Particle-flow Algorithms in America

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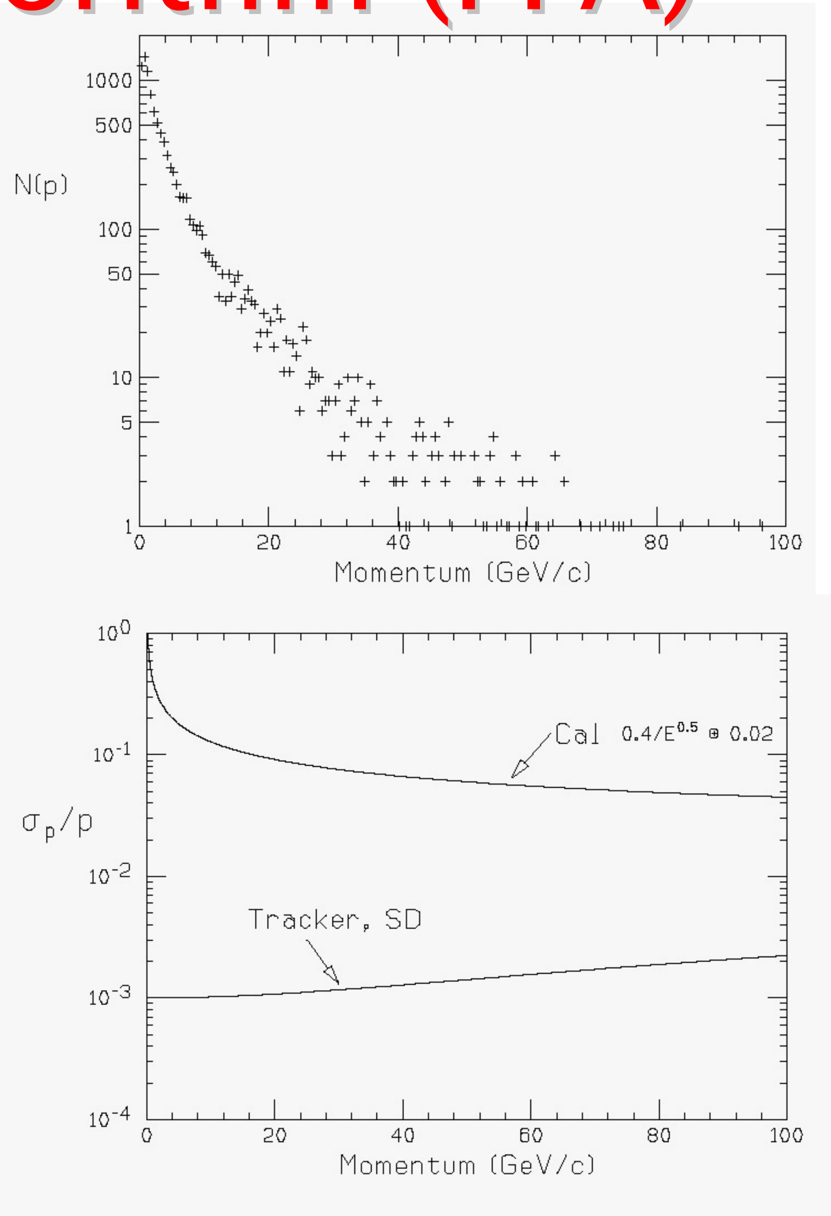
Work done over the past 2 years:

- Algorithms:
  - NICADD/NIU (V. Zutshi)
  - ANL (S. Magill, S. Kuhlmann)
  - SLAC (N. Graf, G. Bower)
- Simulations:
  - NICADD/NIU (D. Chakraborty, G. Lima, J. McCormick)
  - SLAC (R. Cassell)

Particle–Flow Algorithm (PFA)

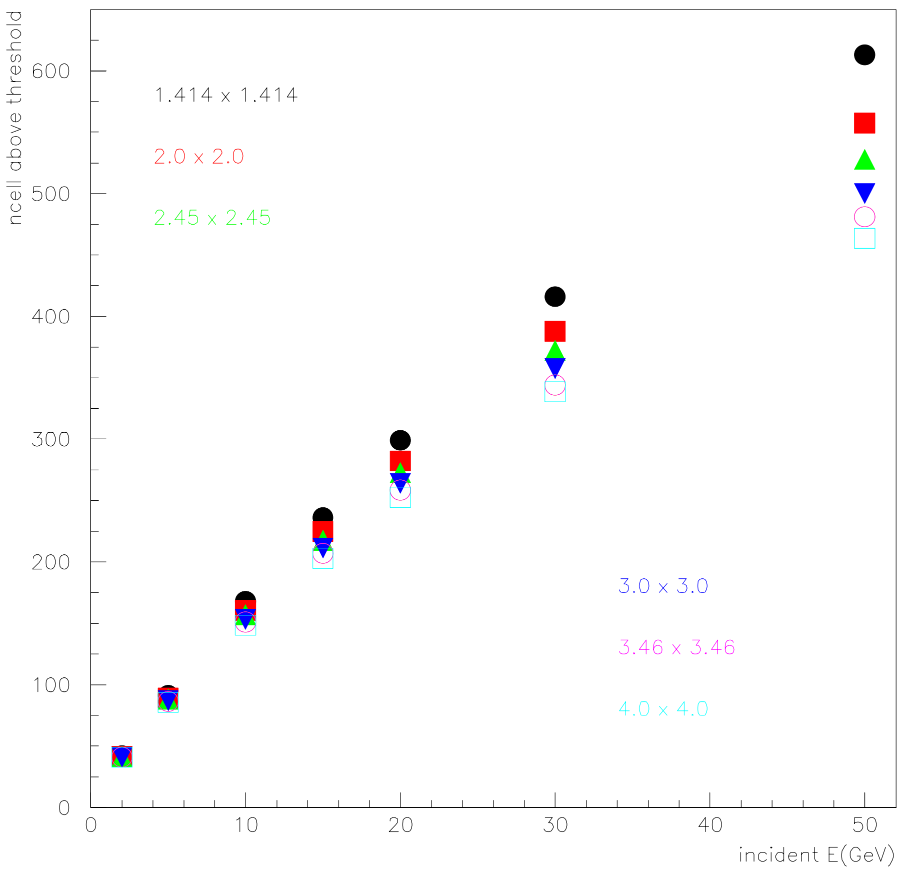
- Charged particles in a jet are more precisely measured in the tracker
- A typical jet consists of:
  - 64% charged particles
  - 21% photons
  - 11% neutral hadrons
- Use tracker for charged,
- Calorimeter for neutrals only
- Must be able to separate charged particle energy clusters from neutrals inside a jet in calorimeter

  ⇒ fine 3d granularity

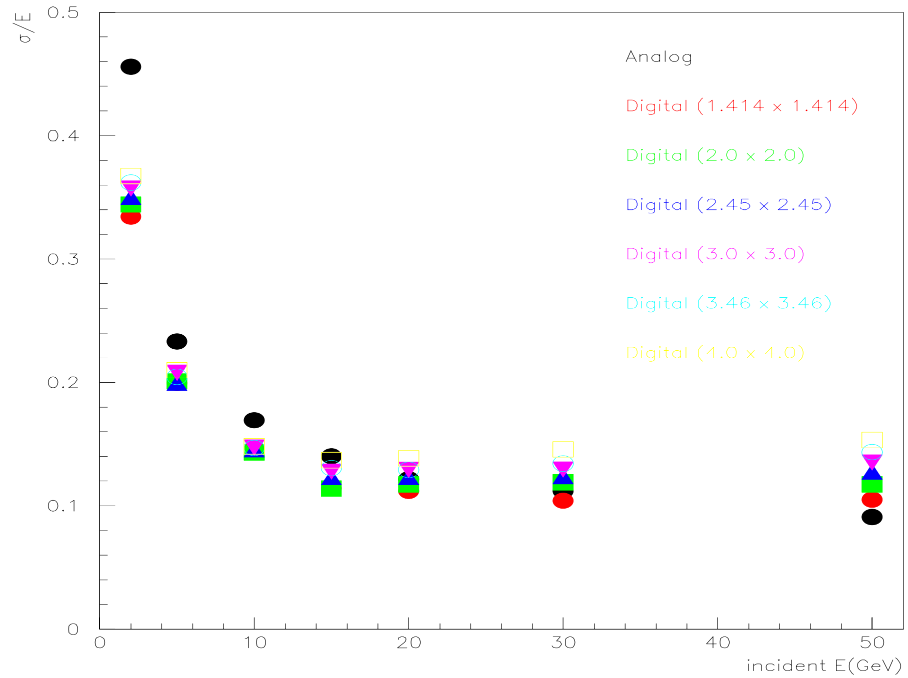


Technology/Design simulations: Scintillator semi-Digital HCal (NIU)

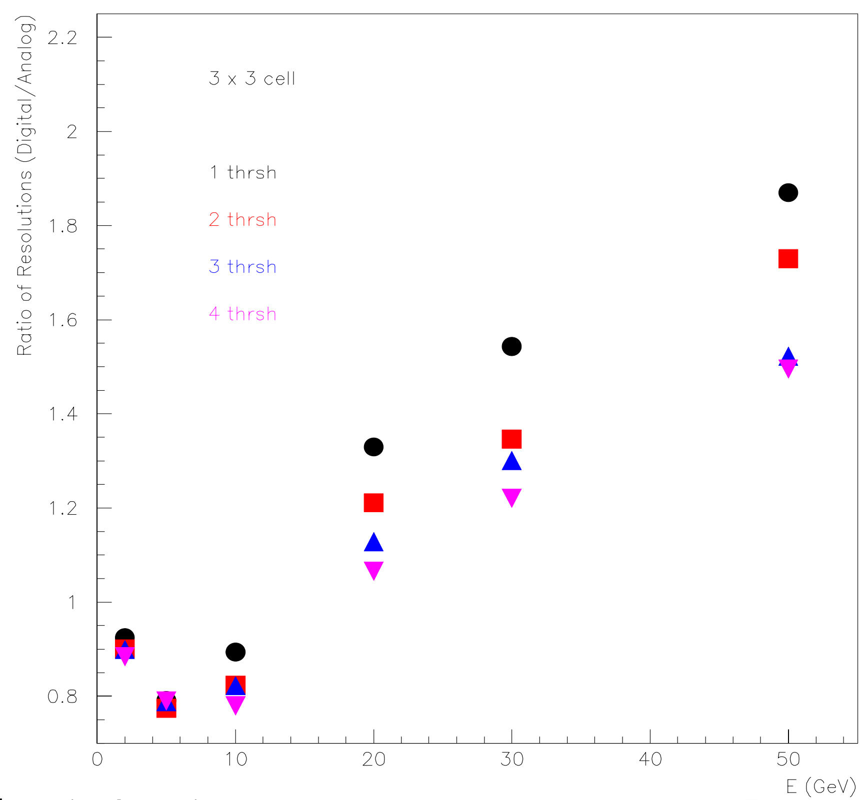
- Studies with GISMO and G4 based simulations
- Detailed comparisons of GISMO-LCDG4-Mokka
- Steel(20mm)-Scint(5mm) sandwich with varying transverse segmentation



Scintillator (semi)Digital HCal: cell size and thresholds



Non-projective geometry



- Single charged pions
- Plain cell-counting only
- 10–12 cm^2 acceptable
- 3 thresholds optimal

SD Detector: a Particle-flow detector for the LC

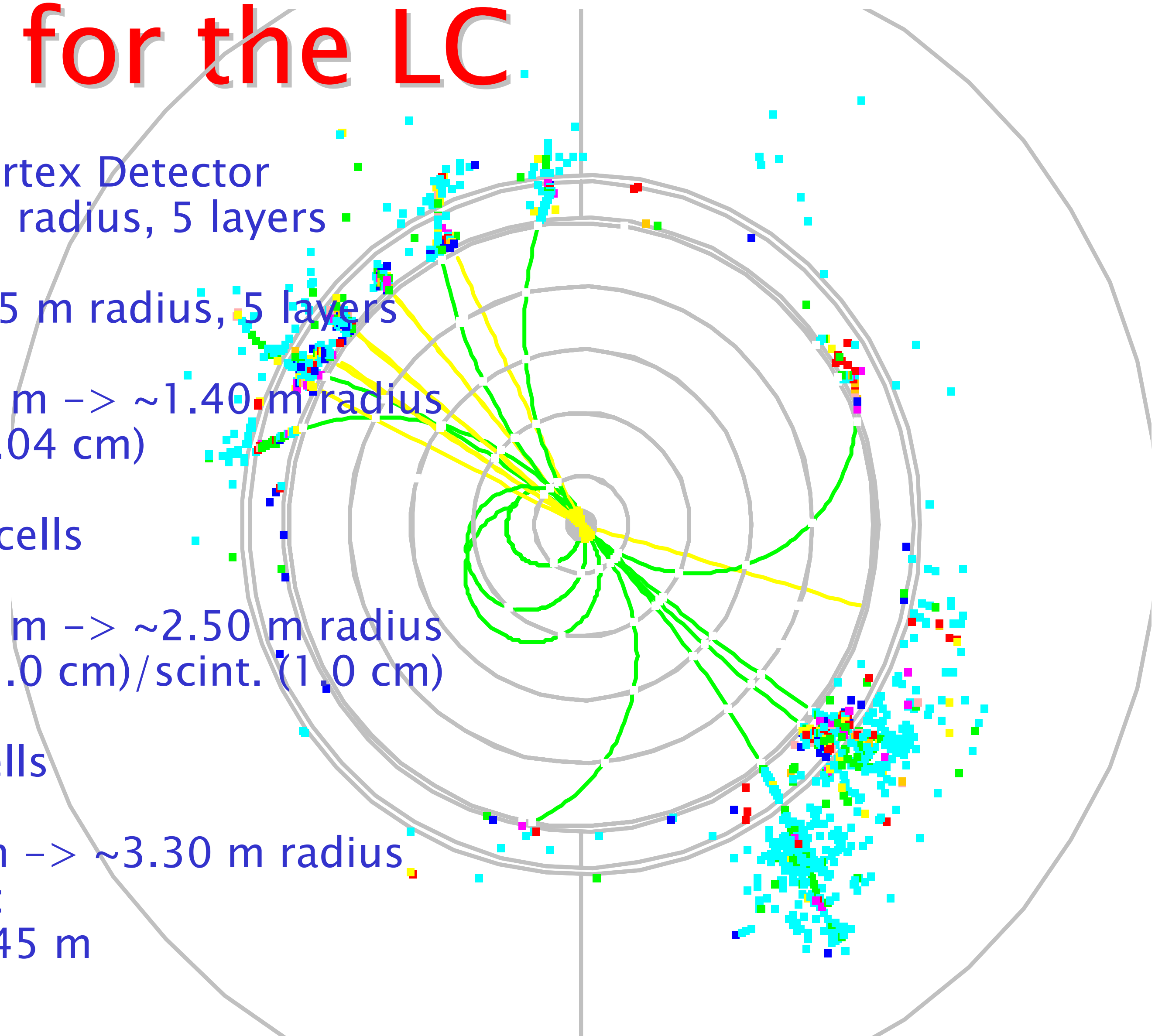
Tracking :
- Multi-layer Si Vertex Detector
- ~1 cm -> ~7 cm radius, 5 layers
- Si-Strip Tracker
- ~20 cm -> ~1.25 m radius, 5 layers

ECAL :
- 30 layers, ~1.25 m -> ~1.40 m radius
- W(0.25 cm)/Si(0.04 cm)
- ~20 X_0, 0.8 λ_I
- ~5 mm X 5 mm cells

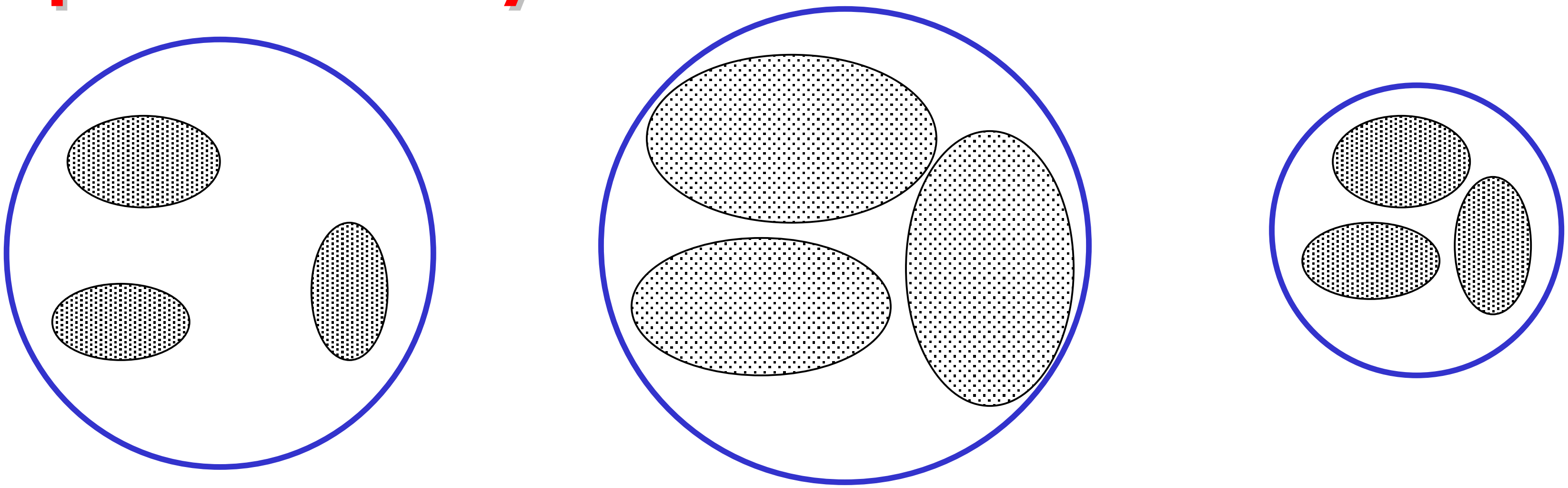
HCAL :
- 34 layers, ~1.45 m -> ~2.50 m radius
- stainless steel (2.0 cm)/scint. (1.0 cm)
- ~40 X_0, 4 λ_I
- ~1 cm X 1 cm cells

Solenoid Coil :
- 5 Tesla, ~2.50 m -> ~3.30 m radius

Muon (Tail Catcher) :
- ~3.40 m -> ~5.45 m



Separability of clusters



Best separability is achieved when spread within a class is small & distance between classes large.

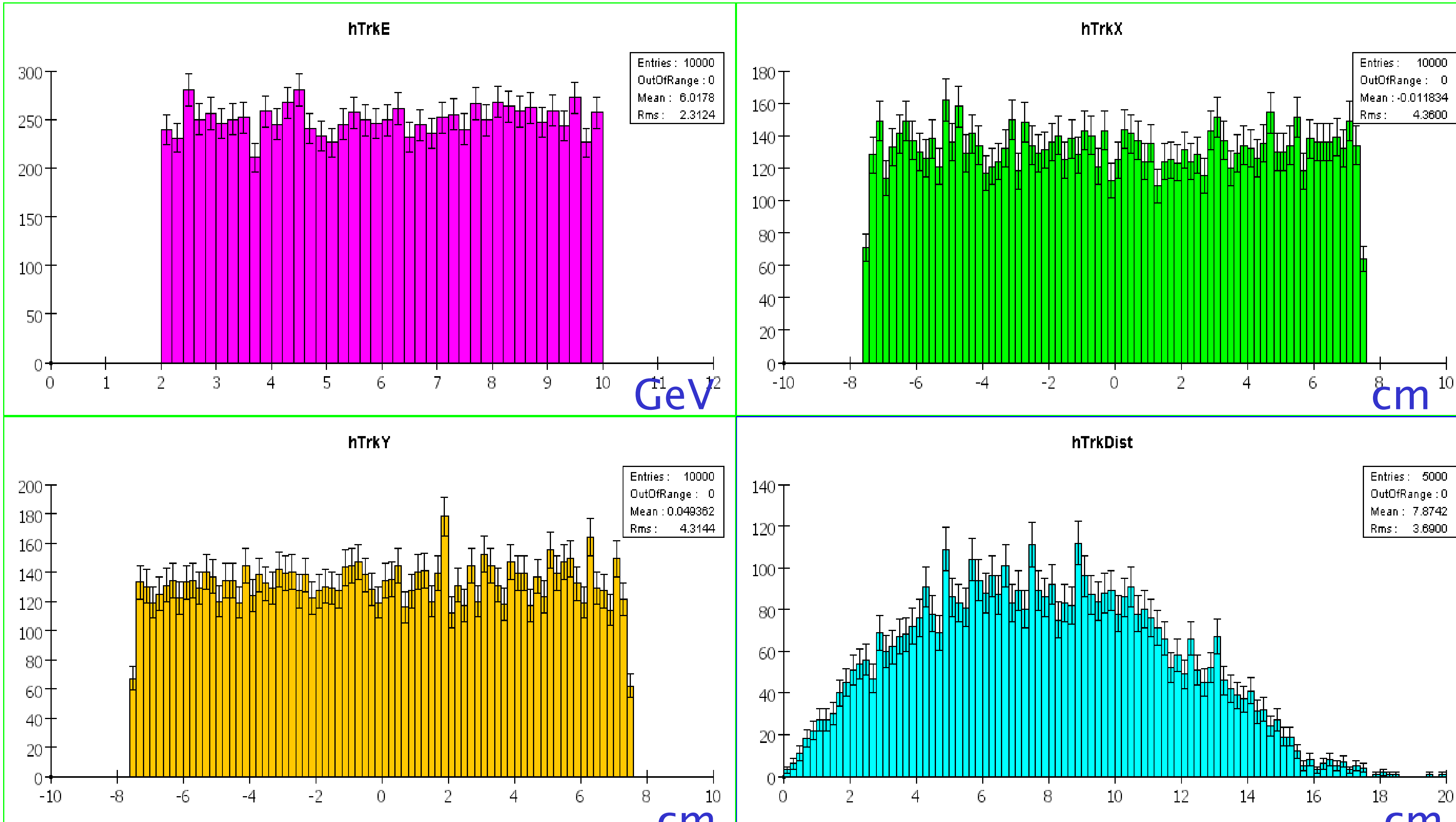
$$J = \mathrm{Tr}\{S_w^{-1} S_m\}$$

where $S_w = \Sigma_i W_i S_i$

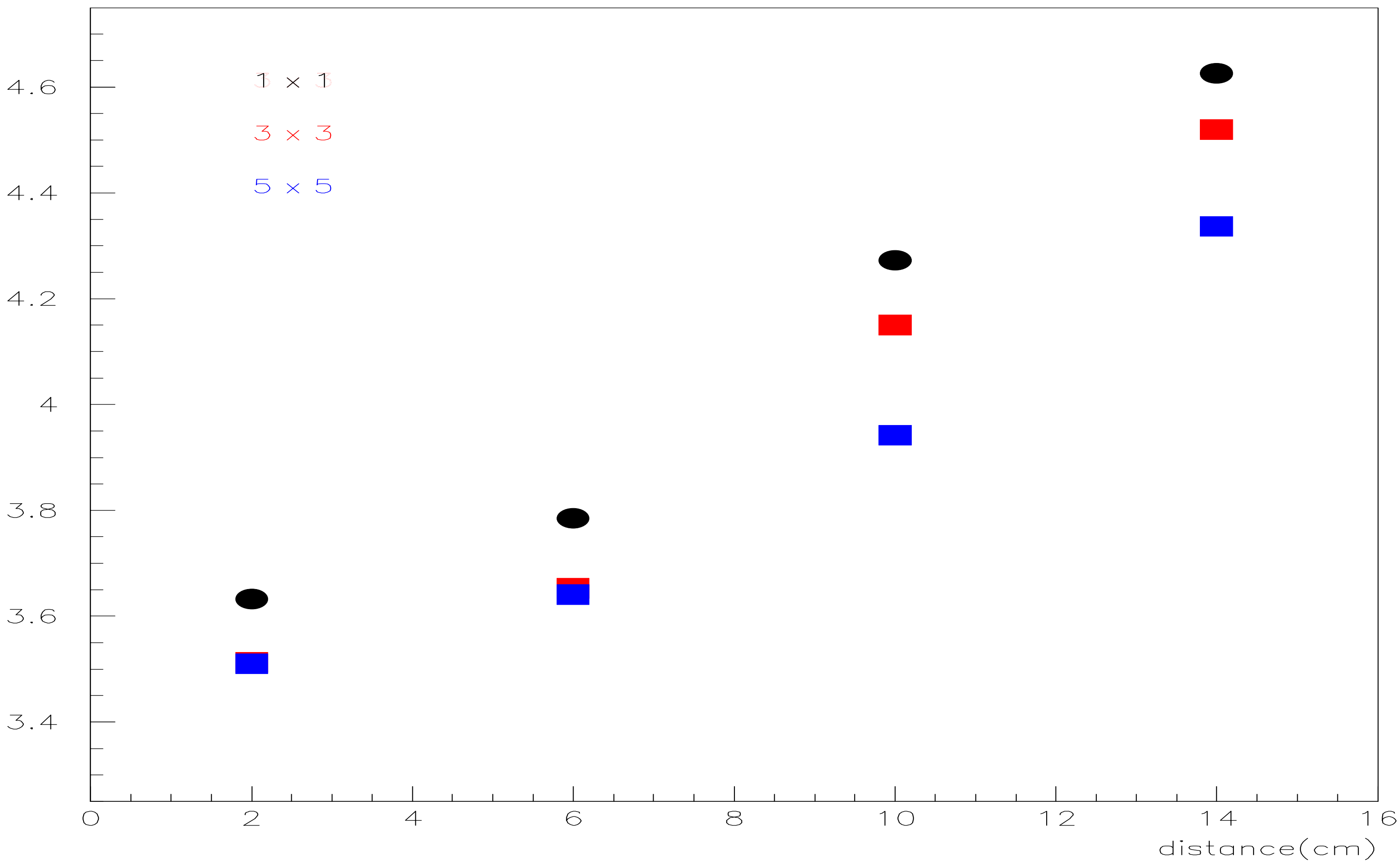
S_i = covariance matrix for cluster c_i (in x, y, z)

S_m = covariance matrix w.r.t. the global mean

Two (parallel) π^+'s in TB sim:



Two (parallel) π^+'s in TB prototype sim: separability (J) vs. track distance for different cell sizes



Another measure of separability

$$B = a\,(\mu_i - \mu_k)^T\,(\{S_i + S_k\}/2)^{-1}\,(\mu_i - \mu_k)\; +$$
$$b\,\ln\{(|(S_i + S_k)|/2)(|\,S_i\,||\,S_k\,|)^{-½}\}$$

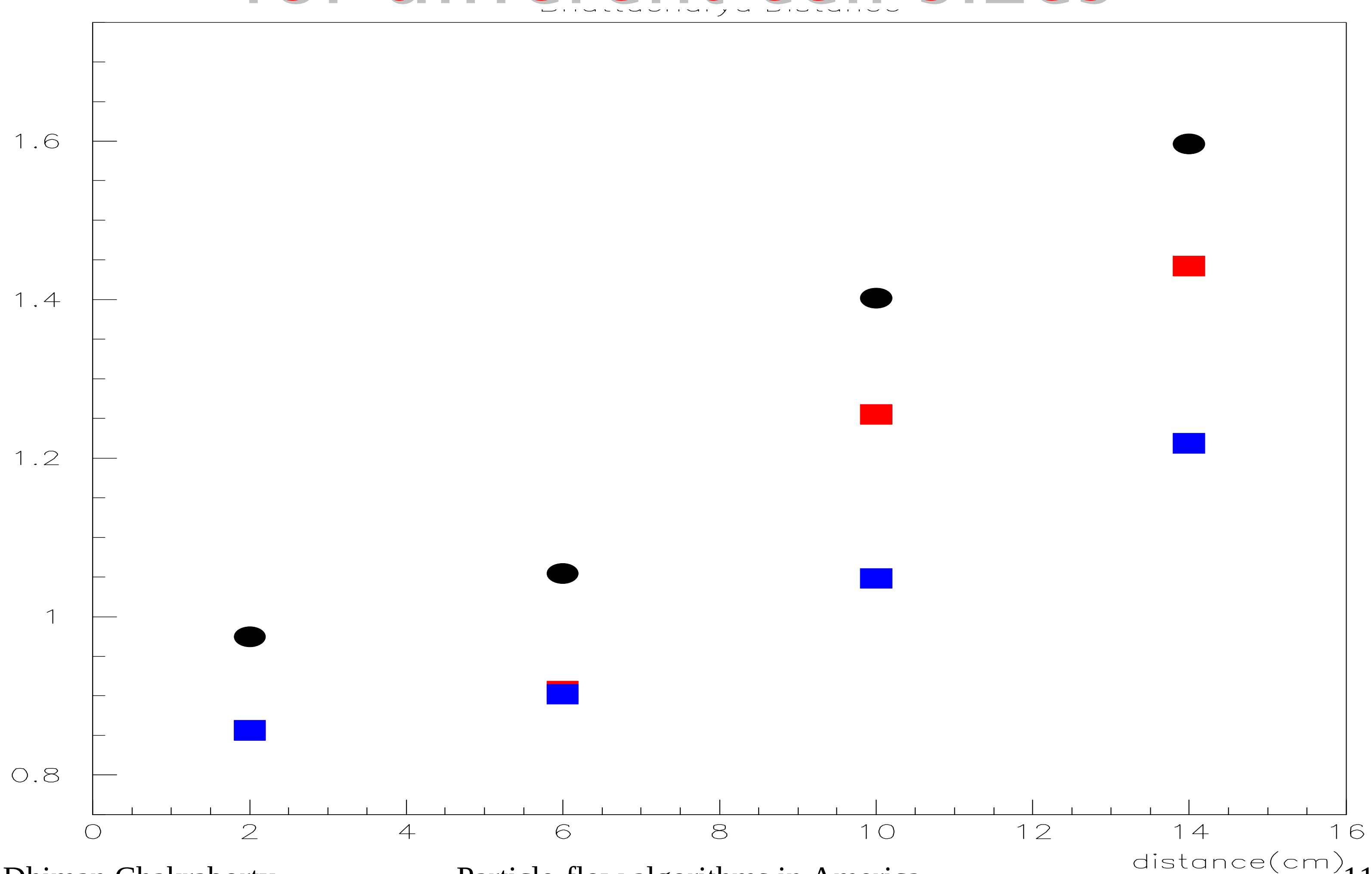
$a,b > 0$

μ_i = mean, S_i = covariance of i-th cluster

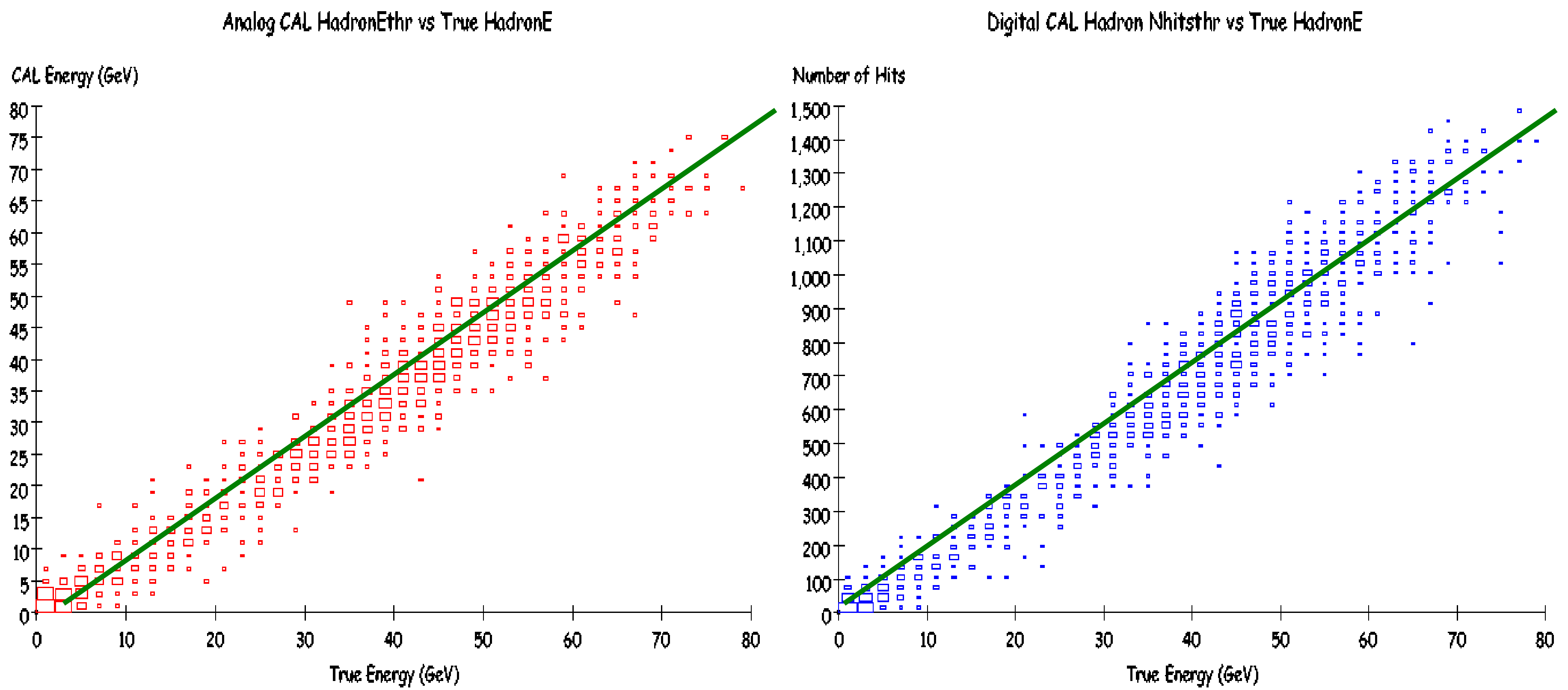
1st term gives separation due to mean difference,

2nd term due to covariance difference

Two (parallel) π+'s in TB sim: separability (*B*) vs. track distance for different cell sizes



Analog/Digital response to hadrons



development in terms of "track length" :

Track Length (T) = sum of tracks of all charged particles in a shower – Analog sampling calorimeters sum energy, Digital sampling calorimeters sum hits

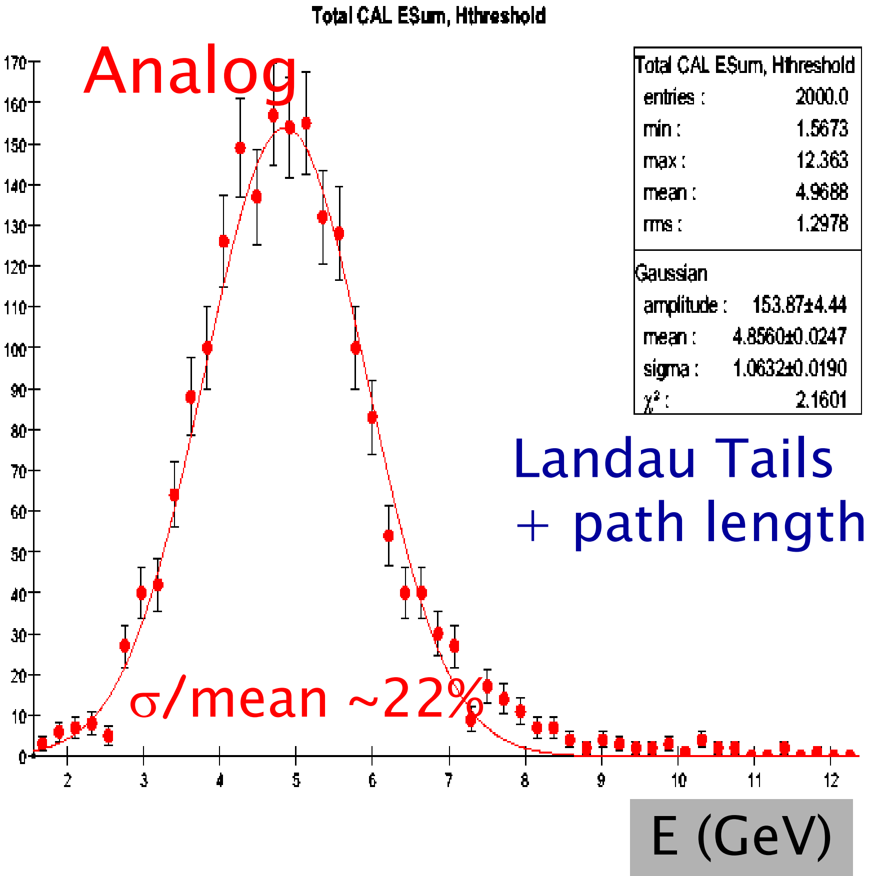
$T \propto E$ (particle energy) – what about spread in energy?

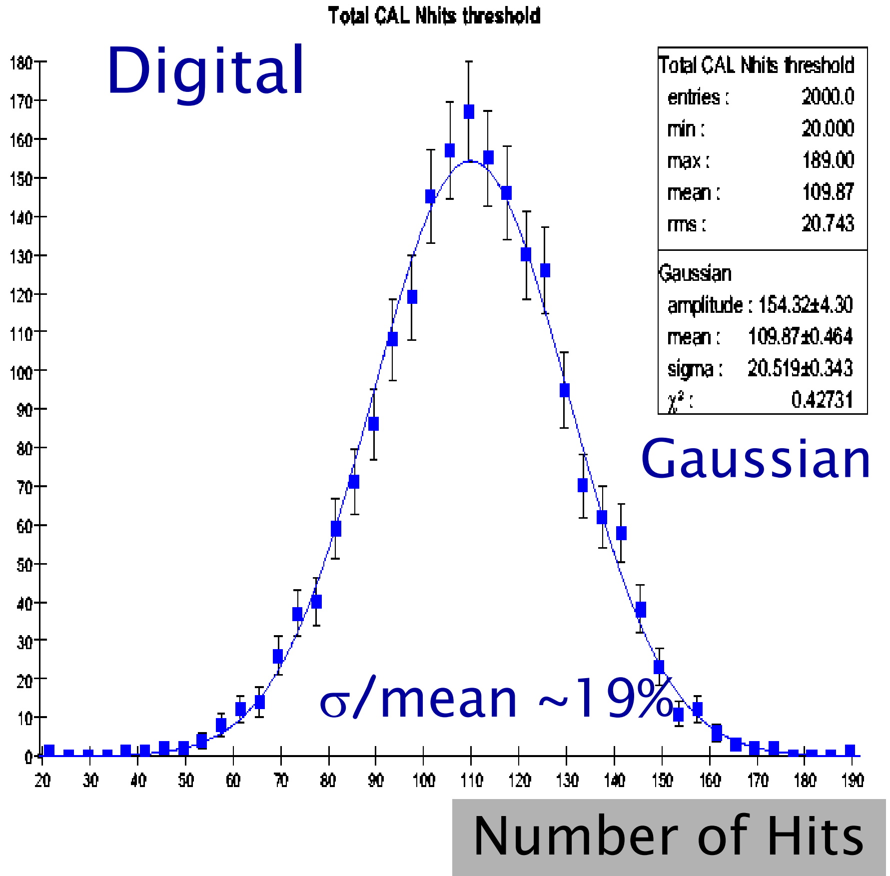
Energy resolution with analog & digital calorimetry

GEANT4 Simulation of SD Detector (5 GeV π^+)

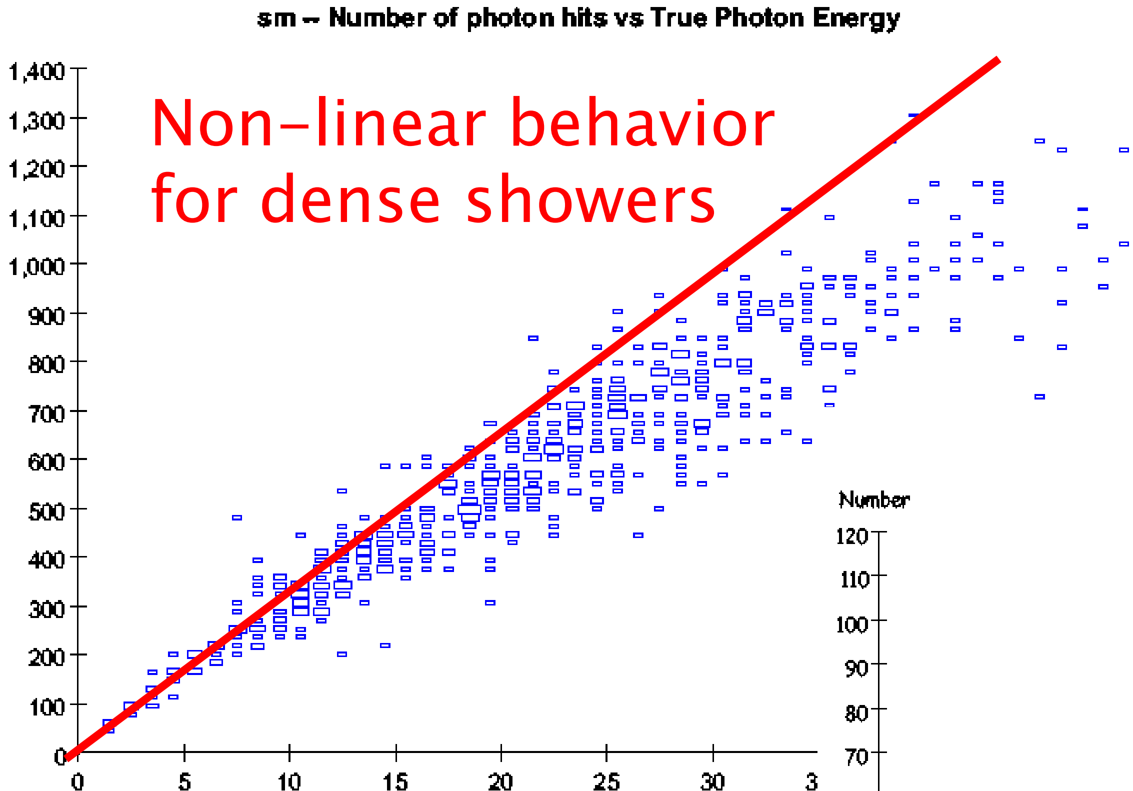
Analog: sum of ECAL and HCAL analog signals

Digital: number of hits with 10 MeV threshold in HCal



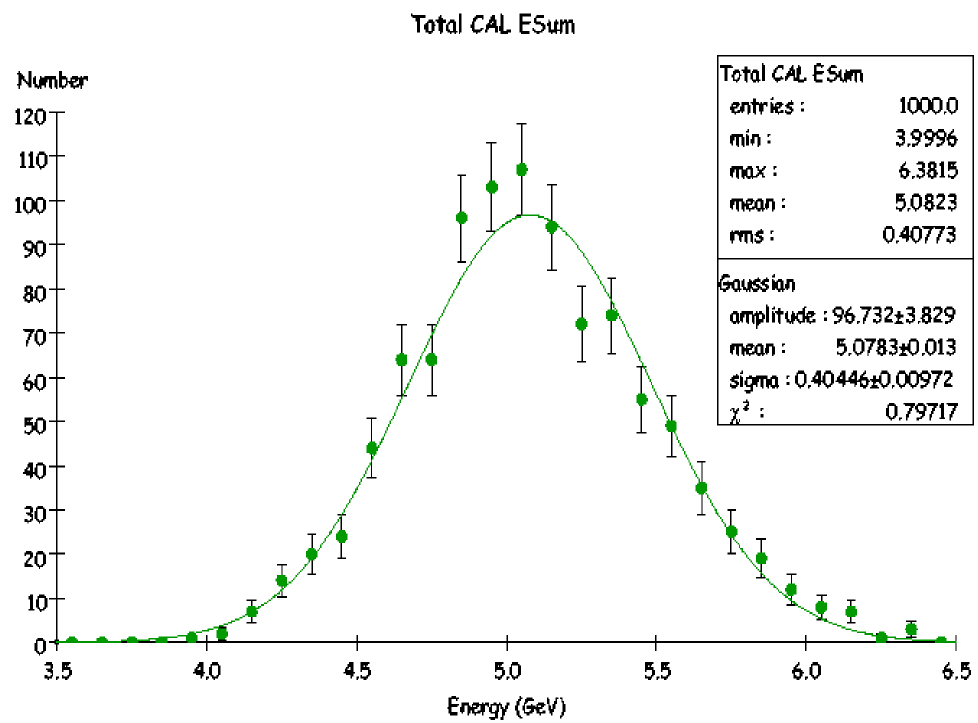


Digital calorimetry for photons?



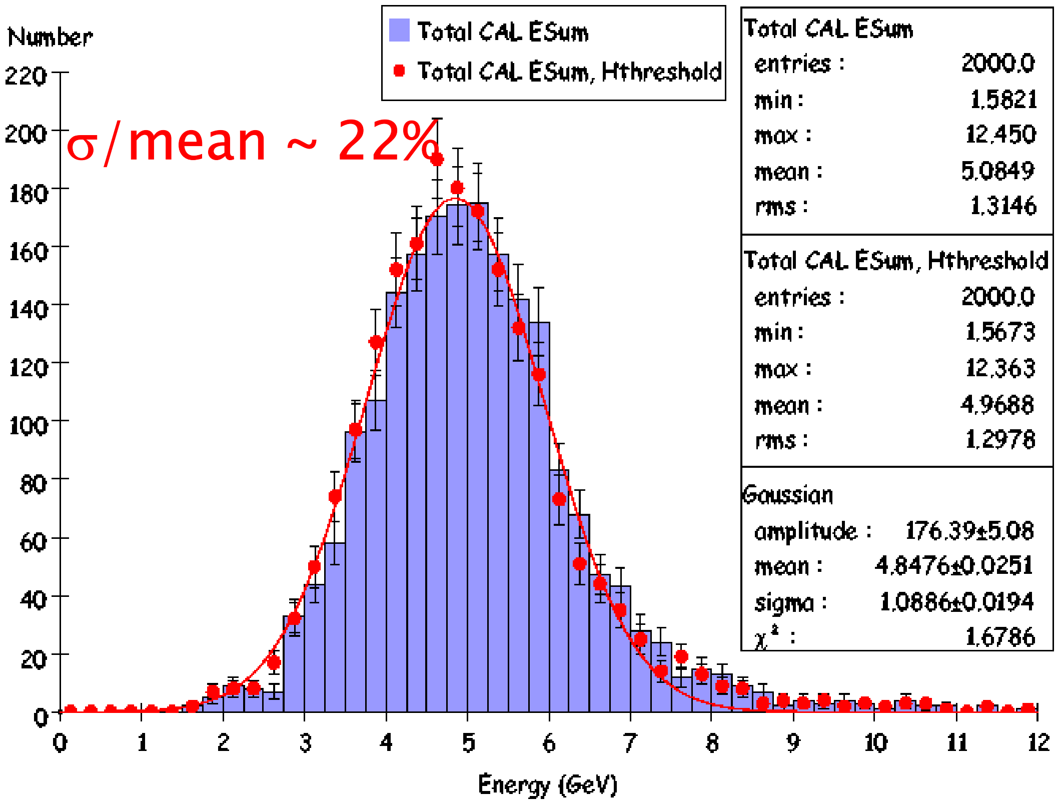
Analog ECal

σ/mean ~ 16%/√E



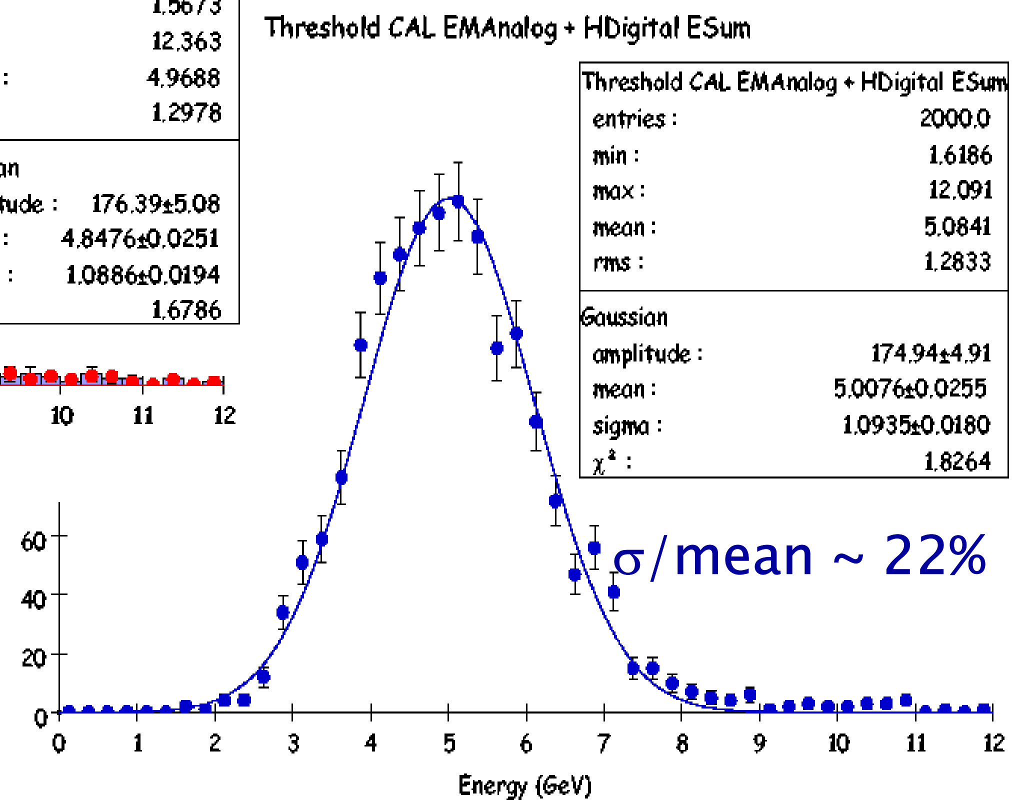
5 mm X 5 mm EM cells

Analog ECal + Digital HCal



Analog sum – ECal + HCal

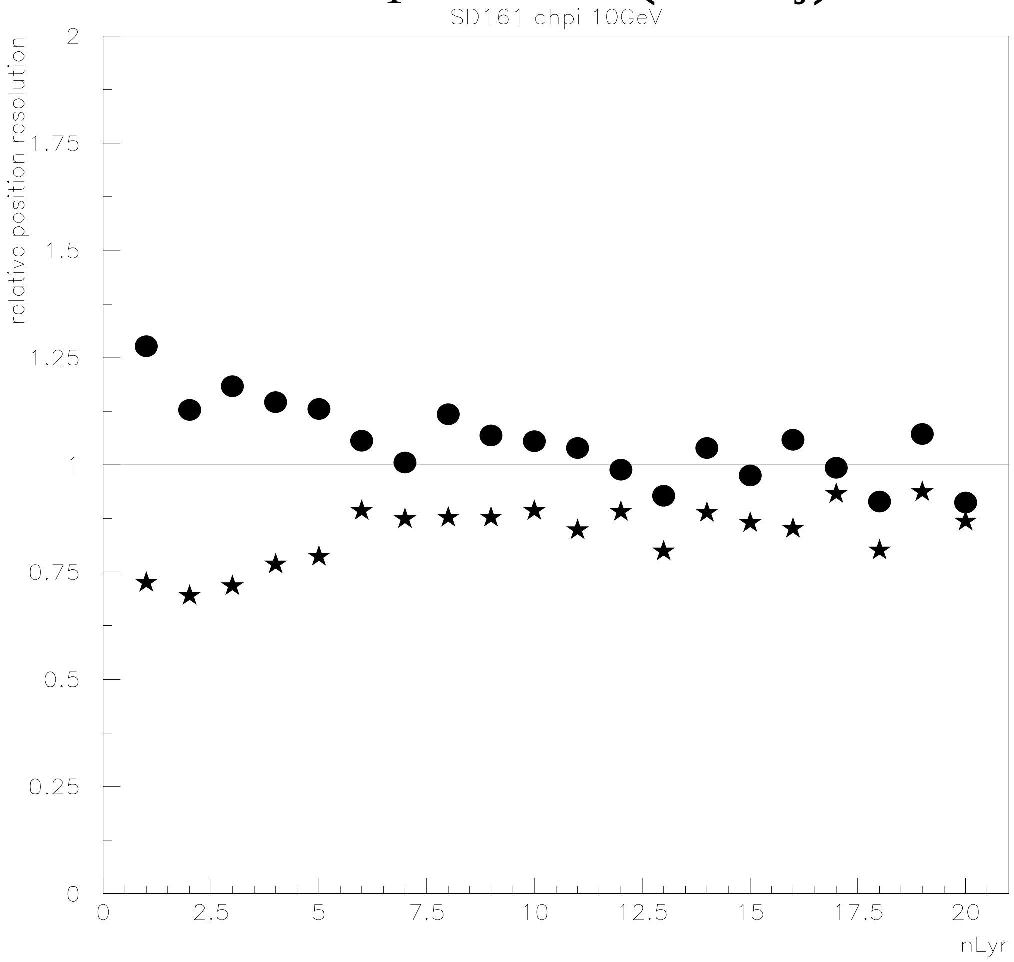
Analog sum – ECal
+
Digital sum – HCal



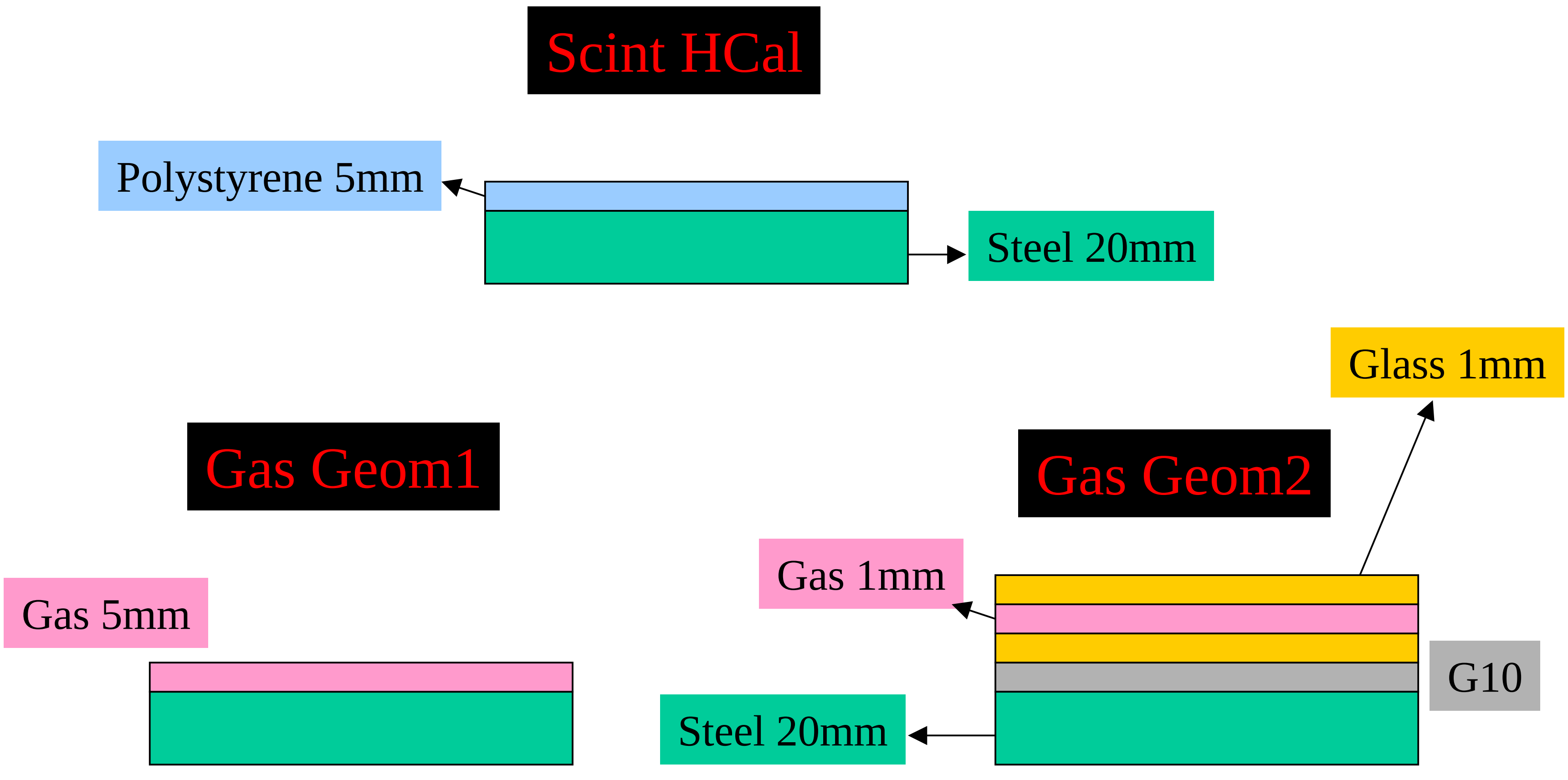
DHCal: Density-weighted Clustering

$$d_i = k\,\Sigma\,(1/R_{ij})$$

- Density-based clustering in both ECal and HCal
- Clusters matched to tracks replaced by their generated momentum
- For ECal clusters, use energy of assoc. cells
- For HCal clusters, use number of hits to estimate energy.

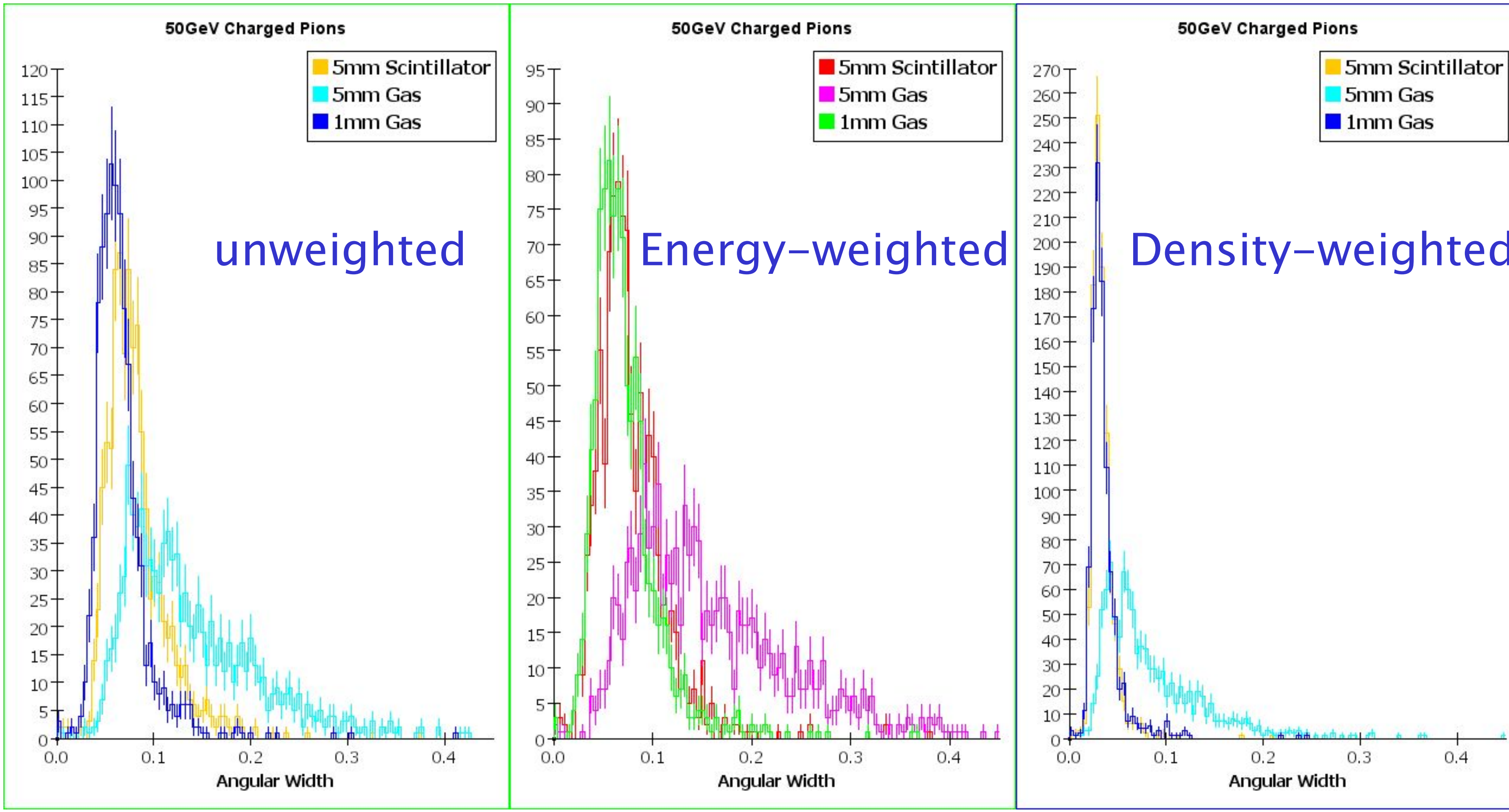


Scintillator & gas-based DHCal geometries modelled in simulation:

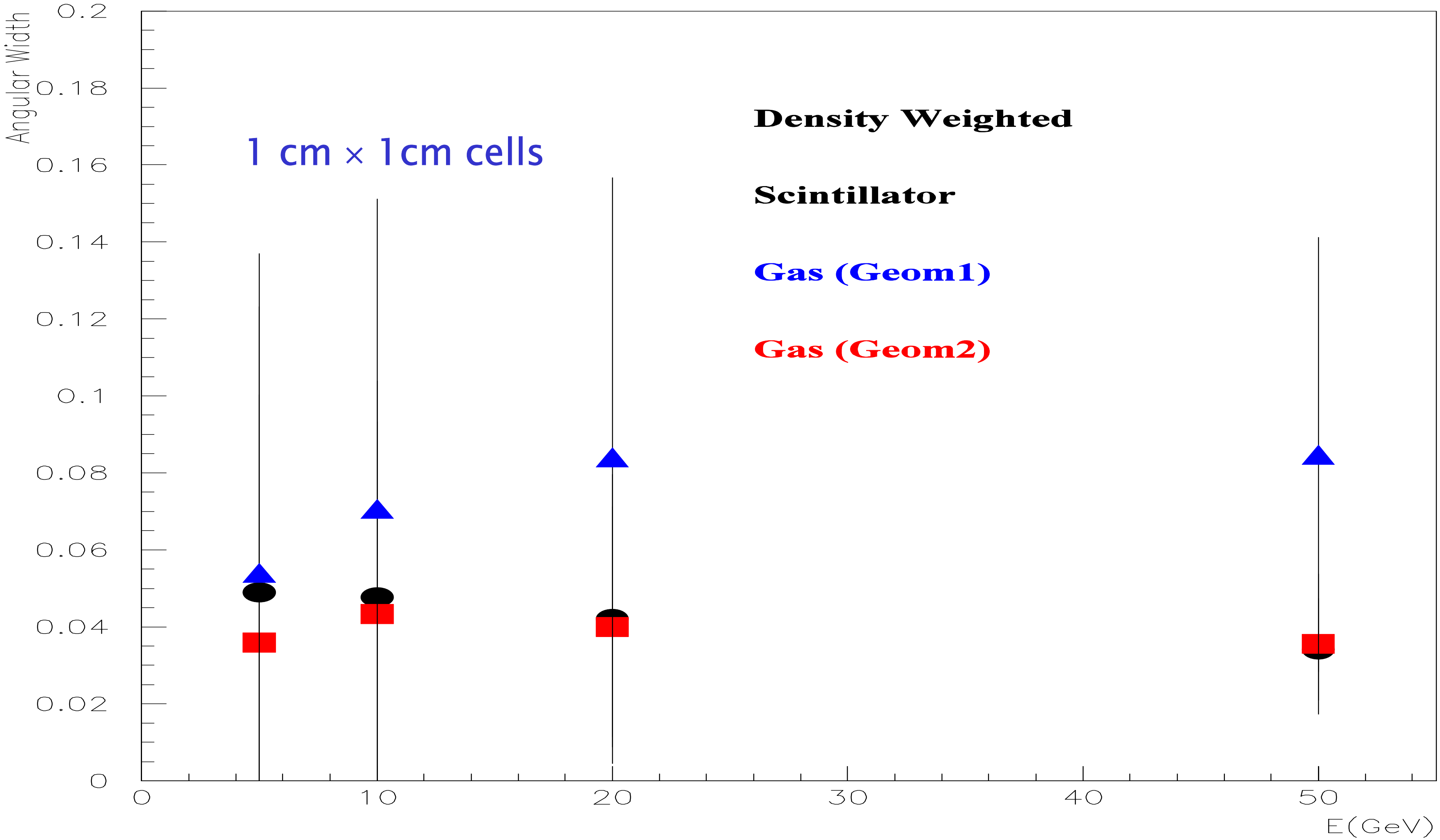


Shower widths with Scintillator and gas-based HCal designs

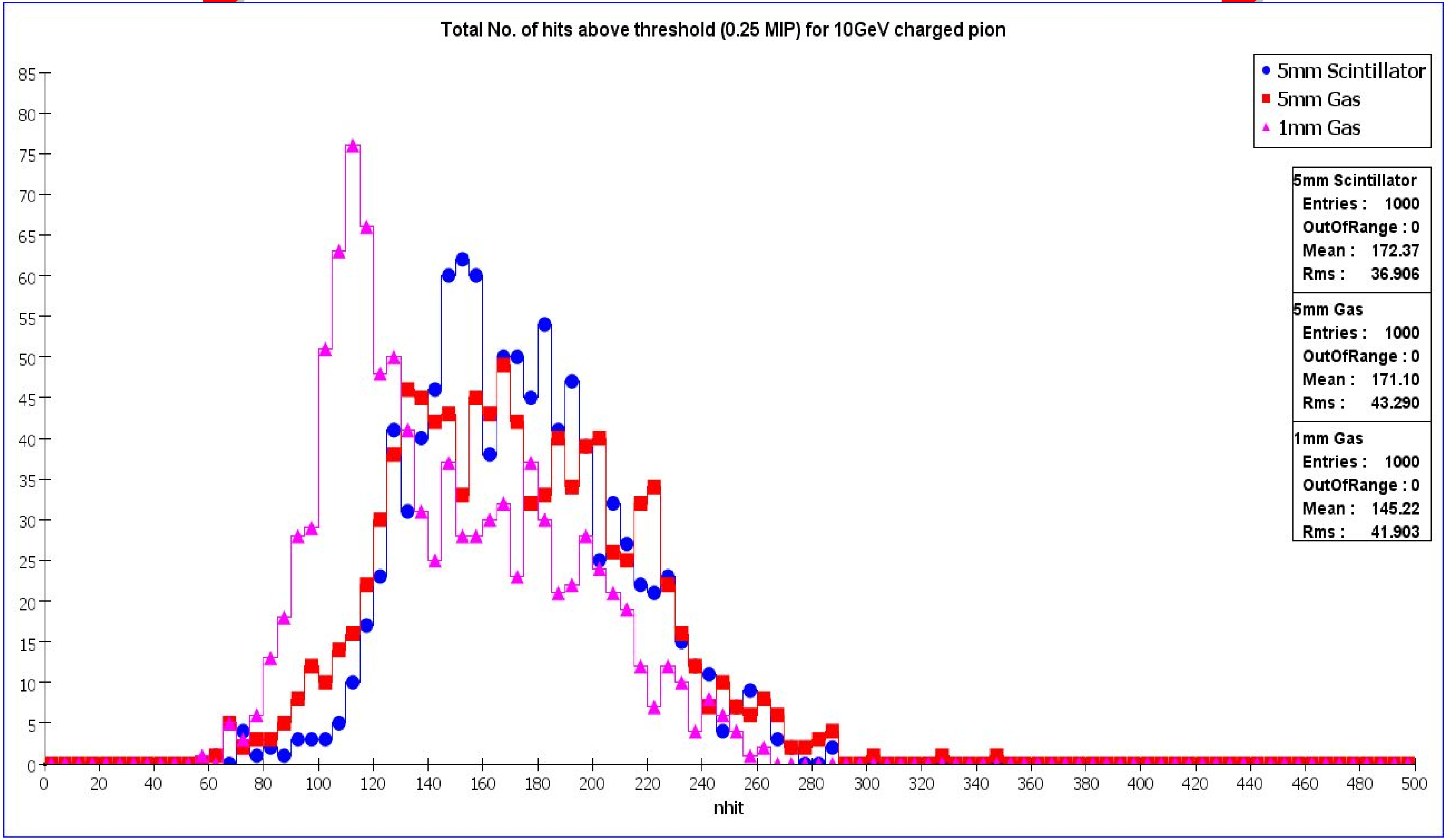
1 cm × 1cm cells



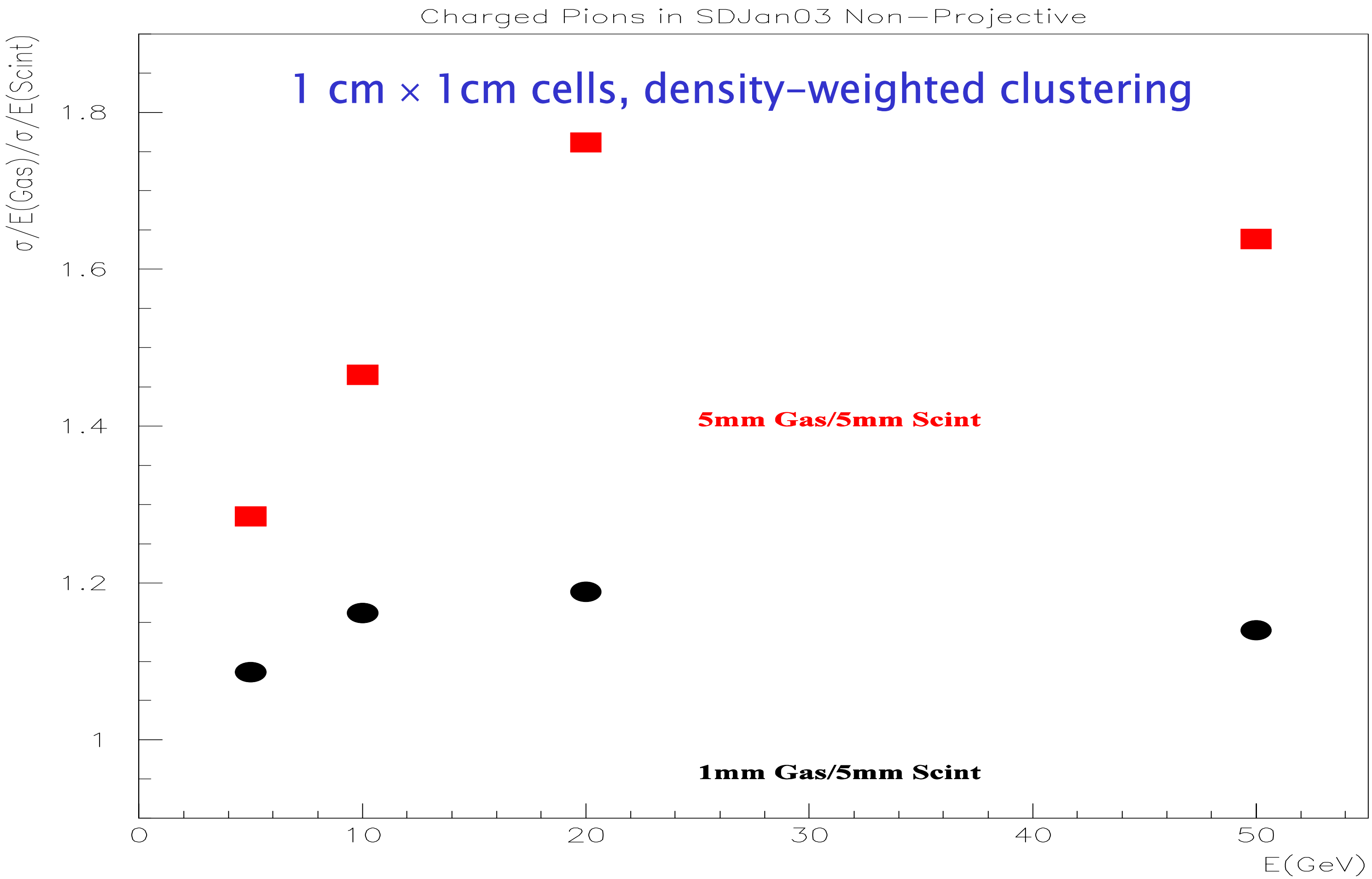
Shower widths vs. E(π^+)



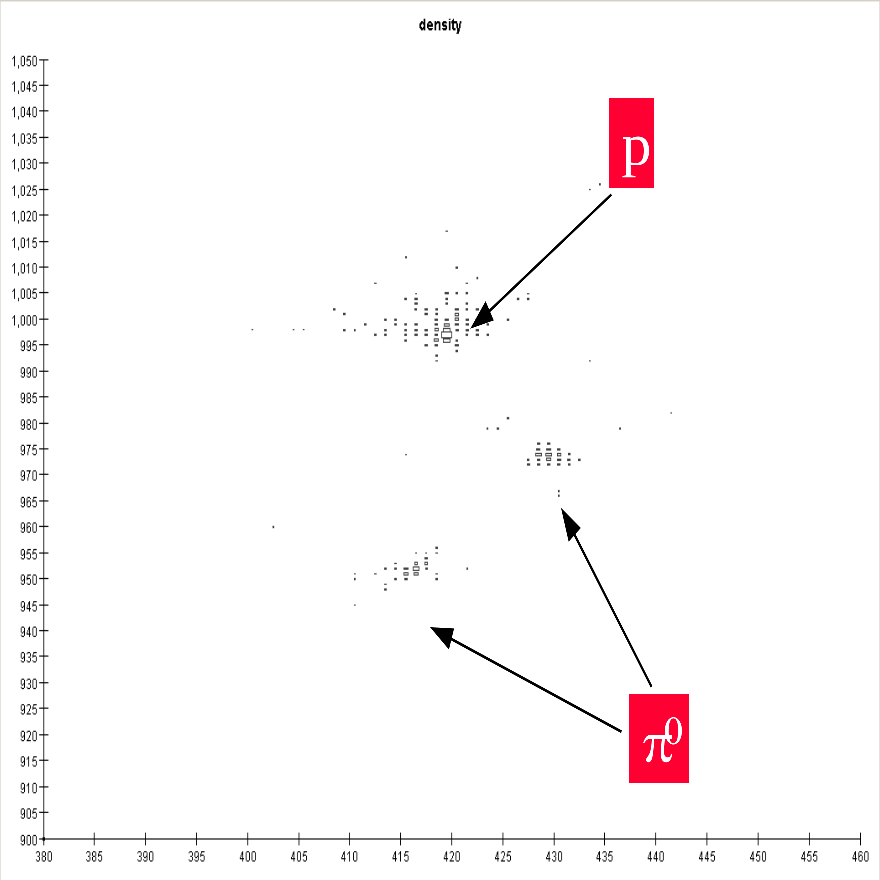
Number of hits with Scintillator and gas-based DHCal designs



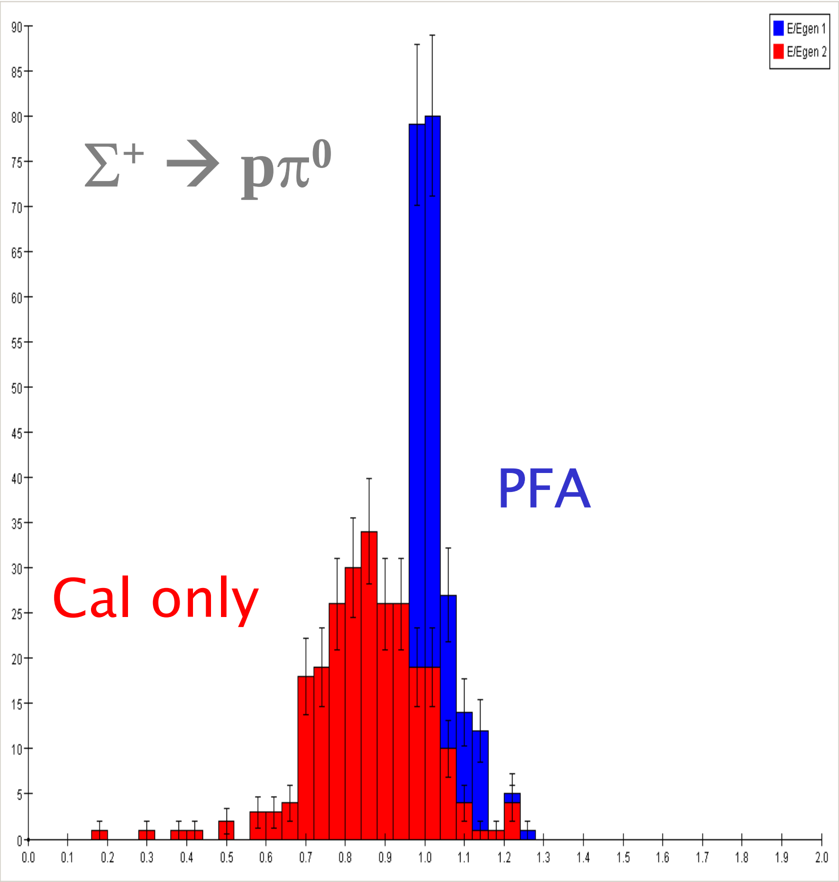
Energy resolution with Scintillator and gas-based DHCal designs



DHCal: Particle-flow algorithm (NIU)



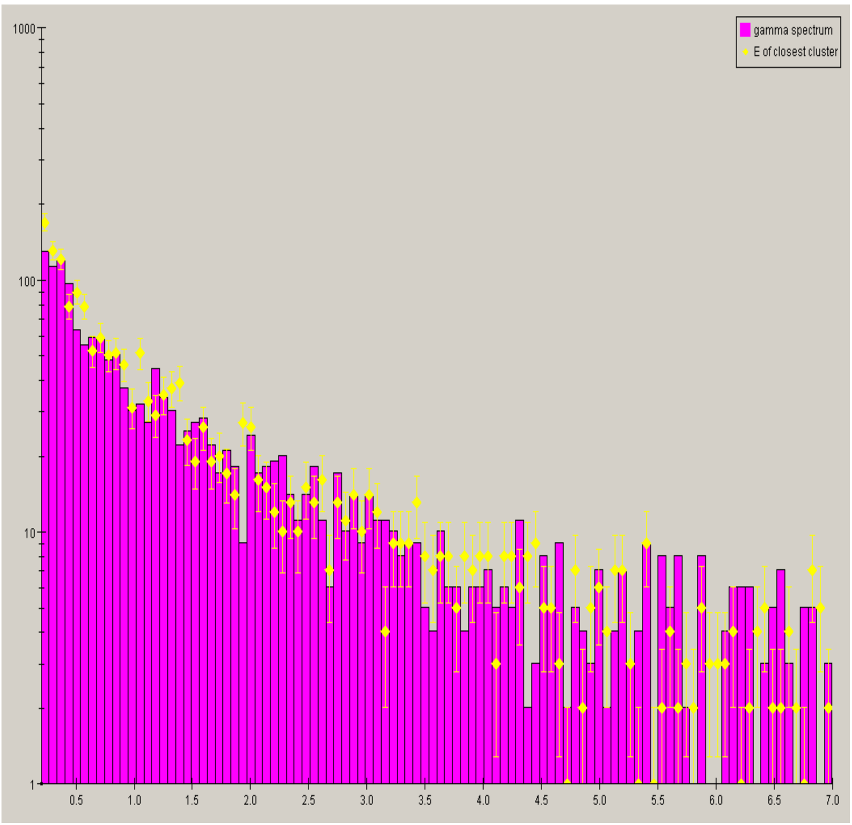
- Nominal SD geometry
- Density-weighted clustering

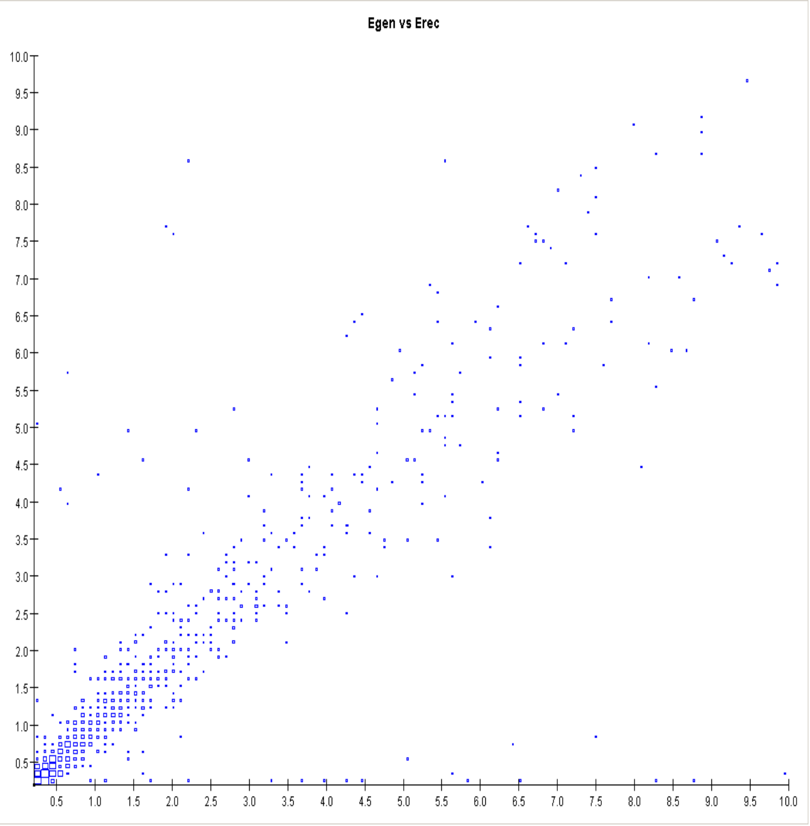


- Track momentum for charged,
- Calorimeter E for neutrals

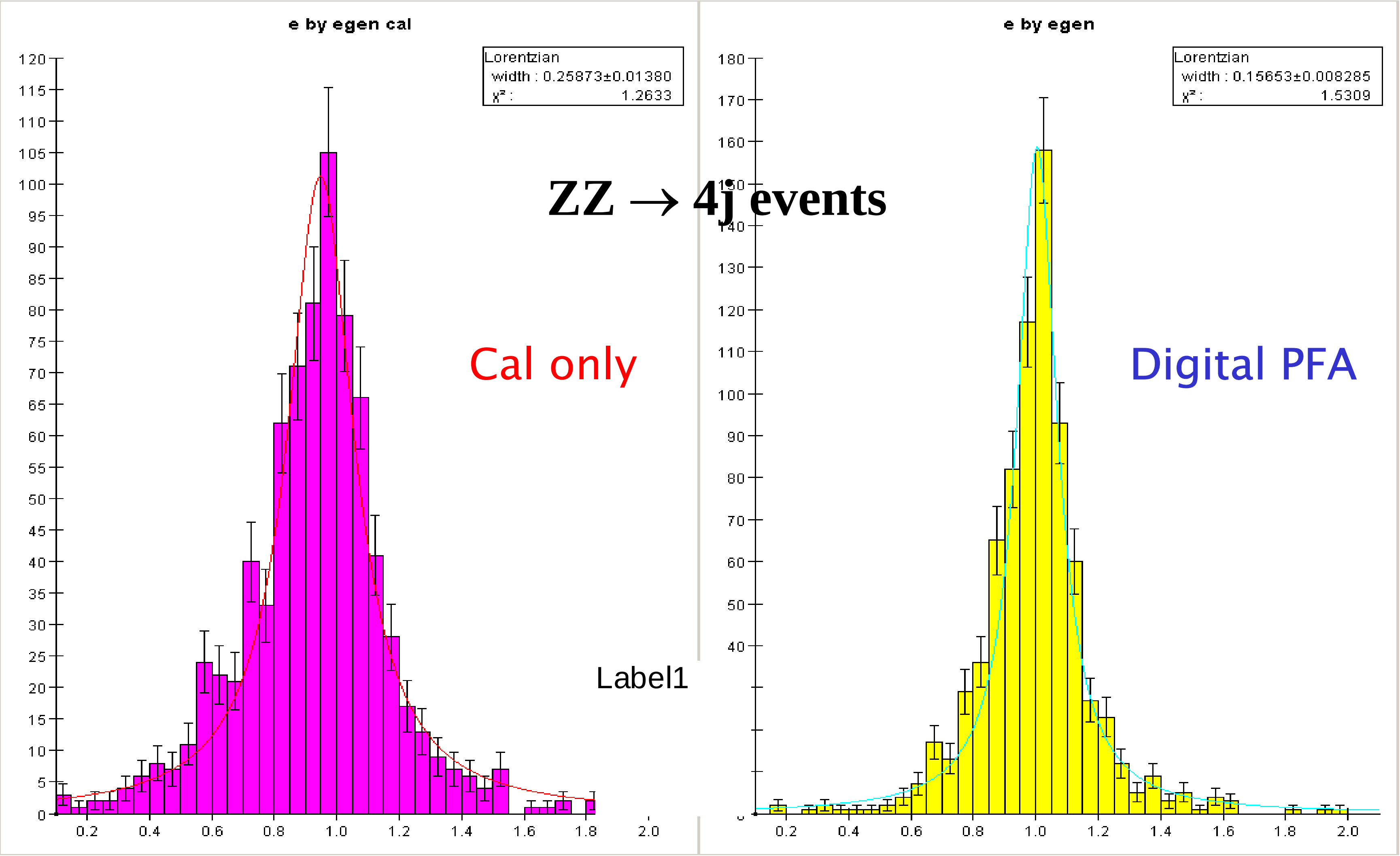
DHCal: Particle-flow algorithm (NIU) Photon Reconstruction inside jets

Excellent agreement with Monte Carlo truth:





DHCal: Particle-flow algorithm (NIU) Reconstructed jet resolution



Track–first Particle–flow algorithm (ANL, SLAC)

Step 1: Track extrapolation through Cal

- substitute for Cal cells (MIP + ECAL shower tube + HCAL tube; reconstruct linked MIP segments + density–weighted hit clusters)
- analog or digital techniques in HCAL
- Cal granularity/segmentation optimized for separation of charged & neutral clusters

Step 2: Photon finder

- use analytic long./trans. energy profiles, ECAL shower max, etc.

Step 3: Jet Algorithm

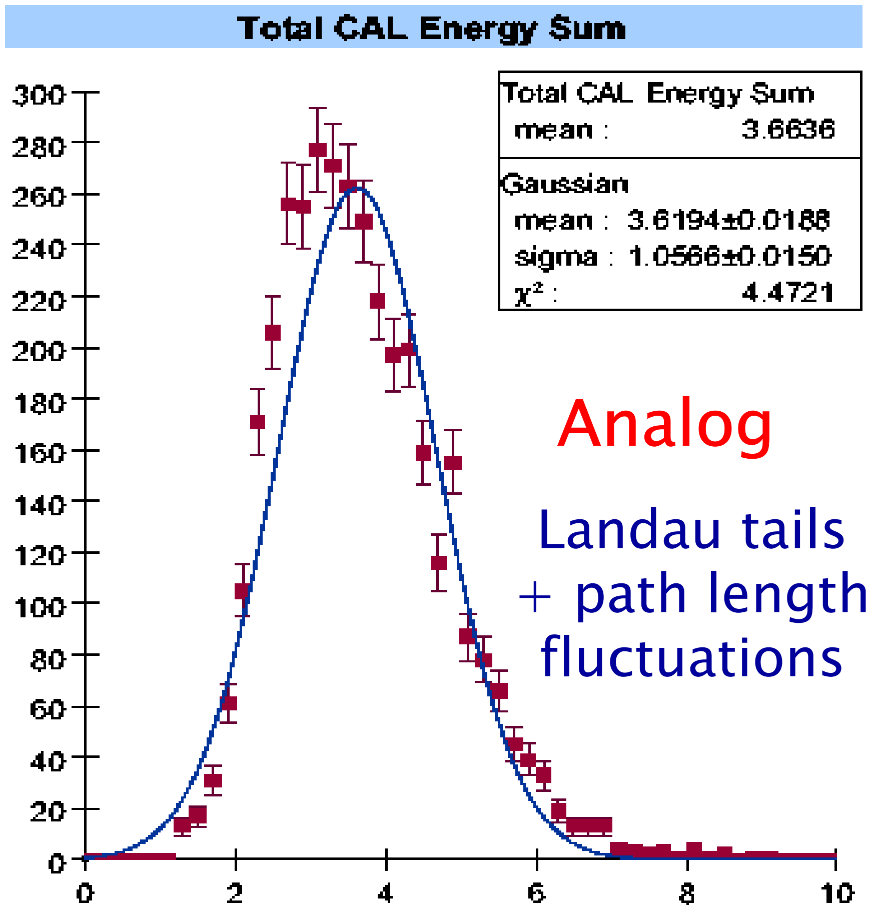
- tracks + photons + remaining Cal cells (neutral hadron contribution)
- Cal clustering not needed –> Digital HCAL?

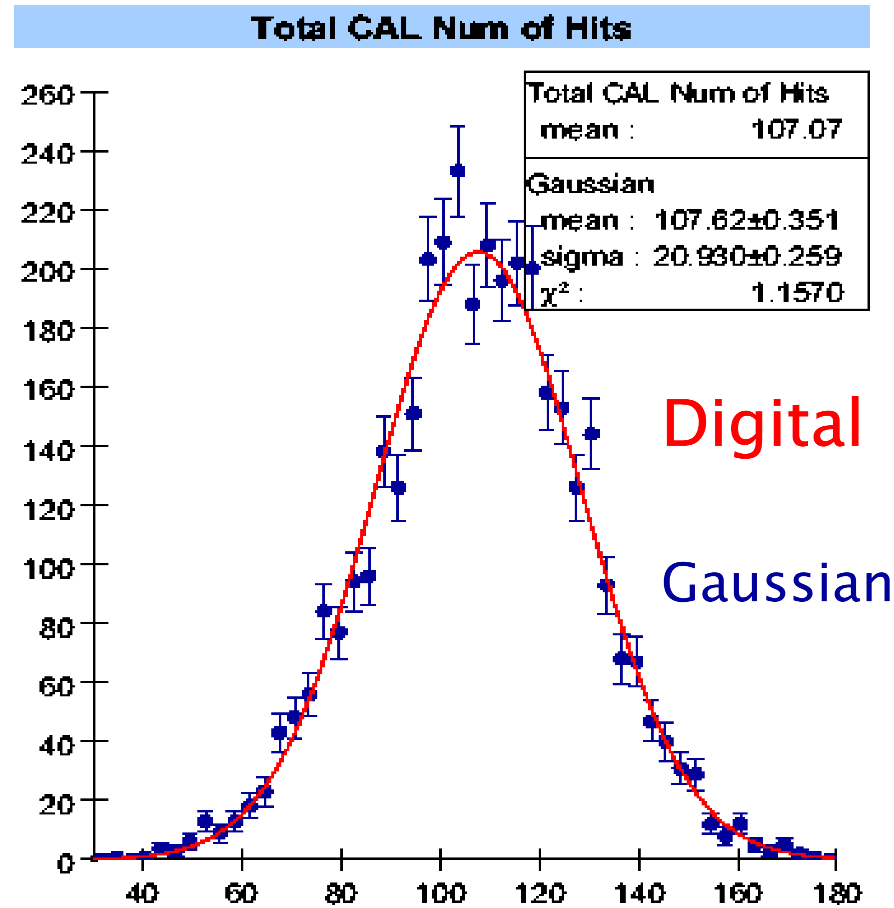
Analog vs Digital Energy Resolution

GEANT 4 Simulation of SD Detector (5 GeV π^+)

-> sum of ECal and HCal analog signals – Analog

-> number of hits with 7 MeV threshold in HCAL – Digital



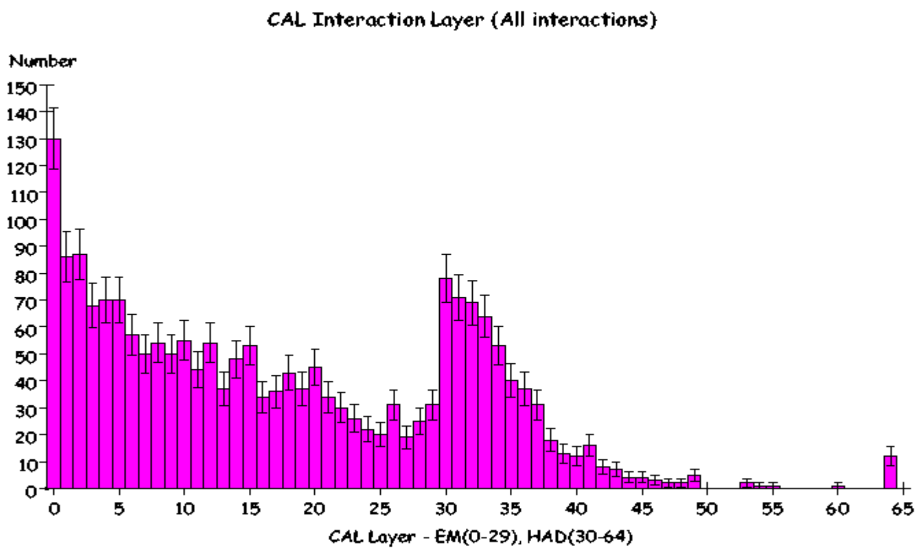


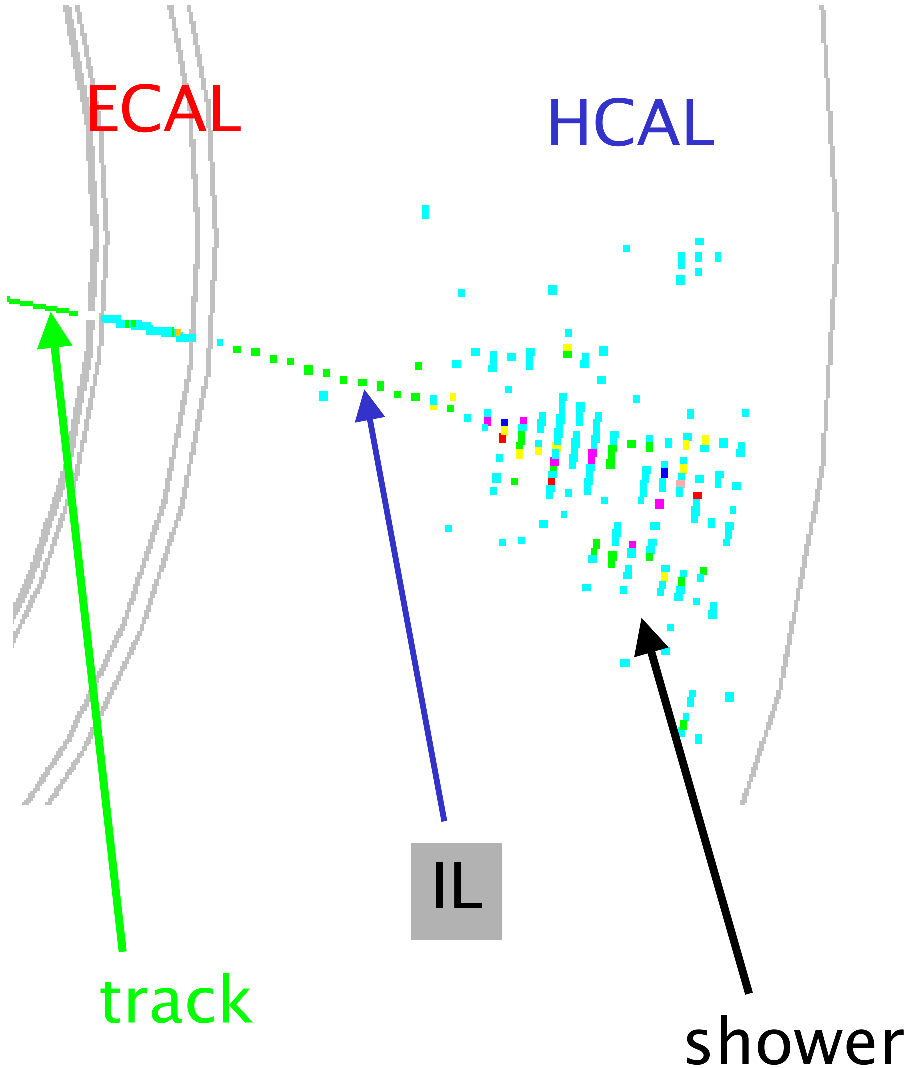
Shower reconstruction by track extrapolation

- Extrapolate track through CAL layer-by-layer
- Search for “Interaction Layer” (IL)
- -> Clean region for photons

Shower reconstruction :

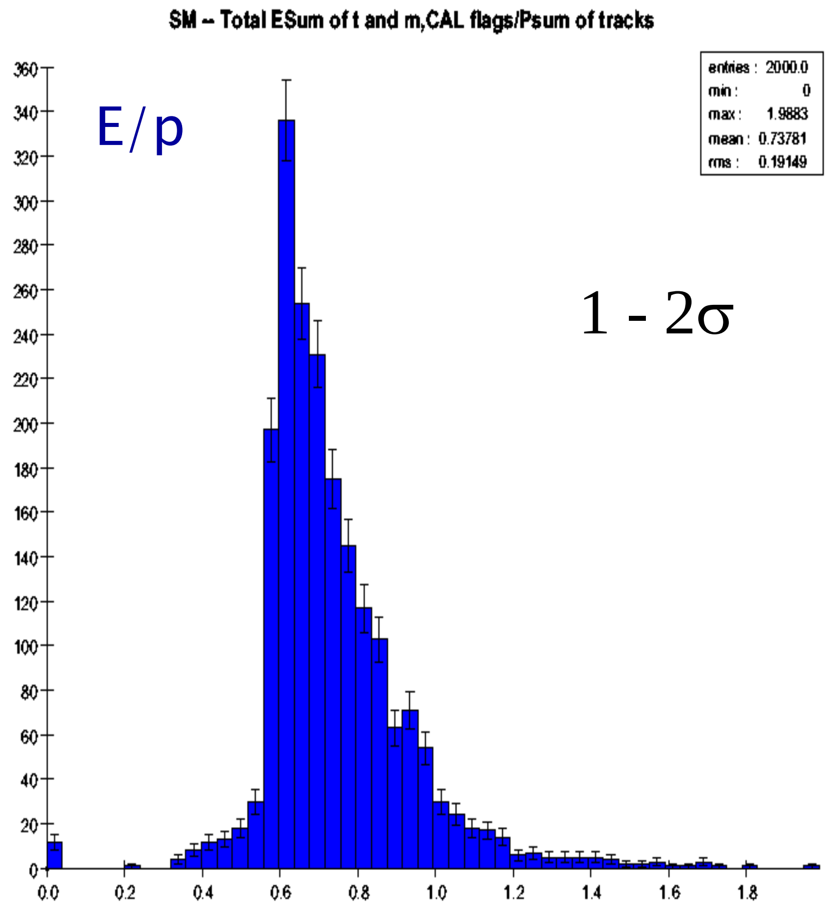
- Define tubes for shower in ECAL & HCAL after IL
- Optimize, iterating tubes in ECal & HCal separately (E/p test)

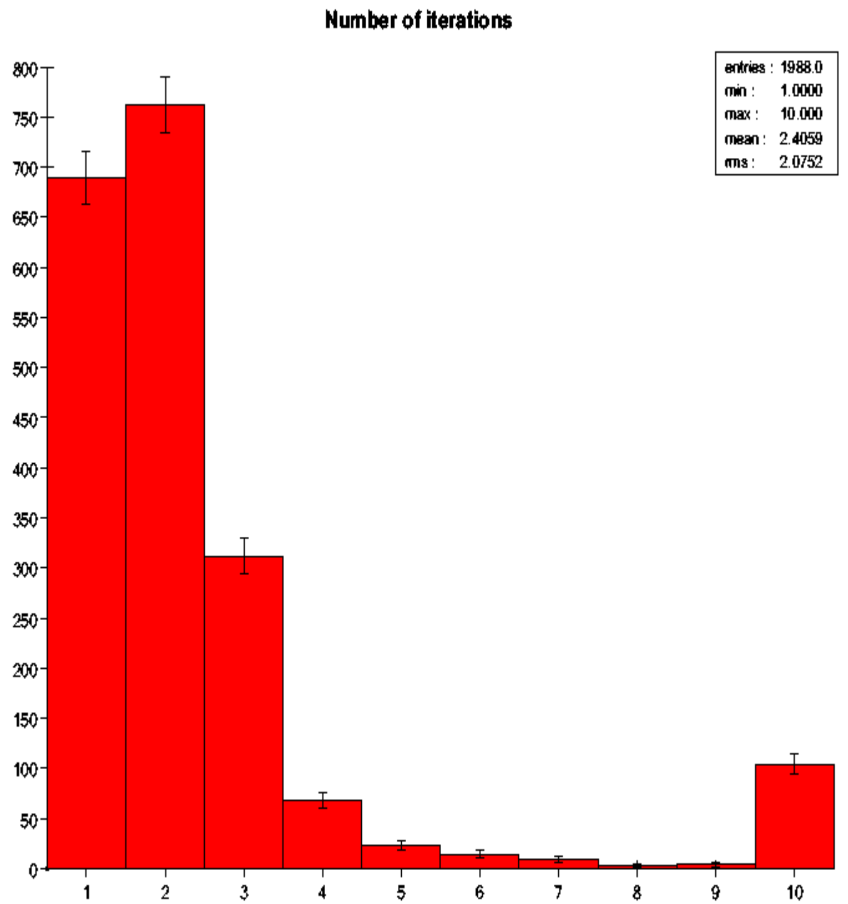




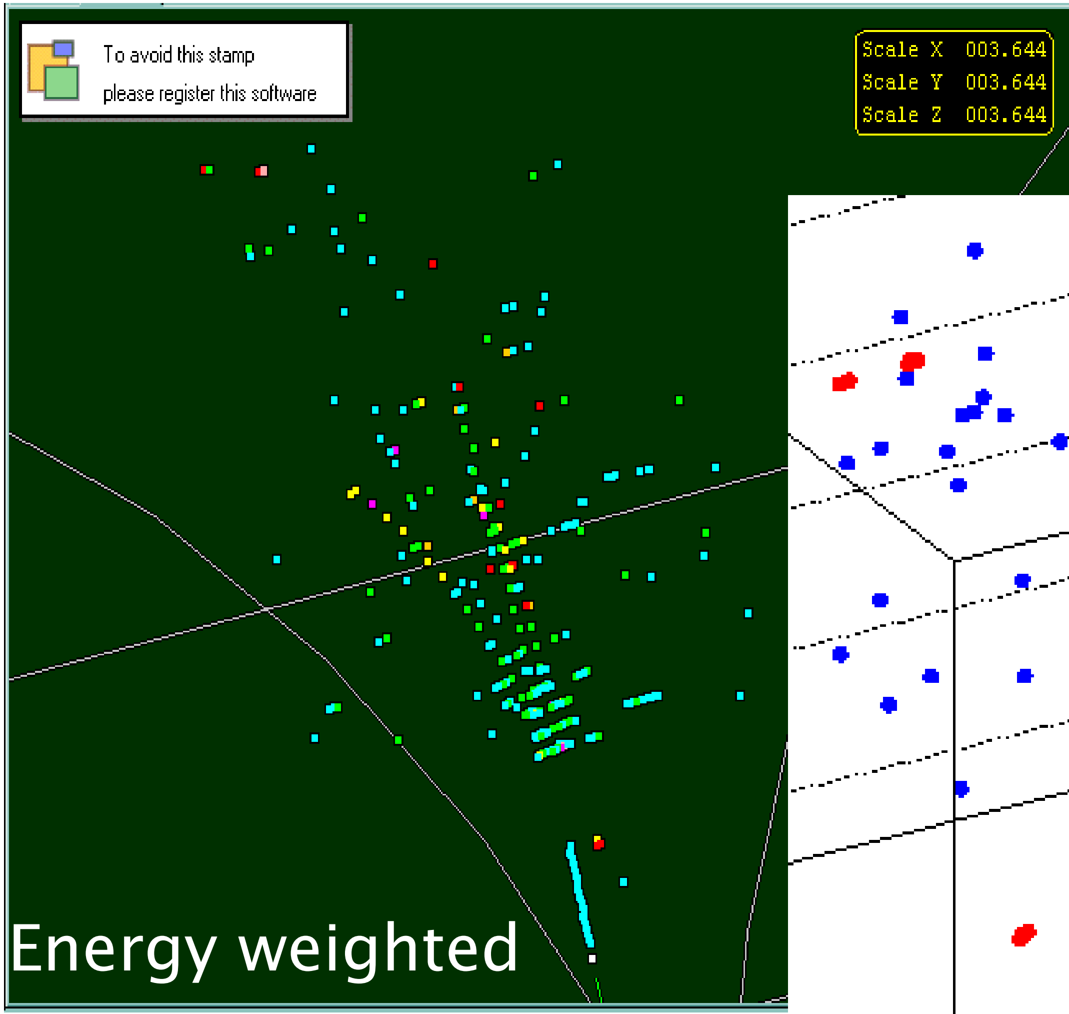
Single particle track substitution results

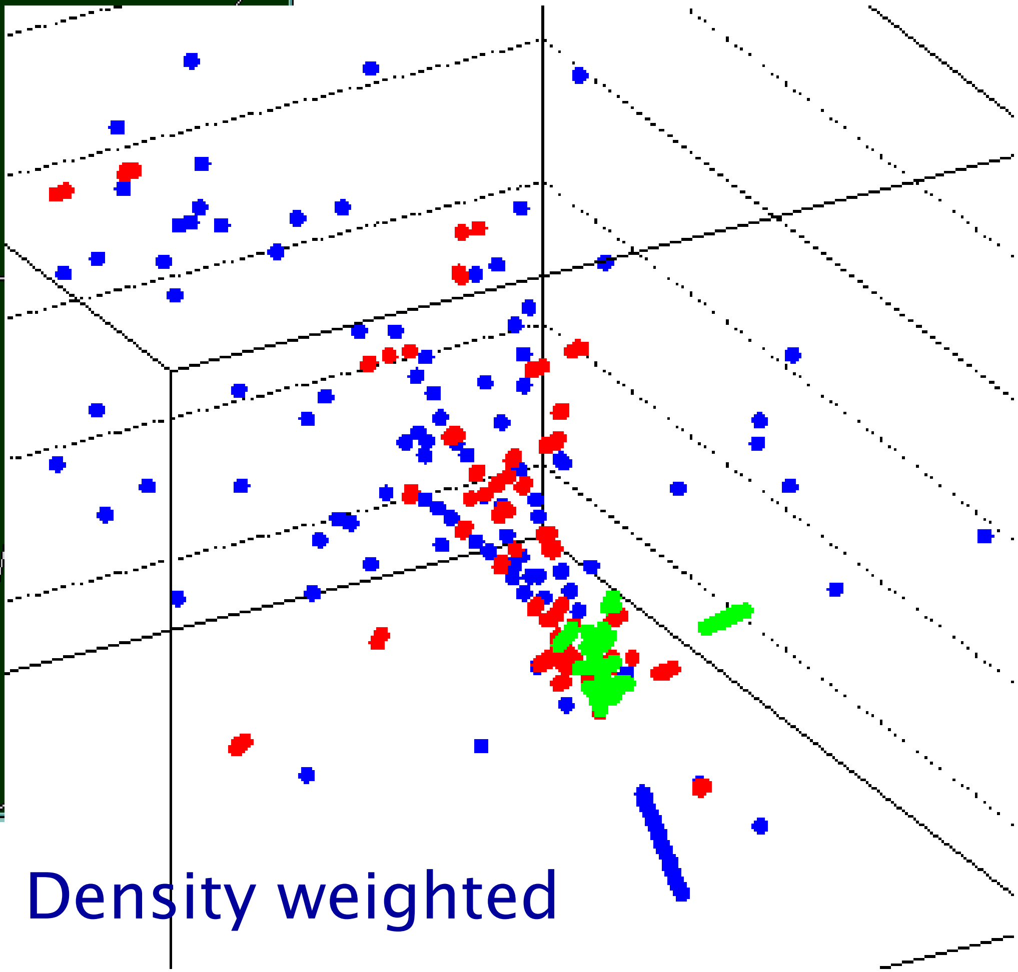
Increment window around extrapolated track in each layer by 0.025 in the ECAL and 0.045 in the HCAL – check E/p>test parameter to stop iterations; test parameter = 1 ± 0,1,2 σ (σ~55%/√E)





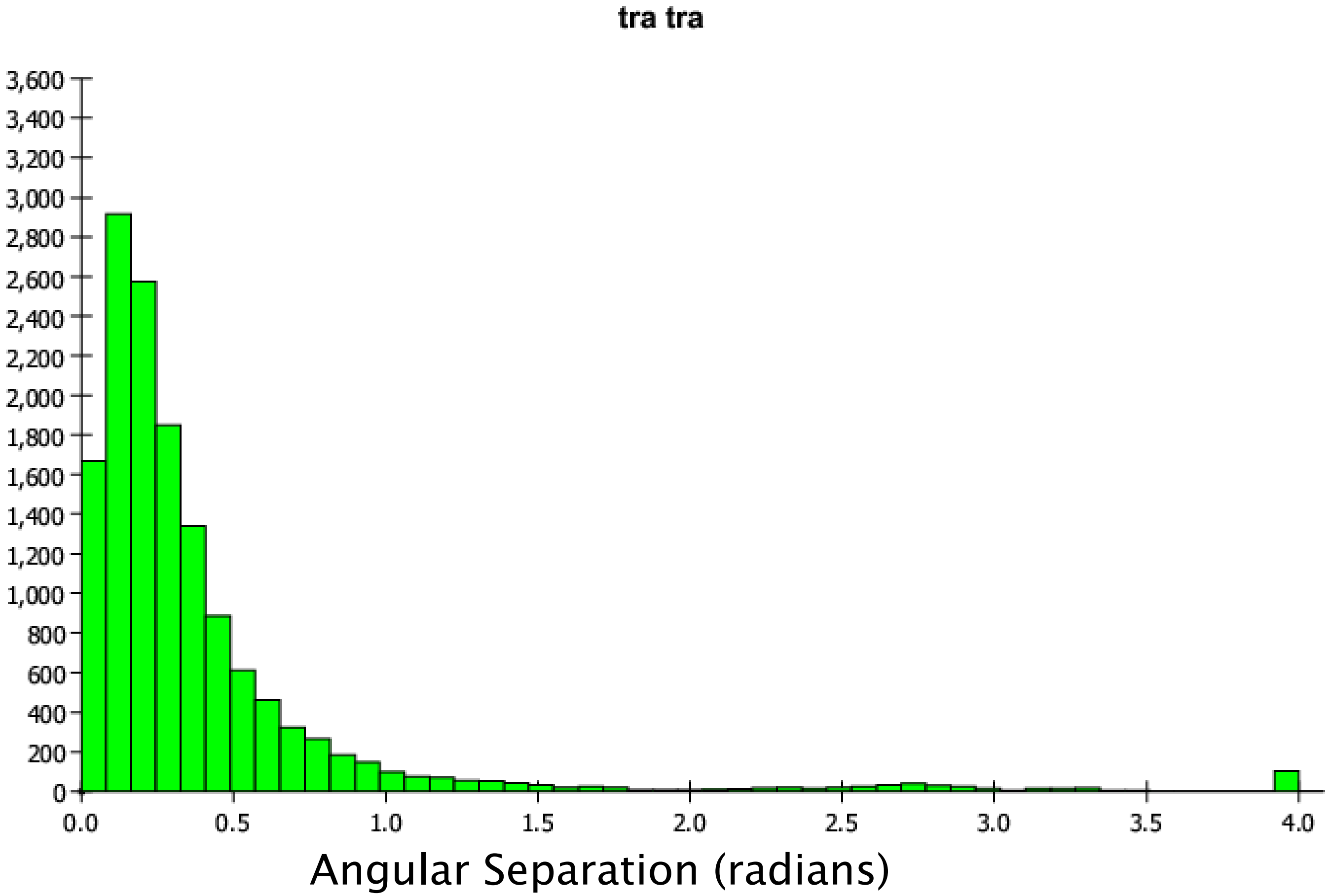
Single 10 GeV π^+: event display comparison





Overlapping showers from other tracks

Separation between random >2 GeV track and closest >2 GeV track



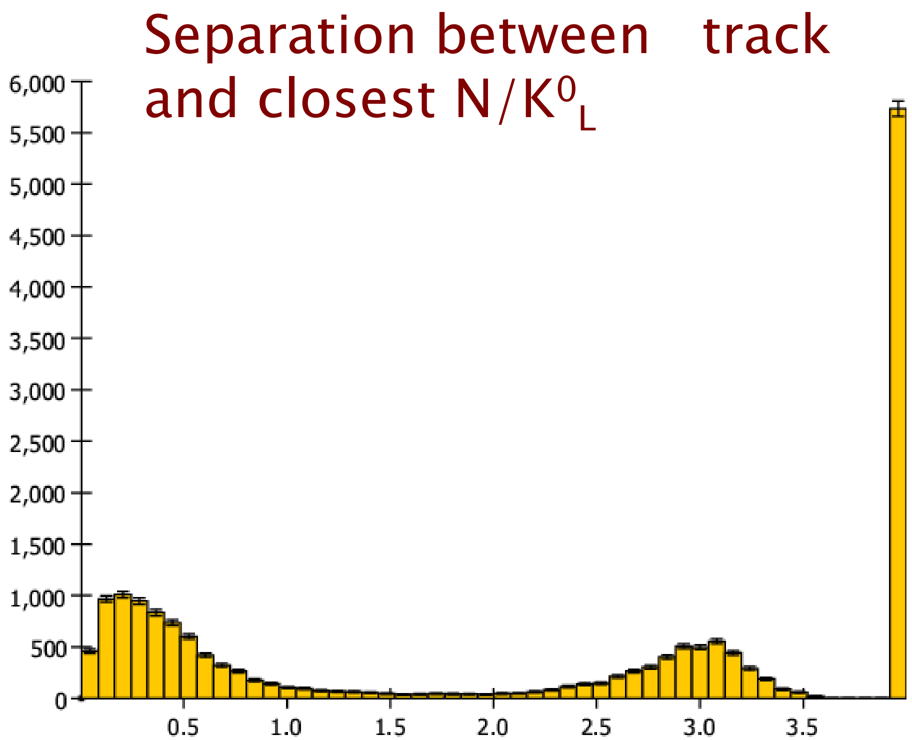
16% overlap within Sep<0.1

41% overlap within Sep<0.2

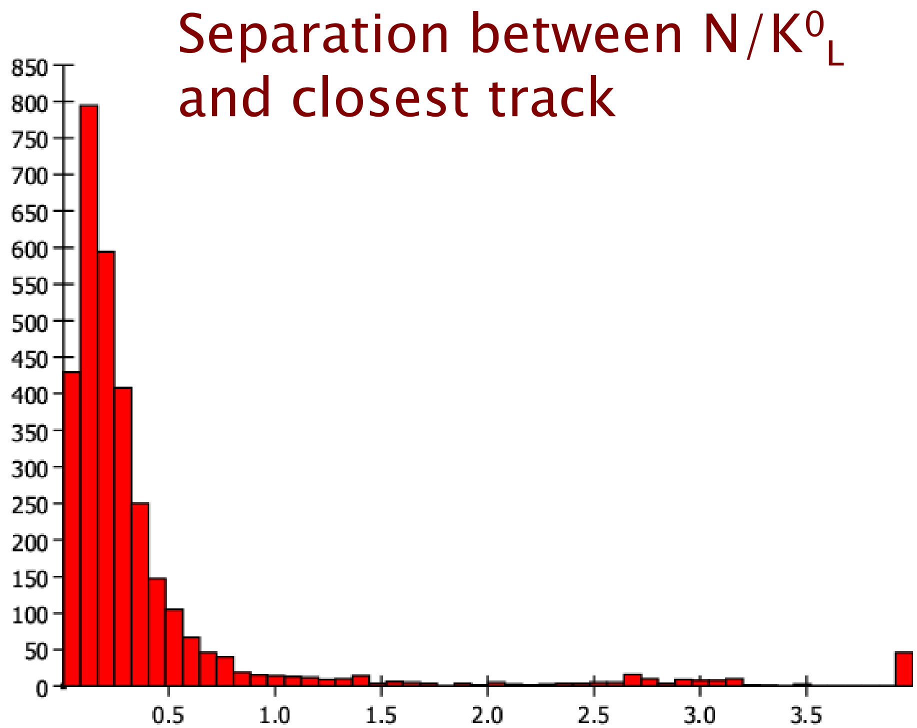
59% overlap within Sep<0.3

72% overlap within Sep<0.4

2+ GeV N/K^0_L overlapping 2+ GeV tracks



Angular Separation (radians)



Angular Separation (radians)

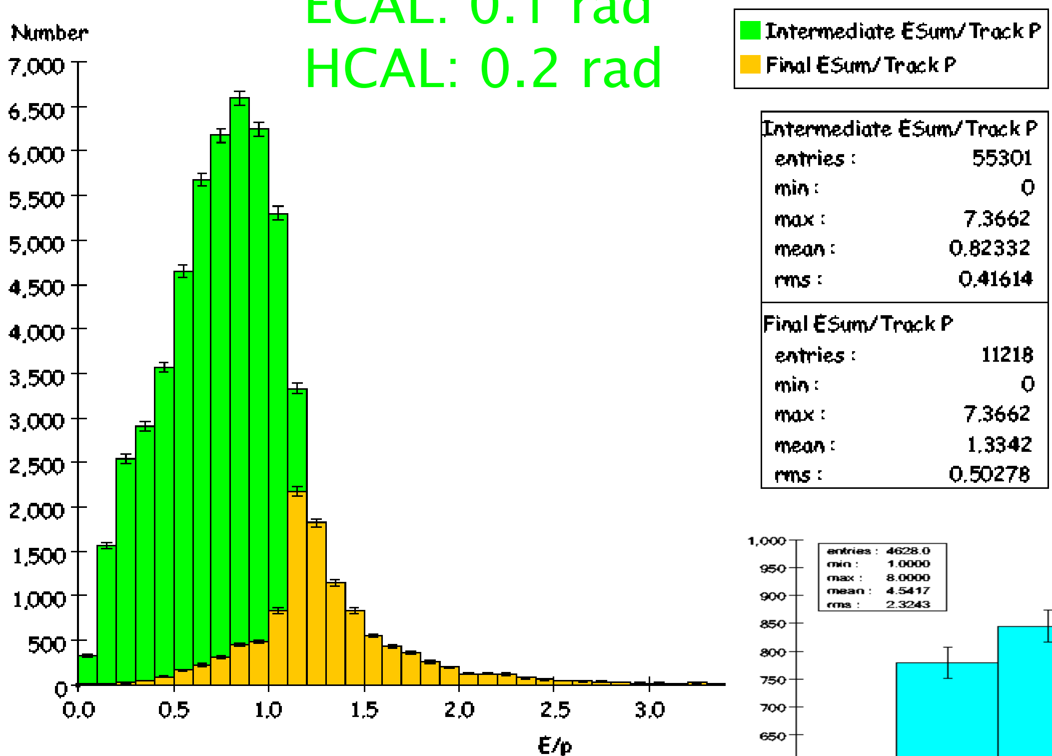
10% overlap within Sep<0.2

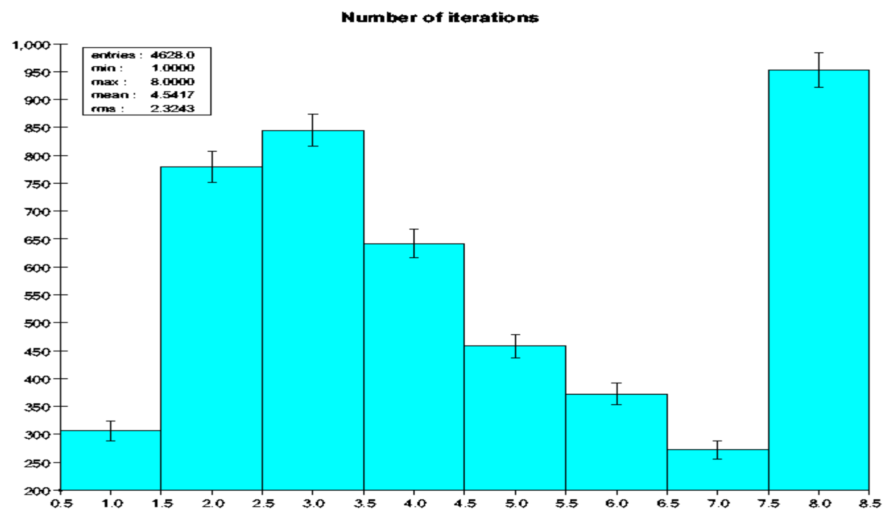
48% overlap within Sep<0.2

Track-first PFA Results

Average tube size as determined by the number of iterations:

ECAL: 0.1 rad
HCAL: 0.2 rad



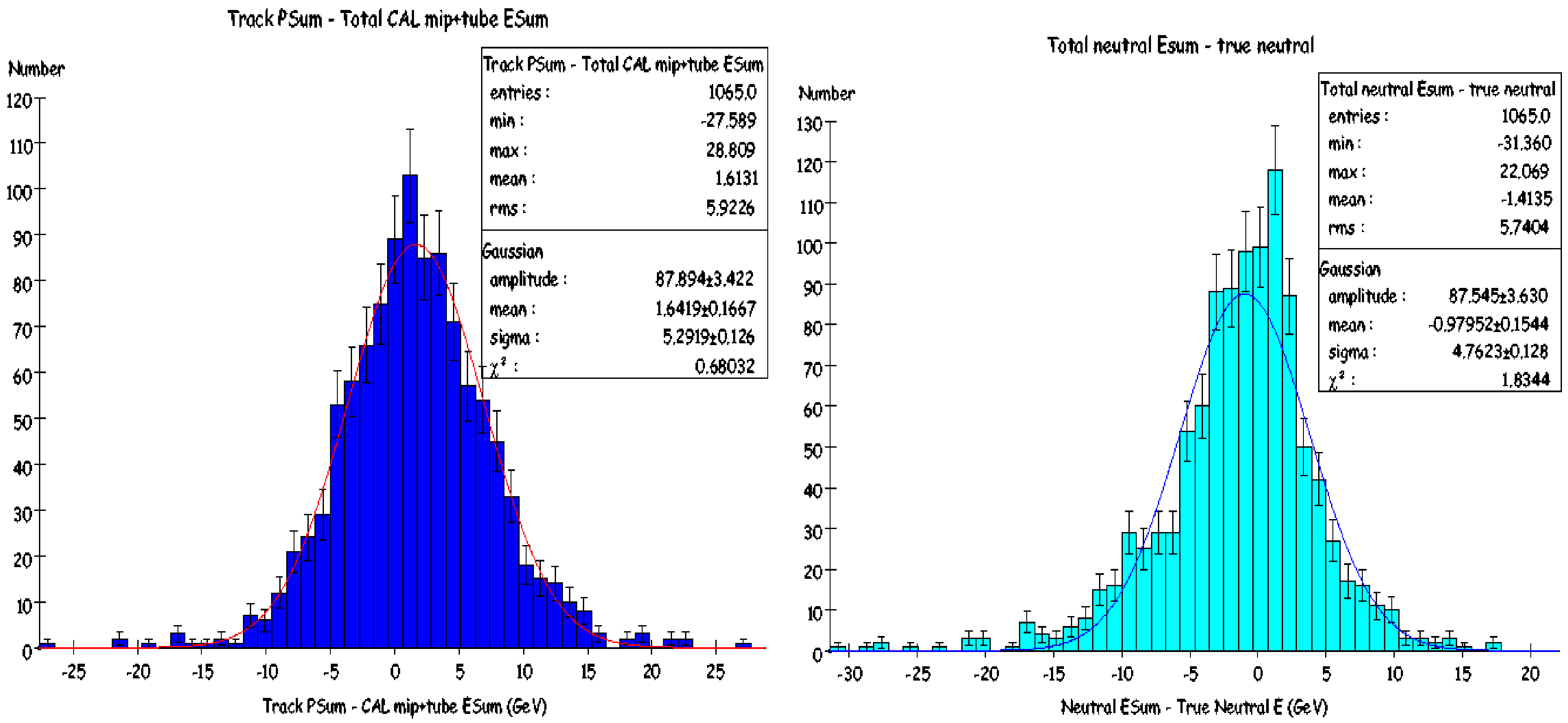


Start with green distribution,
end with yellow

Track Substitution, Neutral Sum Results

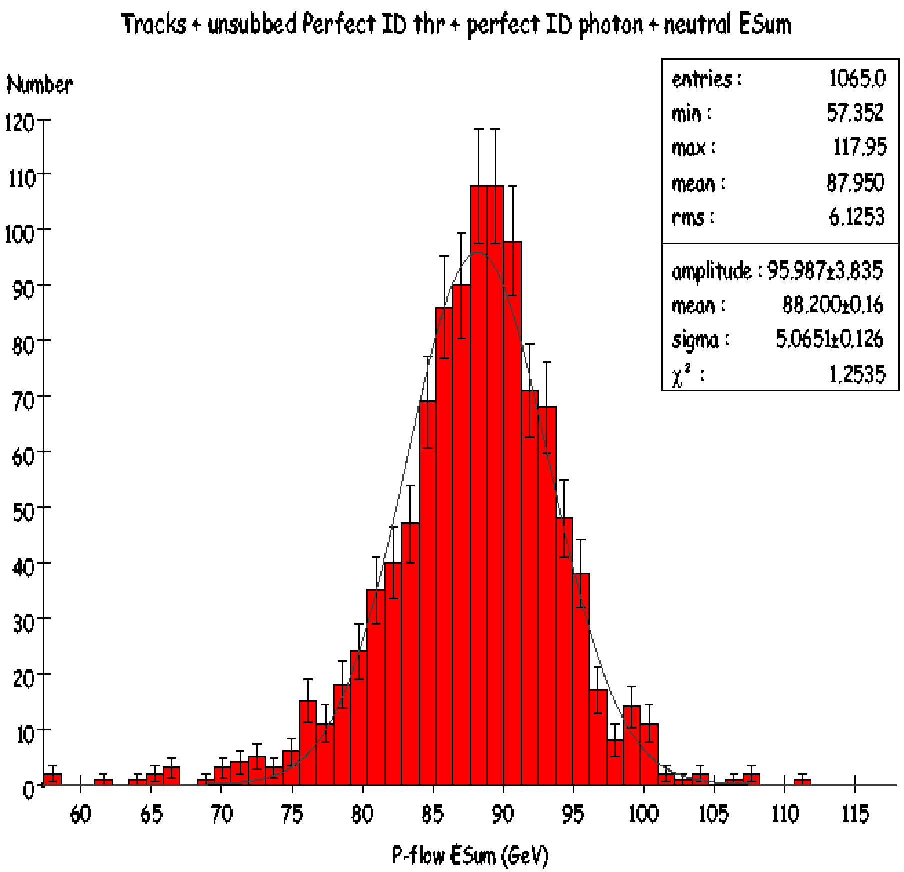
Includes MIPs + cell E's in tubes (further E/p tuning needed)

Jet cones: 0.55; Neutral contribution to E sum: ~4.8 GeV; Goal: ~3 GeV

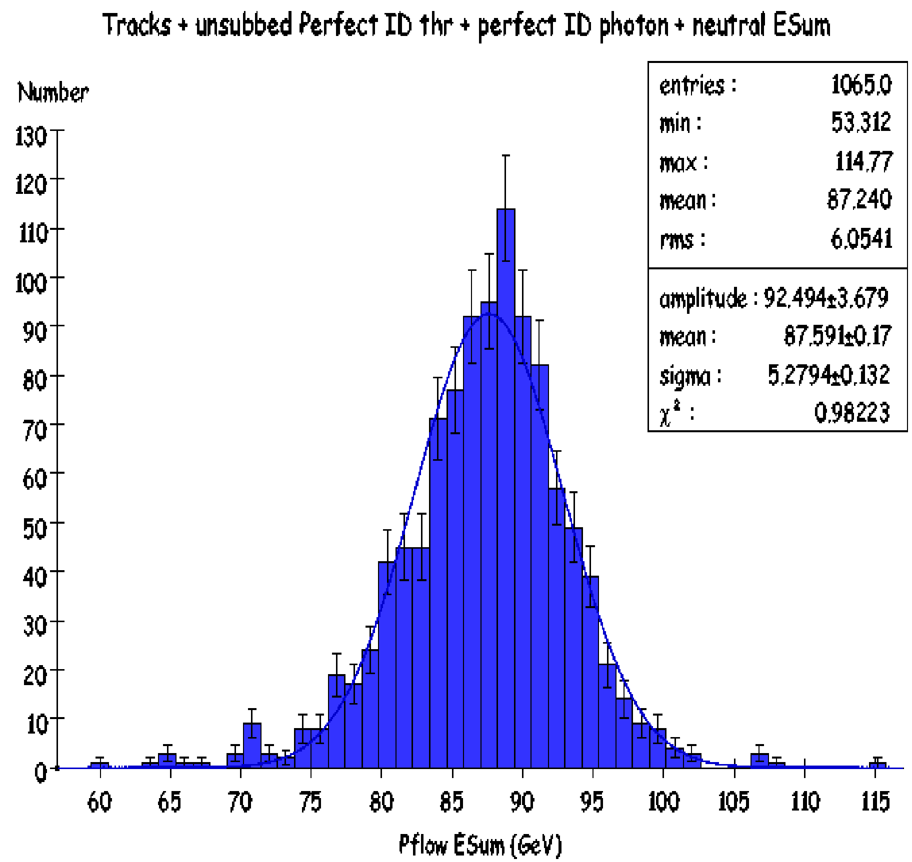


Results for Analog and Digital HCal

Analog HCAL



Digital HCAL

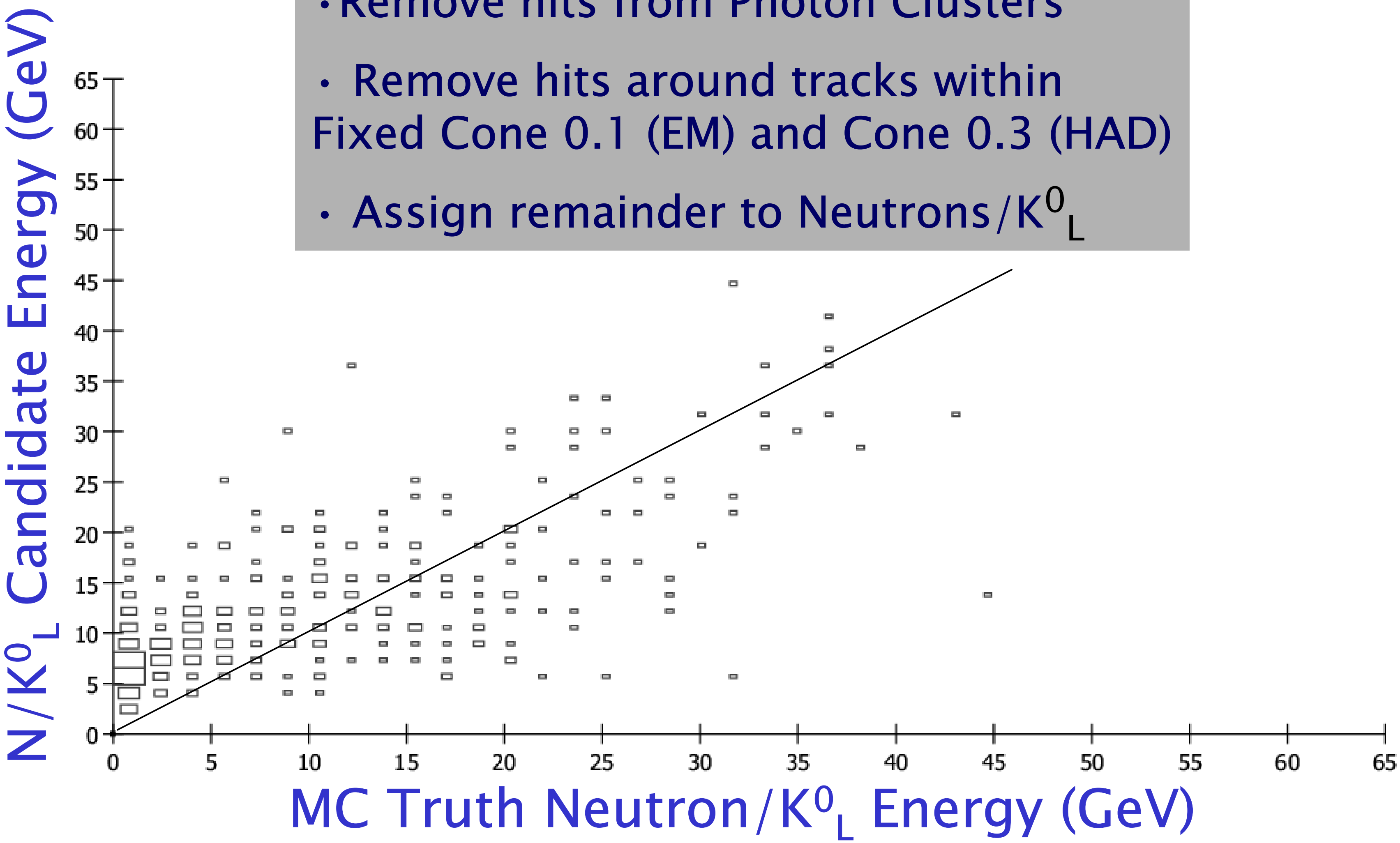


Very similar results for Analog/Digital HCal
Both still too wide!

Neutral Hadrons in Z → jj decays

Simple Neutron/K^0_L Estimator:

- Remove hits from Photon Clusters
- Remove hits around tracks within Fixed Cone 0.1 (EM) and Cone 0.3 (HAD)
- Assign remainder to Neutrons/K^0_L



Overlapping tracks & n/K^0_L

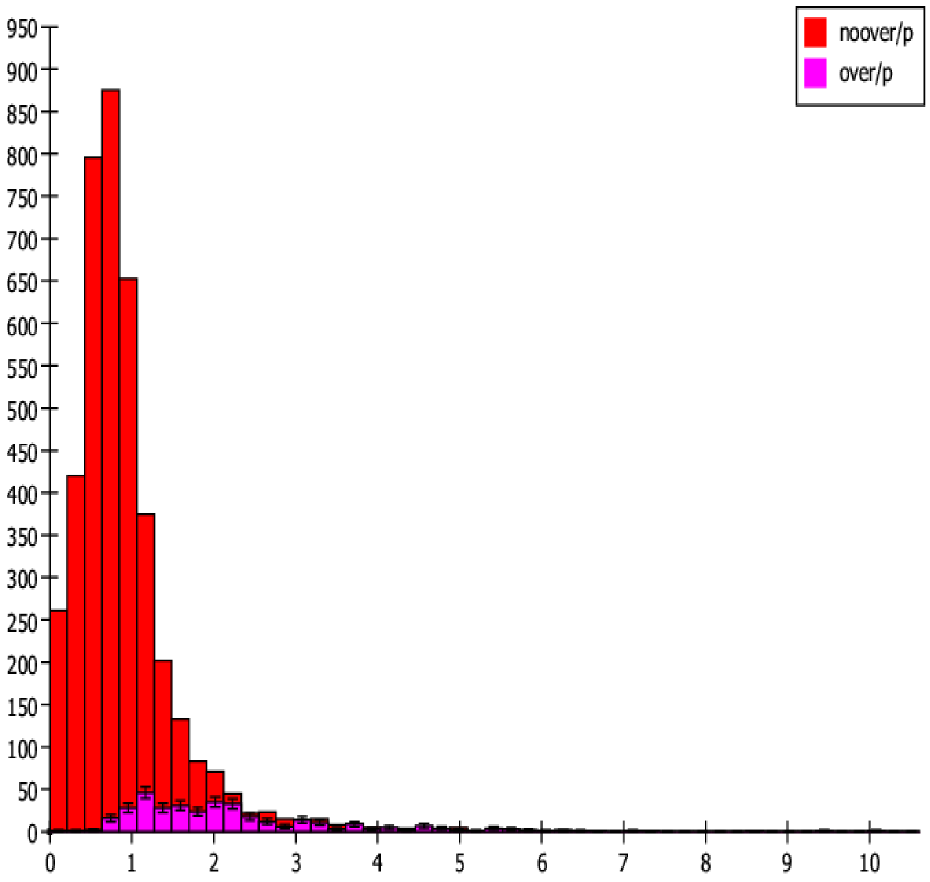
Two approaches being investigated:

- Put calorimeter and track properties in a neural net

15 Discriminators

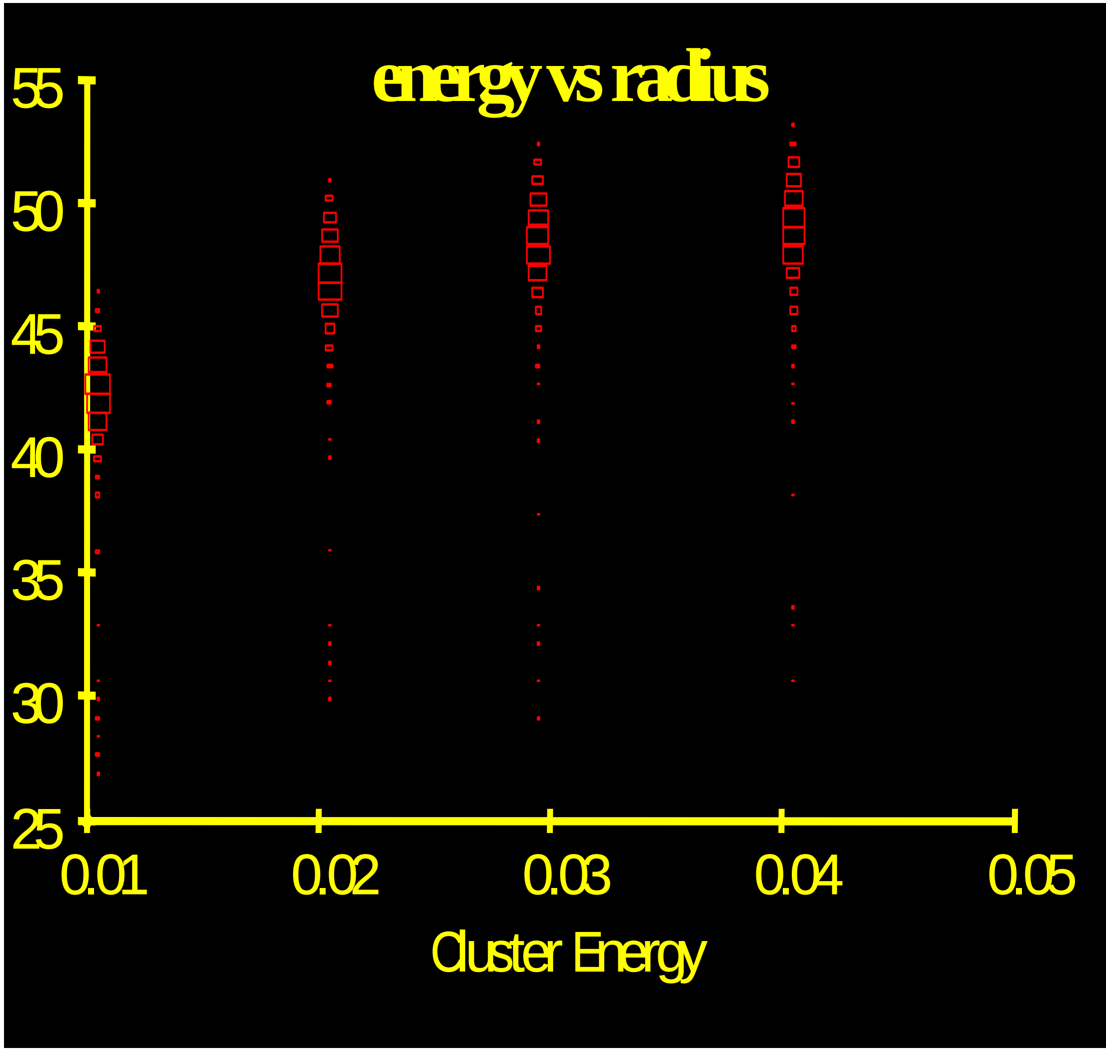
- 3 normalized energy tensor eigenvalues, ne1,ne2,ne3.
- ne1/ne2, ne2/ne3.
- First layer hit, last layer hit, length of cluster, (firstL+1)/length.
- Angular separation between e1-axis and IP.
- Energy in first 5 layers.
- Nhits in first 2 layers.
- z-coordinate of center of energy.
- Nhits
- Measured cluster energy.

- Remove track and gamma hits from the calorimeter ('snark' inspired)



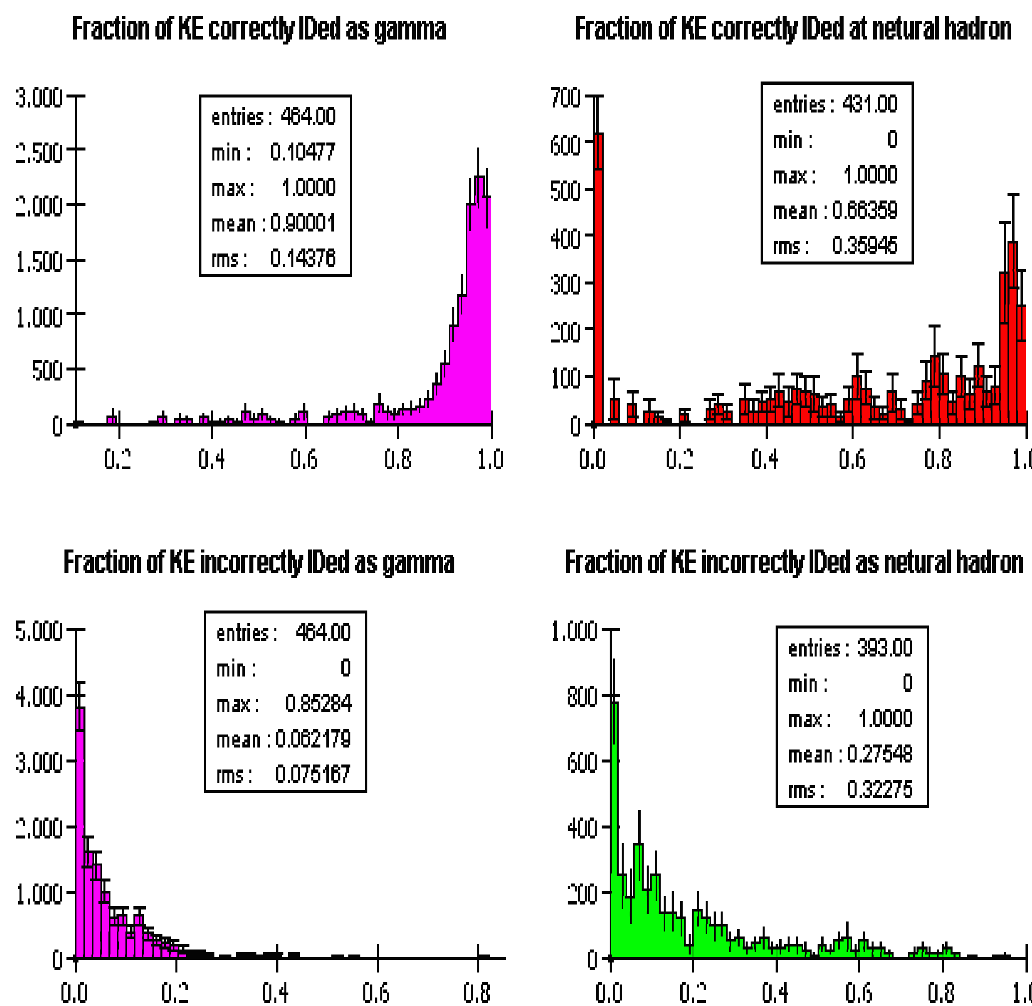
Photon Reconstruction

- Simple cone algorithm to cluster cells in the ECal
- Currently using fixed cone of 0.03
- Splitting based on distance of cell from cone axis
- Plan to use seed-energy-dependent radius

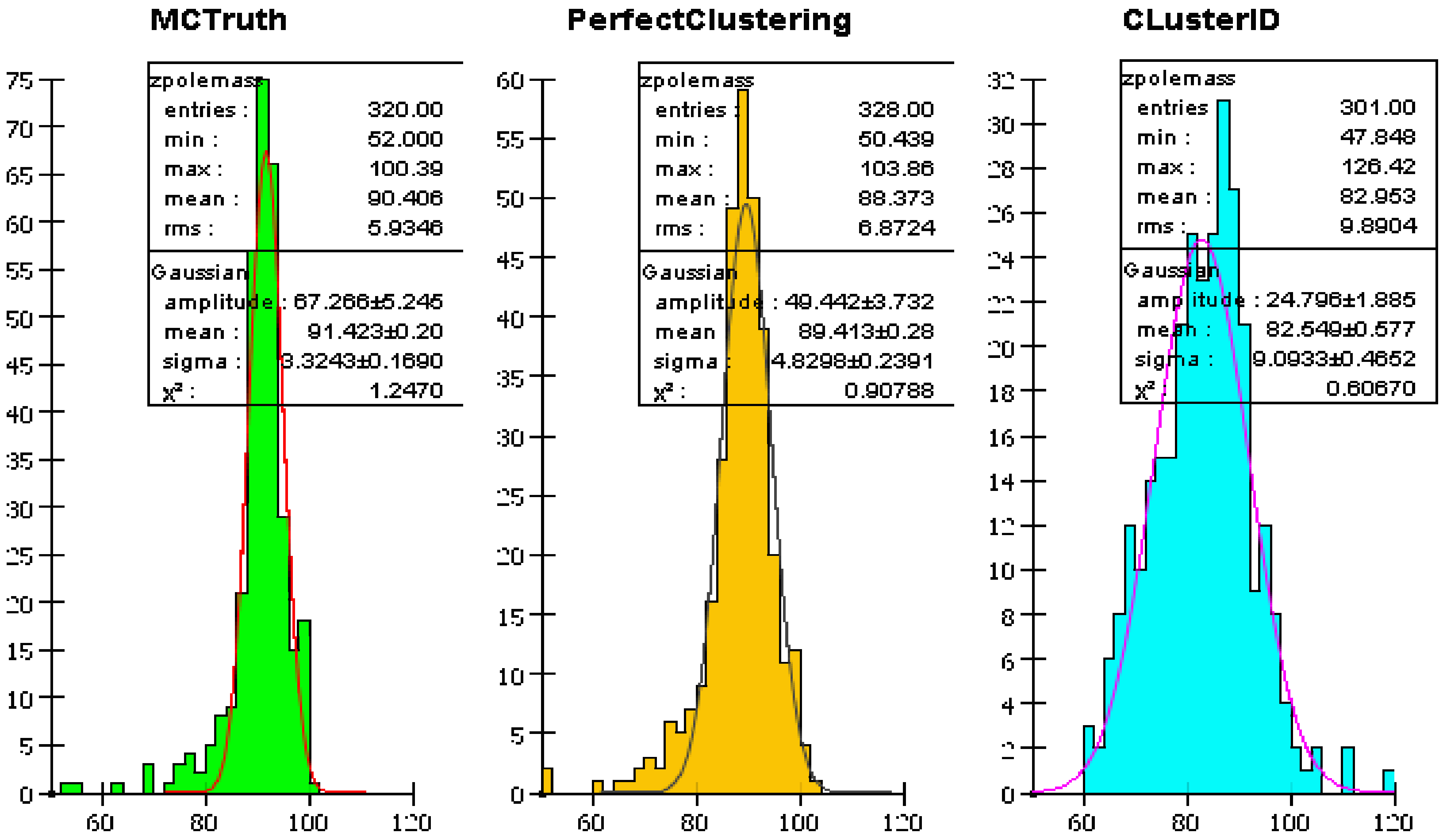


PFA: Cluster identification (SLAC, U. Pennsylvania)

- Make contiguous hit clusters
- Attempt to identify particle type that created cluster based on a set of discriminators
- NN, trained on single particles, being used presently



PFA: Z mass using Cluster identification



Summary

- Digital calorimetry can be as good as analog, may be even better, especially for particle-flow algorithms.
- Several independent approaches to PFAs expected to result in a large software library of algorithms and reconstruction techniques.
- Much work ahead – international collaboration is crucial to our success.