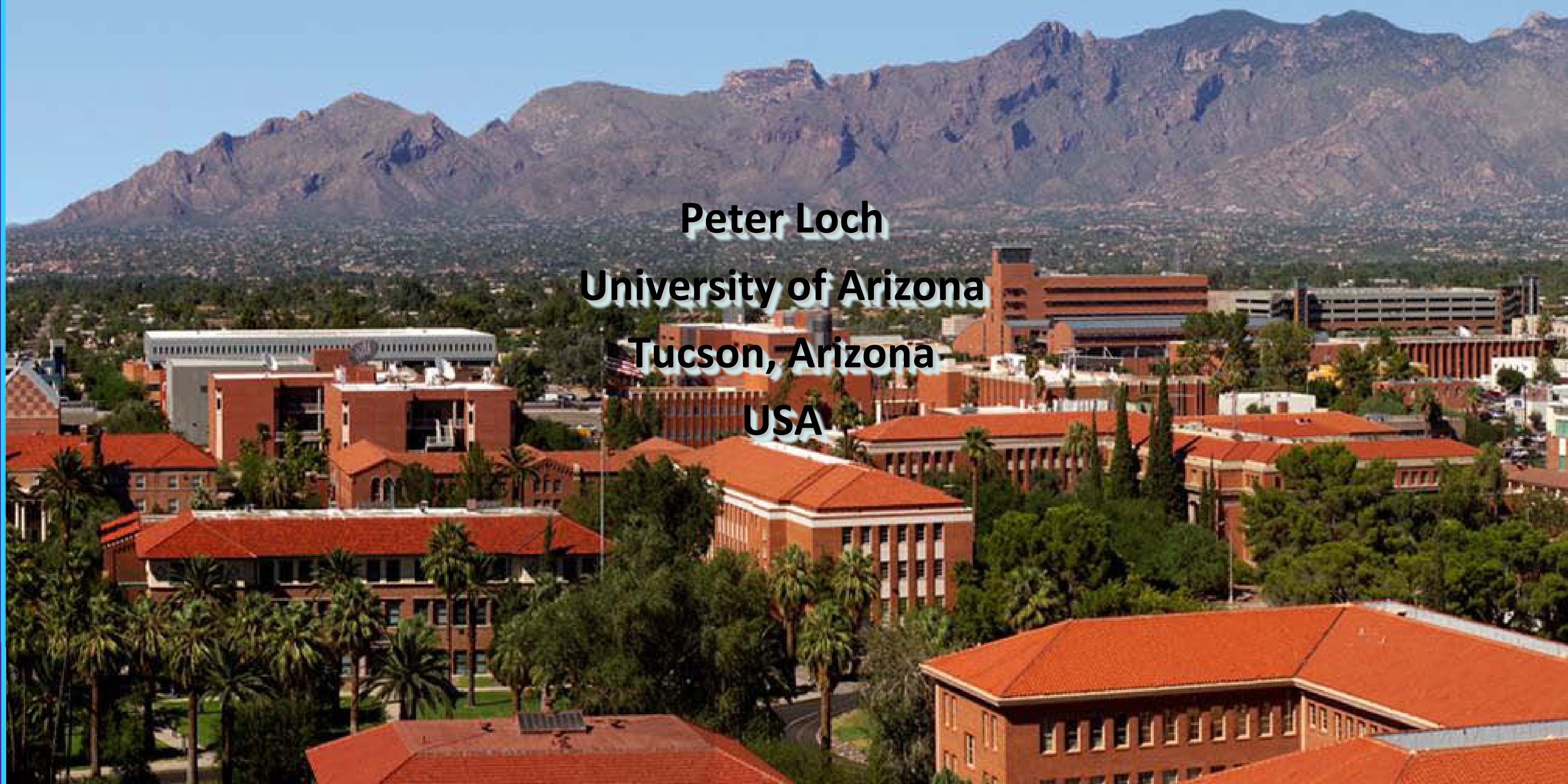
Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part XI)

Peter Loch
University of Arizona
Tucson, Arizona
USA



Cluster Calibration

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General cluster features

- Motivated by shower reconstruction
  - No bias in signal definition towards reconstruction of a certain, possibly very specific, physics signal object like a jet
- Clusters have shapes and location information
  - Spatial cell energy distributions and their correlations drive longitudinal and lateral extensions
  - Density and energy sharing measures
  - Signal center of gravity and (directional) barycenter
- Shapes are sensitive to shower nature
  - At least for a reasonable clustering algorithm

Local (cluster) calibration strategy

- First reconstruct truly deposited energy at cluster location…
  - e/h, mostly
- …then correct for other energy losses in the vicinity of signal cluster
  - Dead material energy losses and signal losses due to noise suppression

Calibration input

- Reconstructed cluster shapes represent shower shapes
  - E.g., dense and compact clusters indicate electromagnetic shower activity anywhere in the calorimeter
    - Can be intrinsic to a hadronic shower!
  - Calibration functions can exploit the cluster shapes to apply the corrections for $e/h \neq 1$ dynamically
- Location of cluster together with shape
  - E.g., dense and compact clusters located in electromagnetic calorimeter indicate electron or photon as particle originating the signal
    - Cluster not (part of) hadronic shower signal!
  - Clusters can classified before calibration
    - Electron/photon clusters need different calibration than dense clusters from hadronic showers!

Cluster calibration extensions

- Shapes, location and size also indicate possible energy losses around the cluster
  - Some correlations between energy losses in inactive material in front or inside of clusters
- Cluster size and signal neighbourhood sensitive to lost true signal in noise suppression algorithm
  - Out-of-cluster corrections

ATLAS

Cluster Calibration Sequence

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U of Arizona
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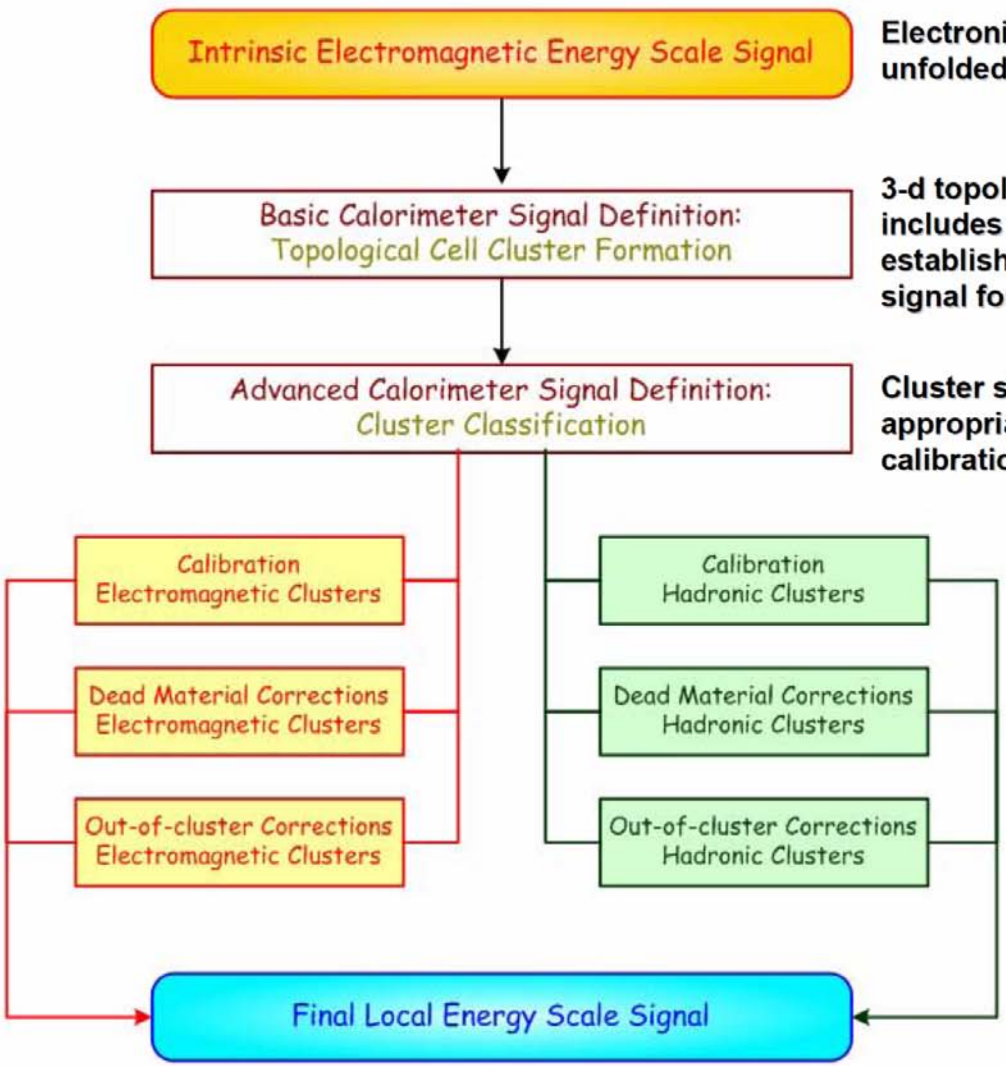


Electronic and readout effects unfolded (nA->GeV calibration)

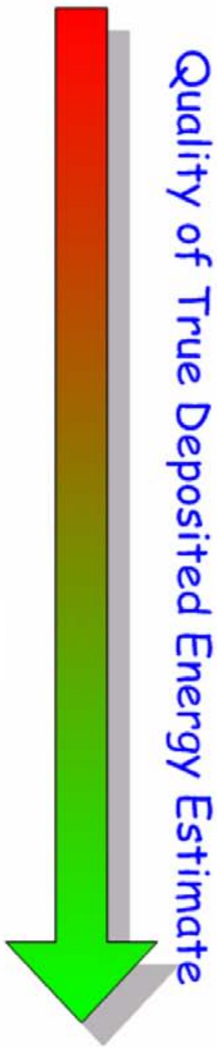
3-d topological cell clustering includes noise suppression and establishes basic calorimeter signal for further processing

Cluster shape analysis provides appropriate classification for calibration and corrections

Cluster character depending calibration

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

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



Phase-space pion counting method

Classify clusters using the correlation of

Shower shape variables in single $\pi^{\pm}$ MC events

$$\lambda_{\text{cluster}} = \text{cluster center of gravity depth in calorimeter}$$

$$\bar{\rho}_{\text{cluster}} = \frac{1}{E_{0,\text{cluster}}} \sum_{\text{cells in cluster}} E_{0,\text{cell}} \cdot \rho_{\text{cell}}$$

Electromagnetic fraction estimator in bin of shower shape variables:

$$F \equiv \frac{\varepsilon(\pi^0)}{\varepsilon(\pi^0) + 2\varepsilon(\pi^-)}$$

$$\varepsilon(X) = \frac{N(X) \text{ producing a cluster in a given } (\eta, E_{0,\text{cluster}}, \lambda_{\text{cluster}}, \bar{\rho}_{\text{cluster}})}{N(X) \text{ total}}$$

Implementation

keep F in bins of η, E, λ, ρ of clusters for a given cluster

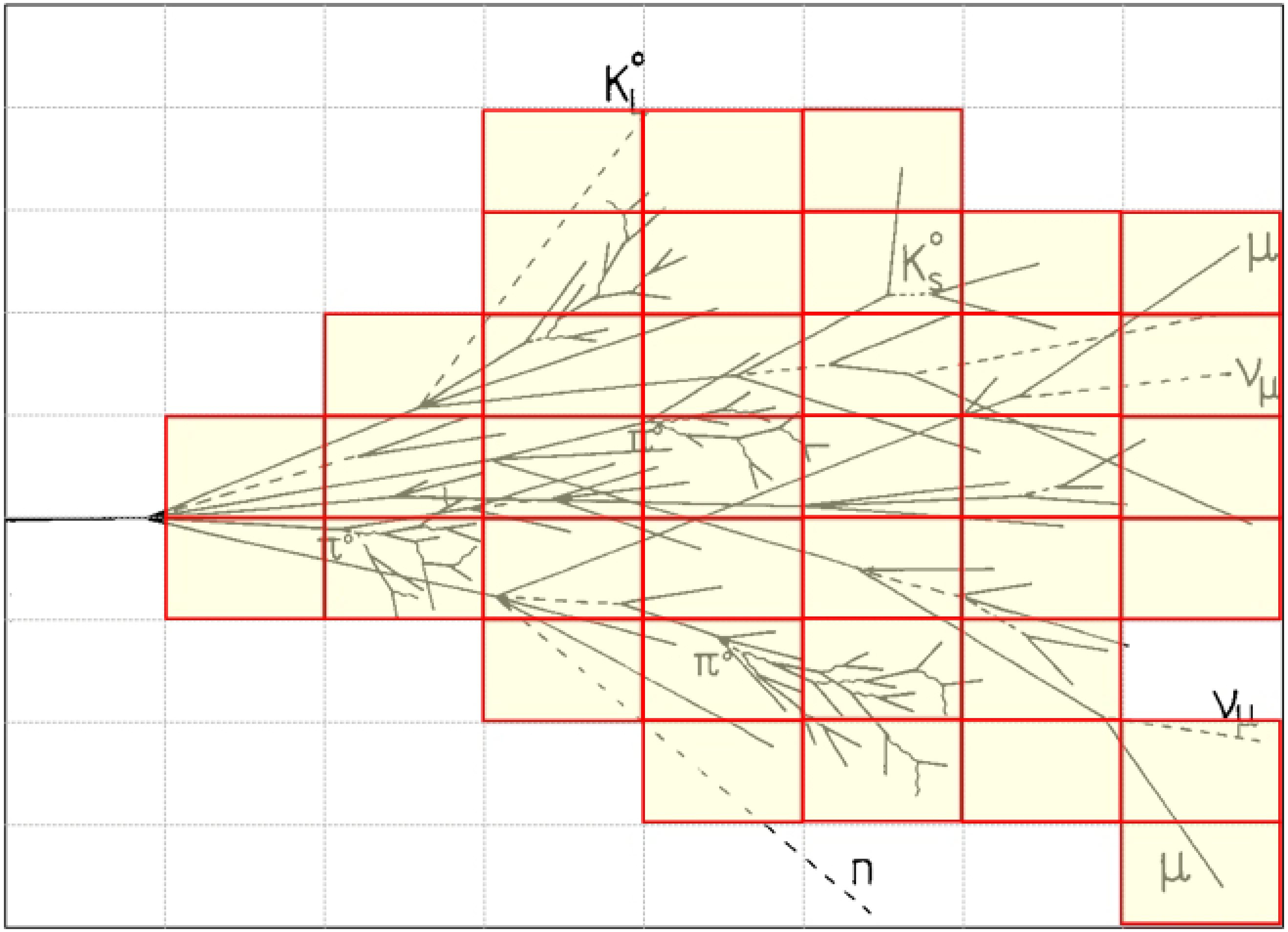
If $E < 0$, then classify as unknown

Lookup F from the observables $|\eta|$, E, λ, ρ

Cluster is EM if $F > 50\%$, hadronic otherwise

Calibration with cell signal weights

- Idea is to compensate for lack of pion response in each cell
  - Pioneered in CDHS and applied in H1



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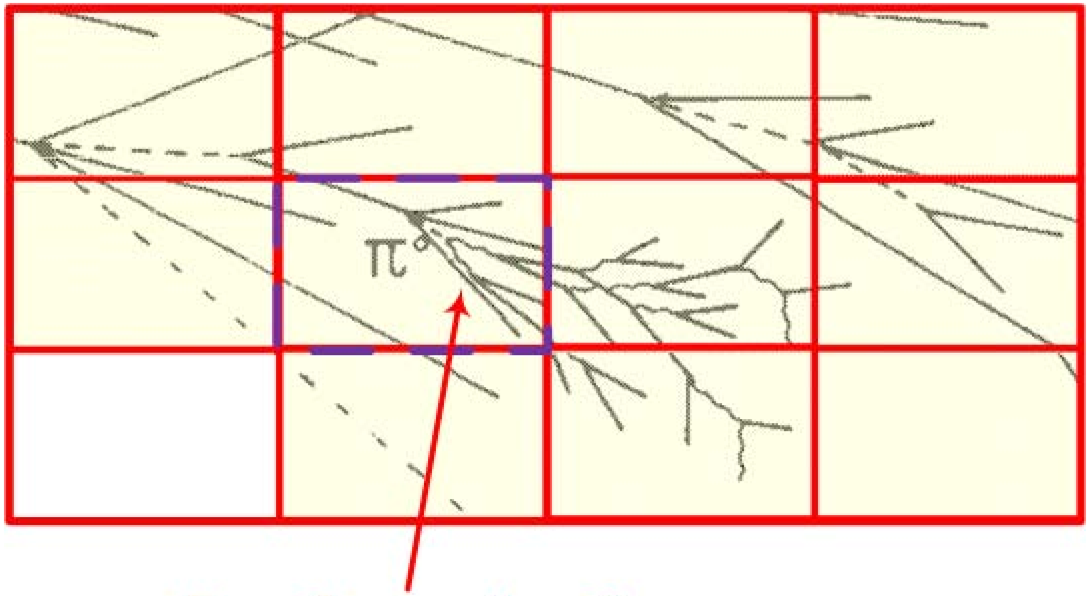

$$E_{\text{cell}}^{\text{em}} = \left[E_{\text{cell}}^{\text{em}}\right]_{\text{active}} + \left[E_{\text{cell}}^{\text{em}}\right]_{\text{passive}}$$

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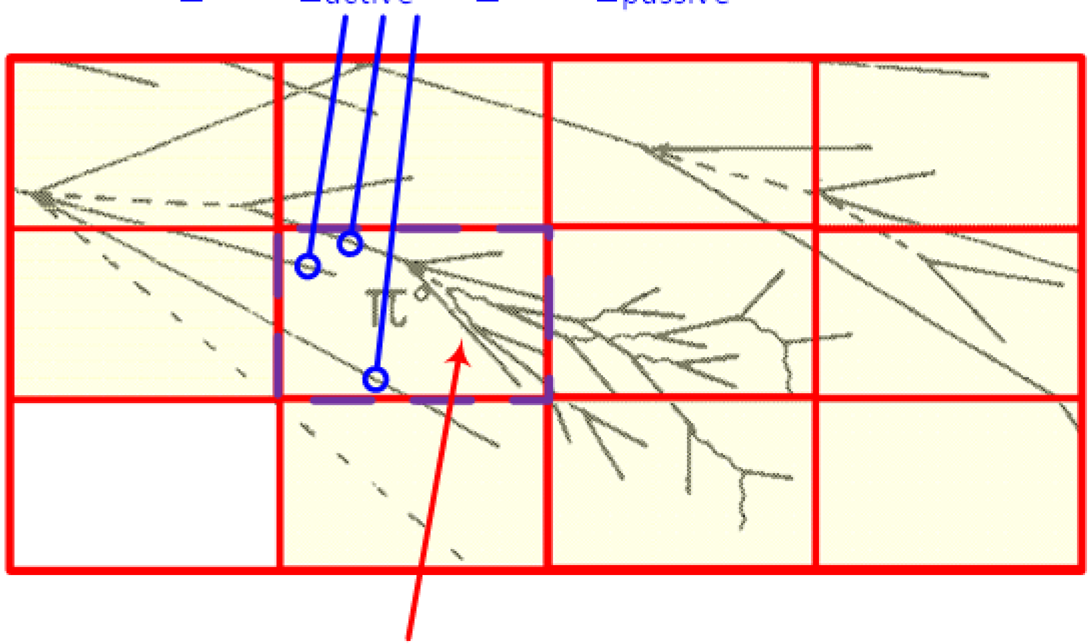

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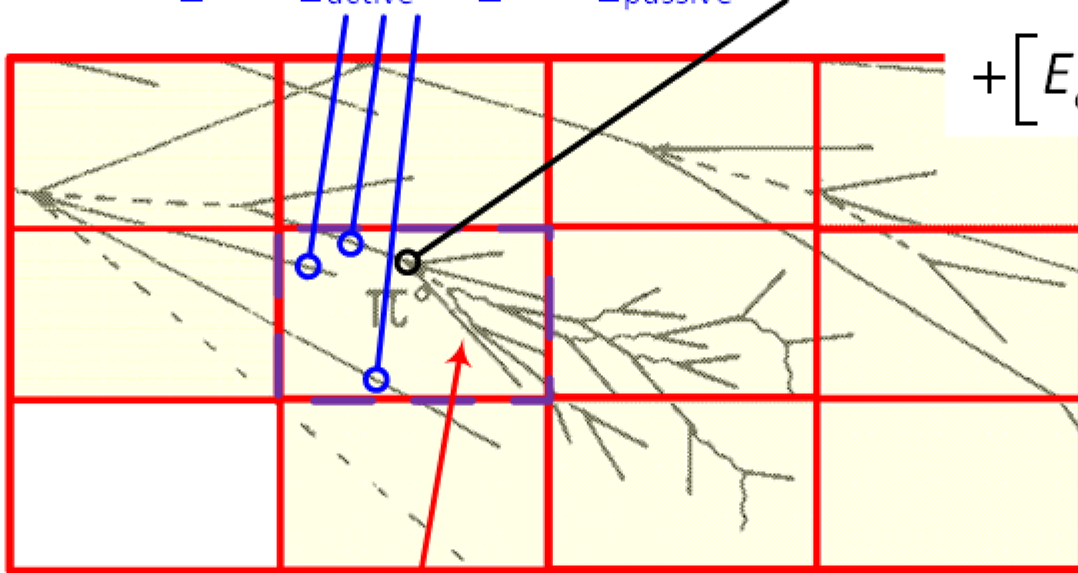

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Calibration with cell signal weights

- Idea is to compensate for lack of pion response in each cell
  - Pioneered in CDHS and applied in H1
- Uses deposited energies in cells
  - Deposit can be in active or passive medium of calorimeter!

$$w_{\text{cell,cluster}}^{\text{calib}} = \left\langle \frac{\underbrace{E_{\text{deposited,cell}} = E_{\text{cell}}^{\text{em}} + E_{\text{cell}}^{\text{ion}} + E_{\text{cell}}^{\text{invisible}} + E_{\text{cell}}^{\text{escaped}}}_{\text{"deposited" energy anywhere within cell boundaries}}}{\underbrace{E_{0,\text{cell}} = c_{\text{em}} \cdot A\left(\left[E_{\text{cell}}^{\text{em}} \oplus E_{\text{cell}}^{\text{ion}}\right]_{\text{active}}, t, \vec{x}, \ldots\right)}_{\text{reconstructed em scale signal}}} \right\rangle$$

($E_{\text{cell}}^{\text{escaped}}$ is the energy escaping the calorimeter, i.e. carried by neutrinos - it is often assigned to the cell in which the neutrino vertex is located)

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Only signal contribution from energy deposited by electromagnetic sub-showers and through ionization by charged particles!

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Energy deposited in cell not available in experiment

- Use of detector simulations
  - Deposited energy and signal available
  - Use "unit cell" volume concept to collect invisible energies
  - Shower model dependent!
- Use single pion testbeam data
  - Develop model for weights in cells
  - Fit parameters of model using cells testbeam
    - Minimize resolution with beam energy constraint
  - Statistical – does not necessarily produce the correct weights!

Cell Signal Weights

Basic idea

- Use a dynamically self-adjusting calibration weight
  - High cell signal density → electromagnetic deposit
  - Low cell signal density → hadronic deposit
- Principal weighting function characteristics
  - Depends on cell energy density
  - Depends on cell location
  - Accidental application to electron signals should yield correct energy as well

Extraction of weighting functions

- Minimize resolution in (pion) testbeam data
  - Fitting function model
  - May not produce the correct weights – may even be unphysical!
- Use simulation
  - Deterministic approach relates signal to deposited energy within cell volume – no fitting!
  - May depend on details of (hadronic) shower modeling

$$E_{\text{rec,cell}} = w_{\text{cell}}(\ldots) \cdot E_{0,\text{cell}} = E_{\text{deposited,cell}}$$

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$$w_{\mathrm{cell}}(\ldots) = w(\rho_{\mathrm{cell}} = E_{0,\mathrm{cell}} / V_{\mathrm{cell}}, \vec{x}, \ldots)$$

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e.g. in H1:

$$E_{\text{rec,cell}} = \underbrace{\left(1 + \alpha(\vec{x}, \ldots) \cdot e^{-\beta(\vec{x},\ldots)\cdot \rho_{\text{cell}}}\right)}_{= w(\rho_{\text{cell}}, \vec{x}, \ldots)} \cdot E_{0,\text{cell}},$$

with $\lim_{\rho_{\text{cell}} \to \infty} E_{\text{rec,cell}} = E_{0,\text{cell}}$

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Fit $\alpha(\vec{x},\ldots)$, $\beta(\vec{x},\ldots)$ with

$$\chi^2 = \sum_{\text{events}} \frac{\left(E_{\text{rec,cell}} - E_{\text{beam}}\right)^2}{\sigma^2} = \min$$

i.e.:

$$\frac{\partial \chi^2}{\partial \alpha} = 0 \text{ and } \frac{\partial \chi^2}{\partial \beta} = 0$$

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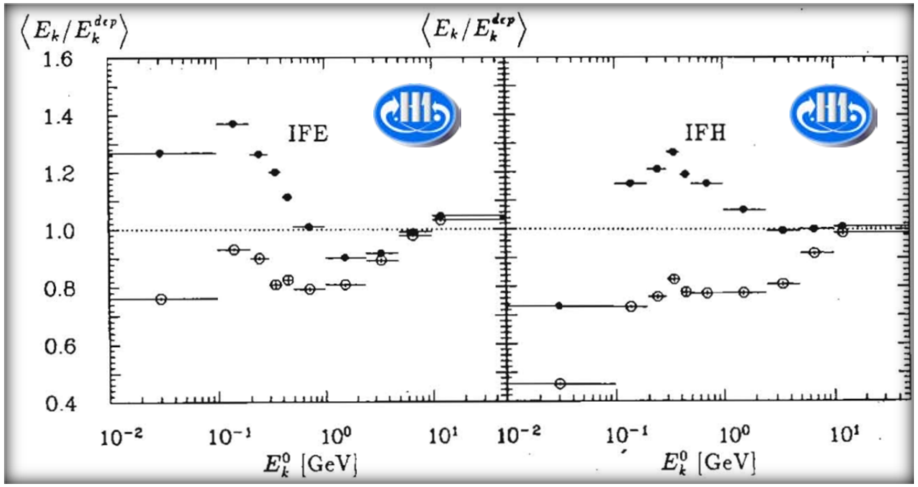

○ $\frac{E_{\text{rec,cell}}}{E_{0,\text{cell}}}$ ● $\frac{E_{\text{deposited,cell}}}{E_{0,\text{cell}}}$

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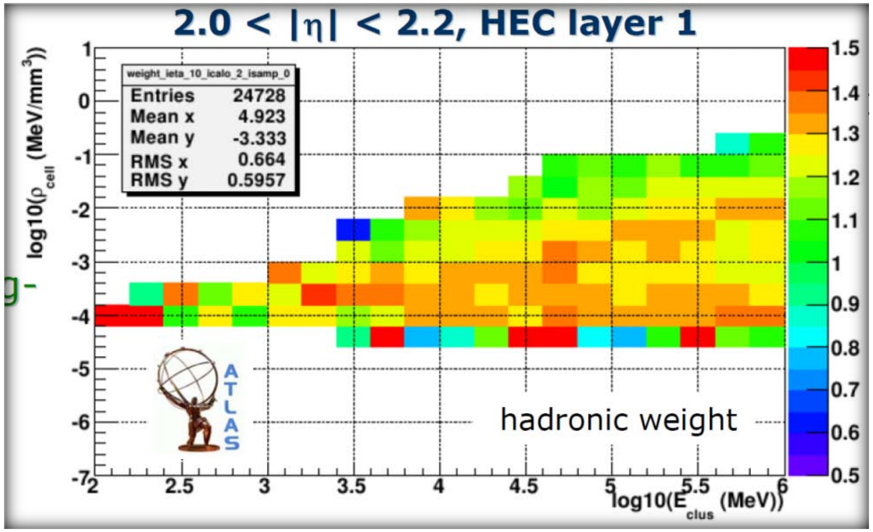
ATLAS cluster-based approach:

1. Use only cells in hadronic clusters
2. Cluster sets global energy scale as a reference for densities
3. Calculate $E_{deposited,cell}/E_{0,cell}$ from single pion simulations in bins of cluster energy, cell energy density, cluster direction, and calorimeter sampling layer
4. Store $[E_{deposited,cell}/E_{0,cell}]^{-1}$ in look-up tables



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4. Store $[E_{\mathrm{deposited,cell}}/E_{0,\mathrm{cell}}]^{-1}$ in look-up tables
5. Retrieve weights for any cell in any cluster from look-up table to reconstruct cell and cluster energies

$$E_{\mathrm{rec,cluster}}^{\mathrm{calib}} = \sum_{\text{cells in cluster}} E_{\mathrm{rec,cell}} = \sum_{\text{cells in cluster}} w_{\mathrm{cell,cluster}}^{\mathrm{calib}}\left(E_{0,\mathrm{cluster}}, \eta_{\mathrm{cluster}}, S_{\mathrm{cell}}, \rho_{\mathrm{cell}}\right) \cdot E_{0,\mathrm{cell}}$$

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Cluster Dead Material Corrections

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U of Arizona
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Dead material

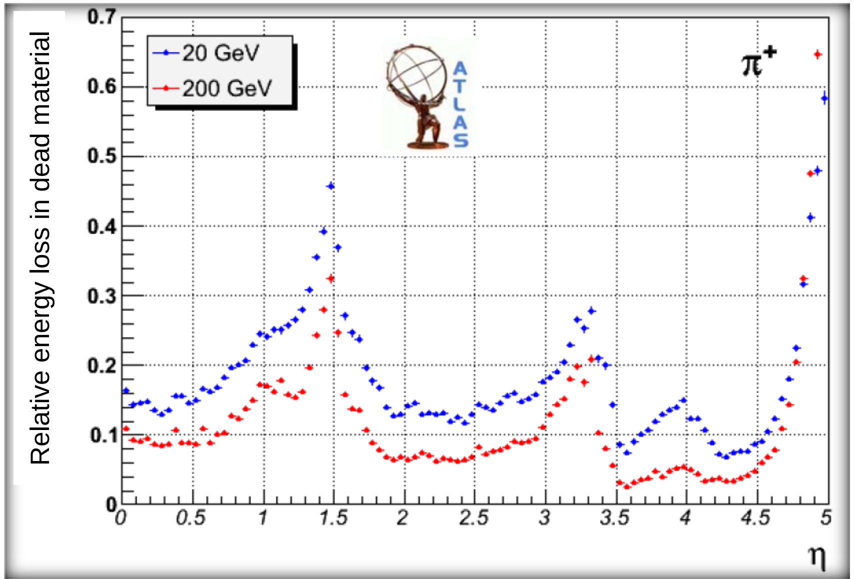
- Energy losses not directly measurable
  - Signal distribution in vicinity can help
- Introduces need for signal corrections up to O(10%)
  - Exclusive use of signal features
  - Corrections depend on electromagnetic or hadronic energy deposit
- Major contributions
  - Upstream materials
  - Material between LArG and Tile (central)

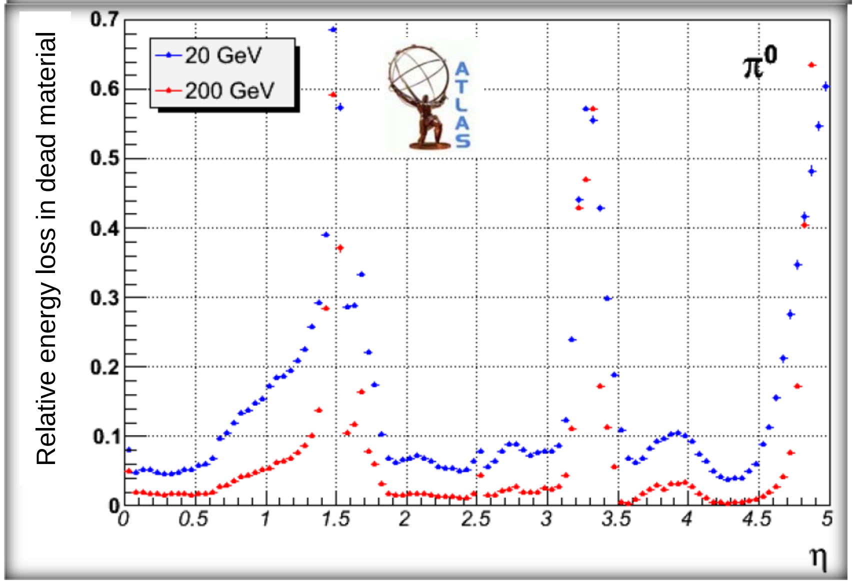
Cracks

- dominant sources for signal losses
  - |η|≈1.4-1.5
  - |η|≈3.2
- Clearly affects detection efficiency for particles and jets
  - Already in trigger!
  - Hard to recover jet reconstruction inefficiencies
- Generate fake missing Et contribution
  - Topology dependence of missing Et reconstruction quality

Additive correction:

$$E_{\text{rec,cluster}}^{\text{calib+DM}} = E_{\text{rec,cluster}}^{\text{calib}} + E_{\text{rec,cluster}}^{\text{DM}}(\vec{x}_{\text{cluster}}, \ldots)$$





Out-of-cluster Corrections

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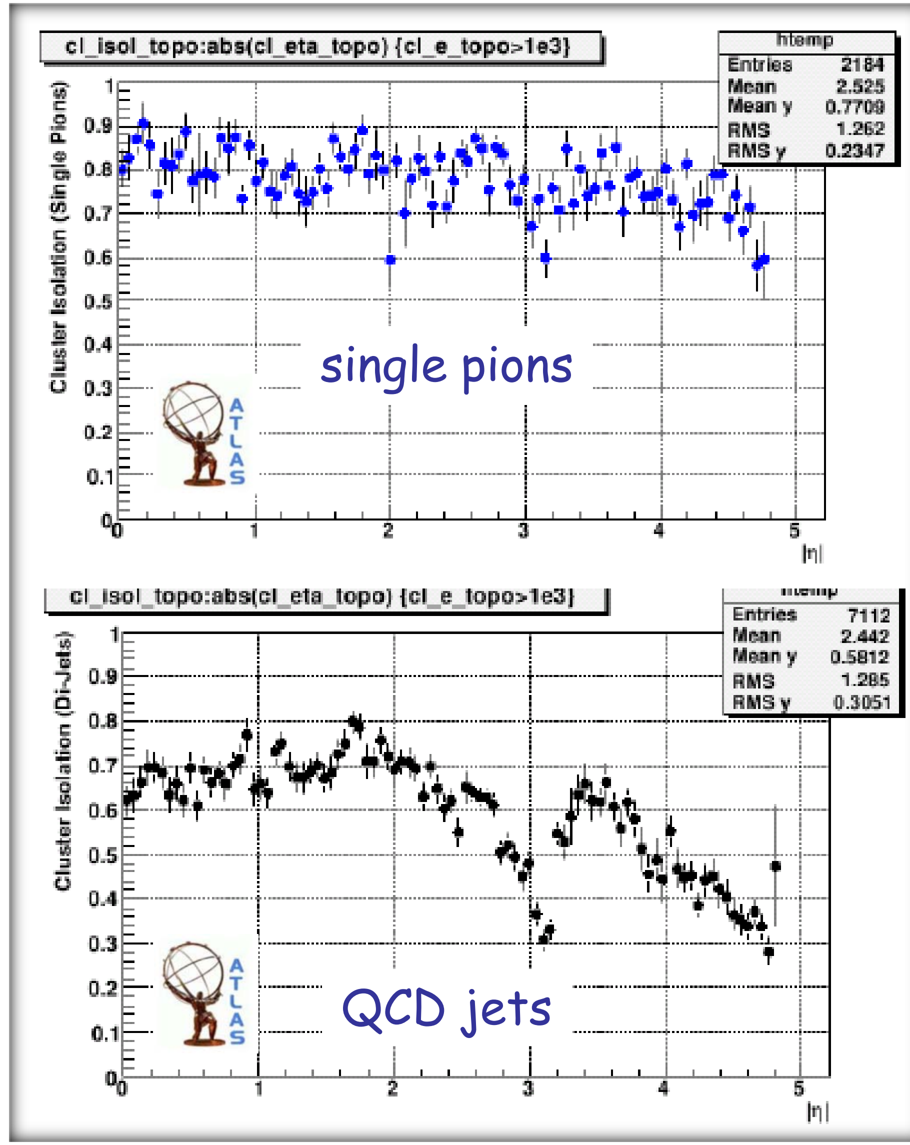
Compensate loss of true signal

- Limited efficiency of noise suppression scheme
  - Discard cells with small true energy not close to a primary or secondary seed
  - Accidental acceptance of a pure noise cell
- Can be significant for isolated pions
  - 10% at low energy
- Correction derived from single pions
  - Compensates the isolated particle loss
  - But in jets neighboring clusters can pick up lost energy
- Use isolation moment to measure effective "free surface" of each cluster
  - Scale single pion correction with this moment (0…1)



Additive correction:

$$E_{\text{rec,cluster}}^{\text{calib+DM+OOC}} = E_{\text{rec,cluster}}$$

$$= E_{\text{rec,cluster}}^{\text{calib+DM}} + E_{\text{rec,cluster}}^{\text{OOC}}(\vec{x}_{\text{cluster}}, m_{\text{isol}}, E_{0,\text{cluster}}, \ldots)$$

Local Calibration Features

P. Loch
U of Arizona
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Attempt to calibrate hadronic calorimeter signals in smallest possible signal context

- Topological clustering implements noise suppression with least bias signal feature extraction
  - Residual concerns about infrared safety!
- No bias towards a certain physics analysis
  - Calibration driven by calorimeter signal features without further assumption
- Good common signal base for all hadronic final state objects
  - Jets, missing Et, taus

Factorization of cluster calibration

- Cluster classification largely avoids application of hadronic calibration to Electromagnetic signal objects
  - Low energy regime challenging
- Signal weights for hadronic calibration are functions of cluster and cell parameters and variables
  - Cluster energy and direction
  - Cell signal density and location (sampling layer)
- Dead material and out of cluster corrections are independently applicable
  - Factorized calibration scheme

Local calibration does not reproduce jet energy

- Energy losses not correlated with cluster signals can not be corrected
  - Magnetic field losses
  - Dead material losses
- Needs additional jet energy scale corrections
  - Use specific jet context to derive those

Only applicable to cluster jets!

$$E_{true}^{jet} = E_{dep}^{calo} + E_{mag}^{loss} + E_{low}^{loss} + E_{leak}^{loss} + E_{out}^{loss} - E_{UE\otimes PU}^{gain} - E_{env}^{gain}$$

E_{dep}^{calo}	energy deposited in the calorimeter within signal definition
E_{mag}^{loss}	charged particle energy lost in solenoid field
E_{low}^{loss}	particle energy lost in dead material
E_{leak}^{loss}	energy lost due to longitudinal leakage
E_{out}^{loss}	energy lost due to jet algorithm/calorimeter signal definition
$E_{UE\otimes PU}^{gain}$	energy added by underlying event and/or pile-up
E_{env}^{gain}	energy added by response from other nearby particles/jets

only source of signal!

Global Calibration Techniques

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Use jet context for cell calibration

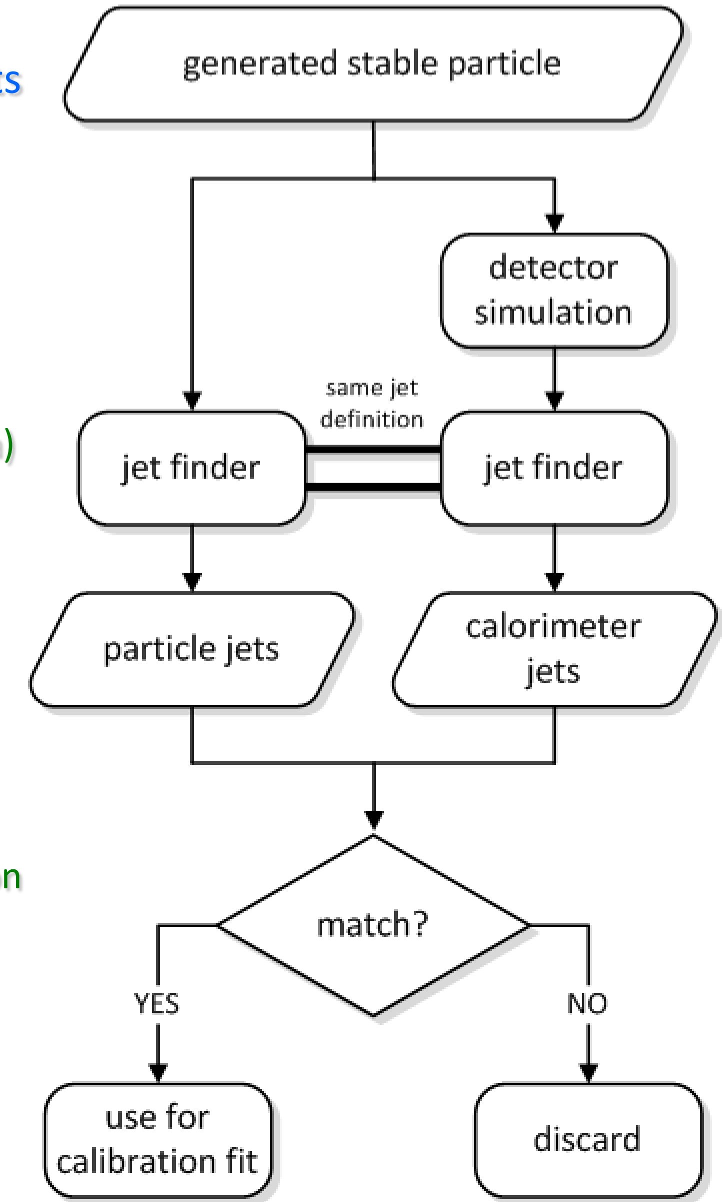
- Determine cell weights using jet energy constraints
  - Same principle idea as for local cell weighting, but different global energy scale
  - Needs jet truth reference
- Jet context relevant
  - Supports assumption of hadronic signal activity
  - Has enhanced electromagnetic component contributing to the weighting function parameterizations of all cells – larger (volume/area) context than topological clustering
  - May be biased with respect to calorimeter signal definition and jet algorithms

Jet energy references for calorimeter jets

- Simulation
  - Matching particle level jet (same jet definition) energy
- Experiment
  - pT balance with electromagnetic system like photon or Z-boson
  - W mass spectroscopy

Sampling energy based jet calibration

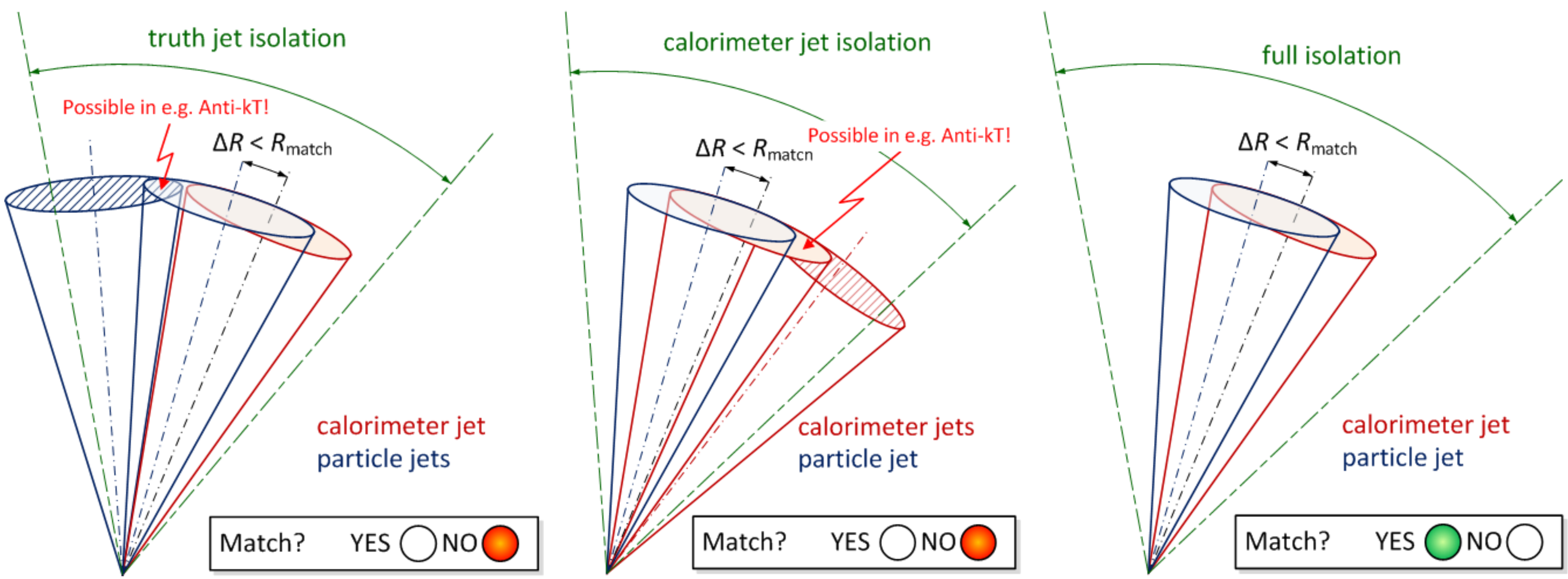
- Coarser than cell signals but less numerical complexity
  - Fewer function parameters



Simulated particle jets

- Establish “true” energy reference to constrain calibration function fits for calorimeter jets
  - Attempt to reconstruct true jet energy
- Need matching definition
  - Geometrical distance
  - Isolation and unique 1-to-1 jet matching

$$\Delta R = \sqrt{(\eta_{\text{particle,jet}} - \eta_{\text{rec,jet}})^2 + (\varphi_{\text{particle,jet}} - \varphi_{\text{rec,jet}})^2}$$



Global Calibration Fits Using Simulations

P. Loch
U of Arizona
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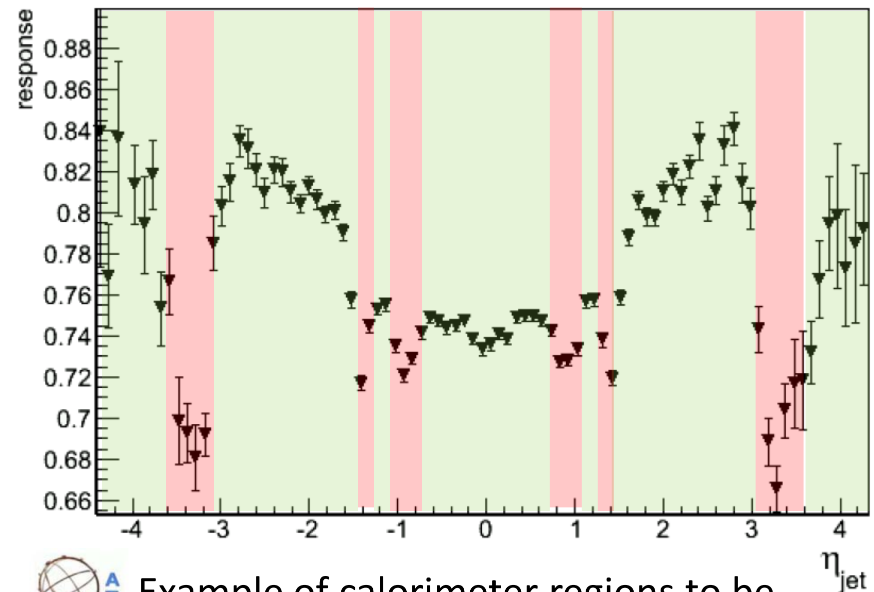
Select matched jet pair

- Typically small matching radius
  - $R_{match} = 0.2 - 0.3$
- Restrict jet directions to regions with good calorimeter response
  - No excessive dead material
  - Away from cracks and complex transition geometries

Calibration functions

- Cell signal weighting
  - Large weights for low density signals
  - Small weights for high density signals
- Sampling layer signal weighting
  - Weights determined by longitudinal energy sharing in calorimeter jet
- Functions can be complex
  - Often highly non-linear systems



Example of calorimeter regions to be considered for jet calibration fits in ATLAS (tinted green). The red tinted regions indicate calorimeter cracks and transitions. The points show the simulated jet response on electro-magnetic energy scale, as function of the jet pseudorapidity.
(figure for illustration purposes only!)

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$$E_{\mathrm{rec,cell}} = w_{\mathrm{cell}}(\rho_{\mathrm{cell}},\ldots)\cdot E_{0,\mathrm{cell}}$$

$w_{\mathrm{cell}}(\rho_{\mathrm{cell}},\ldots)$ ↗ for ρ_{cell} ↑ ; ↘ for ρ_{cell} ↓

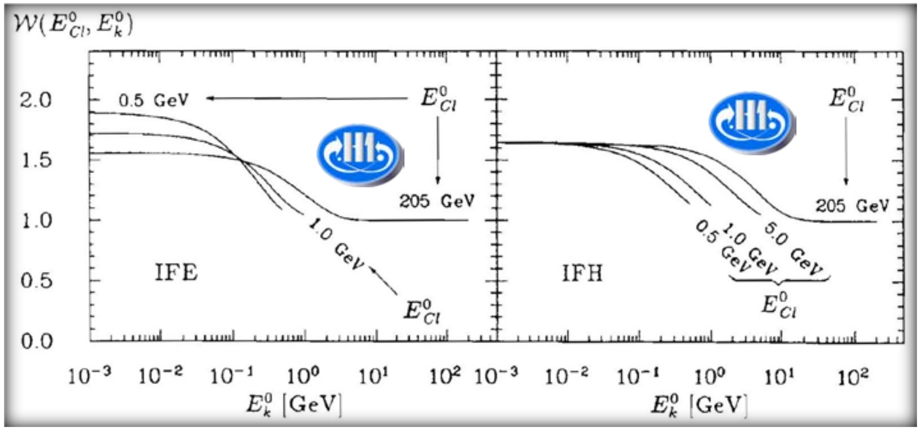
Typical boundary conditions:

$\max(w_{\mathrm{cell}}(\rho_{\mathrm{cell}},\ldots)) \approx 1.5 - 3.0$

(avoid boosting noise!)

$\min(w_{\mathrm{cell}}(\rho_{\mathrm{cell}},\ldots)) = 1.0$

(avoid suppressing em response!)



Example: cell signal weights $\mathcal{W}$, parameterized as function of the cell energy E^0_k and the cluster energy E^0_{cl}

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$$E_{\text{rec,cell}} = w_{\text{cell}}(\rho_{\text{cell}},\ldots)\cdot E_{0,\text{cell}}$$

$$w_{\text{cell}}(\rho_{\text{cell}},\ldots) \nearrow \text{ for } \rho_{\text{cell}}\uparrow \qquad w_{\text{cell}}(\rho_{\text{cell}},\ldots) \searrow \text{ for } \rho_{\text{cell}}\downarrow$$

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Example for non-algebraic functional form:

(similar in ATLAS)

$$w_{\text{cell}}(\rho_{\text{cell}},\Re_{\text{cell}}) = \omega_{ij} \text{ for } \begin{cases} \log(\rho)_i \le \log(\rho_{\text{cell}}) < \log(\rho)_{i+1} \\ \Re_{\text{cell}} \in \Re_j \end{cases}$$

$\Re_{\text{cell}}$ is a region descriptor for a given cell,

like $\Re_{\text{cell}} = \underbrace{\{M_{\text{cell}}, S_{\text{cell}}\}}_{\text{calorimeter module id, sampling id}}$

Global Calibration Fits Using Simulations

P. Loch
U of Arizona
April 13, 2010

Select matched jet pair

- Typically small matching radius
  - $R_{\mathrm{match}} = 0.2 - 0.3$
- Restrict jet directions to regions with good calorimeter response
  - No excessive dead material
  - Away from cracks and complex transition geometries

Calibration functions

- Cell signal weighting
  - Large weights for low density signals
  - Small weights for high density signals
- Sampling layer signal weighting
  - Weights determined by longitudinal energy sharing in calorimeter jet
- Functions can be complex
  - Often highly non-linear systems

$$E_{\mathrm{rec},S} = w_S E_{0,S} = w_S \cdot \sum_{\substack{\text{cells in} \\ \text{sampling } S}} E_{0,\mathrm{cell}}$$

Possible parameterizations:

$$w_S = w_S(f_{\mathrm{EMC}}), \text{ with } f_{\mathrm{EMC}} = \frac{\sum_{\substack{\text{jet cells in} \\ EMC}} E_{0,\mathrm{cell}}}{\sum_{\text{all jet cells}} E_{0,\mathrm{cell}}}$$

Example for non-algebraic functional form:

$$w_S(f_{\mathrm{EMC}}) = \omega_{S,i} \text{ for } F_{EMC,i} \leq f_{EMC} < F_{EMC,i+1}$$

Global Calibration Fits Using Simulations

Fitting

- Possible constraints
  - Resolution optimization
  - Signal linearity
  - Combination of both
- Regularization of calibration functions
  - Try to linearize function ansatz
  - Use polynomials
  - Can reduce fits to solving system of linear equations
- Non-linear function fitting
  - Use numerical approaches to find (local) minimum for multi-dimensional test functions (e.g., software like MINUIT etc.)

Reconstructed jet energy with cell calibration:

$$E_{\text{rec,jet}} = \sum_{\text{cells in jet}} w_{\text{cell}}(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}}$$

Fit $\{\omega_{ij}\}$ such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\text{rec,jet}} - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}} = \text{min}$$

Reconstructed jet energy with sampling calibration:

$$E_{\text{rec,jet}} = \sum_{S \text{ in jet}} w_S(f_{\text{EMC}}) \cdot E_{0,S}$$

Fit $\{\omega_{i,S}\}$ using the same χ^2 test function!

Note that $\sigma^2_{\text{rec,jet}} \sim E^{-1}_{\text{rec,jet}}$!

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Attempted de-convolution of signal contributions

- Normalization choice convolutes various jet response features
  - E.g., cell weights correct for dead material and magnetic field induced energy losses, etc.
- Limited de-convolution
  - Fit corrections for energy losses in material between calorimeter modules with different functional form
  - Separation in terms, but still a correlated parameter fit

Reconstructed jet energy with cell calibration:

$$E_{\mathrm{rec,jet}} = \sum_{\text{cells in jet}} w_{\mathrm{cell}}(\rho_{\mathrm{cell}}, \Re_{\mathrm{cell}}) \cdot E_{0,\mathrm{cell}} + E_{\mathrm{DM,jet}}$$

Use χ^2 test function such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\mathrm{rec,jet}} - E_{\mathrm{particle,jet}}\right)^2}{\sigma^2_{\mathrm{rec,jet}} + \sigma^2_{\mathrm{particle,jet}}}$$

$$= \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(\left[\sum_{cells\ in\ jet} w_{cell}(\rho_{cell}, \Re_{cell}) \cdot E_{0,cell} + \alpha \cdot \sqrt{E_{0,S=before} \cdot E_{0,S=behind}}\right] - E_{\mathrm{particle,jet}}\right)^2}{\sigma^2_{\mathrm{rec,jet}} + \sigma^2_{\mathrm{particle,jet}}}$$

$$= \min$$

with empirically motivated ansatz for $E_{\mathrm{DM,jet}}$ for dead material between sampling layers $S = \text{before}$ and $S = \text{behind}$, in a combined fit of $\left(\{W_{\mathrm{cell}}\}, \alpha\right)$

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Reconstructed jet energy with cell calibration:

$$E_{\text{rec,jet}} = \sum_{\text{cells in jet}} w_{\text{cell}}(\rho_{\text{cell}}, \Re_{\text{cell}}) \cdot E_{0,\text{cell}} + E_{\text{DM,jet}}$$

Use χ^2 test function such that...

$$\chi^2 = \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(E_{\text{rec,jet}} - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \sum_{\substack{\text{matching}\\ \text{jet pairs}}} \frac{\left(\left[\sum_{\textit{cells in jet}} w_{\textit{cell}}(\rho_{\textit{cell}}, \Re_{\textit{cell}}) \cdot E_{0,\textit{cell}} + \alpha \cdot \sqrt{E_{0,S=\textit{before}} \cdot E_{0,S=\textit{behind}}}\right] - E_{\text{particle,jet}}\right)^2}{\sigma^2_{\text{rec,jet}} + \sigma^2_{\text{particle,jet}}}$$

$$= \text{min}$$

Relatively low level of factorization in this particular approach with correlated (by combined fit) parameters!

with empirically motivated ansatz for $E_{\text{DM,jet}}$ for dead material between sampling layers $S = \text{before}$ and $S = \text{behind}$, in a combined fit of $\left(\left\{W_{\text{cell}}\right\}, \alpha\right)$