研究会「LHCが切り拓く新しい素粒子物理学」
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Jet, Missing E_T, and Energy Flow

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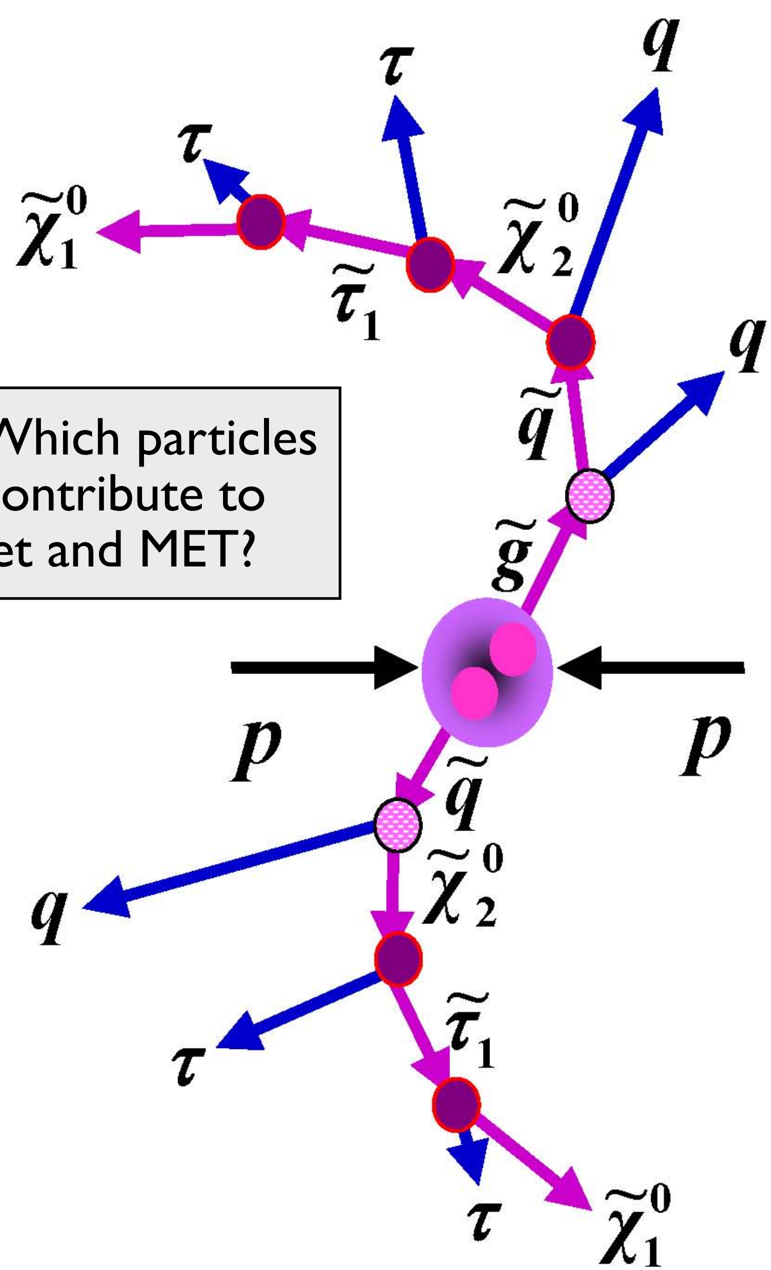
Jet and MET



Which particles contribute to jet and MET?

- Jets and MissET are copiously produced at hadron colliders
  - mini-jets, QCD jets
  - tt → WbWb → lν + qq + bb
  - SUSY → multi-jets + 2 LSPs
  - Black Hole → multi-jets
  - .....
- We would like them to represent
  - Jet : collimated spray of particles (or quarks and gluons)
  - MissET: non-interacting particles e.g, neutrinos, LSP in SUSY, ...
- Most challenging physics objects to reliably measure
  - Theoretically not unique (jet)
  - Detector and environmental limitations

Aim (or Outline) of This Talk

How do we measure jets and Missing ET at ATLAS?

- *Hadronic energy measurement in calorimeters*
- *Jet and Missing ET reconstruction*
- *Expected performance*
- *Performance validation with real data*

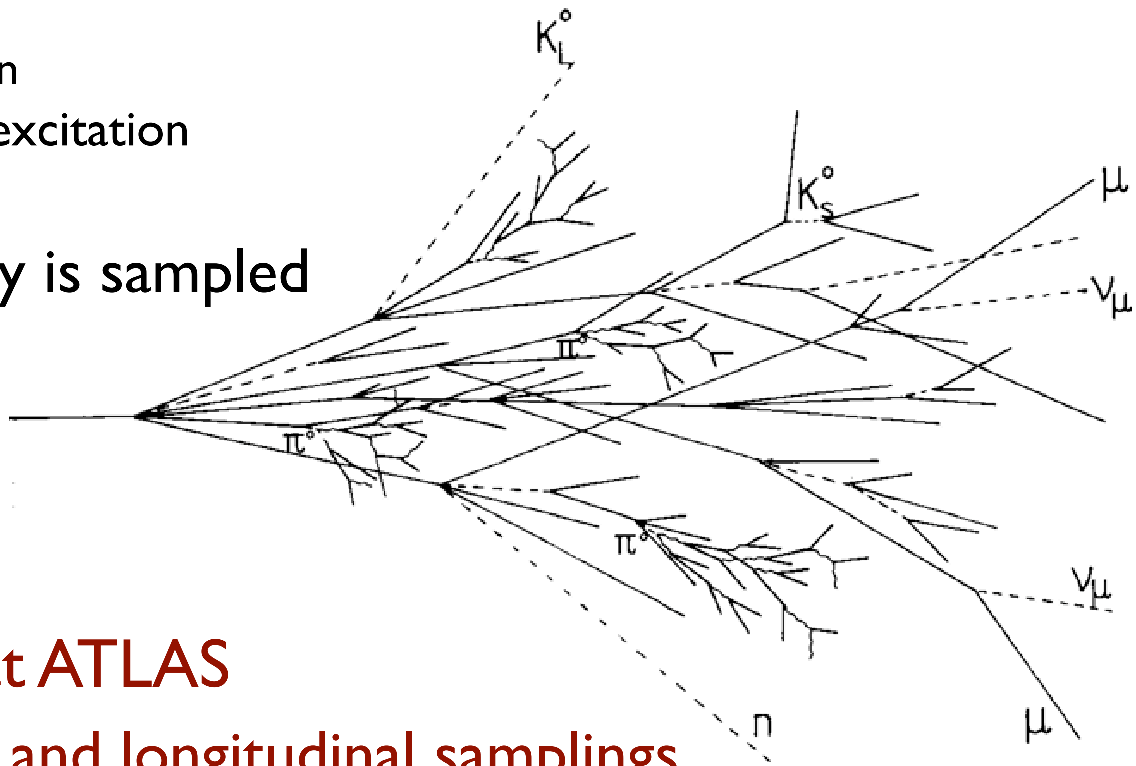
How can we improve baseline performance?

→ *Energy flow approach (one possibility...)*

Hadronic Energy Measurement

Generic feature of hadronic shower in calorimeters

- More complex than EM showers
  - ❖ Visible EM ~50% : e, γ, $\pi^0 \rightarrow \gamma\gamma$
  - ❖ Visible non-EM ~25% : $h^{\pm}$, $\mu^{\pm}$ ionization
  - ❖ Invisible ~25% : nuclear break-up and excitation
  - ❖ Escaped ~2% : ν, $\mu^{\pm}$
- Only part of the deposited energy is sampled
- Fractions are energy dependent
- Large fluctuations



Hadronic energy measurement at ATLAS

❖ Uses similar e/h for LAr and Tile and longitudinal samplings (→3-D signal clustering)

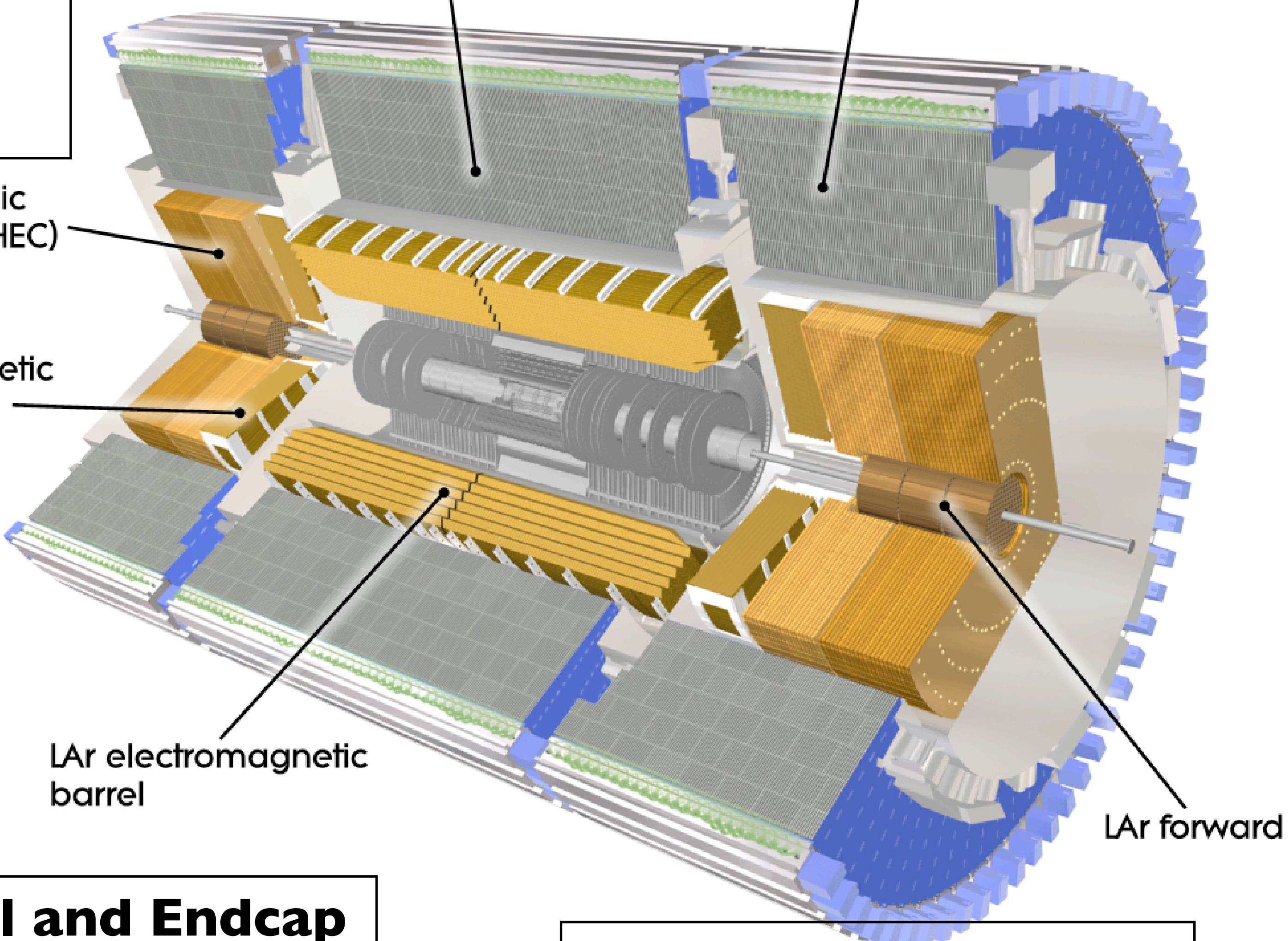
❖ Provides some degree of software compensation

❖ Accounts for invisible and escaped energy

ATLAS Calorimeters

Hadronic Endcap

- Liquid Argon/Cu parallel plate structure
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ ($1.5<|\eta|<2.5$)
- $\Delta\eta \times \Delta\varphi = 0.2 \times 0.2$ ($2.5<|\eta|<3.2$)
- 4 samplings



Hadronic Barrel

- Scintillator/Fe in tiled readout
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- Coverage $|\eta|<1.7$
- 3 longitudinal samplings

Electromagnetic Barrel and Endcap

- Liquid Argon/Pb accordion structure
- Highly granular readout (~170,000 channels)
- $0.0025 \leq \Delta\eta \leq 0.05$, $0.025 \leq \Delta\varphi \leq 0.1$
- Coverage $|\eta|<3.2$, pre-sampler up to $|\eta|<1.8$
- 2-3 longitudinal samplings

Forward

- Liquid Argon/Cu or W absorbers
- Non-projective geometry
- $\Delta\eta \times \Delta\varphi \approx 0.2 \times 0.2$ ($3.2<|\eta|<4.9$)
- 3 samplings

Hadronic Signal in Calorimeters

- LAr/Tile calorimeter readouts sample a shaped physics pulse from the calorimeter in synch with 25 ns clock
- For LAr:
  - ❖ Signal reconstruction based on Optimal Filtering procedure (5 samples)

$$\text{Energy} = \text{ADC2MeV} \cdot \sum_{i=1}^{5} a_i\,(\text{ADC}_i - \text{pedestal})$$

  - ❖ Optimal Filtering Coefficients (OFC) $\boldsymbol{a_i}$ calculated from:
    - ✓ Known physics pulse shape
      - Pulser system in case of EMB, EMEC and HEC
      - Beam tests (so far) for the FCAL
    - ✓ Known pedestals and noise autocorrelation matrix
      - From noise measured in random trigger events
  - ❖ ADC2MeV = ADC2DAC x DAC2μA x μA2MeV (from calibration pulser system and beam tests)
  - ❖ Reconstructed energy is at EM scale (→ subject to hadronic calibration)

Noise in Calorimeters

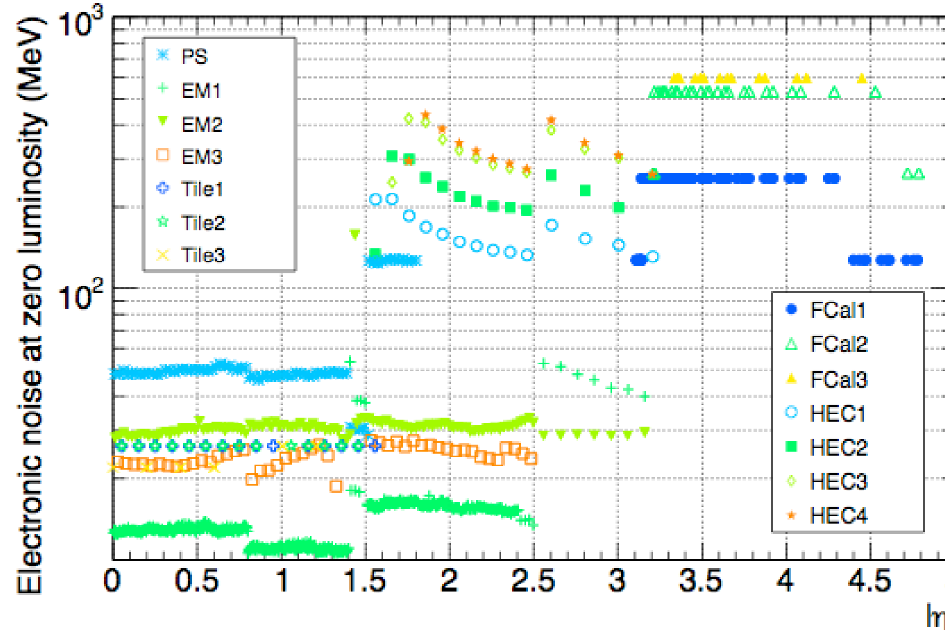
Electronic noise

- Unavoidable basic fluctuation on top of each calorimeter cell signal
- Obtained from test beam and commissioning phase
- Ranges from ~10 MeV (central) to ~600 MeV (forward) per cell

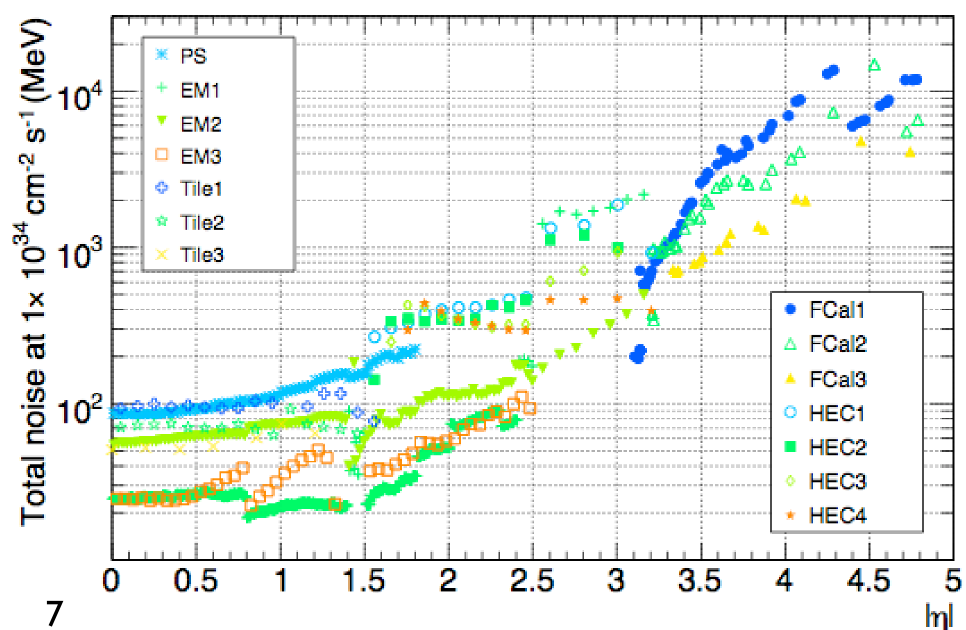
Pile-up noise

- Depends on instantaneous luminosity
- Illuminates entire calorimeter (most significant in forward)
- Major contributions from out-of-time signal due to calorimeter shaping functions
- Ranges from ~20 MeV (central) up to about ~10 GeV (forward) per cell

Electronic Noise



Total Noise (electronic+pile-up) @ 10^{34} $cm^{-2}s^{-1}$



Calorimeter Signal : Towers

Impose regular grid view on event

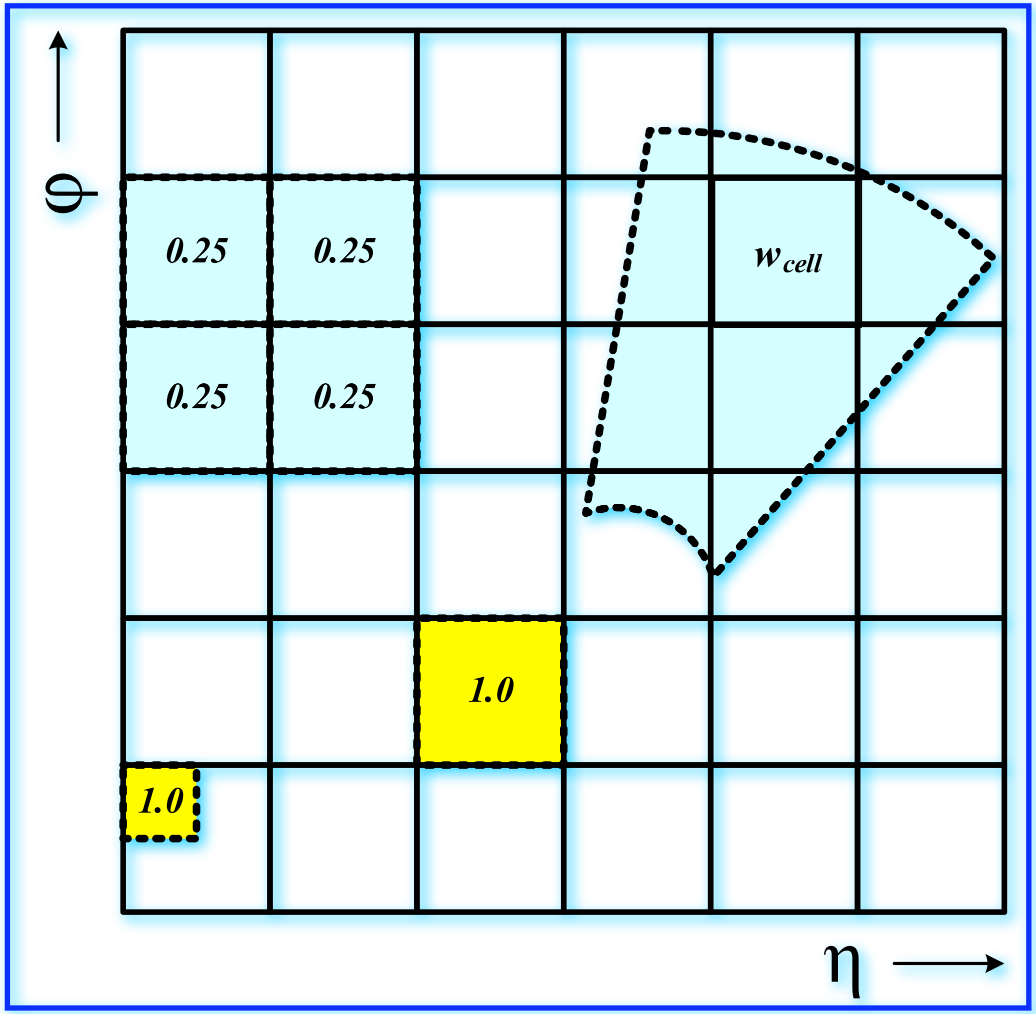
- $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$
- Motivated by event E_T flow
- Natural choice for trigger

Sum cell signals in tower

- Include all cells (no selection)
  → Significant contribution from noise cells
- Sum typically includes geometrical weight

$$E_{\eta\varphi} = \sum_{\substack{|\eta_{cell}-\eta|<\Delta\eta/2 \\ |\varphi_{cell}-\varphi|<\Delta\varphi/2}} w_{cell} E_{cell}$$

$$w_{cell} = \begin{cases} 1 & \text{if } A_{cell}^{\eta\varphi} \leq \Delta\eta \times \Delta\varphi \\ <1 & \text{if } A_{cell}^{\eta\varphi} > \Delta\eta \times \Delta\varphi \end{cases}$$



Calorimeter Signal : Topological Clusters

Cluster energy deposits in 3-D topologically connected cells

- Clustering over different sampling layers and calorimeters
- Based on cell energy significance in units of $\sigma_{noise} = \sigma_{electronics} \oplus \sigma_{pile\text{-}up}$
- Correlated signals taken into account

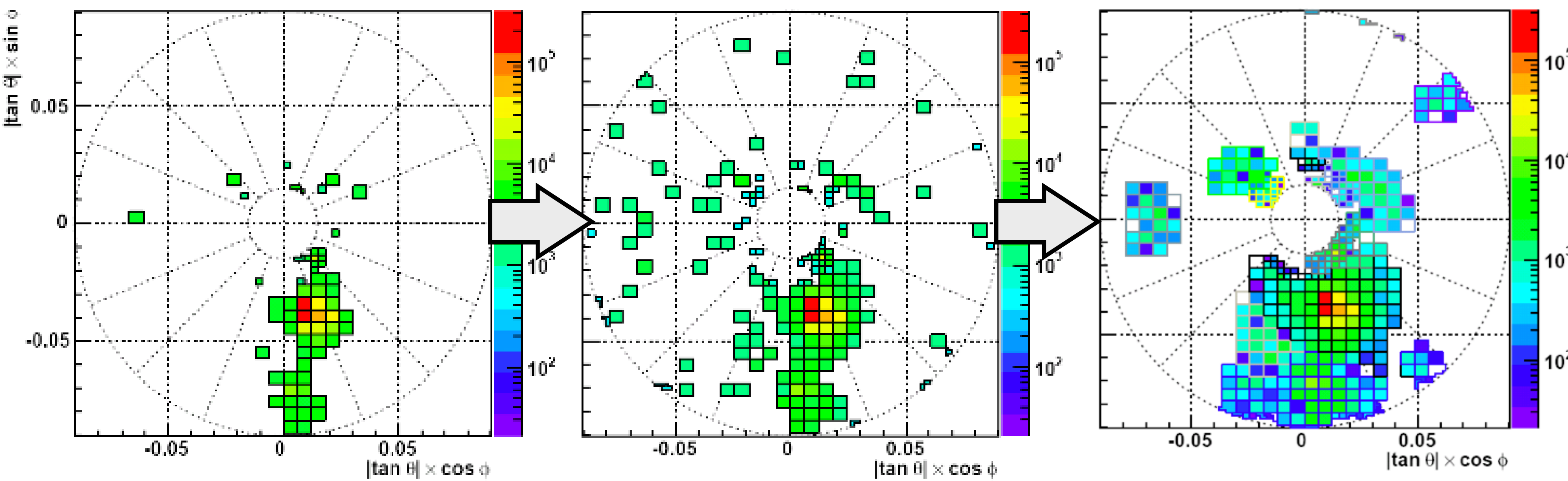
Topo. clusters in 1st FCal layer
(Jet with p_T>50 GeV)

Threshold (default)

Cluster seed : $|E_{cell}|/\sigma_{noise} > 4$

Neighbor cells : $|E_{cell}|/\sigma_{noise} > 2$

Cells along the perimeter of the cluster : $|E_{cell}|/\sigma_{noise} > 0$



→ Best performance in test beam

→ Can include very small signal cells due to neighboring cell signals

Topological cluster studies with cosmic data
→ H. Okawa, JPS meeting 26aZE5, March 26, 2008

Jets in ATLAS

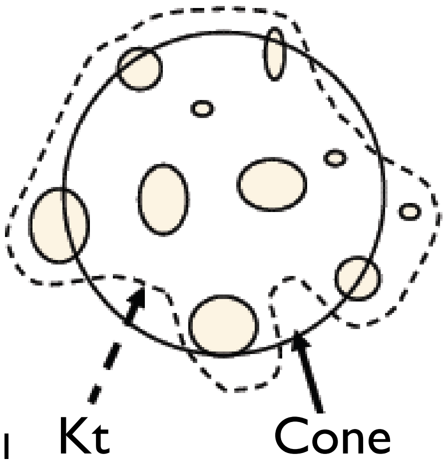
Jet Finders in ATLAS

Cone Jet Finders

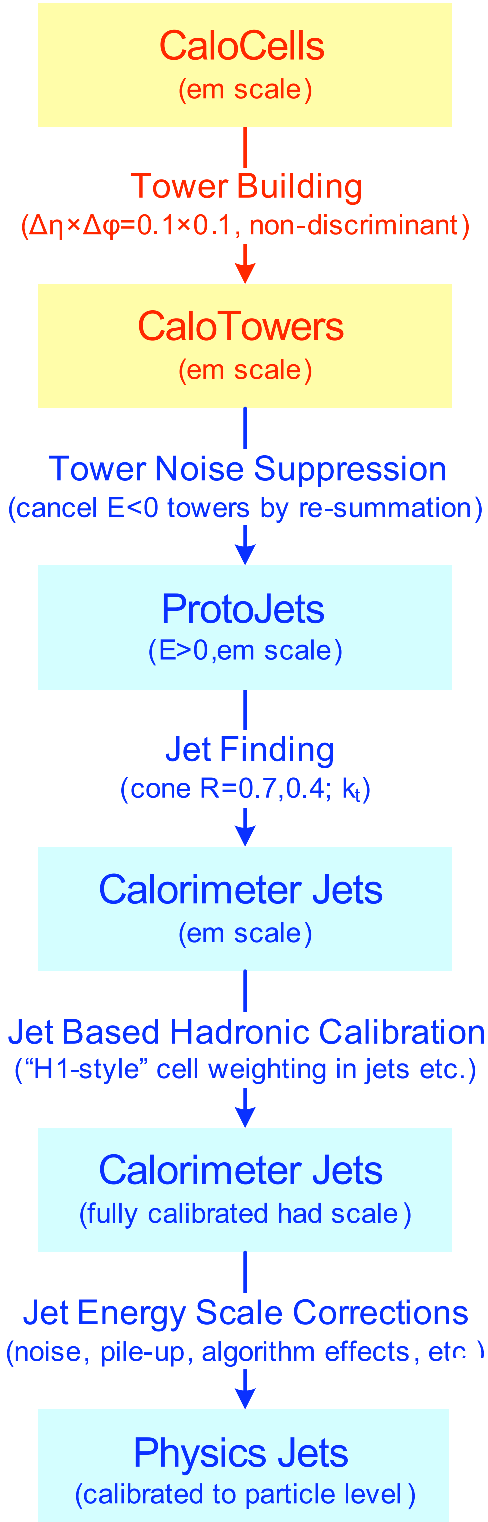
- **Seeded fixed cone**
  - Iterative cone finder starting from seeds
  - Free parameters:
    - seed E_T threshold (typically 1 GeV)
    - cone size R (=0.4 or 0.7)
  - Split and merge with overlap fraction threshold of 50%
  - No infrared or collinear safe
- Alternative approaches
  - Seedless cone
    - Each input is seed (theoretically favored)
    - Infrared and collinear safe
    - Need split and merge
  - MidPoint cone
    - Place new seed between two cones
    - Need split and merge
    - Improved infrared and collinear safe

Dynamic Angular Distance Jet Finders

- **Kt algorithm**
  - Combines proto-jets if relative p_T is smaller than p_T of more energetic proto-jet
  - No seeds needed
  - Fast implementation available
- Alternative approaches
  - Aachen/Cambridge algorithm
    - Similar to Kt, but only distance between objects considered (no use of p_T)
  - Optimal Jet Finder
    - Based on the idea of minimizing a test function sensitive to event shape
    - Use unclustered energy in jet finding



Seeded fixed cone and Kt are popular algorithms at ATLAS



Tower-Based Jet

- Collect all EM energy cell signals into projective towers
  - No explicit use of longitudinal readout granularity in jet finding
  - Input signal = "Uncalibrated" EM energy scale
- Cancel noise by re-summation of the towers
  - Towers with E<0 are added to near-by towers with E>0 until the resulting proto-jet has E>0 (all cells are kept!)
- Run jet finding on the proto-jets
- Apply "global" cell level calibration (→next slide)
  - Retrieve all cells used in the jet
  - Apply cell level calibration weights (derived from MC) as a function of cell energy density and cell location
  - Obtain hadronic energy scale jets with dead material corrections
- Apply residual corrections for (E_T, η) and jet algorithm dependence
  - Results are physics jets calibrated at particle level

Global Hadronic Calibration

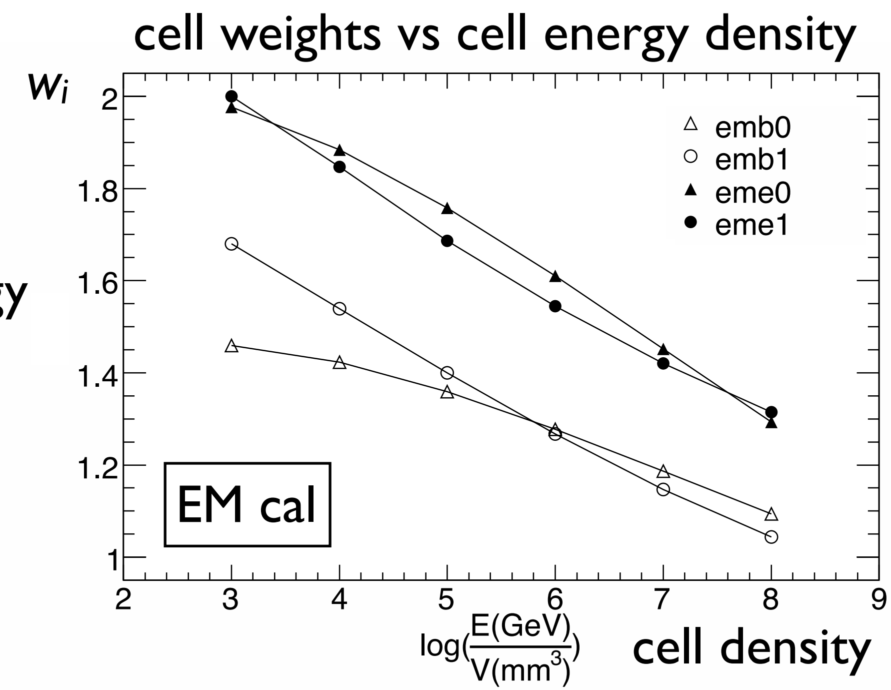
Derived from QCD cone 0.7 jets in Pythia dijet production

- Cover wide p_T range from ~10 GeV to a few TeV

For calorimeter tower jet

- Find a matched (stable interacting) particle jet
- Extract cells from the tower jet
- Determine cell weights as a function of cell energy density and calorimeter region by minimizing

$$\chi^2 = \sum^{N_{events}} \sum^{N_{jets}} \left(\frac{E_{jet}^{Reco} - E_{jet}^{Truth}}{E_{jet}^{Truth}} \right)$$



where

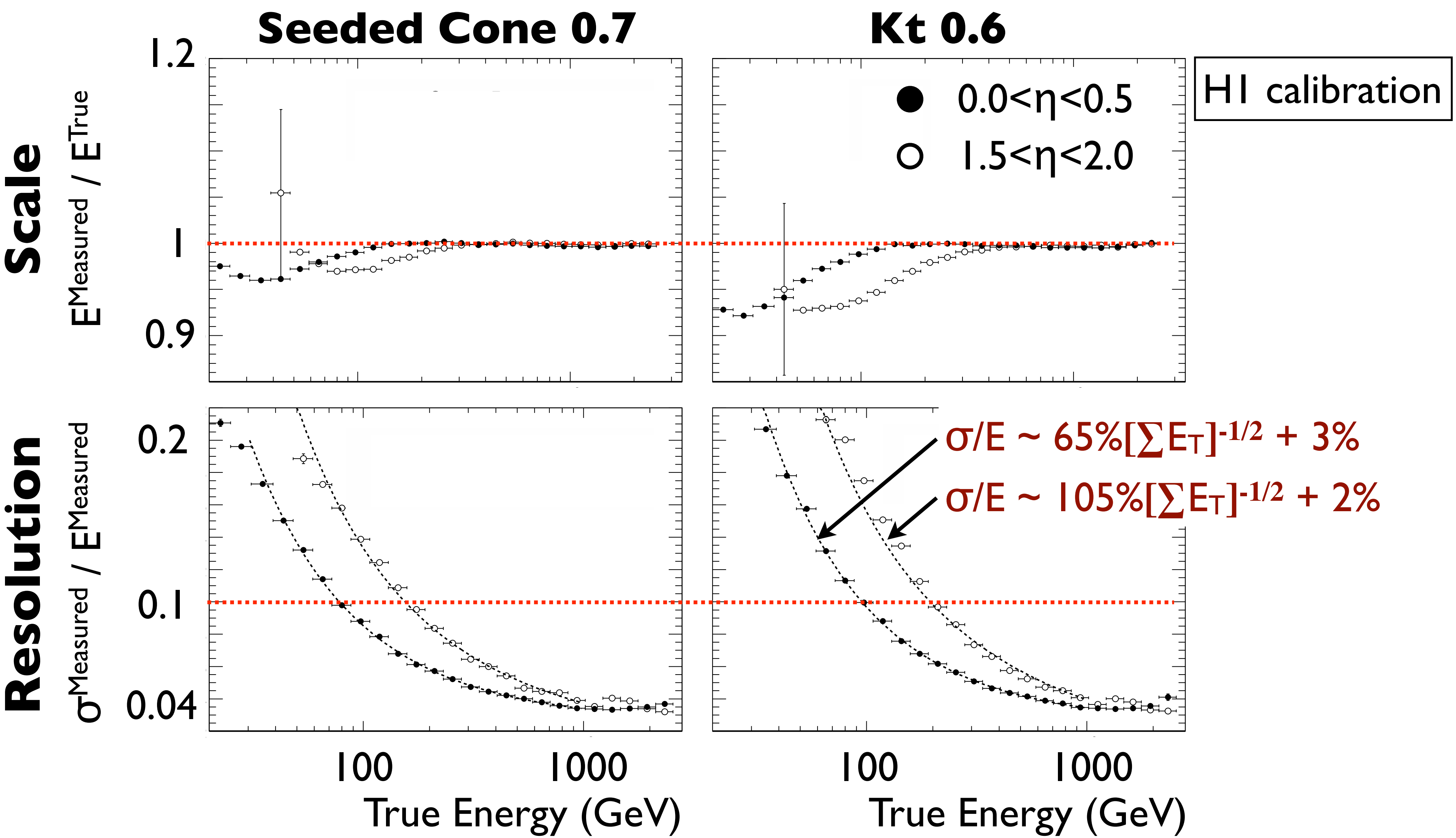
$$E_{jet}^{Reco} = \sum_{i}^{Cells} w_i(\rho_i, X_i) \cdot E_i \qquad \rho_i = \left(\frac{E_i}{V_i} \right)$$

E_i : cell energy (EM scale)
V_i : cell volume
X_i : cell location
w_i : cell calibration weights

- Correct residual (E_T,η)-dependent signal variations after cell weights are fixed

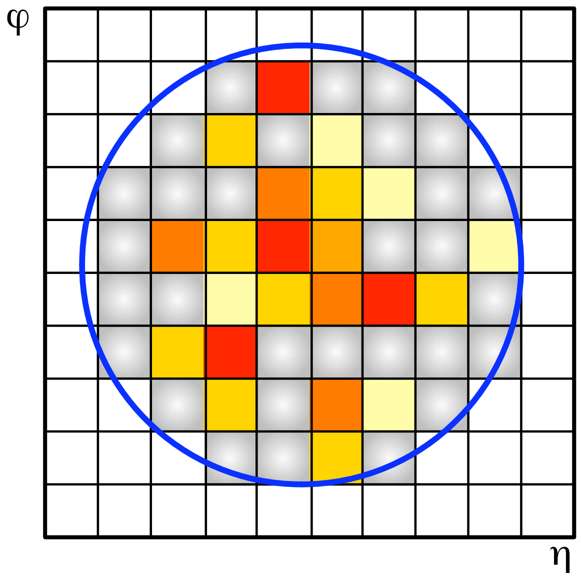
→ This is called H1 calibration

Tower Jet : Performance



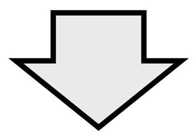
- Similar stochastic and constant terms between two algorithms
- Kt jets have ~30%(50%) larger noise term than cone jets for $0.0<\eta<0.5$ ($1.5<\eta<2.0$)

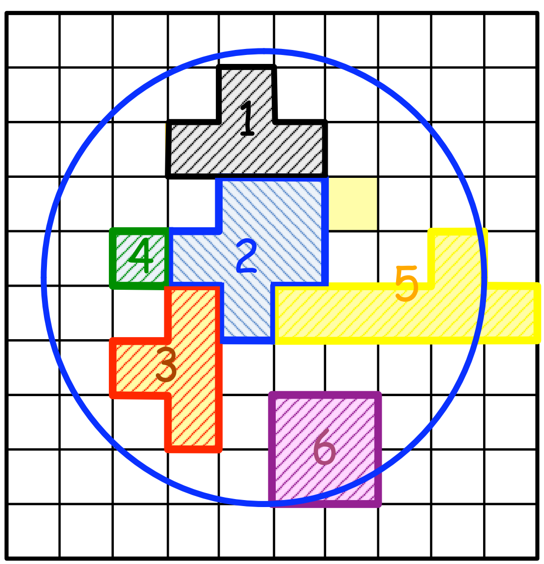
Tower Jet : Problems



Tower-based Jets

- ❖ Too many non-signal cells included in jet
  - Not only lateral but longitudinal sum with (large) fixed area
  - Relatively large noise contribution
- ❖ Input calibrated only at EM scale
  - Relative mis-calibration (>30%) between towers possible
  - Could produce "huge" jets (especially for Kt)





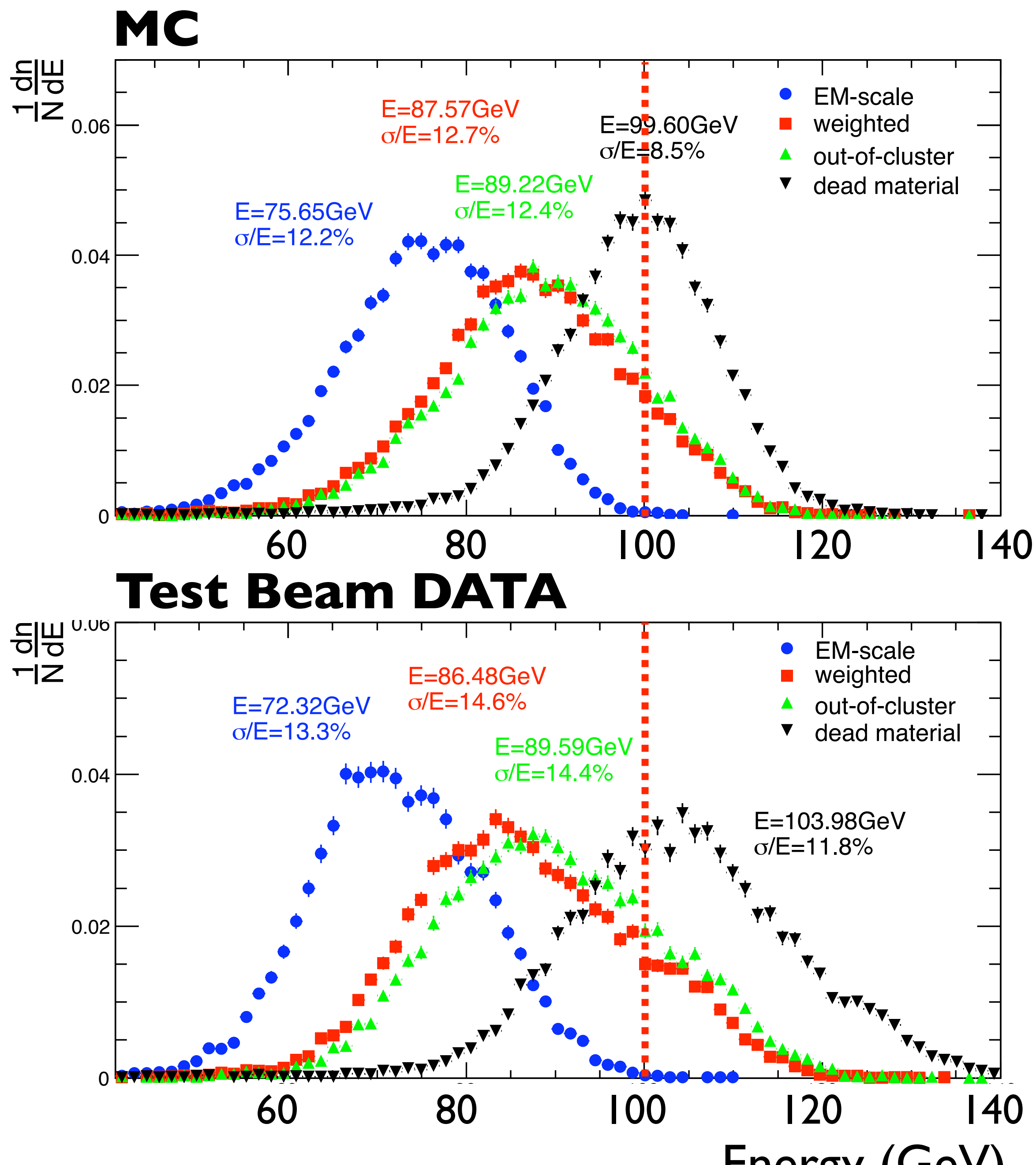
Cluster-based Jets

- ❖ Better control of noise level at input to jet
- ❖ Allow to use "calibrated" input to jet finder
  - **Local hadron calibration** to topological clusters
  - Smaller relative mis-calibration expected (~5% or less)
  - Possible to select inputs like particle selection for truth jets

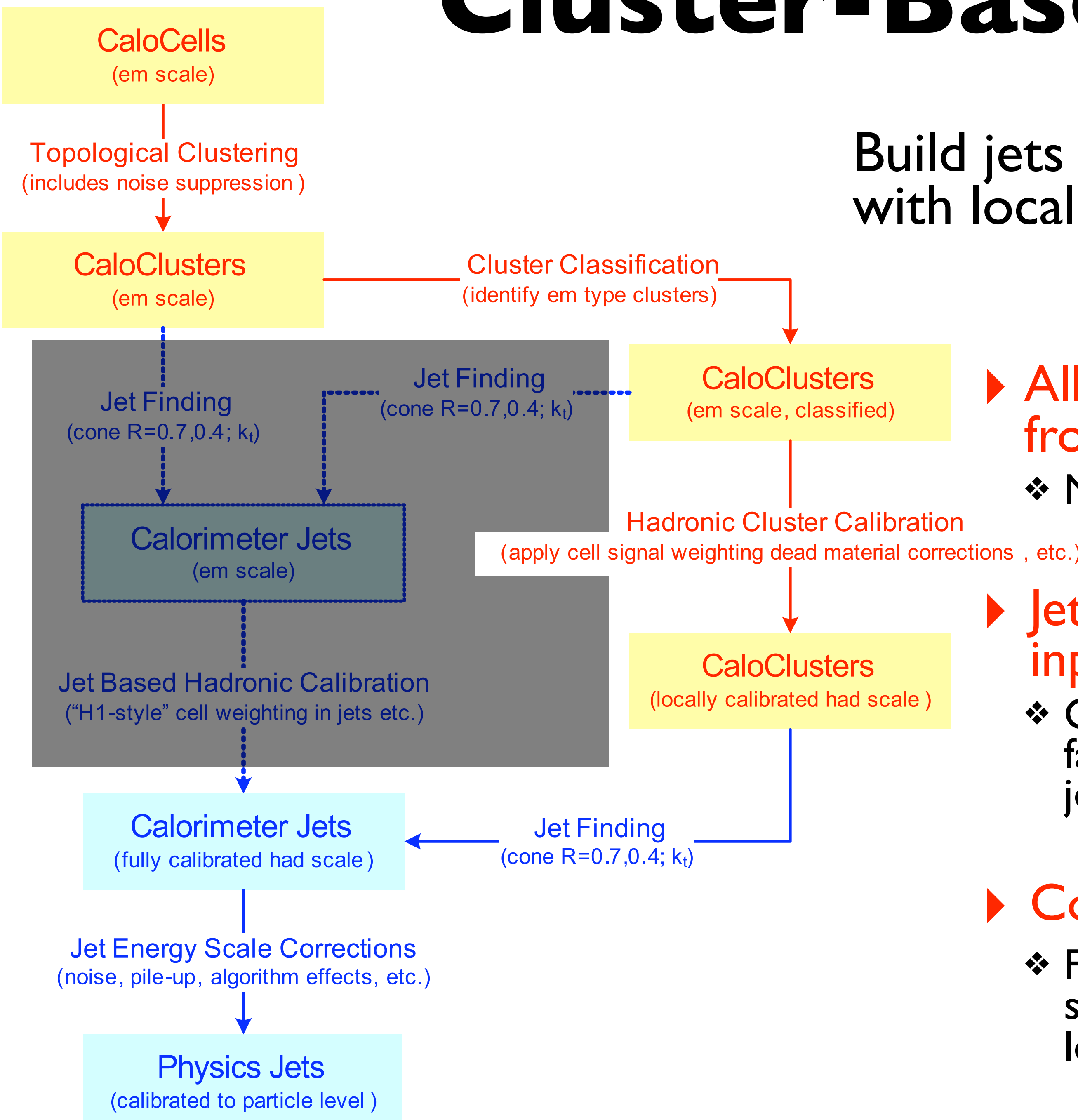
Local Hadron Calibration

- Start with topological clusters
- Cluster classification
  - ❖ Clusters classified as either EM, hadronic or unknown, based on
    - EM fraction
    - cluster shape information
- Hadronic weighting
  - ❖ Derive and apply weights to cells in hadronic clusters
- Out-of-cluster corrections
  - ❖ Correct for energy deposited in calorimeter, but outside of cluster
- Dead material corrections
  - ❖ Correct for energy lost in uninstrumented regions of the detector

Classification, weighting and correction algorithms all based on single particle MC simulation



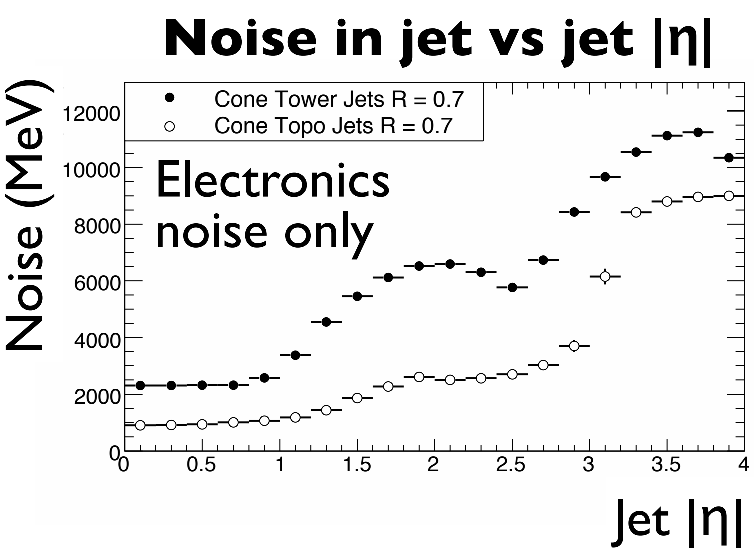
Cluster-Based Jet

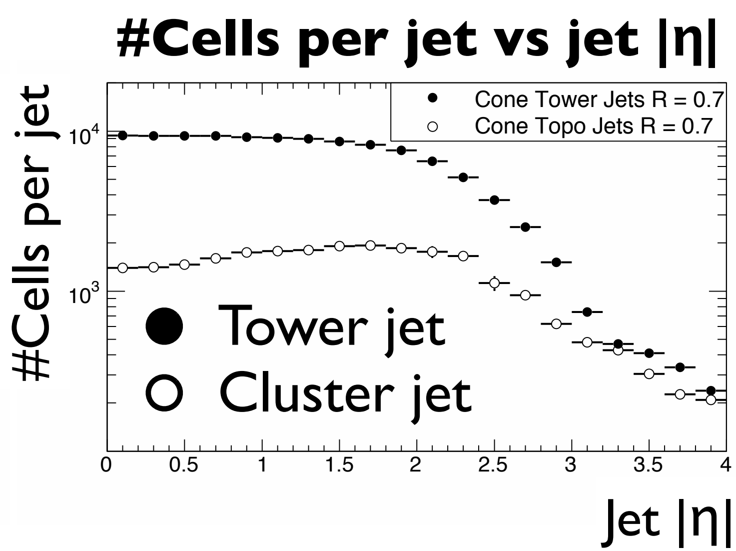


Build jets from topological clusters with local hadron calibration

- All calibrations derived only from single particle MC
  - ❖ No jet context bias (e.g, algorithm)
- Jet calibration factorized at input level
  - ❖ Contrast to CDF and DØ where factorized corrections applied at jet level
- Control of systematics
  - ❖ Factorization allows to address systematic uncertainties at various levels somewhat independently

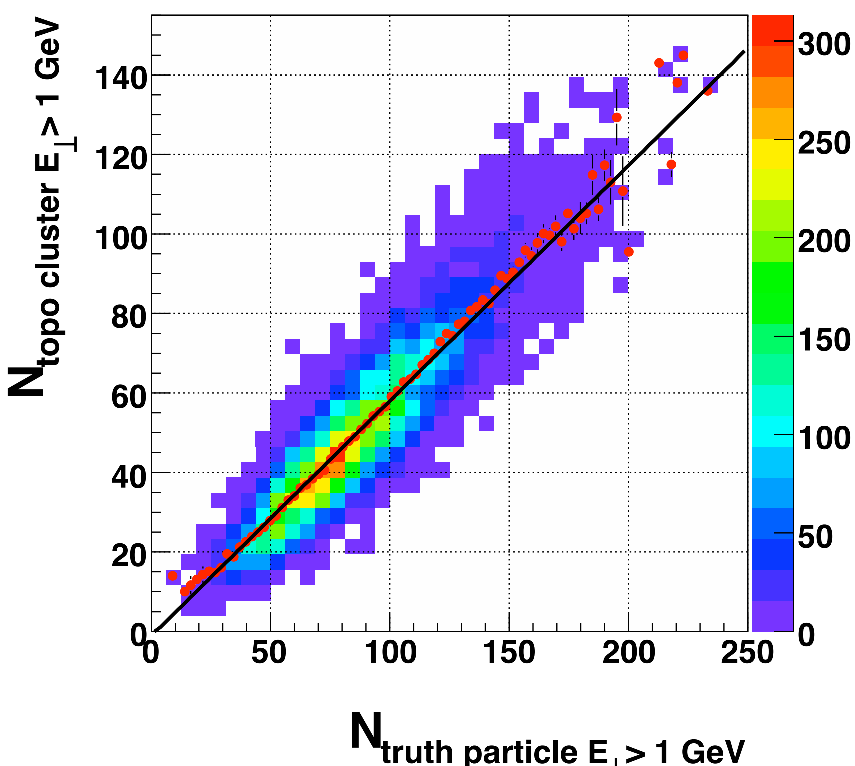
Cluster Jet : Performance (I)





Cone R=0.7
33 < p_T^{Jet} < 67 GeV

Cluster jets:
- much smaller noise
- much fewer cells
  → Is signal not killed?

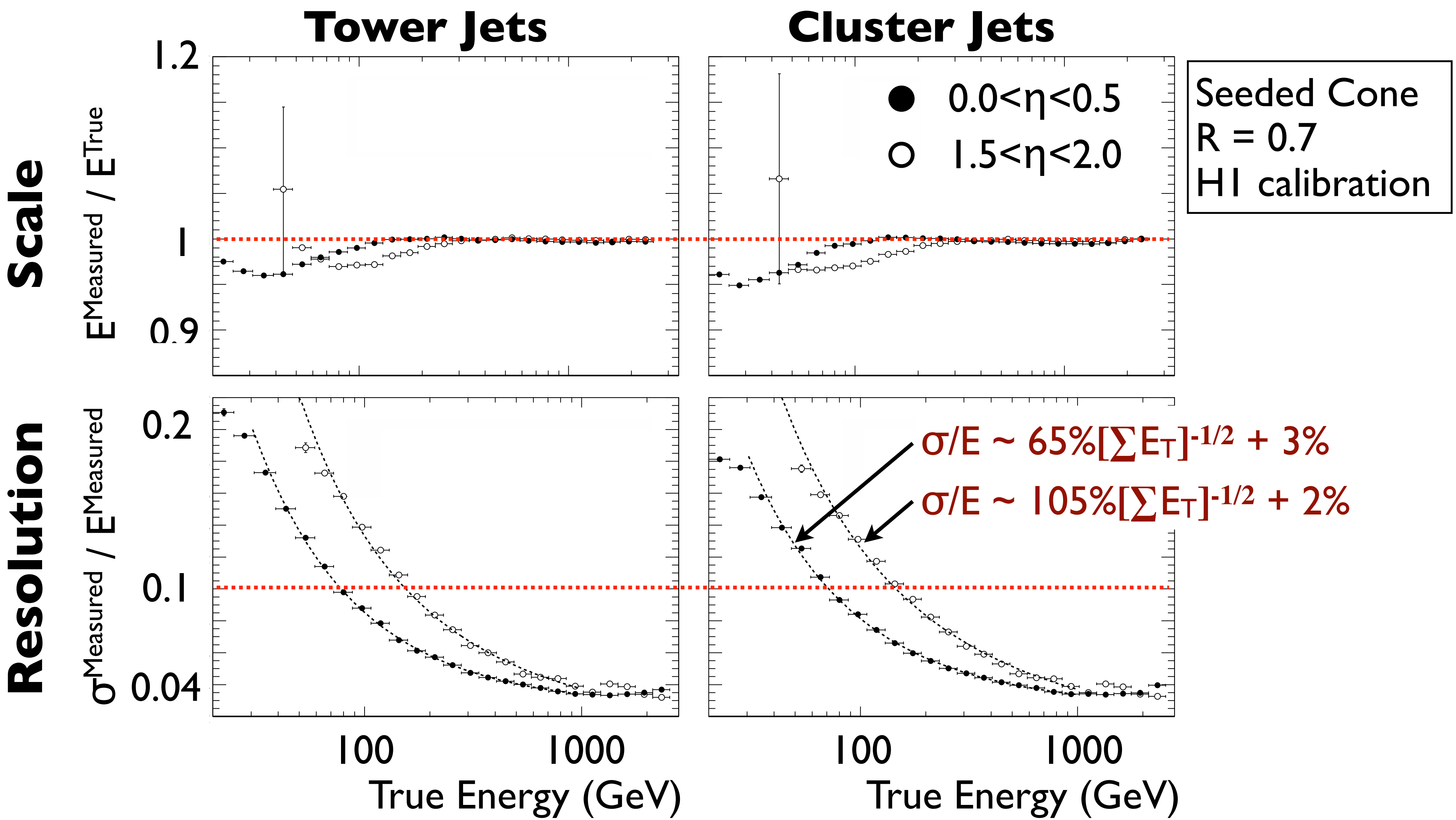


Linear correlation between truth particle and reconstructed cluster multiplicities :

- Pythia QCD di-jet (140<p_T^{Jet}<280 GeV)
- ~1.6(1.1) clusters per particle **in jet** at central (end-cap)

→ Should be better for isolated particles

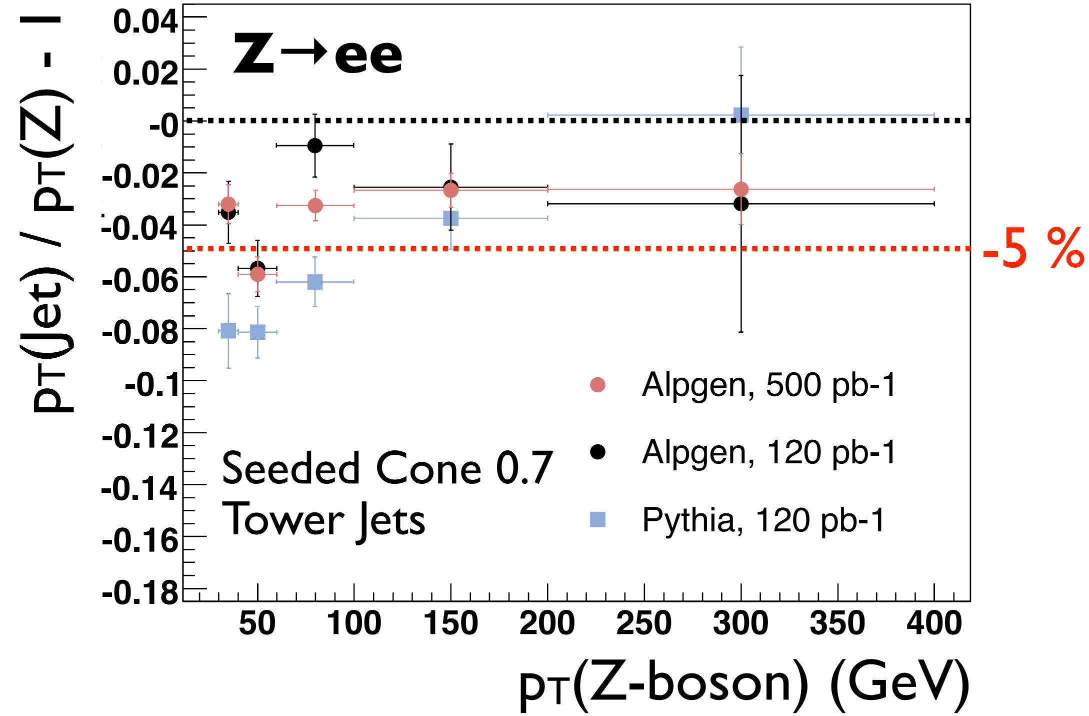
Cluster Jet : Performance (II)



- Similar stochastic and constant terms between two jet types
- Cluster jets have ~13%(23%) smaller noise term than tower jets for 0.0<η<0.5 (1.5<η<2.0)

Performance Validation

Validation with real data is crucial as ATLAS calibration scheme is MC based



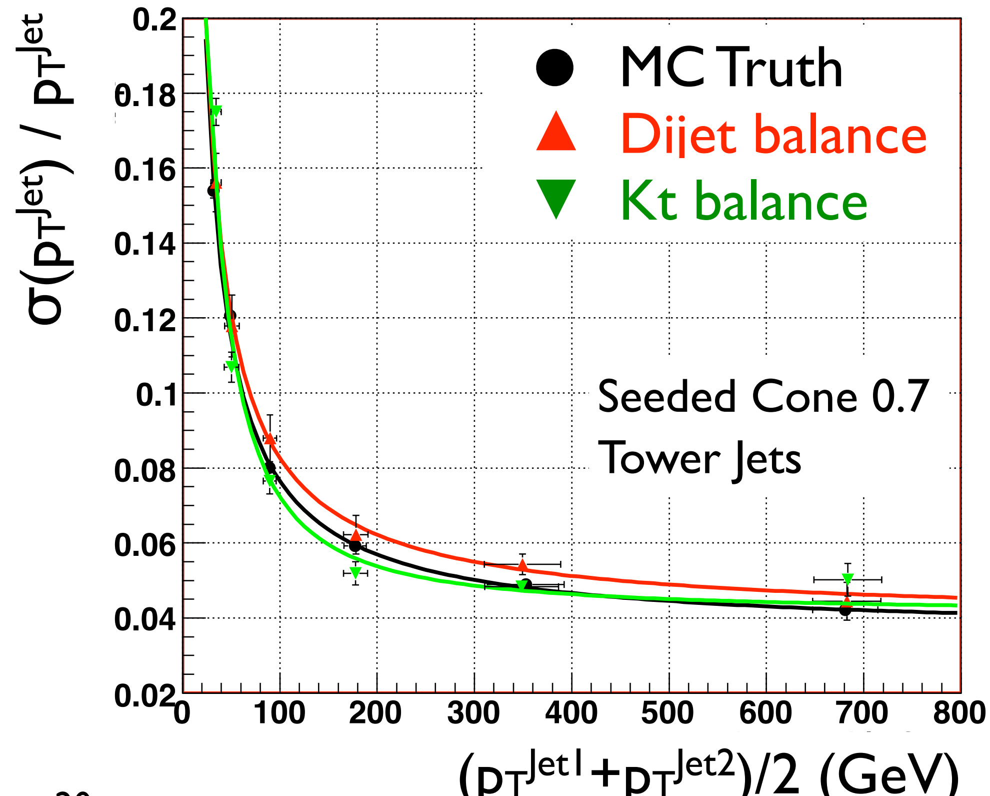
Jet Energy Scale

- γ/Z - jet p_T balance
- W→jj using M_W in tt (light quark)

Jet Energy Resolution

- Dijet balance
- Kt balance

- Based on Tevatron experience
- Utilize p_T balance between 2 jets
- Soft radiation effects taken into account

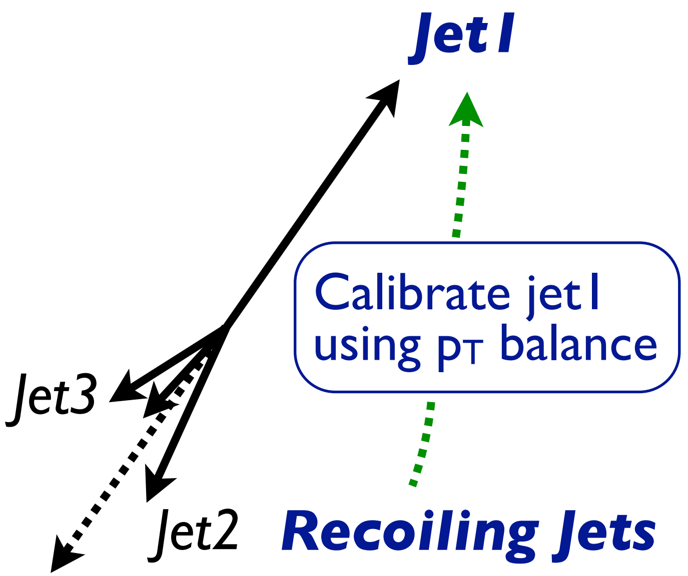


Very High p_T Jet

- Very high p_T jet in TeV range is an unexplored territory at collider experiment
- Calibration challenging as O(TeV) p_T is too high to use γ/Z - jet balance method

→ Exploring the technique to calibrate jets at TeV range

Option 1. **Multi-jet Balance**

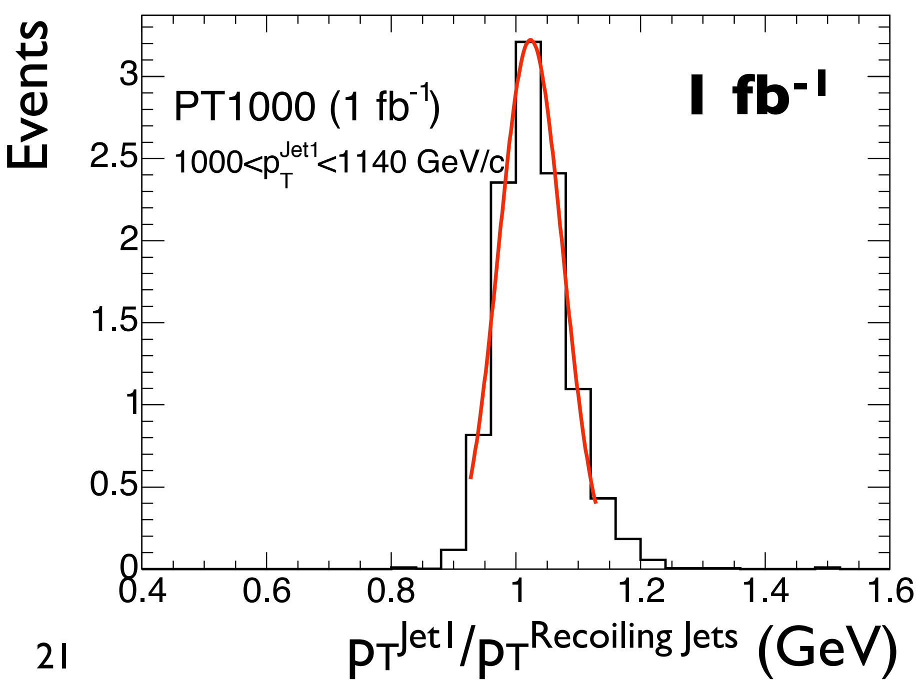


- Use QCD multi-jet events
  - ≥4 jets with p_T>40 GeV
  - Jet p_T cuts : e.g, $1000<p_T^{Jet1}<1140$ GeV, $p_T^{Jet2}<470$ GeV
  - $\Delta\phi$(Jet1, Recoiling jets) > 160 degree
- Evaluate jet1 energy scale from $p_T^{Jet1}/p_T^{Recoiling\ Jets}$
- Possible to extend p_T range by iteration

Potential accuracy of 1 TeV jet scale at 1 fb^{-1}

➡ **< 10%**

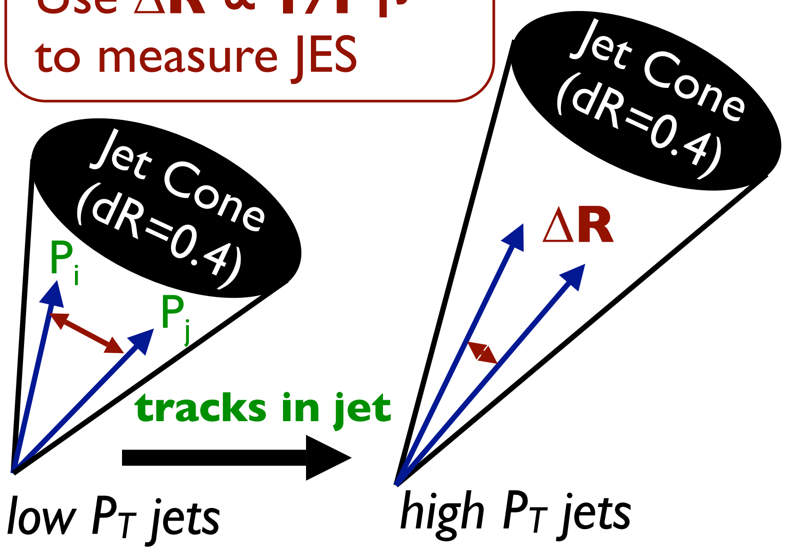
(comparable to low p_T jets)



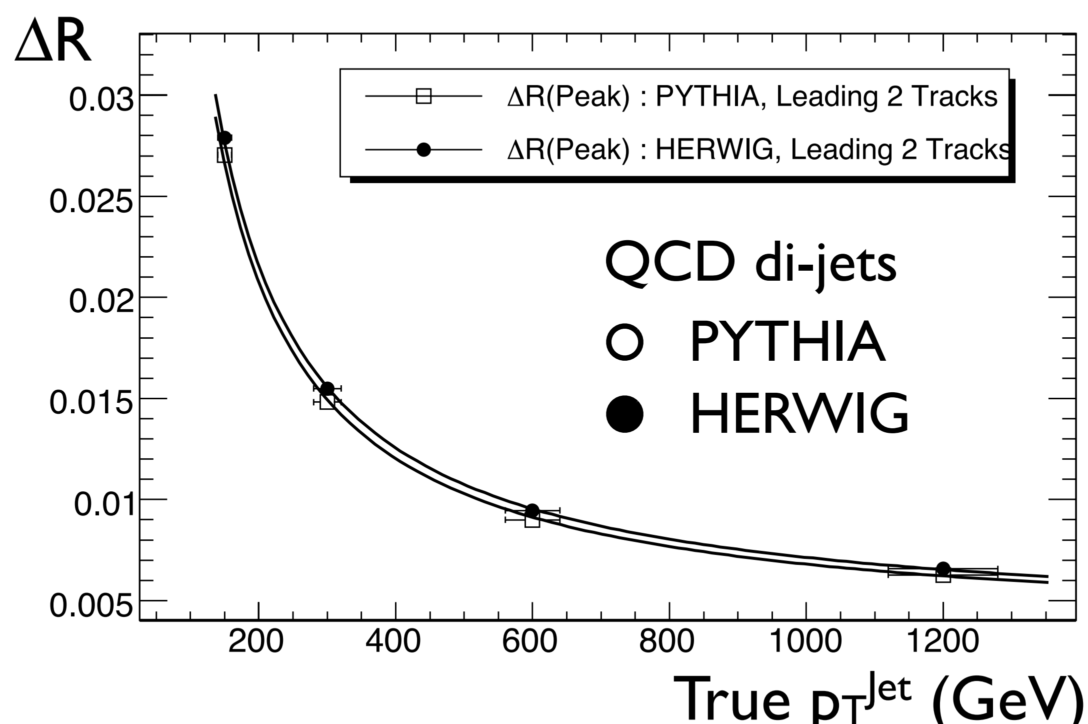
Very High p_T Jet

Option 2. **Track-based Method**

Use Δ**R ∝ 1/P$_T$^{Jet}** to measure JES



- Use QCD di-jet events
  - count all tracks inside the leading jet cone
  - calculate ΔR values over all combinations for leading *N* tracks and take mean value
- Complementary to multi-jet balance method
- Need to study flavor (in)dependence



Potential accuracy of 1 TeV jet scale at 1 fb^{-1}

➡ **~20% level**

MET in ATLAS

MissET in ATLAS

Missing ET is an event variable representing E_T of "invisible" particles

$$\Rightarrow \quad \text{MissET} = \sum_{i=1}^{\nu,\tilde{\chi},\tilde{G},\ldots} E_T^i = -\sum_{i=1}^{\text{detected particles}} E_T^i$$

(concept is simple...)

Measure from calorimeter cells above noise threshold at ATLAS

$$\text{MissE}_{X(Y)} = -\sum_{i=1}^{\text{CaloCells}} E_{X(Y)}^i, \quad \text{MissET} = [\text{MissE}_X^2 + \text{MissE}_Y^2]^{1/2}$$

⇨
- Correct for muons and energy loss in dead materials
- Correct for hadronic jets with cell-level wights (H1 calibration)

Global Calibration

- Apply global cell-level weights to all signal at once

Refined Calibration (default)

- Identify physics objects in an event
  - e, γ, τ, jets, muons, unused topological clusters
- Decompose objects into constituent cells
- Calibrate cells with object calibration weights

MissET Performance

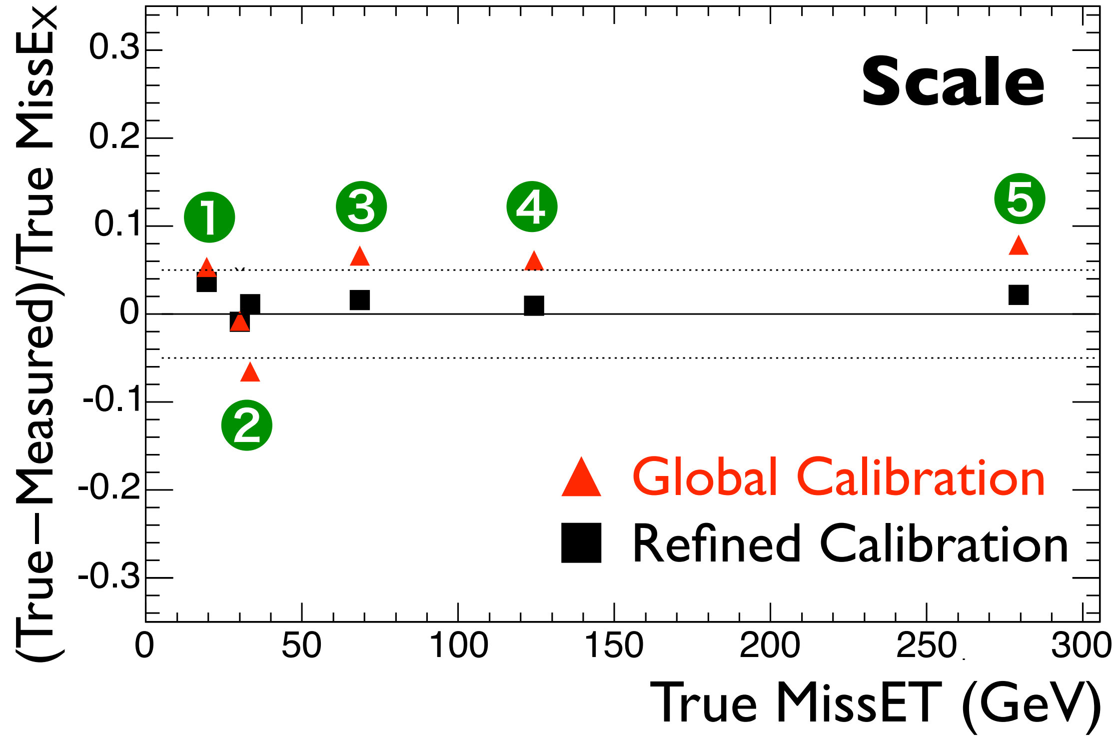
<u>MissET Scale</u>

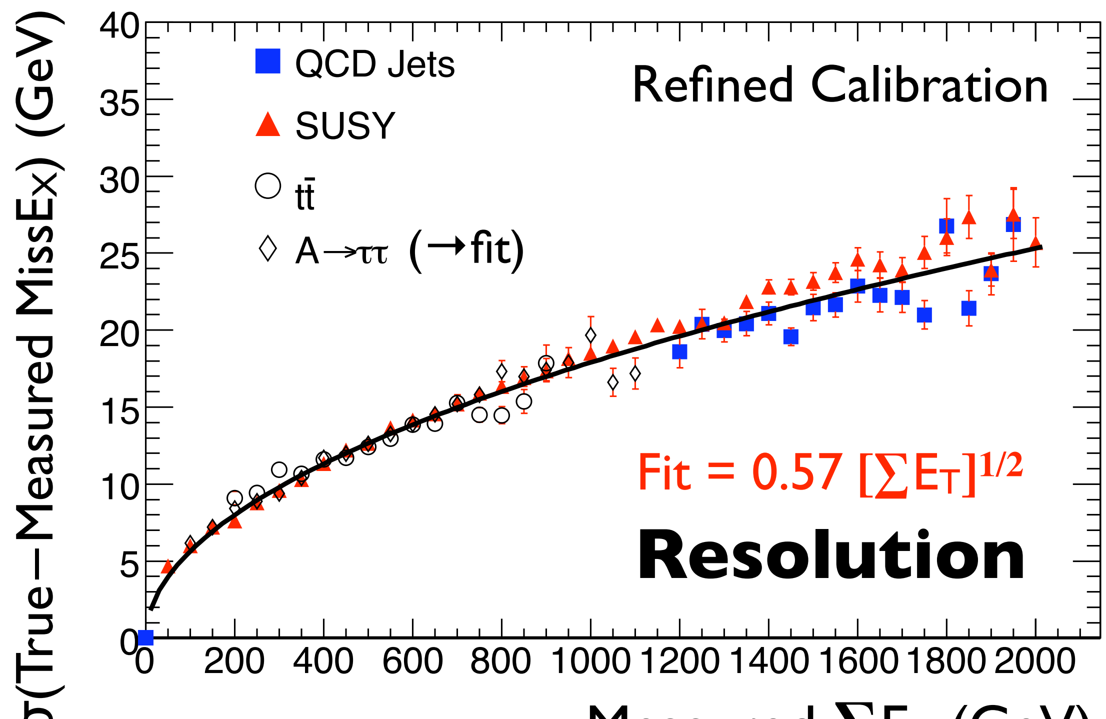
Fairly robust around a few % over wide MissET range and different processes

- ❶ $Z \rightarrow \tau\tau$
- ❷ $W \rightarrow e\nu, \mu\nu$
- ❸ $t\bar{t}$ semi-leptonic
- ❹ $A \rightarrow \tau\tau$ (m_A = 800 GeV)
- ❺ SUSY (~1 TeV mass)

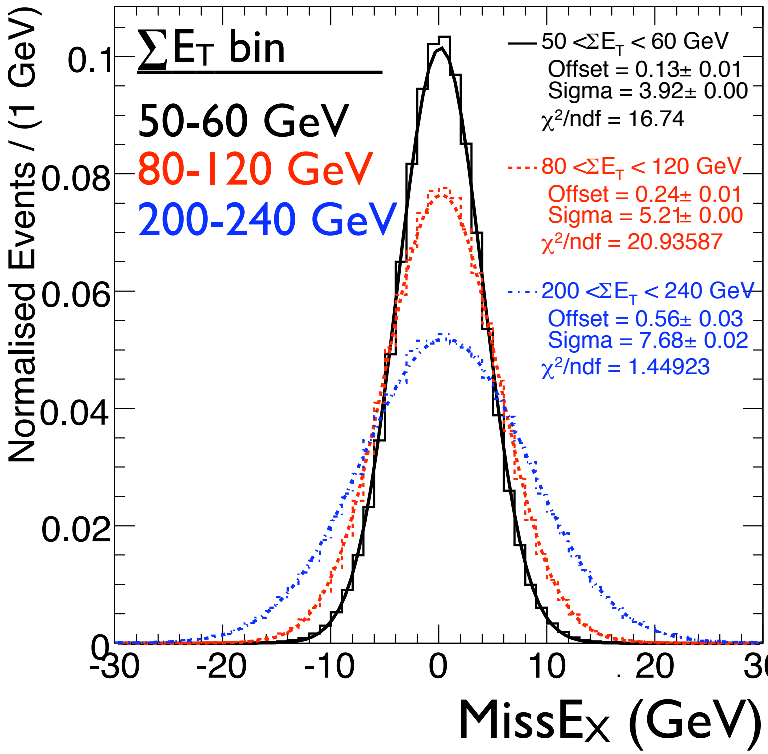
<u>MissET Resolution</u>

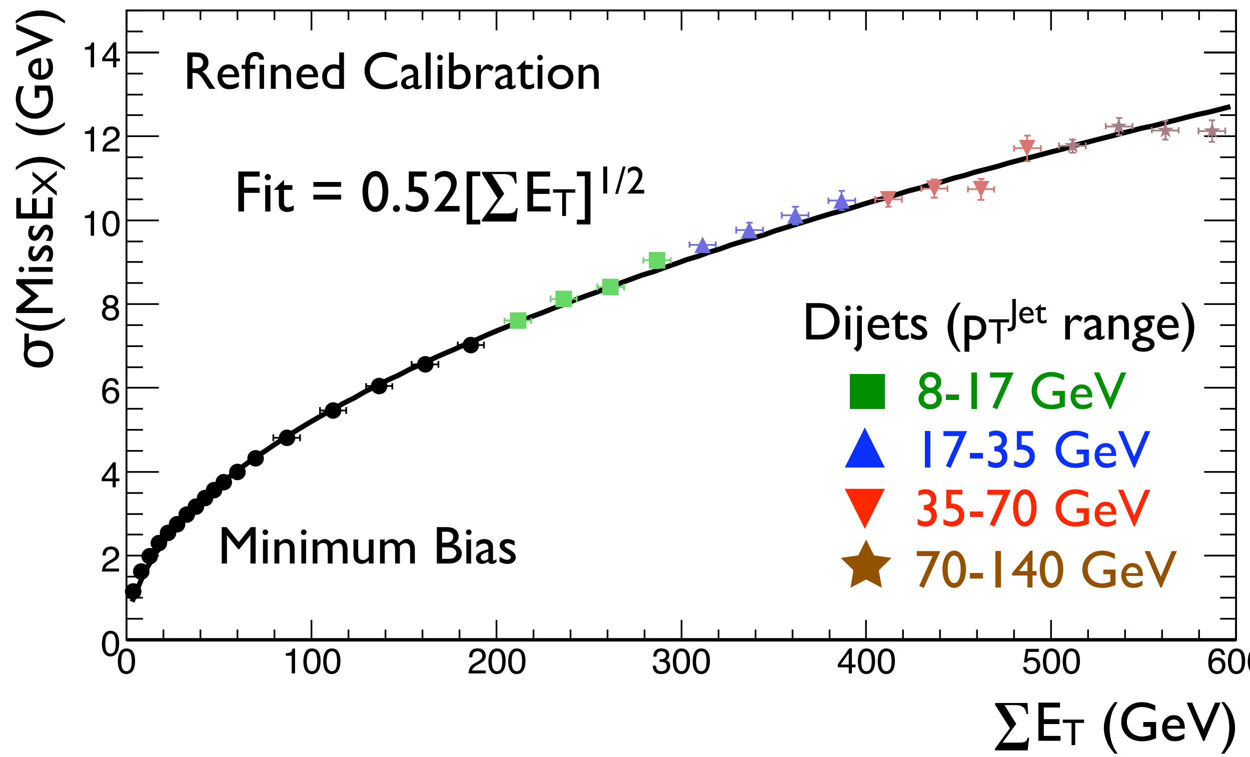
Follow $\sigma = a\,[\sum E_T]^{1/2}$ over a very wide range of $\sum E_T$





MET Validation : Mini. Bias





- Check if various distributions are consistent with expectations
  - MissEX/Y , MissET, ϕ(MissET), MissEX resolution vs ΣET
- Background rejection to be done
  - Beam Gas, Beam Halo, Empty events
  - Any additional quality cut after Minimum Bias Trigger?

For details

- Etmiss CSC notes, MinBias section by Anna Phan, Naoko Kanaya
- Hideki Okawa, MinBias WG Meeting, 10 Sep. 2007

MET Validation : $W \to l\nu$

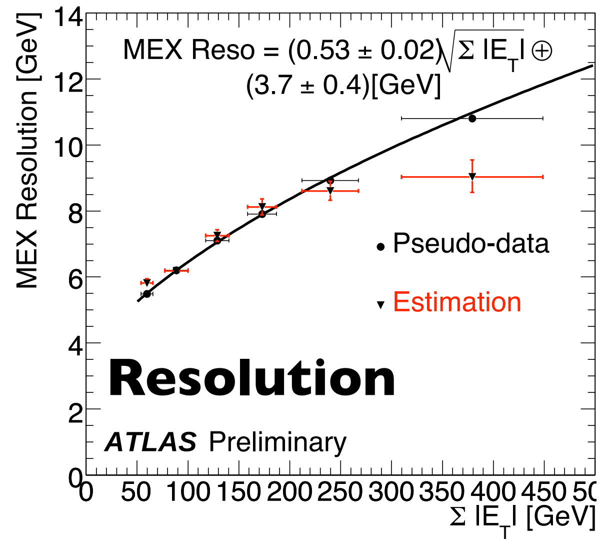
W's Transverse Mass : $M_T = [2\, p_T^{\nu}\, p_T^{\mu}\, (1 - \cos\Delta\phi)]^{1/2}$

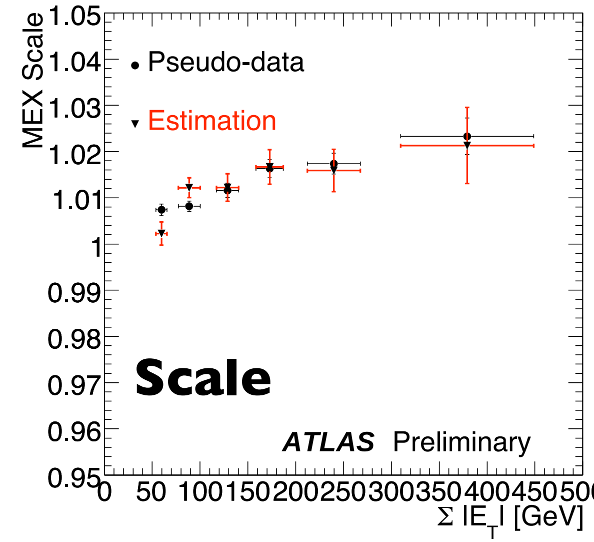
$W \to \mu\nu$ @ 28 pb^{-1}

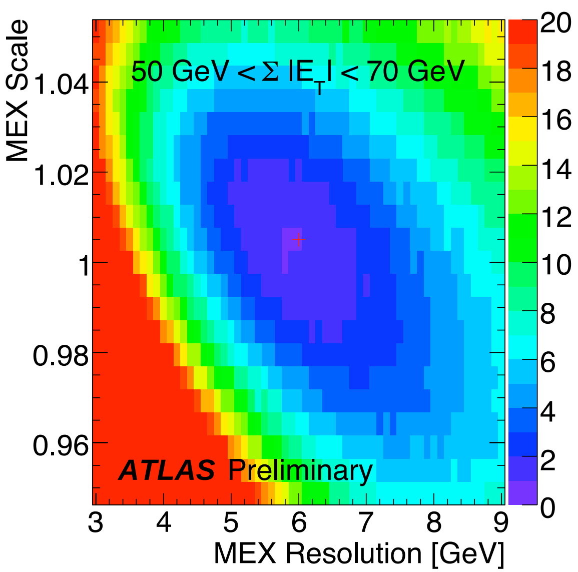
<u>Template Method</u>

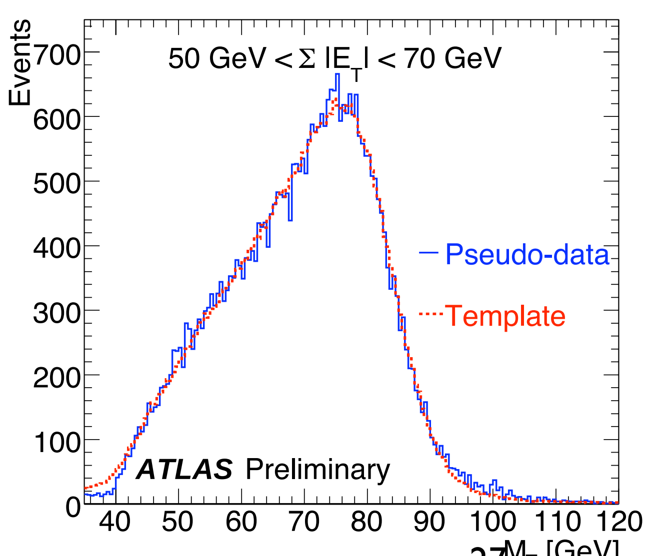
- Use M_T templates constructed from MC truth lepton p_T and MET with 2 smearing parameters: scale factor α & resolution σ
  → **MissEX^{Smeared} =**
  α TruthMissEX + Gauss(0,σ)
- Fit M_T distribution (in each ΣE_T range) from real data with each template, and determine the parameters by minimizing the χ^2

1 Isolated μ with p_T>20 GeV, $|\eta|$<2.5 & MissET>20 GeV









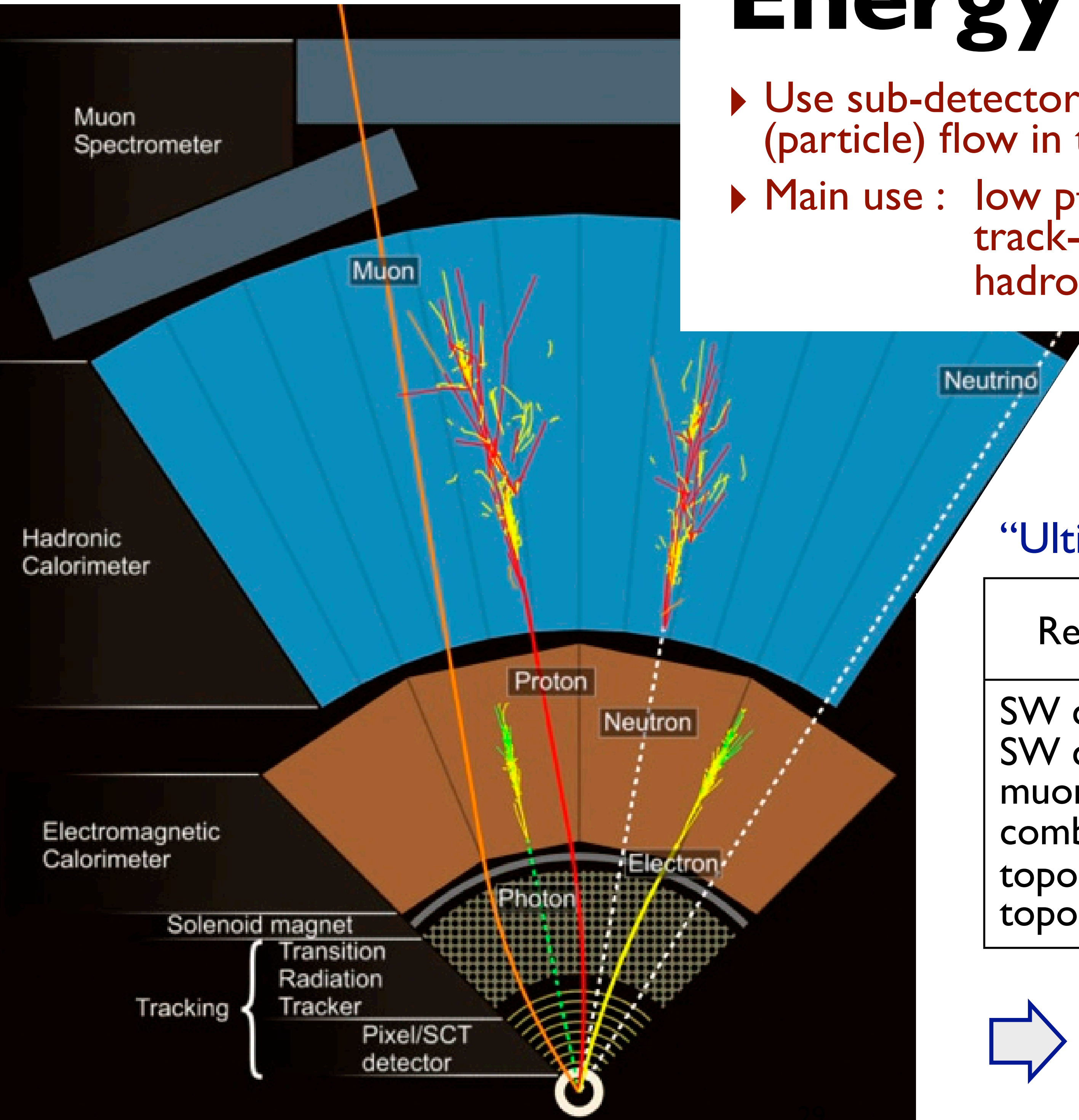
- Resolution well reproduced
- Scale reproduced within ~1 %
- Similar results for $W \to e\nu$ channel

For details:
ETmiss CSC note, Early data - $W \to l\nu$ section by Hideki Okawa & Naoko Kanaya

Energy Flow Approach for Improvement

Energy Flow

- Use sub-detectors to reconstruct energy (particle) flow in the detectors
- Main use : low p_T jet resolution
  track-calorimeter jet association
  hadronic τ identification



"Ultimate" Particle Energy Flow

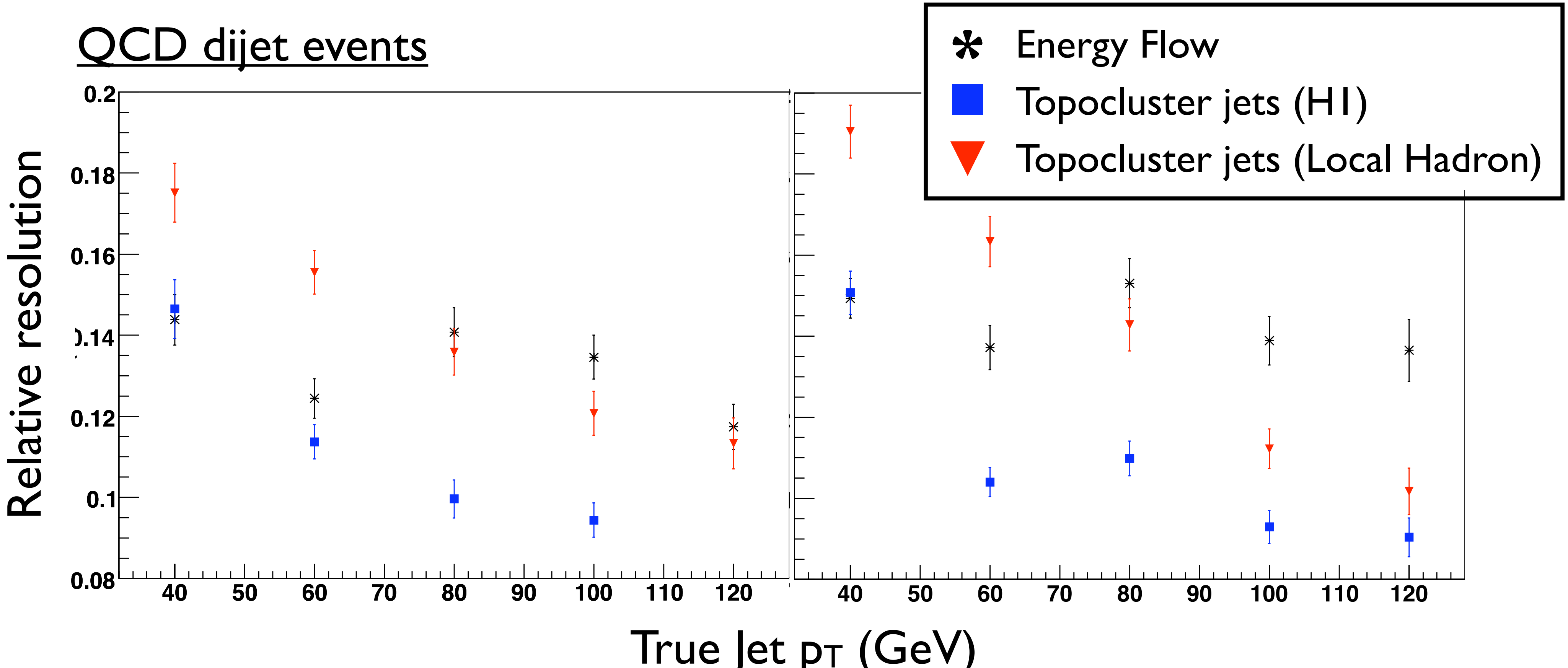
Reconstruction	Identification & Calibration
SW clusters w/ tracks	→ **e**
SW clusters w/o tracks	→ γ
muon hits w/ tracks	→ μ
combined clusters w/ τID	→ τ
topo. clusters w/ tracks	→ $h^{\pm}$
topo. clusters w/o tracks	→ h^{0}

$$P_T^{Jet} = \sum P_T^{e,\gamma,\mu,h\pm,h0,\ldots}$$

$$MET = -\sum P_T^{e,\gamma,\mu,h\pm,h0,\ldots}$$

Energy Flow Implementation

- Extrapolate tracks to calorimeter to find matched cluster(s)
- If matched cluster found, subtract expected energy deposit (obtained from single particle MC) from the cluster
- Subtraction performed using cell removal or adjusting cluster energy
- If E^{clus}(before subtraction) < $E^{expected}$ - $k_2\sigma^{expected}$, use cluster instead of track
- If E^{clus}(after subtraction) < $k_1\sigma^{expected}$, the cluster is discarded



Energy Flow : Hadronic W in Top

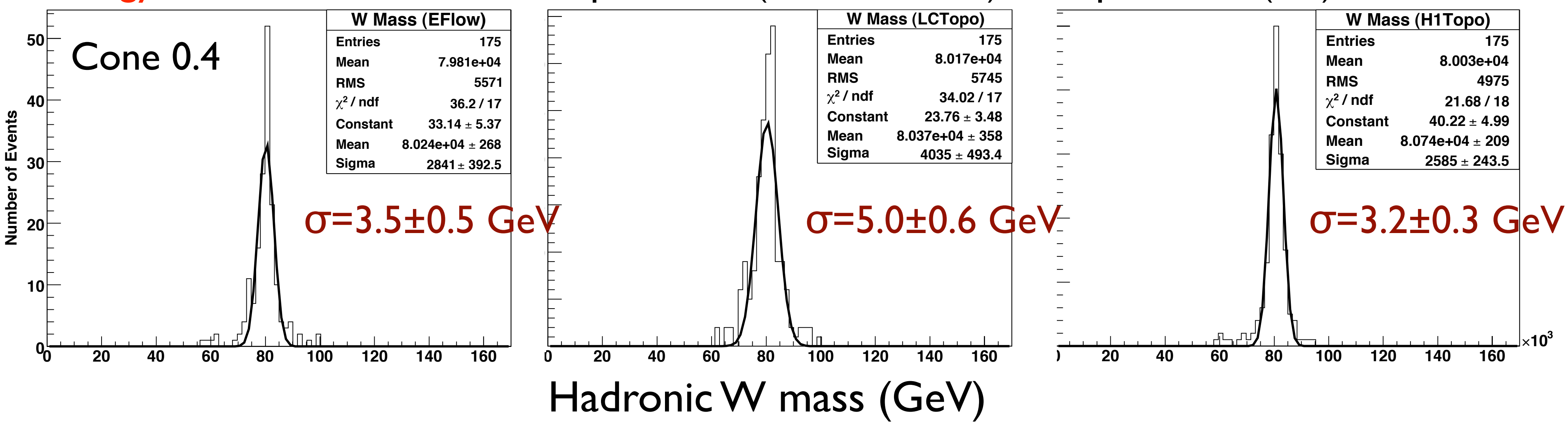
Apply energy flow algorithm to hadronic W decay in all hadronic tt events

- Select jets from $W \to jj$ by looping over all jet combinations and minimizing

$$\sqrt{\left(\frac{m_W{}^{Reco} - m_W{}^{PDG}}{\sigma_W{}^{PDG}}\right)^2 + \left(\frac{m_{top}{}^{Reco} - m_{top}{}^{PDG}}{\sigma_{top}{}^{PDG}}\right)^2}$$

- Select ≥4 jets with p_T > 50 GeV, MissET > 40 GeV

Energy Flow — Topocluster (Local Hadron) — Topocluster (H1)



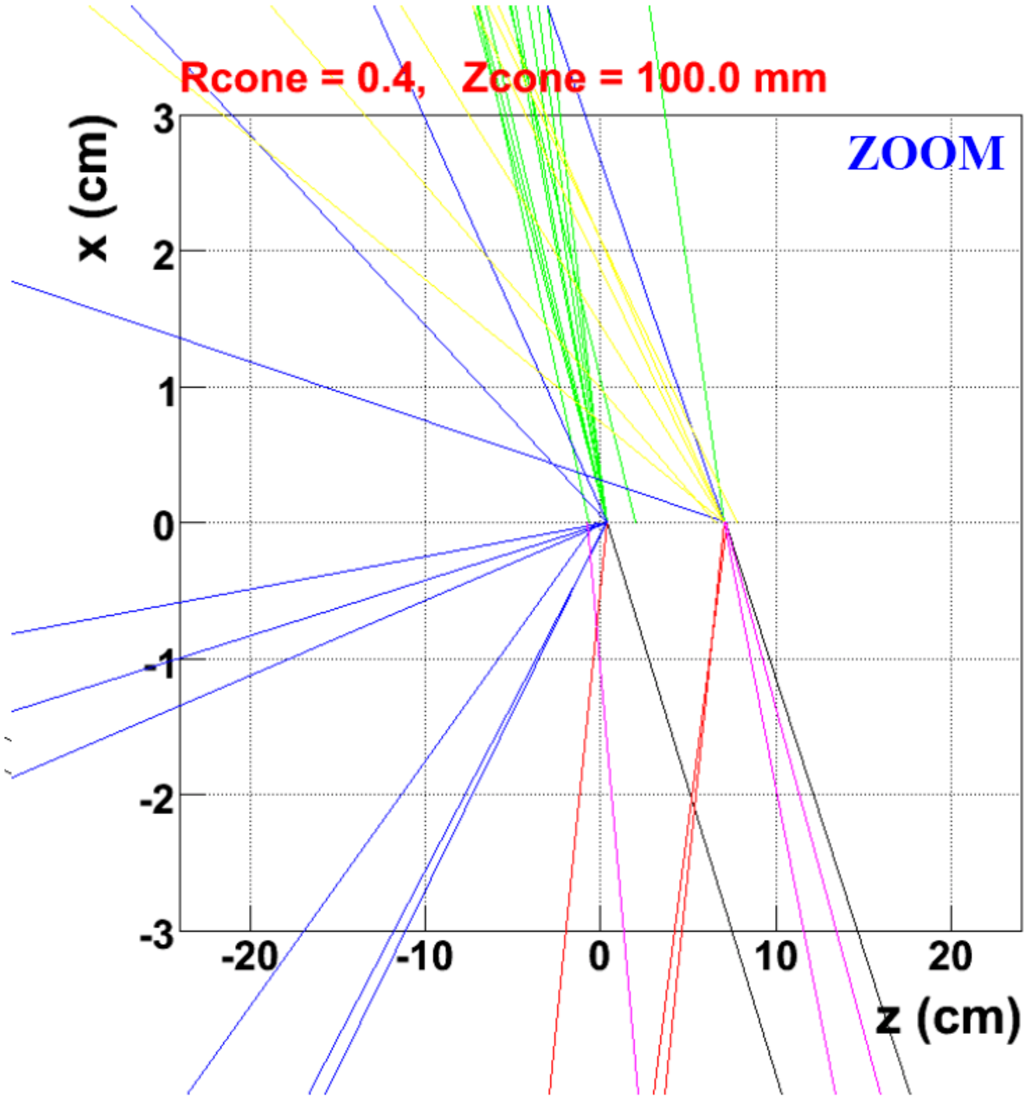
Better angular resolution for energy flow jets than local hadron topocluster jets
→ Improves W mass resolution over local hadron topocluster jets

Track Jet

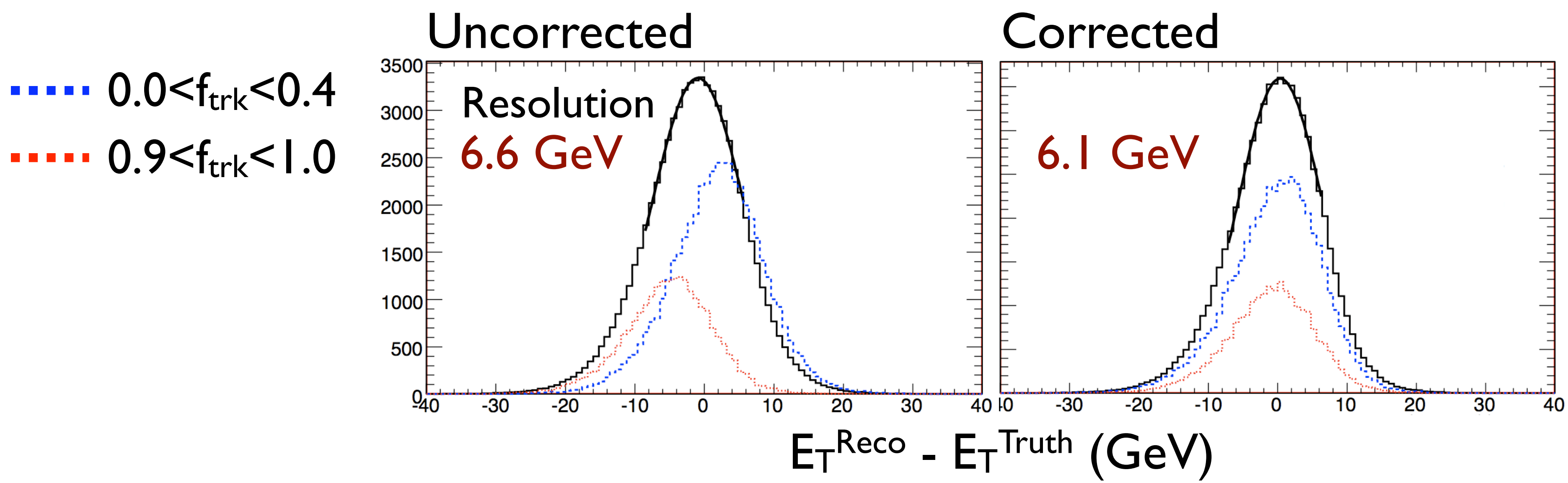
Different jet finding strategy based on 3-D (η,φ,Z) clustering using track info

Lots of useful applications

- Track-based energy scale corrections
  - Charged particle content correlated with calorimeter jet response
- Jet identification
  - Jets from minimum bias pile-up events
  - Jet charge (?)
- Fake missing E_T clean-up
  - Jets in calorimeter cracks
- Low p_T jet reconstruction

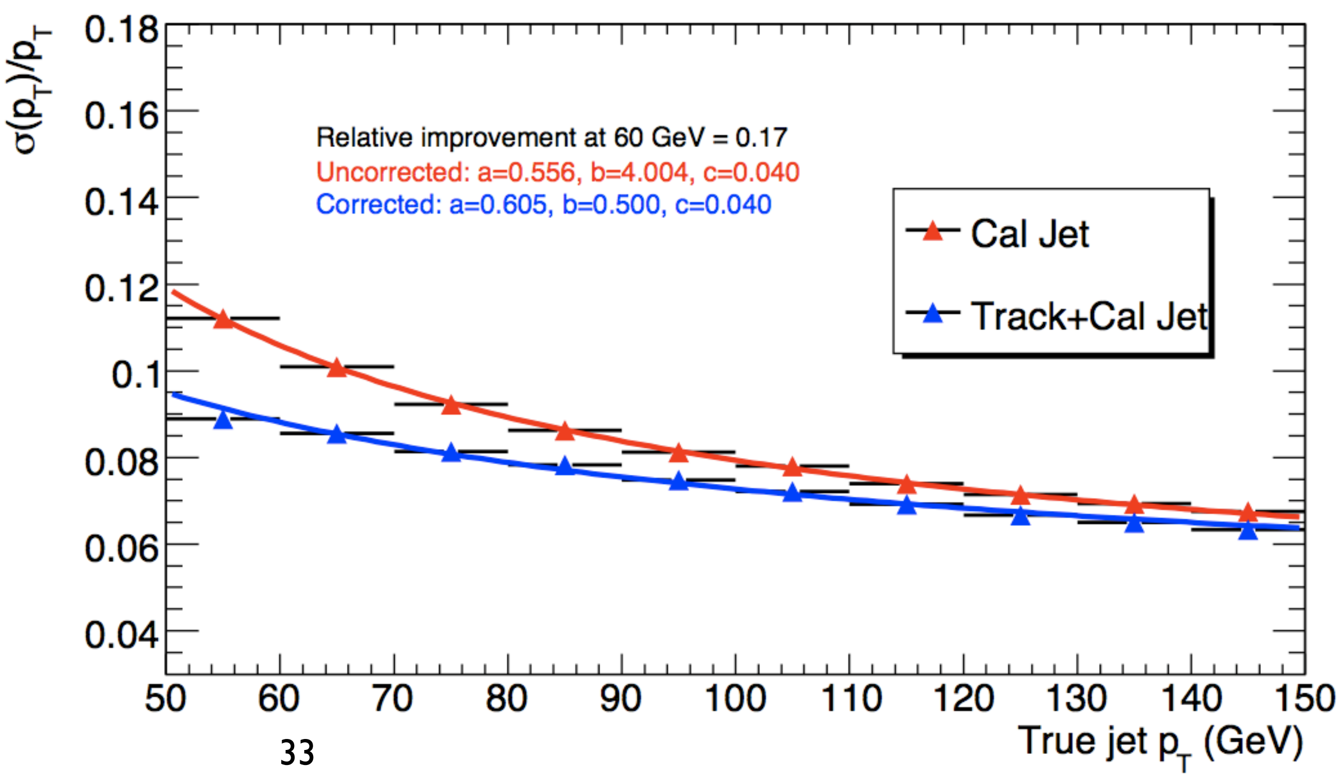


Track Jet : Jet Energy Resolution



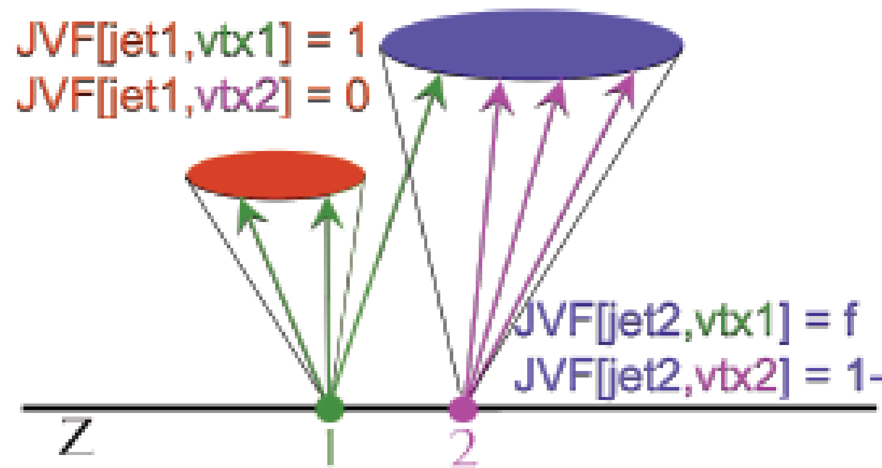
Add information from tracker to improve resolution after JES corrections

- E.g, $\boldsymbol{f_{trk} = \Sigma p_T^{Track} / p_T^{Jet}}$ fraction of jet p_T carried by charged tracks



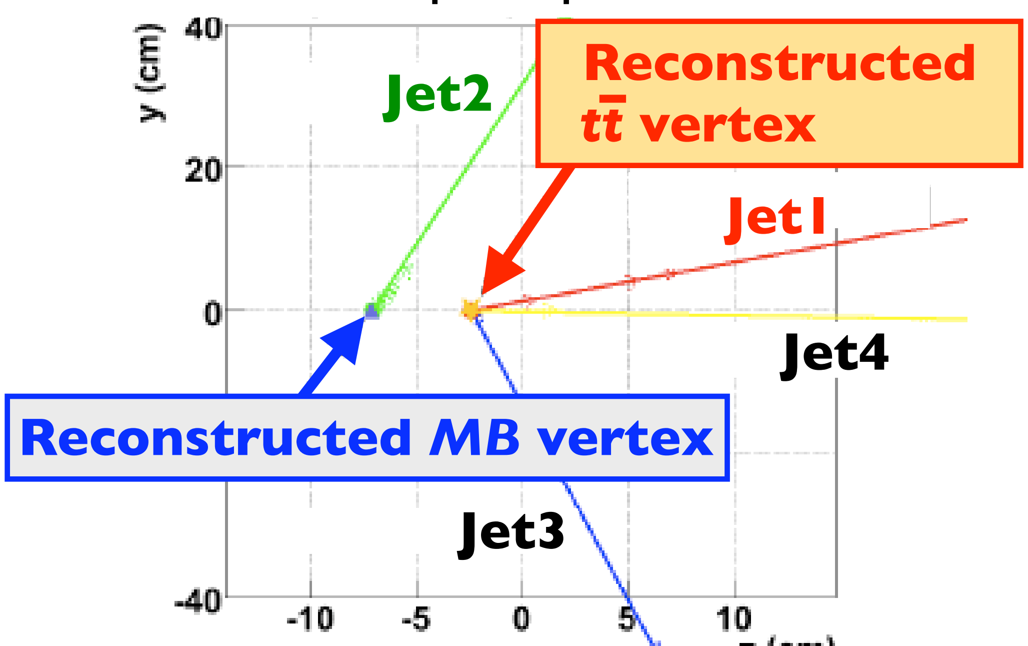
Track Jet : Pile-up Rejection

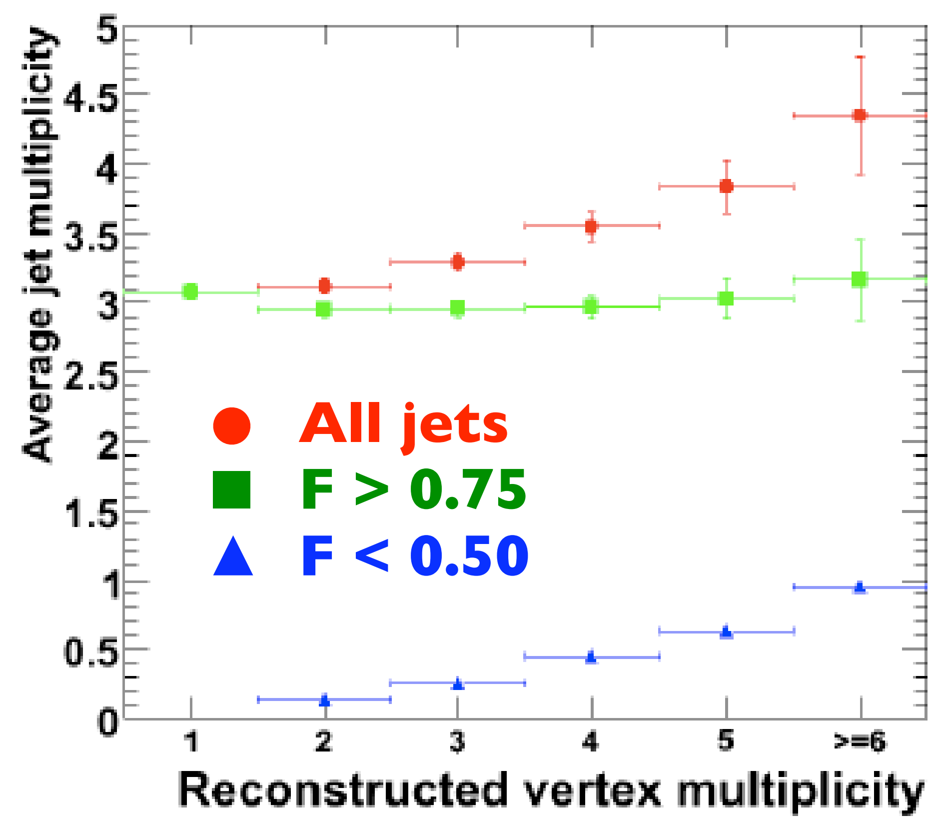
- Soft pile-up noise → Topological Clustering
- "Hard" (minimum bias jet) pile-up?
  - ➔ 3-D (η,ϕ,Z) jet finding using tracks
    - Associate jets to primary vertices
    - Evaluate fraction **F** of charged track energy in each jet originating in each identified primary vertex



Minimum bias events do make hard jets!

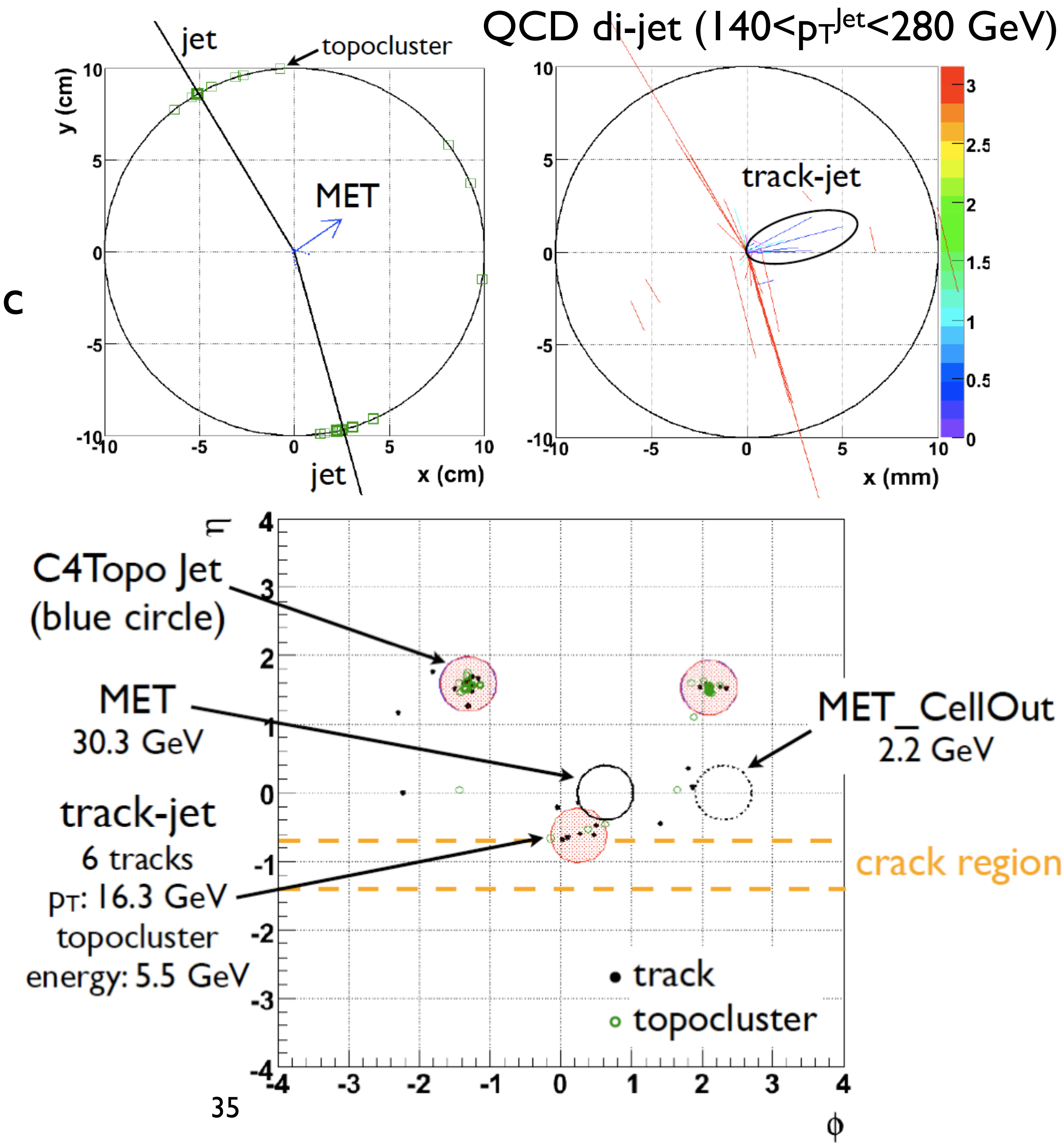
$t\bar{t}$ events with pile-up





Track Jet : Fake MET Rejection

- Select events where MET pointing to any problematic calorimeter regions in ϕ
- See if any track-jet is reconstructed along the direction without accompanying calorimeter jet



Summary

No real summary as performance studies are on going, while ...

- Jet and Missing ET performance at ATLAS looks very promising over wide kinematic range and different processes
- Most ATLAS calibrations and corrections are based on Monte Carlo simulations
  → Validation of detector simulation and calibration with real data is very crucial
- Many (unexpected) challenges ahead of us, but being ready to attack problems with useful tools