Development of Highly Granular Hadronic Calorimeters for the ILC

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for the CALICE - Germany Collaboration

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(Werner-Heisenberg-Institut)

Calorimeter for ILC

Excellence Cluster Universe

Outline

- CALICE: Overview and Introduction
- Analysis Results: Selected Topics
  - Shower Properties, Comparison to Simulations
  - Energy Resolution, Software Compensation
  - Shower Separation
- R&D for the next Generation Prototype
  - Activities at German Institution
- Summary

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➾ The usual disclaimer: My own very biased selection...

Motivation: Jets at the ILC

- The full potential of the International Linear Collider can only be realized with unprecedented precision: A challenge for the detectors!
  - Jet energy resolution better than $30\%/\sqrt{E}$ (about a factor 2 better than ATLAS)

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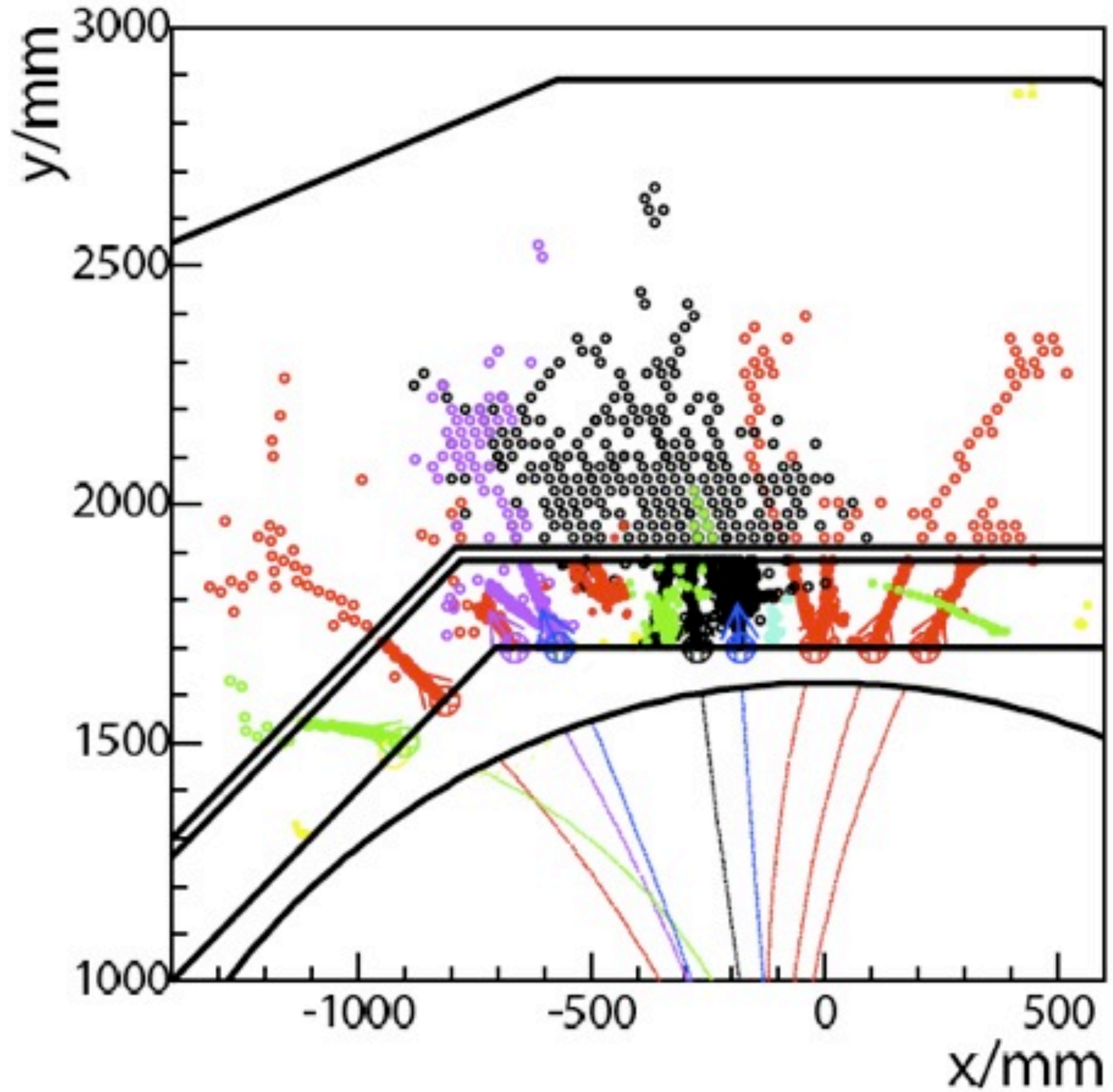
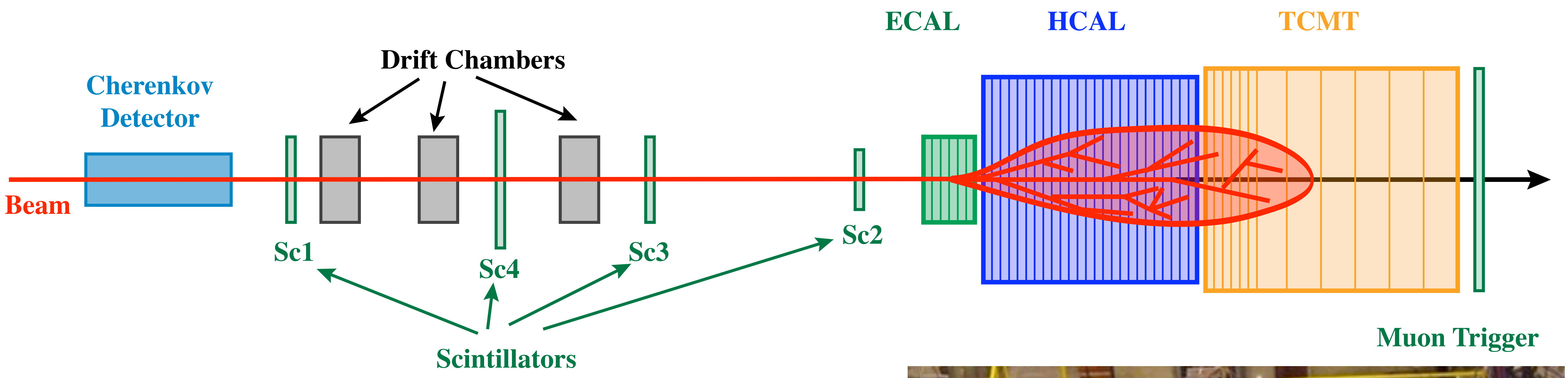
Particle **F**low **A**lgorithms:

- Use information from all detector systems for jet reconstruction
- Separation of particles in the calorimeters more important than energy resolution
- Requires extreme granularity: Possible with novel detector technologies

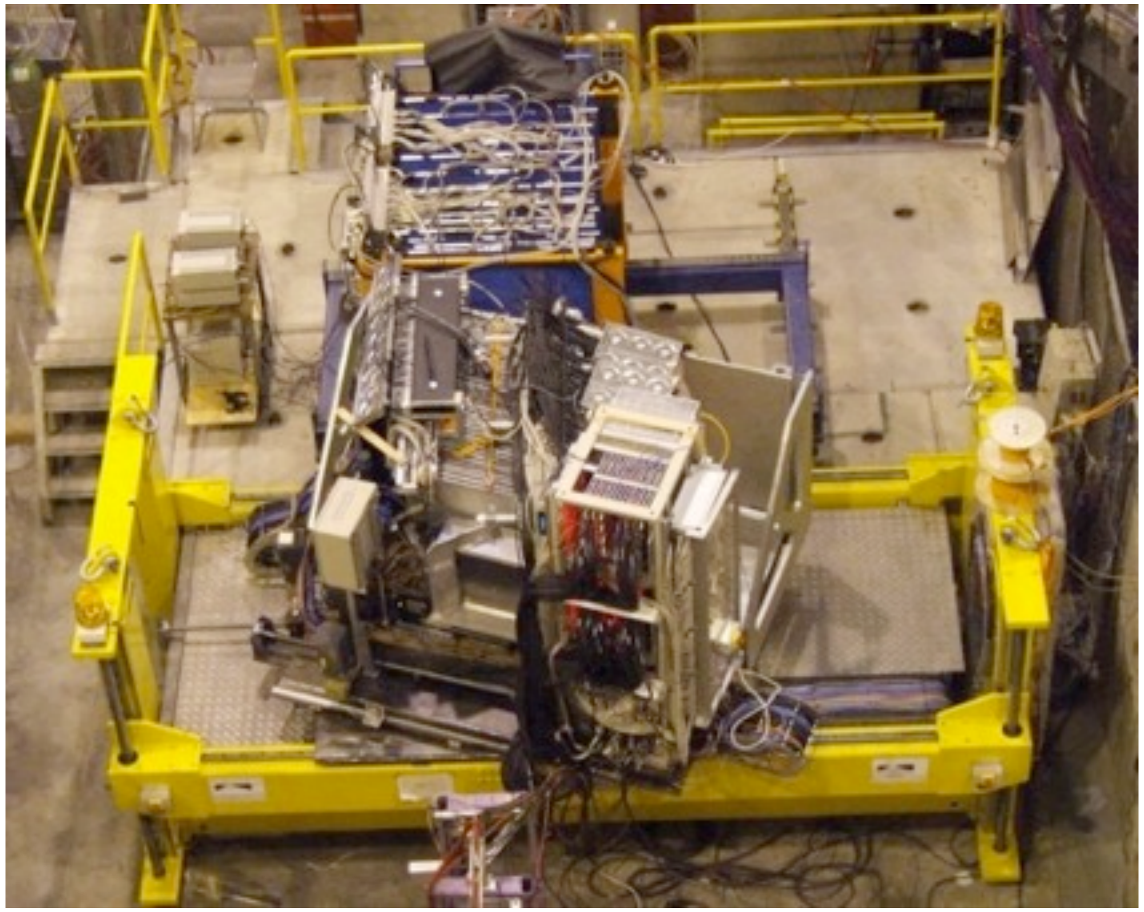


The CALICE Program

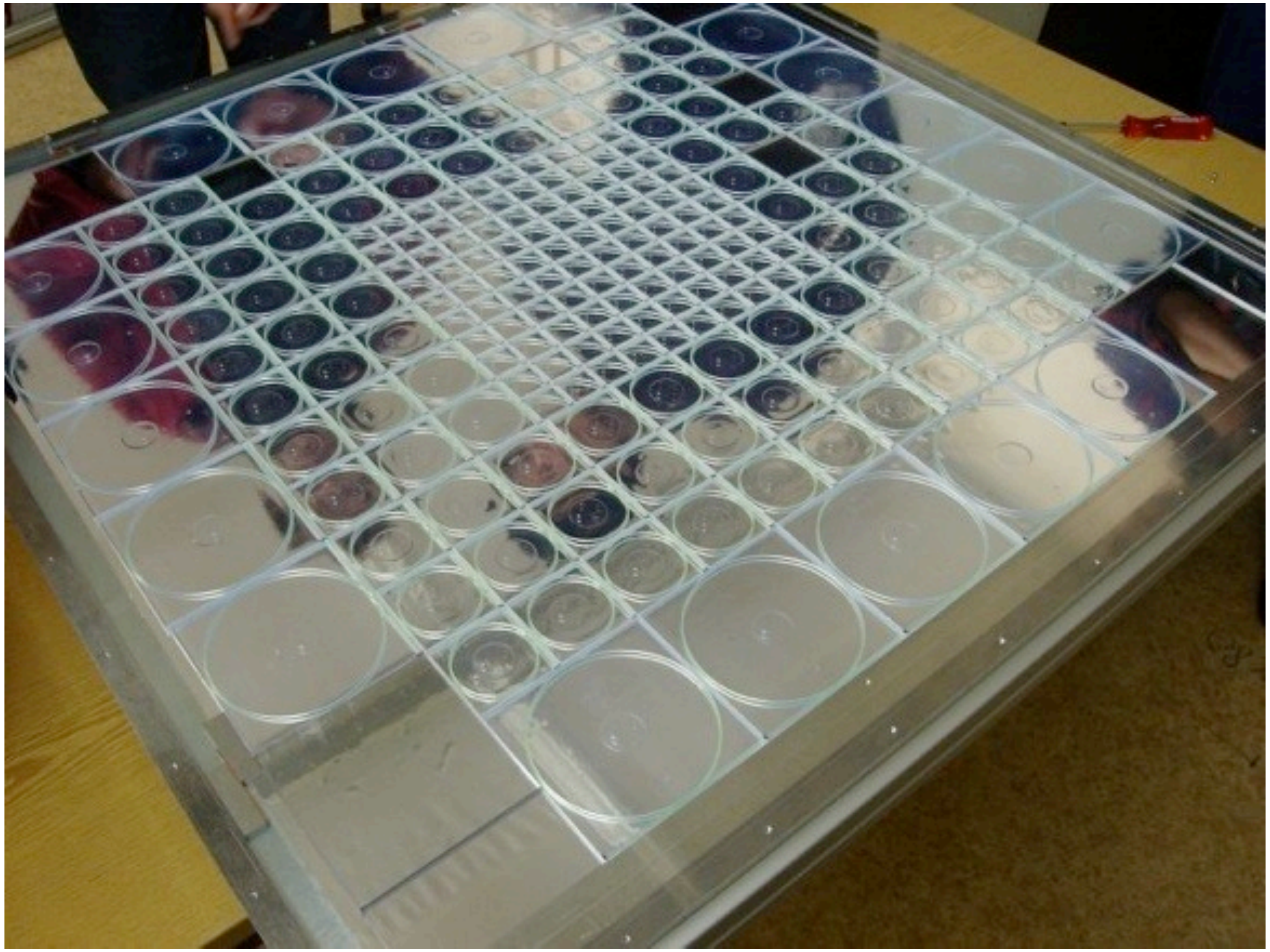
The goal: Evaluate technologies for calorimetry at the ILC



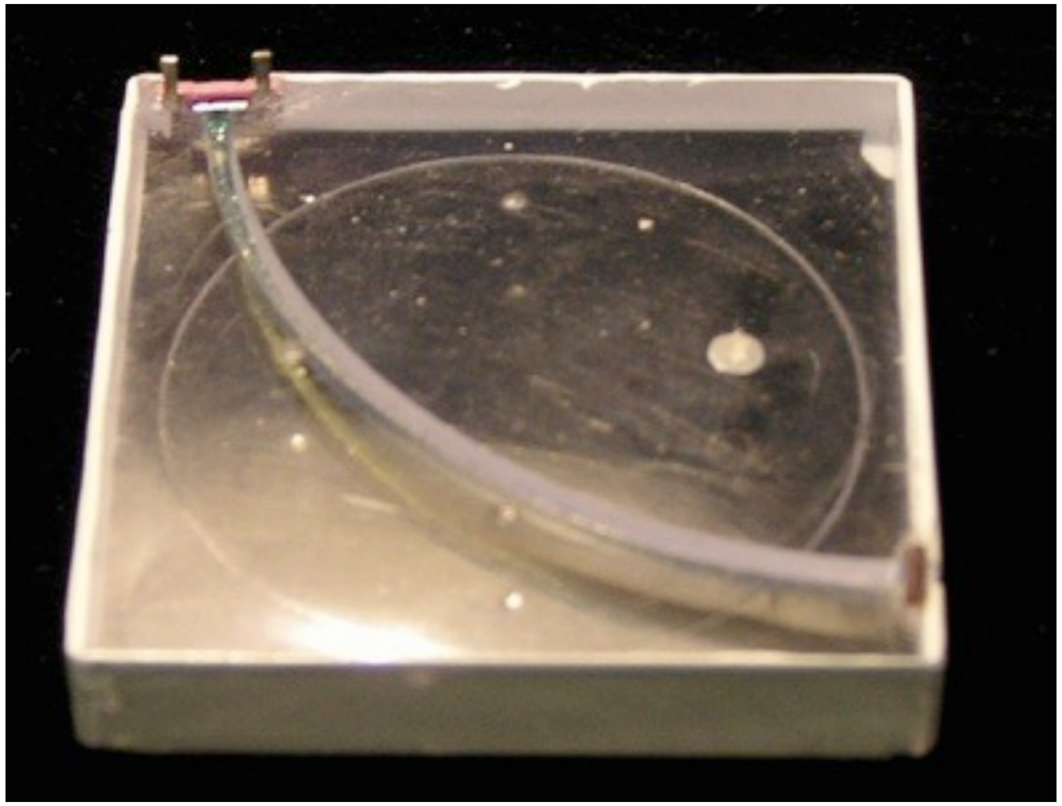
- Extensive test beam campaign
  - DESY: 2006
  - CERN: 2006, 2007
  - FNAL: 2008, ...
- Wide variety of energies and particle species
  - 2 GeV to 80 GeV
  - muons, $e^{\pm}$, $\pi^{\pm}$, unseparated hadrons



The CALICE Analog HCAL



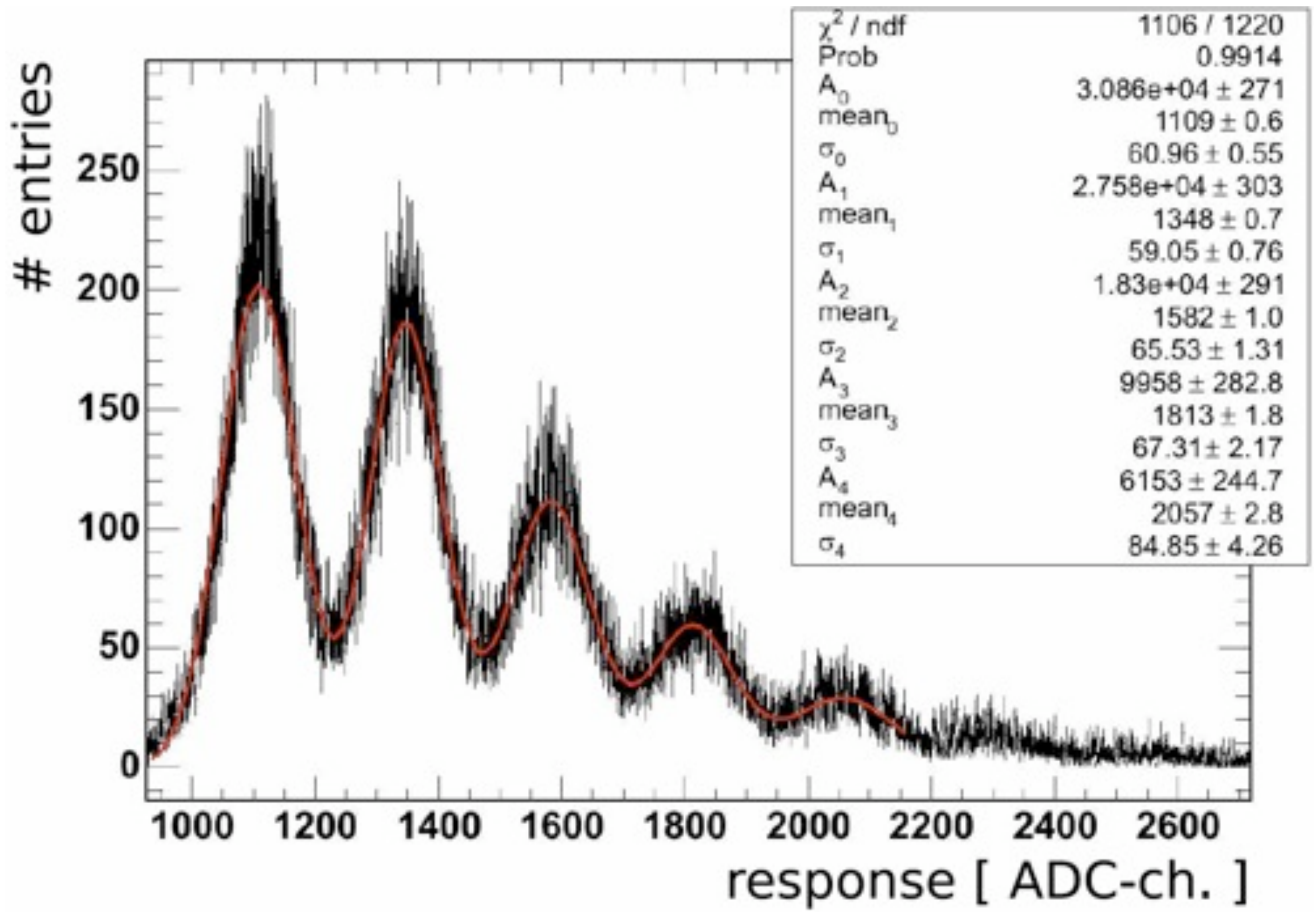
- Steel absorber structure:
  - 38 layers
  - 2 cm total absorber thickness per layer (1.1 X_0, 0.12 λ)
  - total ~ 4.5 λ



- Active layers: Scintillator tiles
  - high granularity in the layer center: 100 3x3 cm^2 tiles, then 6x6 cm^2 and 12 x12 cm^2
  - light collection via wls fiber, read out with SiPM

Analog HCAL: Calibration

- Auto-calibration of SiPM gain: Individual photons can be resolved
  - Low-intensity LED light coupled into each detector cell
  - Absolute LED intensity not important!



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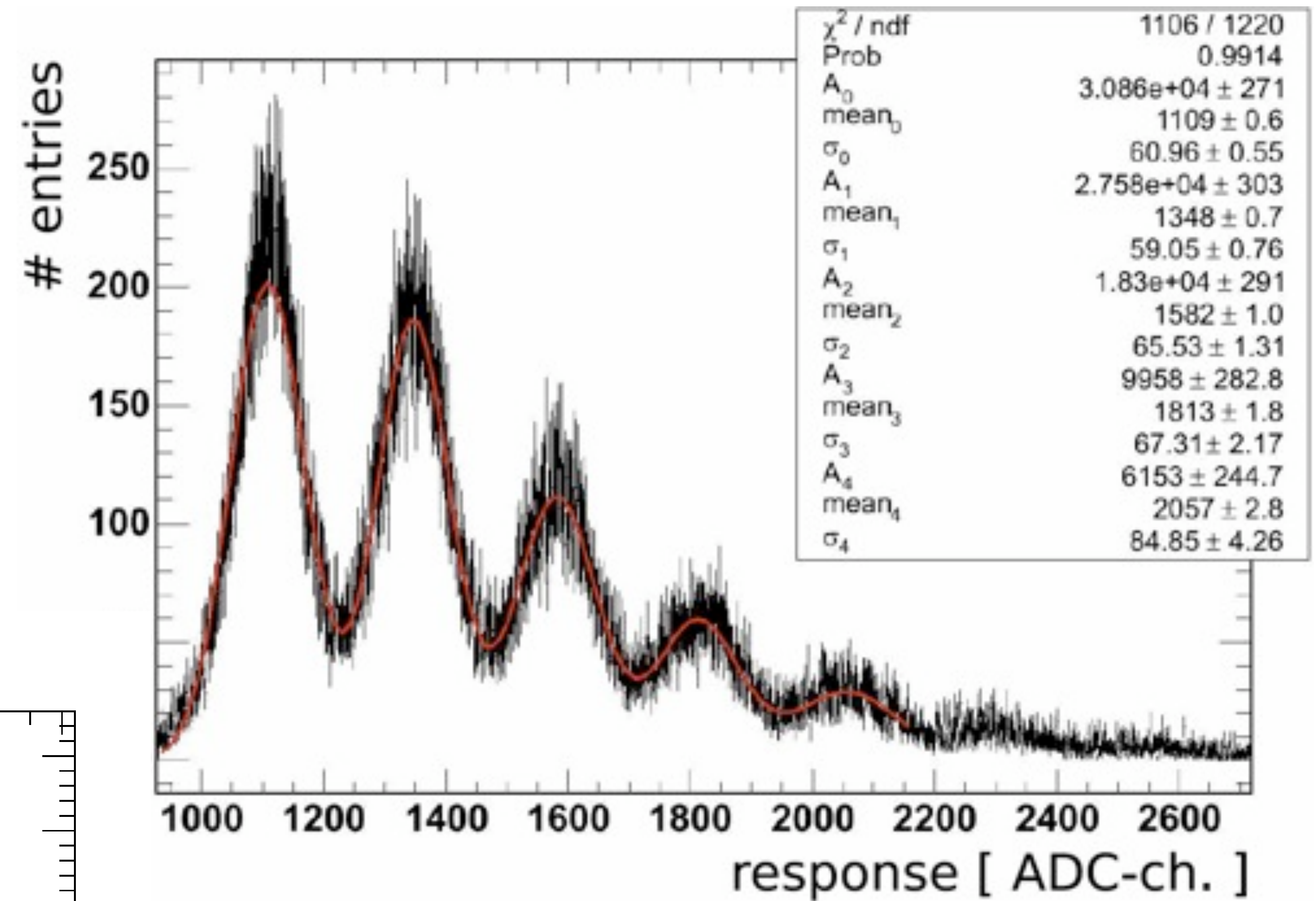
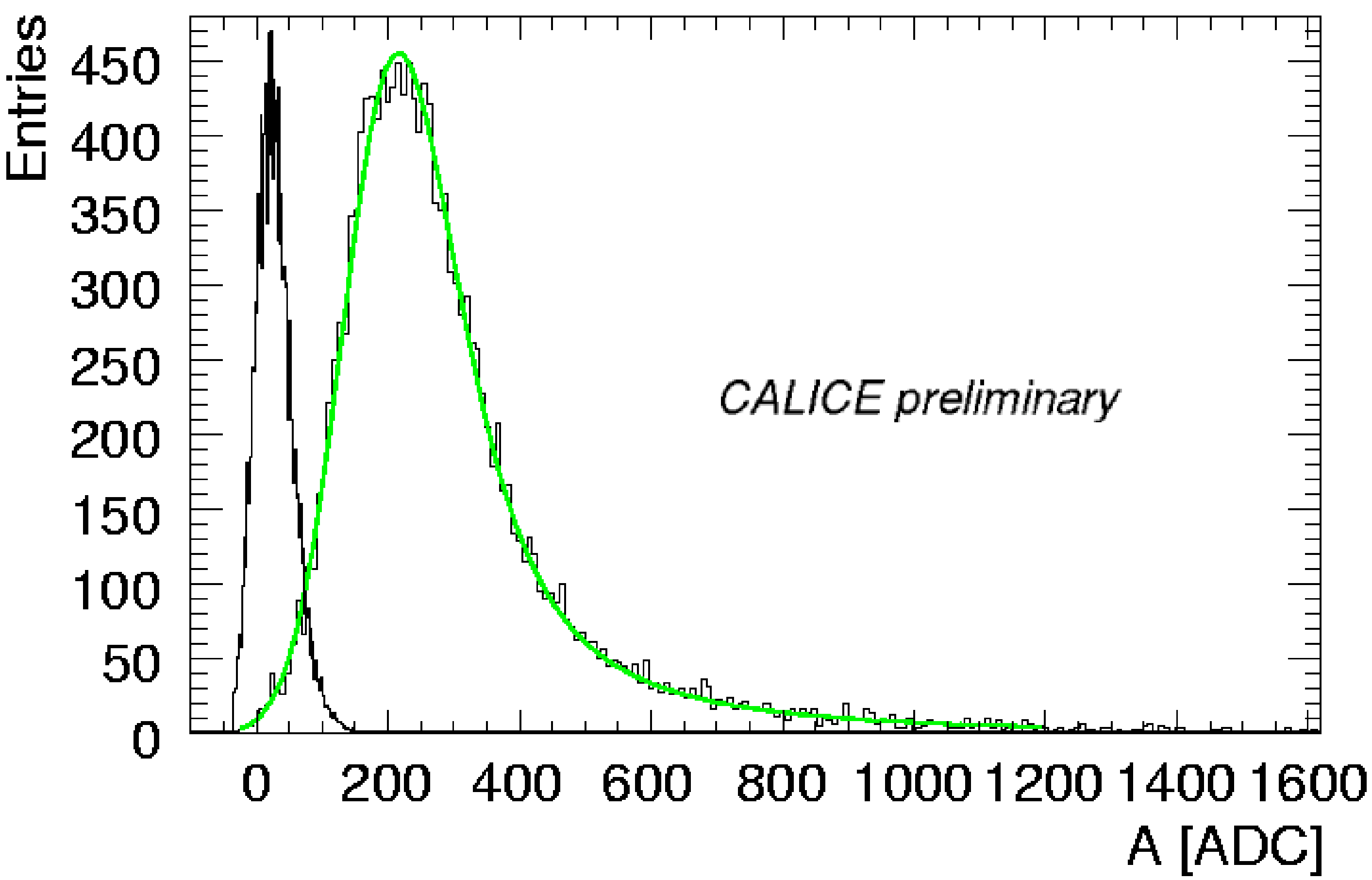
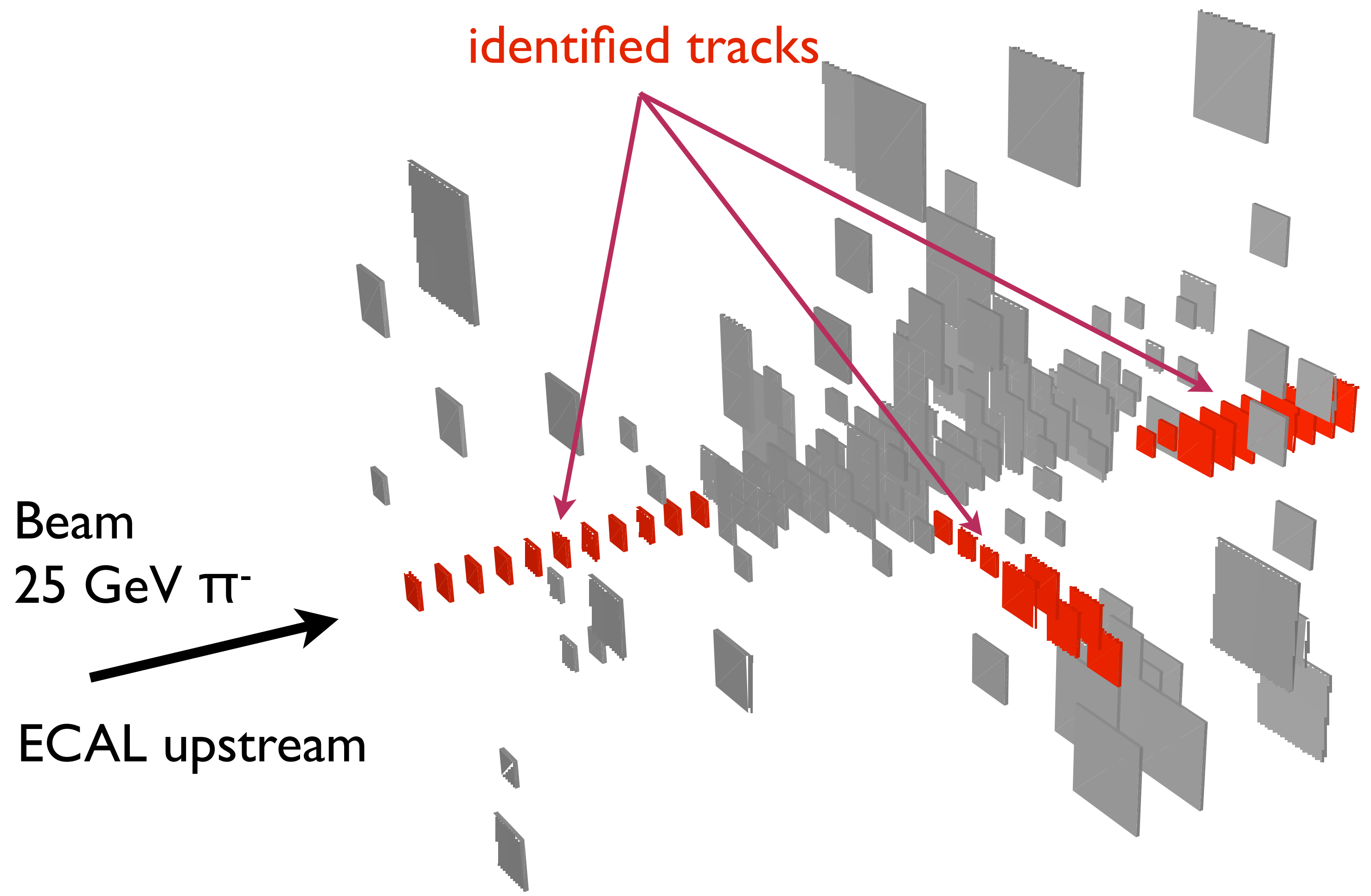




- MIP-Calibration with Muons
  - Complete detector illuminated with high energy muons
  - equalization of response of all cells by matching the MPV position

Tracking in Hadronic Showers



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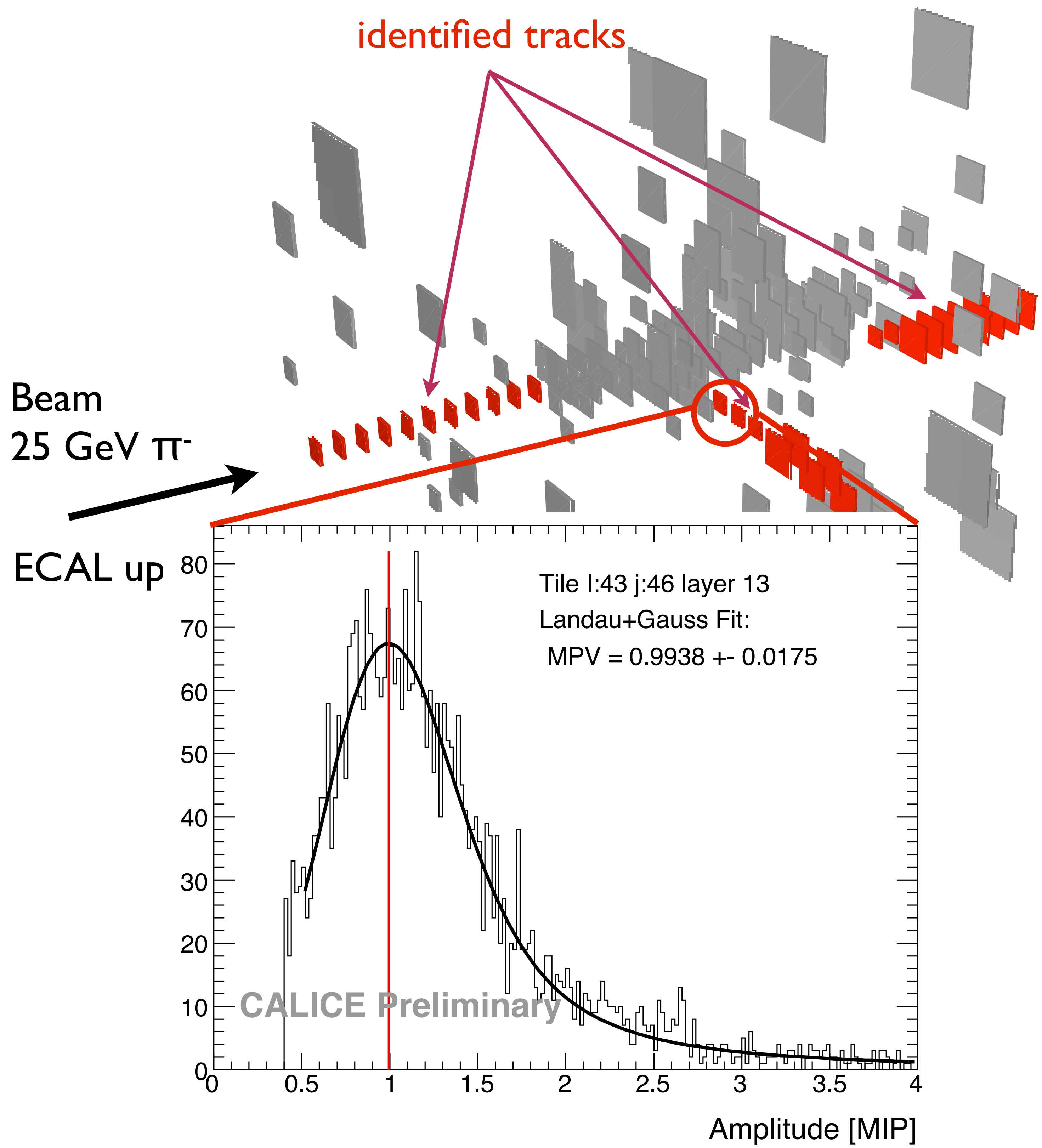
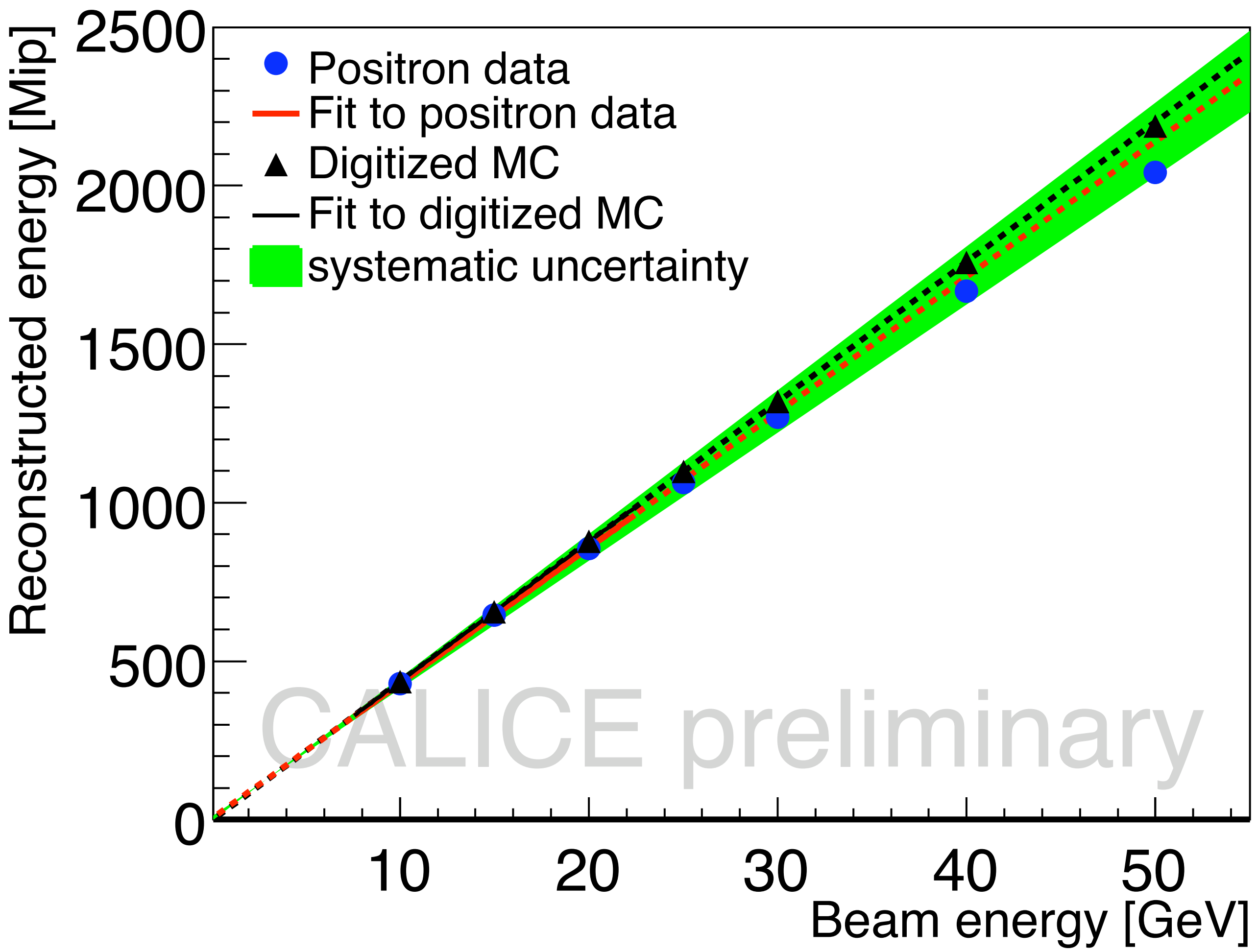


- High granularity allows identification of track segments within hadronic showers
  - requirement: isolated hits, tracks separated from other activity
- Track identification provides a clean sample of minimum ionizing particles: An alternative calibration tool!
  - Studies with a realistic model of an ILC detector suggest need for significant integrated luminosity: O(1 fb^{-1}) at Z pole

Analysis Results: Selected Topics

Setting the Stage: Positrons

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



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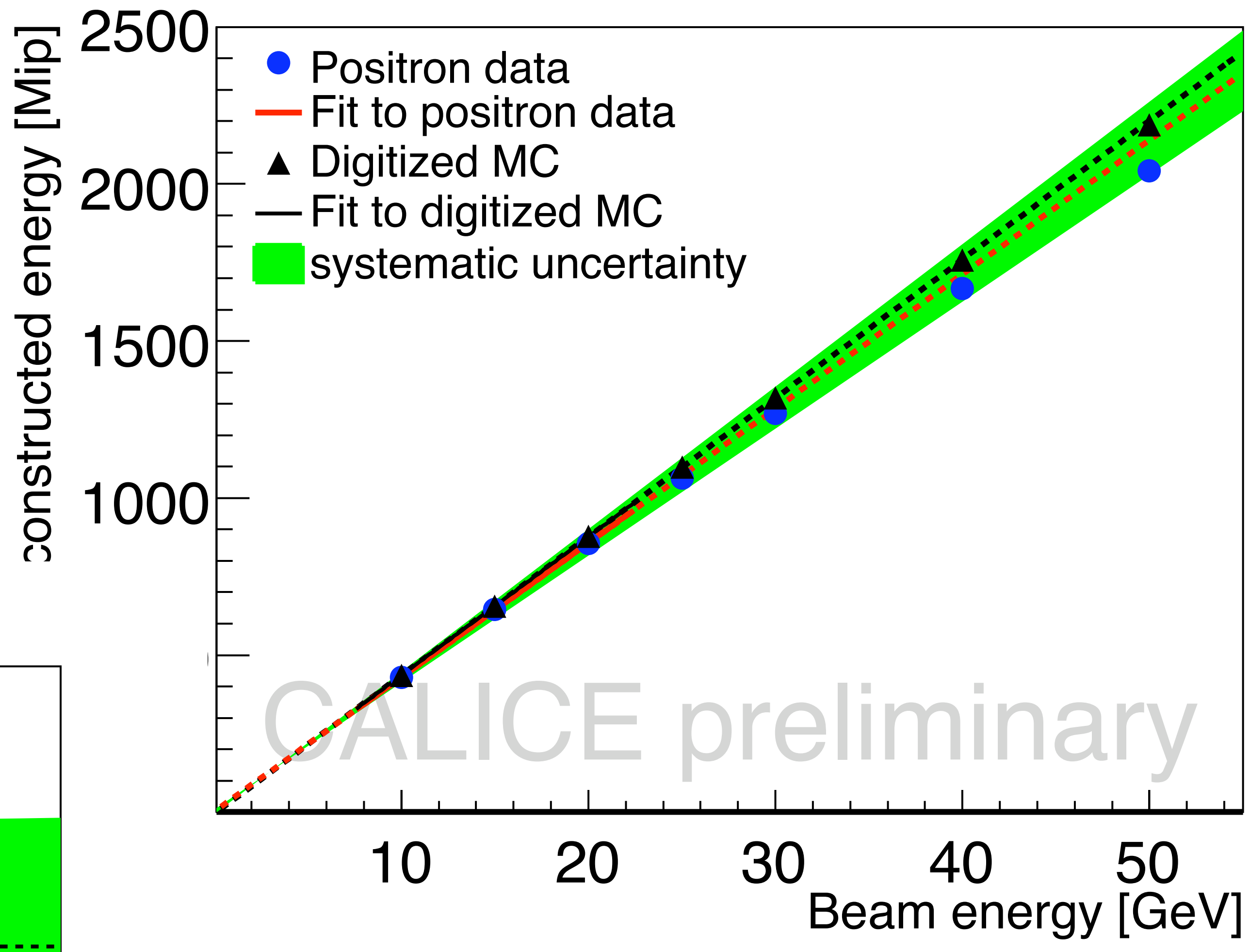
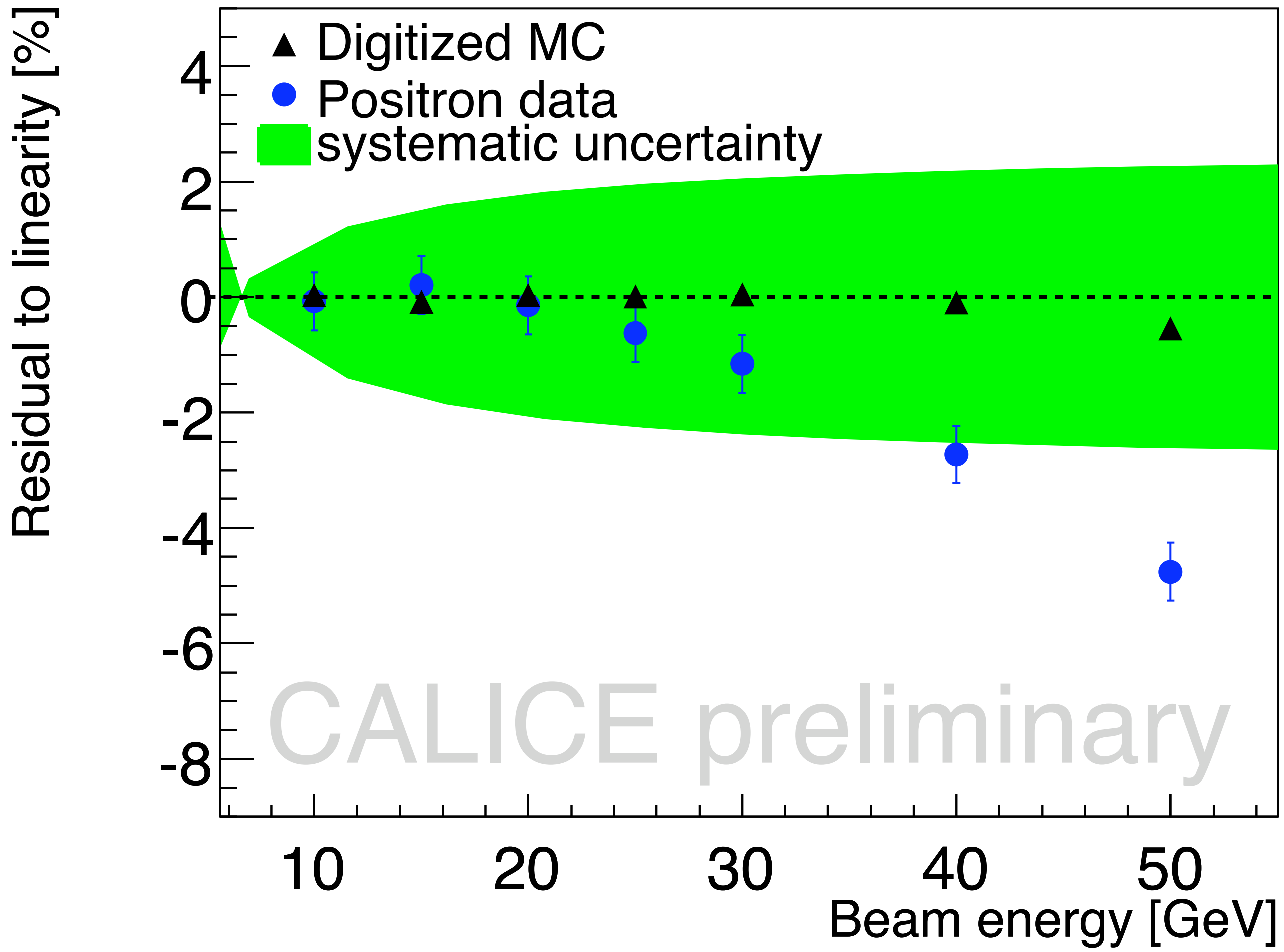


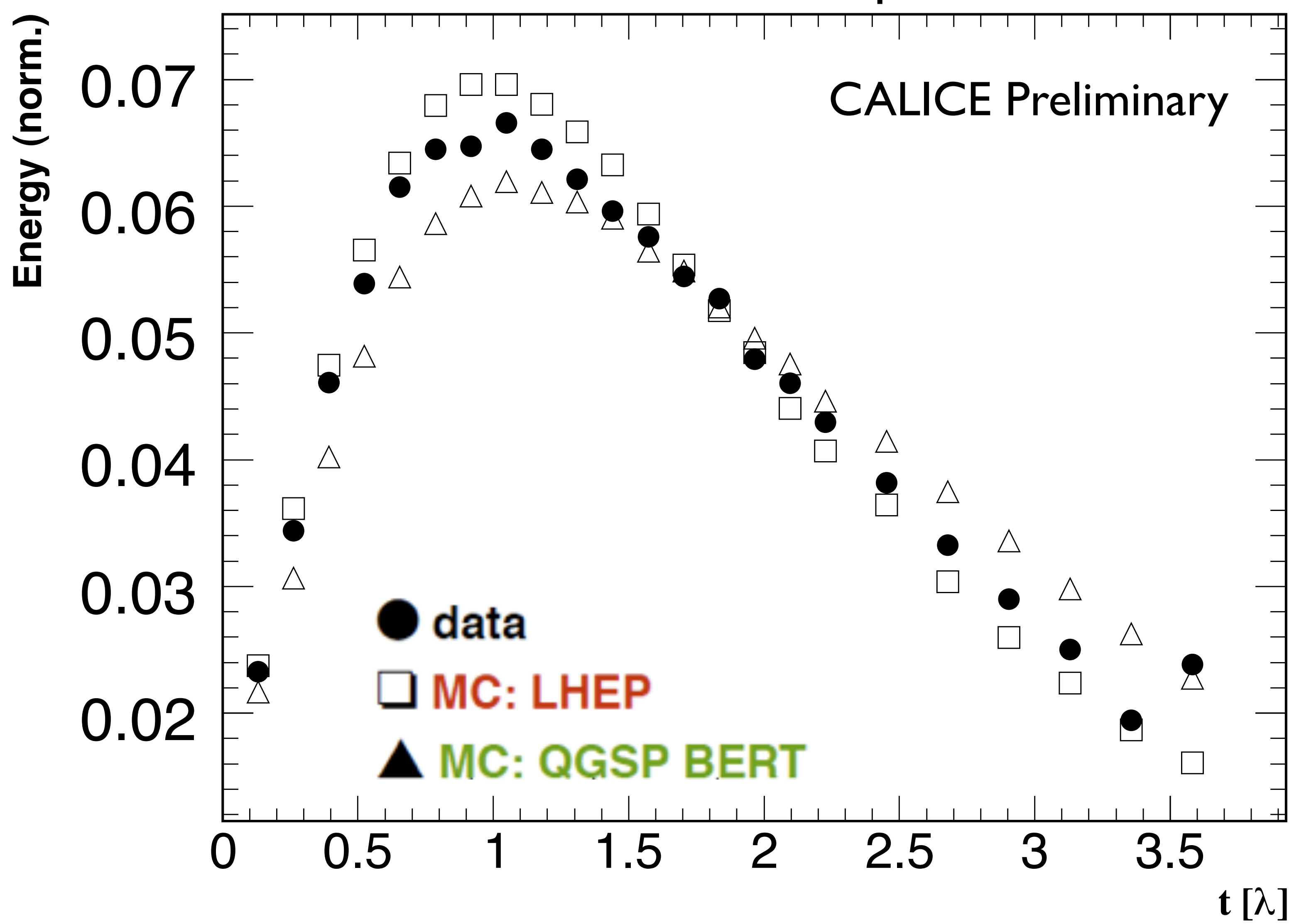


- Good linearity of the detector response observed: within 5% up to 50 GeV, within 1.5% up to 30 GeV
- Non-linearity with increasing energy not yet reproduced by MC

Shower Properties: Longitudinal Profile

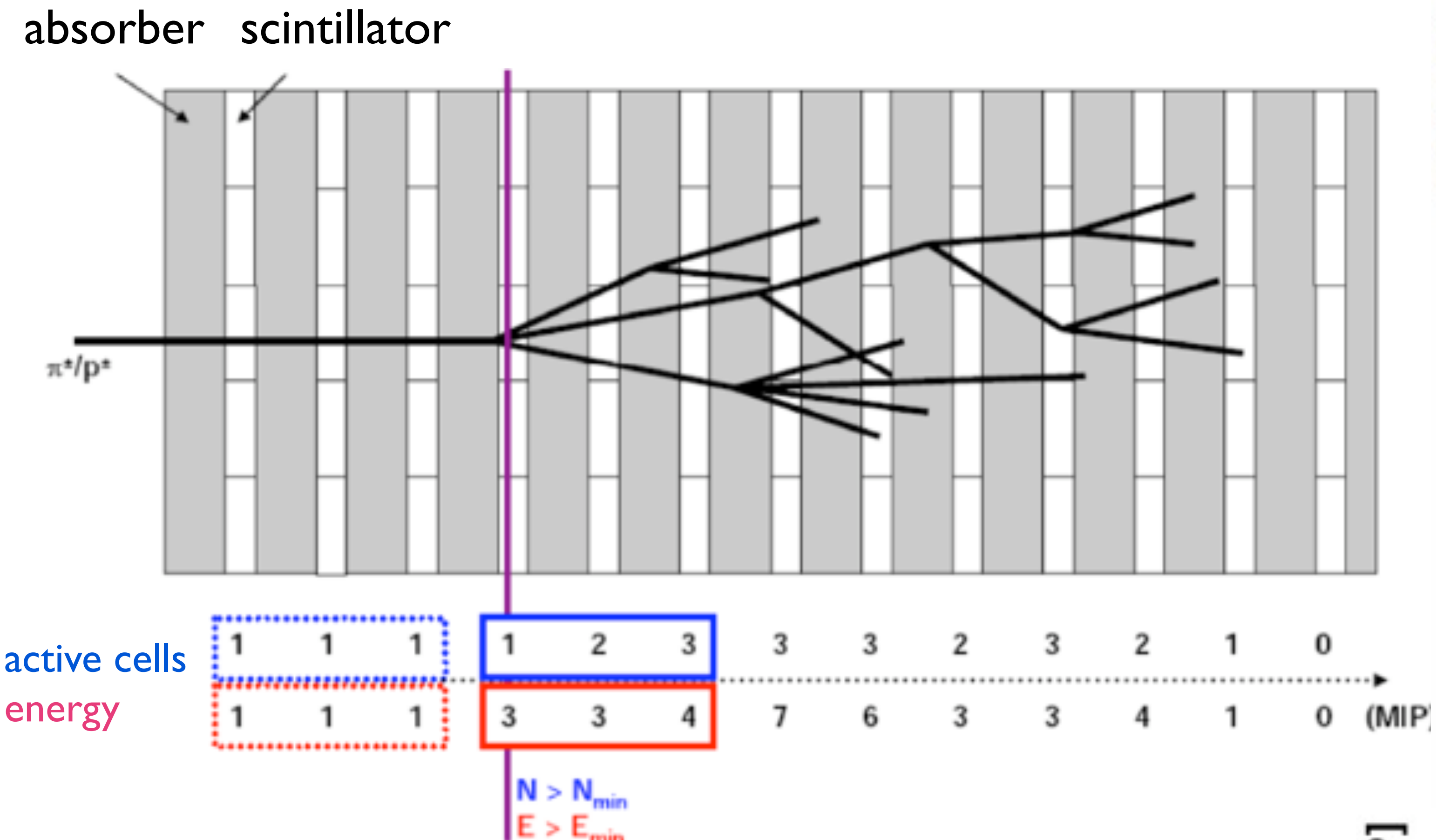
- Longitudinal shower profile for 2006 data: HCAL with 23 layers, reduced sampling fraction in the second half of the detector
- Simulations using GEANT4 and two different physics lists
  - simulation of digitization in detector
  - Birk's law in scintillators included

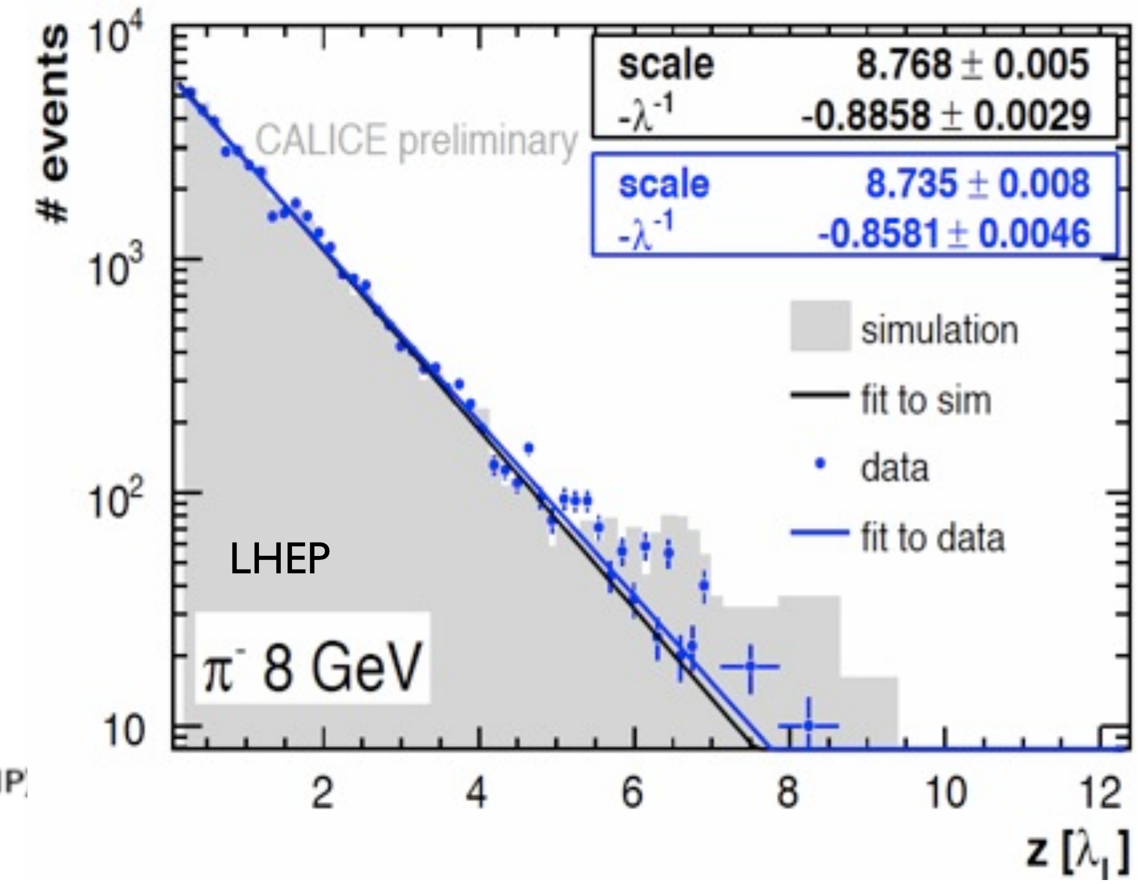
t: calorimeter depth

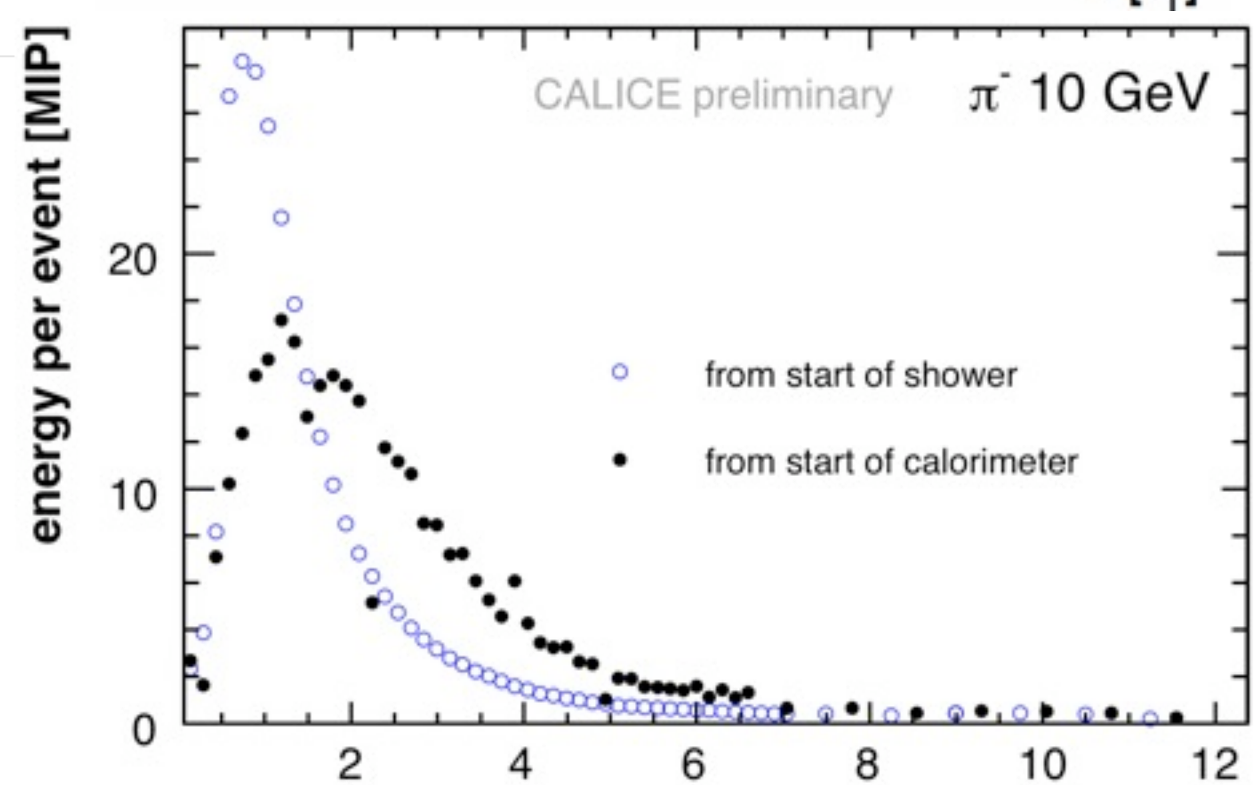


➡ High granularity provides detailed information of shower properties, can constraint for hadronic shower models

Shower Properties: Shower Starting Point







- High granularity allows identification of the shower start: Increased activity, track turns into shower
- starting point shows expected exponential fall-off
- longitudinal profile corrected for starting point optimal for MC comparison

Hadronic Energy Resolution: Weighting Techniques

- Hadronic showers have an electromagnetic and a hadronic component
  - Relative fraction of these components fluctuates significantly from event to event and changes with energy
- Non-compensating sampling calorimeters (like the CALICE calorimeters) have a higher response to the electromagnetic than to the hadronic component

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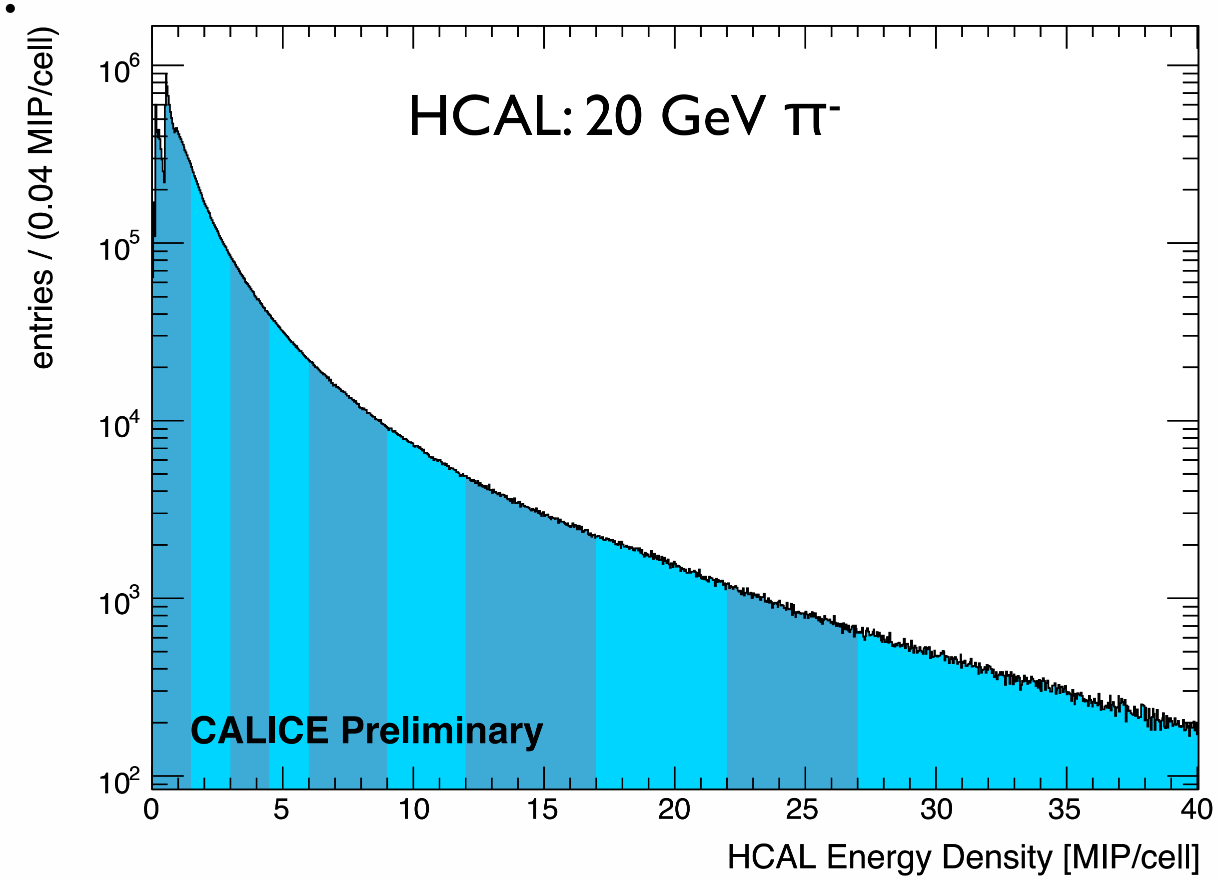
The energy resolution can be improved by equalizing the response: Needs identification of different shower components!

Simple approach: Weight calorimeter cells according to their energy content:

- Electromagnetic subshowers are denser
- ▸ Apply higher weights to cells with low energy density

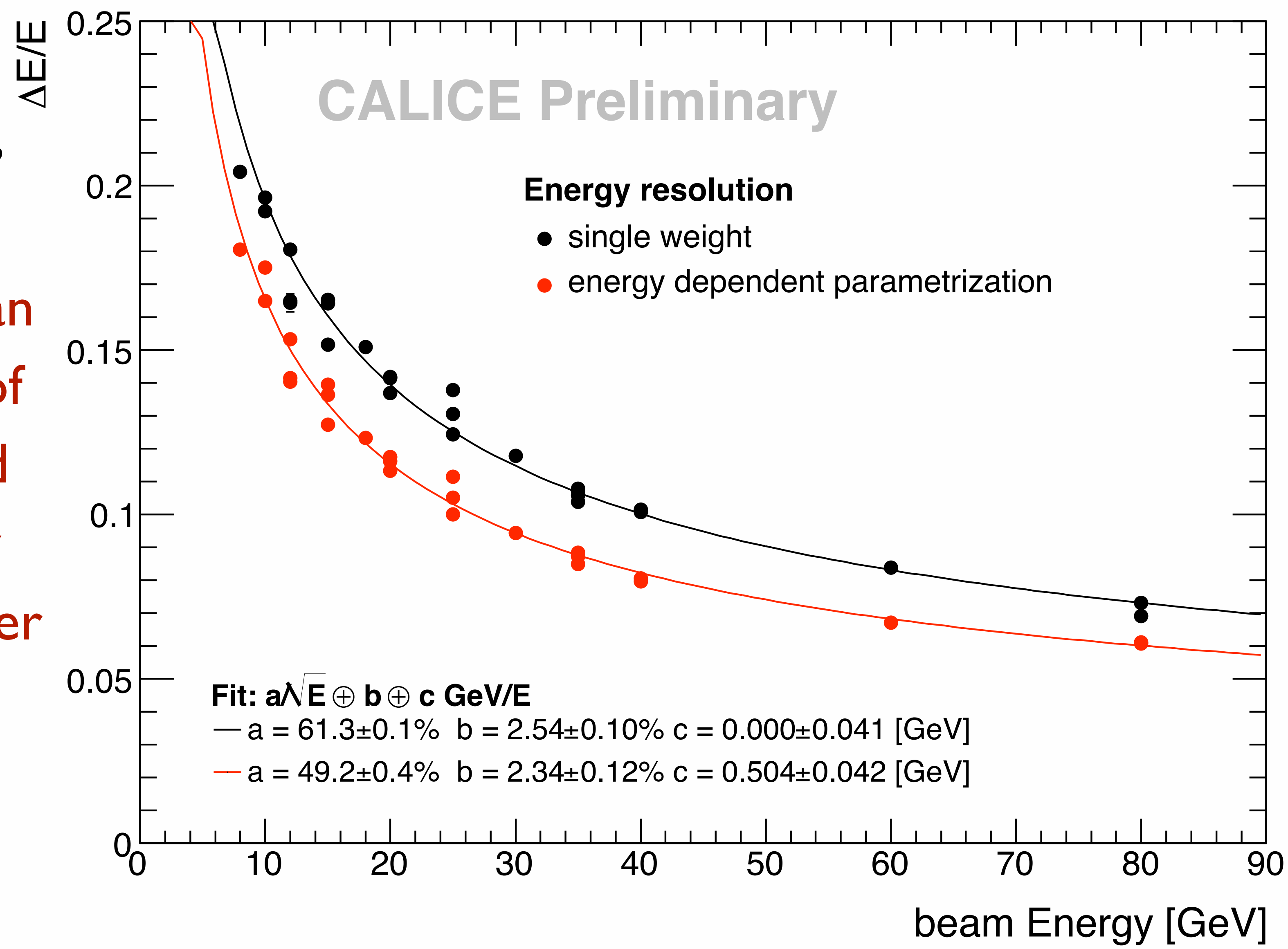


Energy Resolution of the Complete Setup

- Hadrons at various energies in the complete CALICE setup (ECAL, HCAL, TCMT)
  - No requirements on containment
  - Temperature corrections not included: big variations run to run

2 ways to reconstruct the energy:

- One conversion factor per detector, no density dependent weighting
- 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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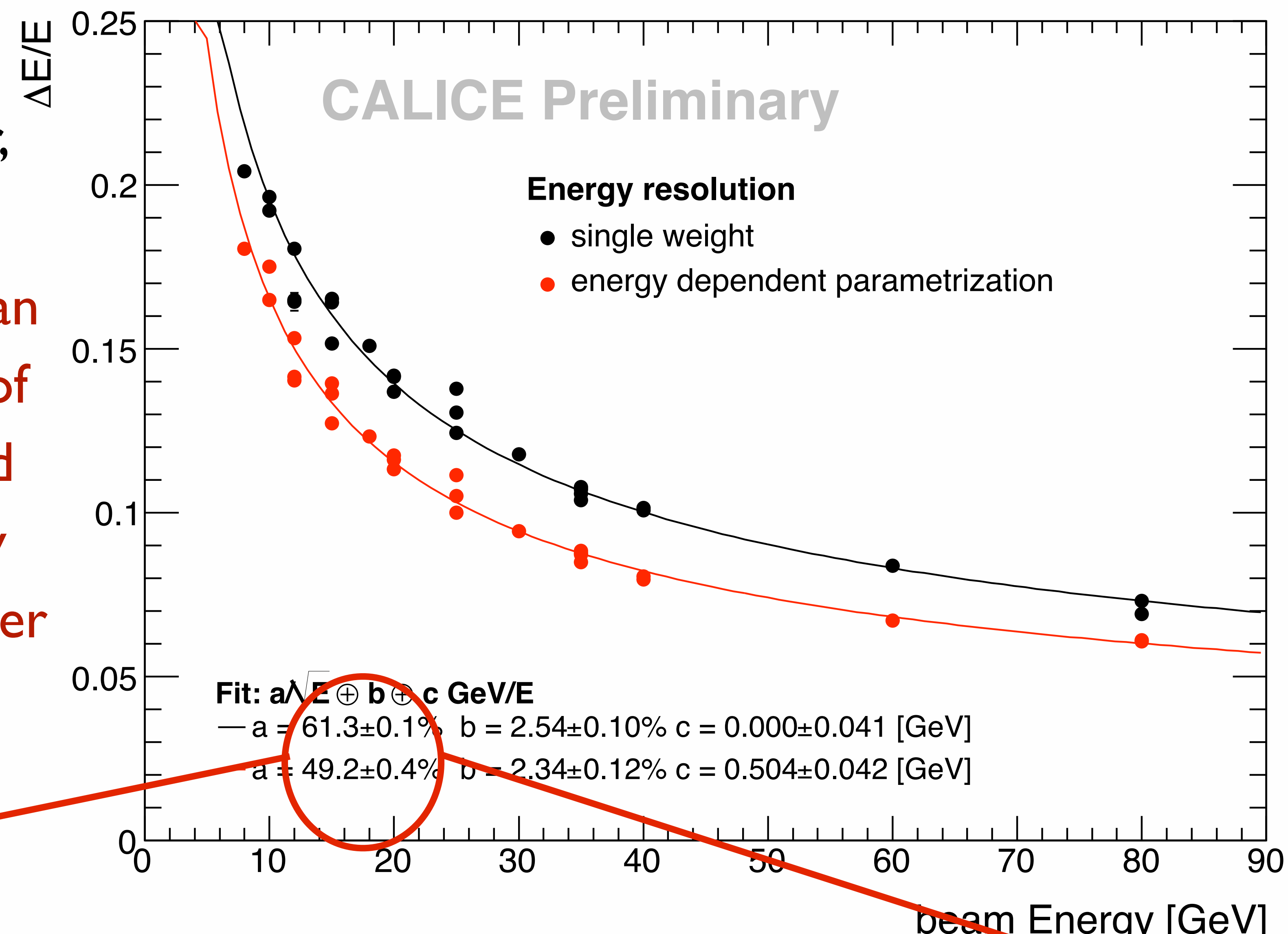
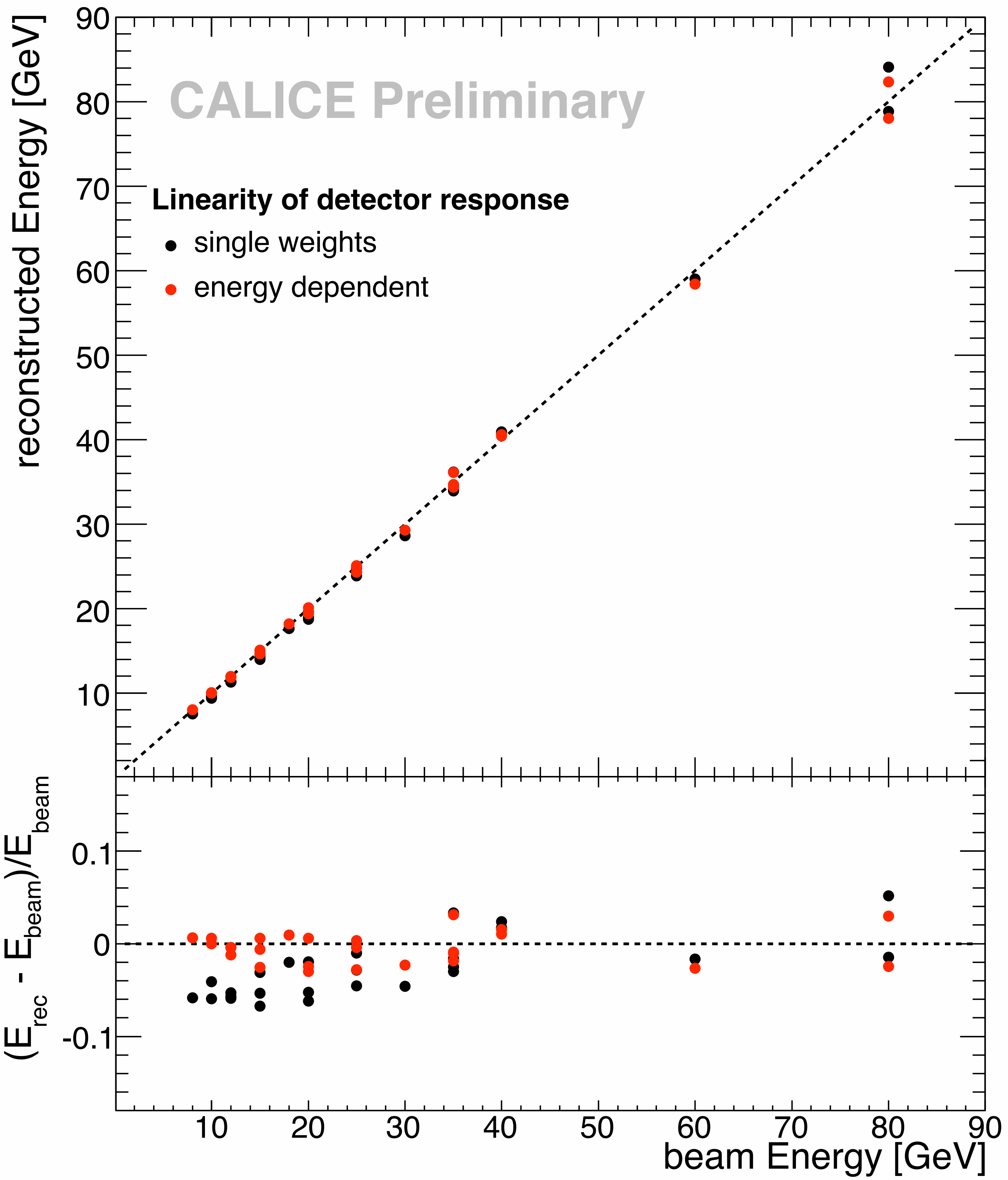


stochastic term w/o weighting: 61.3%, with parametrized weighting 49.2%

Linearity of Energy Response: Combined Setup

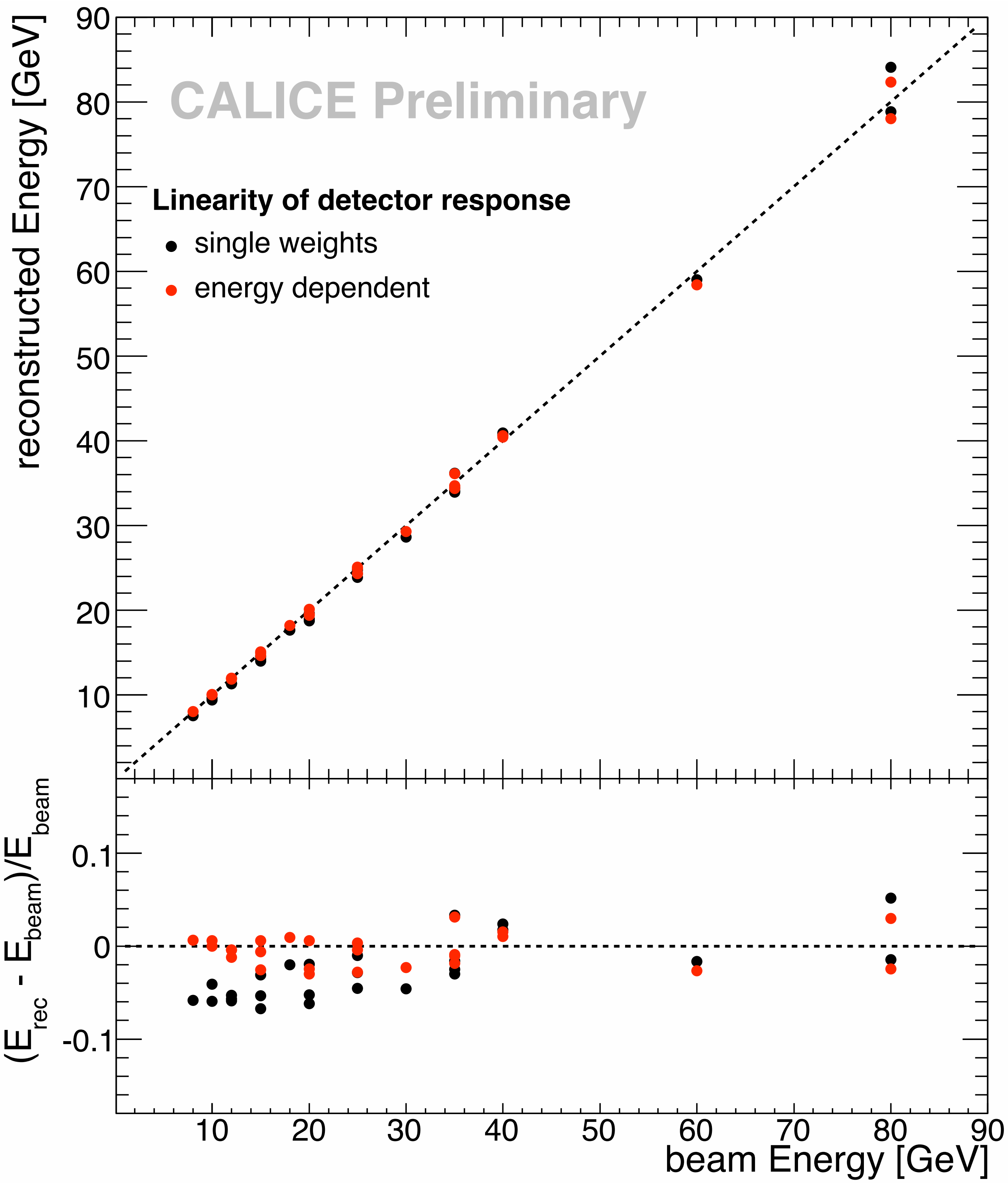
- Energy reconstructed with single conversion factors and with parametrized density dependent weighting
- Noise rejection: Isolated noise hits (and isolated neutrons) rejected in the analysis



Linearity of Energy Response: Combined Setup

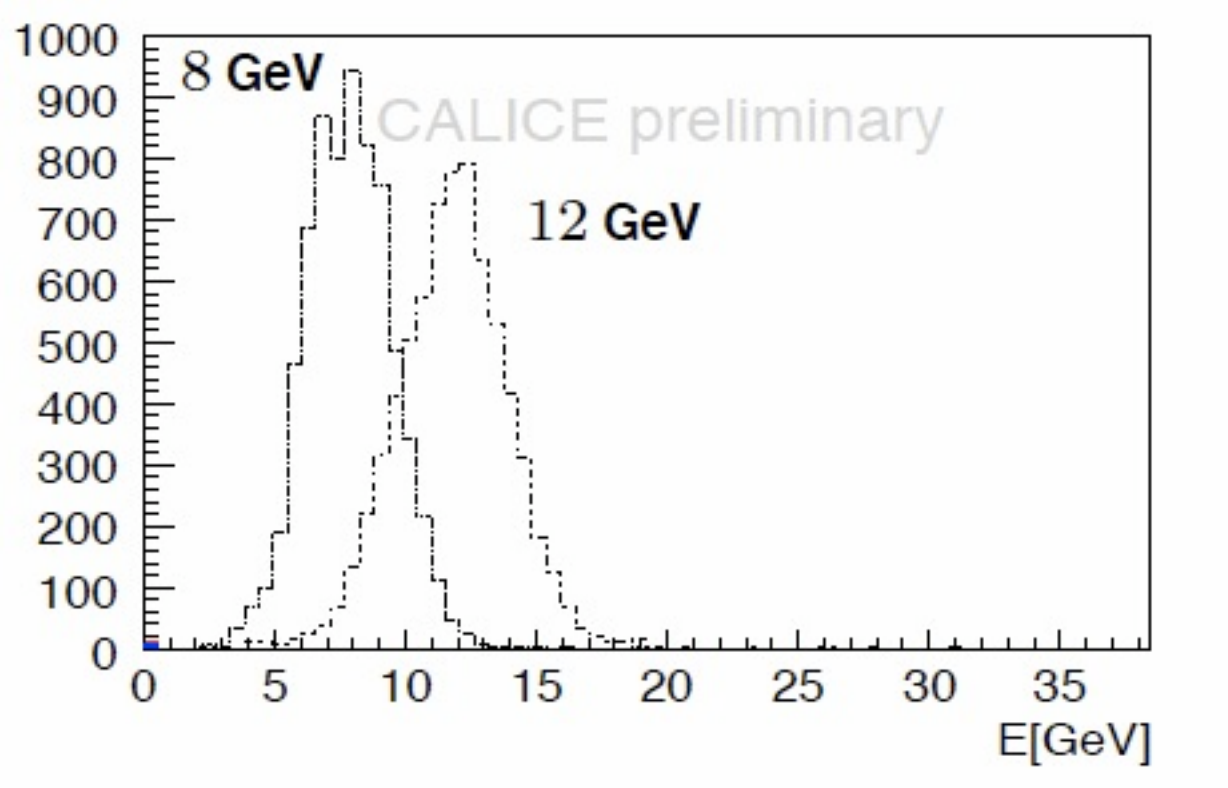
- Energy reconstructed with single conversion factors and with parametrized density dependent weighting
- Noise rejection: Isolated noise hits (and isolated neutrons) rejected in the analysis

- 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



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:



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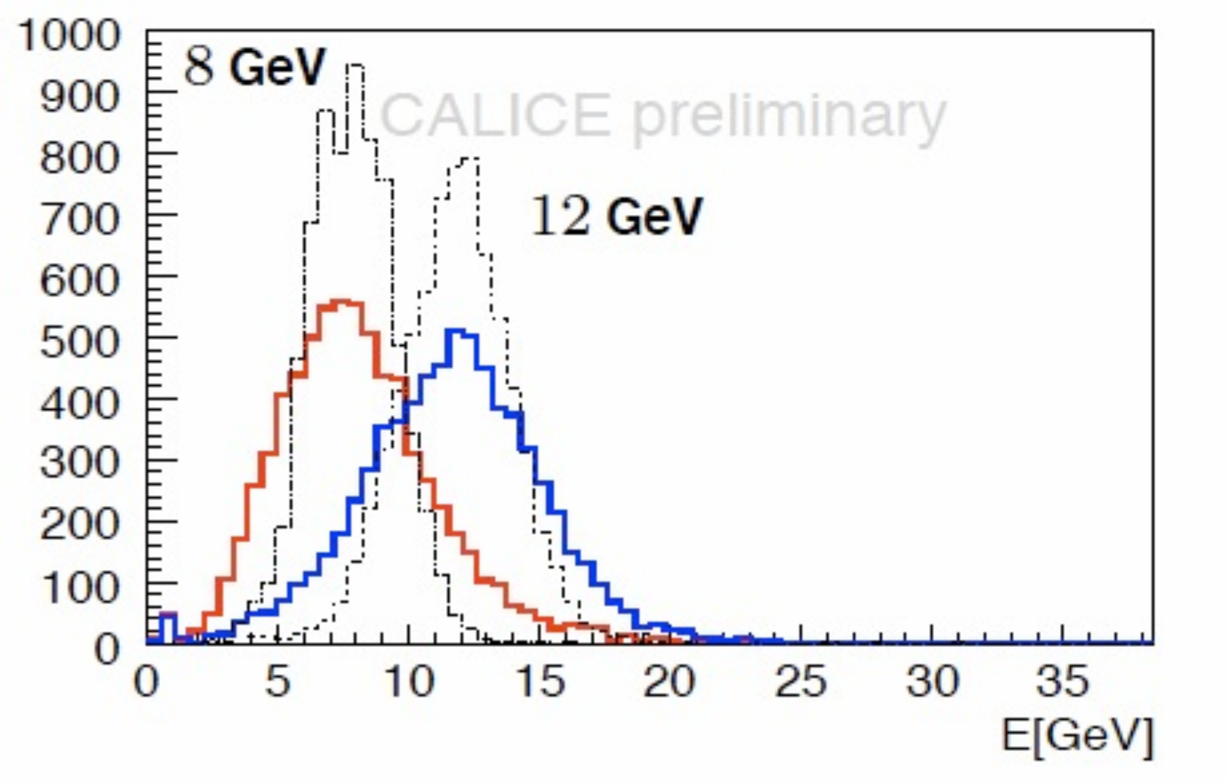

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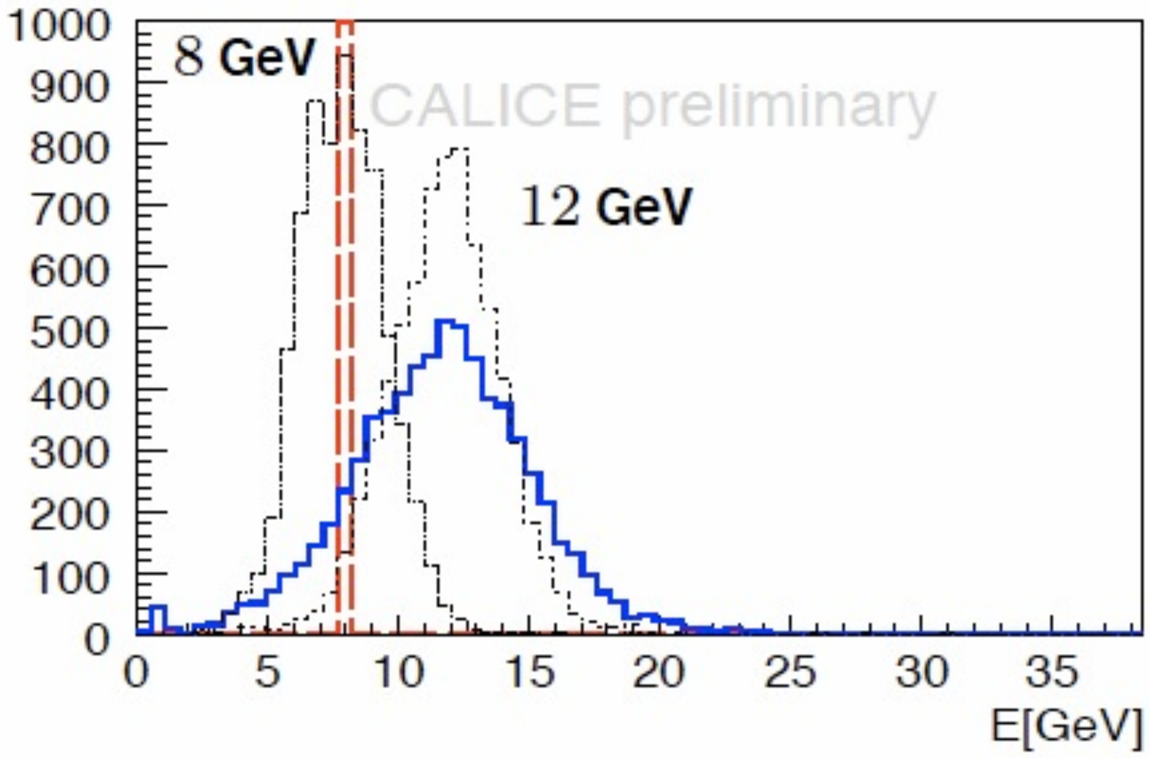

1. Overlay events from different energies
2. Reconstruct the showers
3. Assume PFA scenario: One well-measured charged track associated with one particle in the calorimeter, no association (neutral particle) for the other

Shower Separation: A Test of Particle Flow

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

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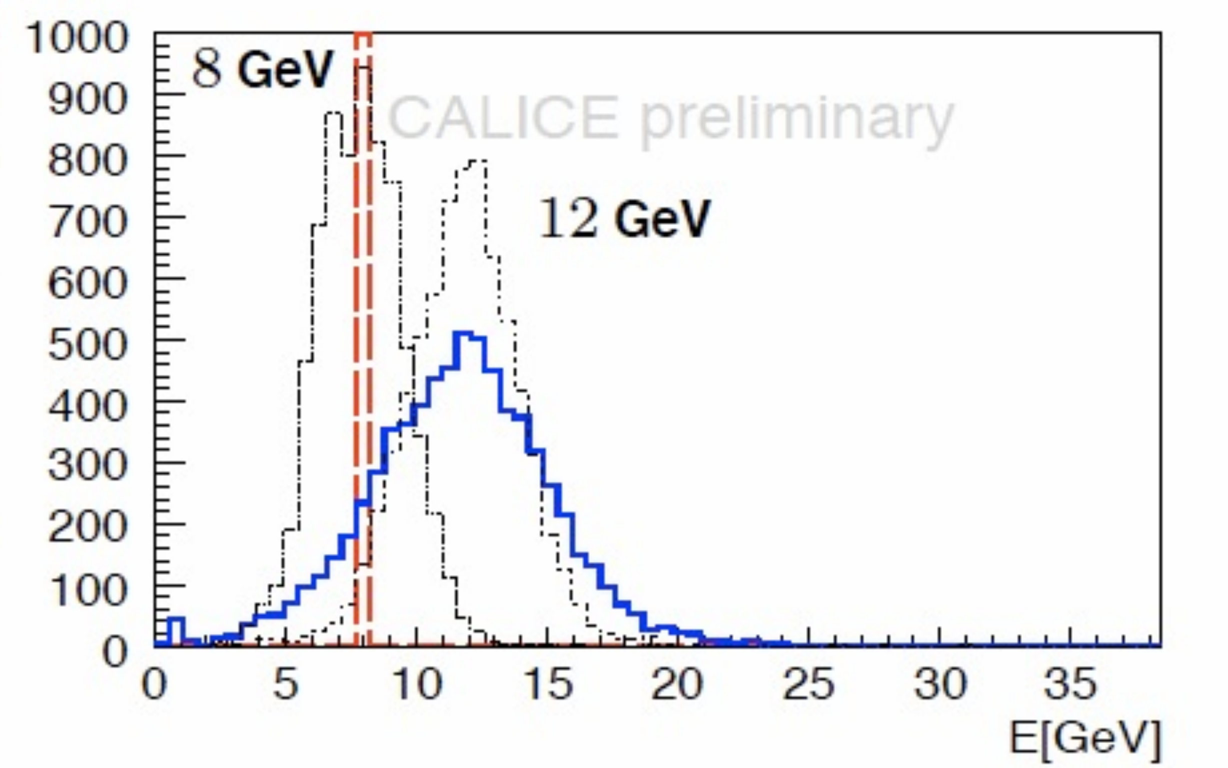
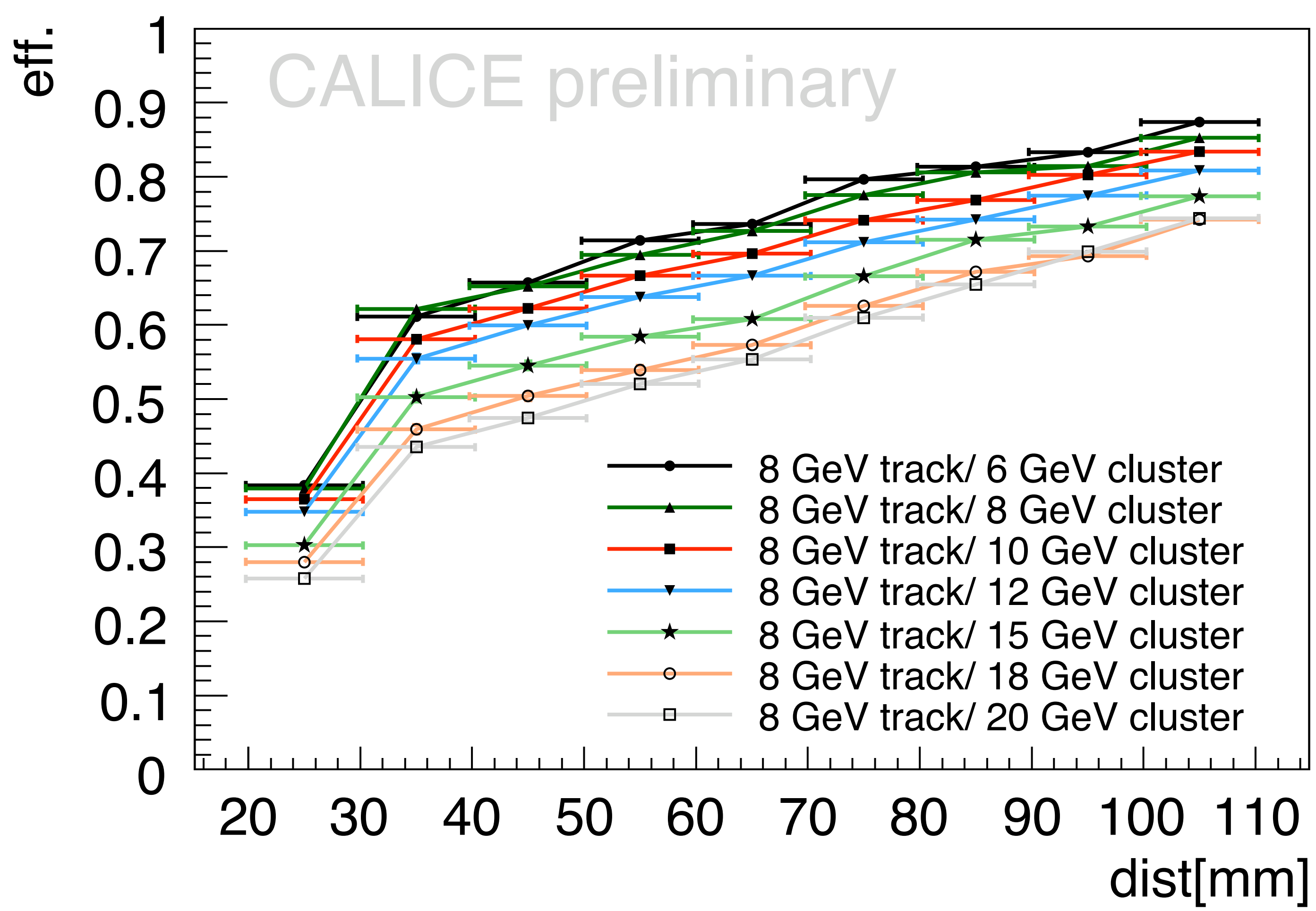


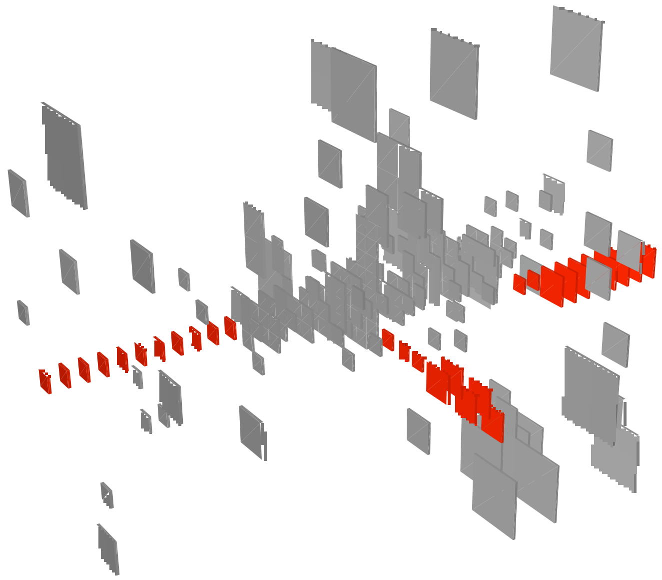
1. Overlay events from different energies
2. Reconstruct the showers



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

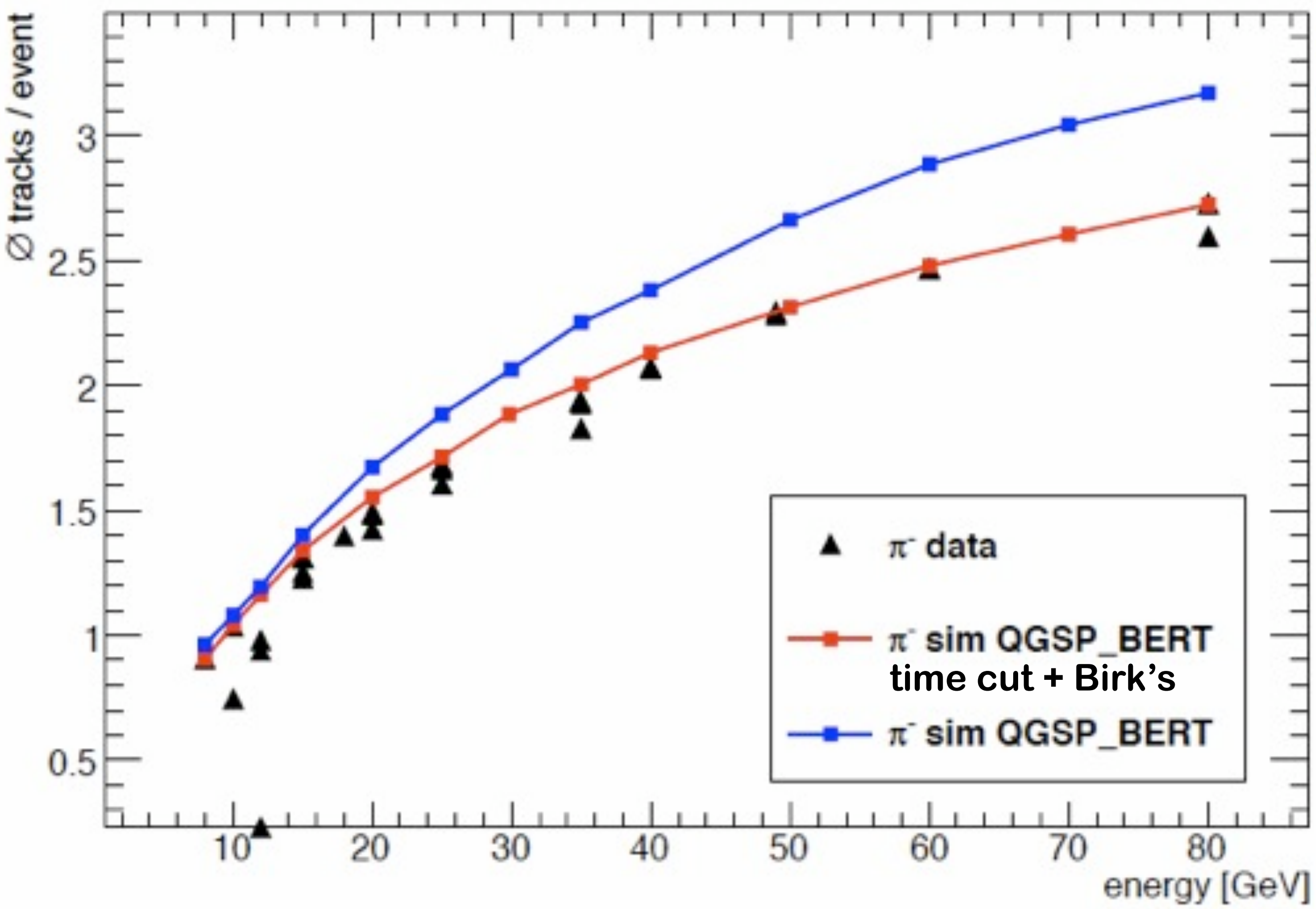
- Currently only very small distances due to available data set

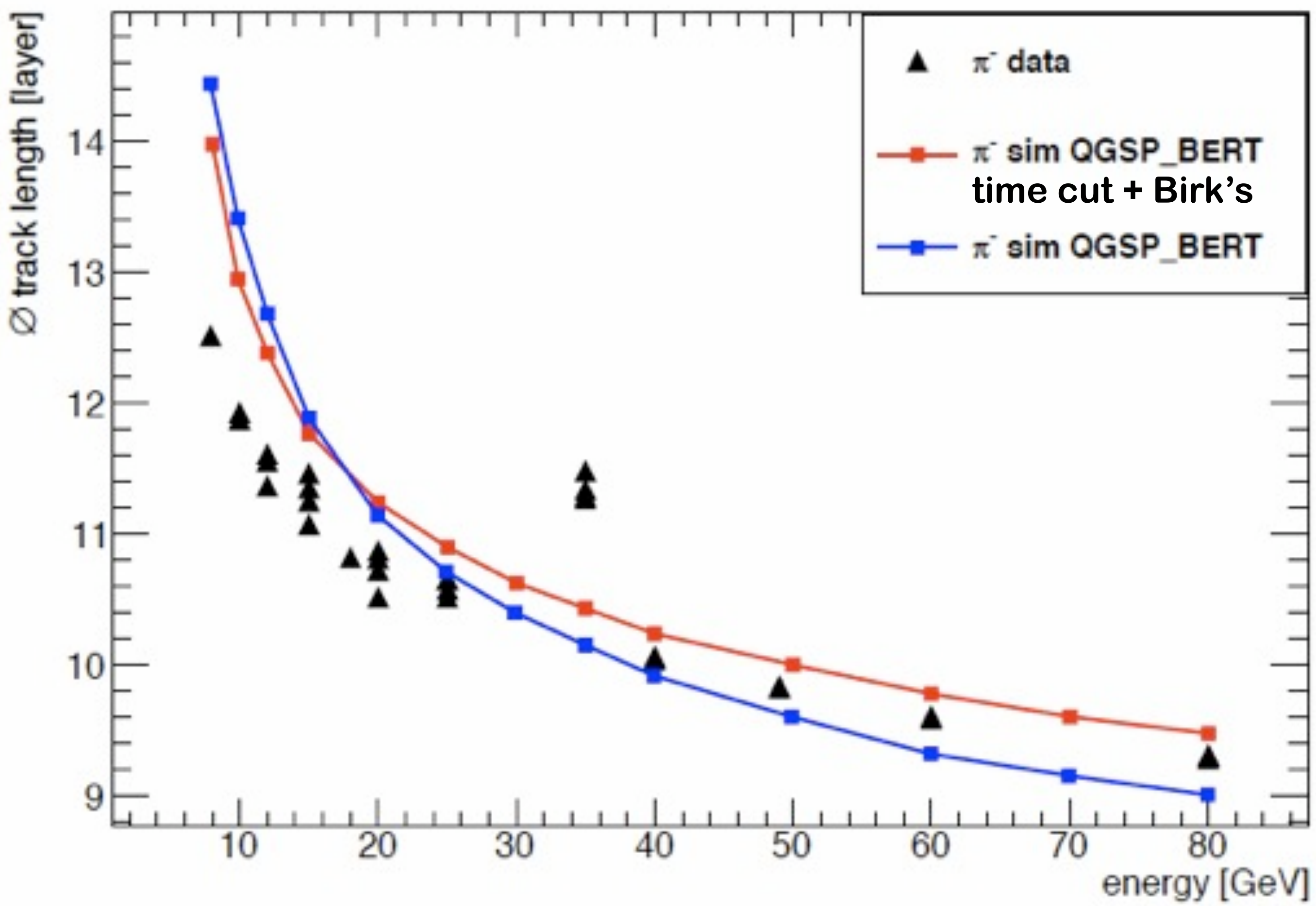
Shower Substructure & Simulations



- Good modeling of the hadronic shower substructure crucial for reliable MC studies of PFA performance
  - Compare identified track segments in data and MC

CALICE unofficial: student thesis work





Collaboration with GEANT4 developers established

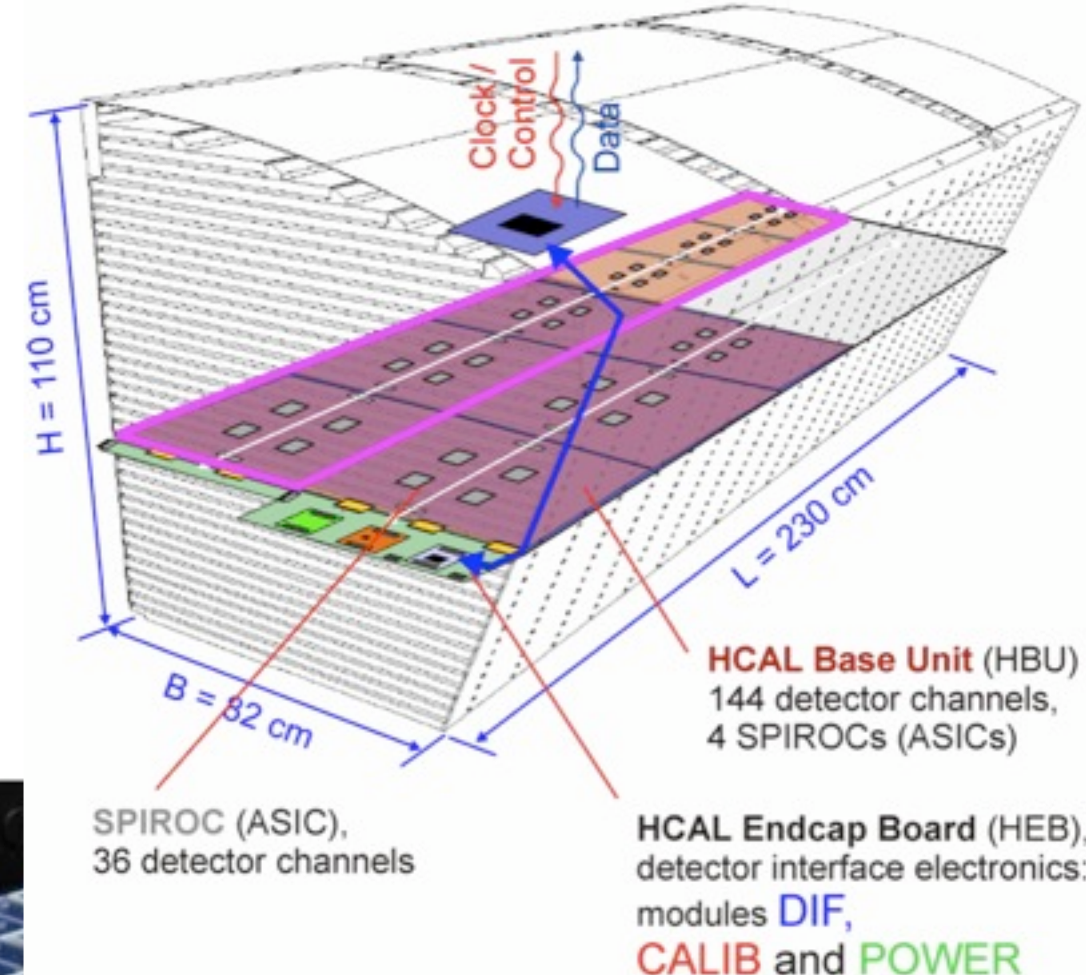
R&D for the Next Generation Prototype

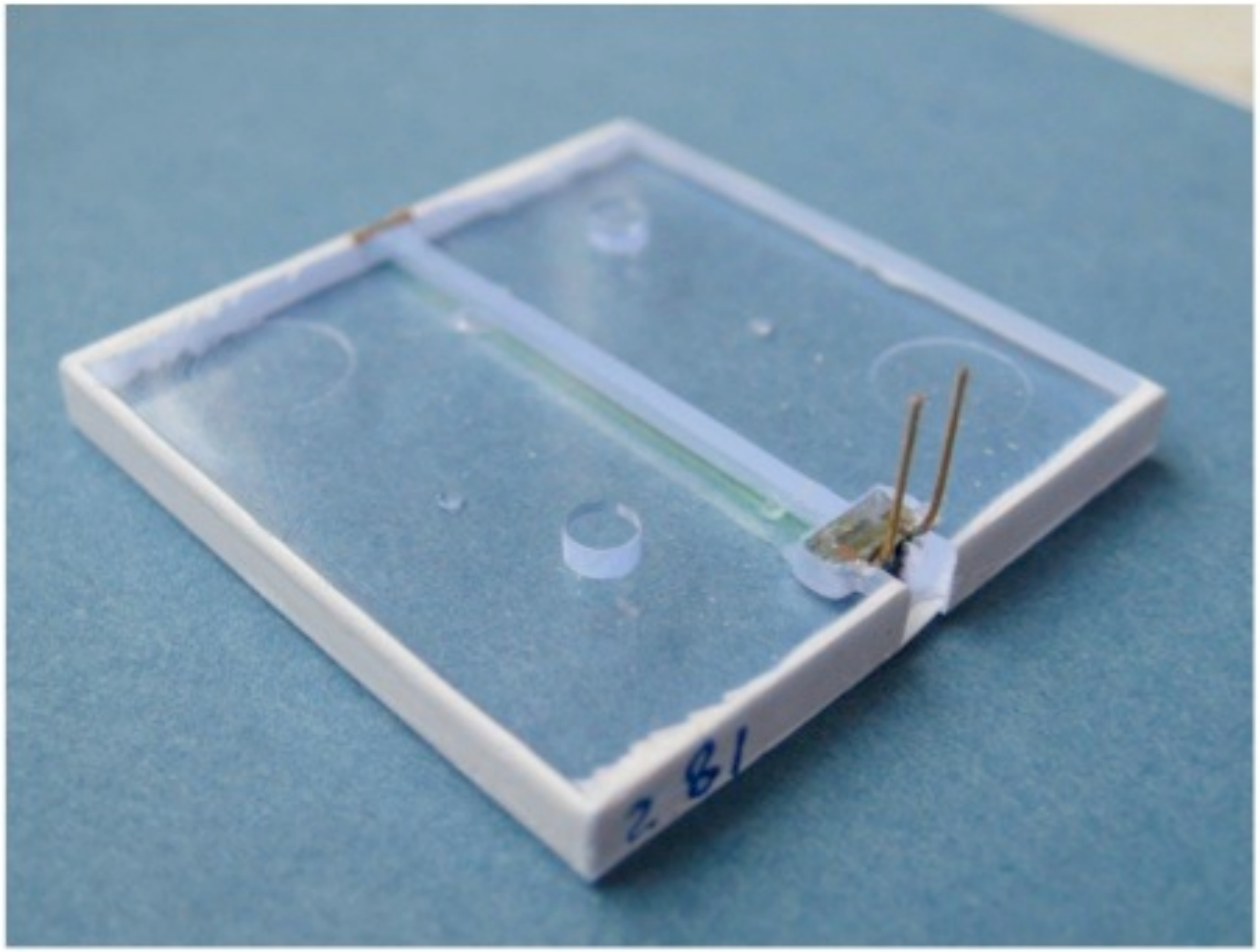
Activities in Germany: Overview

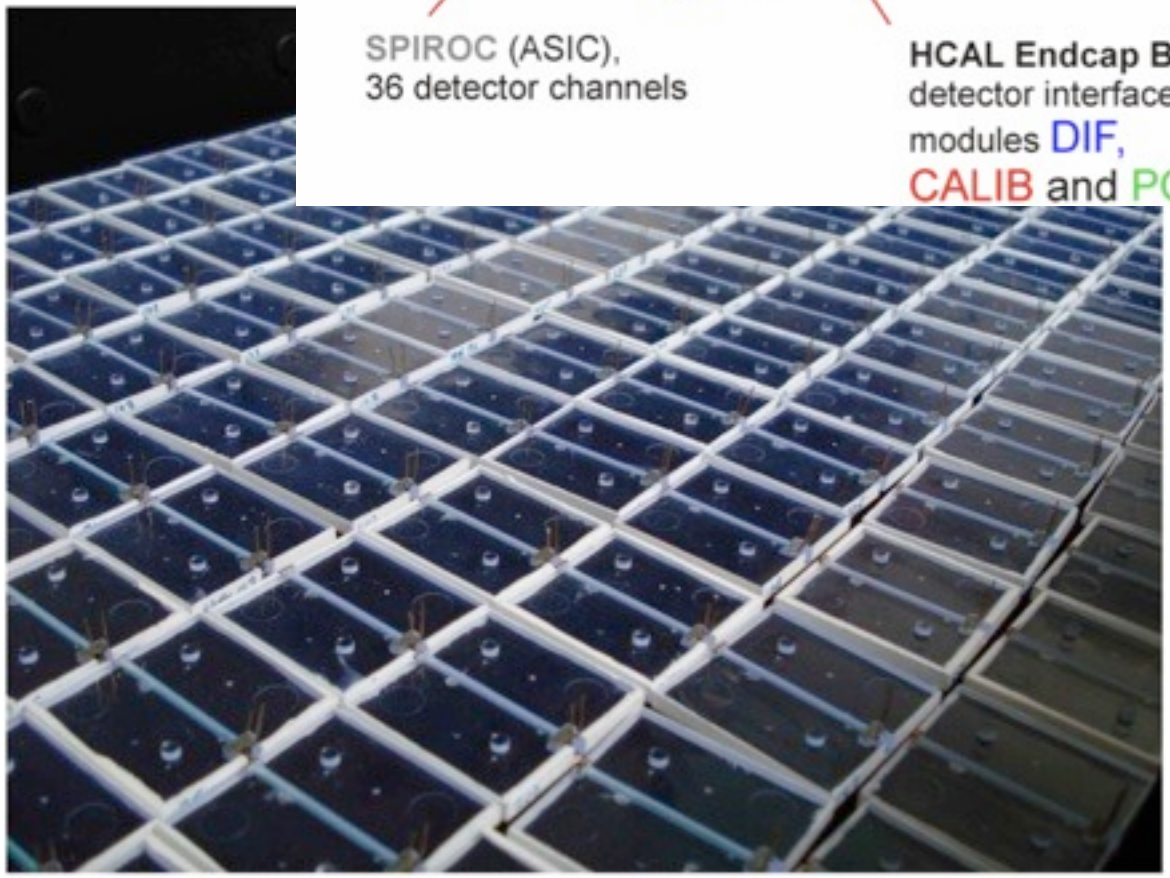
- DESY: mechanics, electronics integration, coordination
- Heidelberg: SiPM characterization, electronics
- MPI Munich: SiPM development and characterization, study of scintillator tiles, (mechanics)
- Wuppertal: calibration system

Next Generation Prototype

- Development of the next generation prototype for the AHCAL: Active layers, electronics
  - 152 tiles at DESY (144 needed for 1 HBU)
    - WLS fiber, CPTA SiPM, made at ITEP

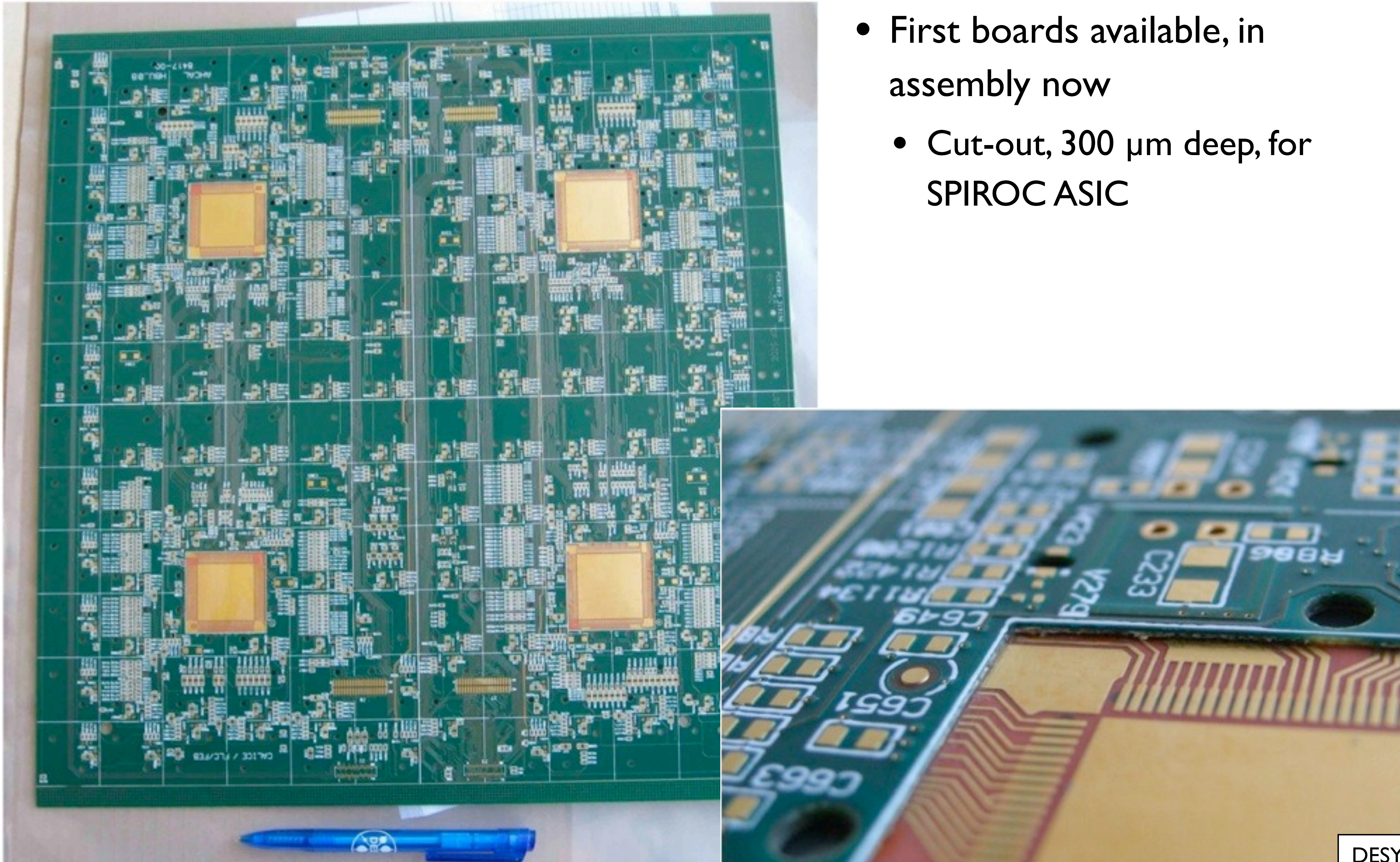






DESY

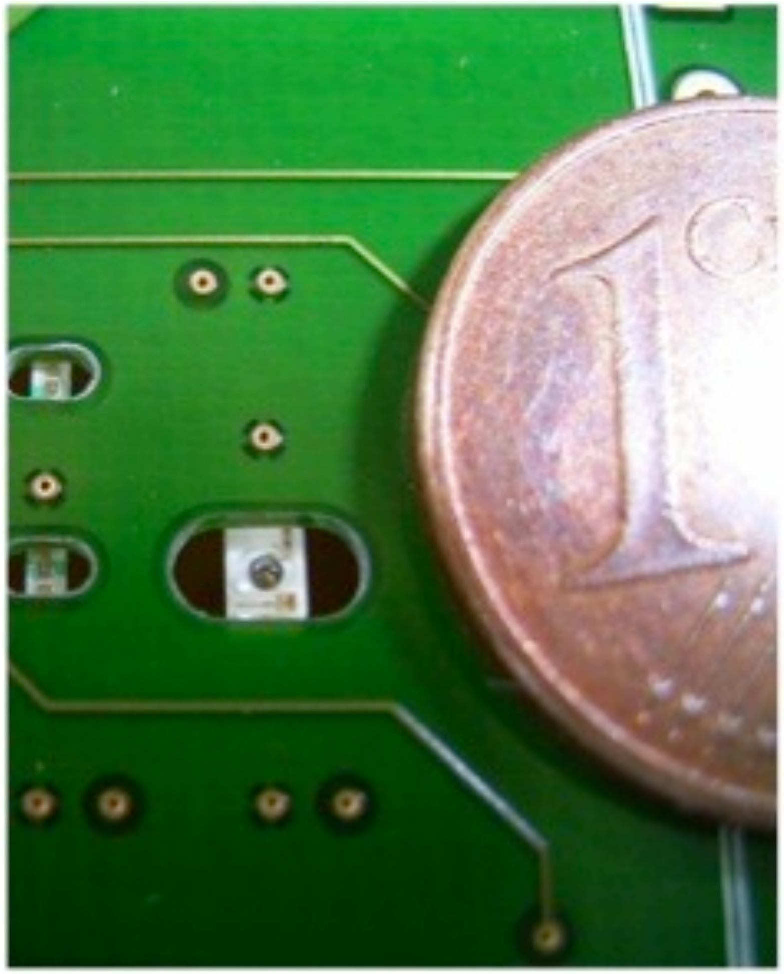
The HCAL Base Unit HBU



- First boards available, in assembly now
    - Cut-out, 300 μm deep, for SPIROC ASIC

LED Calibration for the Next Generation

- Concept of single channel calibration
  - Use LED to inject low level of light into scintillator tile
  - LED directly imbedded in electronic board
- Optimization procedure
  - LED type and the position of the LED above the tile
  - Pulsing electronics
- Current activities
  - µDAQ
  - Test stand



Wuppertal

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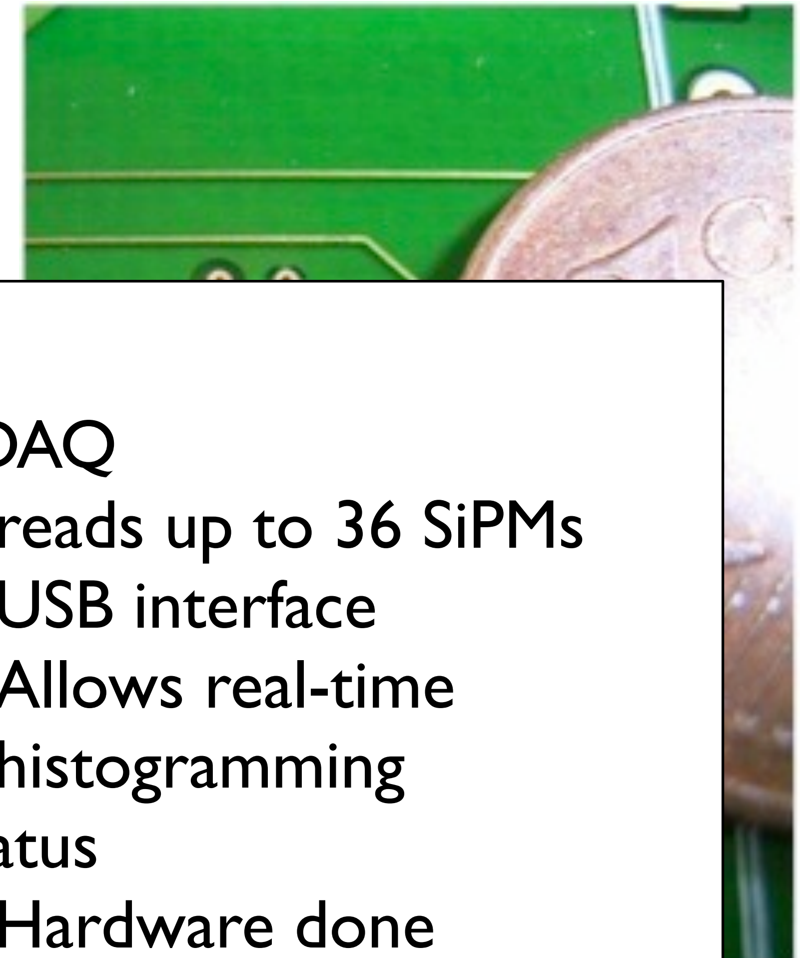


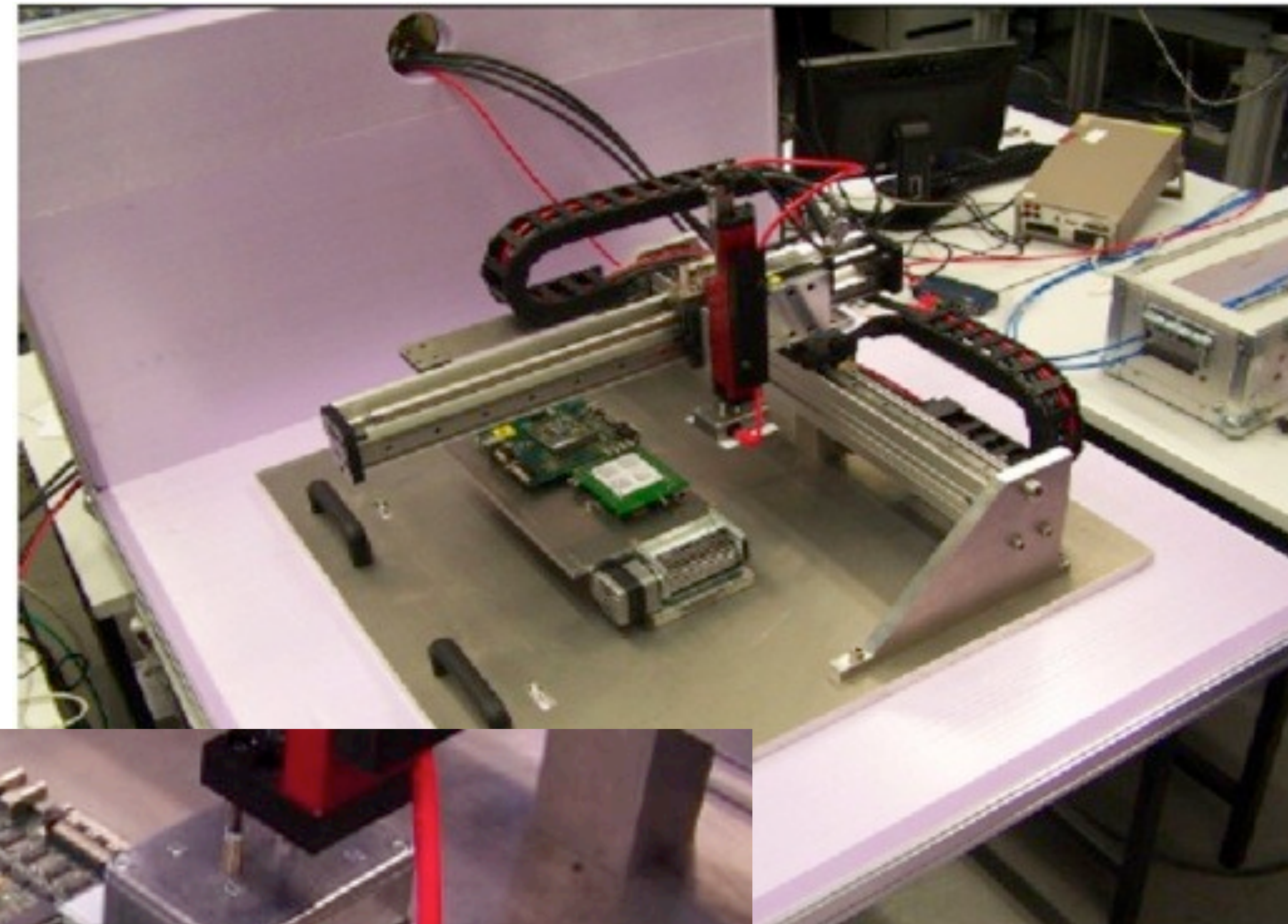
µDAQ
- reads up to 36 SiPMs
- USB interface
- Allows real-time histogramming

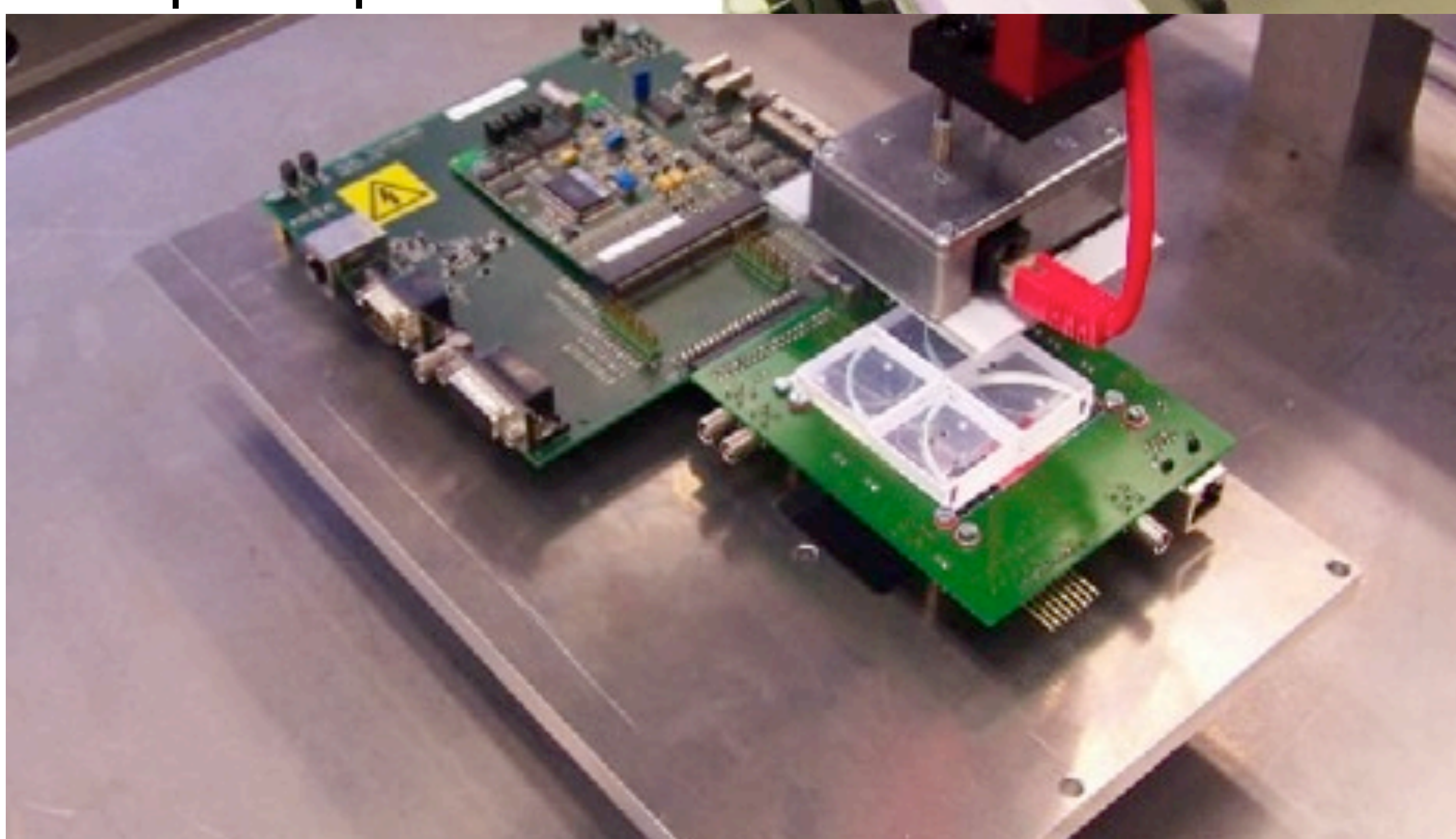
Status
- Hardware done
- Firmware done
- PC Software done, Labview based

Wuppertal

Calibration Test Stand

- Test stand: Light tight xy-table
  - Control Software done
  - Read out done
  - Temperature control nearly done
  - Scan head contains circuit to pulse LED
- Measurements starting
  - First tests with LED pulser performed





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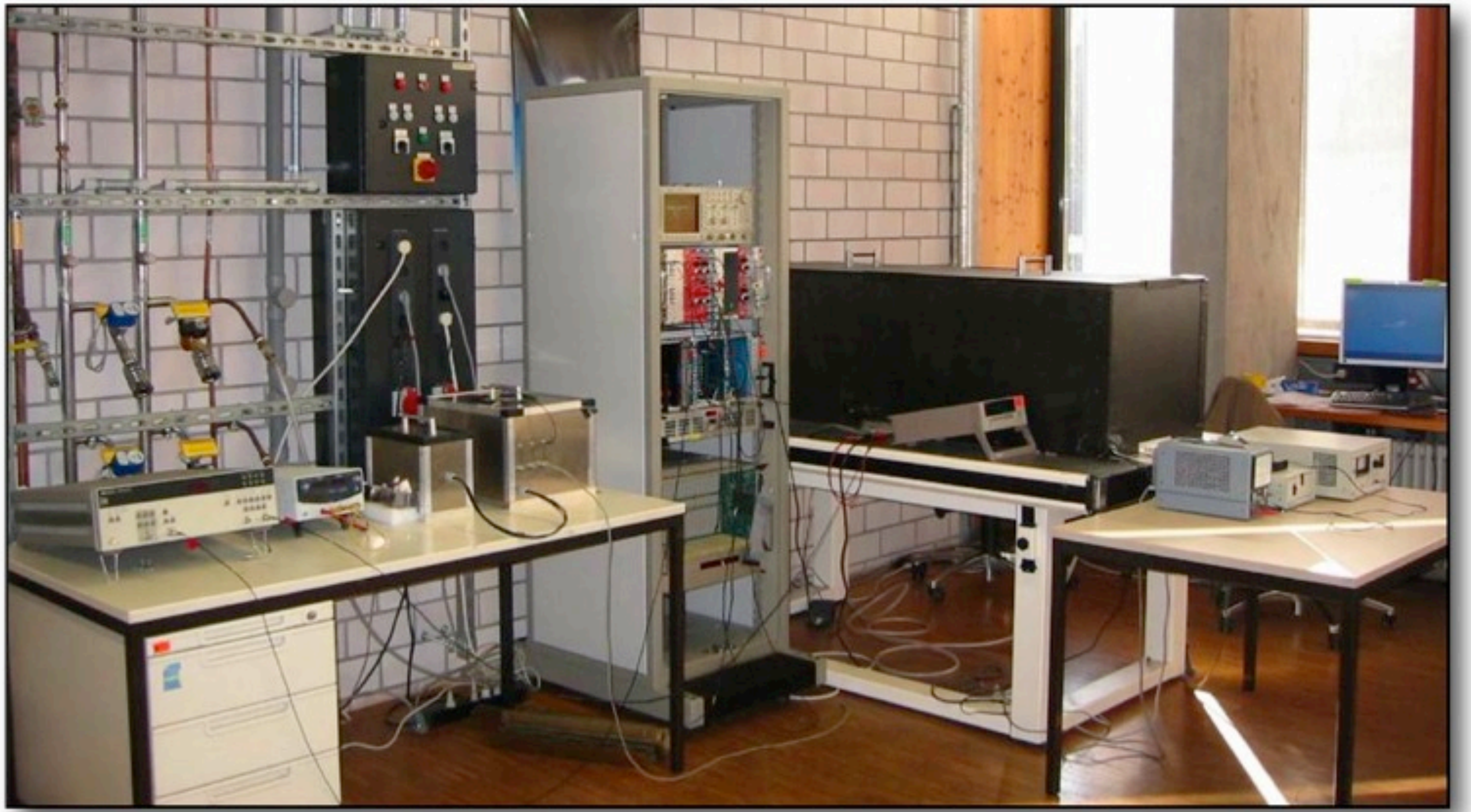
Characterization of SiPMs

- Highly accurate scanning across SiPM surface with a focused light spot
  - HD: Blue LED light, MPP: IR laser
- Measure uniformity, cross talk, ...



Heidelberg, MPI Munich

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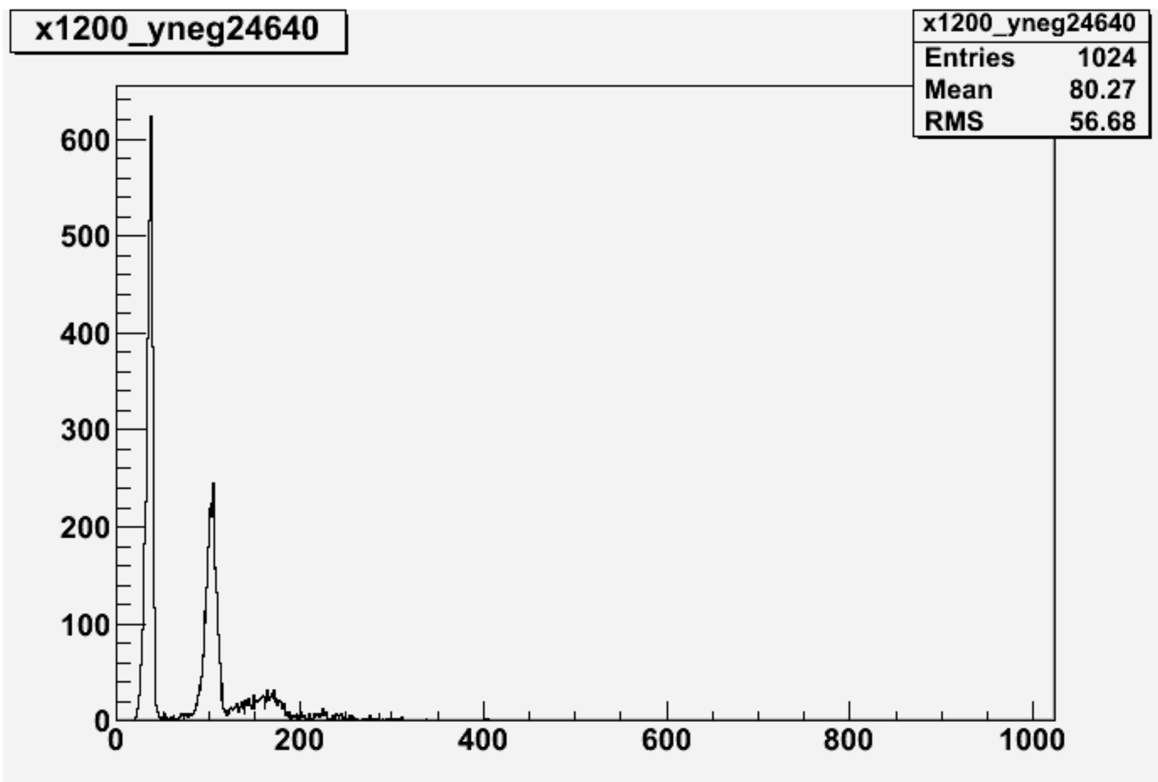

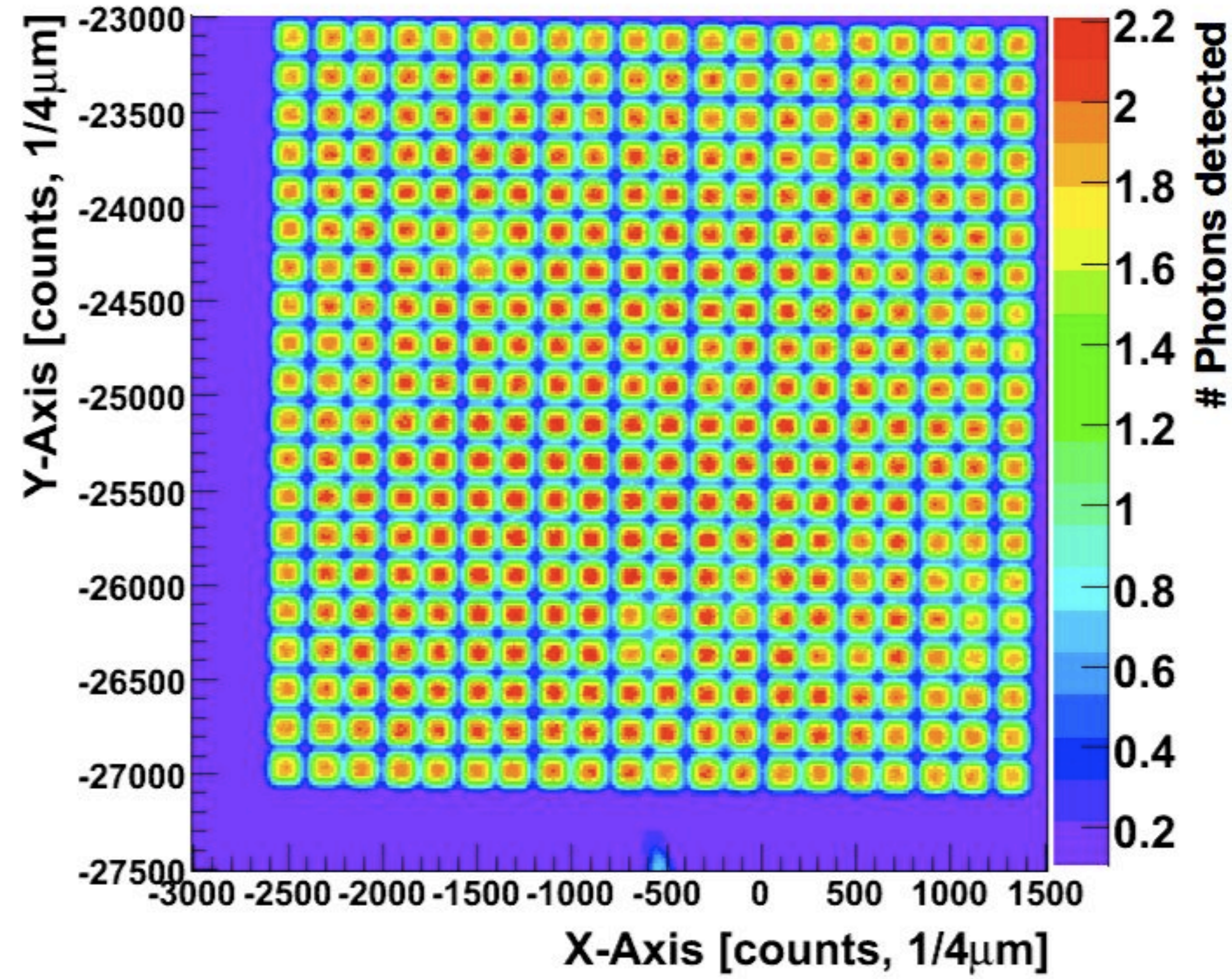

Versatile Analysis (position sensitive)
#photons(x,y),
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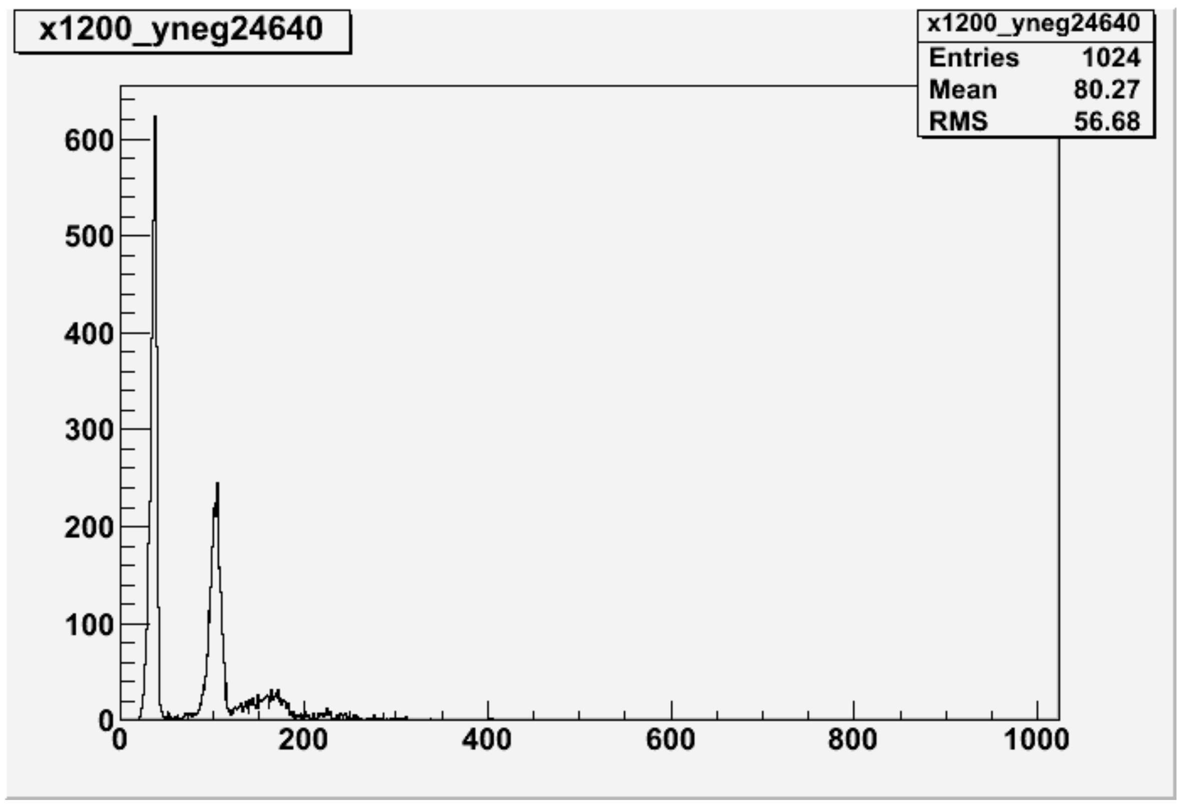

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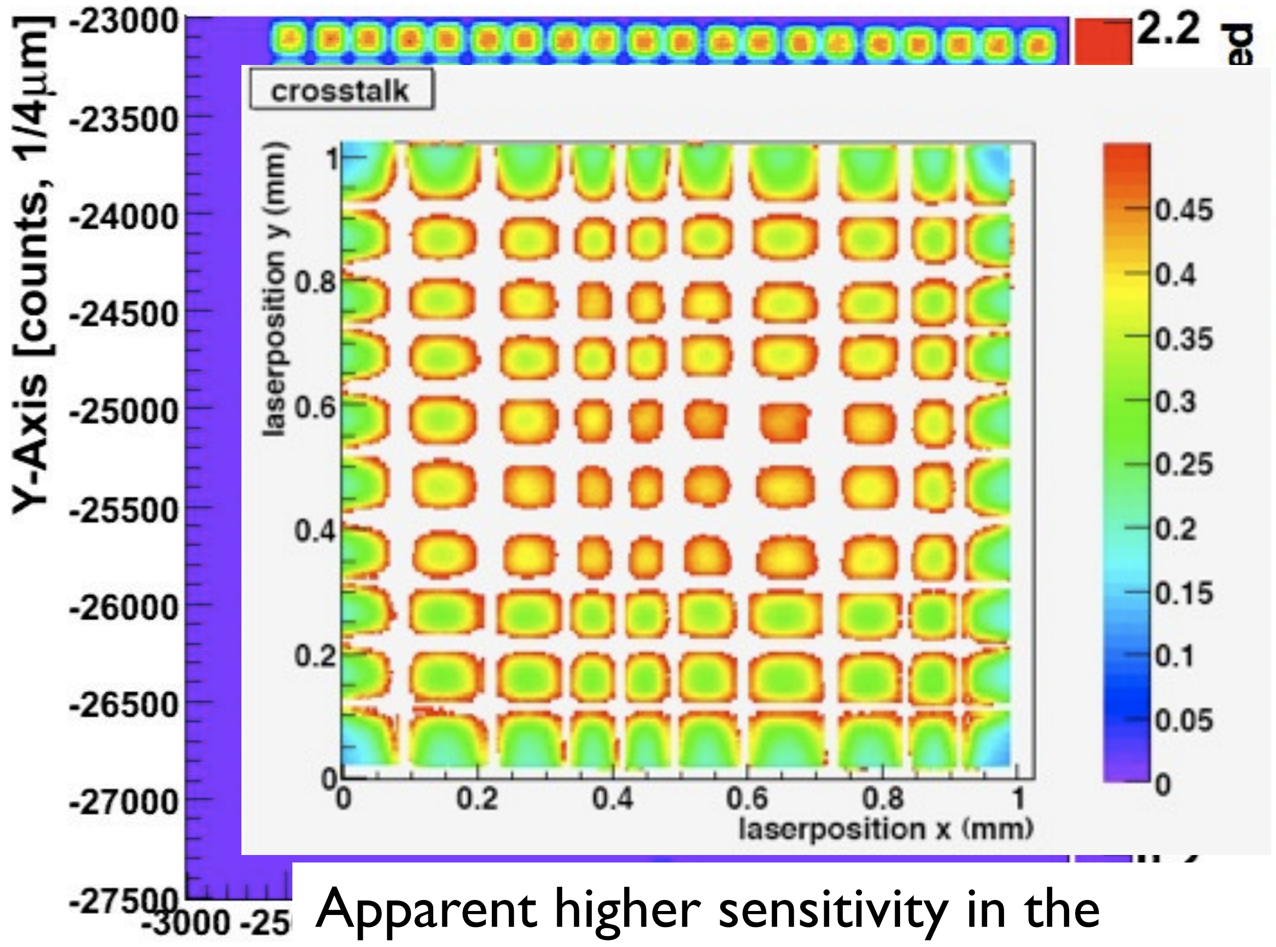
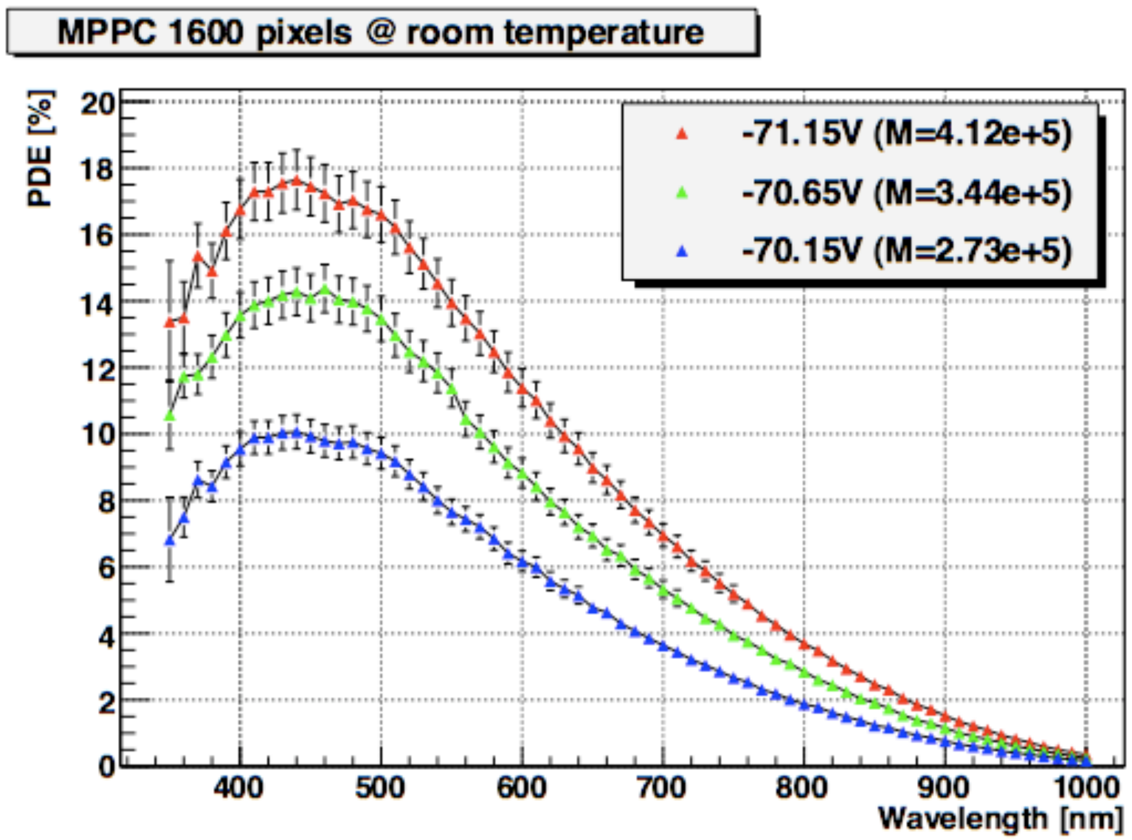


Apparent higher sensitivity in the center due to cross talk (linearity issues with MPP positioning stage)

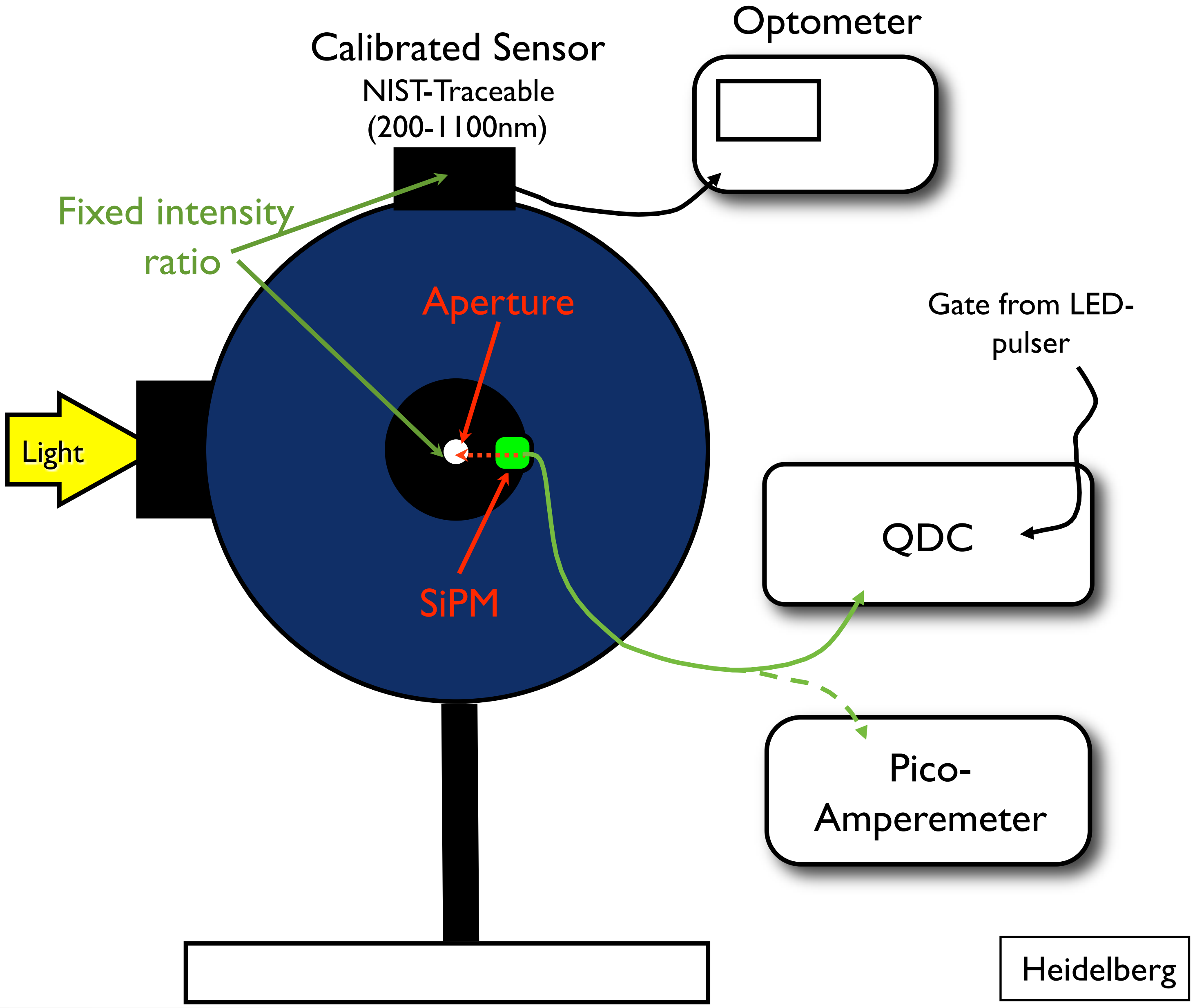
Characterization of SiPMs: Photon Detection Efficiency

- Measurement of PDE using a Xe Lamp with monochromator
  - Relative measurements compared to calibrated PIN diode
  - Includes cross talk and afterpulses



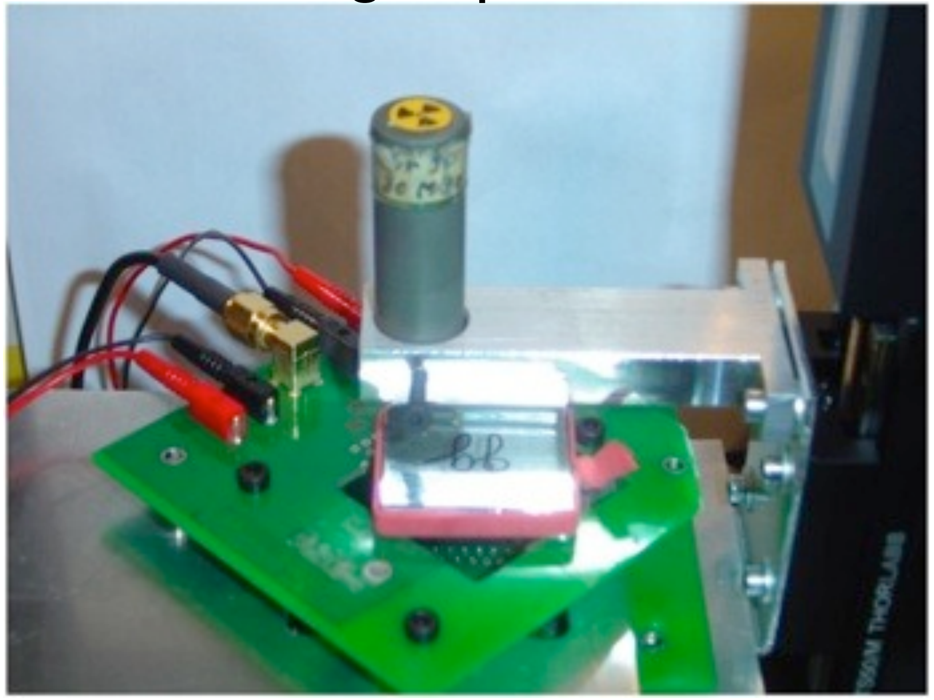
Next steps:

- measurements with improved setup
- pulsed light source to reject cross talk and afterpulses: LEDs at 375 nm, 635 nm, 870 nm



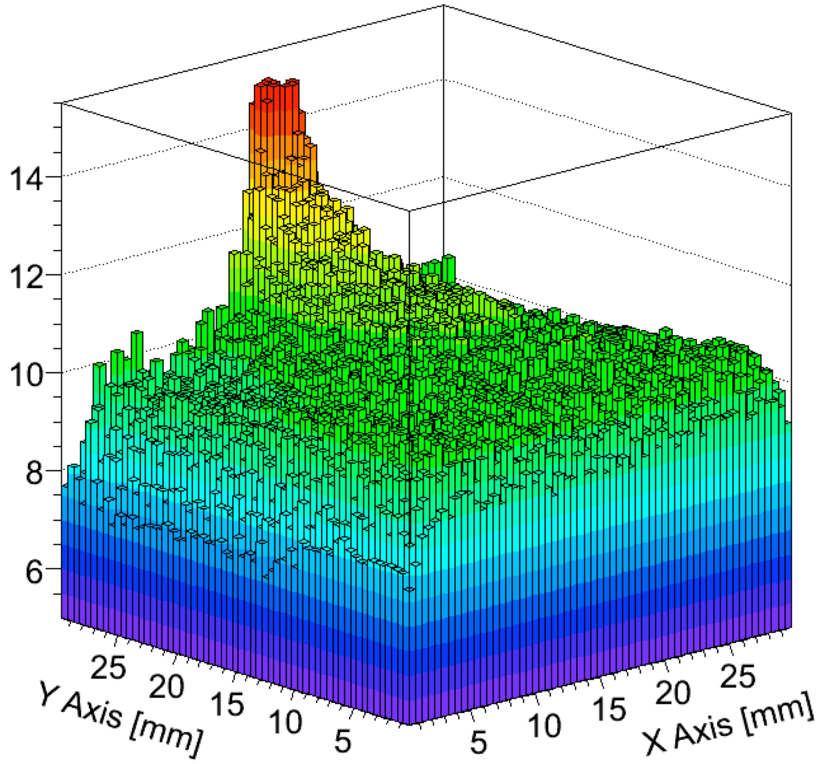
Coupling of SiPMs to Scintillator Tiles

- With blue-sensitive SiPMs wavelength shifting fibers are not required anymore
  - they do help with light collection, and improve the uniformity of the response
  - Investigate possibilities for direct coupling of SiPMs



Scan across the tile surface with a ^{90}Sr source, trigger on penetrating electrons

direct coupling of SiPM to tile on one side



MPI Munich

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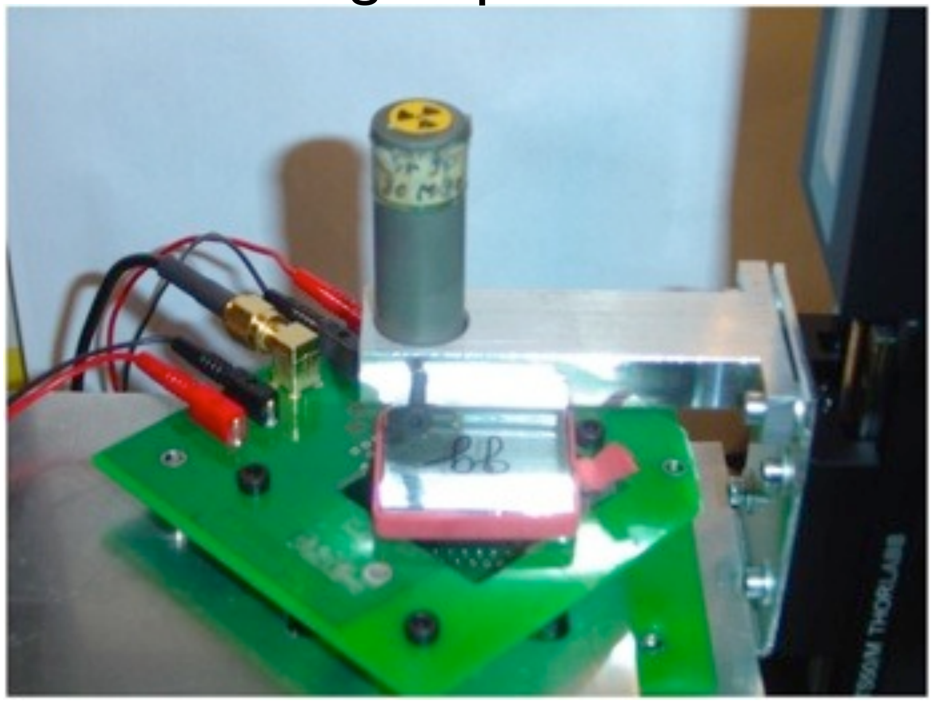
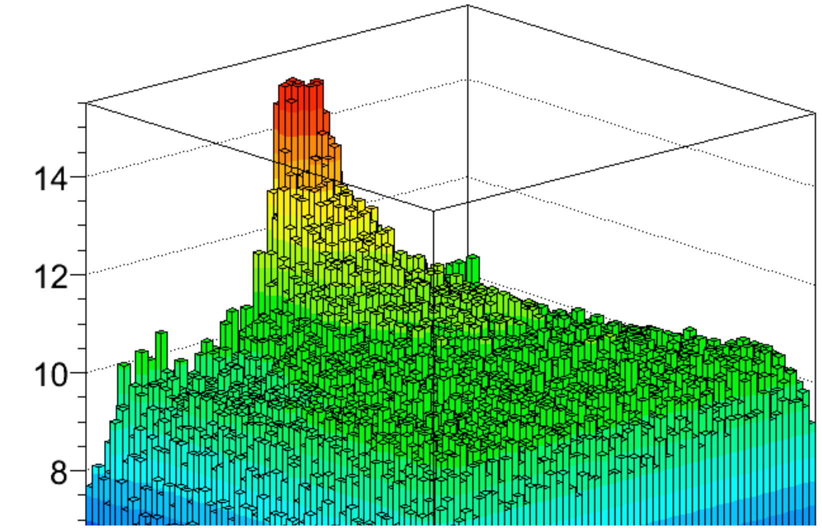
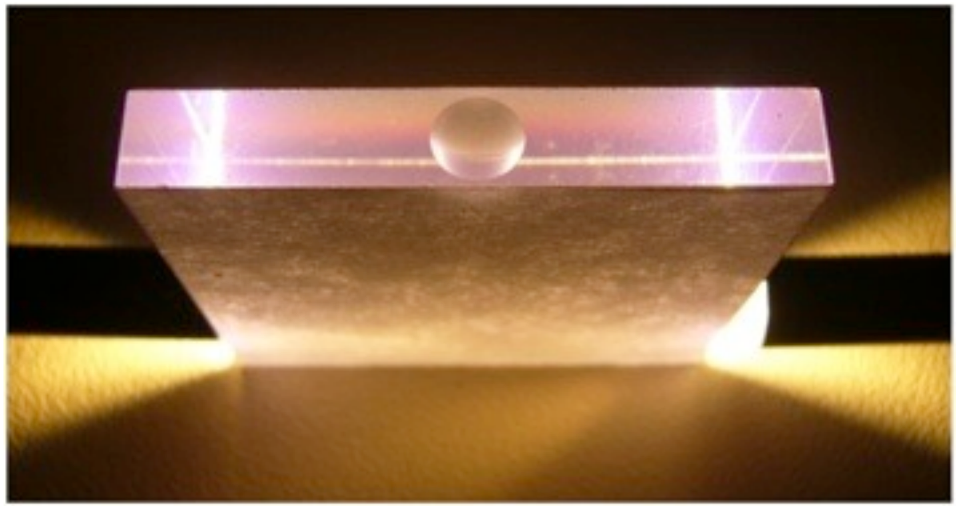
  - they do help with light collection, and improve the uniformity of the response
  - ▸ Investigate possibilities for direct coupling of SiPMs



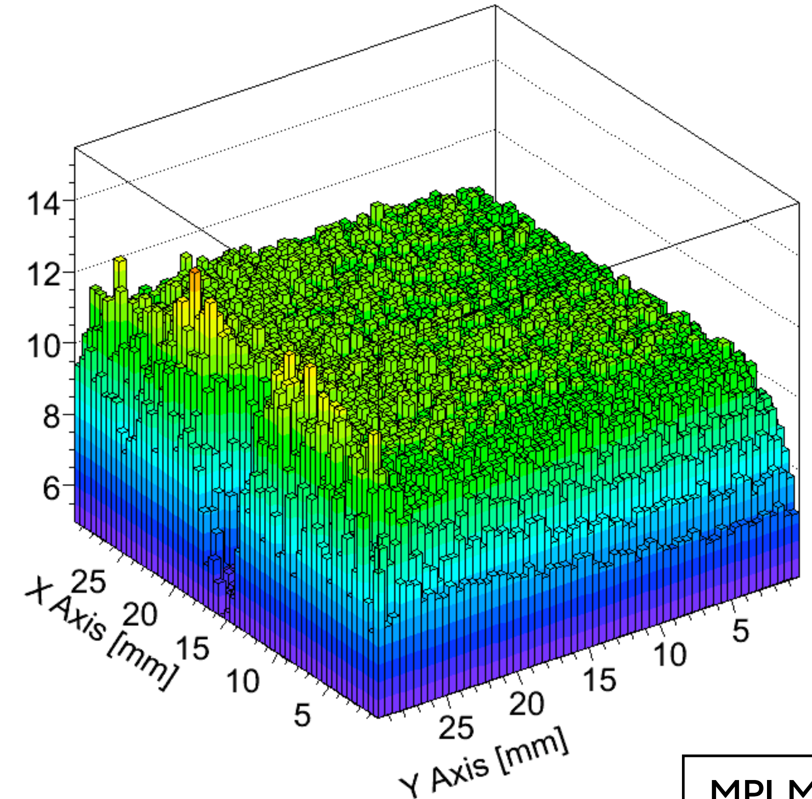
Scan across the tile surface with a ^{90}Sr source, trigger on penetrating electrons



direct coupling of SiPM to tile on one side



Tiles with a small "dimple" at the SiPM position: Half-sphere with 2 mm radius

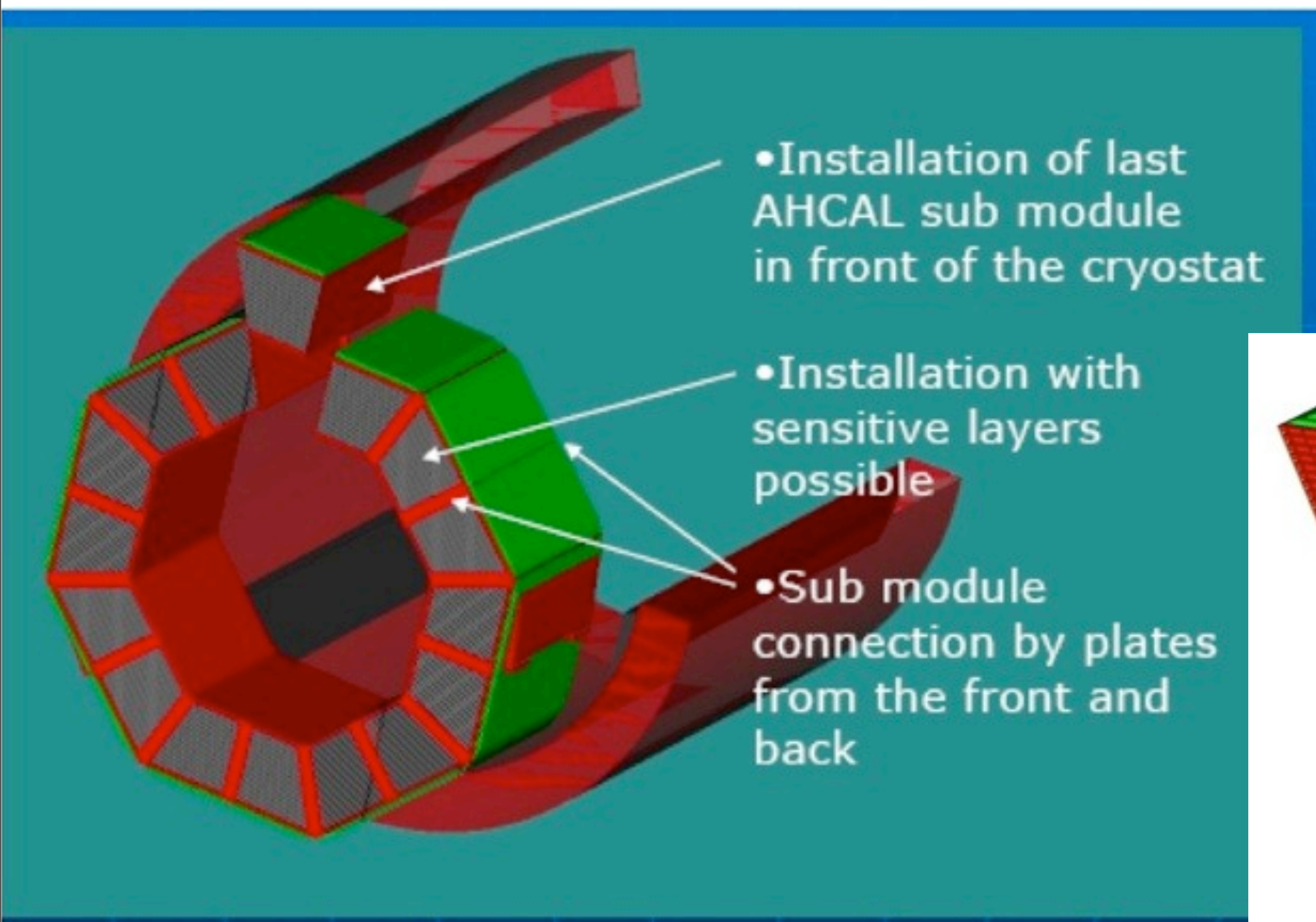


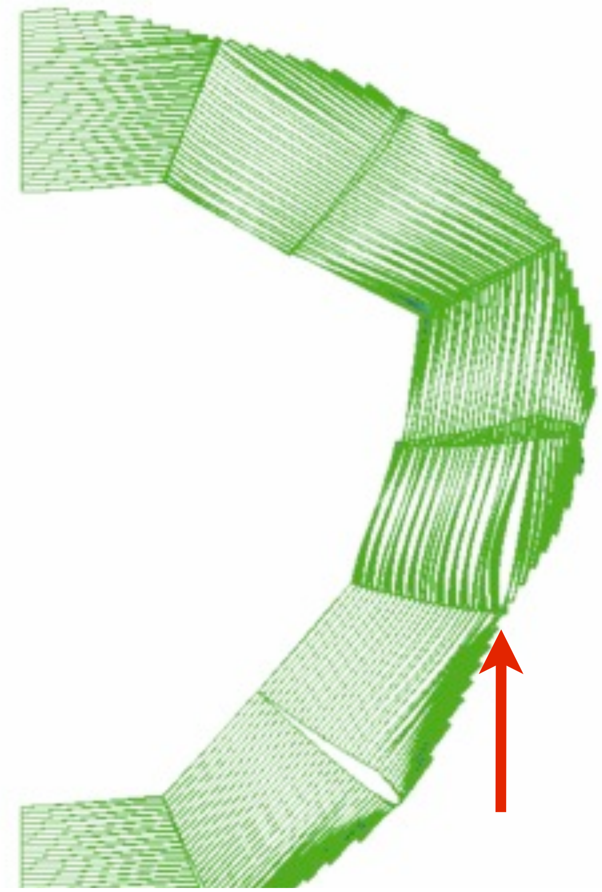
➯ Significant improvement of uniformity

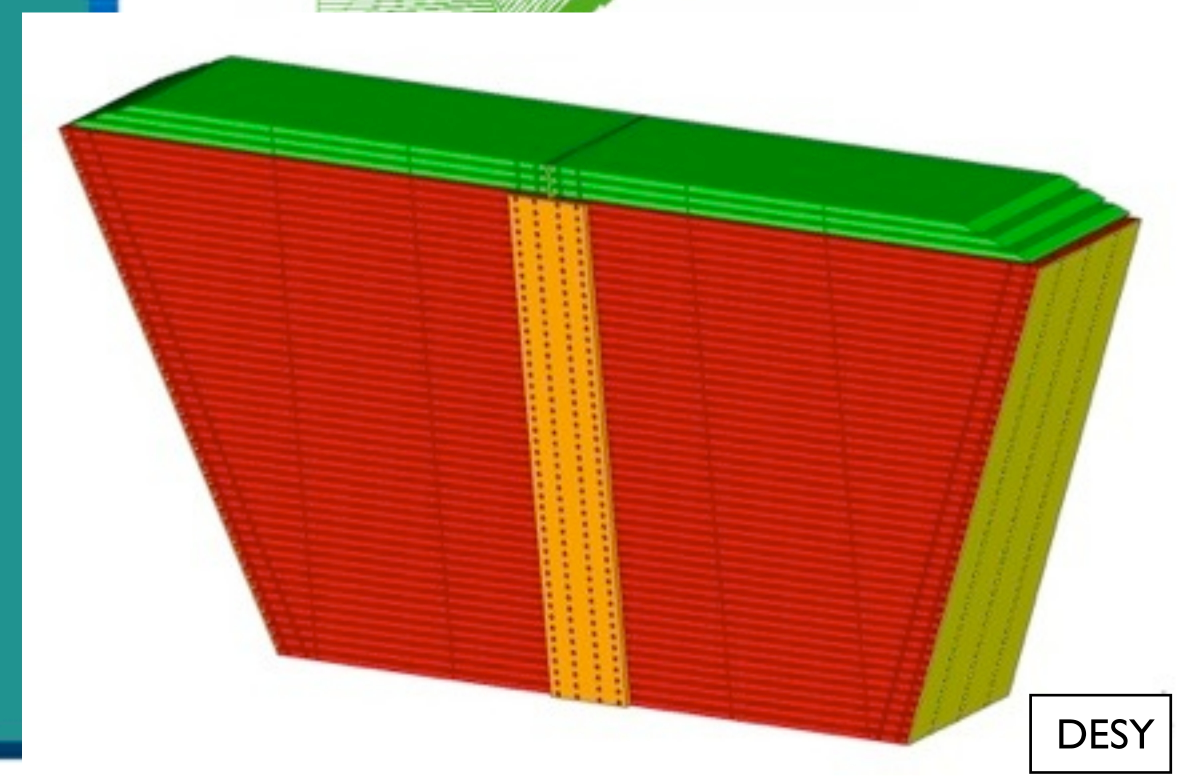
MPI Munich

Mechanical Studies for a Full Barrel

- Based on the ILD detector concept
  - Study of different designs with FEM calculations
  - Construct vertical prototypes, 36 cm deep
  - Steel plates available, material test ongoing



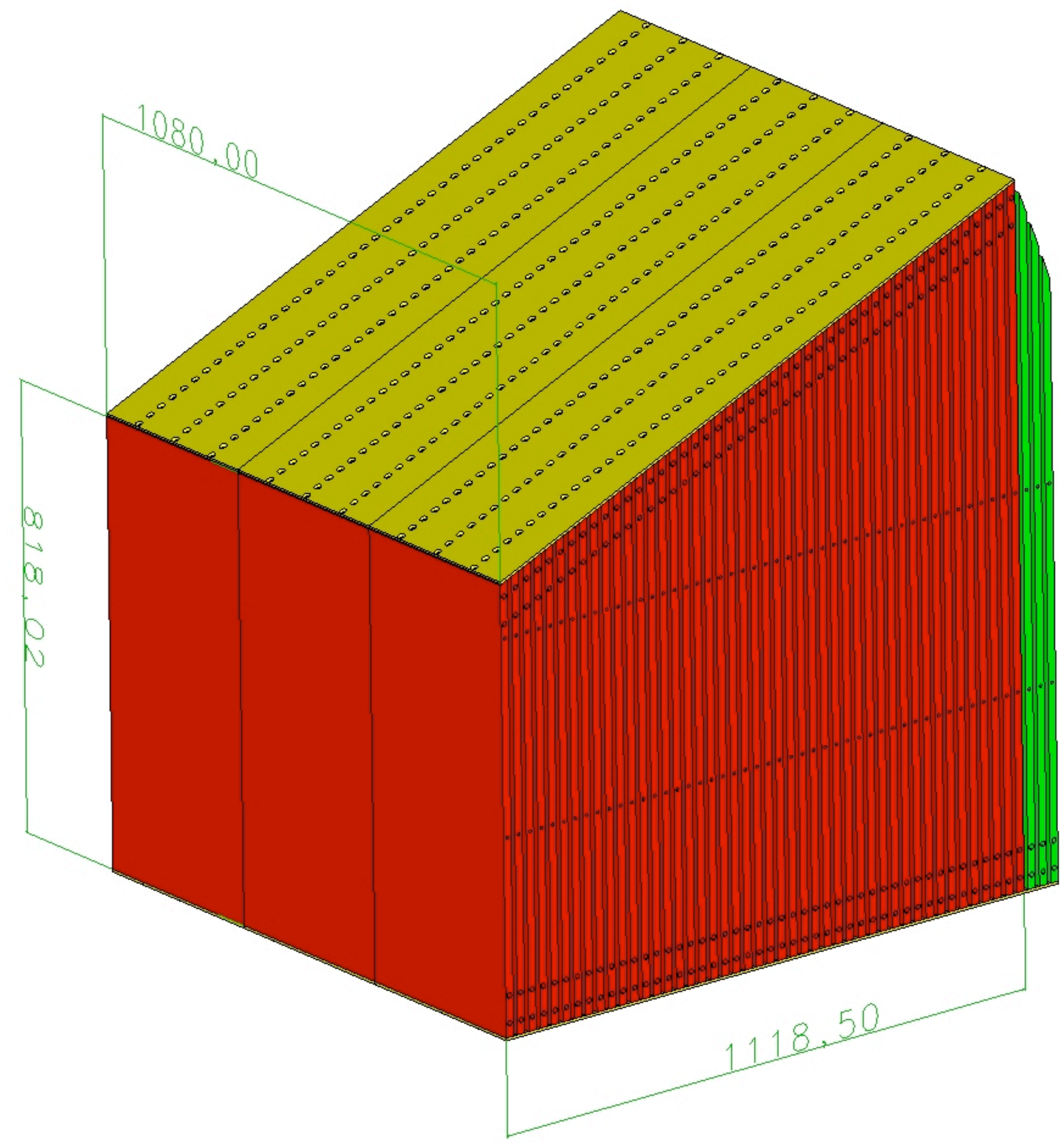




Mechanical Structure: Plans

Scalable structure:

- Three vertical slices can be converted into a next generation test beam prototype (~ 1 m^3)
  - towards a full HCAL module prototype
  - can use existing moving table



DESY

Summary and Outlook

- Active development for ILC hadron calorimeter within the CALICE collaboration, significant participation from German institutions
- CALICE has been taking data for the past 3 years with varying configurations, next test beam period beginning in 3 weeks at Fermilab
  - First results from electromagnetic and hadronic showers and comparison to simulations
    - Study and validation of hadronic shower models: Close collaboration with GEANT4 developers
    - The application of a simple weighting technique in the energy reconstruction in the complete setup reduces the stochastic term of the energy resolution to ~ 50%/$\sqrt{E}$
  - Much more to come!
- Many projects for the next generation of prototypes:
  SiPM studies, calibration systems, electronics, mechanics,...