Analog HCAL Status & Prospects

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Munich, Germany

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

CALICE
Calorimeter for ILC

TUM
ESO
LMU
Excellence Cluster
Universe

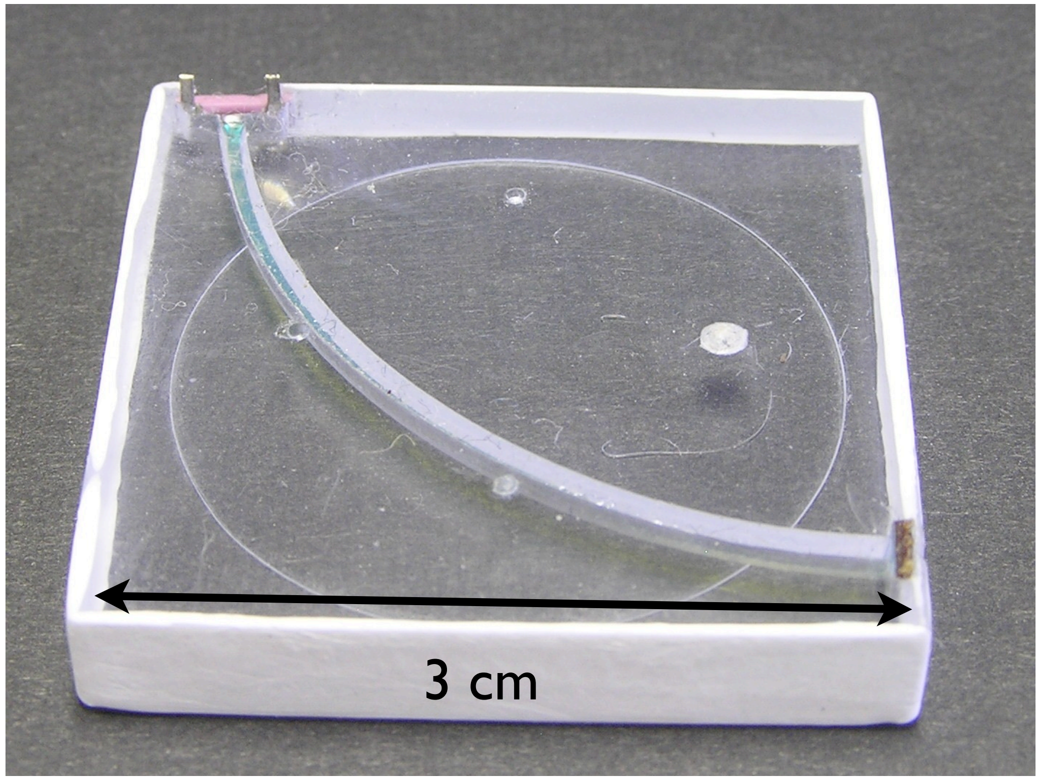
Outline

- The AHCAL Physics Prototype
- 2nd Generation Prototype and Electronics
- Engineering Designs for ILD
- Simulation Model
- Selected Results for Hadrons:
  - Validation of PFA Simulations
  - Energy Resolution

AHCAL Hardware

The AHCAL Physics Prototype

- The unit: scintillator tile with SiPM



Key SiPM properties:

- extremely compact
- insensitive to magnetic field
- high gain, low operating voltage, very low power consumption

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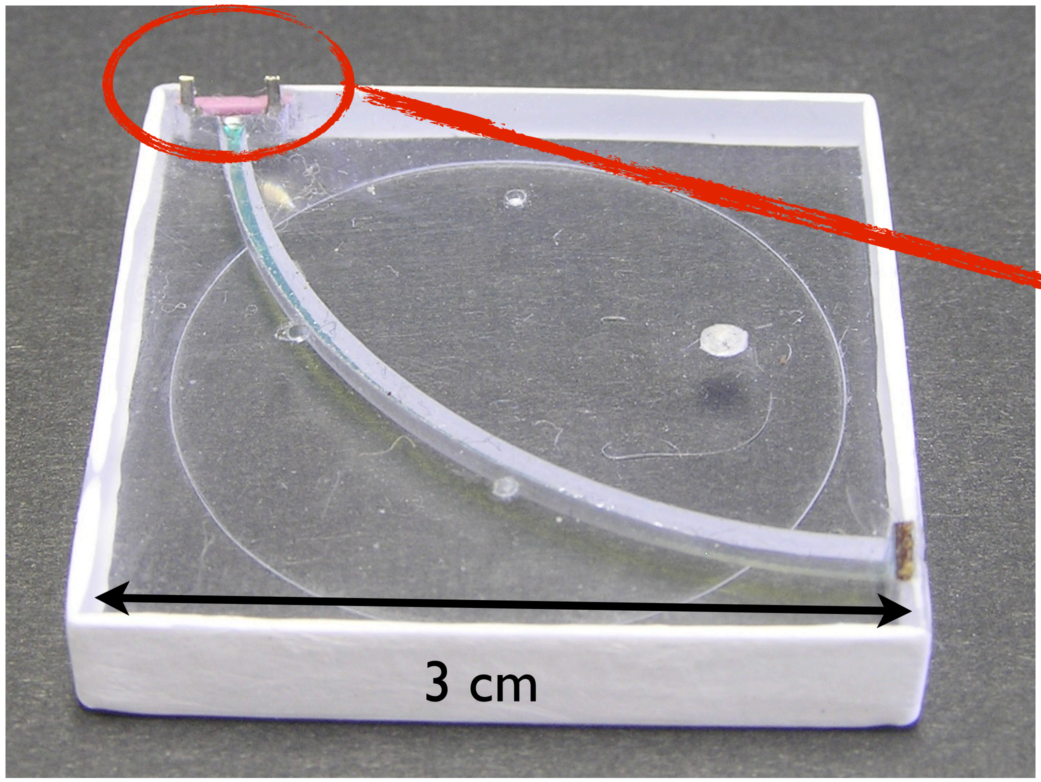
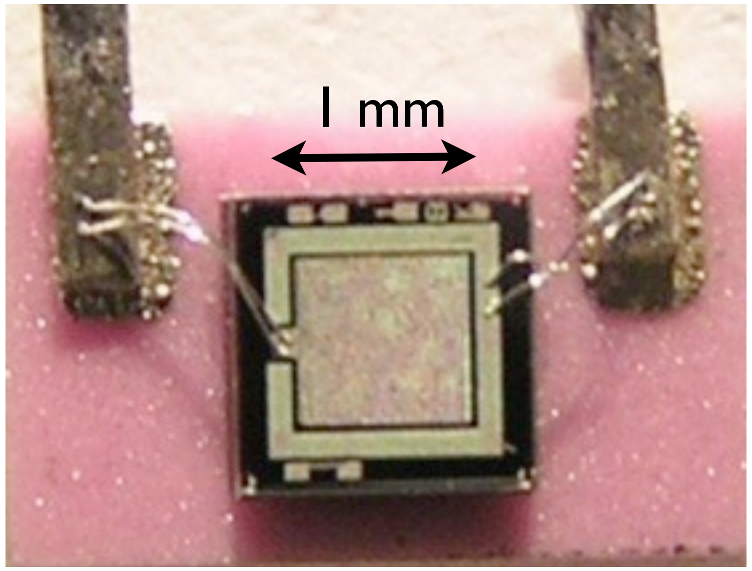


- SiPM: 1156 pixels, manufactured by MePhI/PULSAR



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

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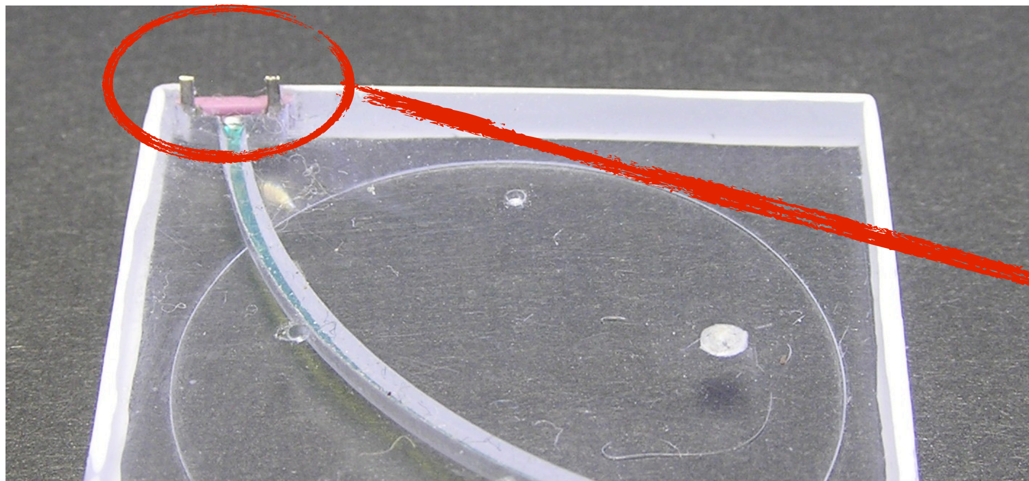

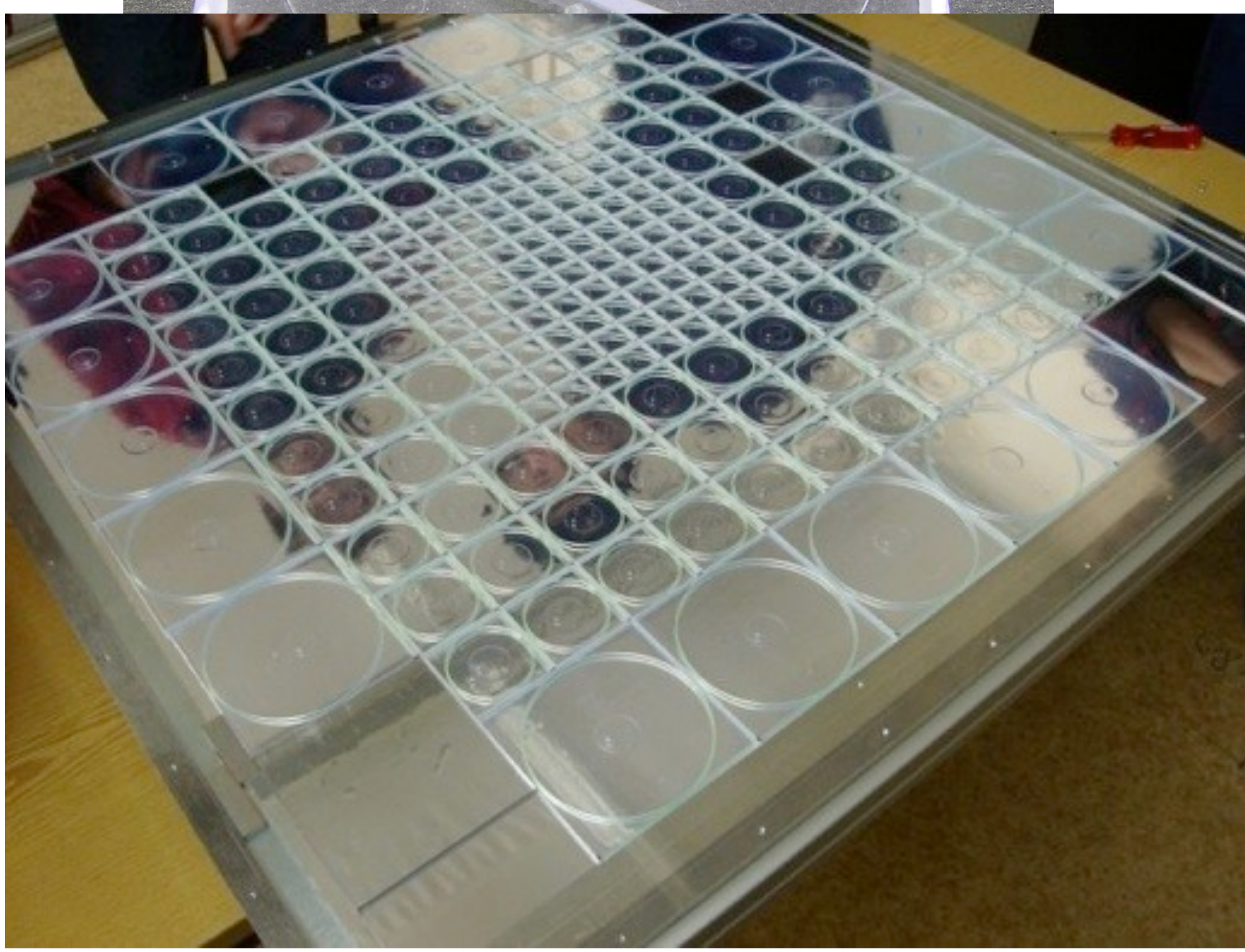

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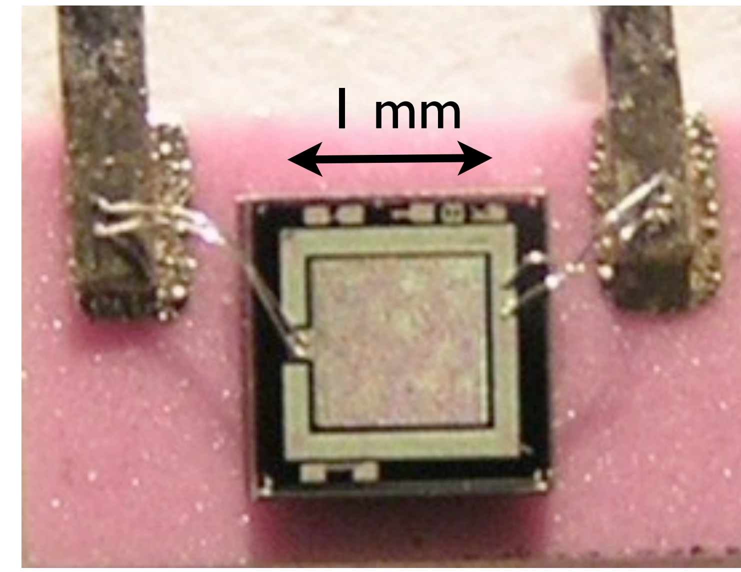

ximum efficiency in green spectral range:
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e scintillation light

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

The AHCAL Physics Prototype

- Remember: The AHCAL was constructed in 2005/6:
  The first large-scale use of SiPMs in HEP world-wide!

The CALICE AHCAL has been at the front of the global trend towards SiPMs
Now many other users: T2K, various medical imaging projects, CMS upgrades,...

- The technology is extremely robust:
  The AHCAL active elements are now entering their 6th year of data taking
  - 2006 & 2007: CERN
  - 2008 & 2009: FNAL
  - 2010 & 2011: CERN

Many trips with disassembly & reassembly of the calorimeter:
DESY - CERN - DESY - FNAL - DESY - CERN PS - CERN SPS
... and the SiPMs still work without problems!

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

Calibrating the Detector

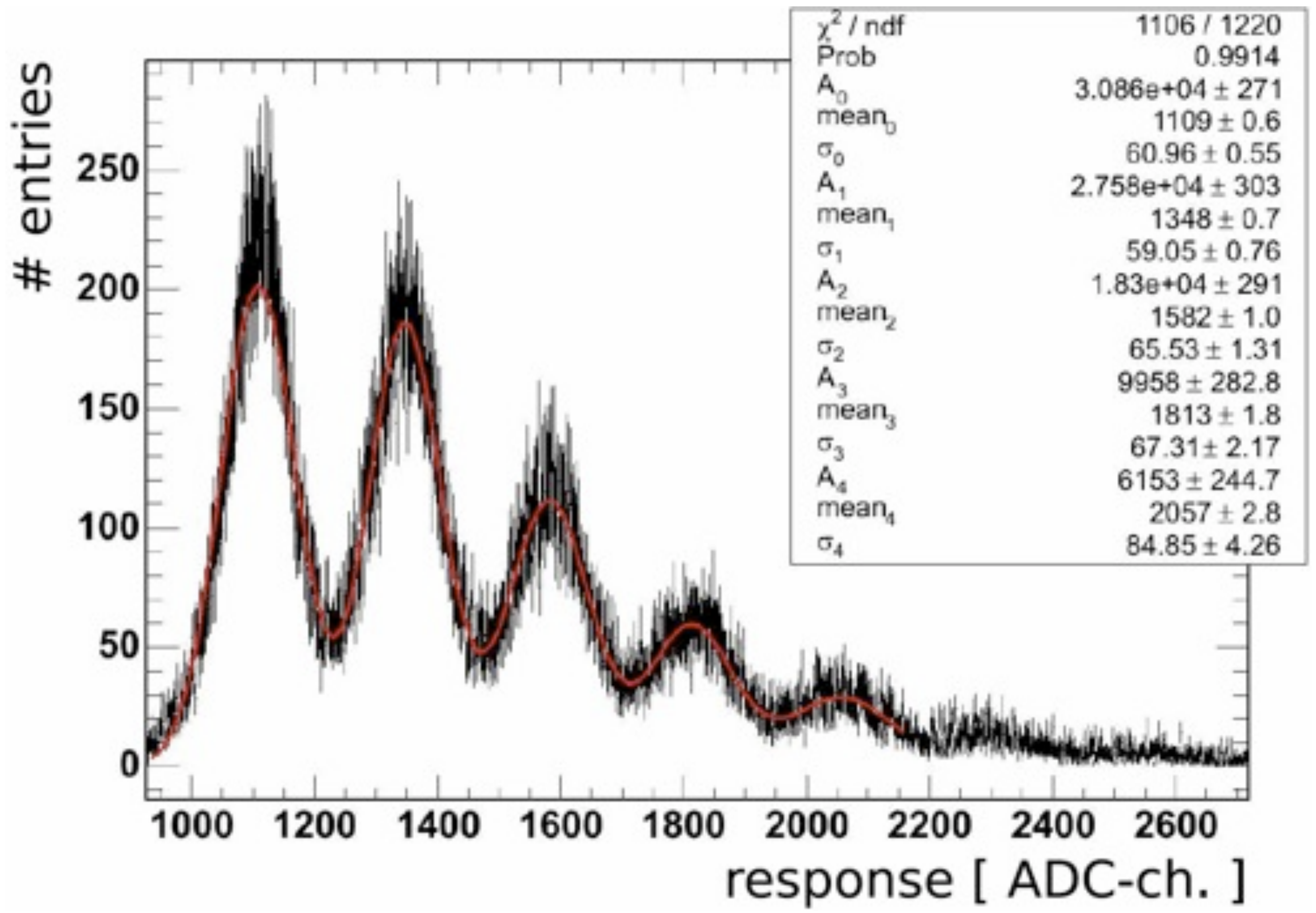
- Actually it is very easy: Per cell, we need
  - A MIP constant (determined with muons)
  - The saturation scale (can be determined on the test bench)
  - The gain (needed for saturation correction, can also be used for temperature corrections!)

- Global factors in addition: Calibration to the em scale, e/pi ratio to get hadronic scale

- The required precision for a hadronic calorimeter is actually very moderate!
- For the physics prototype, we push far beyond those requirements to
  - Fully understand all aspects of high granular calorimetry with SiPM readout
  - Also provide excellent performance for electromagnetic showers

How we Calibate

- Auto-calibration of SiPM gain: Individual photons can be resolved
  - Low-intensity LED light coupled into each detector cell
  - In prototype: Light distributed by fiber, can also be done trivially by SMD LED at each tile



Documented in arXiv:0811.2431, paper in preparation

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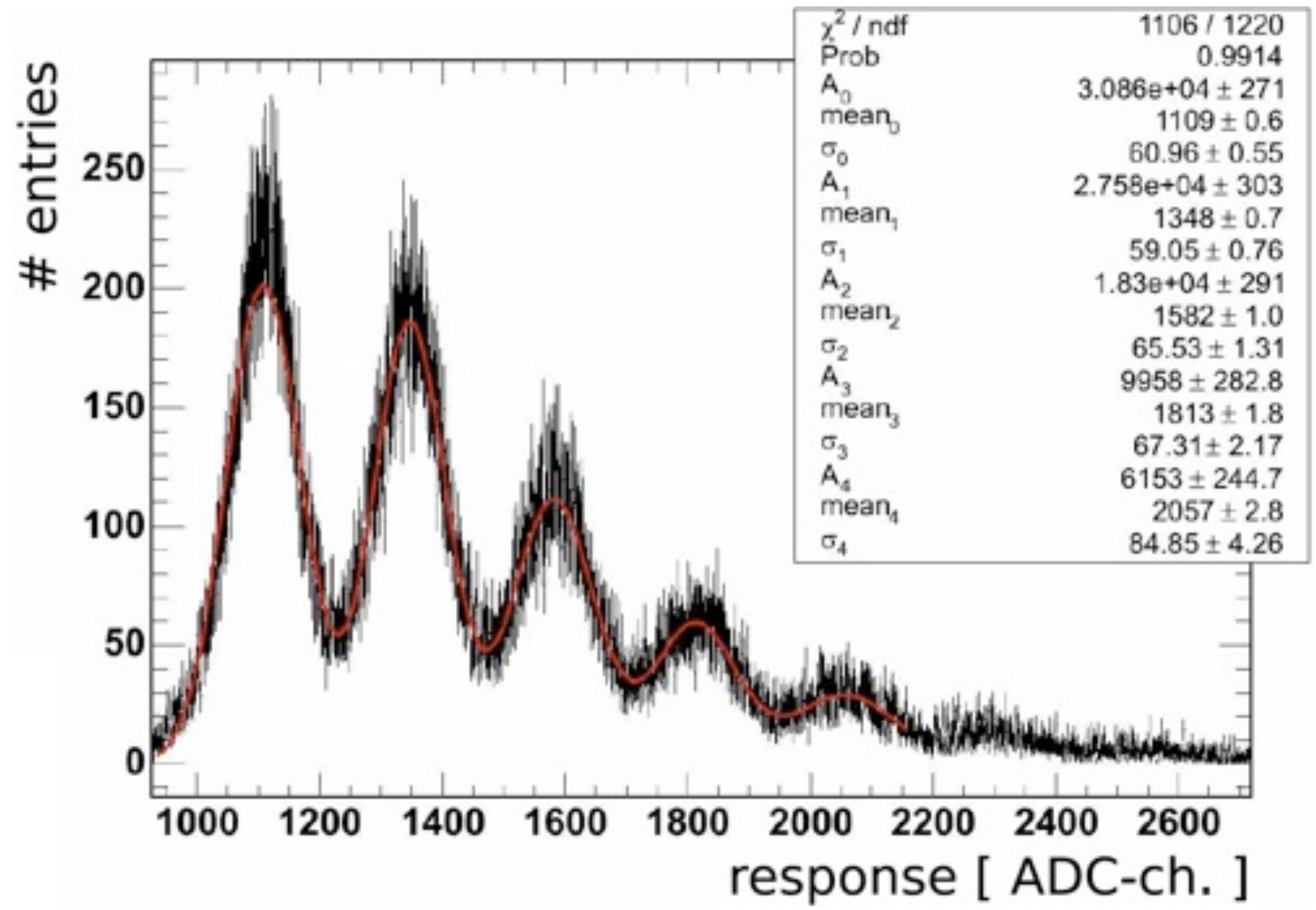
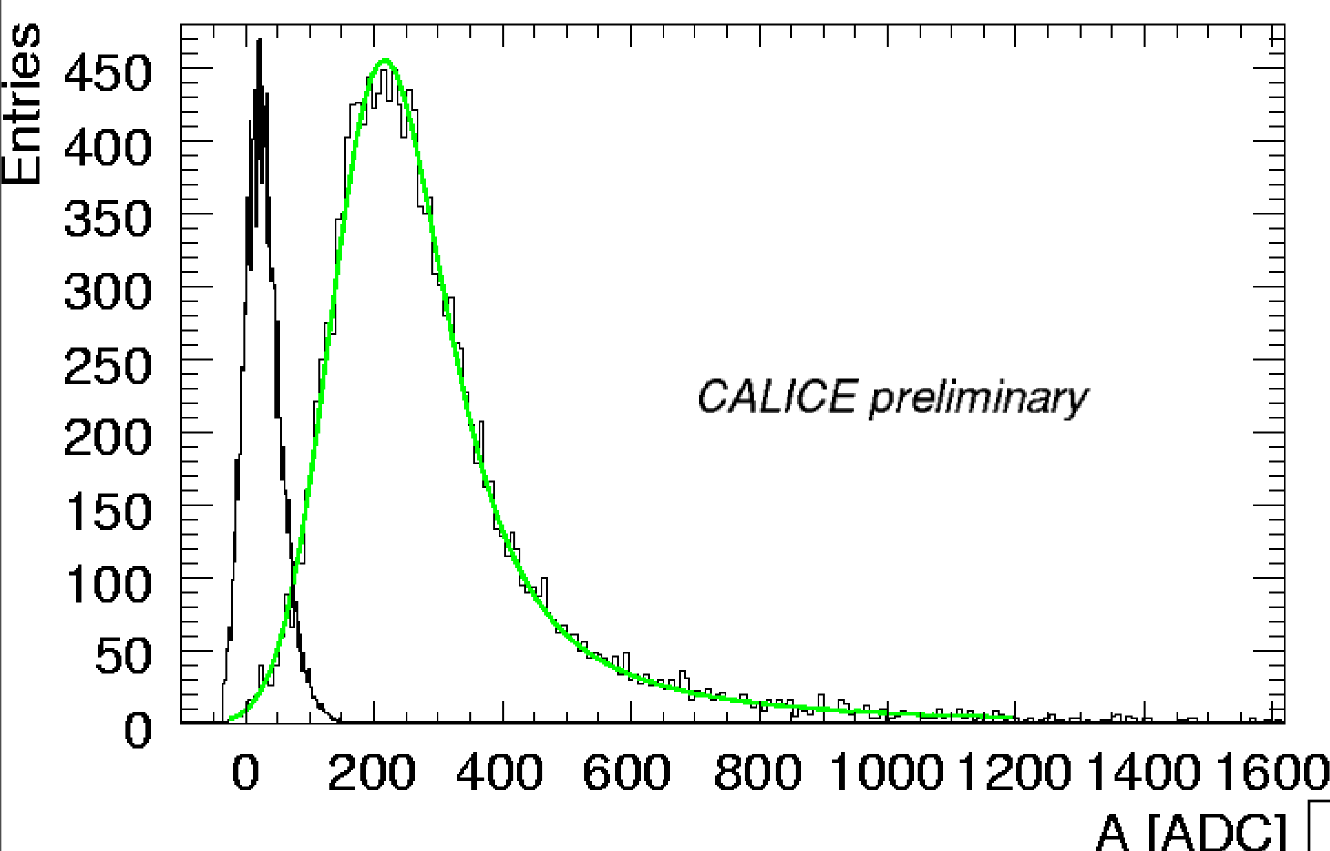


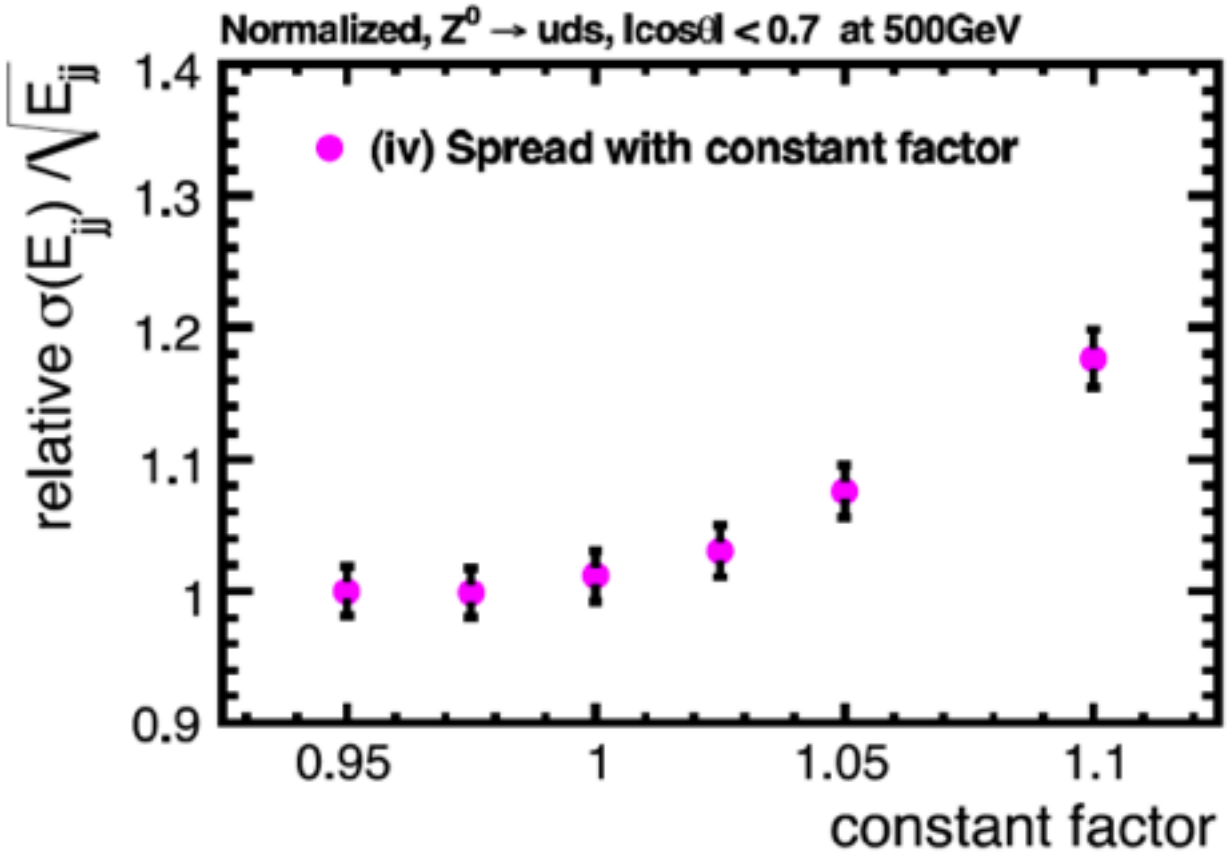


- MIP-Calibration with Muons
  - Complete detector illuminated with high energy muons
  - equalization of response of all cells by matching the MPV position

Documented in arXiv:0811.2431, paper in preparation

Calibration Requirement

- Study of required HCAL calibration precision for a complete detector: Full simulations with PandoraPFA reconstruction



Overall energy scale needs to be well controlled, in particular upward shifts are dangerous

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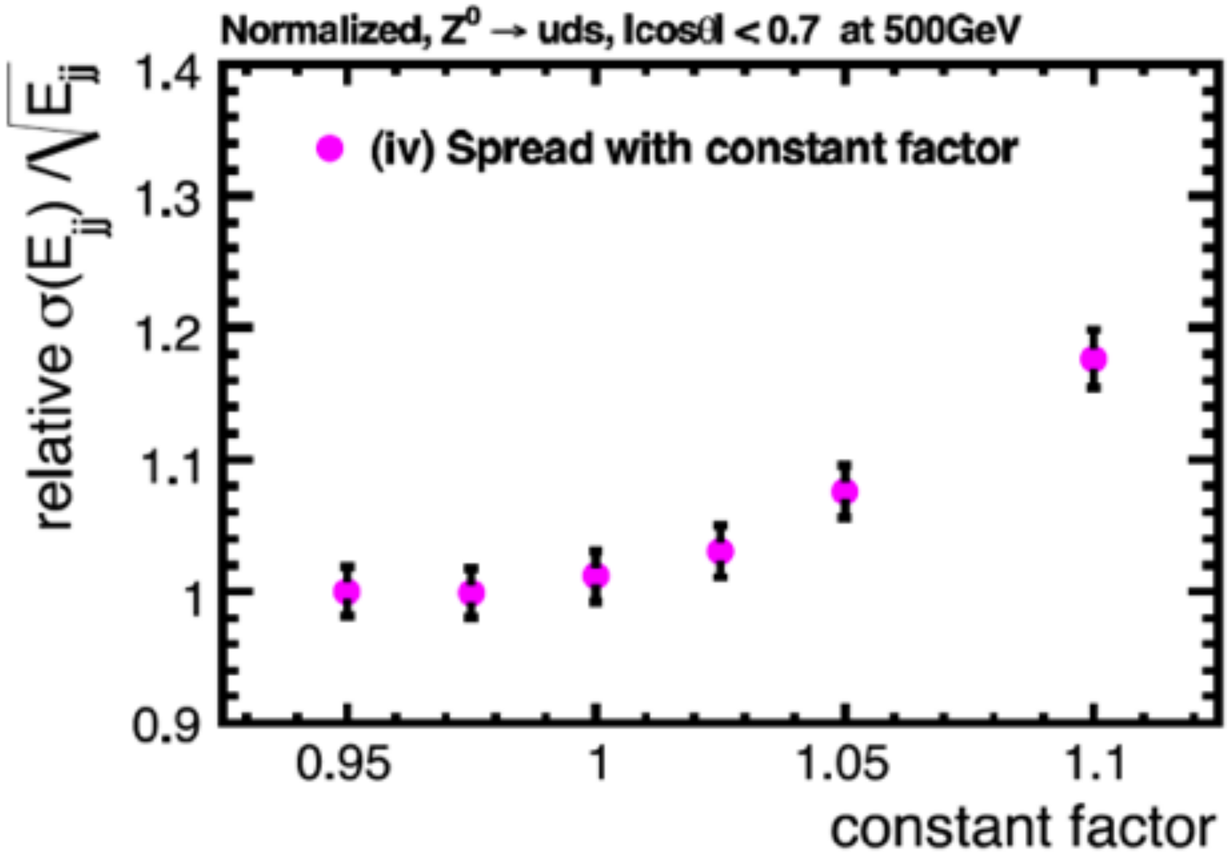

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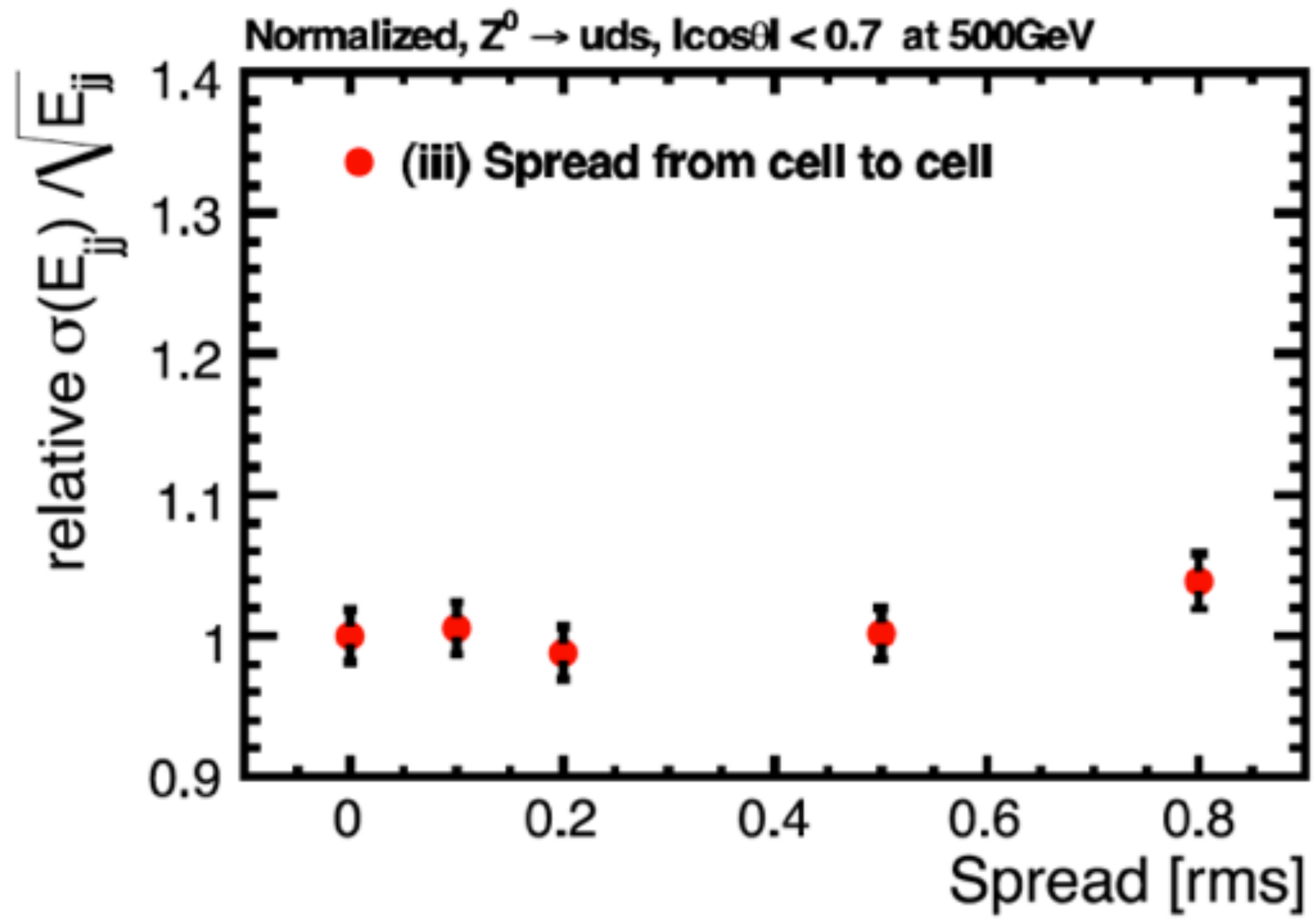


Statistics saves you: Large cell-to-cell variations can be tolerated, since many cells contribute to the signal.

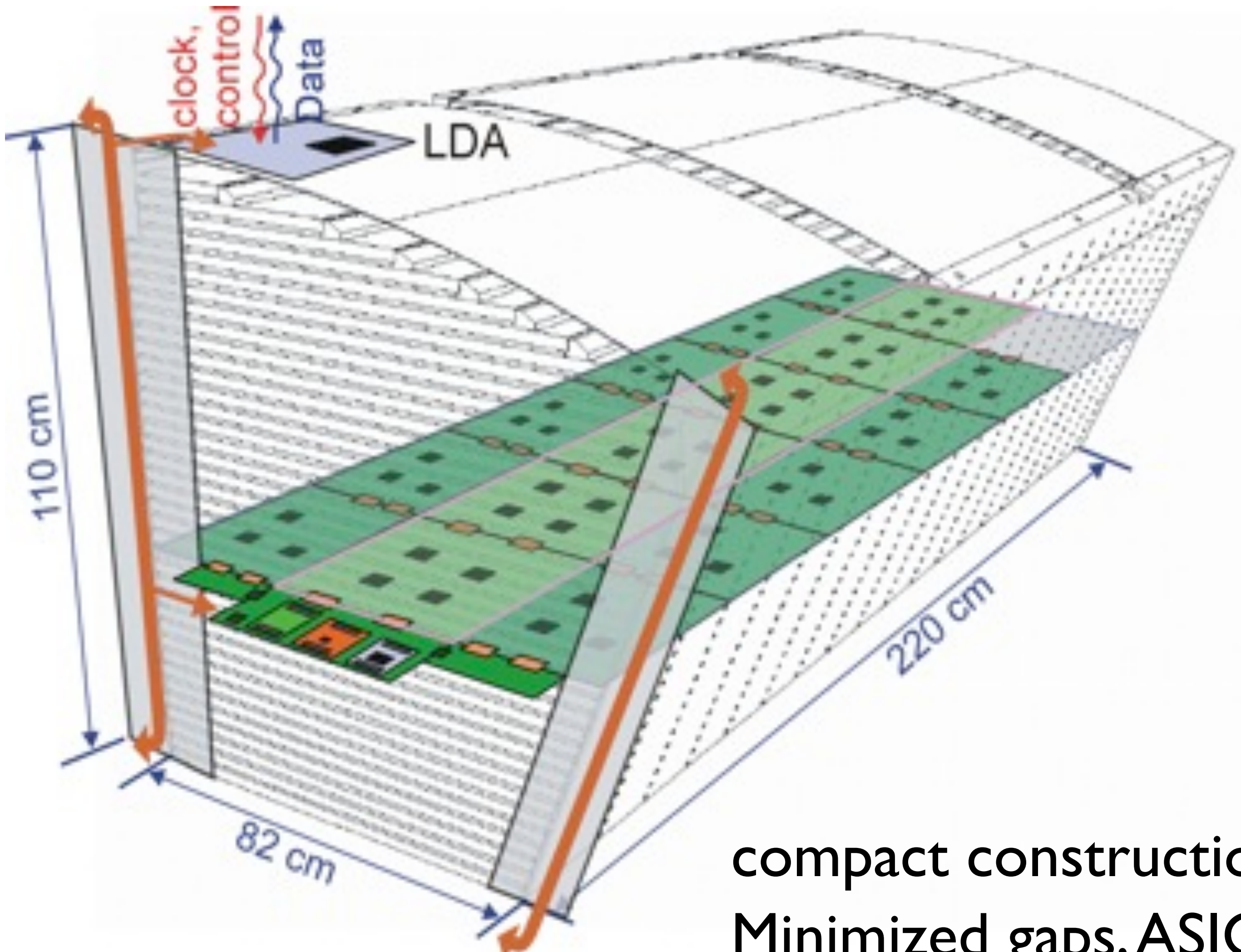
Requirement here is not set by resolution, but by possibility for calibrating in groups

Expected requirement: ~ ± 10%

Documented in ILD LOI & arXiv:0910.3820

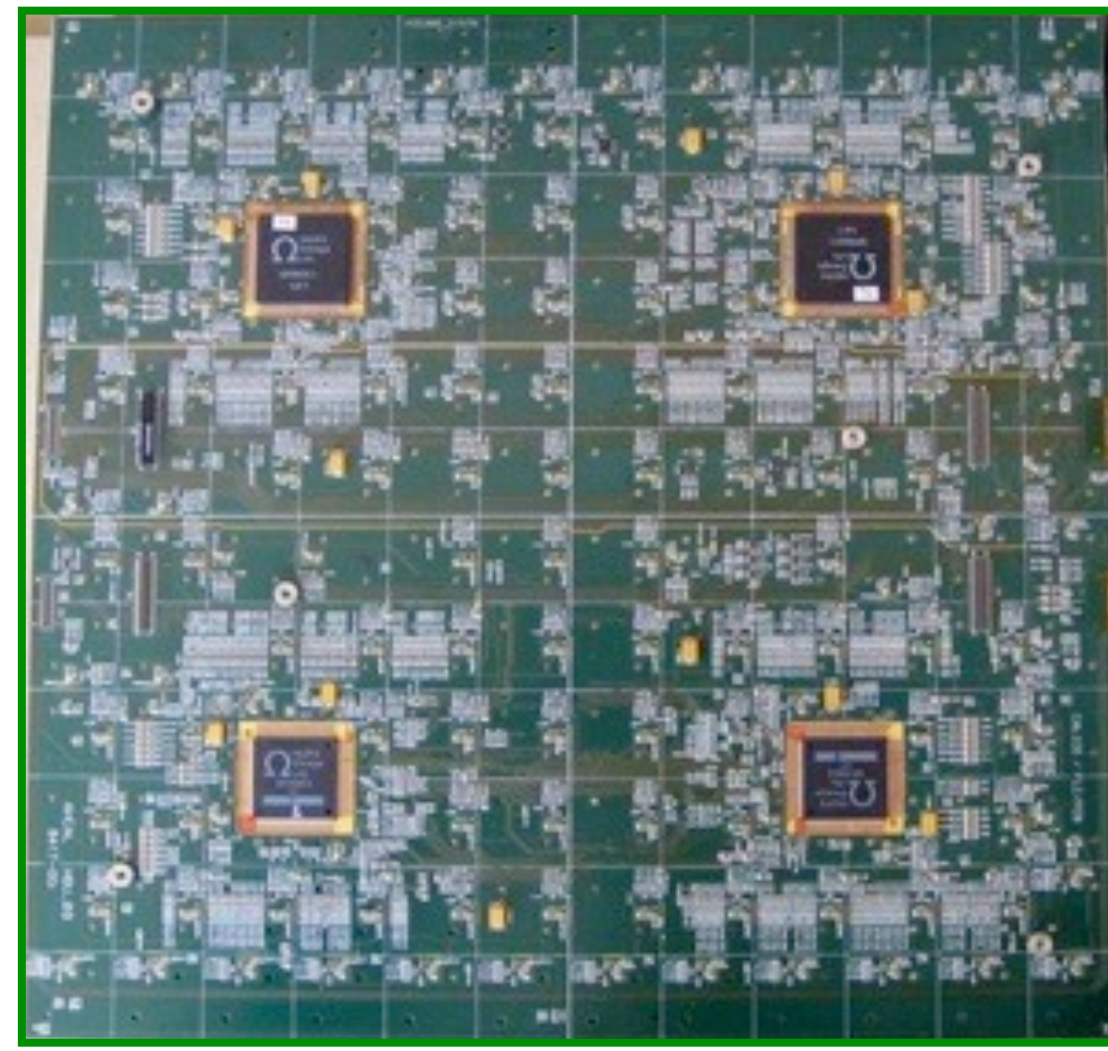
2nd Generation Prototype

- Goal: Realistic design with fully integrated electronics - Based on SPIROC



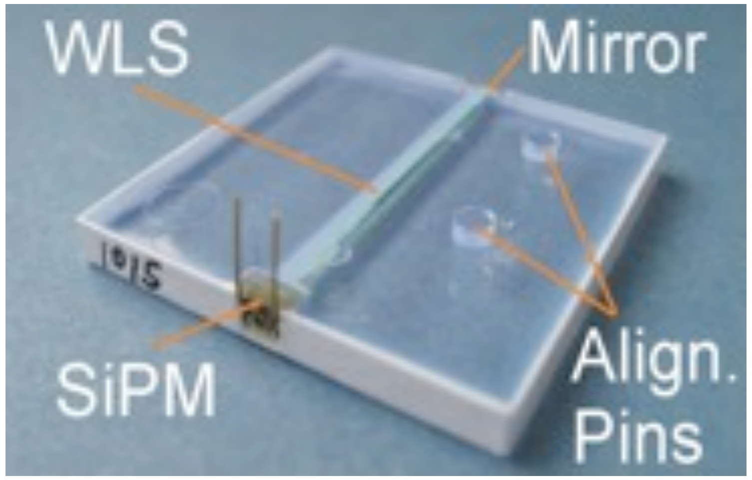
compact construction: Minimized gaps, ASICs embedded in PCB

Powerpulsing - no active cooling needed

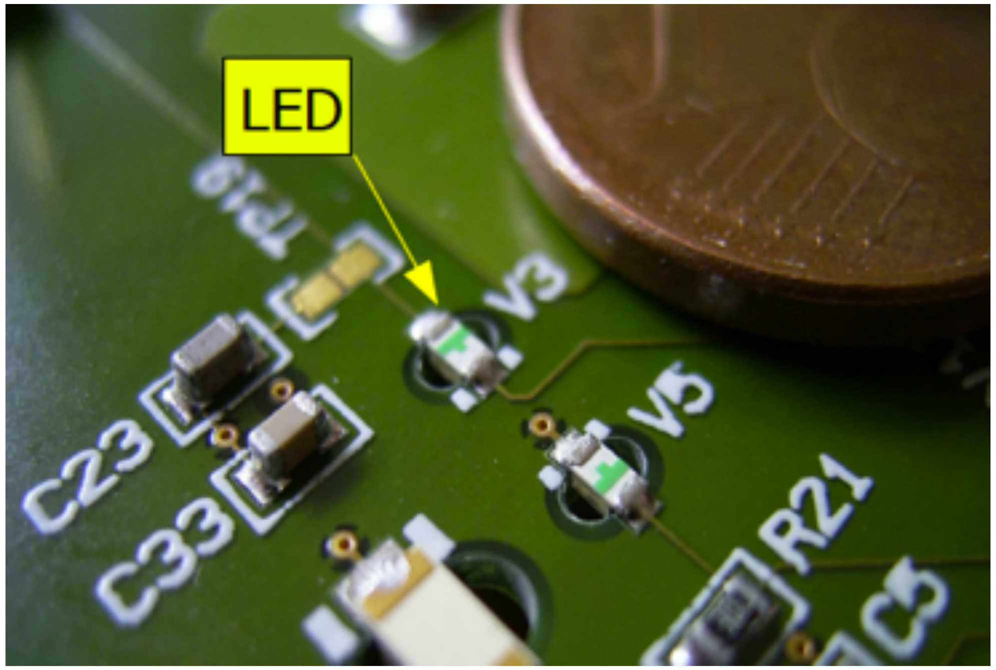


interconnected electronics boards (HBUs), FE electronics at module ends

2nd Generation Prototype

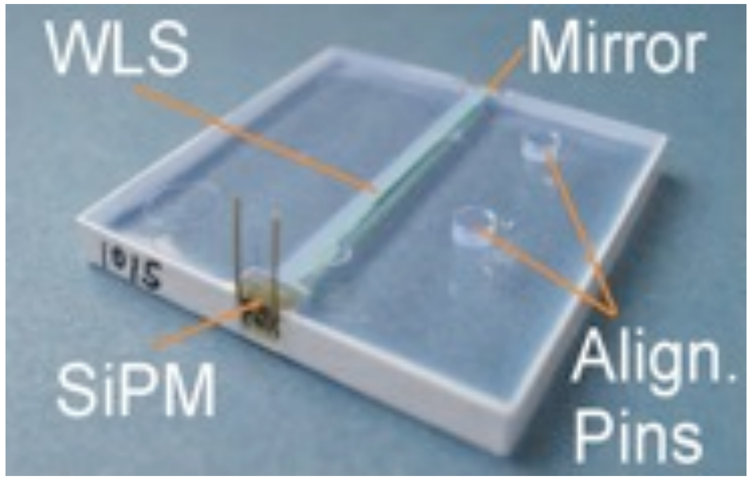


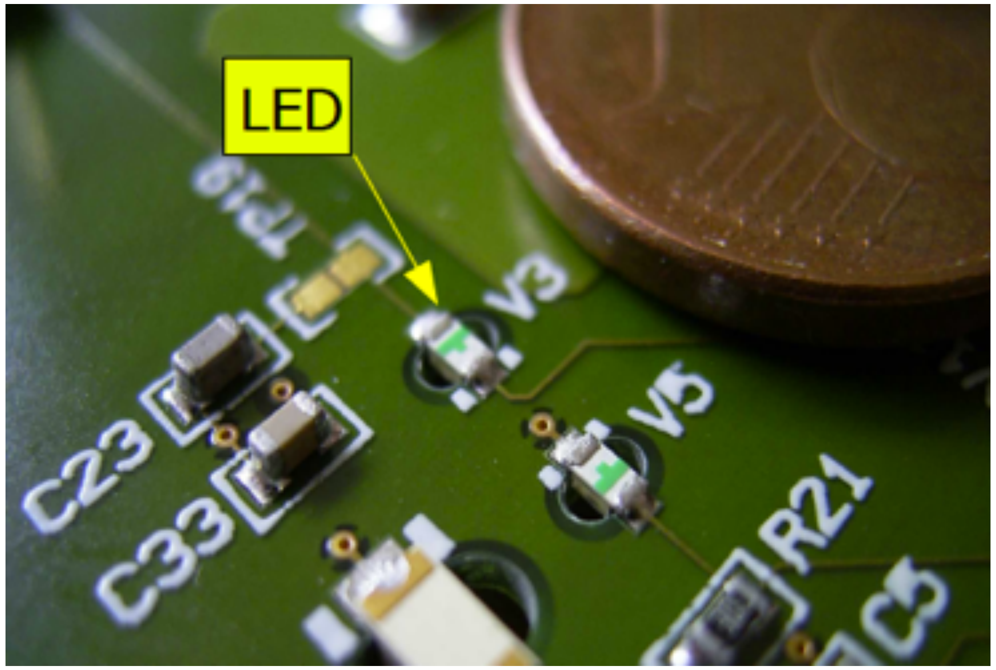
3 mm thick scintillator tiles integrated SiPMs "Lego" alignment Easy testing and characterization before installation



- SMD LEDs embedded in PCB, one for each Tile: Easy, robust calibration

2nd Generation Prototype





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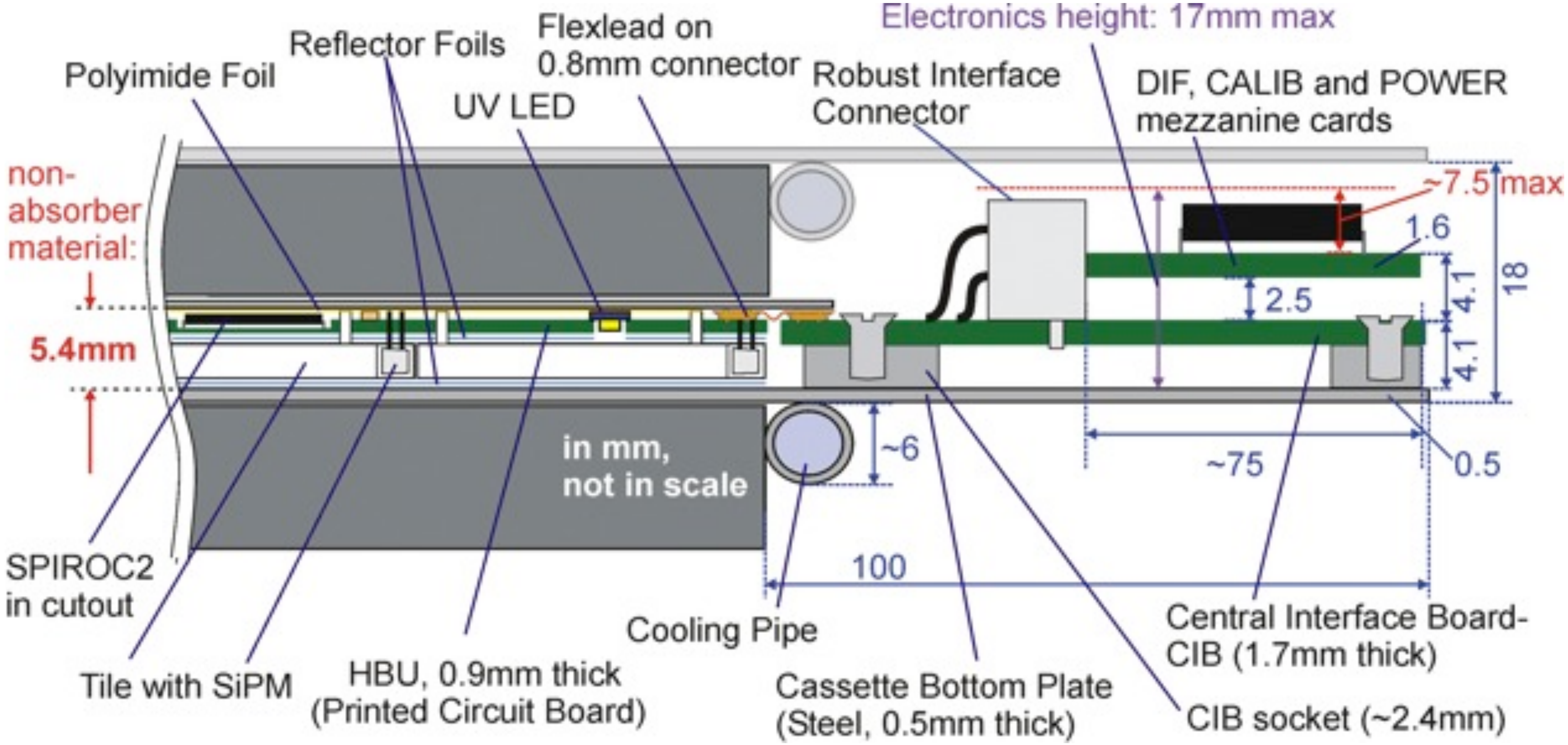
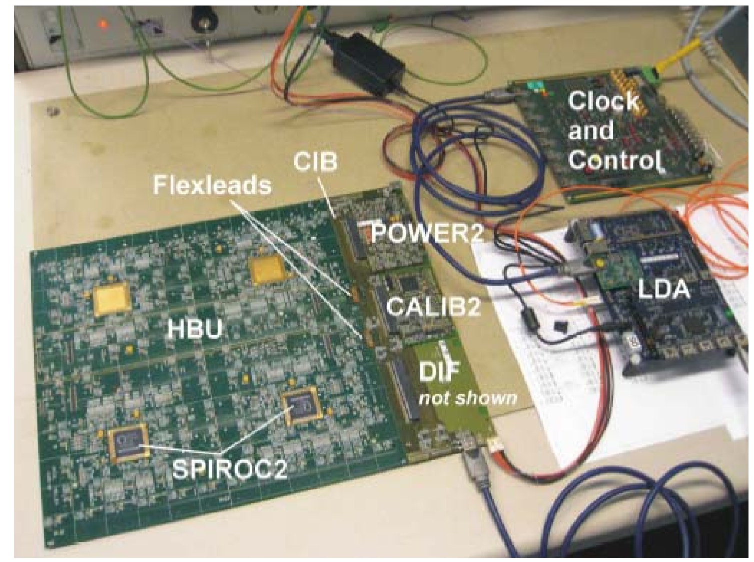
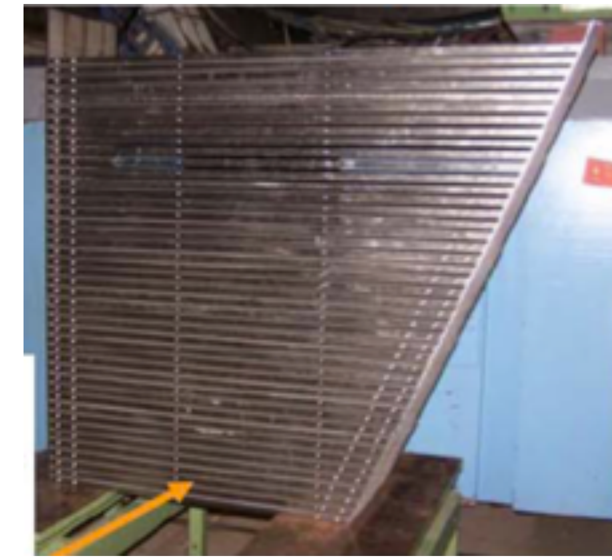
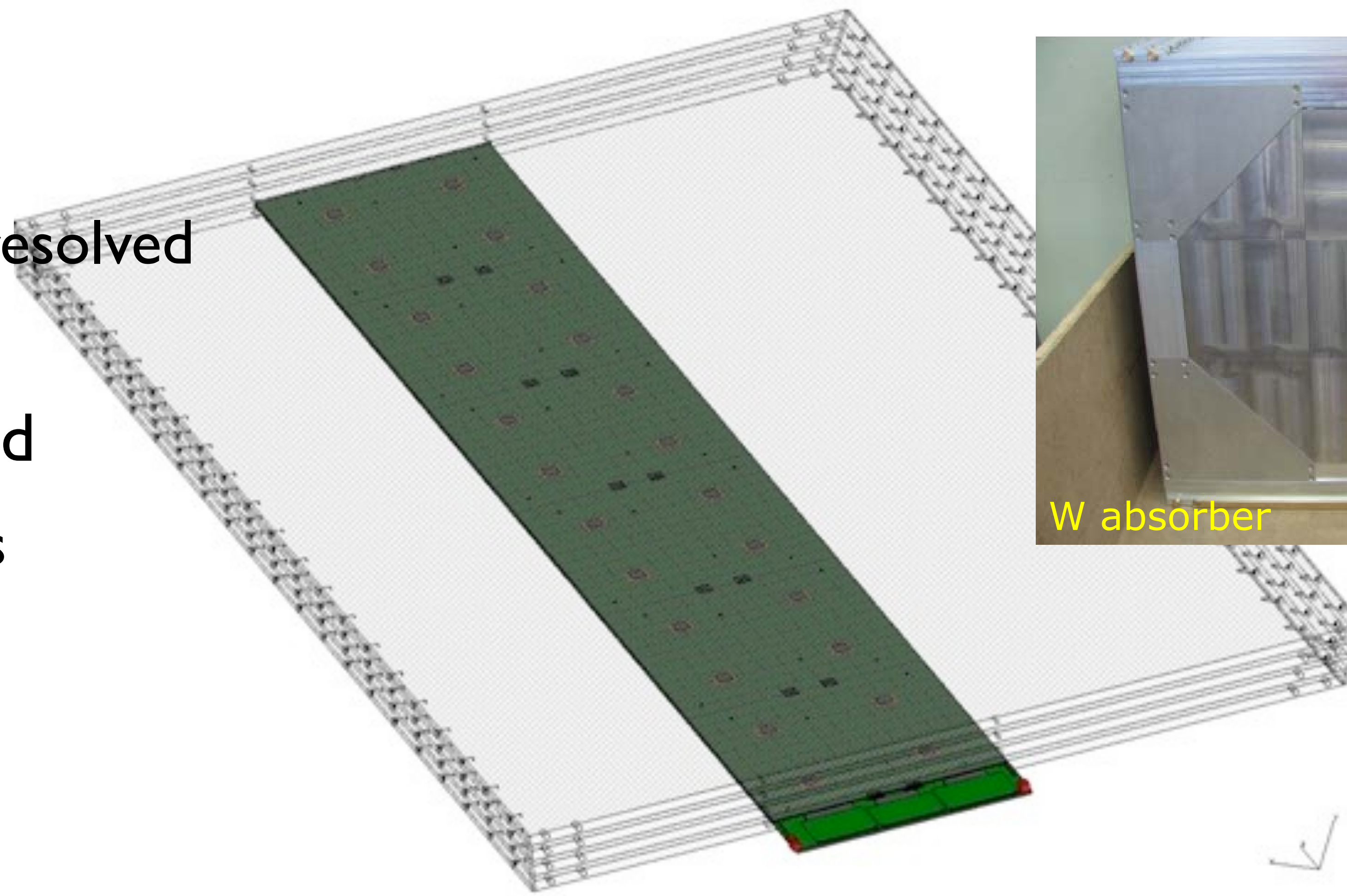


Next Steps with New Readout

- ASICs and DAQ are in hand
- 1-2000 tiles with SiPMs on the way at ITEP
- different existing absorber structures open different options
  - EUDET stainless steel
  - AIDA tungsten: time-resolved shower images
- PCBs and SiPMs needed
  - 22000 ch for 40 layers







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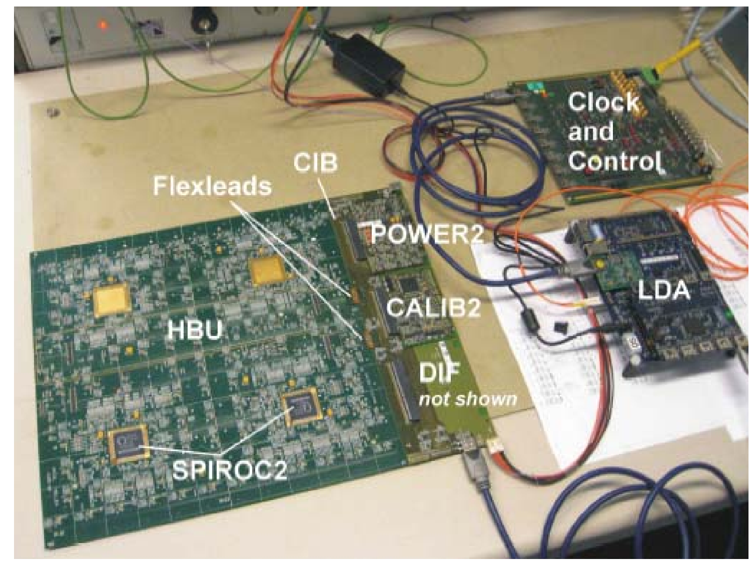

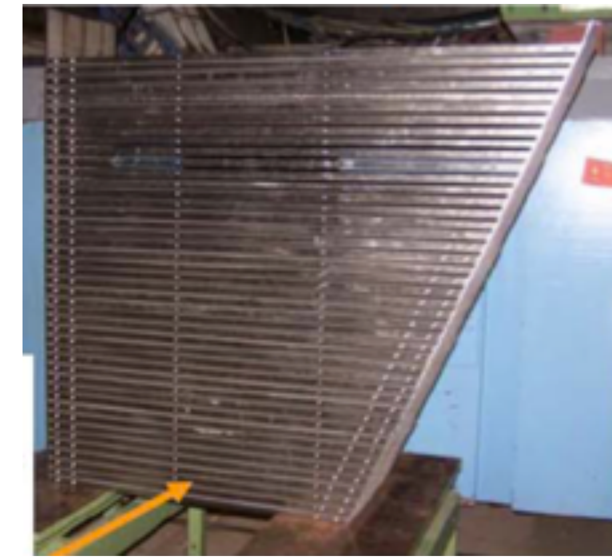

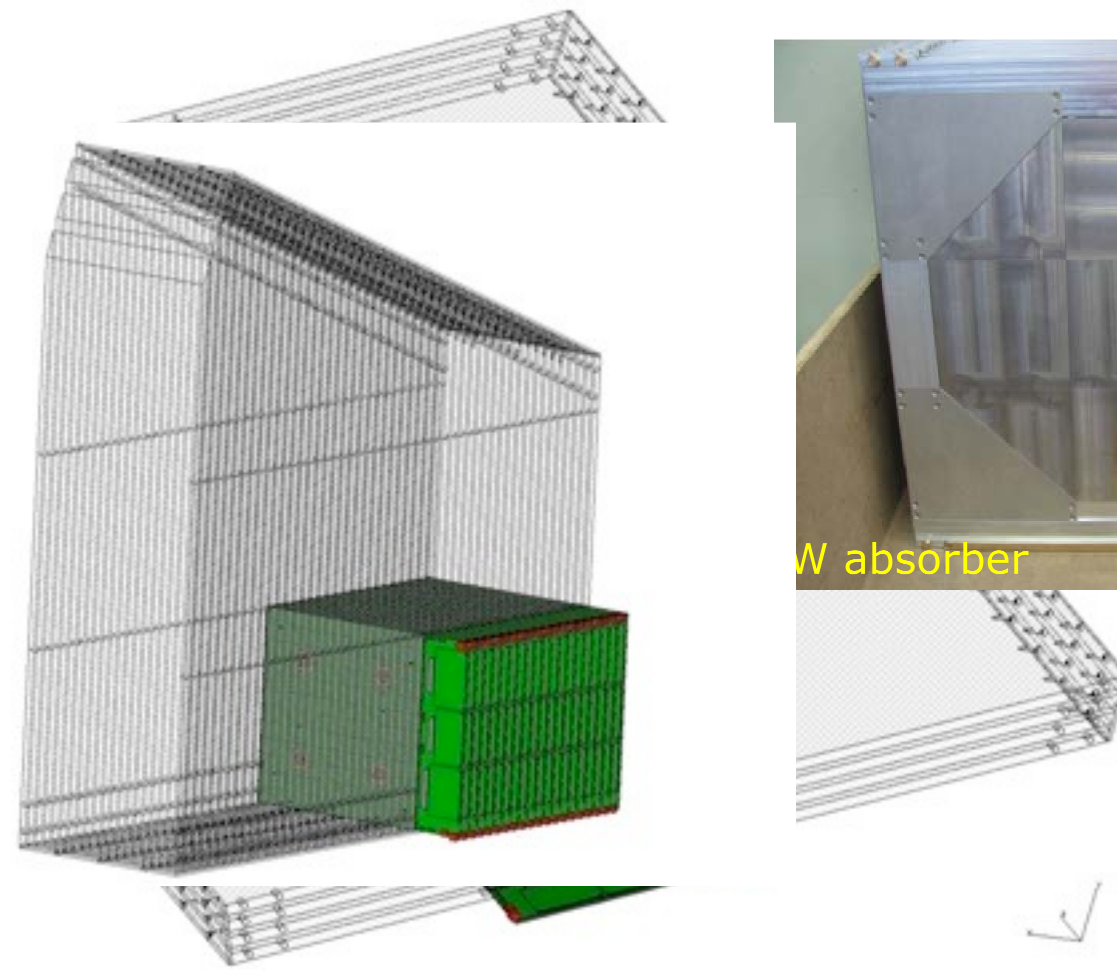

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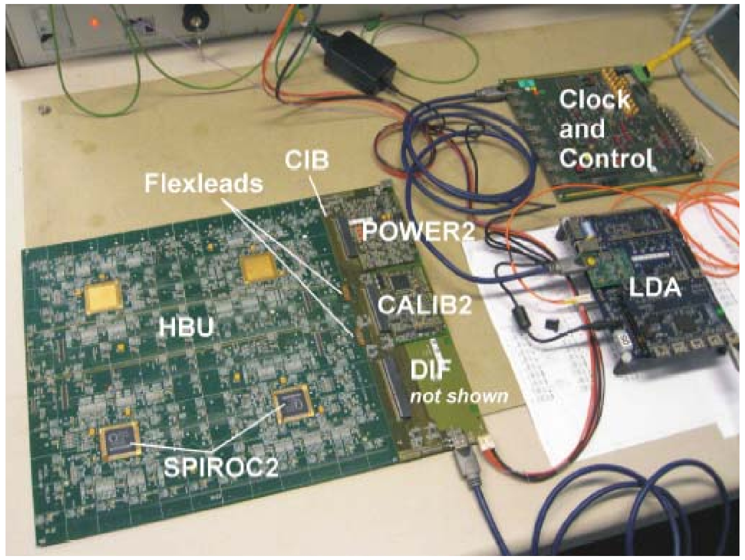
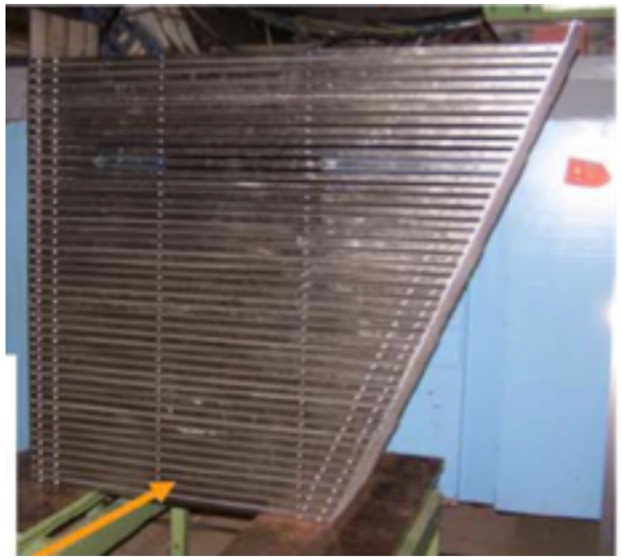
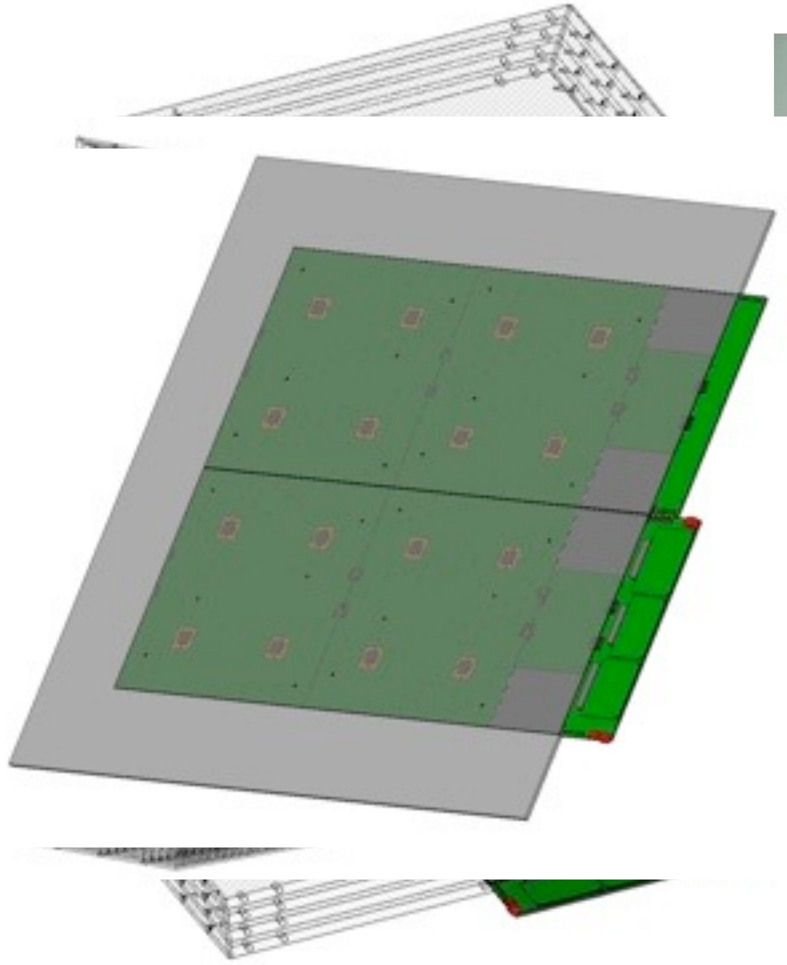


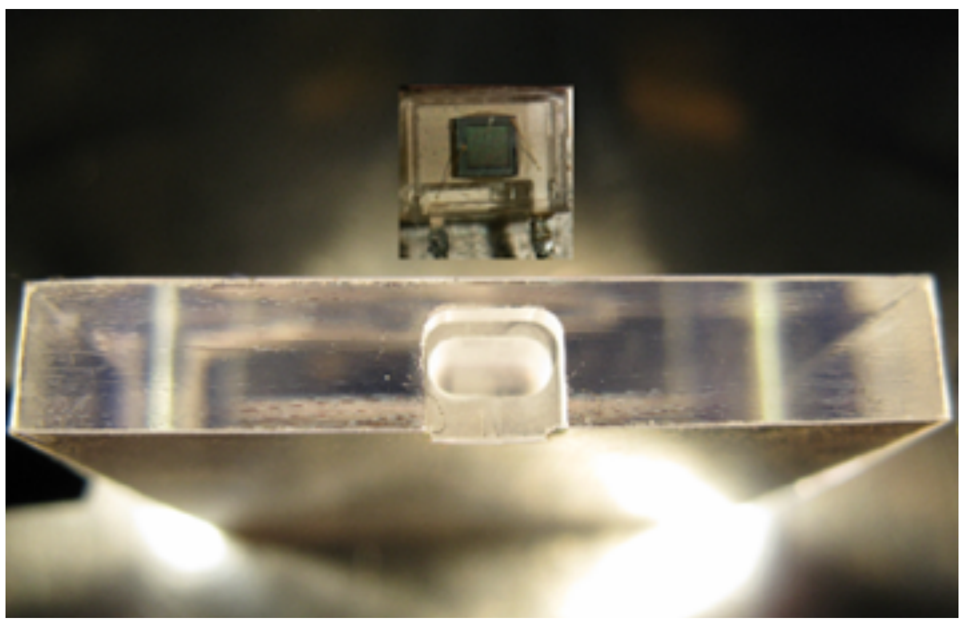


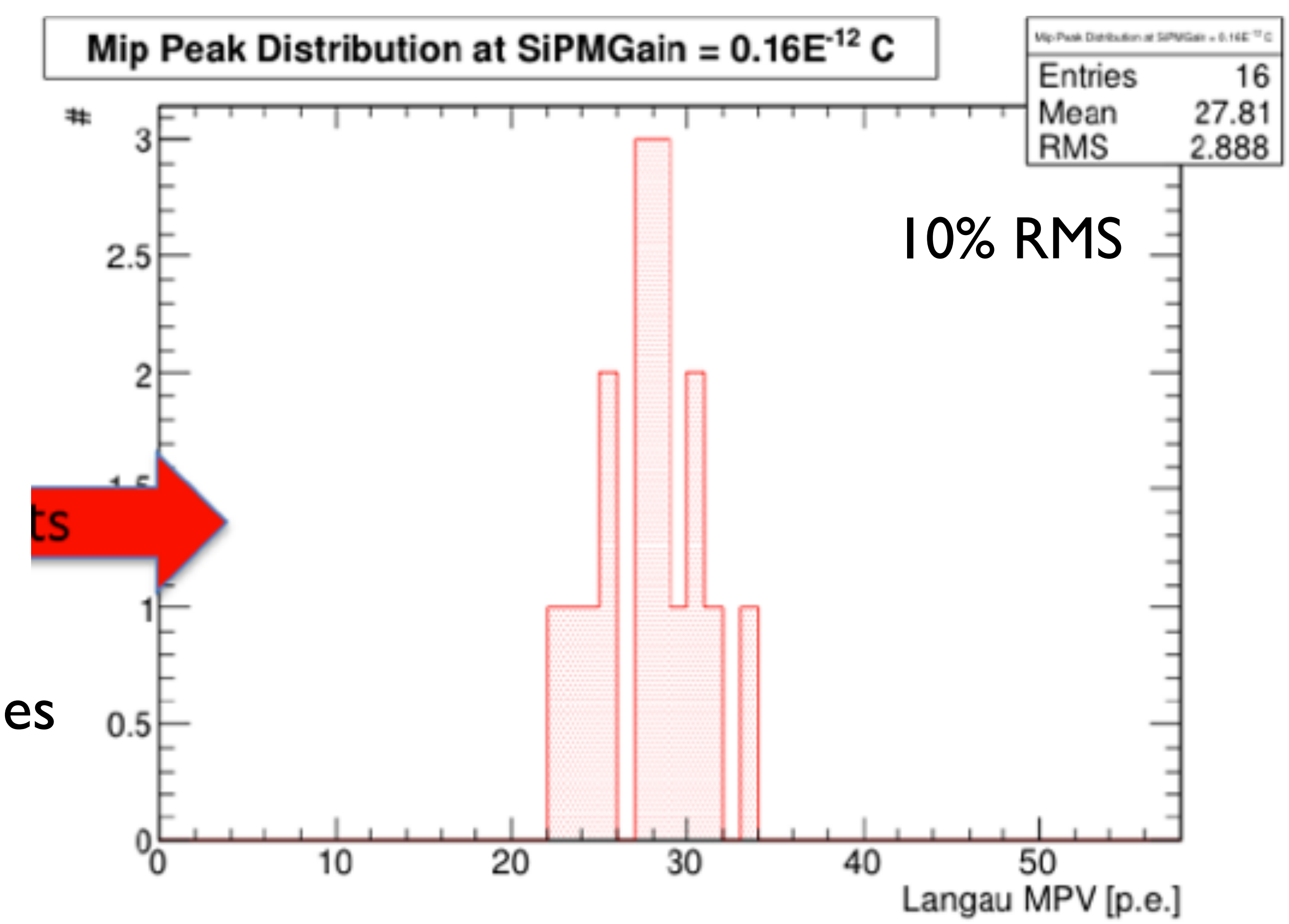


Alternative Options for Scintillator Tiles: Direct Readout

- Current commercial SiPMs (Hamamatsu MPPC, ...) have their sensitivity maximum in blue spectral range: No need for a WLS fiber
  - Reduced mechanical complexity: no fiber to integrate
    Relaxed tolerances: No alignment of SiPM wrt fiber

Strategy: Reduce scintillating material close to photon sensor, diffuse light in air gap
Coupling at bottom face (low signal): NIM A605, 277 (2009), at side: NIM A620, 196 (2010)



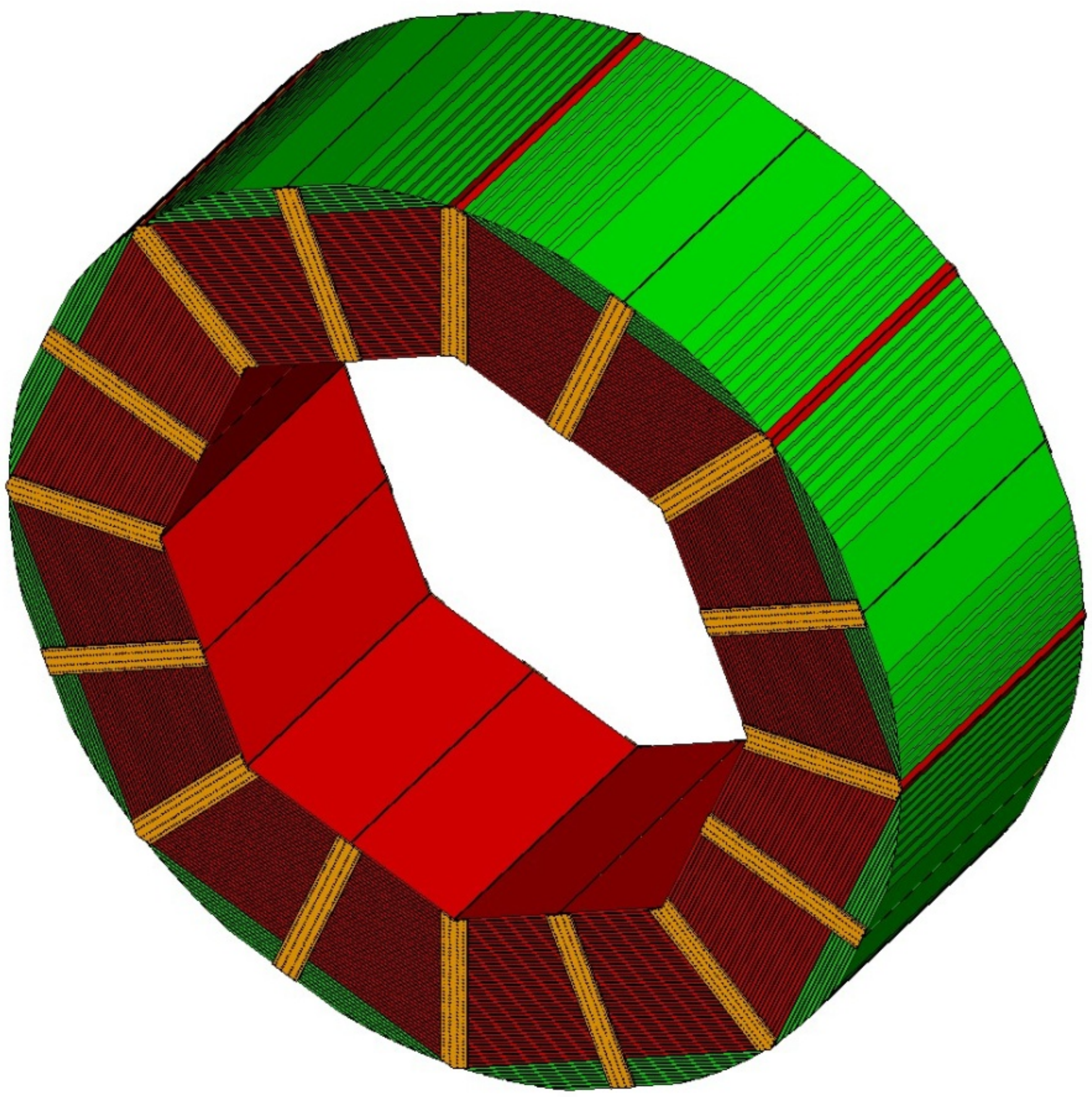


Light yield distribution of 16 hand-drilled tiles
expect even better uniformity
with mass-production techniques

Mechanical Concept & Simulation Models

Mechanics - Fully Engineered Design

- Mechanical design for HCAL structure exists; high level of realism

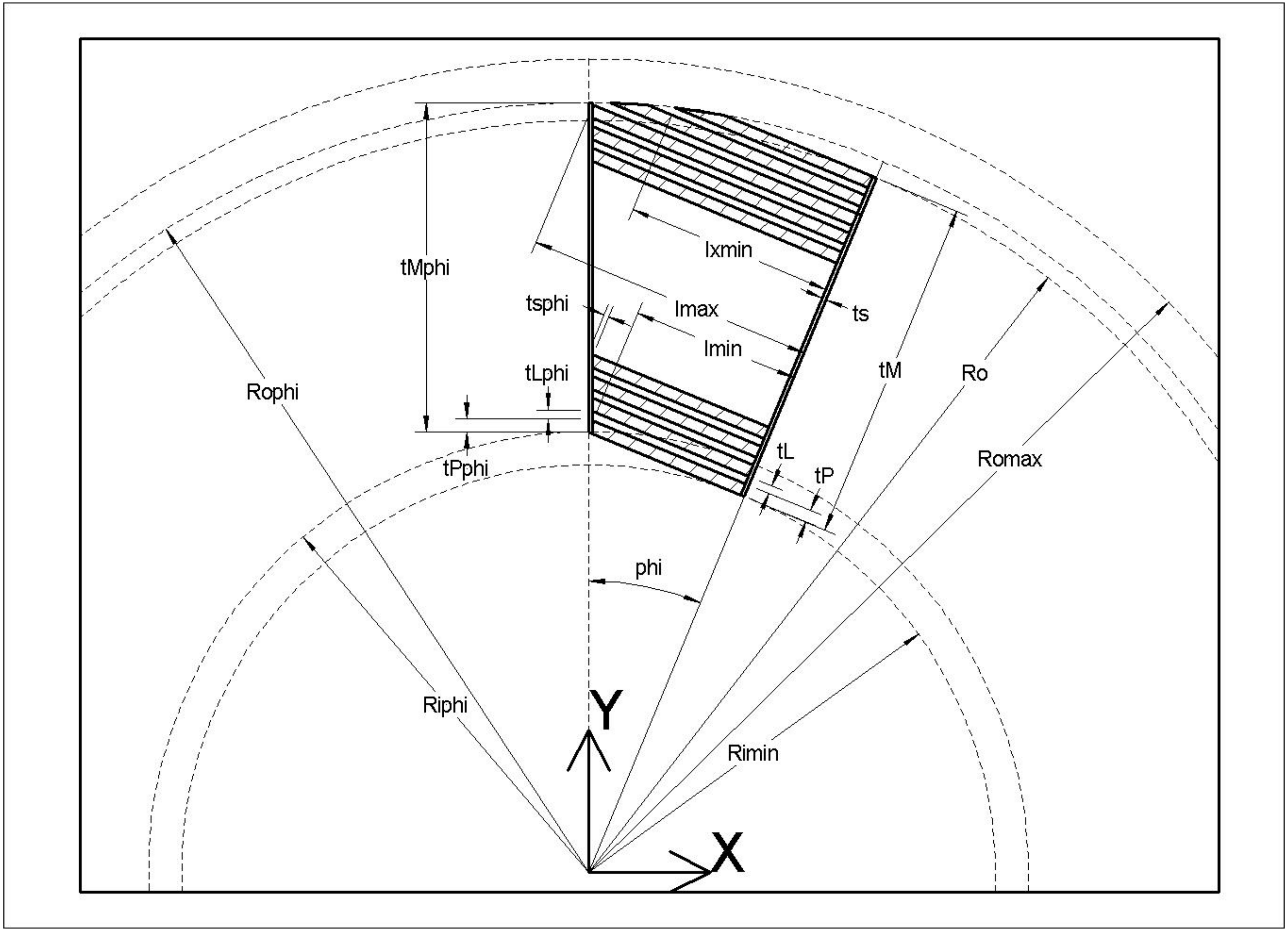


AHCAL half barrel absorber structure

- 8 modules per half barrel,
  2 sub-modules per module
  (40 layers, 5.2 λ)
- 2 side plates per sub-module: 5 mm thick
- 16 backpacks (8 layers, total 5.7 λ)
- 32 connector bars
  (15 mm thick 200 mm wide)
- 16 back plates to fill gap between half barrel (15 mm thick)
  Avoids air gap at z = 0

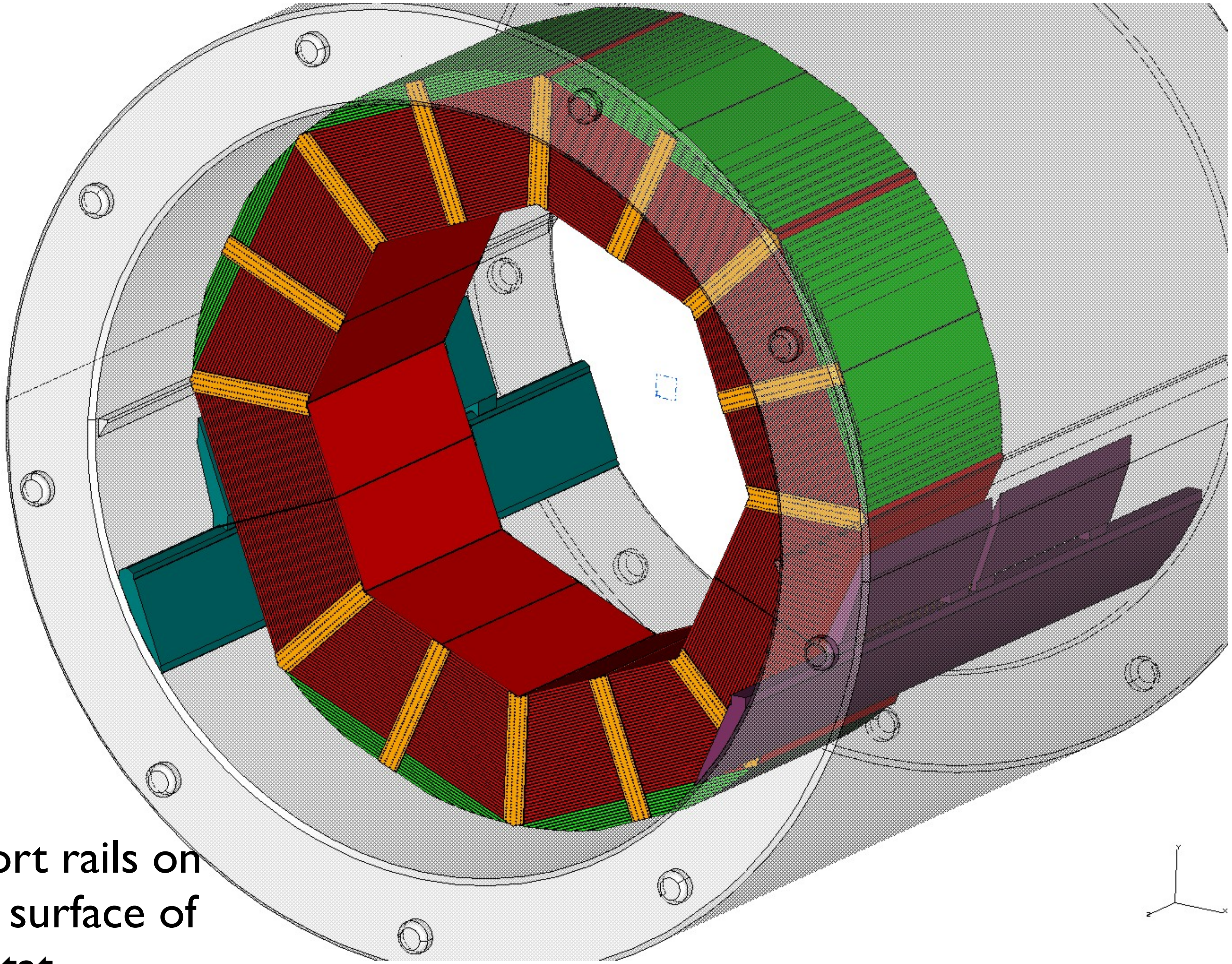
Mechanics - Fully Engineered Design

- Detailed numbers for all aspects / components available



Mechanics - Fully Engineered Design

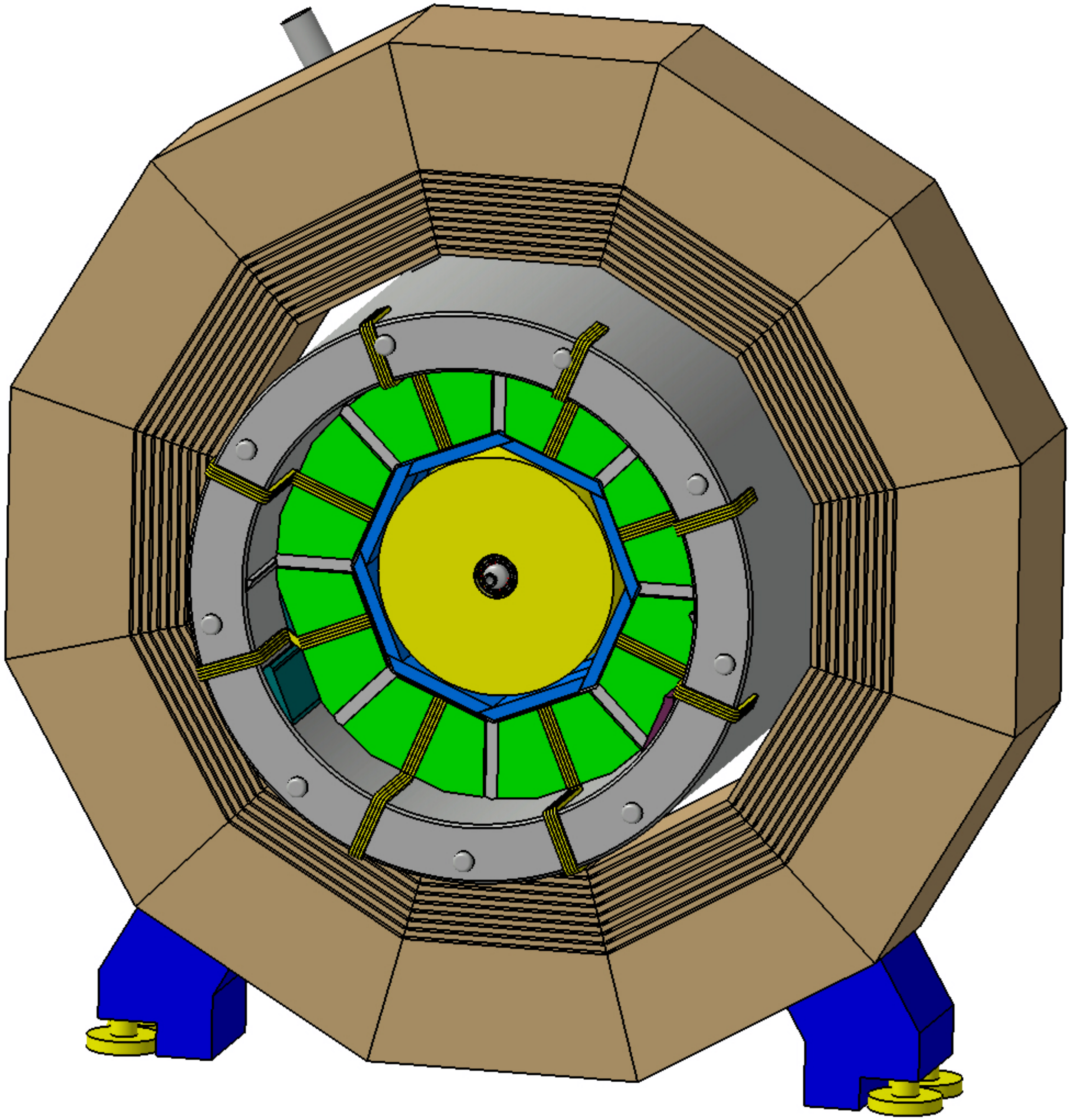
- Integration into ILD fully established



support feet of HCAL absorber structure

support rails on inner surface of cryostat

Mechanics - Fully Engineered Design



- And it fits together with the ECAL...

Steel Structure: Proof of Principle

- Required tolerances of steel plates can be achieved by “roller leveling”: Successful tests of horizontal and vertical mechanical prototypes

- Active layers fit in all calorimeter layers: Mechanical tolerances and structural stability under control!
- ▸ Use 2nd generation demonstrator to study all integration issues with fully equipped active layer

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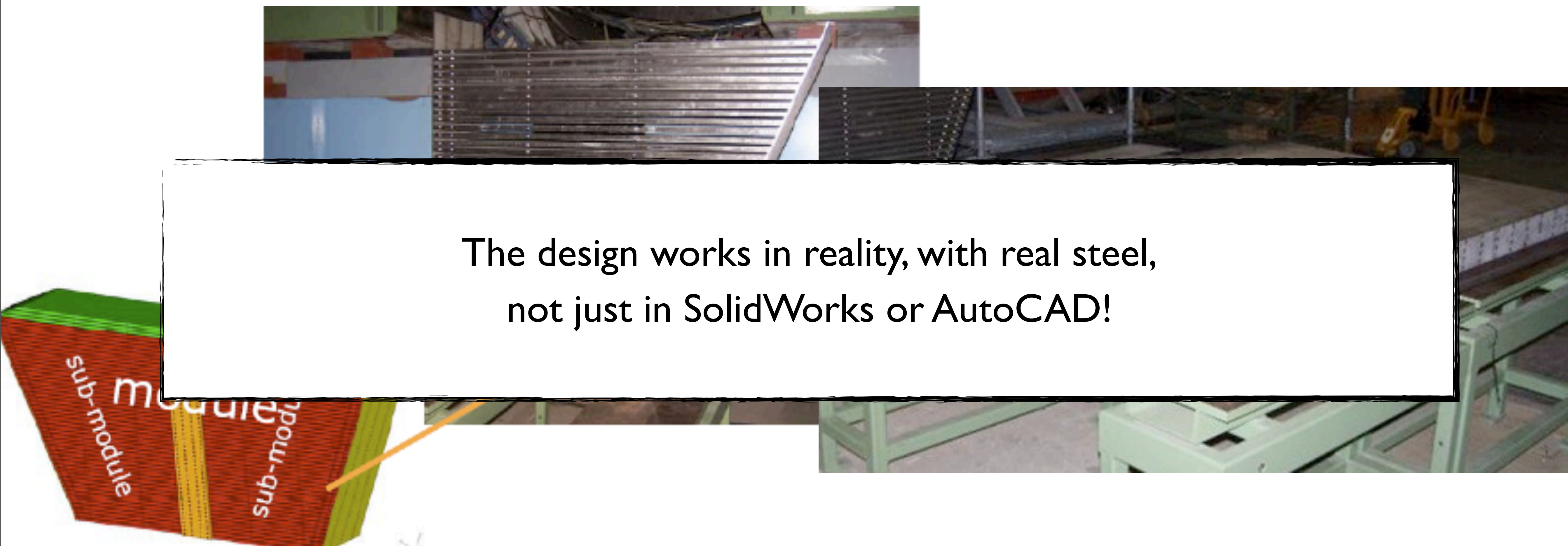
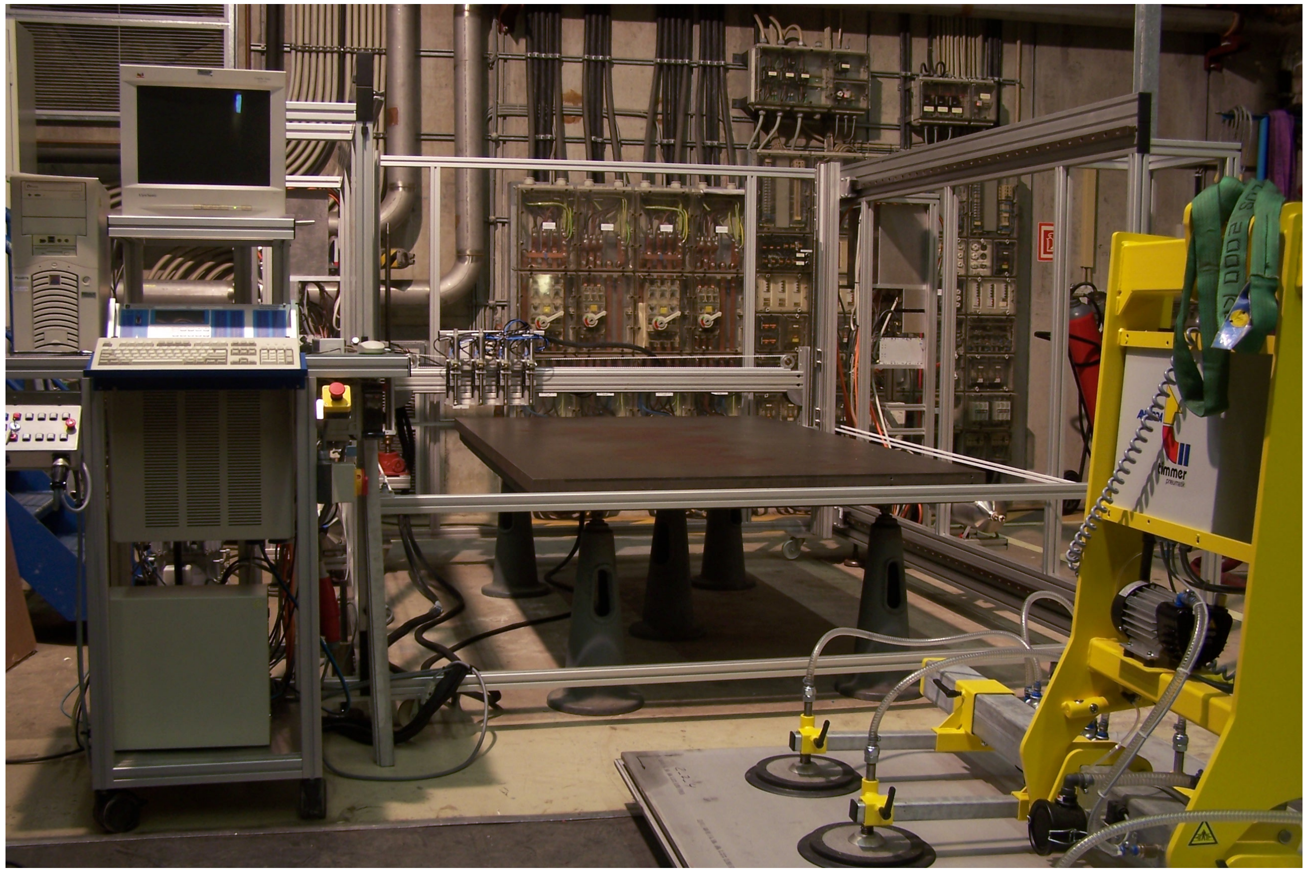


The design works in reality, with real steel, not just in SolidWorks or AutoCAD!

- Active layers fit in all calorimeter layers: Mechanical tolerances and structural stability under control!
  - Use 2nd generation demonstrator to study all integration issues with fully equipped active layer

Steel Structure: Achieving the required Flatness



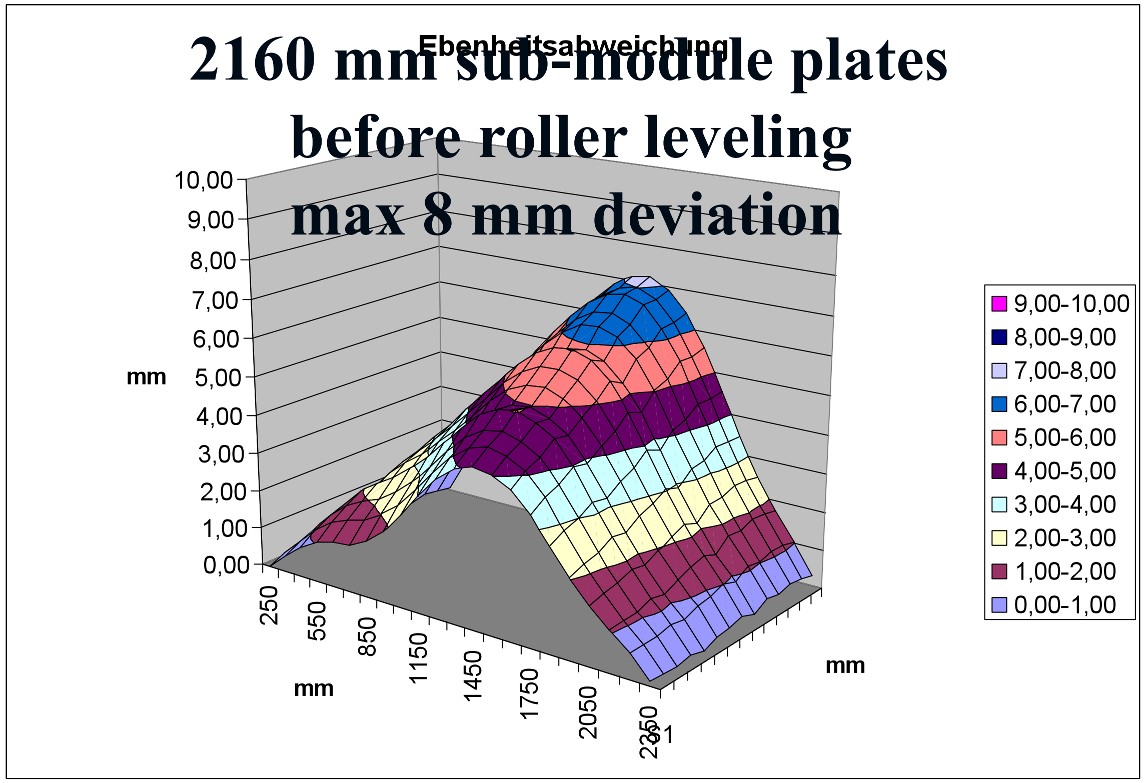
- At DESY: Facilities for precise measurement of large steel plates

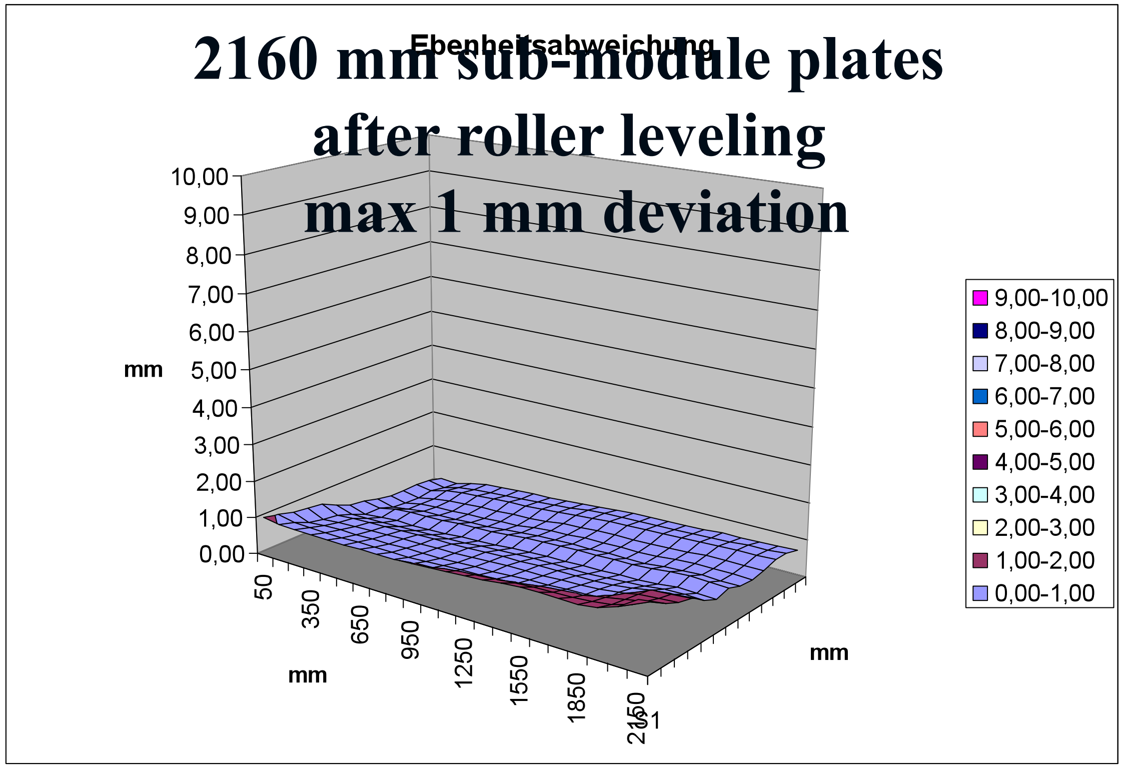
Specifications for purchased steel:

- thickness -0.3 + 1.6 mm
- flatness:

  < 10 mm over 1 m

  < 13 mm over 2 m

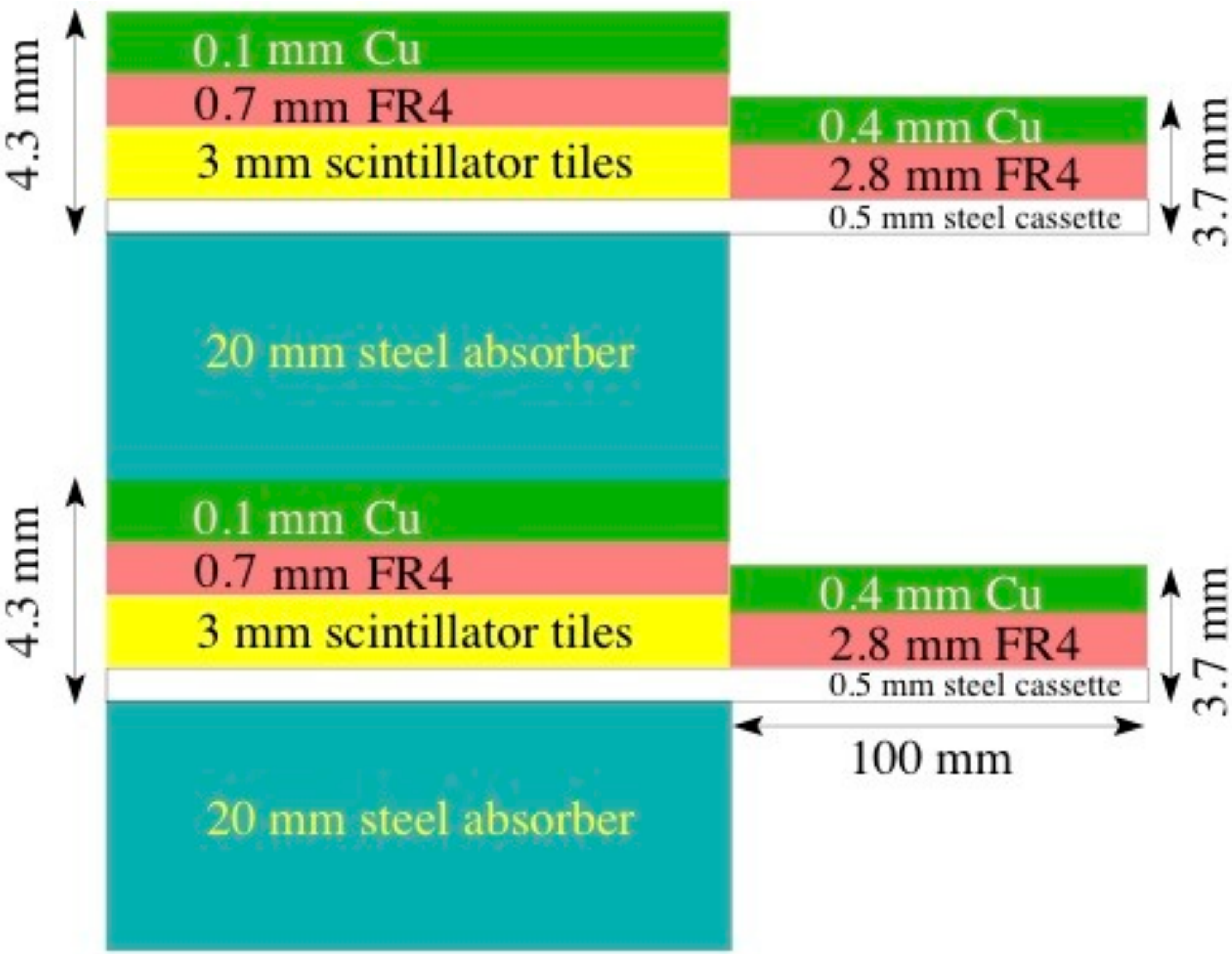




Data Analysis and Simulation - Overview

- Identical frameworks are used for test beam analysis and full ILD simulations
- Detailed implementation of AHCAL exists in Mokka (both CALICE test beams and full ILD)
  - Much work already went into the model for the LOI, which had a high degree of realism
  - Built-in possibility for realistic accounting for tolerances by air gaps at various locations: This needs uniform treatment for different designs, because requirements for tolerances are universal
  - Small further tweaking required to update it to the current engineering design
    - Fill current air gap between half barrels with steel: Model the back plates now included in the mechanical design
    - Add air gap in layer description to account for added height required by connectors, ASICs, solder pins

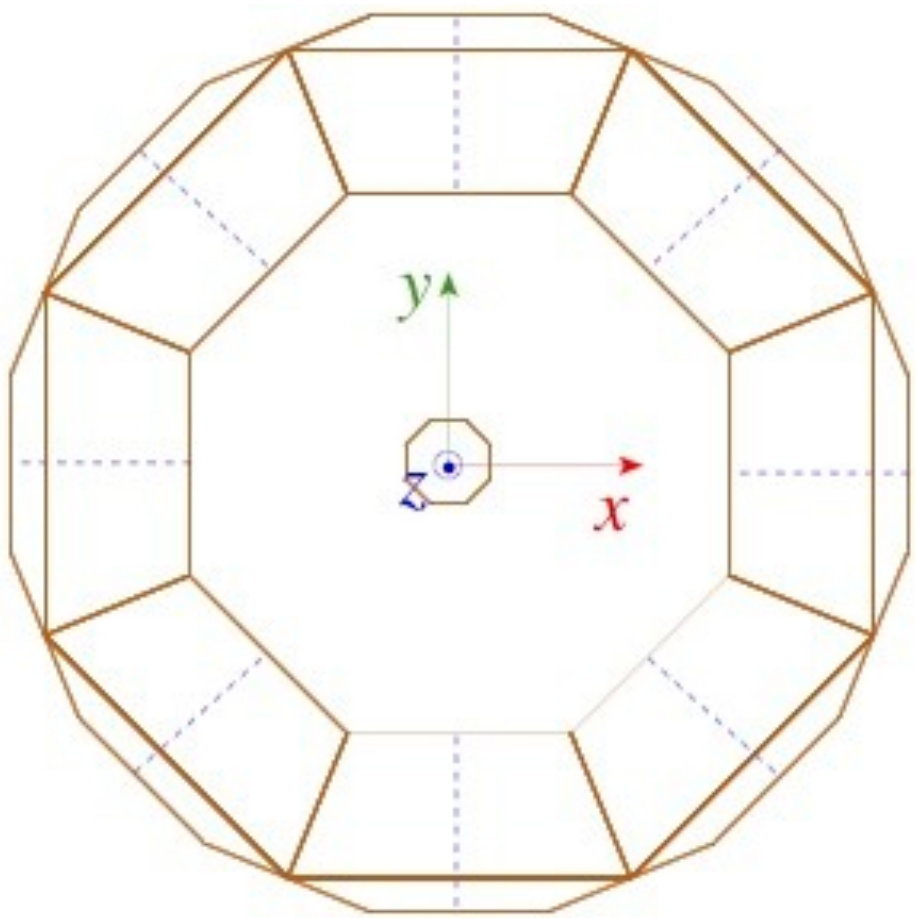
Simulation Geometry - Current Implementation

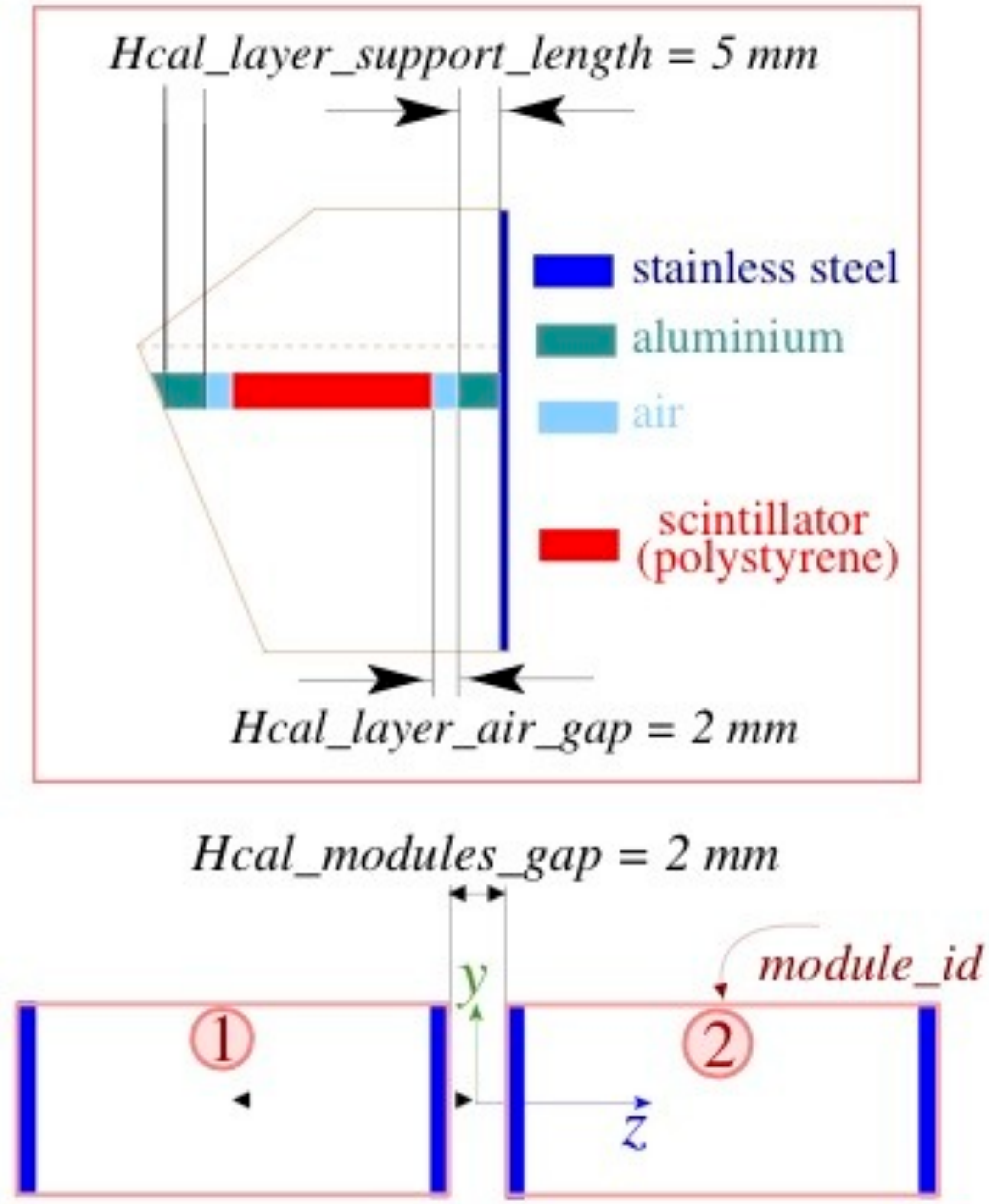


- Current implementation of detector layers:
  - 3 mm thick scintillator tiles
  - readout board with integrated ASICS simulated by FR4 & Cu
    - Missing: Air gap for connectors, solder pins, ...
  - Front-end electronics at module ends implemented

Implementation of Gaps

- Gaps between half barrels, between sub-modules and modules as well as within modules and layers implemented in the geometry
  - Parameters and materials can be chosen





Detailed description documented in Linear Collider note LC-TOOL-2008-001

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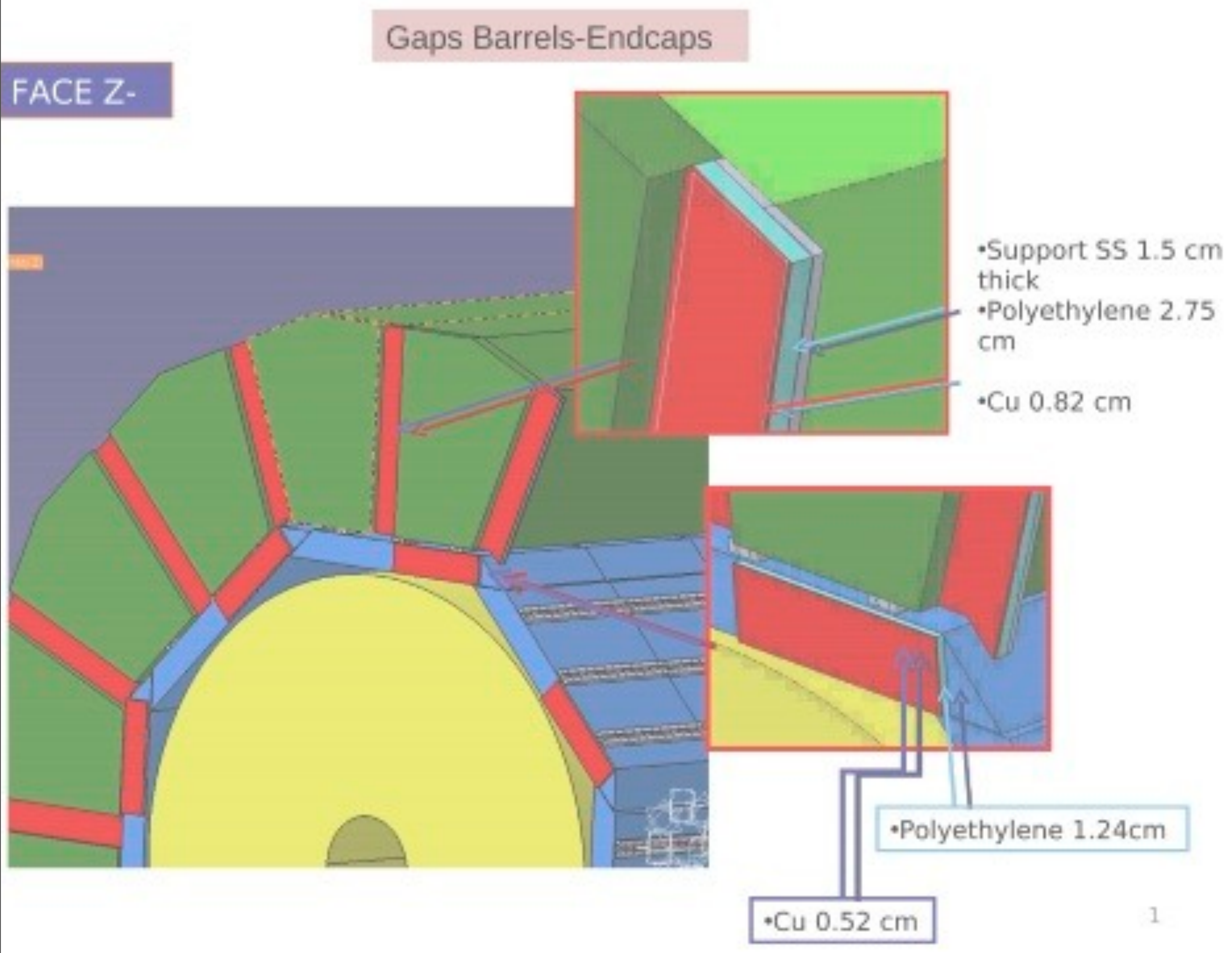

- Modeling of the gap between barrel and endcap
  - ECAL & HCAL services: Support structures, modeling of cables for HCAL & ECAL

Cell and Module Boundaries

- In a realistic detector, there is a very small gap, and corresponding local loss of efficiency for ionizing particles, between tiles and at module boundaries: Do these effects need to be simulated, or is 3 x 3 cm^2 simulation granularity sufficient?

Cell and Module Boundaries

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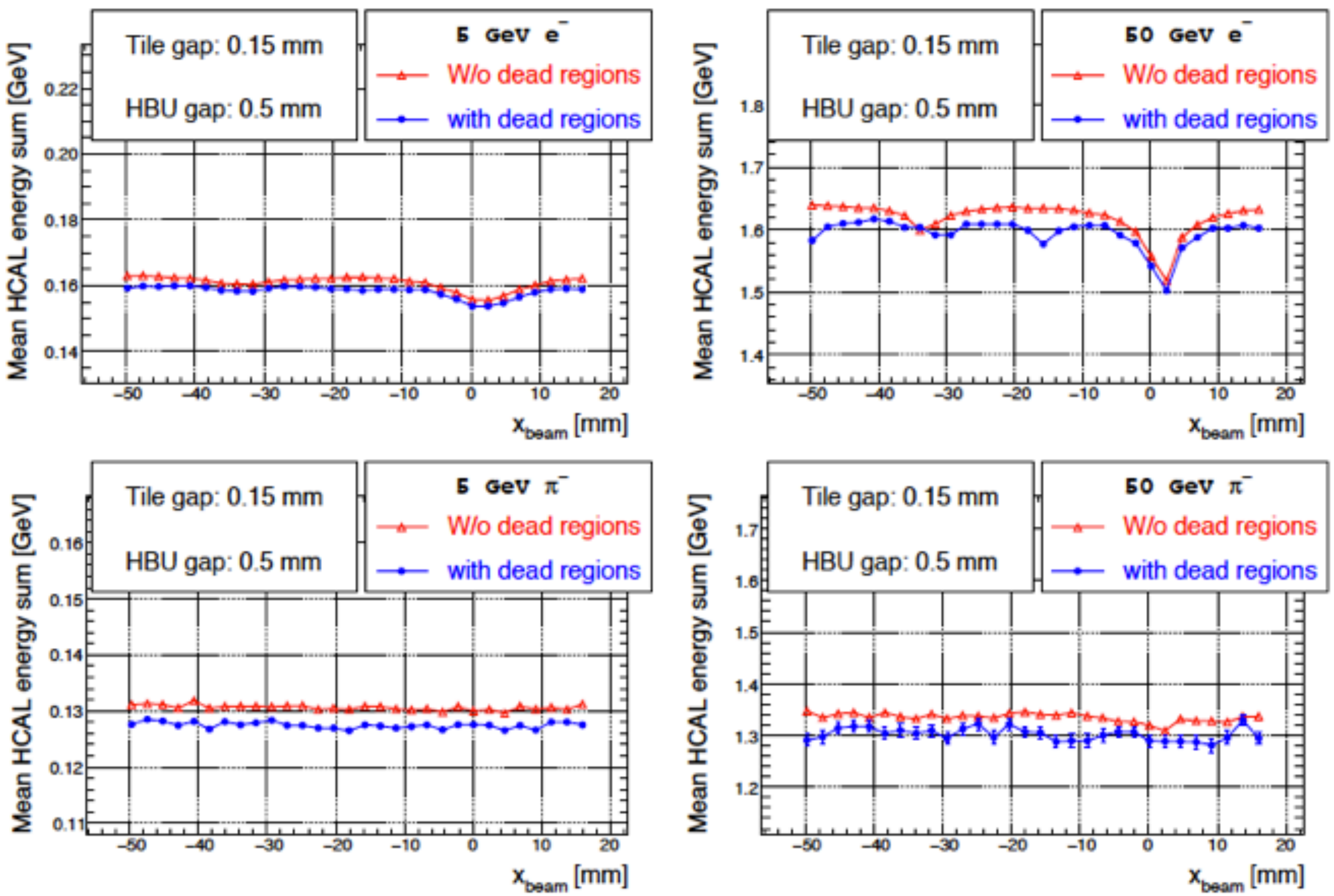


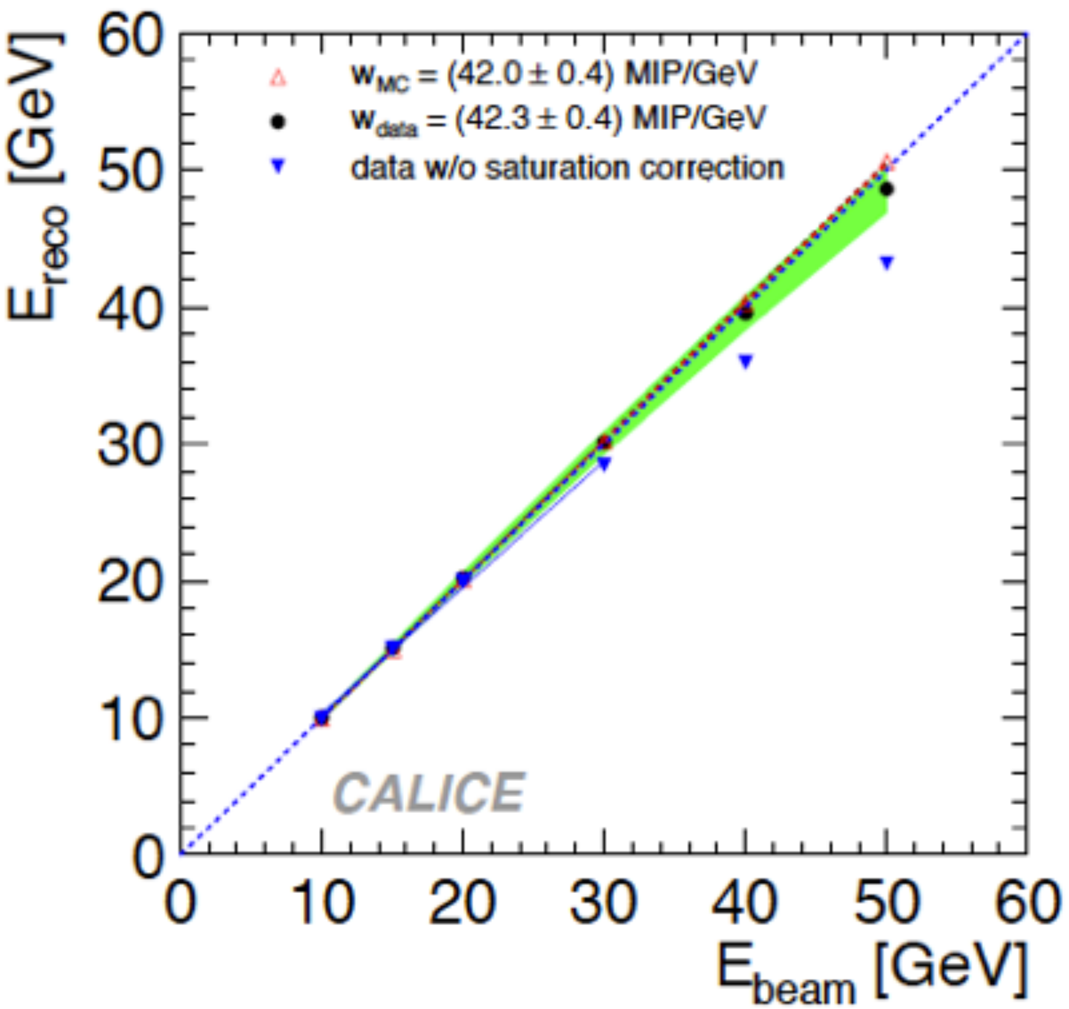
Clear answer:
No simulation necessary!

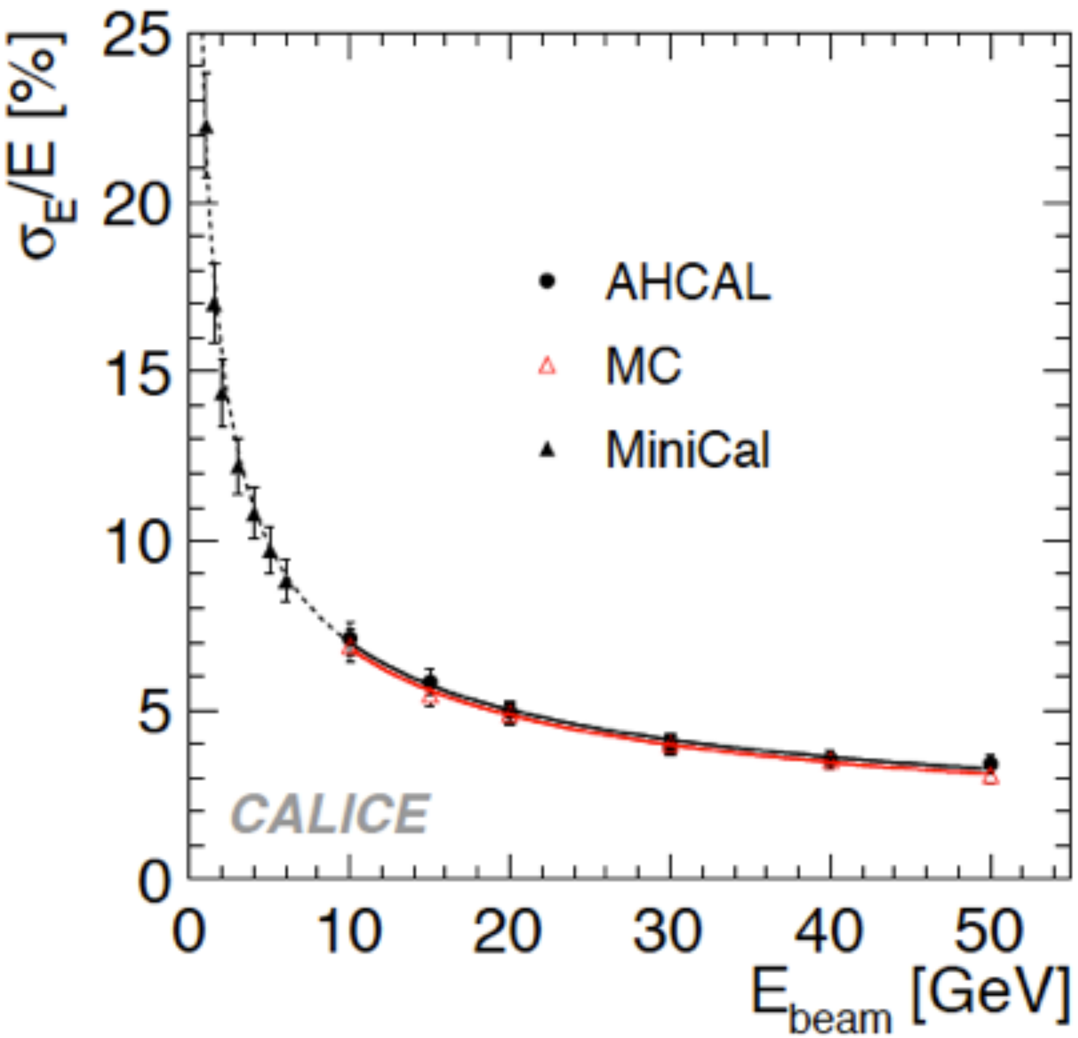
Detailed studies show some effect at HBU gaps for electrons (almost no effect at tile gaps)
No effect (beyond overall scale) for hadrons

Documented in arXiv:1006.3662

Electromagnetic Performance of the Prototype

- The performance for electrons and positrons provides a detailed validation of the simulation model of the AHCAL





- Spectacular agreement, no surprises: AHCAL geometry description, simulation and digitization in excellent shape - This knowledge also enters into ILD!

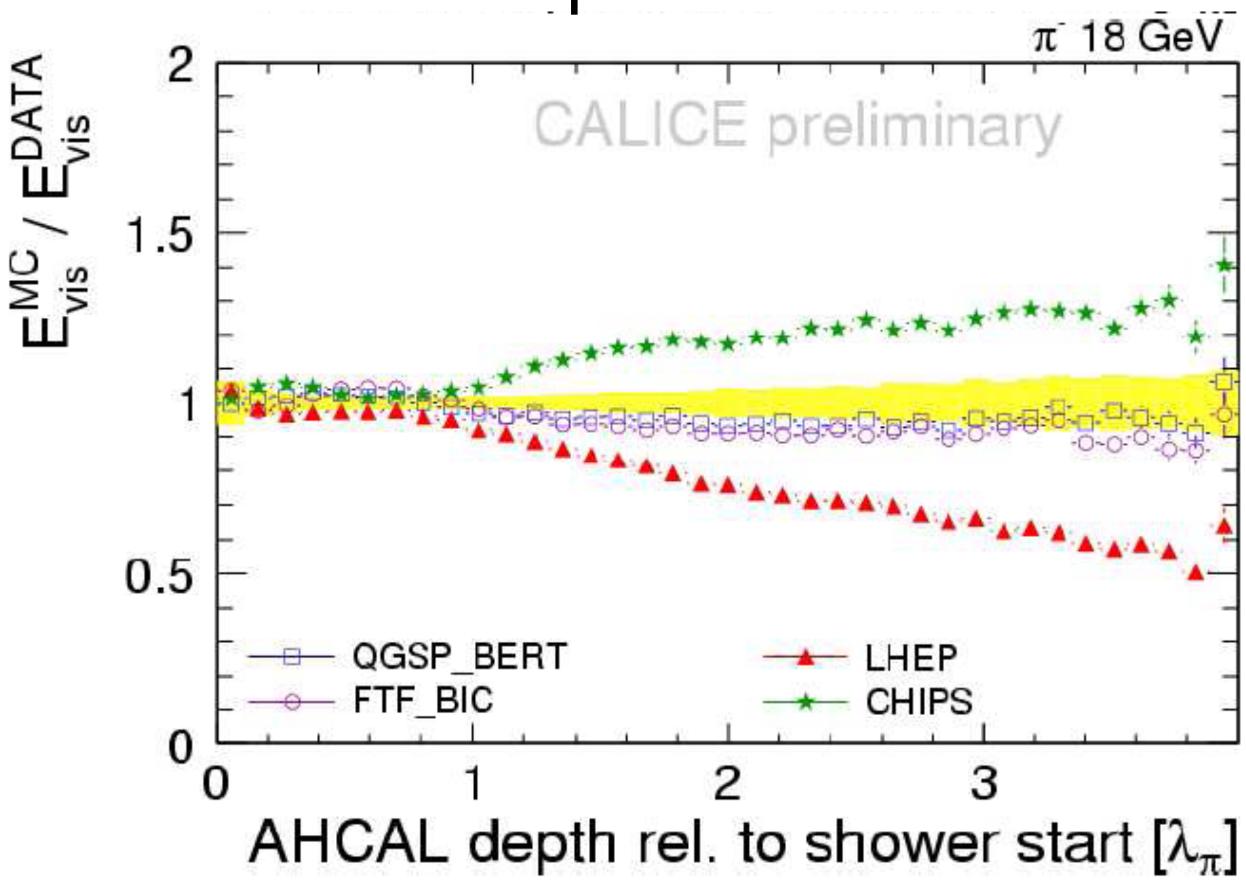
Published in JINST 6, P04003 (2011)

Selected Results for Hadrons
&
Validation of Full Detector Simulations

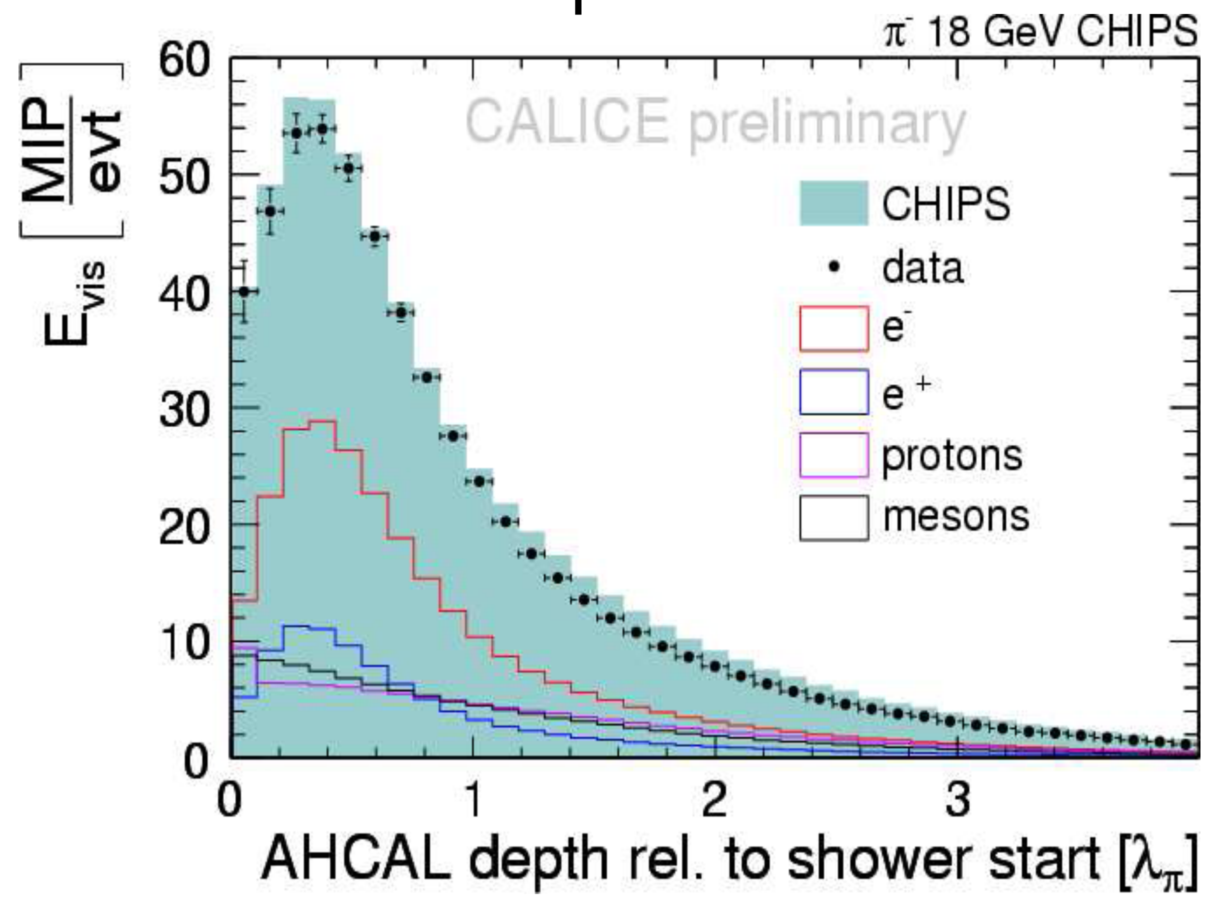
Validation of GEANT4 Simulations

- All our performance studies depend on GEANT4: To what level can we trust it?

shower development:



shower sub-components:



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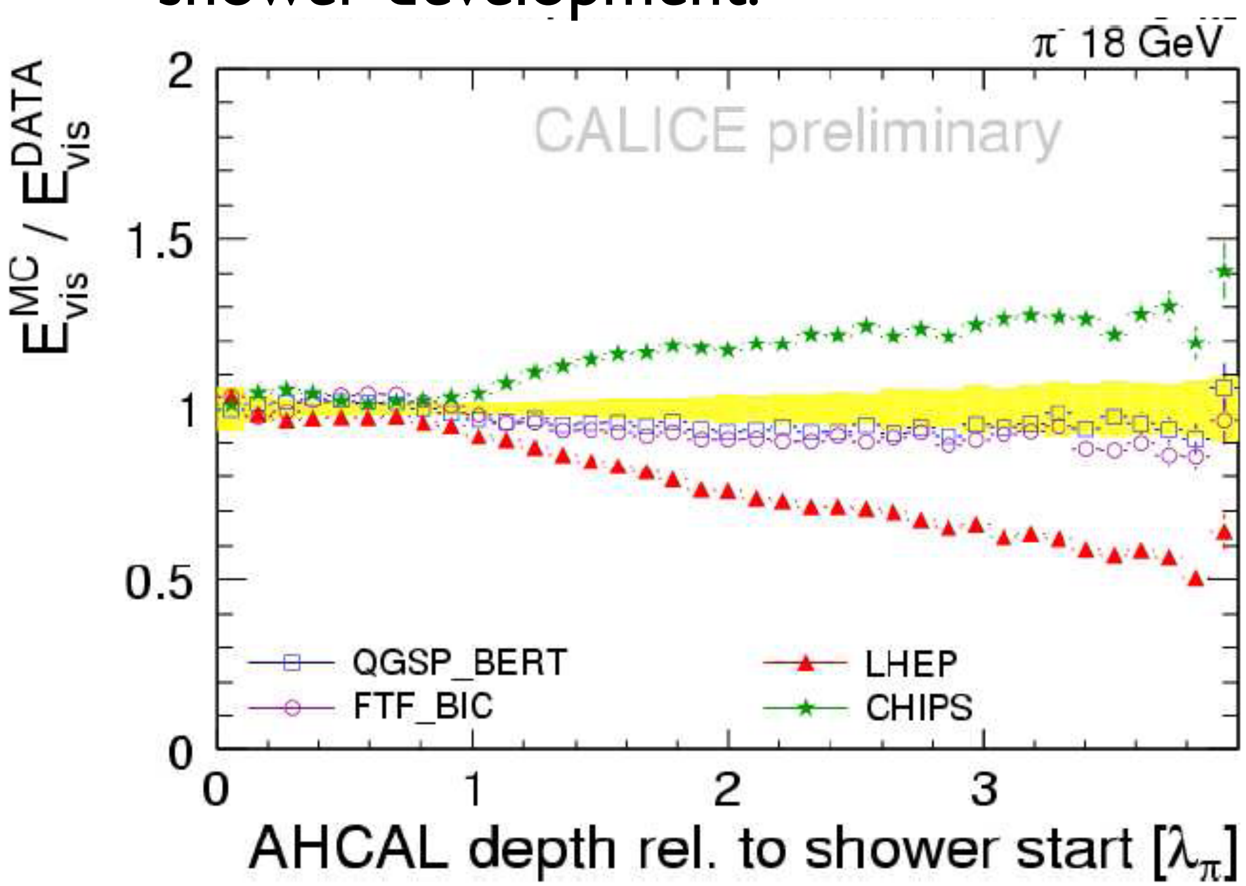
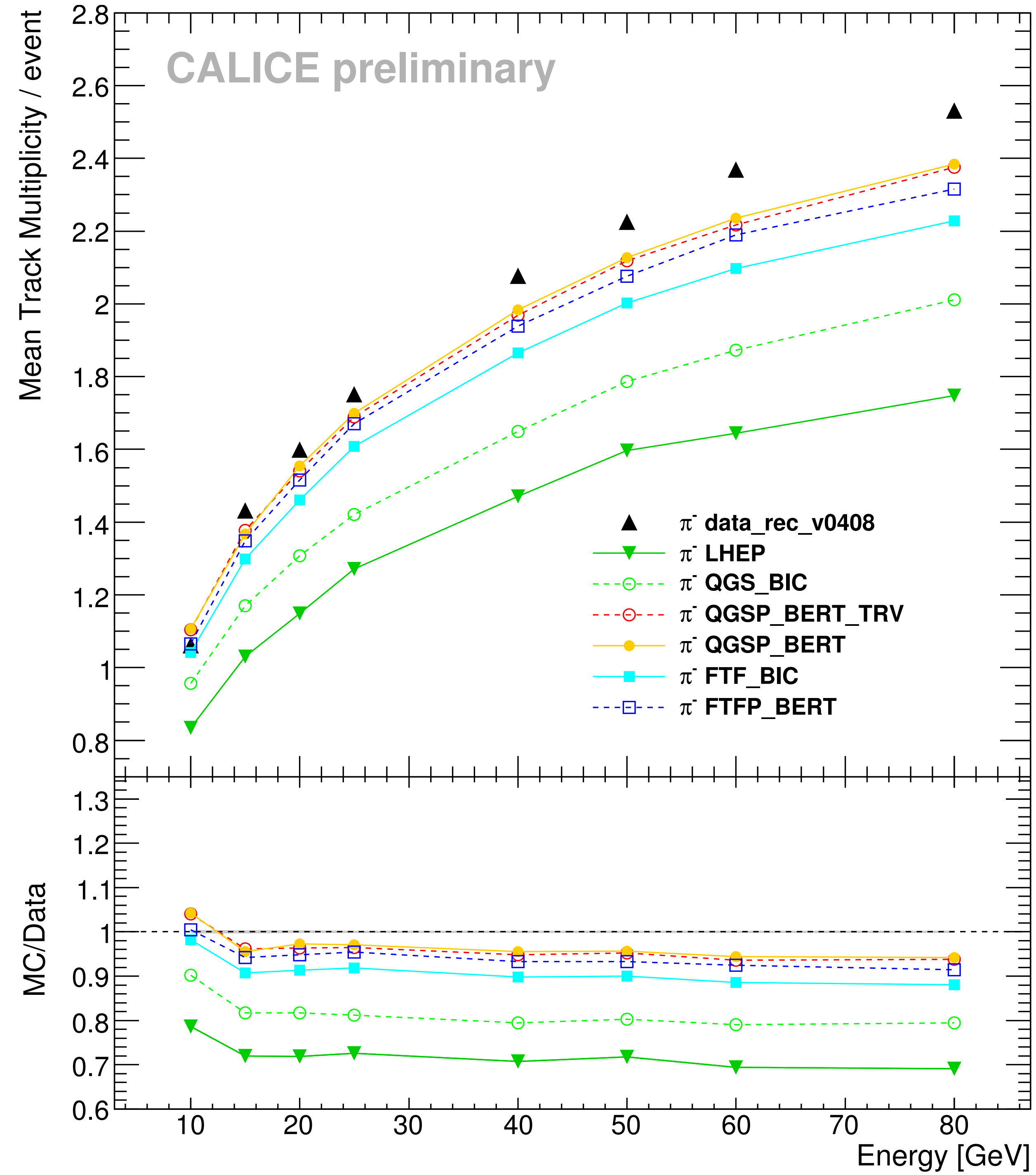


3D substructure: track segments, identified within hadronic showers

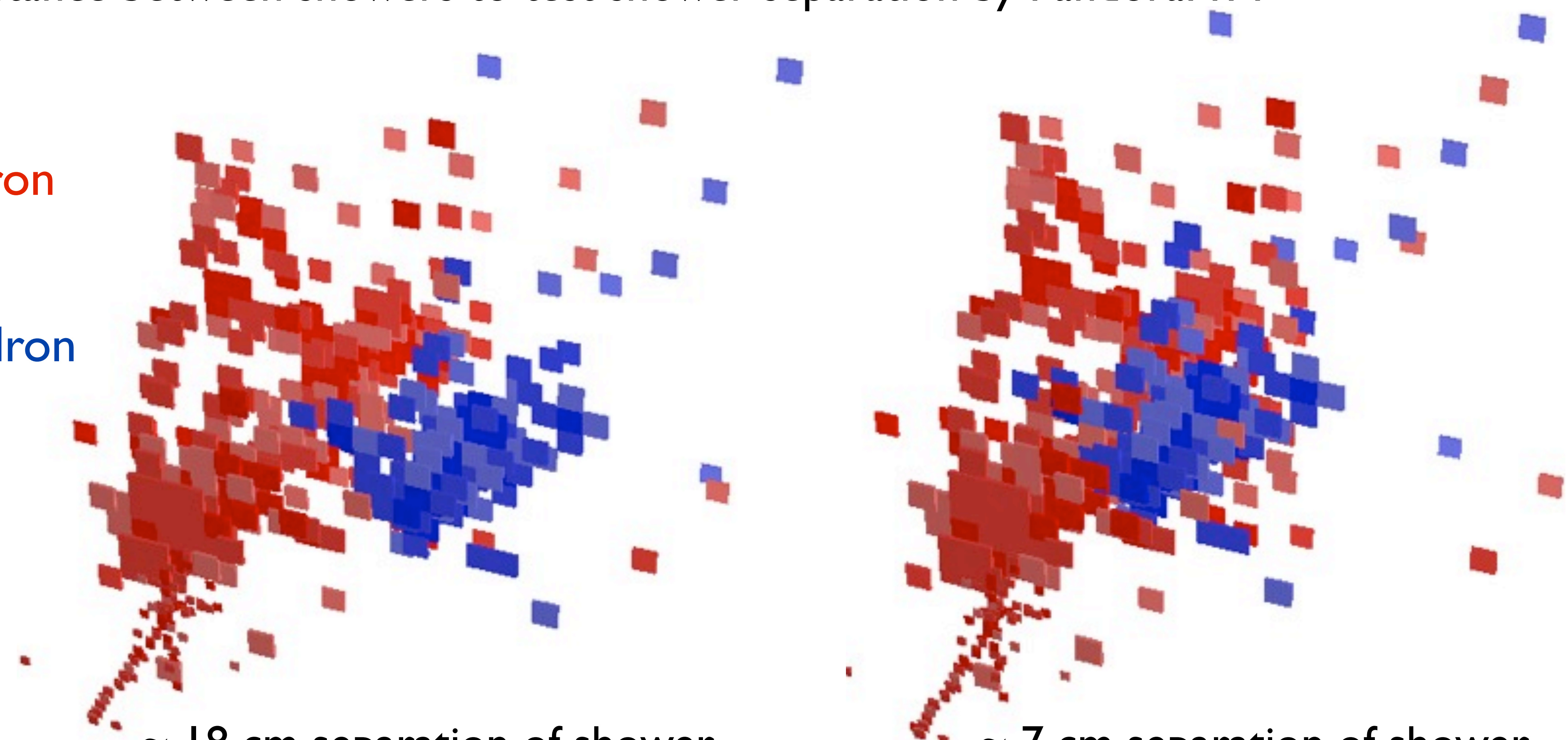


PFA Performance: Level of Realism?

- A key question: Can we trust the PFA performance predicted by full simulations with an analog HCAL?
  Test it! ➯ Use real hadronic showers recorded with AHCAL, map them into ILD
  - Take one shower as a charged hadron (with tracking information), one shower as a neutral hadron (remove hits before the shower start)
  - Vary distance between showers to test shower separation by PandoraPFA

30 GeV
charged hadron

10 GeV
“neutral” hadron



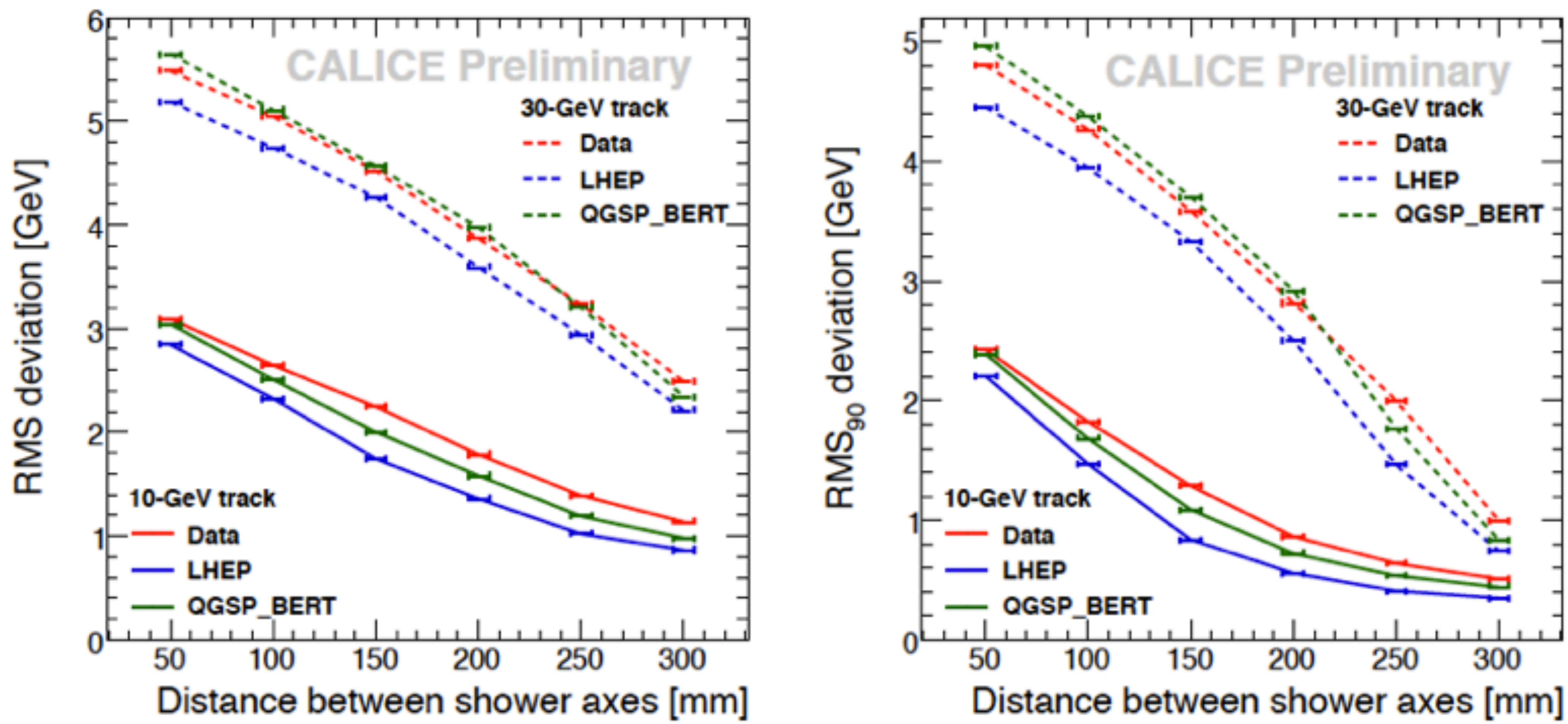
~ 18 cm separation of shower

~ 7 cm separation of shower

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

arXiv:1105.3417, submitted to JINST

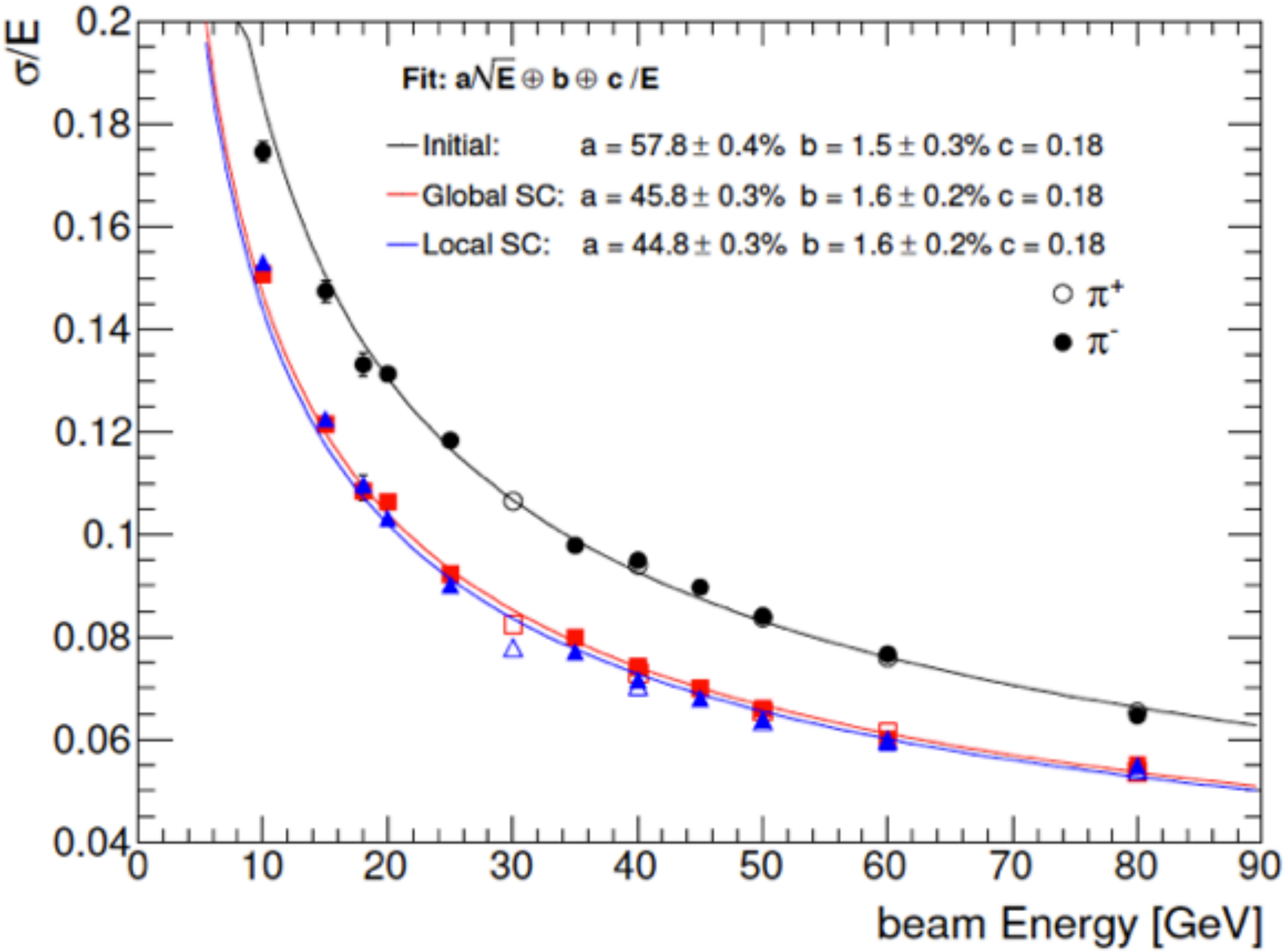


Note: Performance reduced compared to PFA in a real Experiment: No magnetic field, mapping of cells, ...

Key point: Validation of simulations - PFA for AHCAL works as expected from simulation we can trust our full detector simulation!

Energy Reconstruction & Software Compensation

- The AHCAL is non-compensating: e/π ~ 1.3 (energy dependent)
- High granularity provides detailed information that can be used for software compensation: Can be done on local (cell) or global (cluster) level



Resolution of 45%/√E with small constant term for pions ***in data***

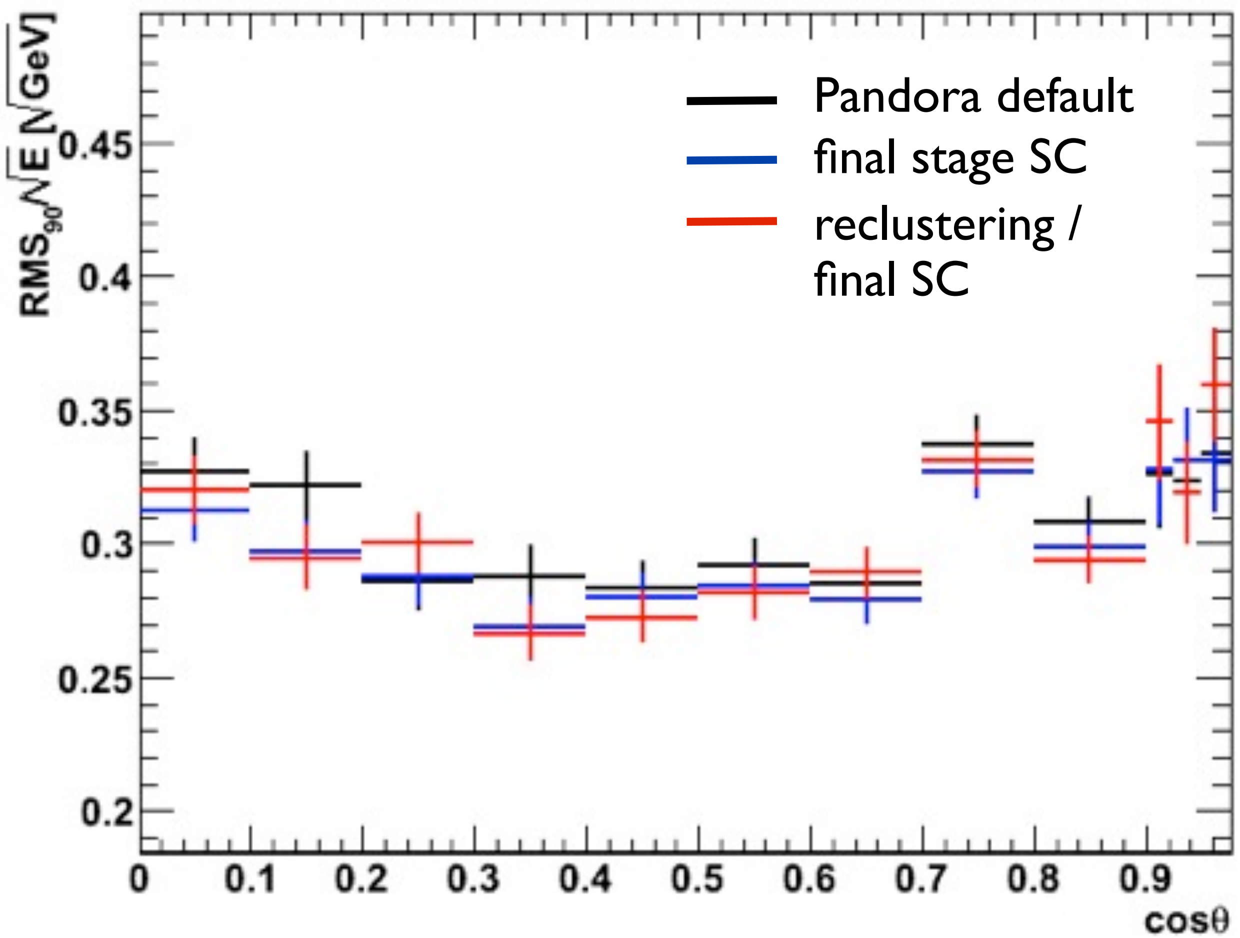
Linear energy reconstruction within 1.5% over the full energy range from 10 GeV to 80 GeV

Simulations with QGSP_BERT predict ~ 10% better energy resolution (both with and w/o SC), in agreement with observations by LHC experiments

Documented in several proceedings, for example arXiv:1008.2318, publication in preparation.

Transfer to Full Detector Simulations / PFA

- Local compensation has been transferred to Particle Flow in full detector simulations
  - Two areas of improvement:
    - Better energy measurement for identified neutral hadrons
    - Improved association of calorimeter hits to tracks ("iterative reclustering")



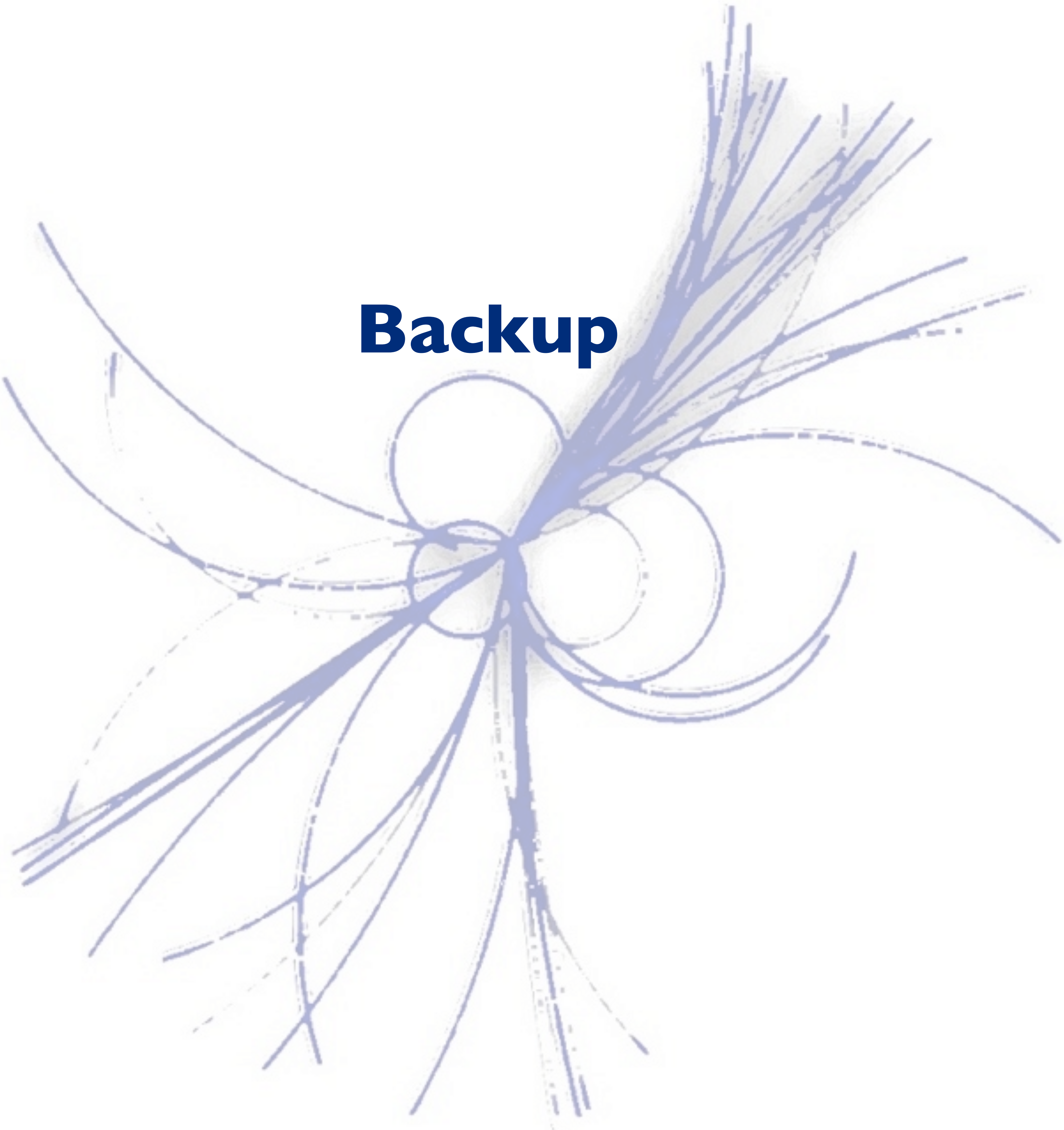
Dijet energy resolution here: 200 GeV

Software compensation leads to a noticeable improvement in jet energy resolution

Summary

- The Analog HCAL is a success story of ILC-driven R&D:
  - First large-scale detector with SiPM readout (and today, everybody is using them!)
  - Large number of results, from calibration to shower studies and energy resolution
- Clear path forward:
  - Measurements with Tungsten - Open the door to high high energies
  - Next generation electronics: Adding a 4th dimension
- Mature design:
  - Detailed engineering model for ILD
  - Realistic software model, with some fine tuning now in the pipeline
- Proof of key concepts of ILD event reconstruction:
  - Particle flow performance validated with real data -
    Proof that the concept is realistic with an analog HCAL

Backup



AHCAL & ILD

- The AHCAL and its results have already been recognized by IDAG, and have played a crucial role for the validation of the LOI

5. EVALUATION OF THE THREE CONCEPTS

5.1 ILD

The ILD Collaboration has presented a LOI which documents the impressive quantity and quality of work performed. A particular strength of the LOI is the very extensive R&D effort made in test beams with full-size prototypes of the calorimeter having been constructed and operated at DESY, CERN and Fermilab. Indeed, alternative technologies for the calorimetry are also being explored in the test beam program. Integrated with these calorimeter tests their data have been taken with a "tail catcher" for one of the possible muon system options. This large data set will allow ILD to validate the PF strategy which is central to their design. The data will also enable ILD to revisit some of their parameter choices, for example the total depth of their calorimeter.

In future, tests in a full strength magnetic field will be made. Initial layout of power and other components in the high field can be studied. Prototyping of the TPC is ongoing in other tests.

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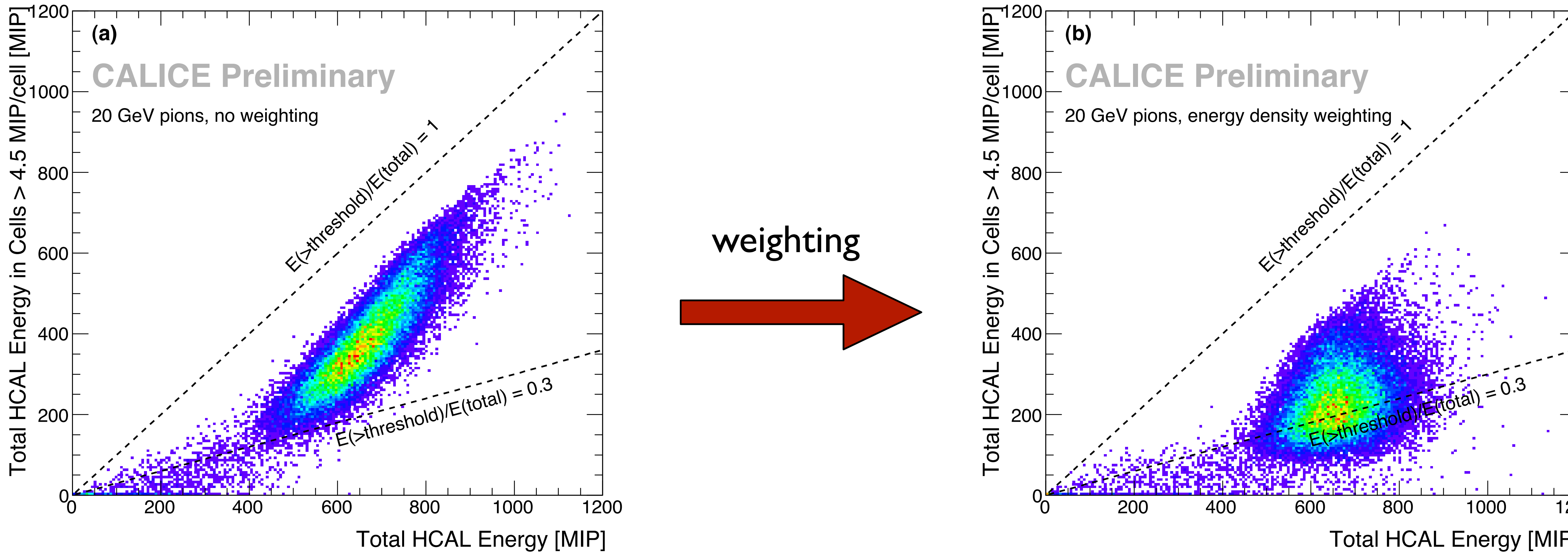
The AHCAL has now delivered this validation of PFA!

Energy Reconstruction & Software Compensation

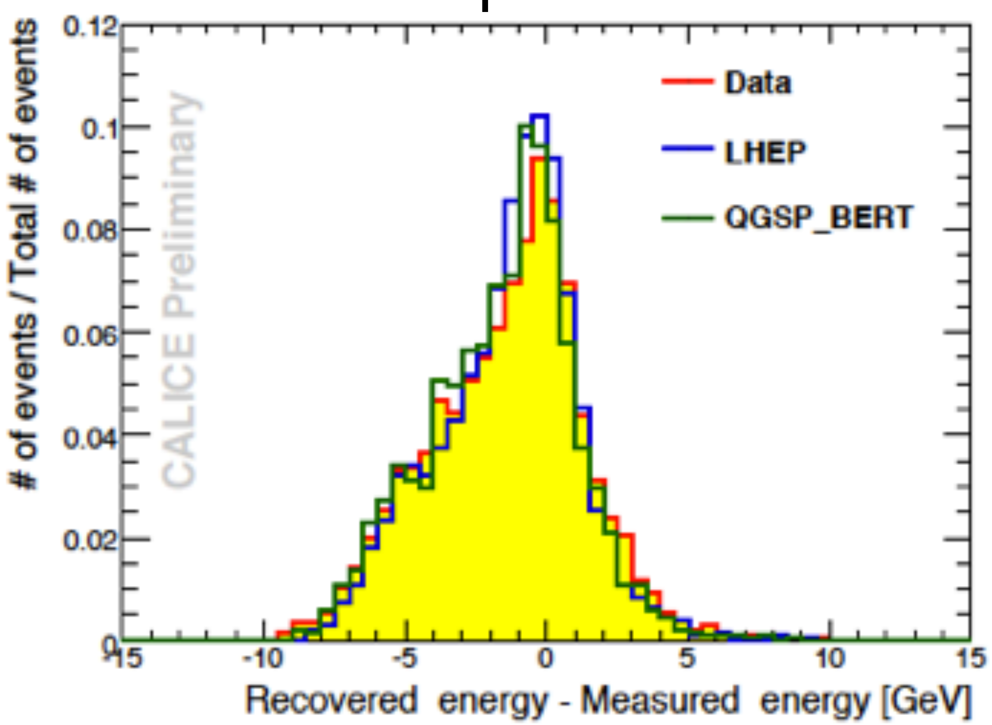
- The CALICE HCAL is non-compensating: e/π ~ 1.3 (energy dependent)
- High granularity provides detailed information for software compensation:
  - Electromagnetic energy deposits tend to be denser than hadronic ones
  - Improvement studied on the cell (local) and on the cluster (global) level

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

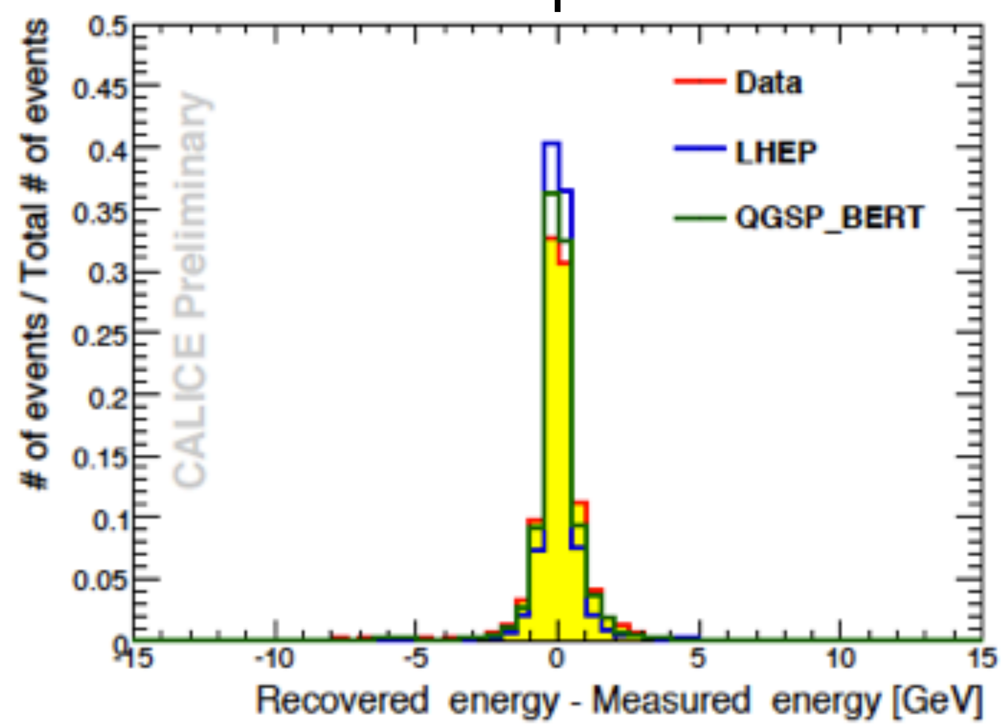


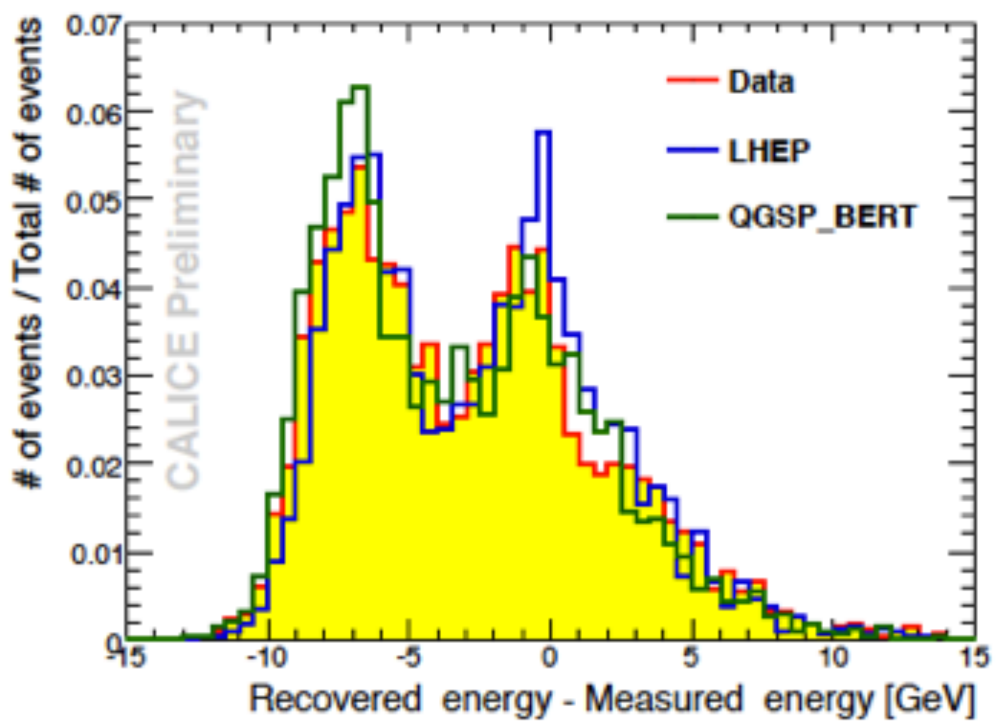
Shower Separation: Energy & Distance

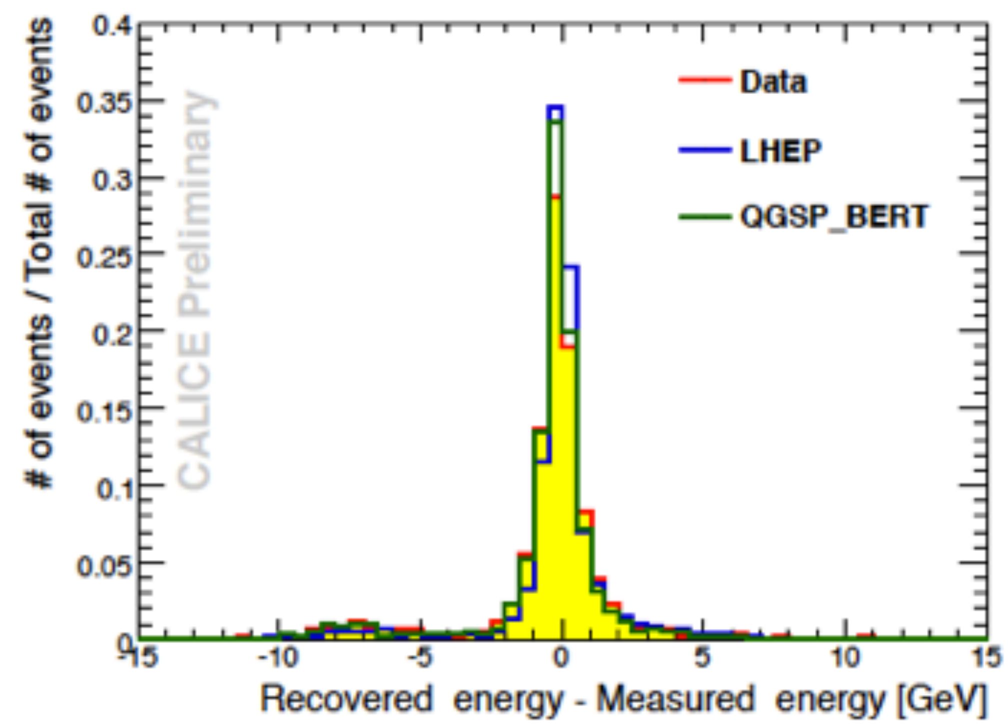
5 cm separation



30 cm separation







- 10 GeV neutral hadron

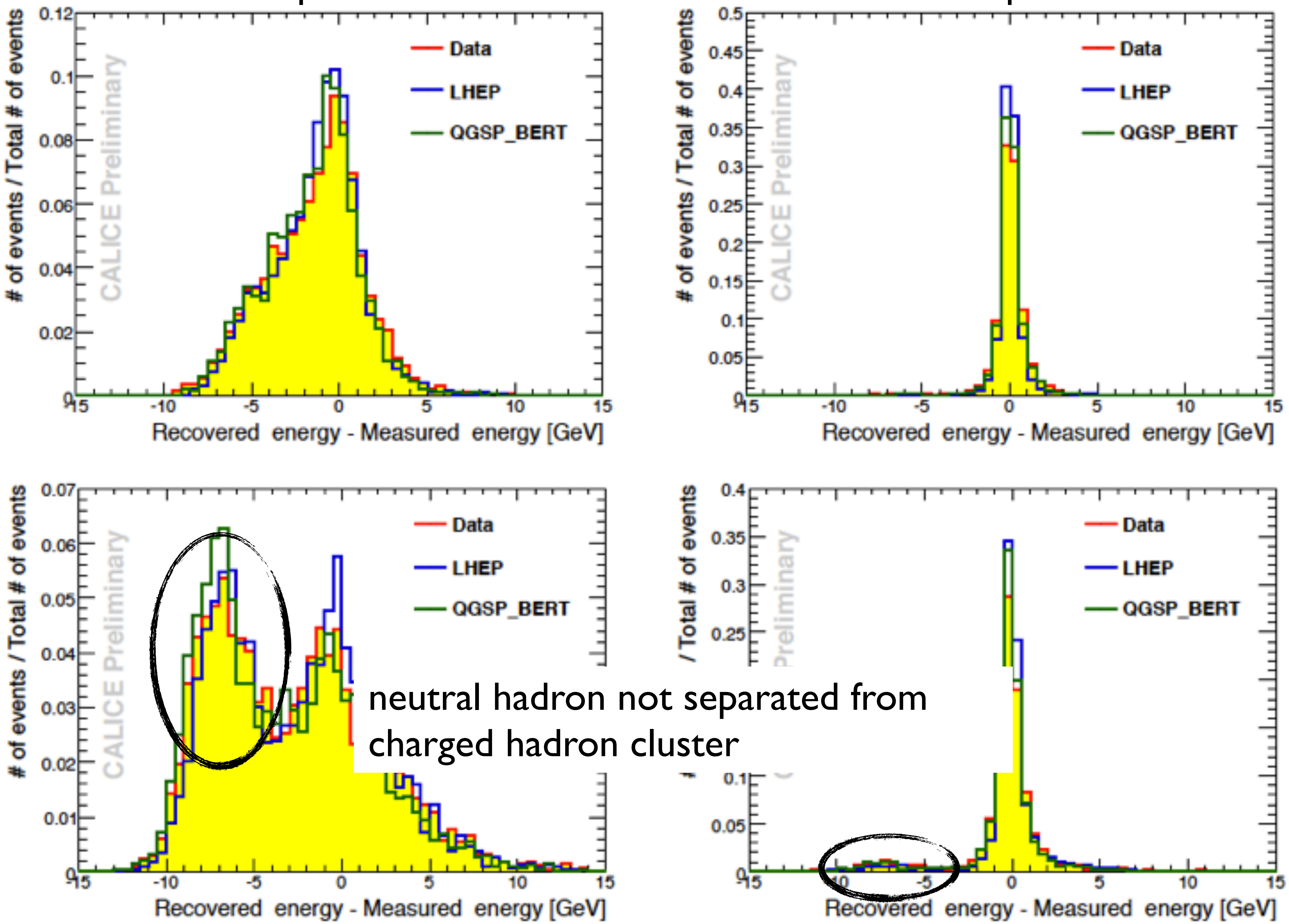
10 GeV charged hadron

30 GeV charged hadron

Shower Separation: Energy & Distance

5 cm separation

30 cm separation



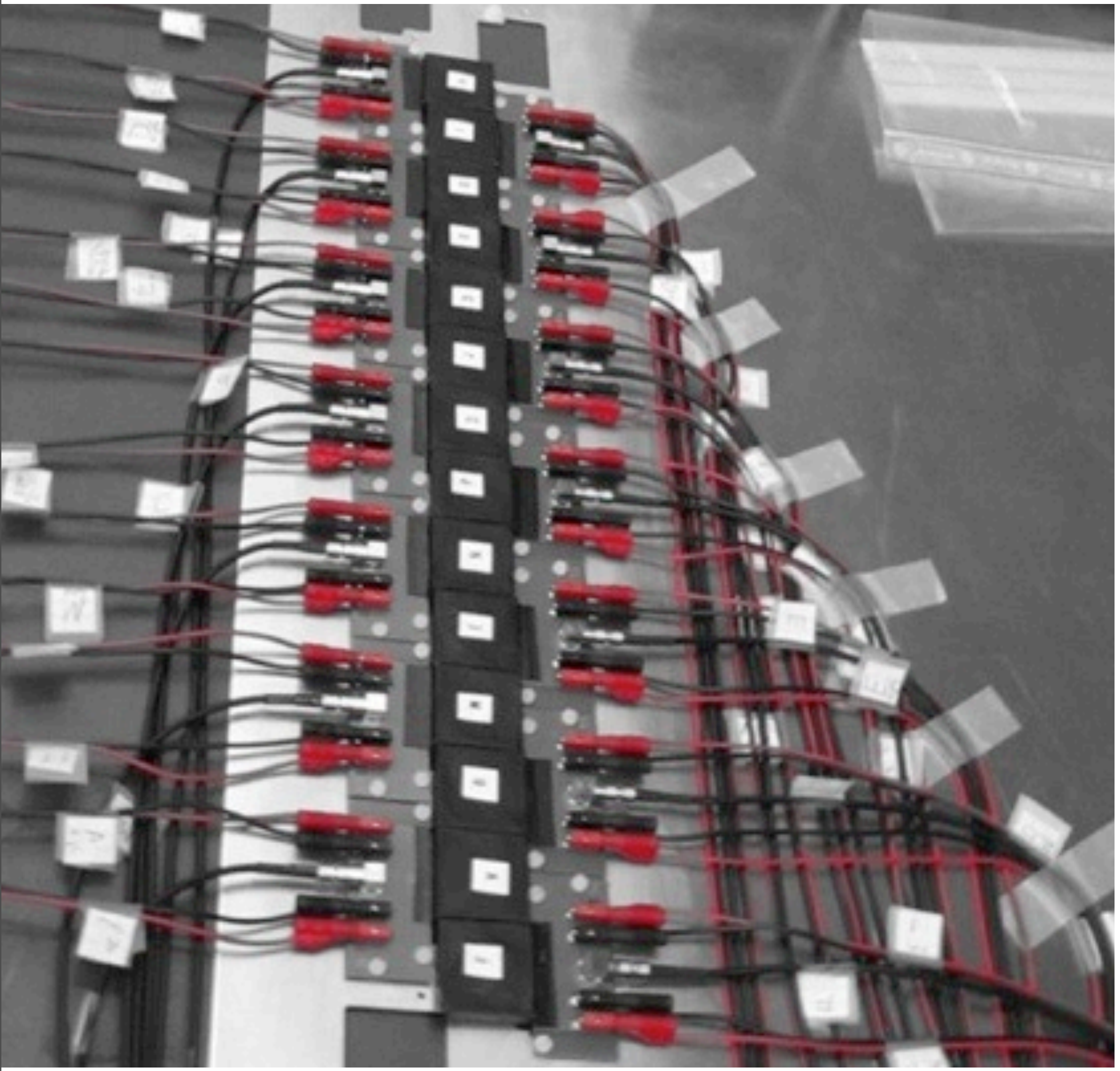
- 10 GeV neutral hadron

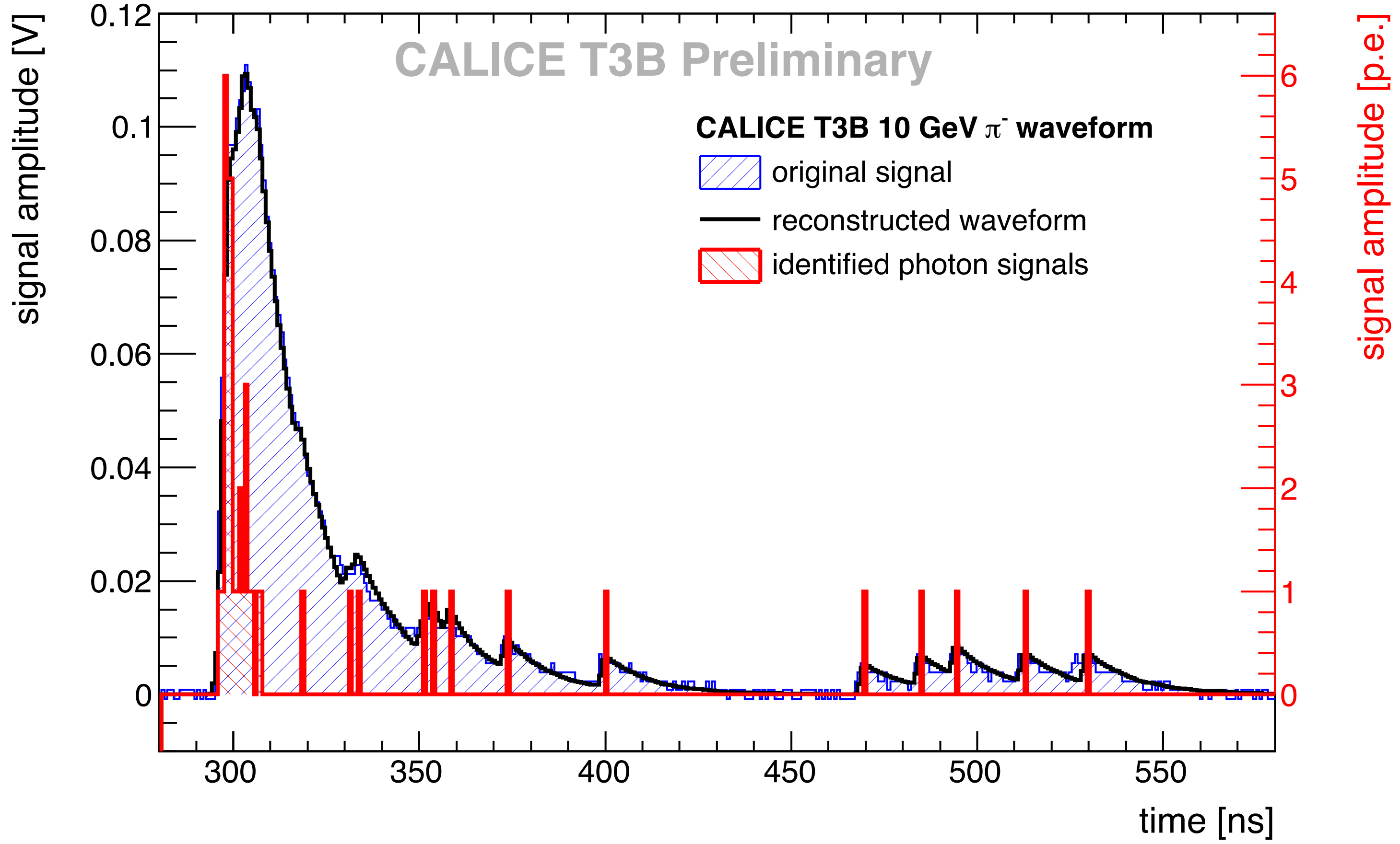
10 GeV charged hadron

30 GeV charged hadron

The T3B Setup

- Runs currently together with the Tungsten analog HCAL, at a depth of 4 λ
  - 15 scintillator cells (direct coupling), read out with fast digitizers over 2.4 μs with 800 ps sampling
  - Identify the time of arrival of each photon on the SiPM - Measure time structure of response by averaging over many events

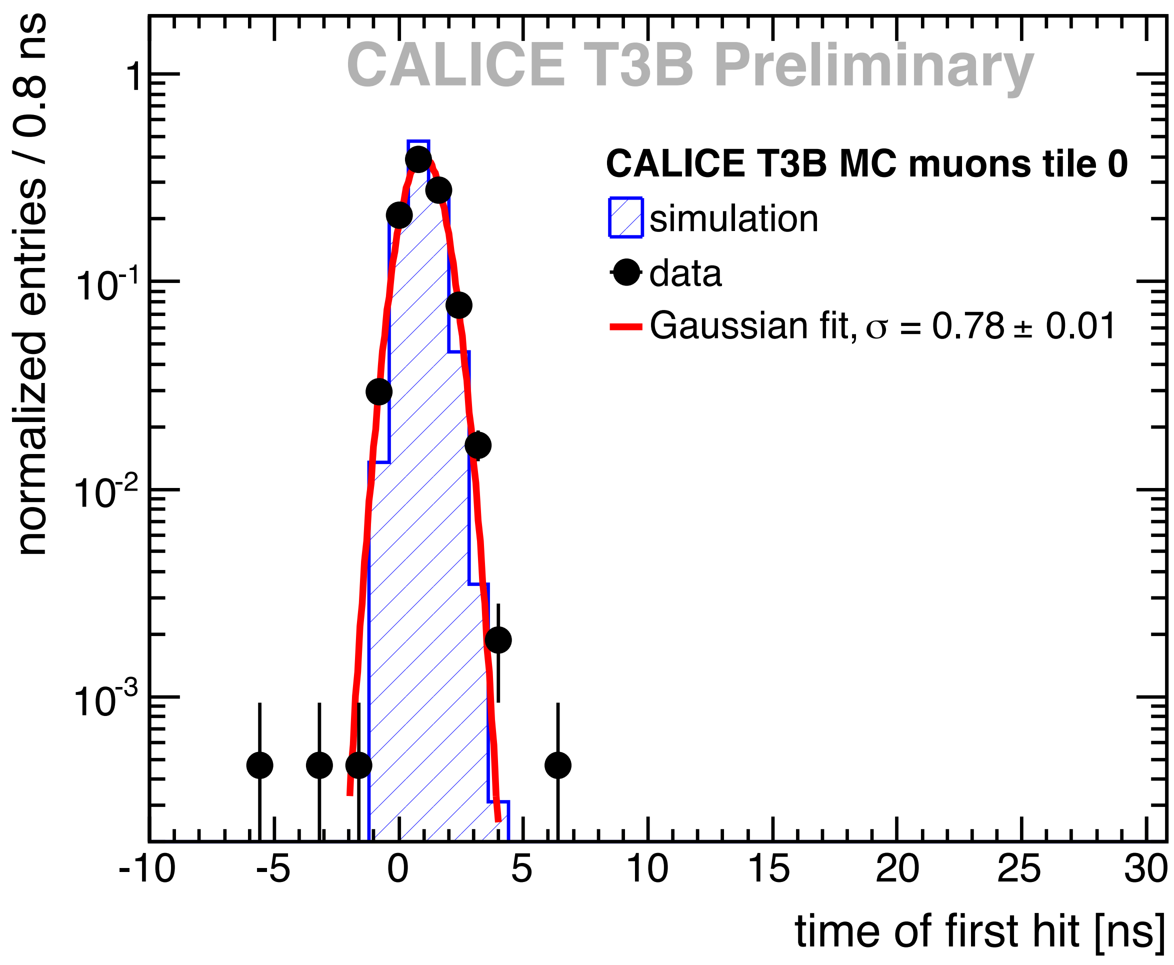




Signal on one tile, decomposed into individual single photon signals

First T3B Results

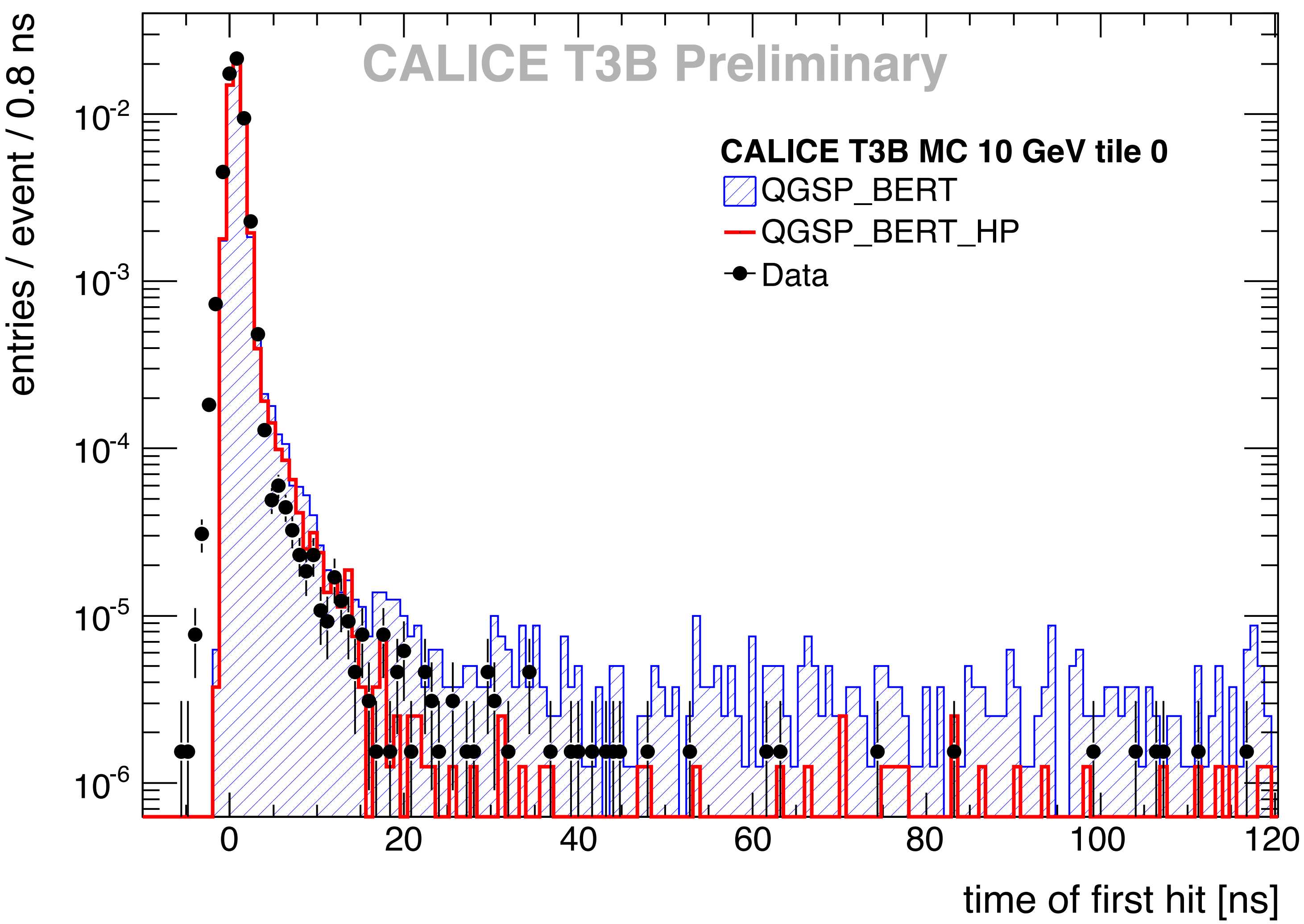
- Time resolution for muons, including CALICE trigger jitter: 800 ps

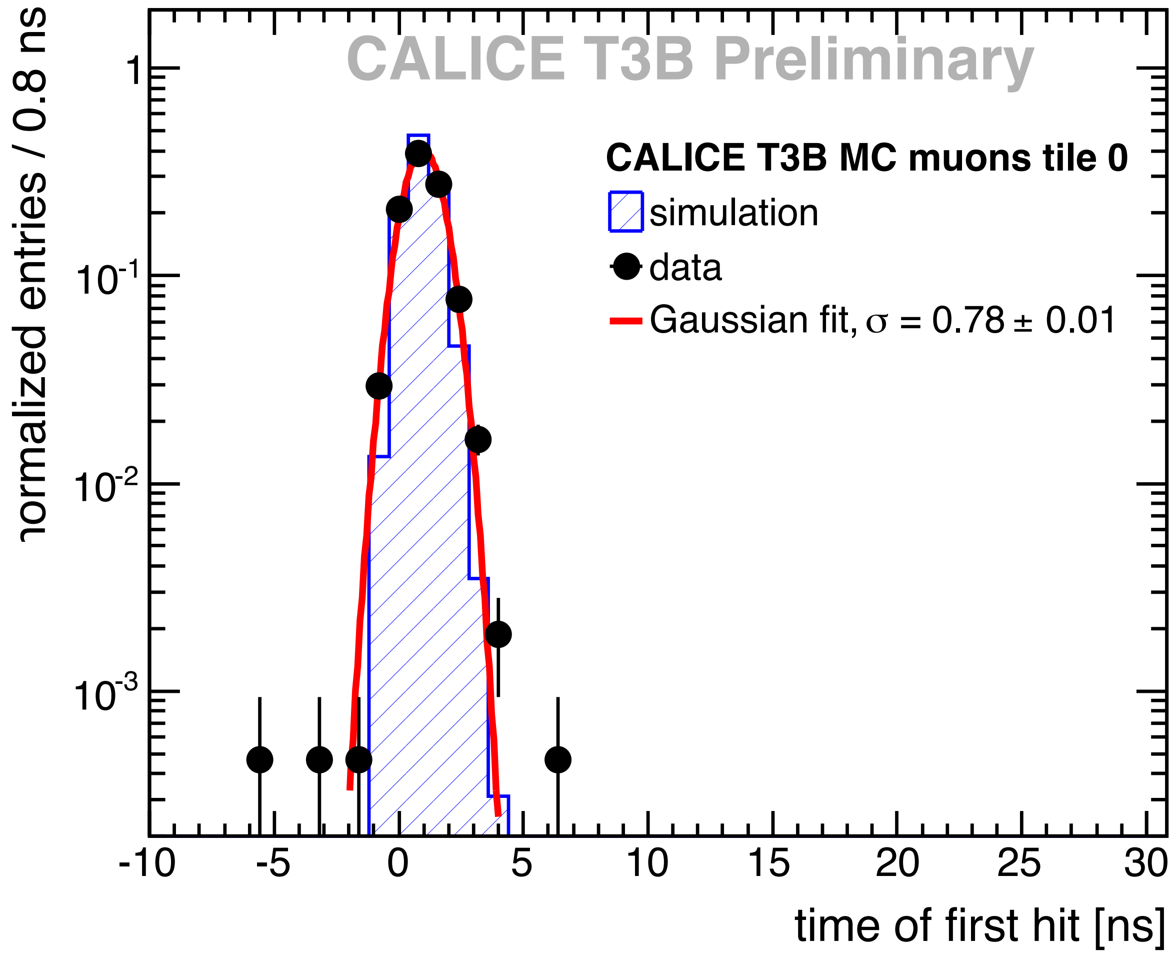


First T3B Results

- Time resolution for muons, including CALICE trigger jitter: 800 ps
- First study of the time structure: Measurement of the time of first hit

scintillator tile on beam axis, behind 4 λ W





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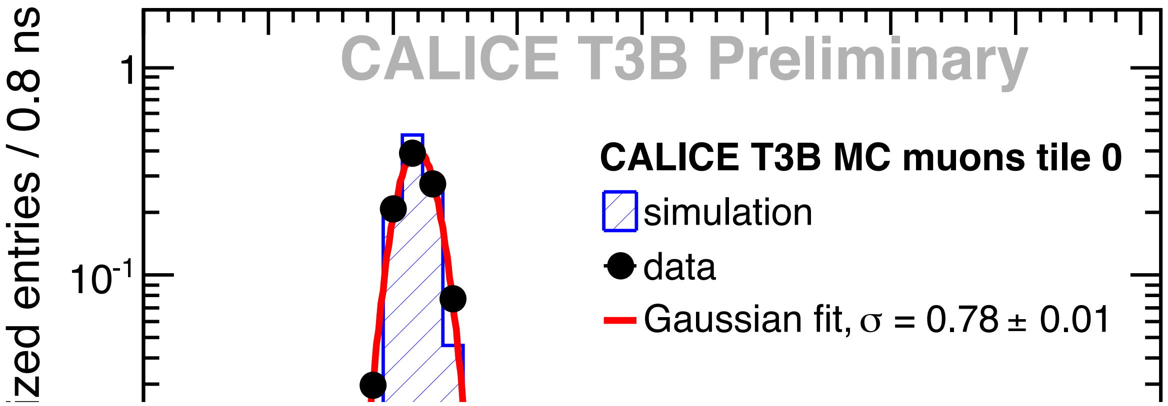
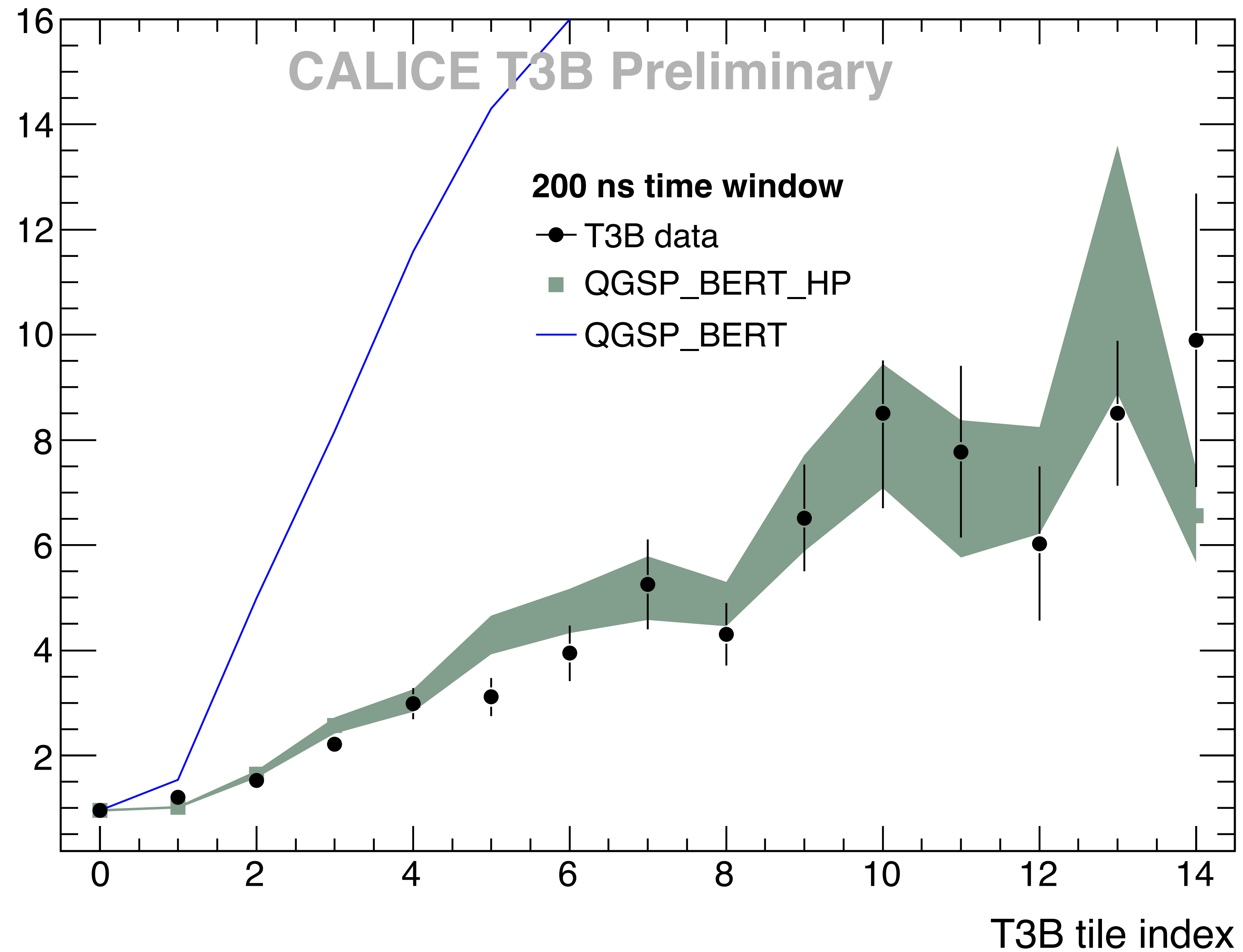


Compact Comparison:

Mean Time of First Hit

- calculated in a time window of 200 ns (-10 ns to 190 ns from maximum in tile 0)
- Clear preference for shower model with high precision neutron tracking



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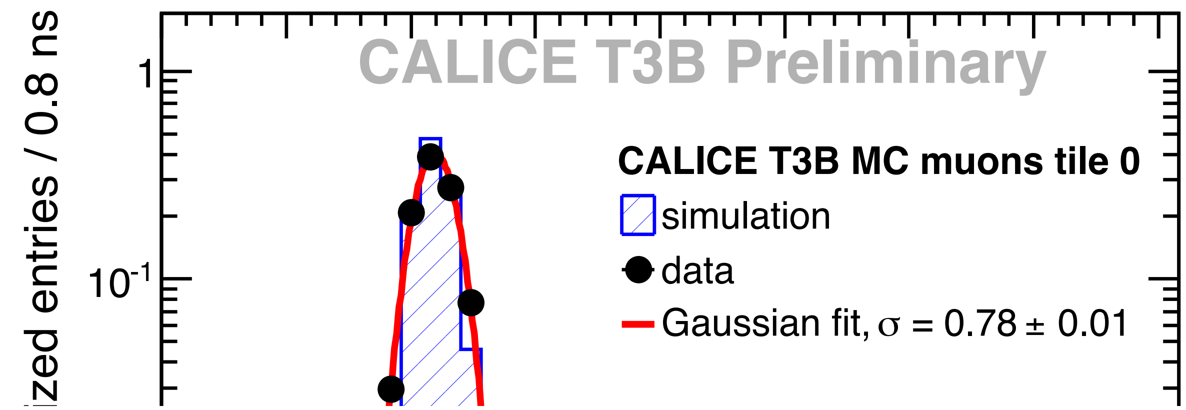

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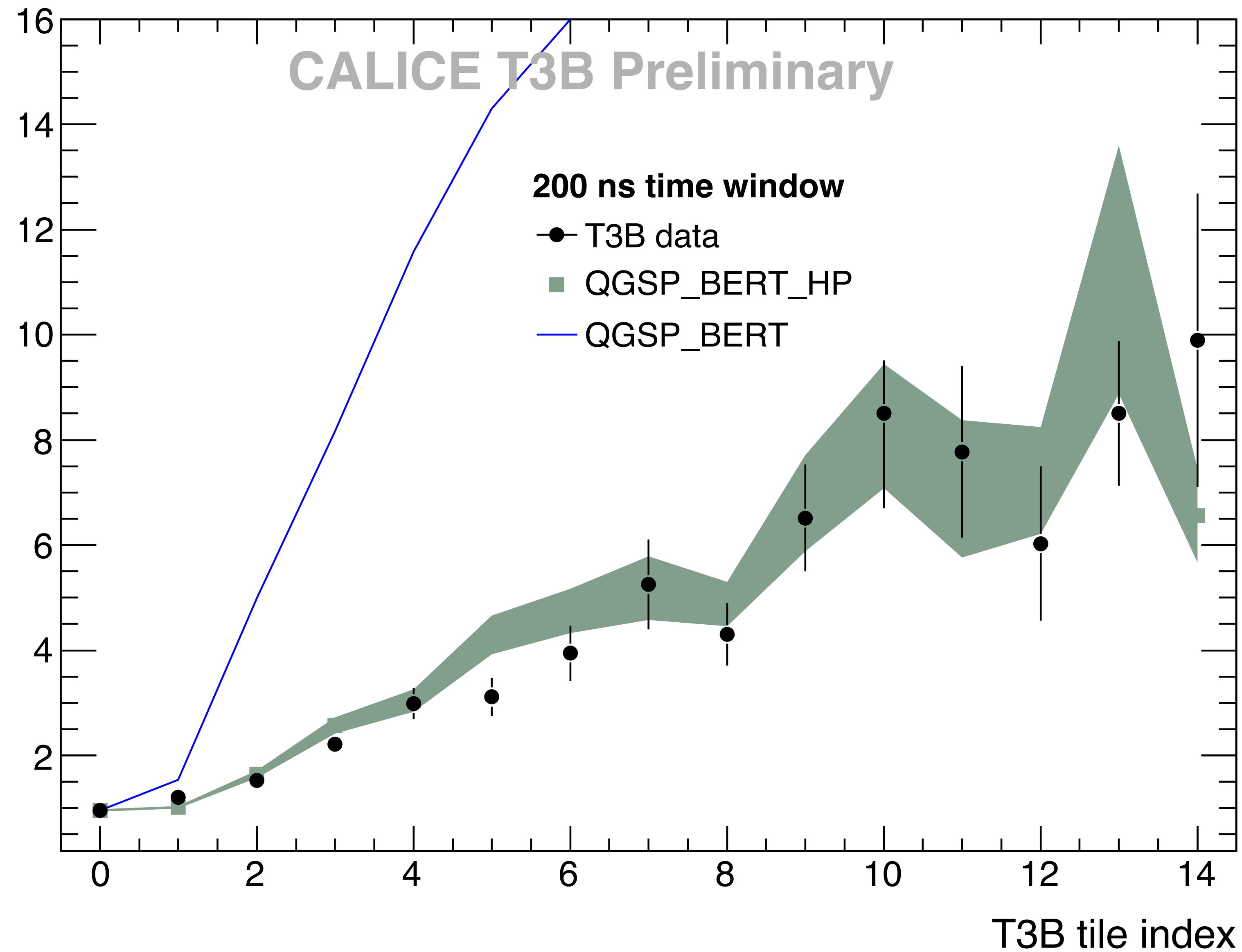

Now: Preparing for measurements at higher energy and with steel absorbers