The CALICE
Analog Hadron Calorimeter

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CALICE
Calorimeter for ILC

TUM
LMU
Excellence Cluster
Universe

Lecture Overview

I. **The Analog Hadron Calorimeter**

- Detector Overview
- Scintillator Tiles & SiPMs
- Detector Calibration
- Electromagnetic Showers in the HCAL

II. **Understanding Hadronic Showers**

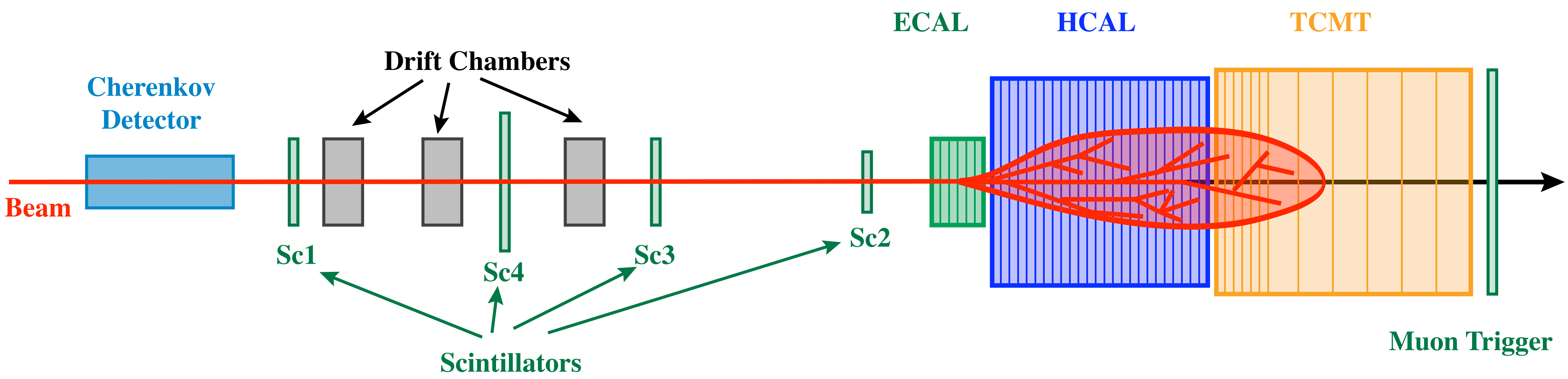
- Detector Simulations
- Shower Profiles & Shower Properties

III. **The Power of Granular Calorimeters**

- Calibration Possibilities with Hadron Data
- Shower Separation: Towards Particle Flow
- Energy Resolution, Software Compensation

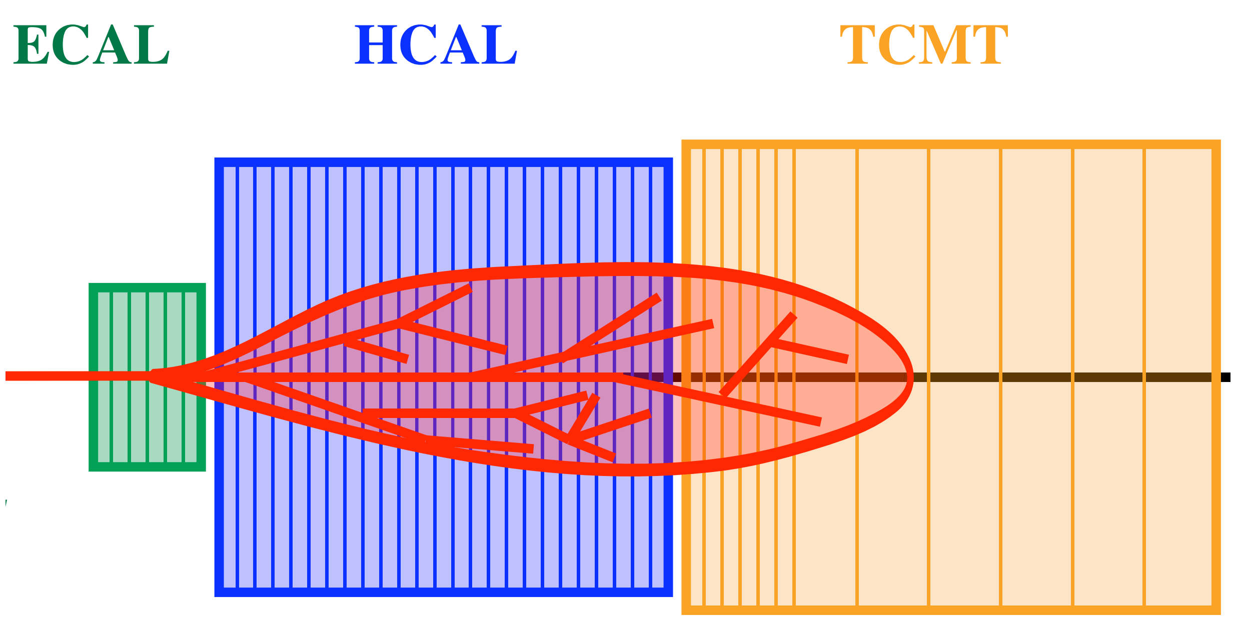
I.
The Analog Hadron Calorimeter
-
Detector Overview

The CALICE Test Beam Setup



- More or less typical test beam installation:
  - trigger detectors (scintillators)
  - tracking detectors to determine particle location (drift chambers)
  - particle identification (differential cherenkov counter)
- Global mobility: Already tests at DESY, CERN, FNAL
- Wide variety of beam energies and particle species
  - 2 GeV to 80 GeV
  - muons, $e^{\pm}$, $\pi^{\pm}$, unseparated hadrons

The CALICE Program



- Hadron Calorimeter downstream of ECAL: electrons and photons do not reach the HCAL
  - Special studies without the ECAL to test HCAL with electrons
- Tail Catcher behind HCAL to measure shower leakage, important for energy measurements

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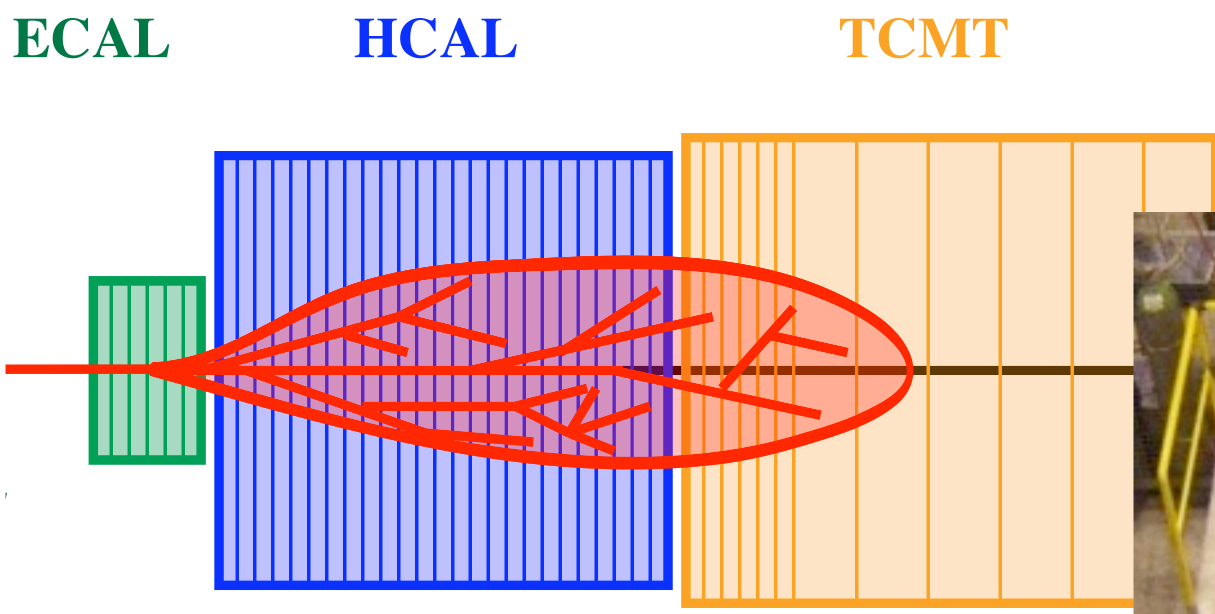

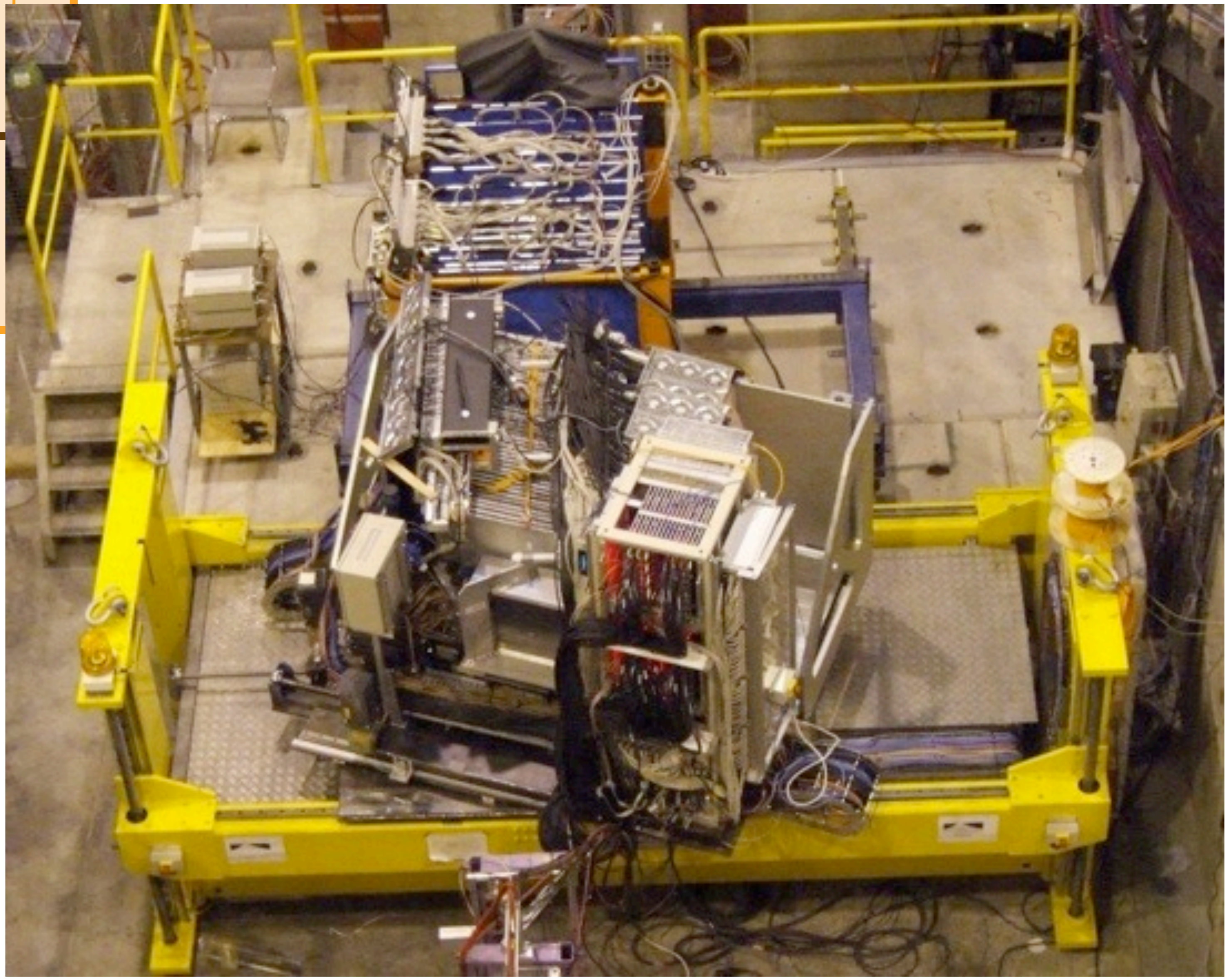

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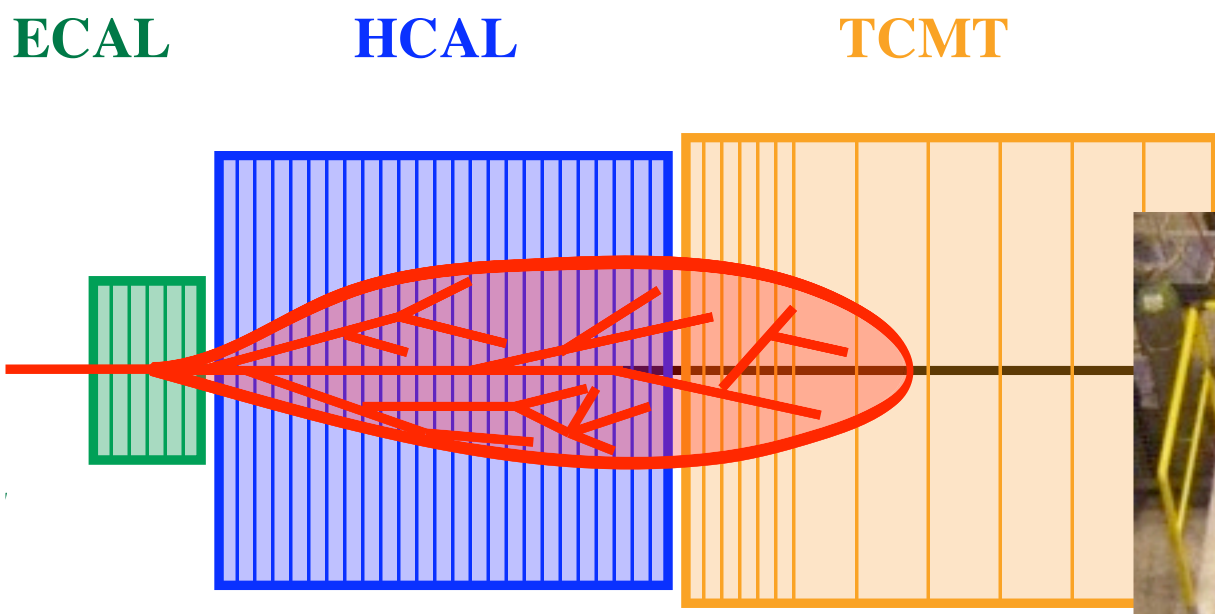

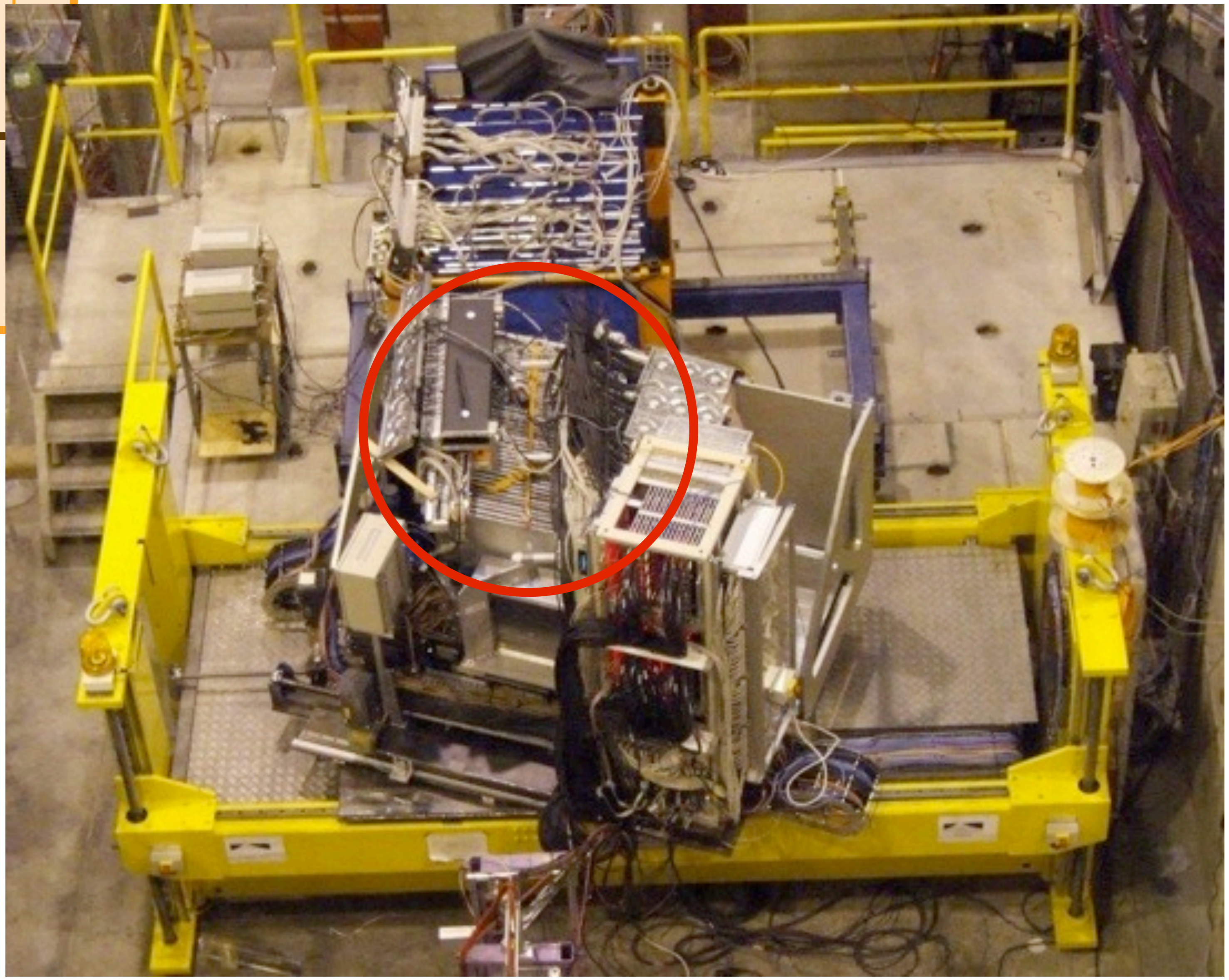

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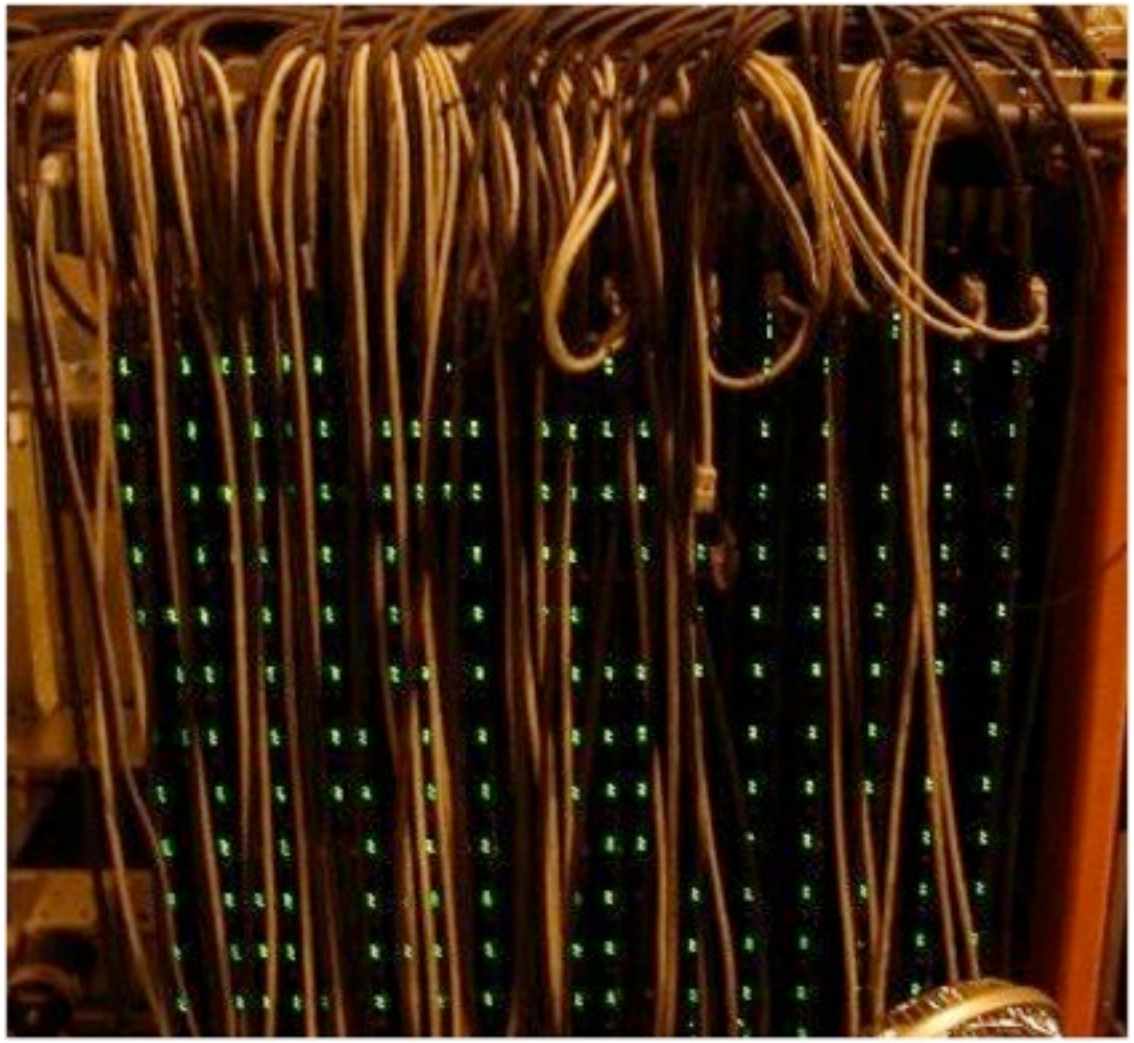
Frank Simon (frank.simon@universe-cluster.de)

The Hadron Calorimeter: Structure



- The Analog HCAL is a sampling calorimeter:
  - Active layers interleaved between absorber plates
- 38 layers, each layer has 2 cm stainless steel as absorber material (1.6 cm as a thick plate, 4 mm in the housing of the active elements): 1.1 X_0 per layer

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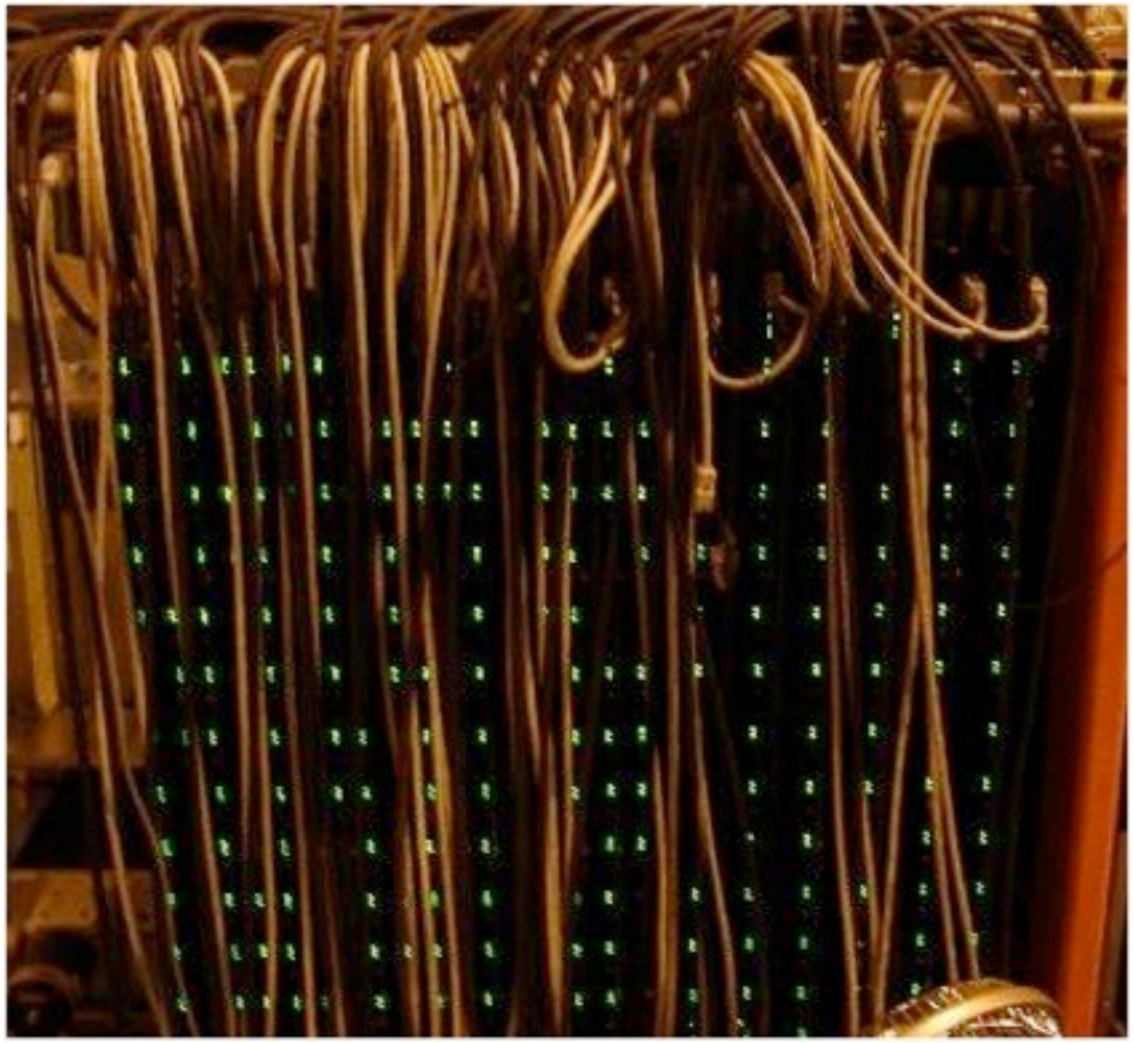

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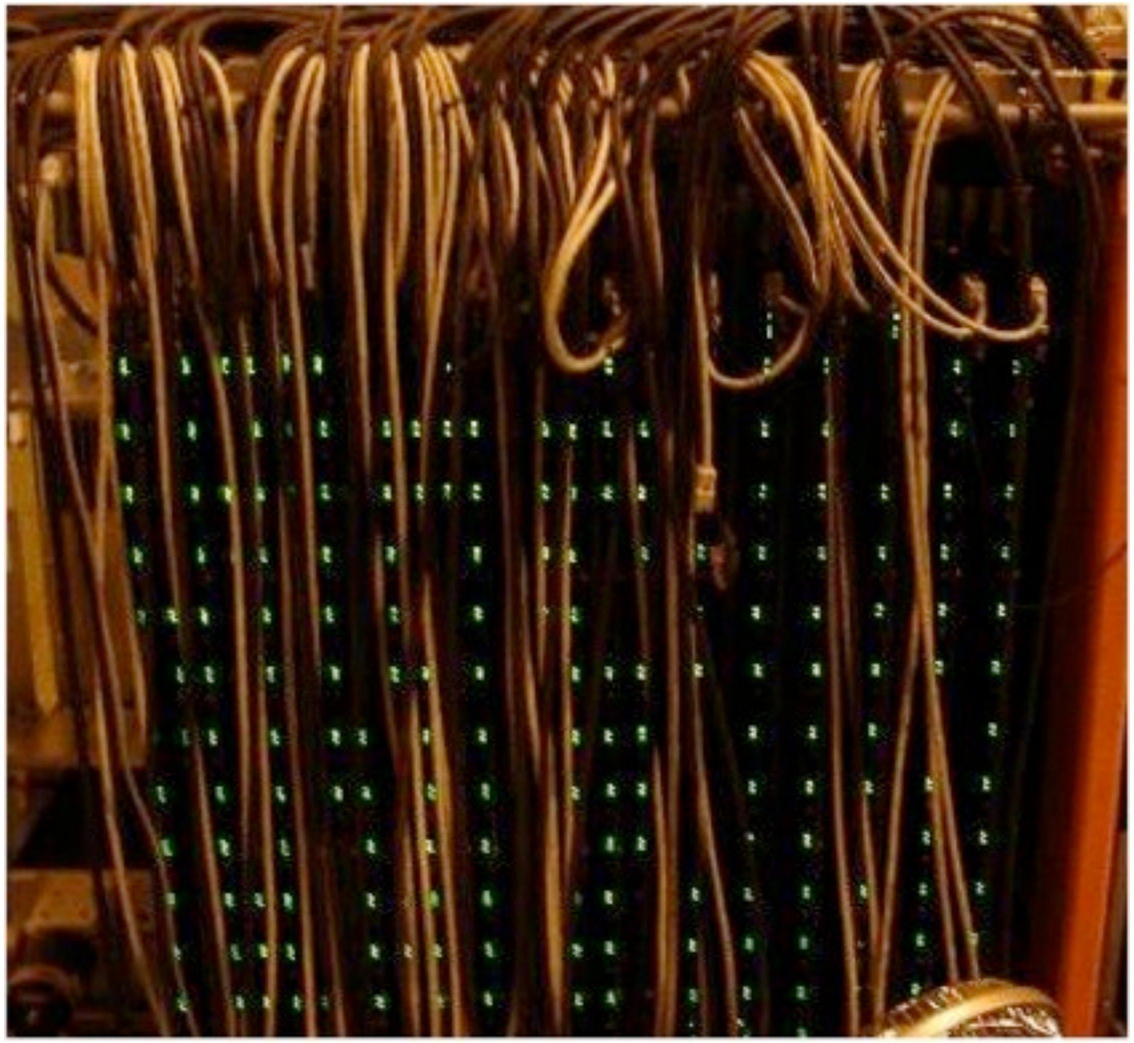

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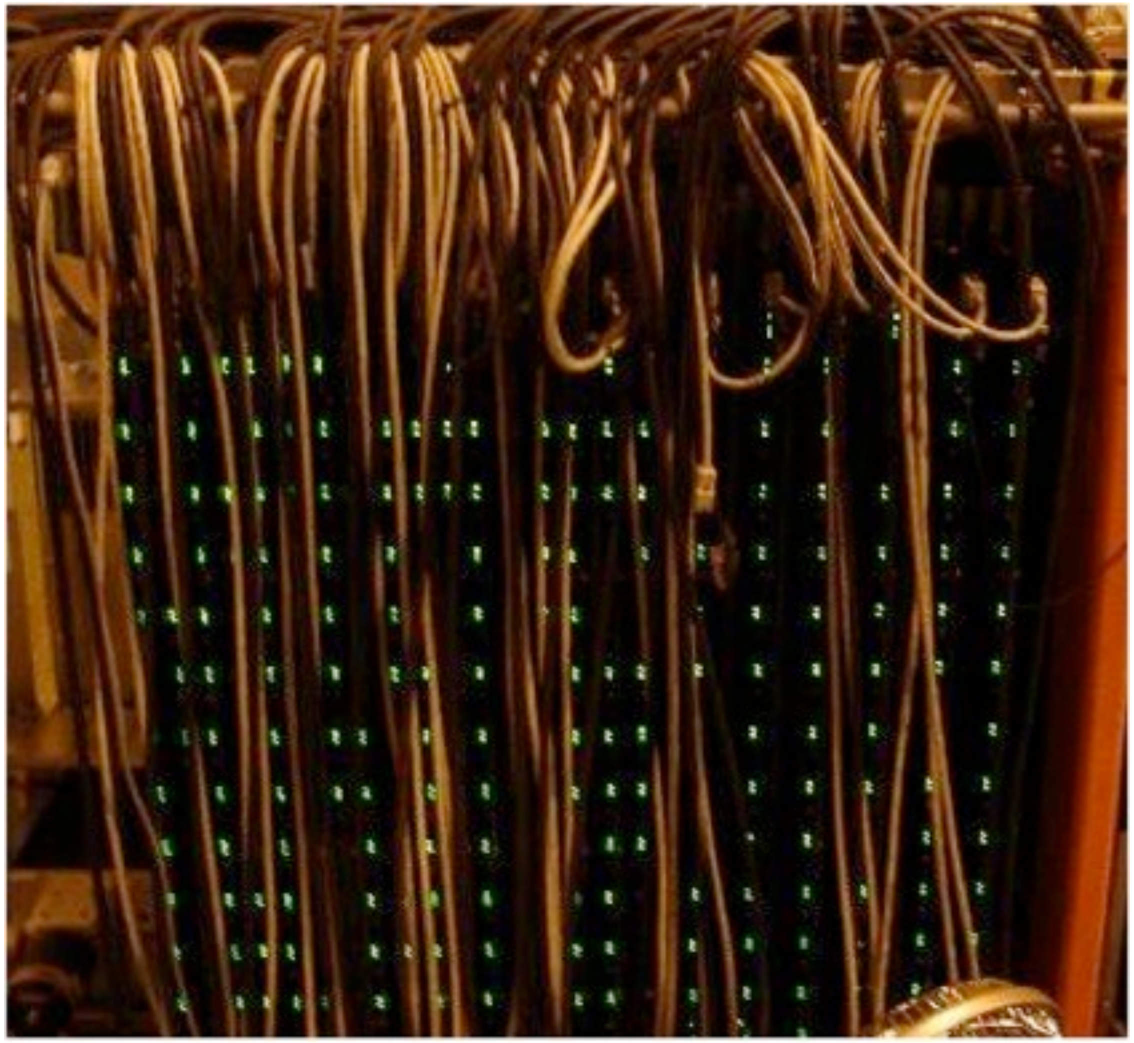

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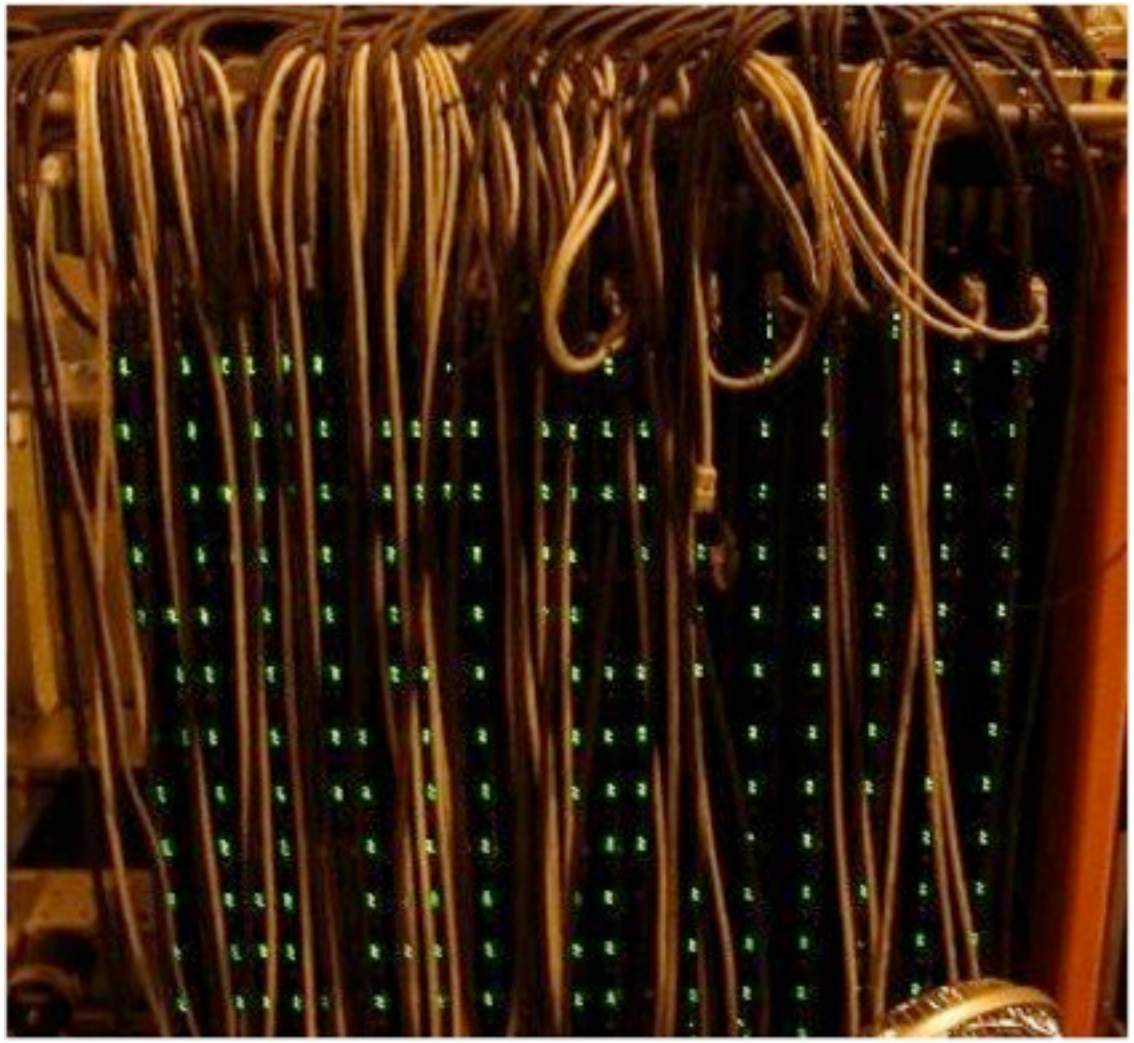

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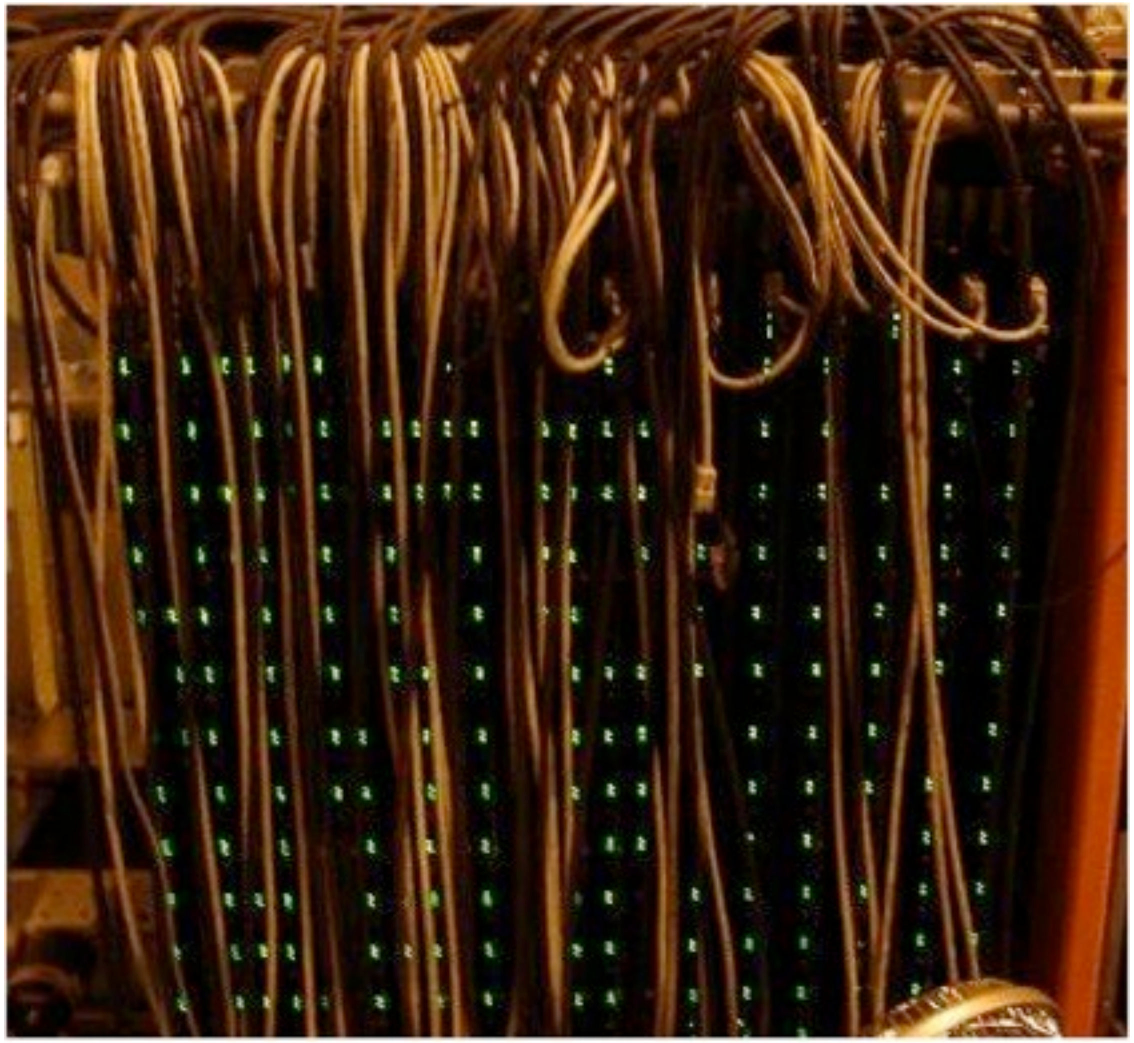

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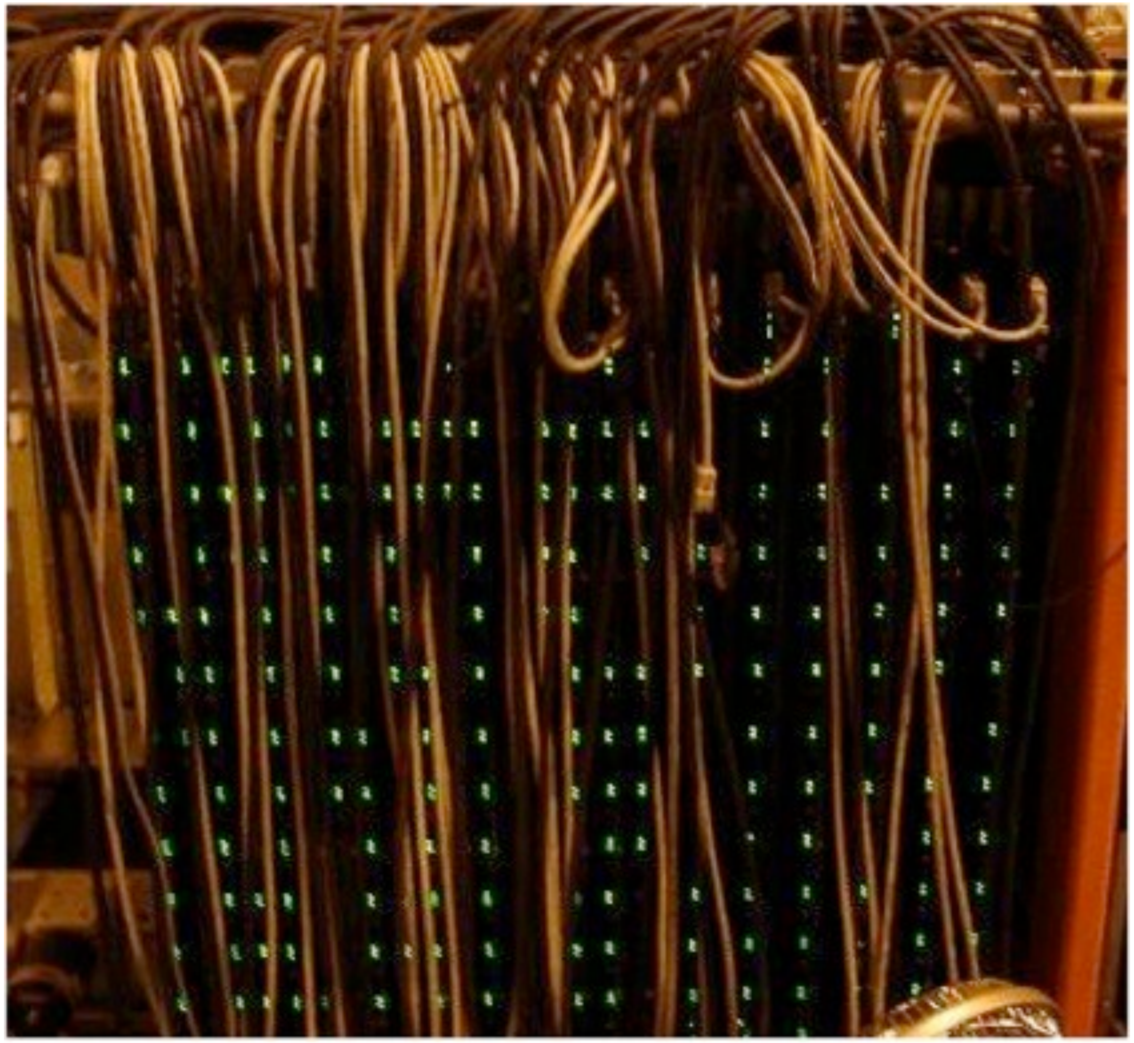

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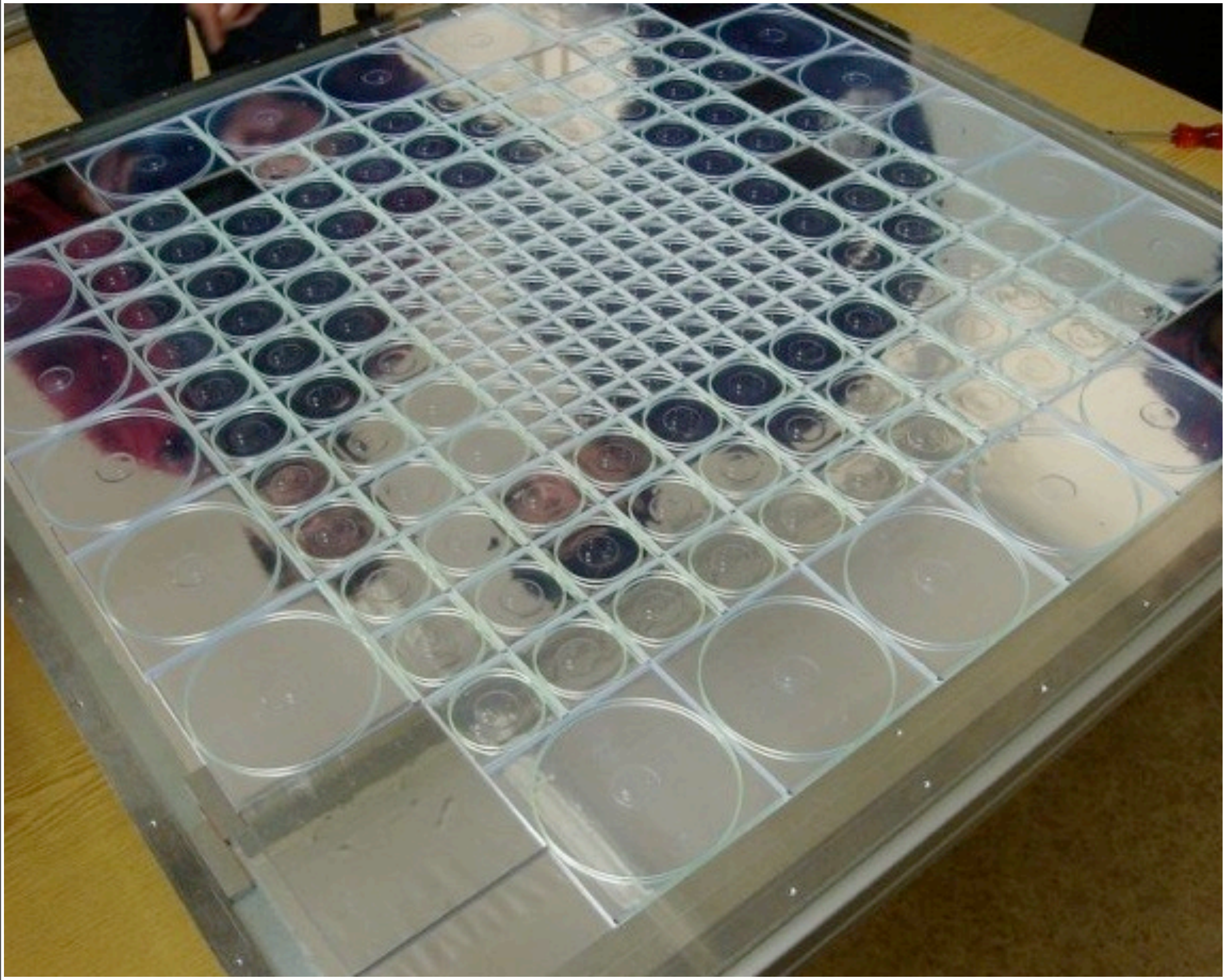
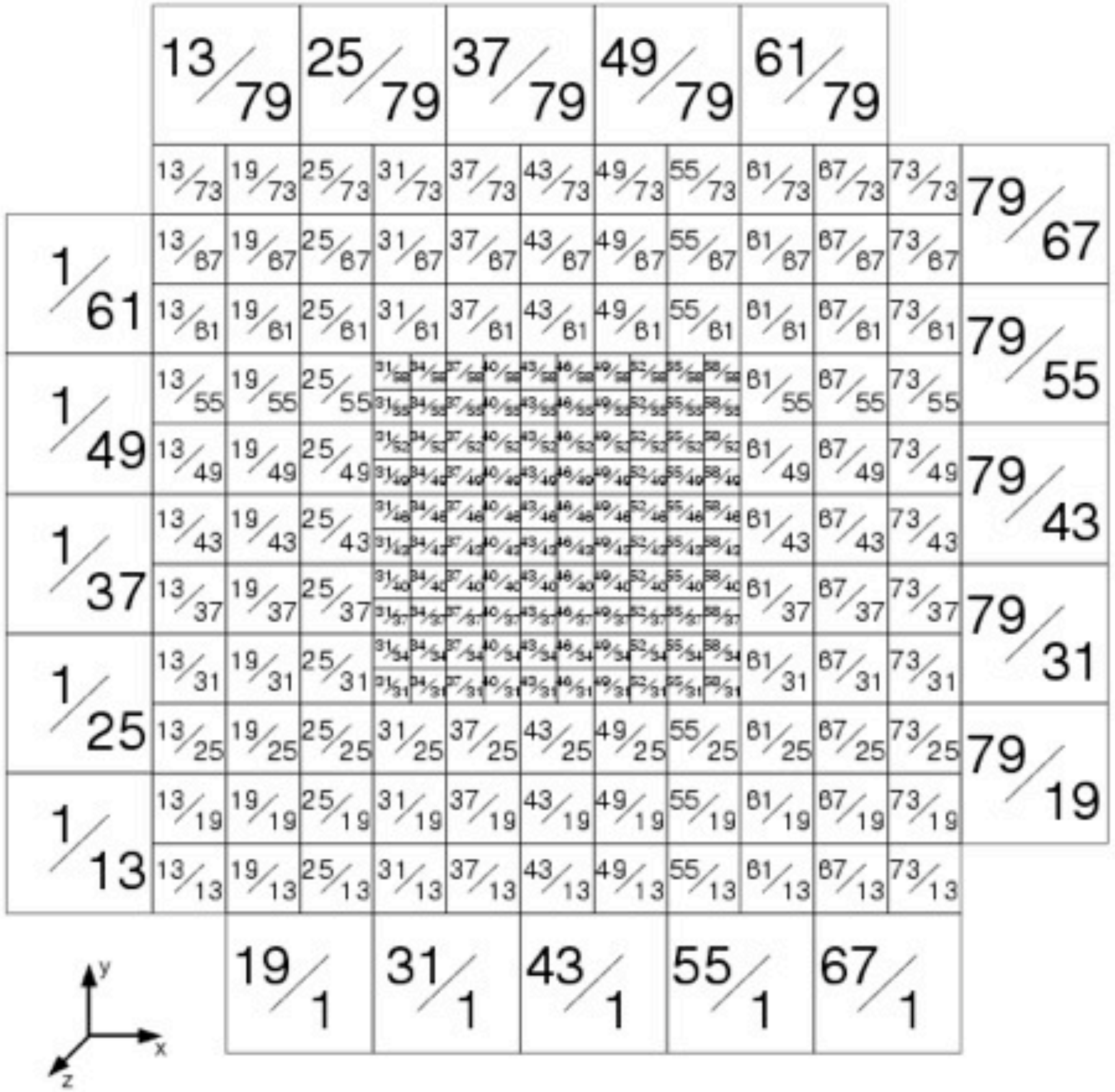
The Active Layers



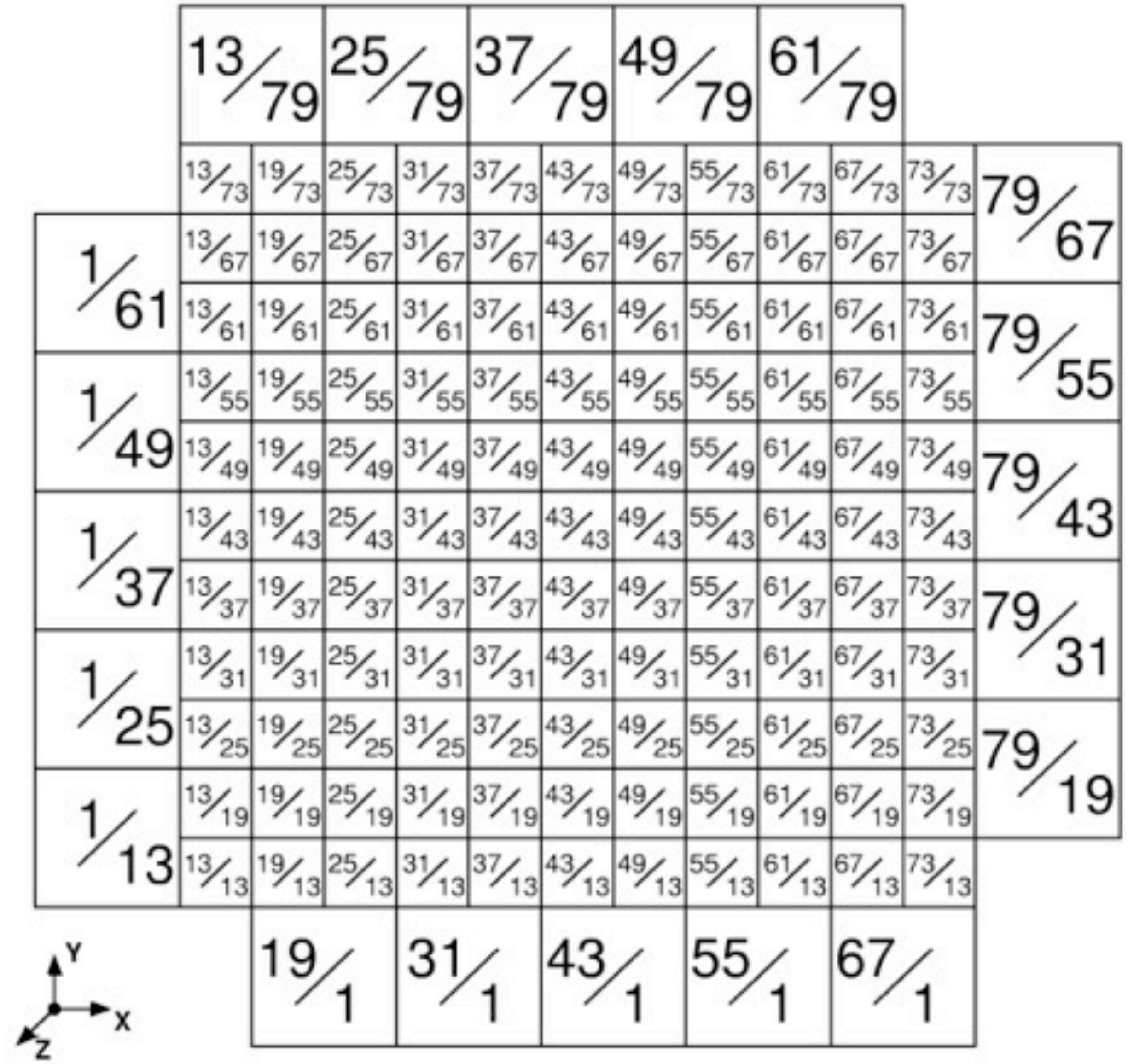
- Active detector material between absorber: Plastic scintillator, 5 mm thick
  - Particle detection via scintillation light: throughgoing charged particles excite the molecules, which then emit light
- Granular readout achieved by subdividing scintillator layers into individual cells

The Active Layers

Layers 1 - 30



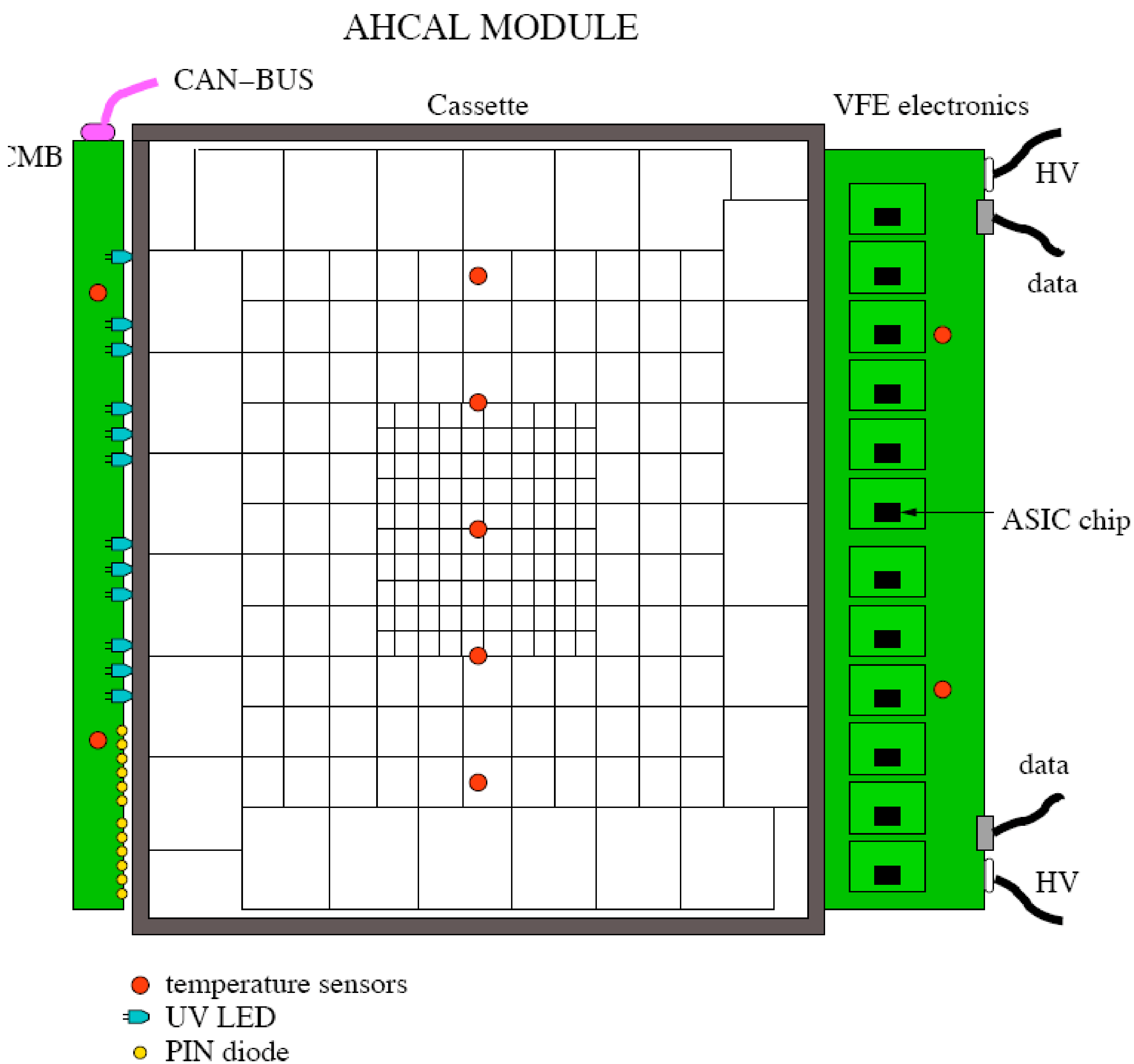
Layers 31 - 38



- Highest granularity 3 x 3 cm^2, only in the center, only for the first 30 layers: Cost reasons
- Coarser readout on the sides and in the later layers of the calorimeter

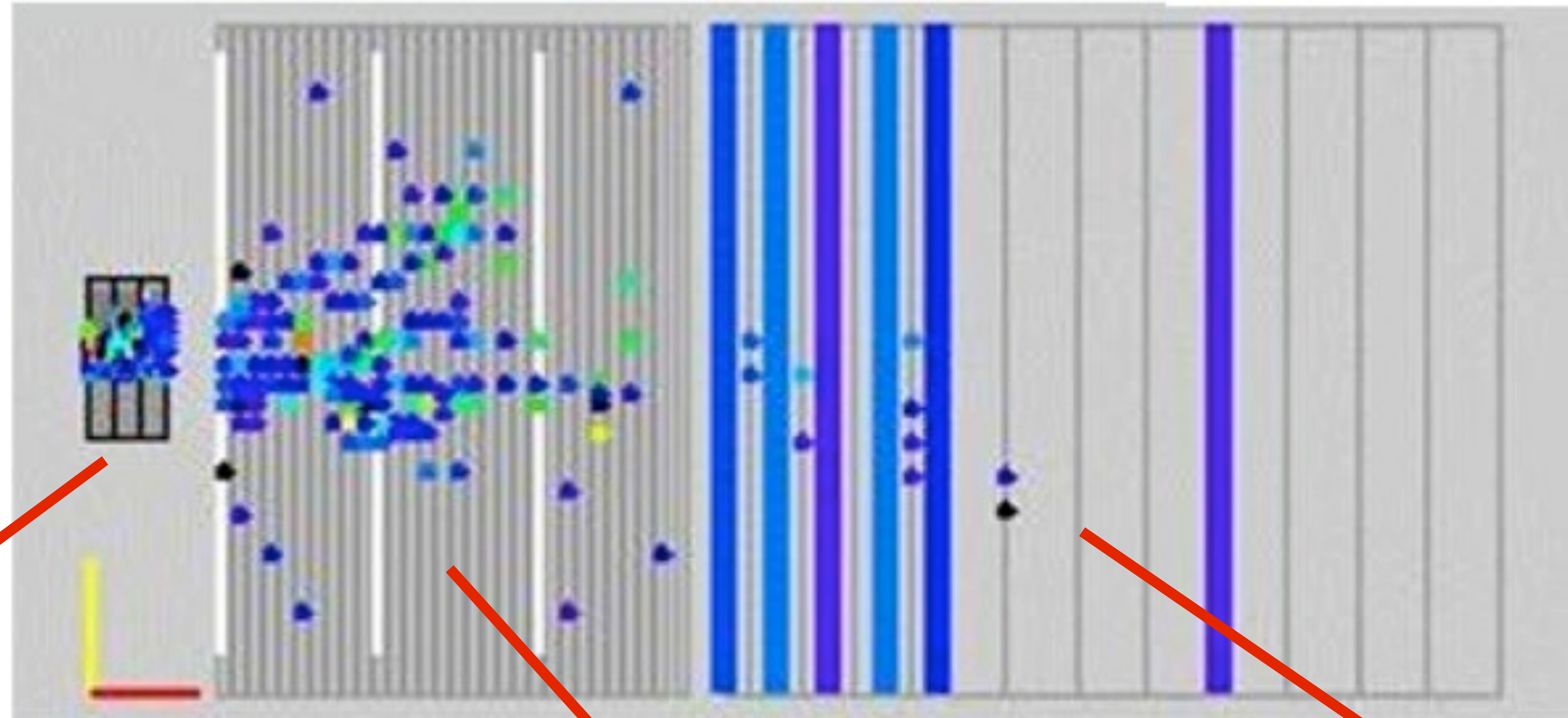
Monitoring and Calibration Tools

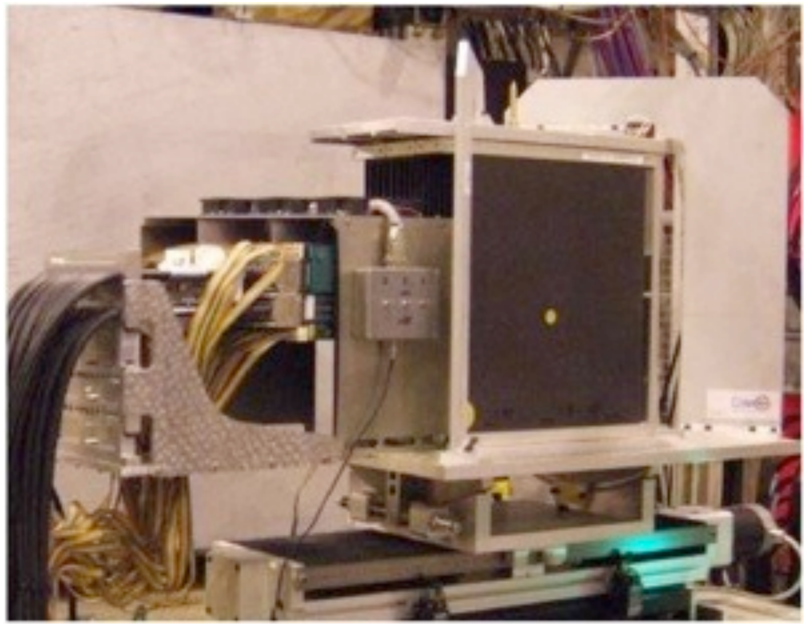
- 5 temperature sensors within the active volume of each layer
- 12 UV LEDs, the light is distributed to each scintillator cell by a clear fiber
- 12 PIN diodes to monitor the LED light intensity



CALICE Calorimeter Setup

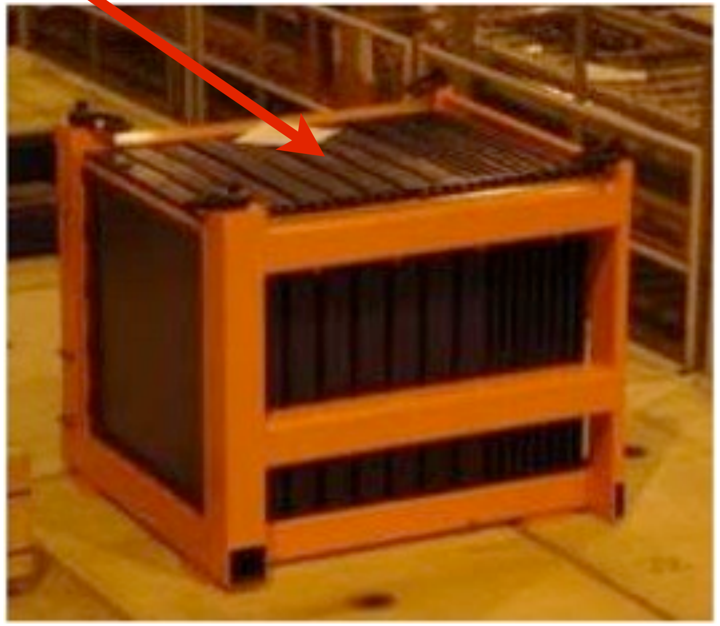
- 40 GeV negative pions





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

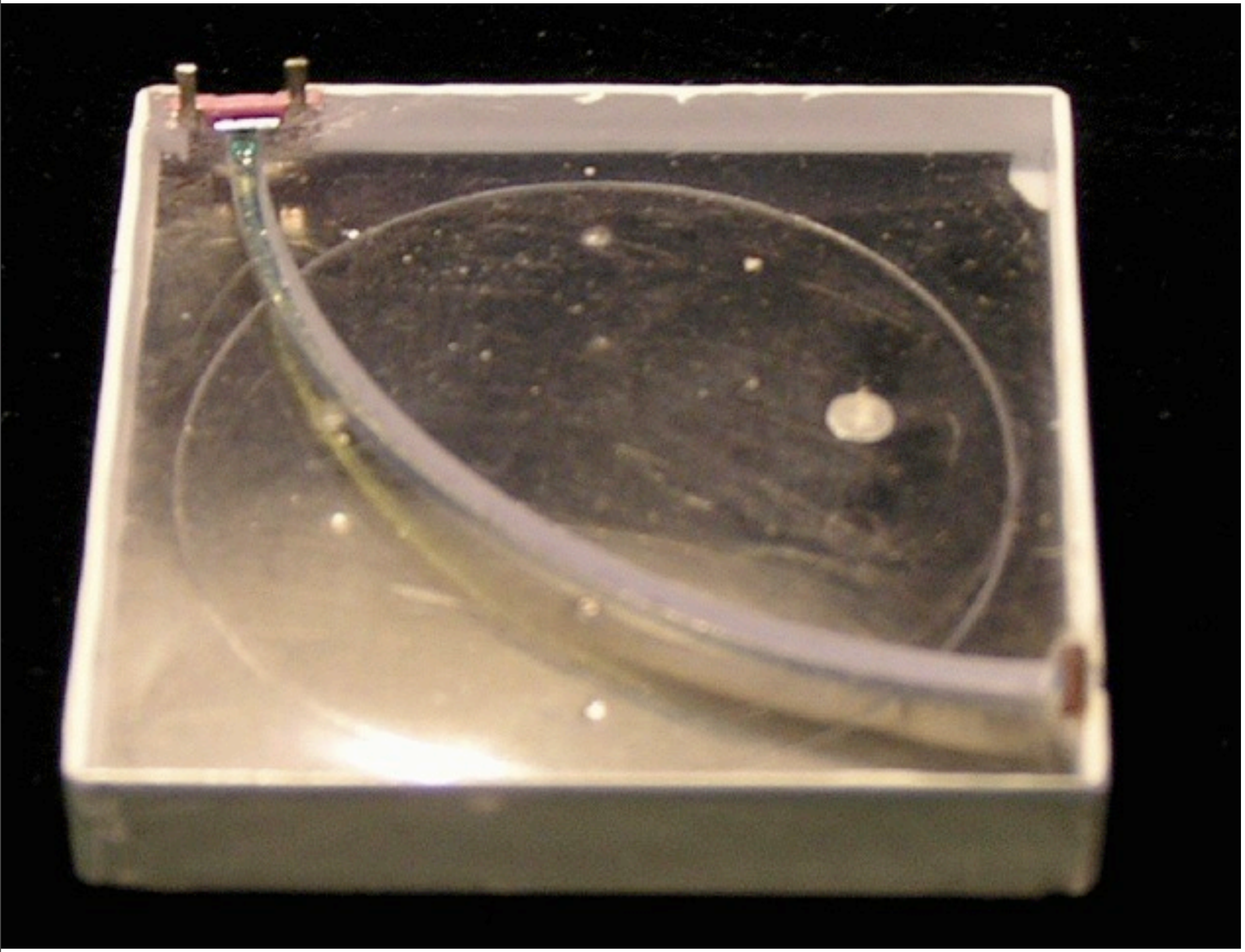
Analog HCAL
3×3 - 12×12 cm^2 lateral segmentation
38 layers, ~ 4.5 λ
~ 8 k channels



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

I.
The Analog Hadron Calorimeter
-
Scintillator Tiles & SiPMs

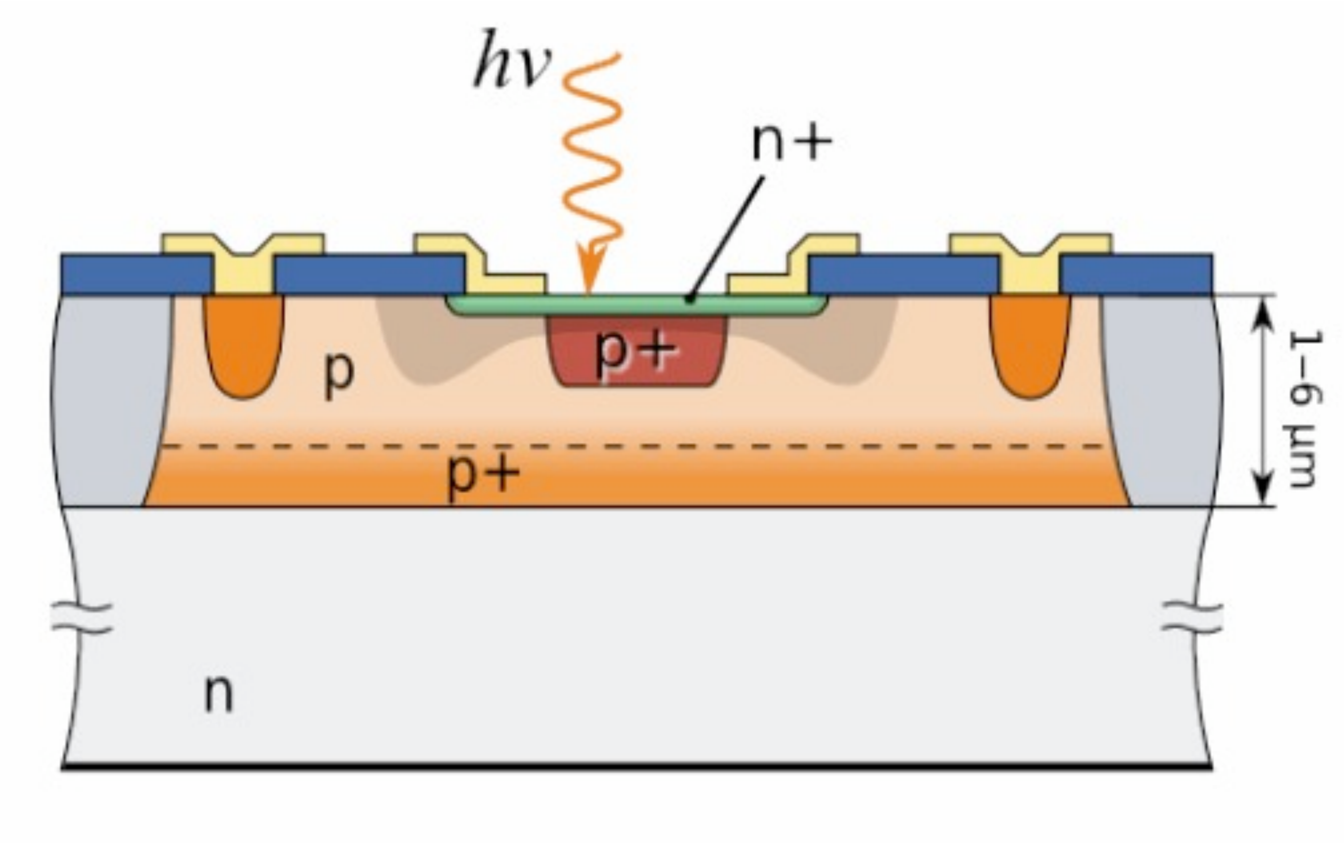
The Scintillator Cells

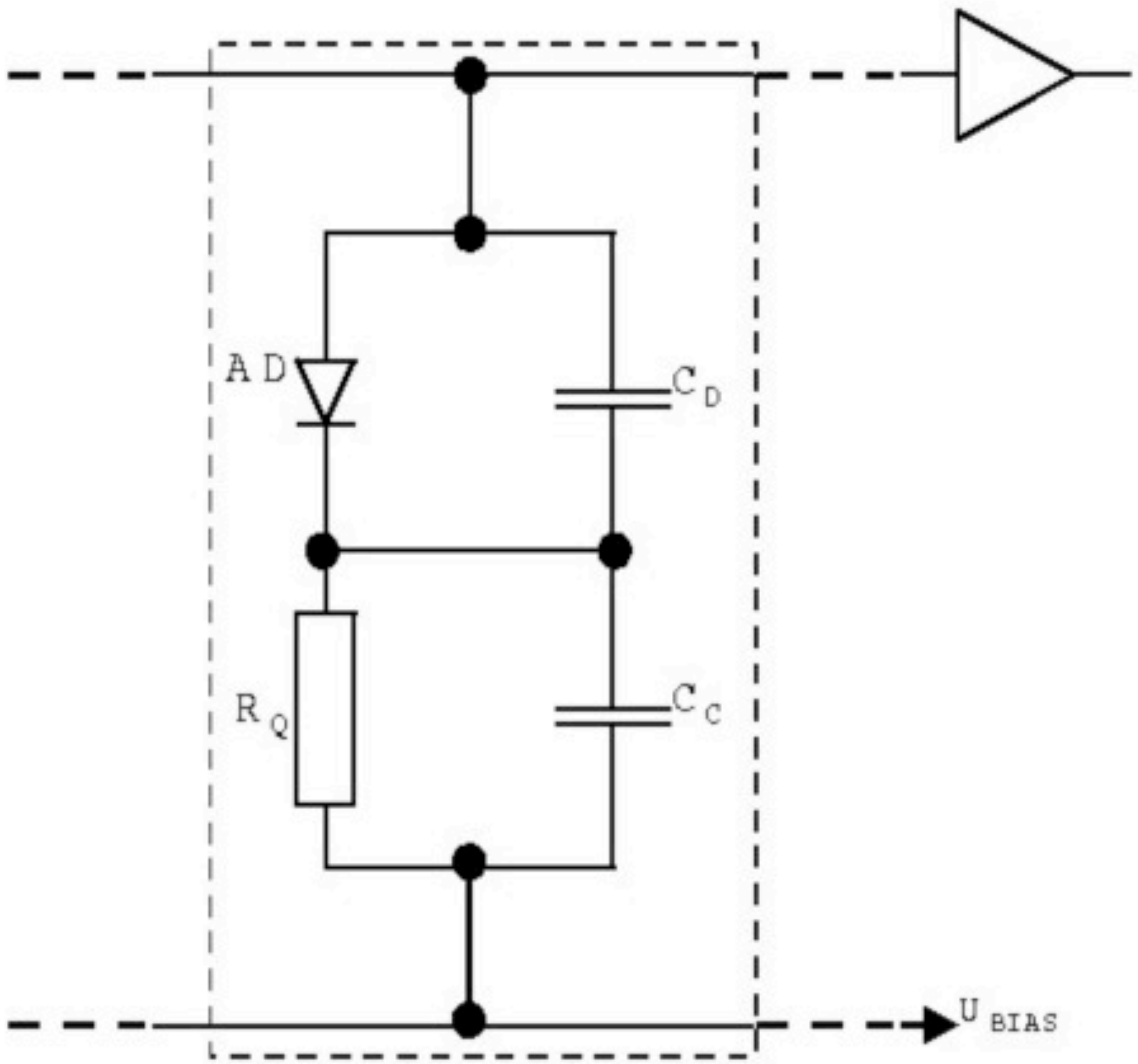


- Plastic scintillator tile, with a wavelength shifting fiber in a machined grove
- Photon detector (Silicon Photomultiplier) coupled to the WLS fiber

The Photon Detector: SiPM

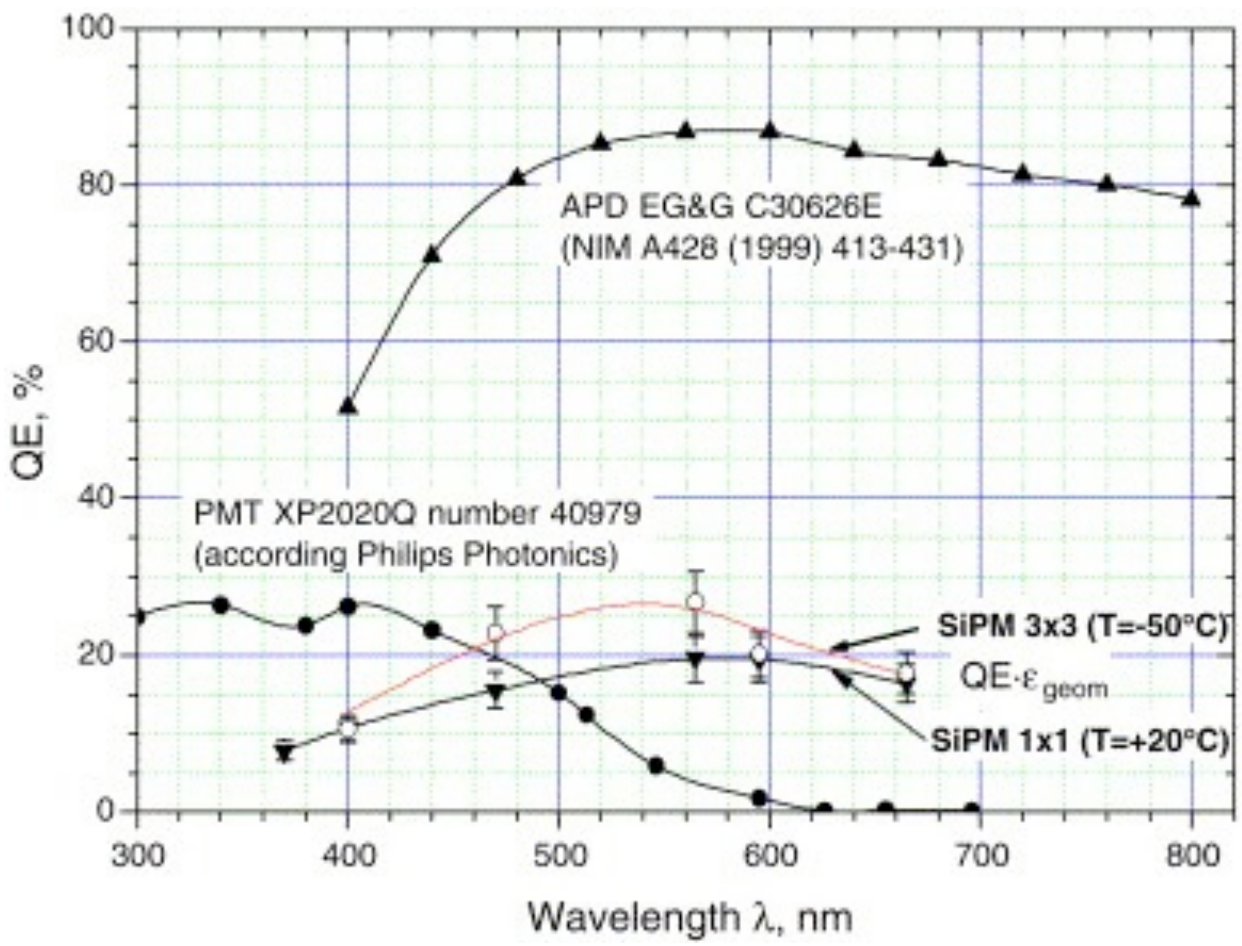
- Silicon Photomultiplier (reminder): An array of avalanche photo diodes, read out over one common line: The signal amplitude is proportional to the number of detected photons





Why the Fiber?

- First version of SiPMs are not sensitive to blue light (but the scintillation light is mostly blue!)
  - The fiber absorbs blue light and re-emits green light, which is near the maximum sensitivity of the photon sensor

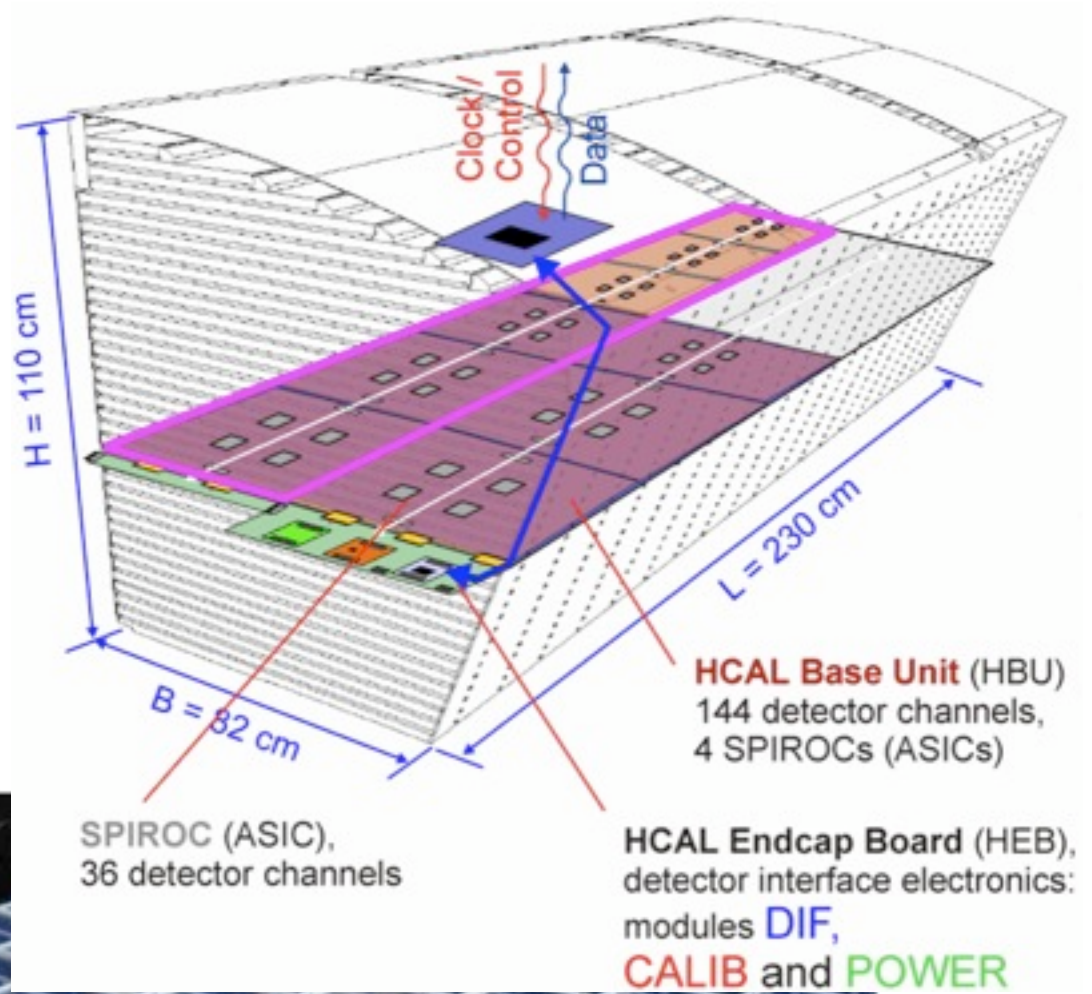


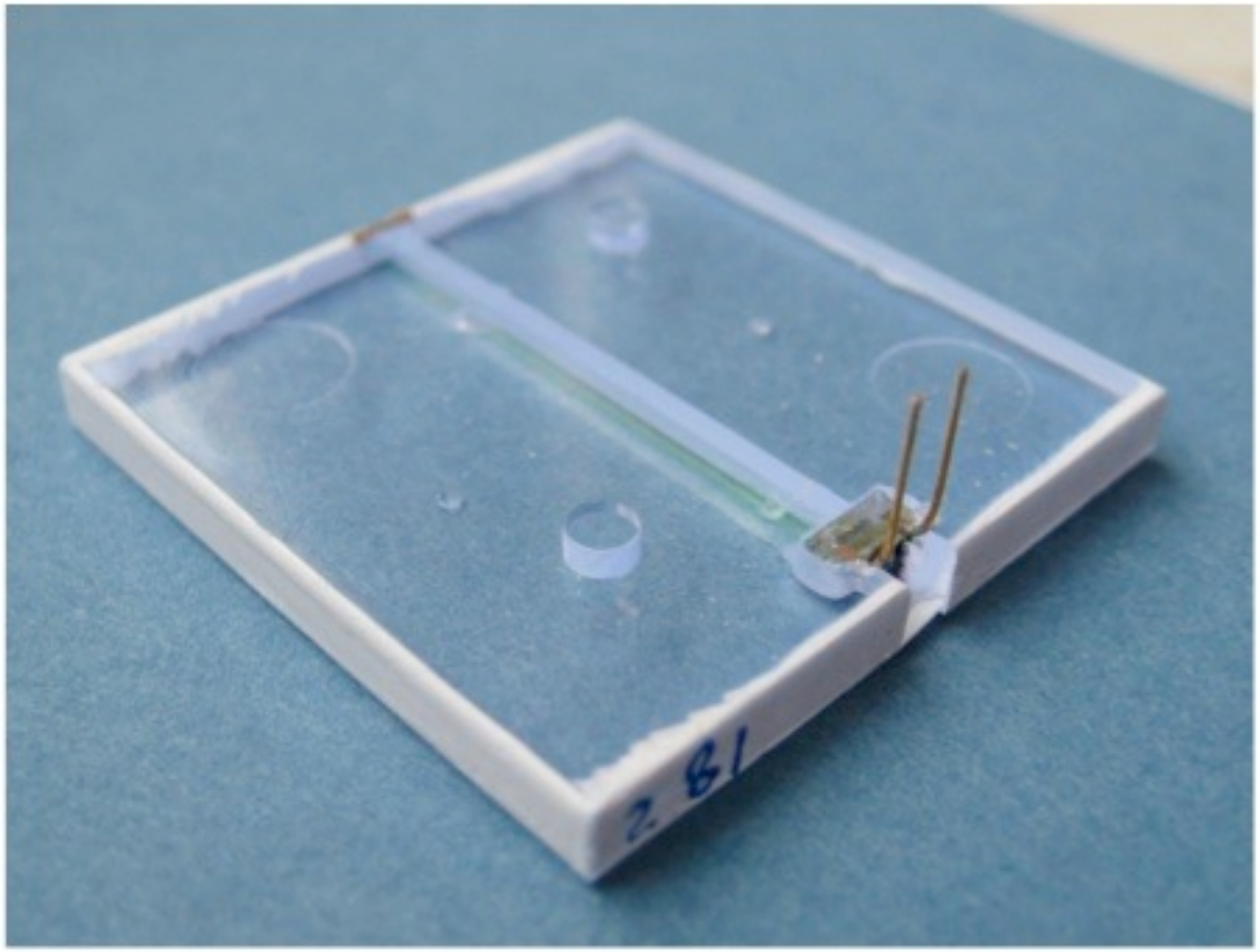
NIM A563, 368 (2006)

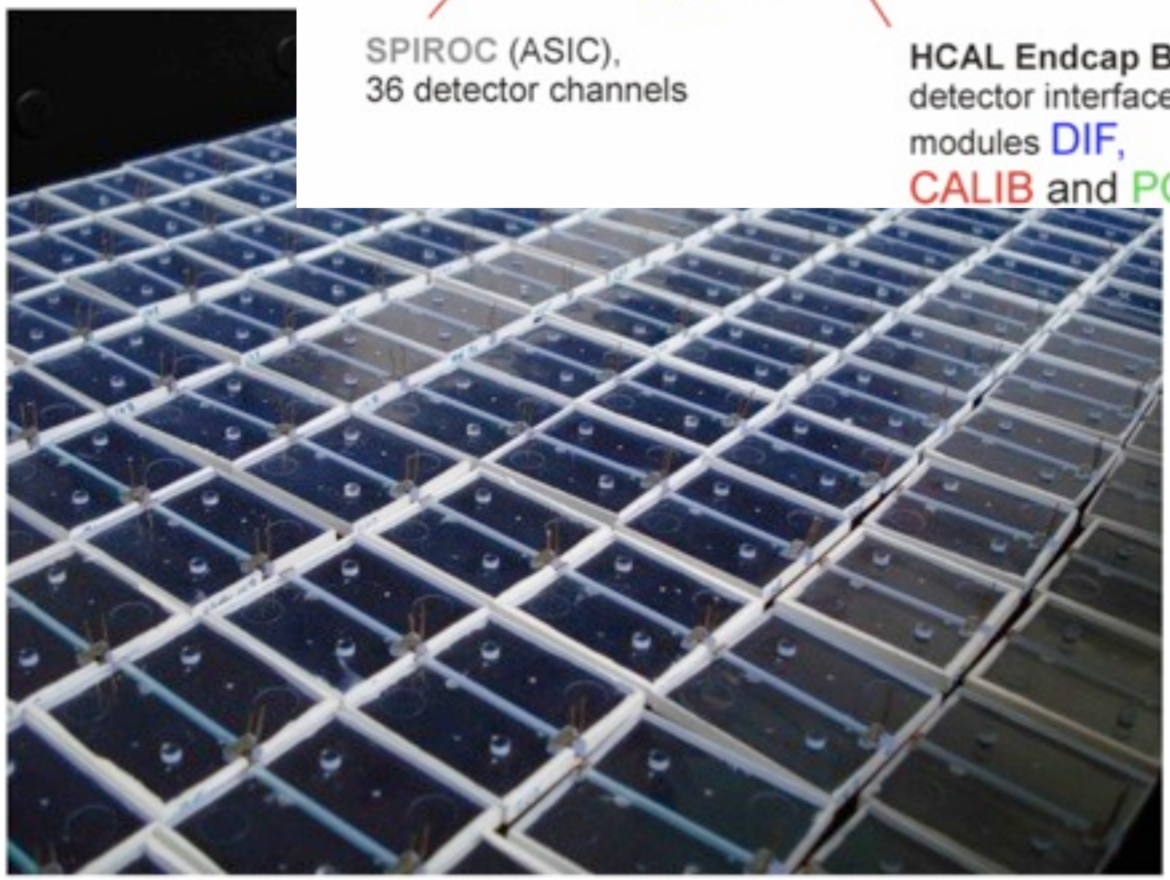
- Additional benefit:
  The fiber "collects" light in the cell, and channels it to the SiPM. Photons re-emitted in the fiber have a good chance to travel along the fiber through total reflection at the fiber surface

Next Generation Prototype

- Changes in scintillator design for the next generation prototype:
  - 3 mm thick
  - straight fiber in the tile center
  - SiPM embedded in the scintillator



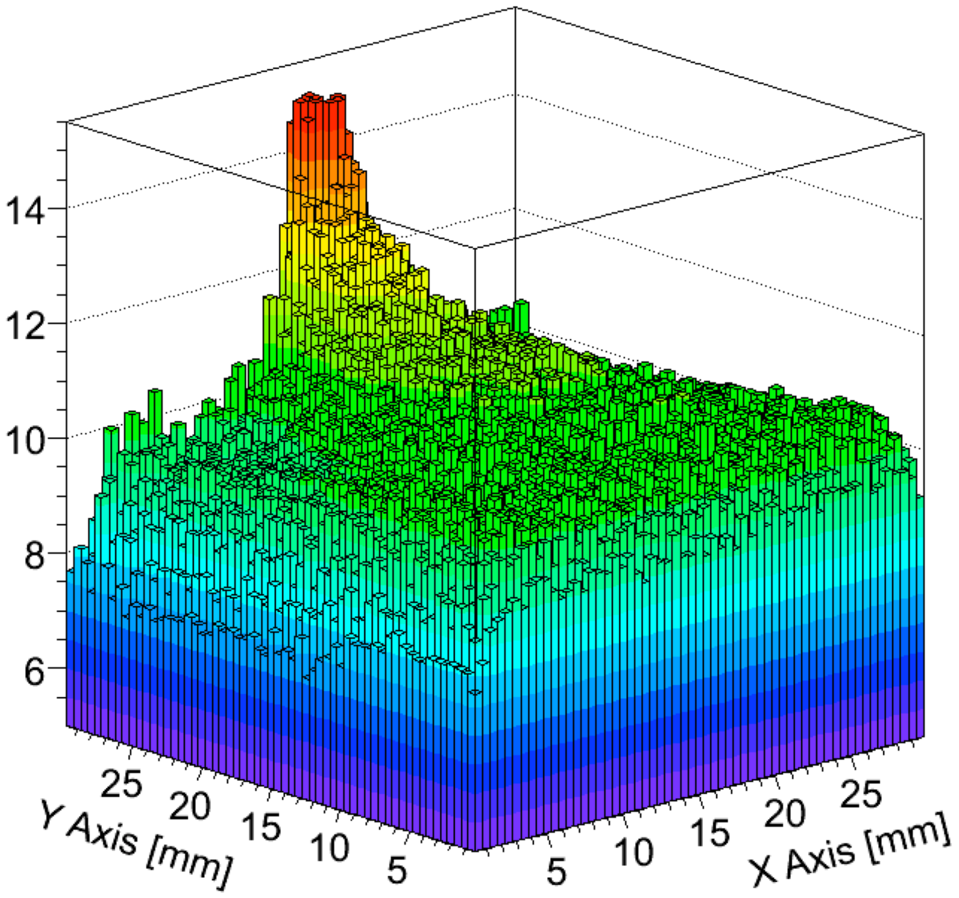




Coupling of SiPMs to Scintillator Tiles: New Ideas

- Can it work without a fiber?
  - Put the SiPM directly on the side (or below) the scintillator: direct coupling

The problem: Very non-uniform signal across the surface of the scintillator tile



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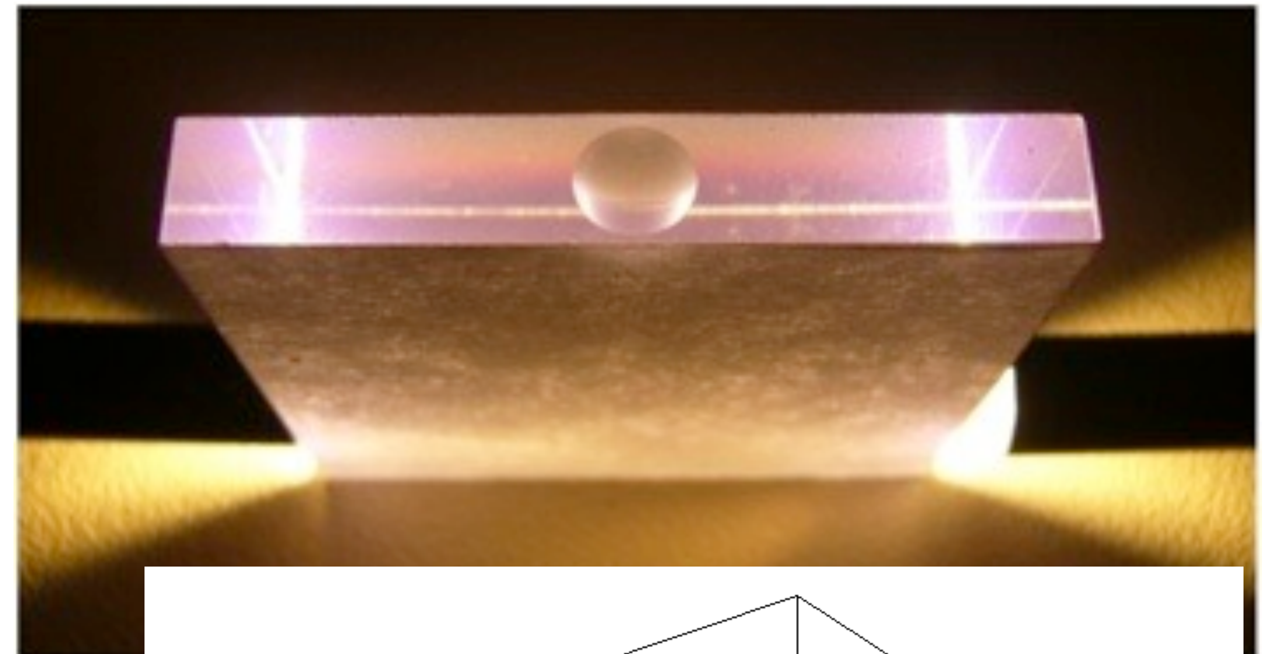

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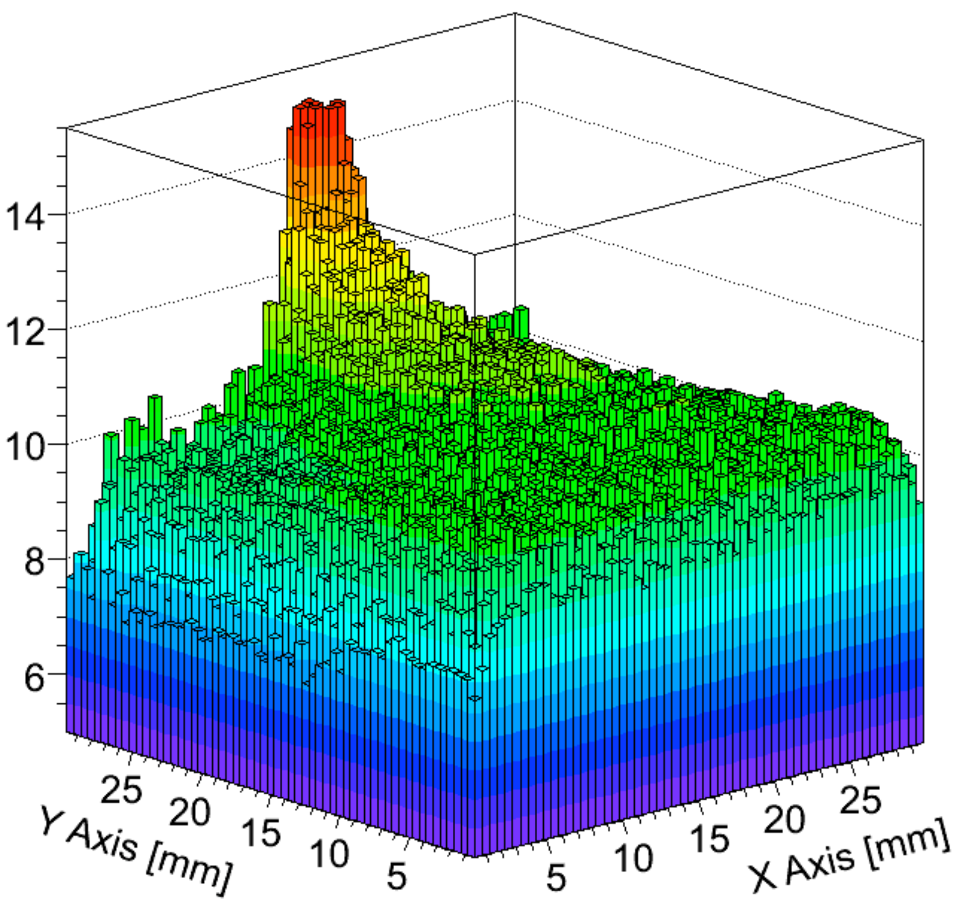
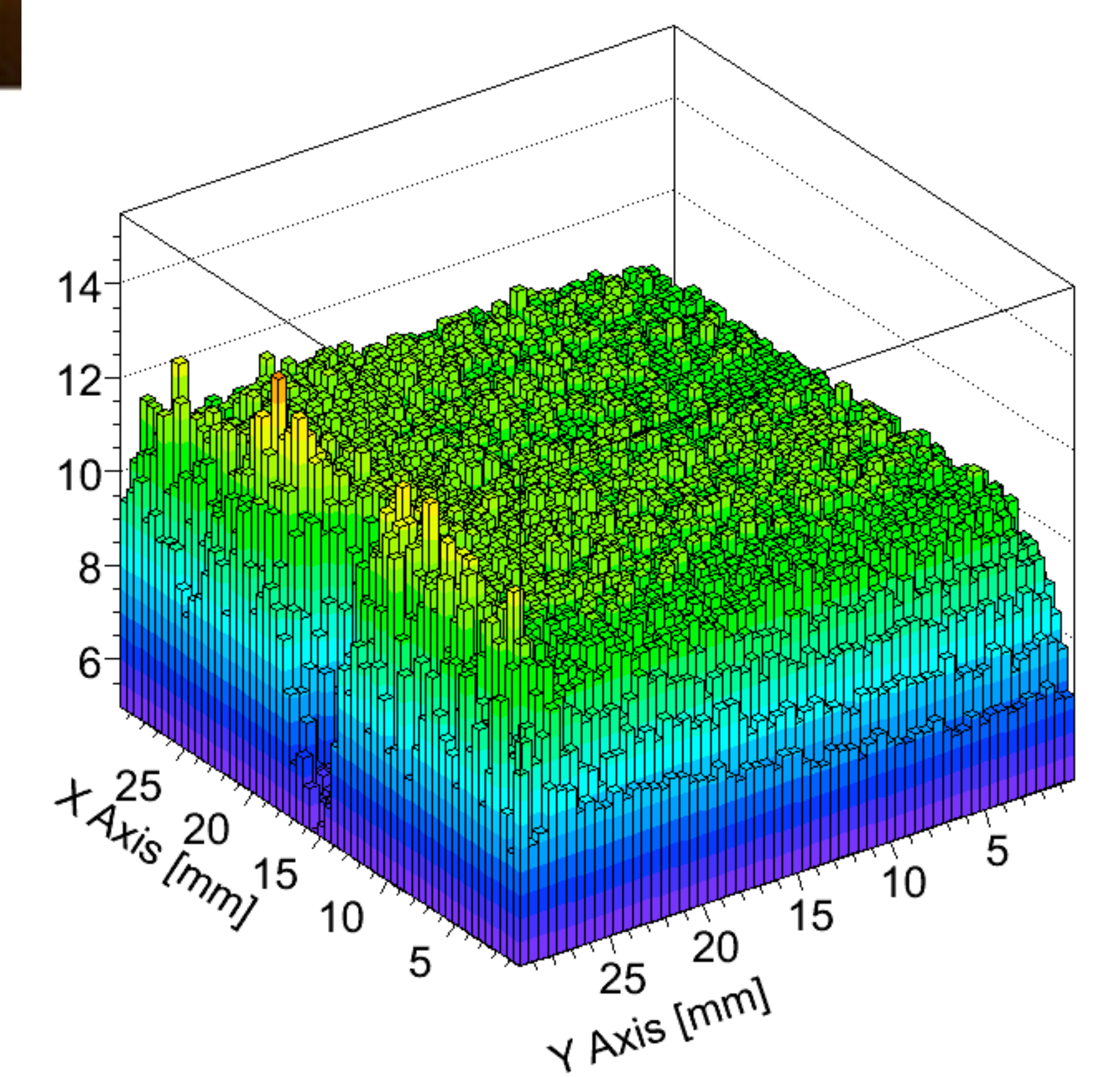


Putting a “dimple” on the side of the tile helps a lot!

A “dimple” underneath the tile, with the SiPM below also has the same good effect (studied in the US at NIU)



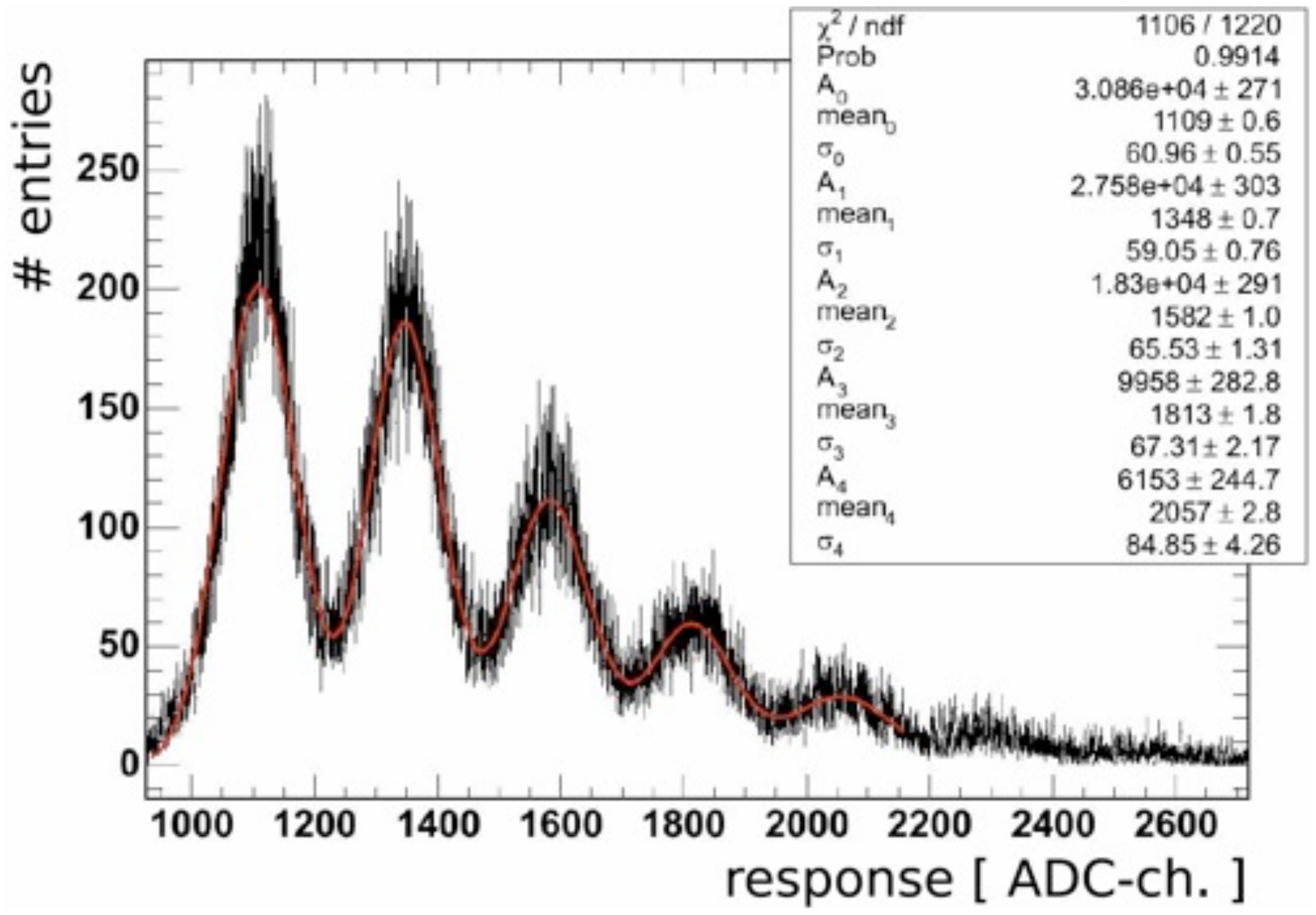
I.
The Analog Hadron Calorimeter
-
Detector Calibration, Measuring the Energy

What does Calibration mean?

- Several calibration steps:
  - Understanding the photosensor
    - Gain calibration, temperature effects,...
  - Cell-by-cell calibration
    - response to particles, includes light yield, coupling effects,...
  - Energy Calibration

Photon Sensor: Calibration

- Auto-calibration of SiPM gain: Individual photons can be resolved
  - Low-intensity LED light coupled into each detector cell
  - high gain setting of front-end electronics



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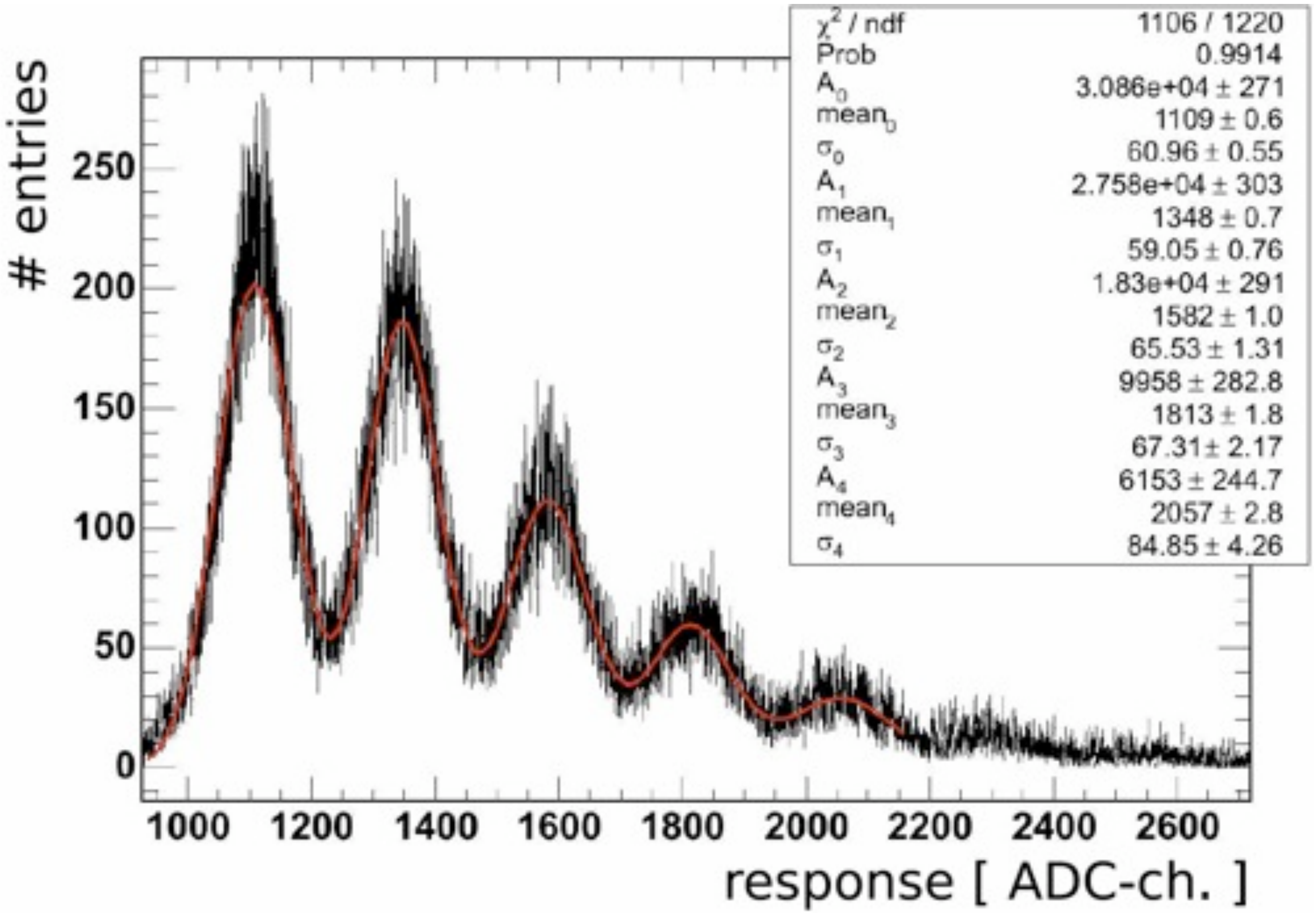

How do you get the gain of the SiPM out of a plot like that?

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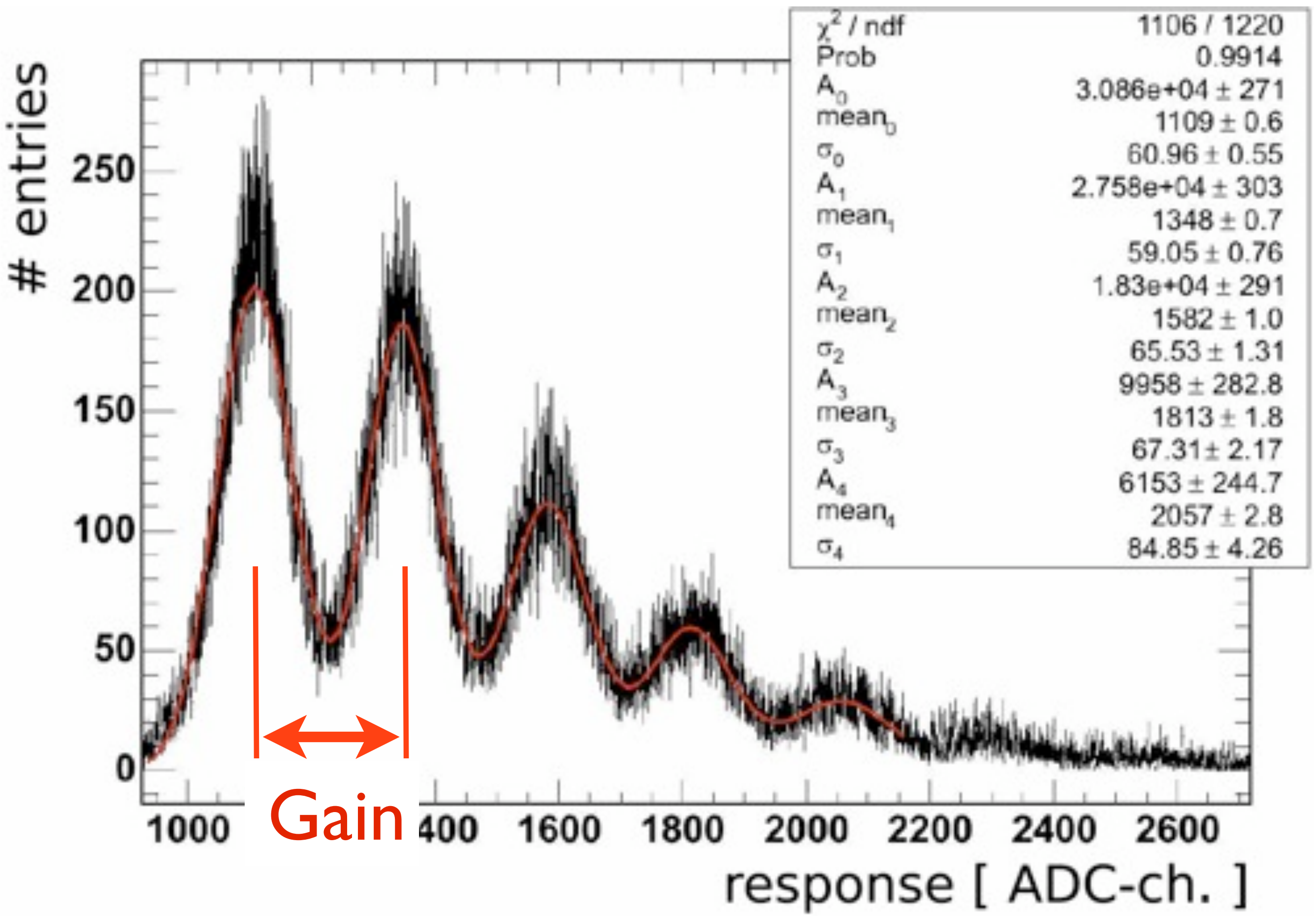

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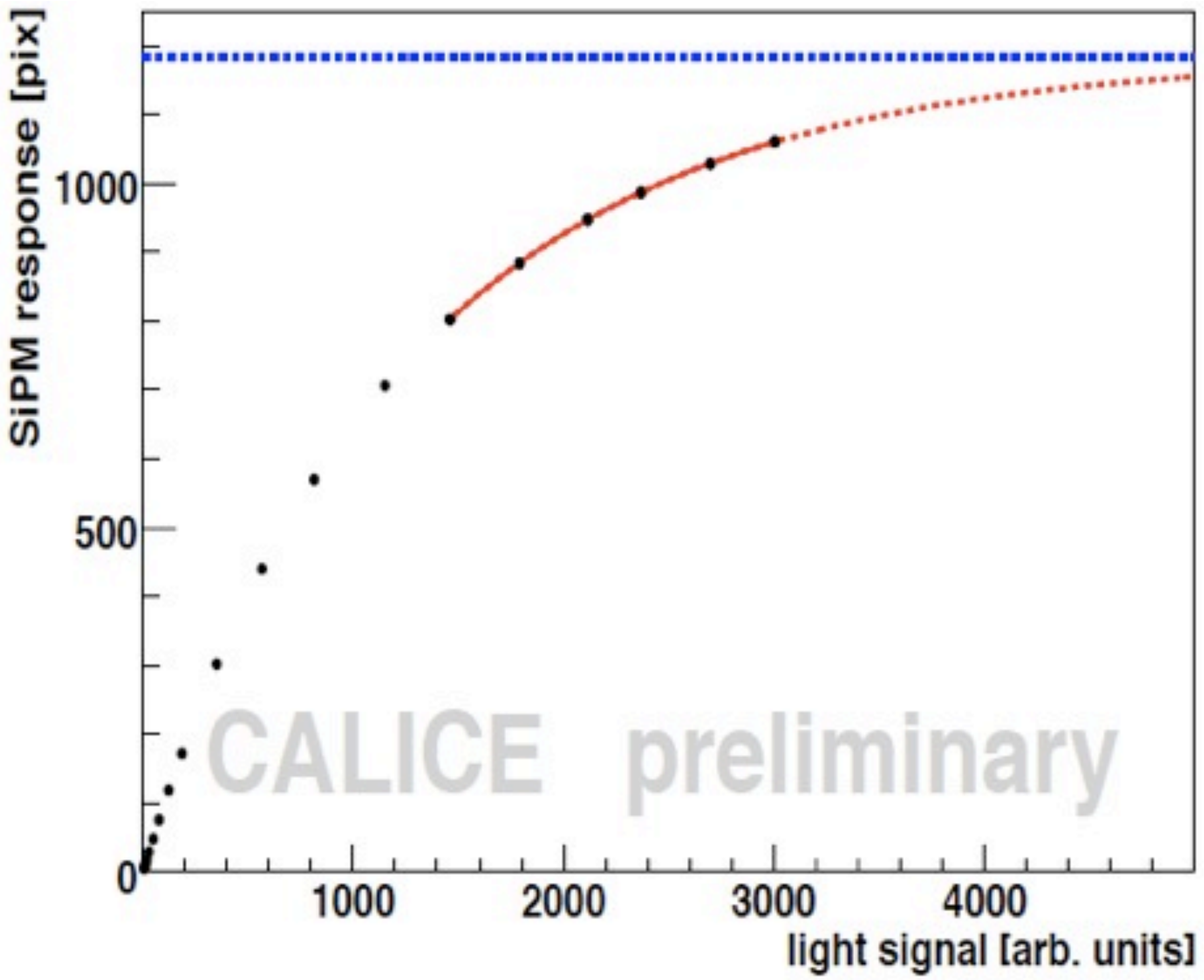
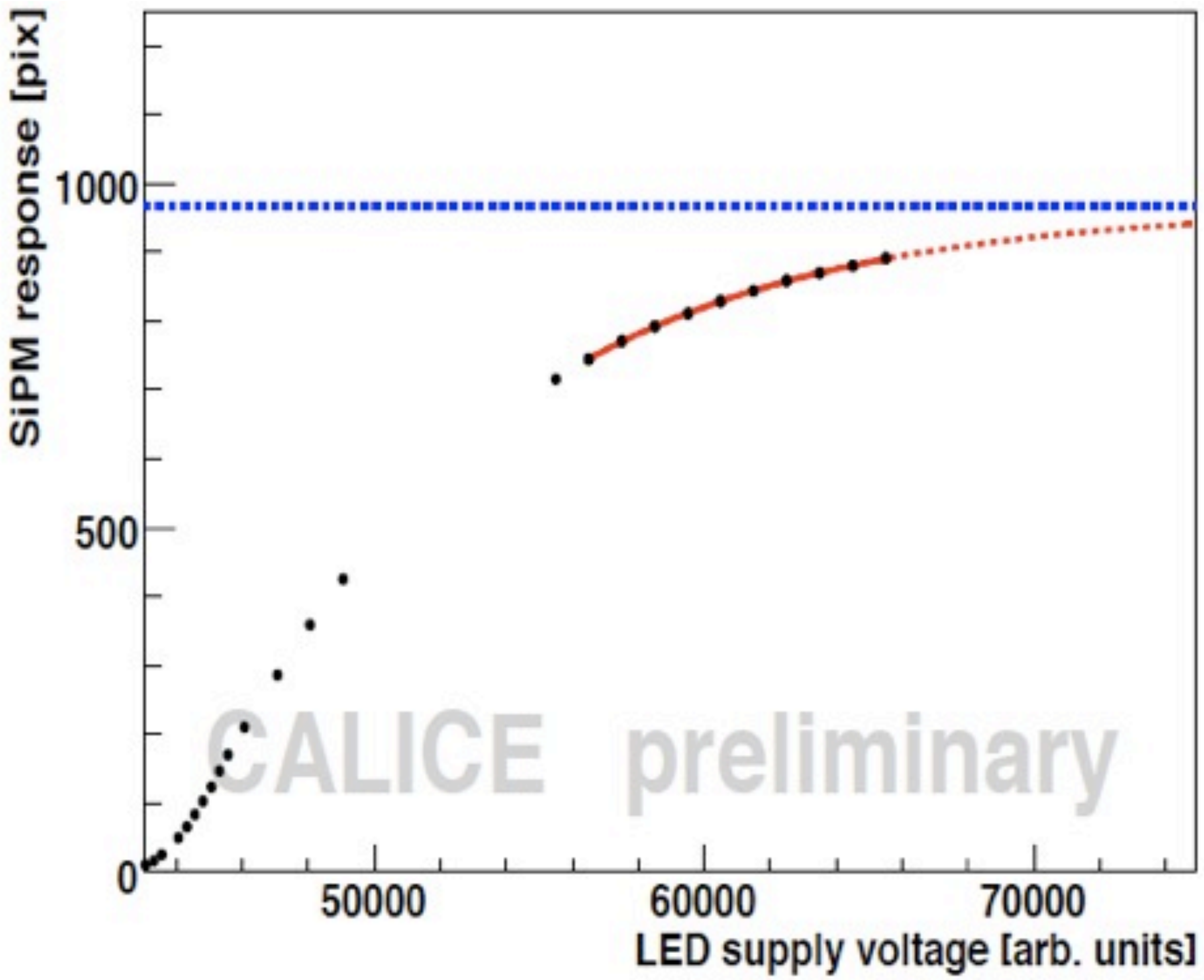
Signal Saturation

- A crucial feature: A SiPM has a fixed (and finite!) number of pixels, it can only count a limited number of Photons: For the HCAL 1158 pixels
  - Photons hit cells at random, so even for less photons there is a certain probability that a cell has already been hit and will not count a second time





This saturation effect has to be taken into account in the data reconstruction!

Cell-by-Cell Calibration

- In addition to the calibration of the photo-sensor: Calibration of each detector cell:
  - What is the response of the complete cell (scintillator + SiPM) to through-going particles?
  - Includes the coupling of the SiPM to the tile: can vary from cell to cell, photons might be lost here!

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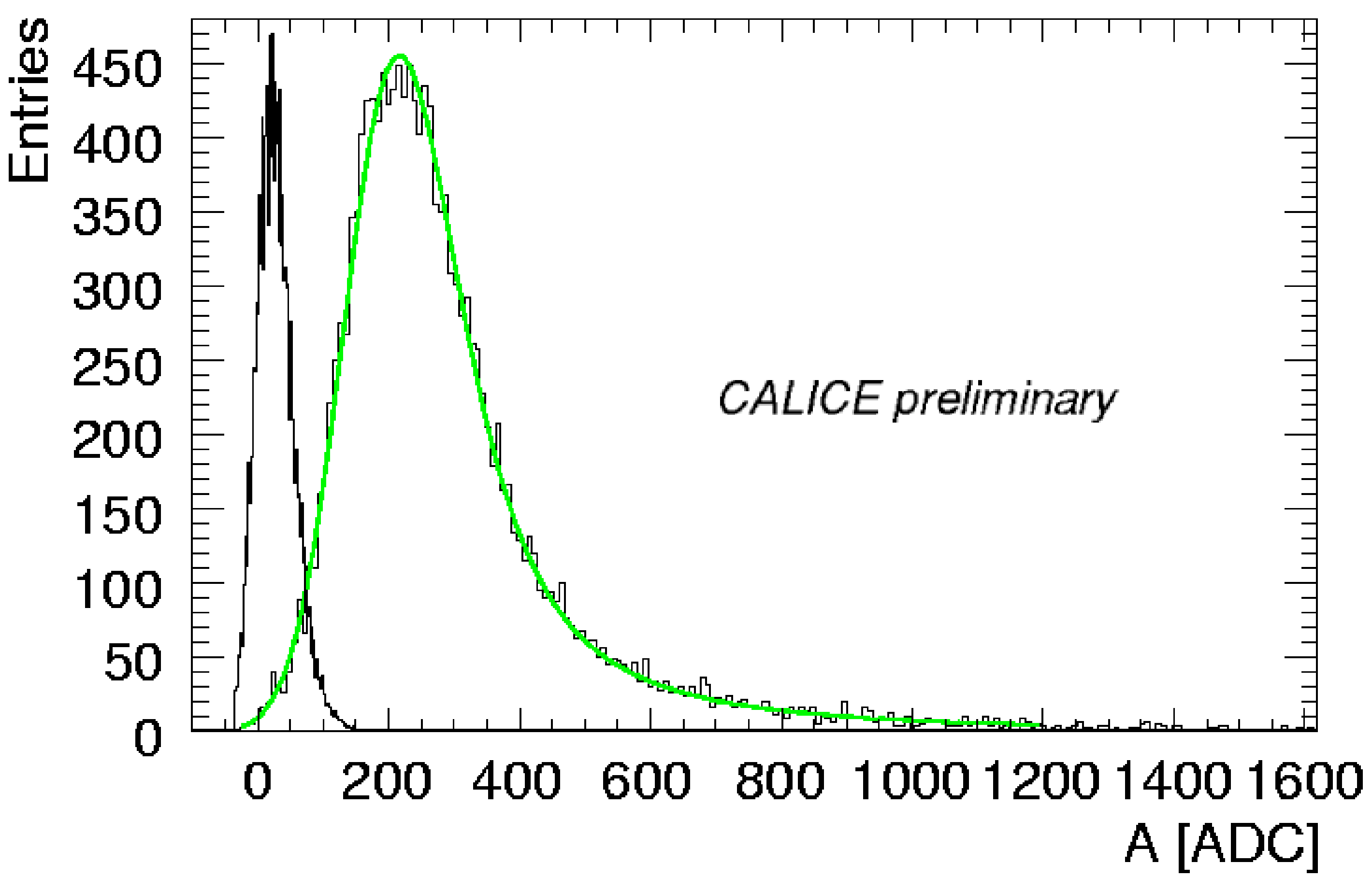
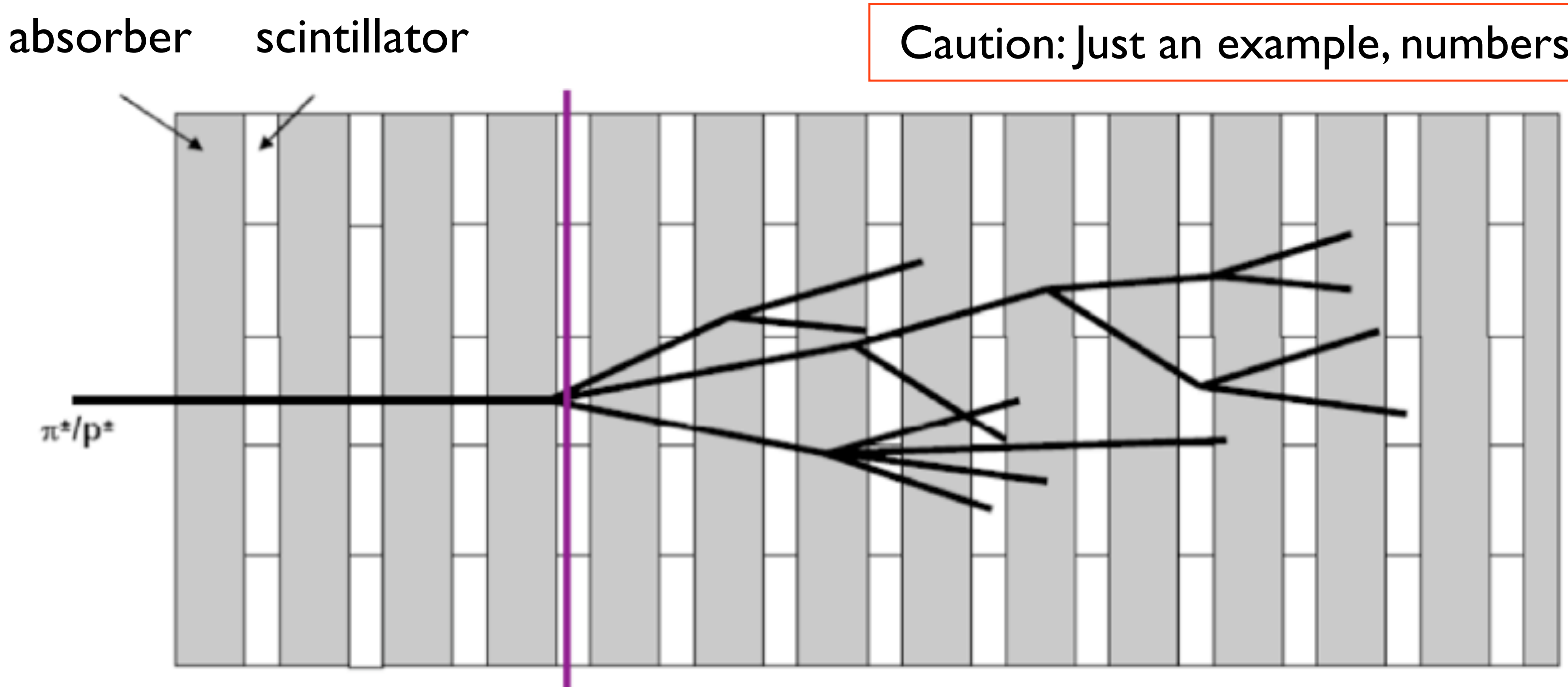


- MIP-Calibration with Muons
  - Complete detector illuminated with high energy muons
  - equalization of response of all cells by matching the MPV position

How does the HCAL measure Energy?

Caution: Just an example, numbers not realistic!



Energy sum per detector layer (in units of MIP): 1 1 1 3 3 4 7 5 3 3 4 1 0

➩ Total energy sum in the detector: 36 MIP

- So: The energy of a particle in the calorimeter is measured by measuring how much energy (corresponds ~ to the number of particles seen!) is seen in the active layers of the detector

How does the HCAL measure Energy?

- What is then needed: Transform the measured energy into the particle energy (in GeV): Use real particles with known energy (like in a test beam!)
  - This is mainly given by the geometry of the detector: The thickness of the absorber, the thickness of the active layers, ...

- The number depends on the type of particle: Differences between Hadrons and Photons/ Electrons: Remember Romans introduction!

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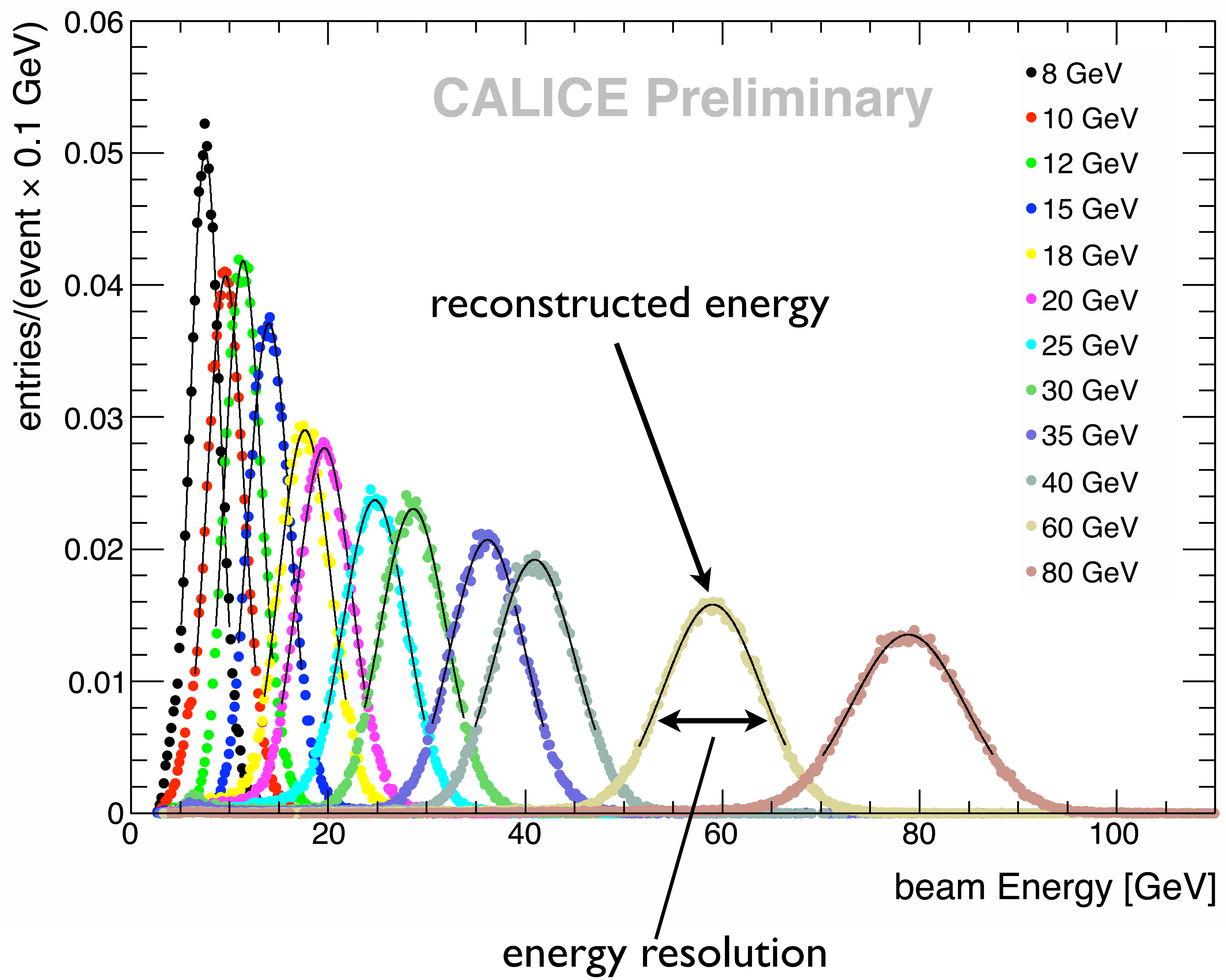
For which type of particle do you see more?

- For Electrons: 1 MIP ~ 0.025 GeV: 40 Particles seen per 1 GeV deposited energy
- For Hadrons: 1 MIP ~ 0.03 GeV: 33 Particles seen per 1 GeV deposited energy

Hadrons: Energy in the HCAL



I.

The Analog Hadron Calorimeter

-

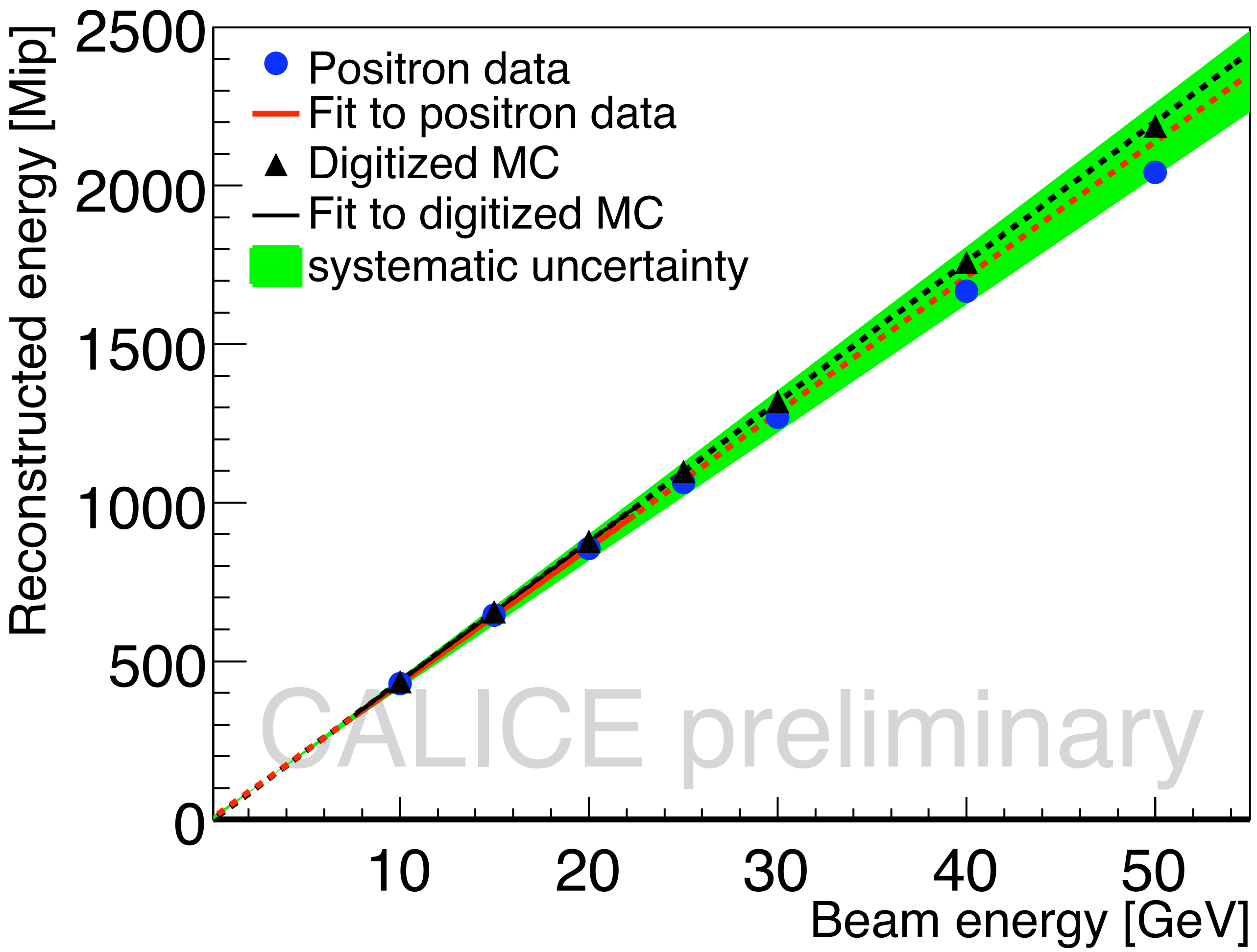
Electromagnetic Showers in the HCAL

Electromagnetic Probes in the Hadron Calorimeter

- Remember: Electromagnetic showers are much simpler than hadronic showers
  - They can be much better described!
- Use electromagnetic probes (electrons, photons) to test detector understanding

Setting the Stage: Positrons

- Positron data without the ECAL in front of the HCAL
- Temperature corrections applied



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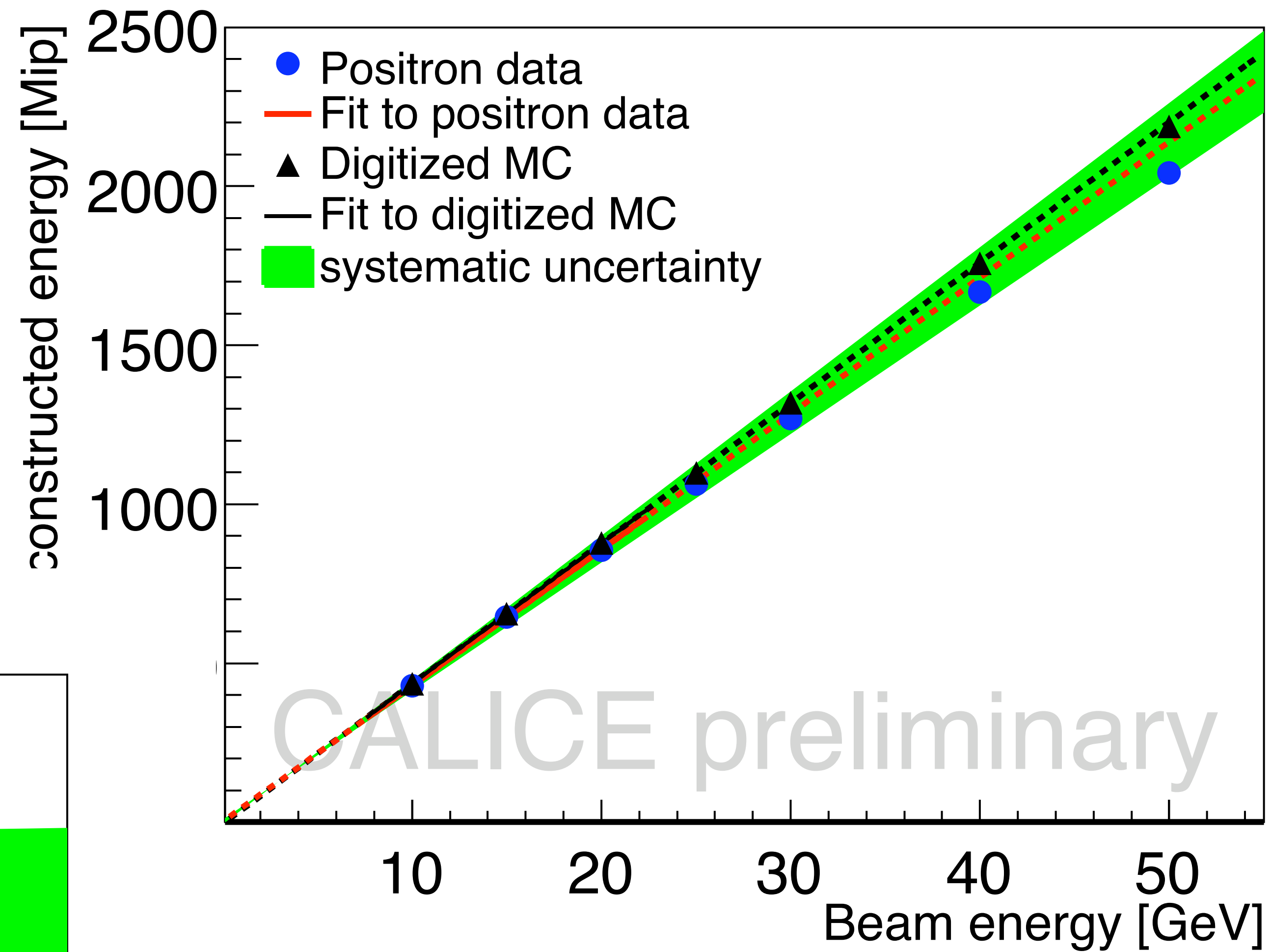
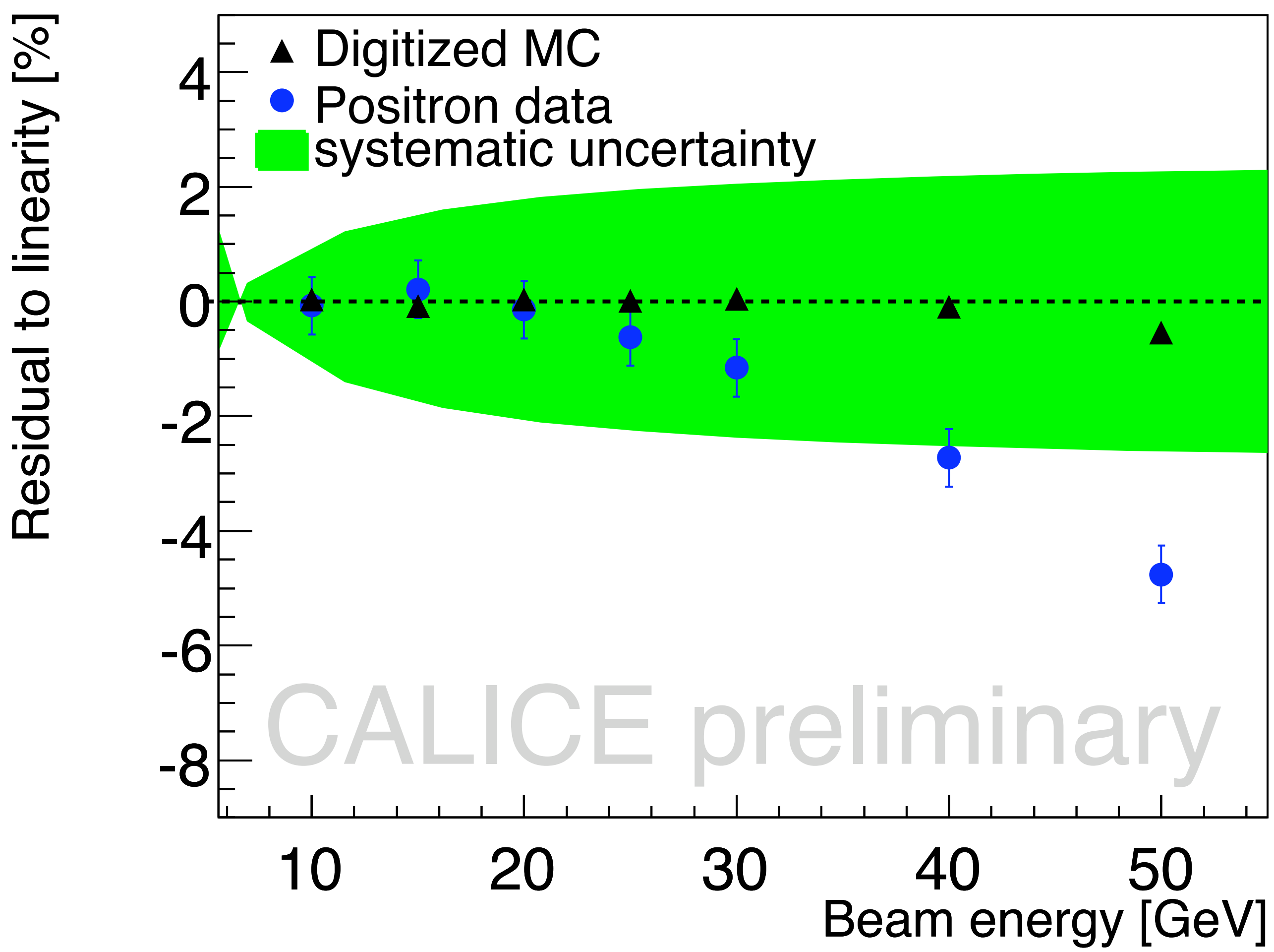


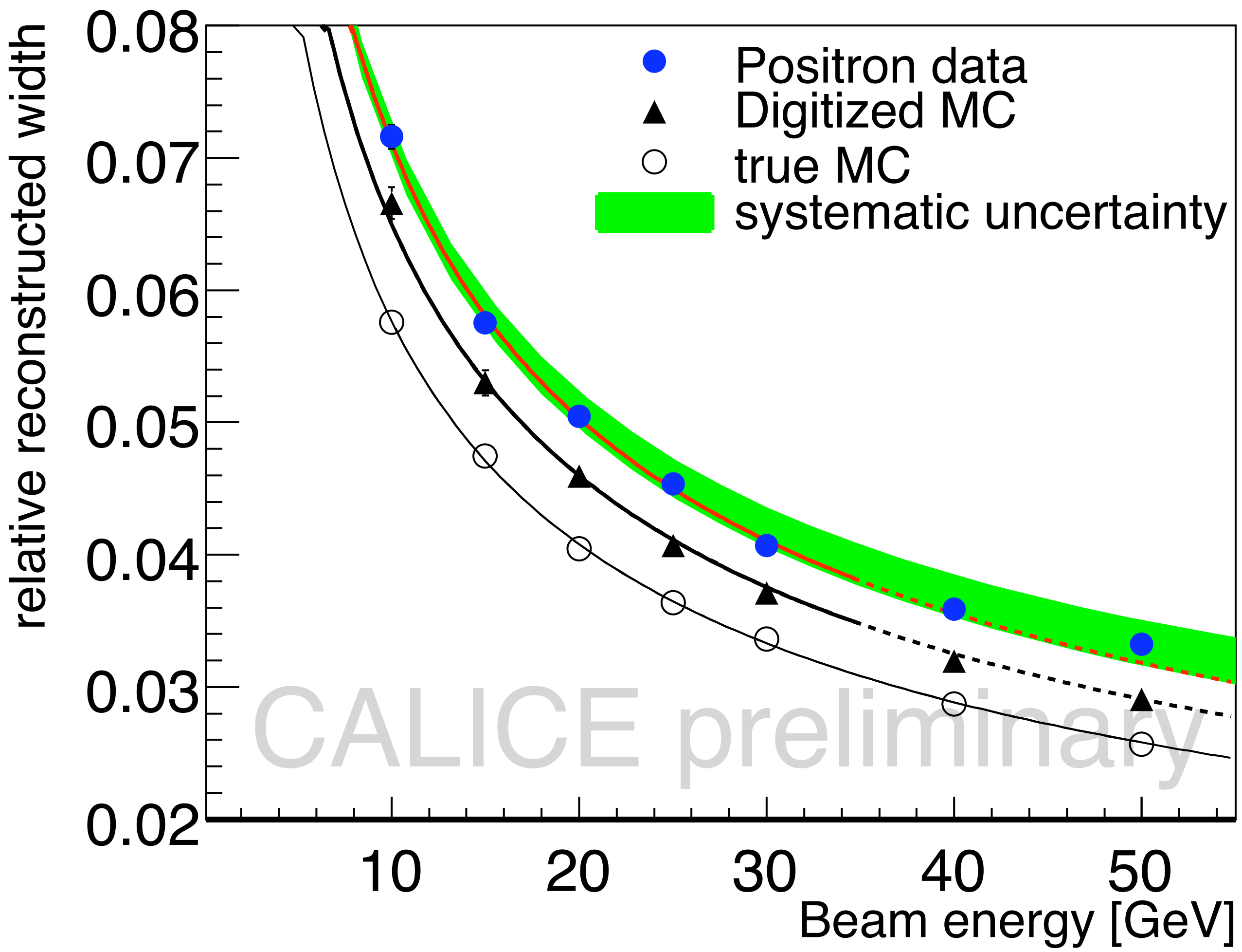


- Good linearity of the detector response observed: within 5% up to 50 GeV, within 1.5% up to 30 GeV
- Non-linearity with increasing energy not yet reproduced by MC

Energy Resolution for Positrons

- Energy resolution for positrons in the HCAL
  - compared to MC
  - Fit in the range from 10 GeV to 30 GeV with:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$



Data fit results:

Stochastic term a = 22.5 ± 0.1(stat) ± 0.4(syst) %

Constant term b = 0 ± 0.1(stat) ± 0.1(syst) %

Noise term fixed to 2 MIP (~ 50 MeV), taken from the RMS width of pedestal events

II.

Understanding Hadronic Showers

-

Detector Simulations

Why Detector Simulations?

Why do we need simulations? Where are they important?

- The Goal: Completely describe the response of a detector system with computer codes to simulate its behavior
- Crucial for the optimization of detectors: Test the influence of many different parameters without actually having to build anything!
- Comparison of simulation to data helps in the understanding of the underlying physics

What do we simulate?

- Roughly: 2 Steps

- The passage of particles through matter
  - simulate the energy deposit in the detector material, and all reactions that take place, in high detail
    - needs high detail of detector geometry and materials, magnetic fields, ...
    - requires good models of the interactions of many different particles in many different materials
- The response of the detector (often referred to as "Digitization")
  - simulate how the detector converts the deposited energy into signals read out by the data acquisition
    - may include charge or light collection, amplification, ...
    - includes effects of readout electronics

The Tool: GEANT4 & Physics lists

- GEANT4 is used to simulate the passage of particles through matter
  - follows particles in small steps, randomly chooses types of interaction based on their probability

- A challenge: Hadronic interactions: Very complex, with many different underlying processes
  - Interactions are described by a variety of models, either based on theory or driven by existing data, which are valid in different energy ranges and often not for all particles
  - ▸ Create a complete description by combining several models to cover all energy ranges: A physics list

Where does CALICE contribute?

- The CALICE calorimeters study hadronic showers with unprecedented spacial precision
  - Will provide important input for the hadronic shower models and for the creation of physics lists! In particular: 3D shower shapes

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So, why is this particularly important for simulations for the ILC?

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- The CALICE calorimeters study hadronic showers with unprecedented spacial precision
- Will provide important input for the hadronic shower models and for the creation of physics lists! In particular: 3D shower shapes

So, why is this particularly important for simulations for the ILC?

- Particle Flow is based on the separation of showers in the calorimeters
  - Precise knowledge of longitudinal and transverse shower extend as well as shower substructure necessary
  - Good reproduction by MC mandatory to provide reliable detector simulations

GEANT4 Physics Lists: Models

Models with different validity ranges in energy (particle energy in detector frame)

- High energy (E > ~ 20 GeV) :
  - QGS (Quark-Gluon-String)
  - FTF (Fritjof string model)

  theory driven models of hadron-nucleus collisions

- Low energies (E < ~ 10 GeV)
  - Bertini cascade, more data driven
  - Binary cascade, more theory based

  simulate initial interaction within the nucleus, producing high-energy secondaries, highly excited nuclear remnant

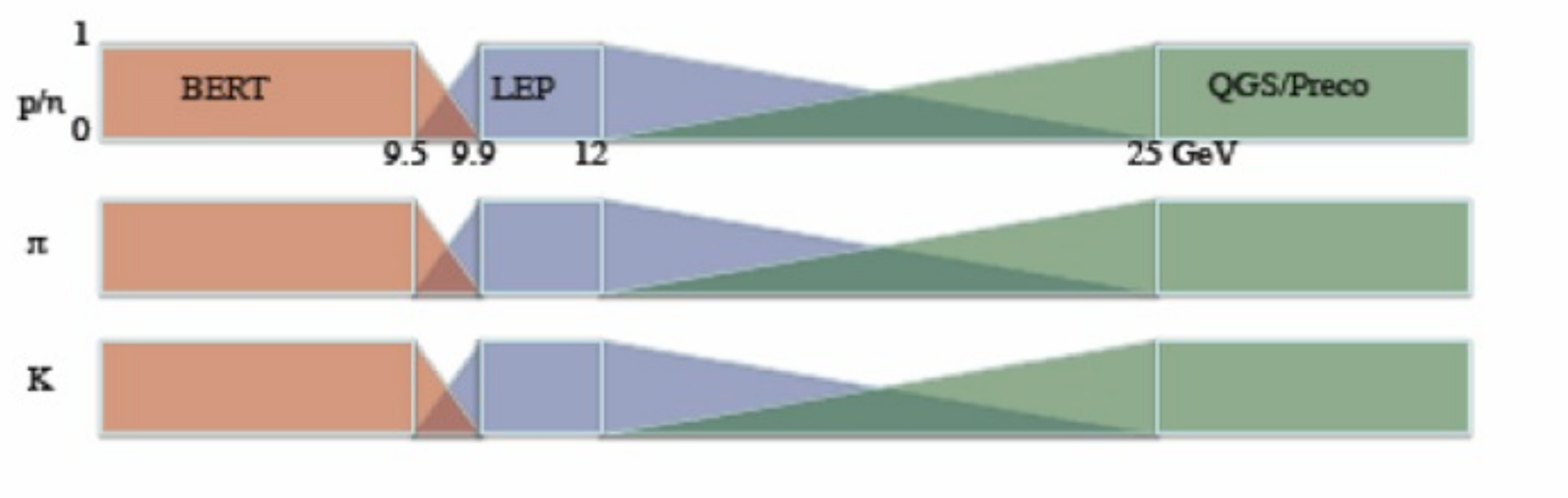
Then: models for nuclear de-excitation (fission, breakup, fragmentation, evaporation)
Commonly used: precompound model, as well as others for the slowest particles (< 20 MeV)

In addition:
parametrized models (based on data) for all long-lived particles:
LEP (Low Energy Parametrized) and HEP (based on GEISHA used in GEANT3)
➩ LEP particularly interesting: covers the range from 10 to 20 GeV, where the theory driven models are not reliable

GEANT4 Physics Lists: The Combinations

- No single model covers the complete energy range of particles in the detector
  - Combinations of different models are used to have a description that is valid for all energies: called a "Physics List"
  - The overlap regions are handled by randomly selecting which of the two models to use, with a linear change of probability for a given model

Currently the most popular model: QGSP_BERT



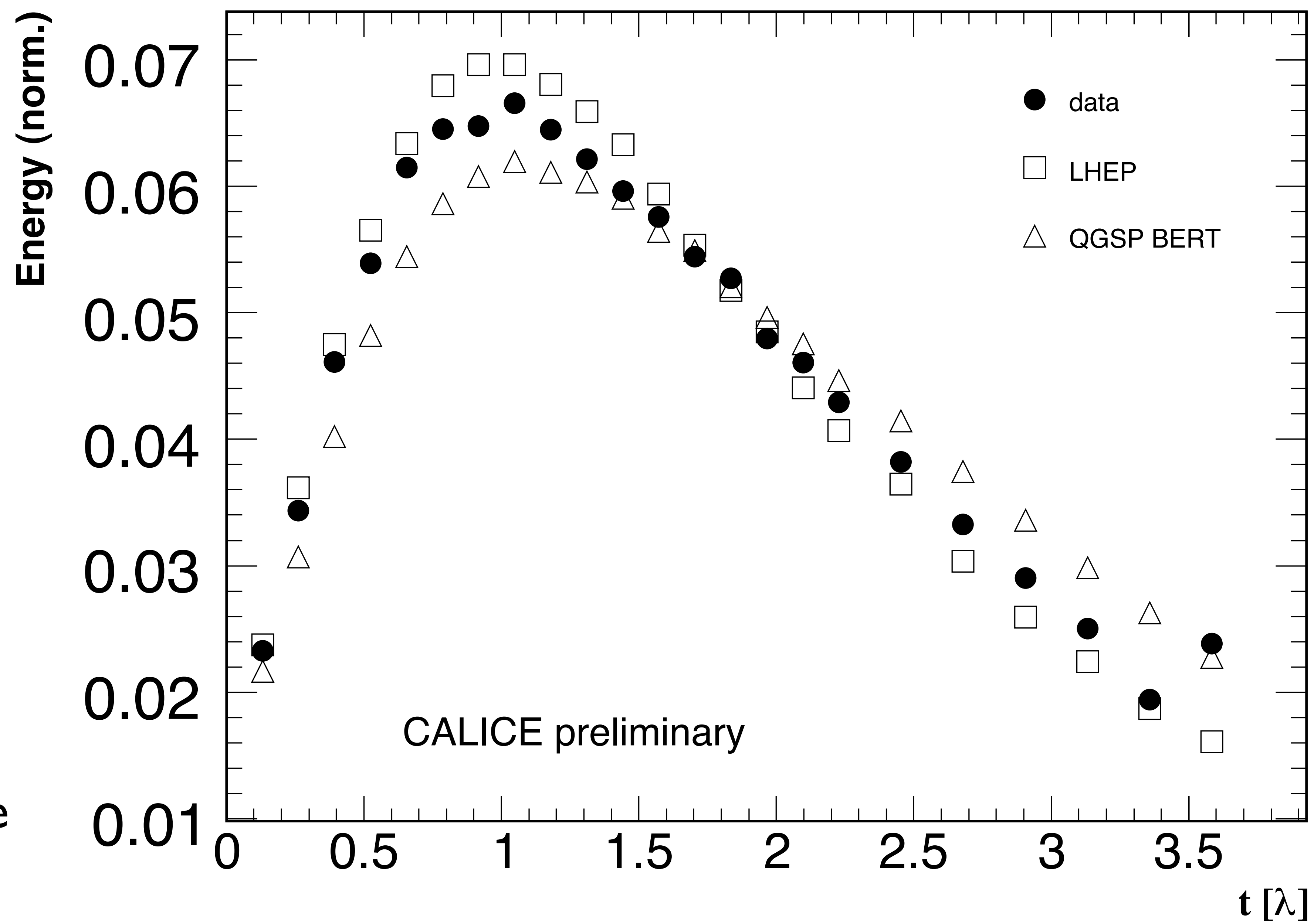
for other particles (i.e. hyperons) LEP + HEP is used

II.
Understanding Hadronic Showers
-
Shower Profiles & Shower Properties

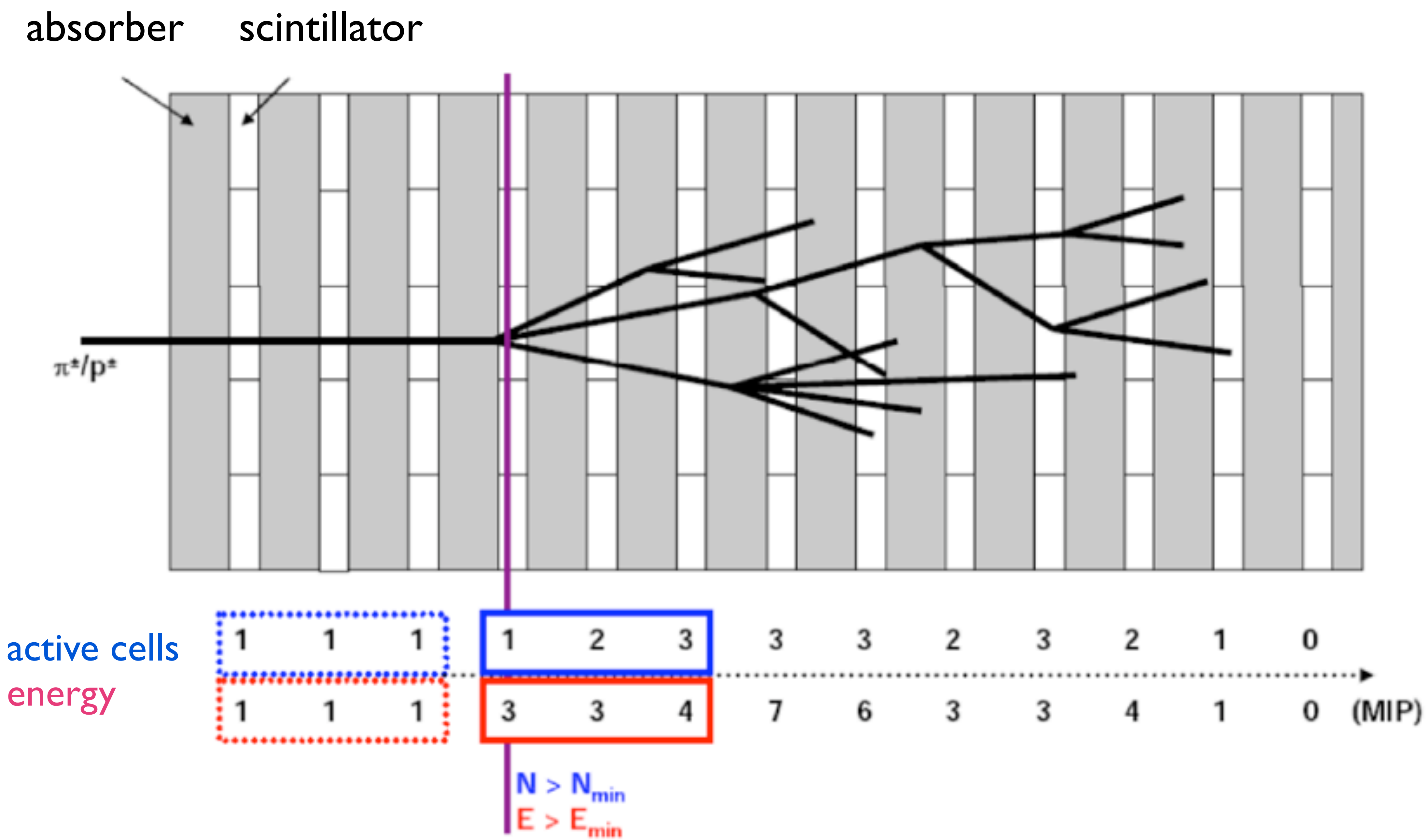
Longitudinal Shower Profile

- Longitudinal shower profile for 2006 data: HCAL with 23 layers, reduced sampling fraction in the second half of the detector
- Simulations using GEANT4 and two different physics lists
  - simulation of digitization in detector, no time cut to mimic integration time of electronics
  - Birk's law in scintillators included

t: depth in calorimeter

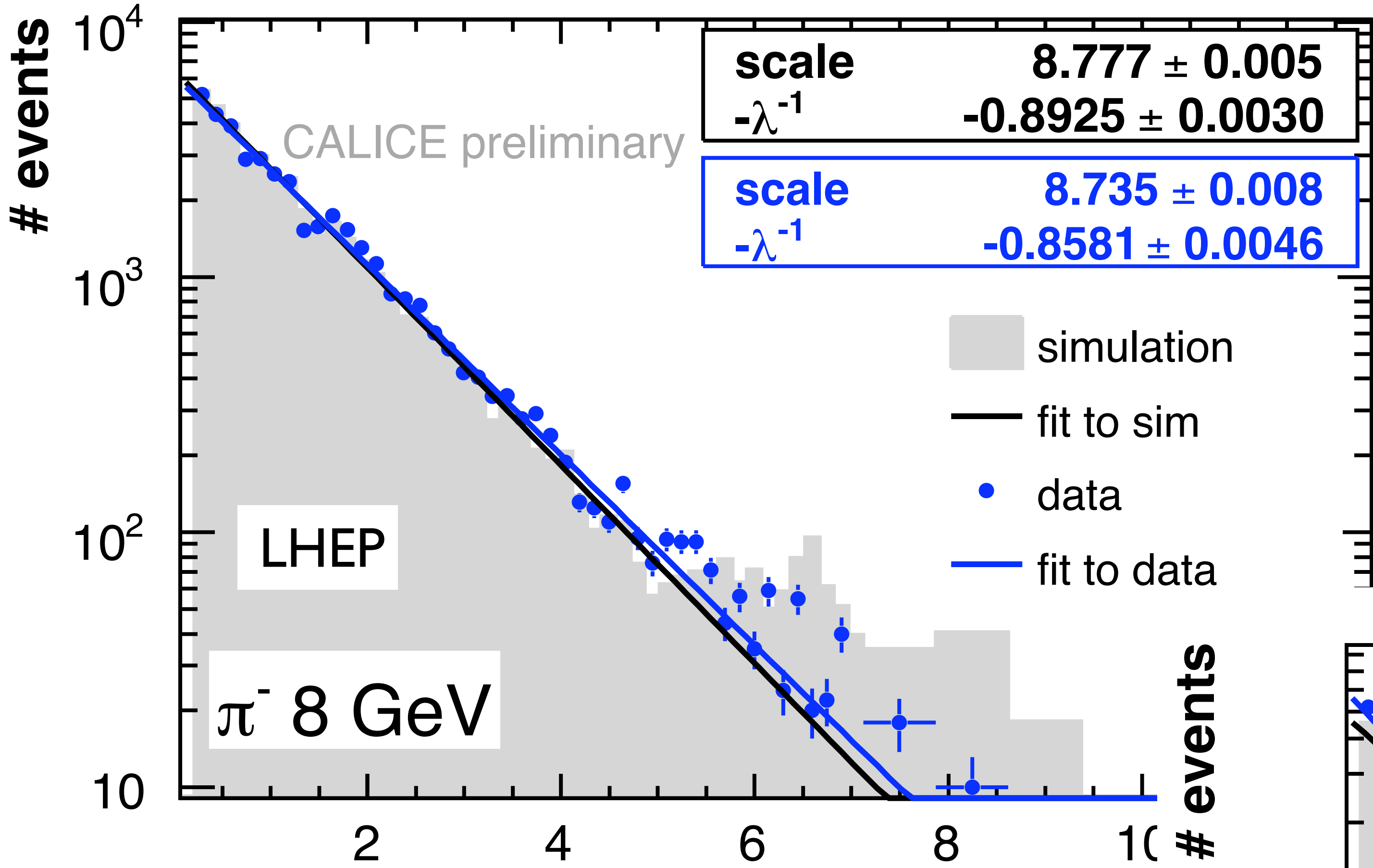


A Closer Look: Shower Starting Point

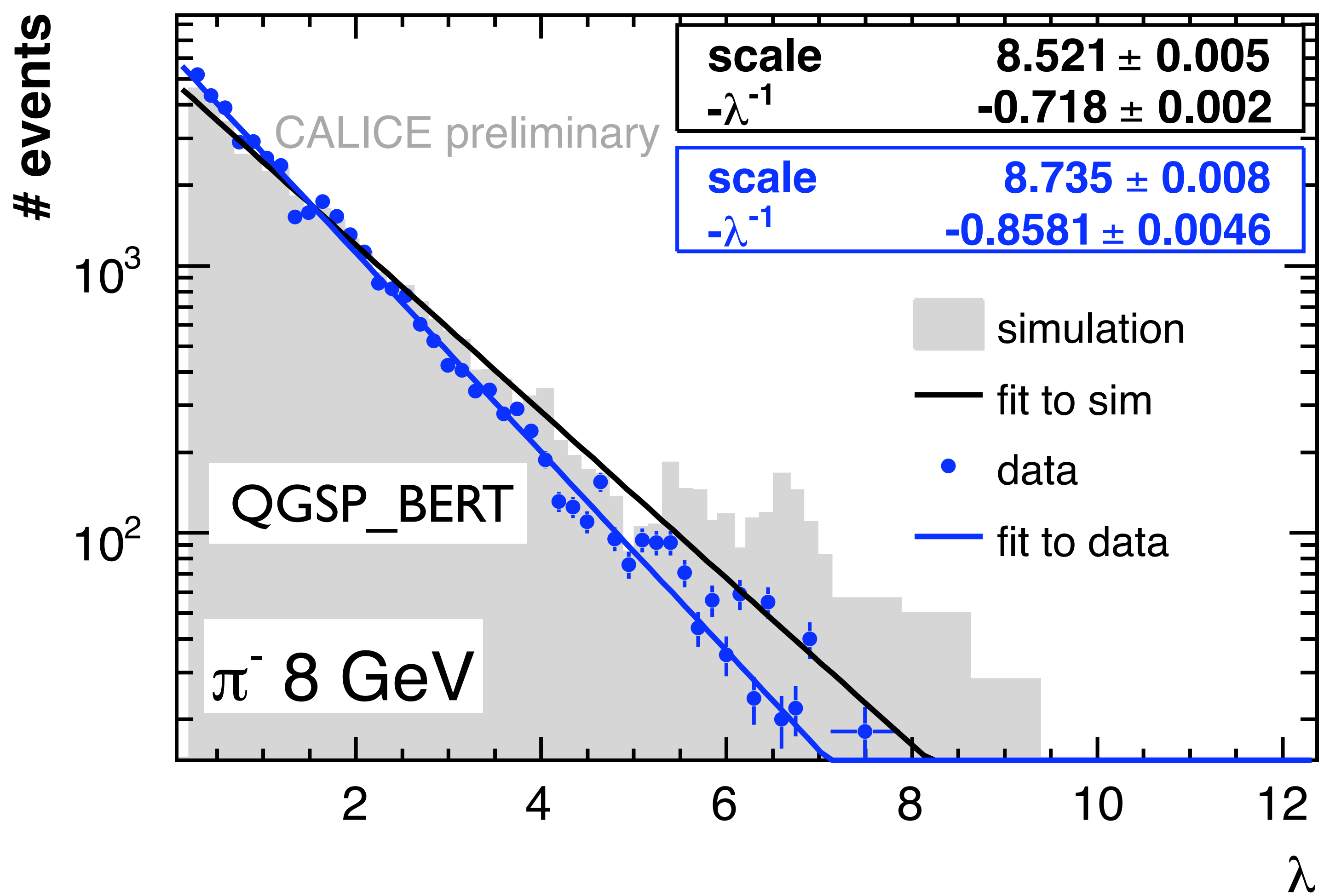


- High granularity allows identification of the shower start: Increased activity, track turns into shower

Shower Properties: Shower Starting Point



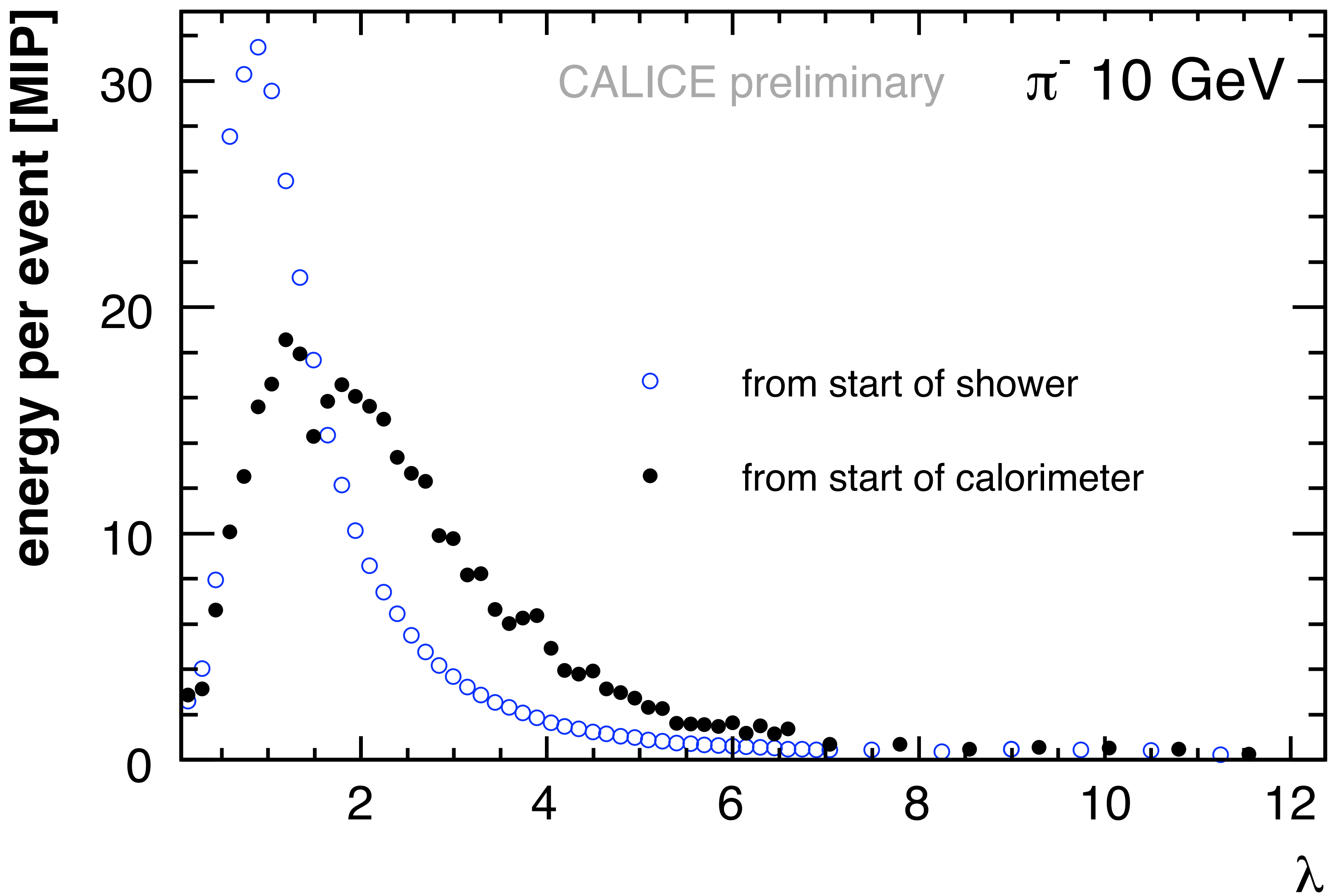
- starting point shows expected exponential fall-off



- Difference between physics lists: much better agreement with LHEP
- at higher energies (not shown) both LHEP and QGSP_BERT agree very well

Profile from Shower Start

- Longitudinal profile from shower start compared to start of detector
  - Interesting subject for future MC study!



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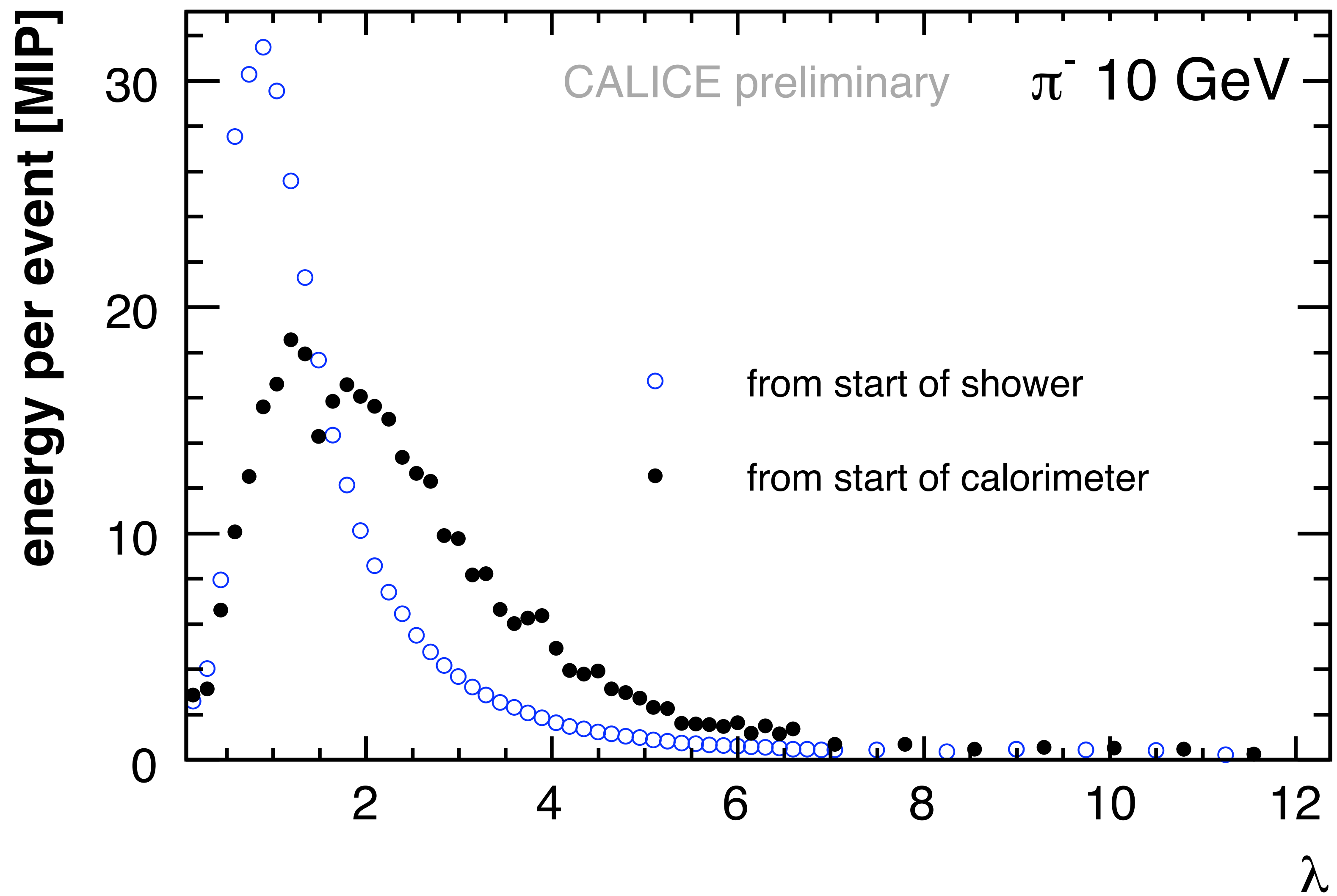
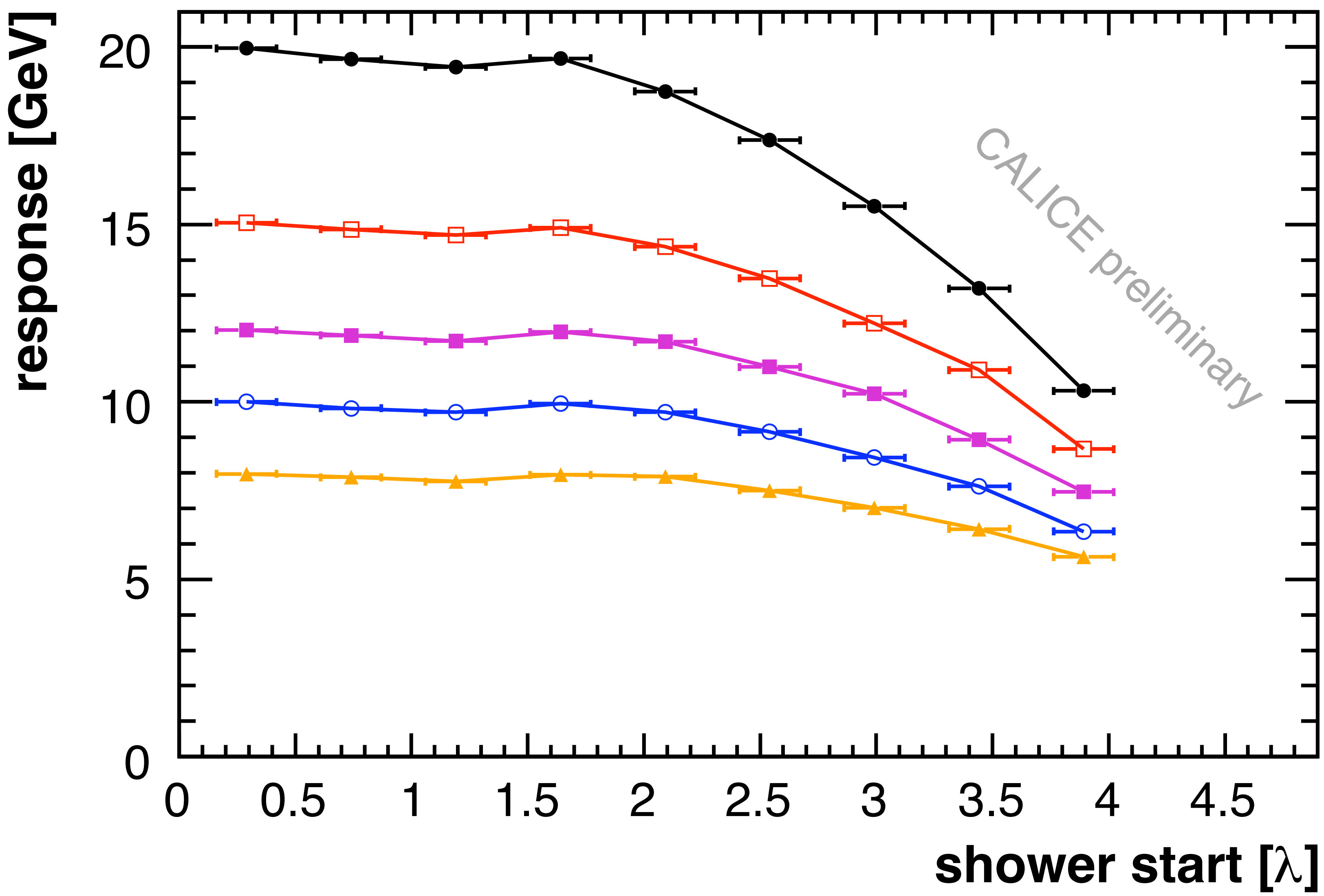


Food for thought: How do we get data out to 12 λ, with fine sampling out to 7 λ?

Why have a Tail Catcher? Shower Leakage!



- Late-starting showers have significant "leakage" out of the back of the calorimeter: If there is no other detector this information is lost

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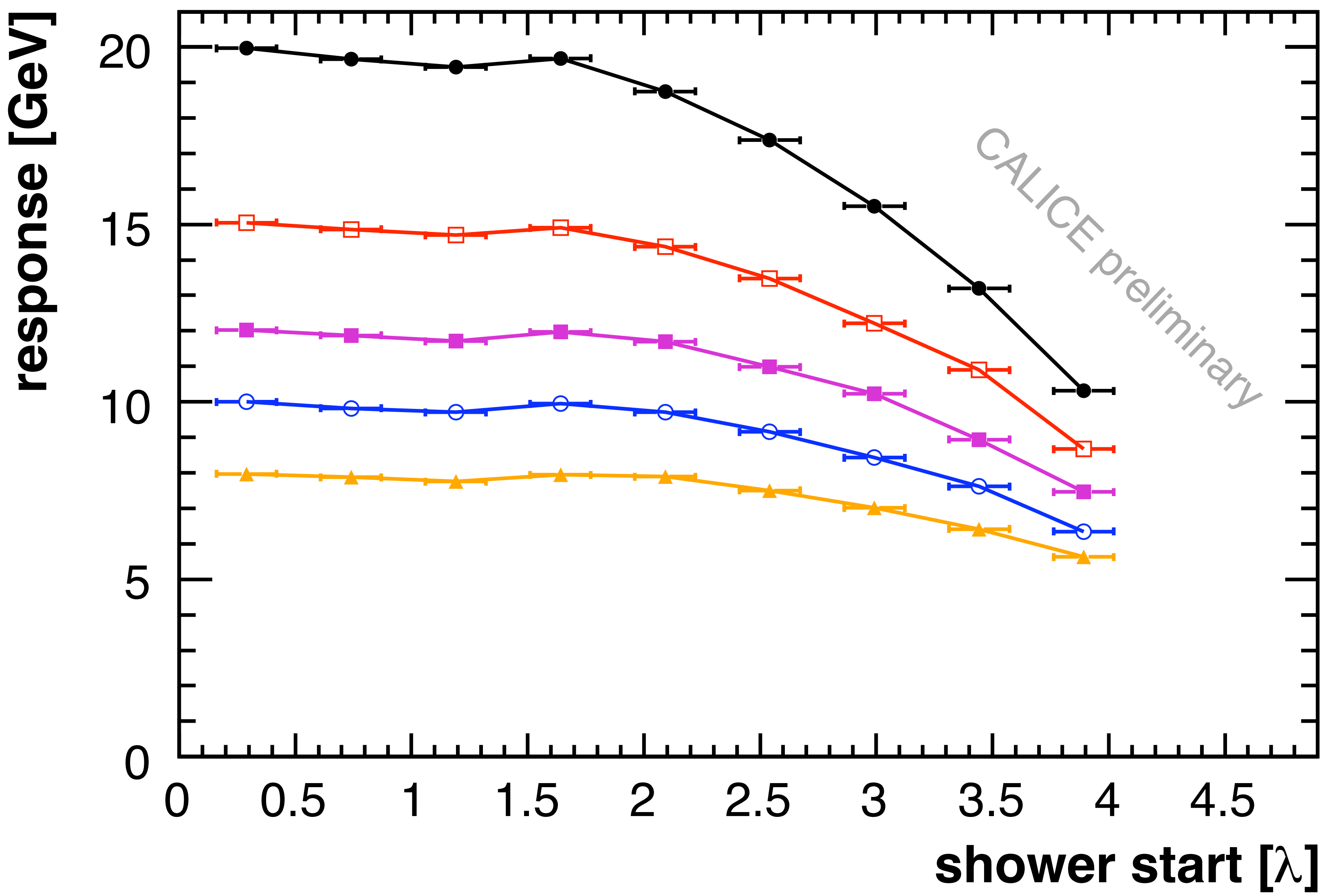

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What else could be done to recover the right energy?

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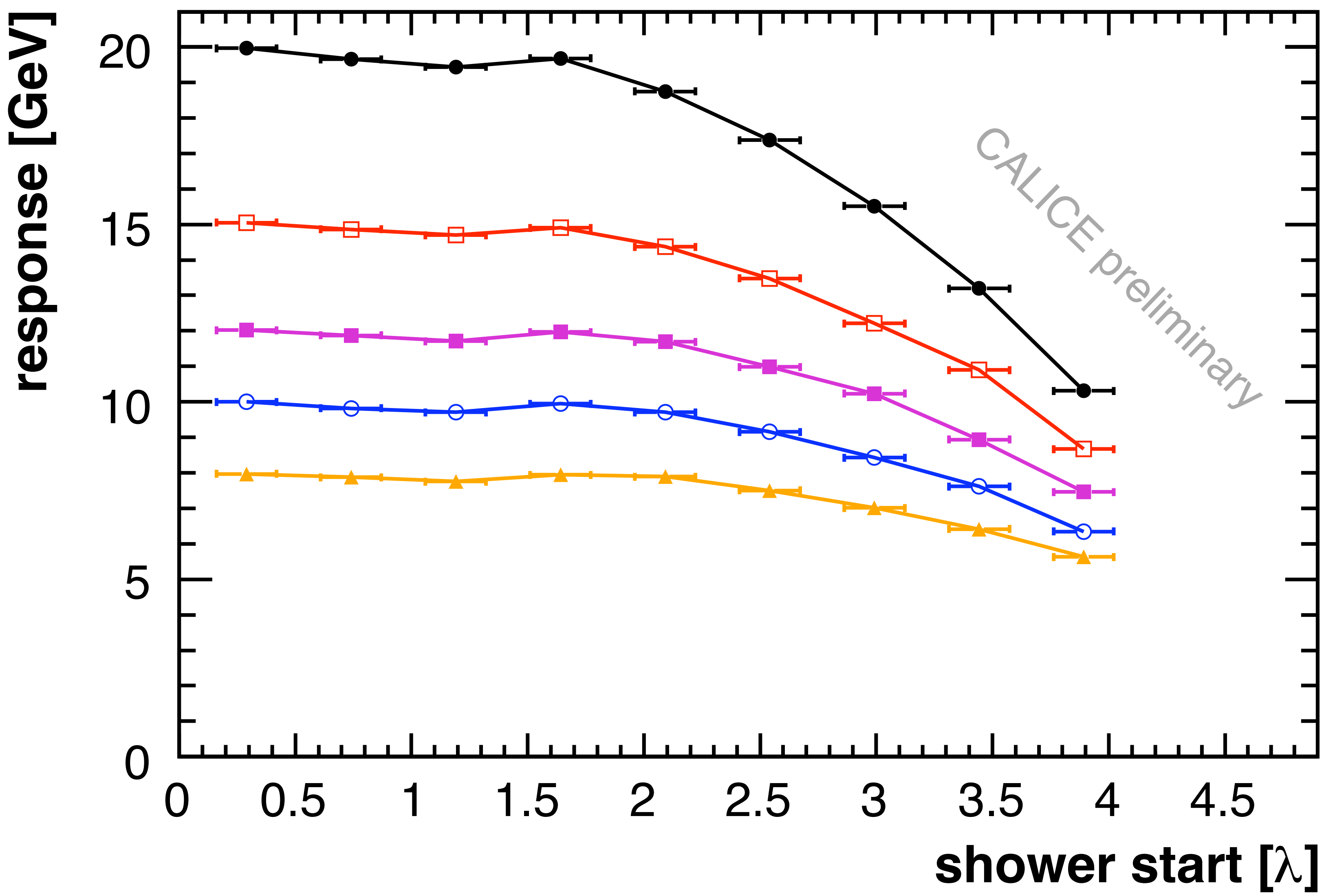
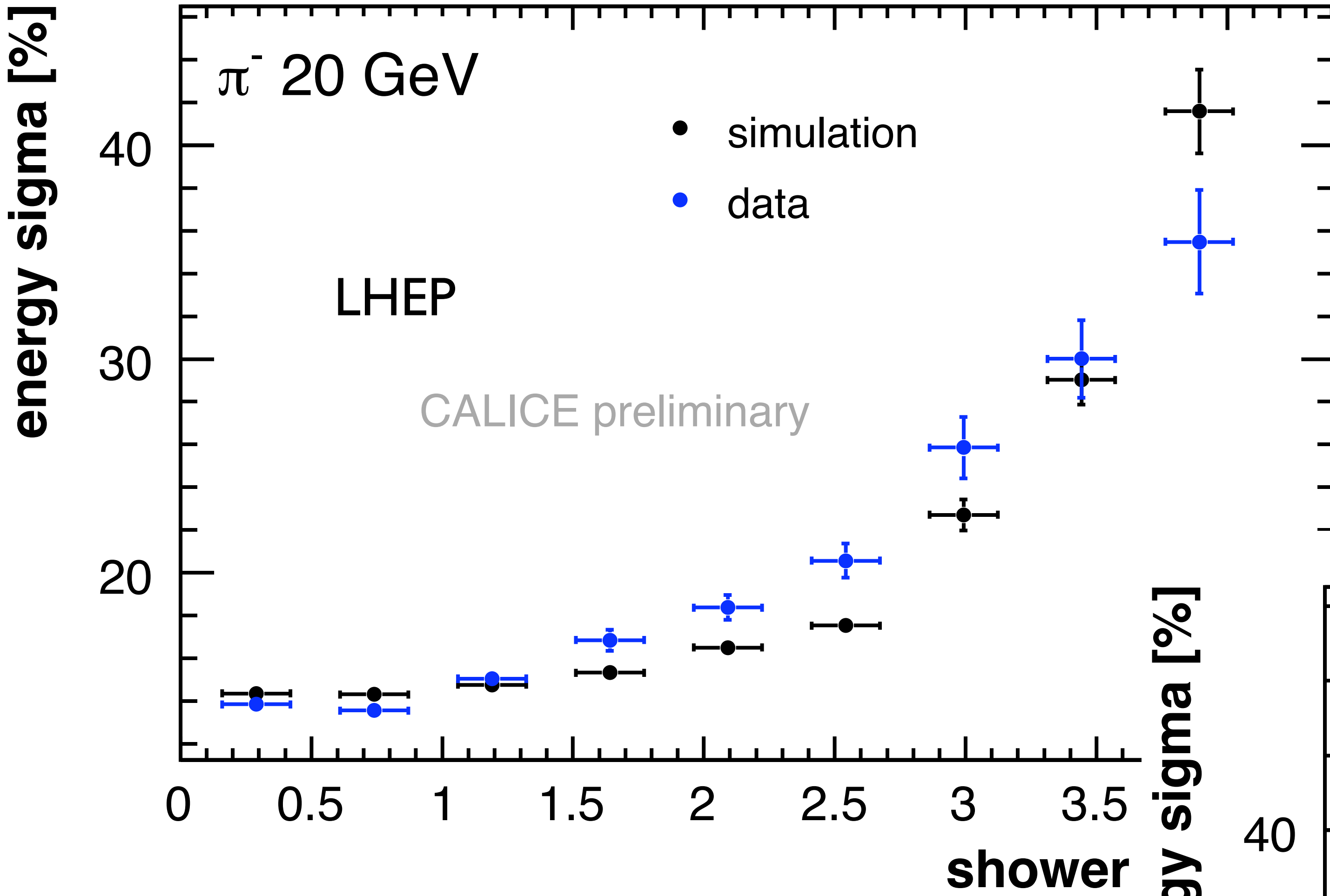


- Late-starting showers have significant "leakage" out of the back of the calorimeter: If there is no other detector this information is lost

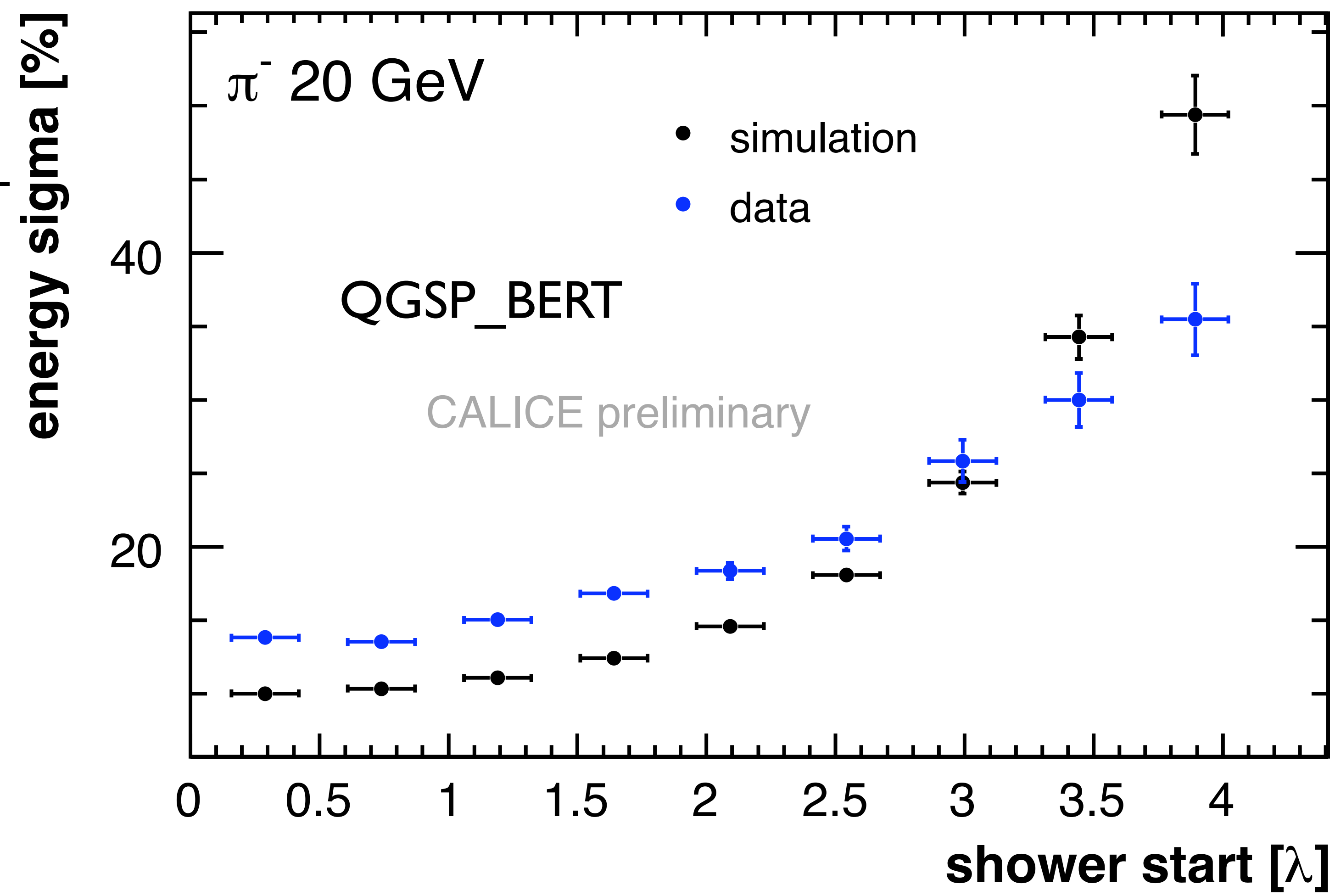
What else could be done to recover the right energy?

➡ Use the position of the shower start to correct the reconstructed energy (this works! ... but has a very bad energy resolution (no way to recover lost info)

Why have a Tail Catcher? Energy Resolution!

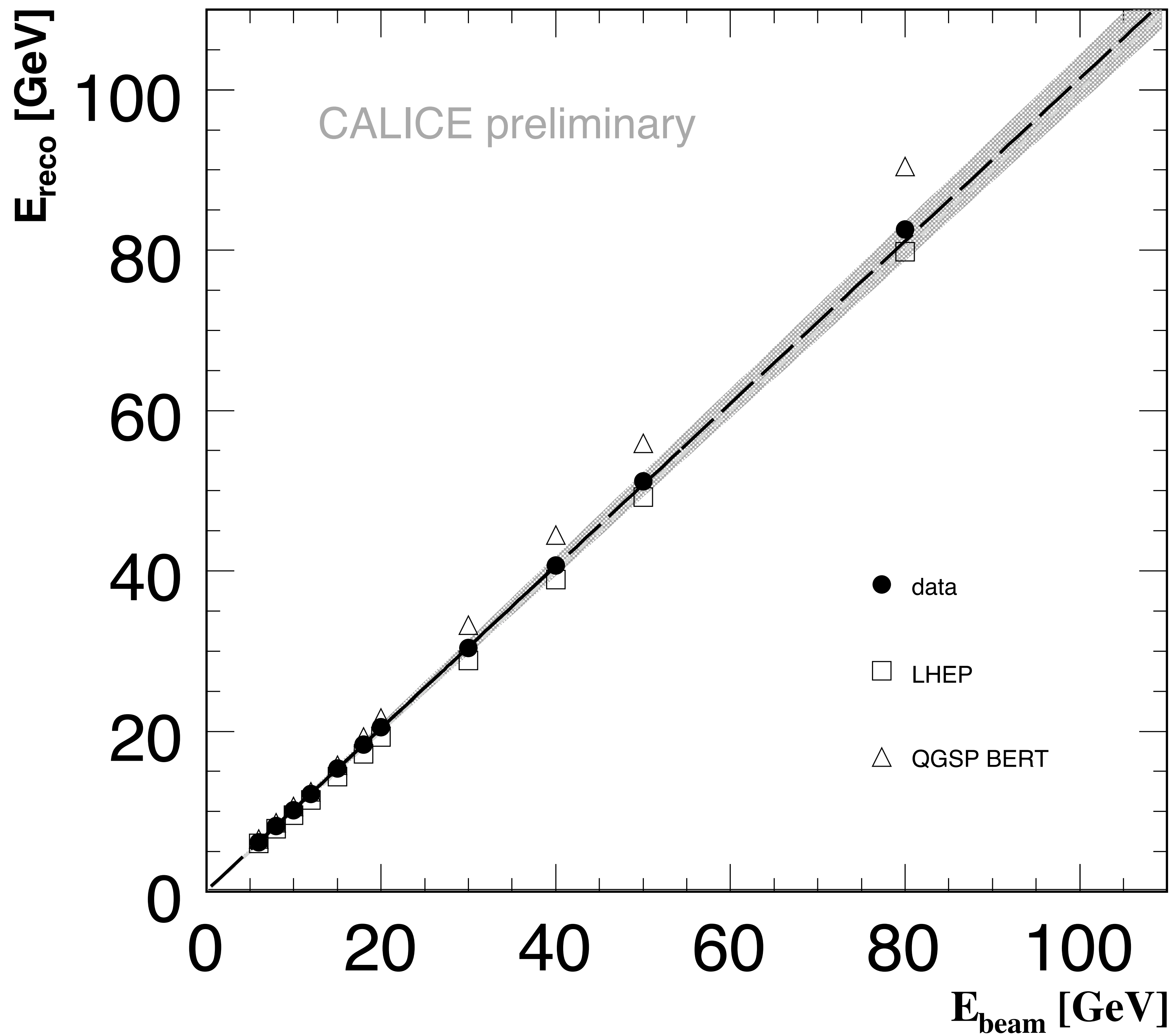


- Energy resolution depends on the start position of the shower: late starting showers have significant worse resolution (due to leakage, see previous slide)

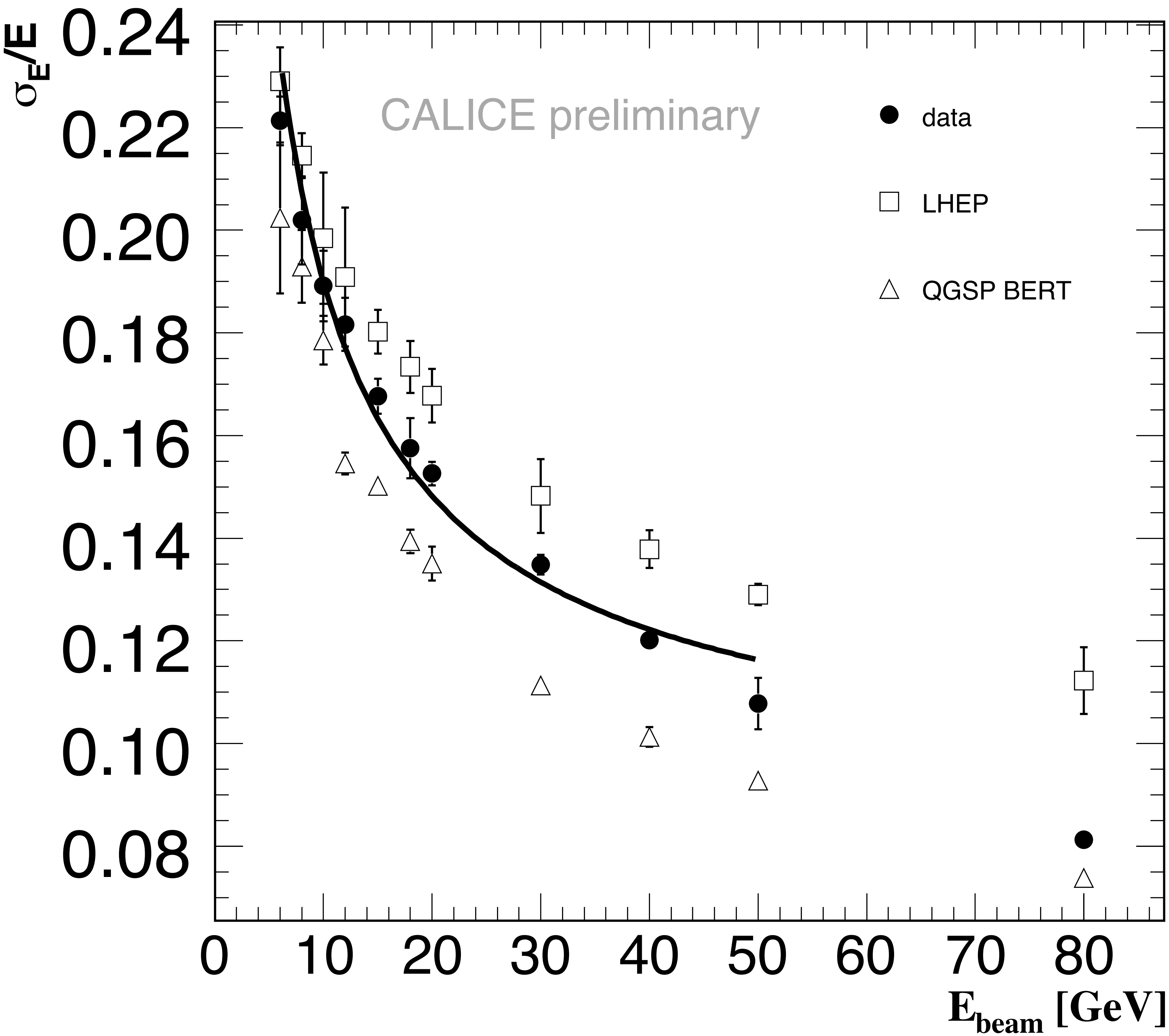


Energy Reconstruction & MC Comparison: First Look

- Remember: Hadronic showers contain nuclear reactions with delayed emission of particles, mostly neutrons
  - Inclusion of the integration time of the electronics in the simulations important (not done here)
  - A “time cut” seems to improve the agreement of data with QGSP_BERT, still under study



Energy Resolution: First Look

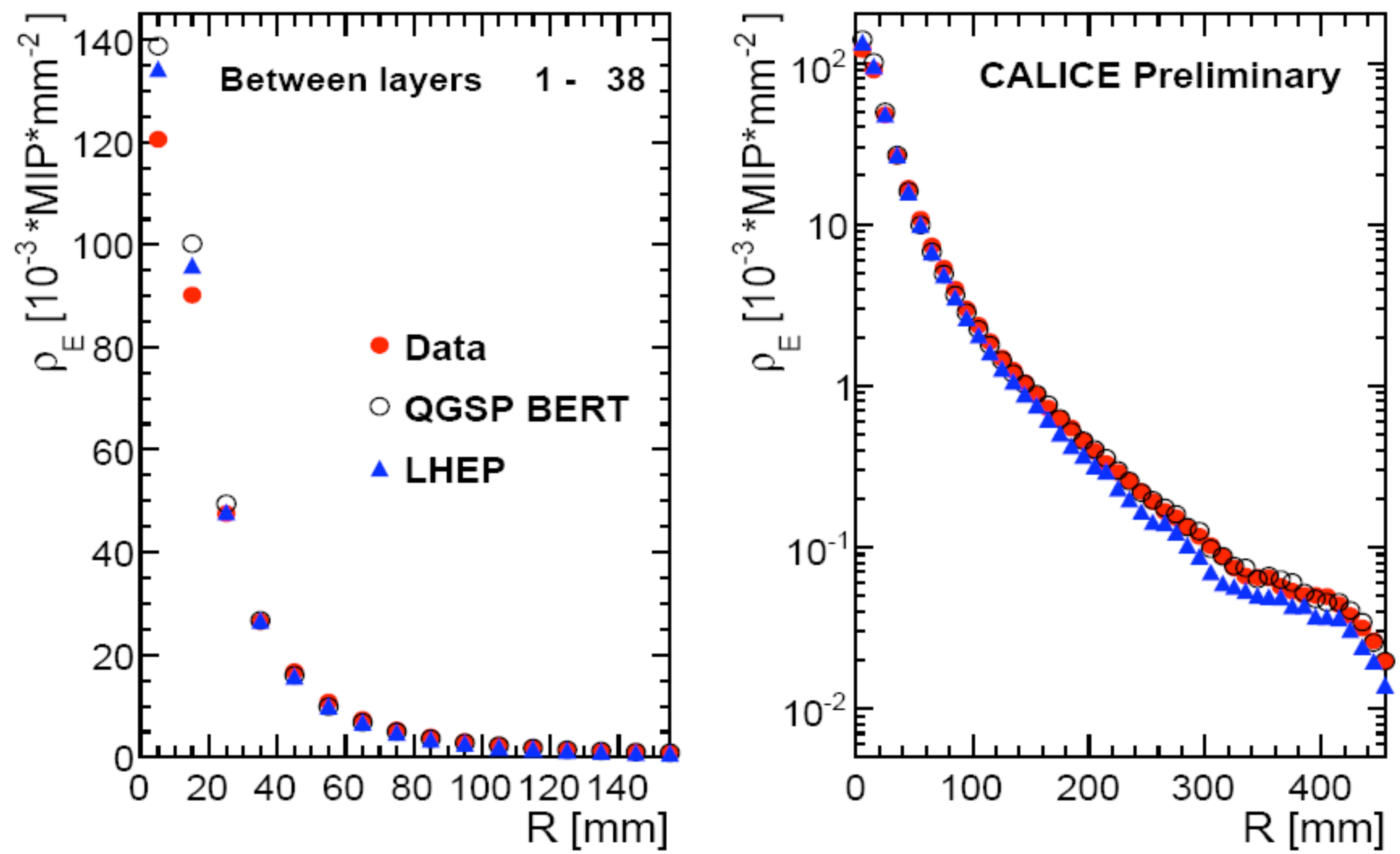


Transverse Shower Profile

- Important variable: Crucial for Particle Flow, defines how well showers can be separated
    - compared to simulations using a time cut to simulate electronics integration time

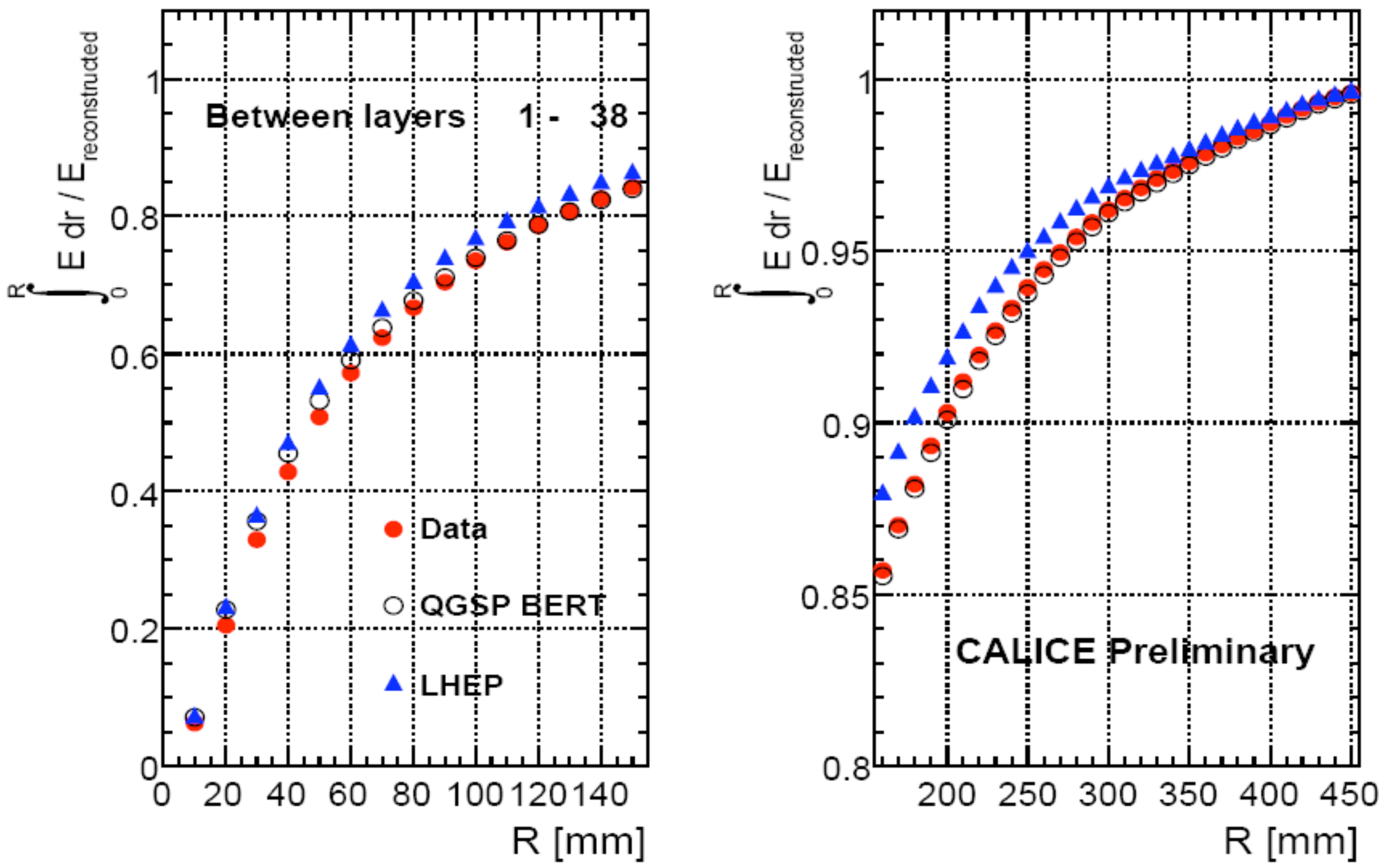
18 GeV π^-

Look at showers starting in the HCAL, take extrapolated track of the incoming particle, count the energy in rings with 10 mm distance around the track (summed in depth)



Lateral Containment

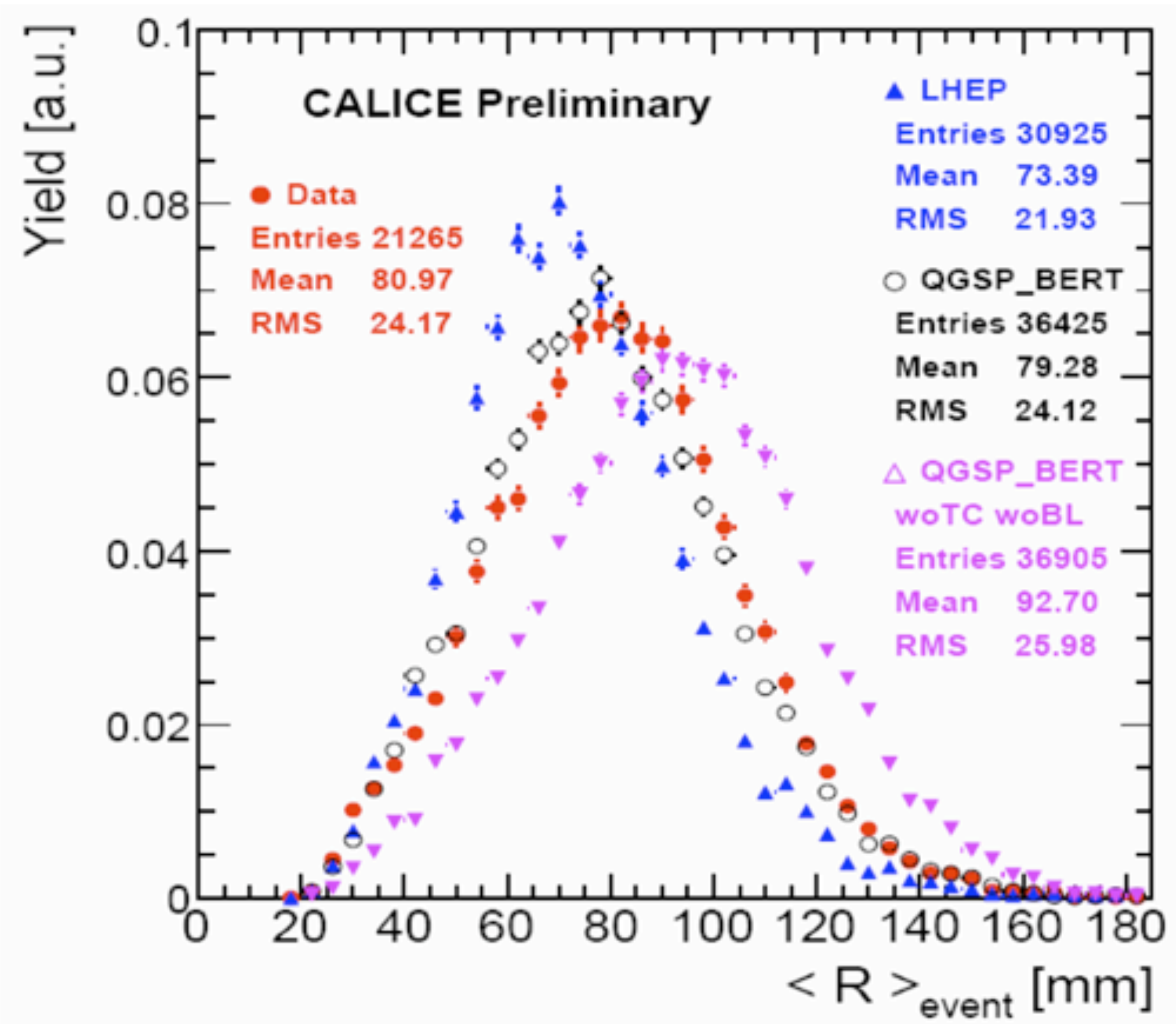
- Integral of energy as a function of radius around the shower axis

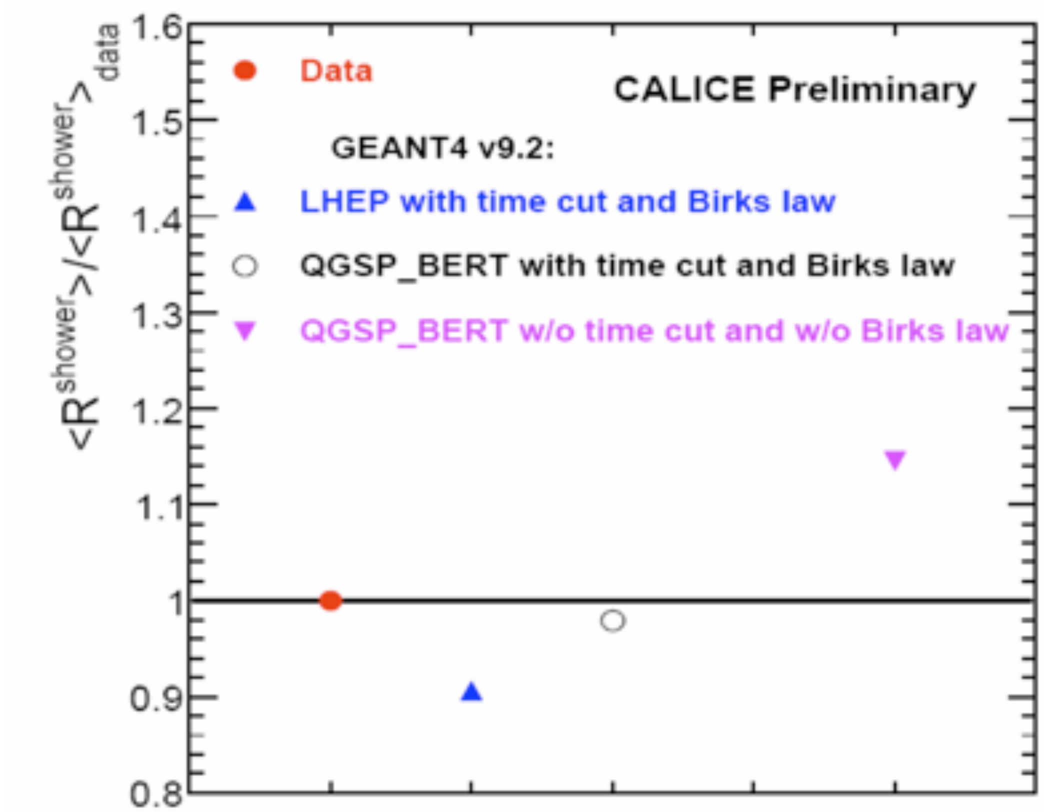


- simulations including time cut reproduce the structure quite well

The Shower Radius

$$\langle R \rangle = \frac{\Sigma E_i \, R_i}{\Sigma E_i}$$

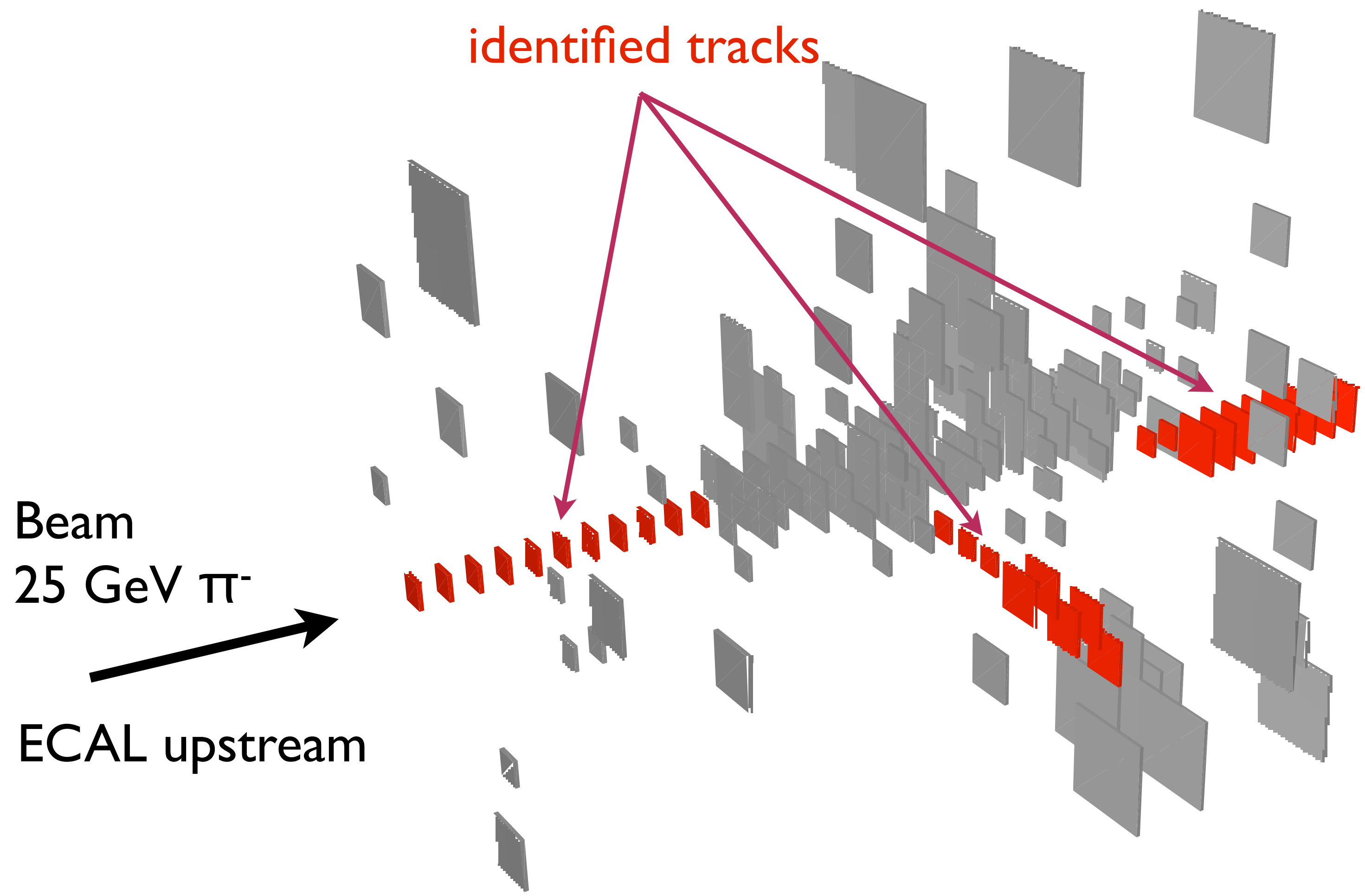




- Good description by MC when using time cut
  - proper treatment of neutron component in the shower evolution crucial for a realistic description!

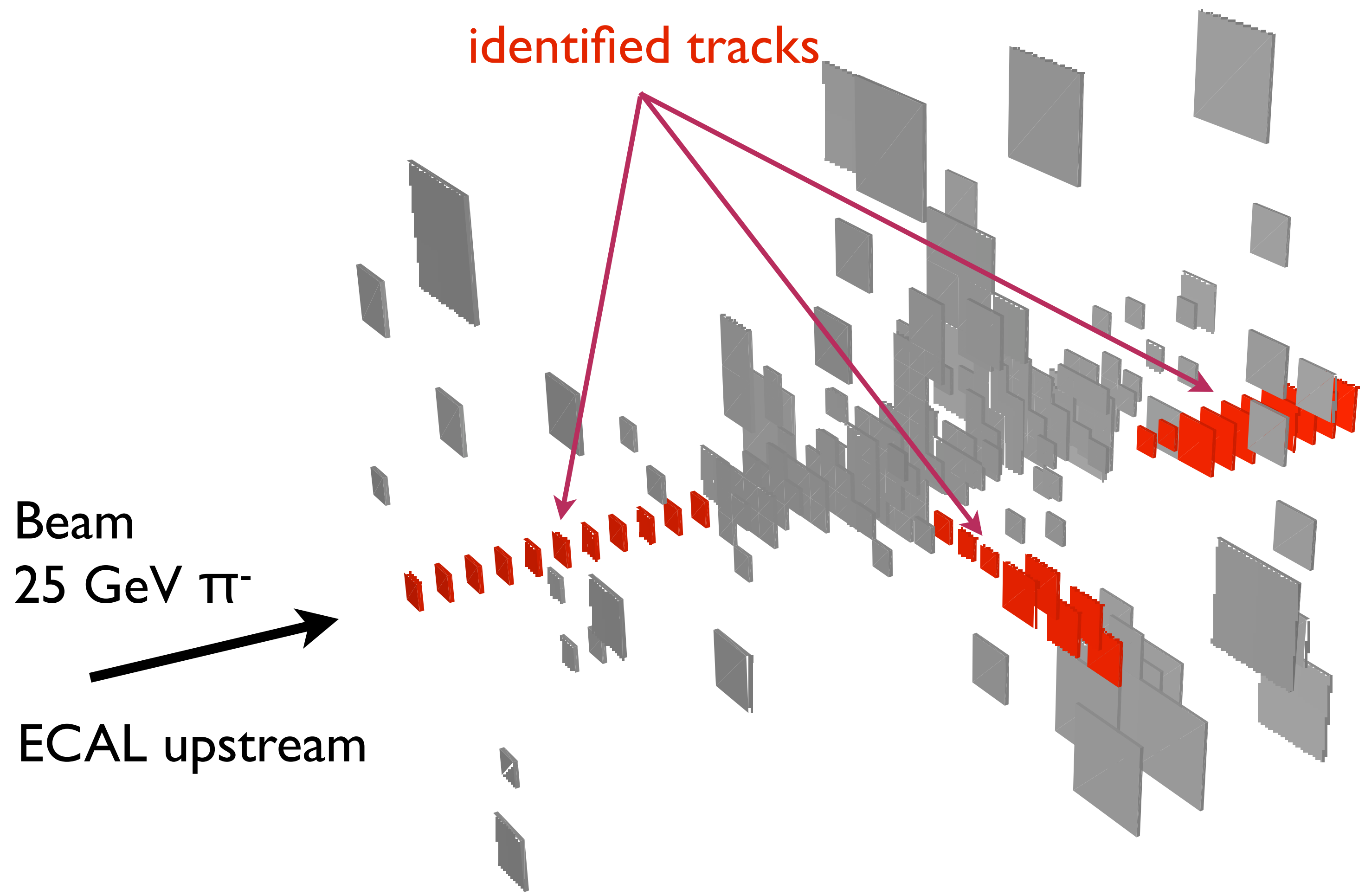
III.
The Power of Granular Calorimeters
-
Calibration Possibilities with Hadron Data

Tracking in Hadronic Showers



- High granularity allows identification of track segments within hadronic showers
  - requirement: isolated hits, tracks separated from other activity

Tracking in Hadronic Showers



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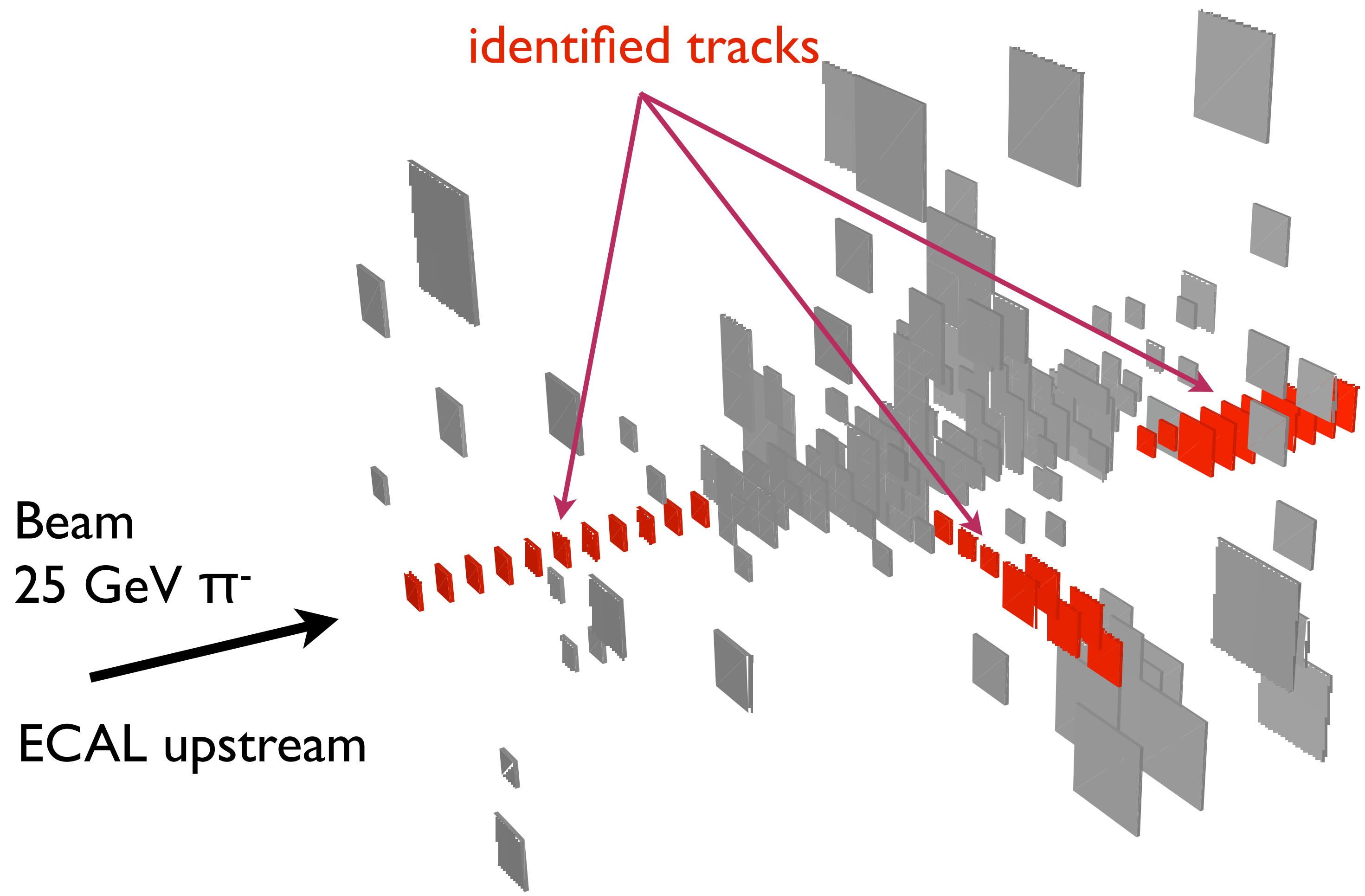
Why does this work in hadronic showers?

Tracking in Hadronic Showers

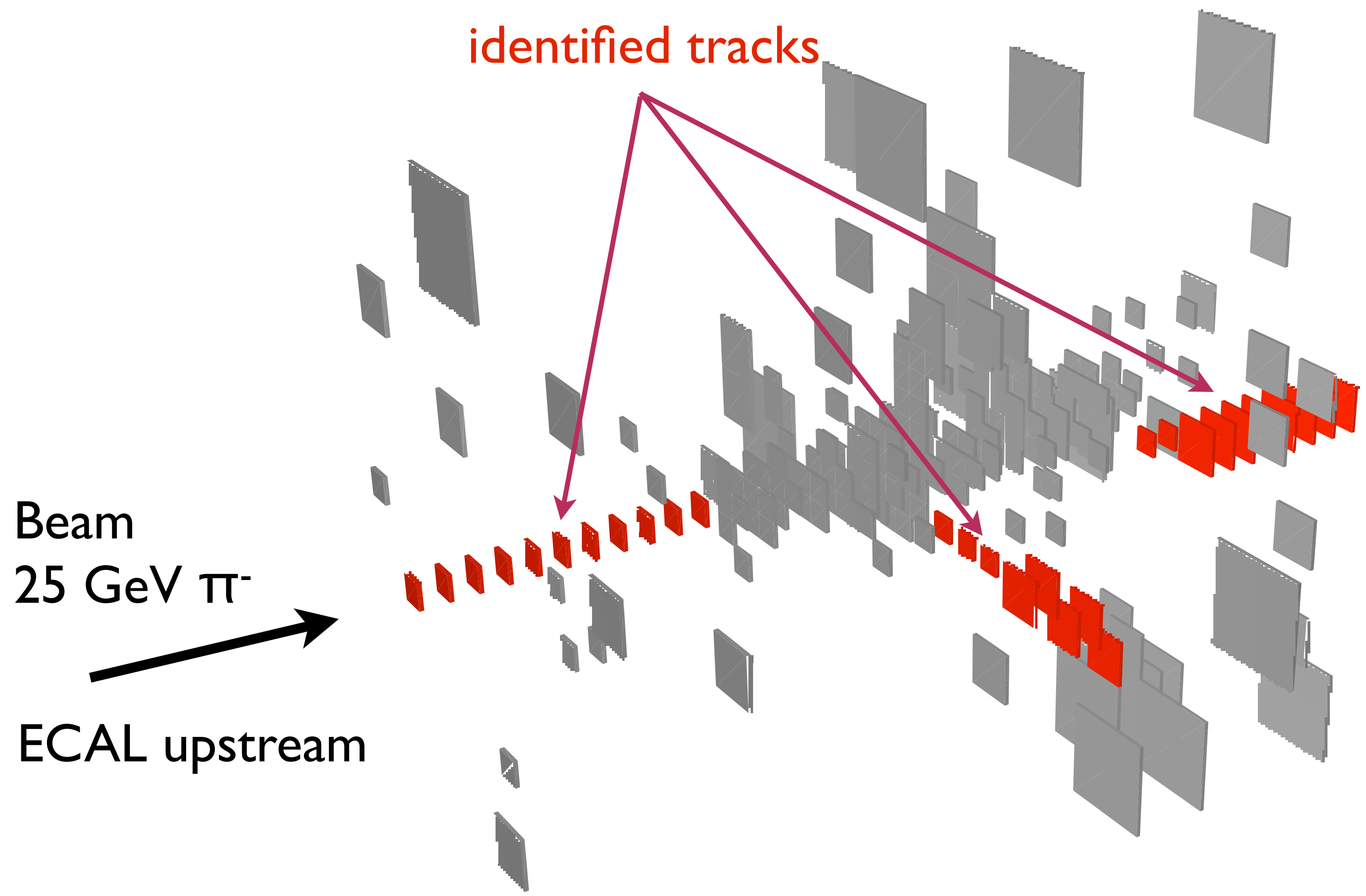


- High granularity allows identification of track segments within hadronic showers
  - requirement: isolated hits, tracks separated from other activity

Why does this work in hadronic showers?

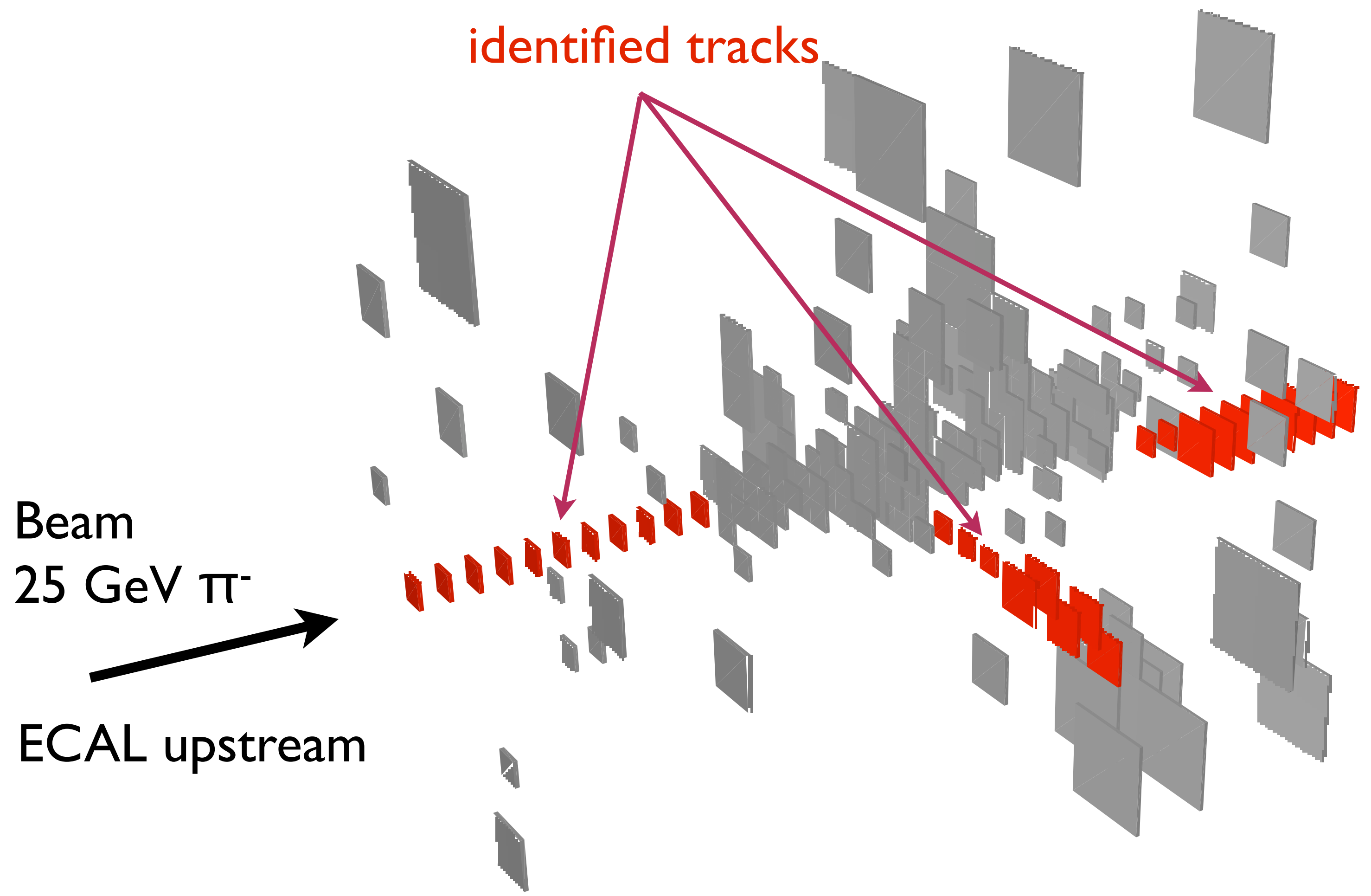
Hadronic showers are typically quite “sparse”: A hadronic interaction takes place, quite a few particles are produced, but depending on their type, they might actually travel an appreciable distance before interacting again.

Tracking in Hadronic Showers: Hits on Track



- Special properties of cells on identified tracks:

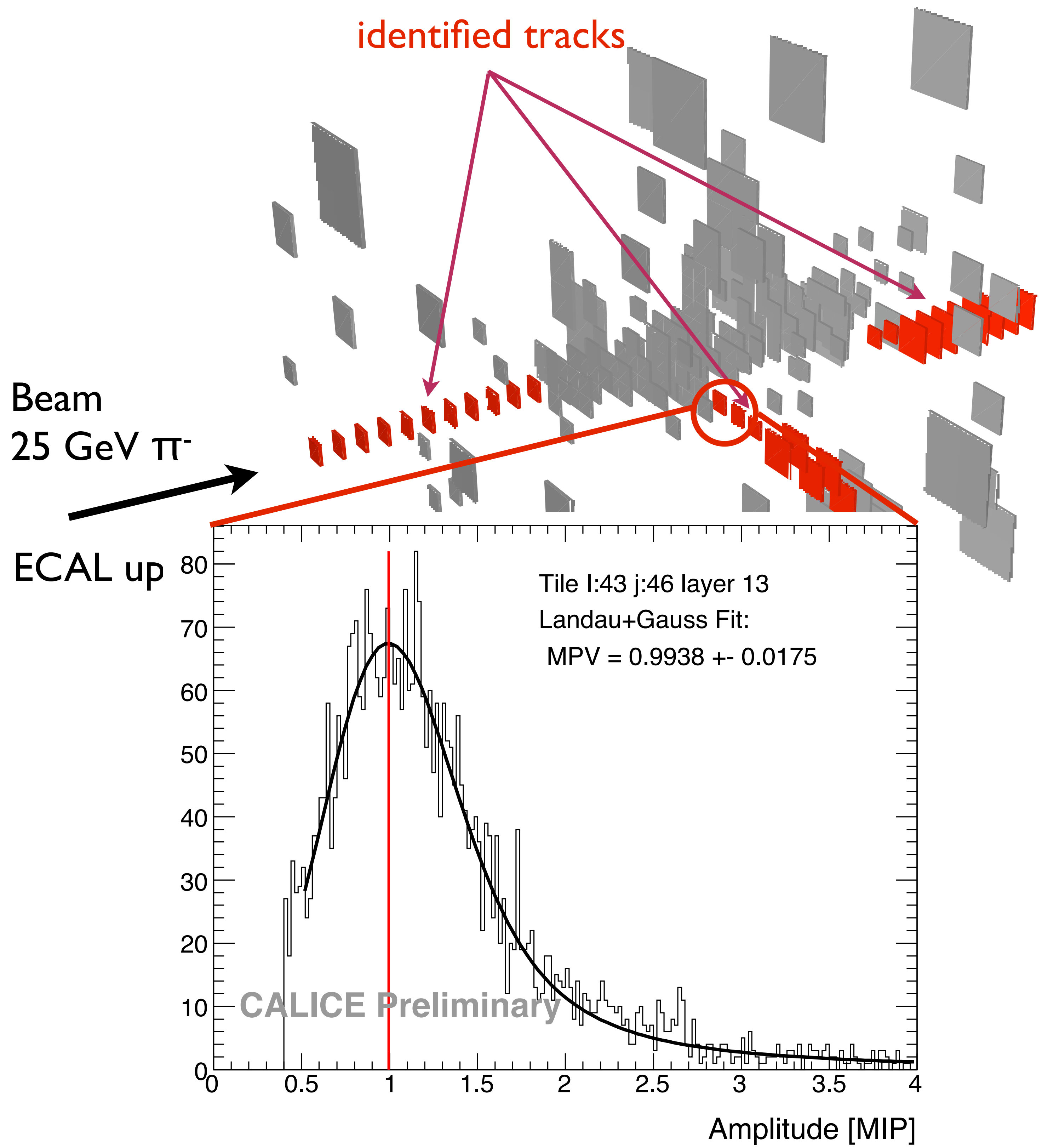
Tracking in Hadronic Showers: Hits on Track



- Special properties of cells on identified tracks:

What does the energy deposit look like?

Tracking in Hadronic Showers: Hits on Track



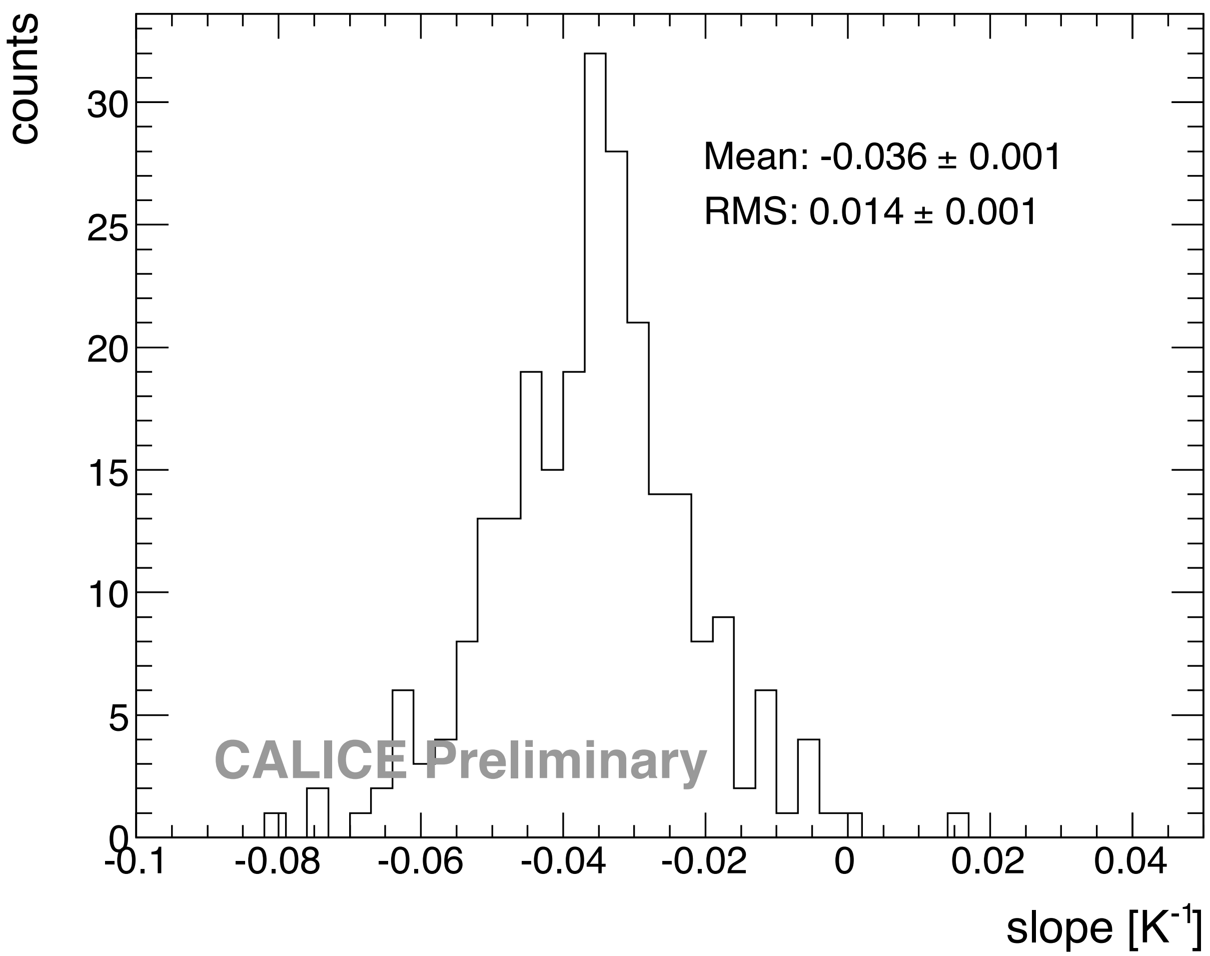
- Special properties of cells on identified tracks:

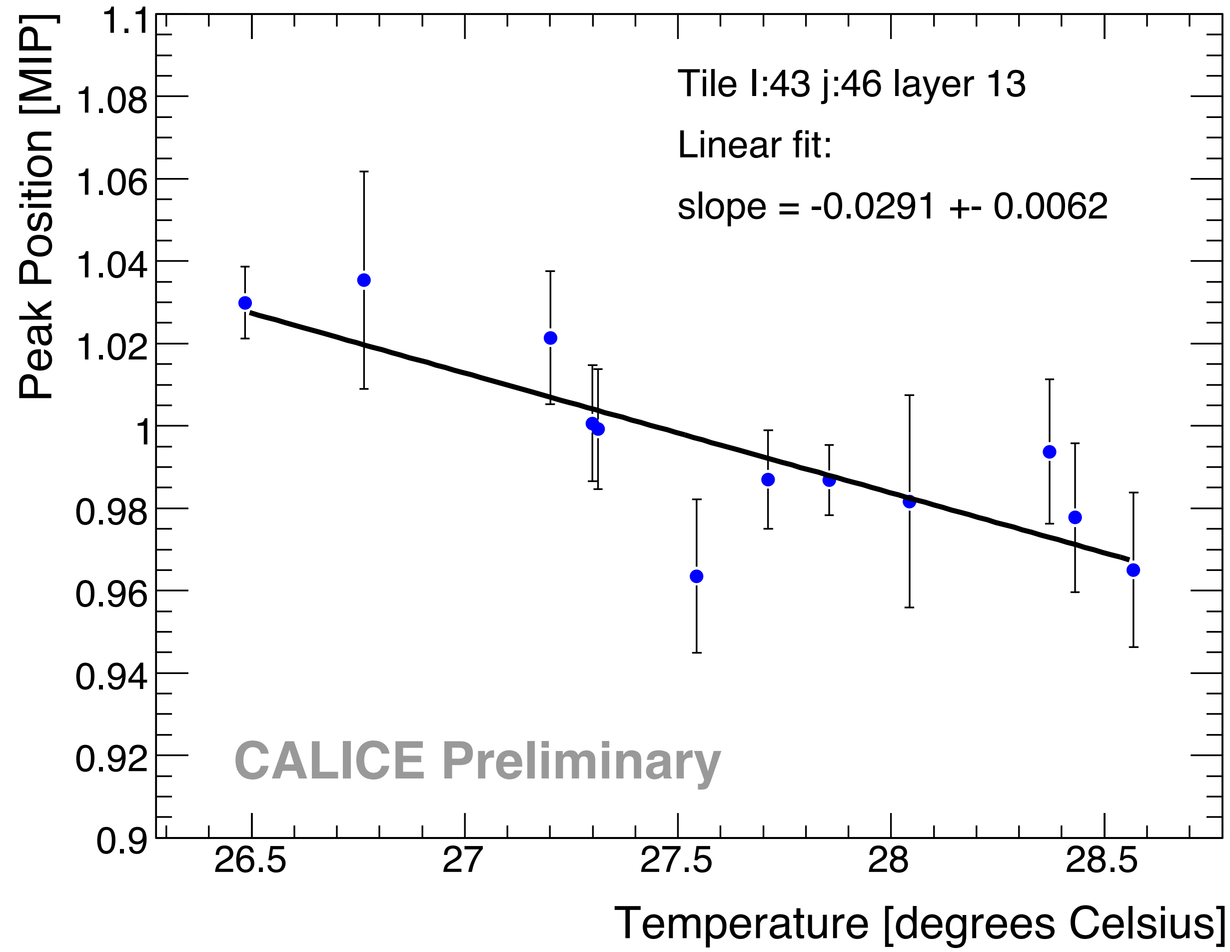
> What does the energy deposit look like?

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

Track Segments in Hadronic Showers

- Track segments used to study temperature dependence of SiPM response: Change of MPV of Energy distribution with cell temperature
  Mean Temperature dependence: -3.6%/K





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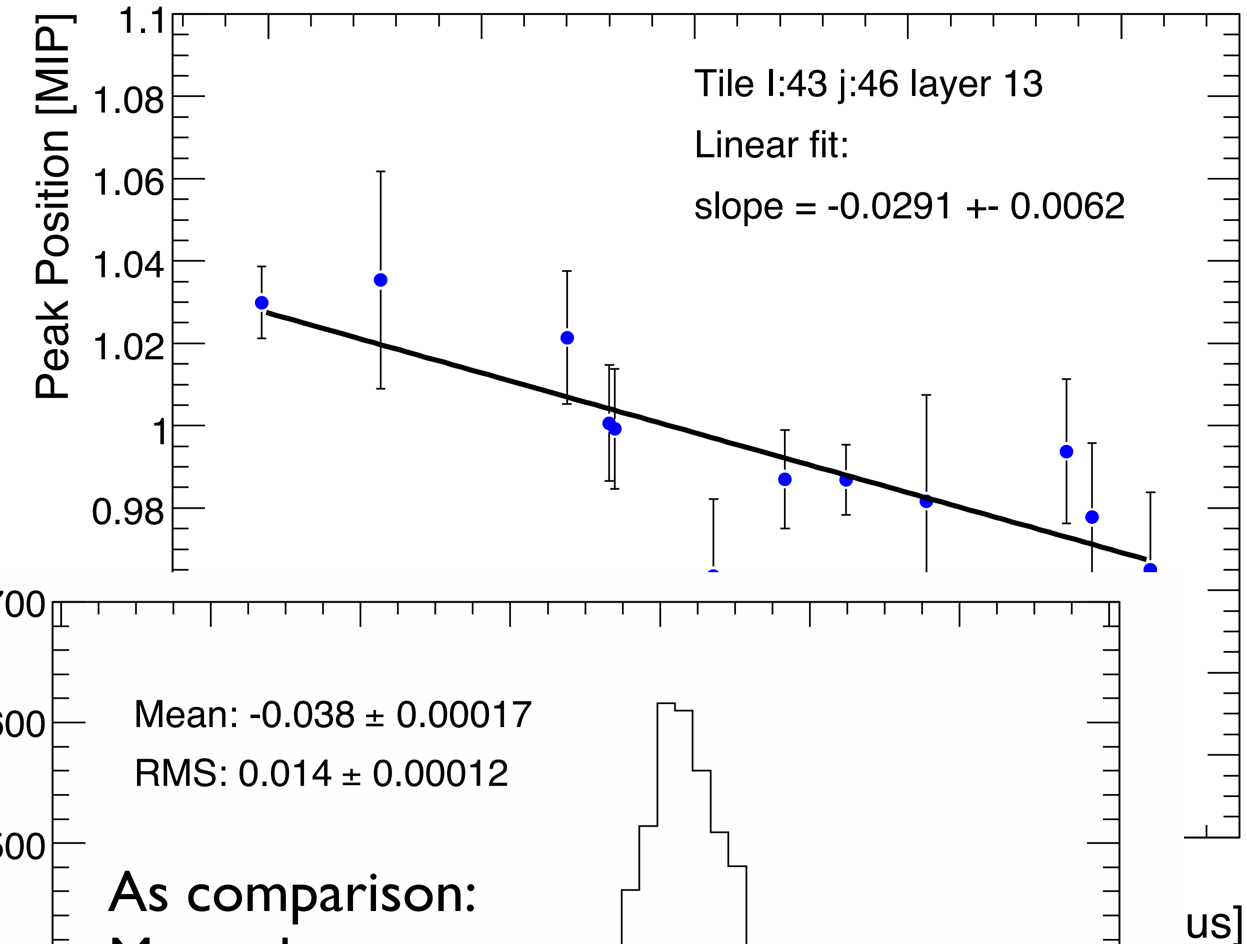

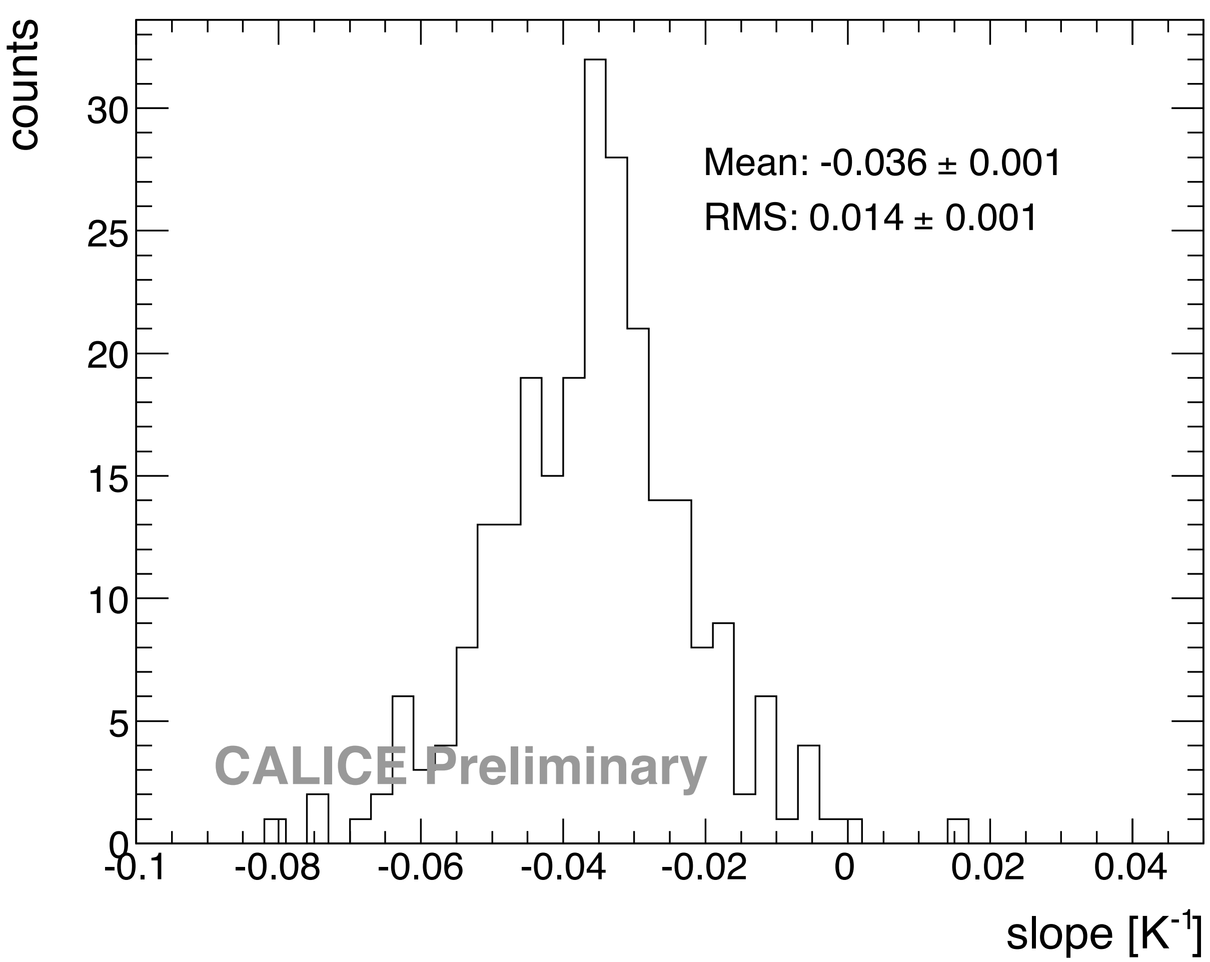

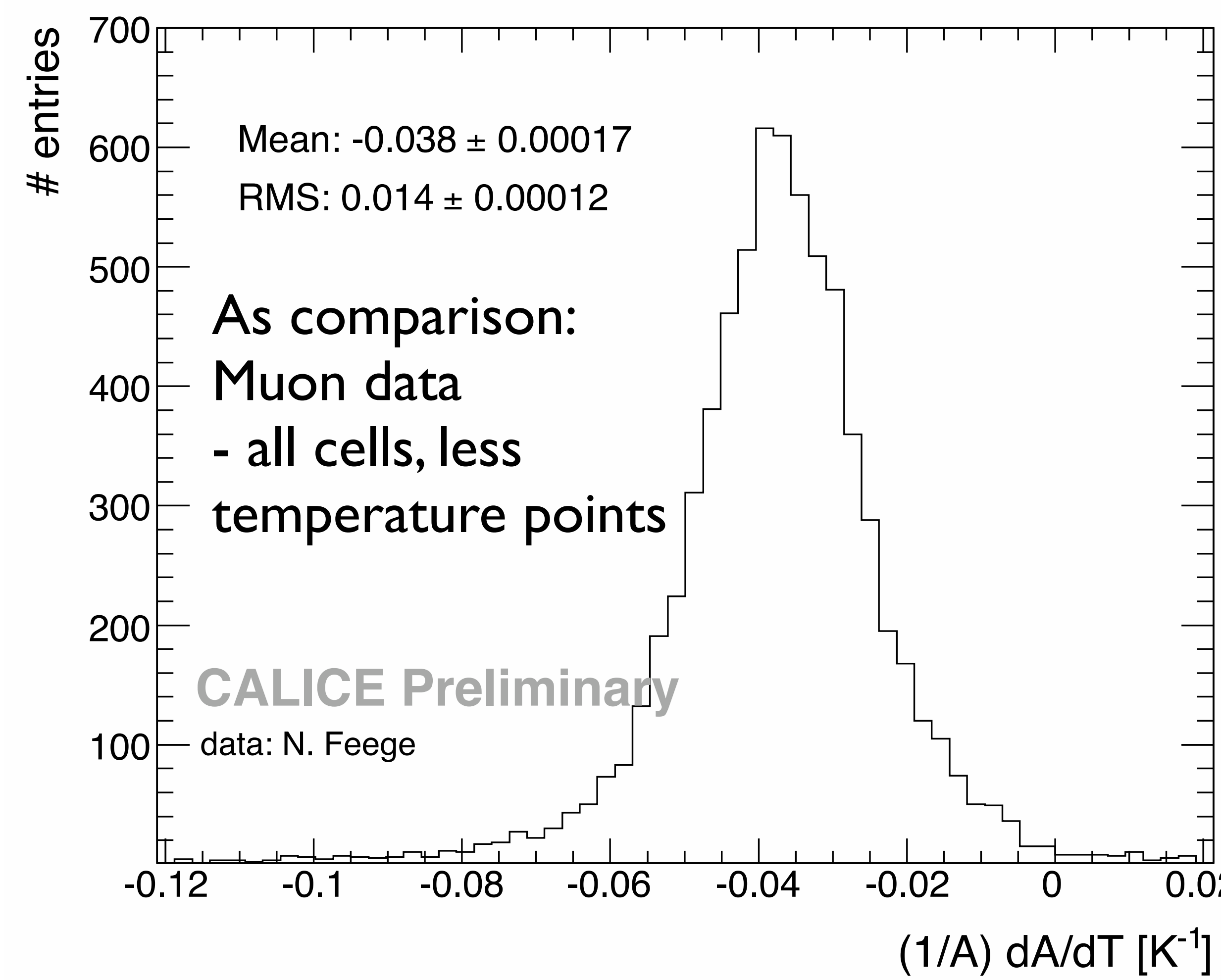

Track Segments: Depth in the Calorimeter

- If such track segments are to be used to study the detector properties, it is important that they go all the way through the detector

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What do you expect for the distribution? How likely is it to find a track at the front compared to the back of the detector?

Track Segments: Depth in the Calorimeter

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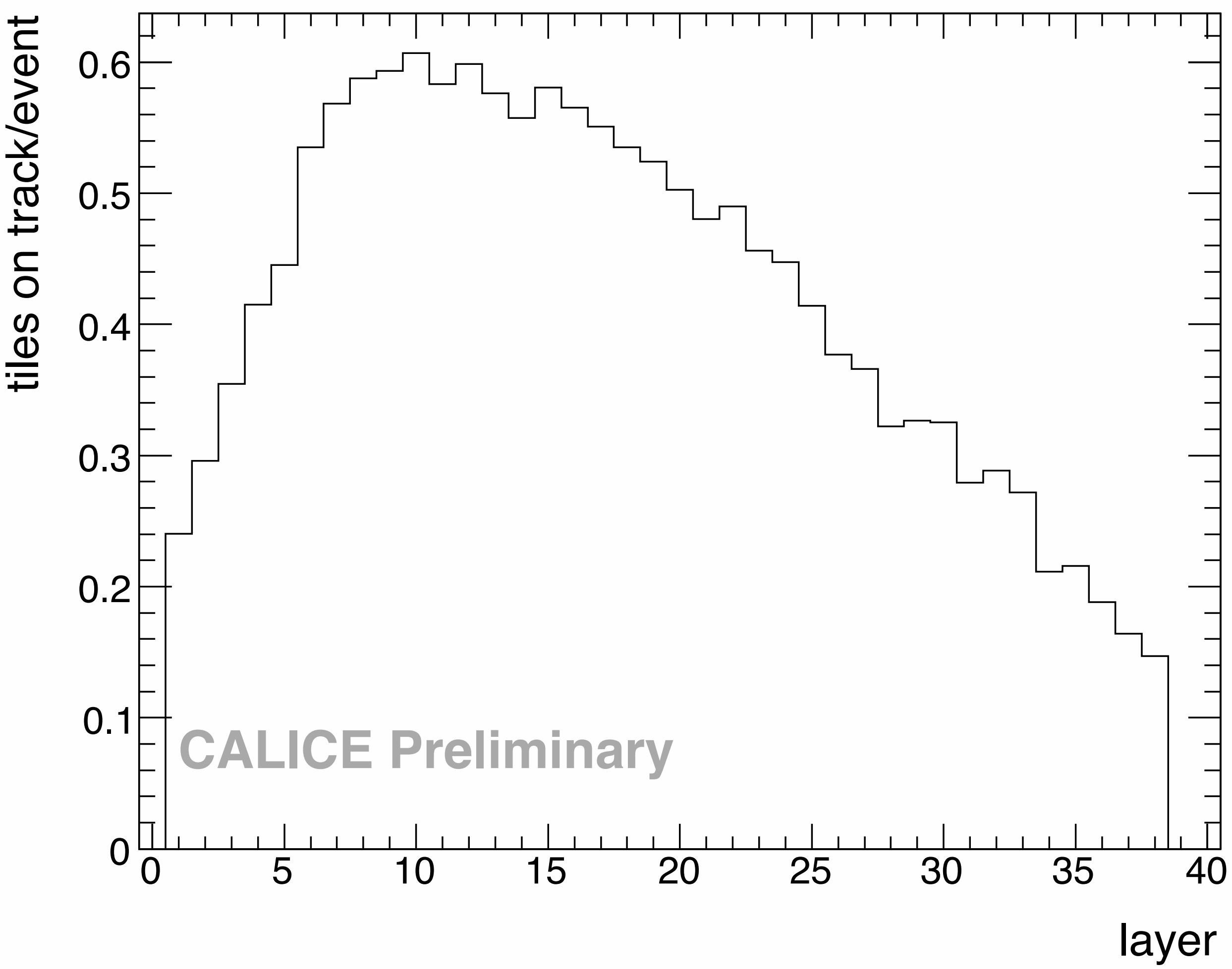
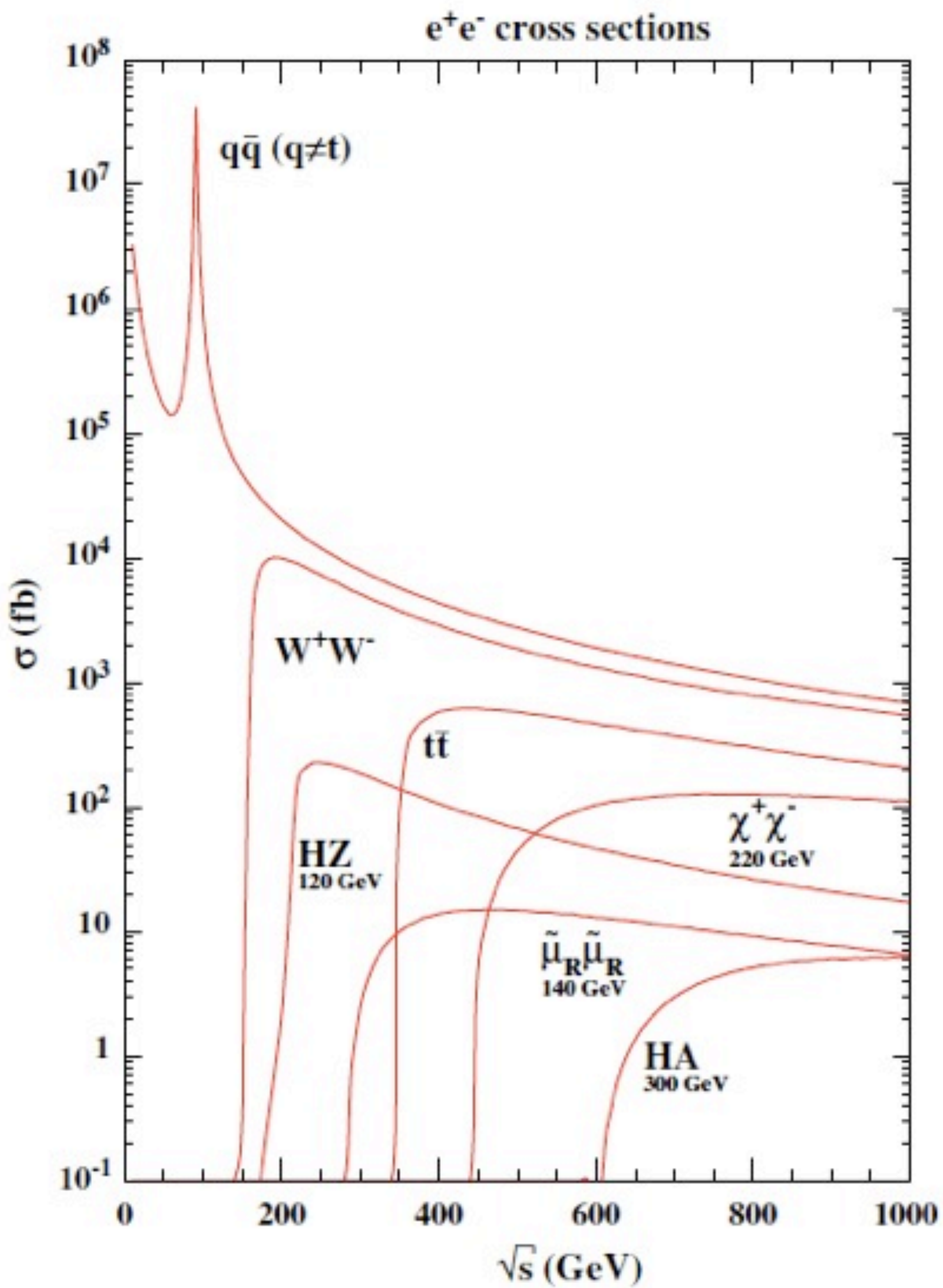
What do you expect for the distribution? How likely is it to find a track at the front compared to the back of the detector?



- Tracks in all layers of the detector
- the initial increase is due to the tracking algorithm: uses only HCAL information, requires a minimum track length of 8 layers
- some contribution from muons (~ 5%)

Expanding to a real Detector

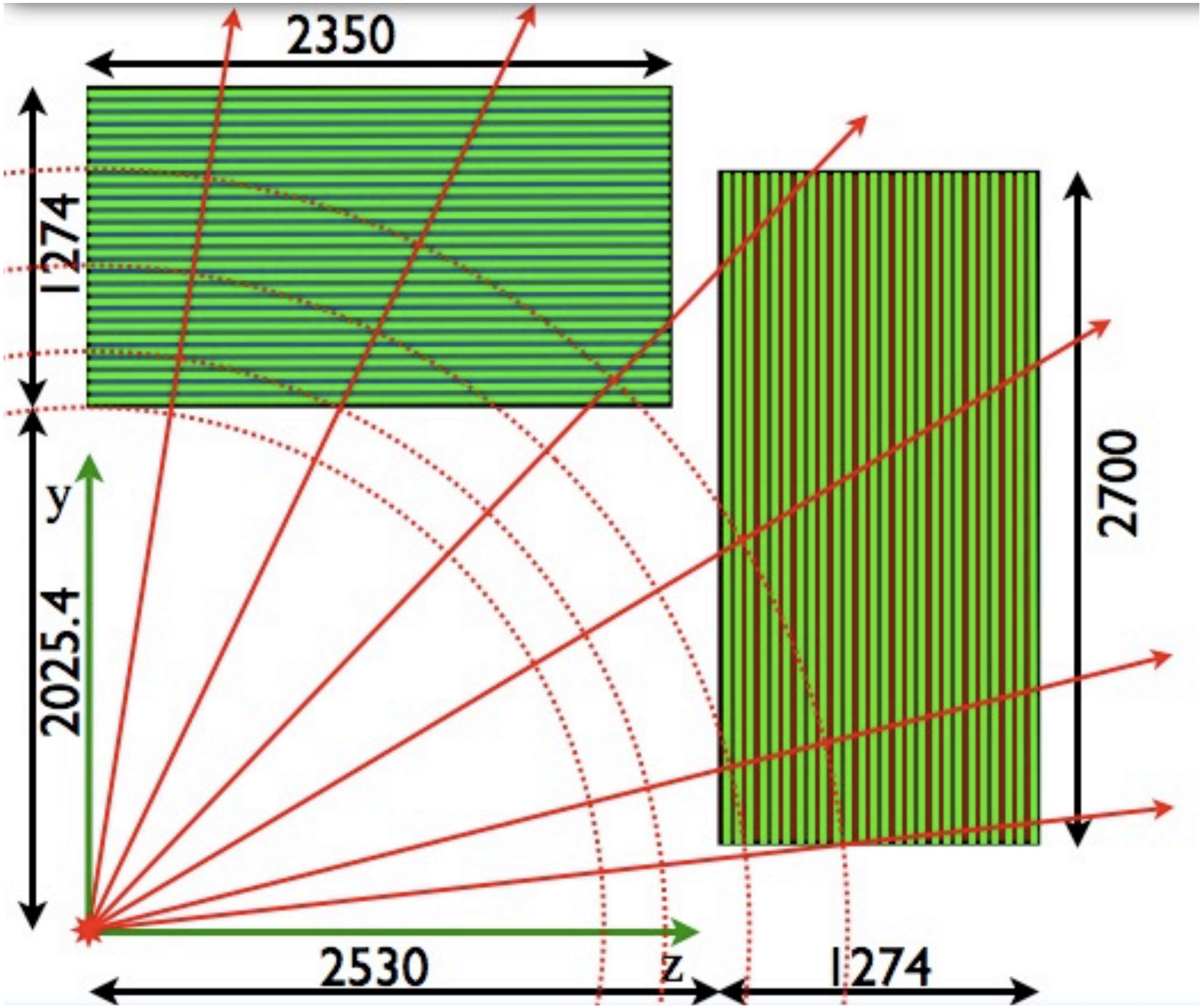
- Ideally use real data to constantly calibrate the detector



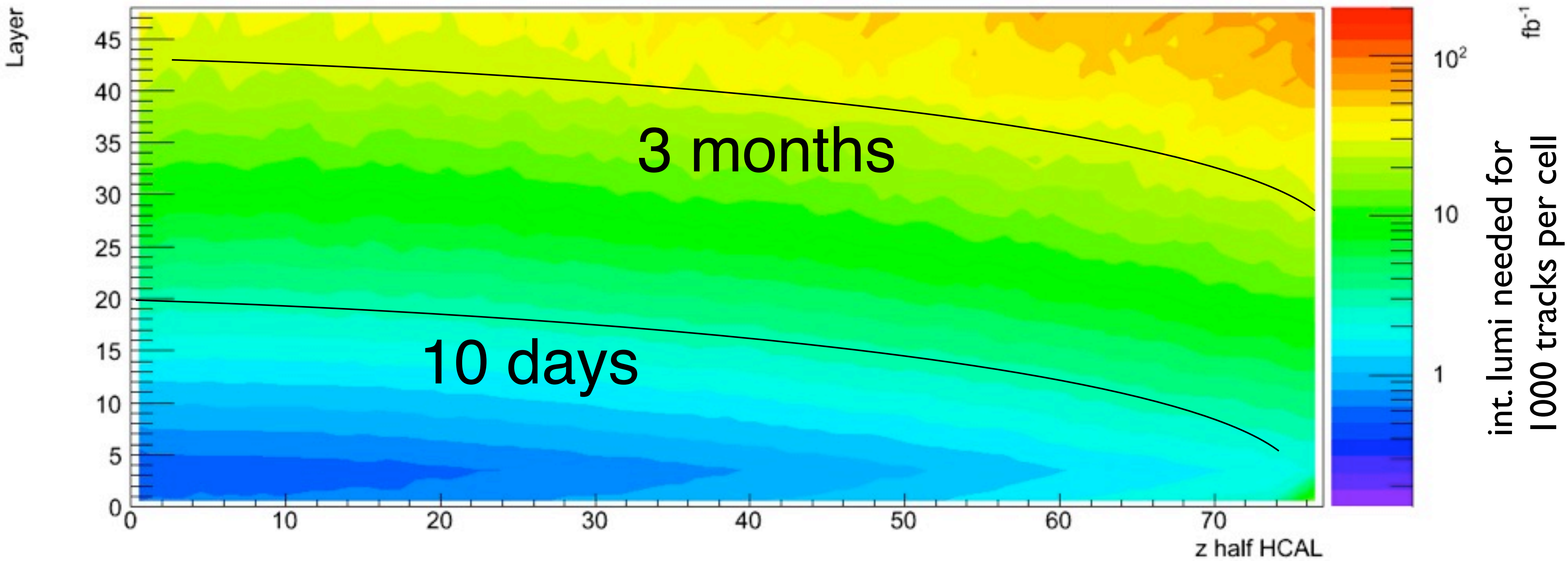
- But: A lot of events needed to get good statistics: A complete HCAL system (Barrel and Endcap) has ~ 8 million channels, and you need many tracks in each of them!

- The only hope: A process with a large cross section: Run the accelerator at the Z resonance: ~ 30 nb cross section, compared to ~ 3 pb at 500 GeV

HCAL Barrel and Endcap in the ILD Detector Concept



Rough Estimate for the Barrel HCAL

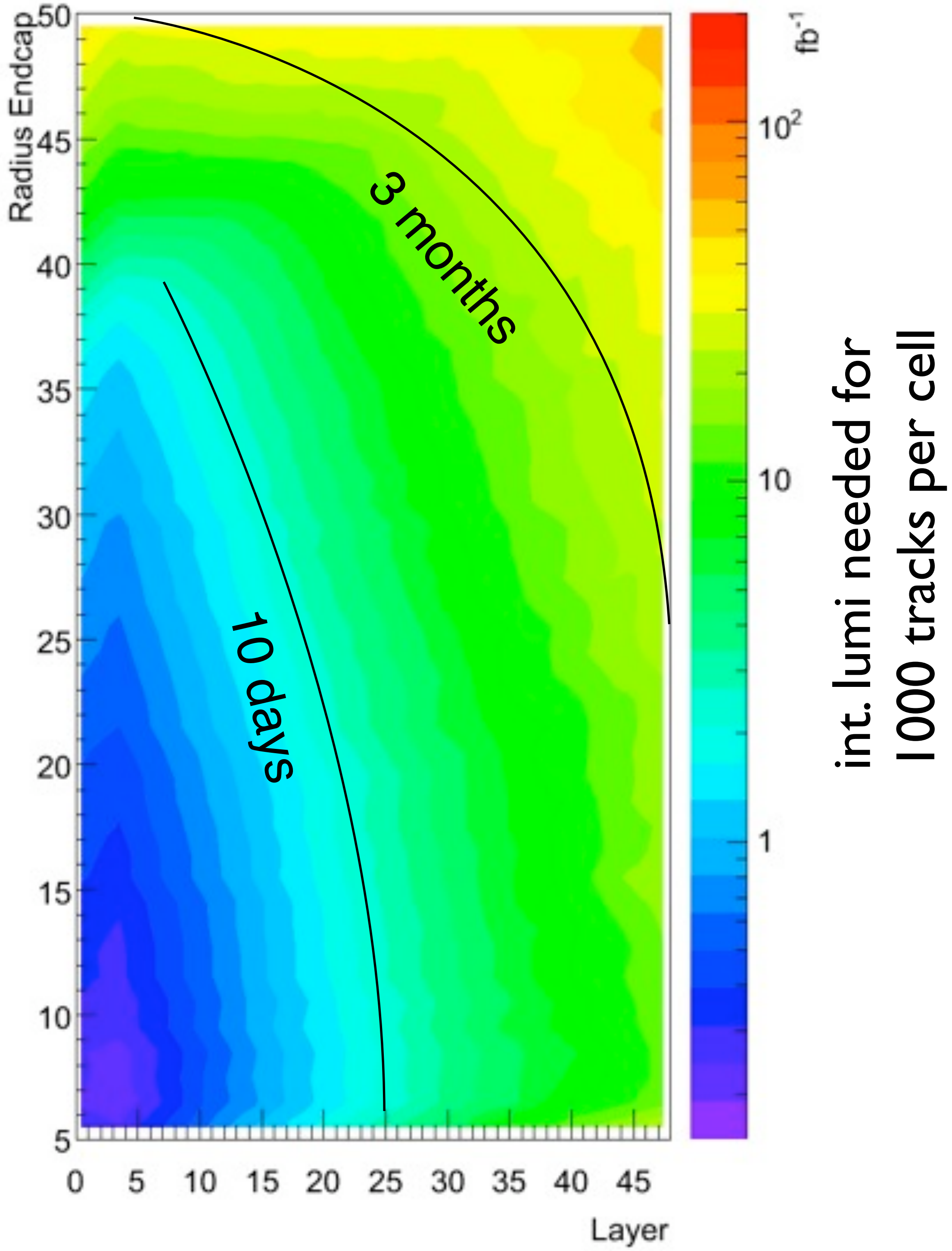


- For a good cell-by-cell calibration: 1000 entries per cell assumed
- combining several cells will significantly reduce luminosity needs, does not compromise the calibration studies
- Natural unit: One electronics board (HBU) with 144 scintillator tiles
- already get somewhere with a few 10 pb-1!

Rough Estimate for the Endcap HCAL

- For a good calibration: 1000 entries per cell
- Same as for the barrel: Grouping of cells can make things much faster

- Need a good intercalibration within the individual modules before installation: Careful construction and subsequent testing necessary



III.

The Power of Granular Calorimeters

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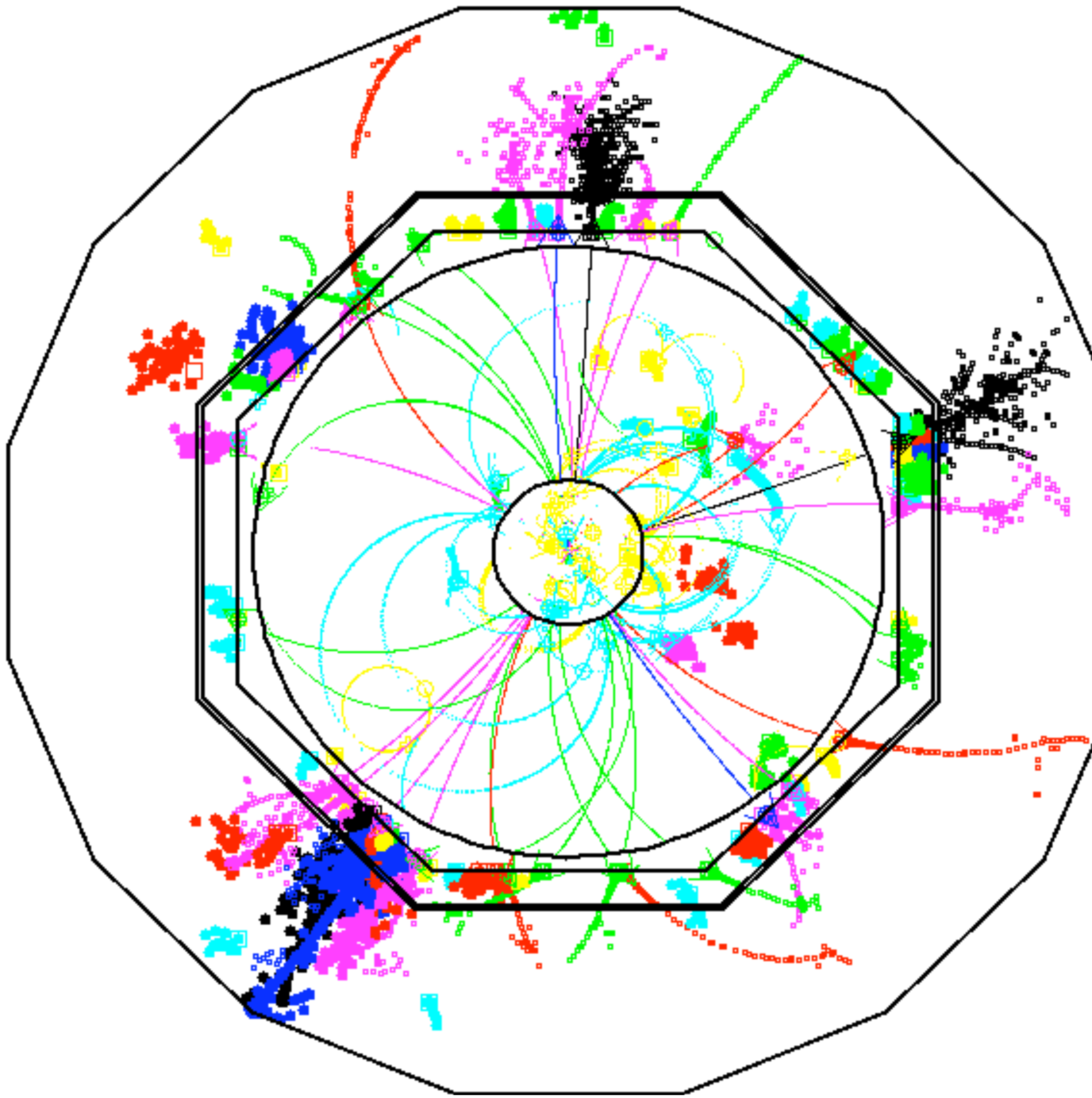
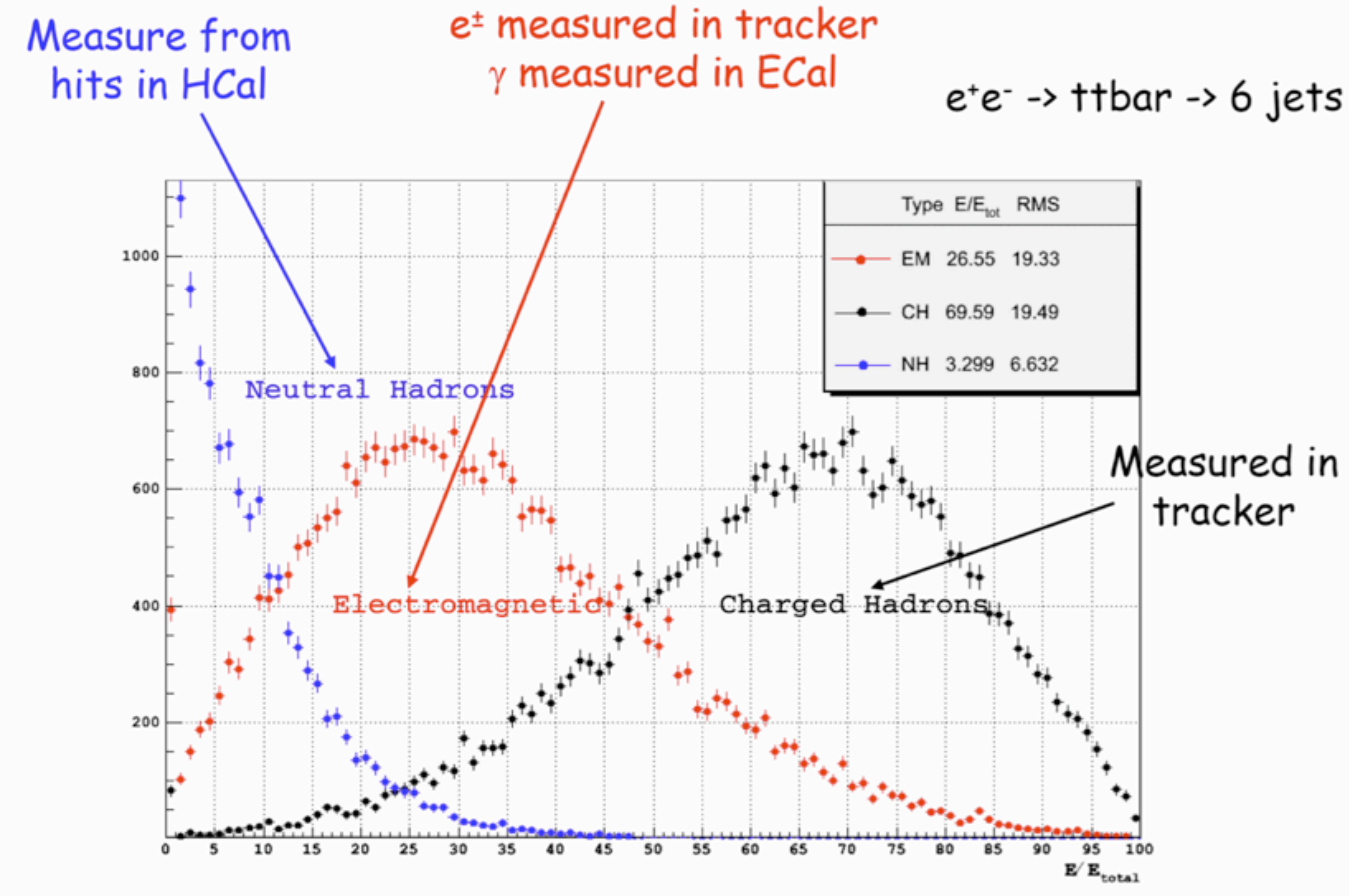
Shower Separation: Towards Particle Flow

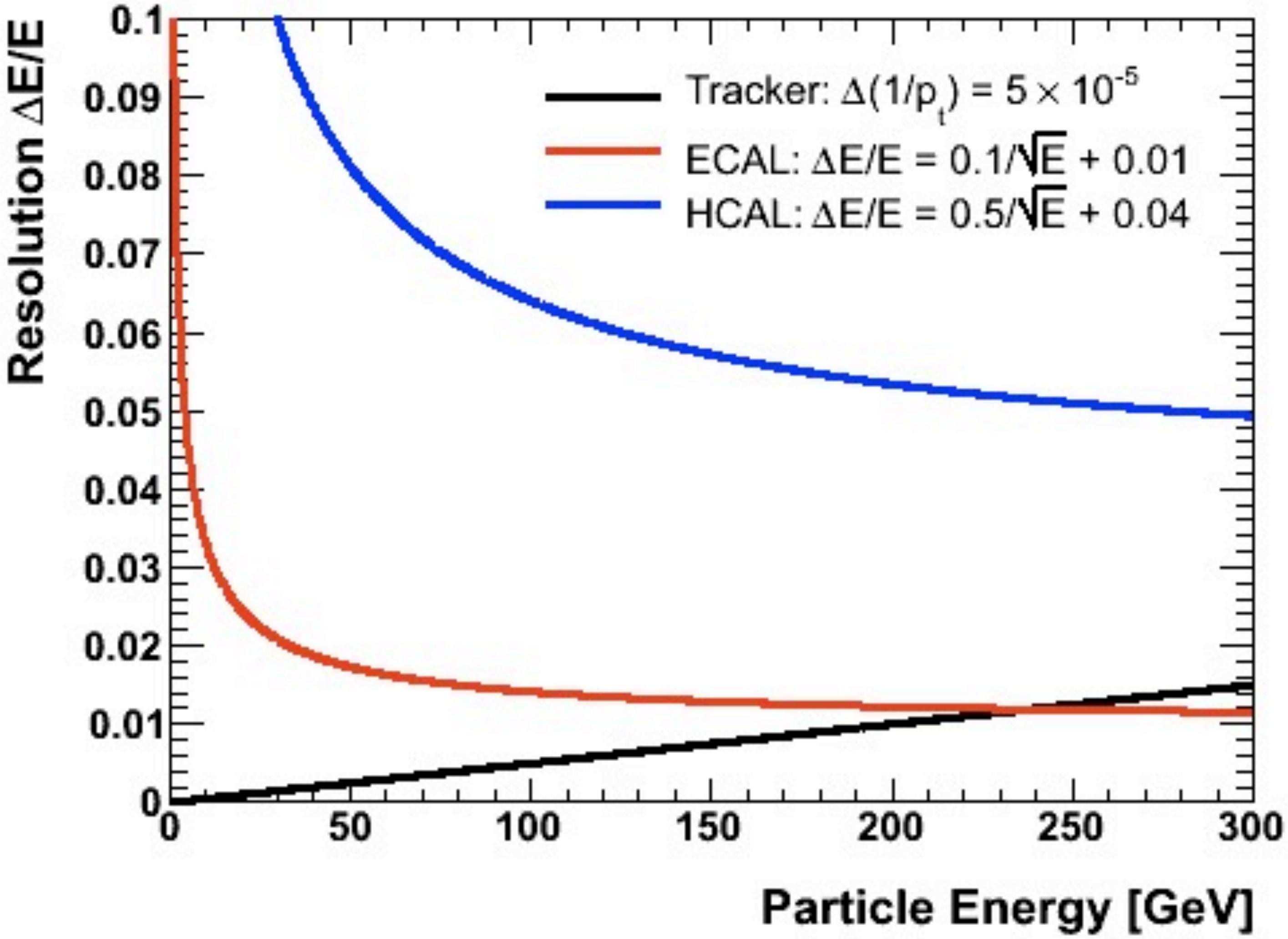
ILC: Measuring Jets

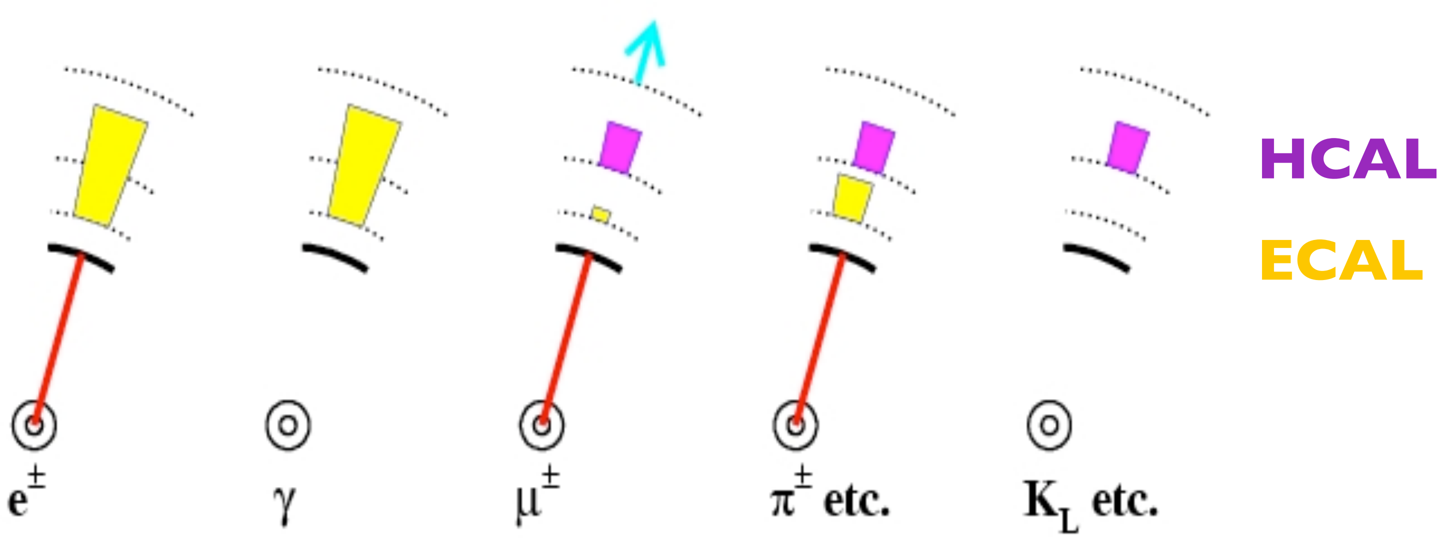


The Composition of a Jet



Optimized Jet Energy Resolution: Particle Flow

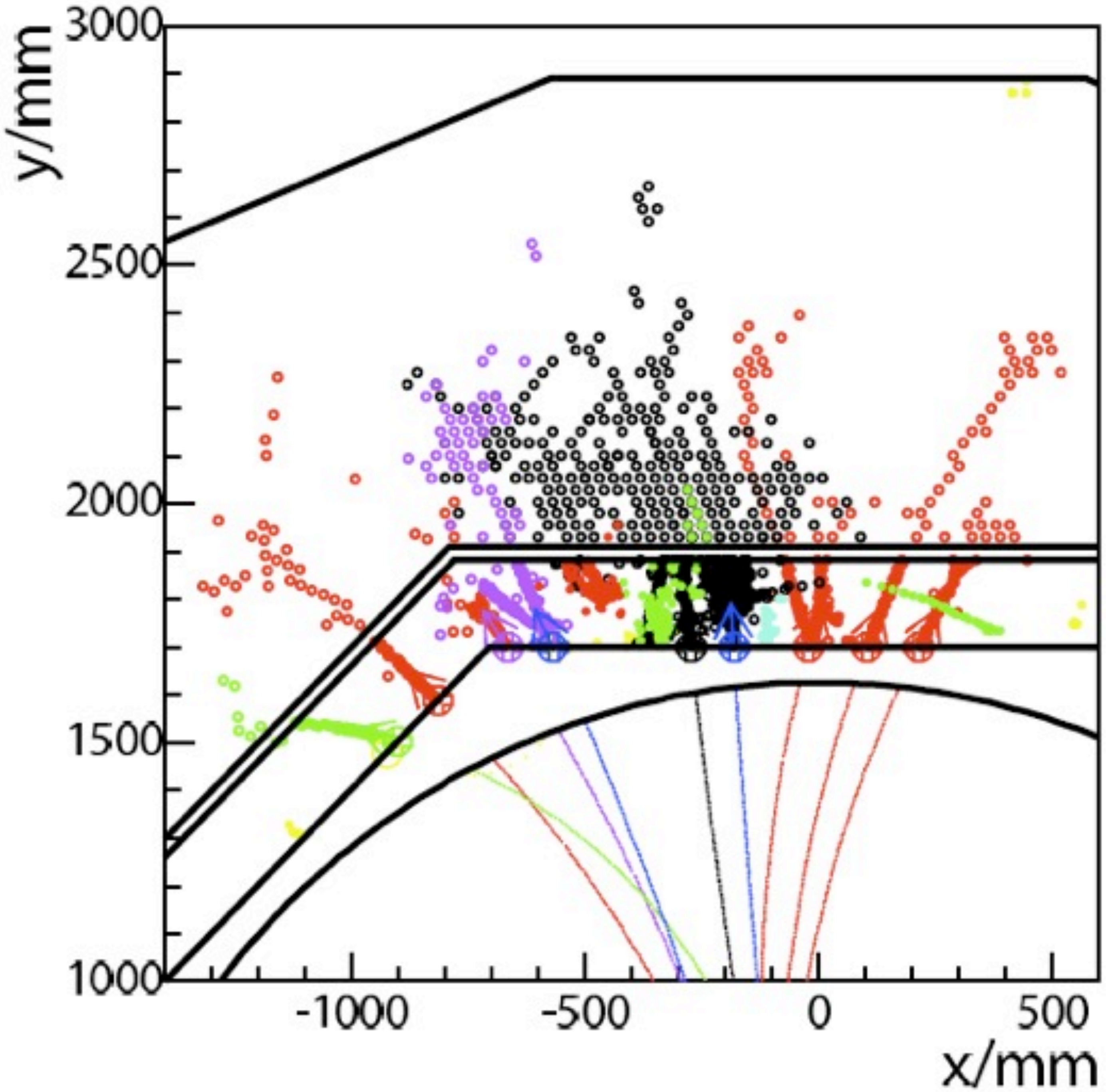




The idea:

- Combination of information from all detector systems
  - classical jet finding: Calorimeters only (ECAL und HCAL)
- The tracker gives the best resolution for charged particles over most of the momentum range
  - Only neutral particles are measured with the calorimeters: Photons in the ECAL; n, K_L in the HCAL

Particle Flow: What is needed from the Detectors?



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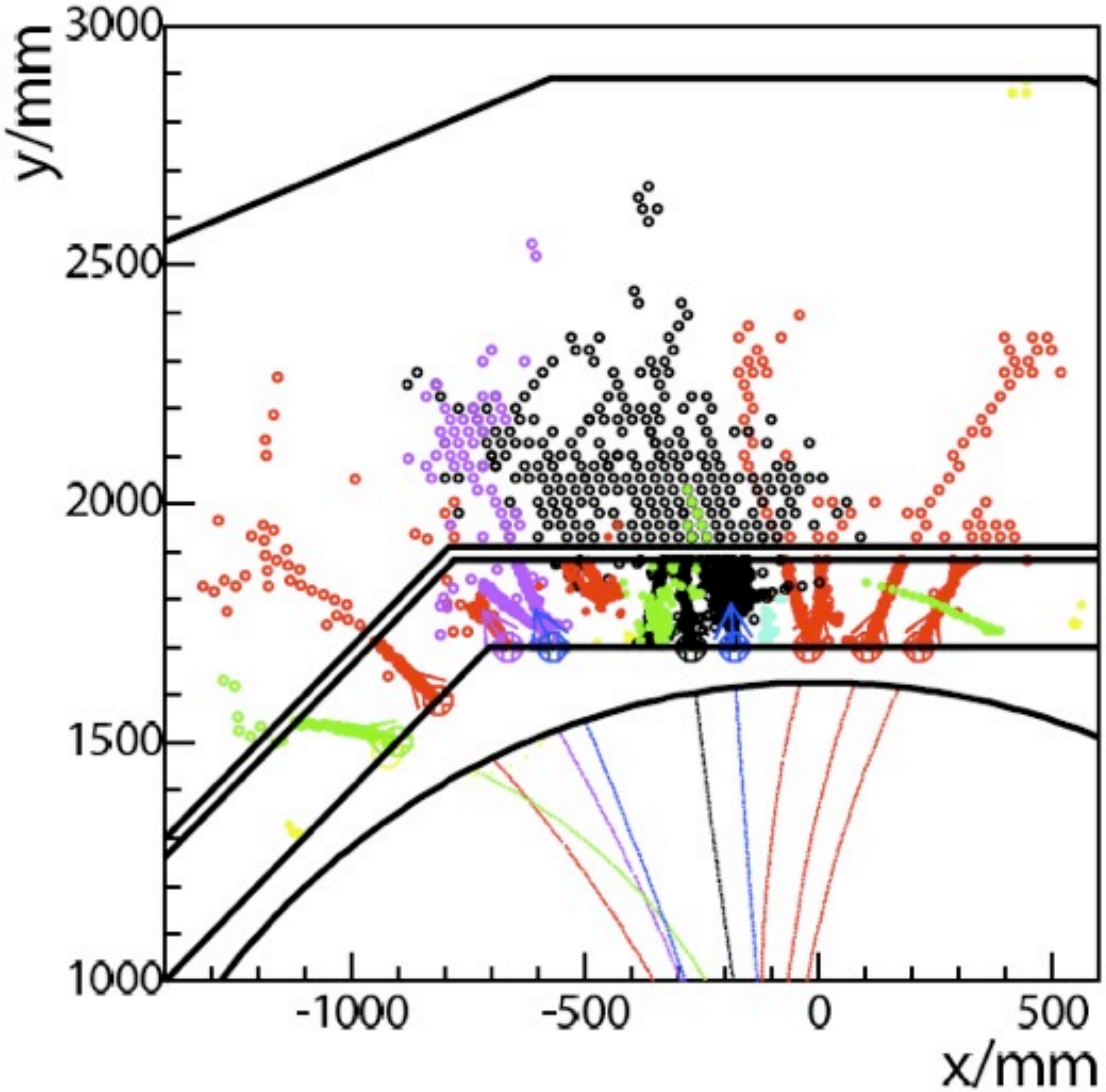
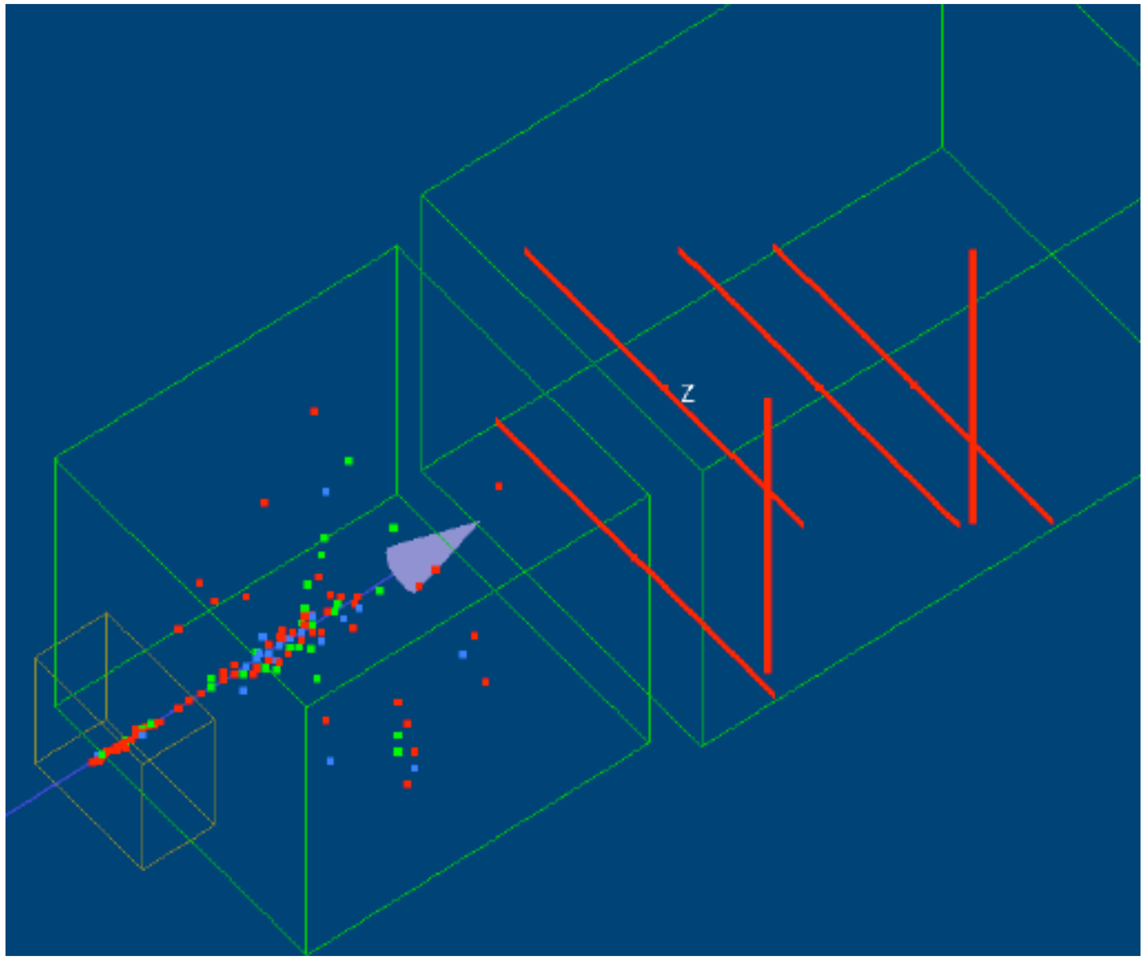


- Crucial: Avoid double counting! Charged hadrons and electrons also deposit energy in the calorimeters, so you can only use the tracker measurement if you know what to ignore in the calorimeters!
  - High granularity of the detectors, to separate showers of different particles!

Studying PFA Performance

- How do you study PFA performance in a test beam? Remember: You only get single particles with known energy!



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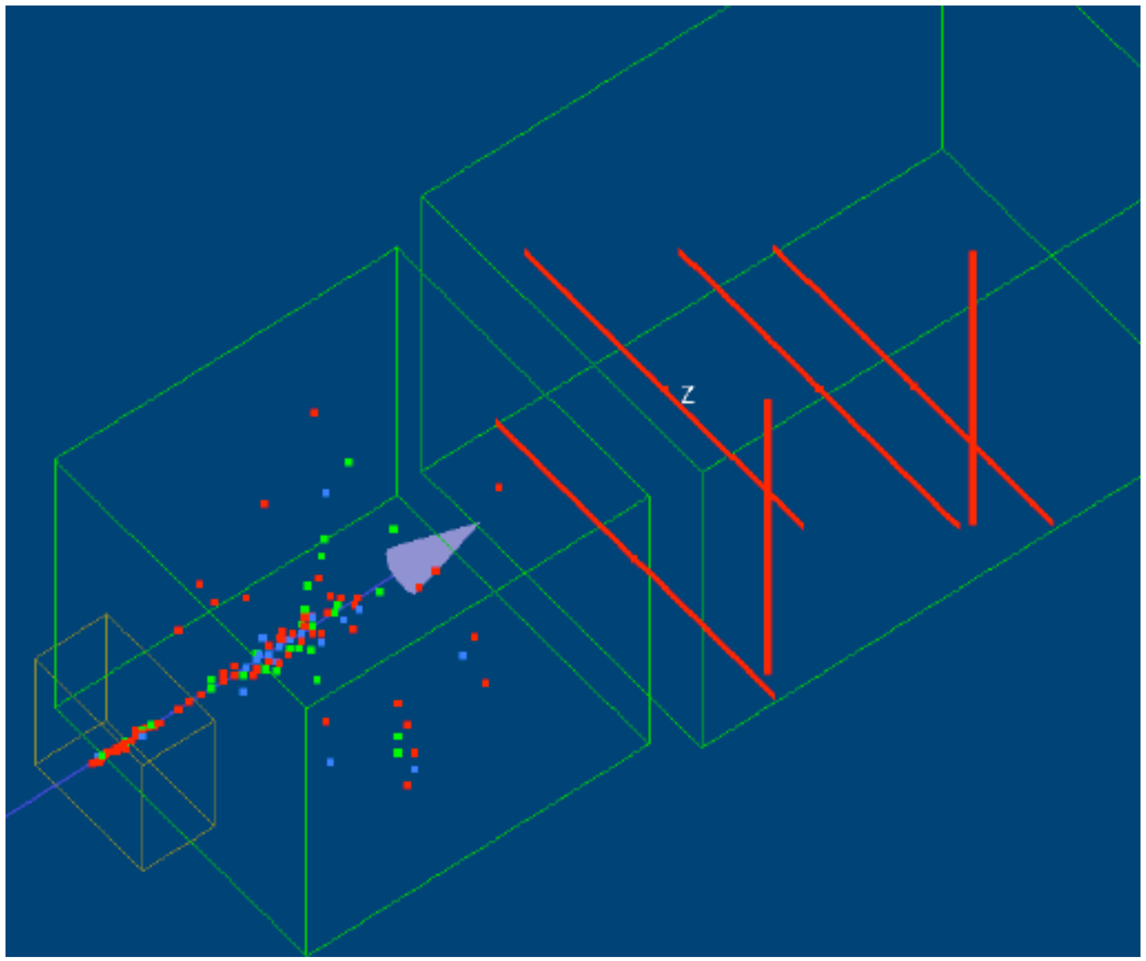
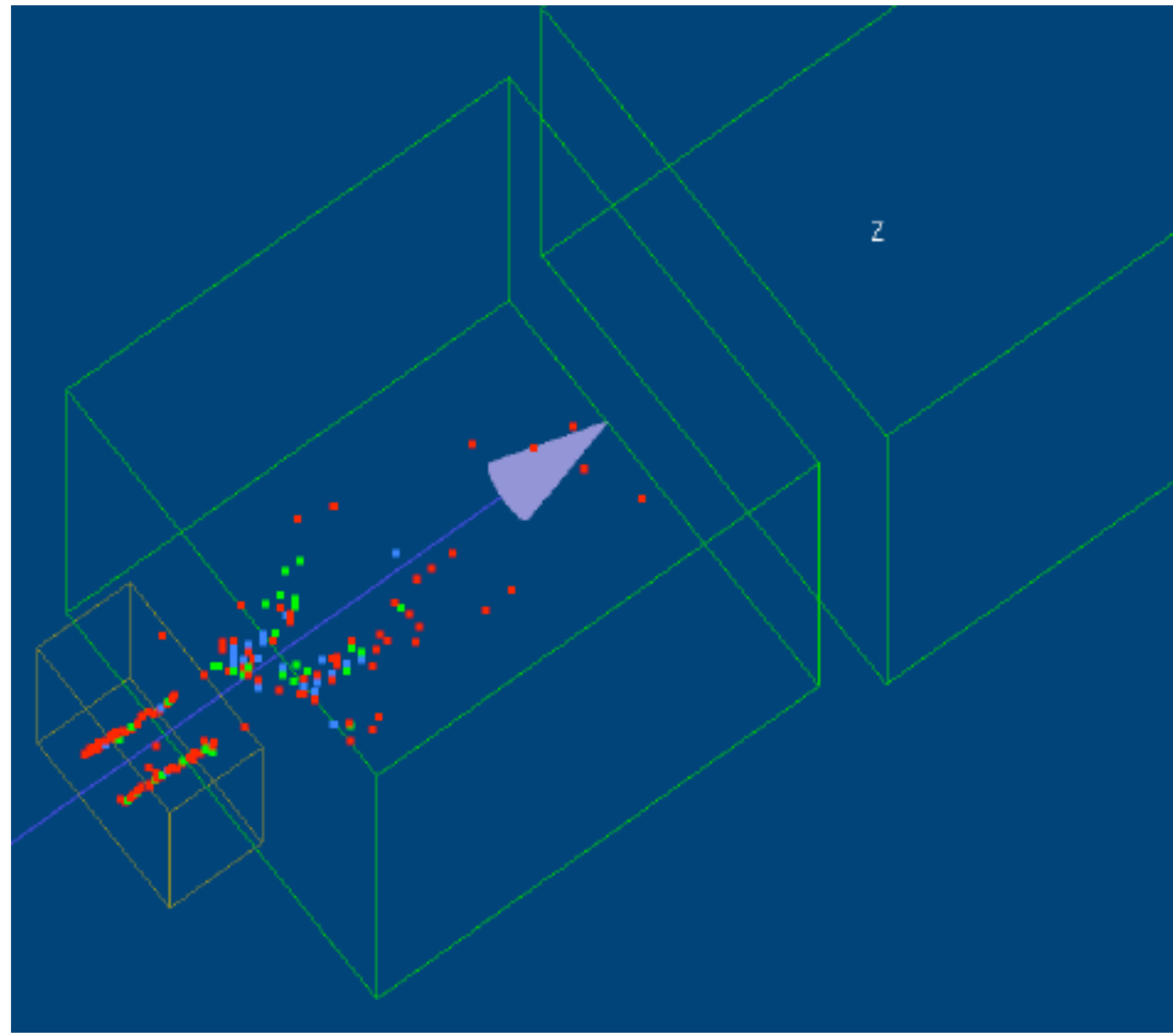


Combine two real events (in software)!



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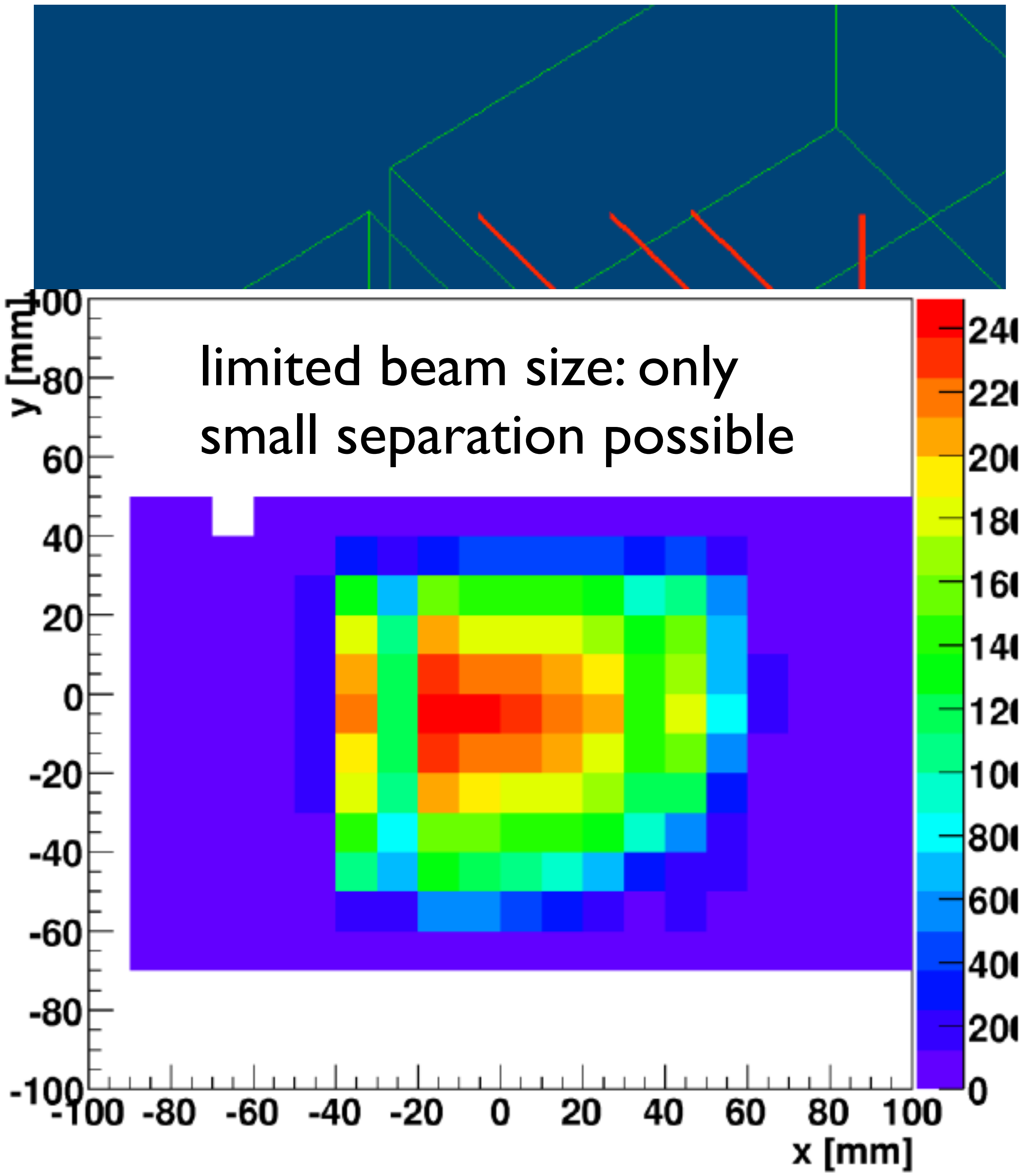

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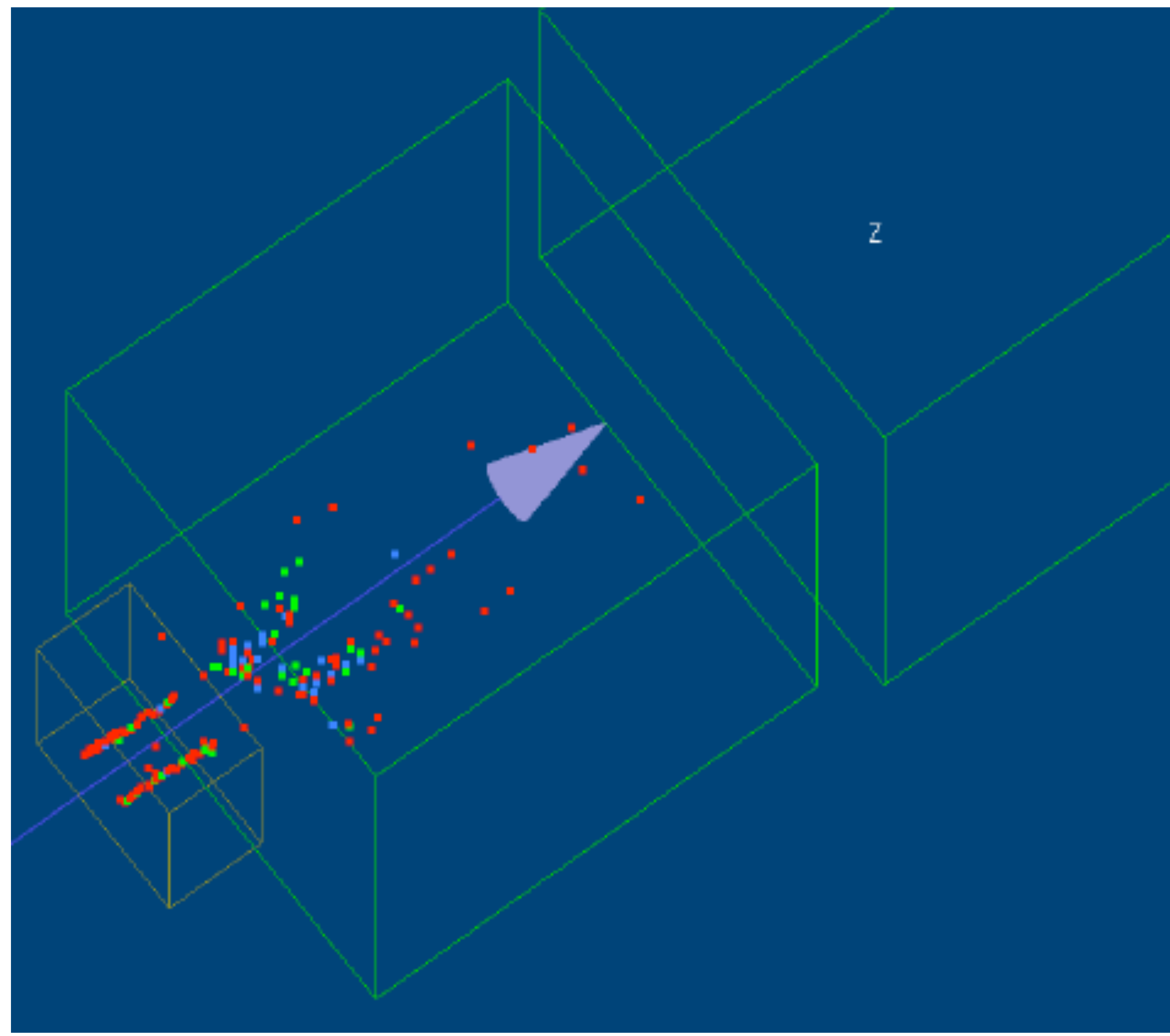
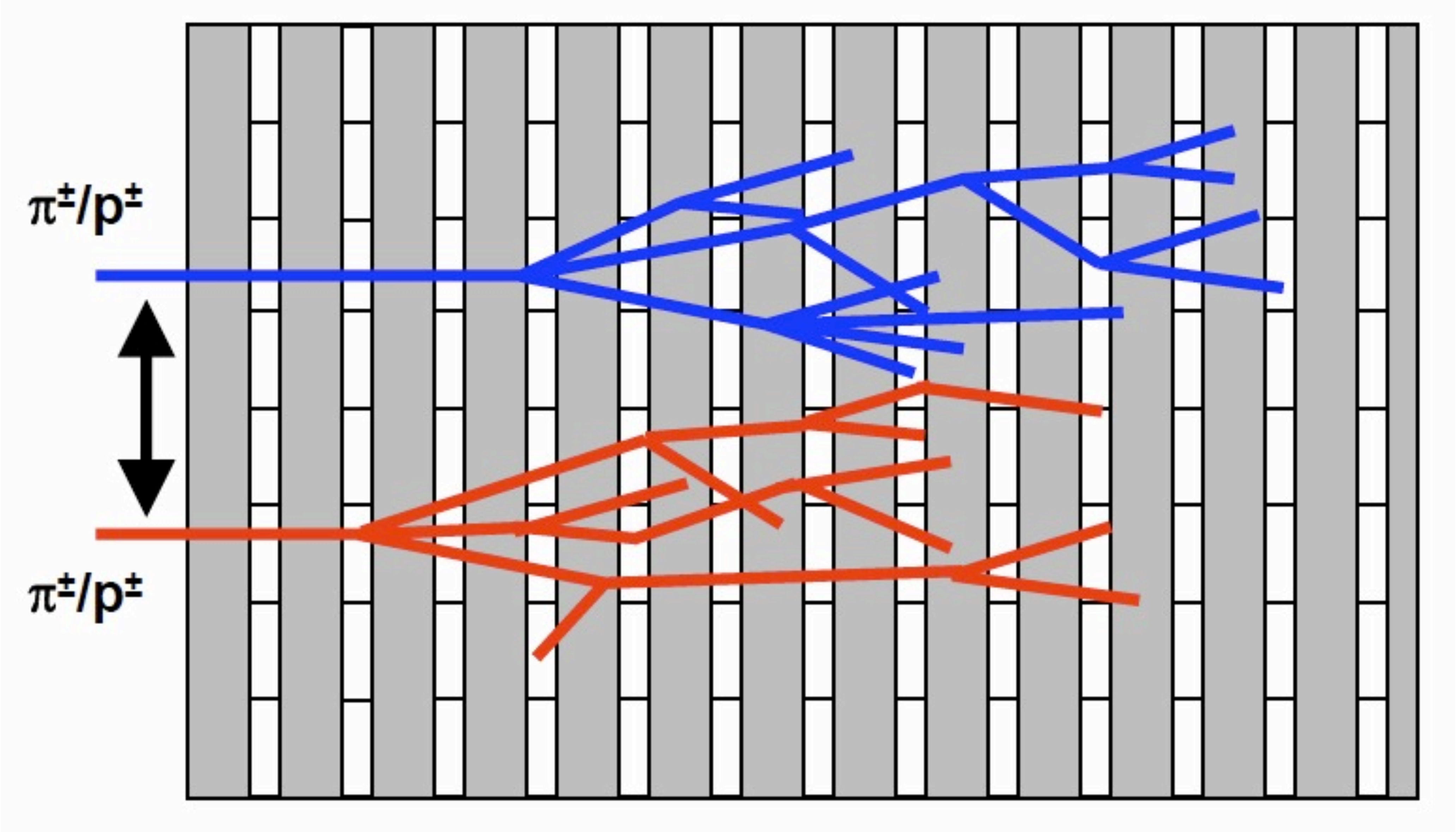
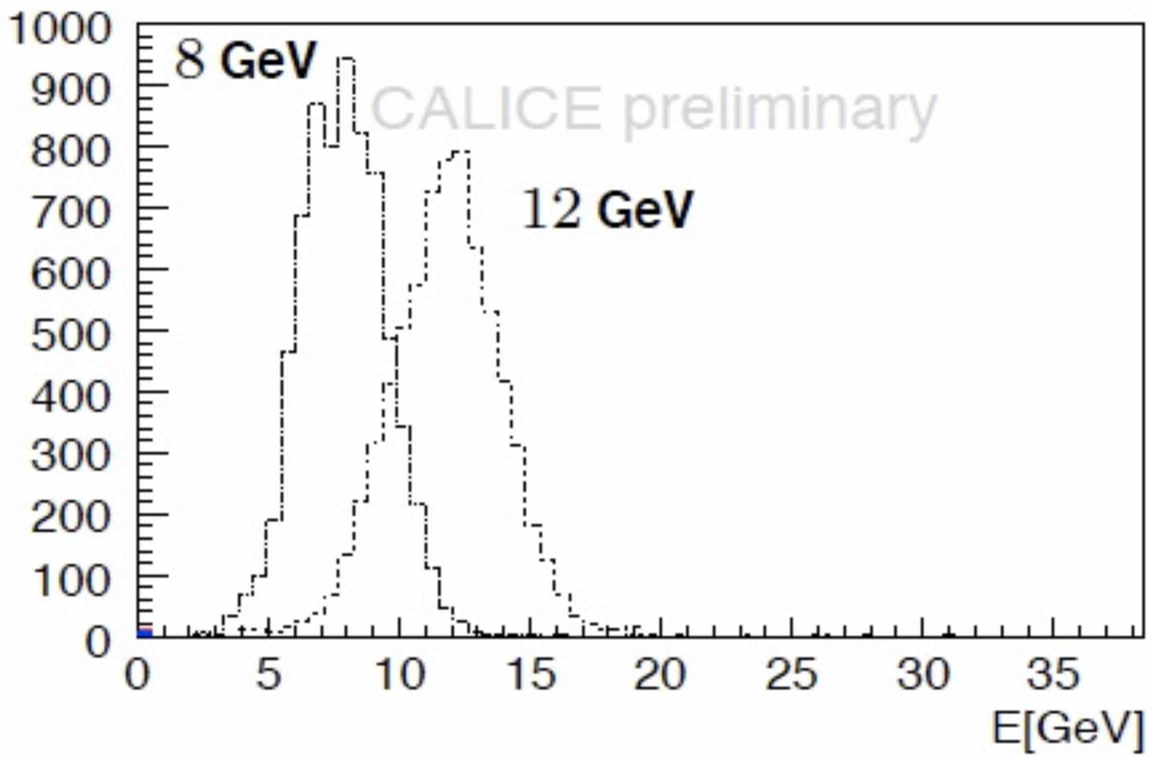


Shower Overlay



Shower Separation: A Test of Particle Flow

- Test suitability of HCAL for PFA by investigating shower separation power
  - Build up a sample of overlapping showers by combining two hadron events at different energy:



1. Overlay events from different energies

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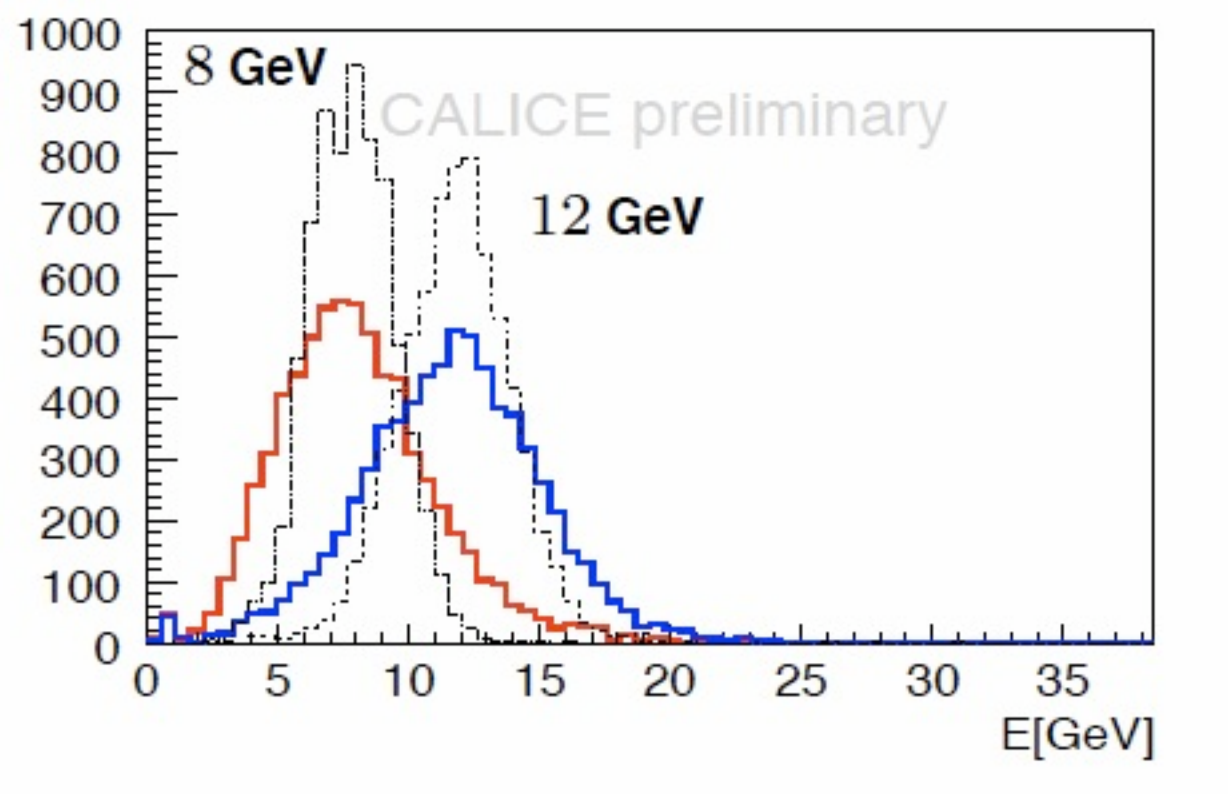

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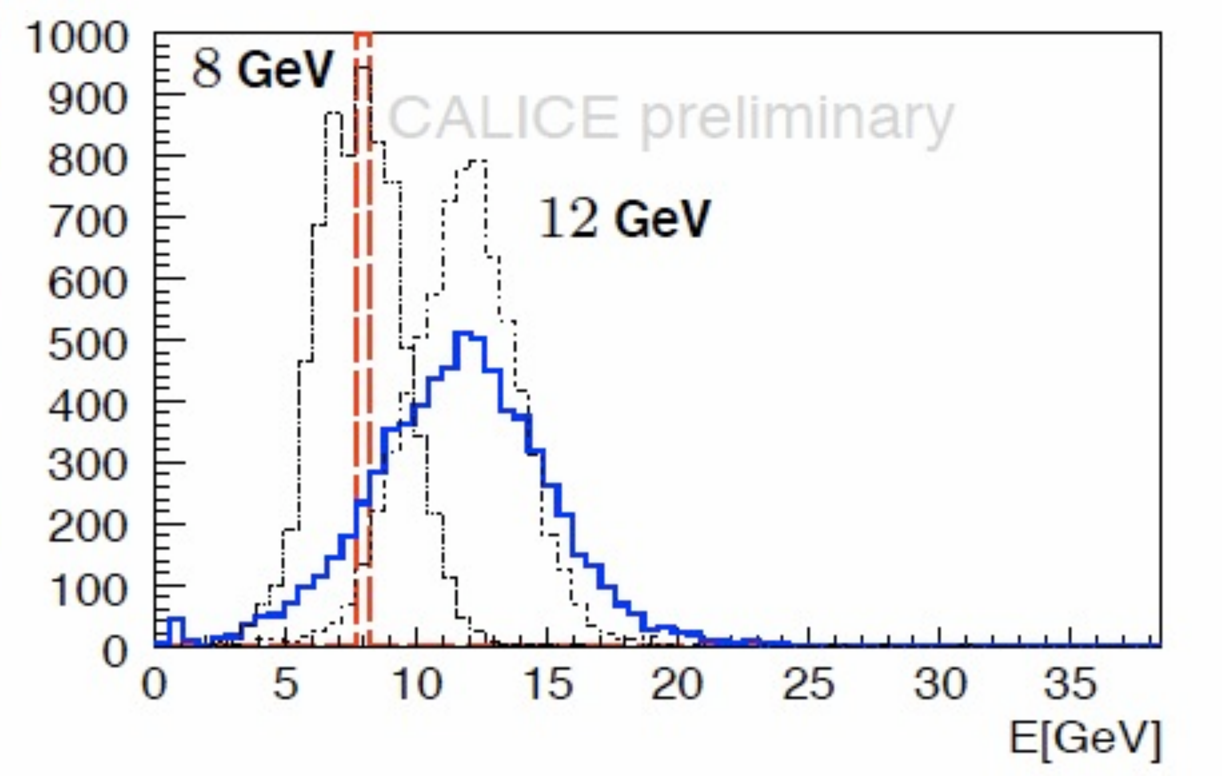
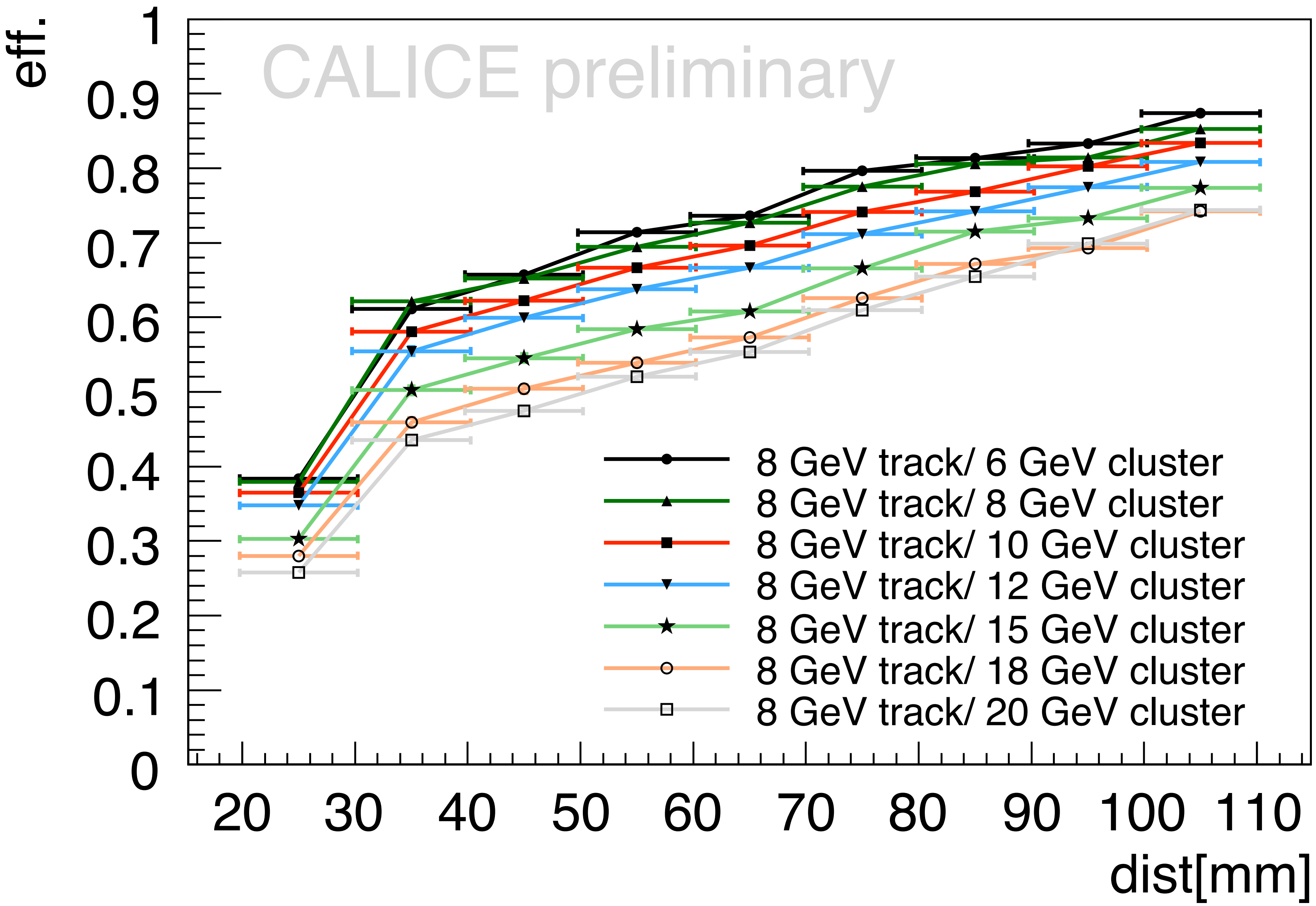


1. Overlay events from different energies
2. Reconstruct the showers
3. Assume PFA scenario: One well-measured charged track associated with one particle in the calorimeter, no association (neutral particle) for the other

The PFA Performance



Efficiency for correctly reconstructing the neutral particle with an energy within 3 σ as a function of shower distance

- Currently only very small distances due to available data set

III.
The Power of Granular Calorimeters
-
Energy Resolution, Software Compensation

Energy in Hadronic Showers

- In hadronic showers, some energy completely goes “missing”: binding energy, neutrons emitted outside the integration window of the electronics,...
  - Detectors only see charged particles in the cascade (and neutrons, depending on the detector)

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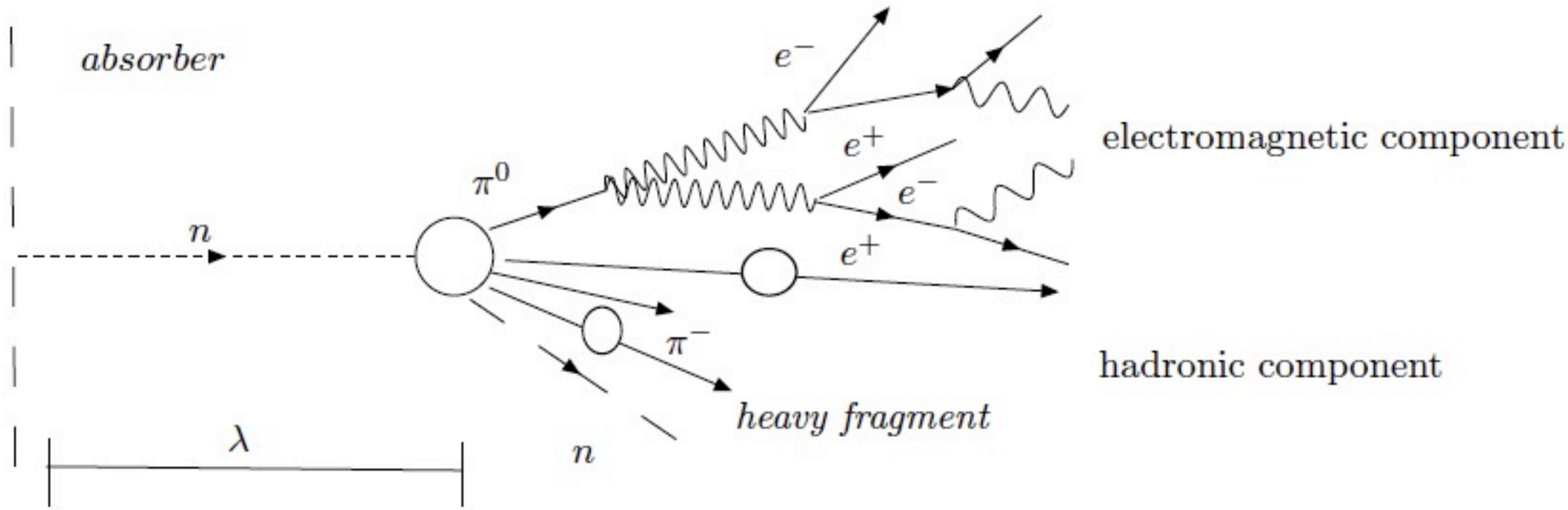
➯ Typically the response of a calorimeter will be less for hadrons than for electrons of the same energy! (non-compensating calorimeter)

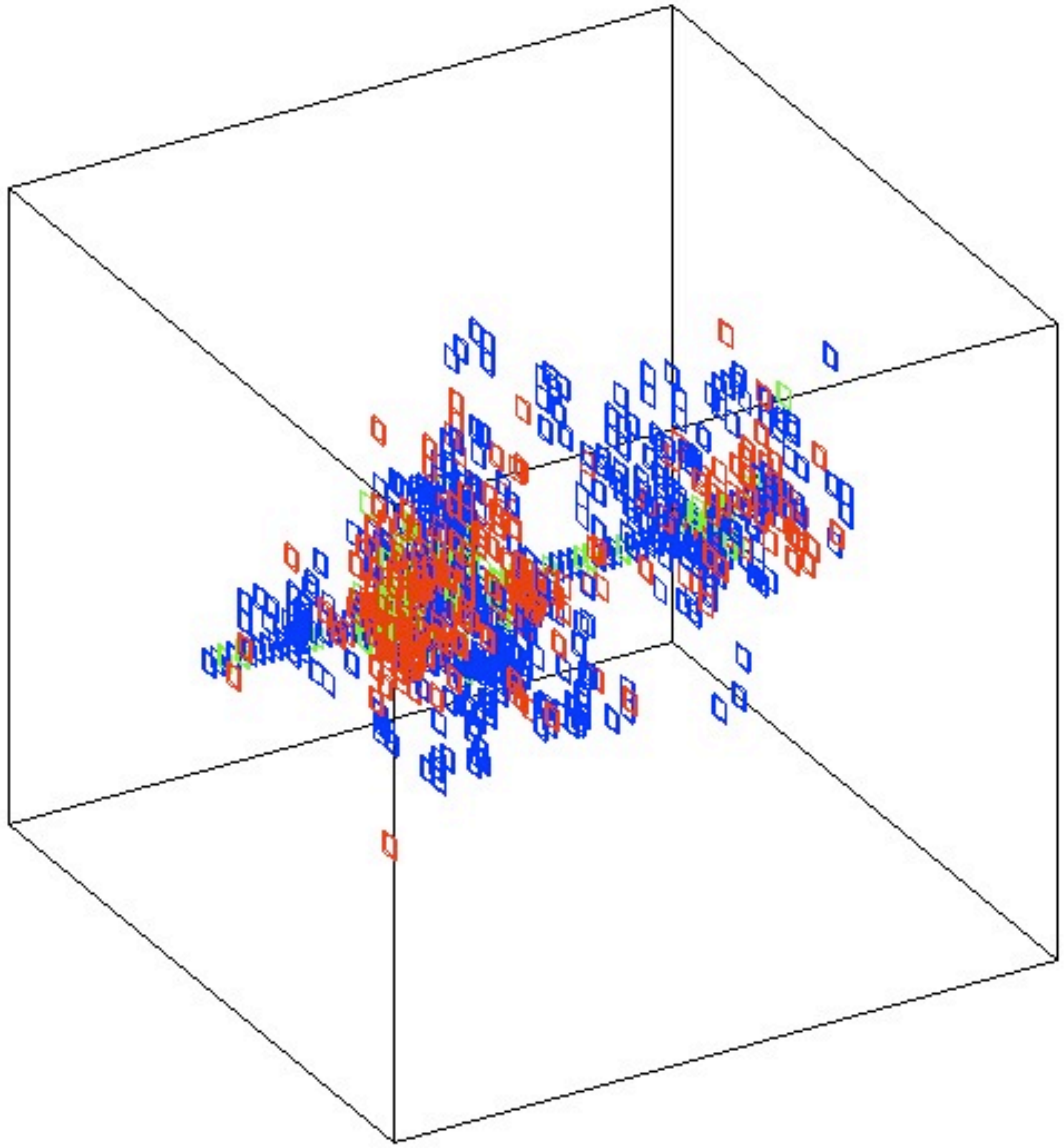
➯ Since the electromagnetic fraction of a hadronic shower varies from event to event and changes with energy, this leads to non-linearities of the detector response, and overall bad energy resolution

Hadronic Showers: Substructure

- Reminder: Hadronic showers are complicated!



Electromagnetic and Hadronic Component in Showers



Simulated 30 GeV π^+ shower

electromagnetic hits

hadronic hits

hybrid: both em and had

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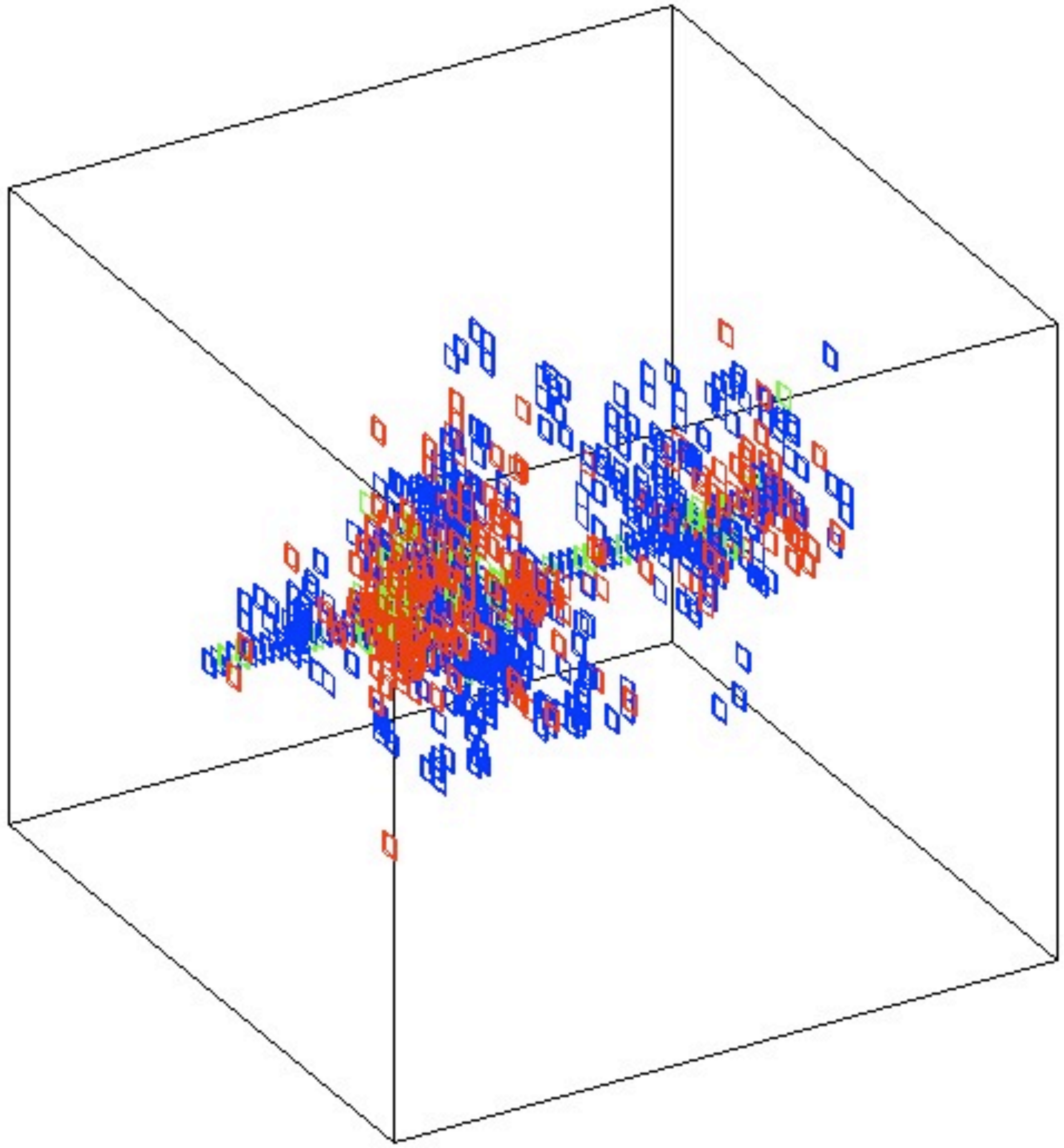

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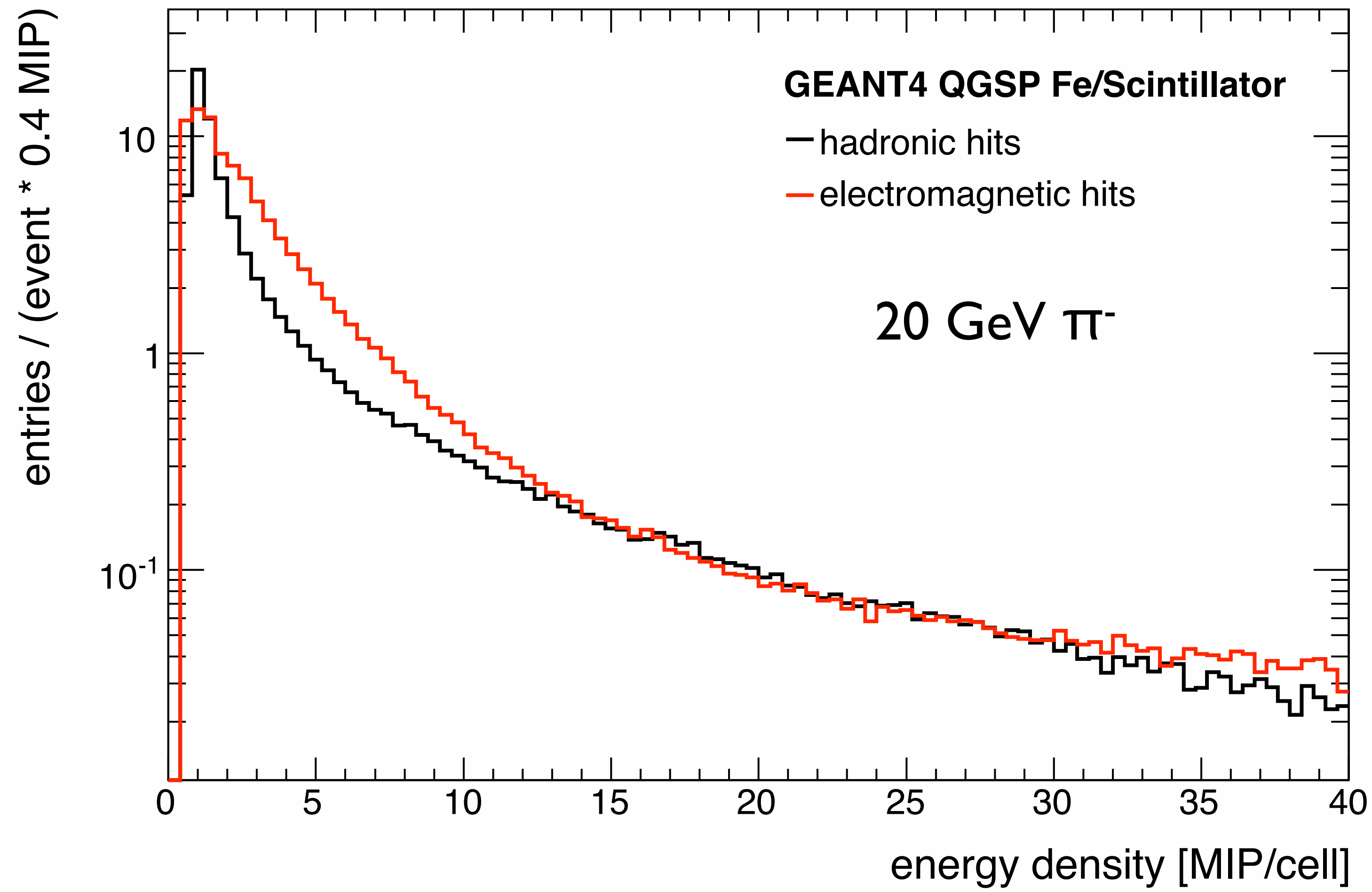
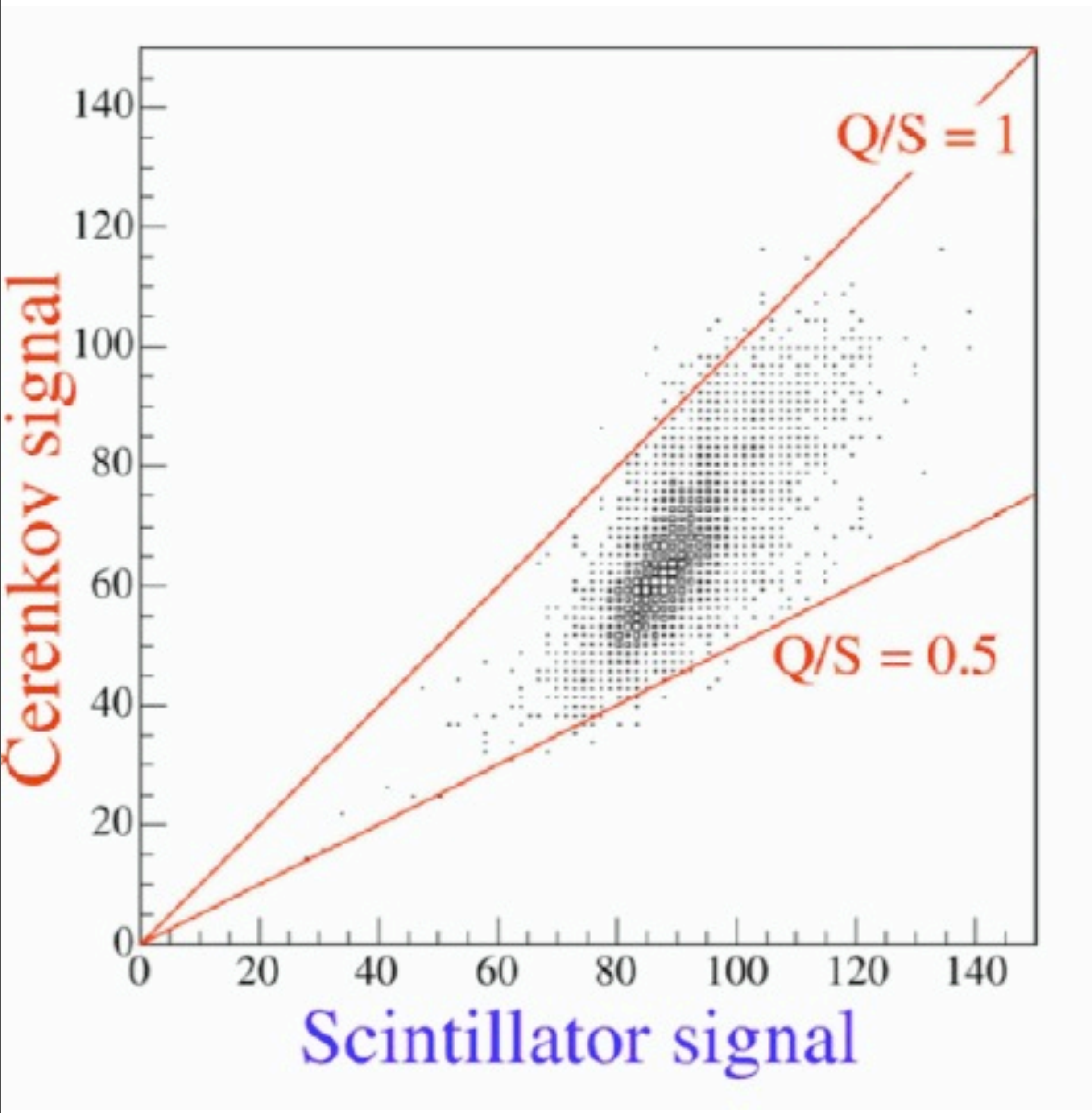
- Electromagnetic subshowers usually in the shower core

Energy Density & Type of Deposit



- Simple GEANT4 simulation: CALICE-like geometry: 2 cm Fe, 5 mm scintillator, 3x3 cm^2 cells
  - Hit classification: if more than 50% of the energy in the cell is deposited by electrons it is called electromagnetic
- Electromagnetic hits tend to have higher energy density: Basis for software compensation

DREAMing of Compensation



The DREAM "money plot": the reconstructed energy given by the scintillator signal can be improved with the Cherenkov signal (e.m. component) since the slope of the distribution is ≠ 1

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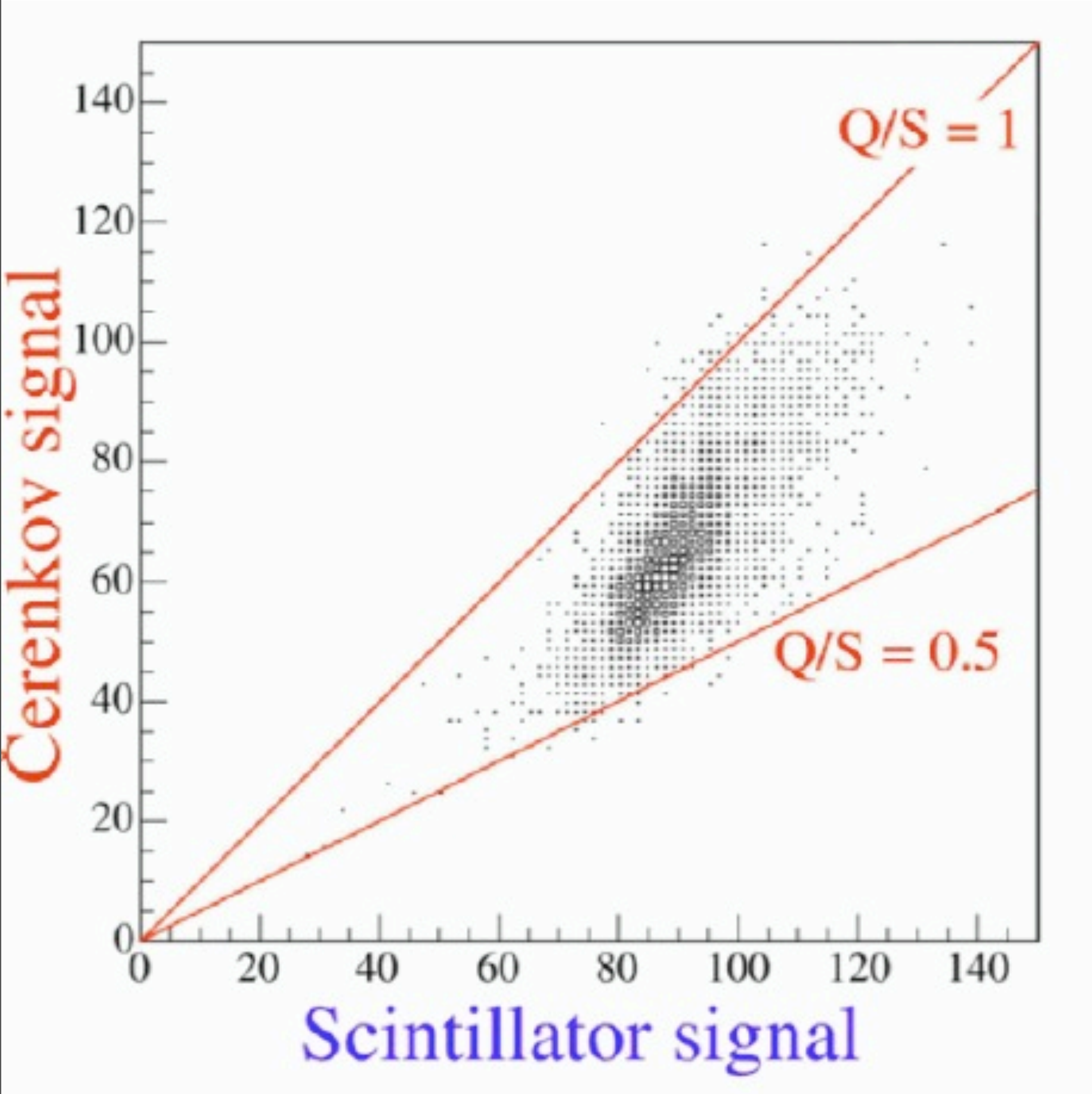

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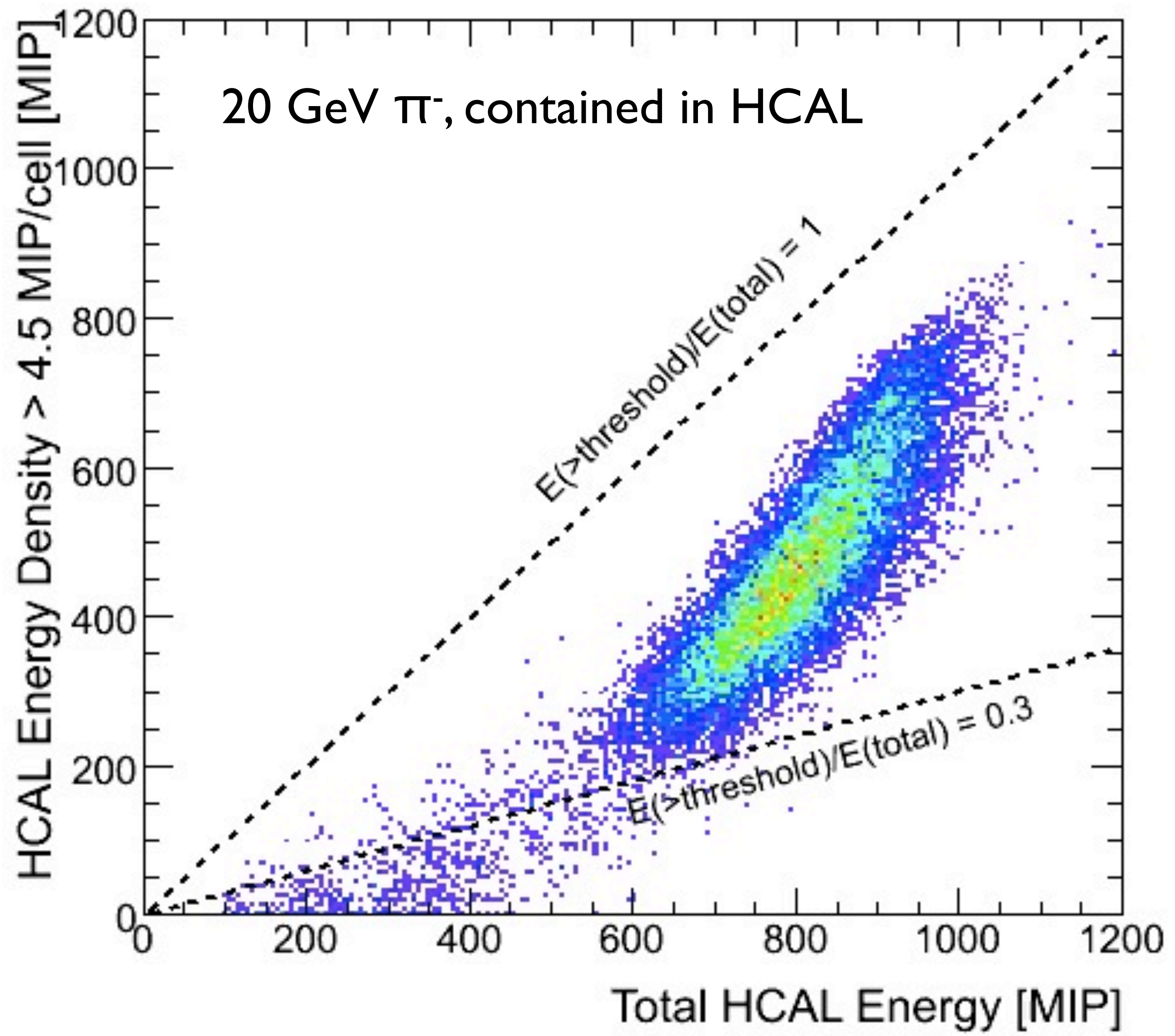
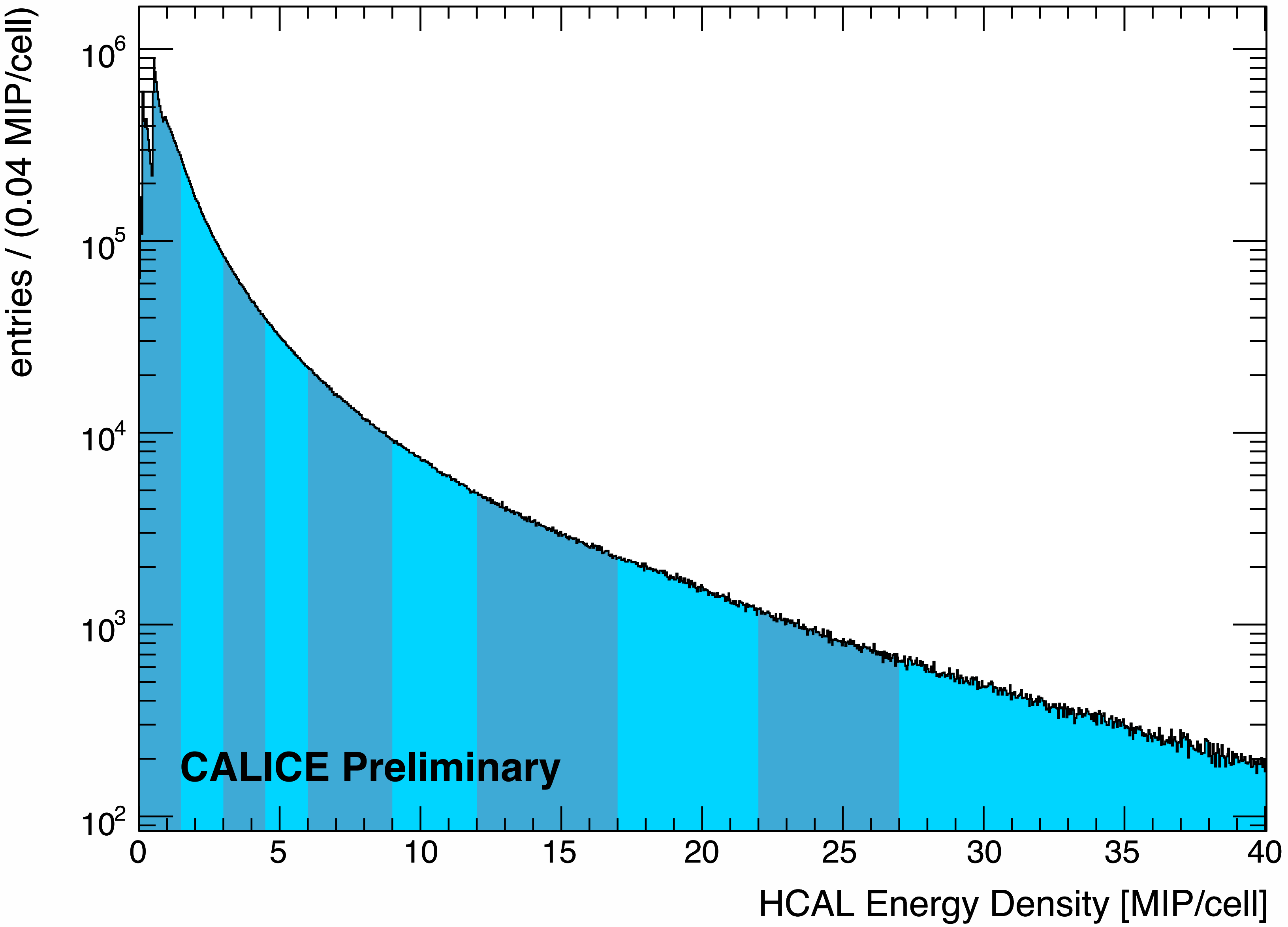


Local energy density works pretty much the same: events with a low total energy have a lower fraction of high density cells, this information can be used to improve the resolution: We can "DREAM", too...

Energy Density in the HCAL



- Local energy density in a very simple-minded way: Take the energy per detector cell, divide it by the cell volume (1 for small cells, 4 and 16 for the larger ones)
  - Potential problem: Susceptible to noise in single cells

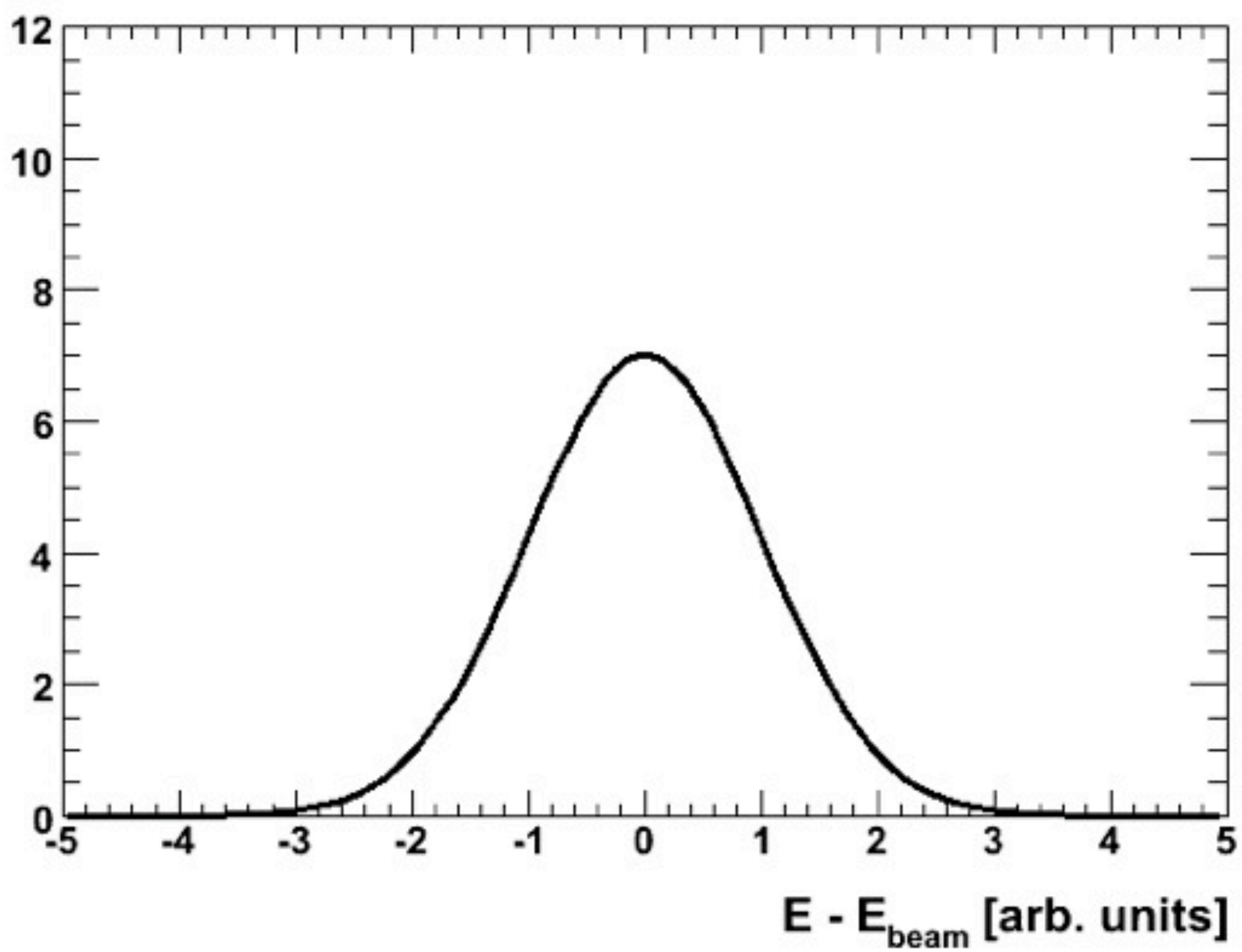
Cells are sorted into 10 different bins according to their energy density

We actually use all three detectors in CALICE, the ECAL, HCAL and TCMT

Determining the Weight

- Assign different weights for cells according to the density bin it is in
- Determine the weights to use by optimizing the energy resolution (using a standard χ^2 minimization procedure):

$$\chi^2 = \sum_{events} \left(\sum_i E_i \omega_i - E_{beam} \right)^2$$



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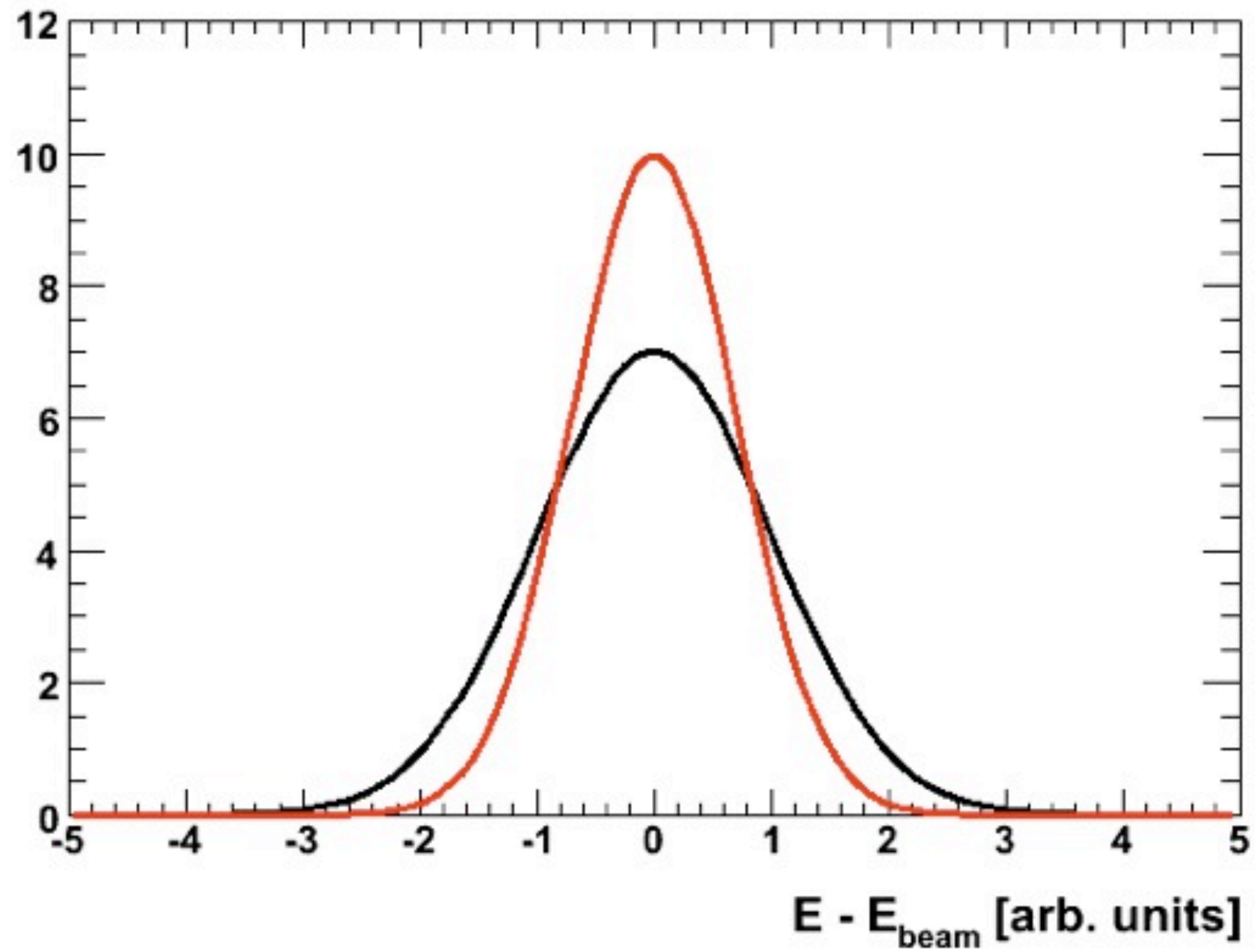
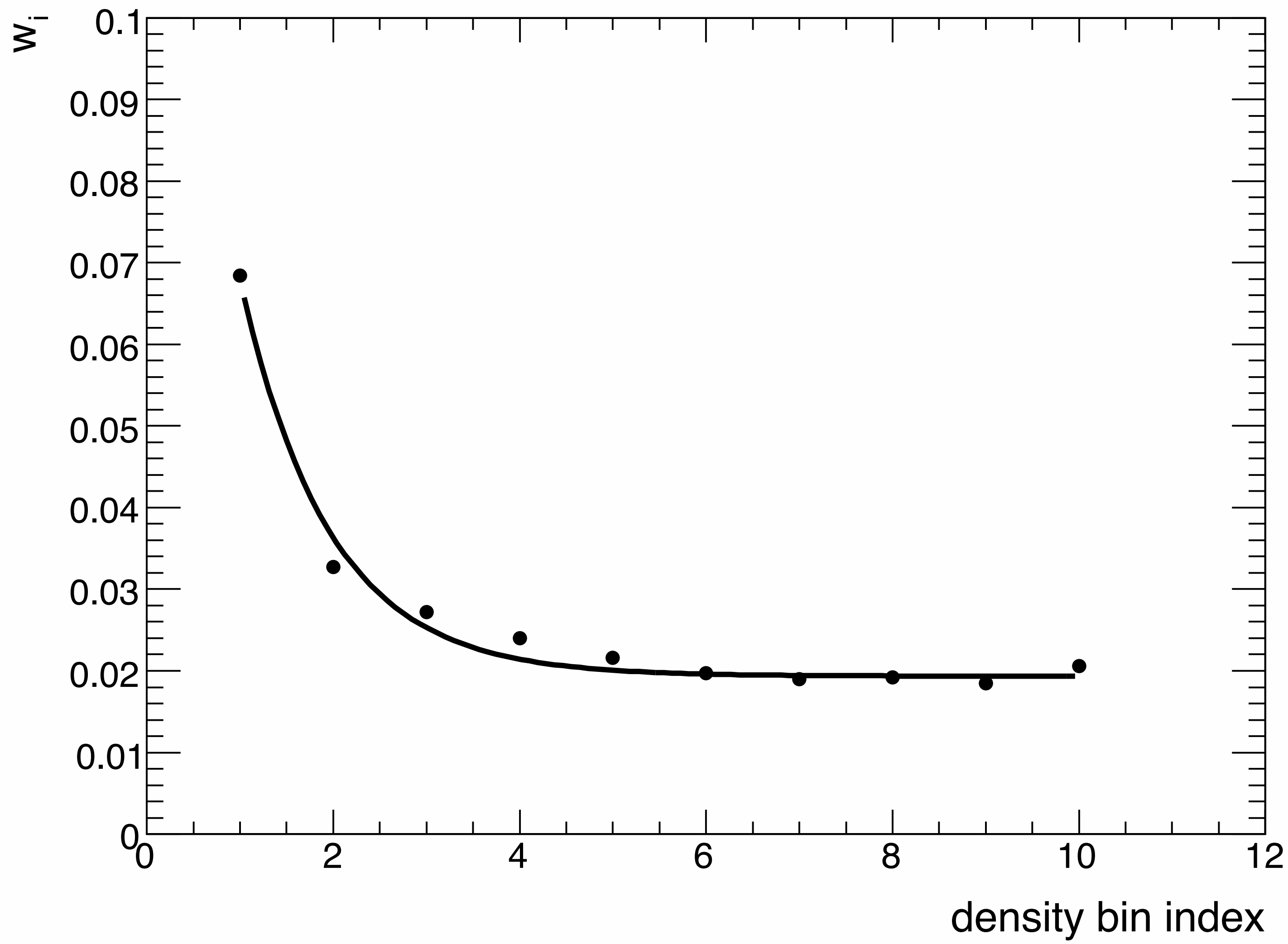


Reduction of the width of the energy distribution:

Improved resolution!

Weights as a Function of Density



As expected:

- Cells with low energy content get weighted more
- Cells with high energy content get weighted less

Average weight (when using one common number for all densities): 0.03 GeV/MIP

- Weights are energy dependent (no surprise there, shower properties change with energy), parametrize the weights with a simple function with E-dependent parameters

$$\omega_i(E) = p_1(E)\, e^{(p_2(E)*i)} + p_3(E)$$

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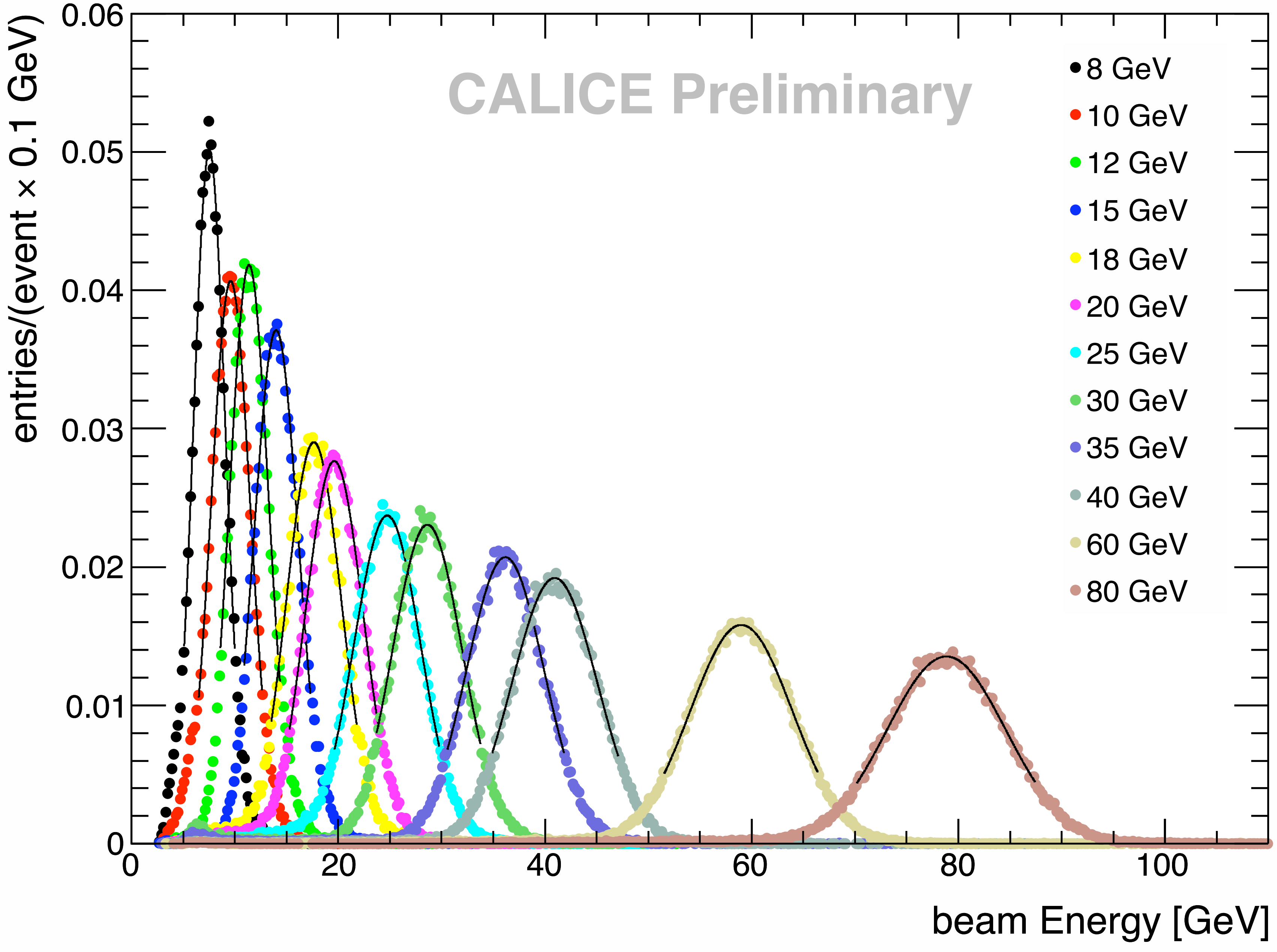
- ▸ Develop a parametrization of the weights as a function of energy: Then you can interpolate, apply it to energies you did not directly use to obtain the weights
- This parametrization can be used in real experiments: Make a "first guess" of the particle energy using the constant conversion factor, then use this energy to select the right weight
- Apply the parametrized weights to reconstruct the energy

Reconstructed Energy



- Significant improvement of energy resolution with the use the parametrized weights (no knowledge of beam energy necessary!)

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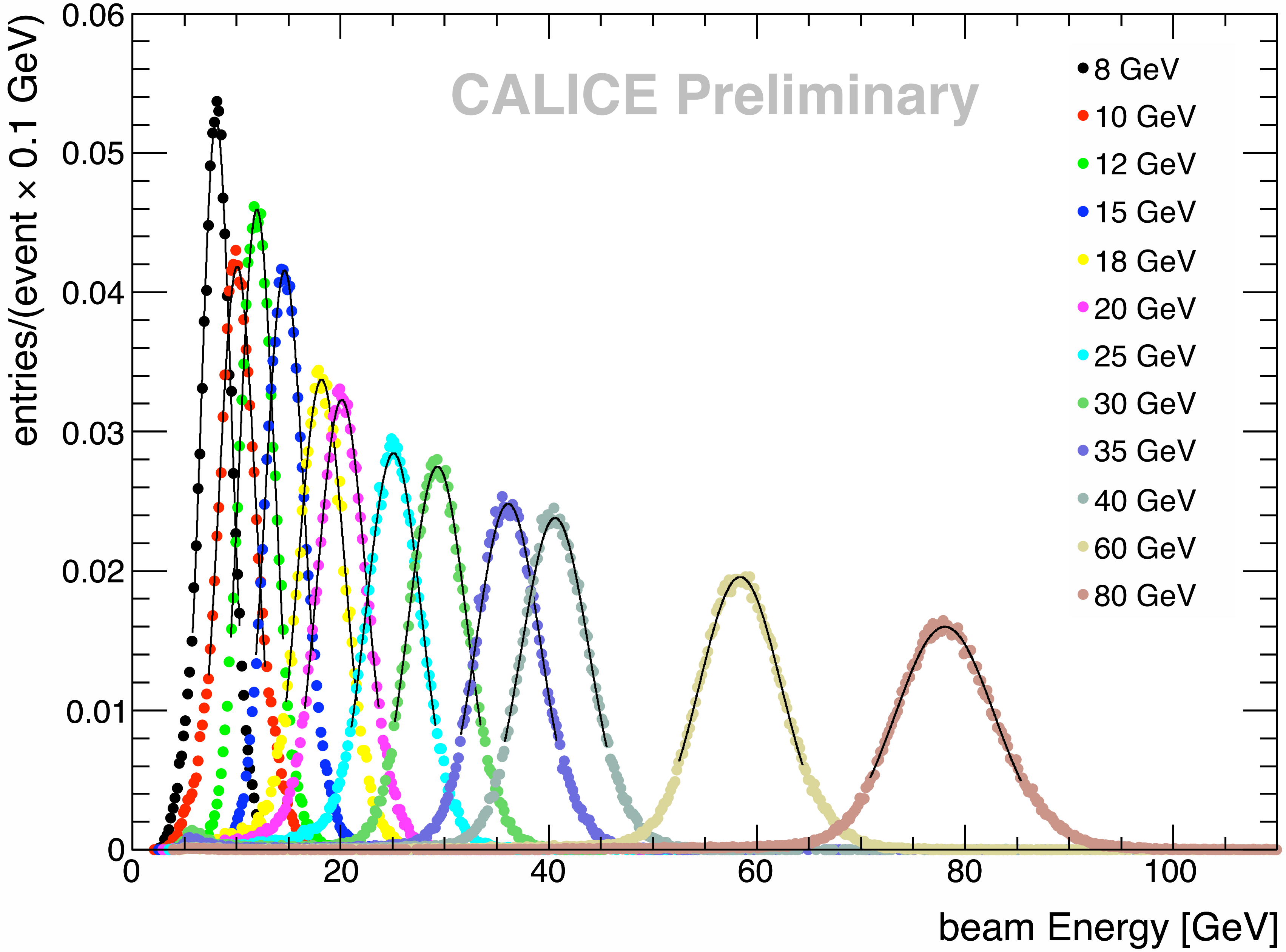

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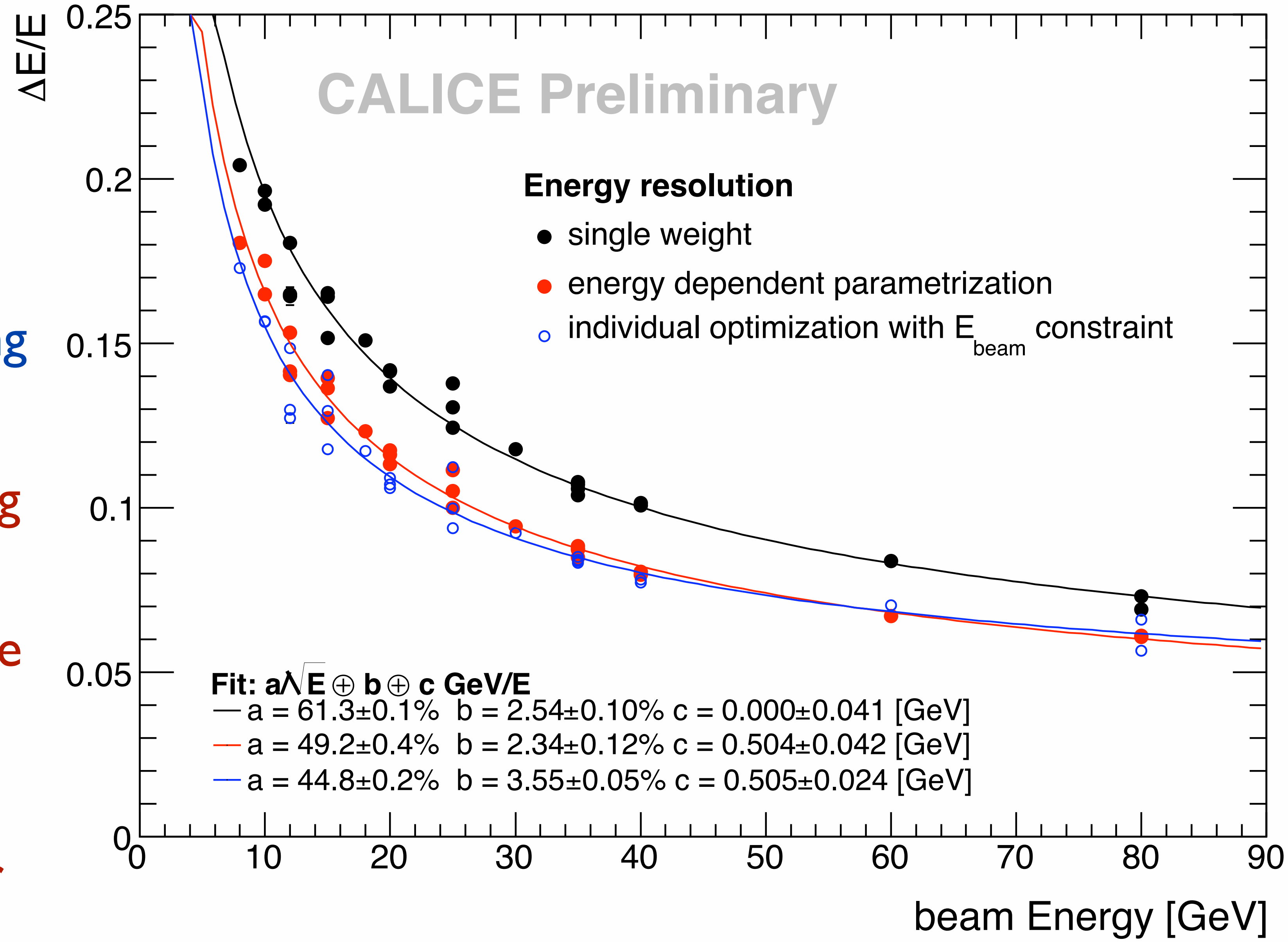
Energy Resolution of the Complete Setup

- Hadrons at various energies in the complete CALICE setup (ECAL, HCAL, TCMT)

3 ways to reconstruct the energy:

- One conversion factor per detector, no density dependent weighting
- Density dependent weighting, using a beam energy constraint
- Density dependent weighting using an energy dependent parametrization of the weights, the weights are selected event by event using the first energy estimate obtained with one factor per detector: prior knowledge of beam energy not necessary!



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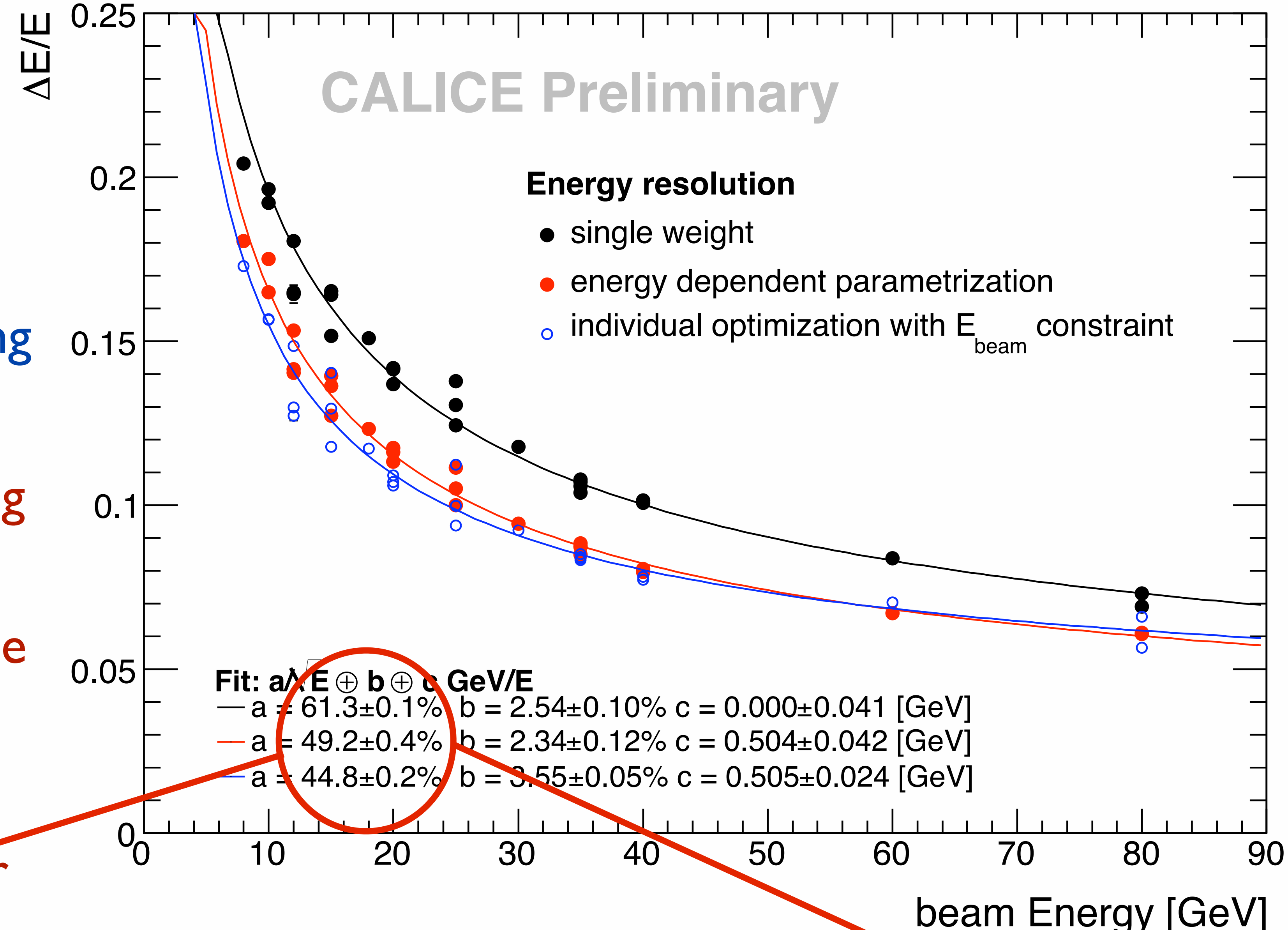
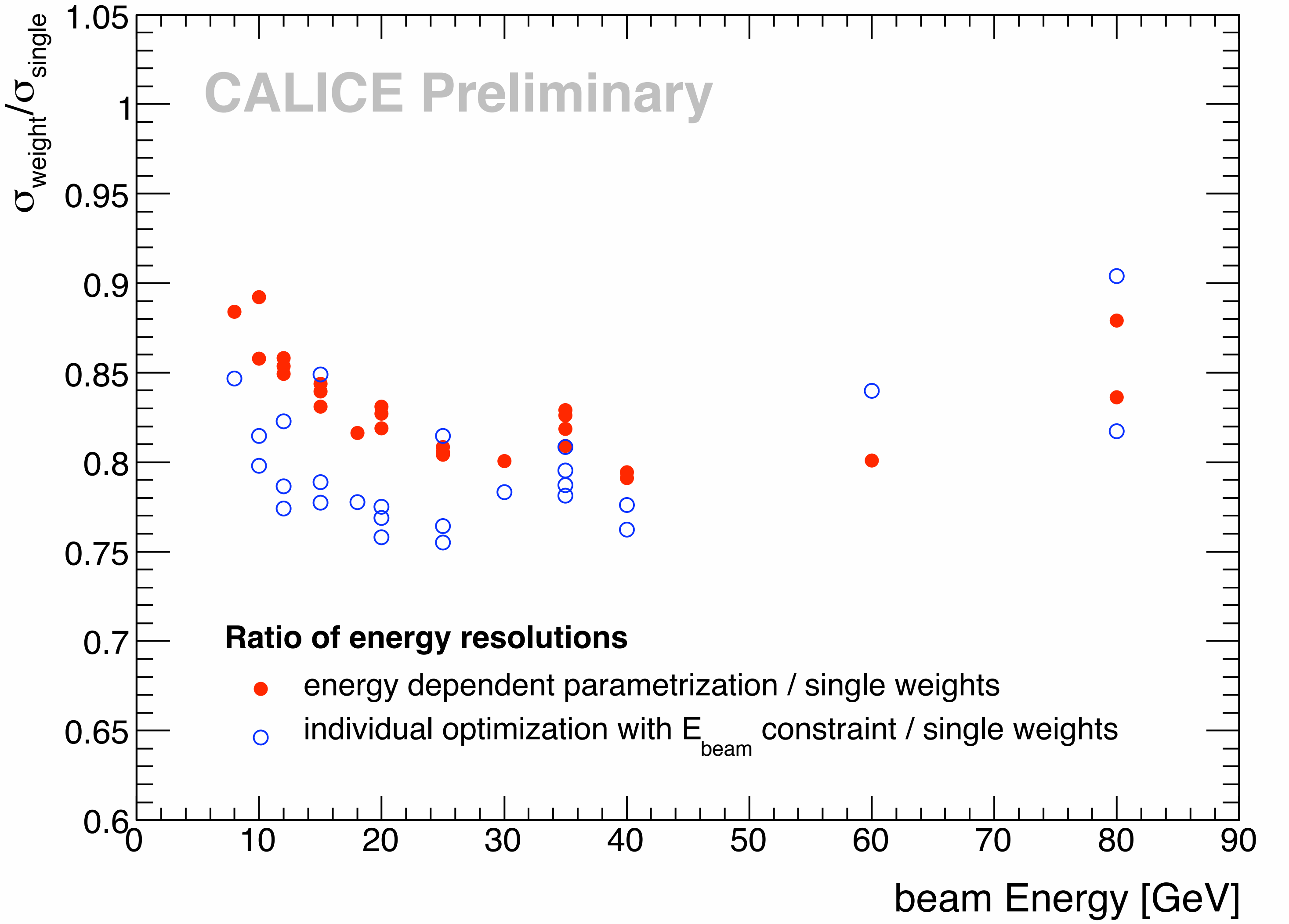


stochastic term w/o weighting: 61.3%, with parametrized weighting 49.2%

Improvement with Weighting



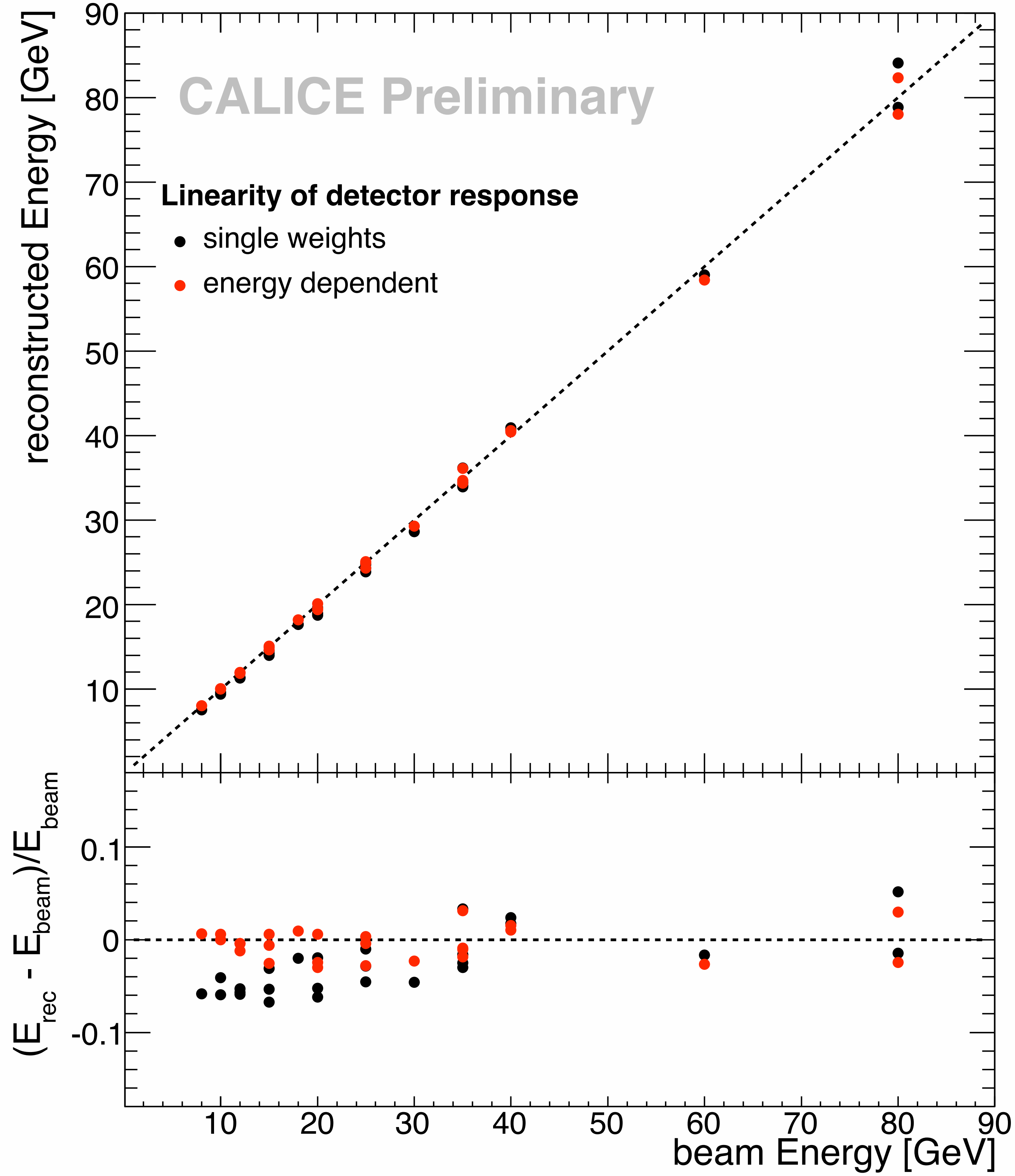
- Improvement with parametrized weights typically 18%, almost as good as the cheated case of using the perfect weights for each energy
  - in particular at lower energy more improvement seems possible

Linearity of Response

- Very crucial: Not only good energy resolution (meaning narrow distribution), but also: Get the right energy (right mean of the distribution)
- In hadronic showers this is quite an issue:
  Non-compensating calorimeters (with different response to em and had) are inherently non-linear: The electromagnetic fraction of hadron showers increases with energy, so the detector signal increases more than it should
- Weighting techniques (if not done right) can further increase this problem: This has to be watched very carefully

Linearity of Energy Response: Combined Setup

- Energy reconstructed with single conversion factors and with parametrized density dependent weighting
- Noise rejection: Isolated noise hits (and isolated neutrons) rejected in the analysis



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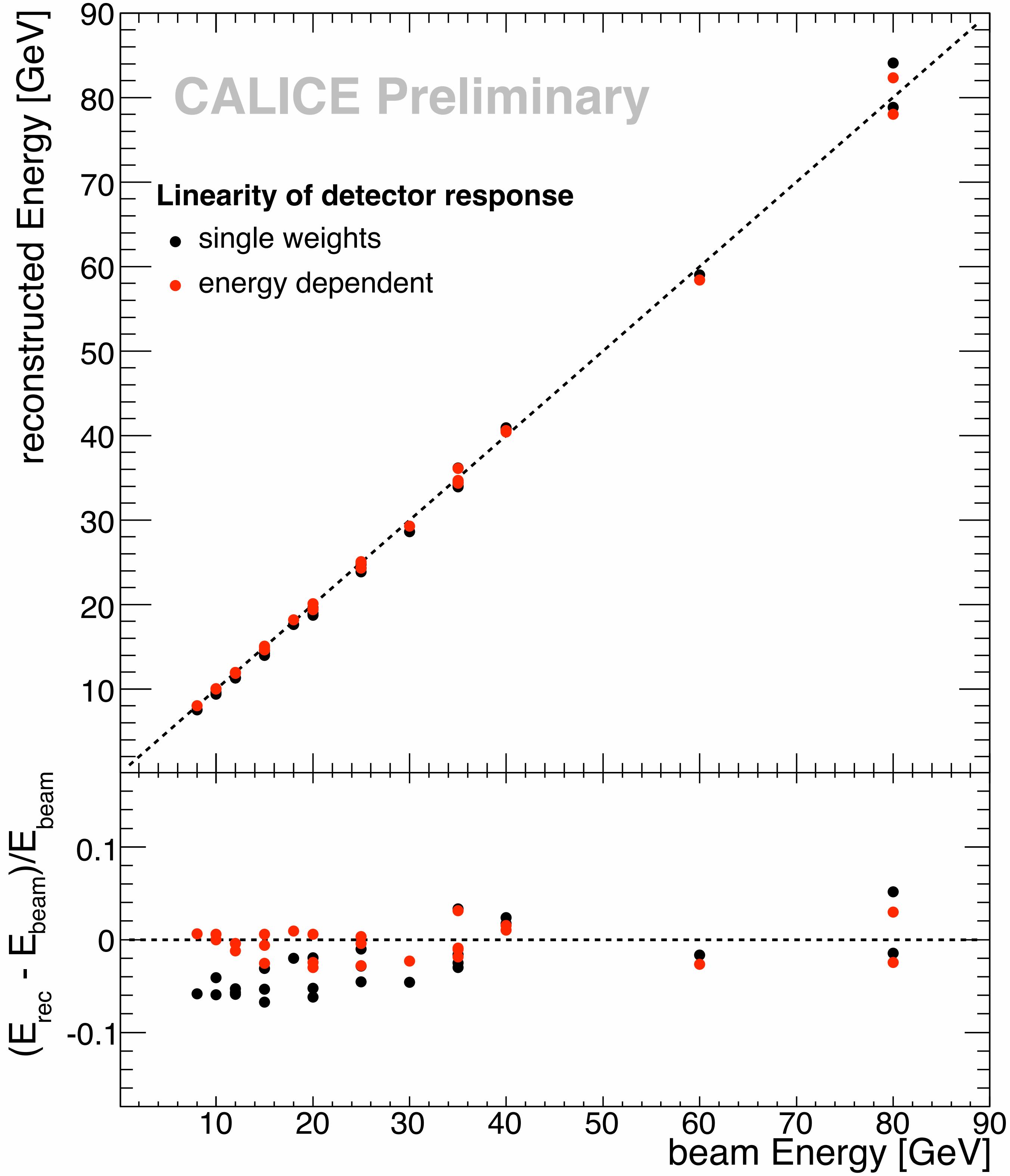
▸ Weighting of cells according to their energy content improves linearity of the detector: better than 4% from 8 to 80 GeV

▸ Cell-by-cell temperature correction in development, will reduce run to run fluctuations



Summary I

- CALICE studies (among other detector technologies) the performance of a scintillator tile HCAL with SiPM readout
  - Highly granular: 3 x 3 cm^2 cells, 38 layers, 4.5 λ
- The goals:
  - Establish the best technique for the HCAL at a future ILC detector
  - Improve the understanding of hadronic showers via comparison to simulations: validation of hadronic shower codes, crucial for simulation studies of future detectors, also very helpful for data analysis for example at the LHC
- Calibration: 3 distinct steps
  - Gain calibration of the SiPM: Use single photon counting capability
  - Cell-by-cell intercalibration using minimum-ionizing particles
  - Energy calibration: Conversion from the MIP to the GeV scale

Summary II

- Detector simulation, based on GEANT4 are used with different physics lists, which describe the reactions in a hadronic cascade
- Measurements of longitudinal and transverse shower shapes are used to constrain these models
  - Important insight: The integration time of the electronics has to be taken into account, models with realistic modeling of delayed neutron emission are particularly sensitive to this effect
- First studies of particle flow performance indicate shower separation capability well below 10 cm particle distance
- The high granularity allows the use of software compensation methods based on the local shower densities: First test show ~ 20% improvement in energy resolution and better linearity of the response