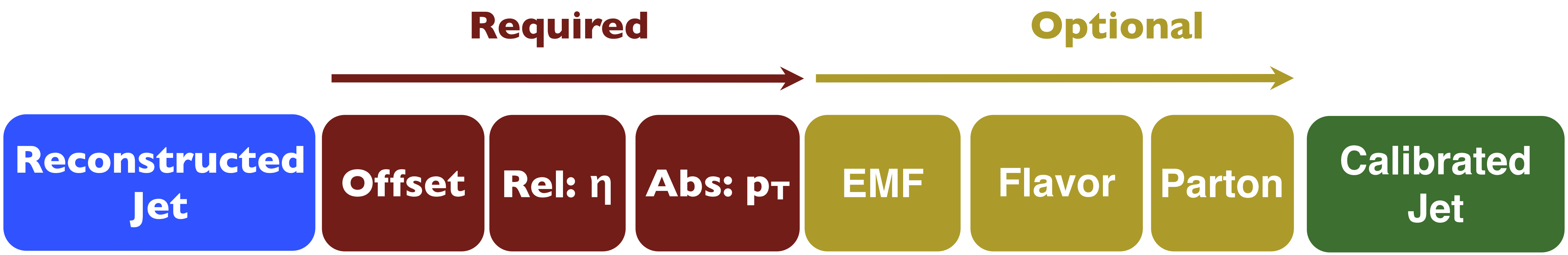






- ✦ geometrical matching between particle jets and reconstructed jets
- ✦ average correction to the particle level
- ✦ fixes the scale but does not improve the resolution
- ✦ used for MC studies
- ✦ starting point for the jet calibration in data

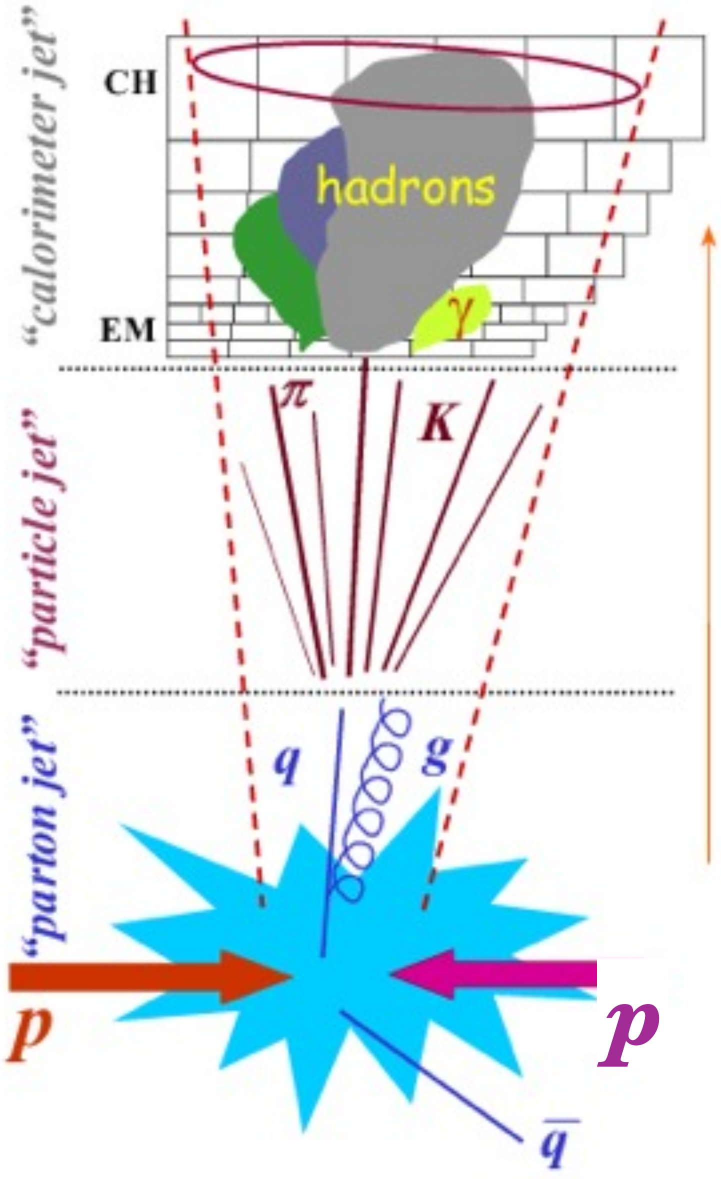
CMS's Sequential Approach



Required

Optional

Reconstructed Jet → **Offset** → **Rel: η** → **Abs: p_T** → **EMF** → **Flavor** → **Parton** → **Calibrated Jet**



Why a multi-step approach?

☑ Each sub-correction corrects for a different effect.

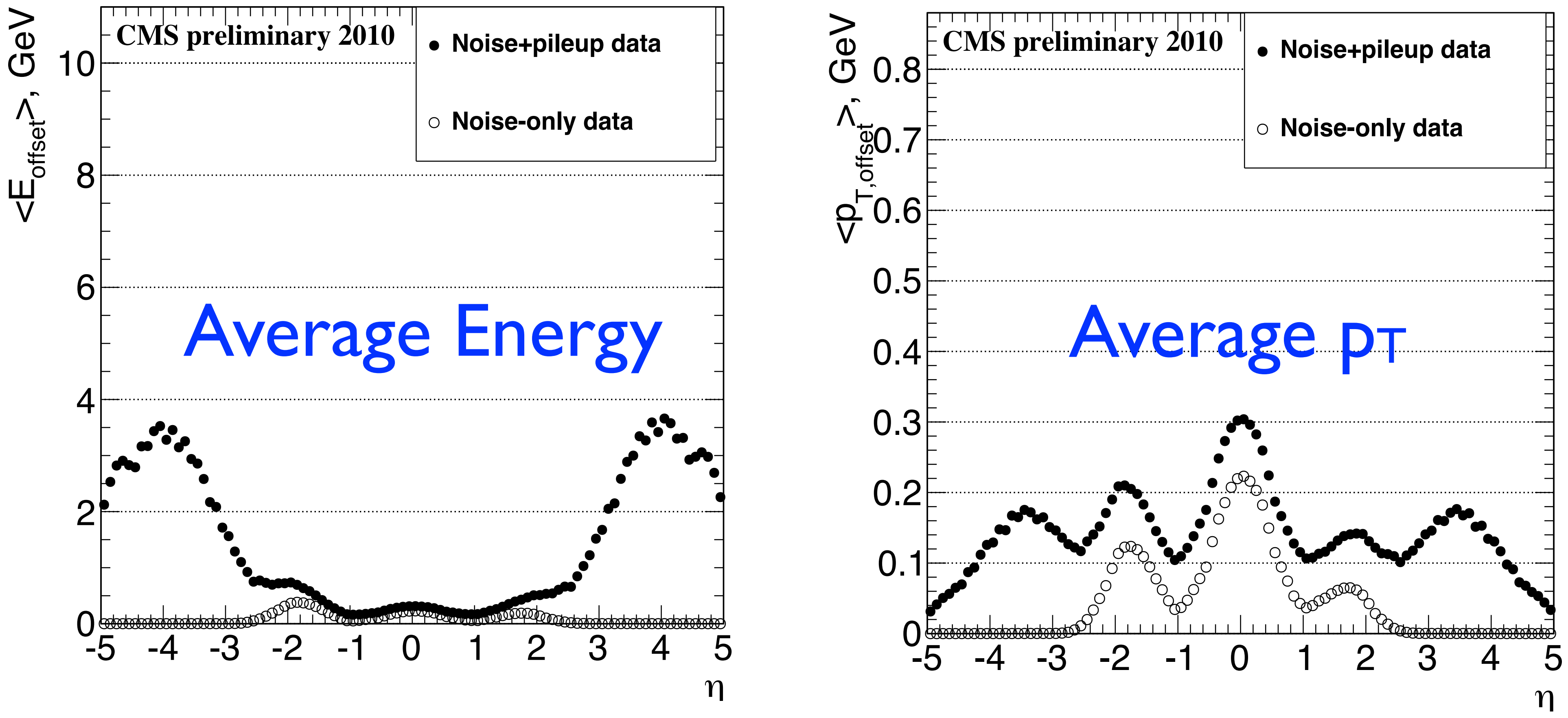
☑ Each sub-correction can be separately studied and optimized.

☑ Easier to develop data driven methods.

☑ Systematic uncertainties are easier to estimate.

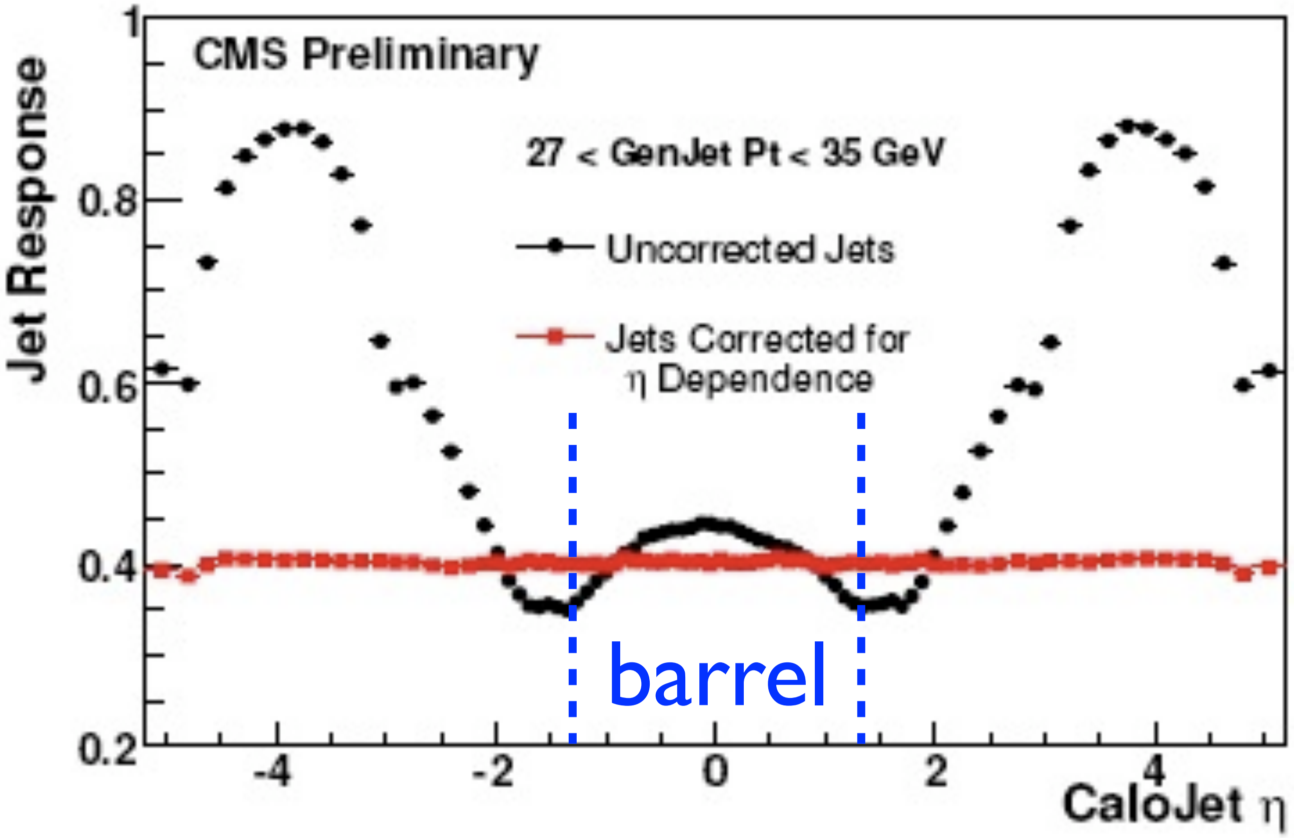
- **Required corrections:**
  - correct on average the energy scale, from detector level to particle level
- **Optional corrections:**
  - improve the energy resolution
  - take care of sample differences (flavor)
  - correct to parton level

Offset Correction



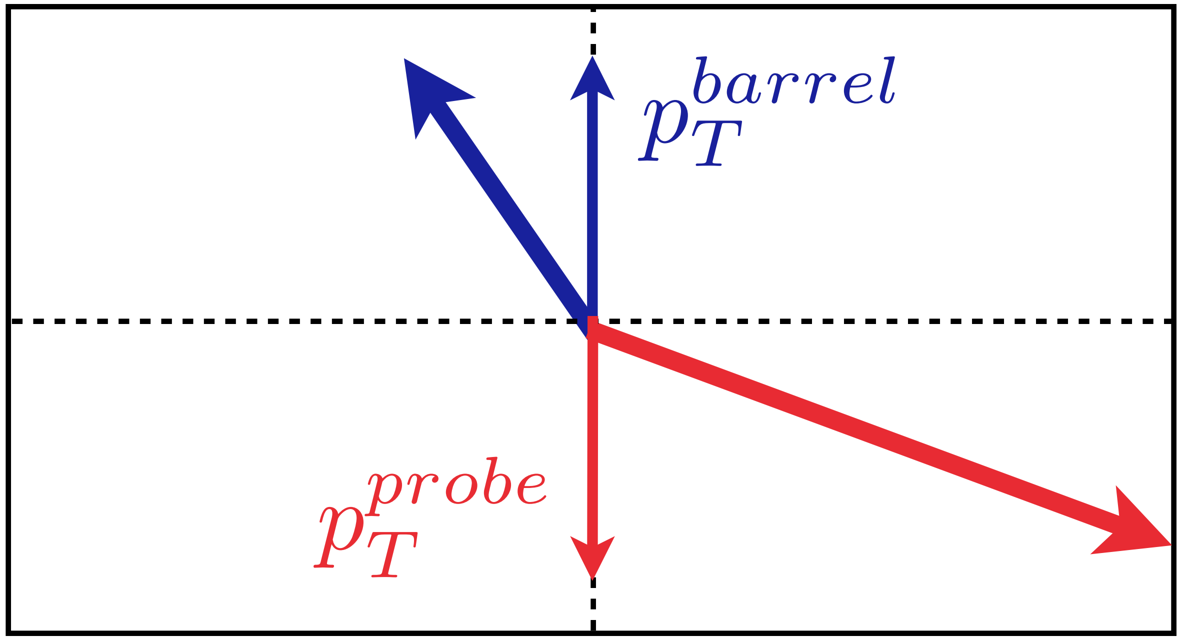
- the *Offset* correction removes unwanted energy due to noise and pile-up
  - allows us to have luminosity independent jet energy corrections
- the noise contribution is measured from Zero Bias events by vetoing the Minimum Bias trigger
- the overall offset is measured from inclusive Zero Bias events
- **CAVEAT**: this approach systematically underestimates the offset correction due to the zero suppression thresholds
  - in a random cone, without real jet activity, soft contributions do not pass the zero suppression thresholds but they do in the presence of real jets. The underestimation an be as large as a factor of 4.

Uniformity in η



- **the jet energy response is not uniform across η**
  - the response is energy dependent. For fixed p_T, jets in outer η have more energy and better response.
  - the material budget in front of the calorimeters is not uniform
  - noise and reconstruction thresholds are not uniform
- **uniformity in η is achieved by correcting all jets with respect to the average scale in the barrel (|η|<1.3)**
  - the barrel has the largest p_T reach
  - the barrel has small response variations
  - the barrel can be absolutely calibrated with in-situ measurements

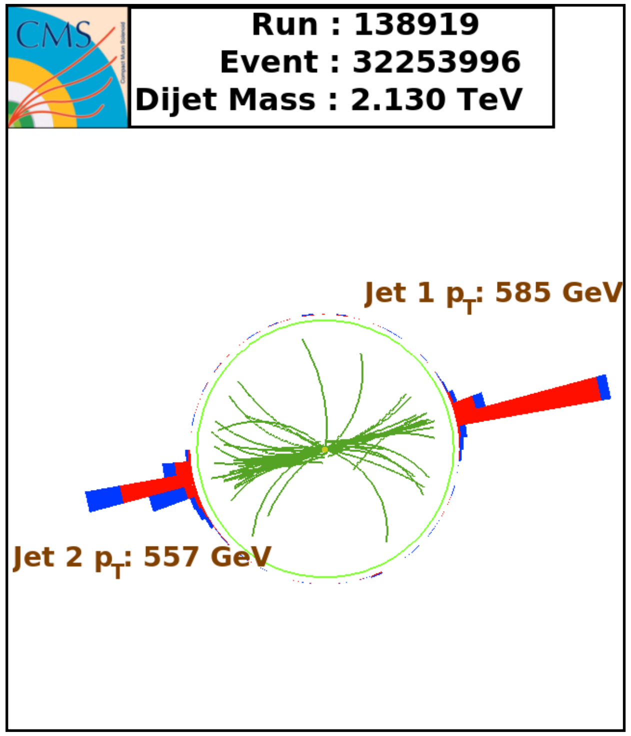
Dijet p_T Balance (I)



$$p_T^{dijet} = \frac{p_T^{probe} + p_T^{barrel}}{2}$$

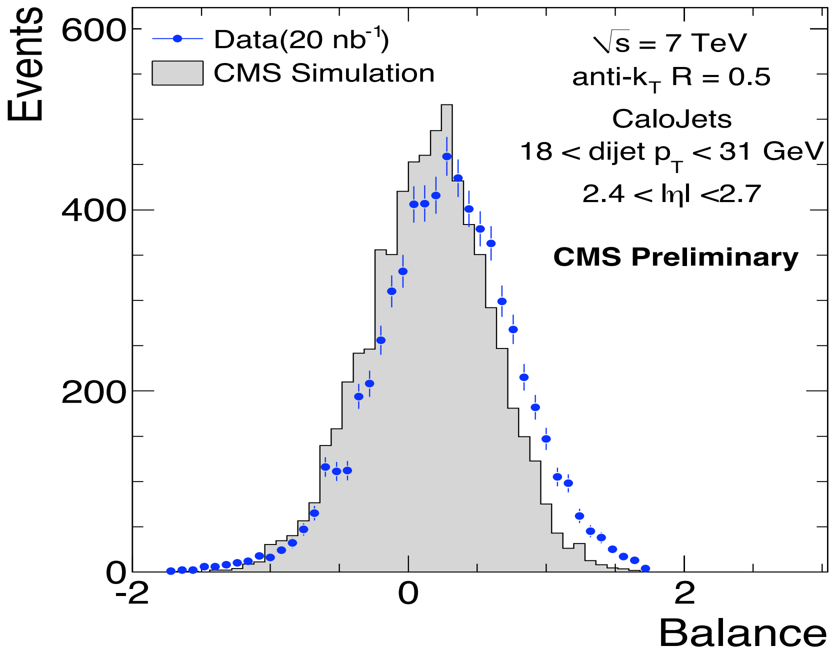
$$B = \frac{p_T^{probe} - p_T^{barrel}}{p_T^{dijet}}$$

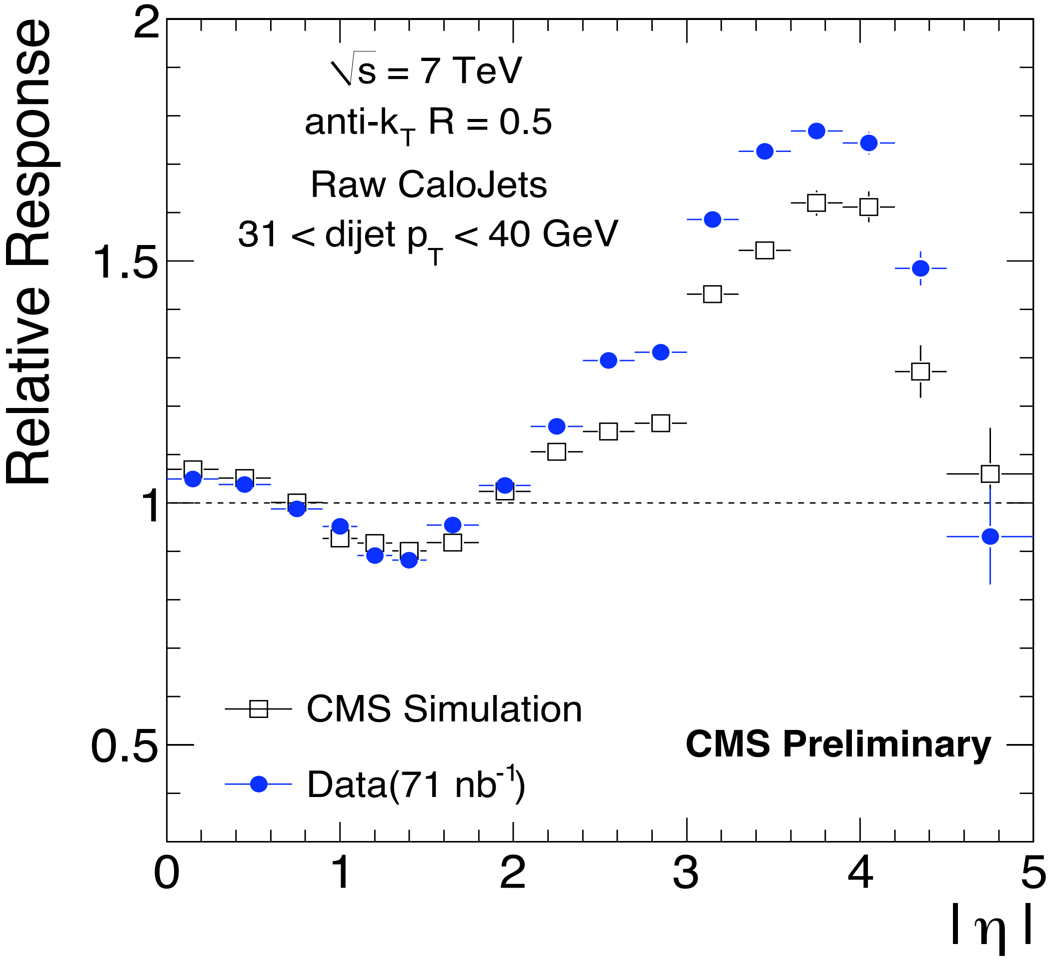
$$r = \frac{2+ < B >}{2- < B >}$$



- ✦ the dijet p_T balance measures the **relative** jet energy response
- ✦ the quantity **r** is the least biased estimator of the relative response (as opposed to < probe p_T / barrel p_T > which is maximally biased)

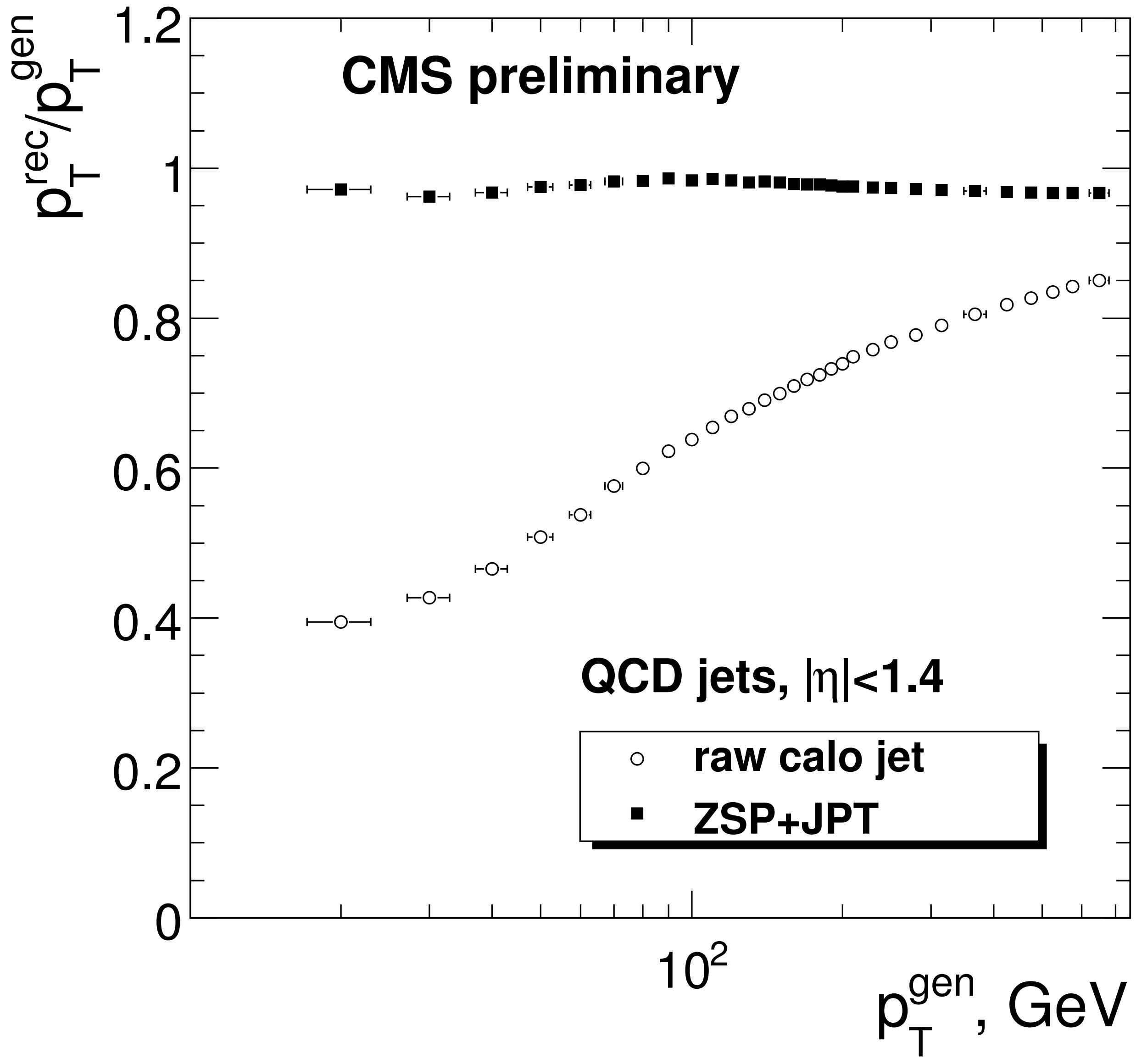
Dijet p_T Balance (II)





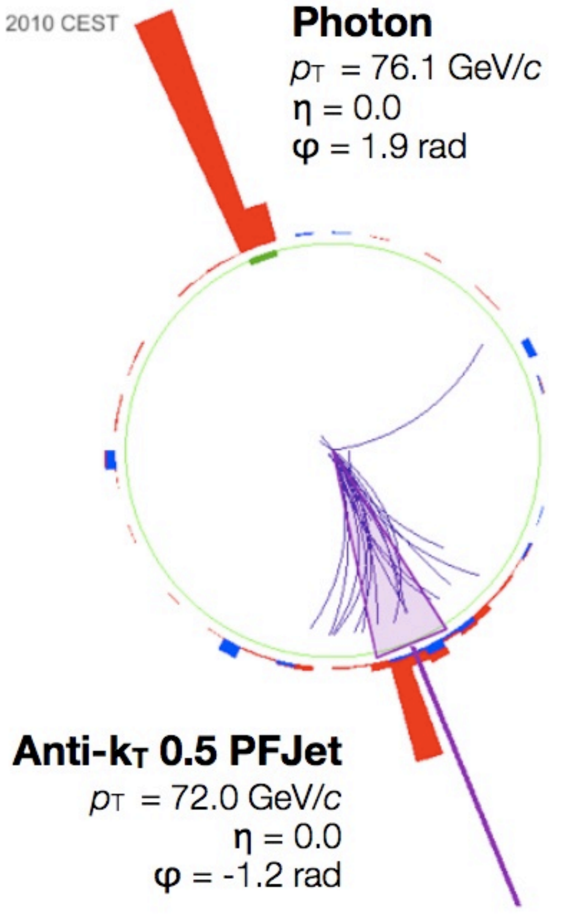
- **Analysis essentials**
  - bins of dijet p_T (reduces the resolution bias)
  - bins of probe jet η
  - cut on the 3rd jet p_T (not very sensitive, no extrapolation to 0 needed)
- **Resolution bias**
  - leading systematic uncertainty
  - needs to be explicitly corrected for
  - caused by the different resolution of the barrel and probe jets and the steeply falling jet p_T spectrum
- **First CMS data**
  - bins of |η| due to limited statistics
  - clear disagreement observed between data and MC in outer rapidities (consistent with higher single particle response)

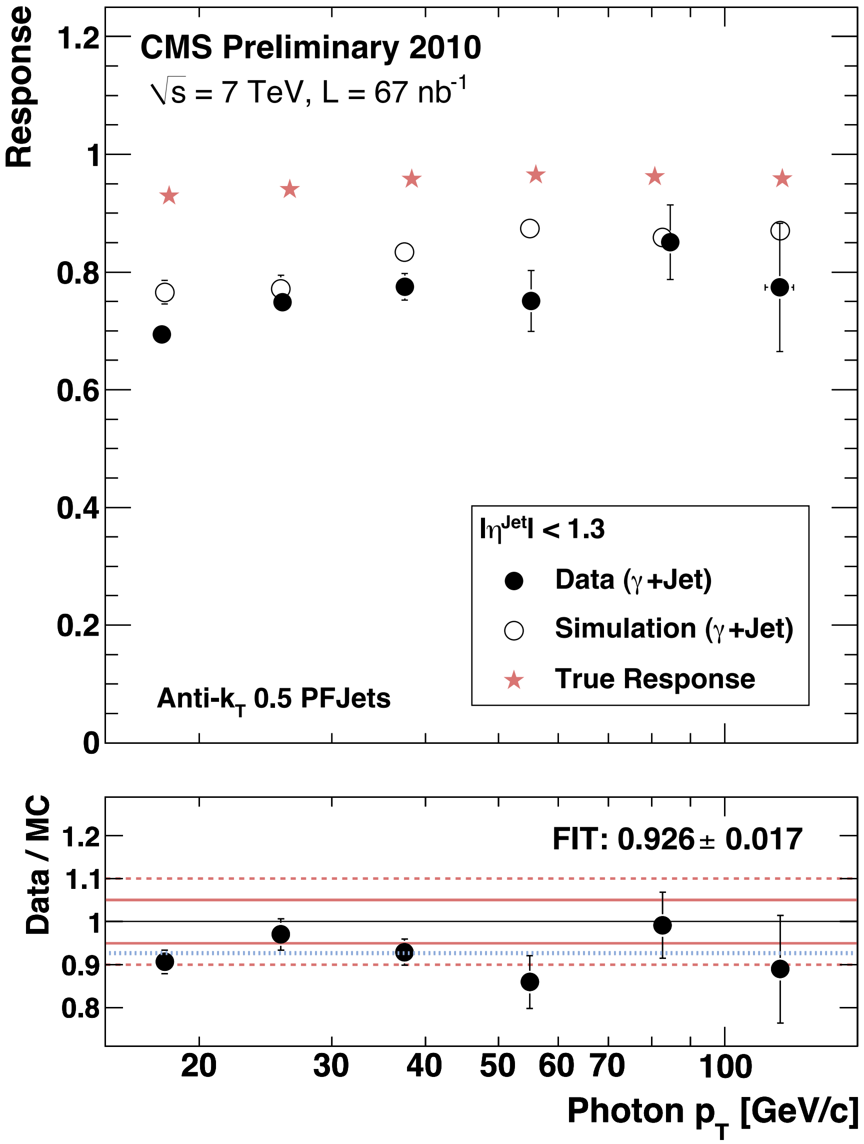
Uniformity in p_T

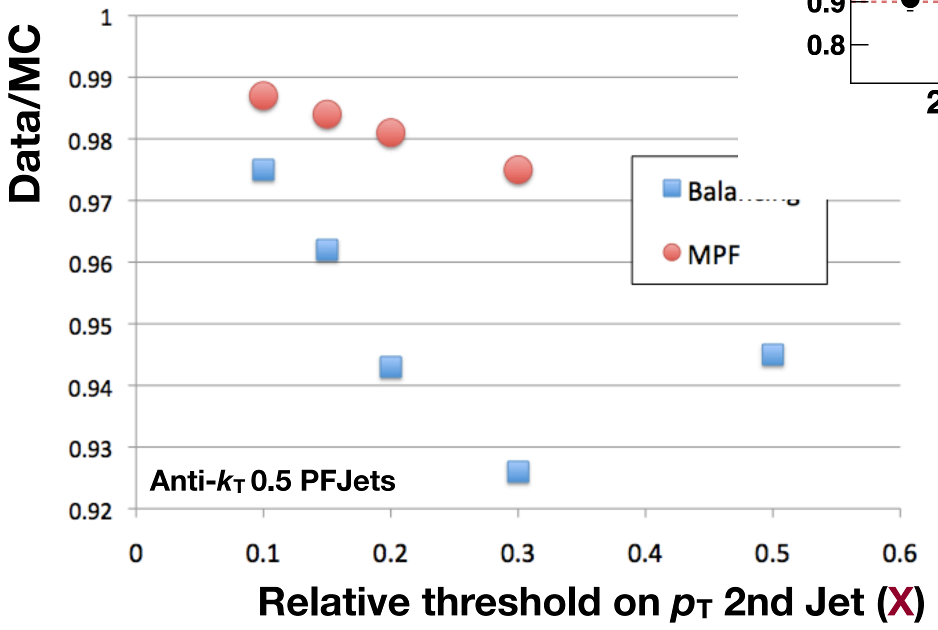


- ✦ the relative jet energy correction makes the response uniform in η but does not fix the absolute scale
- ✦ looking at the p_T dependence of the response in the reference region (barrel)
- ✦ non-linearity observed
  - ▸ in other words: the response depends on the p_T (closer to unity as p_T increases)
- ✦ **absolute** energy correction
  - ▸ restores the average scale to unity
  - ▸ applied to all jets, although measured in the reference region

γ+jet p_T Balance







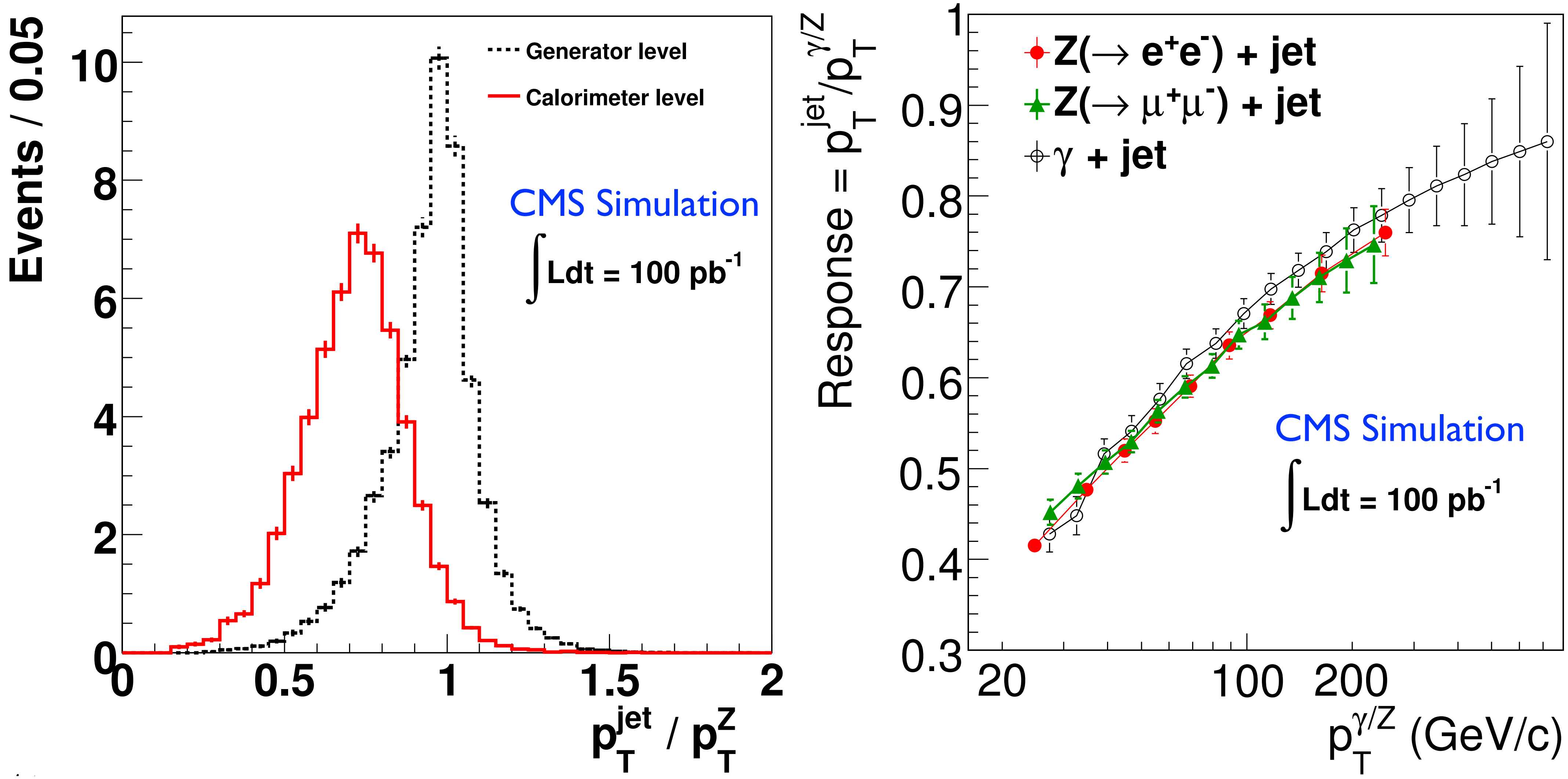
- measures the absolute energy scale
- look for events with a photon and a jet, back-to-back in azimuth
- the photon scale is known to ~1% accuracy $\Longrightarrow$ absolute jet energy scale
- jets in the barrel region
- veto on the second jet
- parton level measurement

CAVEATS

➡ sensitivity to the second jet veto. Extrapolation to 0 needed (limiting statistics).

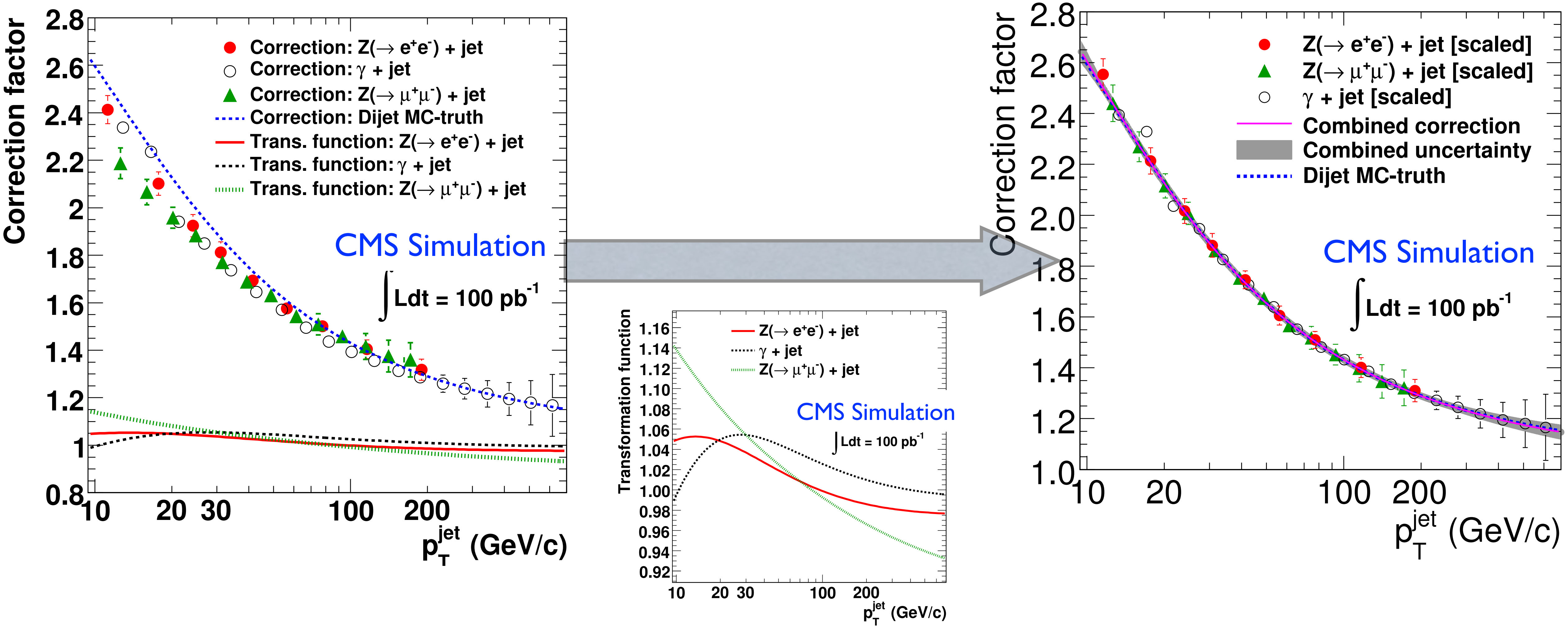
➡ contamination by QCD background

Z+jet p_T Balance



- look for events with a Z and a jet, back-to-back in azimuth
- the Z p_T scale is known to ~1% accuracy ⟹ absolute jet energy scale
- jets in the barrel region
- veto on the second jet
- parton level measurement
- free of QCD background ⟹ more precise measurement at low p_T
- smaller p_T range than photon+jet balancing

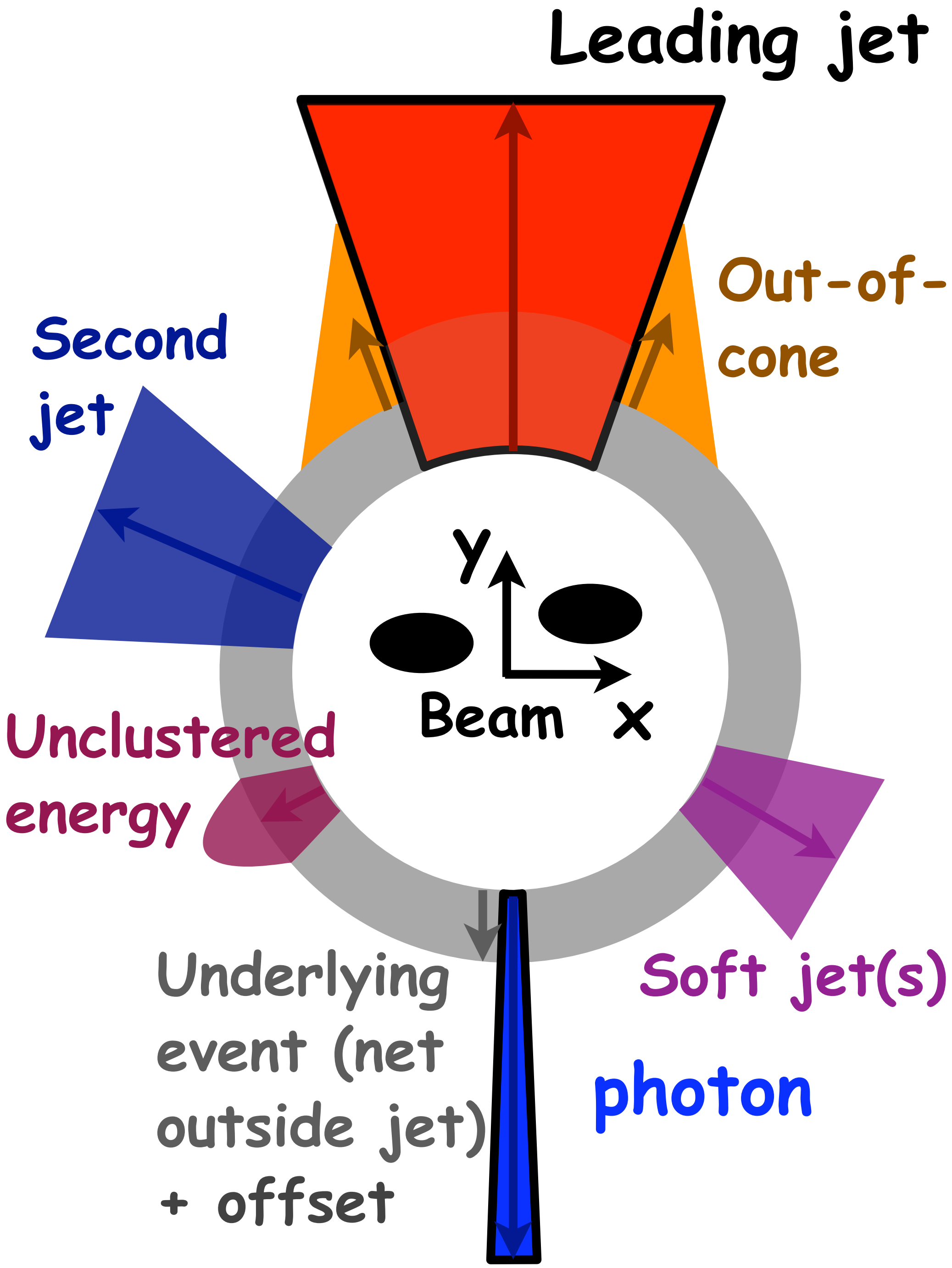
γ/Z+jet: Putting Everything Together



Transformation factors

- ✦ mapping to QCD flavor content
- ✦ from parton level to particle level
- ✦ event selection residuals
- ✦ dominant source of systematic uncertainty

The MPF Method (I)



$$\vec{p}_{T,\gamma} + \vec{p}_{T,recoil} = \vec{0}$$

$$R_{\gamma}\vec{p}_{T,\gamma} + R_{recoil}\vec{p}_{T,recoil} = -\vec{E}_T^{miss}$$

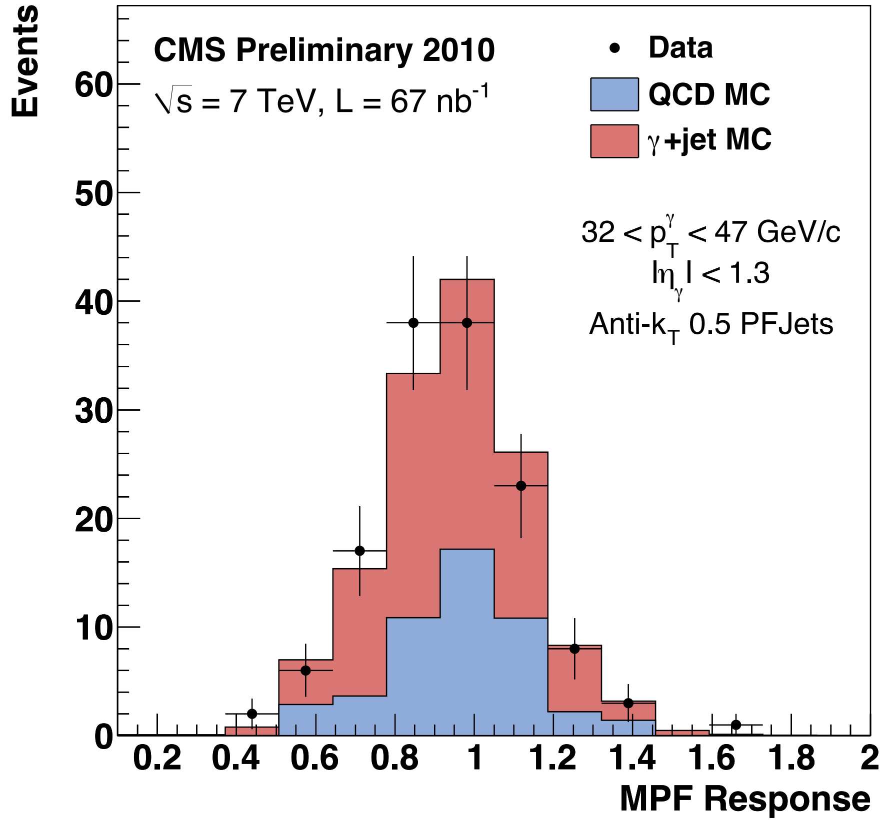
$$R_{MPF} = R_{recoil} = 1 + \frac{\vec{E}_T^{miss} \cdot \vec{p}_{T,\gamma}}{(p_{T,\gamma})^2}$$

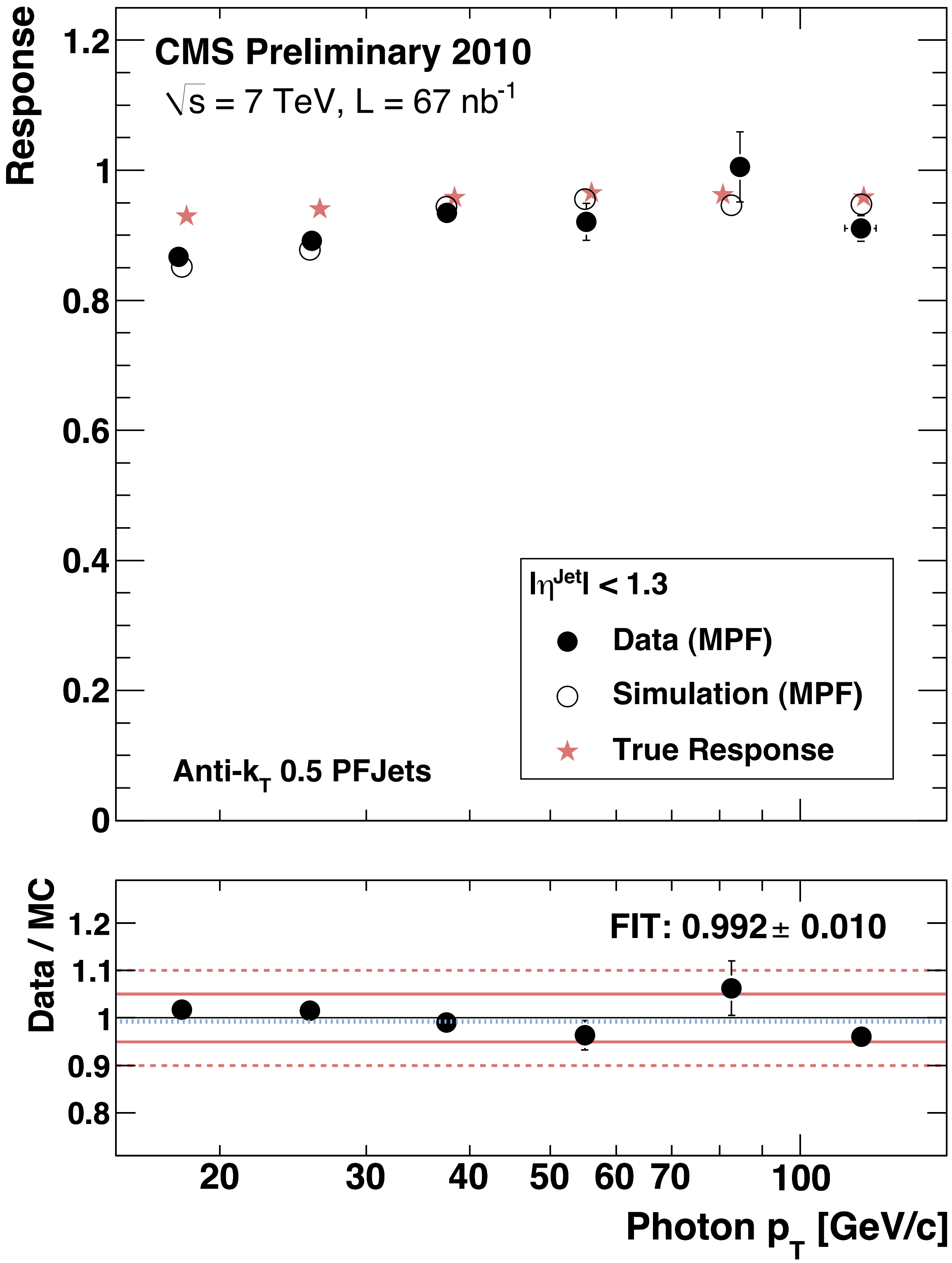
✦ balances the photon with the full hadronic recoil in events with no real missing energy

✦ relies on the MET measurement

✦ the recoil response can be translated to jet response

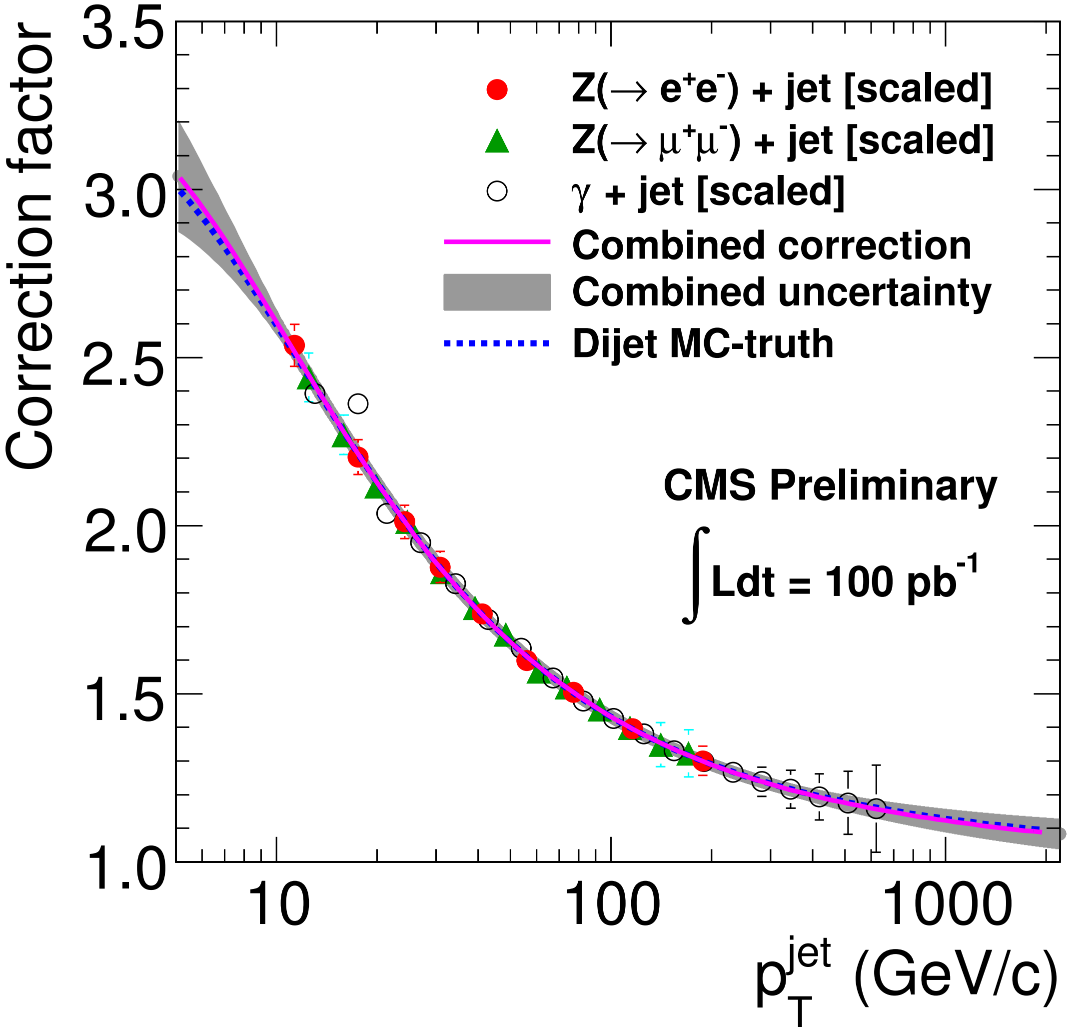
The MPF Method (II)



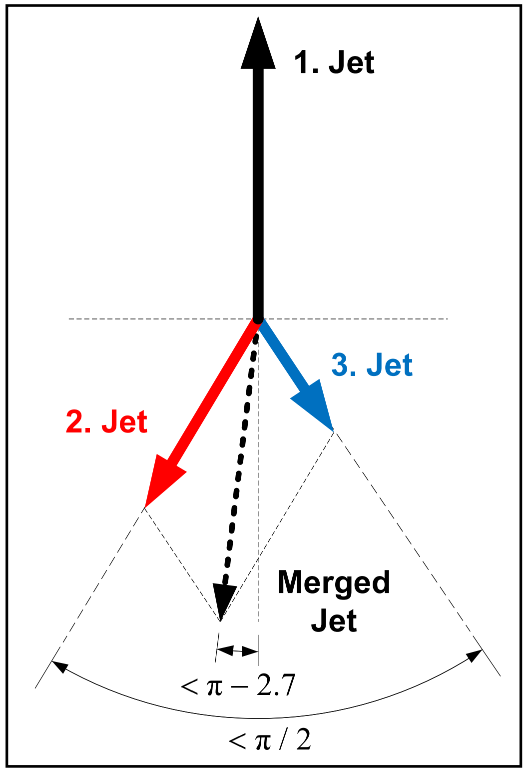


- ✦ better use of the available statistics than γ+jet p_T balancing
- ✦ veto on second jet and extrapolation to 0 needed (weaker dependence than γ+jet p_T balancing)
- ✦ **necessary conditions:**
  - MET and jet reconstruction identical
  - jet response similar to recoil response

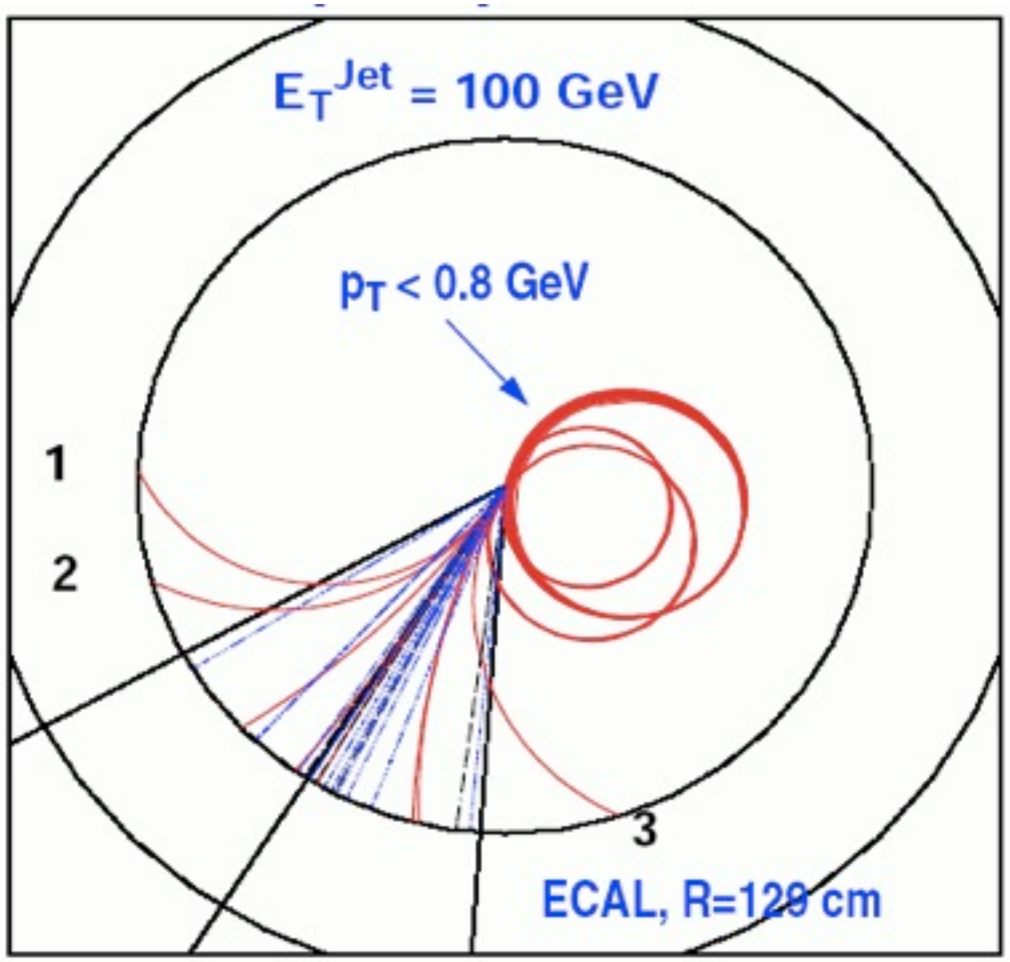
Extrapolation to the Highest p_T

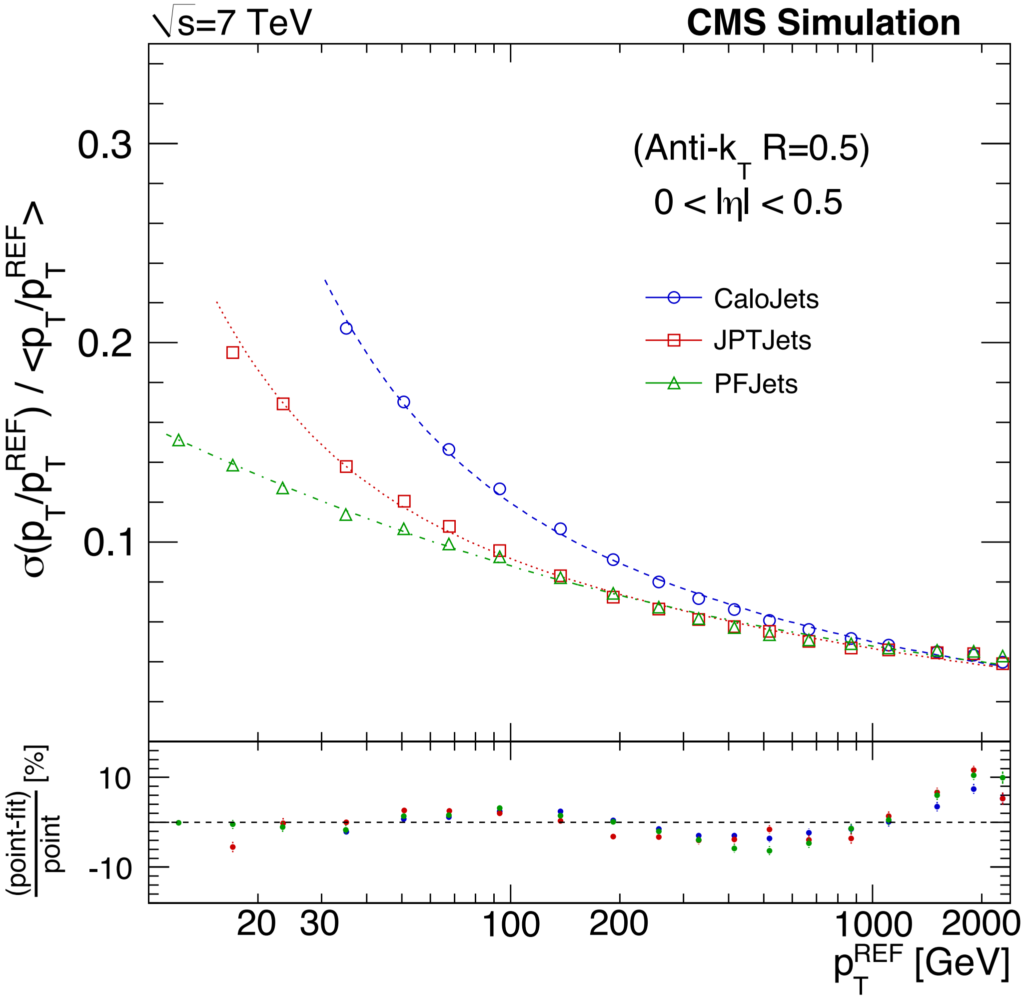


- photon/Z+jet balancing methods cover only ~1/3 of the available jet p_T range
- how to check the highest jet p_T?
  - through a tuned MC
    - single particle response (directly measured)
    - fragmentation modeling (Pythia, Herwig++)
  - through 3-jet p_T balancing
    - statistically limited but feasible
    - important biases related to the event selection



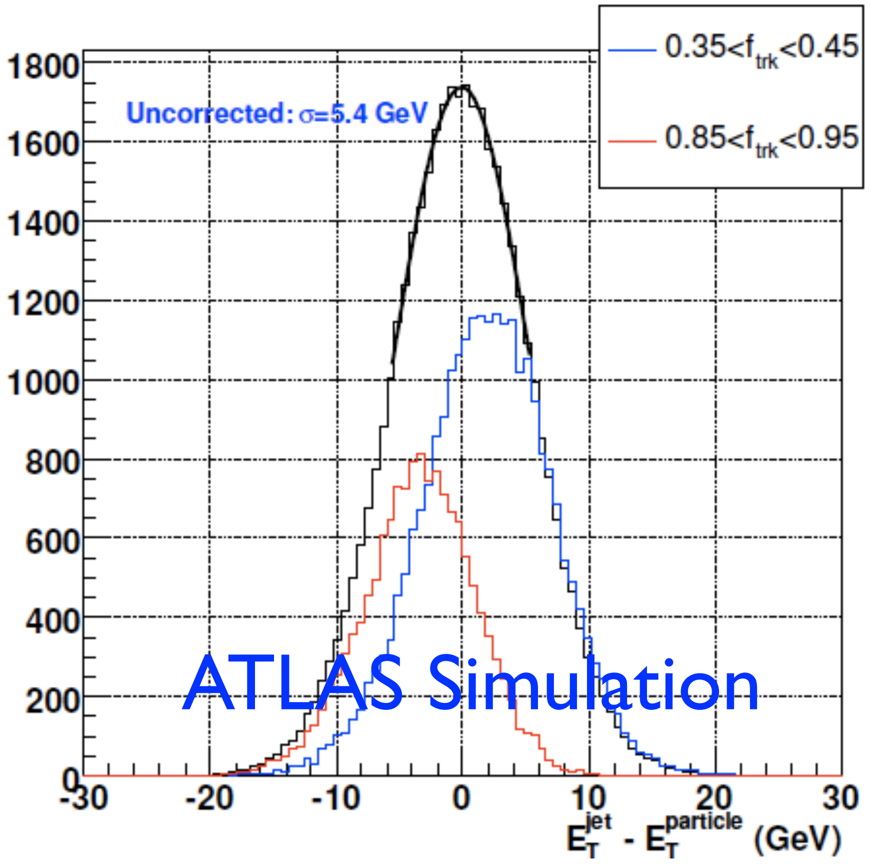
Jet-by-Jet Calibration: the JPT Algorithm

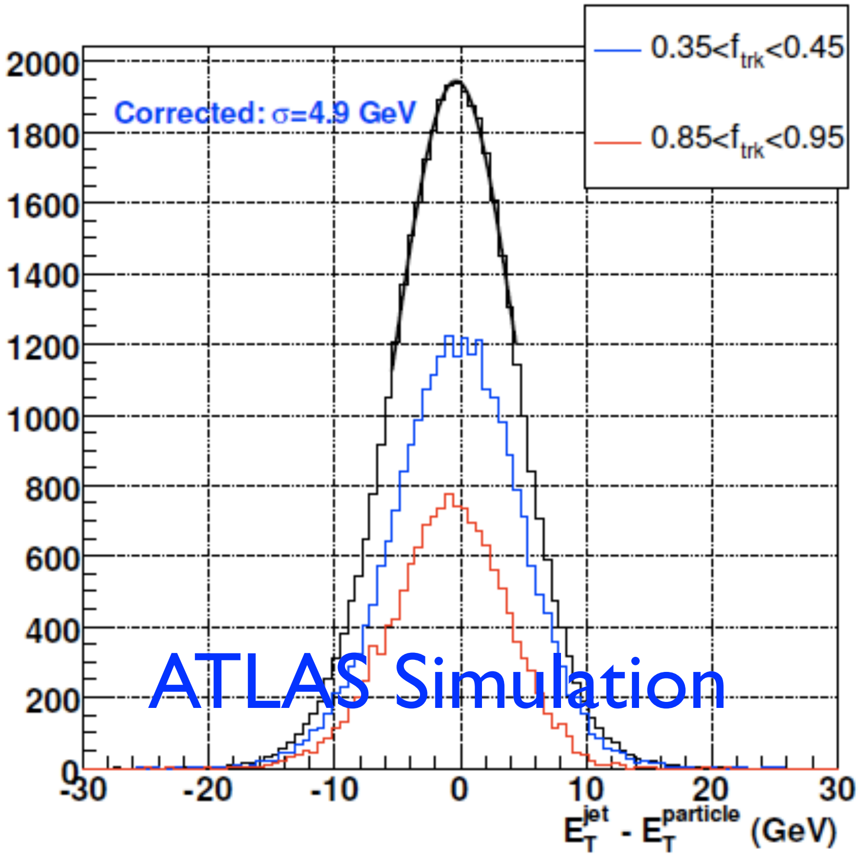


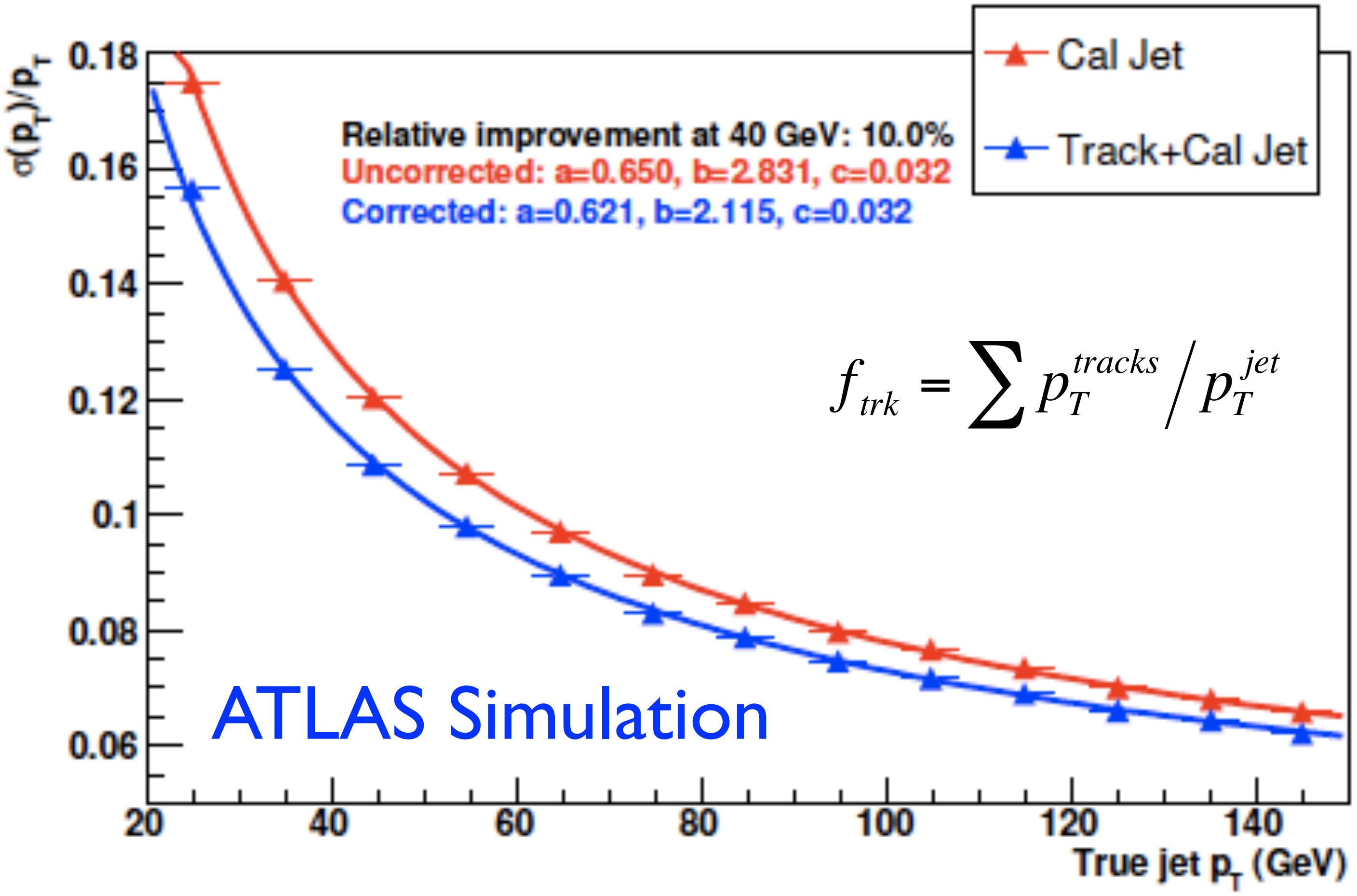


- the Jet-plus-tracks algorithm starts with a reconstructed calorimeter jet and improves its energy and direction measurement with tracker information
- the momentum of “out-of-cone” tracks is added to the jet energy
- the momentum of “in-cone” tracks is added to the jet energy and the average expected calorimeter deposition is subtracted
- key element: the single particle response

Jet-by-Jet Calibration: ATLAS Example

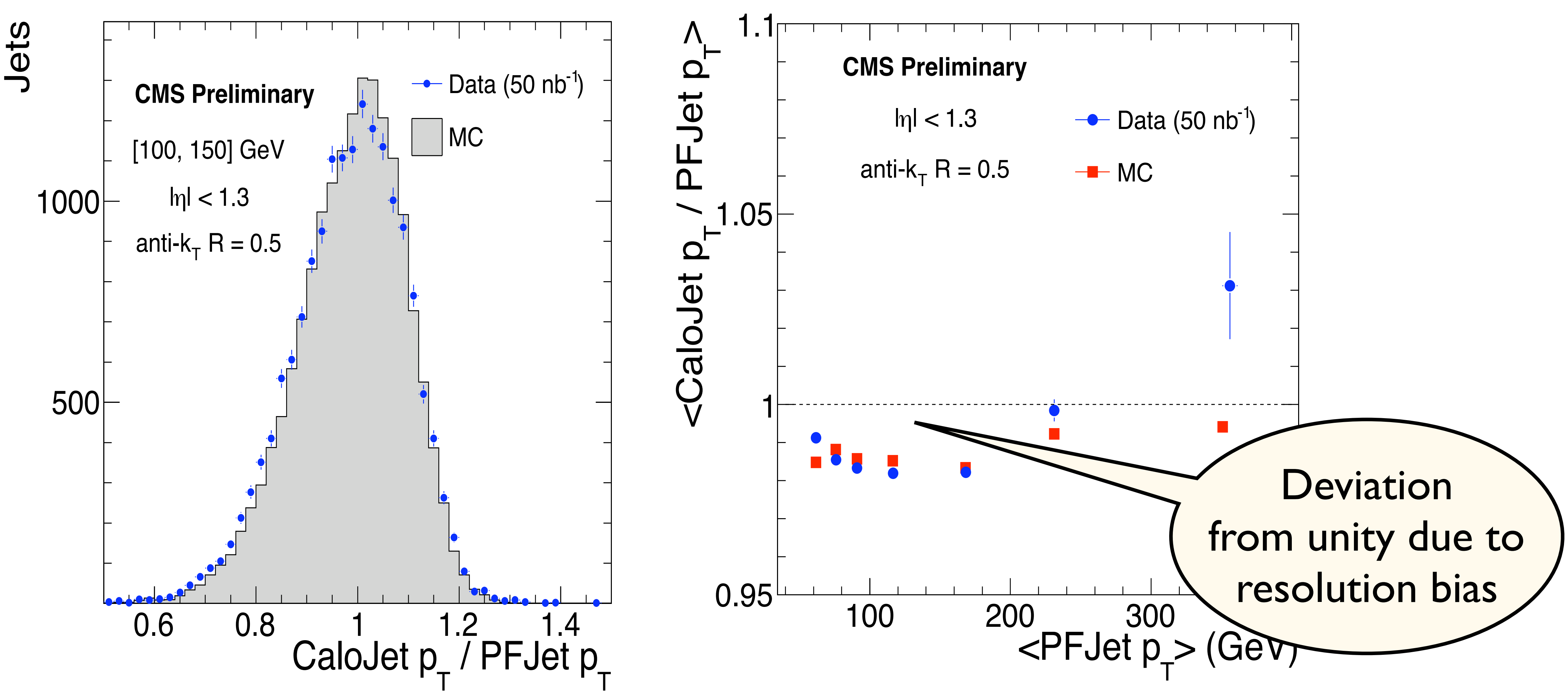






- start by reconstructed calorimeter jets, corrected for the average energy scale
- classify jets in bins of f_{trk}
- apply an average residual correction for each bin (not purely "jet-by-jet")
- energy resolution improvement

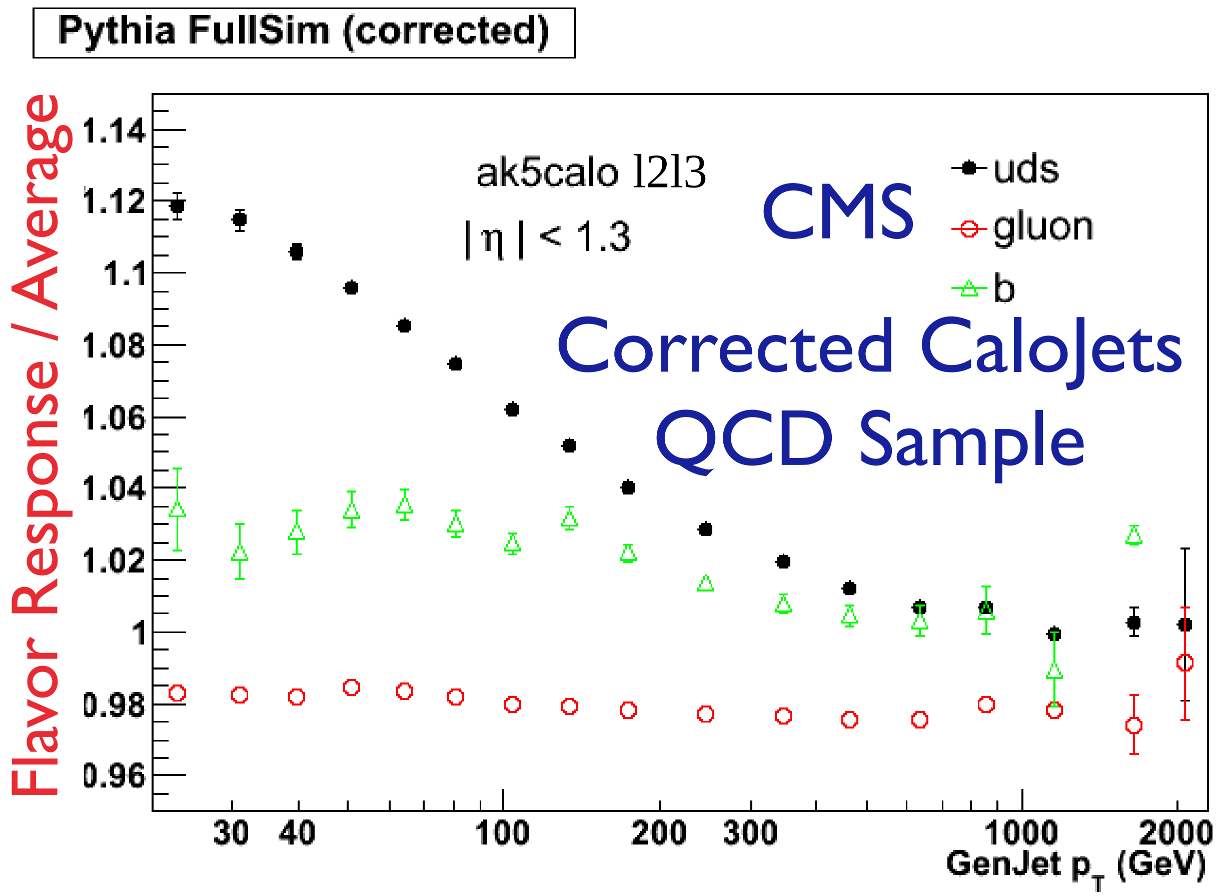
Internal Consistency



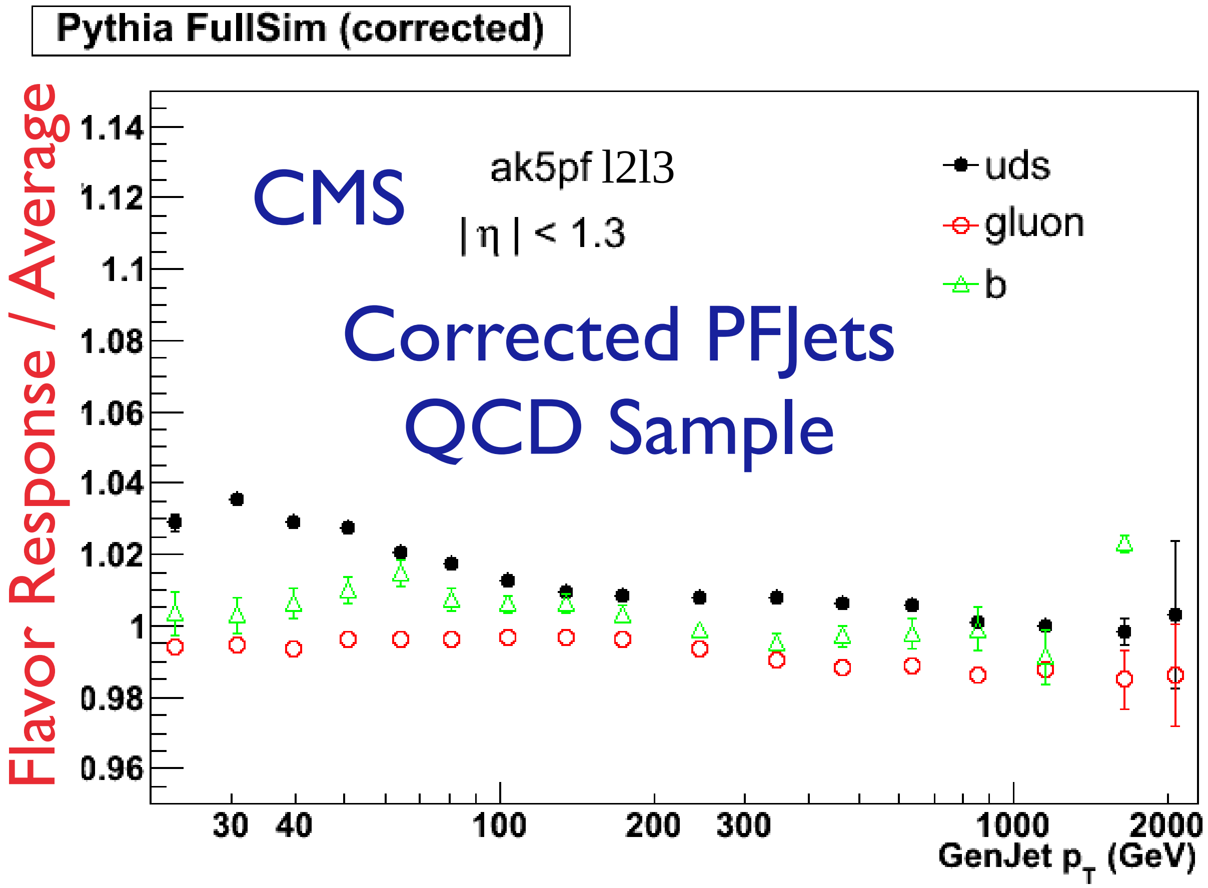
Deviation from unity due to resolution bias

- ✦ the multiple jet reconstruction techniques allow for jet-by-jet comparisons
  - ‣ each jet is a unique object, despite the reconstruction ambiguity
  - ‣ geometrical matching of different jet types (same reconstruction algorithm)
  - ‣ can help constrain the energy scale of the simpler jet types with respect to the more sophisticated and accurate ones

Flavor Dependence

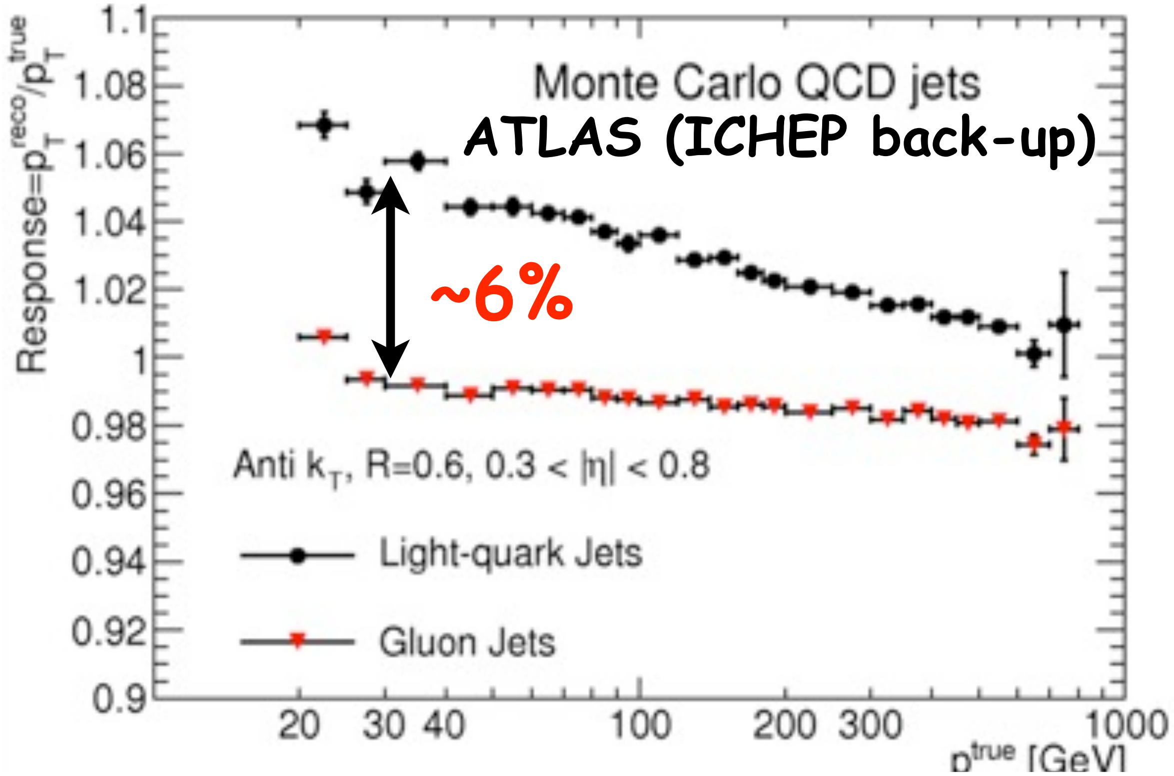


Corrected CaloJets
QCD Sample



Corrected PFJets
QCD Sample

- ✦ significant response variations observed, depending on the jet flavor
  - ▸ light quarks are overcorrected by up to 12% (for the QCD mixture)
- ✦ sophisticated reconstruction and jet-by-jet residual corrections reduce the flavor dependence to ~5%

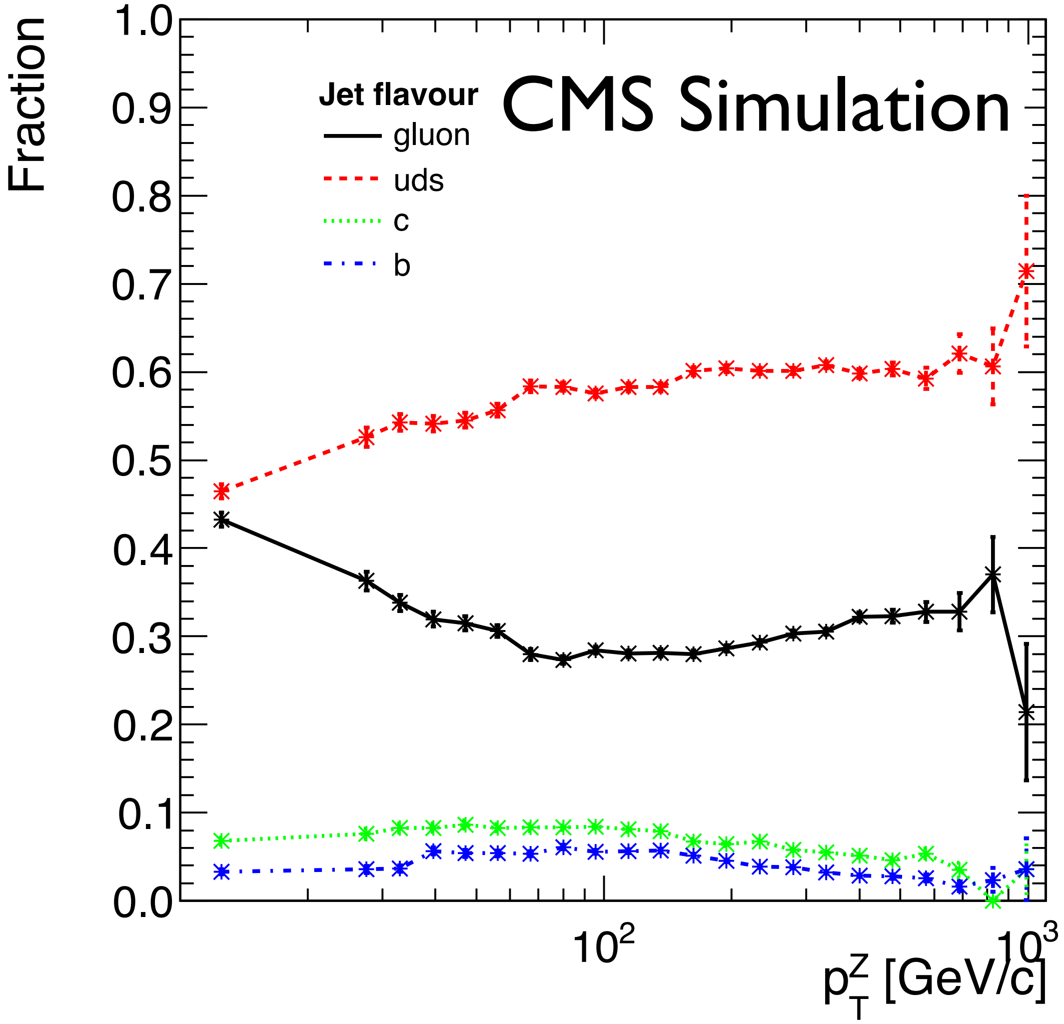


ATLAS (ICHEP back-up)

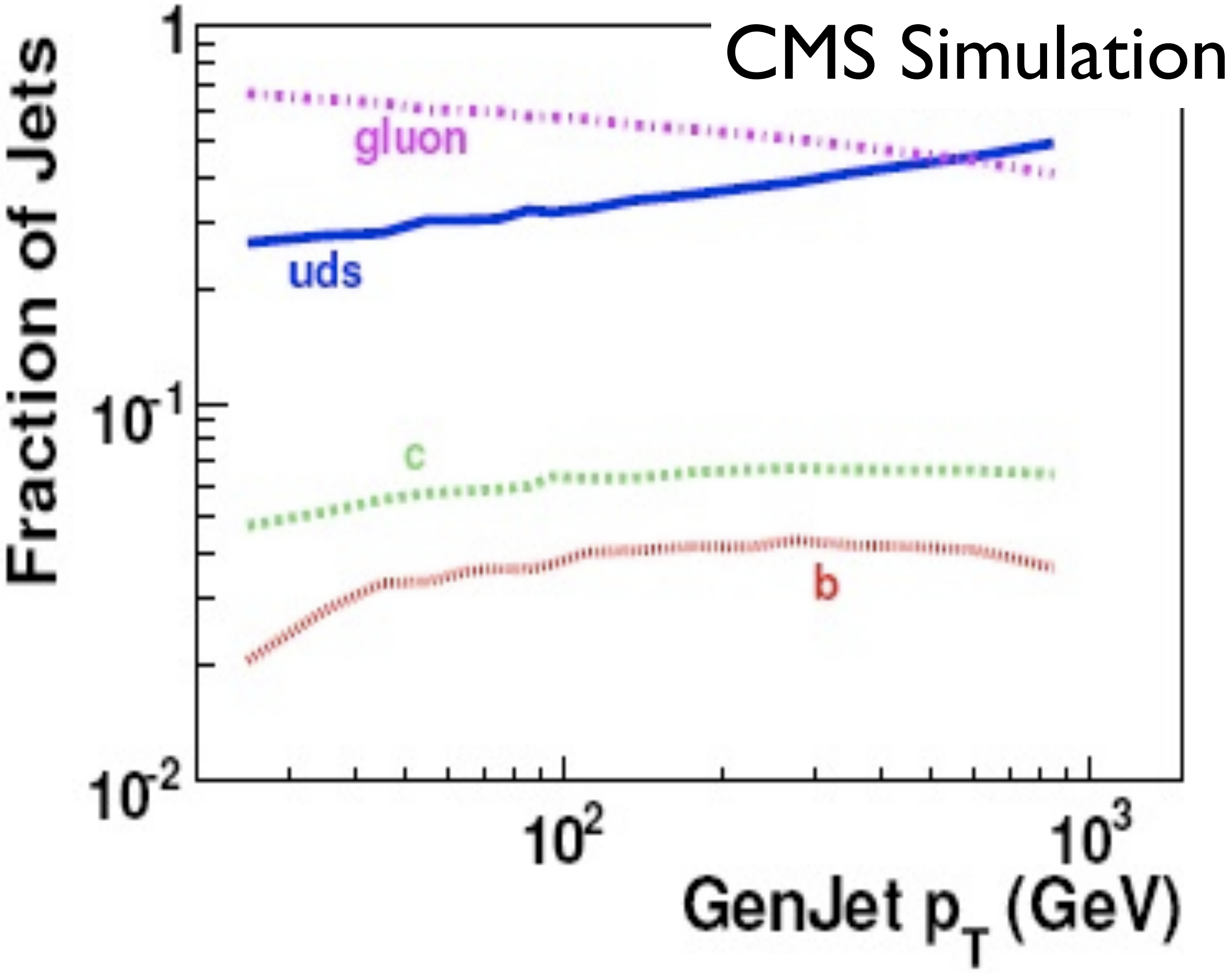
~6%

Sample Flavor Composition

Z+jet sample

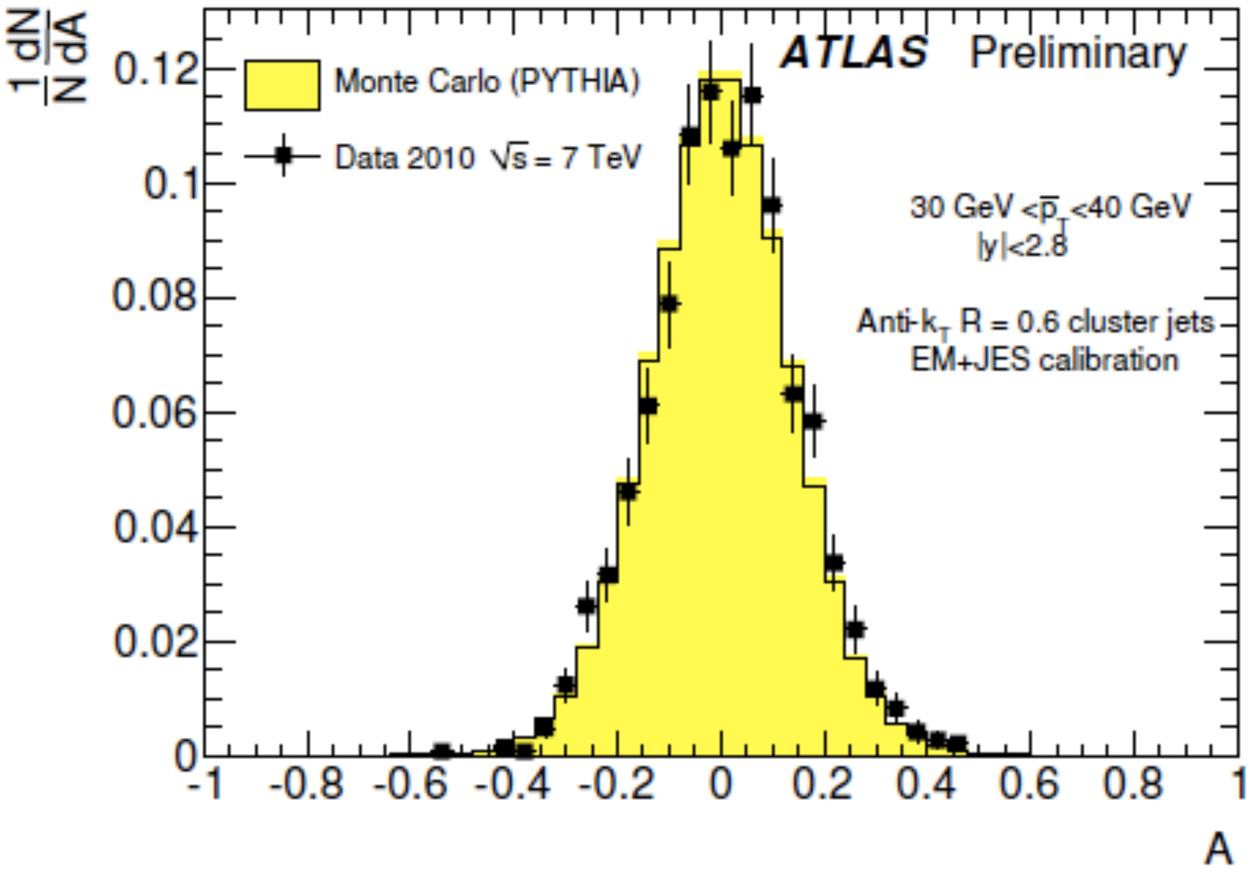


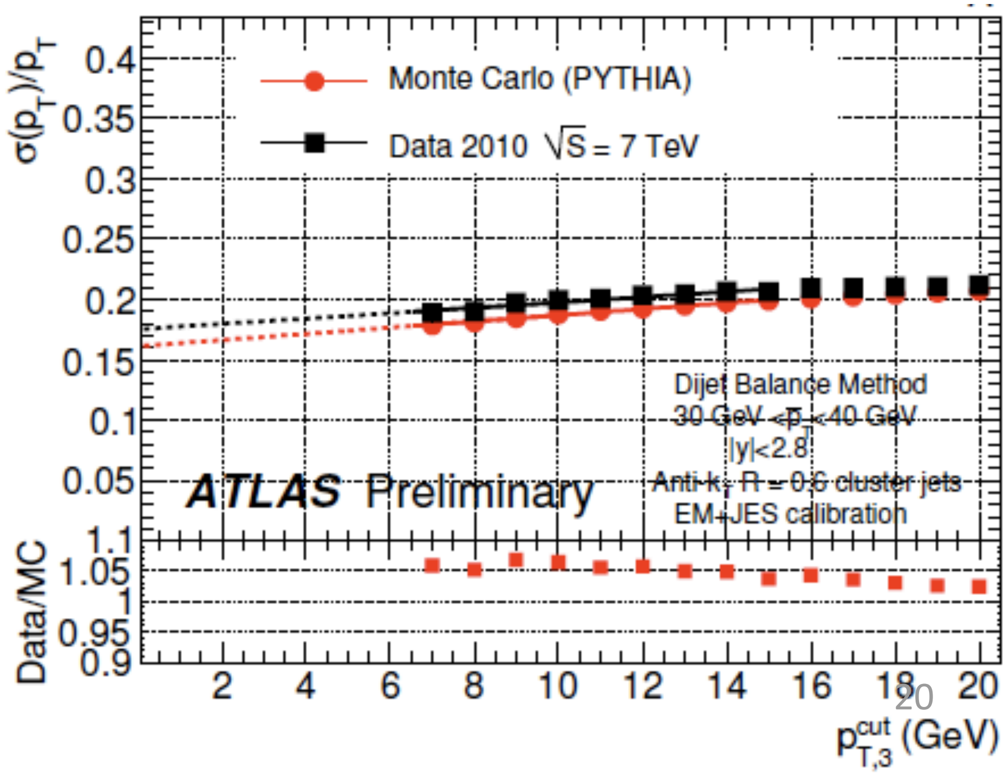
QCD sample



- **the flavor composition depends on the physics sample**
  - QCD sample is dominated by gluon jets
  - Z/W + jets samples are dominated by light quark jets
  - top quark samples contain b and light quark jets
- each analysis should look very careful into the flavor composition. Jet energy scale accuracy of ~1% can only be achieved with careful use of flavor corrections

Measuring Resolution: Asymmetry Method





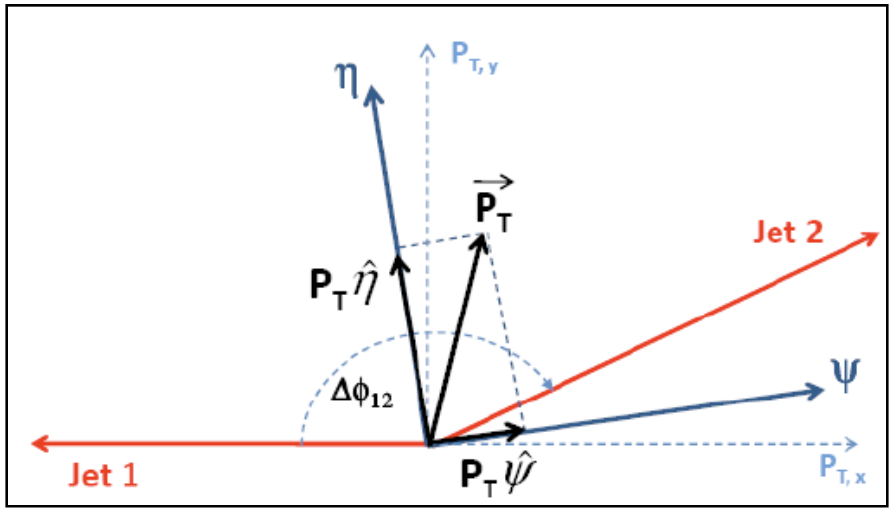
$$A \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \longrightarrow \frac{\sigma_{p_T}}{p_T} = \sqrt{2}\sigma_A$$

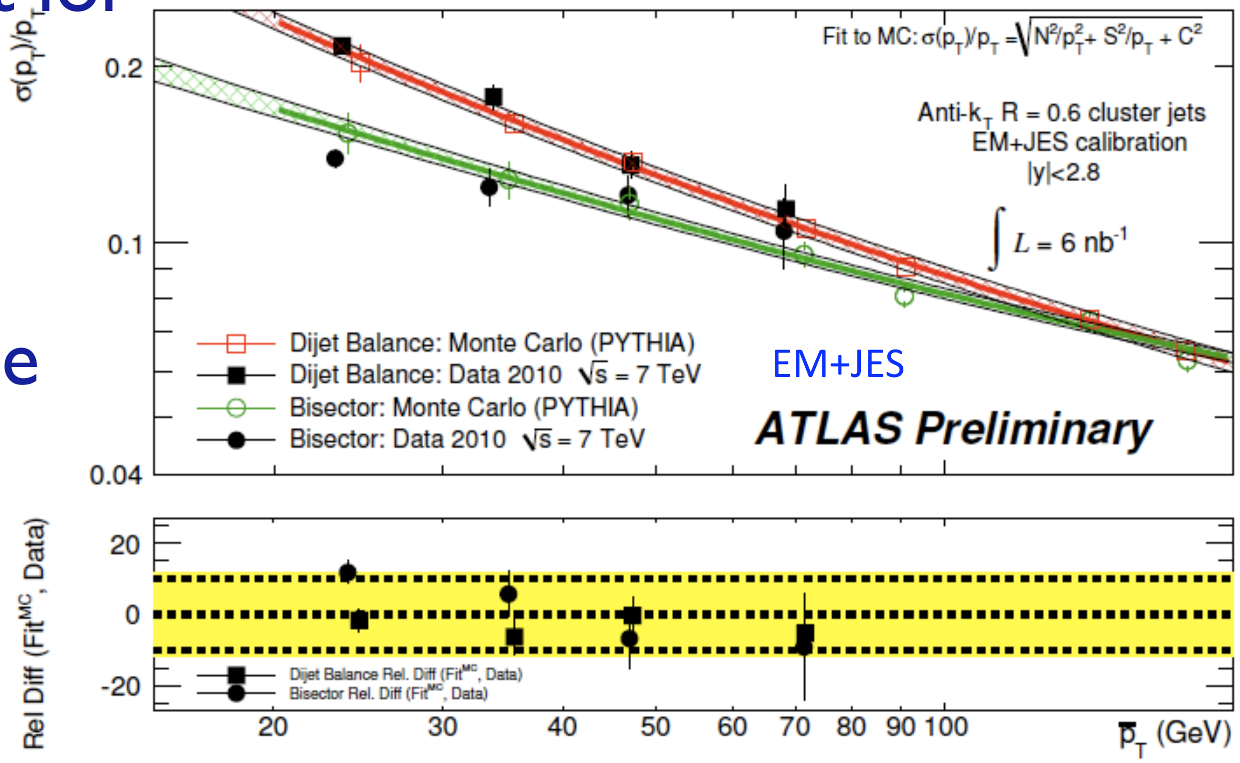
- ✦ **asymmetry method: another word for dijet balance**
  - ▸ applied to corrected jets
- ✦ **analysis essentials**
  - ▸ both jets in the same η bin
  - ▸ bins of dijet p_T
  - ▸ jets "1" and "2" are the randomized two leading jets
  - ▸ cut on the 3rd jet p_T
- ✦ **caveats**
  - ▸ only the core of the jet p_T resolution can be measured (the dijet p_T binning truncates the tails)
  - ▸ very sensitive to the 3rd jet extrapolation to 0

Measuring Resolution: Other Methods

- **Bisector method**
  - uses dijet events
  - measures the variance along the bisector axis and the axis perpendicular to it
  - sensitive to the third jet
- **γ+jet p_T balance**
  - similar to energy scale measurement
  - the only data-driven method that can measure the resolution tails (important for predicting the MET tails due to QCD)
- **MC truth**
  - a tuned MC is needed
  - sensitive to the fragmentation and the hadron shower modeling

$$\frac{\sigma(p_T)}{<p_T>} = \frac{\sqrt{\sigma_{\Psi}^{2\,calo} - \sigma_{\eta}^{2\,calo}}}{\sqrt{2} < p_T > |\cos(\Delta\phi)|}$$

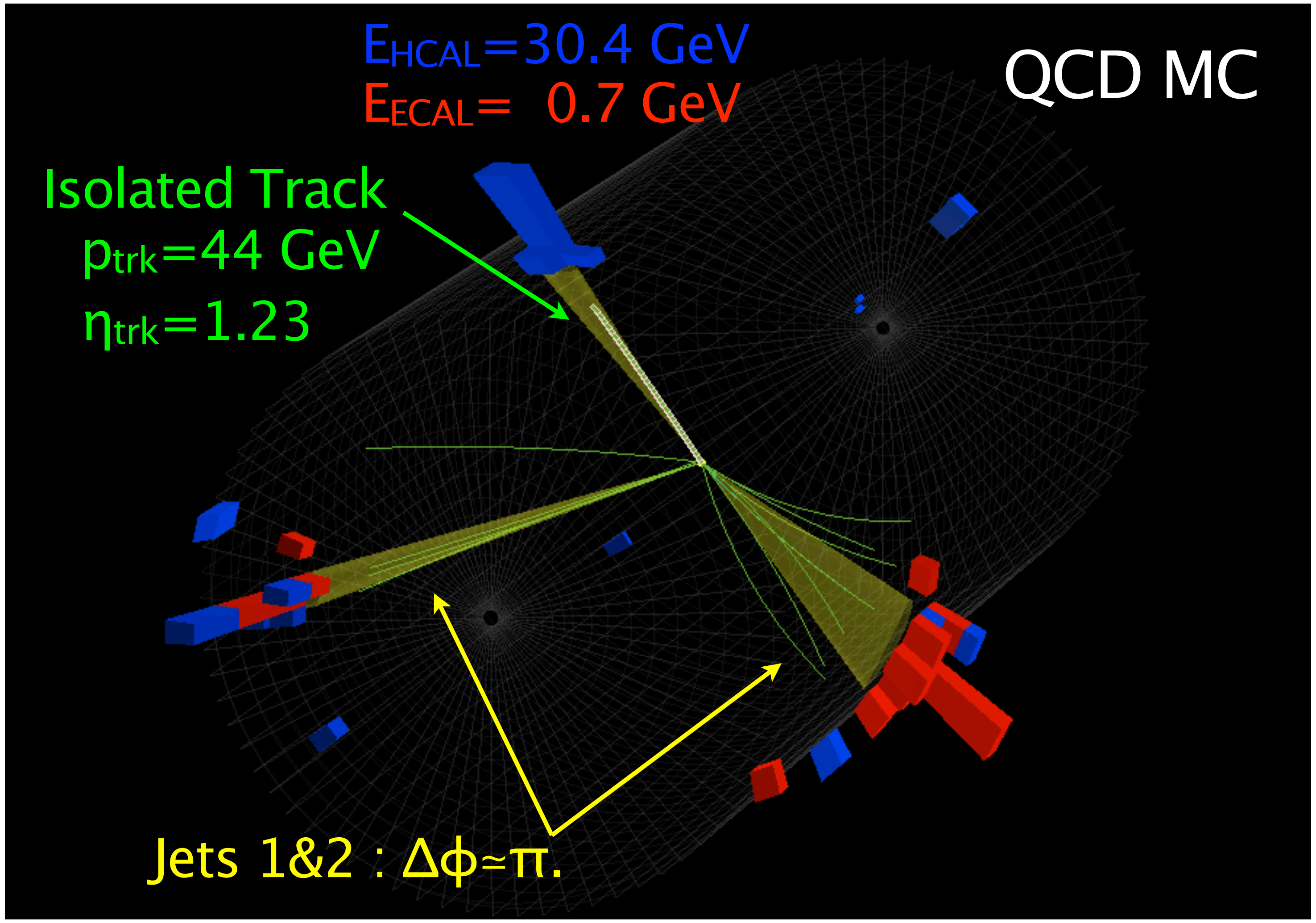


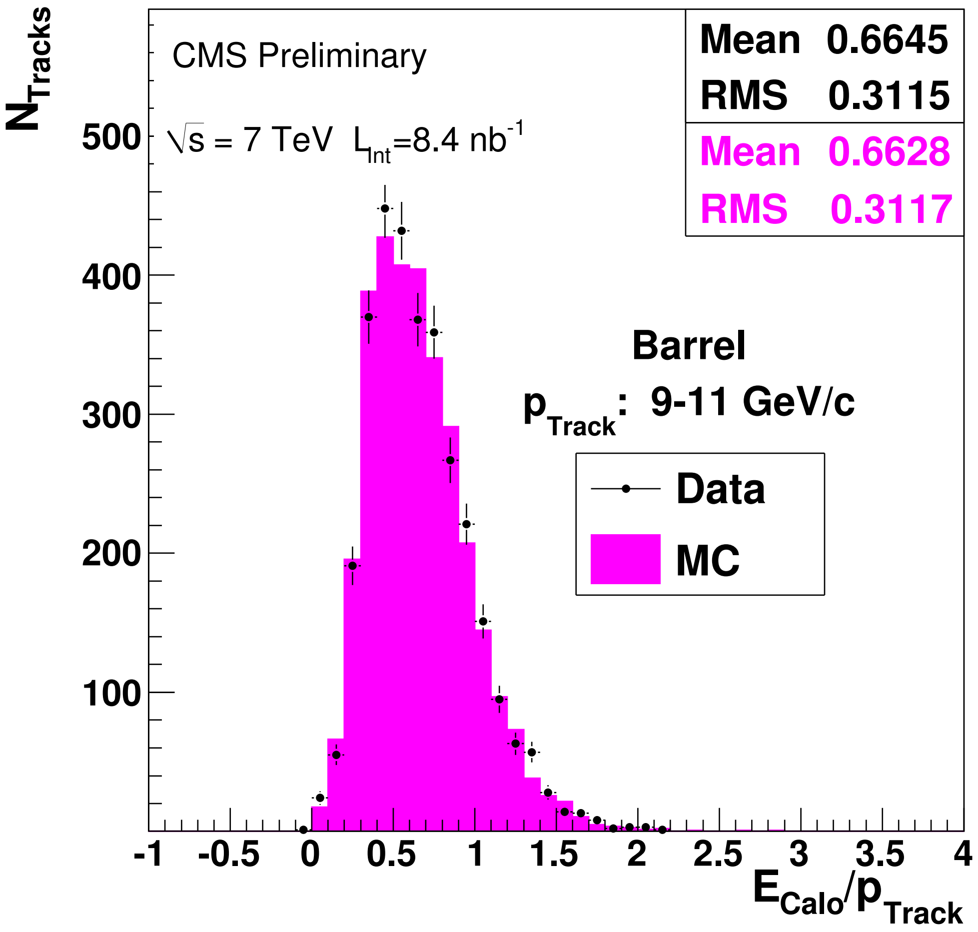


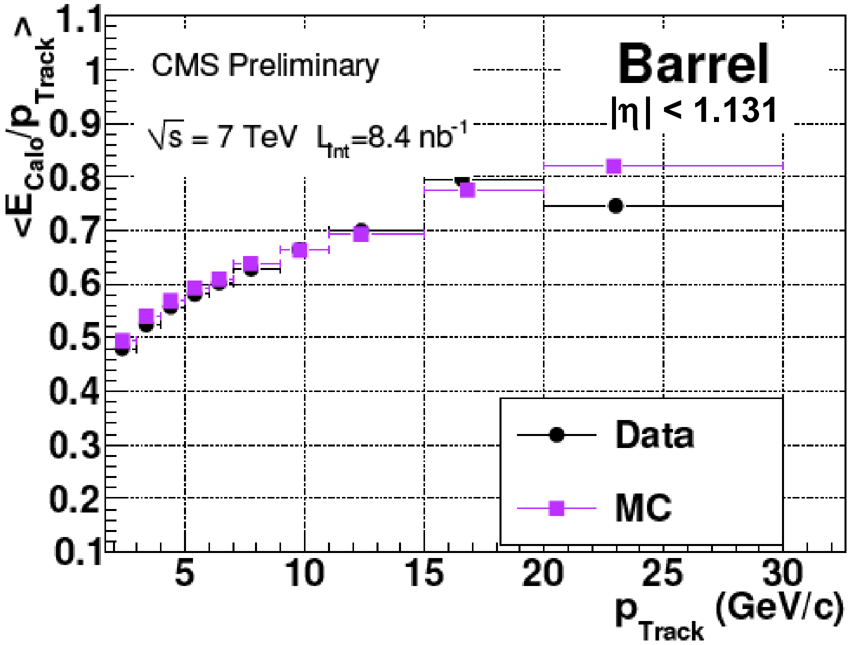
(III) “*Bottom-up*” Calibration

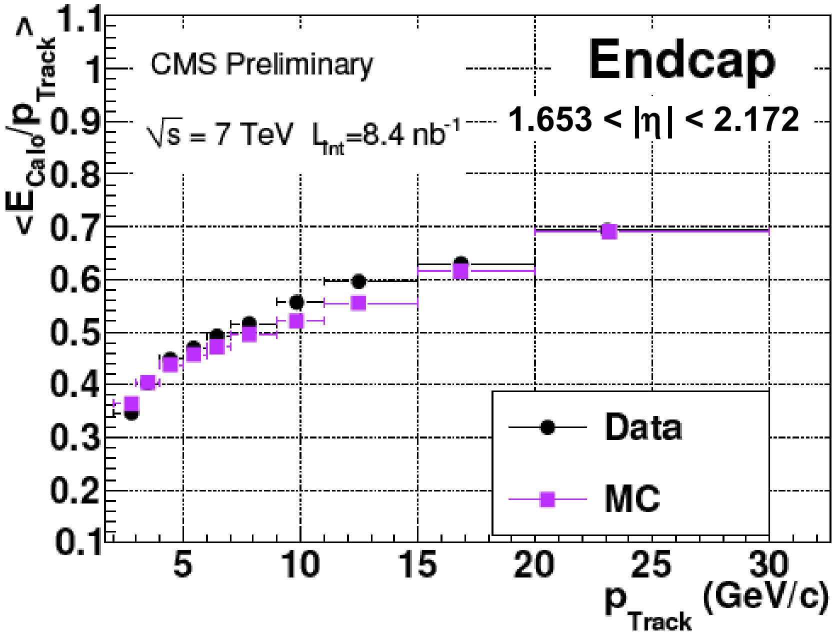
Single Particle Response

- ✦ initially measured in Test Beam experiments: not the same as the real detectors !!!
- ✦ key ingredient for the hadron calibration
- ✦ looking for isolated tracks
- ✦ measuring the ratio E_{calo}/p_{trk}

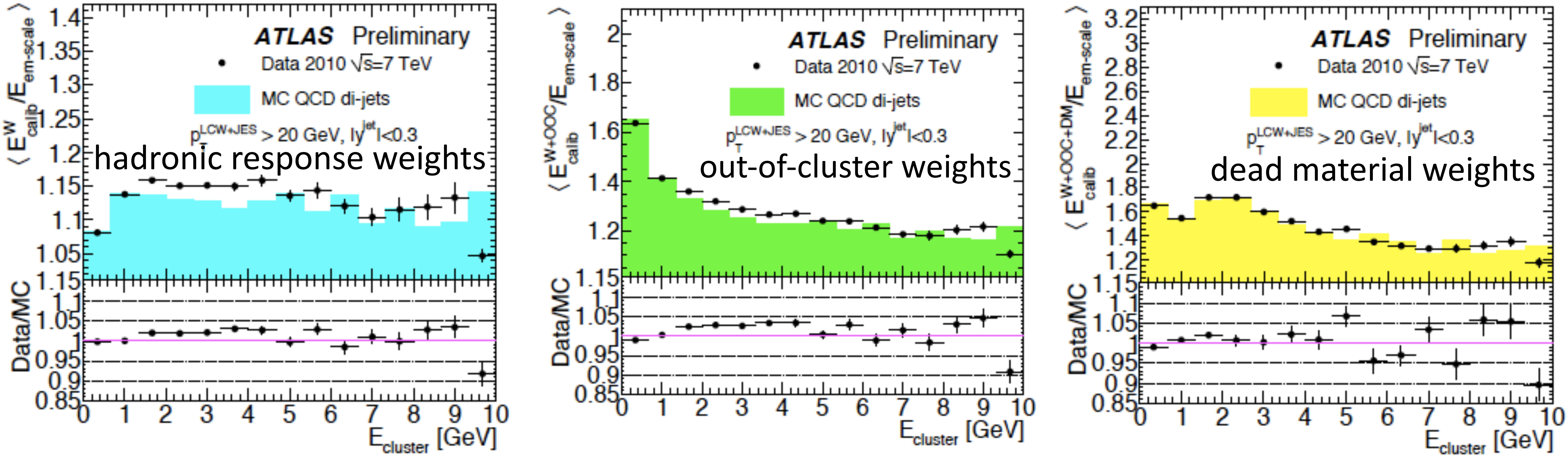








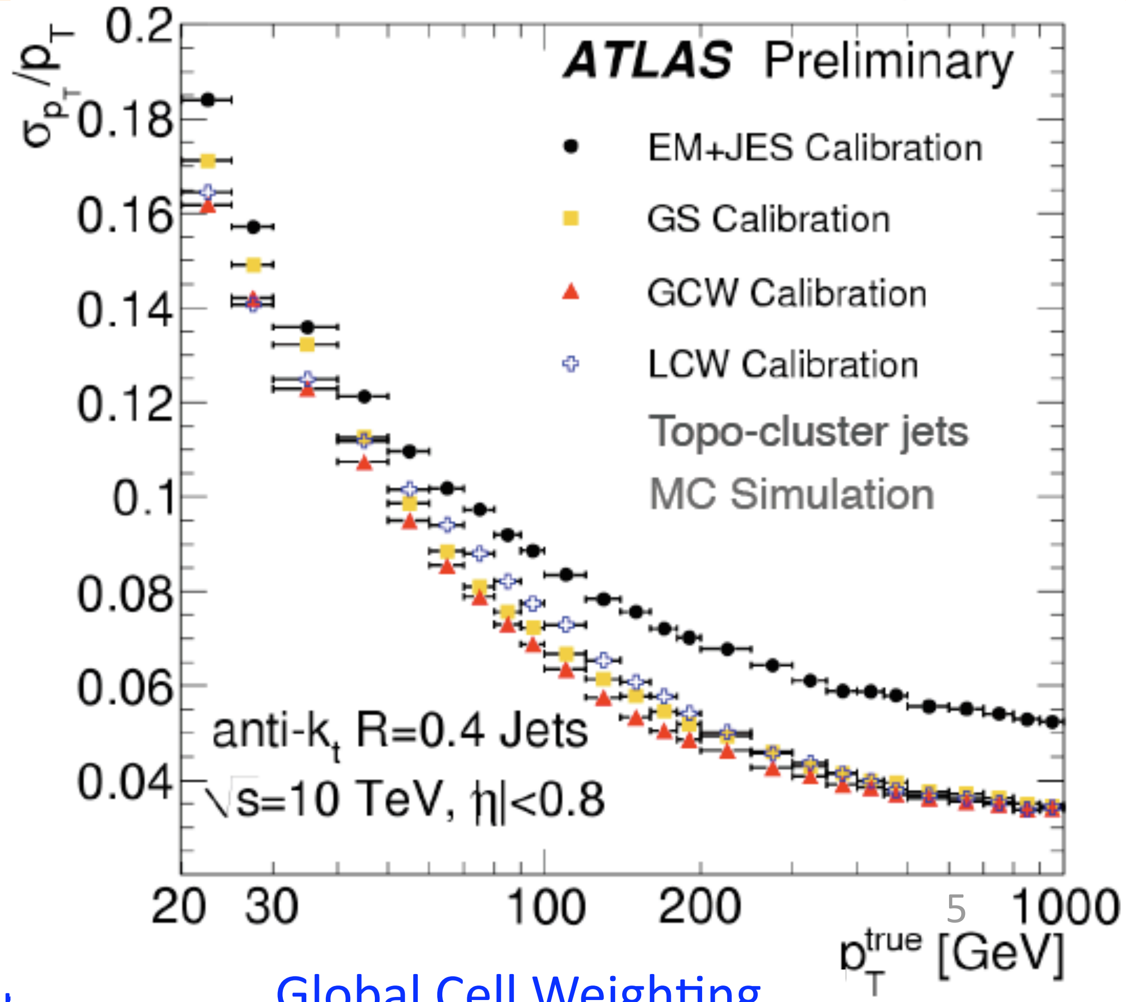
ATLAS: Local Cluster Weighting

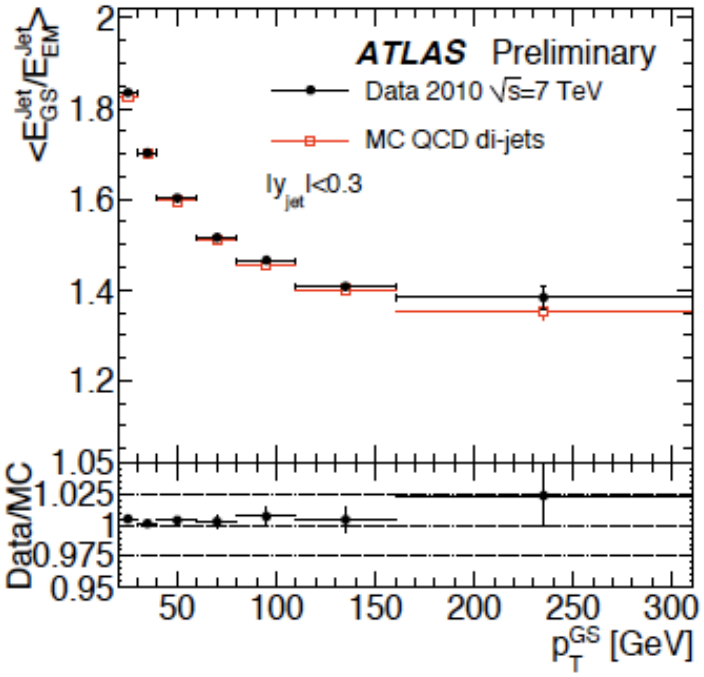


- ✦ individual cluster calibration, prior to jet reconstruction
- ✦ clusters classified as EM or HAD with a discriminant (η, depth, cell energy density
- ✦ cluster weights
  - ▸ hadronic response (cell energy density and cluster energy)
  - ▸ out-of-cluster (cluster depth and energy deposited out of the cluster)
  - ▸ dead material (fractional energy deposited in each calorimeter layer and cluster energy)
- ✦ cluster weights calculated from the MC

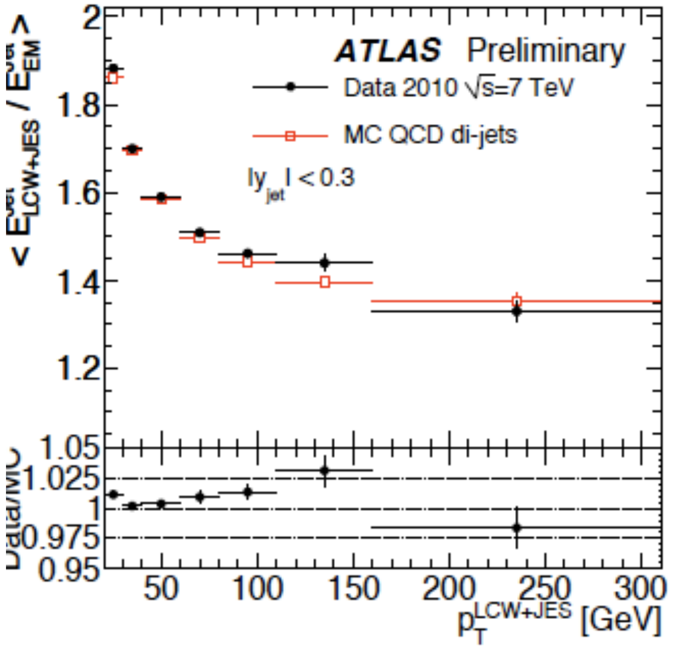
ATLAS: Global Cell Weighting

- individual cell weights
  - dependent on the cell energy density
  - compensating for lower calorimeter response to hadrons
  - compensating for energy losses in dead material
- cell weights calculated from the MC
- improvement of the energy resolution
- all calibration methods result on the same average correction

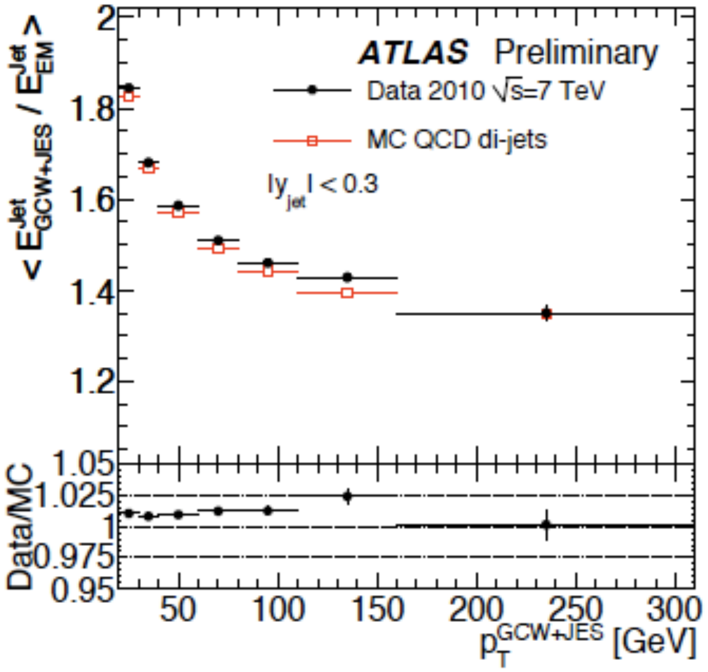




Global Sequential Calibration

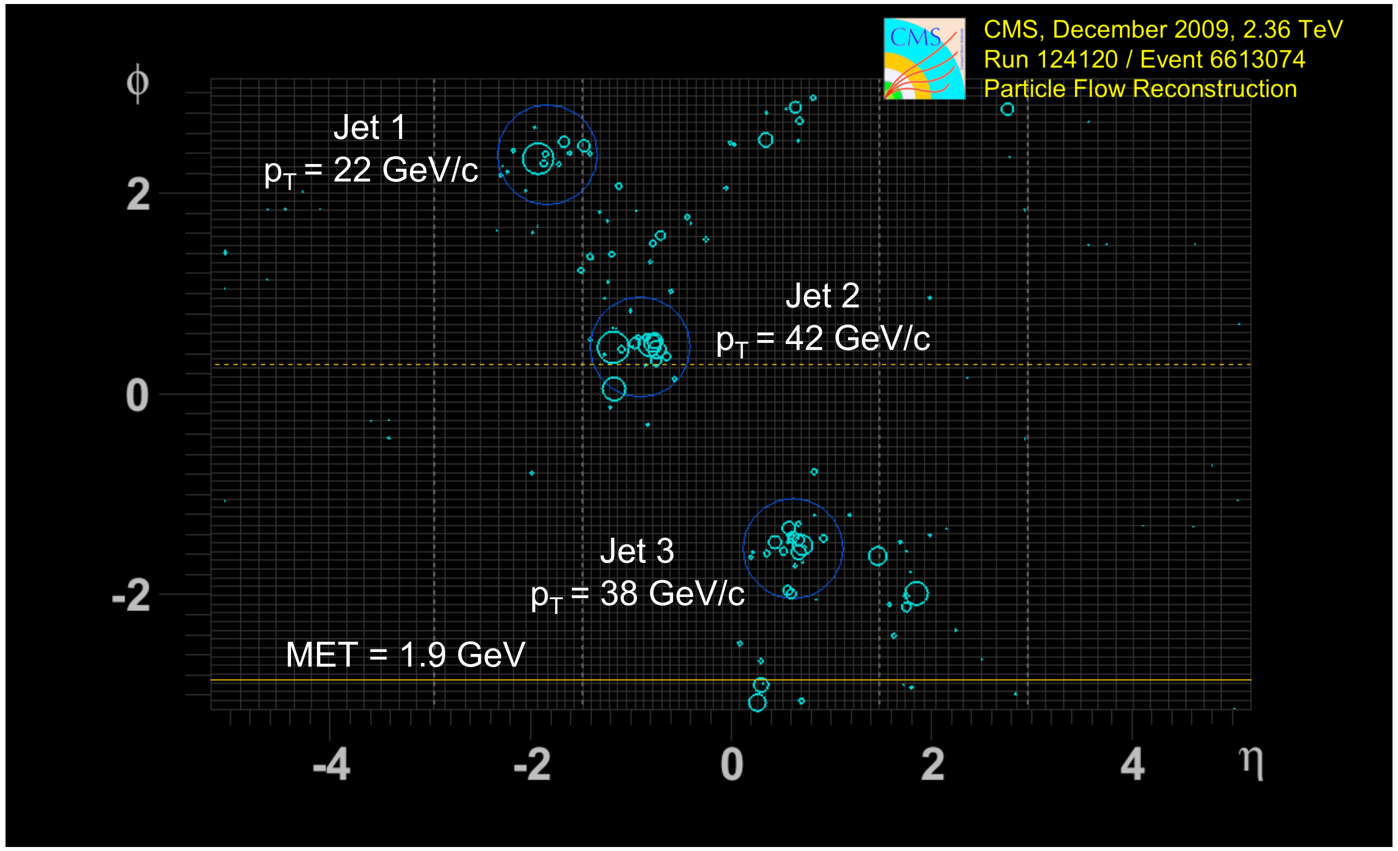


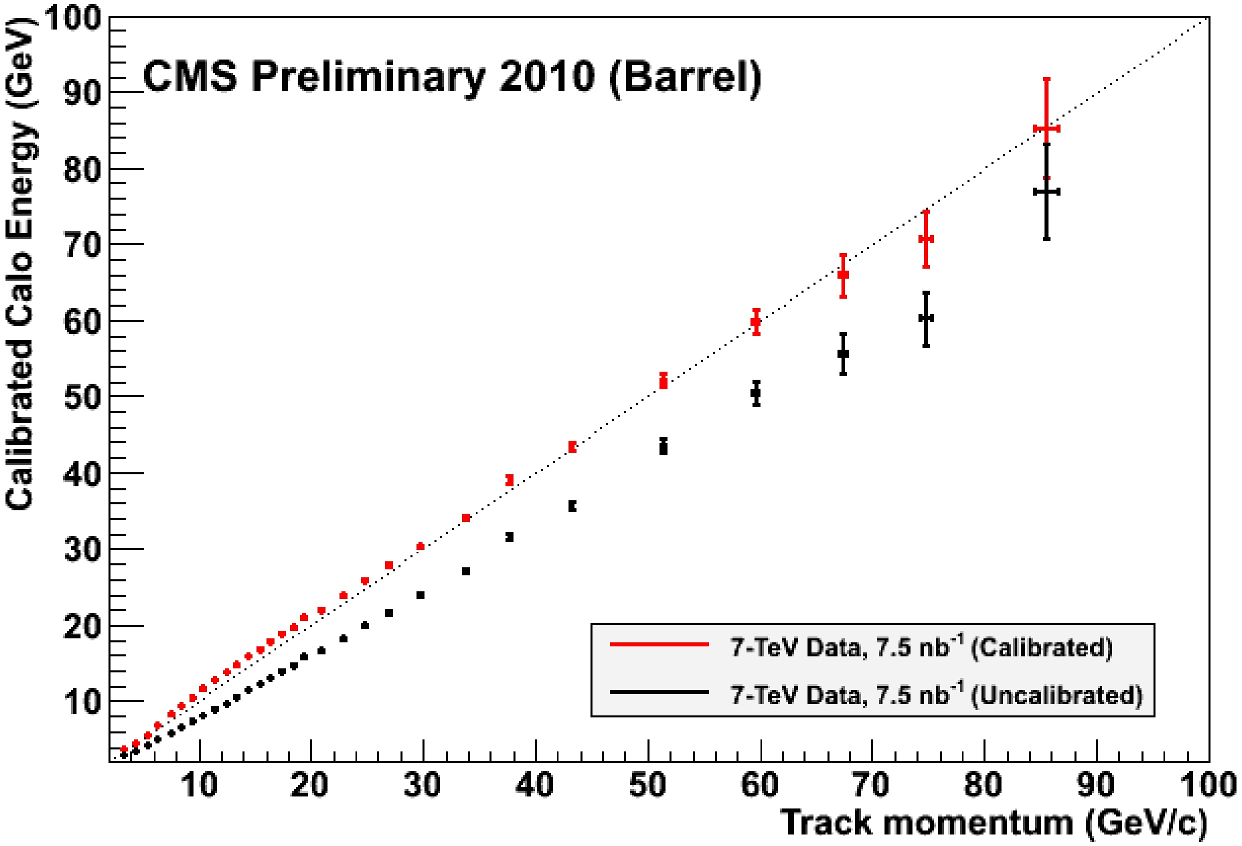
Local Cluster Weighting



Global Cell Weighting

CMS: Particle Flow





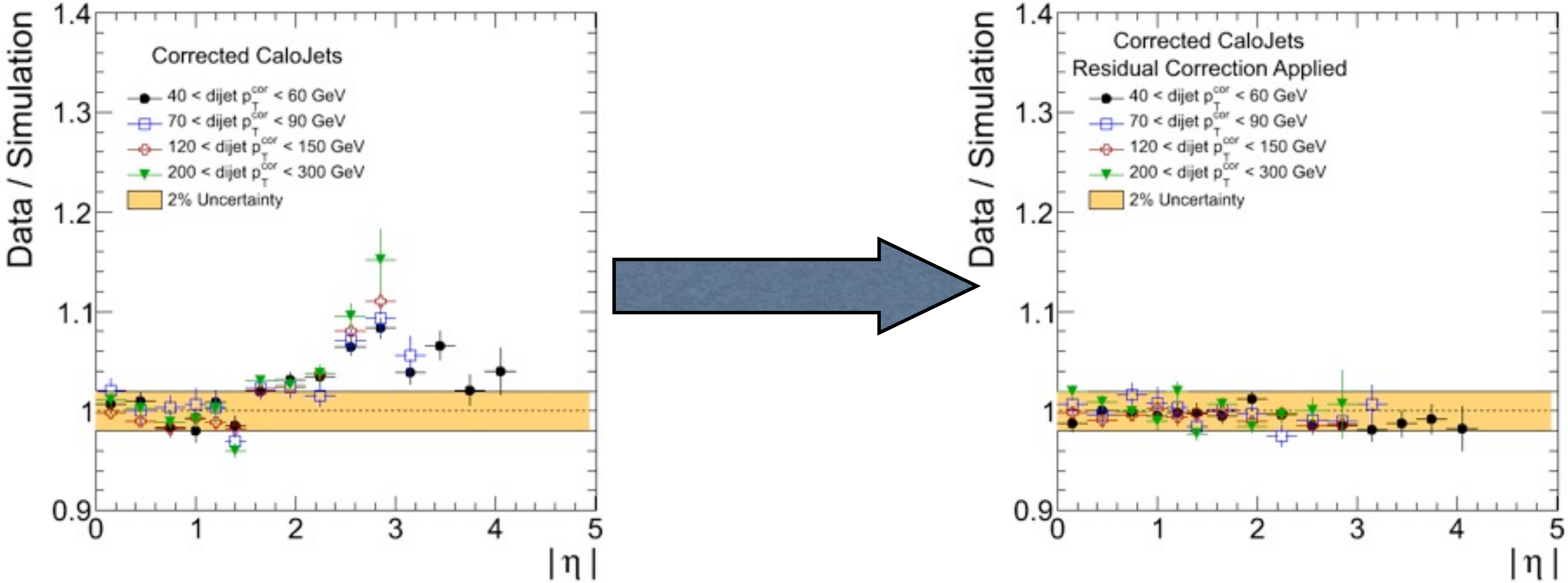
- ✦ sophisticated algorithm that reconstructs individual particles
  - optimal use of all sub-detectors
  - possible due to excellent CMS tracker and ECAL resolution
- ✦ hadrons are calibrated before jet clustering
  - calibration derived from the MC
- ✦ the particle flow jets reconstruct more than 90% of the true jet energy
  - the residual is due to the neutrals and is corrected on average
- ✦ particle flow jets have very good resolution, even at low jet p_T
- ✦ a new era in the jet reconstruction

A Final Word: the Current Reality

“No battle plan survives contact with the enemy”
(Helmuth von Moltke the Elder)

The first data brought a pleasant surprise: the MC truth JEC is very successful !!! Only a small (<10%) residual is needed !!! Needed to modify the CMS plan.

$$C(p_T,\eta) = C_{MC}(p_T,\eta) \times C_{res}(p_T \cdot C_{MC}(p_T,\eta),\eta)$$



Summary

✦ Jets are special objects due to the ambiguity of their definition.

✦ The jet energy scale is the most important uncertainty related to jets.

✦ Despite the complexity of the task, there are many handles to achieve the jet calibration:

- multiple "in-situ" measurement techniques
- very accurate, modern era simulations

✦ The first CMS and ATLAS studies indicate a remarkable accuracy of the jet energy scale, even at startup (huge success of the detector simulations).

- currently the accuracy of both experiments is better than 5%
- the 1% uncertainty will be achieved sooner than expected (after 20 years of operation, D0 reports 1% and CDF 3%)

✦ However: the jet energy scale is analysis dependent and analyzers should get involved in order to help derive the most suitable calibration for their sample.

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A. ICHEP 2010 Talks

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B. ATLAS Conference Reports

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   https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-052/
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4. *Commissioning of the Particle-Flow reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV*
   http://cdsweb.cern.ch/record/1279341/files/PFT-10-002-pas.pdf

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3. *Determination of the jet energy scale using Ze+e− + jet pT balance and a procedure for combining data driven corrections*
   http://cdsweb.cern.ch/record/1194492/files/JME-09-005-pas.pdf
4. *Jet energy calibration with photon+jet events*
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5. *Determination of the Relative Jet Energy Scale at CMS from Dijet Balance*
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