Particle Flow Calorimetry and CALICE Detectors

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Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

CALICE Calorimeter for ILC

TUM LMU Excellence Cluster Universe

Outline

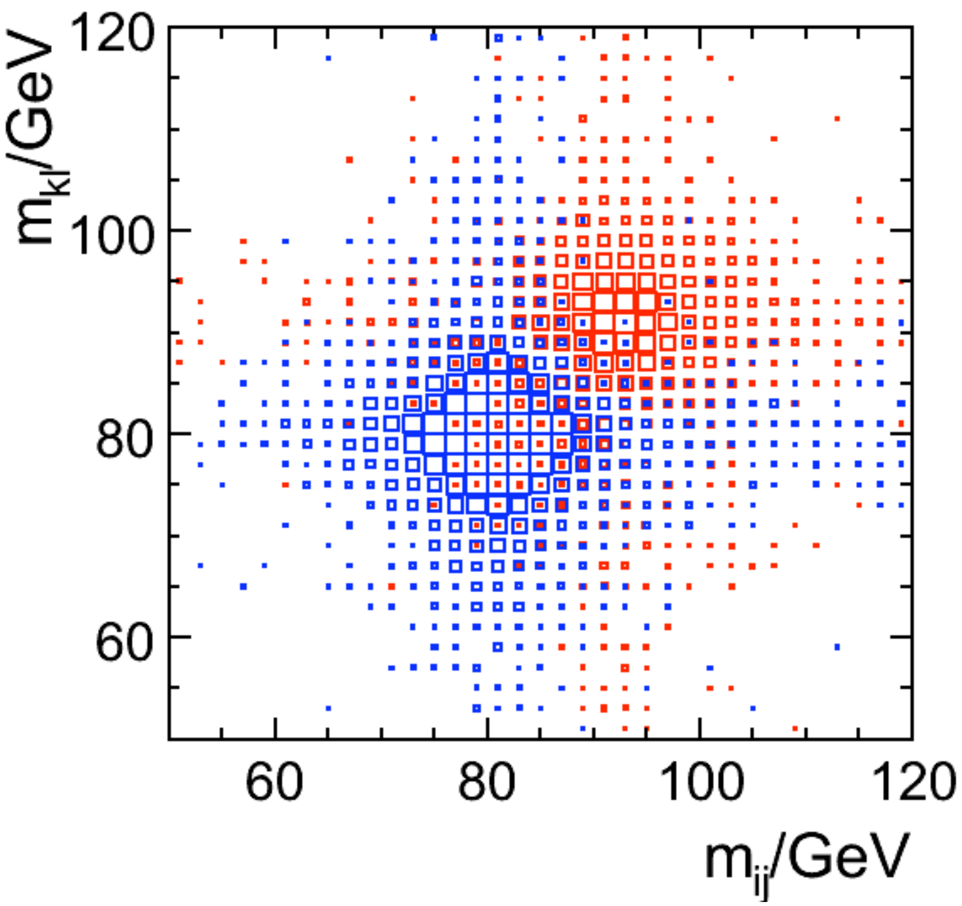
- Jets and jet reconstruction requirements at Linear Colliders
- Particle Flow: The Concept
- Imaging Calorimeters
- Selected CALICE Results:
  - Shower Substructure
  - Hadronic Energy Resolution
  - Particle Separation with PFA

The Environment at a Linear Collider

- Events at a Linear Collider are characterized by multi-fermion final states
  - Often multiple (non-boosted) jets, with O(100 GeV)
- Electron-Positron collisions:
  - Clean events (no underlying event)
  - Small cross sections (no pileup)
  - Moderate background (but: hadron background at high energies [CLIC])

The goal: Precision physics!

- High jet energy resolution (target: x2 better than ATLAS)
- One requirement: Separate W, Z bosons in their hadronic final states:
  Requires jet energy resolution of ~ 3.5% (or better) over a wide energy range



The PFA Paradigm

- Typical jet composition
  - 60% charged hadrons
  - 30% photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons (mainly n, K_L)

- Classical jet reconstruction relies exclusively on calorimetry: 70% of jet energy measured in the hadron calorimeter

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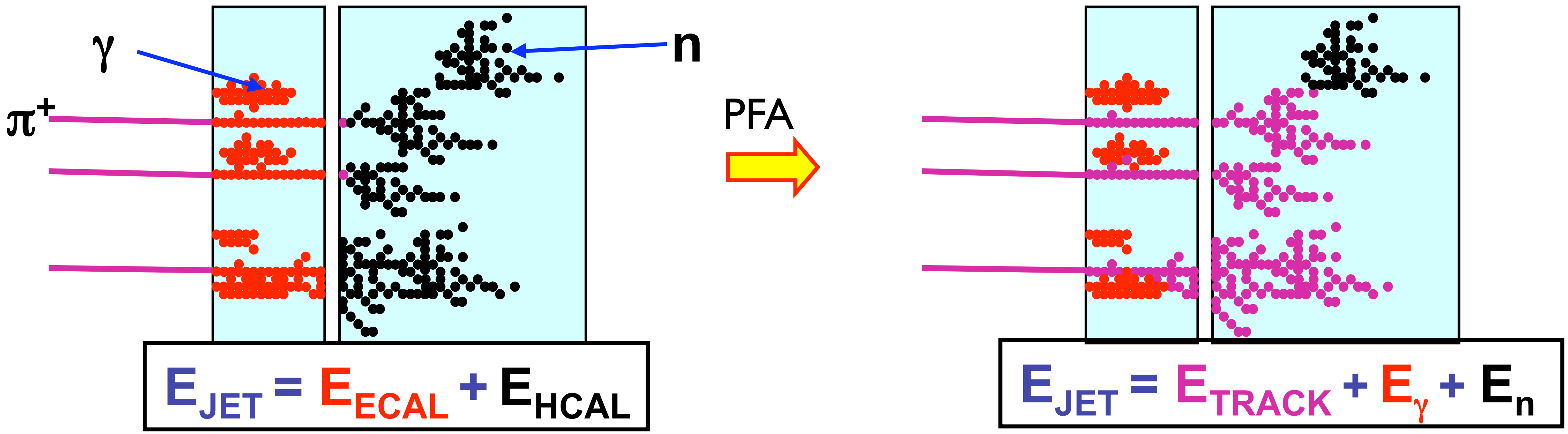

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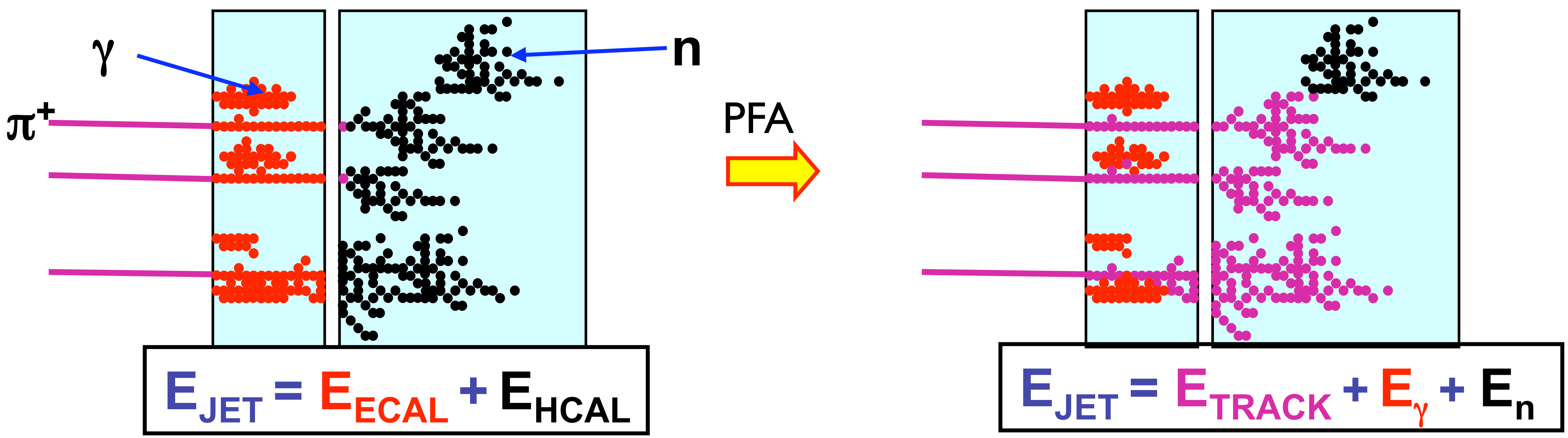

The key to PFA: Avoid double counting of energy, or ***confusion*** of energy deposits by different particles: Much more important than calorimeter resolution!

Requirements for PFA

- PFA: Reconstruction of every single particle in the jet (measured with the best possible precision provided by all detector systems)

Requirements:

- Separated particles in the calorimeters - Physics limits:
  - Moliere radius in the ECAL
  - Nuclear interaction length in the HCAL (not that strict, since hadronic showers are sparse)

- Detector: Very high granularity - Reconstruct showers of individual particles, provide separation:

  Imaging Calorimeters!

Imaging Calorimeters

- Particle Flow needs extreme granularity:
  - Electromagnetic Calorimeter
    - Small Moliere radius for shower separation: Tungsten absorber
    - Imaging capabilities: Read each layer separately, pads on each layer < Moliere radius: ~ 5 x 5 mm^2
  - Hadronic Calorimeter
    - Steel or Tungsten absorber (Tungsten to limit leakage for high energy jets)
    - Imaging capabilities: Read each layer separately (sampling ~ 1 X_0 to retain resolution for em subshowers), small cells: 3 x 3 cm^2

- Explosion of the channel count!
  - ILD: ~100 M channels in ECAL, ~10 M channels in the HCAL
  - Compare to LHC: CMS ECAL: 76 k channels, ATLAS HCAL: ~10 k channels

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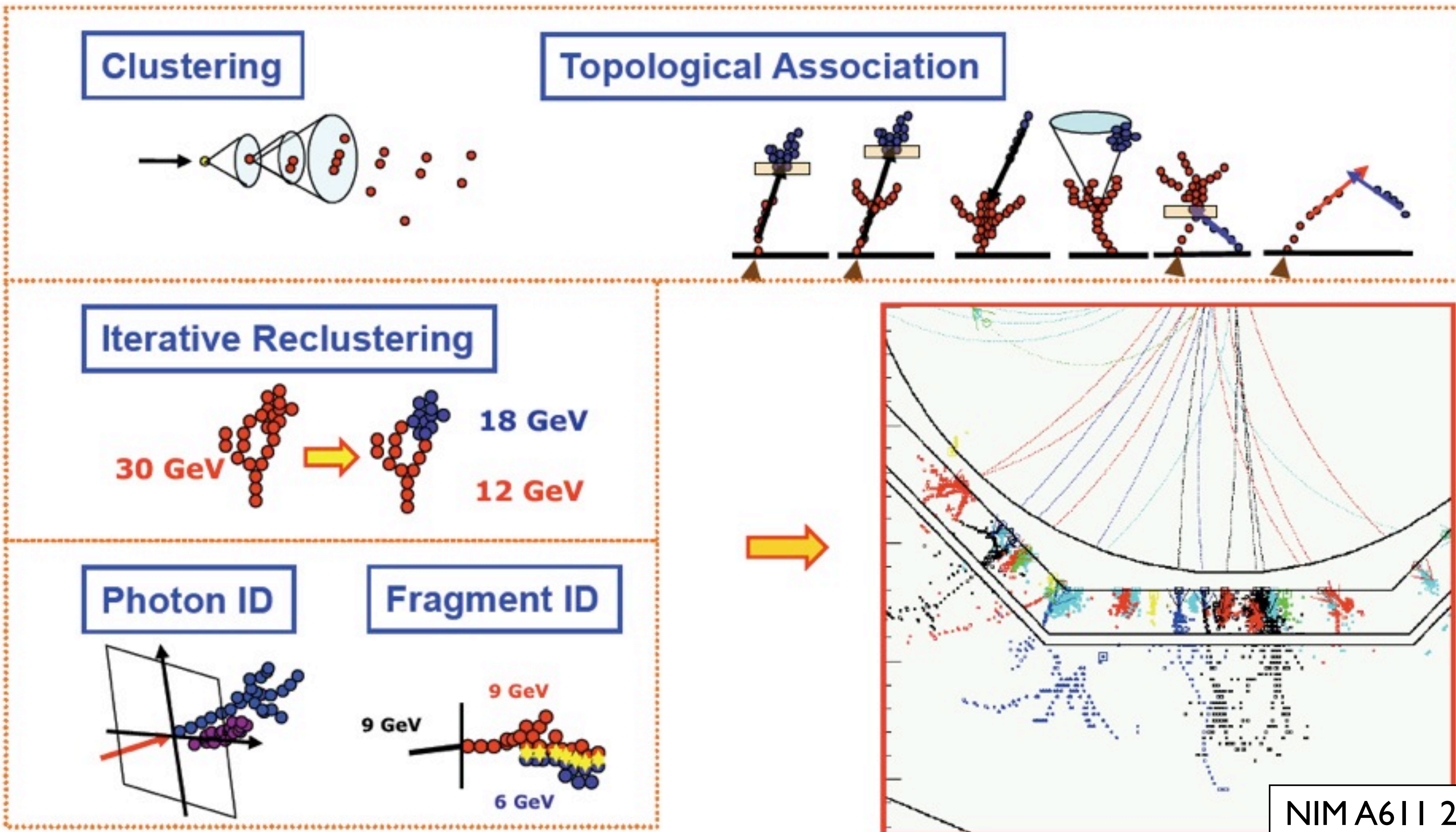
About a factor of 1000 more channels: A totally different calorimeter technology!

Particle Flow Algorithms: Technology

- The most performant PFA at present: PandoraPFA (Mark Thomson, Cambridge)
  - highly complex software package



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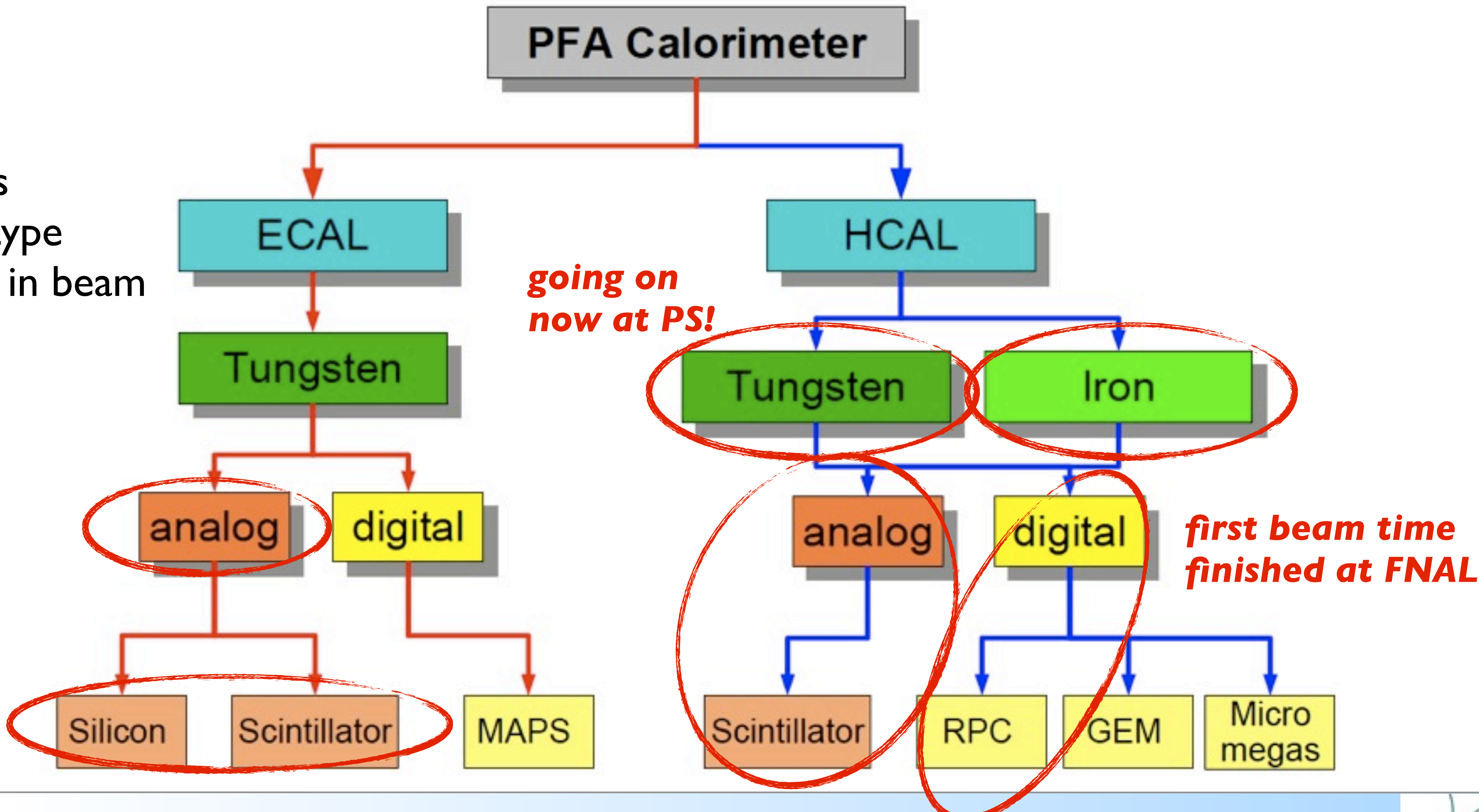
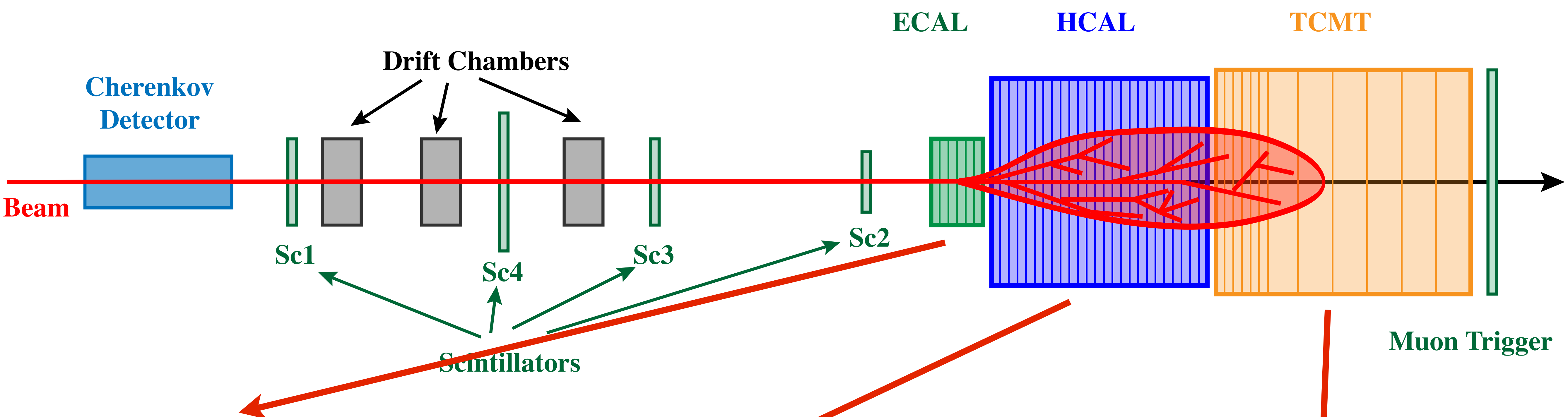
CALICE: Proving the PFA Calorimetry Concept

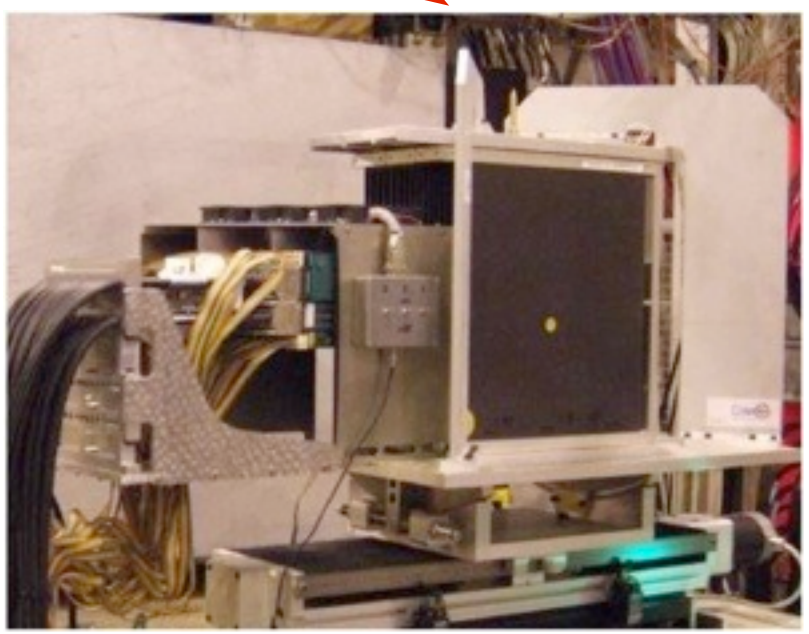
- Global Collaboration: ~330 Scientists from 57 Institutions in 17 countries on 4 continents
- The goal: Study different technologies for PFA calorimetry

physics prototype tested in beam

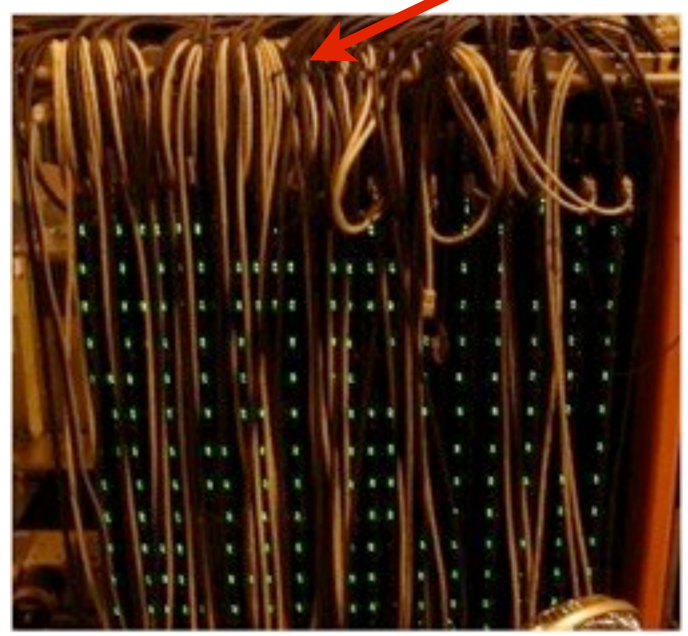


CALICE: Putting it all together





Si-W ECAL
1x1 cm^2 lateral segmentation
30 layers, ~ 0.9 λ, 30 X_0
~ 10 k channels

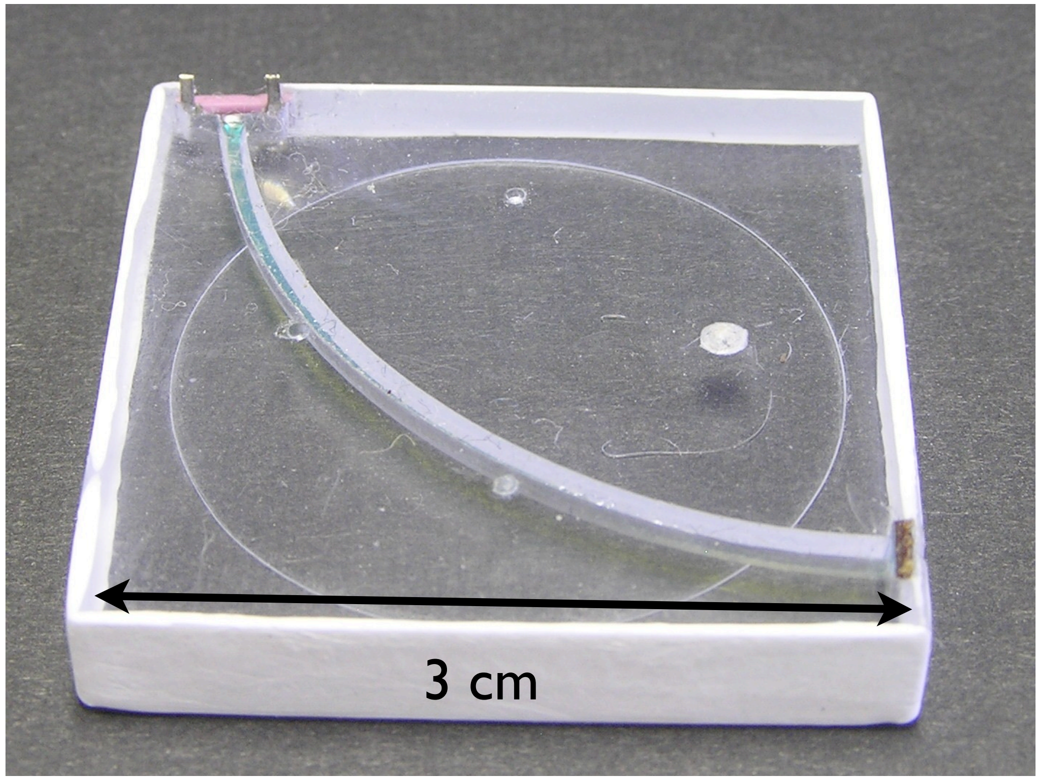


Analog HCAL
3x3 - 12x12 cm^2 lateral segmentation
38 layers, ~ 5.3 λ
~ 8 k channels

Tail Catcher / Muon Tracker
5 x 100 cm^2 Scintillator Strips
16 layers
~ 300 channels

Analog HCAL: Active Elements

- The unit: scintillator tile with SiPM



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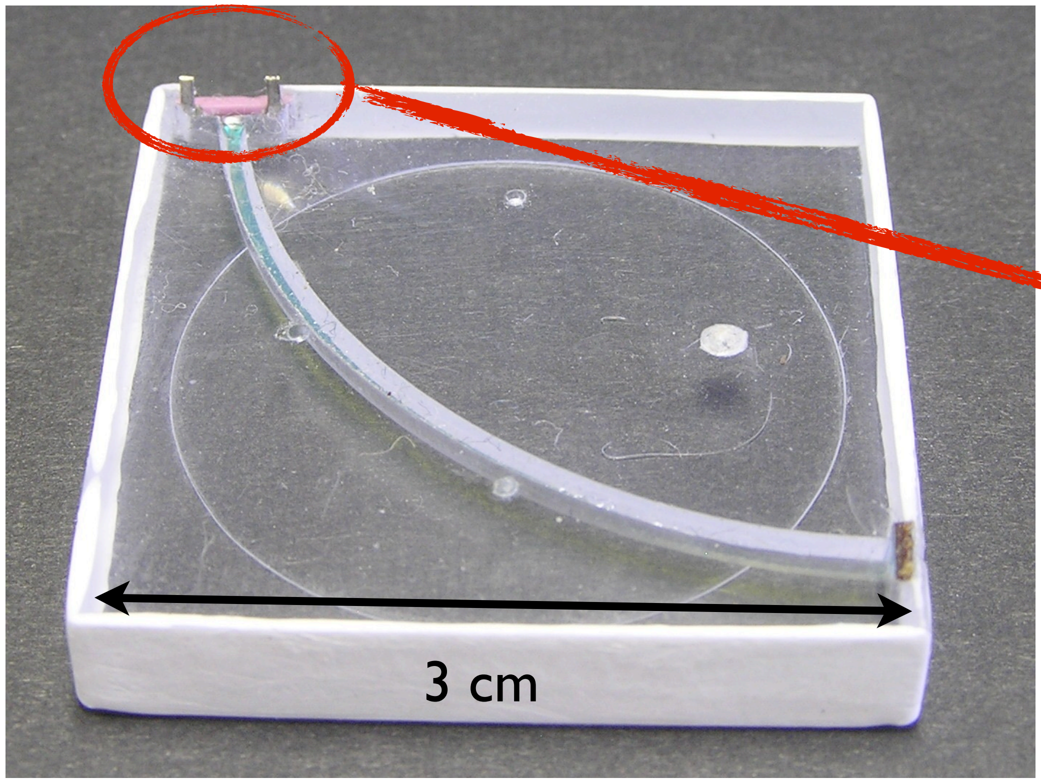
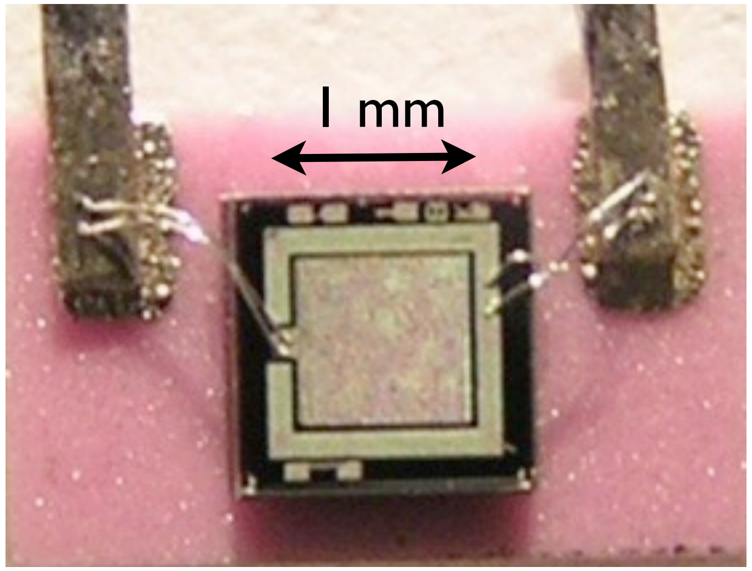


- SiPM: 1156 pixels, manufactured by MePhI/PULSAR



Maximum efficiency in green spectral range: Wavelength shifting fiber to collect and shift blue scintillation light

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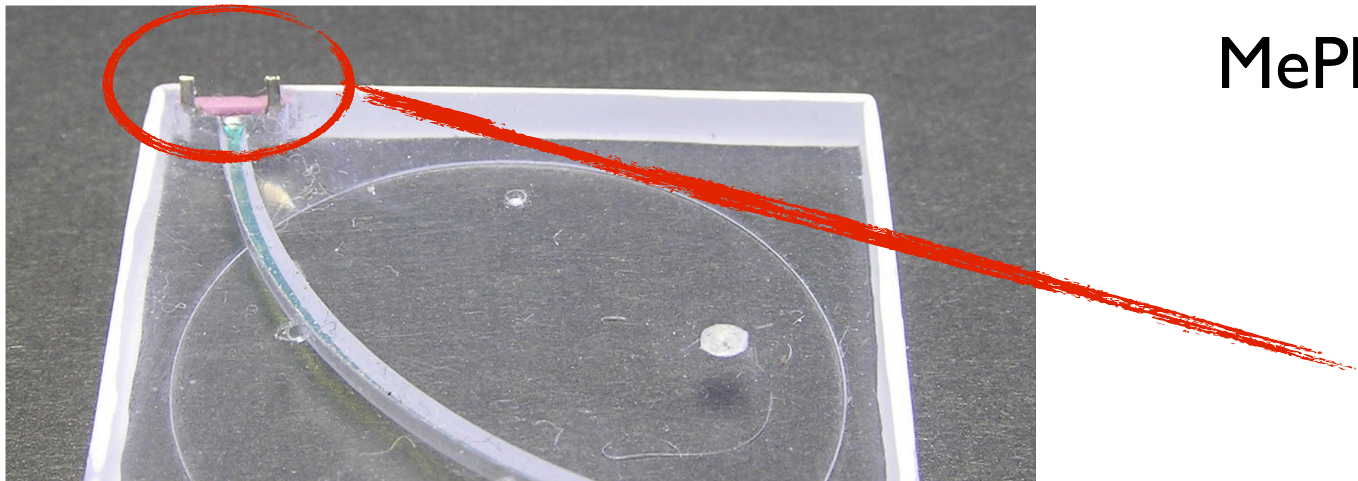

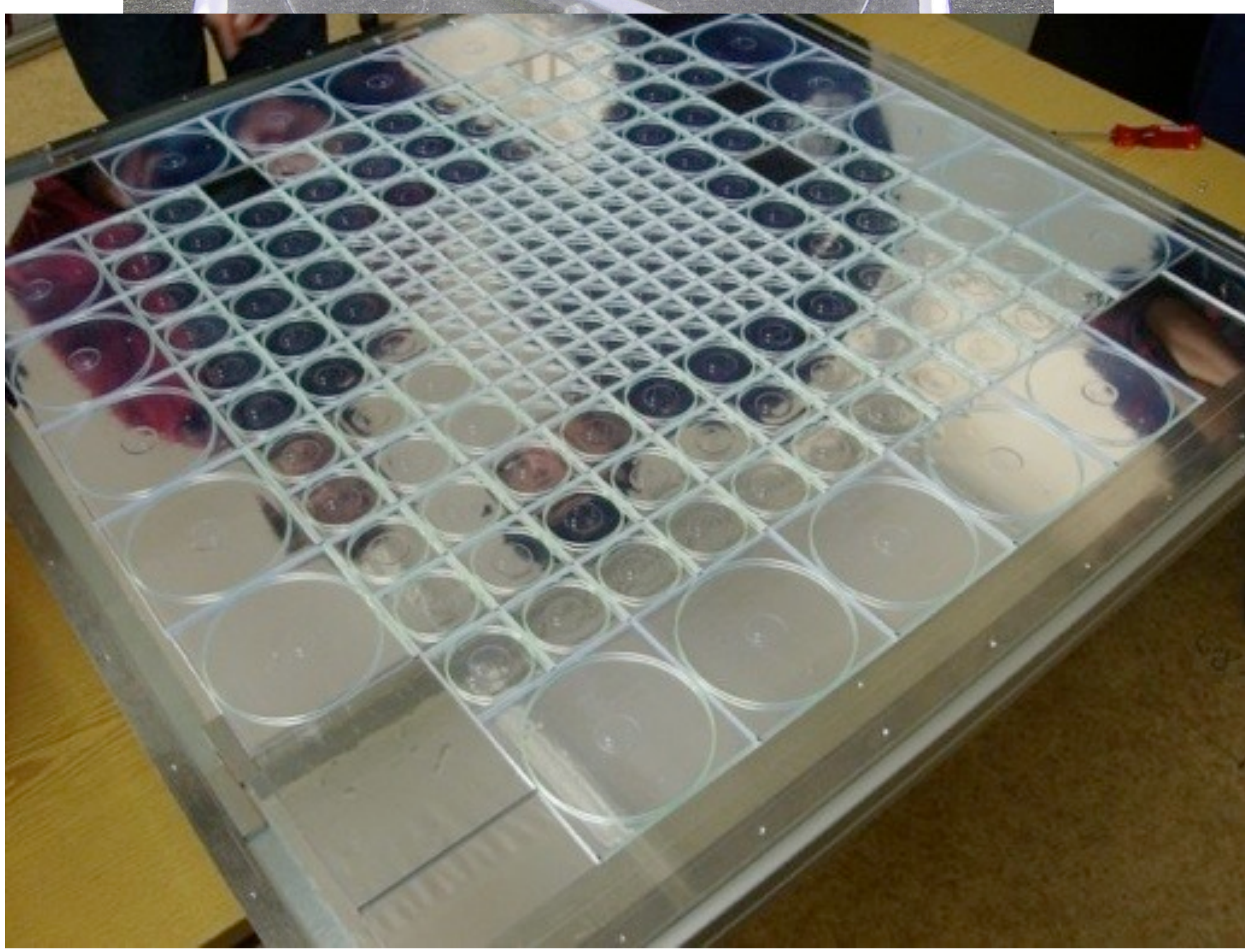

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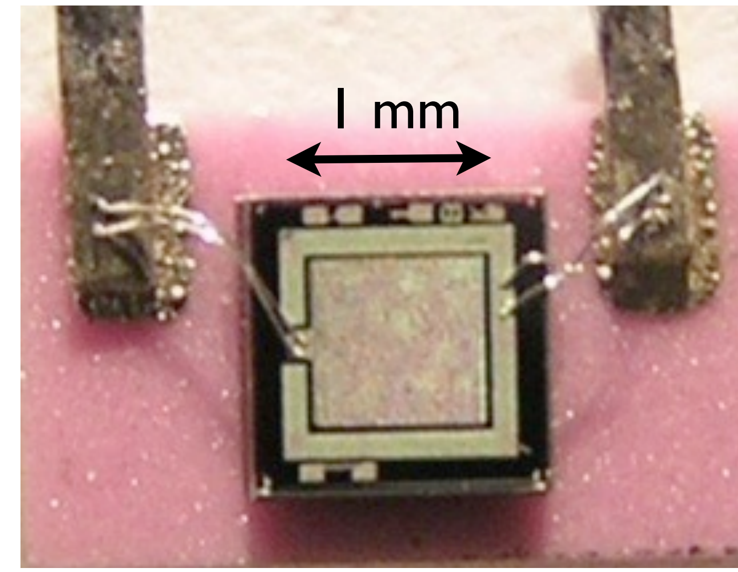

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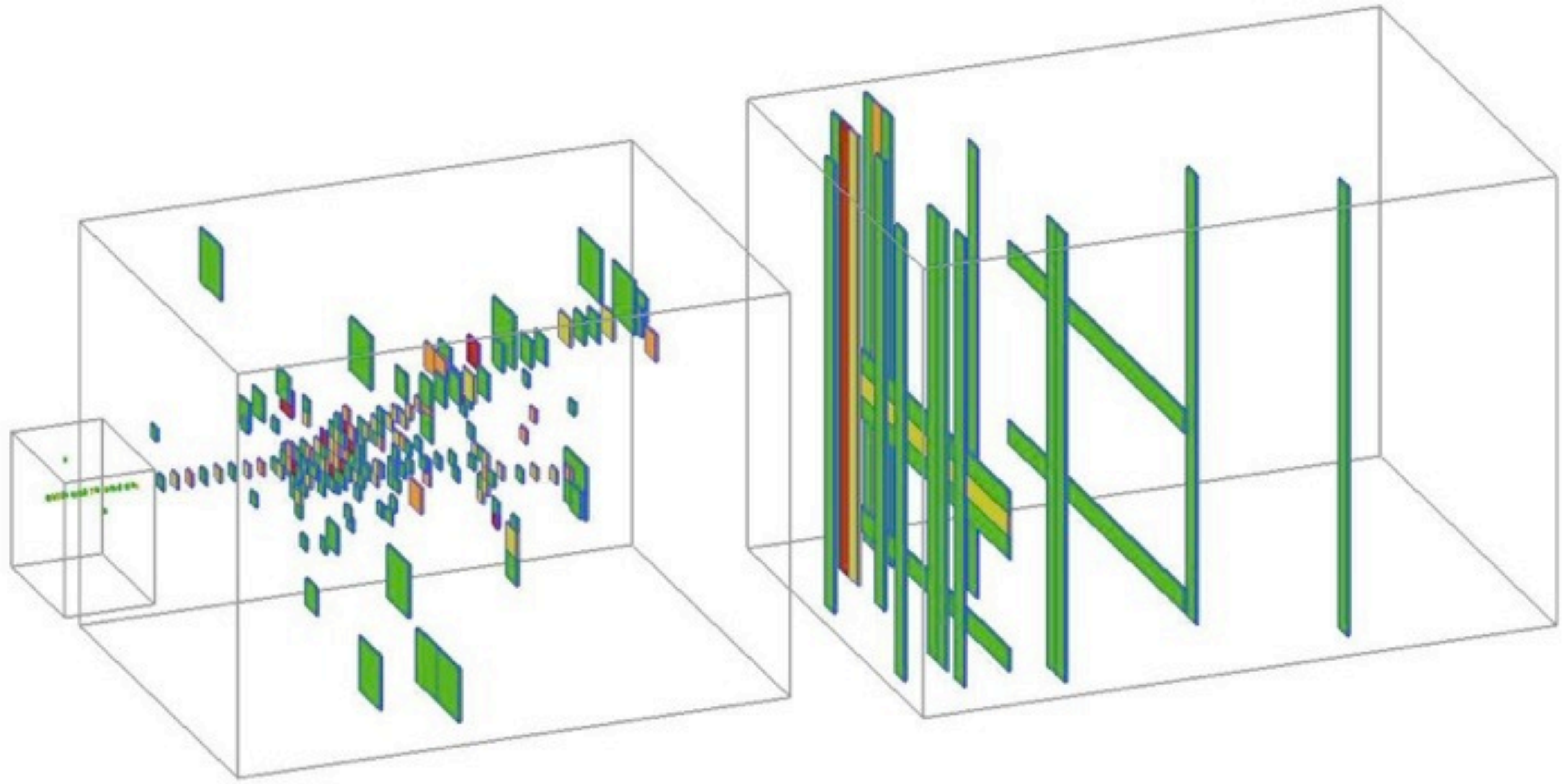
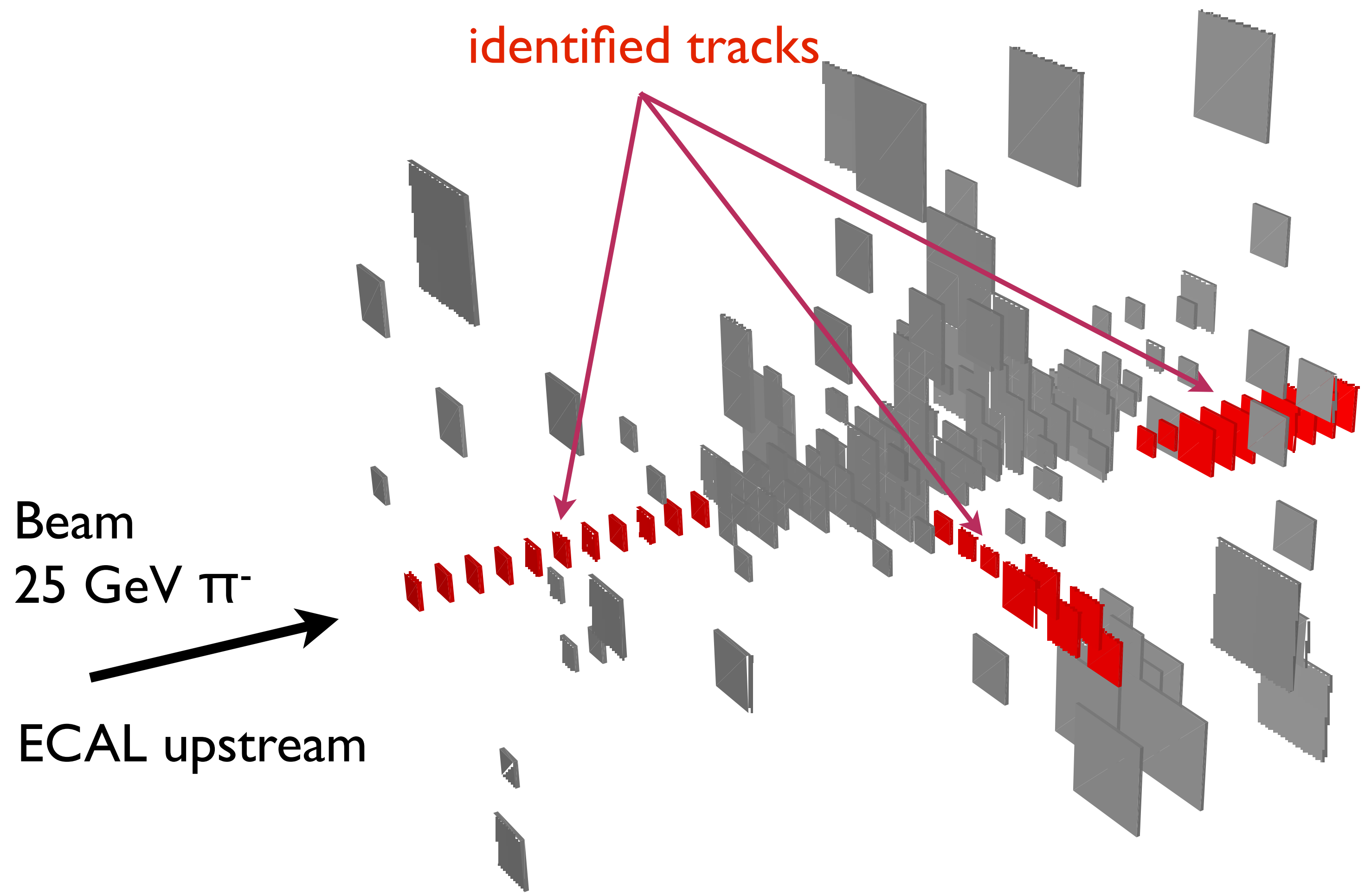
- Active layers: 90 x 90 cm^2
  212 scintillator tiles (100 in high granular core)

Detailed 3D Images of Particle Showers



- Study hadronic showers in a realistic detector in great detail
  - Provide input for next-generation detectors
  - Validate shower simulations
    - Crucial to establish the reliability of PFA simulation studies
    - Further improve shower modeling in GEANT4

3D Substructure of Hadronic Showers - Particle Tracks



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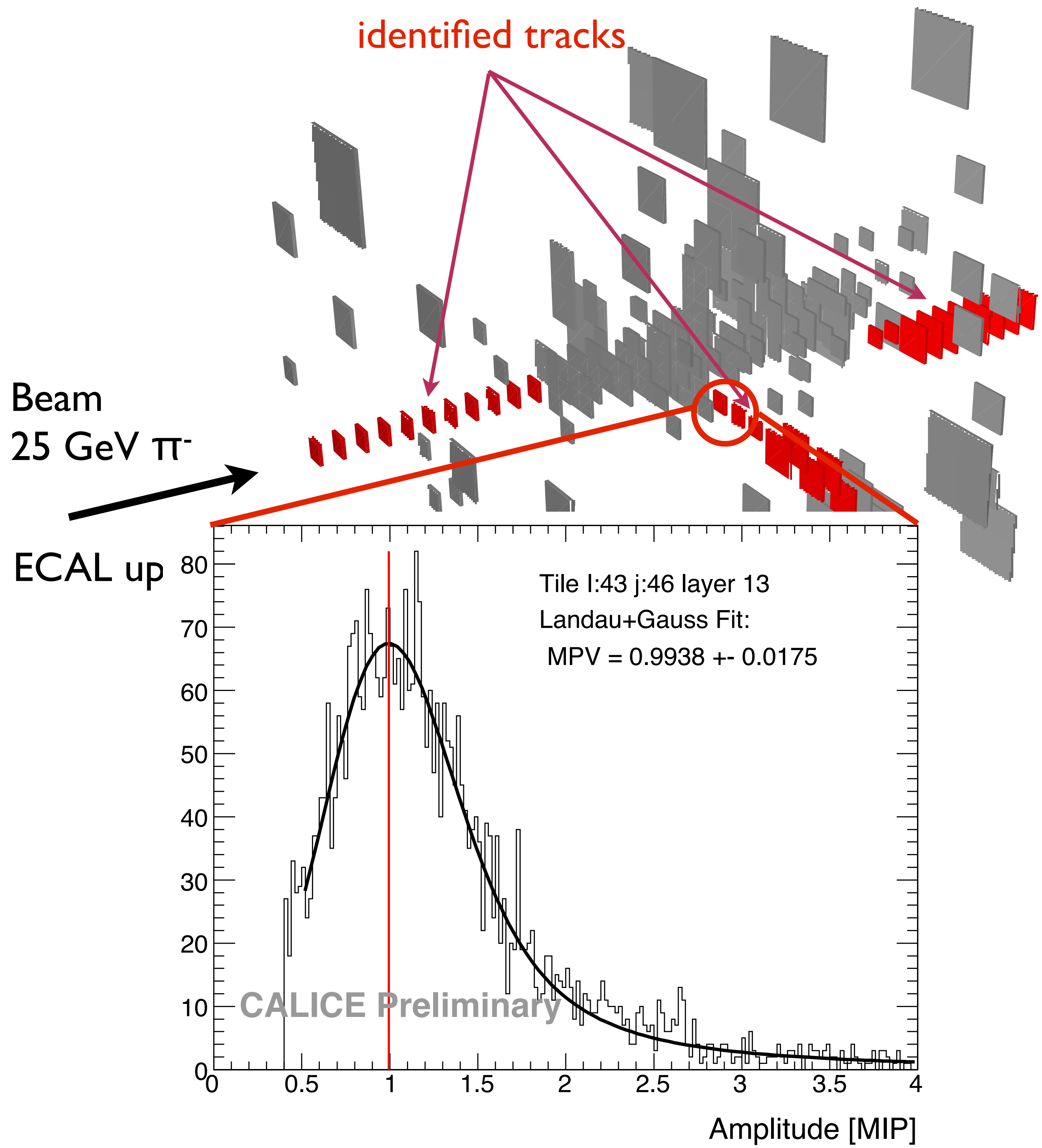


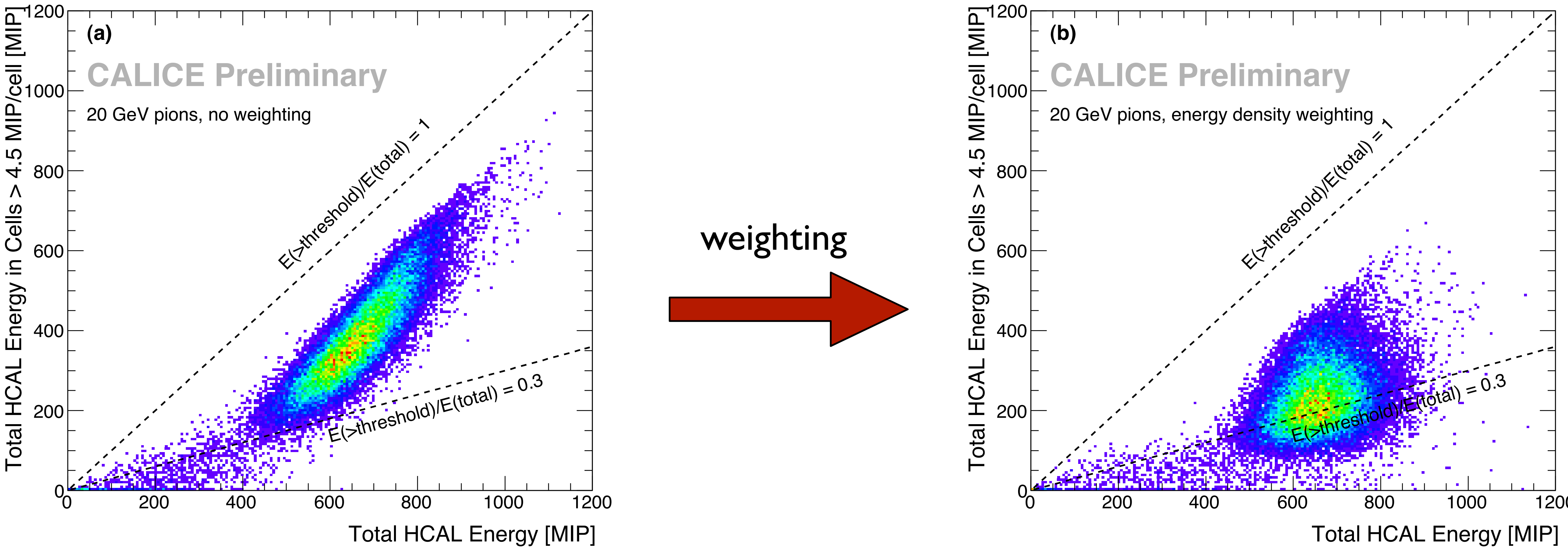
- Imaging capability of detector allows the identification of individual MIP-like tracks within hadronic showers

- Track identification provides a clean sample of minimum ionizing particles: An alternative calibration tool!

Energy Reconstruction & Software Compensation

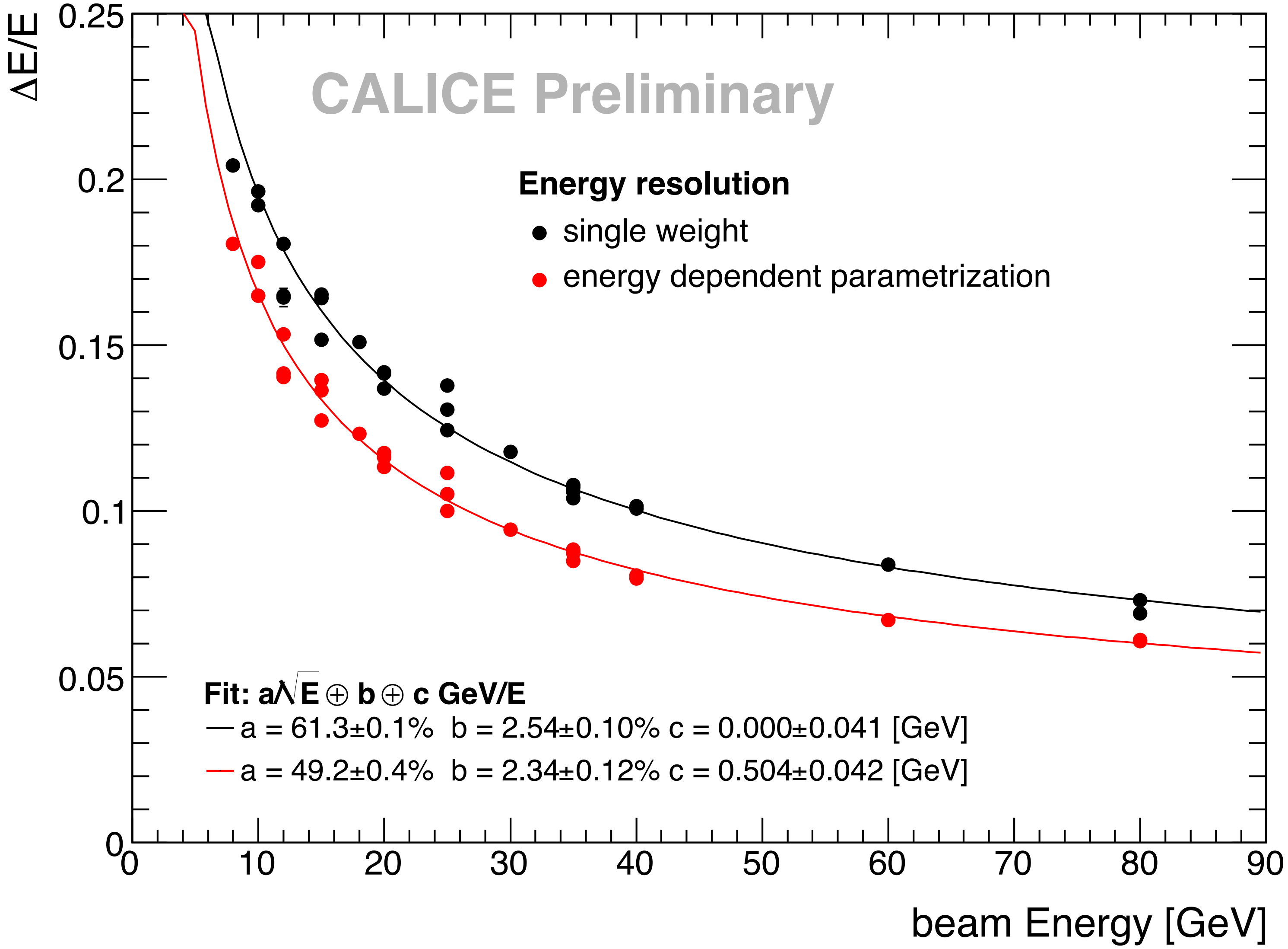
- The CALICE HCAL is non-compensating: e/π ~ 1.3 (energy dependent)
- High granularity provides detailed information for software compensation:
  - Electromagnetic energy deposits tend to be denser than hadronic ones
  - Improvement studied on the cell (local) and on the cluster (global) level

Local method: apply weight to cells according to their energy, lower weight for cells with higher energy content, weights are determined with a minimization technique



Software Compensation: Local Method

- Weights determined from data, parametrized energy dependence
  - No prior knowledge of beam energy necessary for application
- Improved linearity of response, within ~3% from 8 to 80 GeV
  - without temperature correction, proton rejection: Better performance expected in the near future!



Complete CALICE Setup (ECAL, HCAL, TCMT):

Resolution improved by ~ 18%

Resolution given by Gaussian sigma / mean of a fit to the distribution within 1.5σ of peak

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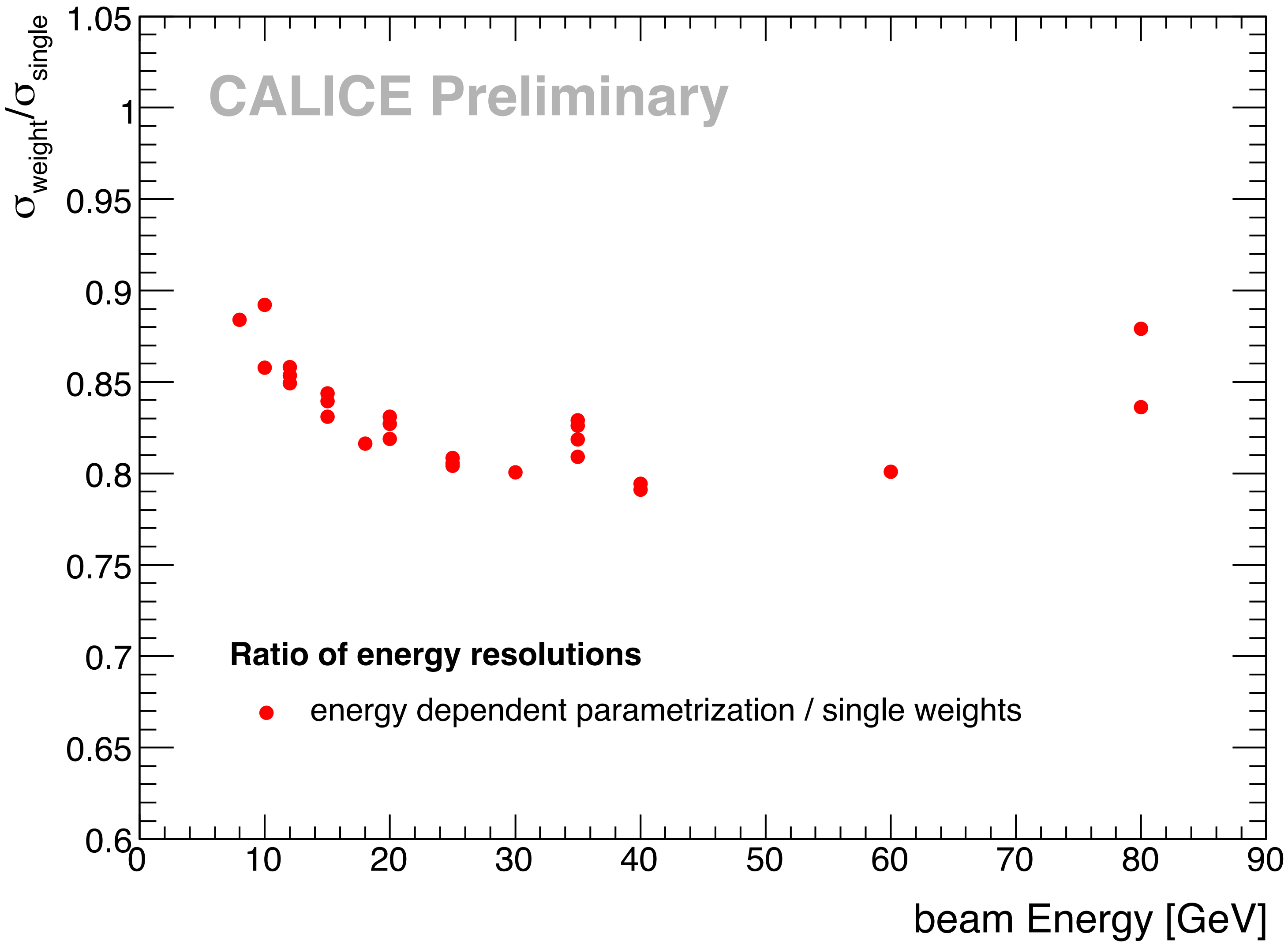

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- Cluster finding in HCAL and TCMT to determine properties of the shower: total energy, volume, length, width, energy in TCMT, energy in last 5 HCAL layers
  - Used as input for a neural net, training of the NN with simulations (quasi-continuous energy)
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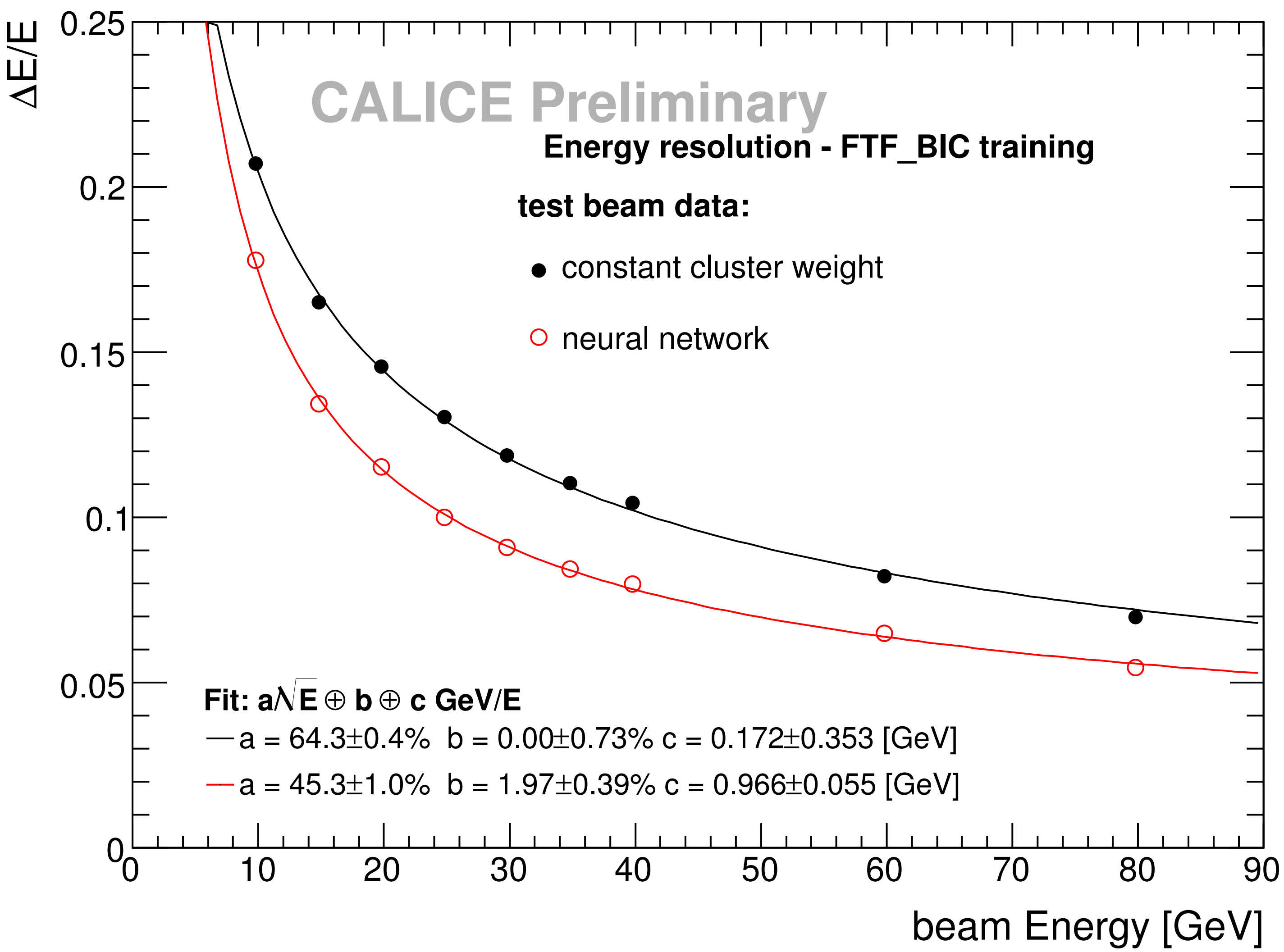

HCAL+TCMT
NN trained with FTF_BIC

Resolution improved by ~25%
(~15% at 10 GeV, ~20% at 15 GeV)

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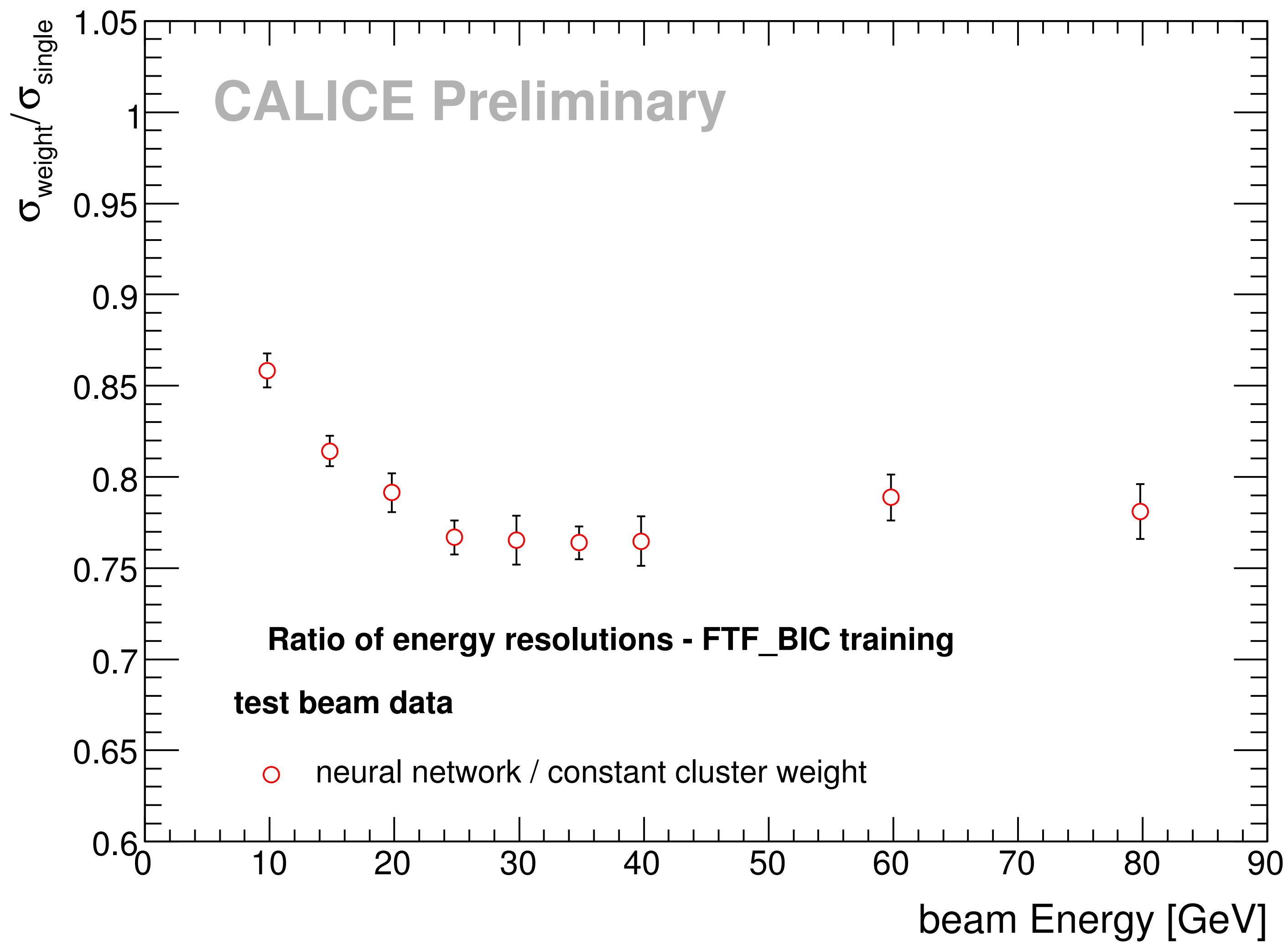

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Testing Particle Flow with CALICE Data

- A realistic test of the PFA algorithm: Use real hadronic showers recorded with CALICE, map them into the ILD detector
  - Take one shower as a charged hadron (with tracking information), one shower as a neutral hadron (remove hits before the shower start)
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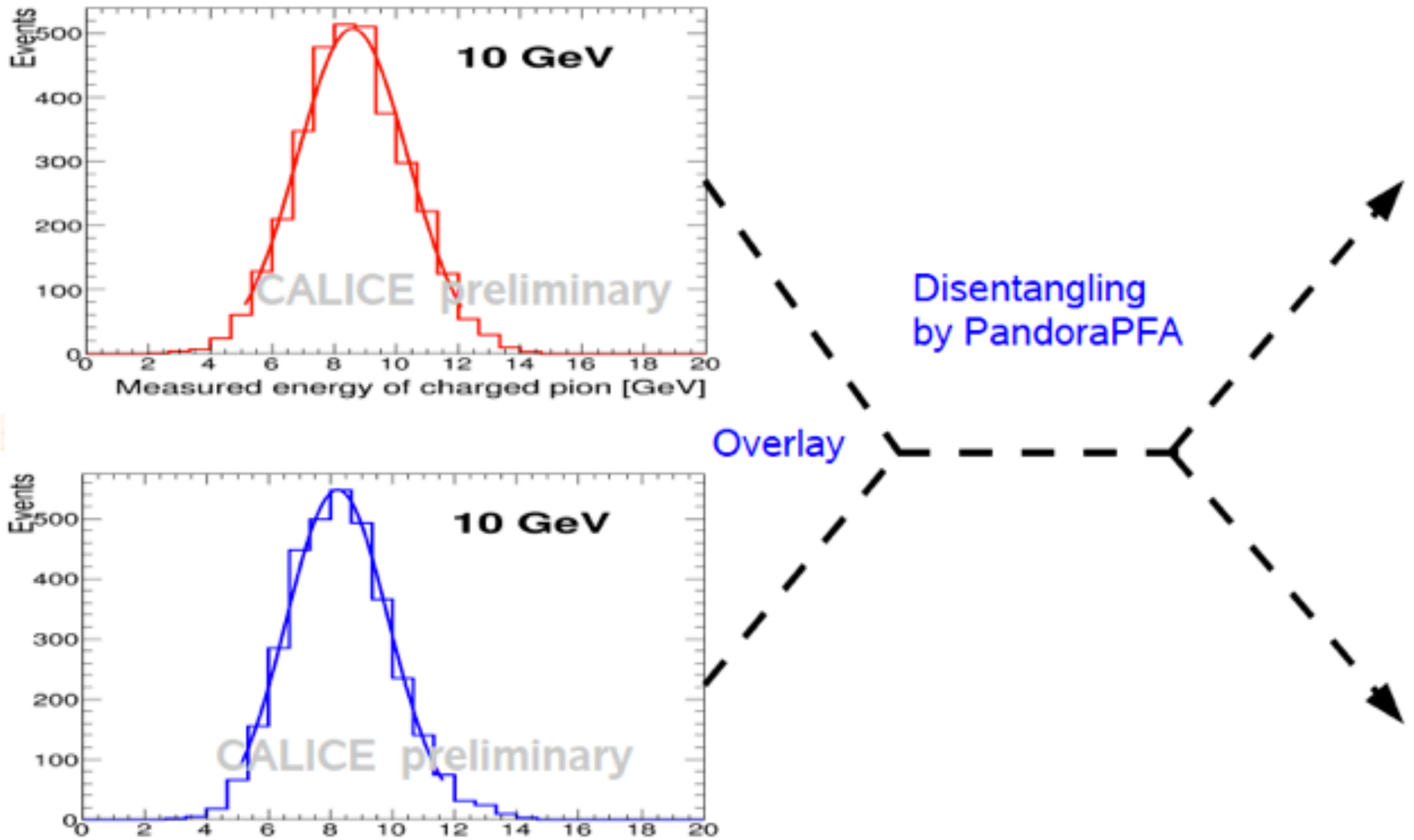

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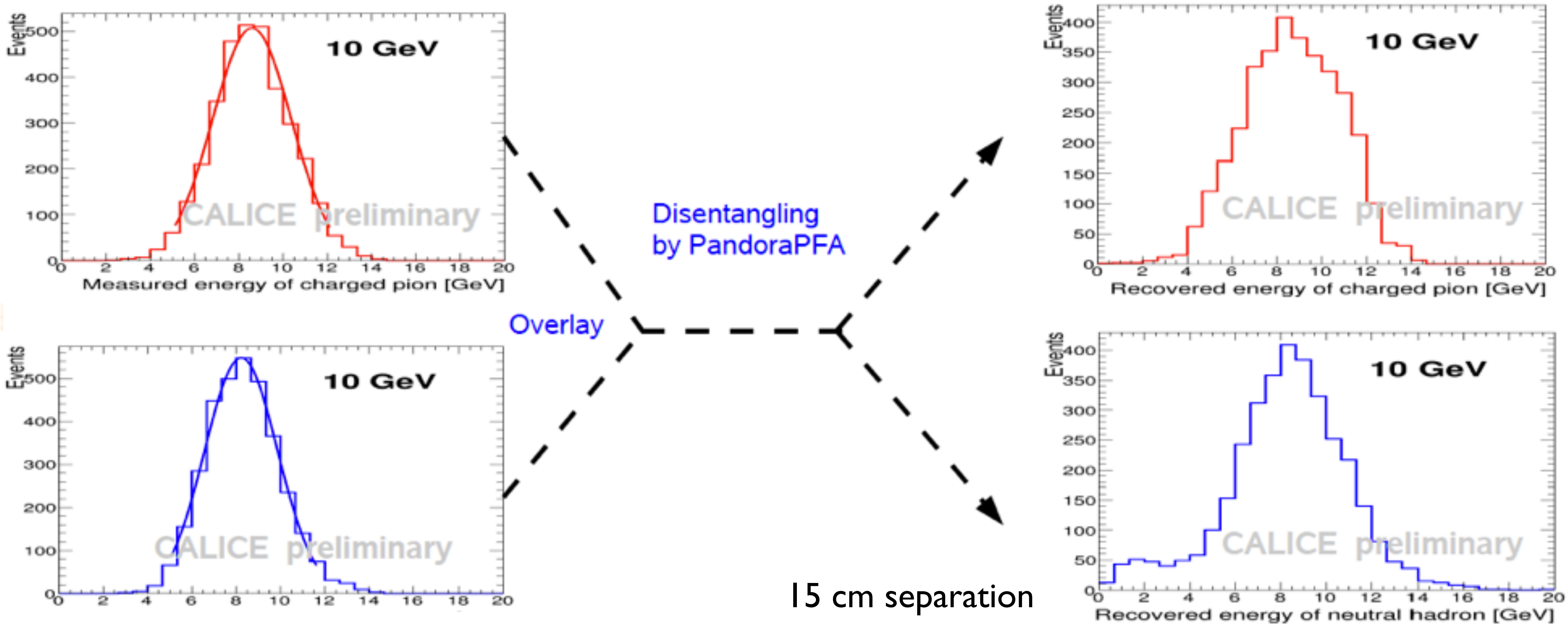
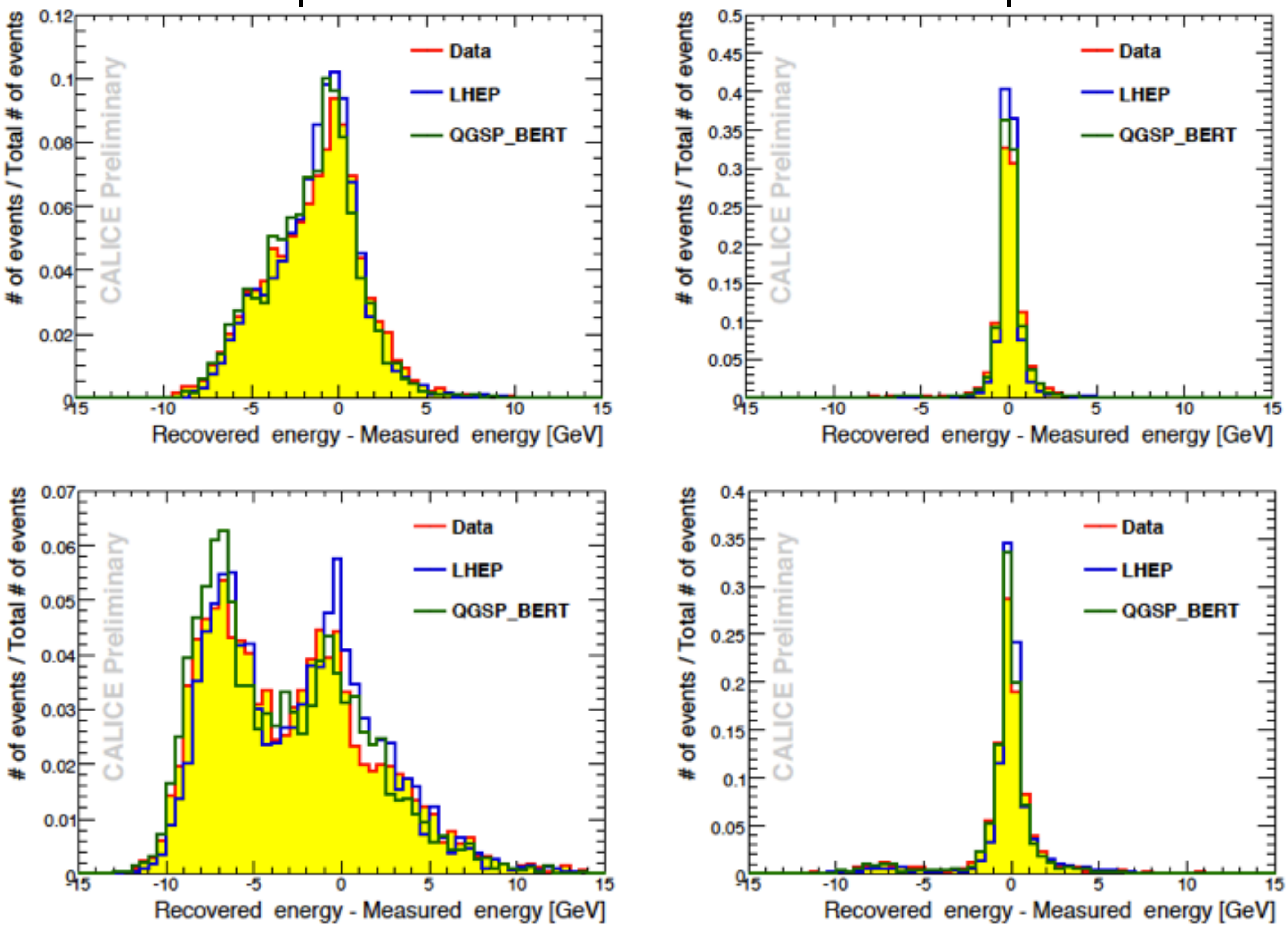


Shower Separation: Energy & Distance

5 cm separation

30 cm separation



- 10 GeV neutral hadron

10 GeV charged hadron

30 GeV charged hadron

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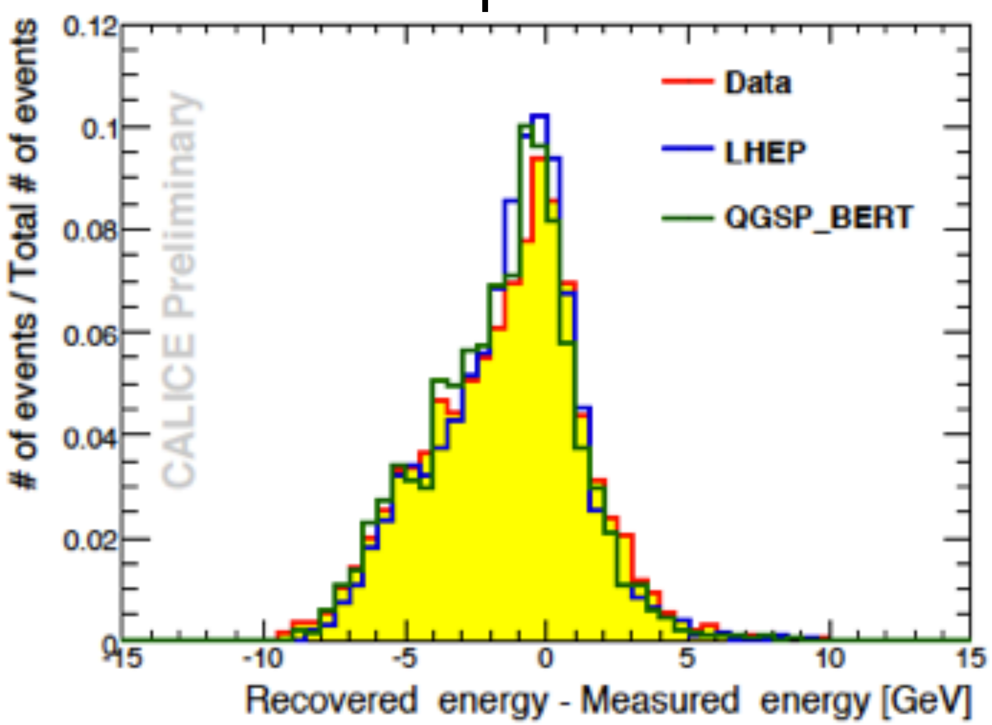
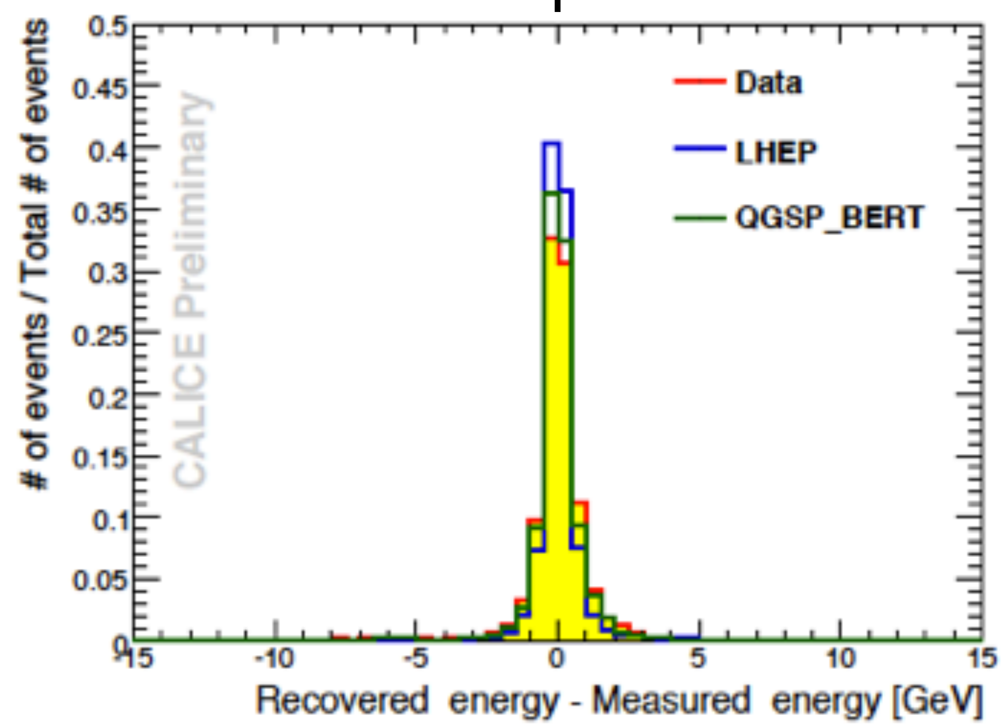
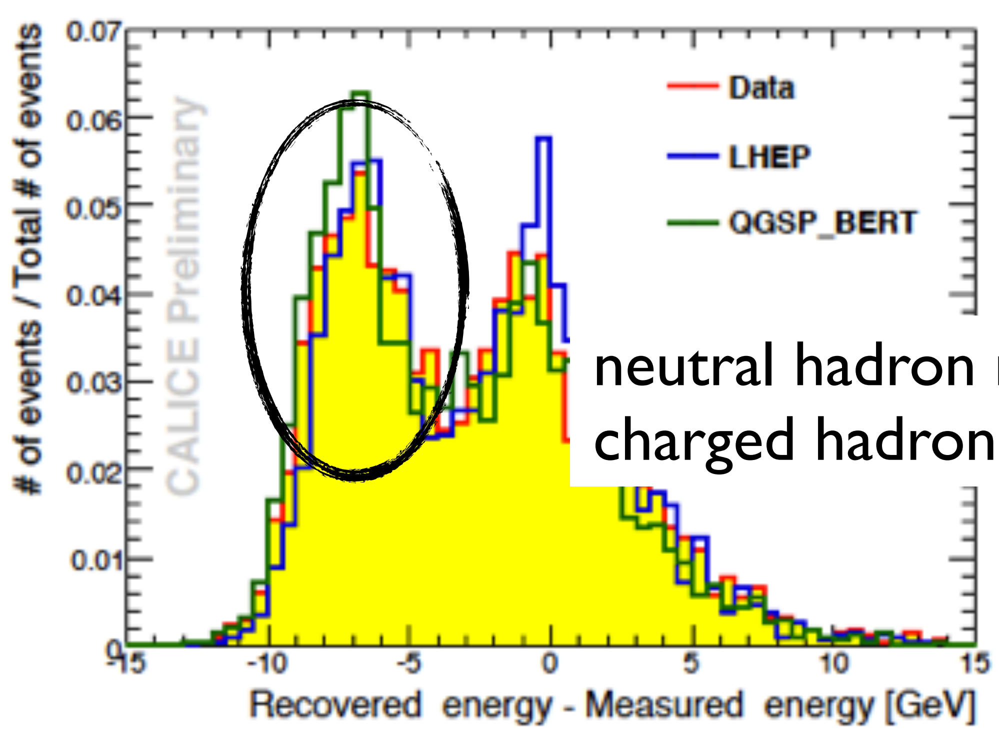
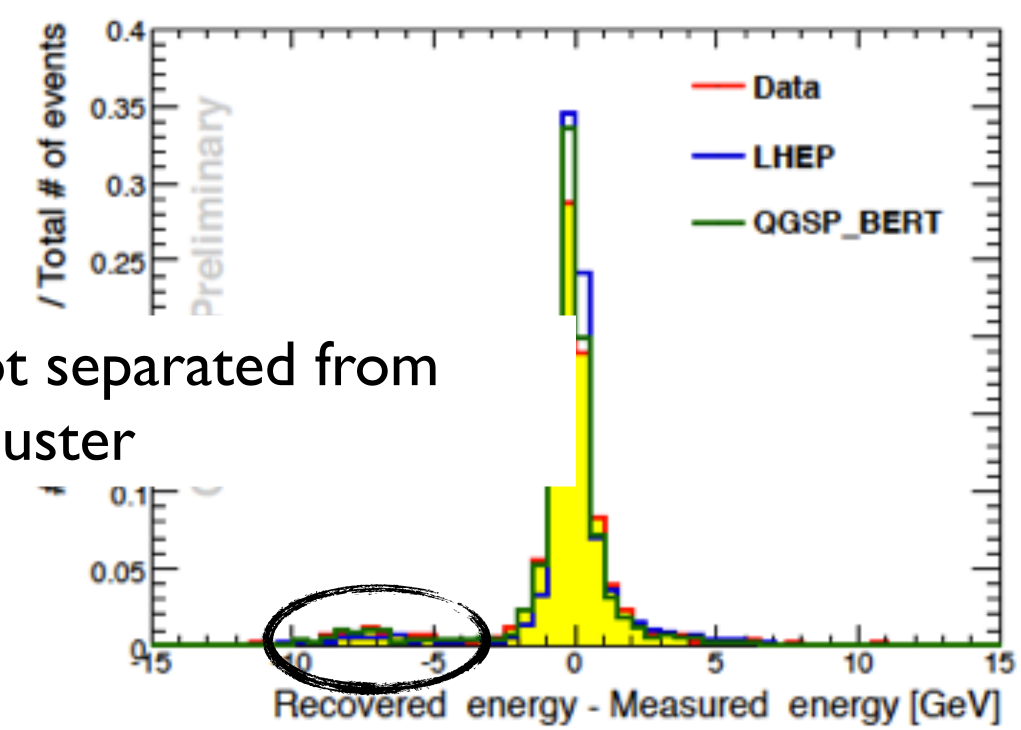








neutral hadron not separated from charged hadron cluster

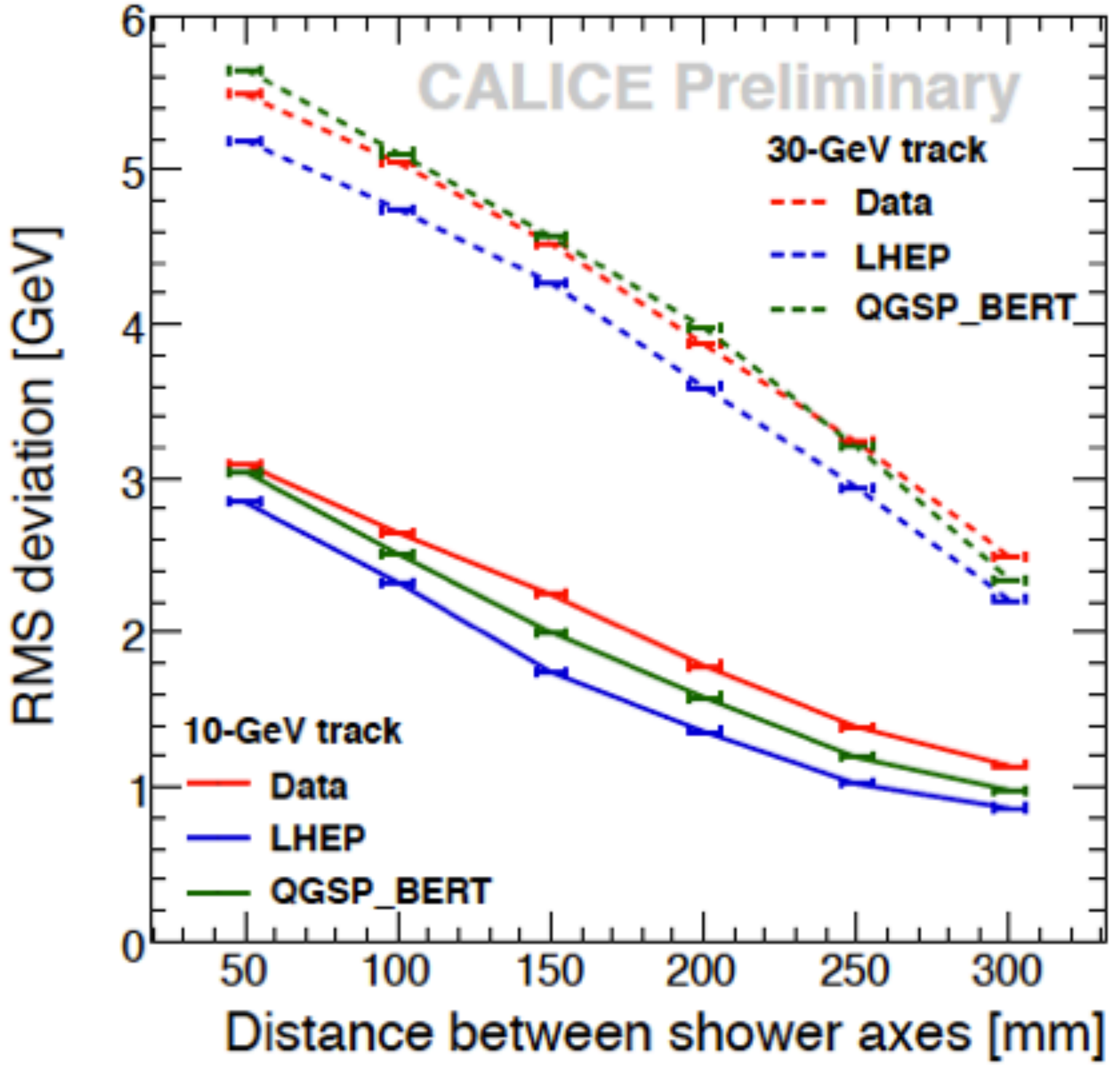
- 10 GeV neutral hadron

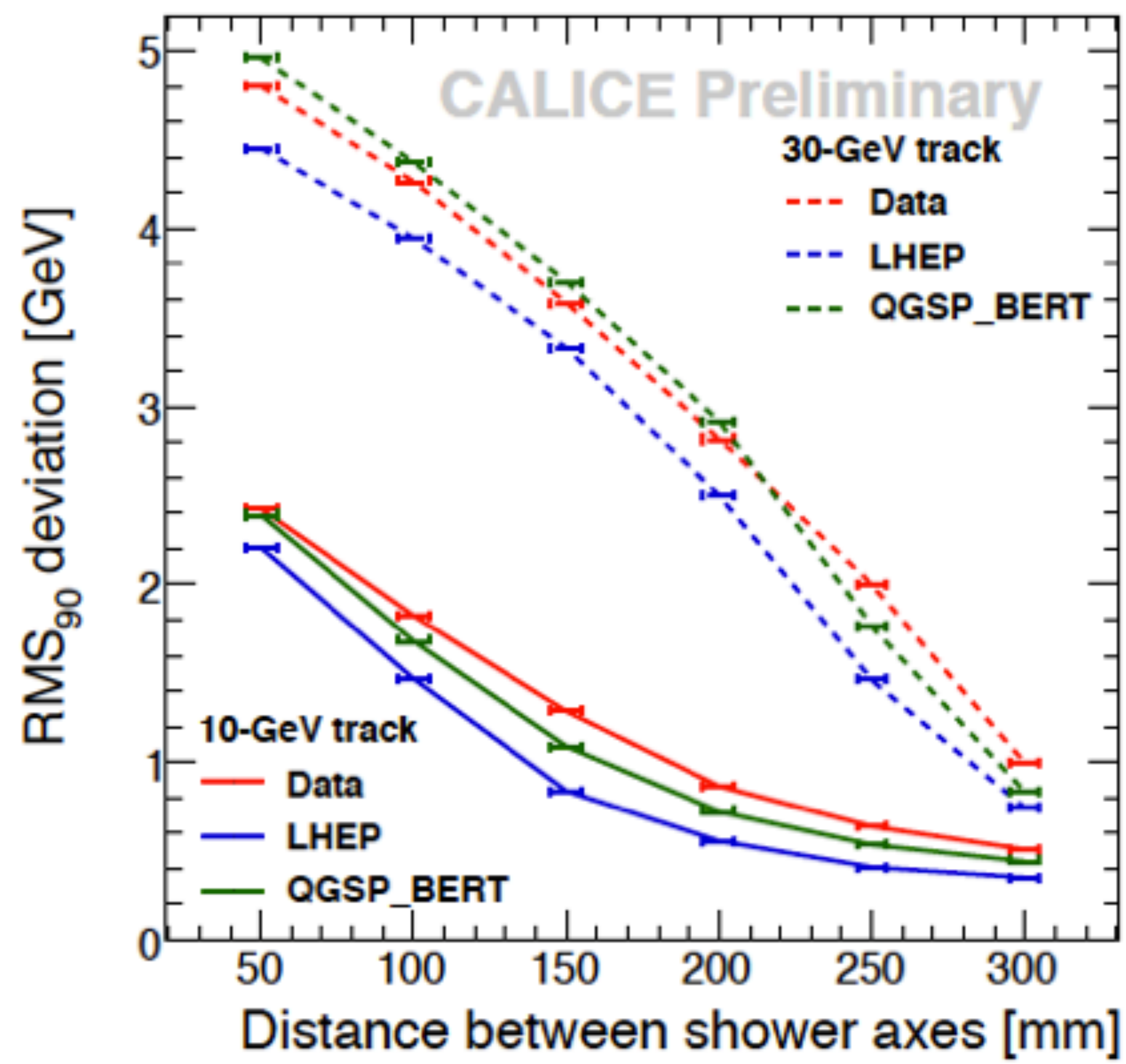
10 GeV charged hadron

30 GeV charged hadron

Shower Separation: Energy & Distance

- Energy recovery for neutral hadron close to a 10 (30) GeV track
  - ~ 15 cm distance required to provide energy association comparable to hadronic resolution of calorimeter





Summary

- Particle flow and imaging calorimeters promise excellent jet energy resolution at future colliders

- Key requirement: Highly granular calorimeters to provide separation of particles within hadronic jets

- CALICE results show that
  - The substructure of hadronic showers can be resolved in detail: Important input for Geant4 physics lists
  - Software compensation techniques using the shower information are possible
  - PFA performance already well reproduced by simulations