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Boston Jet Physics Workshop
Harvard University, January 12-14, 2011

Experimental Aspects of Jet Reconstruction in ATLAS

Peter Loch
University of Arizona
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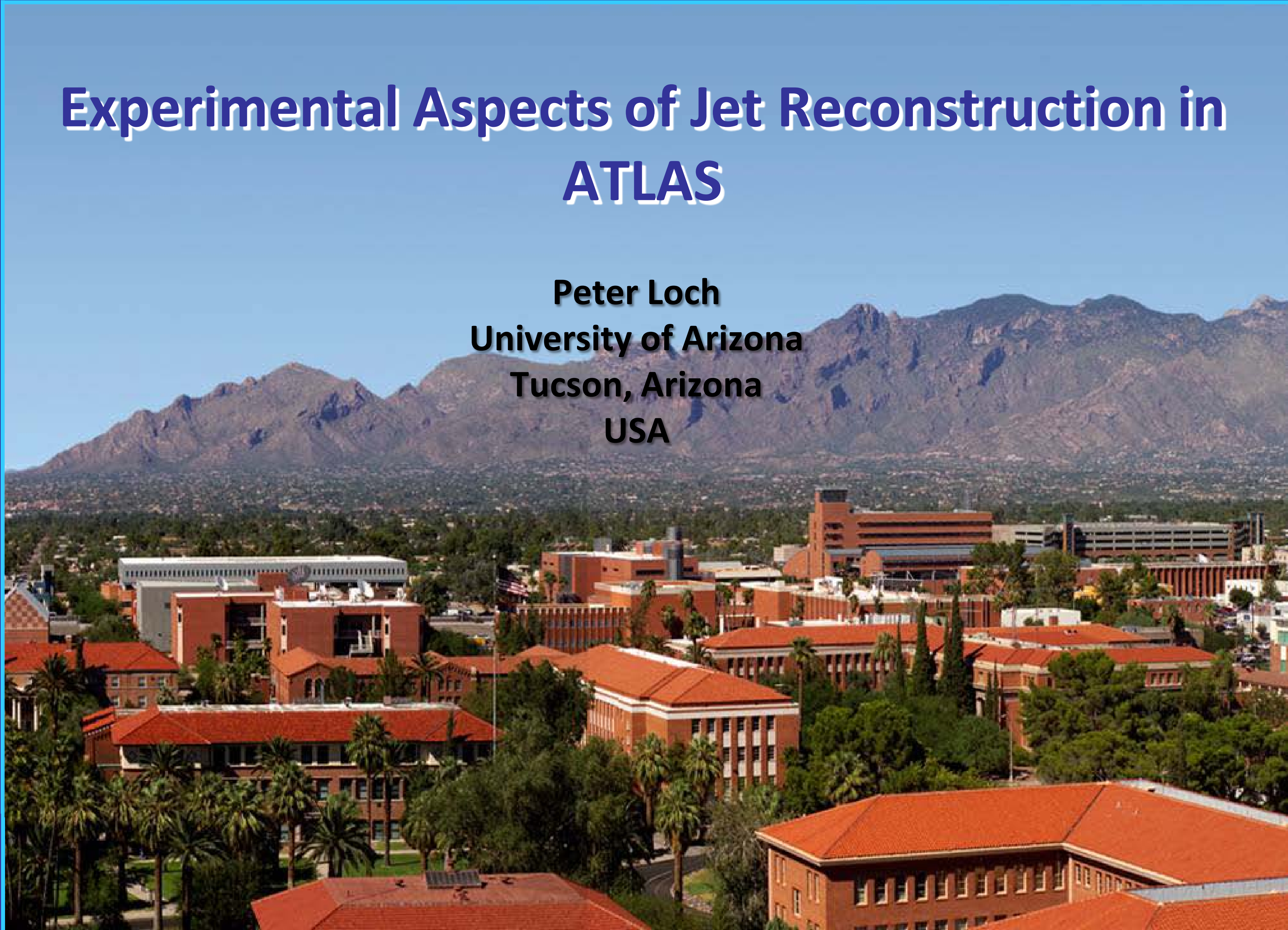

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ATLAS – Multipurpose LHC Detector

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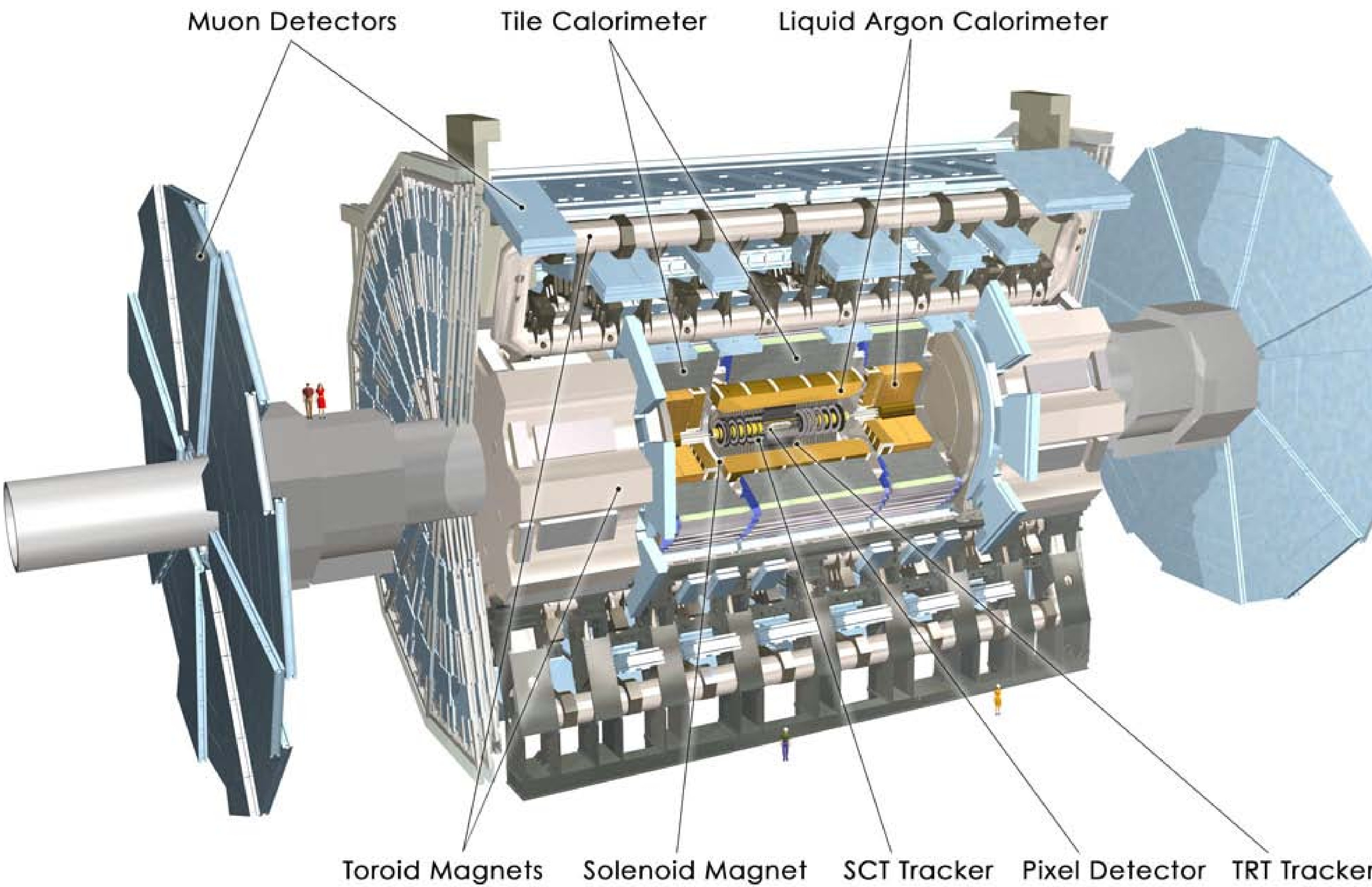
U of Arizona
August 25, 2010



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

ATLAS

The ATLAS Experiment

ATLAS Calorimeters

- EM: $|\eta| < 3.2$,
  - Pb/LAr calorimeter,
  - 22-26 X_0, 1.2 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.025 \times 0.025 - 0.1 \times 0.1$
  - $\sigma/E \simeq 10\%/\sqrt{E}$.
- Central Hadronic: $|\eta| < 1.7$,
  - Fe/Scintillator sampling calorimeter
  - 7.4 λ,
  - 3 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.1$,
  - $\sigma/E \simeq 50\%/\sqrt{E} \oplus 0.03$.
- EndCap Hadronic: $1.7 < |\eta| < 3.2$,
  - Cu/LAr sampling calorimeter,
  - 4 longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1 - 0.2 \times 0.2$
- FCAL: $3 < |\eta| < 4.9$,
  - EM: Cu/LAr, HAD: W/LAr calorimeter,
  - 10 λ,
  - 1 EM + 2 HAD longitudinal sections,
  - $\Delta\eta \times \Delta\Phi = 0.75 \times 0.65 - 5.4 \times 4.7$

~200,000 channels in total

6-7 longitudinal segments for |eta|<3.2

3 longitudinal segments for 3.2<|eta| <4.9

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ATLAS Calorimeter Summary

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August 25, 2010

Non-compensating calorimeters

- Electrons generate larger signal than pions depositing the same energy
  - Typically $e/\pi \approx 1.3$

High particle stopping power over whole detector acceptance $|\eta|<4.9$

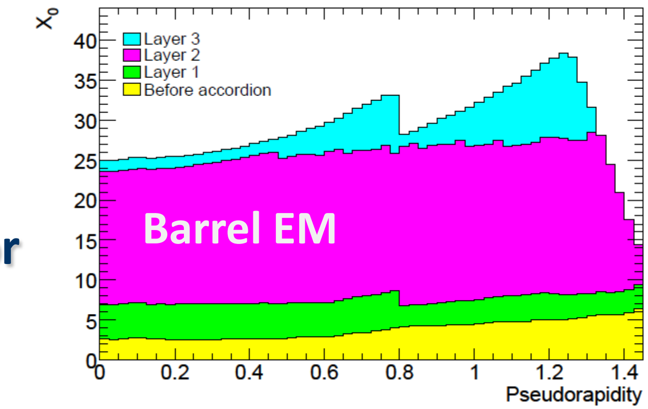
- $\sim$23-35 X_0 electromagnetic calorimetry
- $\sim$ 10 λ total for hadrons

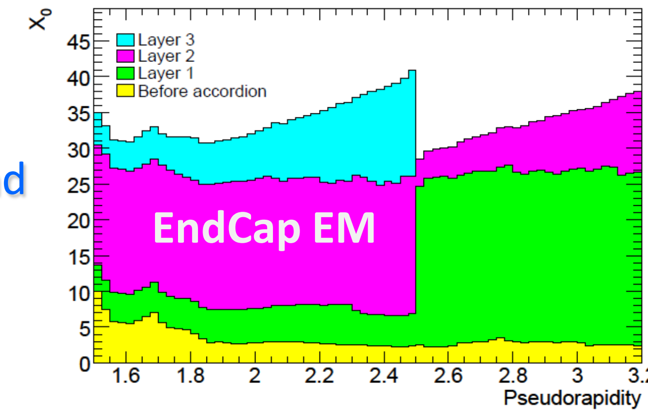
Hermetic coverage

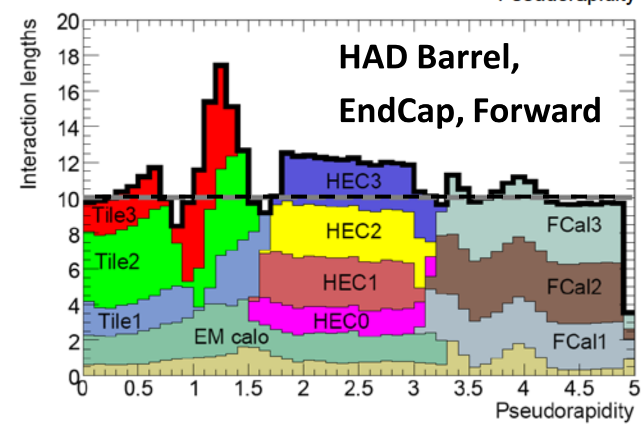
- No significant cracks in azimuth
- Non-pointing transition between barrel, endcap and forward
  - Small performance penalty for hadrons/jets

High granularity

- About 190,000 readout channels
  - Highly efficient particle identification
  - Jet substructure resolution capabilities
  - Local hadronic calibration using spatial signal distributions
  - Signal processing optimized for pile-up (see appendix)







Calorimeter signal scales

- Electromagnetic (EM) scale for calorimeter cells
  - Derived from electron test beams & simulations
- Hadronic (HAD) scale from cell signal weighting
  - 2 different schemes – global in jet context, and local in cluster context

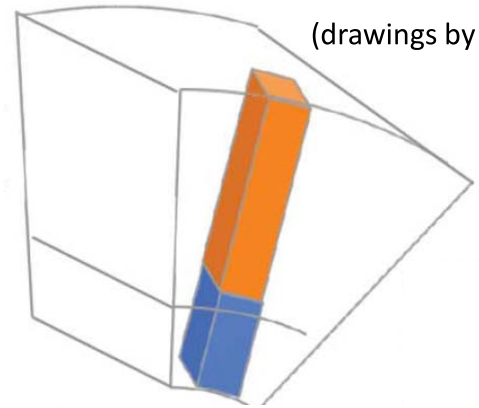
Signal summation

- Towers (EM scale only)
  - sum EM energy of all or selected cells on regular $\Delta\eta\times\Delta\phi=0.1\times0.1$ grid
- Clusters (EM & HAD scale)
  - Collect topologically connected cells with significant signals into 3-dim energy blobs
  - Implies noise suppression at cell level – can be used to select cells before tower formation
  - Can be used to apply local HAD scale

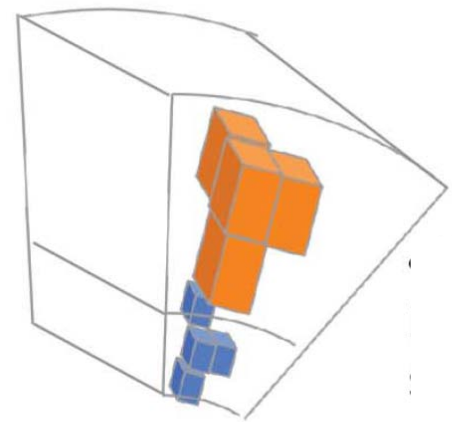
Towers and clusters are massless pseudo-particles

- Convention in ATLAS
  - Can really only accept E>0 input in jet finding

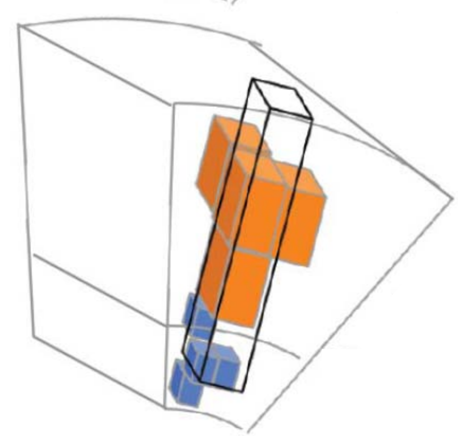
(drawings by K. Perez, Columbia University)



Unbiased calorimeter tower is a "slab" of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in this frame of reference)



Topological cell cluster is a "blob" of energy dynamically located inside the calorimeter (even crossing sub-detector boundaries)



Noise suppressed towers are sparsely populated slabs of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)

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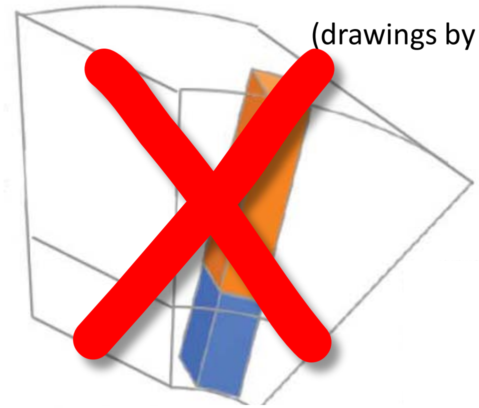

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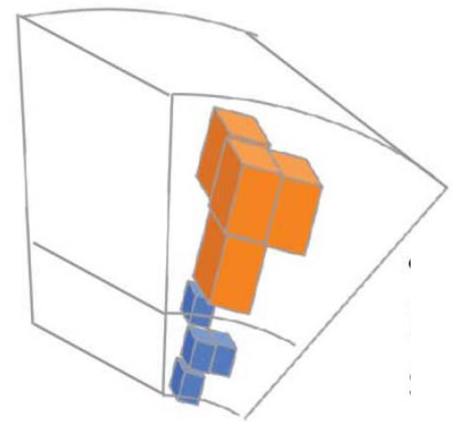

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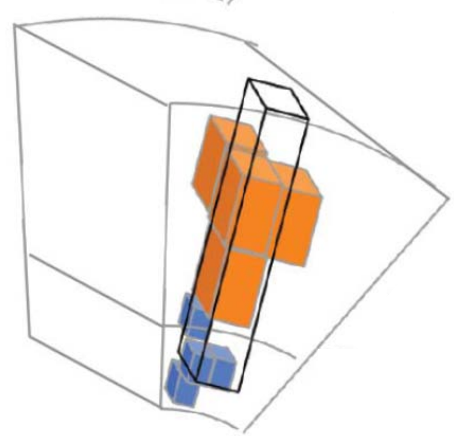

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Signal Scales for Hadronic Final State

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Electromagnetic (EM) scale

- Suffers from large fluctuations due to calorimeter signal features
  - Static calibration without jet-by-jet corrections for hadronic signal characteristics
- Least algorithm biases
  - Good control for systematic uncertainties for first collision data
  - Still basis of present default jet calibration in ATLAS

Hadronic (HAD) scales

- Attempt to reduce signal fluctuations dynamically
  - Implicit or explicit use of calorimeter signal features, e.g. cell energy density, spatial cell signal distribution
- Global Cell Weighting (GCW) in jet context
  - Apply cell signal weights derived in resolution minimalization fits of matching particle level and calorimeter jets in MC
  - Correlates dead material and other jet particle energy losses (magnetic field) with weights from non-compensation
  - Can be applied to cells in clusters or towers
- Local Cell Weighting (LCW) in cluster context
  - Cluster classification tags clusters with photon-like shower shapes
  - Applying cell signal weights in hadronic cluster reconstructs total deposited energy at cluster location + near-by dead material losses
  - Factorizes corrections for $e/h \neq 1$, out-of-cluster, and local dead material losses
  - No correction for acceptance losses (dead material & magnetic field) in jet context

ATLAS

Jet Energy Scale From EM Scale

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August 25, 2010

EM scale jet response :

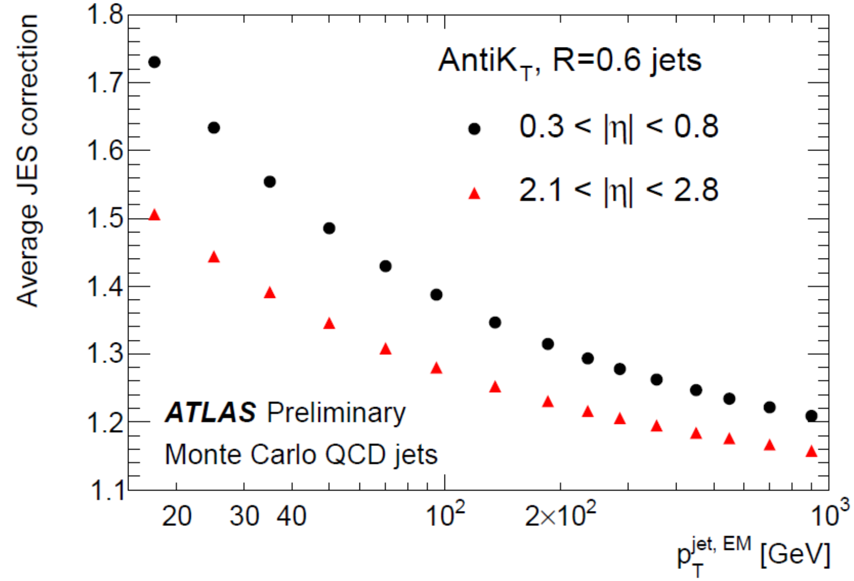
$$\begin{pmatrix} E_{0,\mathrm{jet}} \\ \vec{p}_{0,\mathrm{jet}} \end{pmatrix} = \begin{Bmatrix} \sum_{j=1}^{\mathrm{towers} \in \mathrm{jet}} \left(E_{0,\mathrm{tower}} = \left| \vec{p}_{0,\mathrm{tower}} \right|, \vec{p}_{0,\mathrm{tower}} \right)_j \\ \sum_{k=1}^{\mathrm{clusters} \in \mathrm{jet}} \left(E_{0,\mathrm{cluster}} = \left| \vec{p}_{0,\mathrm{cluster}} \right|, \vec{p}_{0,\mathrm{cluster}} \right)_k \end{Bmatrix} \approx \underbrace{[0.6 - 0.9]}_{\sim 20\ \mathrm{GeV} \to \sim 1\ \mathrm{TeV}} \times \begin{pmatrix} E_{\mathrm{jet,true}} \\ \vec{p}_{\mathrm{jet,true}} \end{pmatrix}$$

Required calibration/corrections for EM scale jet signals

- Missing e/h, dead material, acceptance corrections
  - Energy dependent signal deficits require corresponding corrections

Corrected by application of jet level correction functions

- Functions determined with MC (PYTHIA QCD di-jets)
  - Parameterized in bins of true jet pT and pseudorapidity
  - For each jet algorithm and configuration (e.g., jet size)
- Numerical inversion techniques
  - Maintain response function shape in given phase space bin when transforming input variables from true to measured scales



Response function for true variables:

$$R_{\mathrm{jet}}(p_{\mathrm{T,true,jet}}, \eta_{\mathrm{jet}}) = \left\langle p_{\mathrm{T,EM,jet}} / p_{\mathrm{T,true,jet}} \right\rangle (p_{\mathrm{T,true,jet}}, \eta_{\mathrm{jet}})$$

Response function for measured variables:

$$R_{\mathrm{jet}}(p_{\mathrm{T,EM,jet}}, \eta_{\mathrm{jet}}) = R_{\mathrm{jet}}(R_{\mathrm{jet}}(p_{\mathrm{T,true,jet}}, \eta_{\mathrm{jet}}) \cdot p_{\mathrm{T,true,jet}}, \eta_{\mathrm{jet}})$$

MC Based JES Systematic Uncertainties

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August 25, 2010

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21/09/2010

Determination of contributions from various sources

- Determine default calibrations and corrections with given MC
  - Best detector geometry knowledge
  - Best fitting signal simulation models
  - Workhorse QCD di-jet physics generator Pythia
- Vary used models and setups within reasonable boundaries
  - Models excluded by data not considered
  - Only realistic detector misalignments and material budgets
  - Use of measured range of experimental conditions
- Reconstruct jets in alternative setups
  - Use calibrations from default configuration

Physics modeling contributions

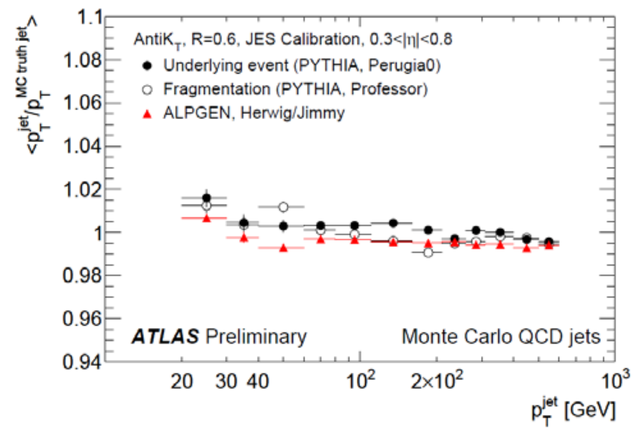
- Underlying event
  - Use alternative tunes for Pythia
- Jet shapes
  - Herwig/Jimmy instead of Pythia (cluster instead of string fragmentation)

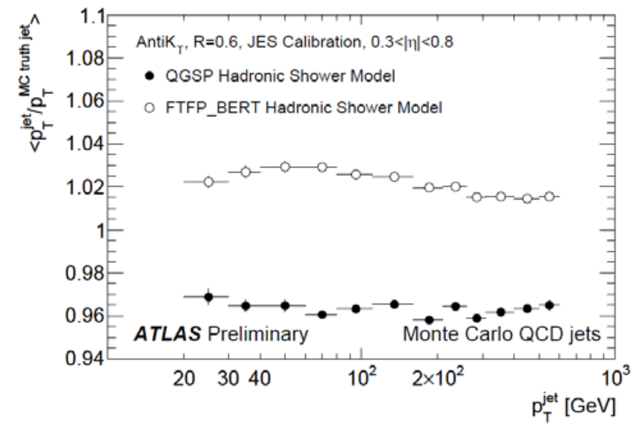
Detector signal modeling

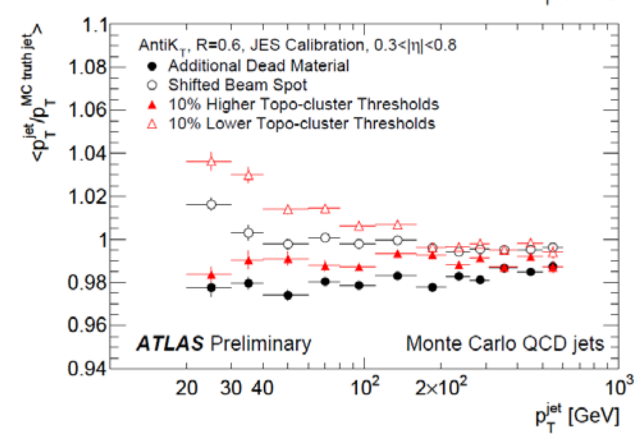
- Variations of detector description
  - Dead material budget and alignment
- Different hadronic shower models in Geant4
  - FTFP_BERT instead of default QGSP_BERT
- Variation of noise suppression thresholds in clustering
  - +/- 10% change in threshold

Experimental conditions

- Effect of shifted beam spot
  - Corresponding shift in response variations, pT/energy







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MC Based JES Systematics Summary

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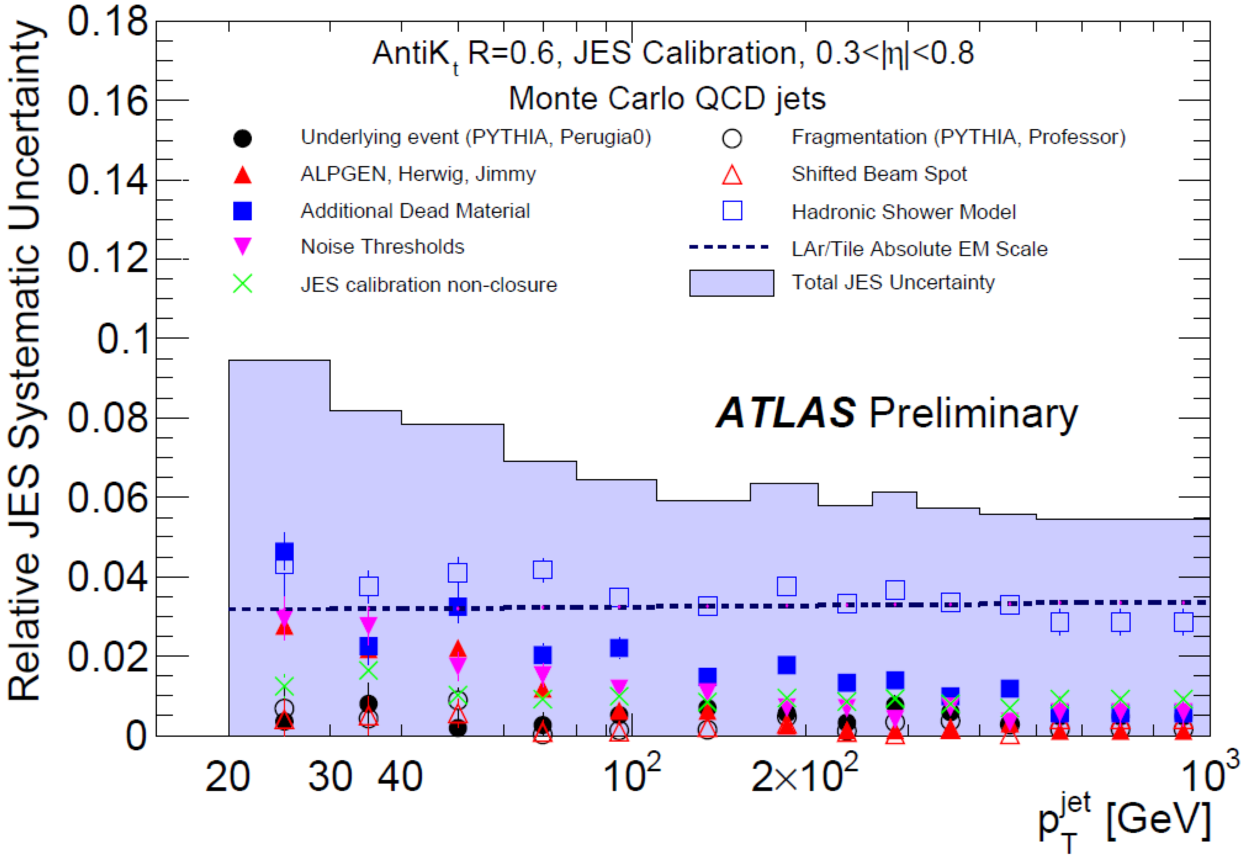
August 25, 2010

Putting it all together

- Conservative estimates for overall systematic uncertainty for first data
  - Dominant contribution for all pT from hadronic shower models
  - Dead material important for low pT regime
- Similar uncertainties from E/p and testbeam
  - Jets composed from single particle response in collision and testbeam data and MC

Systematic uncertainty as of summer 2010! Significant improvements can be expected for winter 2011 conferences!



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Carrying on…

Use of hadronic scales

- Resolution improvements (GCW, LCW)
  - More dynamic calibrations sensitive to individual shower character in jet (GCW) or clusters (LCW)
- Jet constituent calibrations
  - So far jets reconstructed from EM scale calorimeter signals in towers or clusters
  - Using input signals on hadronic scale improves performance and stability of kT and Anti-kT due to better relative signal calibration between photon and hadron component of jet
- Consistent hadronic final state
  - LCW allows use of signals on the same scale for jets and missing transverse energy
- Hadronic scales still need final JES corrections
  - LCW misses jet energy losses from particles completely escaping the calorimeters (dead material, magnetic field) – GCW not fitted in calorimeter crack regions etc.

Complex calibrations derived from MC

- Use of cell signal density
  - Cluster (LCW) and jet context (GCW) cell weighting
- LCW uses cluster structures
  - Location, shape and sizes directly and indirectly used
- Concern about model dependence
  - Observables feeding calibrations need to be well simulated
  - Some dependence on shower model details

Validation of calibration input in collision data

- First task to gain confidence in models and parameters
  - Comparison of signal spectra in minimum bias and jet events
- Factorized approach in LCW
  - Allows understanding each calibration and correction step individually
- Jet shapes and energy sharing
  - Direct and indirect input on hadronic scale
  - Level of understanding also important for jet physics and hadronic event shapes!

Understanding Cells & Clusters in Jets

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August 25, 2010

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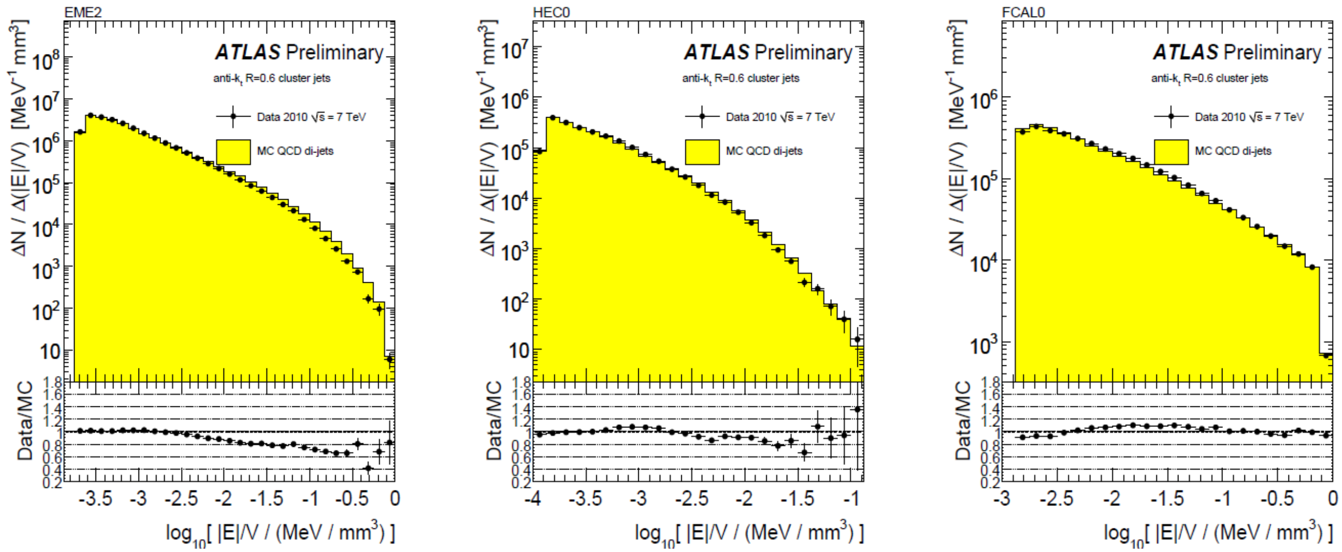
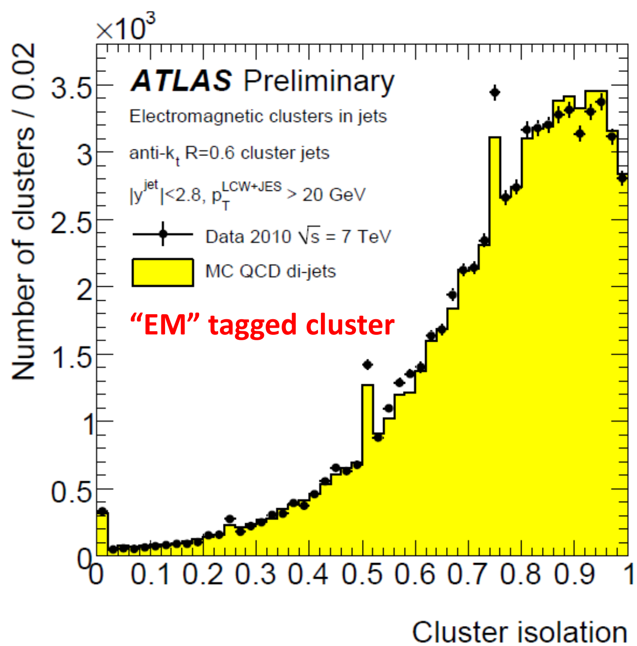
Calorimeter cell energy density distributions (e.g., for GCW, LCW)

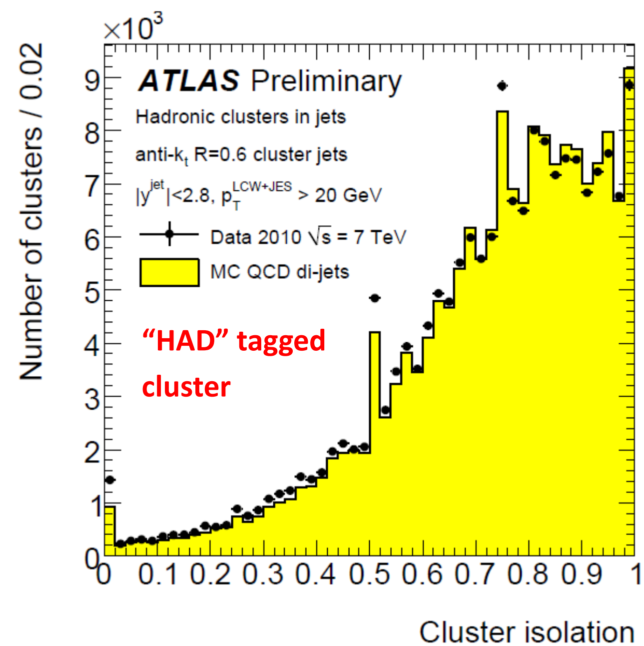
Cells and clusters inside jets!



(a) Second layer of EM endcap (b) First layer of HEC (c) First layer of FCAL

Calorimeter cluster isolation measure (LCW)





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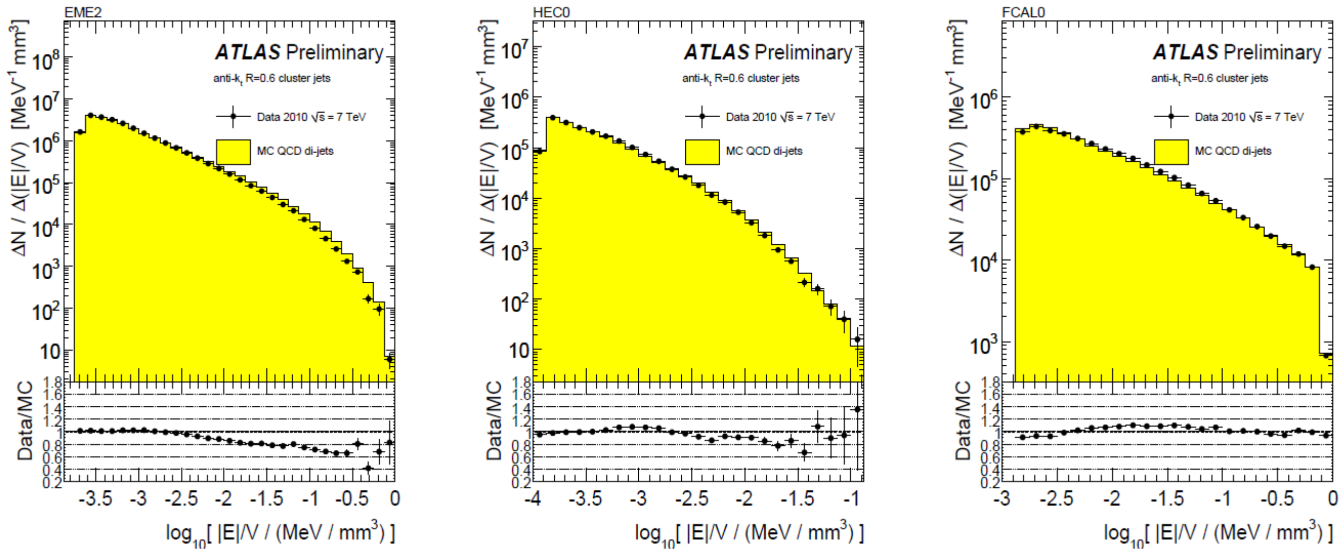

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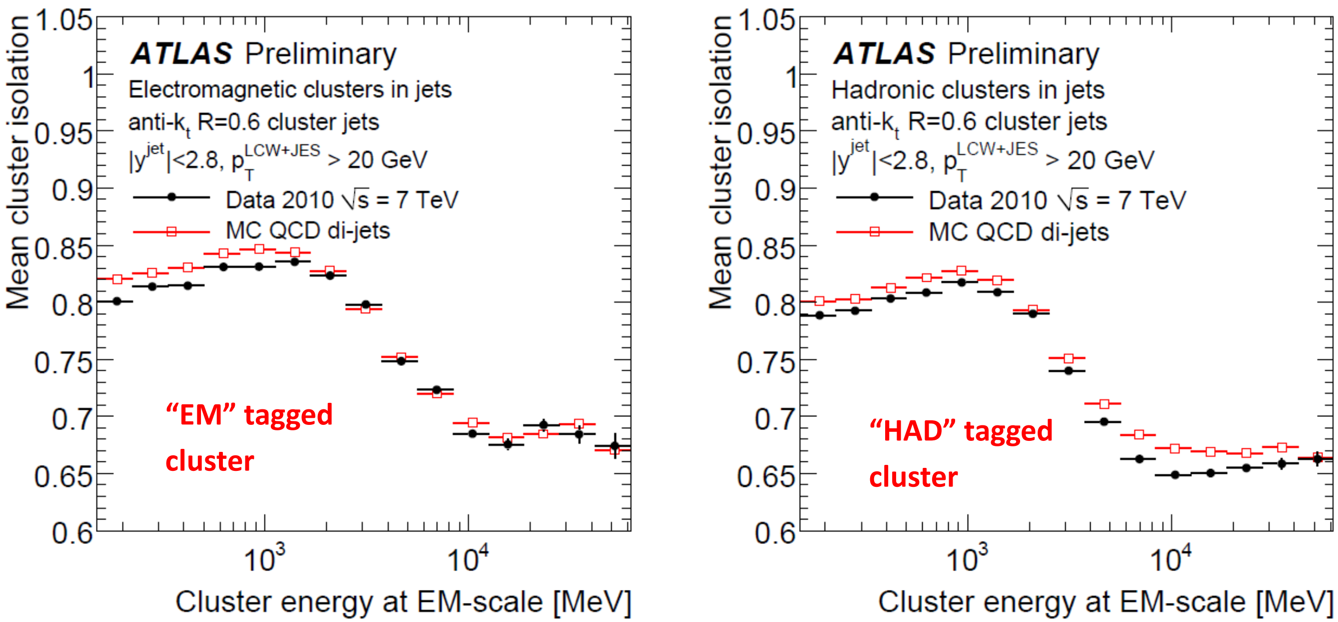

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Understanding Clusters in Jets

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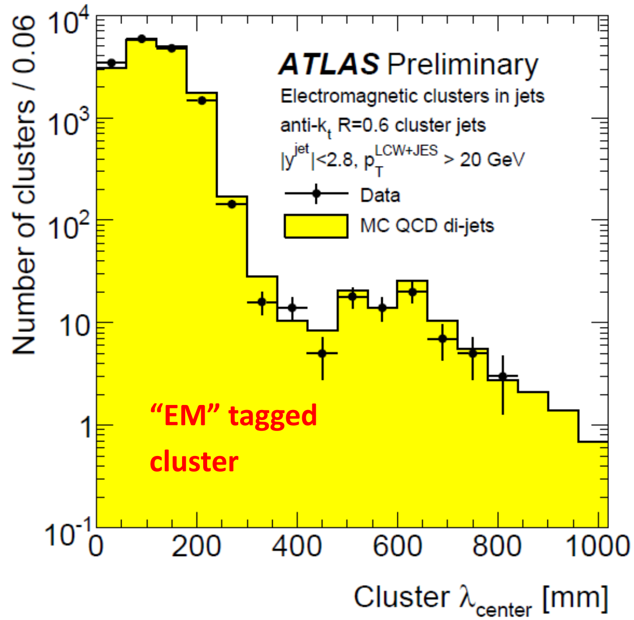
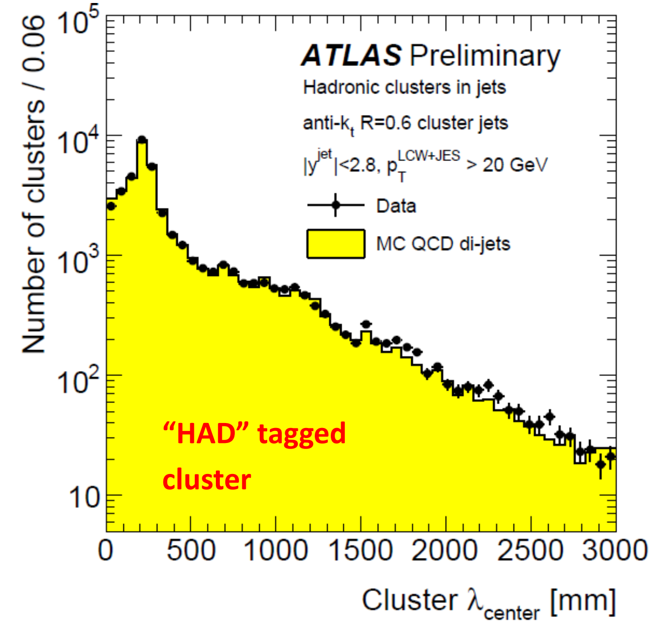
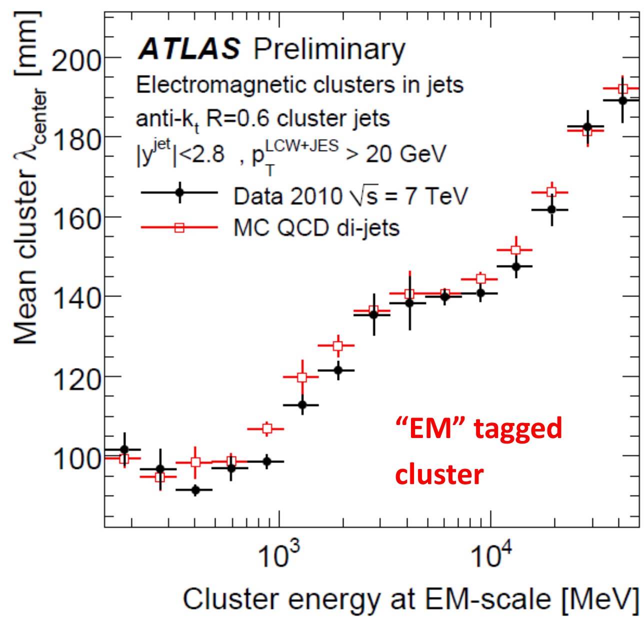
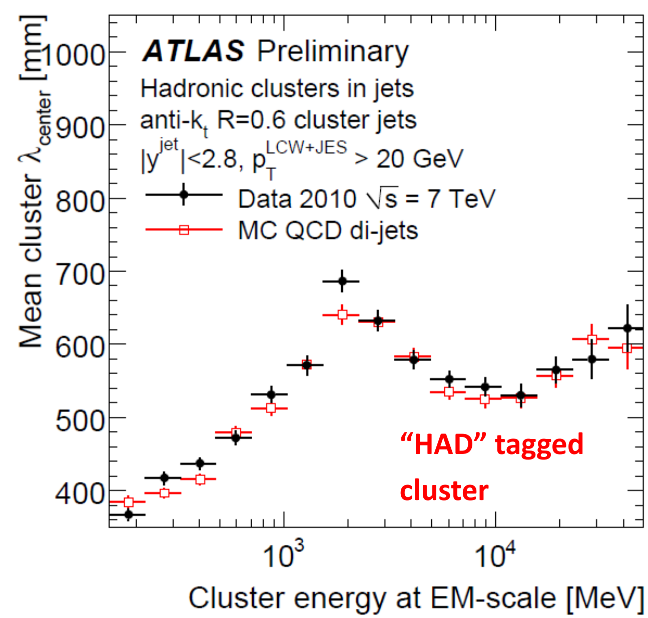
Calorimeter cluster depth in calorimeter (LCW)

Clusters inside jets!









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Test factorized calibration model

- All functions and parameters derived from single particle simulations
  - Non-trivial assumption that they work in collision physics environment!
- Factorization allows validation of each calibration/correction
  - HAD clusters: cell weighting, out-of-cluster, dead material corrections
  - EM clusters: out-of-cluster, dead material (not the same as for HAD!)
- Checked for clusters in and outside of jets
  - Shown here for clusters inside jets

Promising for sub-jet calibration

- Local hadronic scale is jet constituent scale
  - Can be understood at the 1-3% level!
- Needs to be verified with high pT jets
  - Boosted hadronic W and top decays become slowly available in data

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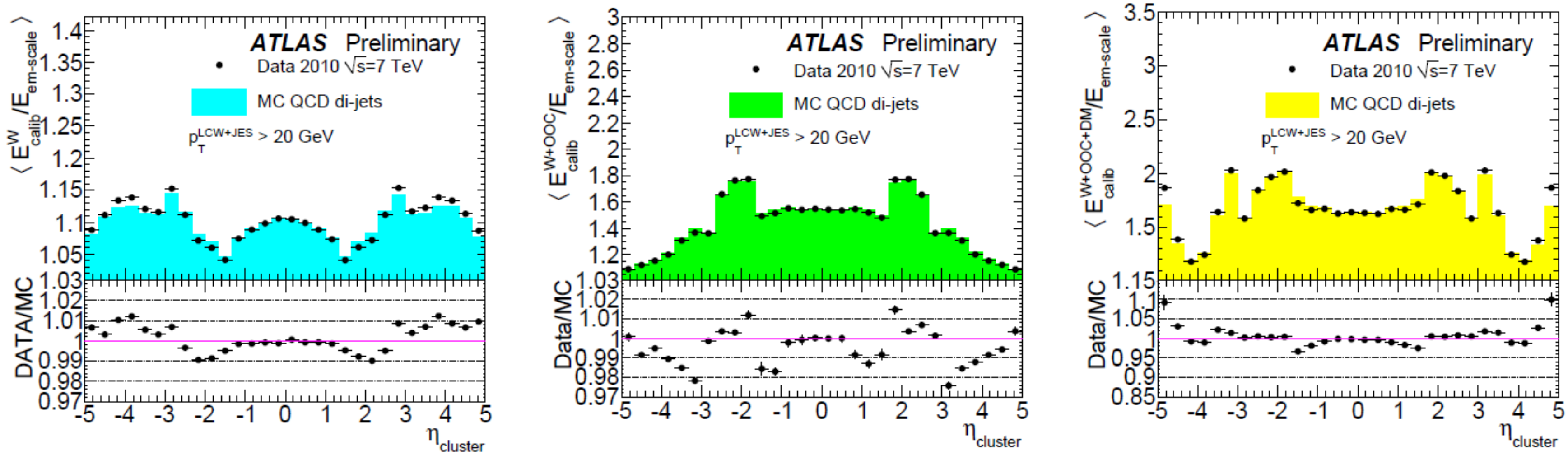

(a) Hadronic response weights (b) Out-of-cluster weights (c) Dead material weights

Jet Feature Reconstruction

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Kinematics and composition

- Understanding dependence of reconstruction quality on calorimeter signal choice
  - Direction and pT for cluster and tower jets
- Number of constituents
  - Tower and cluster jets compared to particle level
- Other observables related to composition
  - Longitudinal energy sharing – access to photon content of jets by measuring energy fractions in EM calorimeters (?)

Jet shapes

- Width
  - Calorimeter width measurement affected by particle flow and shower spread
  - Track jets provide (reference) width with independent bias
- Annular transverse energy flow
  - Jet fragmentation and source (light quark/gluon) sensitivity
  - Use in jet-by-jet calibration to be explored

Note

- Nearly all comparisons in the following plots are to Pythia with the ATLAS MC09 tune!
  - … if not specifically mentioned otherwise!

Cluster & Tower Jet Kinematics

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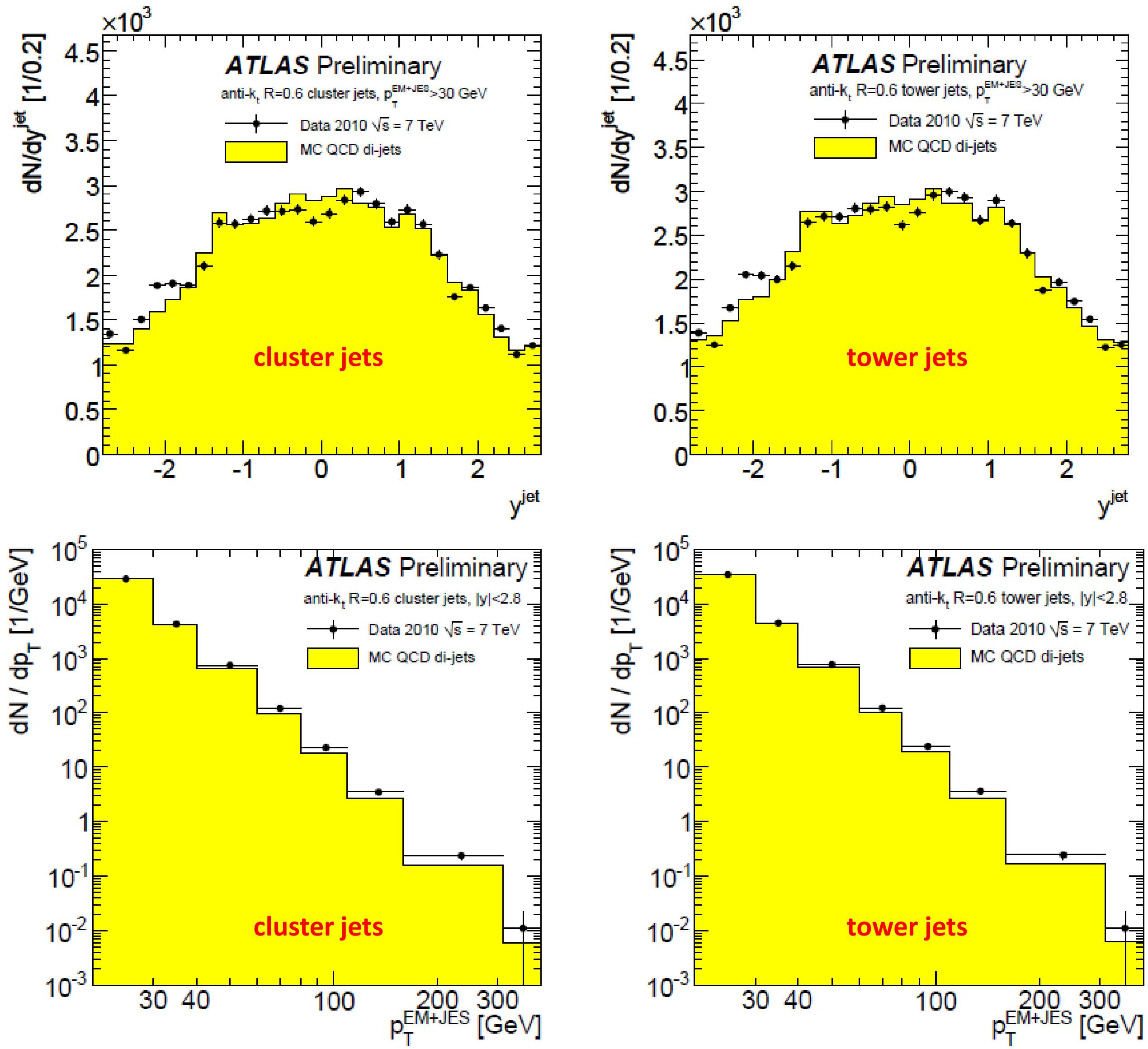
Jet number density in pseudorapidity

$p_{\mathrm{T,jet}} > 30$ GeV

Jet pT spectra



(a) Topological cluster jets (b) Noise-suppressed tower jets

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Calorimeter Jet Composition

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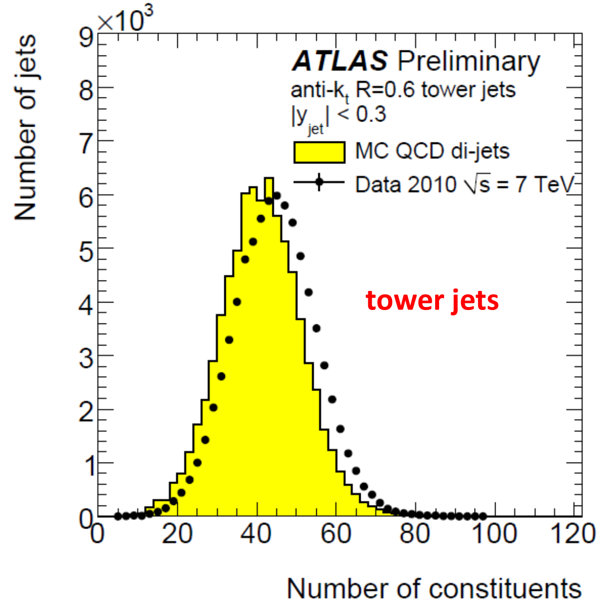
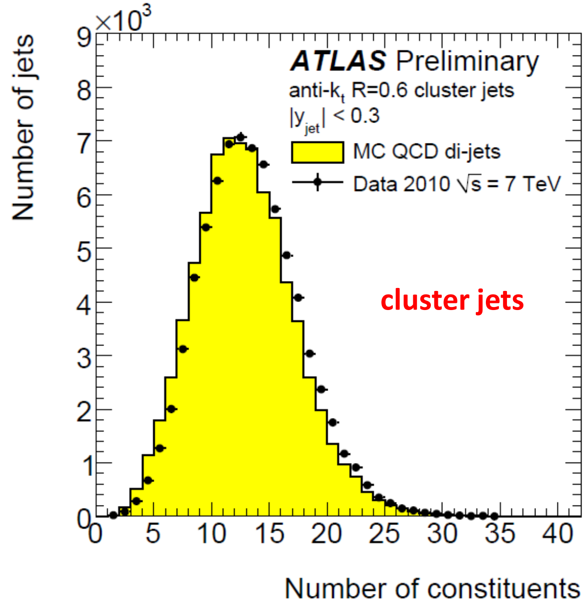
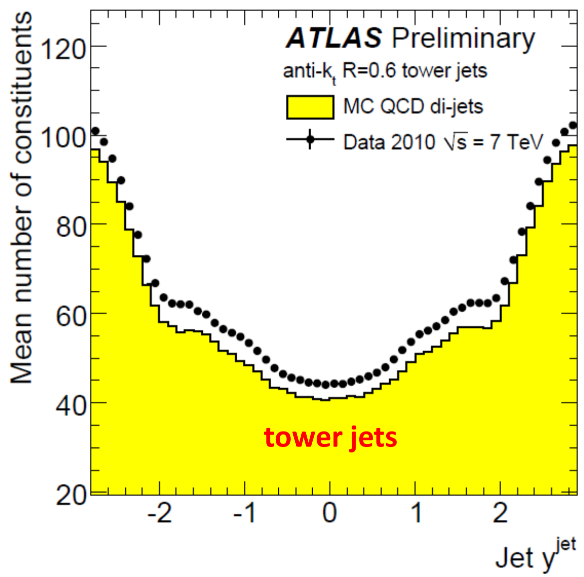
Number of constituents in jets

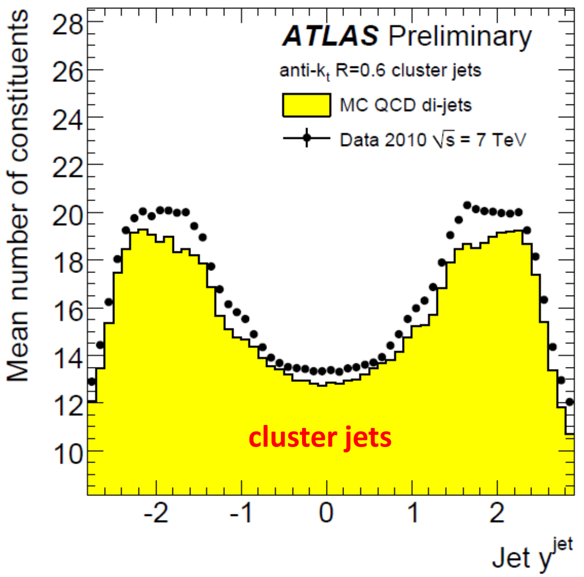
$$p_{\mathrm{T,jet}} > 30\ \mathrm{GeV}$$

Jets in data have more constituents on average









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Calorimeter Jet Composition

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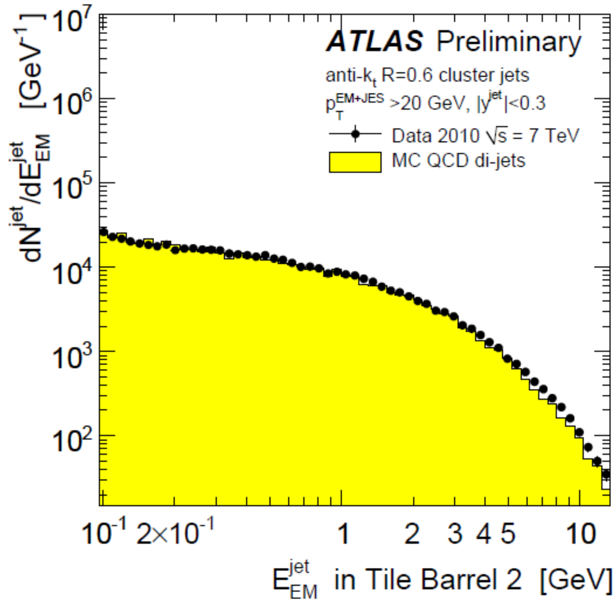
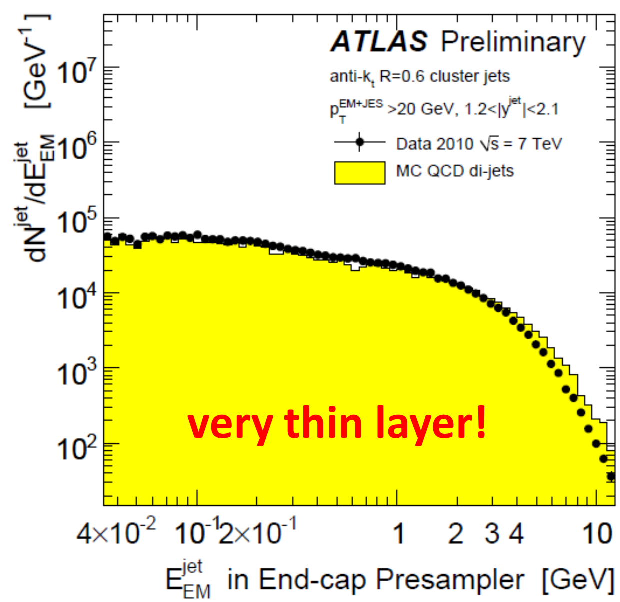
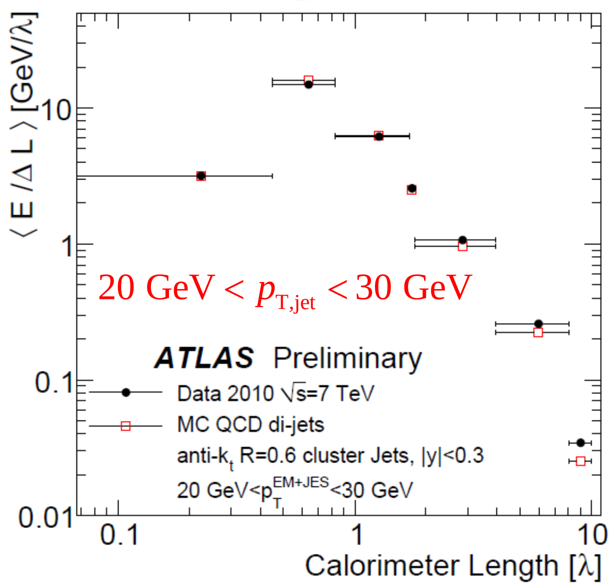
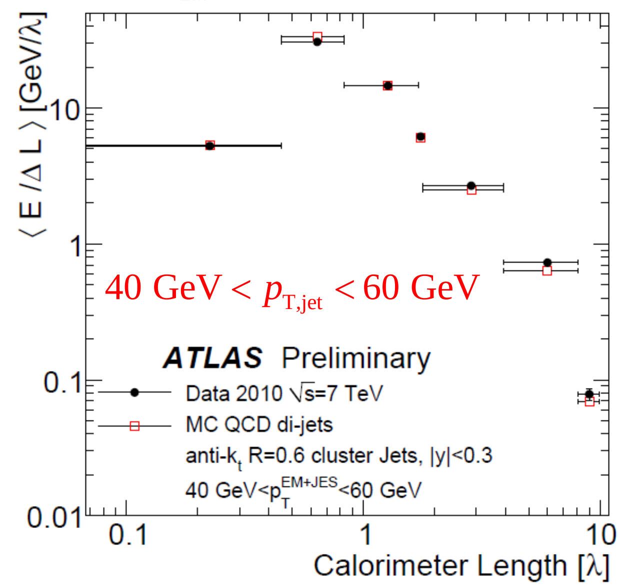
Energy distribution in calorimeter samplings from jets – spectra





Energy sharing in calorimeter samplings – longitudinal shower profiles in jets





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Jet Composition In Tracks

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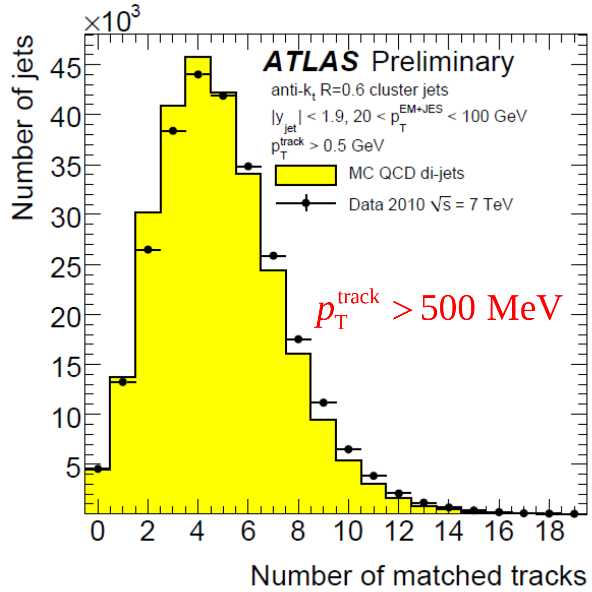
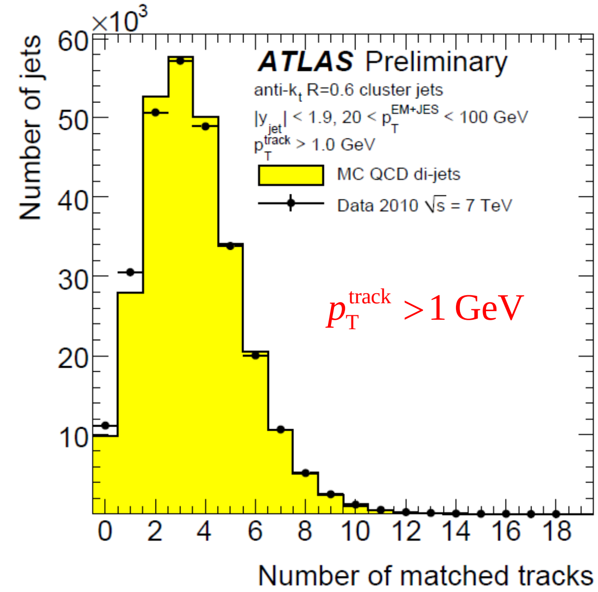
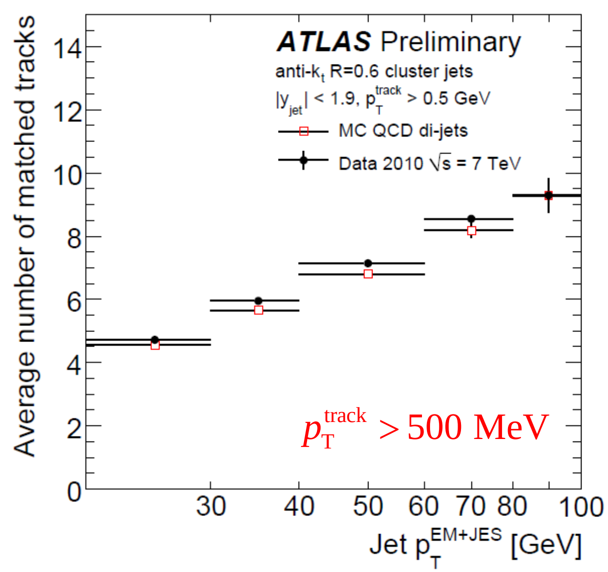
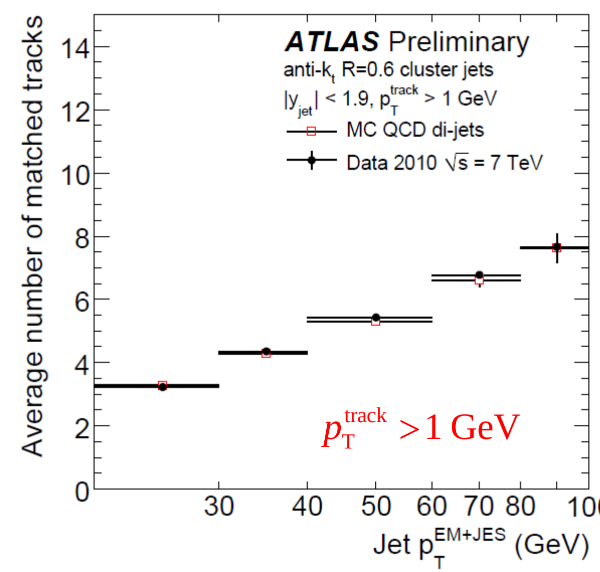
Number of tracks pointing to calorimeter jets – sensitive to fragmentation (model)





Average number of reconstructed tracks pointing to calorimeter jet – more soft tracks in data





$20 \text{ GeV} < p_{T,jet} < 100 \text{ GeV}$

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Jet Composition In Tracks

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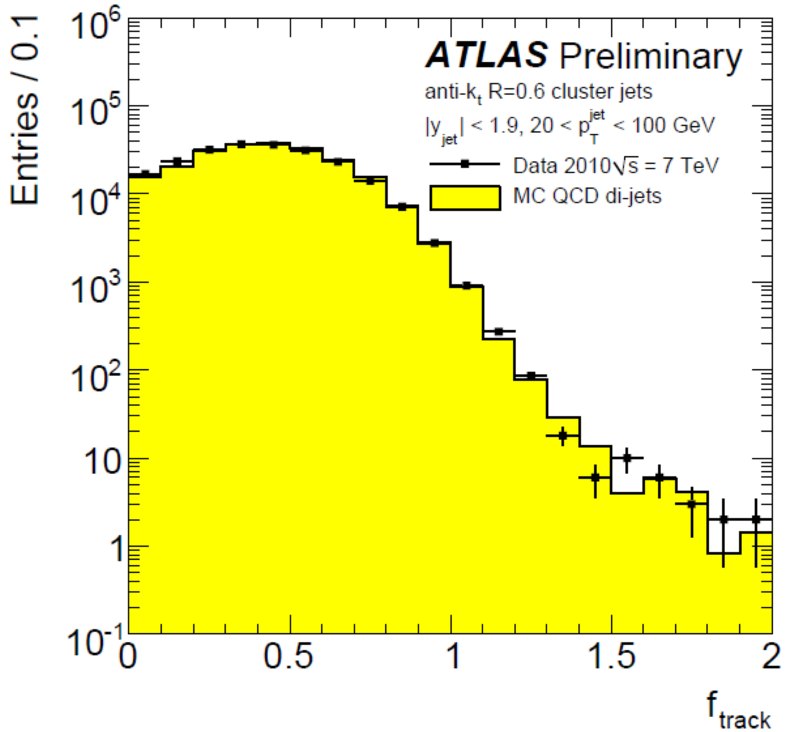
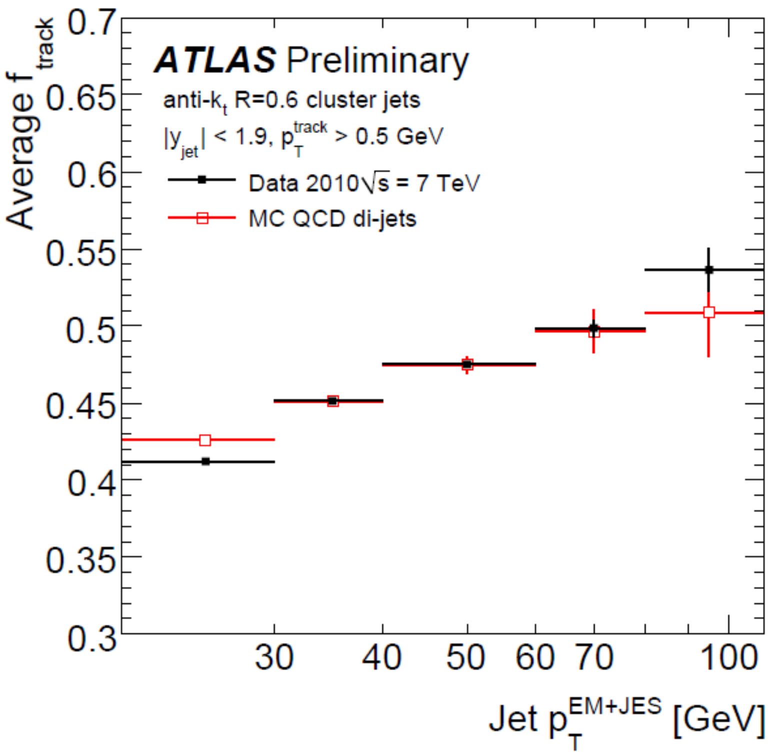
August 25, 2010

Track pT fraction

- Tool for fragmentation validation
  - Needs to be understood in the context of pile-up in jets (least biased estimator?)
- Handle for jet-by-jet calibration
  - Large track momentum fraction indicates hadron rich jet – can be exploited for jet calibration





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Understanding Jet Width

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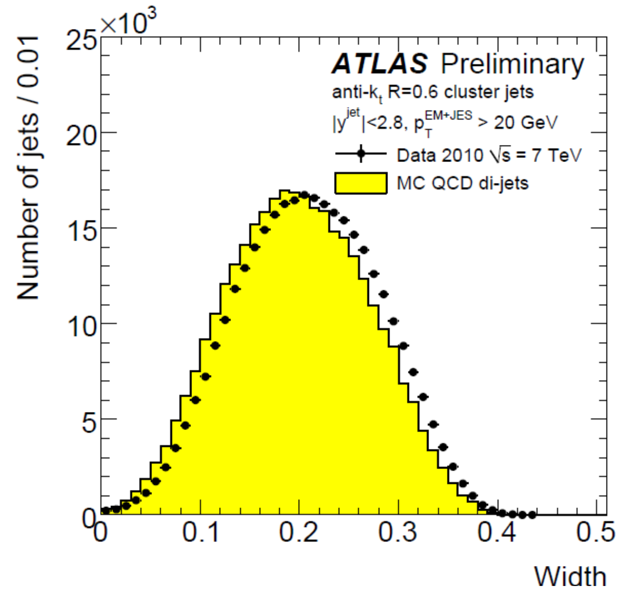
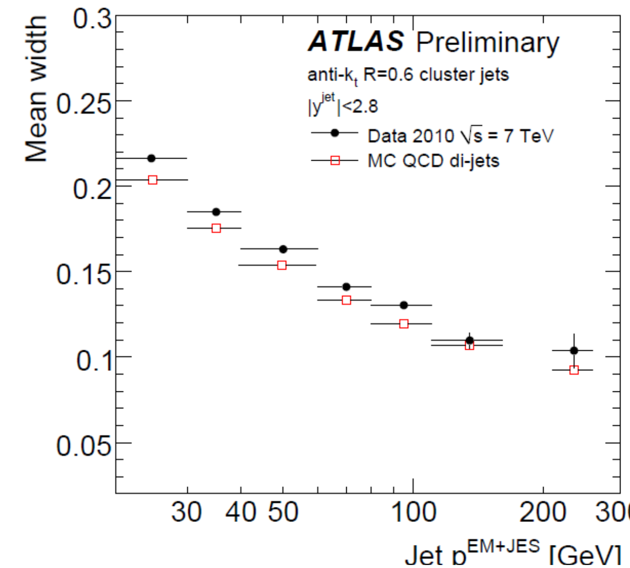
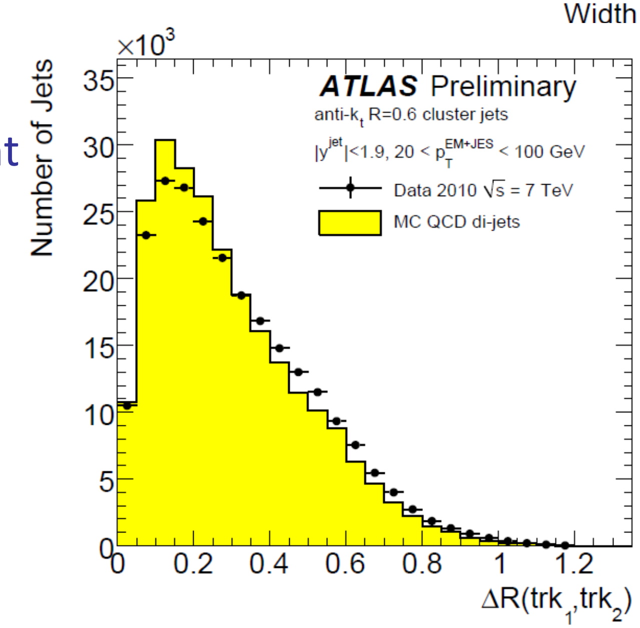
Calorimeter jet width in data and MC

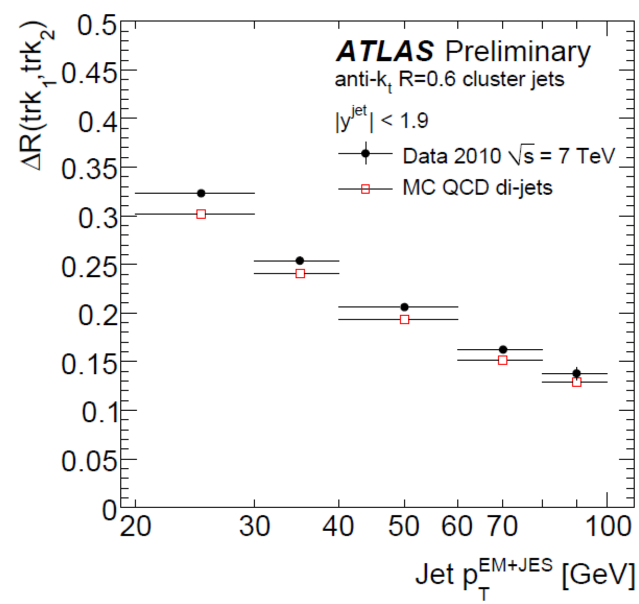




Track jet width estimate (independent measurement)



(a) $\Delta R(\mathrm{trk}_1, \mathrm{trk}_2)$ of the two hardest tracks in jets



(b) Dependence of $\Delta R(\mathrm{trk}_1, \mathrm{trk}_2)$ with p_T^{jet}

(ICHEP2010)

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Radial Jet Shapes in Tracking & Calorimeter

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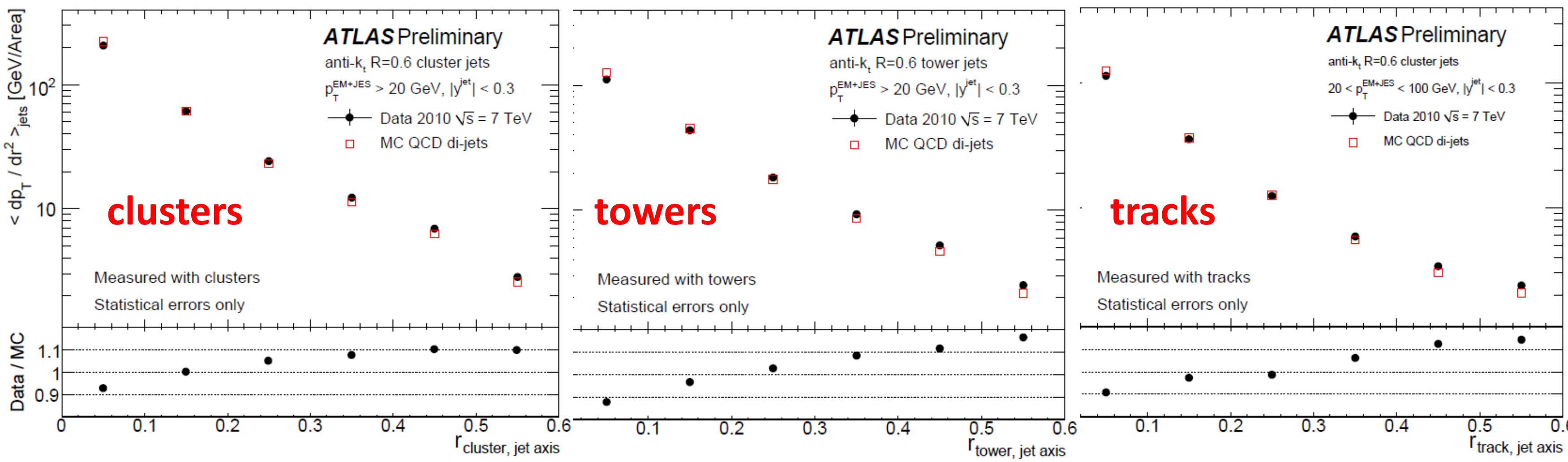

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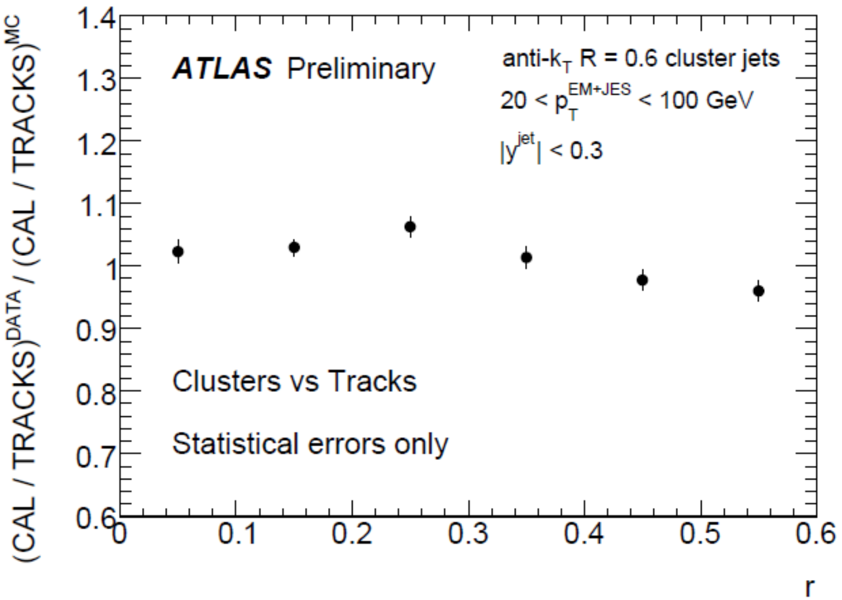

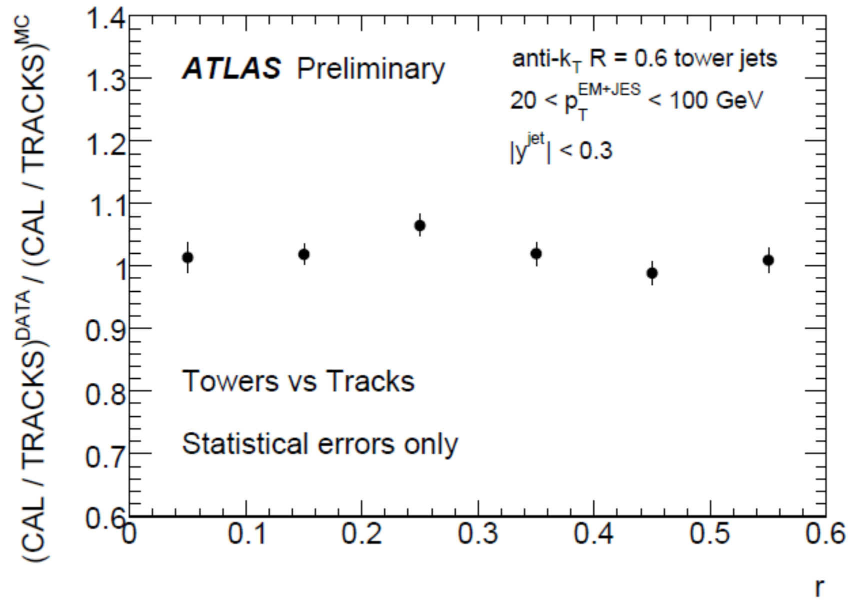

(ICHEP2010)

Potential physics message: fragmentation/UE different in data and MC – to be followed up!

Jet Distances

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Jets seem wider in data than in MC

- Direct width measurement
  - Track width confirms calorimeter observation
- Different composition
  - More towers and clusters in data

Indication of physics sources

- Nearby jet activity
  - More low pT jets close to hardest jet in data than in MC

Measurement

- Distance from hard jet to nearest (soft) jet
  - Hard jet pTmin < pT < pTmax
  - Neighbouring jet pT > 7 GeV
- Di-jet structure clearly emerges
  - Peak at π as expected from back-to-back scattering
- Far distance distribution well modeled
  - More small angle radiation in data?
  - Unclustered jet fragments?

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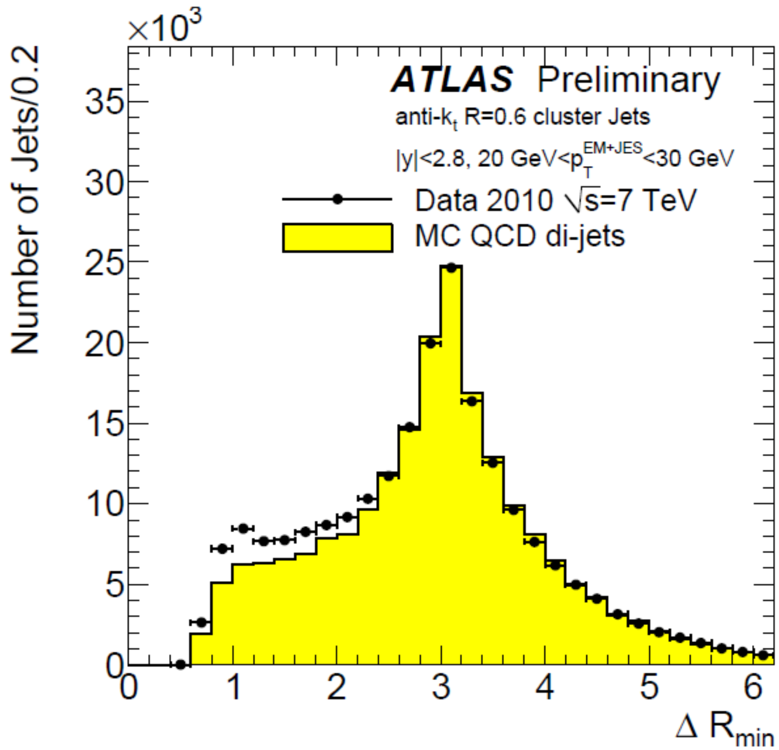
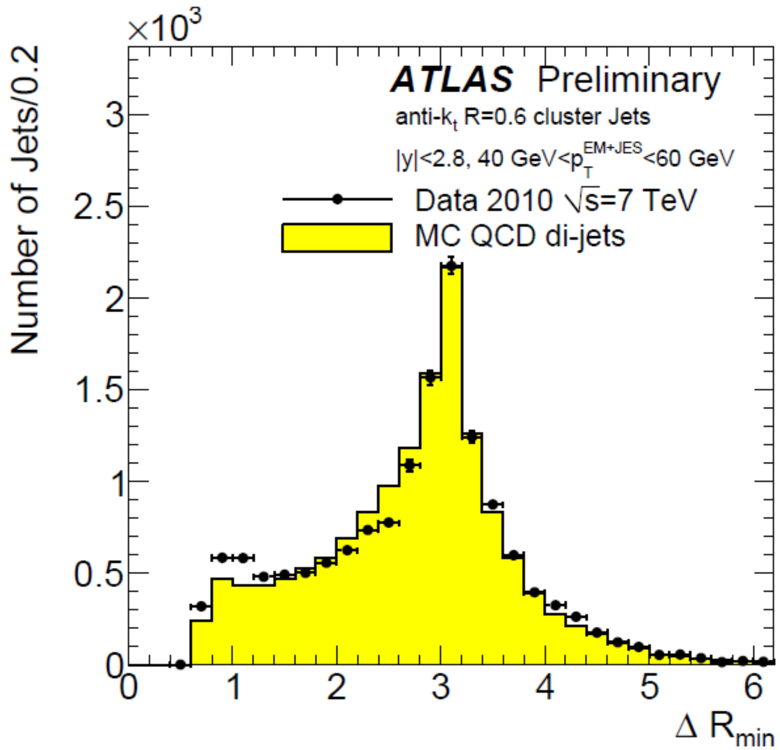




Jet Shape Analysis

Testing various MC models and tunes

- Differential radial jet shape
  - Reconstructed from clusters, corrected to particle level
- Unfolding procedure
  - Bin-by-bin (pT and eta) using fully simulated Pythia-Perugia2010 (best match to data)
  - Correction factors 0.95-1.1, typically

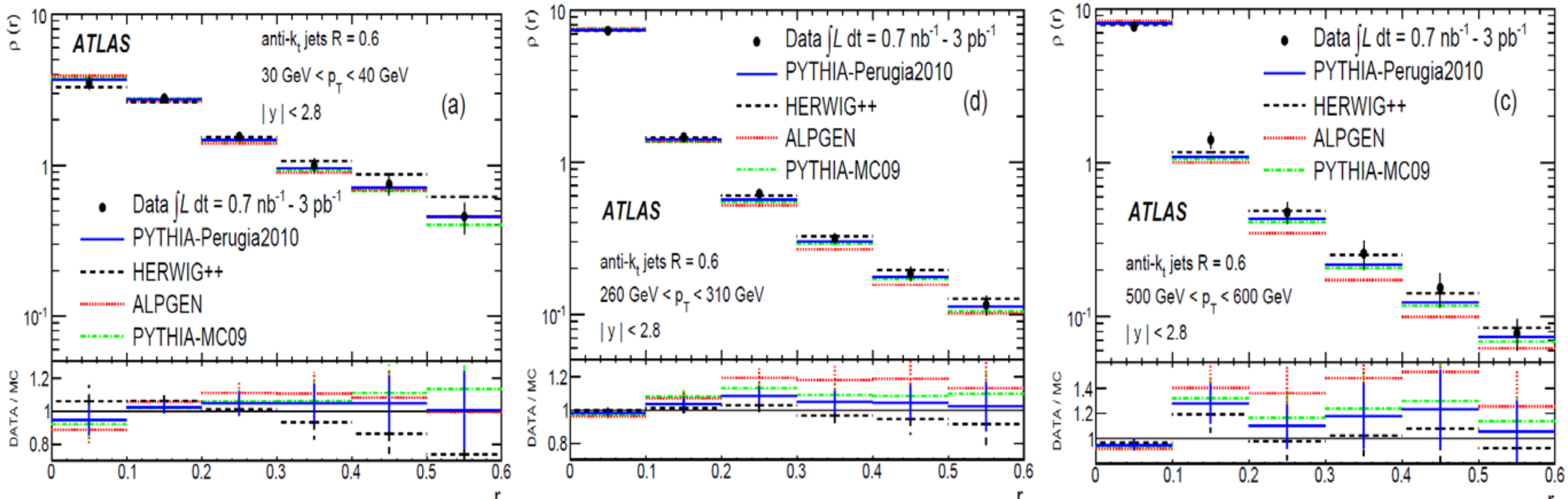
Differential jet shape:

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_{\text{T}}(r-\Delta r/2, r+\Delta r/2)}{p_{\text{T}}(0,R)}$$

with $\Delta r/2 \le r \le R - \Delta r/2$

Integrated jet shape:

$$\Psi(r) = \frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_{\text{T}}(0,r)}{p_{\text{T}}(0,R)} \text{ with } 0 \le r \le R$$

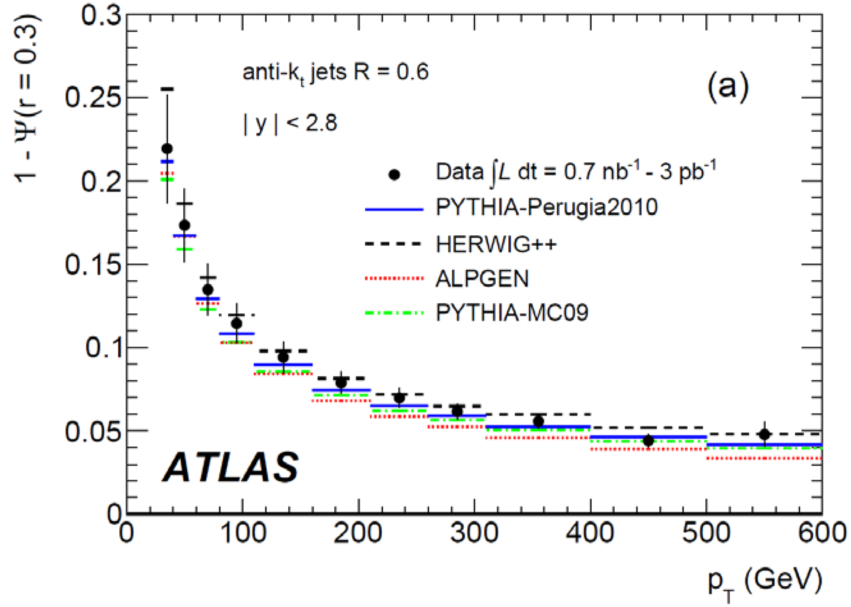


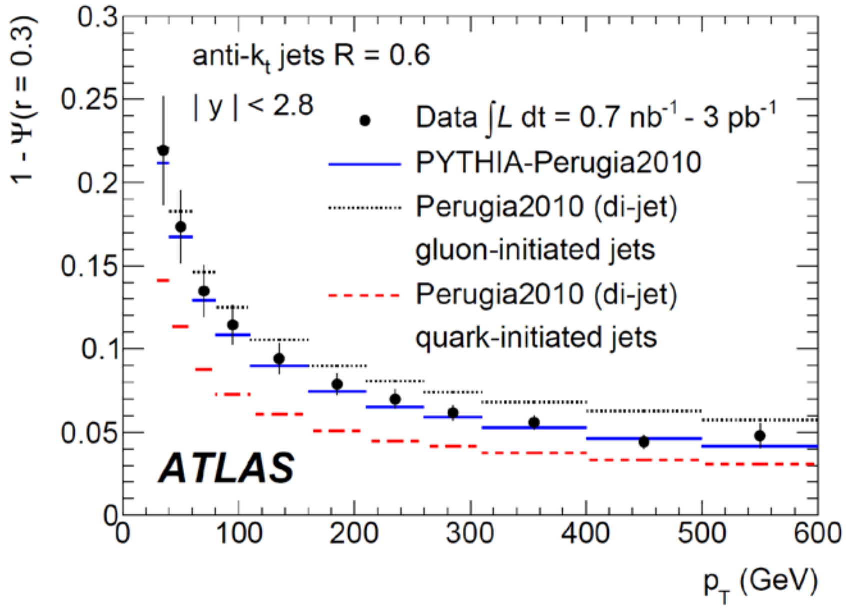
$30 \text{ GeV} < p_{\text{T,jet}} < 40 \text{ GeV}$ $260 \text{ GeV} < p_{\text{T,jet}} < 310 \text{ GeV}$ $500 \text{ GeV} < p_{\text{T,jet}} < 600 \text{ GeV}$

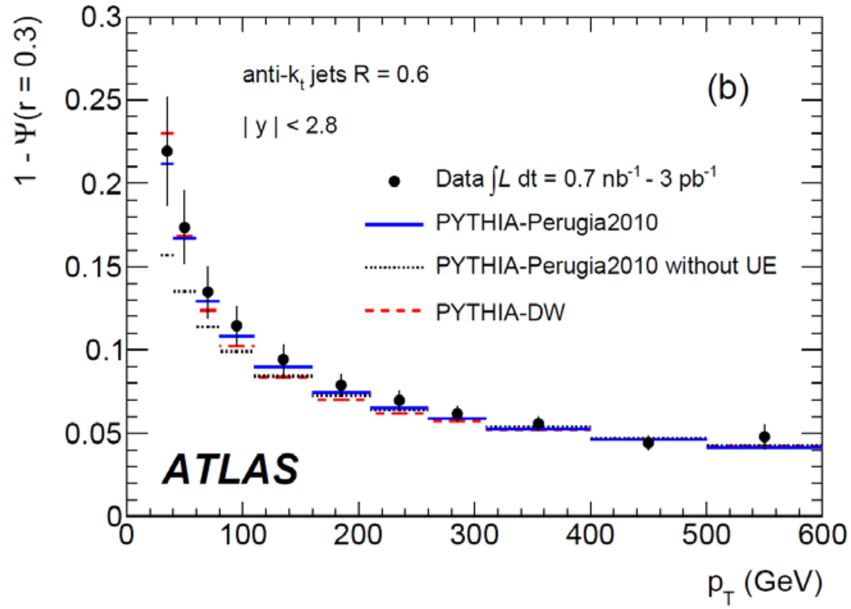
Integrated Jet Shapes

Testing various MC models and tunes

- Integrated jet shape
  - Measured as energy leaking out of a cone with radius 0.3 around the jet axis







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Conclusion & Outlook

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ATLAS jet reconstruction performed very well

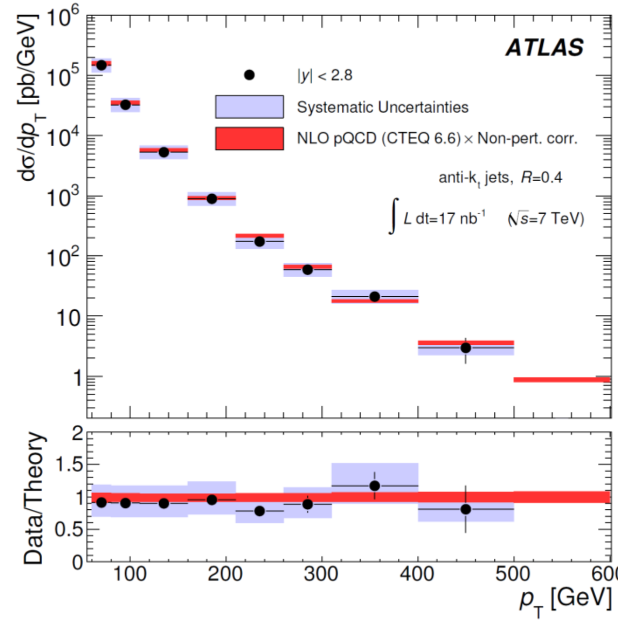
- Detailed understanding of jet reconstruction in first data
  - Topological cell clusters perform very well – formation and local calibration well understood
  - Also confirmed by missing transverse energy reconstruction
- Well motivated systematic jet energy scale error delivered quickly
  - Significant improvements expected in the next few weeks

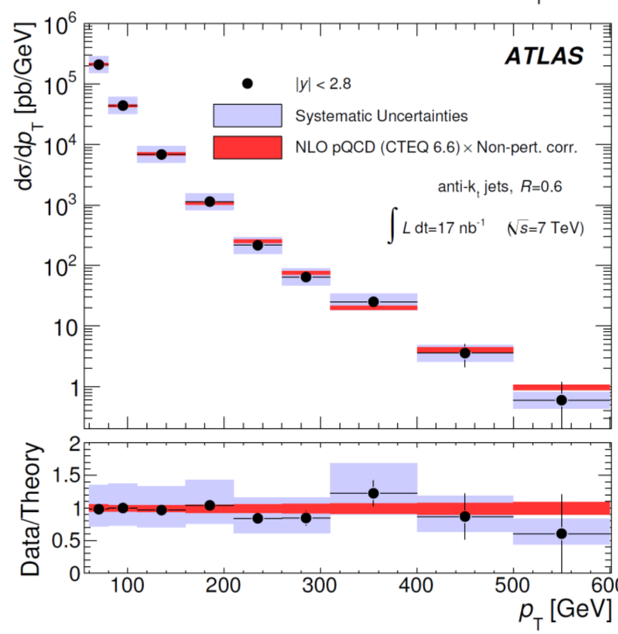
Some jet structures and shapes already well measured

- Cluster jets promising for substructure analysis
  - Need more studies for high pT jets to understand possible merging problem
- Indications that jets in data are wider than in MC (Pythia)
  - Calorimeter width measurement confirmed by jet width in tracker
- Jet substructure reconstruction and calibration under study
  - Local hadronic calibration seems applicable within small systematics – promising starting point for sub-jet calibration
  - Hope to increase data sample with jets including 2-prong (W) and 3-prong (top) hadronic decays
- Single jet mass reconstruction to be validated
  - Performance not yet completely understood – geometry effect in towers adds mass while hadronic shower merging in clusters reduces reconstructed mass

Lots of interesting aspects still to look at!

- And sorry for not being in Boston in person!





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Backup Slides

ATLAS Topological Cell Clusters (1)

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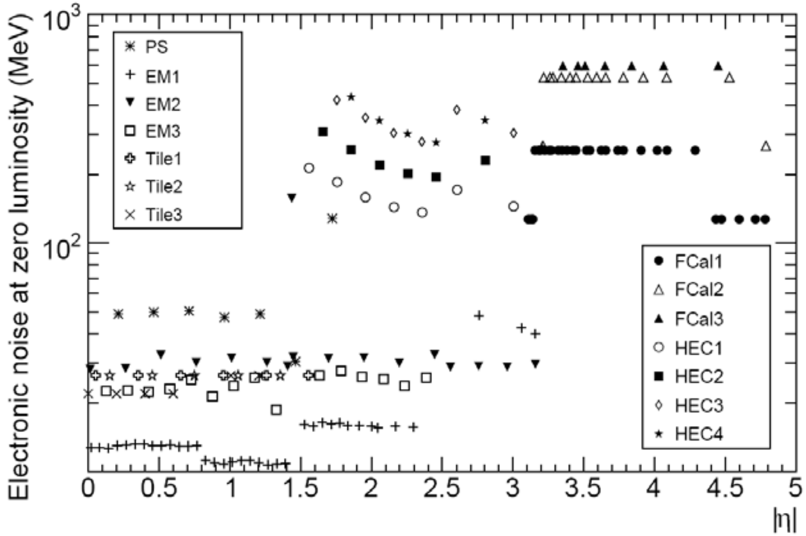
Signal extraction tool

- Attempt reconstruction of individual particle showers
  - Reconstruct 3-dim clusters of cells with correlated signals
- Use shape of these clusters to locally calibrate them
  - Explore differences between electromagnetic and hadronic shower development and select best suited calibration
- Supress noise with least bias on physics signals
  - Often less than 50% of all cells in an event with "real" signal



JINST 3:S08003, 2008

Some implications of jet environment

- Shower overlap cannot always be resolved
  - Clusters represent merged particle showers in dense jets
- Clusters have varying sizes
  - No simple jet area as in case of towers
- Clusters are mass-less 4-vectors (as towers)
  - No "artificial" mass contribution due to showering
- Issues with IR safety at very small scale insignificant
  - Pile-Up environment triggers split as well as merge
  - Note that calorimeters themselves are not completely IR safe

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ATLAS Topological Cell Clusters (2)

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Cluster seeding

- Cluster seed is cell with significant signal above a primary threshold

Cluster growth: direct neighbours

- Neighbouring cells (in 3-d) with cell signal significance above some basic threshold are collected

Cluster growth: control of expansion

- Collect neighbours of neighbours for cells above secondary signal significance threshold
  - Secondary threshold lower than primary (seed) threshold

Cluster splitting

- Analyze clusters for local signal maxima and split if more than one found
  - Signal hill & valley analysis in 3-d

Final "energy blob" can contain low signal cells

- Cells survive due to significant neighbouring signal
- Cells inside blob can have negative signals

ATLAS also studies "TopoTowers"

- Use topological clustering as noise suppression tool only
- Distribute only energy of clustered cells onto tower grid
- Motivated by DZero approach

ATLAS Topological Cell Clusters (3)

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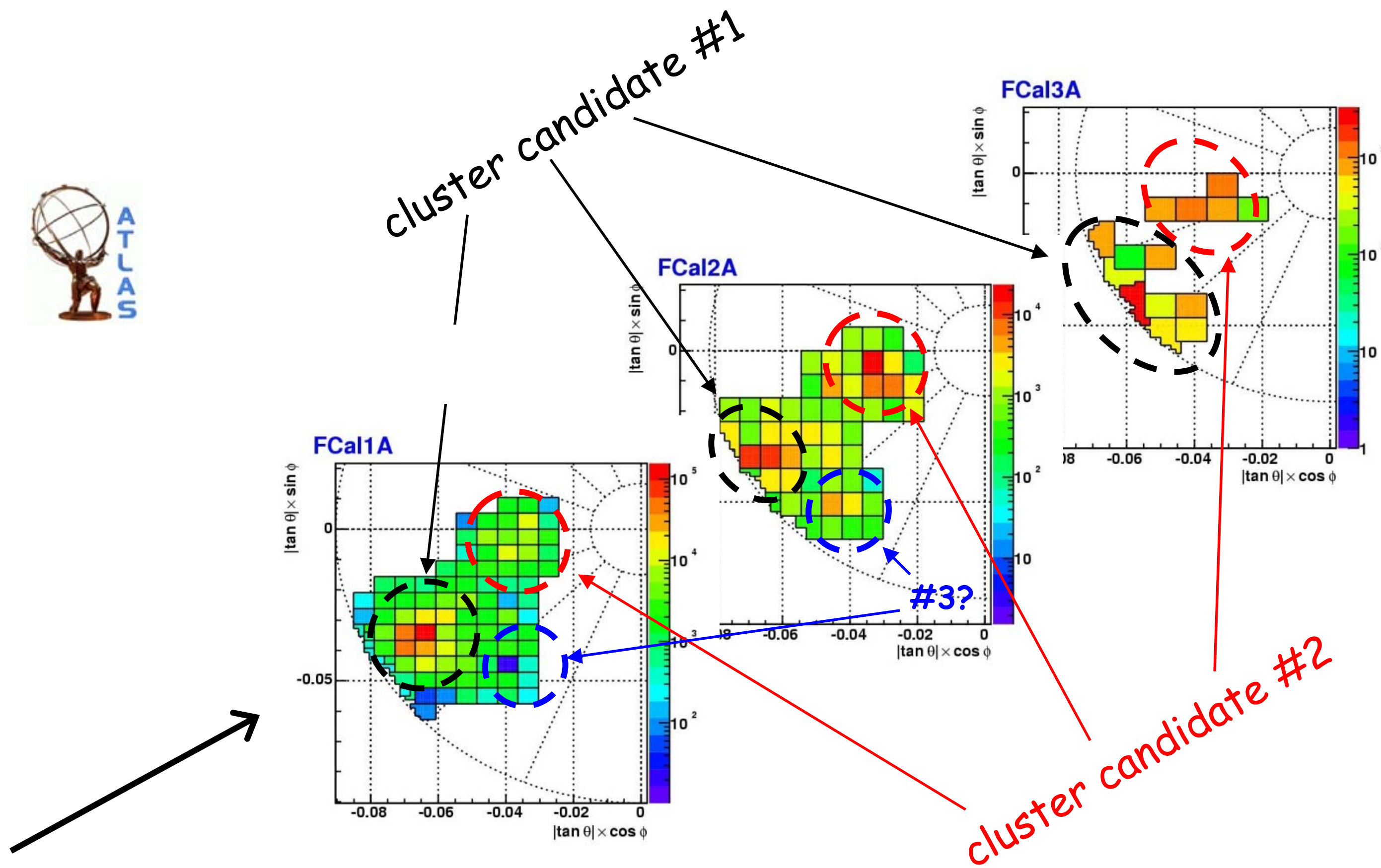

- **Local hadronic energy scale restauration depends on origin of calorimeter signal**
  - Attempt to classify energy deposit as electromagnetic or hadronic from the cluster signal and shape
    - Allows to apply specific corrections and calibrations
- **Local calibration approach**
  - Use topological cell clusters as signal base for a hadronic energy scale
    - Recall cell signals need context for hadronic calibration
  - Basic concept is to reconstruct the locally deposited energy from the cluster signal first
    - This is not the particle energy
  - Additional corrections for energy losses with some correlation to the cluster signals and shapes extend the local scope
    - True signal loss due to the noise suppression in the cluster algorithm (still local)
    - Dead material losses in front of, or between sensitive calorimeter volumes (larger scope than local deposit)
- **After all corrections, the reconstructed energy is on average the isolated particle energy**
  - E.g., in a testbeam
    - But not the jet energy

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ATLAS Local Scale Sequence

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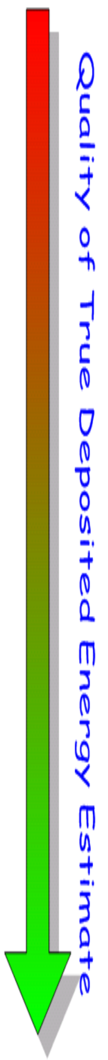

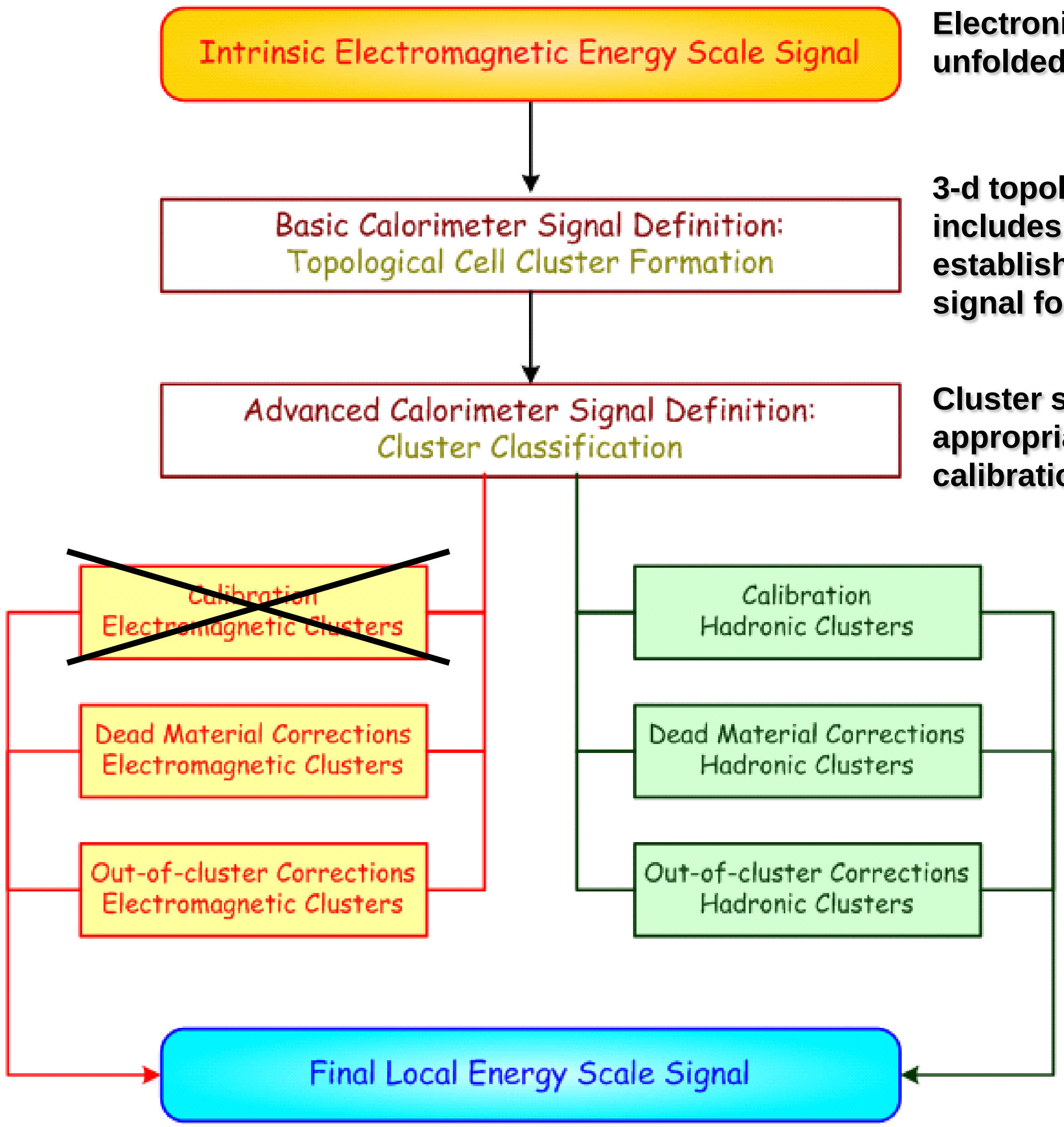

Electronic and readout effects unfolded (nA->GeV calibration)

3-d topological cell clustering includes noise suppression and establishes basic calorimeter signal for further processing

Cluster shape analysis provides appropriate classification for calibration and corrections

Cluster character depending calibration (cell signal weighting for HAD, to be developed for EM?)

Apply dead material corrections specific for hadronic and electromagnetic clusters, resp.

Apply specific out-of-cluster corrections for hadronic and electromagnetic clusters, resp.