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Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part XII)

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ATLAS

Preliminaries

Plots for this session

- Most if not all plots shown in this session are meant as examples and for illustration purposes
  - Educational showcases to highlight certain features of energy scales and calorimeter response
- They do not represent the up-to-date estimates for ATLAS jet reconstruction performance
  - In general much better than the (old) results shown here!
  - Not many new plots can be shown in public yet!
- The performance plots shown are published
  - Reflection of state-of-art at a given moment in time
  - No experimental collision data available at that time!

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Summary Of Jet Inputs

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Experiment and simulation

Calorimeter towers

2-dim signal objects from all cells or only cells surviving noise suppression (topological towers in ATLAS)

Calorimeter clusters

3-dim signal objects with implied noise suppression (topological clusters in ATLAS)

Tracks

Reconstructed inner detector tracks – only charged particles with $pT > pT_{threshold}$ = 500 MeV – 1 GeV (typically)

Simulation only

Generated stable particles

Typically $\tau_{lab} > 10$ ps to be a signal source

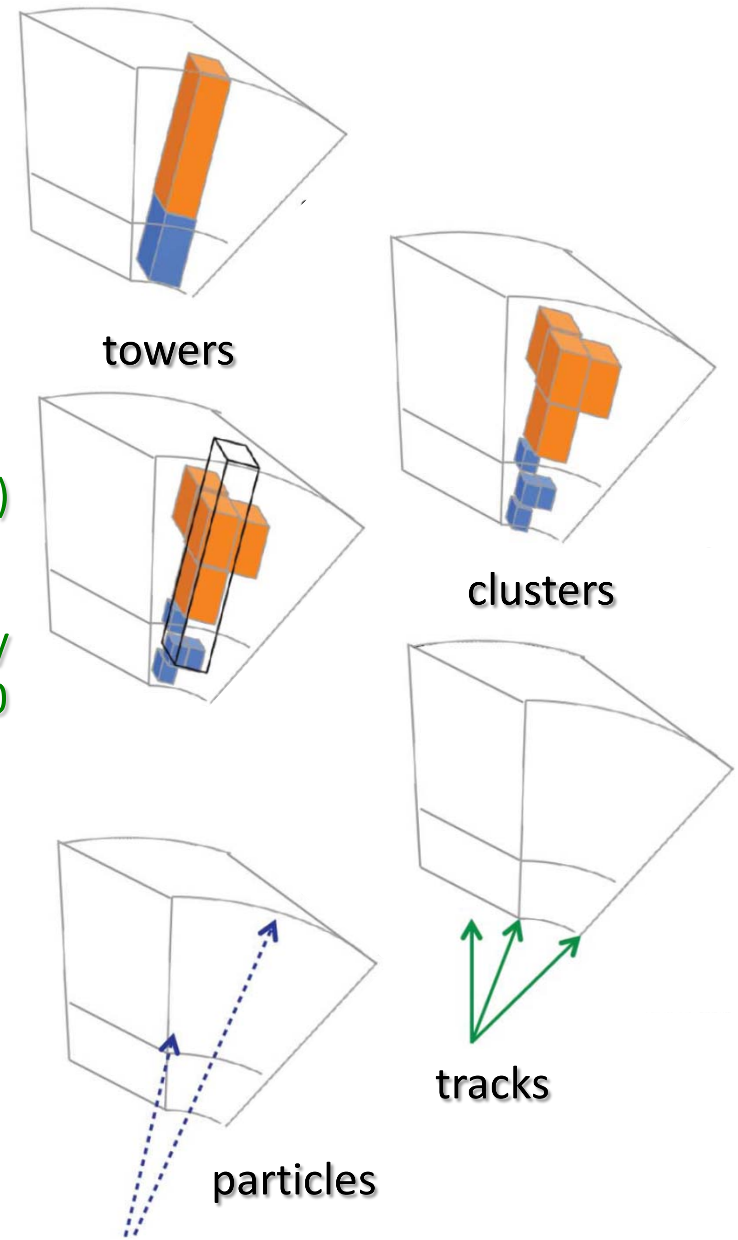

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Image Of Jets In Calorimeter

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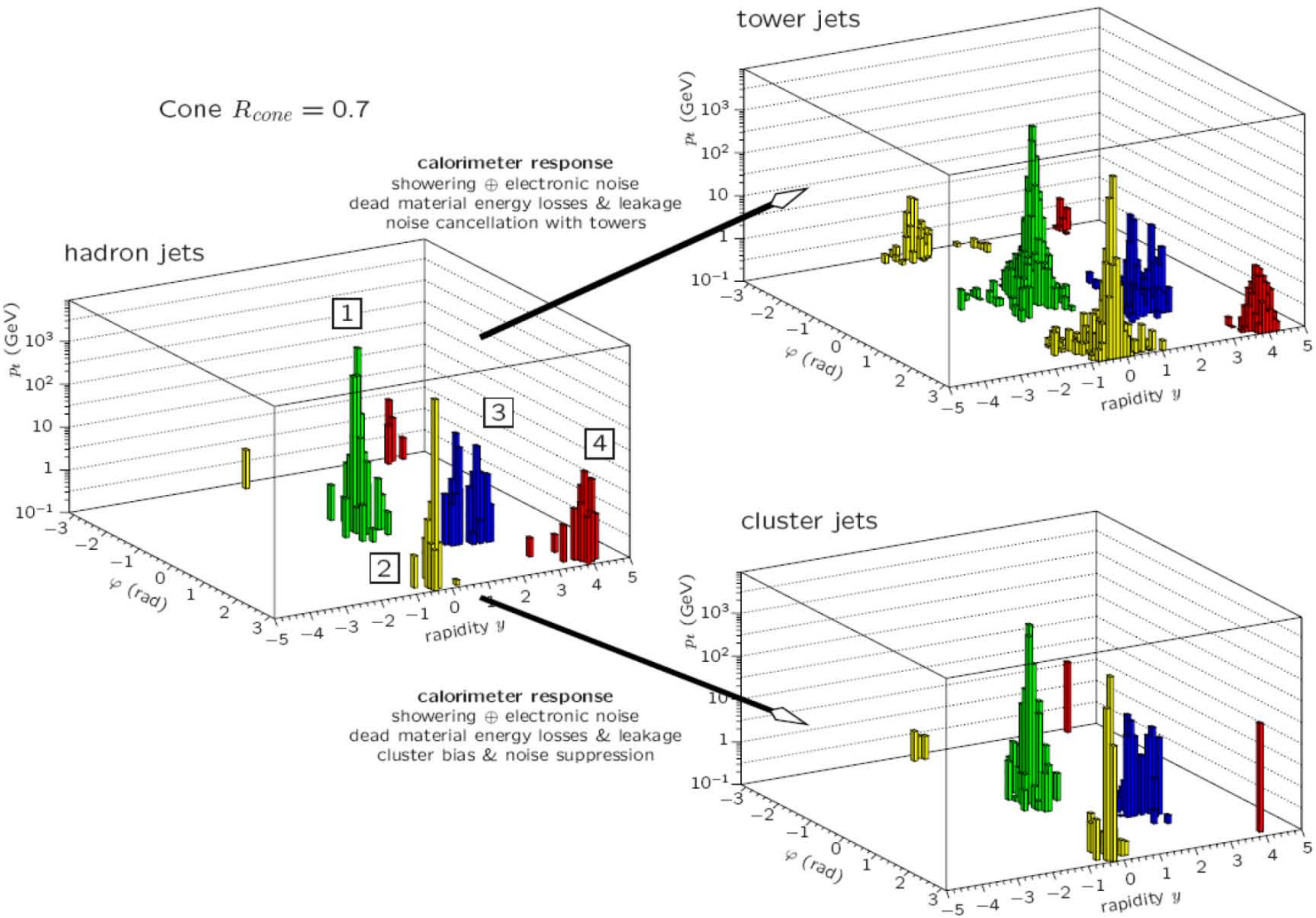

S.D. Ellis, J. Huston, K. Hatakeyama, P. Loch, M. Toennesmann, **Prog.Part.Nucl.Phys.60:484-551,2008**

Calorimeter Jet Response

Calorimeter jet response

- Electromagnetic energy scale
  - Available for all signal definitions
  - No attempt to compensate or correct signal for limited calorimeter acceptance
- Global hadronic energy scale
  - All signal definitions, but specific calibrations for each definition
  - Calibrations normalized to reconstruct full true jet energy in "golden regions" of calorimeter
- Local hadronic energy scale
  - Topological clusters only
  - No jet context – calibration insufficient to recover calorimeter acceptance limitations – no corrections for total loss in dead material and magnetic field charged particles losses)

Unbiased and noise-suppressed towers:

$$\underbrace{\begin{pmatrix} E_{0,\mathrm{jet}} \\ \vec{p}_{0,\mathrm{jet}} \end{pmatrix} = \begin{pmatrix} \sum_{\text{towers in jet}} E_{0,\mathrm{tower}} \\ \sum_{\text{towers in jet}} \vec{p}_{0,\mathrm{tower}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} < \underbrace{\begin{pmatrix} \sum_{\text{particles in jet}} E_{\mathrm{particle}} \\ \sum_{\text{particles in jet}} \vec{p}_{\mathrm{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Topological cell clusters:

$$\underbrace{\begin{pmatrix} E_{0,\mathrm{jet}} \\ \vec{p}_{0,\mathrm{jet}} \end{pmatrix} = \begin{pmatrix} \sum_{\text{clusters in jet}} E_{0,\mathrm{cluster}} \\ \sum_{\text{clusters in jet}} \vec{p}_{0,\mathrm{cluster}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} < \underbrace{\begin{pmatrix} \sum_{\text{particles in jet}} E_{\mathrm{particle}} \\ \sum_{\text{particles in jet}} \vec{p}_{\mathrm{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Note at any scale:

$$m_{\mathrm{jet}} = \sqrt{E_{\mathrm{jet}}^2 - \vec{p}_{\mathrm{jet}}^{\,2}} > 0 \text{ for } N_{\mathrm{towers}}, N_{\mathrm{clusters}} > 1$$

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Cell based calibration for all calorimeter signals and jets in "golden spot":

$$\begin{pmatrix} E_{\mathrm{rec,jet}} \\ \vec{p}_{\mathrm{rec,jet}} \end{pmatrix} = \overbrace{\begin{pmatrix} \sum\limits_{\text{cells in jet}} w(\rho_{\mathrm{cell}},\Re_{\mathrm{cell}}) \cdot E_{0,\mathrm{cell}} + E_{\mathrm{DM}} \\ \sum\limits_{\text{cells in jet}} w(\rho_{\mathrm{cell}},\Re_{\mathrm{cell}}) \cdot \vec{p}_{0,\mathrm{cell}} + E_{\mathrm{DM}} \dfrac{\vec{p}_{0,\mathrm{jet}}}{\left|\vec{p}_{0,\mathrm{jet}}\right|} \end{pmatrix}}^{\text{reconstructed calorimeter jet}}$$

$$= \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\mathrm{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\mathrm{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

(cells are extracted from unbiased or noise suppressed towers or topological clusters forming the jet)

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  - No jet context – calibration insufficient to recover calorimeter acceptance limitations – no corrections for total loss in dead material and magnetic field charged particles losses)

Locally calibrated clusters only:

$$\underbrace{\begin{pmatrix} E_{\text{rec,jet}} \\ \vec{p}_{\text{rec,jet}} \end{pmatrix} = \begin{pmatrix} \sum\limits_{\text{clusters in jet}} E_{\text{rec,cluster}} \\ \sum\limits_{\text{towers in jet}} \vec{p}_{\text{rec,cluster}} \end{pmatrix}}_{\text{reconstructed calorimeter jet}} \leq \underbrace{\begin{pmatrix} \sum\limits_{\text{particles in jet}} E_{\text{particle}} \\ \sum\limits_{\text{particles in jet}} \vec{p}_{\text{particle}} \end{pmatrix}}_{\text{matched particle jet (truth reference)}}$$

Final Jet Energy Scale (JES)

- Final jet calibration
  - All corrections applied
- Best estimate of true (particle) jet energy
  - Flat response as function of pT
  - Uniform response across whole calorimeter
- Relative energy resolution
  - Depends on the calorimeter jet response – calibration applies compensation corrections
- Resolution improvements by including jet signal features
  - Requires corrections sensitive to measurable jet variables
  - Can use signals from other detectors

Determination with simulations

- Measure residual deviations of the calorimeter jet response from truth jet energy
  - Derive corrections from the calorimeter response at a given scale as function of pT (linearity) and pseudorapidity (uniformity) for all particle jets
- Use numerical inversion to parameterize corrections
  - Conversion from truth variable dependence of response to reconstructed variable response

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Signal Linearity

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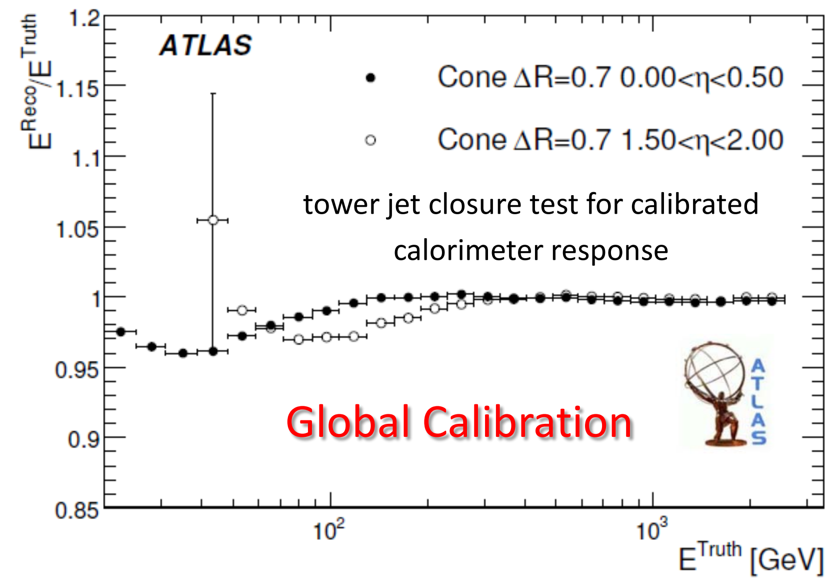
ATLAS plots from **arXiv:0901.0512** [hep-ex]

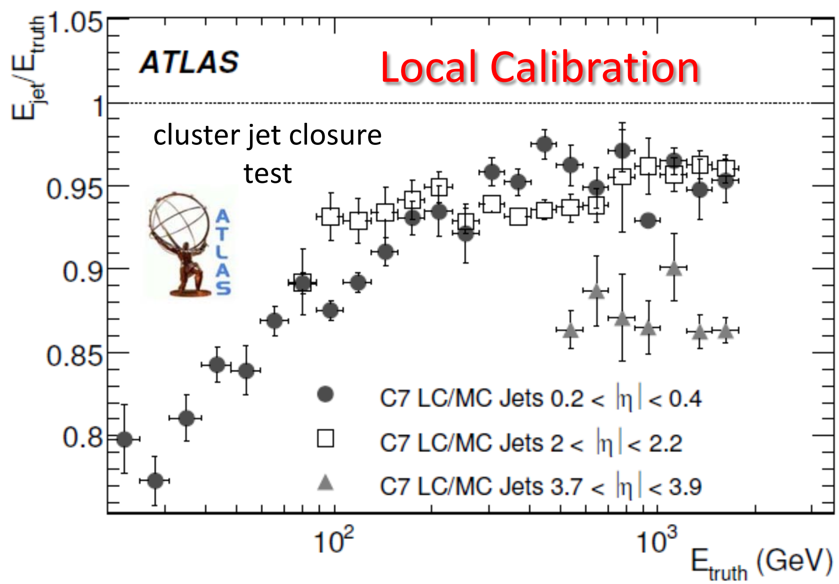
From simulations

- Compare calorimeter response with particle jet energy as function of the particle jet energy
  - All jets, all regions, full kinematic coverage
- Residual deviation from linearity
  - Depend on calorimeter energy scale – large for electromagnetic energy scale and local calibration due to missing jet level corrections
  - Small for global calibration due to jet energy normalization
- Corrections can be extracted from residuals
  - A bit tricky – need to use numerical inversion (see later)

From experiment

- Validate and extract calibrations from collision data
  - W boson mass in hadronic decay is jet energy scale reference
  - pT balance of electromagnetic signal (Z boson, photon) and jet
- Note change of reference scale
  - In-situ channels provide interaction (parton) level truth reference!





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Signal Uniformity

ATLAS plots from **arXiv:0901.0512** [hep-ex]

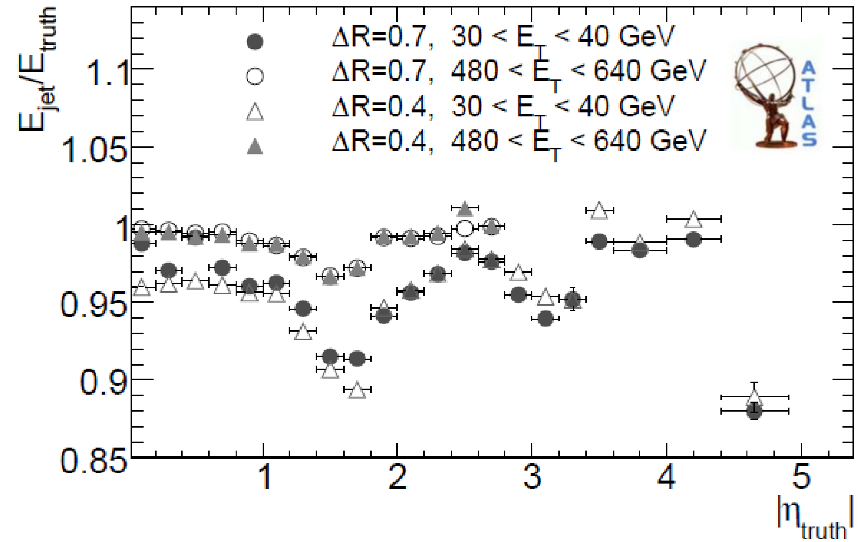
Simulations

- Compare calorimeter response with particle jet energy as function of the jet direction
  - All jets in full kinematic range
- Residual non-uniformities expected in cracks
  - Only jets in "golden regions" used for calibration

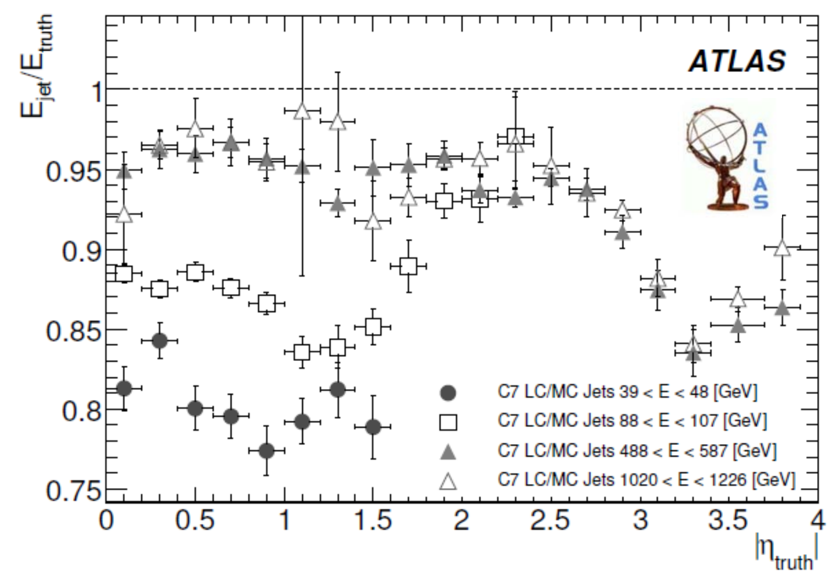
From experiment

- Di-jet pT balance
  - Balance pT of well calibrated jet in "golden region" with jet in other calorimeter regions
  - Can also use photon pT balance with jets outside of "golden region"

Global Calibration



Local Calibration



Relative Jet Energy Resolution

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ATLAS plots from **arXiv:0901.0512** [hep-ex]

Simulations

Measure fluctuations of calorimeter jet energy as function of truth jet energy

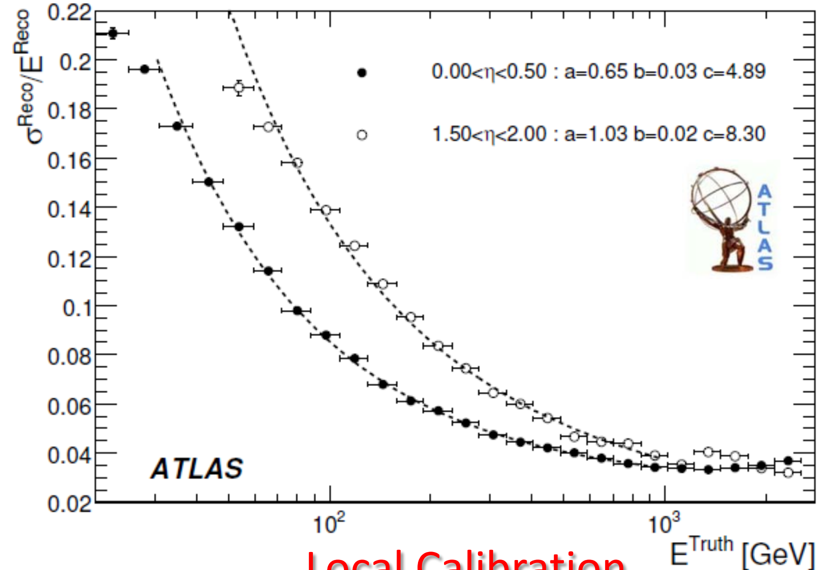
All jets in full kinematic range and in various regions of pseudo-rapidity

From experiment

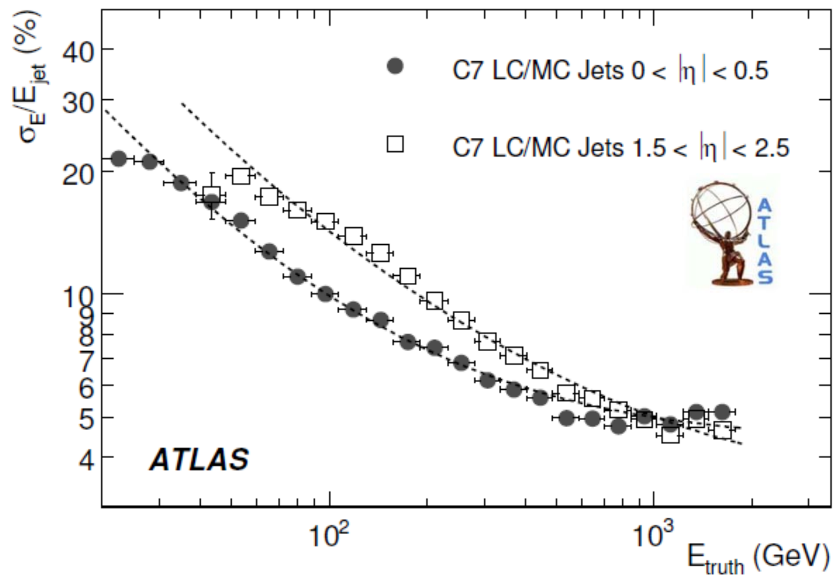
Di-jet final states

Measure relative fluctuations of jet energies in back-to-back (pT) balanced di-jets

Global Calibration



Local Calibration



JES Calibration Parameterizations

Golden rule of calorimetric energy measurement

- The fully calibrated calorimeter signal is most probably the true jet (or particle) energy
  - Interpretation holds only for symmetrically distributed fluctuations – mean value is identical to average value
- The resolution of the measurement is given by the characteristics of the signal fluctuations
  - Can only be strictly and correctly understood in case of Gaussian response distributions
- We need a normally distributed response!

Problem for all calibration techniques

- Residual deviations from expected jet reconstruction performance must be measure as function of true quantities
  - Only then is the fluctuation of the response $R = E_{reco}/E_{true}$ really Gaussian after calibration
- But need to apply corrections to measured jets
  - Need parameterization as function of reconstructed quantities
  - Simple re-binning does not maintain the Gaussian characteristics of the fluctuations – hard to control error!
- Use numerical inversion to transfer the calibrations from true to measured parameters
  - Maintains Gaussian character

Understanding Response Fluctuations

Toy model

- Generate flat jet energy spectrum
  - Uniform energy distribution for E_{jet} in $[E_{min}, E_{max}]$
- Smear true jet energy with Gaussian
  - Assume perfect average calibration
  - Width of distribution follows calorimetric energy resolution function
- Calculate the response
  - In bins of E_{true} and in bins of $E_{smear} = E_{reco}$
- Repeat exercise with steeply falling energy spectrum

Calibrated response:

$$\langle E_{smear} \rangle = \langle E_{reco} \rangle = \langle E_{true} \rangle$$

Calorimeter resolution function (no noise):

$$\frac{\sigma_E}{E} = \sqrt{\frac{a^2}{E_{true}} + c^2}$$

Smeared energy:

$$E_{smear} = E_{true} + r \cdot \sigma_E$$

r is a random number following the Gaussian PDF:

$$g(r) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2} r^2\right]$$

i.e. distributed around 0 with a width of 1

Response fluctuations:

$$R = \frac{E_{smear} - E_{true}}{E_{true}} \text{ with } \langle R \rangle = 0$$

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Response Distributions

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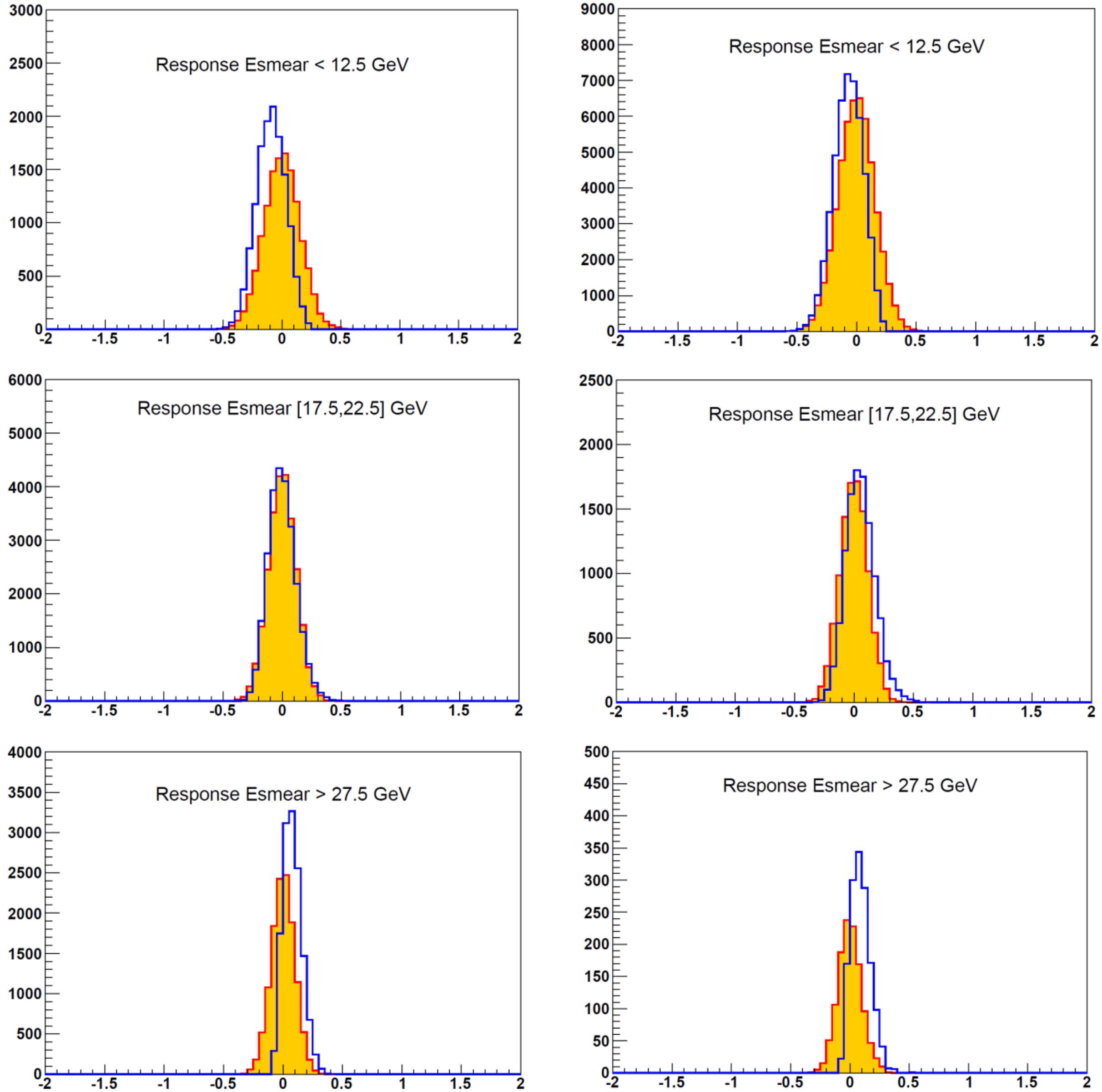
$p(E_{true}) = const$ | $p(E_{true}) \propto E_{true}^{-4}$

binned in E_{true}
binned in E_{smear}



Lower edge of *E* spectrum

Center of *E* spectrum

High end of *E* spectrum

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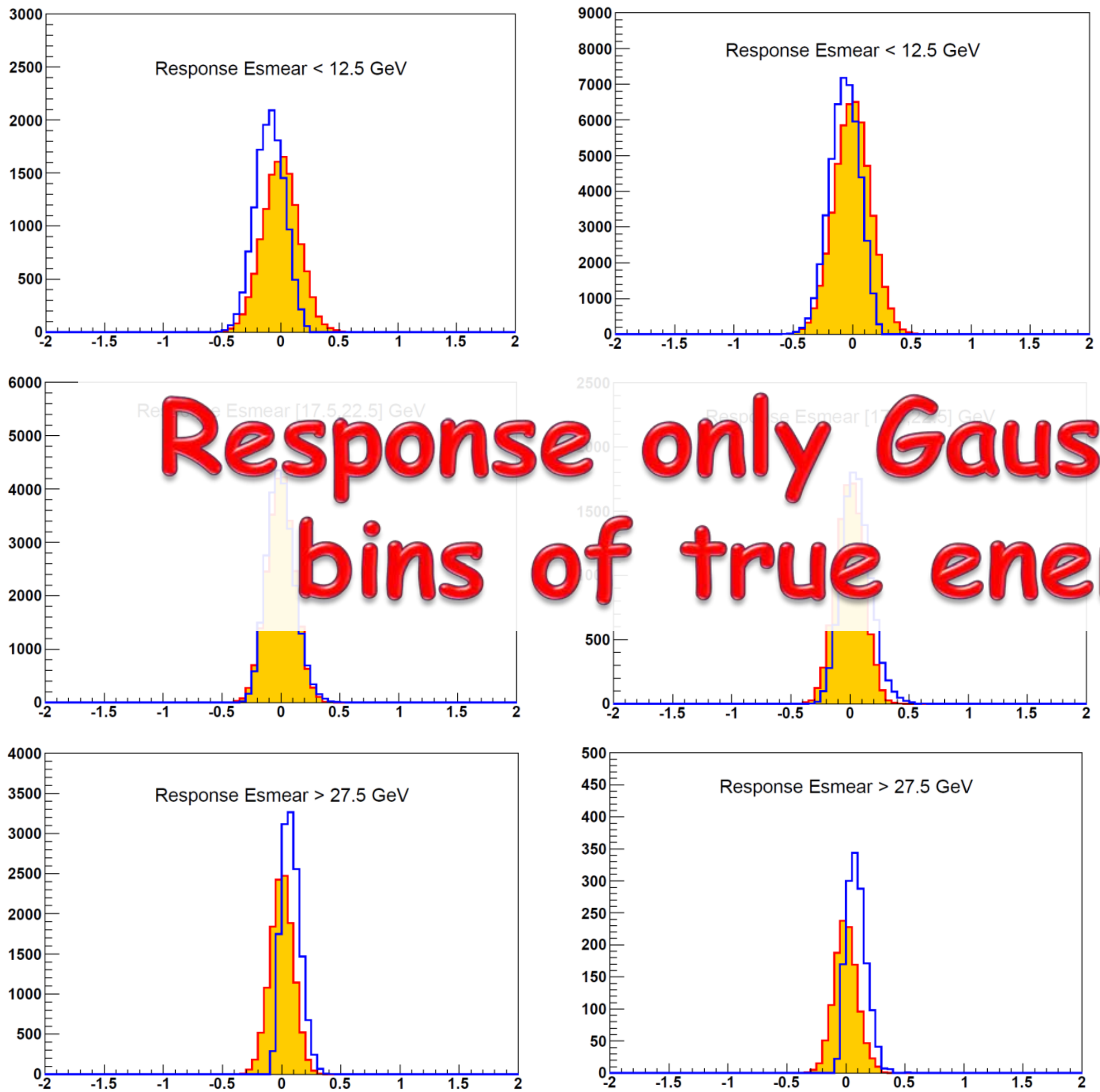
Response Distributions

$p(E_{true}) = const$ $\qquad$ $p(E_{true}) \propto E_{true}^{-4}$



binned in E_{true}

binned in E_{smear}

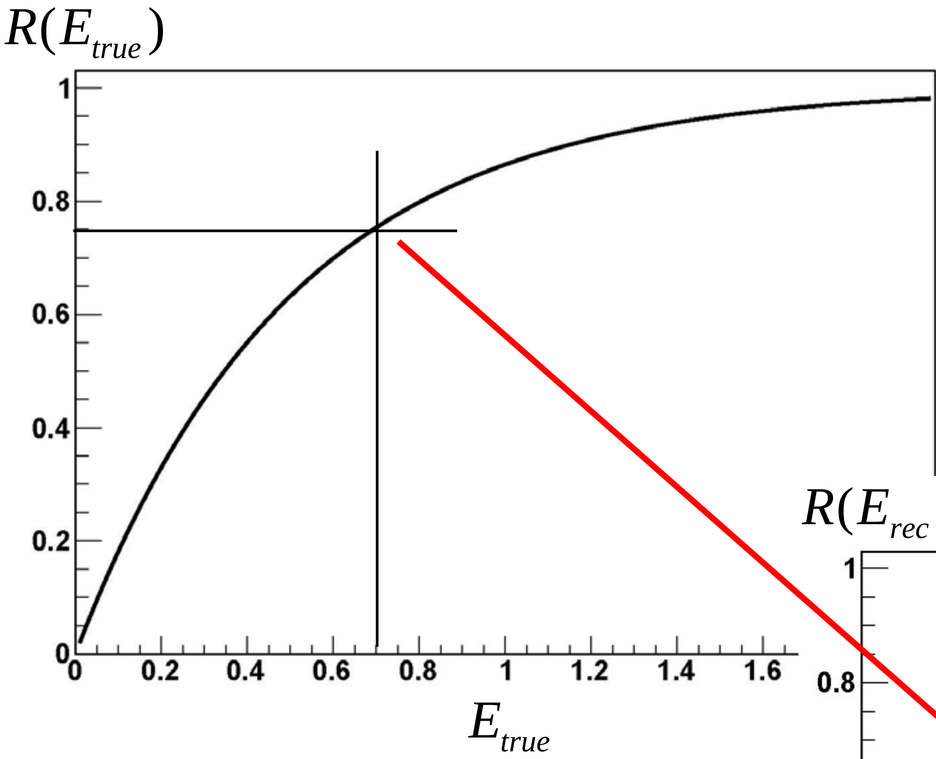
Lower edge of E spectrum

Center of E spectrum

High end of E spectrum

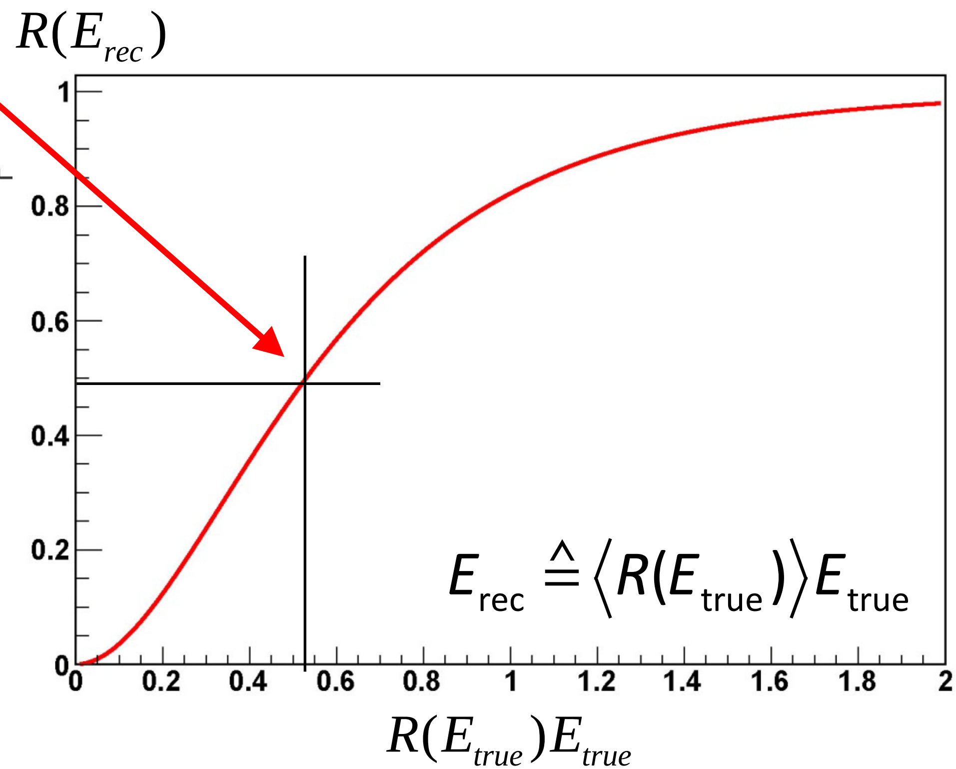
Response only Gaussian in bins of true energy!

Numerical Inversion



Transfer of response function from dependence on true variable to dependence on measured variable

$$R(E_{\mathrm{rec}}) = R\left(\left\langle R(E_{\mathrm{true}})\right\rangle \cdot E_{\mathrm{true}}\right)$$



$$E_{\mathrm{rec}} \triangleq \left\langle R(E_{\mathrm{true}})\right\rangle E_{\mathrm{true}}$$

Numerical Inversion Functions

Often simple functions

- Address residual energy (pT) and direction dependence of calorimeter jet response
  - Determine response functions *R* in bins of true jet pT and reconstructed pseudo-rapidity $\eta_{\mathrm{rec,jet}}$
  - Apply numerical inversion to determine calibration functions in reconstructed variable space ($p_{\mathrm{T,rec,jet}}$, $\eta_{\mathrm{rec,jet}}$)
- Use calibration functions to get jet energy scale
  - Technique can be applied to locally or globally calibrated jet response, with likely different calibration functions

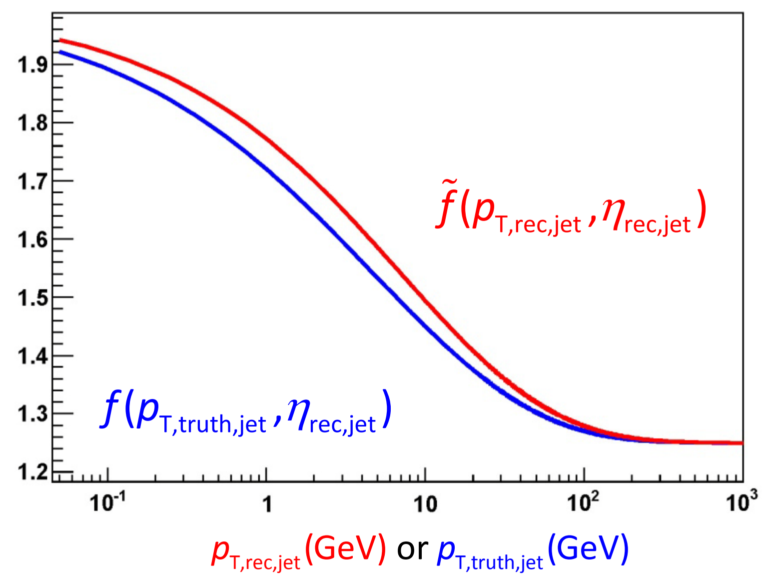
$$f(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) = R^{-1}(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}})$$

with $\eta_{\mathrm{reco,jet}} \simeq \eta_{\mathrm{truth,jet}}$ and

$$R^{-1}(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) = \left\langle \frac{E_{\mathrm{truth,jet}}}{E_{\mathrm{rec,jet}}} \right\rangle (p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}})$$

then apply numerical inversion

$$f(p_{\mathrm{T,truth,jet}},\eta_{\mathrm{reco,jet}}) \overset{\text{numerical inversion}}{\mapsto} \tilde{f}(p_{\mathrm{T,reco,jet}},\eta_{\mathrm{reco,jet}})$$



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global calibration:

$$\begin{pmatrix} E_{\mathrm{calib,jet}} \\ \vec{p}_{\mathrm{calib,jet}} \end{pmatrix} = \tilde{f}(p_{\mathrm{T,reco,jet}},\eta_{\mathrm{reco,jet}})\cdot \begin{pmatrix} \overbrace{\sum_{\substack{\text{cells in}\\ \text{jet}}} w(\rho_{\mathrm{cell}},\Re_{\mathrm{cell}})\cdot E_{0,\mathrm{cell}} + E_{\mathrm{DM}}}^{E_{\mathrm{reco,jet}}} \\ \underbrace{\sum_{\substack{\text{cells in}\\ \text{jet}}} w(\rho_{\mathrm{cell}},\Re_{\mathrm{cell}})\cdot \vec{p}_{0,\mathrm{cell}} + E_{\mathrm{DM}}\frac{\vec{p}_{0,\mathrm{jet}}}{\left|\vec{p}_{0,\mathrm{jet}}\right|}}_{\vec{p}_{\mathrm{reco,jet}},\ \text{with } p_{\mathrm{T,reco,jet}} = \left|\vec{p}_{\mathrm{reco,jet}}\right|\sqrt{1-\tanh^2\eta_{\mathrm{reco,jet}}}} \end{pmatrix}$$

local calibration:

$$\begin{pmatrix} E_{\mathrm{calib,jet}} \\ \vec{p}_{\mathrm{calib,jet}} \end{pmatrix} = \tilde{f}'(p_{\mathrm{T,reco,jet}},\eta_{\mathrm{reco,jet}})\cdot \begin{pmatrix} \sum_{\substack{\text{clusters in}\\ \text{jet}}} E_{\mathrm{rec,cluster}} \\ \sum_{\substack{\text{towers in}\\ \text{jet}}} \vec{p}_{\mathrm{rec,cluster}} \end{pmatrix}$$

$E_{rec,jet}$ Versus $E_{truth,jet}$

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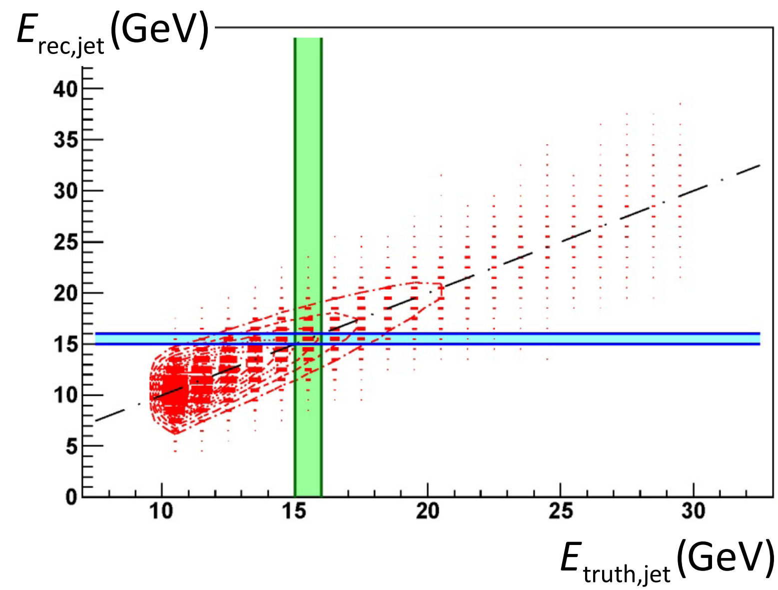
Why not use direct relation between reconstructed and true energy?

- Same simulation data input
  - Has been used in some experiments
- Dependence on truth energy spectrum
  - Need to make sure calibration sample is uniform in truth energy
  - Alternatively, unfold driving truth energy spectrum
- Residual non-gaussian behaviour of truth energy distribution
  - Error on reconstructed energy hard to understand
  - Could still use response distribution → same issues as discussed on previous slide!



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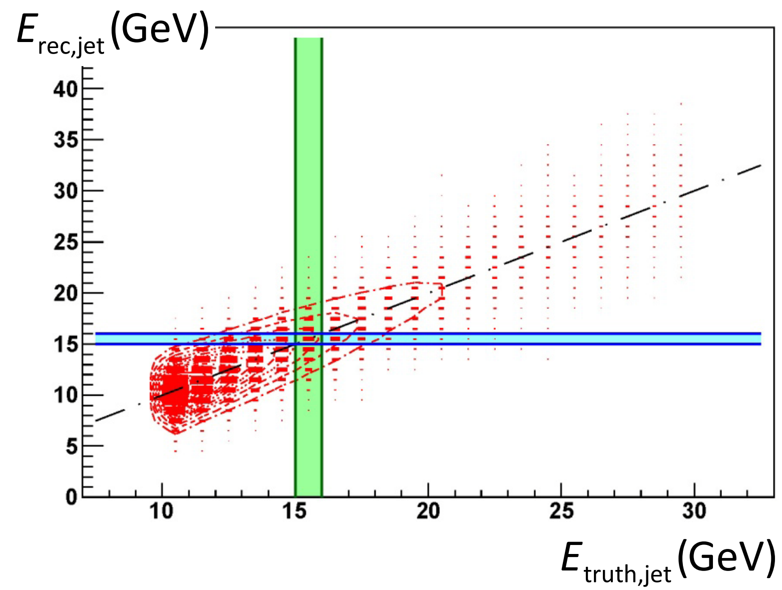

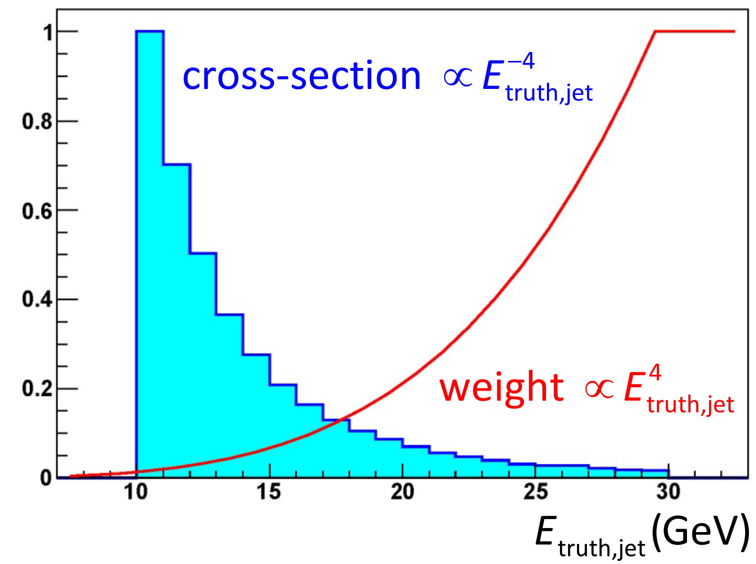

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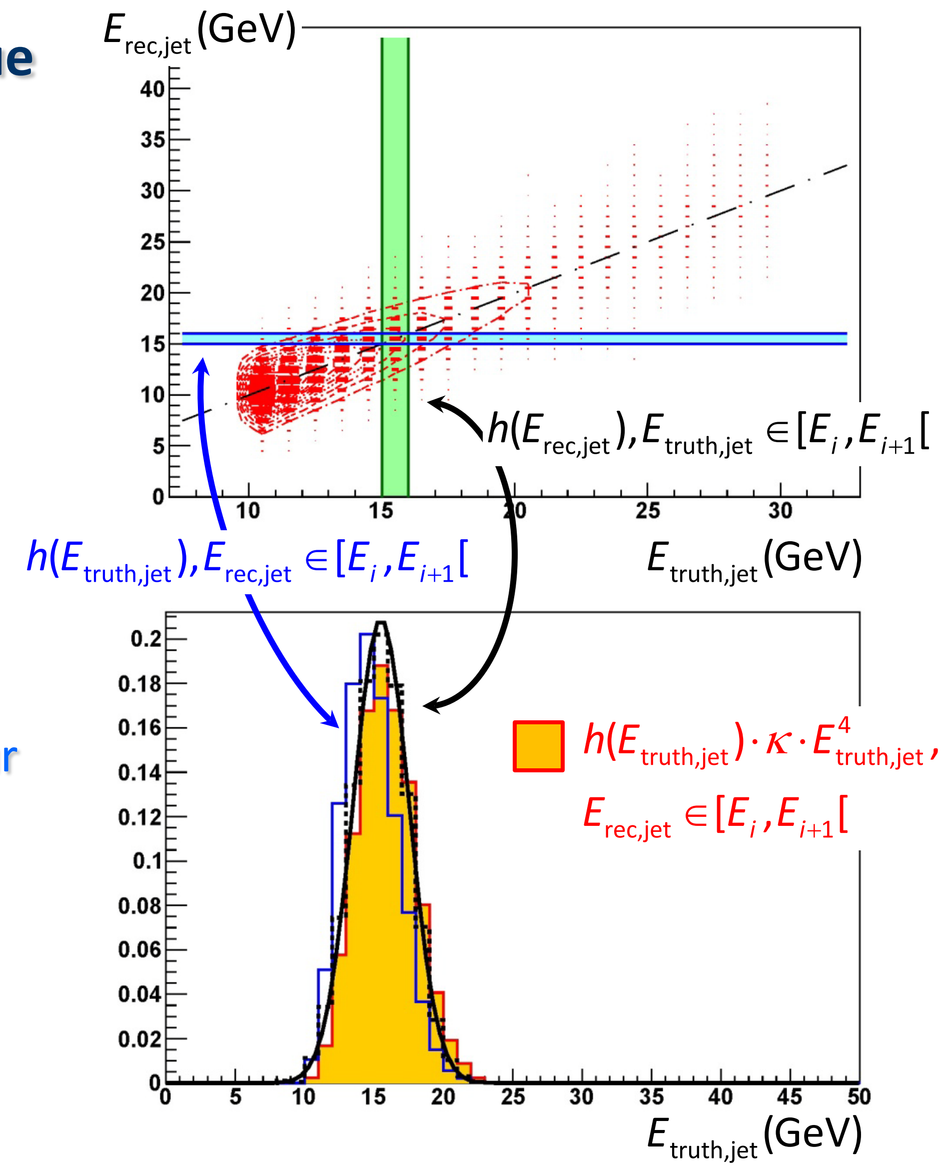

Systematic Error

Strategy from simulations

- Determine all calibrations with fixed conditions
  - Ideal detector model – everything is aligned
  - Fixed (best) GEANT4 shower model – from testbeam evaluations
  - Fixed calorimeter signal definition – e.g., towers
  - Fixed jet definition – like seeded cone with size 0.7
  - Fixed final state – QCD di-jets preferred
- Study change in performance for changing conditions with ideal calibration applied
  - Detector misalignment and changes in material budgets
  - Different shower GEANT4 model
  - Different calorimeter signal definitions – e.g., clusters
  - Different jet definitions – e.g., kT, AntikT, different cone or cone sizes…
  - Different physics final state – preferably more busy ones like SUSY, ttbar,…
- Use observed differences as systematic error estimates

Use of collision data

- Compare triggered final states with simulations
  - Level of comparison represents understanding of measurement – systematic error (at least for standard final states)
- Use in-situ final states to validate calibration
  - Careful about biases and reference levels (see session 9)

Performance Evaluation

- **Calibration functions determined with "perfect" detector description and one reference jet definition**
  - Validate performance in perfect detector
    - Signal linearity & resolution
- **Quality of calibration for a real detector**
  - A priori unknown real detector
    - Absolute and relative alignments, inactive material distributions
  - Estimate effect of distorted (real) detector
    - Implement realistic assumptions for misalignment in simulations
    - Small variations of inactive material thicknesses and locations
    - But use "perfect" calibration for reconstruction
- **Change jet signals**
  - Tower or clusters
    - E.g, change from reference calorimeter signal
  - Different jet finder
    - E.g., use kT instead of cone
  - Different configuration
    - E.g., use narrow jets (cone size 0.4) instead of wide jets (0.7)

Signal Linearity & Resolution

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ATLAS plots from **arXiv:0901.0512** [hep-ex]

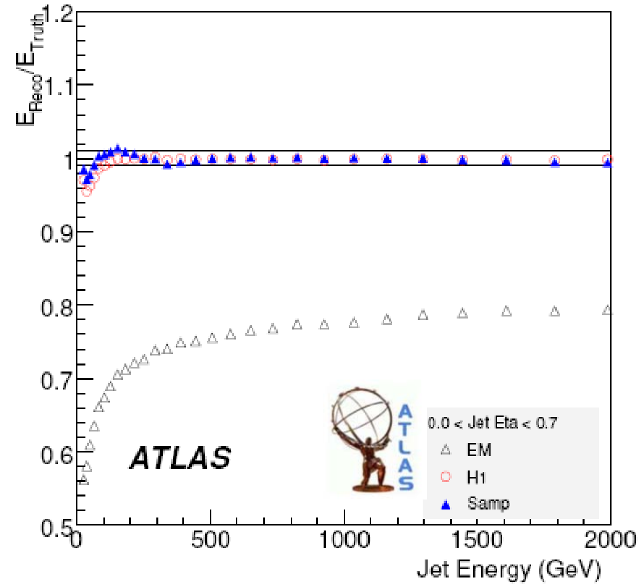
Response

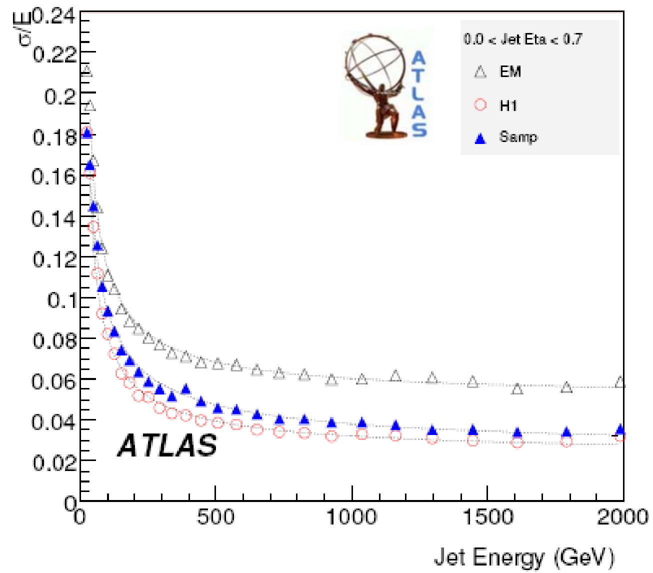
- Linear within +/-1% after calibration applied for pT>100 GeV
  - Clear improvement compared to basic signal scale
- Problems with low pT regime
  - ATLAS limit pT>20-40 GeV, depending on luminosity
  - May be resolution bias – under study

Resolution

- Jet energy resolution clearly improved by calibration as well
  - Slight dependence on calibration strategy
- Close to required performance

$$\frac{\sigma}{E} \approx \frac{65\%}{\sqrt{E}} \oplus 3\%$$





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Signal Uniformity

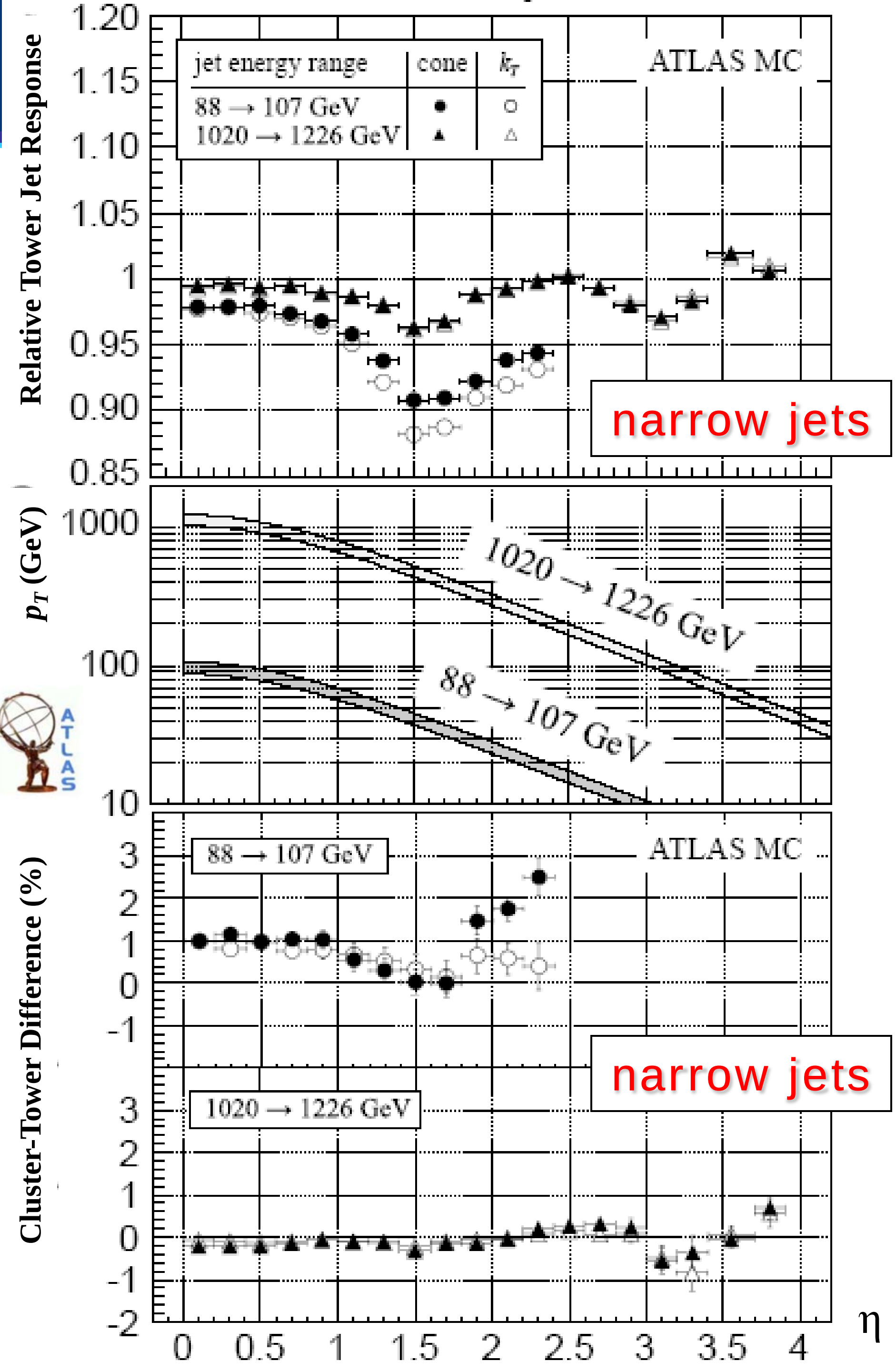
ATLAS plots from **arXiv:0901.0512** [hep-ex]

Characterizes "real" detector jet response

- Variation of response with direction
- Changing inactive material distribution
- Cracks between calorimeter modules

Variations

- No strong dependence on calorimeter signal definition
  - Towers/clusters
- ATLAS cone jet performs better in crack region at low pT



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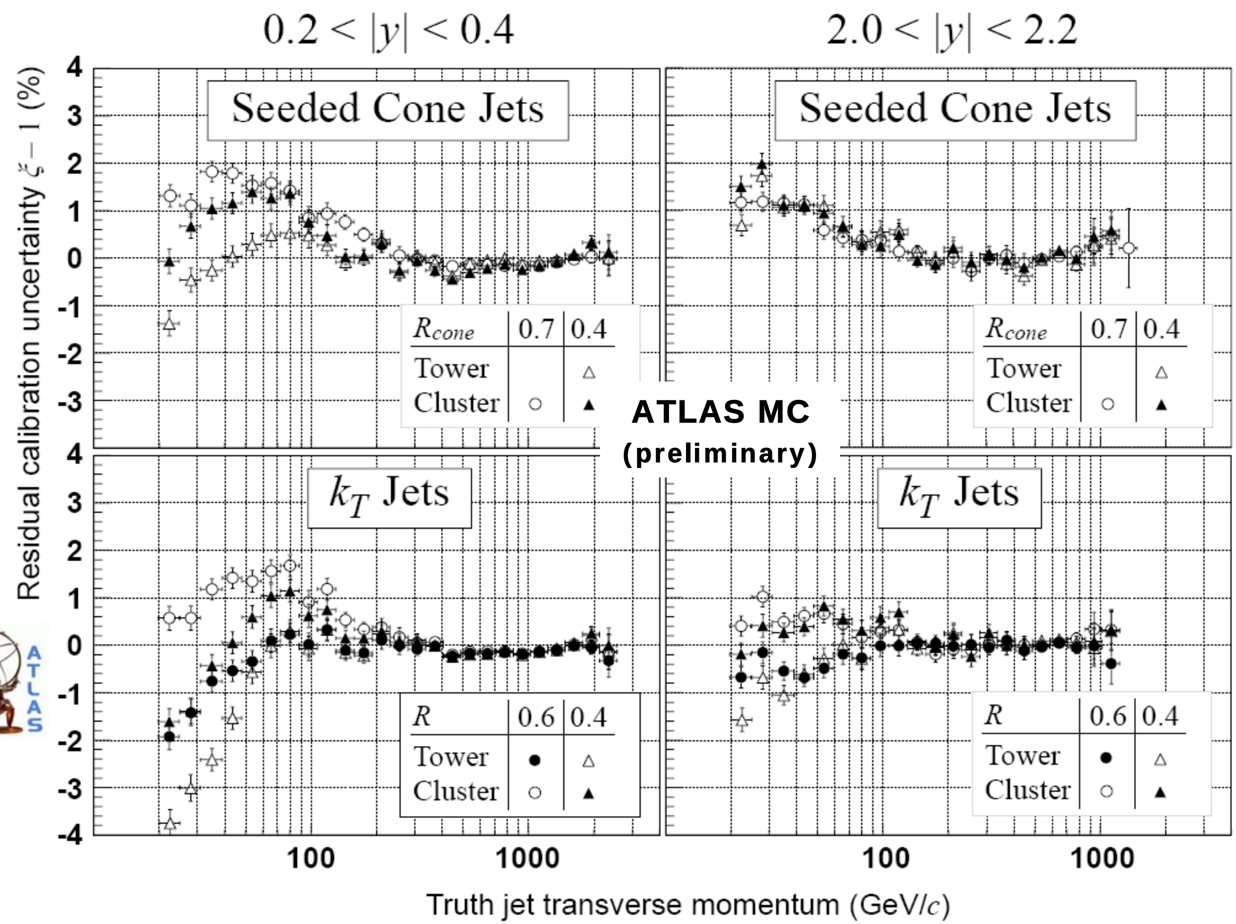
Deviation From Signal Linearity

ATLAS plots from **arXiv:0901.0512** [hep-ex]

Estimated effect of a distorted detector

Effect of detector distortion depends on jet size, calo signal choice, and kinematic domain



$$\xi = \frac{\left(E_{\text{rec,jet}} / E_{\text{truth,jet}}\right)_{\text{distorted}}}{\left(E_{\text{rec,jet}} / E_{\text{truth,jet}}\right)_{\text{ideal}}}$$

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Resolution Direction Dependence

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ATLAS plots from **arXiv:0901.0512** [hep-ex]

Larger fluctuations for kT jets at low pT

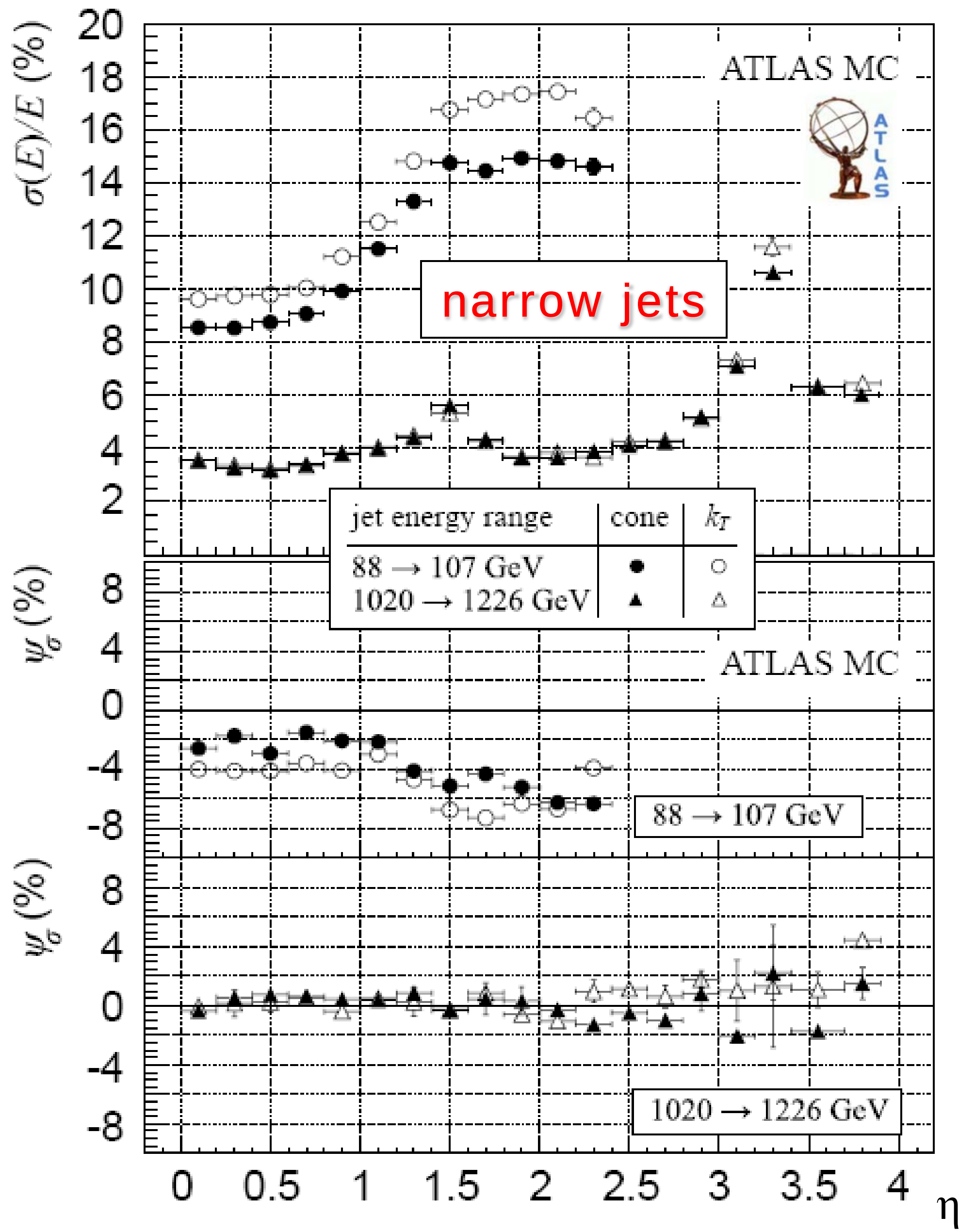
- Vacuum effect for tower jets?
- Less pronounced for cluster jets
  - Noise suppression important in this domain

Very similar resolutions at high pT

- No strong dependence on jet definition
- No strong dependence on calorimeter signal definition
  - No significant noise contribution anymore

$$\Delta_\sigma = \left(\frac{\sigma}{E}\right)^2_{\text{cluster}} - \left(\frac{\sigma}{E}\right)^2_{\text{tower}}$$

$$\psi_\sigma = \begin{cases} \sqrt{\Delta_\sigma} & \text{for } \Delta_\sigma > 0 \\ -\sqrt{-\Delta_\sigma} & \text{for } \Delta_\sigma < 0 \end{cases}$$



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Different Final States: Quark Jets

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