CALICE

Overview of CALICE Calorimeter Studies

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MAX-PLANCK-INSTITUT
FÜR PHYSIK

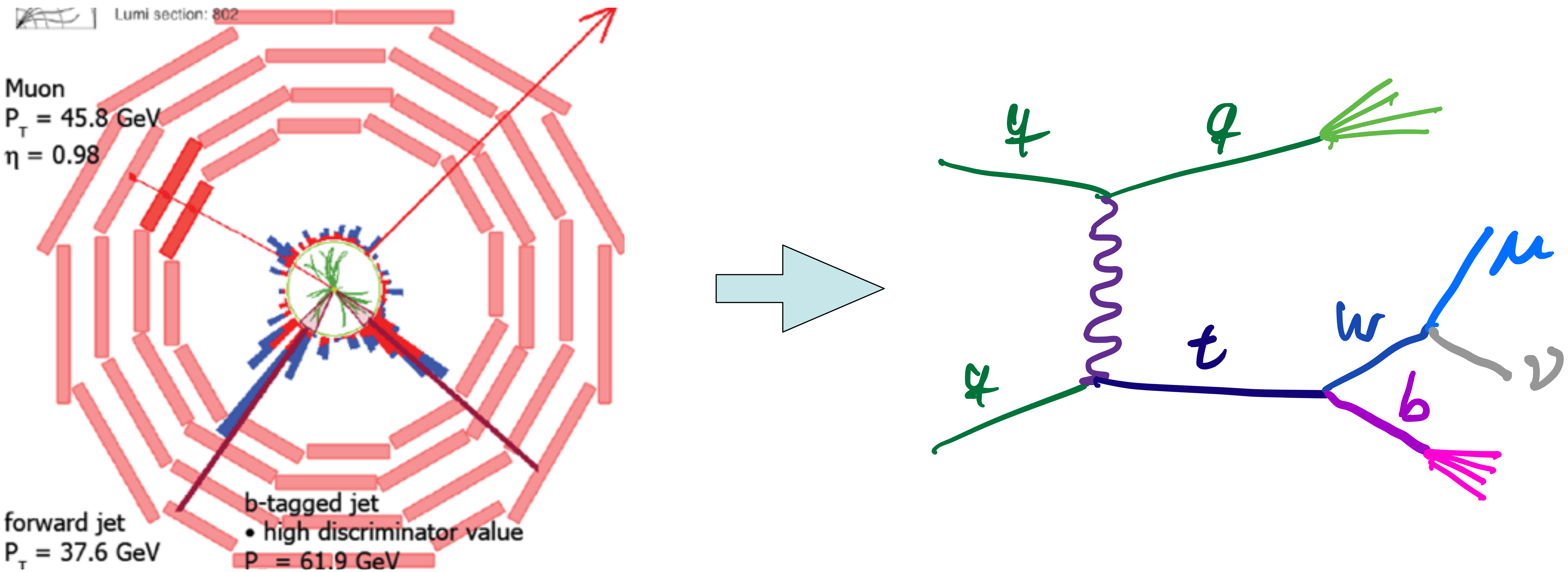
Outline

- Motivation for Granularity
- CALICE Technology
- Selected Results
- Ideas and Plans for the Future

Event Reconstruction at Future Colliders

Dreams…

- For *hadronic* (and all other) final states, we want to solve this problem:



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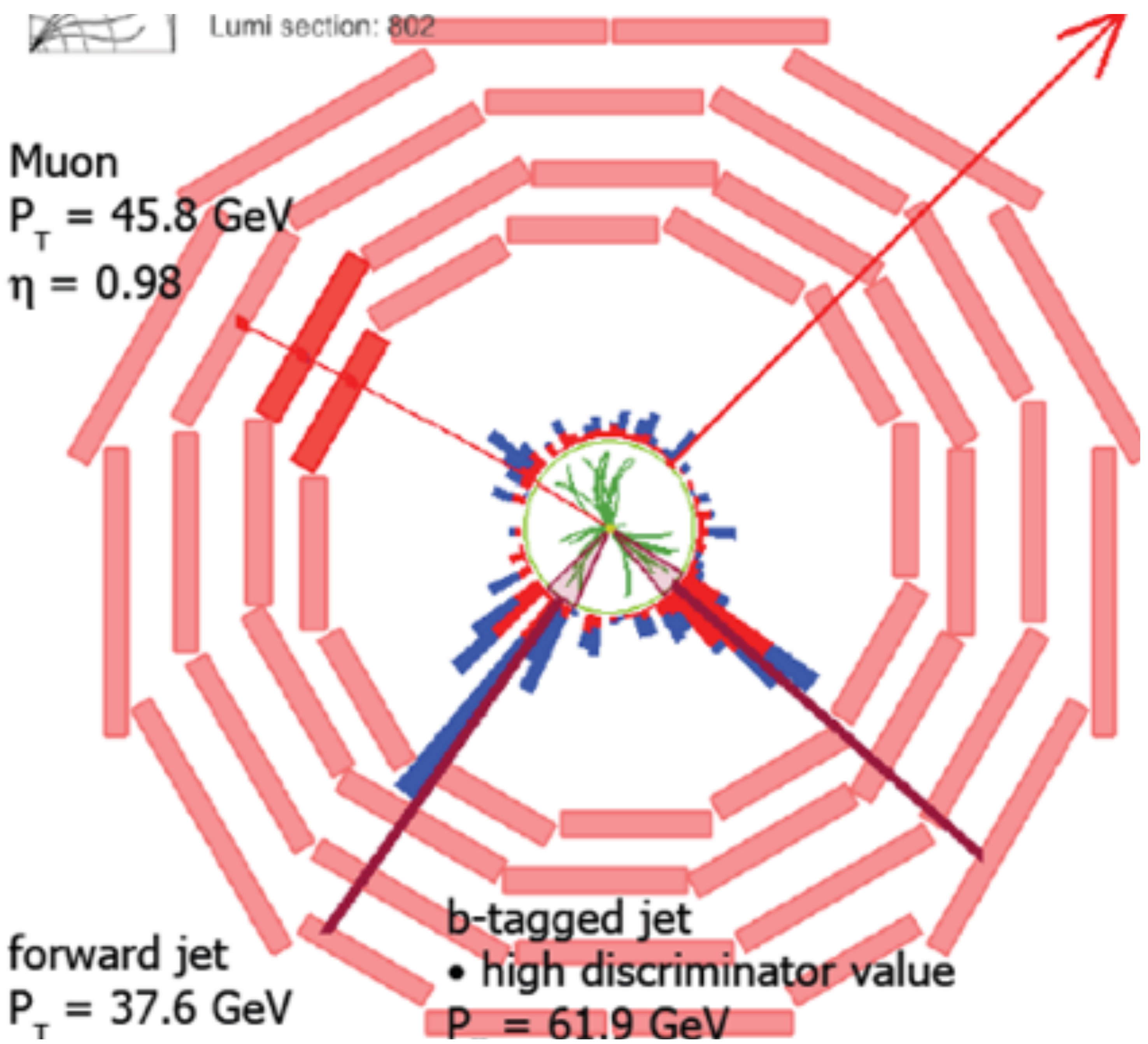
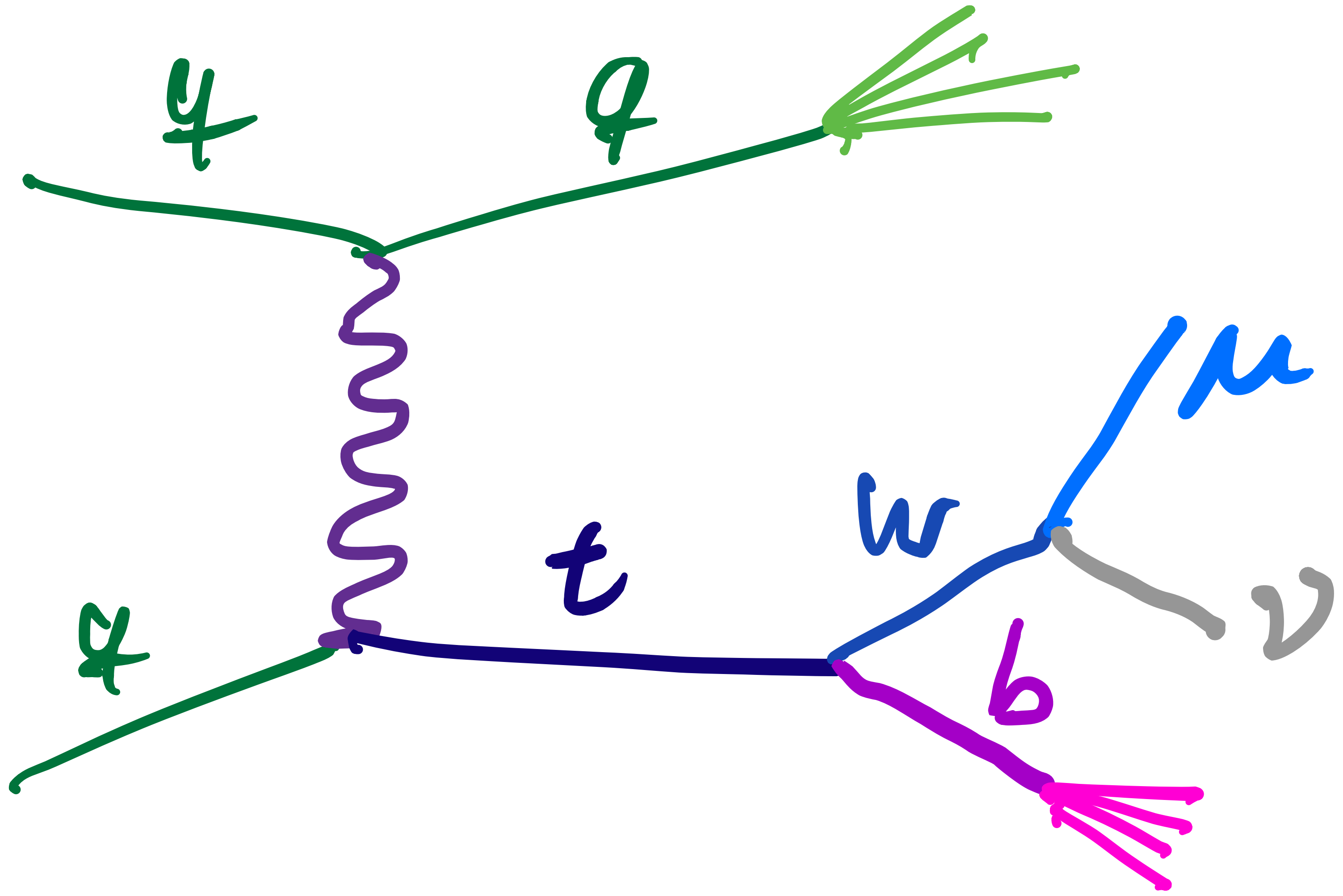


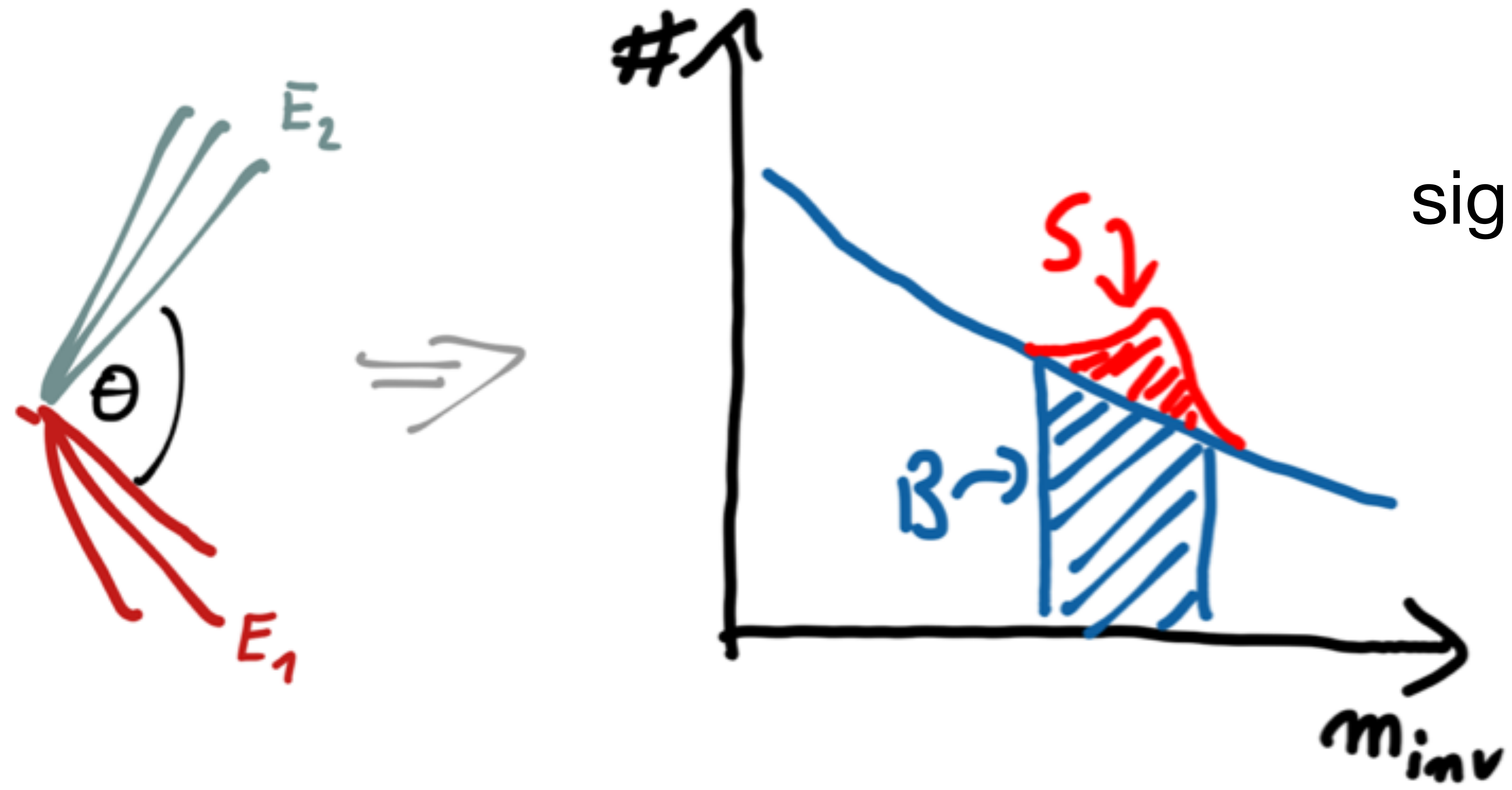


Ideally: reconstruct every single particle in the event - not just leptons + “cones of energy”

Event Reconstruction at Future Colliders

… Goals …

- More practically:



significance: $\frac{S}{\sqrt{S+B}}$

directly depends on mass resolution

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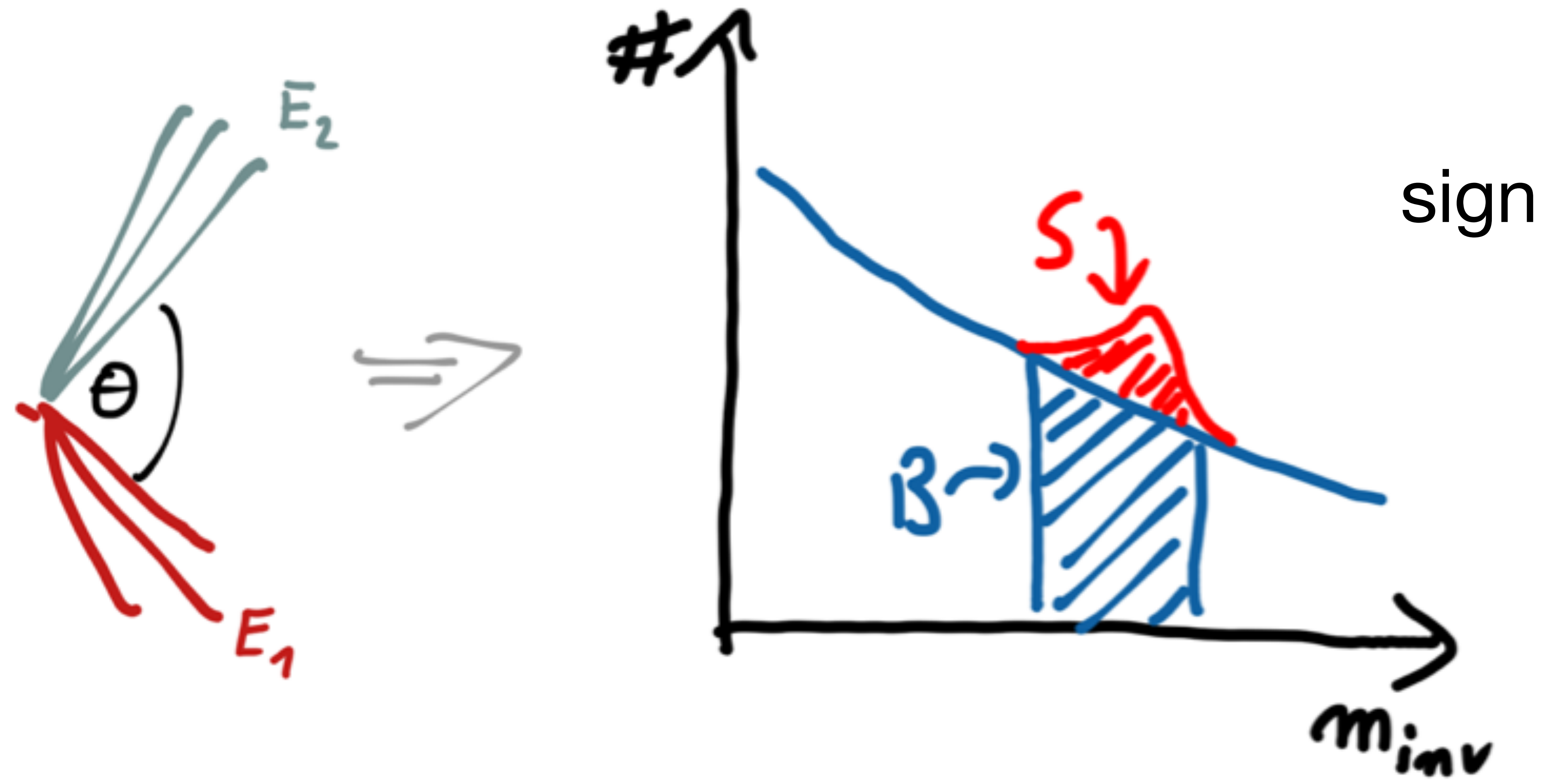

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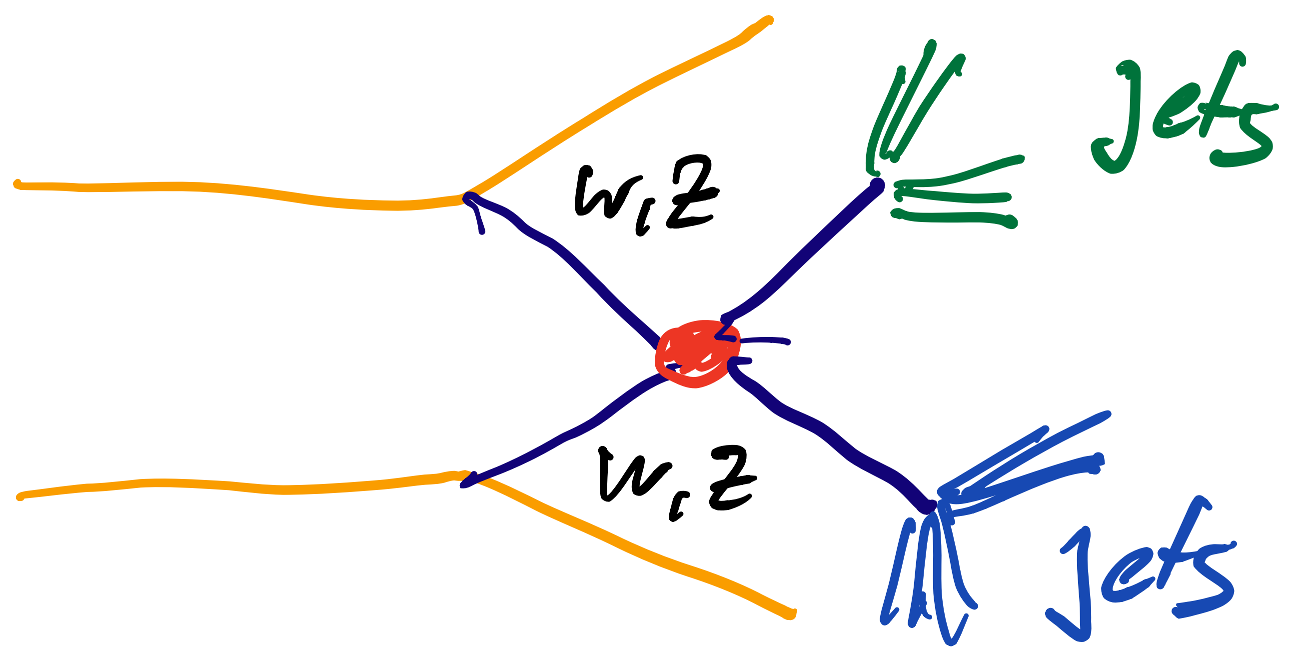
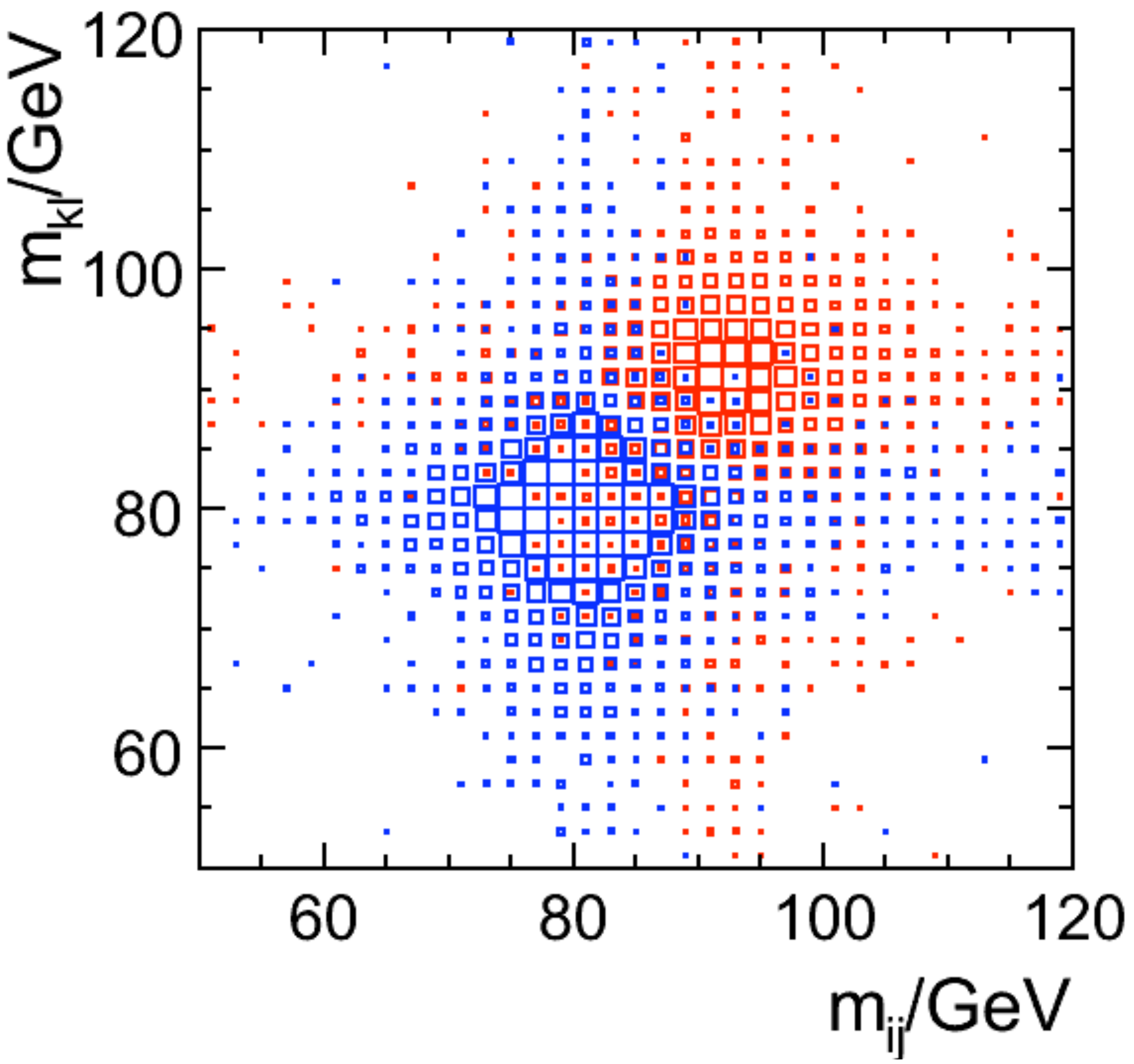
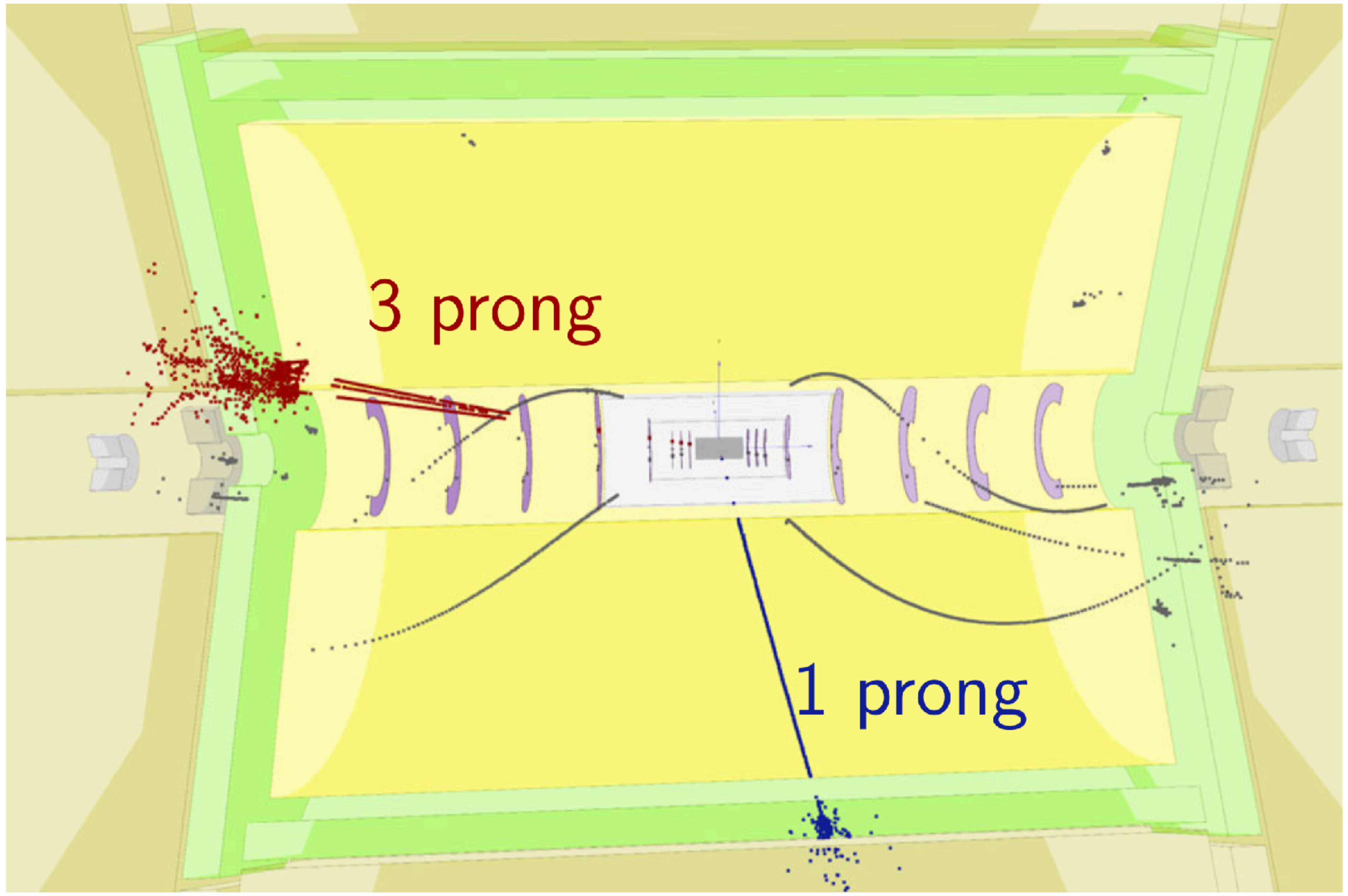
The typical "PR" example:

Separation of hadronic final states of heavy bosons: Requires jet energy resolution of ~ 3.5% over a wide energy range



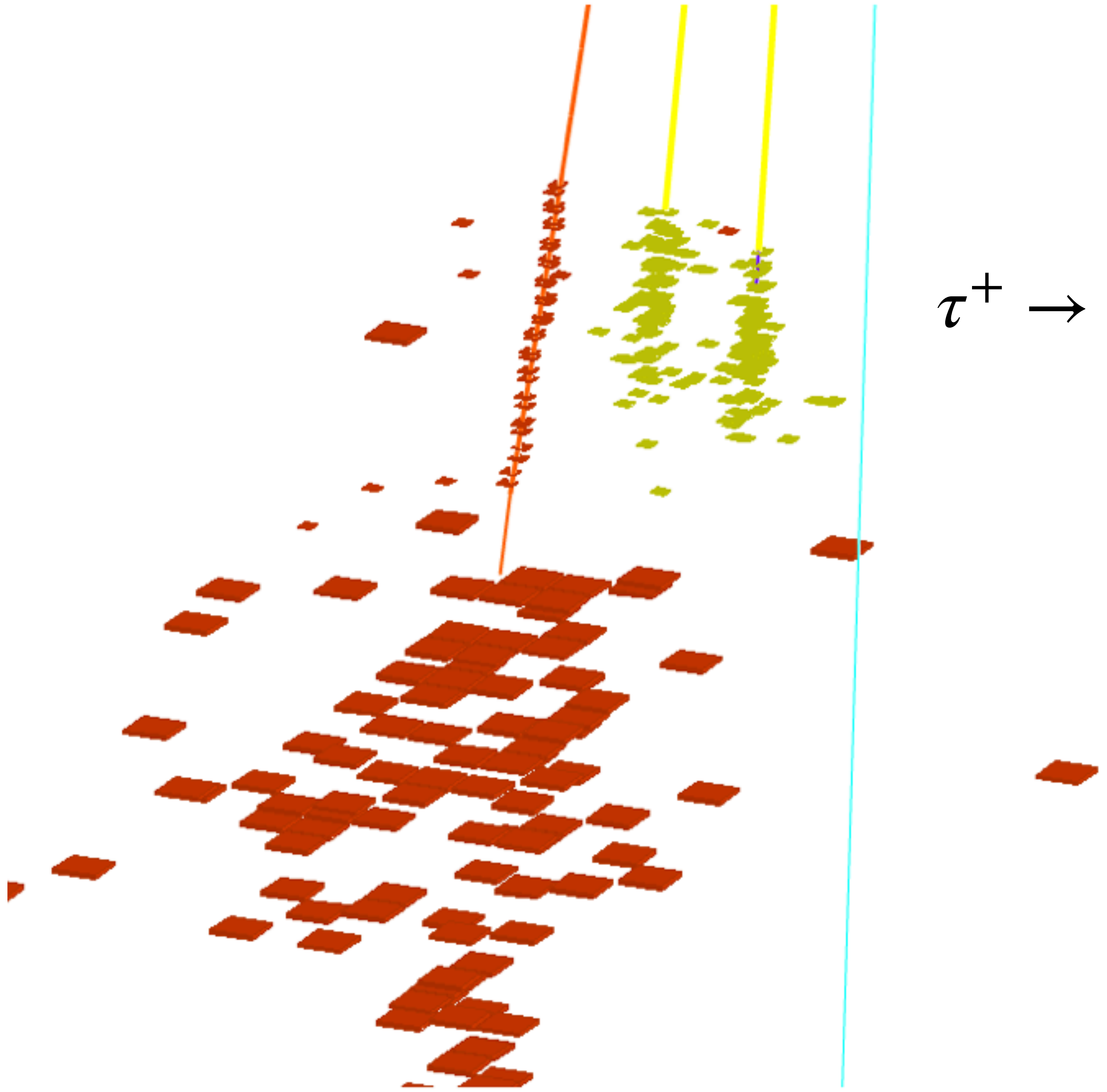


- But also: Identification of particles
  A classic example: Tau reconstruction



$e^+e^- \rightarrow H\nu\bar{\nu} \rightarrow \tau^+\tau^-\nu\bar{\nu}$

@ 1.4 TeV at CLIC

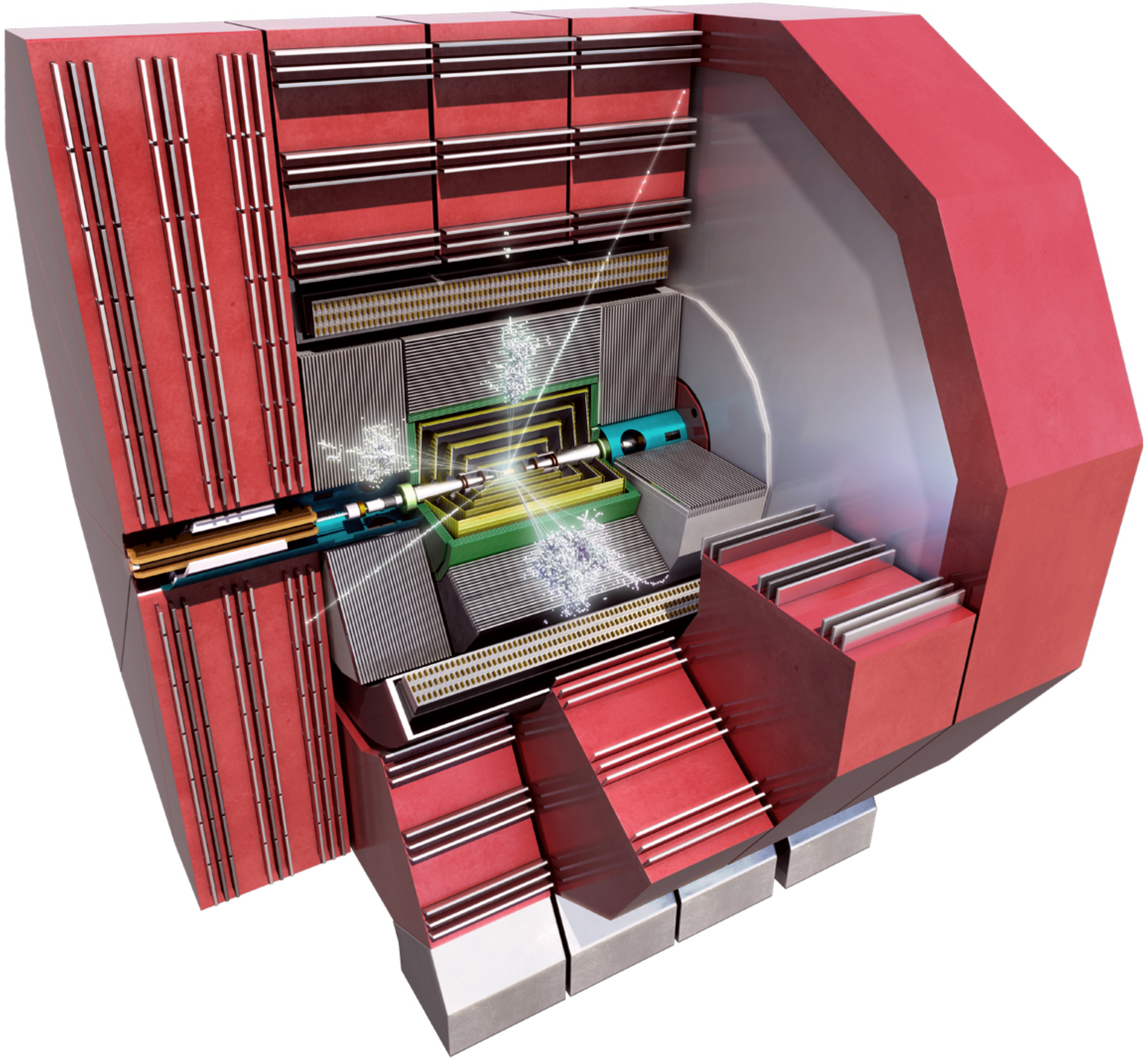


$\tau^+ \rightarrow 2\gamma(\pi^0) + \pi^+ + \bar{\nu}_\tau$

- Results in close-by / overlapping electromagnetic and hadronic showers

Event Reconstruction at Future Colliders

… Tools …



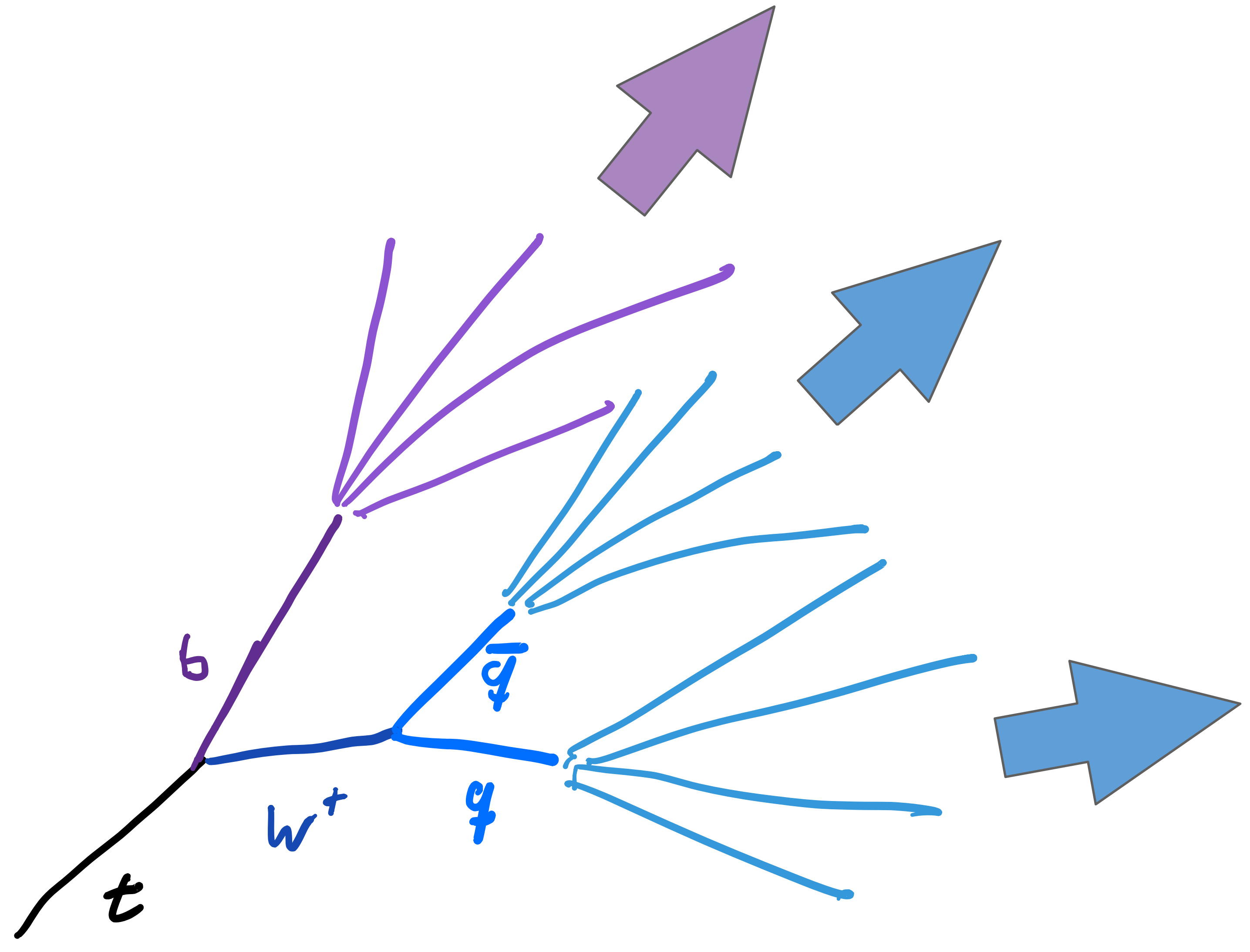
- The hardware to work with: A *Collider Detector*
  - ***Vertex detectors*** to identify heavy quarks and leptons
  - ***Tracking system*** to measure the momentum of charged particles via curvature in magnetic field
  - ***Calorimeter systems*** to measure energy of neutral and charged particles via total absorption
  - ***Muon system*** to identify muons, improve momentum measurement

Event Reconstruction at Future Colliders

… and Algorithms

- Particles decaying into quarks lead to jets: Multiple hadrons originating from final-state quarks

➪ Parton four-vector only accessible via reconstruction of final hadrons



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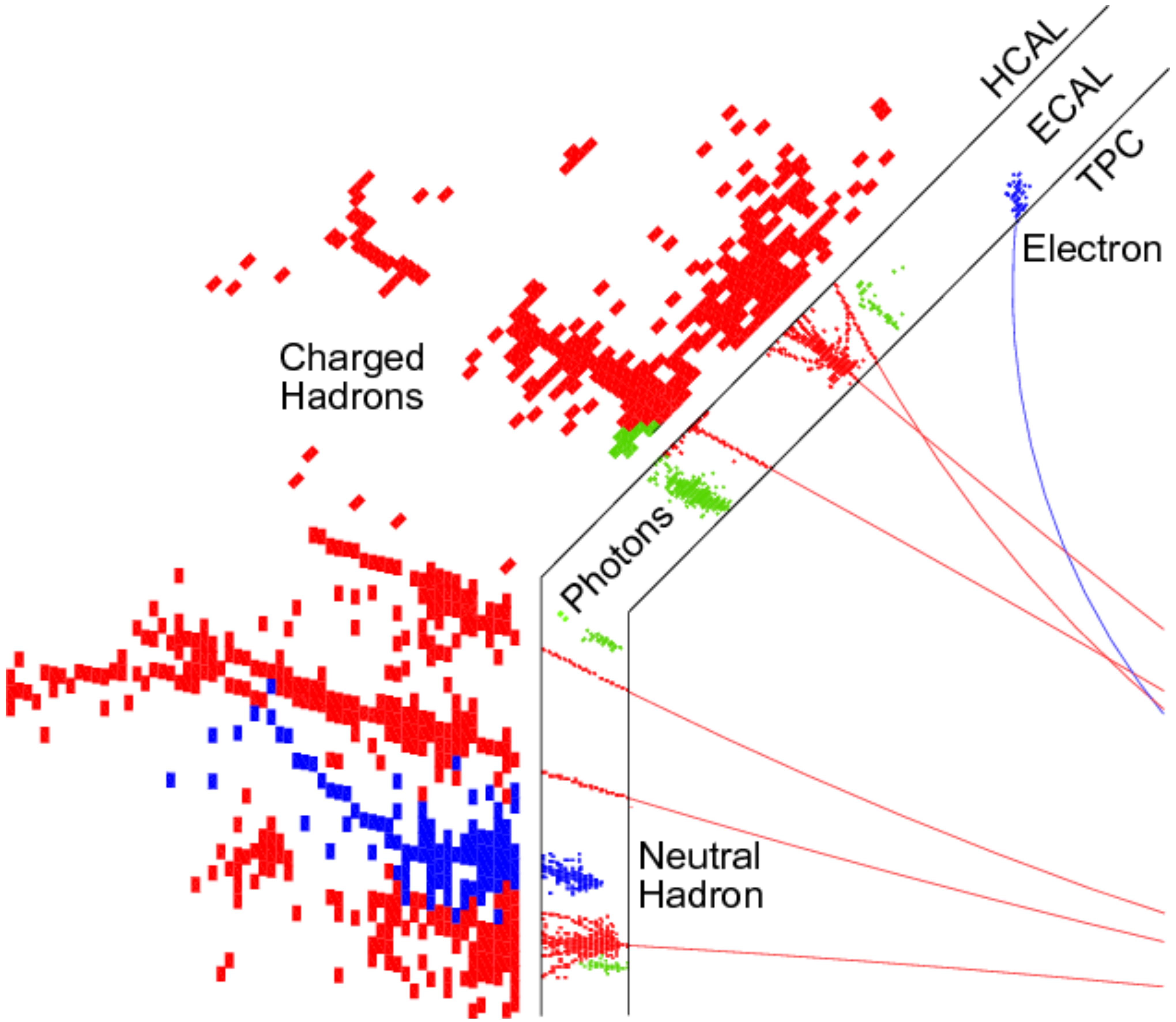

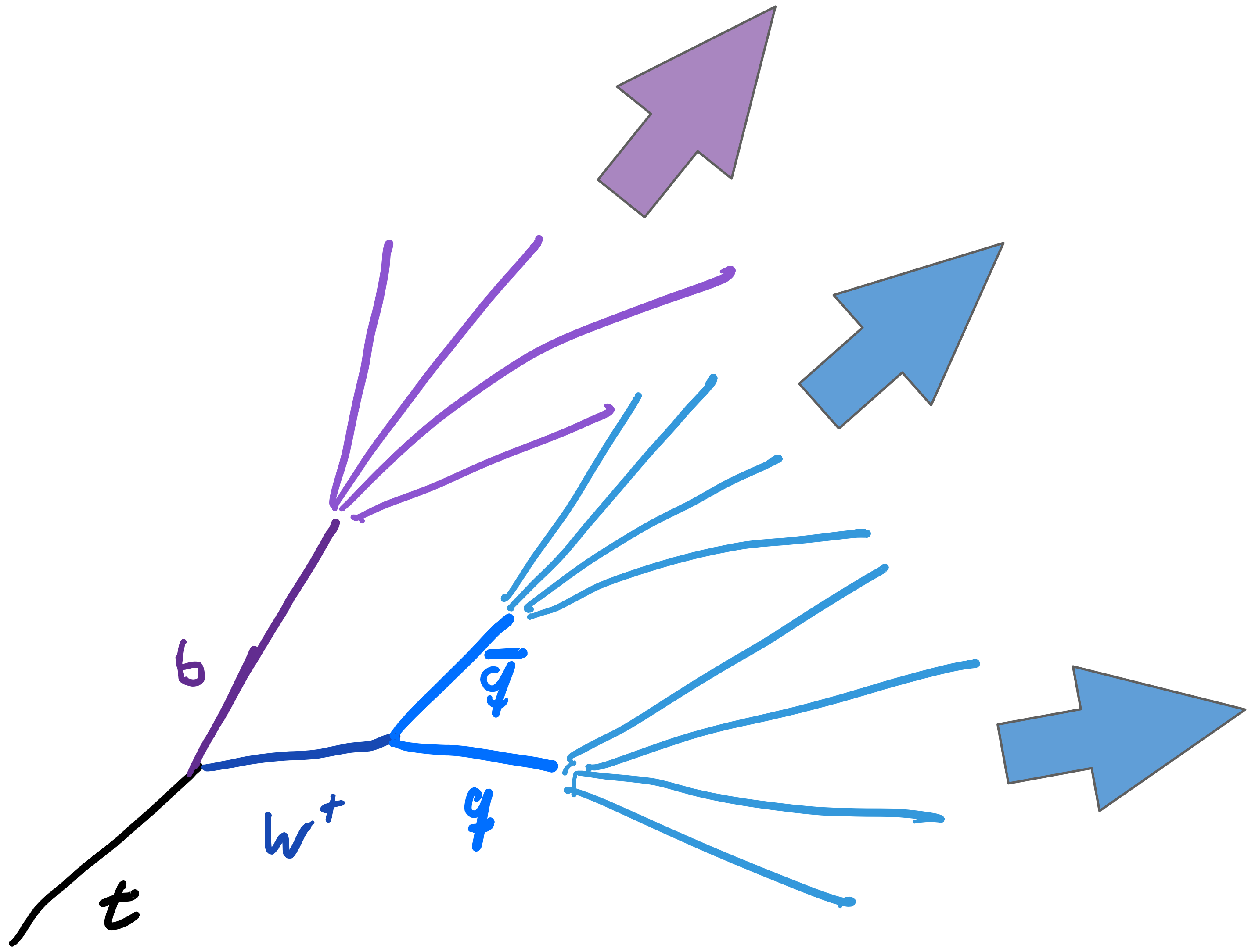

- Requires measuring the energies of different particle types
  - Charged hadrons ($\pi^{+/-}$, …)
  - Electromagnetic particles (γ, $e^{+/-}$)
  - Neutral hadrons (K_L, n, …)

➯ Best performance when optimally combining the information of all subsystems of the experiment: calorimetry & tracking => ***"Particle Flow"*** and ***"Imaging Calorimeters"***

Granularity Requirements

Physics drivers

- Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers in all 3 dimensions

➯ X_0 / ρ_M drive ECAL and HCAL (electromagnetic subshowers)

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Depends on material:
- in W: X_0 ~ 3 mm, ρ_M ~ 9 mm
- in Fe: X_0 ~ 20 mm, ρ_M ~ 30 mm

NB: Best separation for narrow showers particularly important in ECAL
➫ Use W in ECAL!

When adding active elements: ~ 0.5 cm^3 segmentation in ECAL, ~ 3 - 25 cm^3 in HCAL

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➫ *10s to 100s of millions of detector cells (or even more!) for full systems*

Motivations for Granularity

From a technological Perspective

Because we can.

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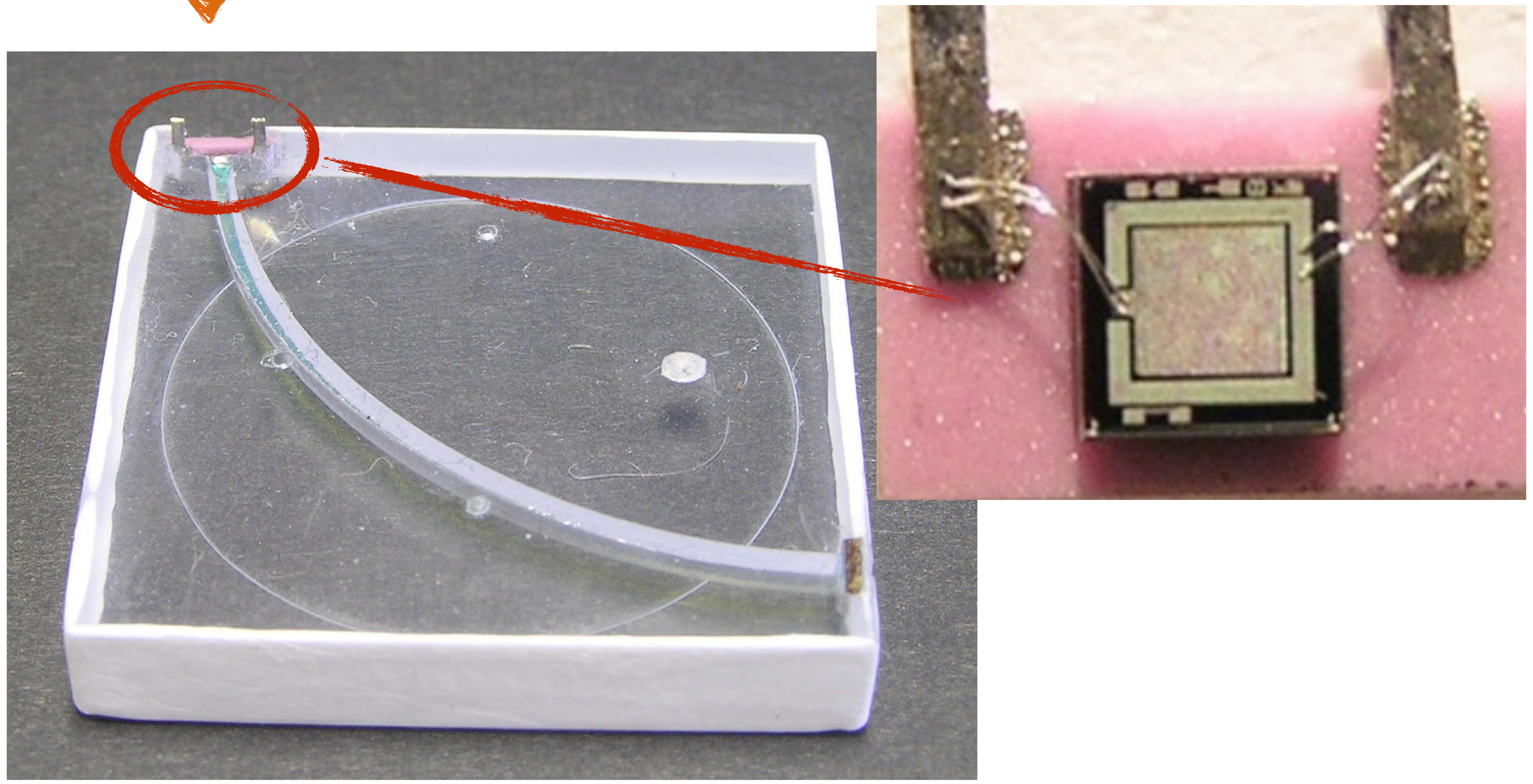

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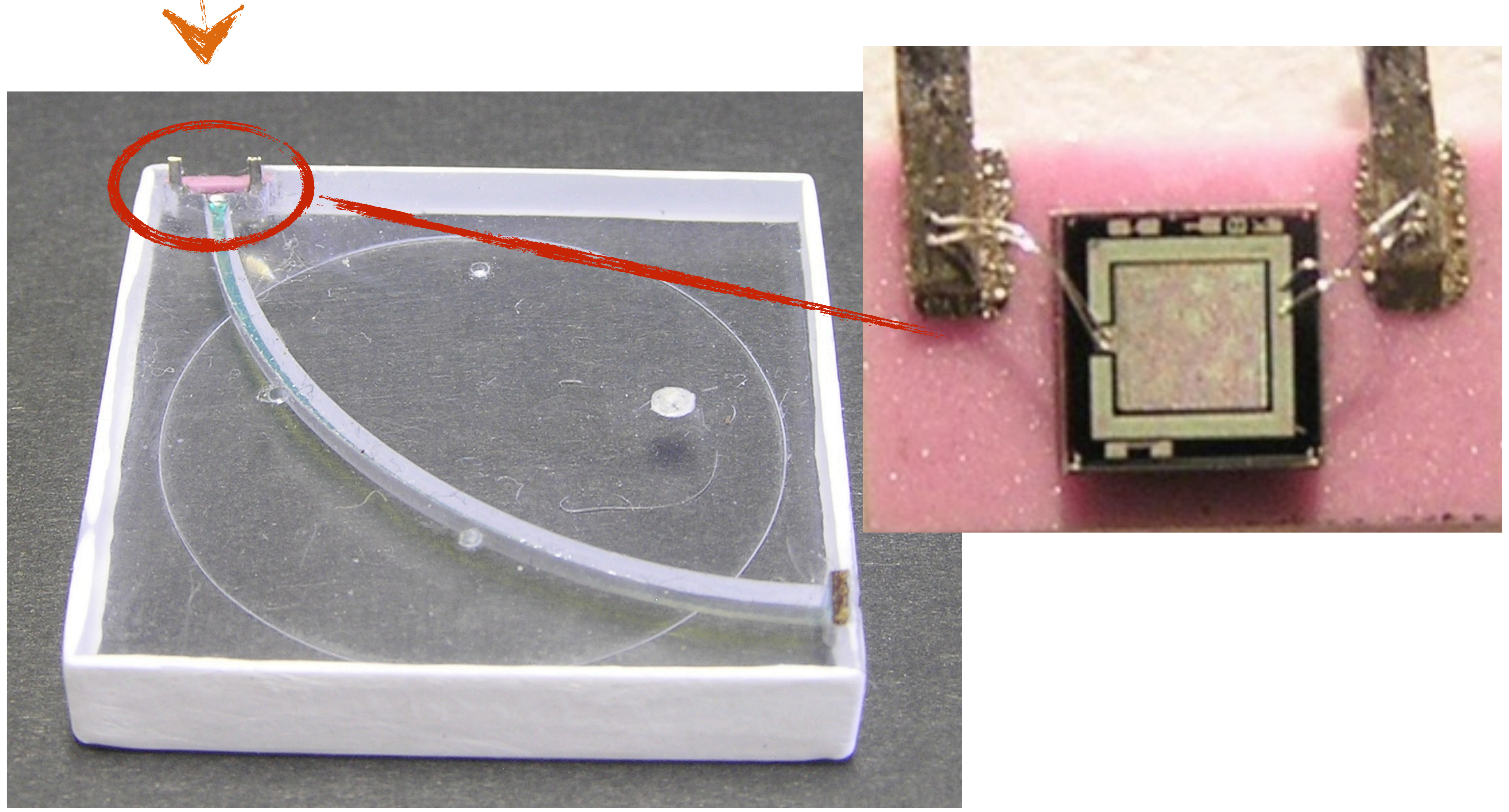

In addition: Advances in microelectronics, large area silicon systems for Si-based calorimetry

The CALICE Program

Phases of CALICE Development

- ***Validation*** of the concept of highly granular calorimetry:
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- ***Application*** of CALICE technology in running experiments:
  - Use of CALICE detector elements
  - Full detector systems based on CALICE technology

CALICE Technologies

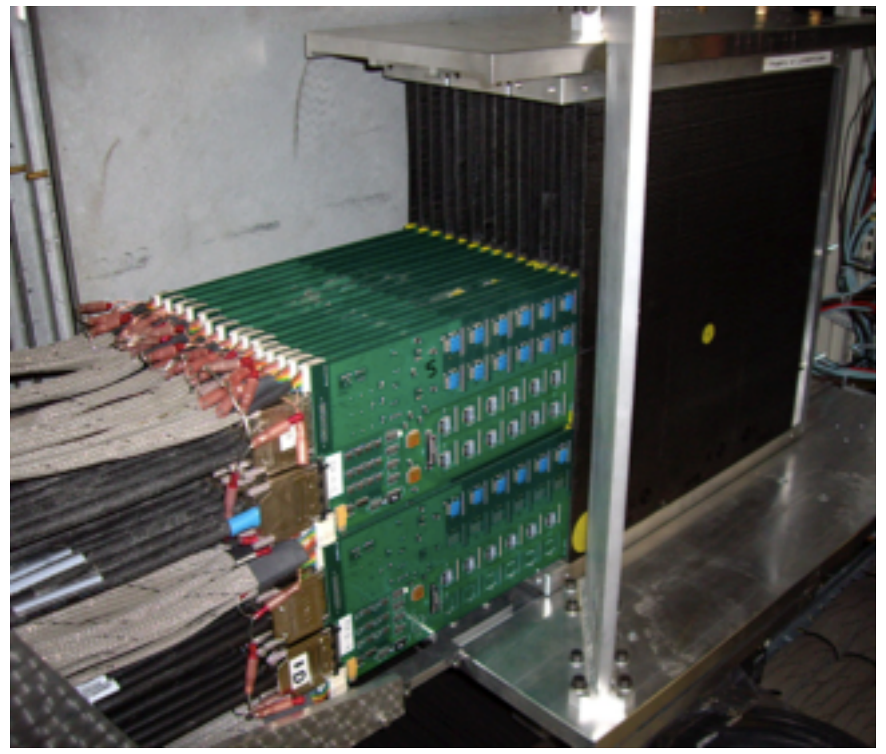
CALICE Technologies

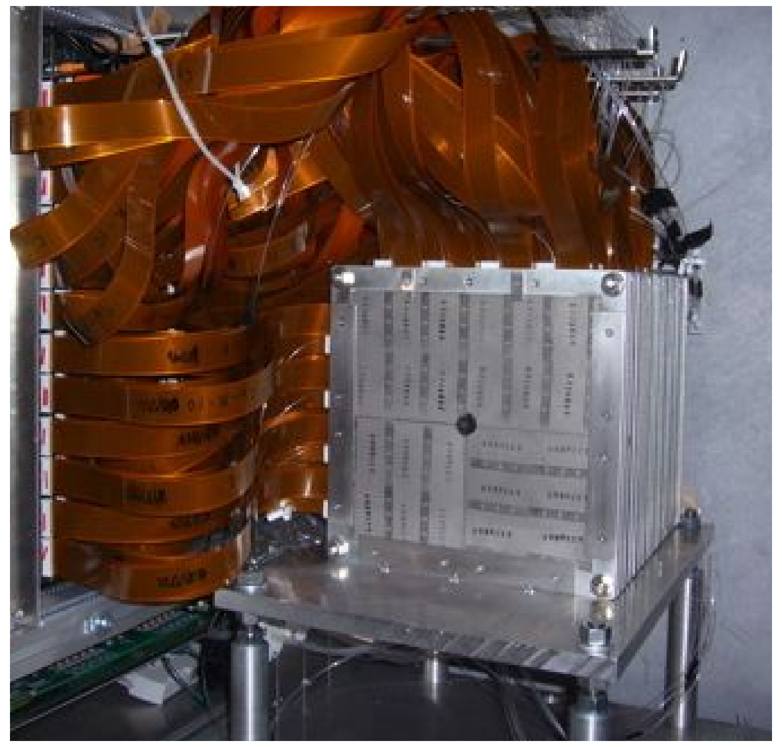
Validation

- A rich test beam program, with a variety of different prototypes

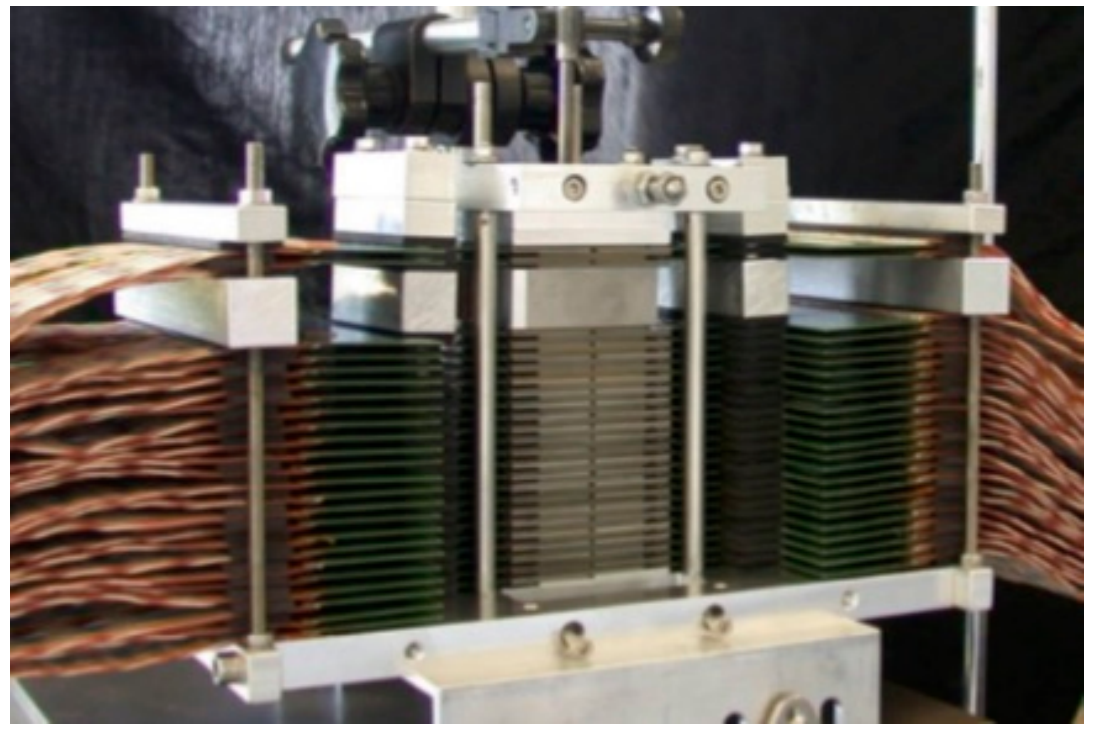
Electromagnetic - Tungsten absorbers

analog: Silicon and Scintillator/SiPM





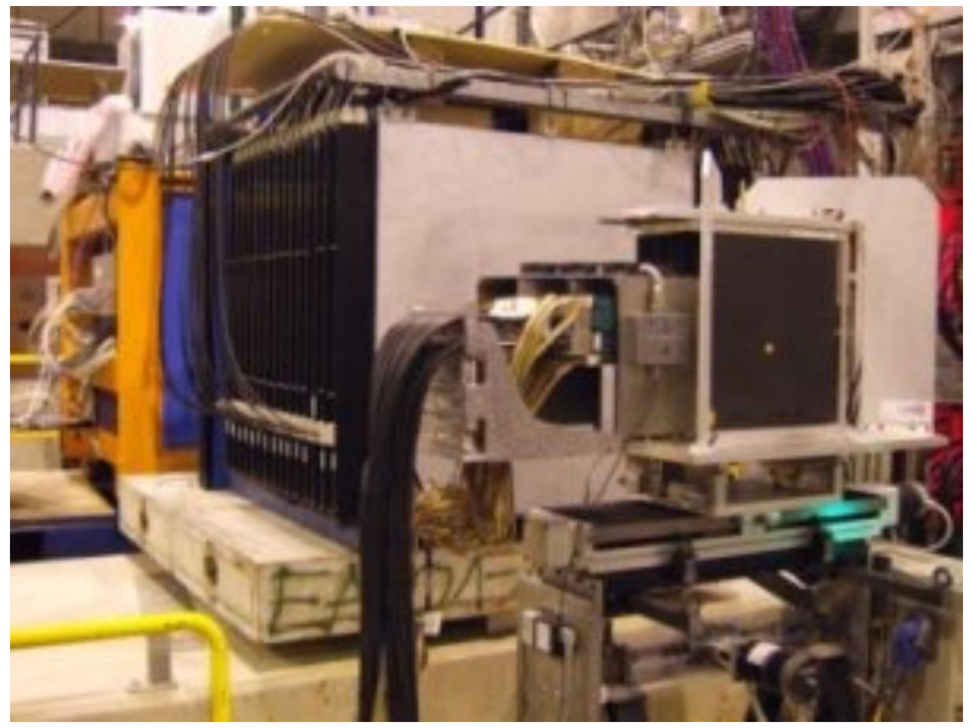
digital: Silicon (MAPS)



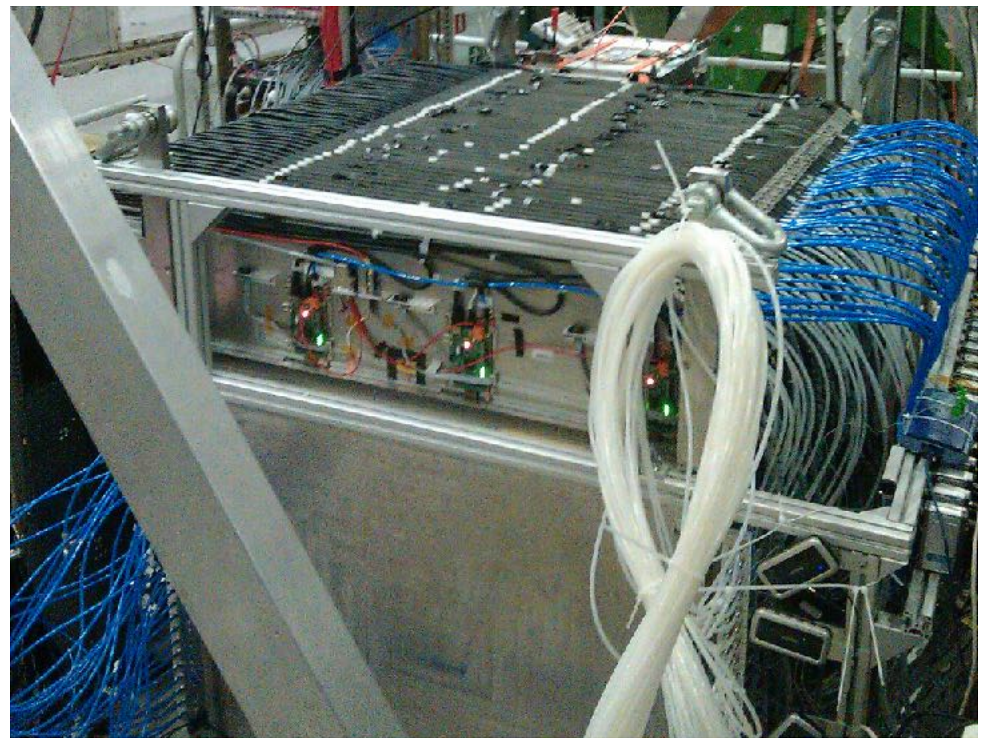
39 Mpixels in 160 cm^2

Hadronic - Steel and Tungsten absorbers

analog: Scintillator/SiPM (Fe and W)



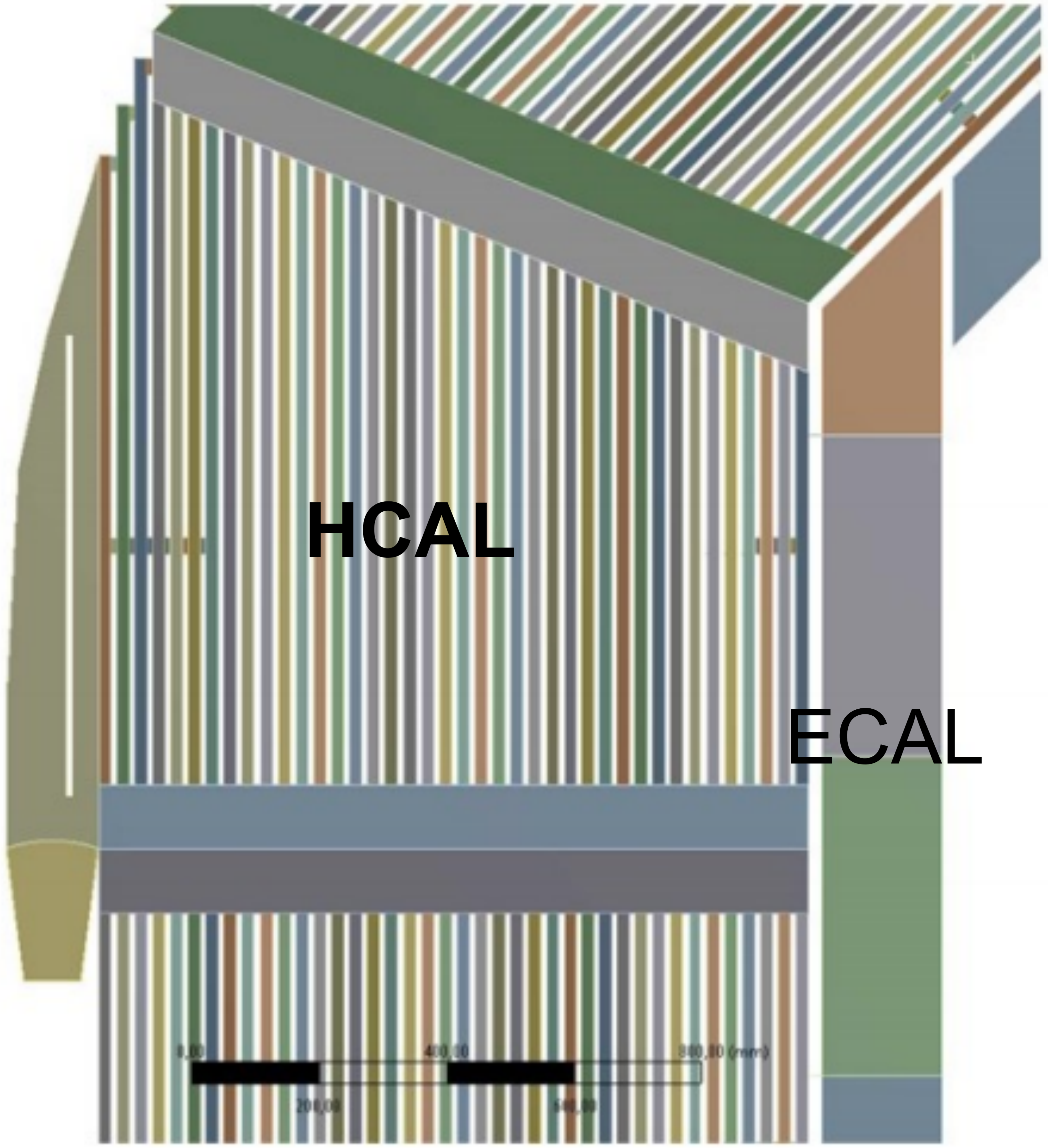
(Semi)digital: RPCs (Fe, W digital only)



+ few-layer SD prototype with Micromegas

Technical Realisation

Key Challenges of Highly Granular Calorimeters



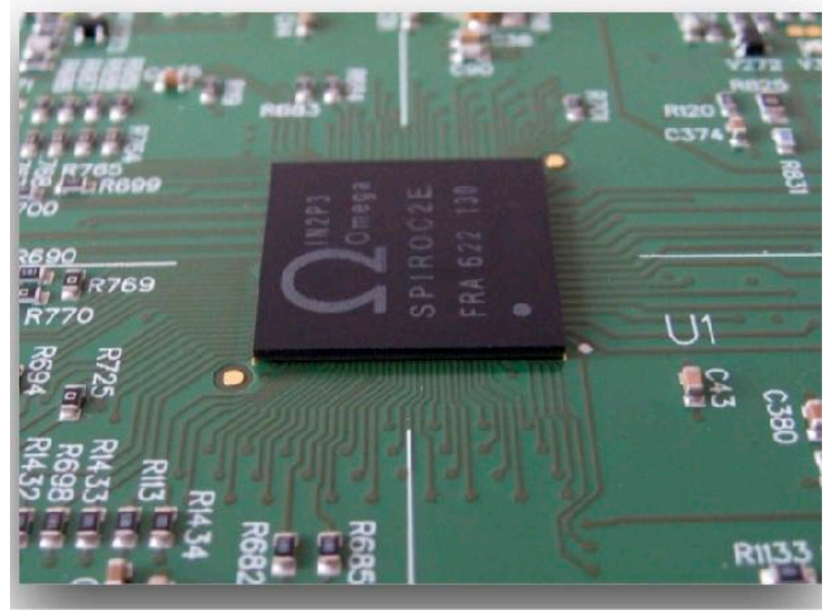
- To fully exploit the potential of highly granular calorimeter systems:
  - Extreme compactness, in particular in ECAL
  - Minimal “dead space” between ECAL and HCAL
  - No non-instrumented cracks
- For the full calorimeter systems, this imposes a number of requirements:
  - Both ECAL and HCAL inside solenoid: Further premium on compactness
  - Fully integrated electronics to support high granularity, minimal dead space outside of active area
  - Ultra low power to reduce or eliminate cooling needs, complex power distribution to support high currents during power pulsing w/o significant voltage drop
  - Very compact interfaces: data concentration, calibration, services
  - Precise mechanics: High number of sampling layers, minimal space
  - Suitability for industrialization and automatization in QA and assembly for all detector elements

Technical Realisation

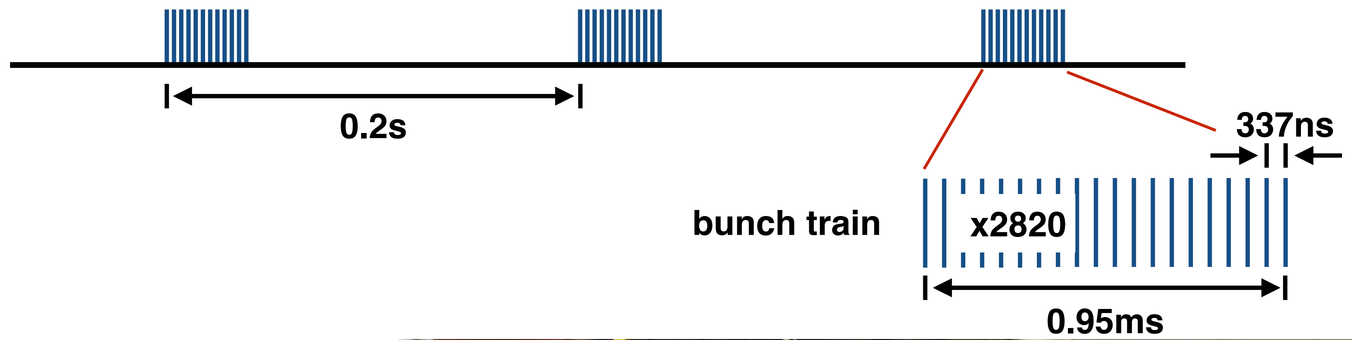
Addressing real-world Constraints with new prototypes

Physics prototypes

integration

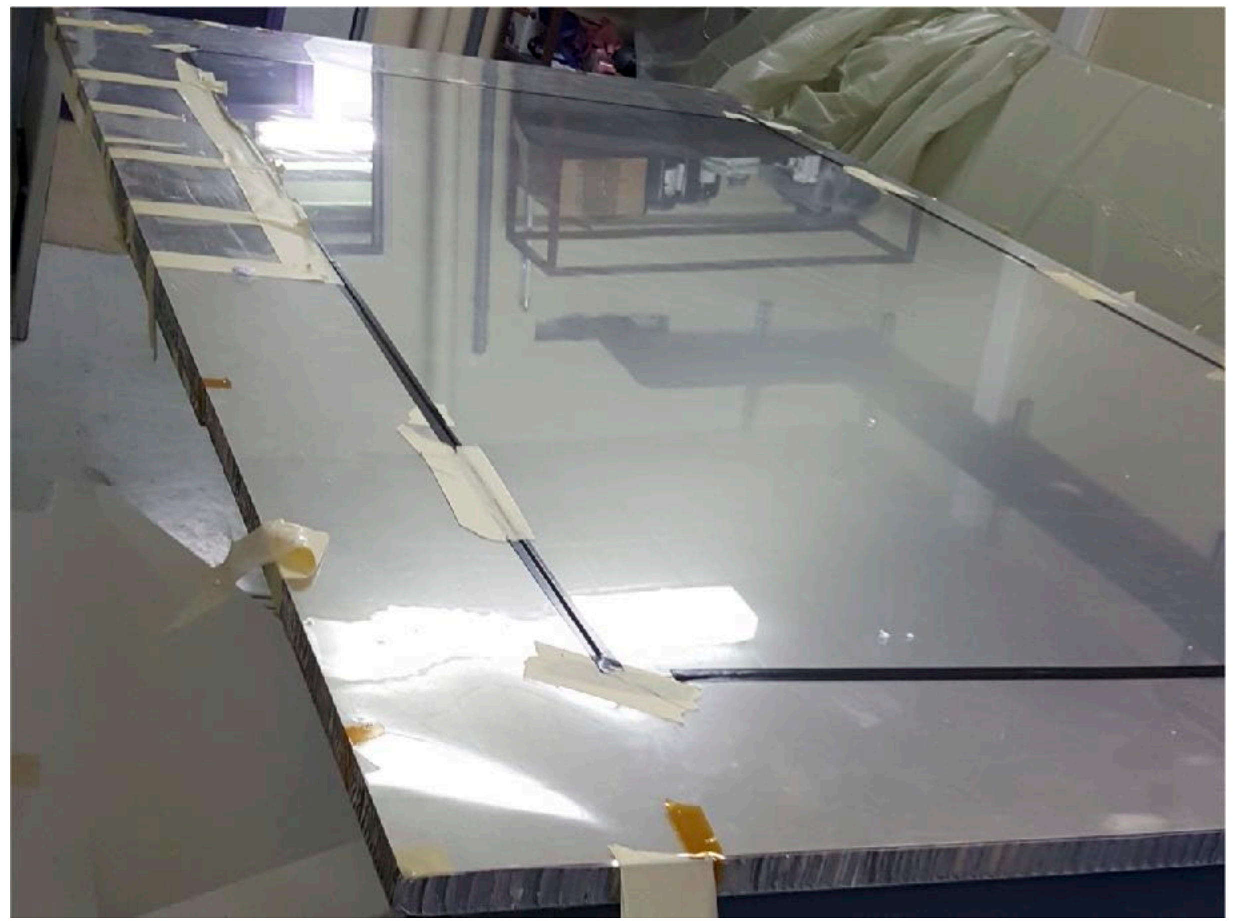


- Common to all new developments: Embedded electronics, power pulsing

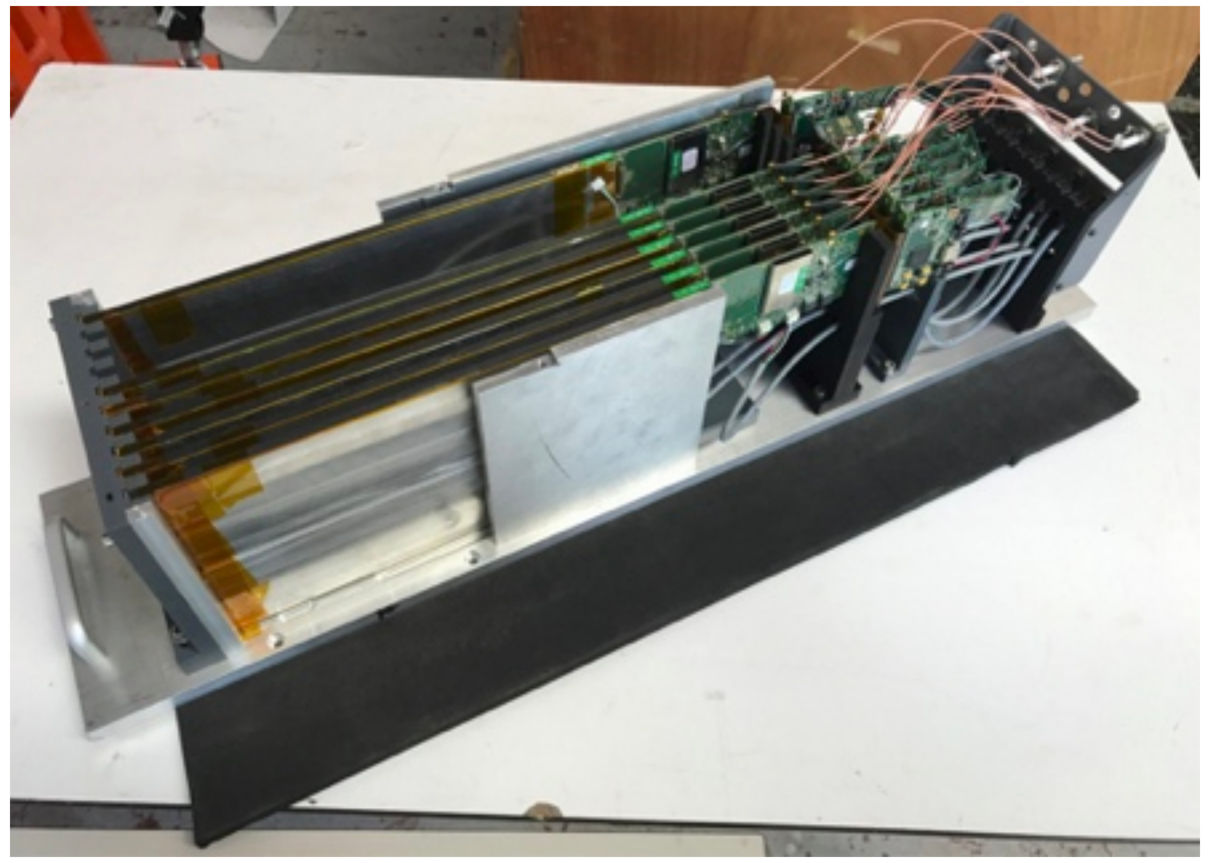


scalability to large areas, automatisation

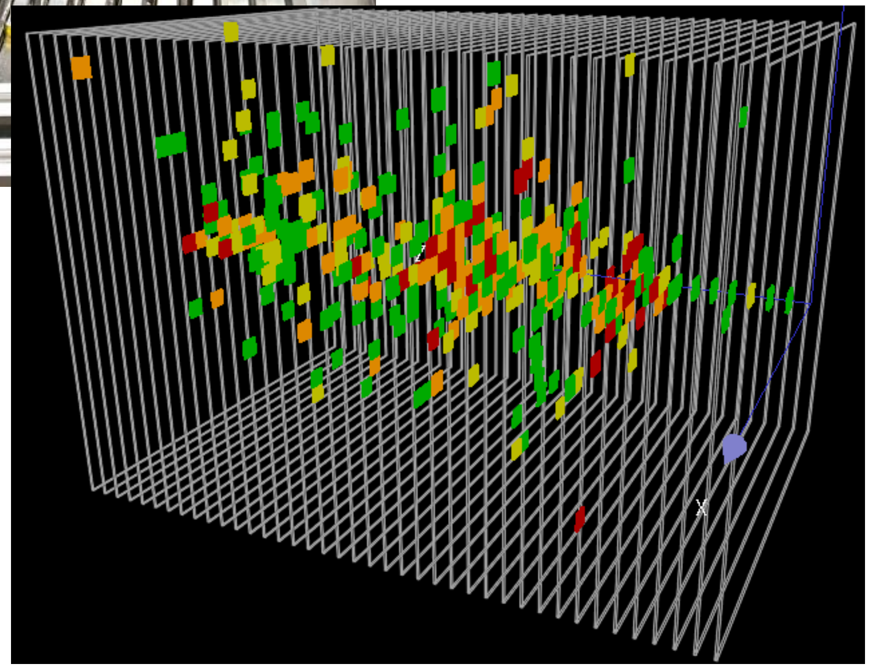
Large RPCs
SDHCAL prototype



SiW ECAL prototype



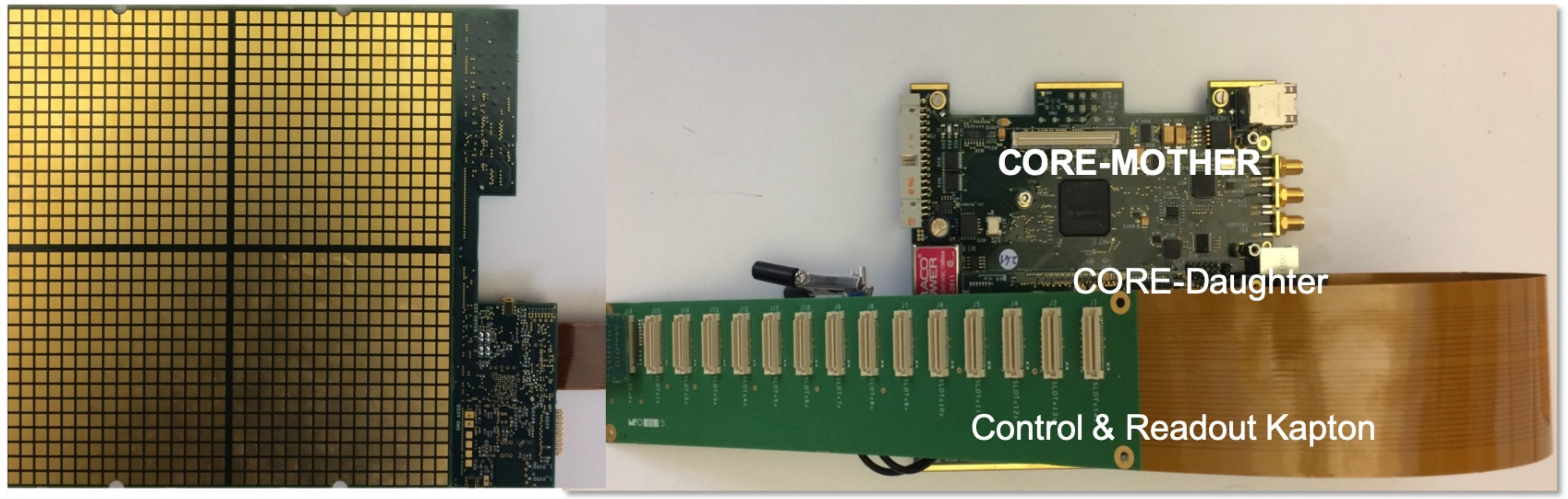
AHCAL prototype



Technical Realisation

The SiW ECAL

- Step-wise construction of a technological prototype with compact interfaces - with validation in test beam



2018

- 1024 channels per layer
- Assembly chains in France and Japan
- Beam tests at DESY and CERN since 2016

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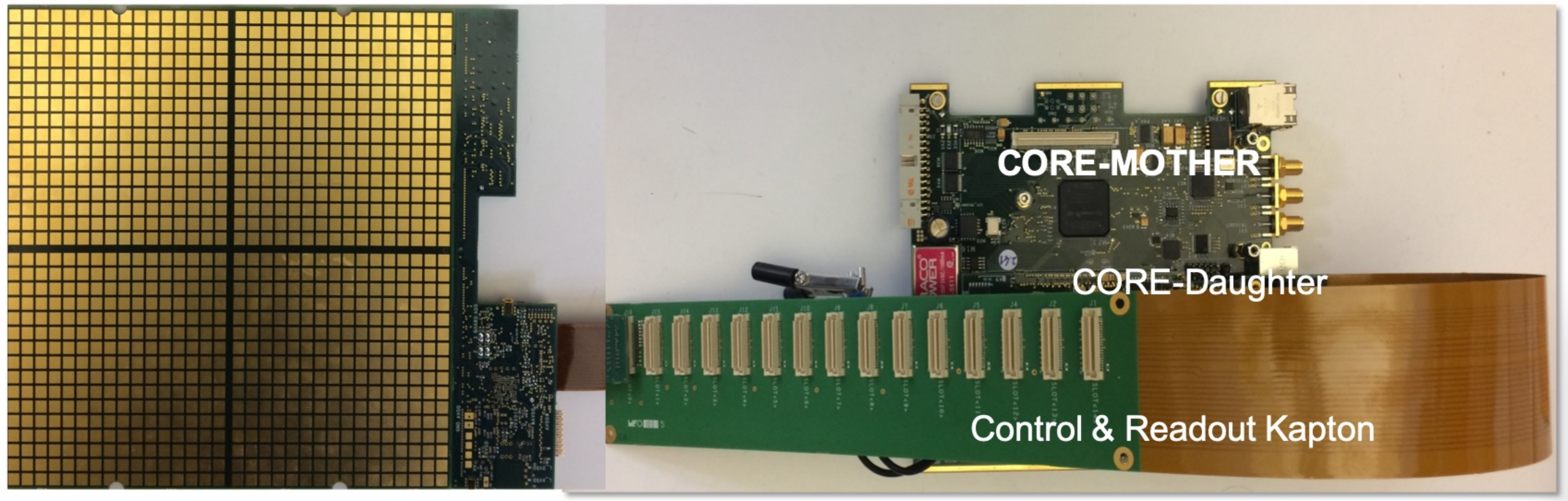
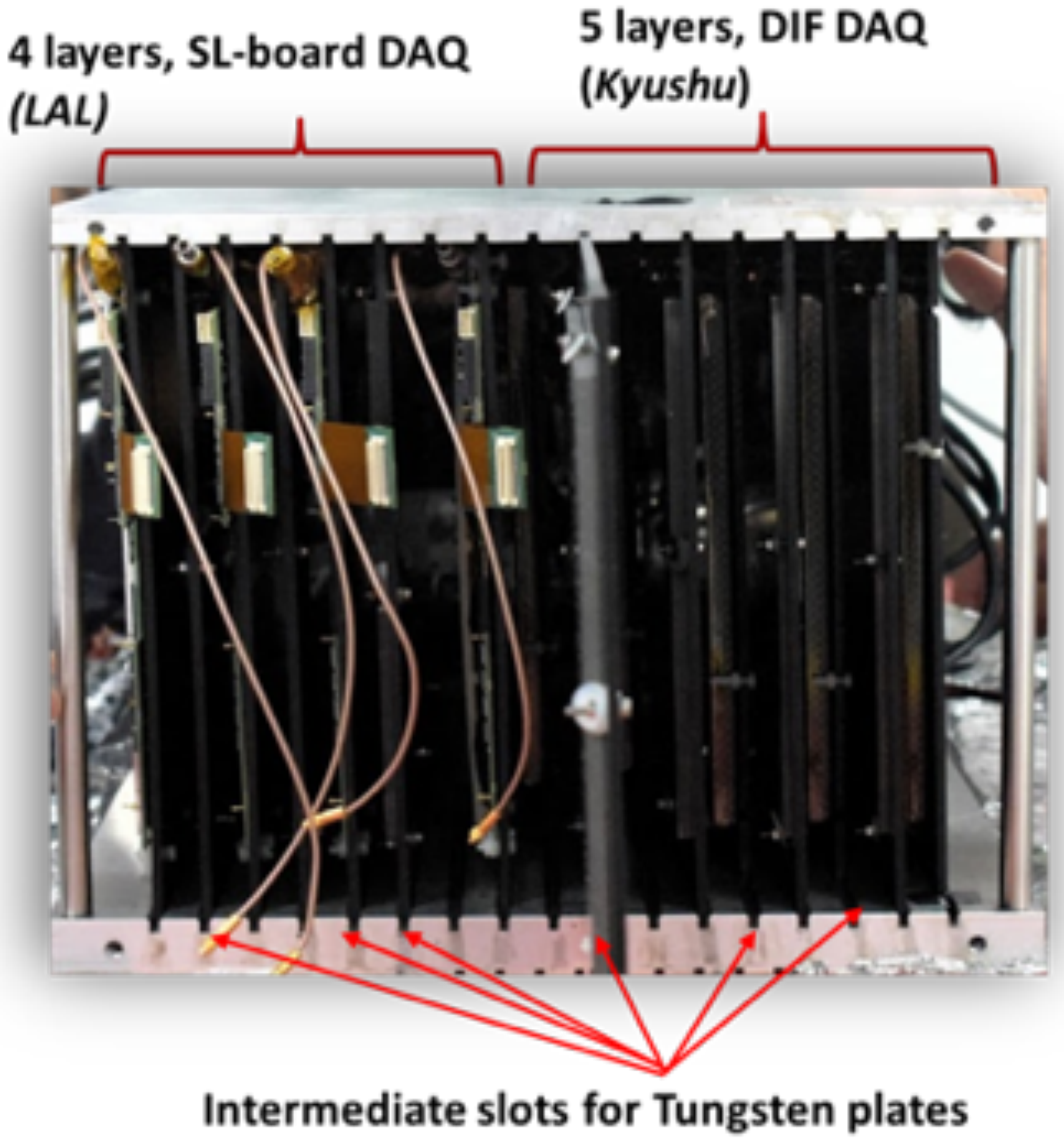


2018

2019 - in various configurations with up to 7 SL-board layers



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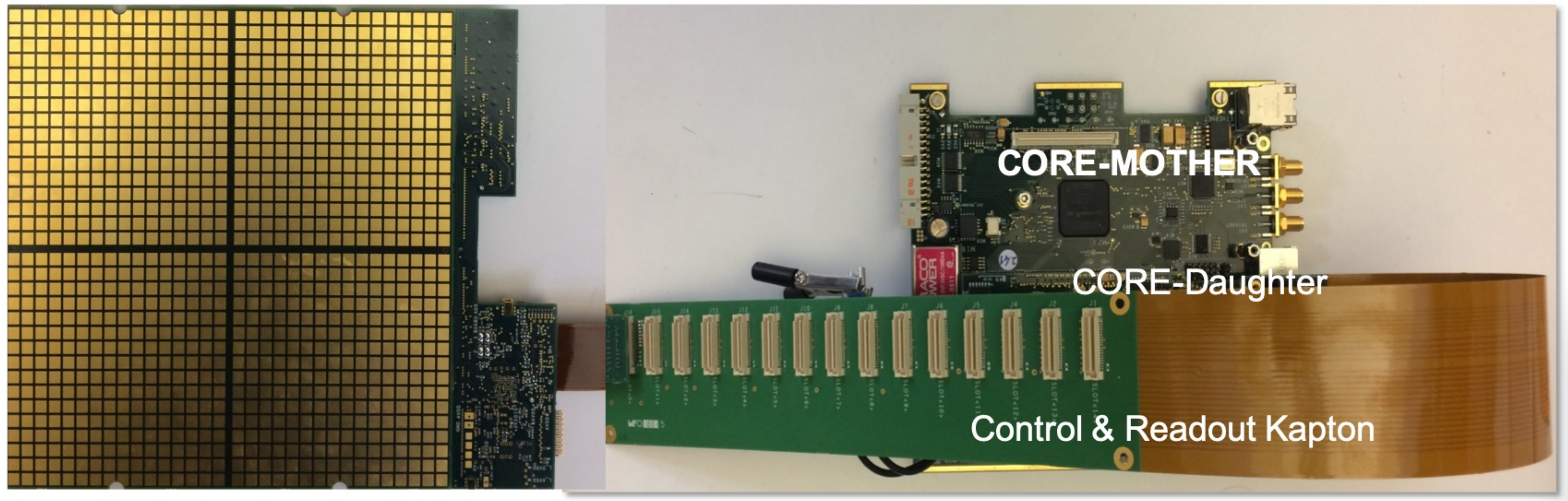

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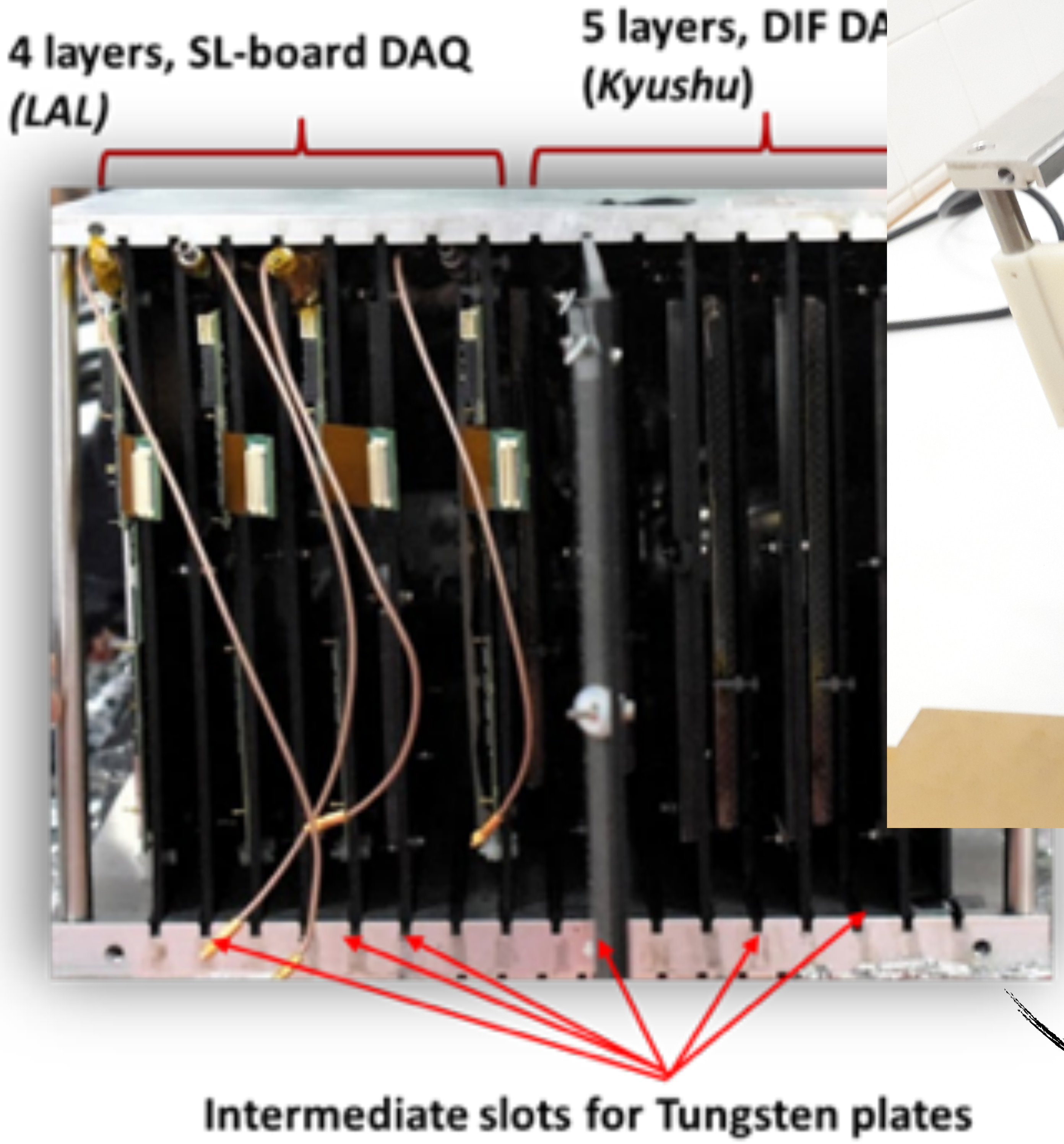
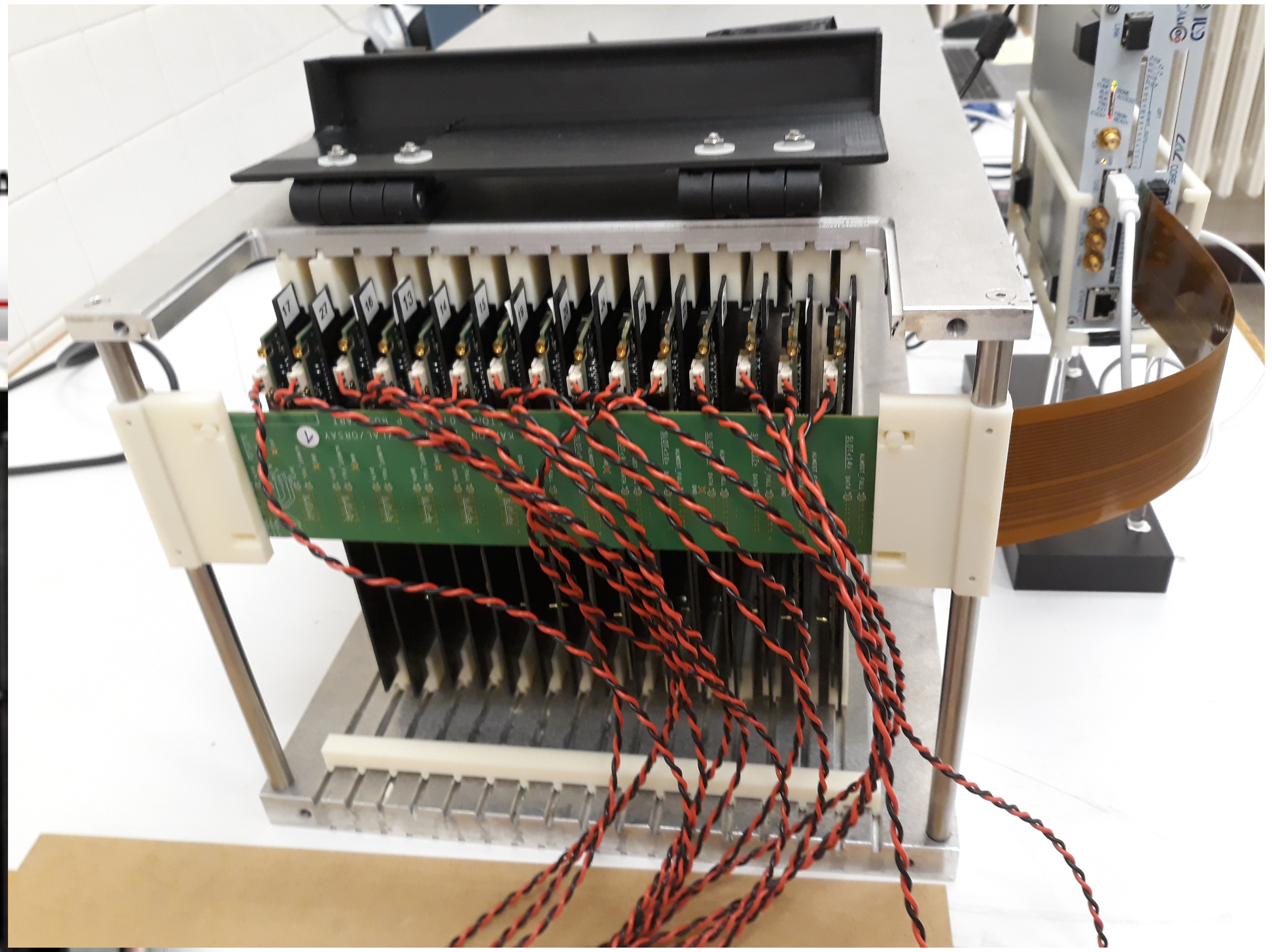


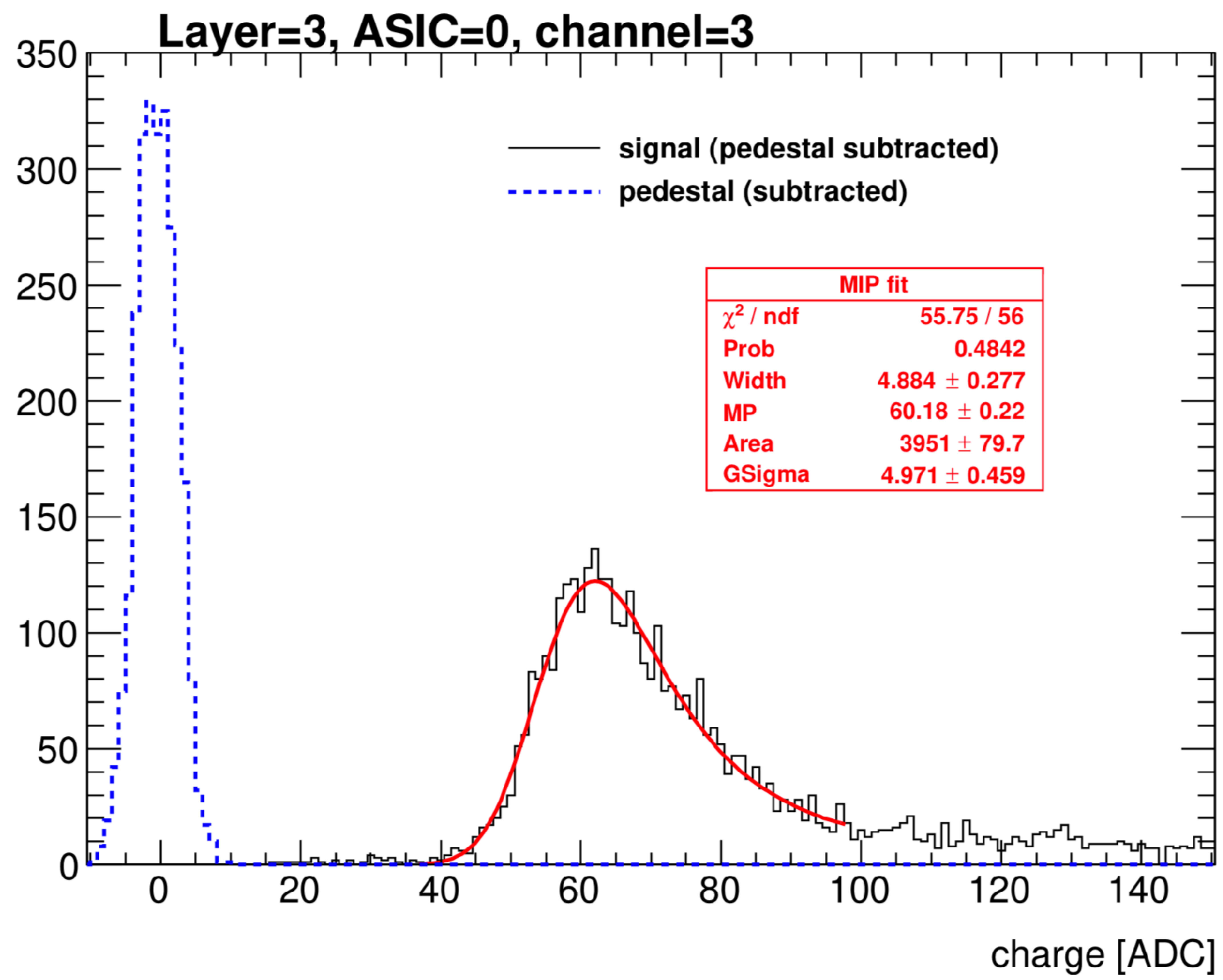


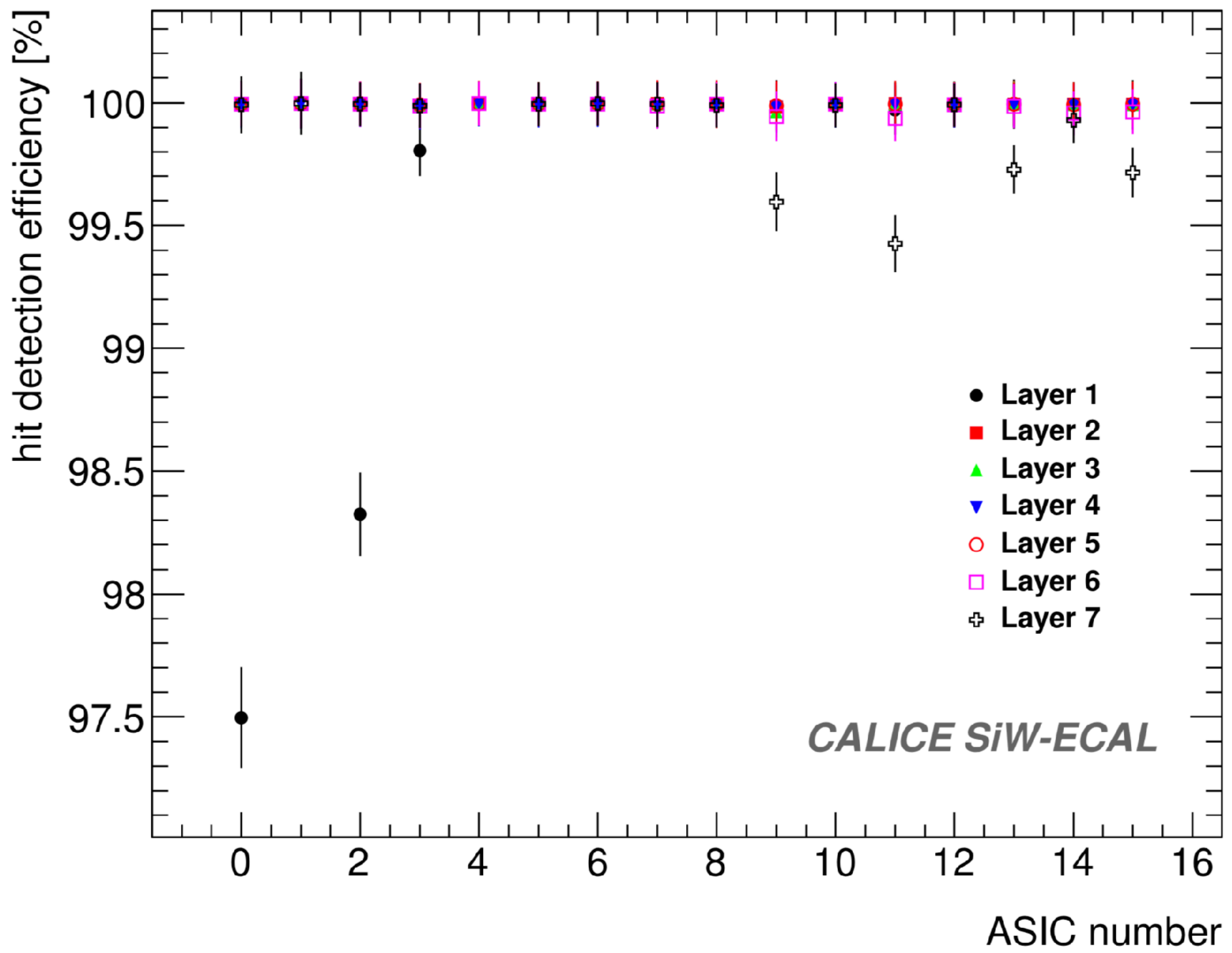
2020: 15 layers

- 1024 channels per layer
- Assembly chains in France and Japan
- Beam tests at DESY and CERN since 2016
- Now a full 15 layer prototype available (15k channels) - going to beam in November / December
  - using “Higgs Factory-ready” technology

The SiW ECAL - In Beam

- Excellent performance of detector channels





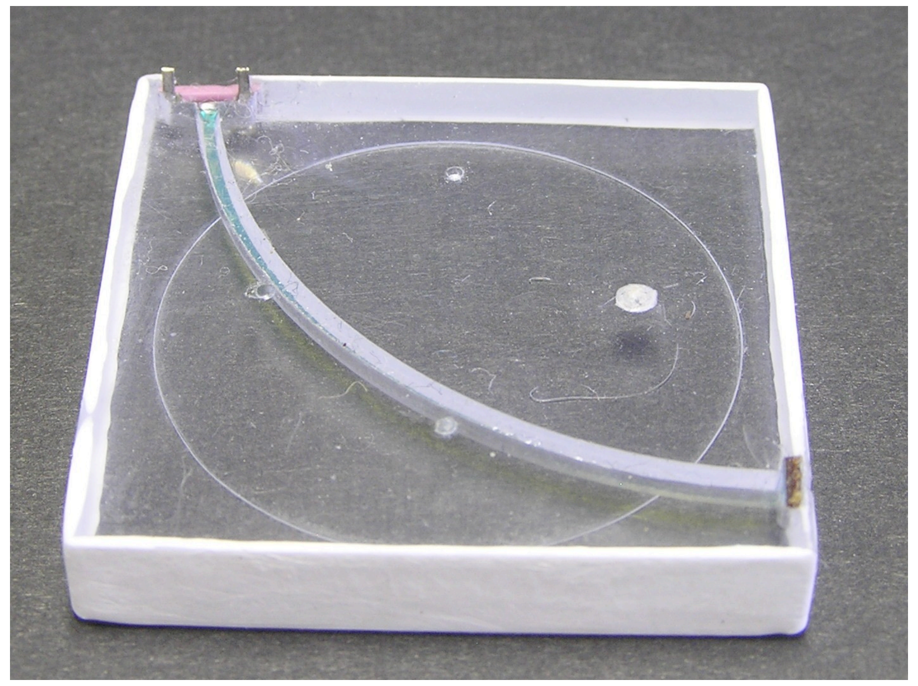
- Full efficiency (slight reductions in layer 1, 7 caused by unmasked noisy channels that saturate memories)

Technical Realisation

The Analog HCAL

- From the first large-scale application of SiPMs to the "***SiPM-on-tile***" technology

2008 - 2016



Physics Prototype

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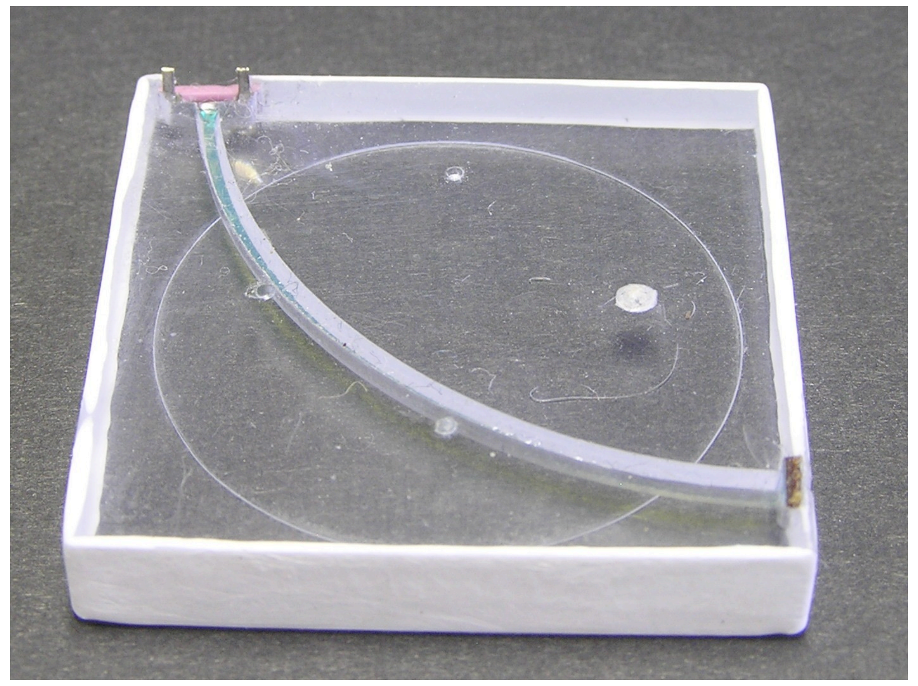

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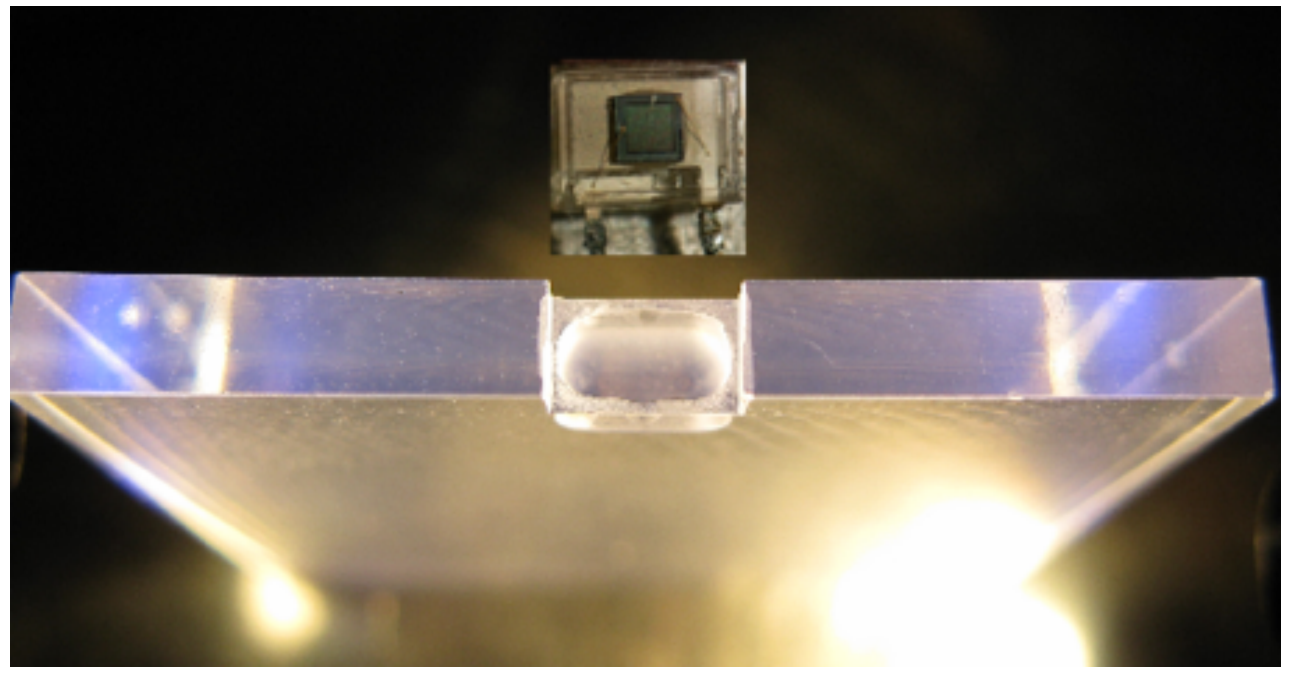

Direct coupling of tiles and photon sensors

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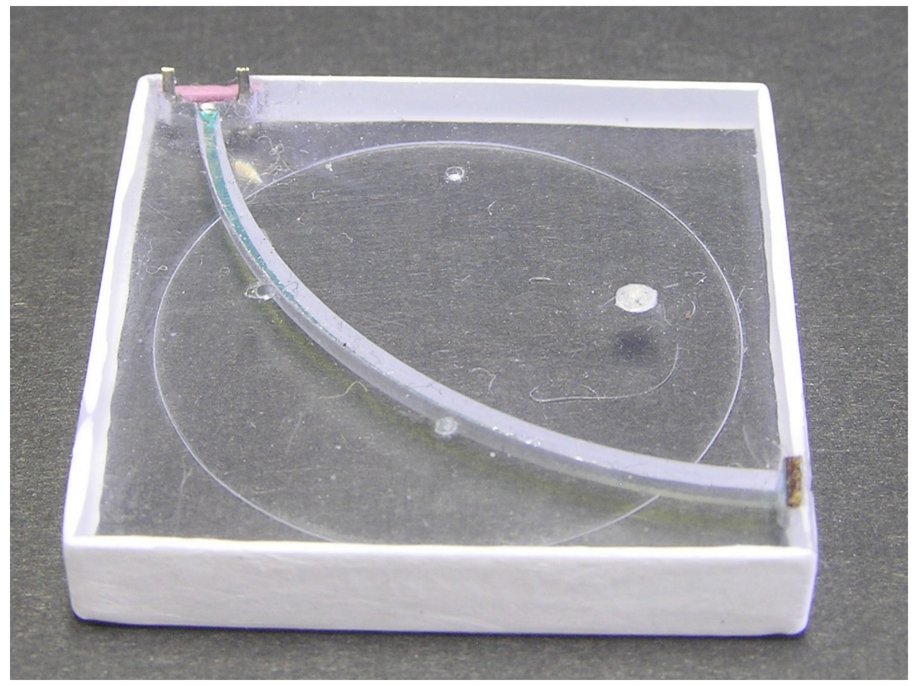

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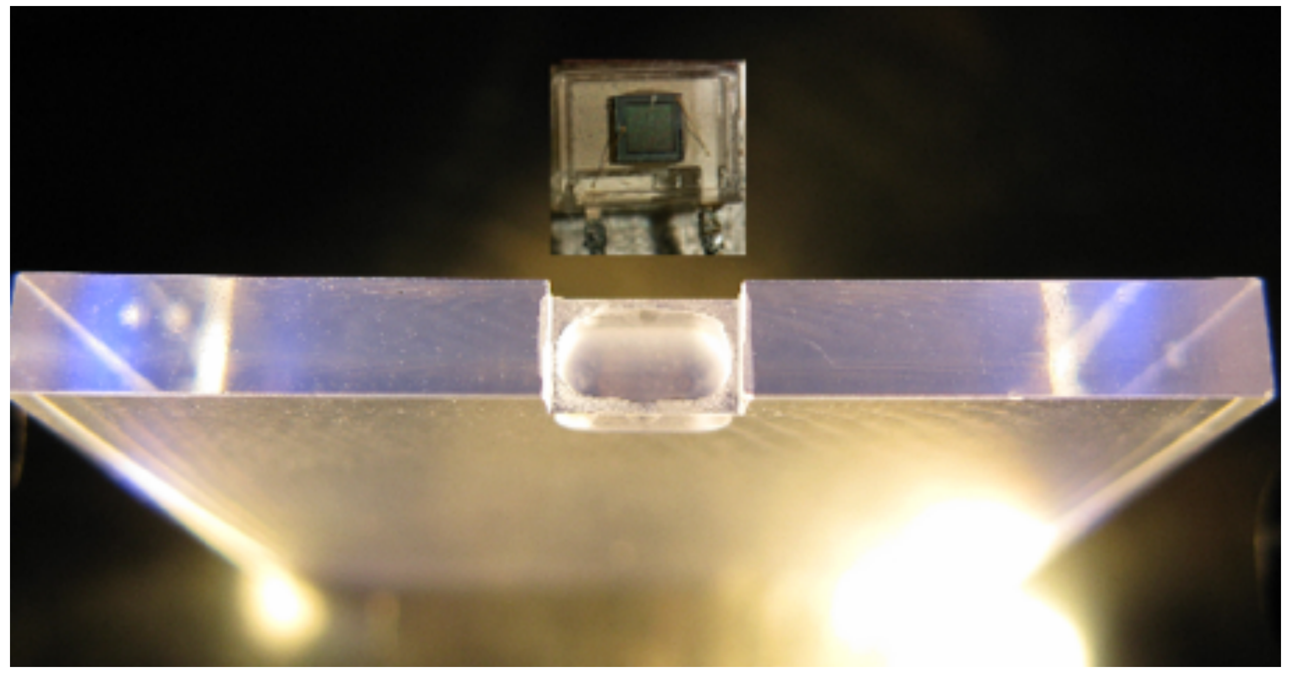

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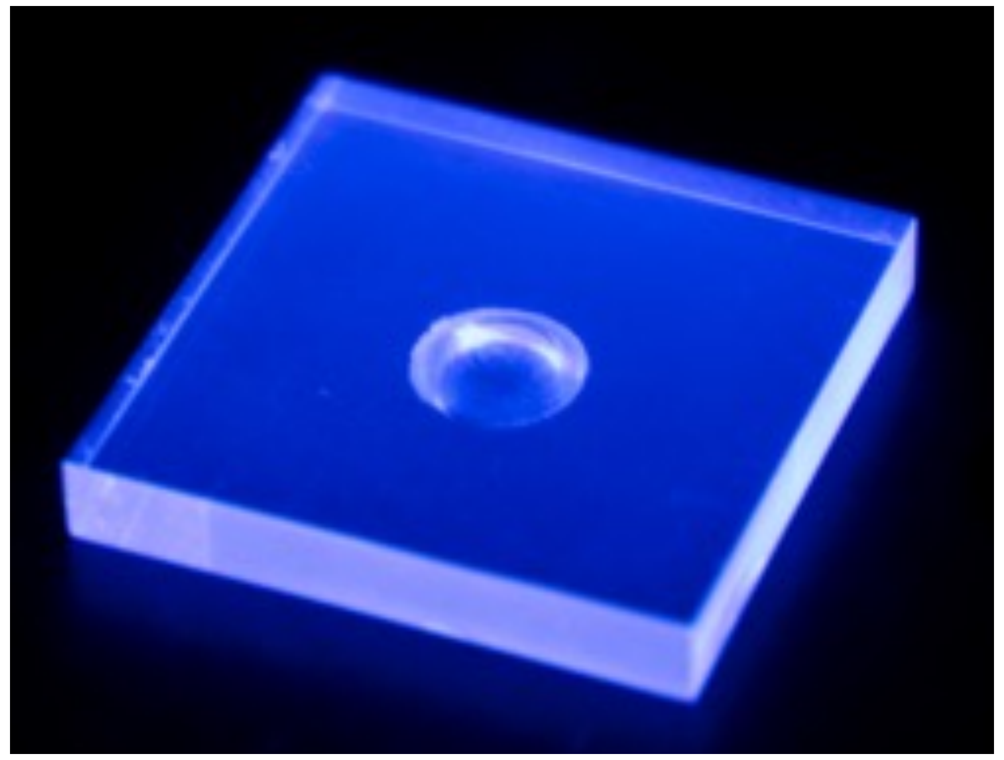

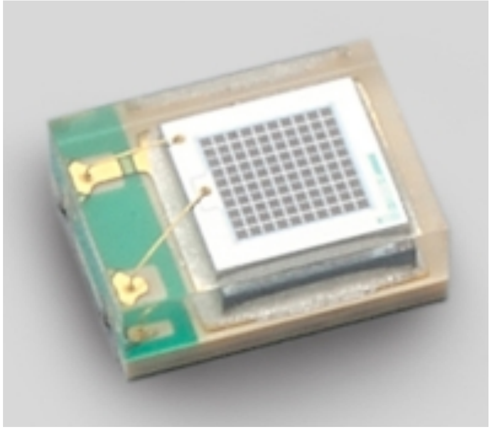

SMD SiPMs, modification of direct coupling

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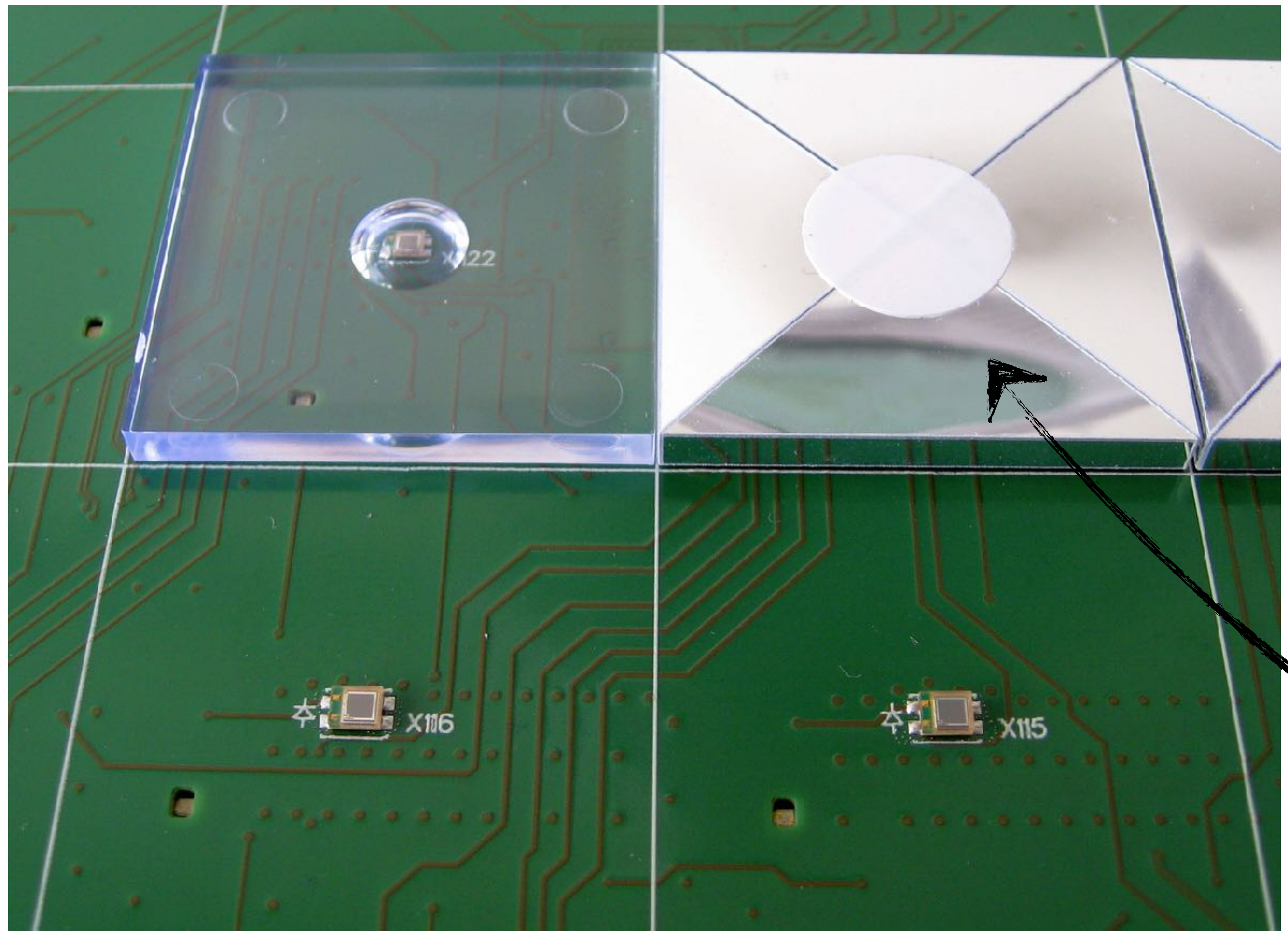

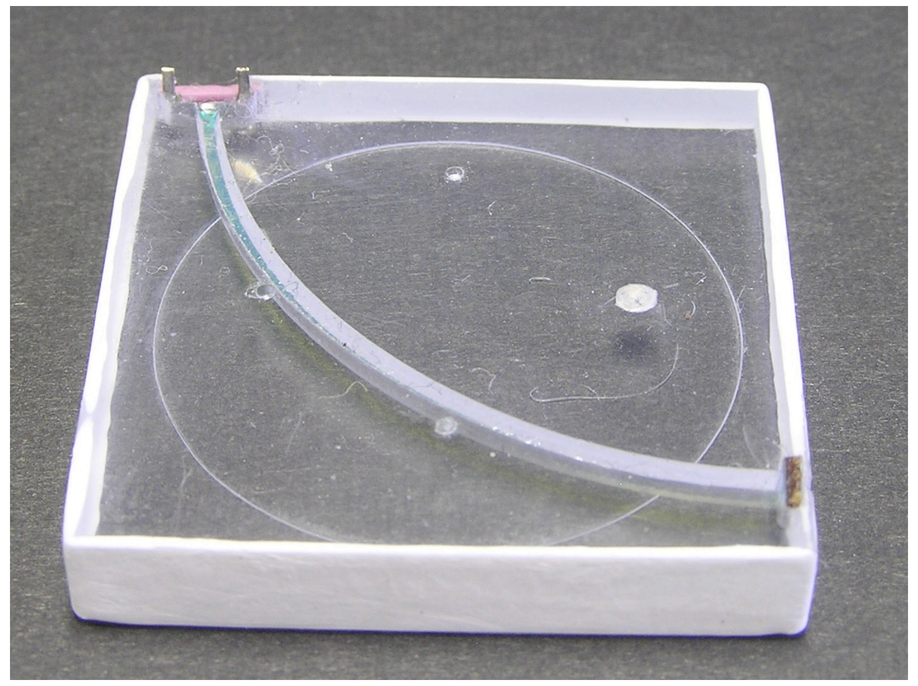

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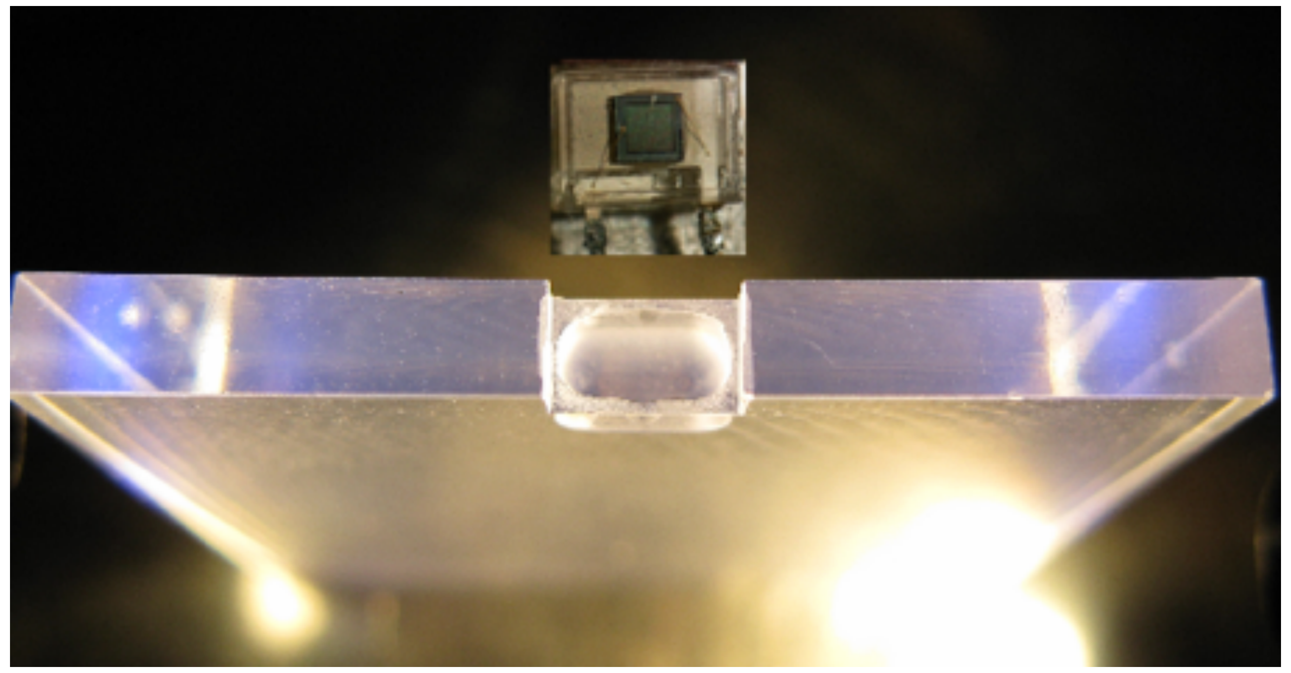

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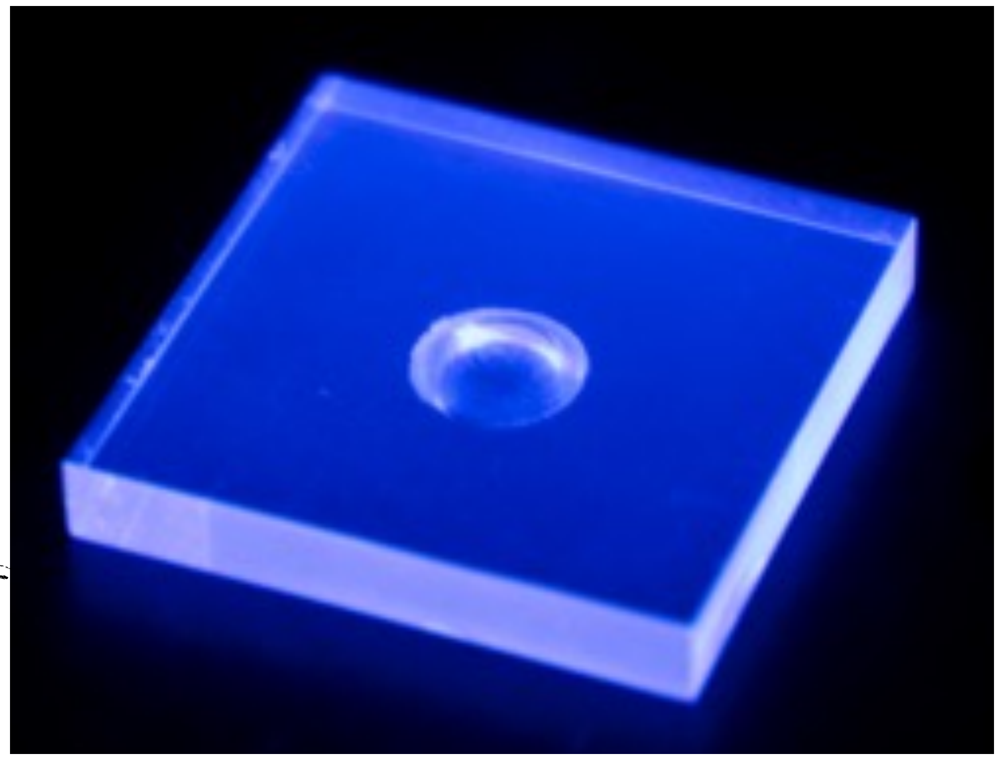

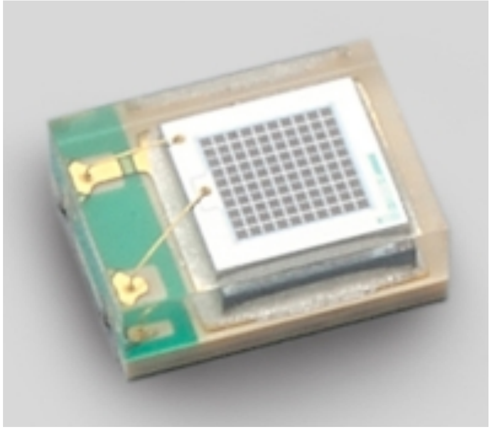

Fully integrated concept with embedded front-end electronics, calibration system

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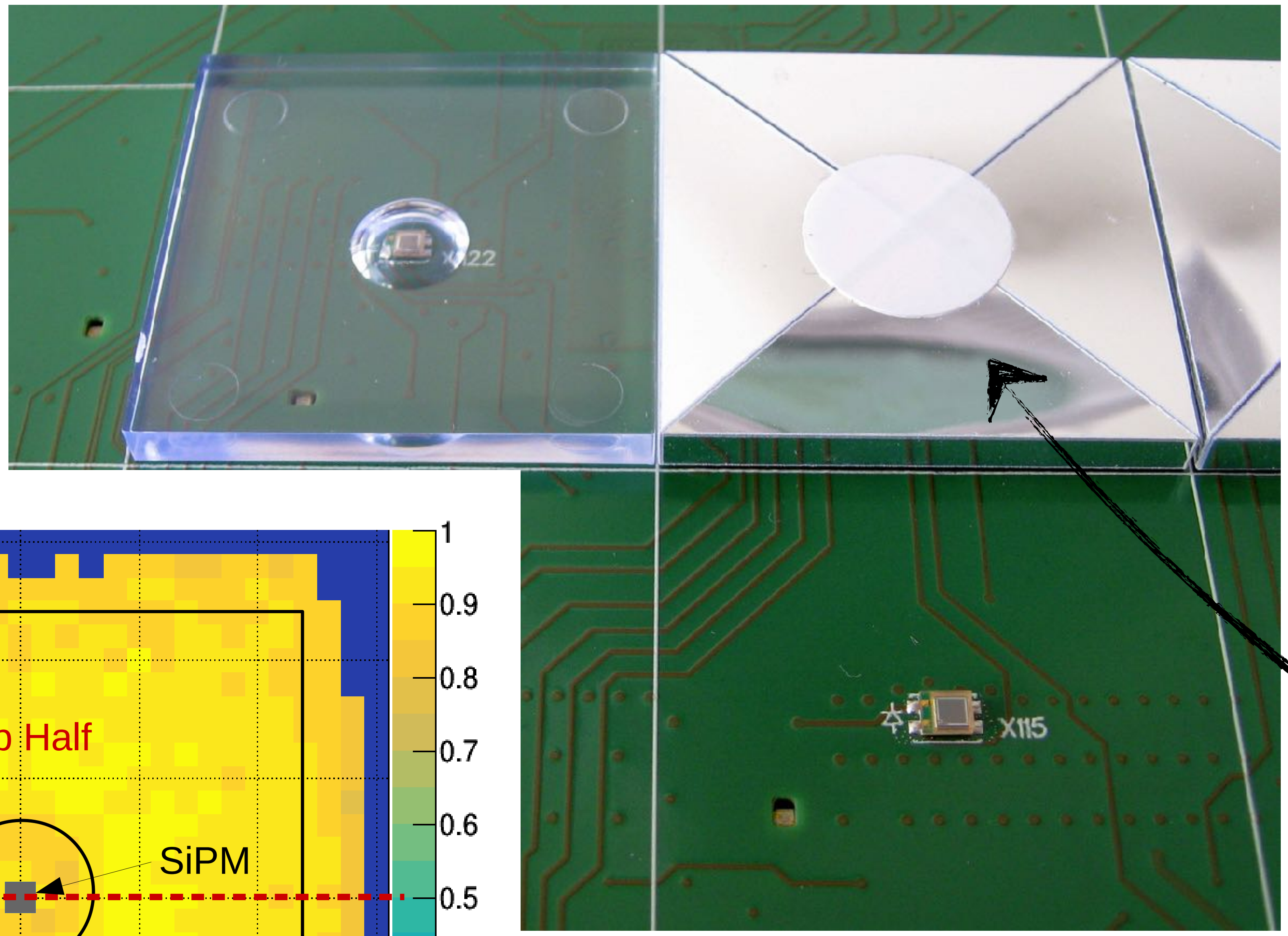
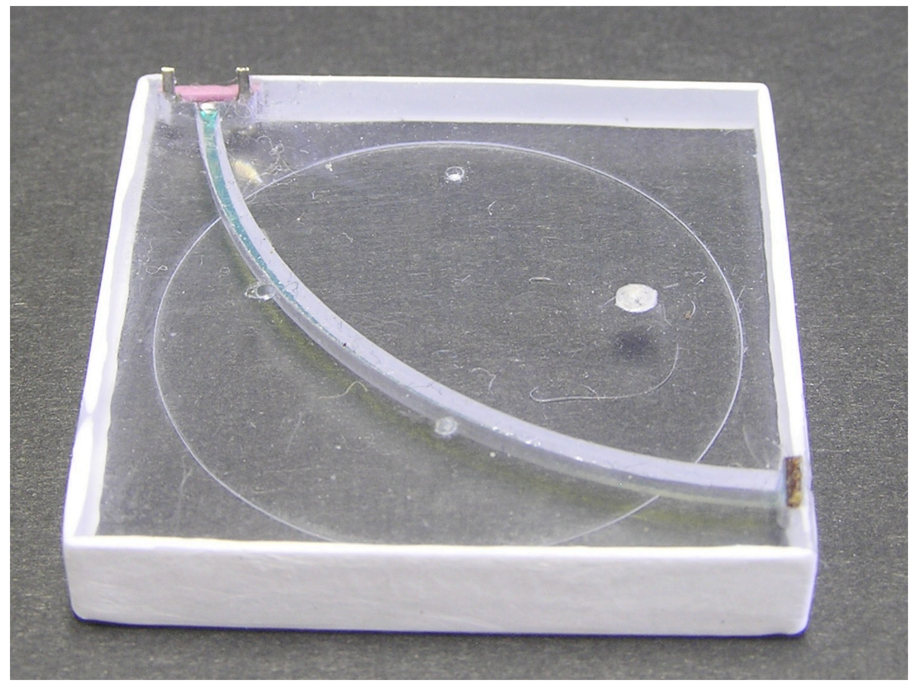
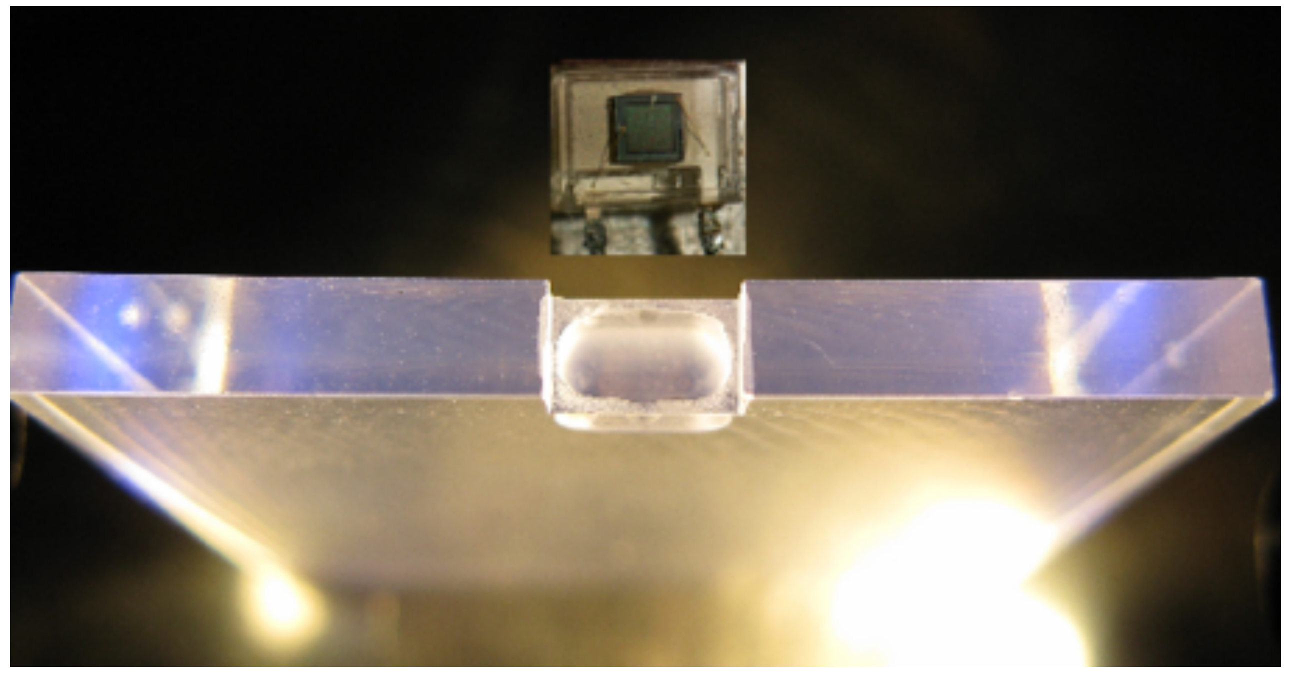
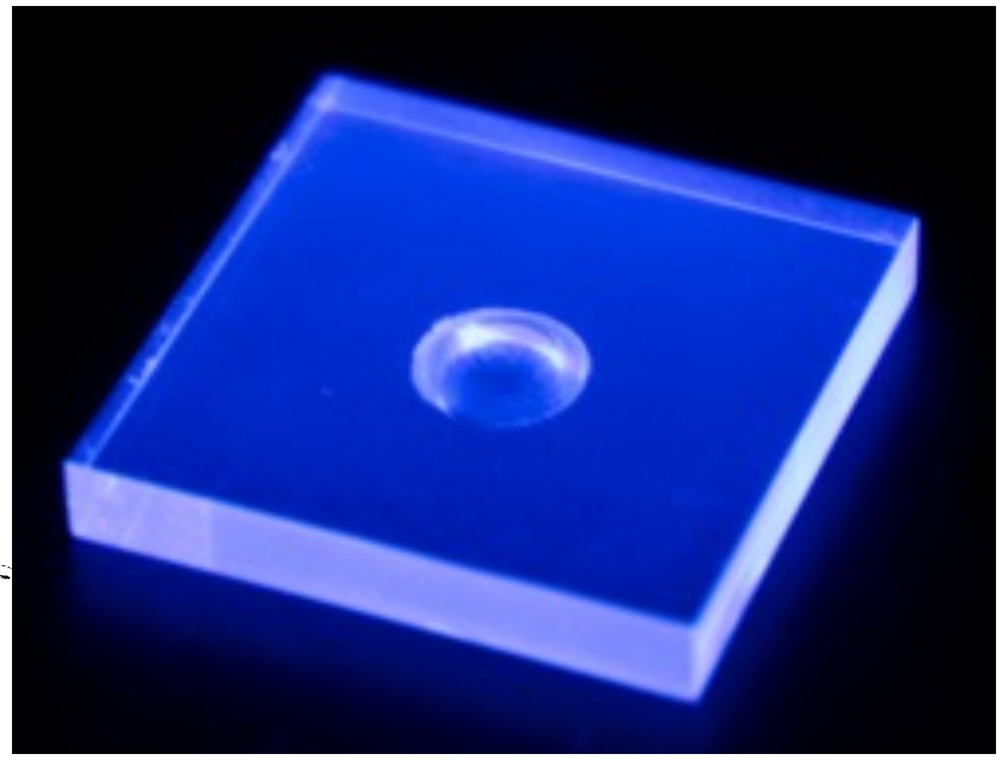


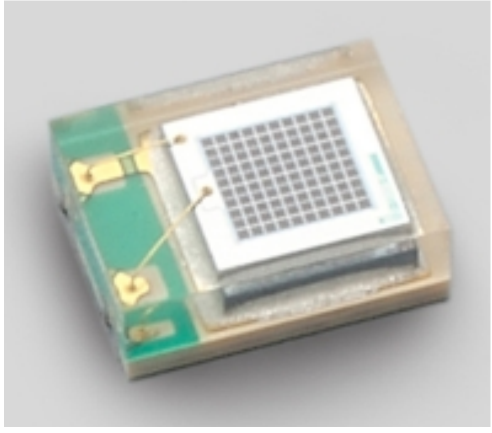


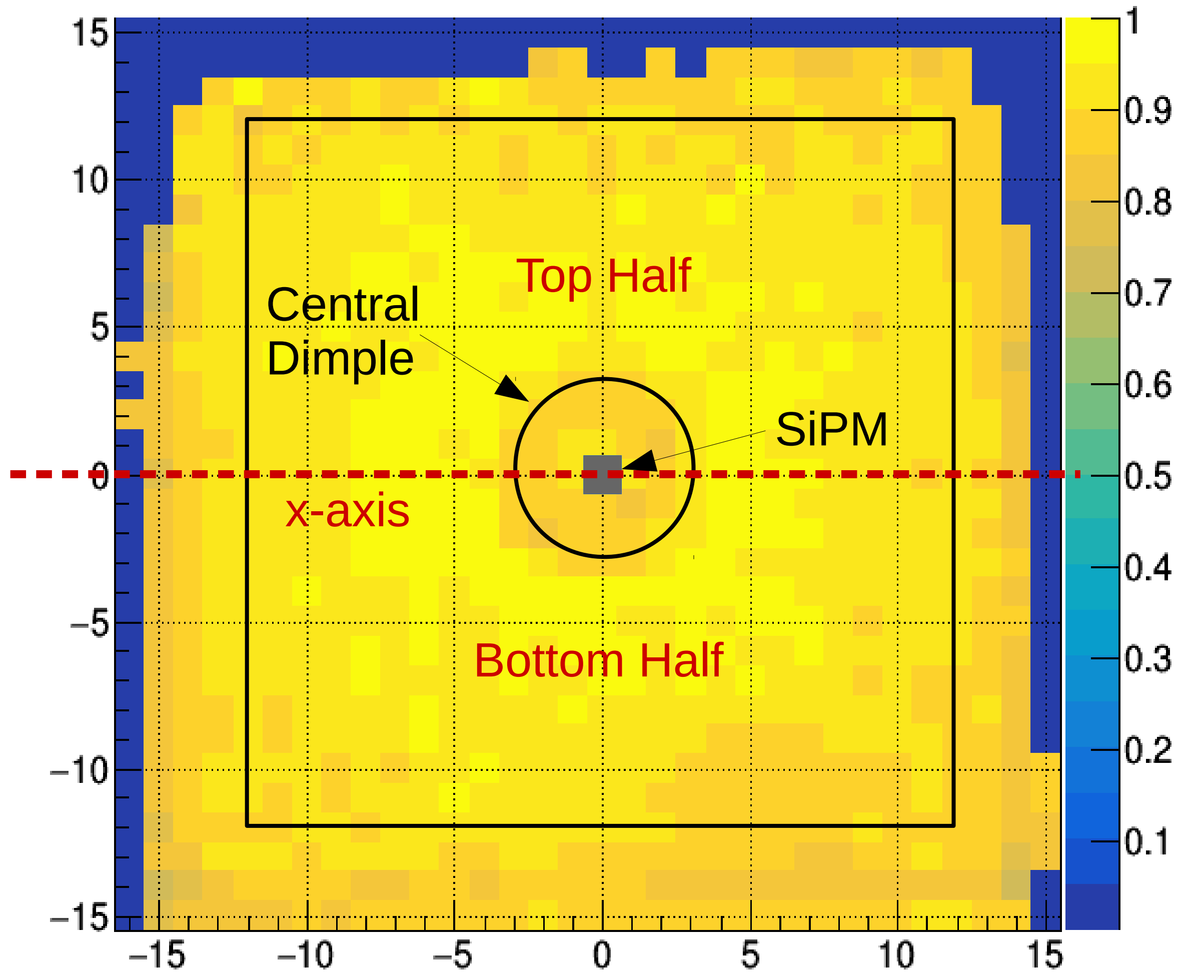
Physics Prototype



Direct coupling of tiles and photon sensors







Validation of element performance

Fully integrated concept with embedded front-end electronics, calibration system

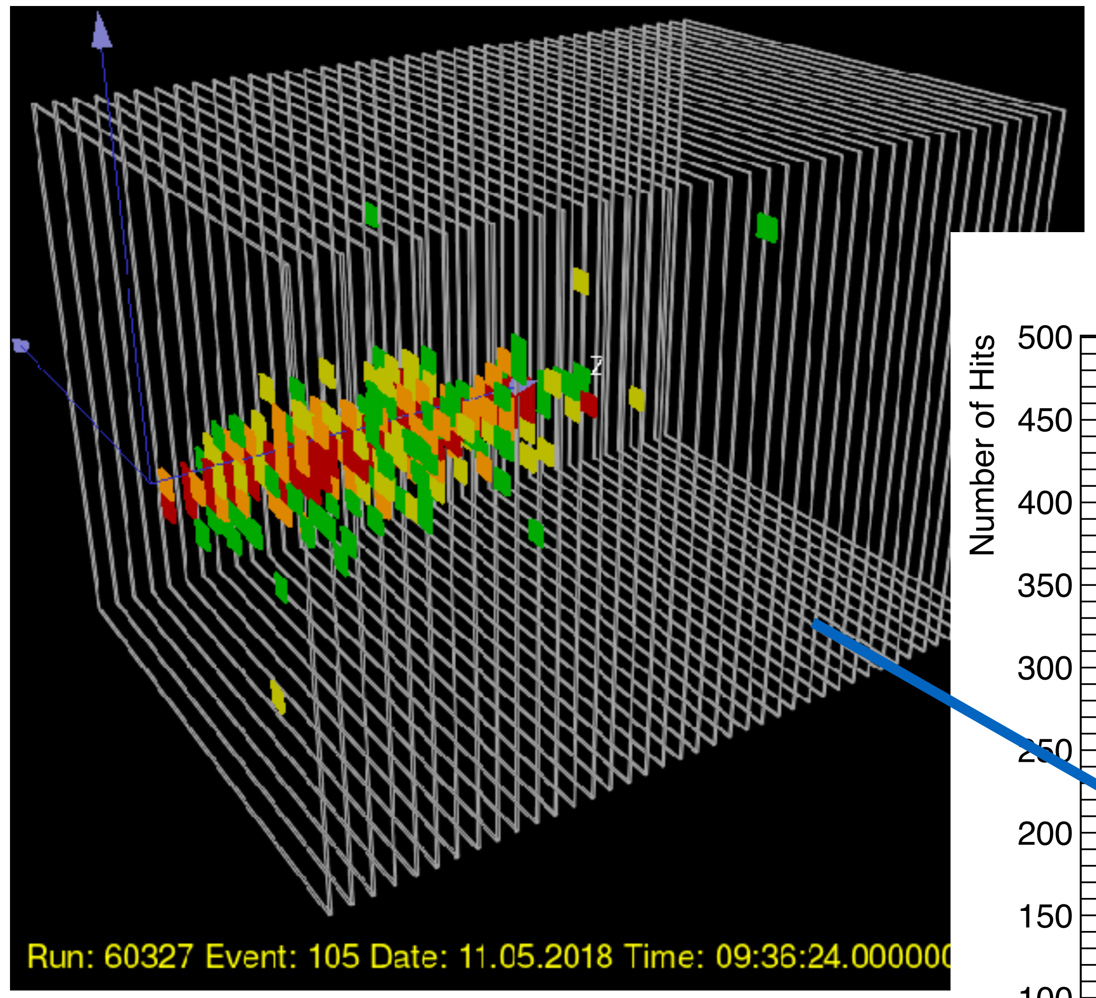
SMD SiPMs, modification of direct coupling

Technical Realisation

The Analog HCAL - In Beam

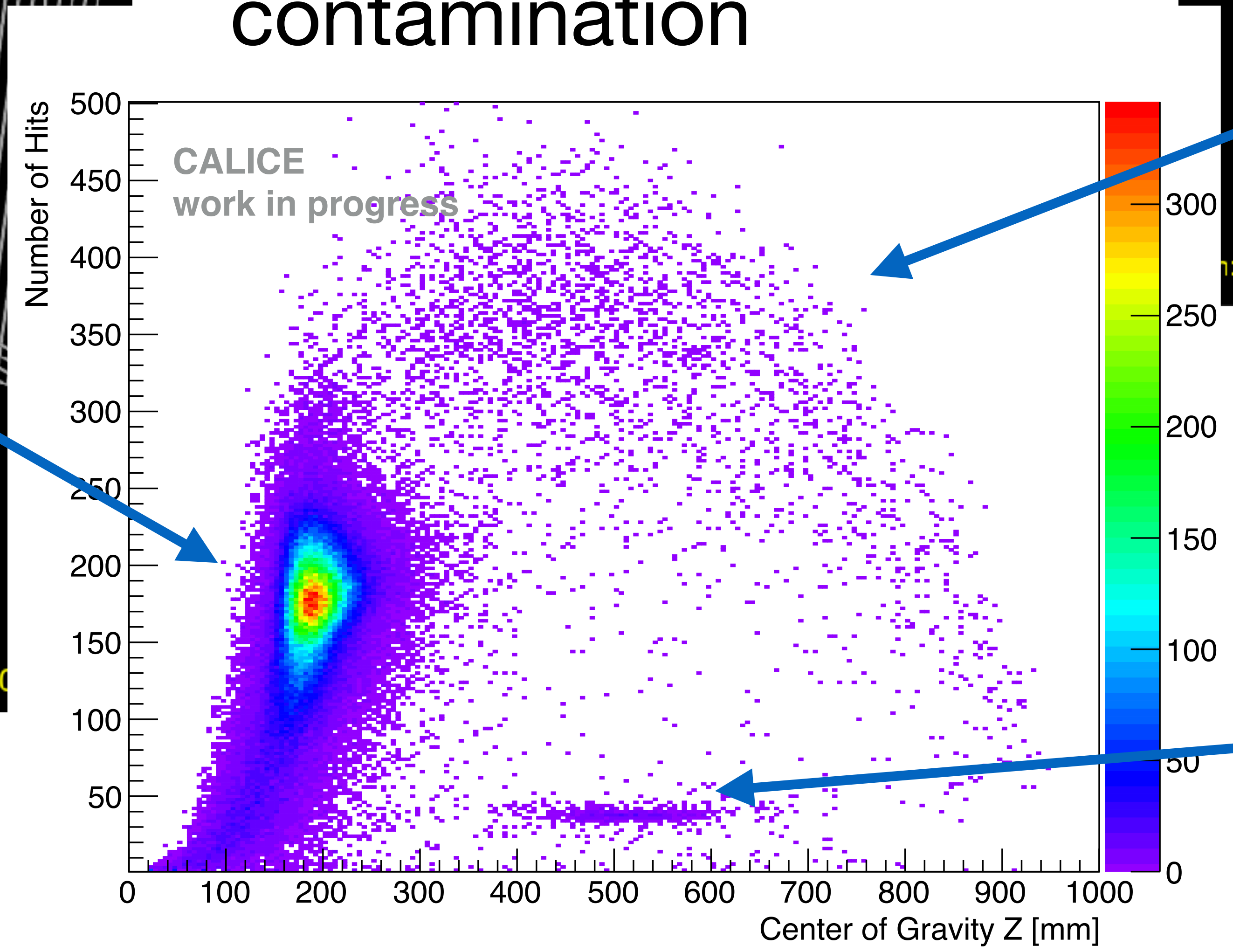
- Detector tested extensively in particle beams at DESY & CERN

electron shower

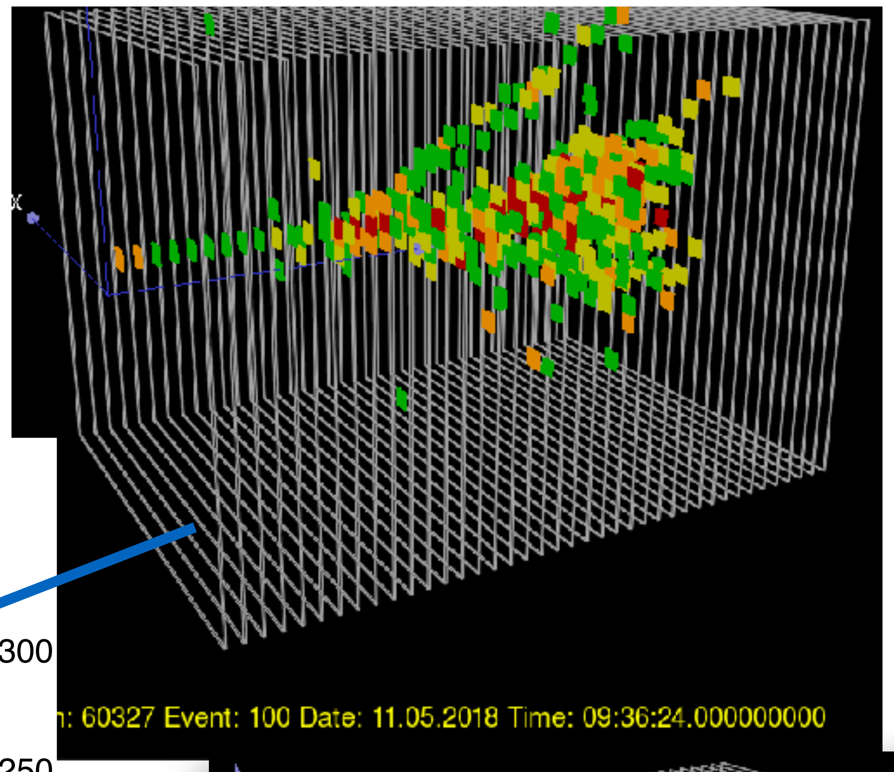


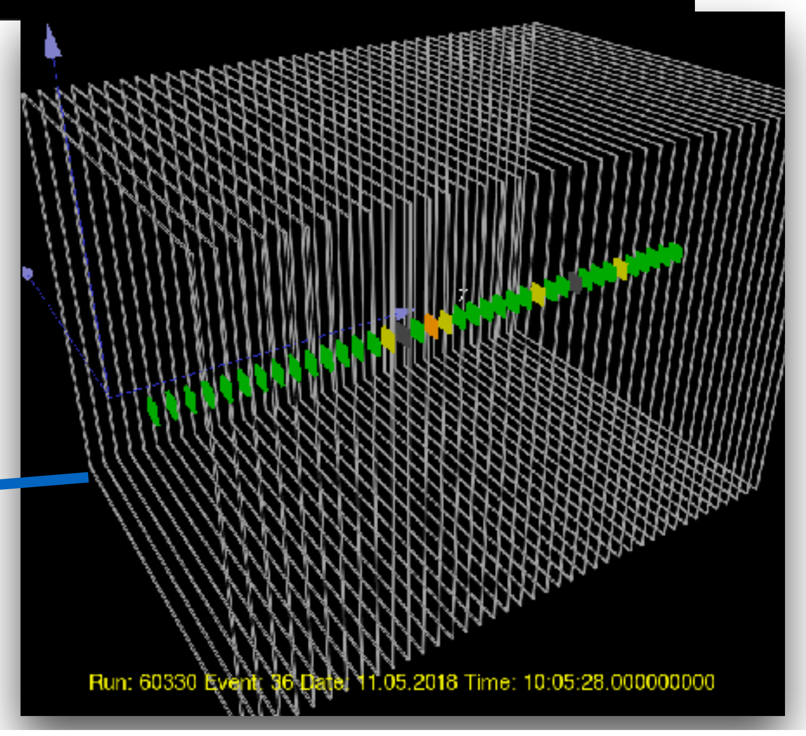
online data

50 GeV electron beam with pion and muon contamination



pion shower





muon track

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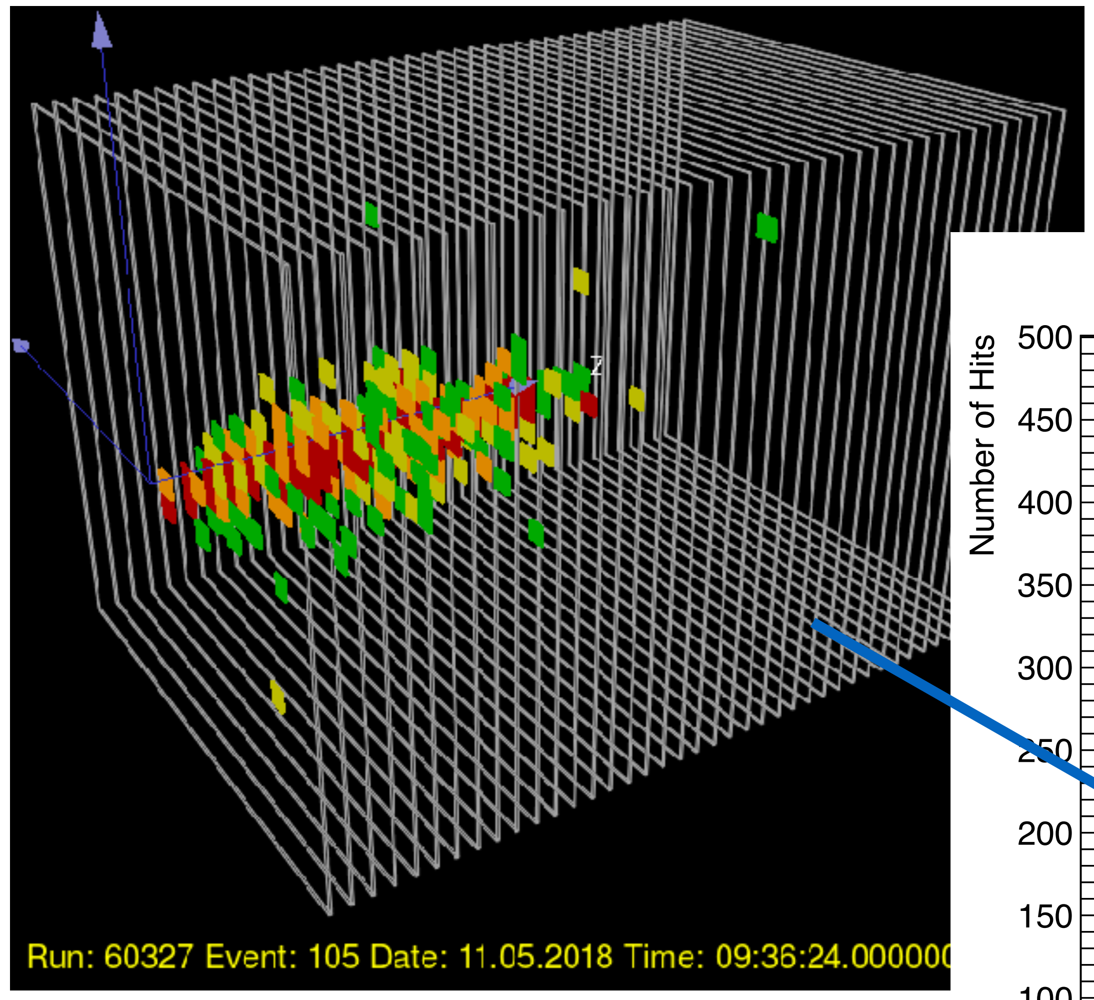

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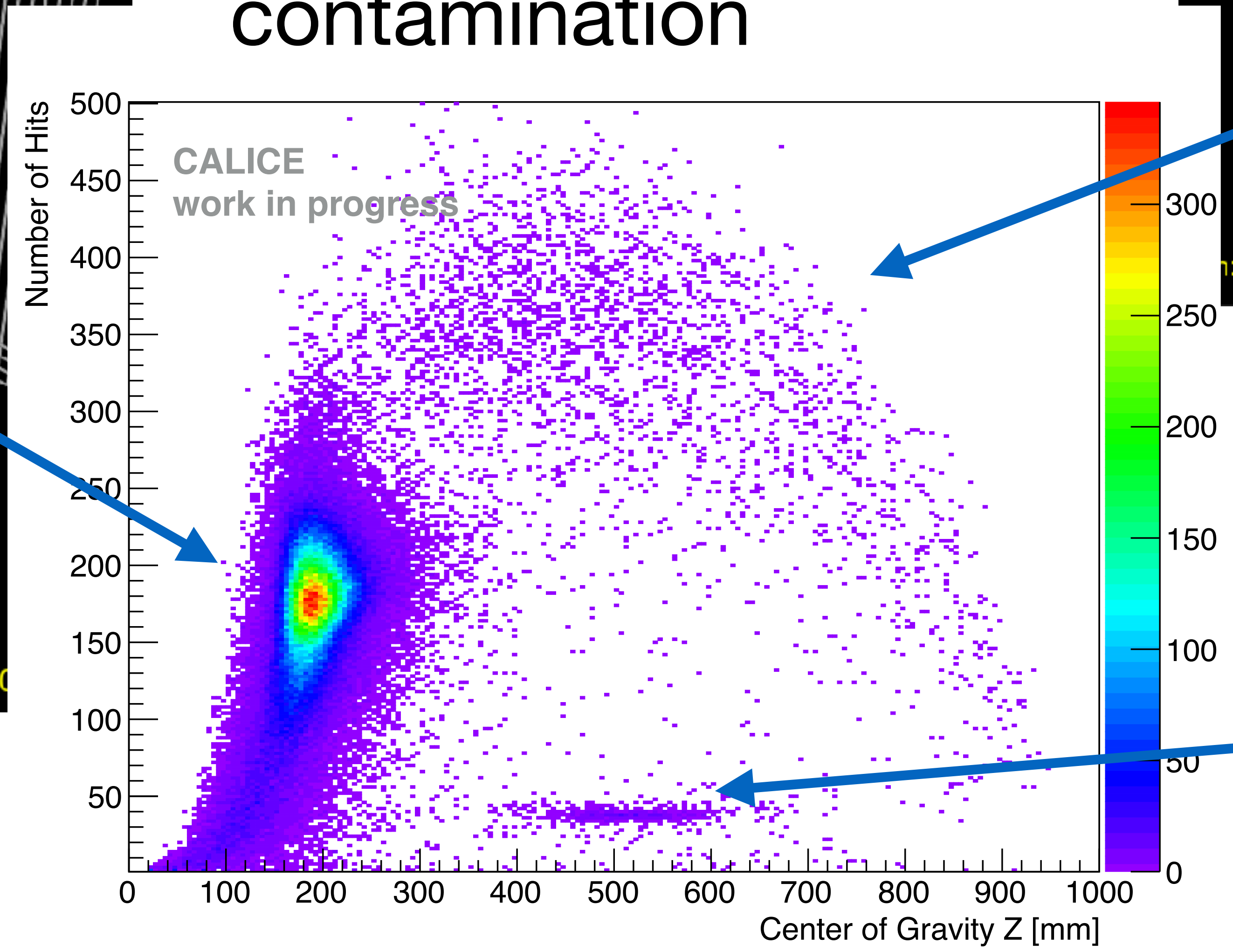

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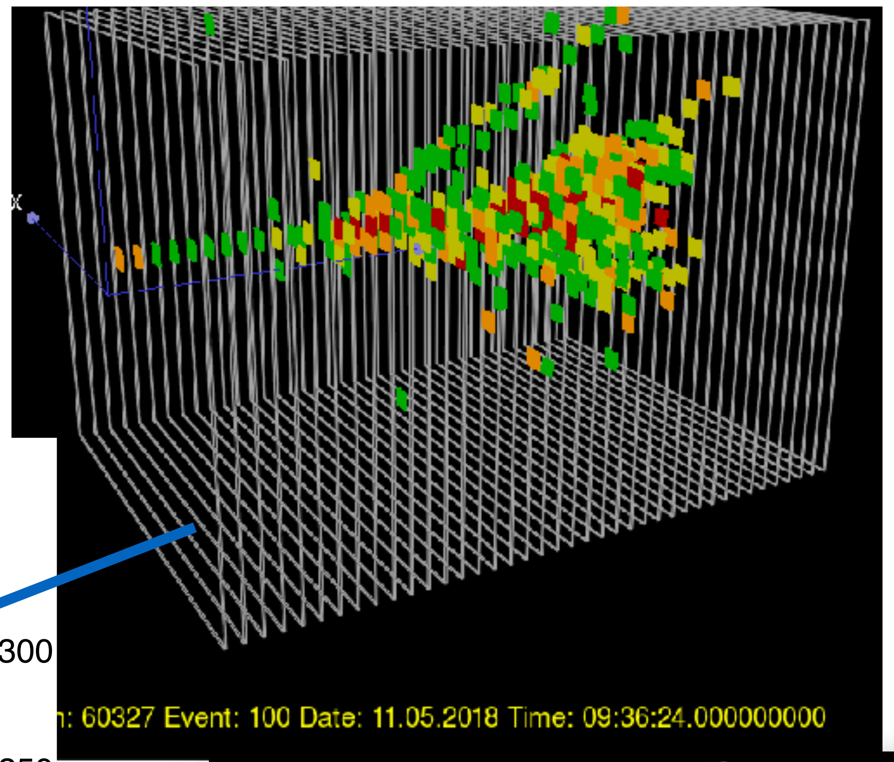
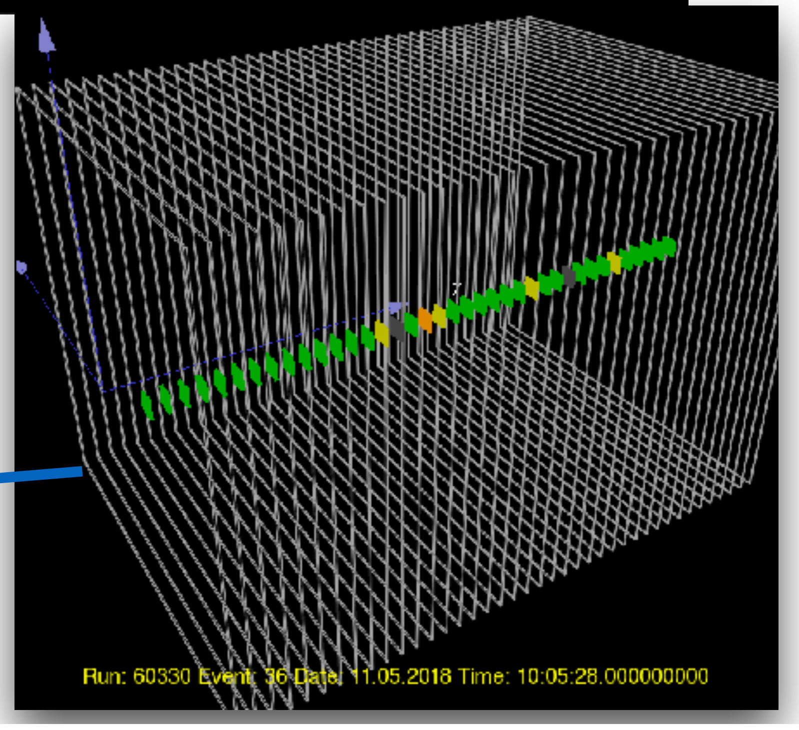
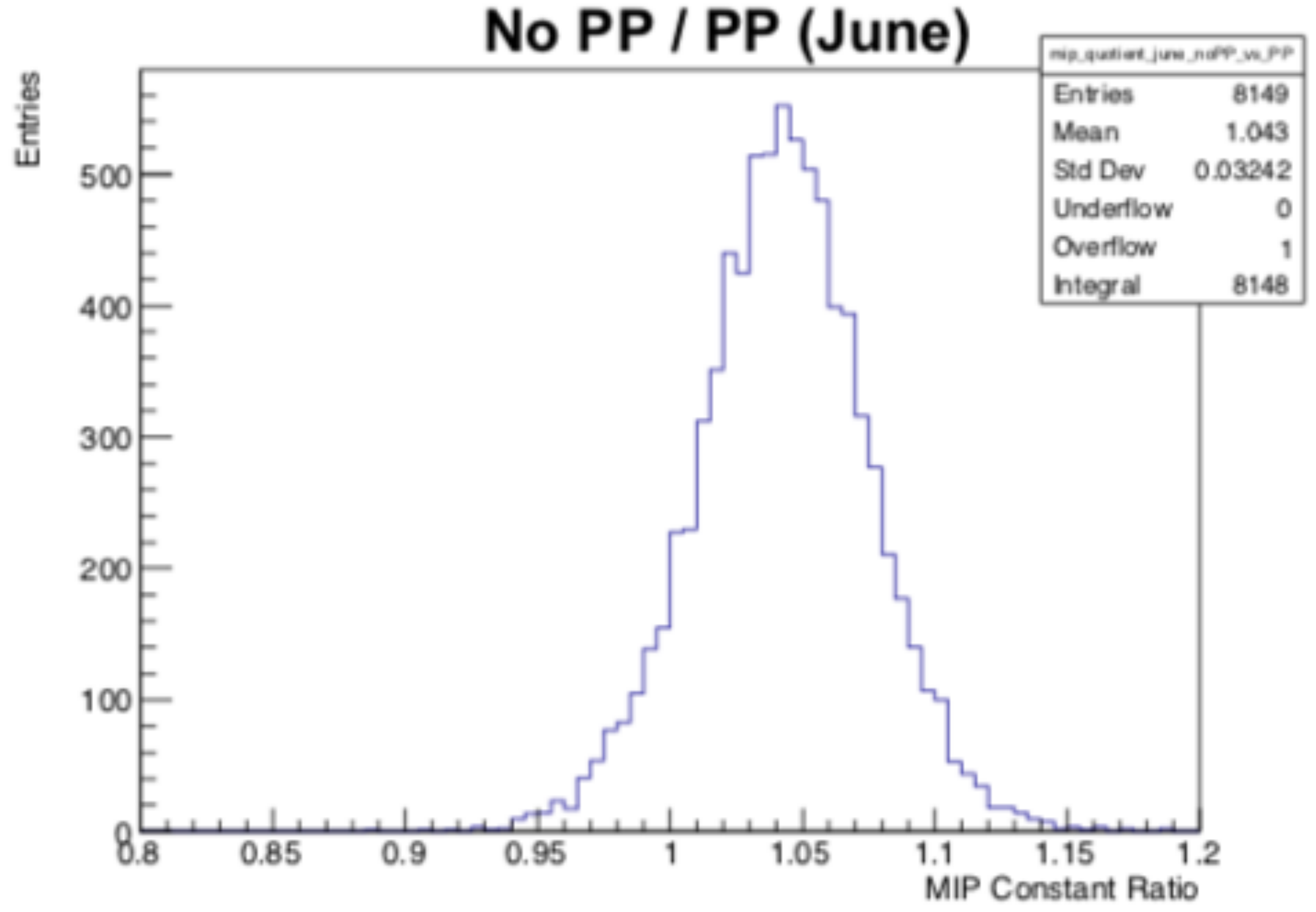




muon track

Validation of power pulsing



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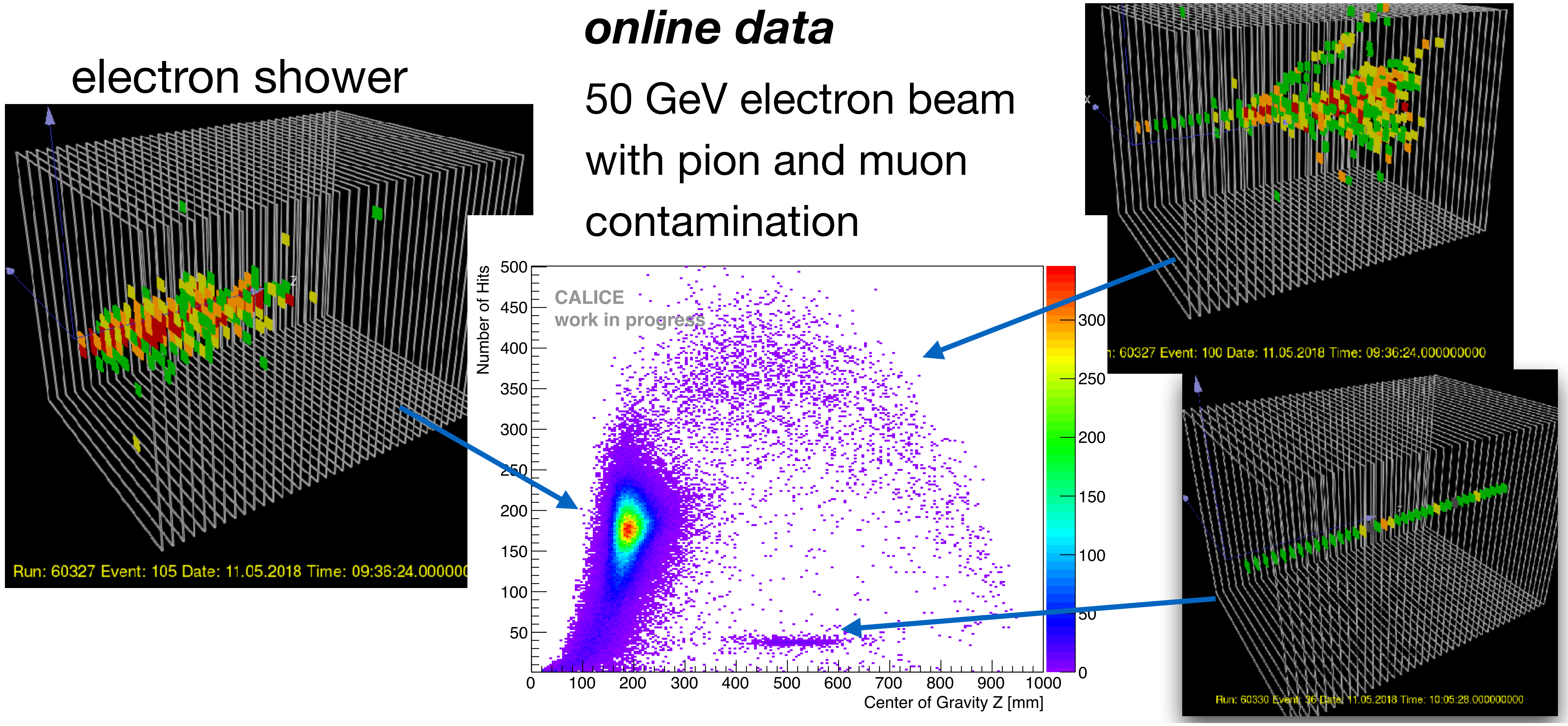

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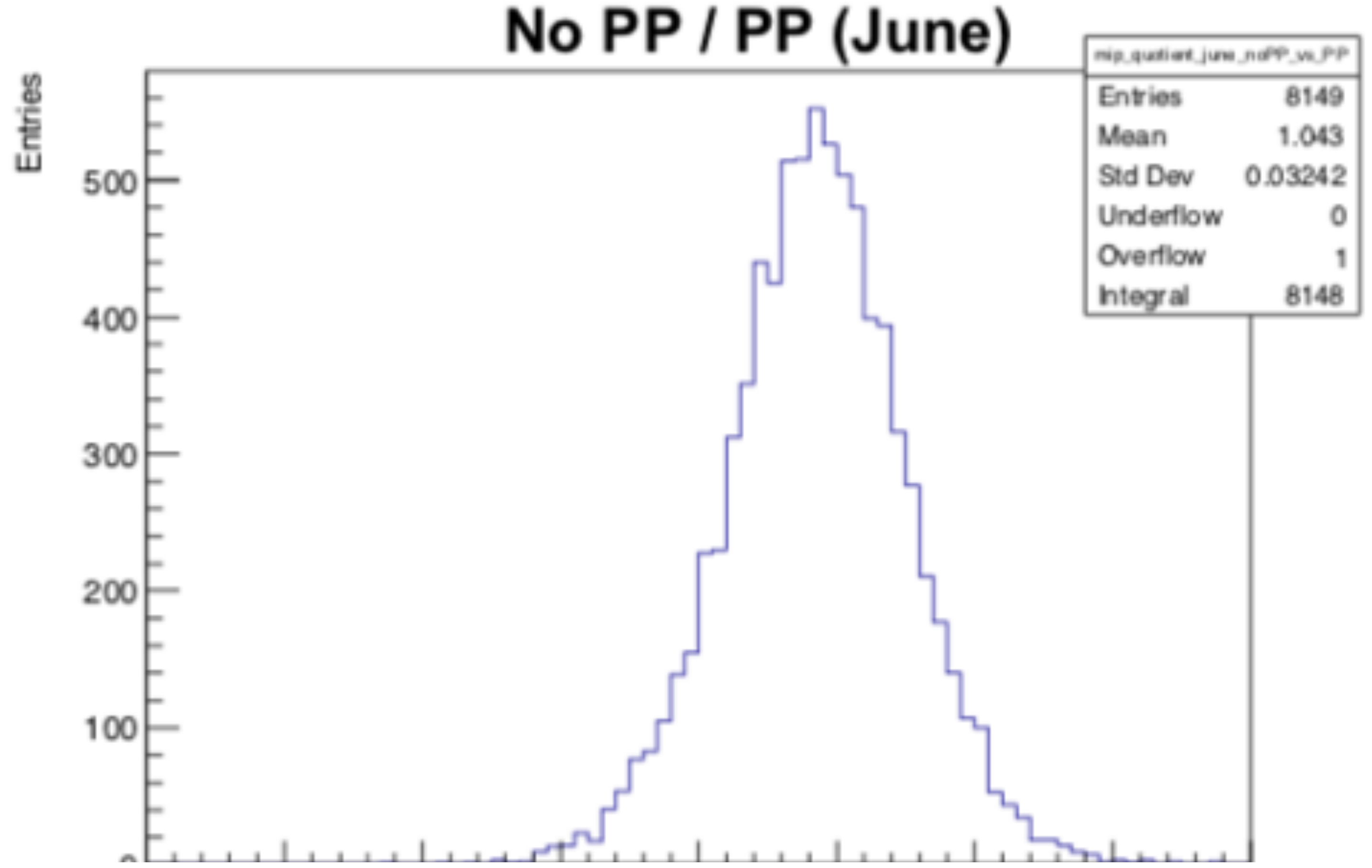
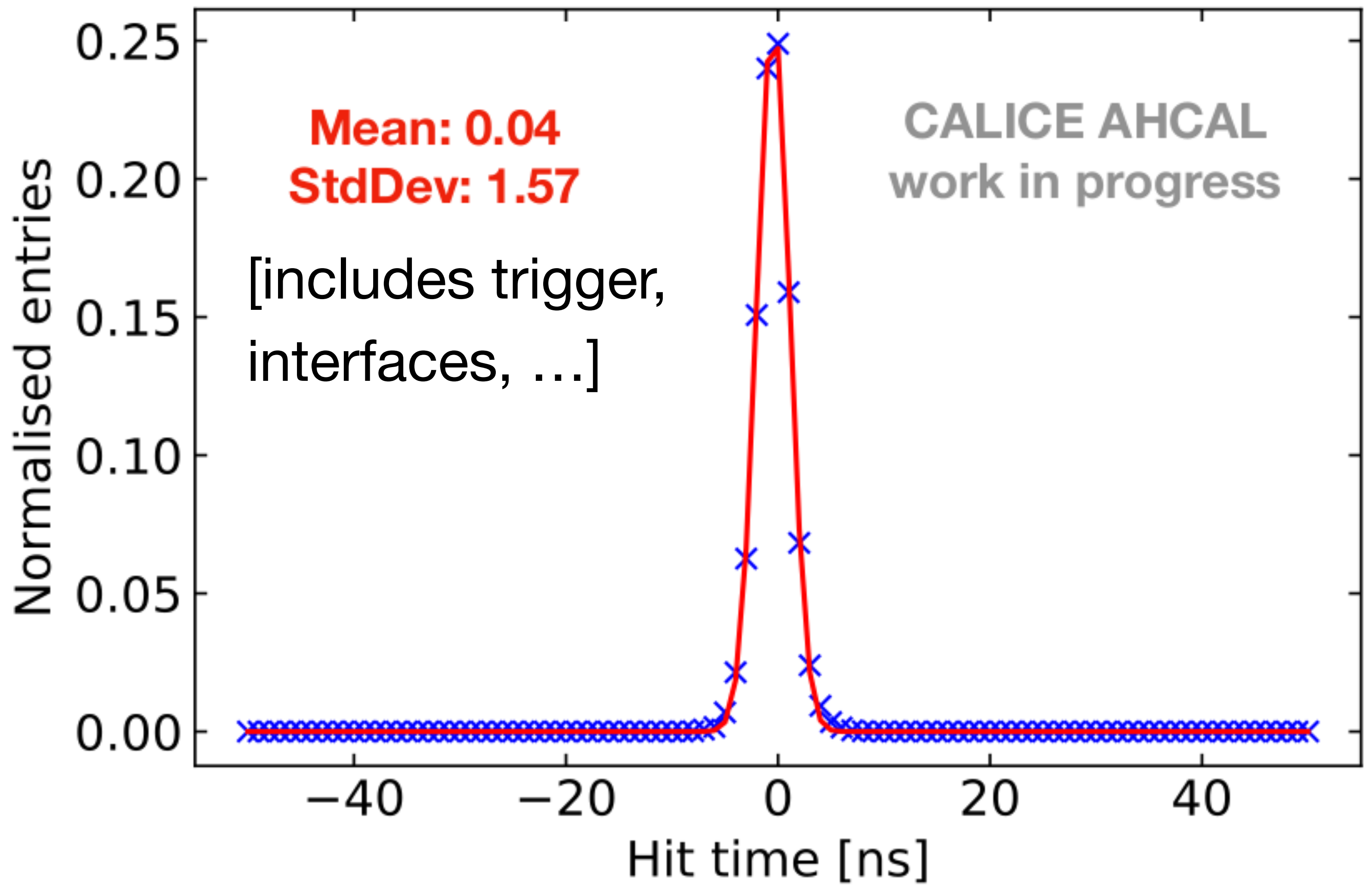


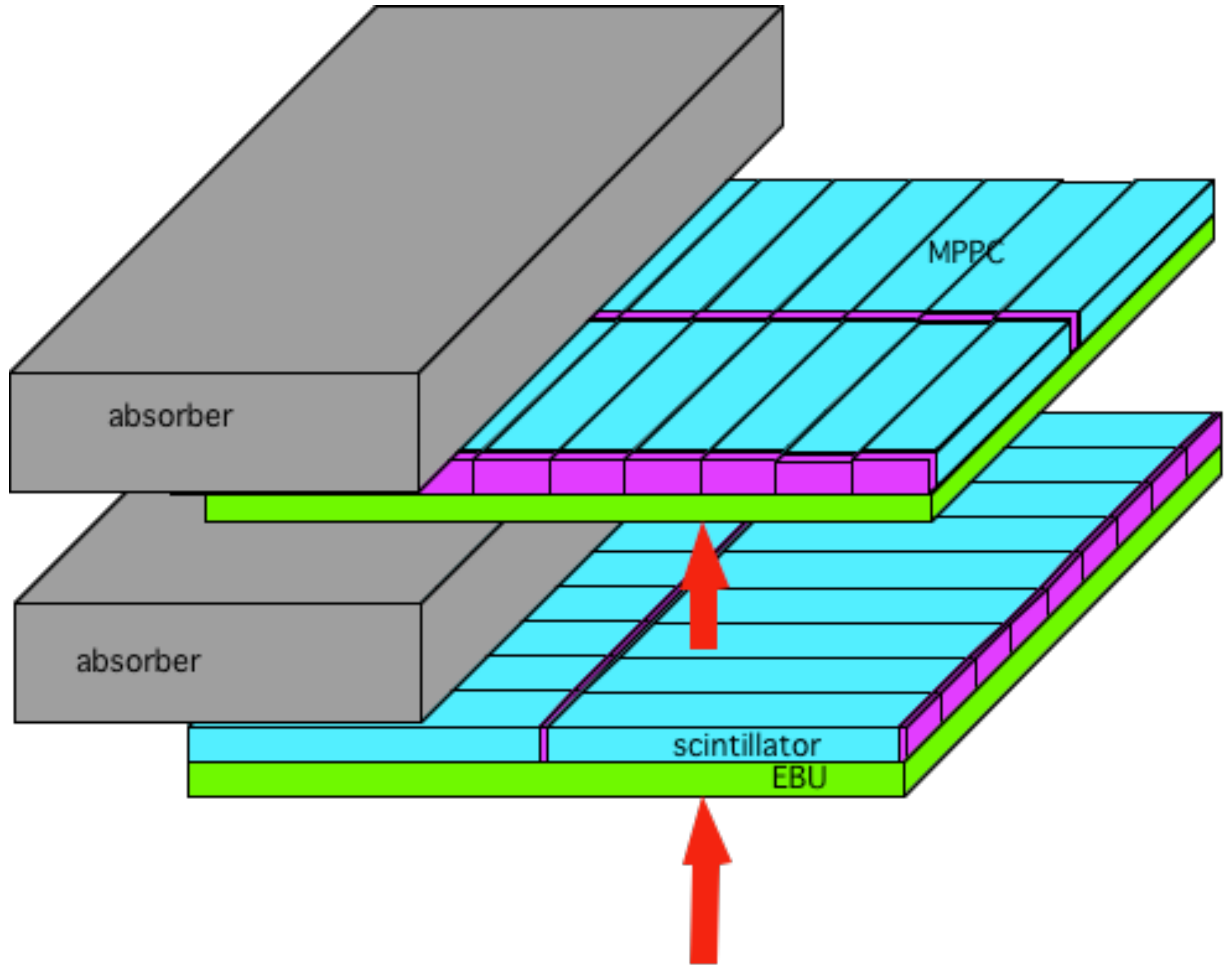


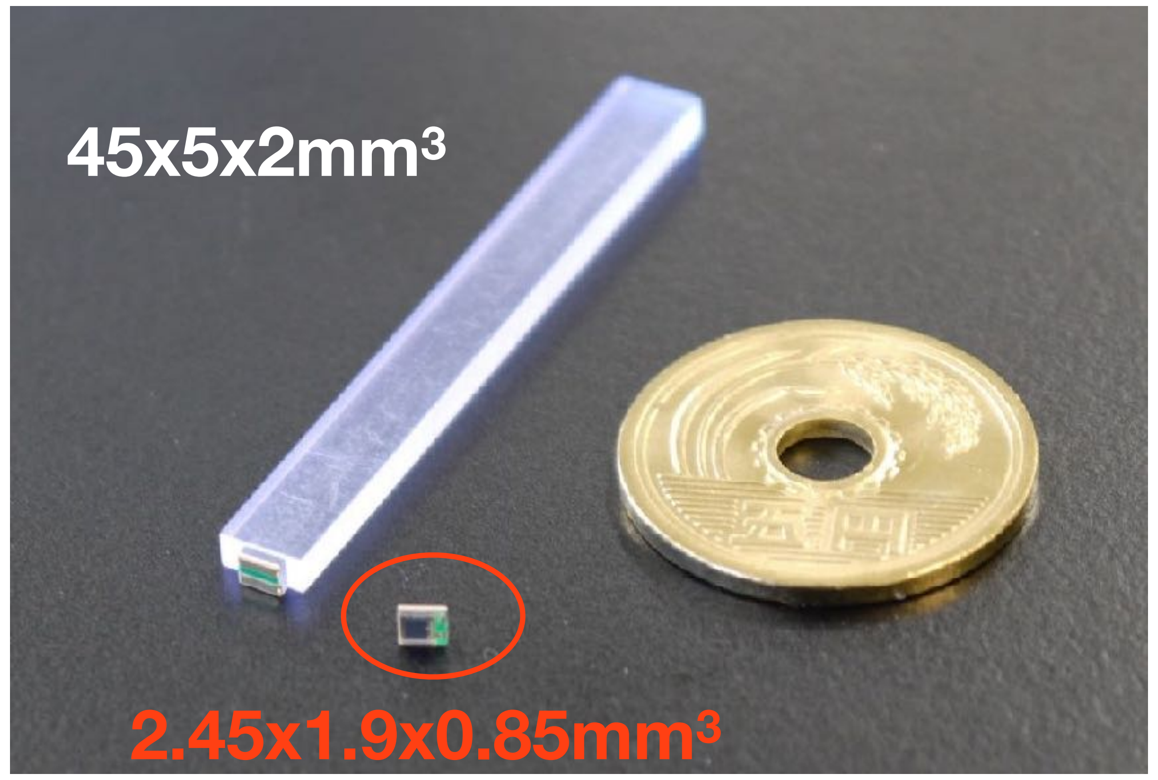
Single cell timing for MIPs ~ 0.8 ns

Technical Realisation

The Scintillator ECAL

- Based on (slightly modified) AHCAL technology
  - 32 layer prototype currently under construction in China in the framework of CEPC (but with LC electronics)





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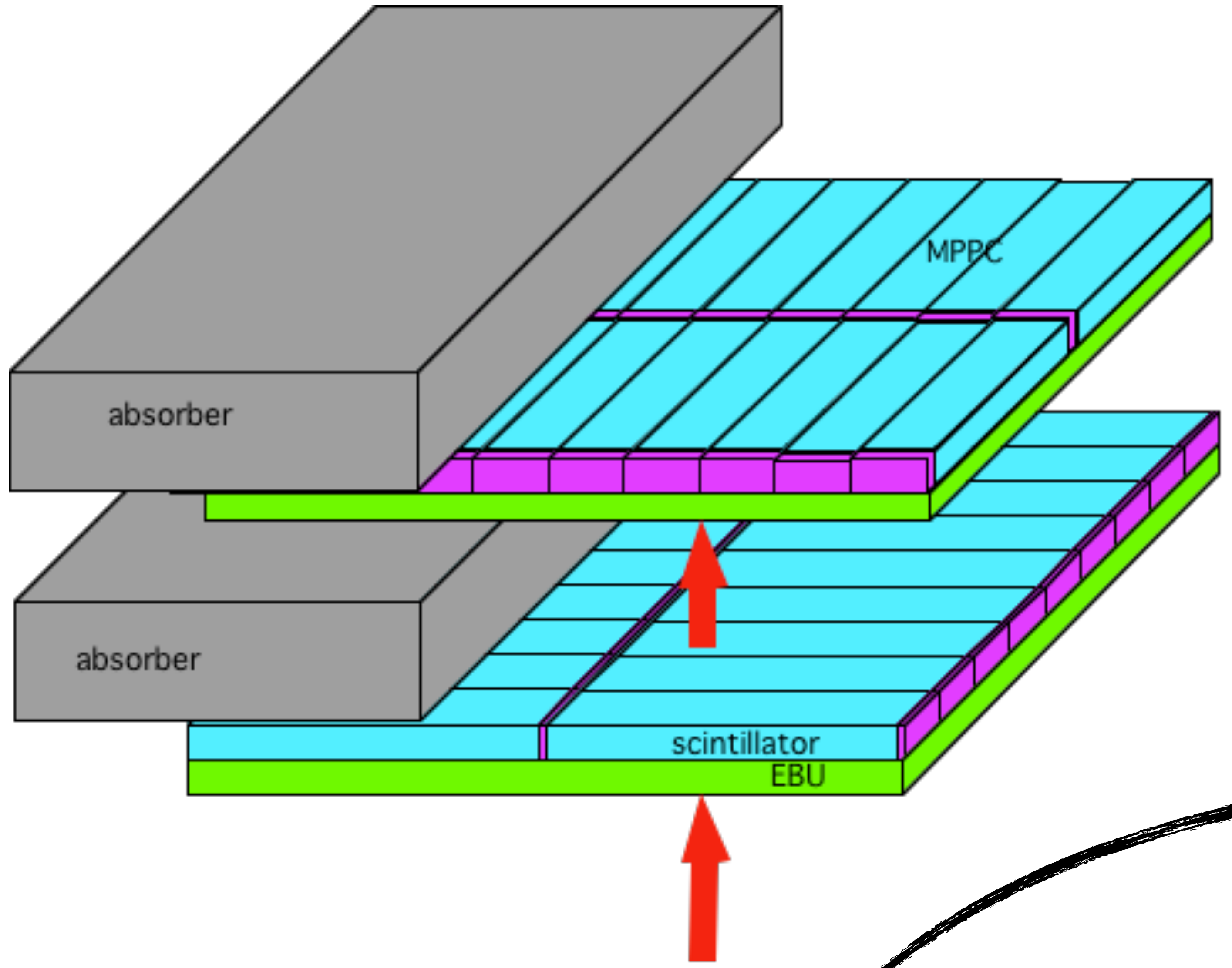

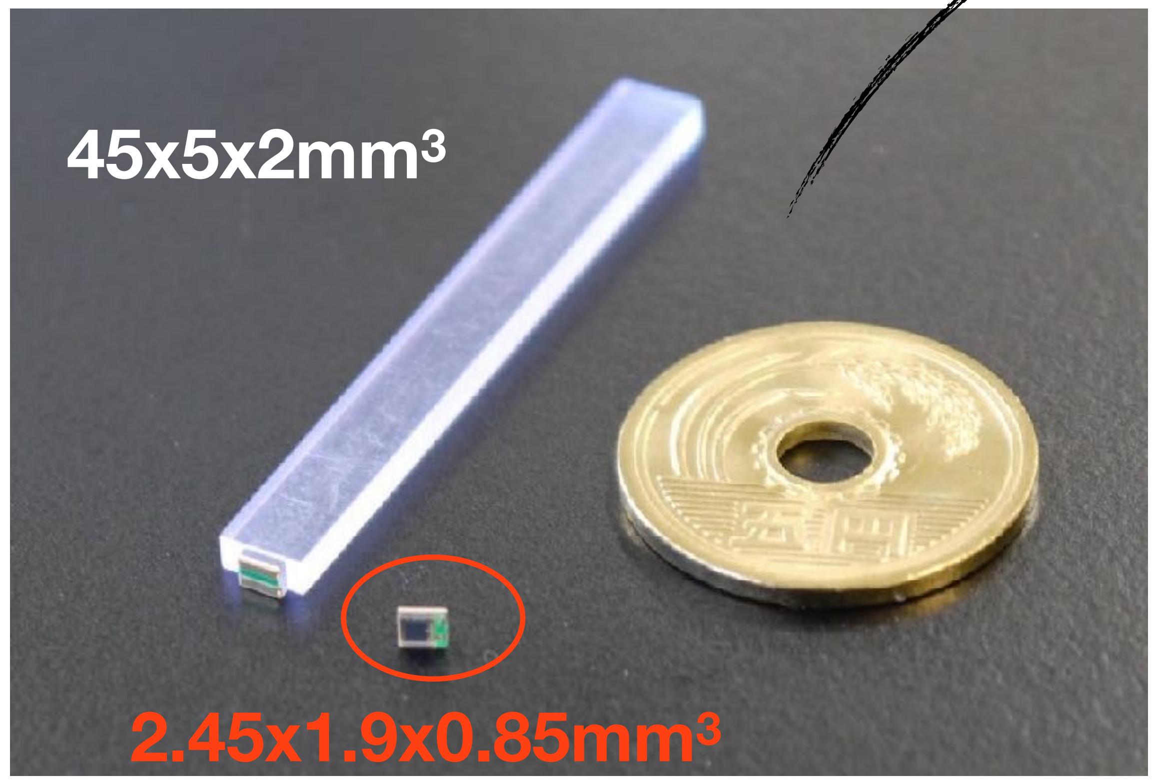

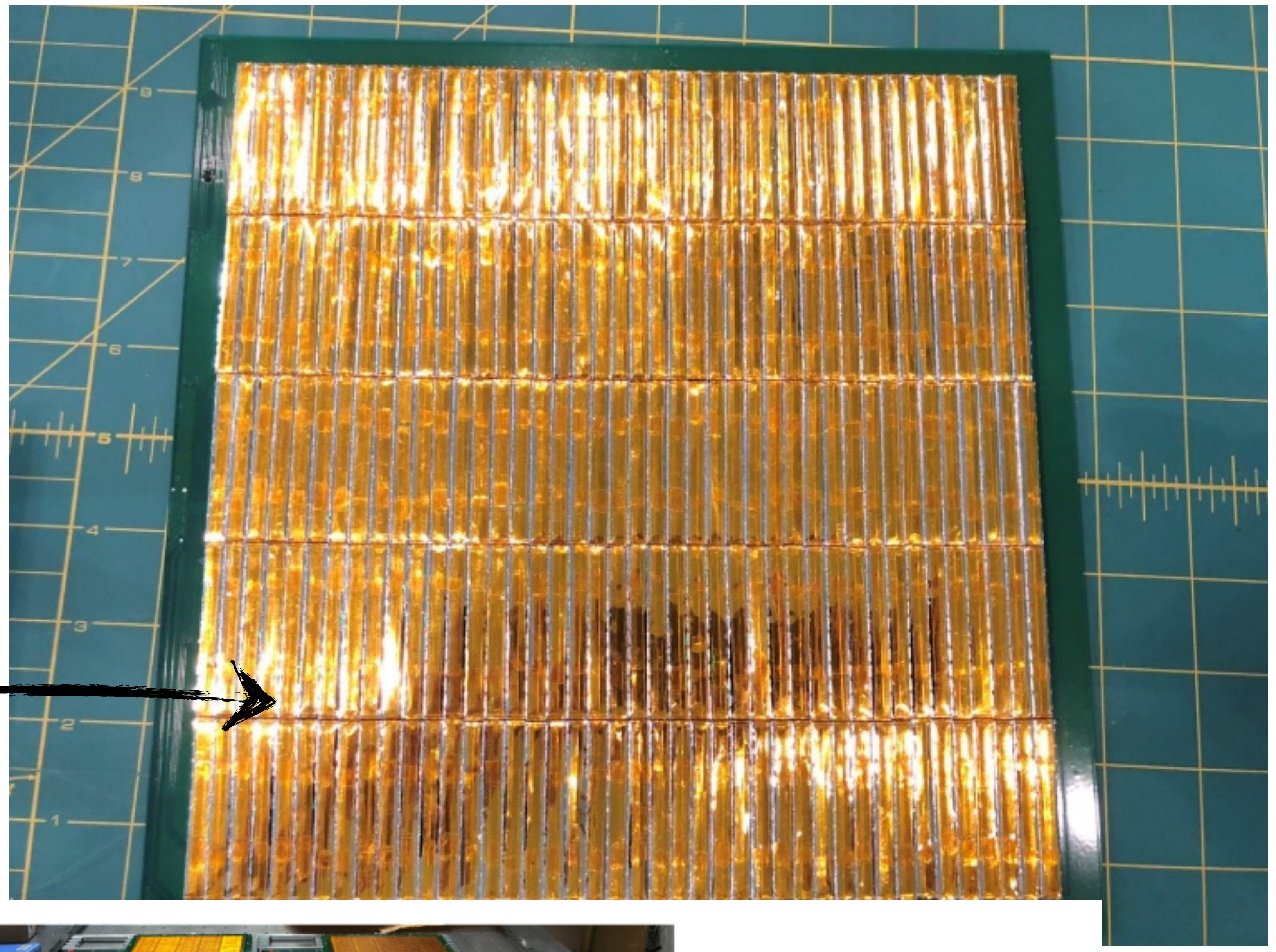

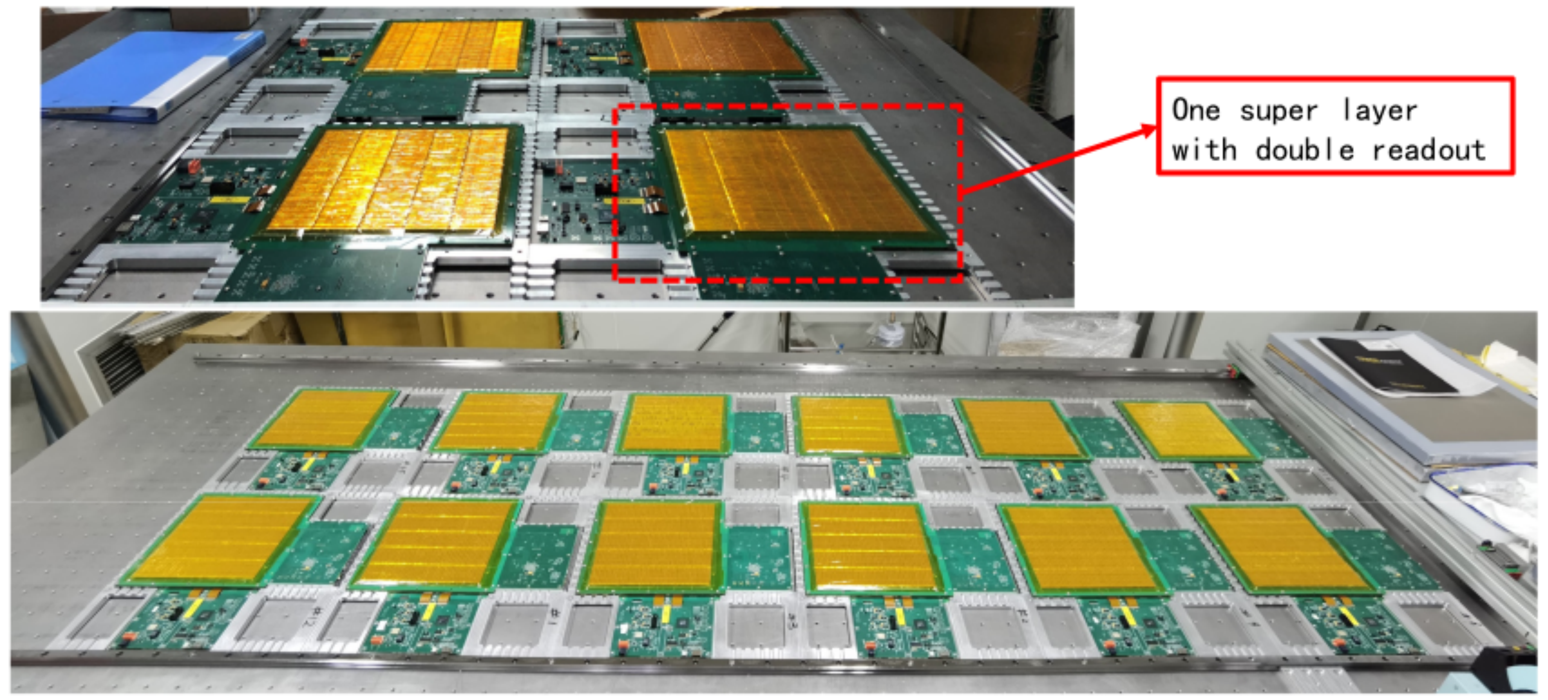

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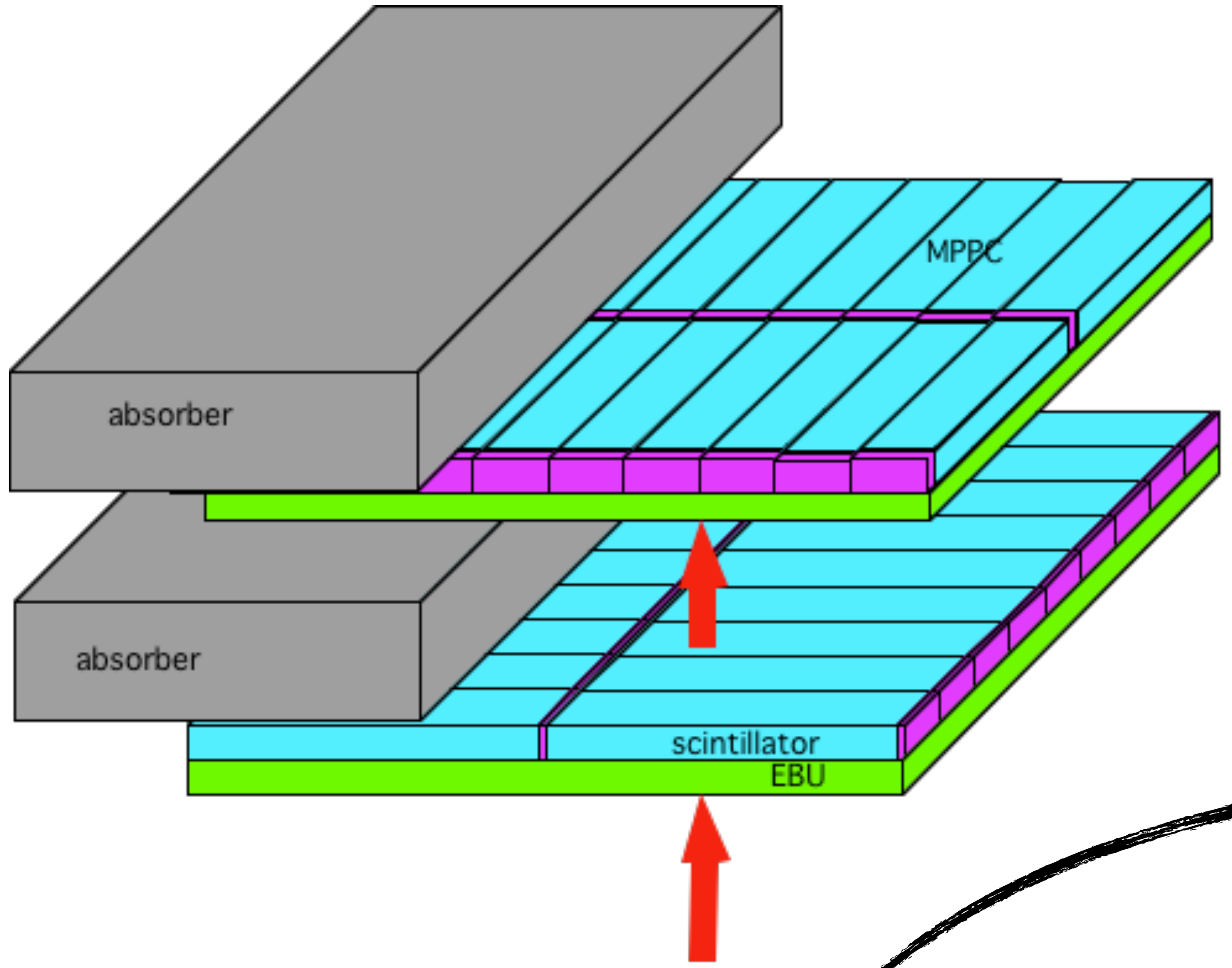
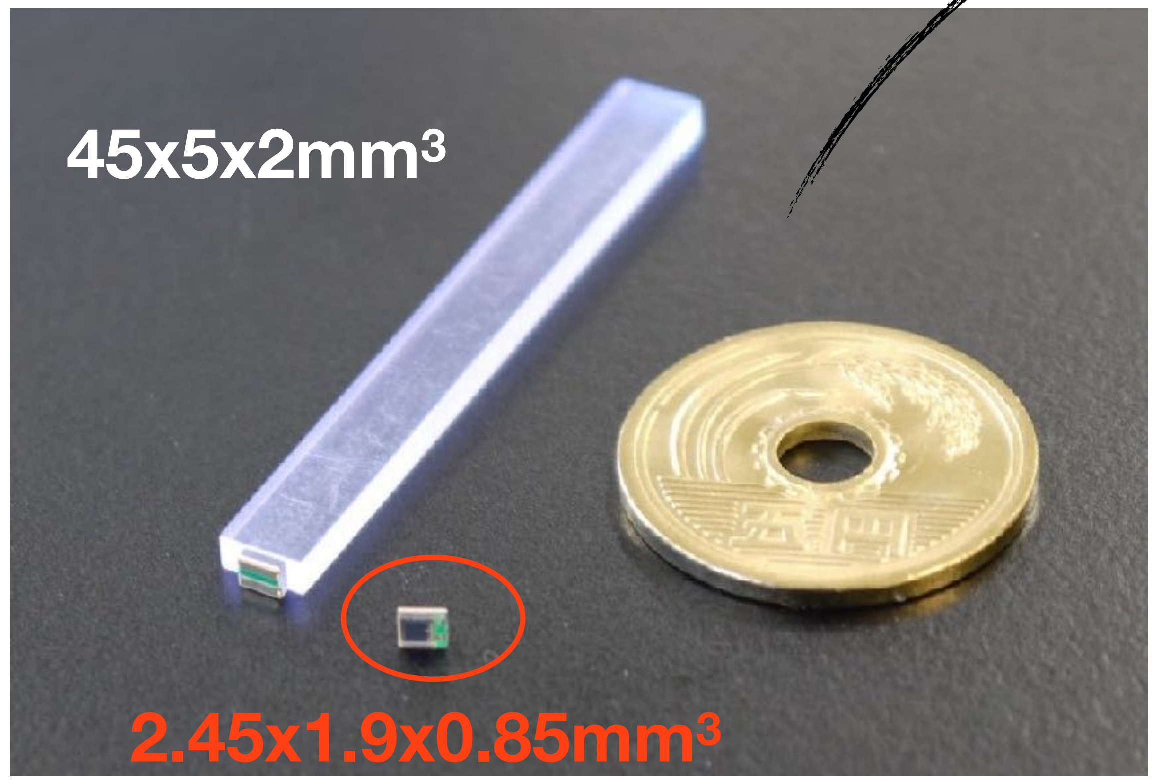
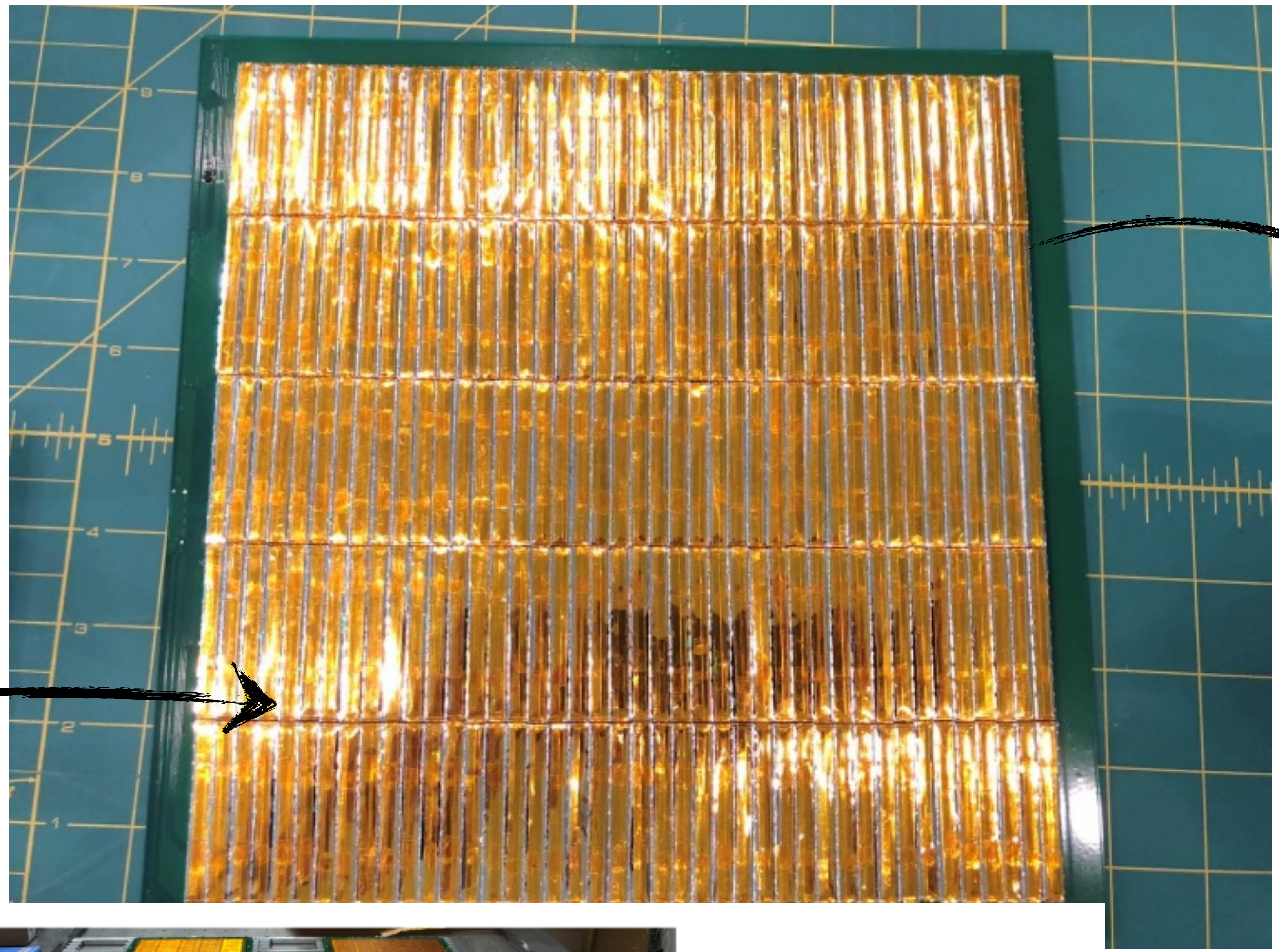
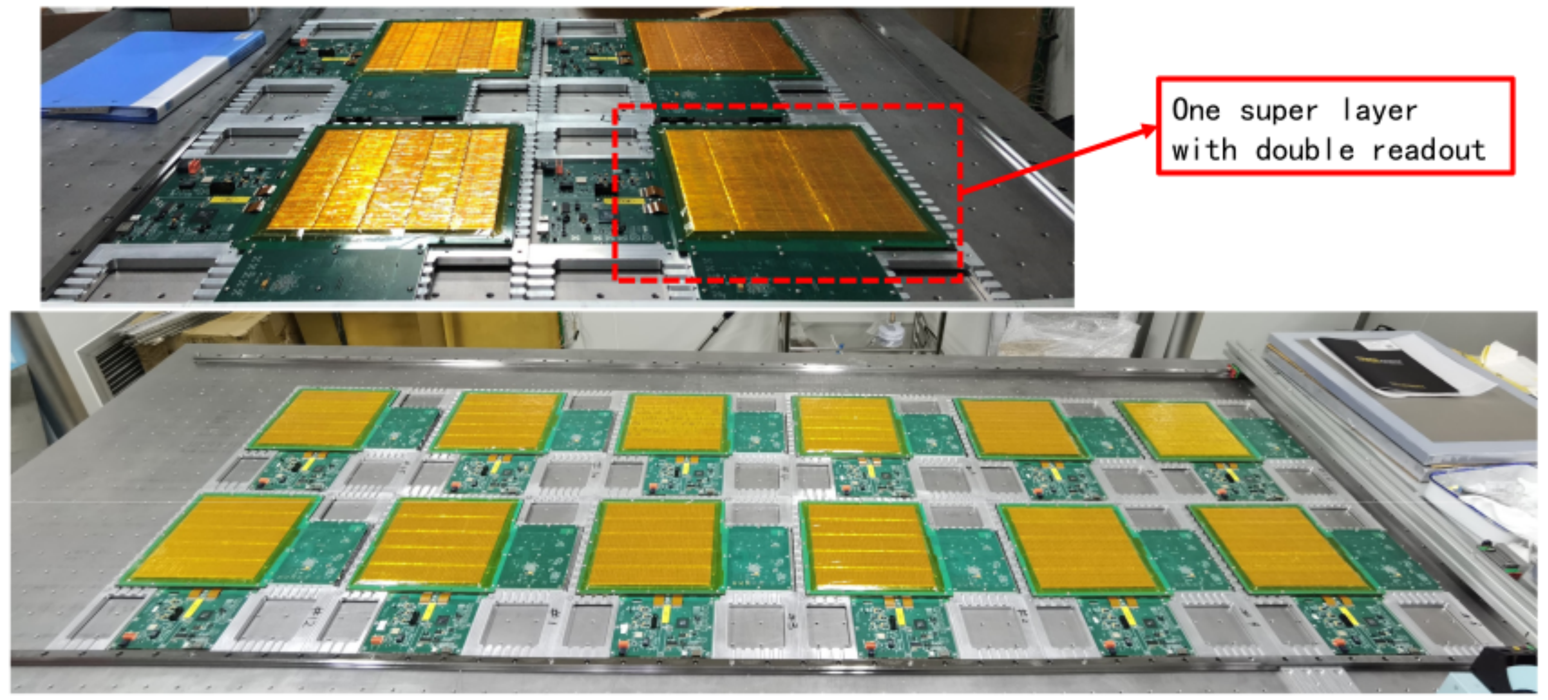
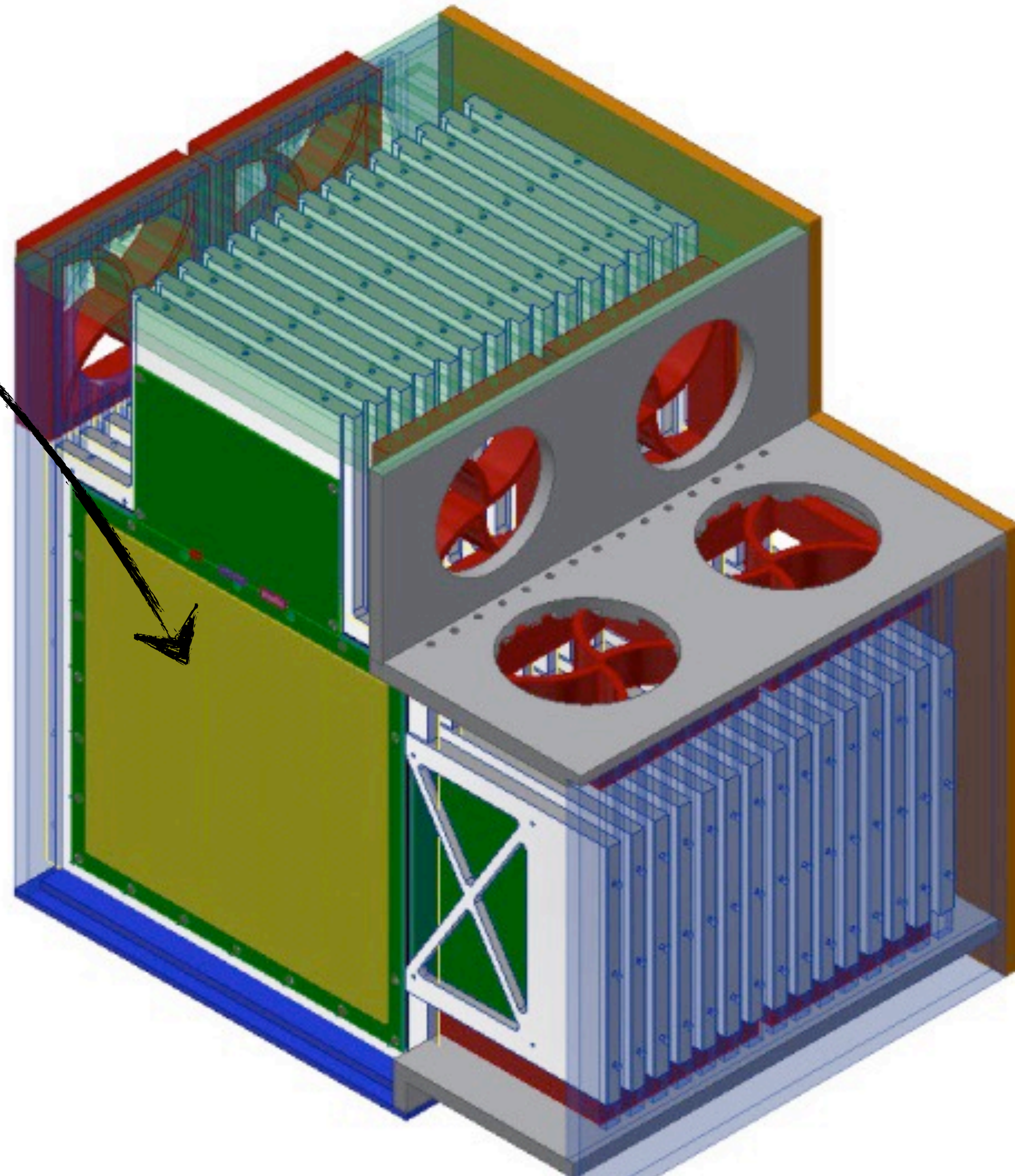








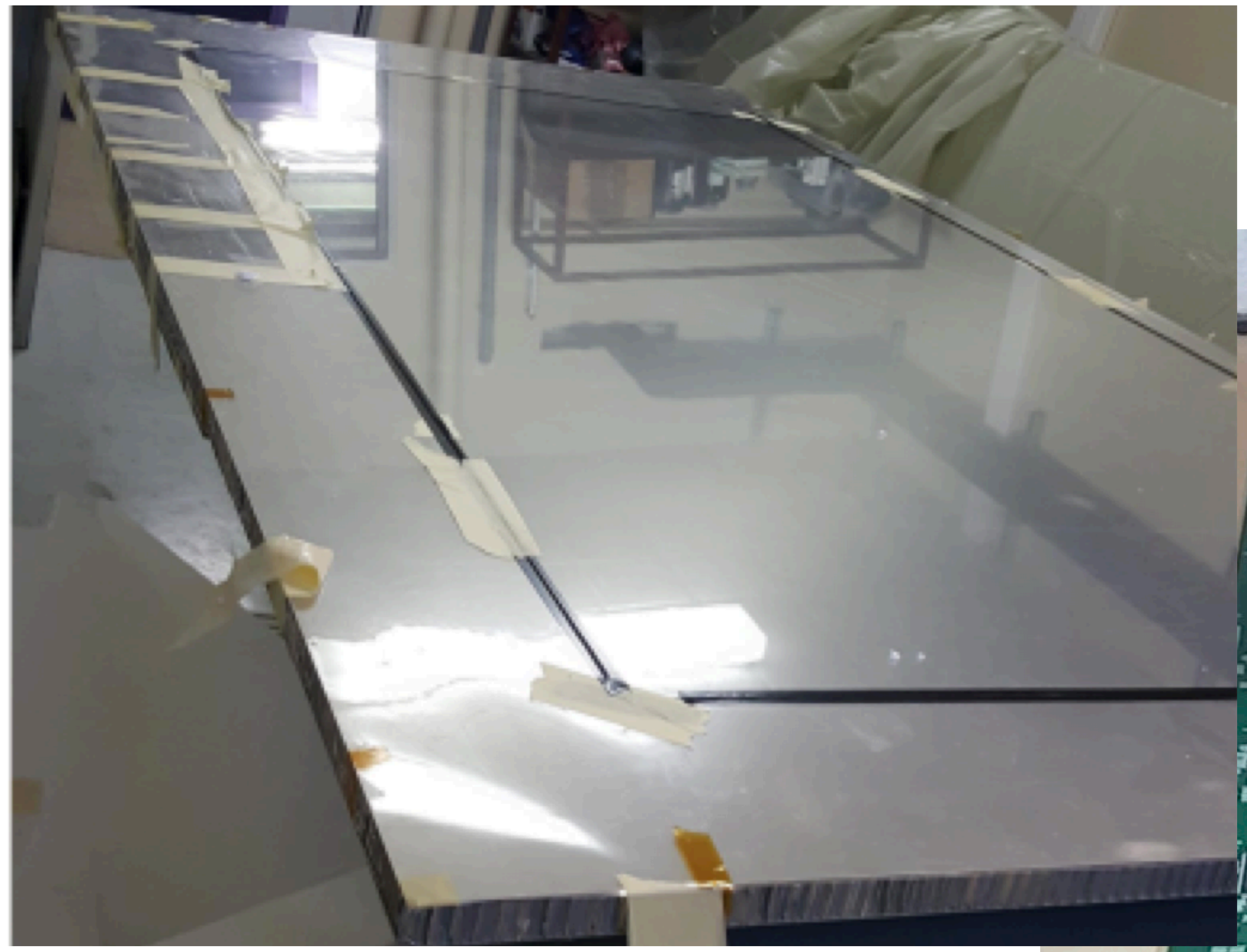


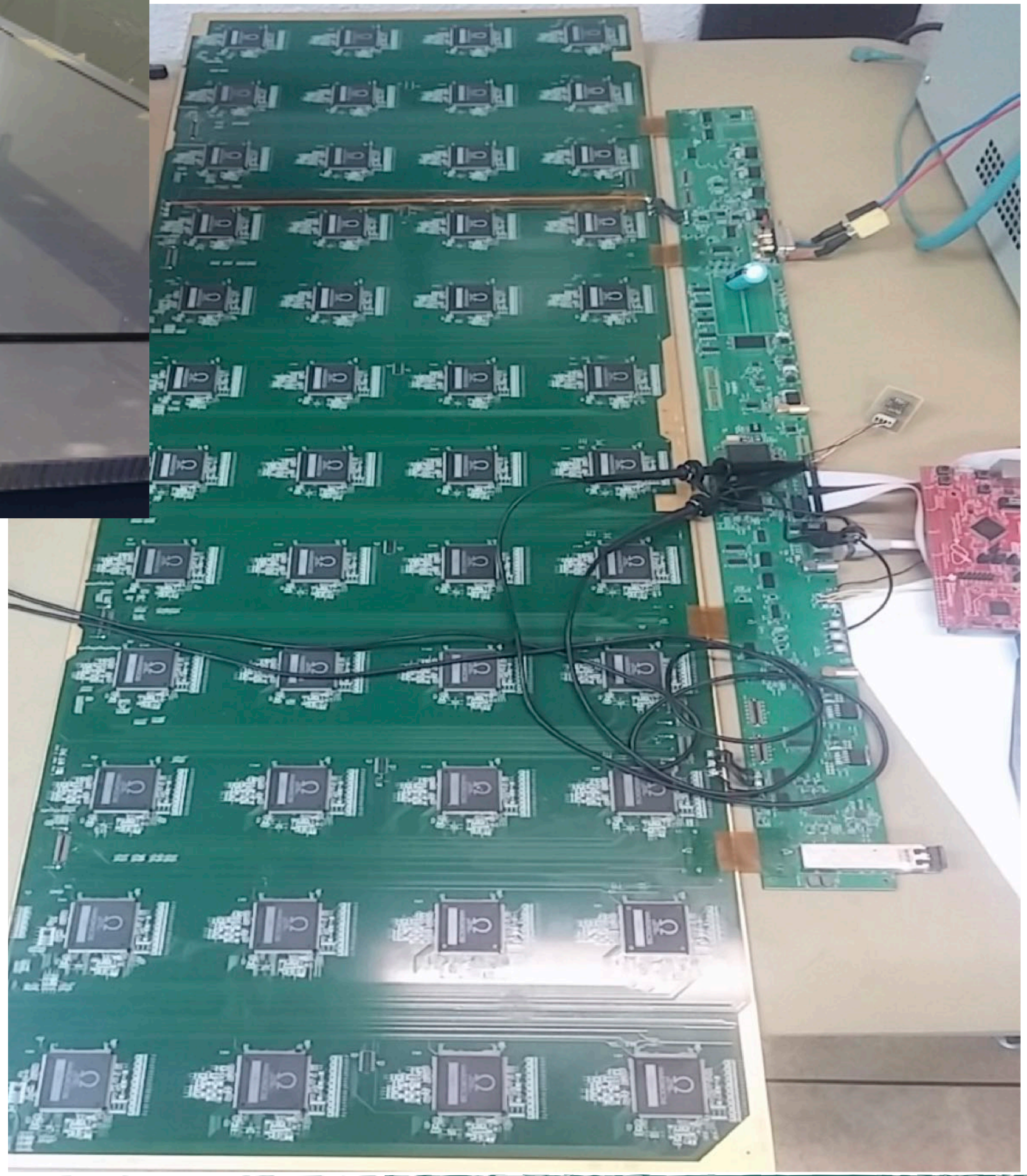
successful test of superlayers with cosmics, preparing for beam at DESY in early 2021

Technical Realisation

Semi-digital HCAL

- Large-area RPCs with integrated electronics





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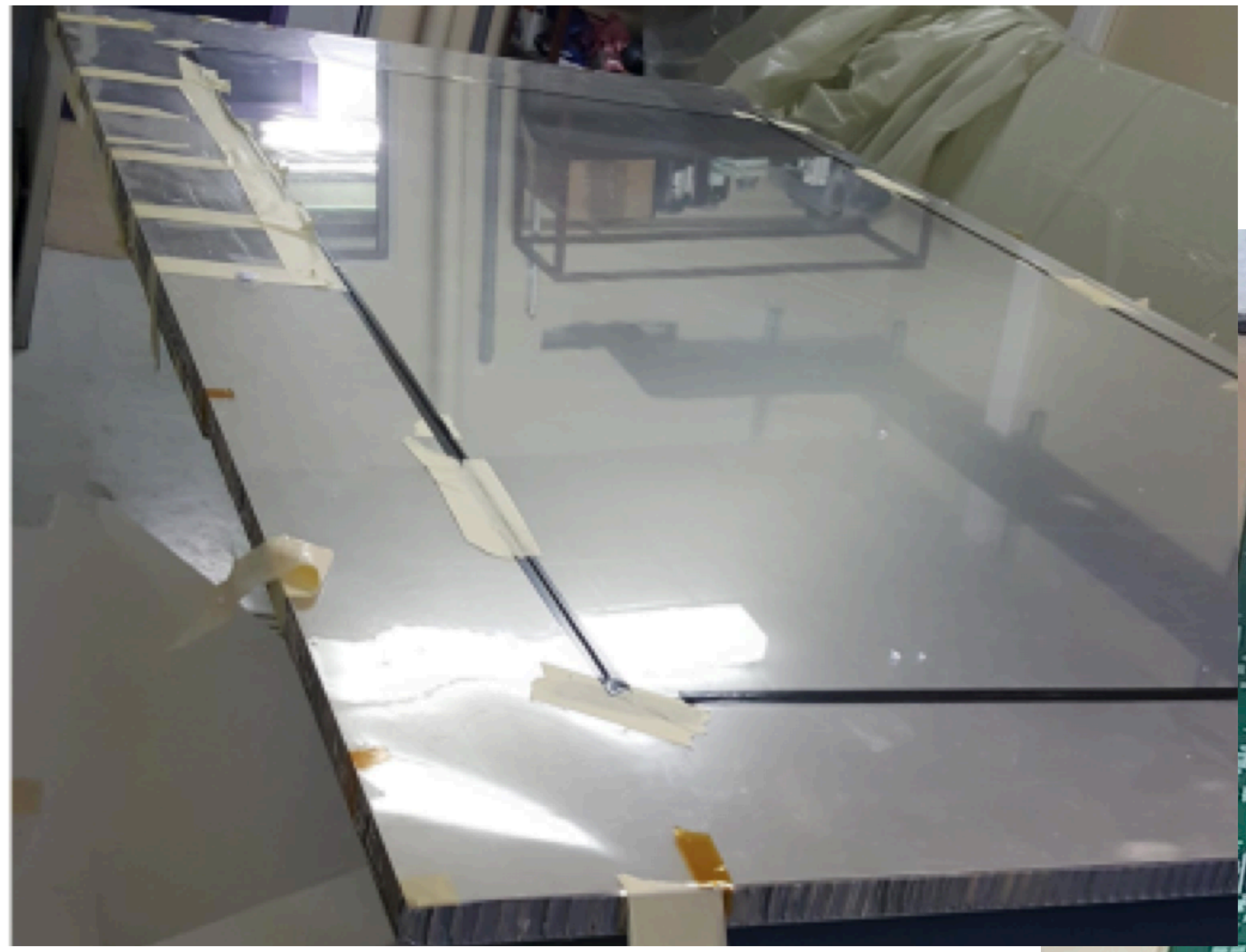
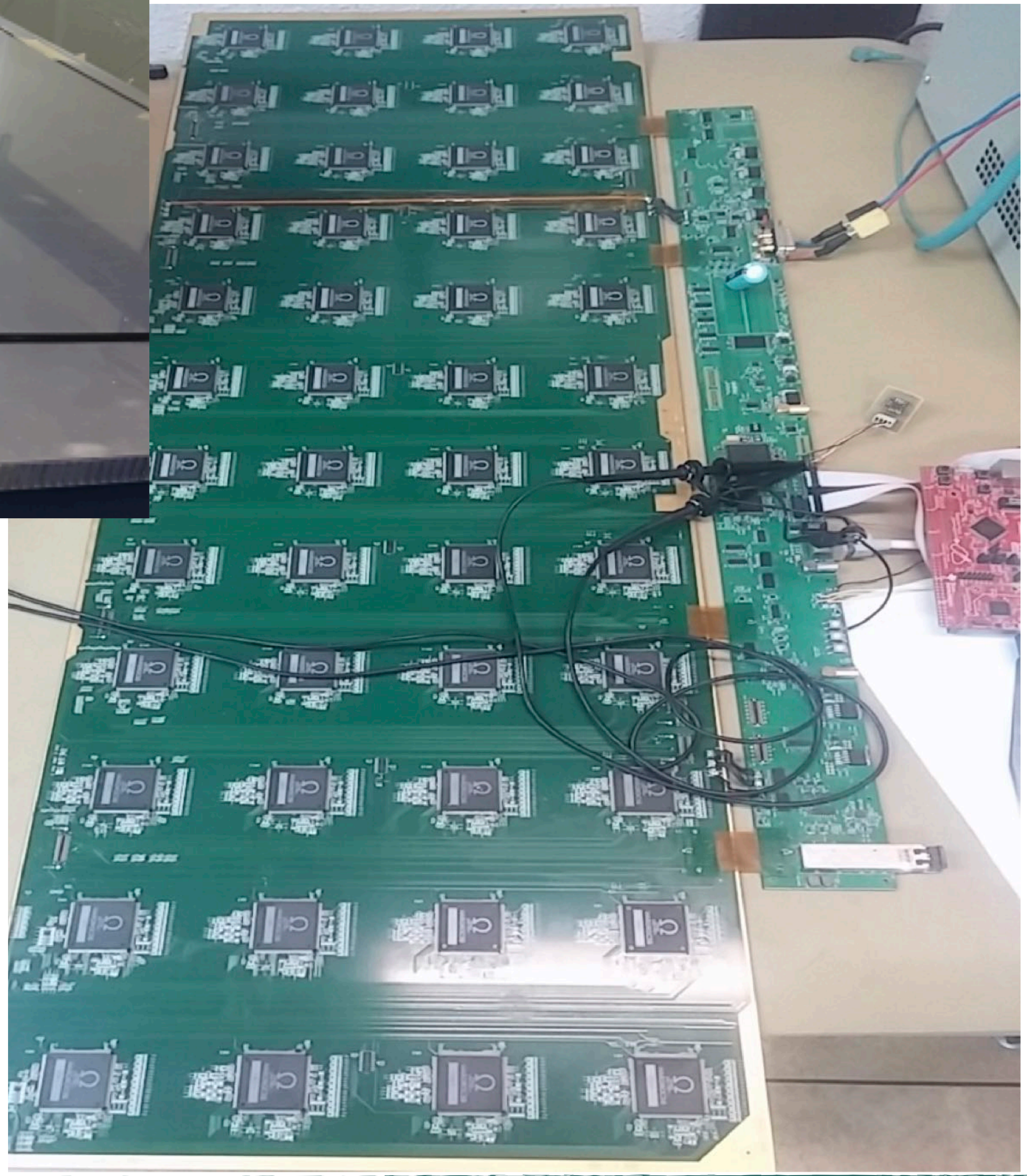




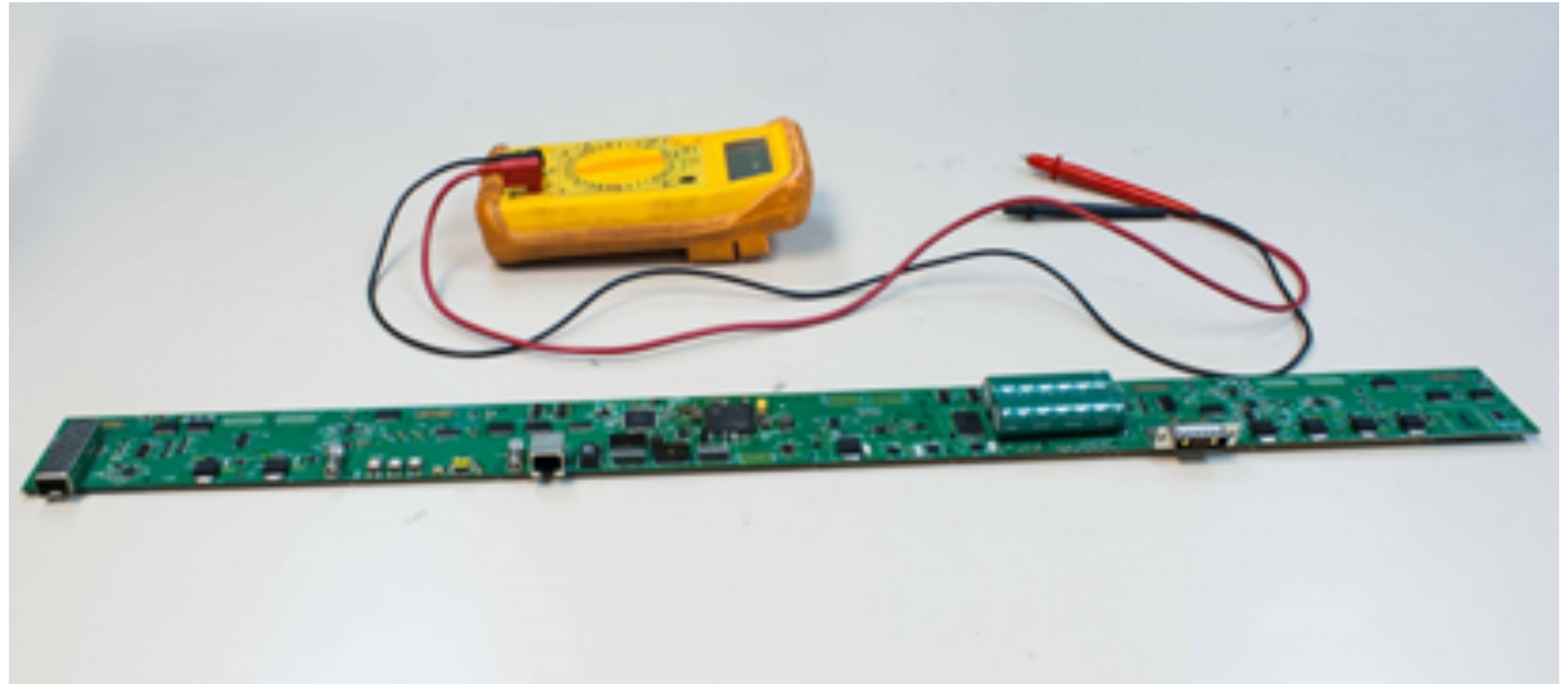
… and highly precise mechanical structures.

R&D on Electronic Interfaces

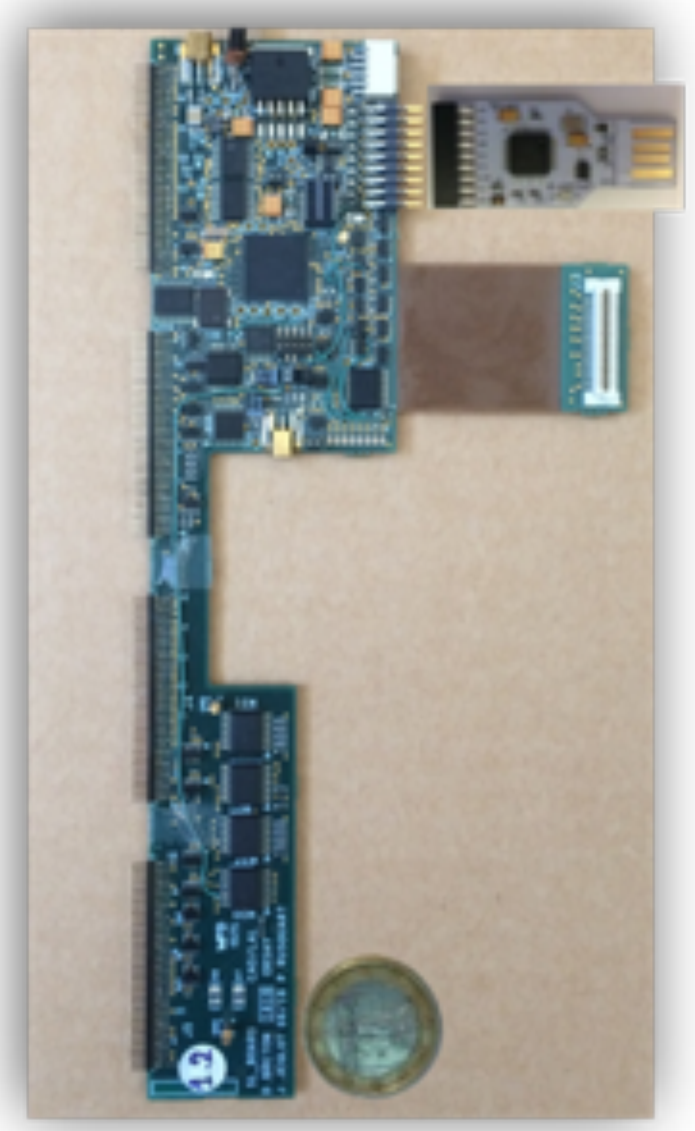
A Common-interest Item

Current ***AHCAL*** detector interface card

Current ***SDHCAL*** detector interface card



Current ***SiW ECAL*** detector interface card and thin detector unit

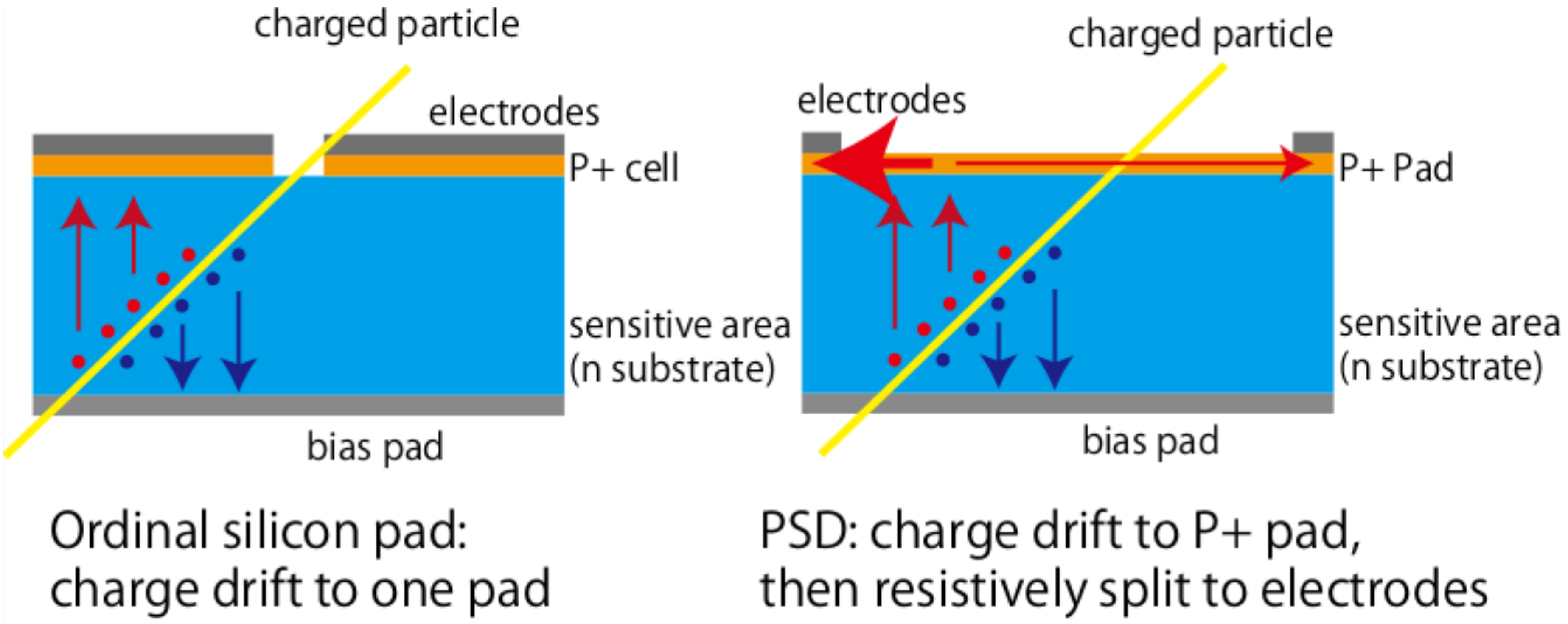


- Realize “dead-space free” calorimeter systems with maximum compactness
- Applicable in a variety of different contexts

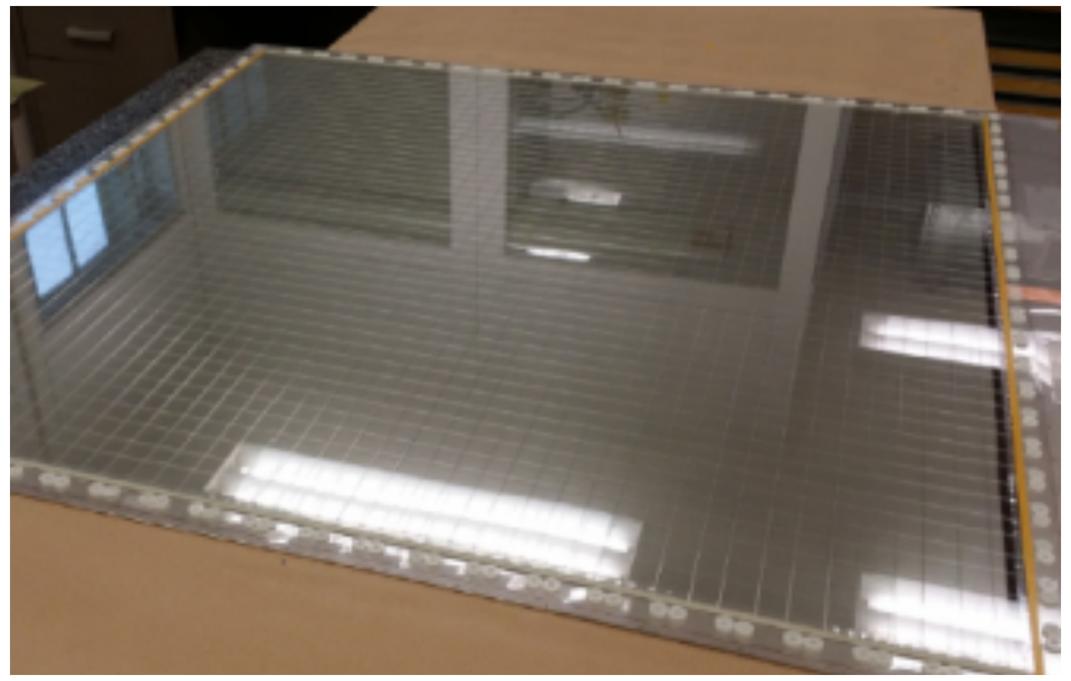
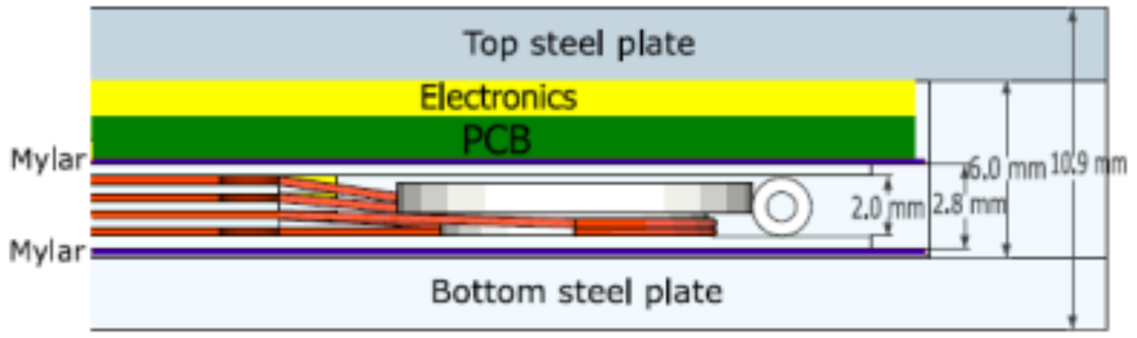
R&D on Materials and Sensors

Evolving existing concepts, adding new ideas

- Position-sensitive silicon sensors



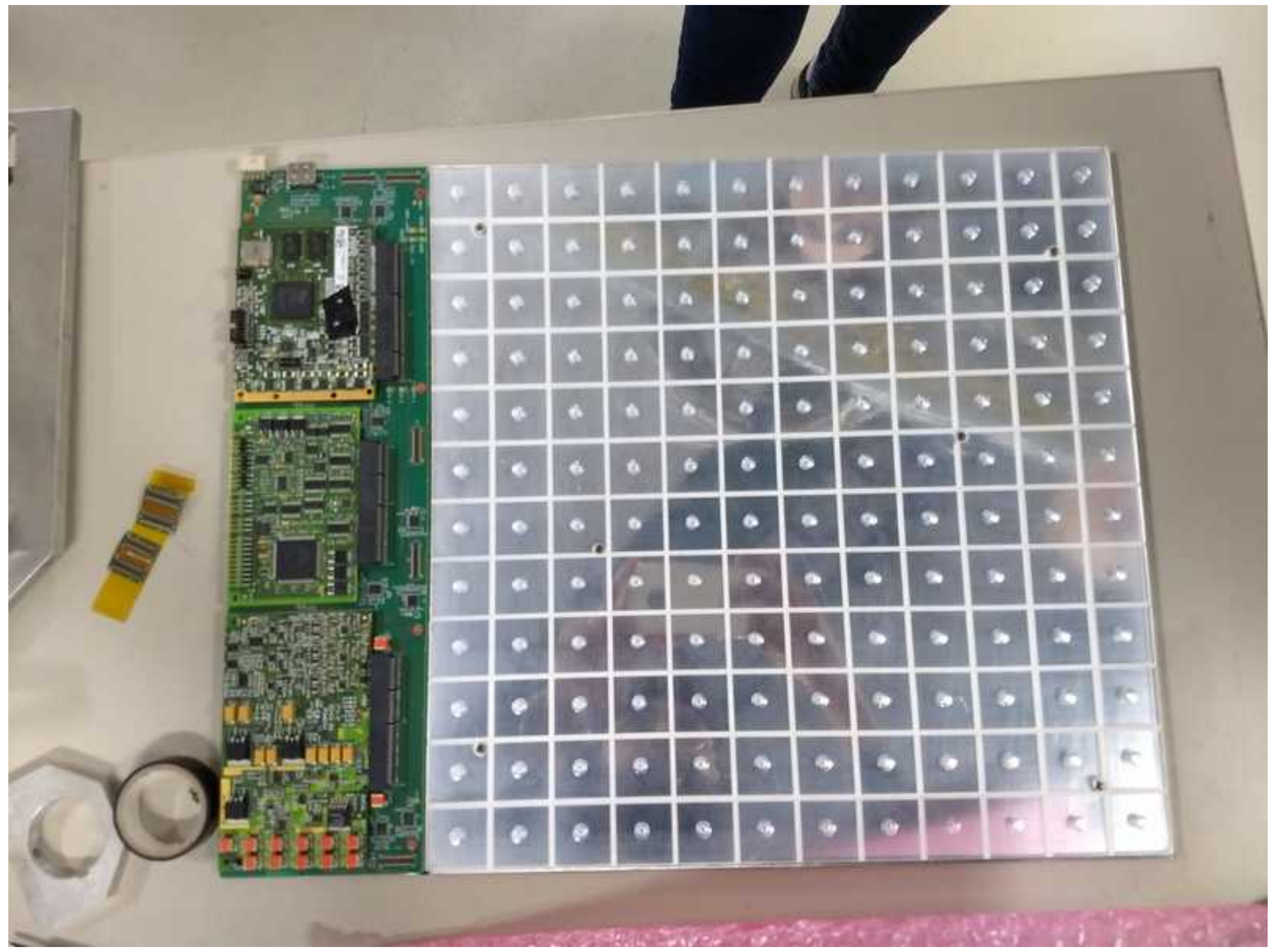
- 10s of ps - level timing

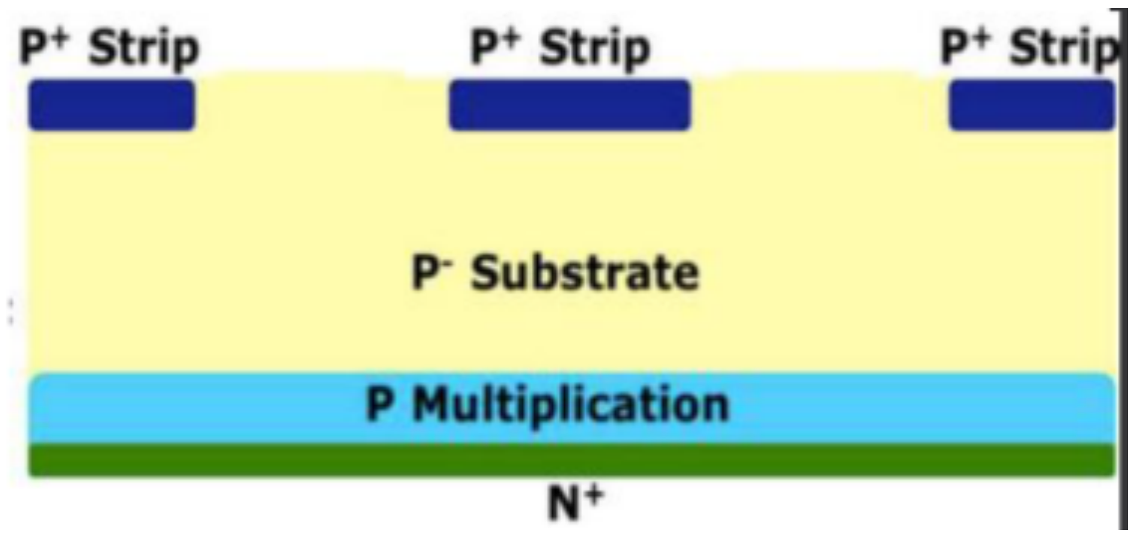



GRPCs with

< 20 ps time jitter

- Megatiles for scintillator-based calorimeters





Silicon-based timing sensors

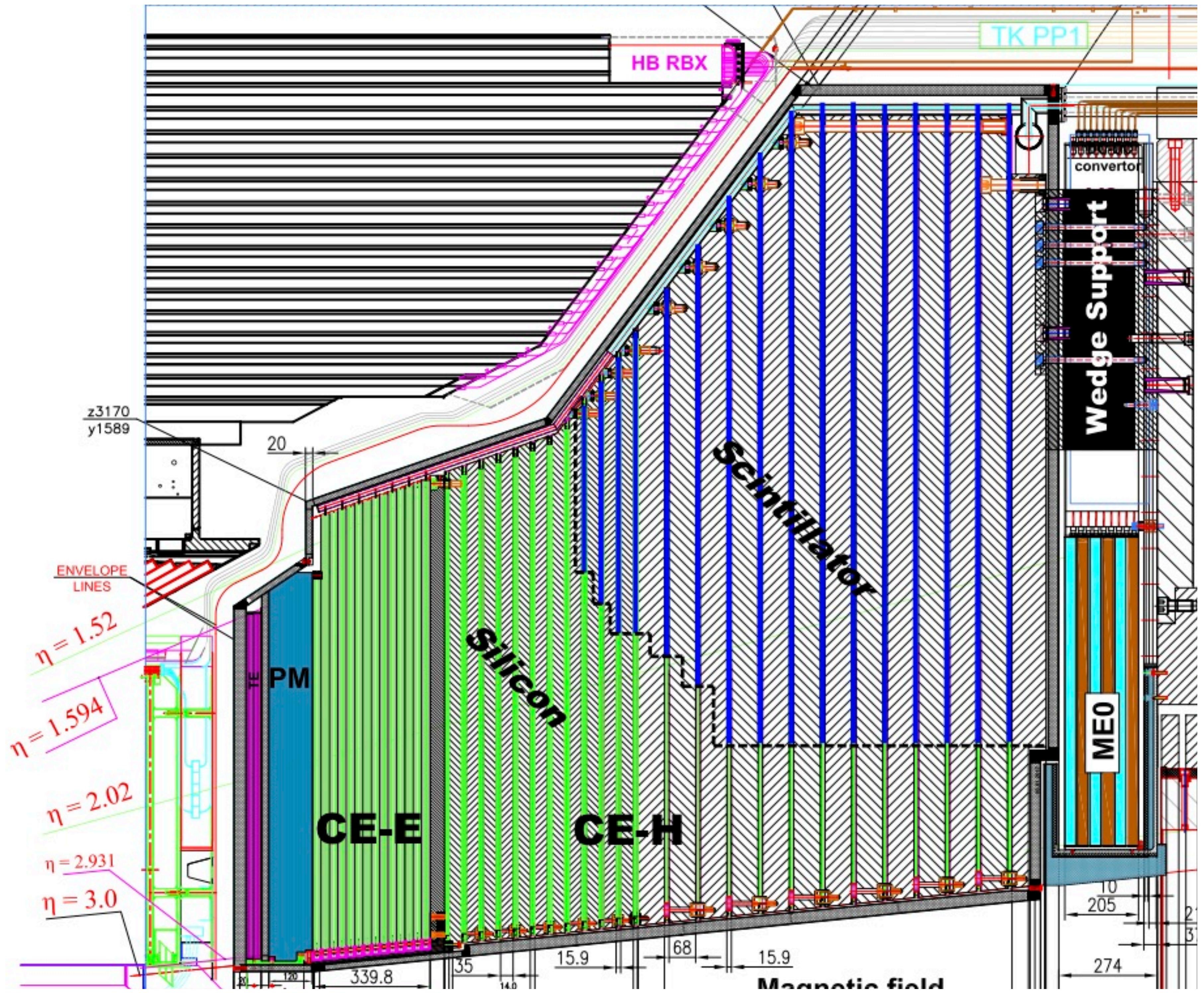
for example: Inverse APD as LGAD

Applications of CALICE Technologies

Highly granular calorimeters now widely adopted

- The developments in CALICE have paved the way for a number of applications of highly granular calorimeters and related technologies in HEP

Most prominent: The CMS Endcap Calorimeter Upgrade HGCal



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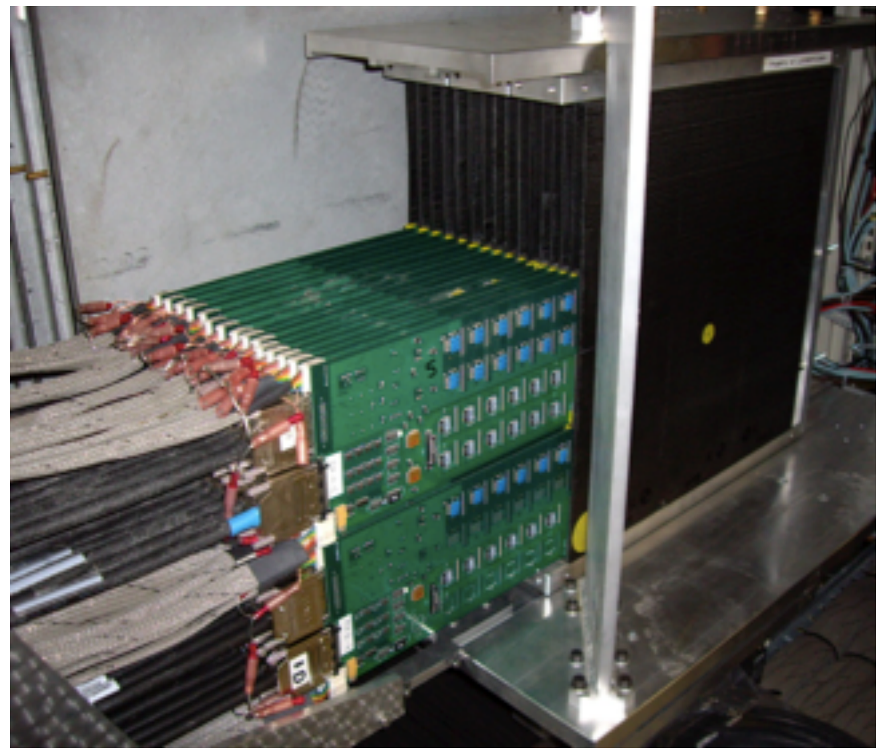

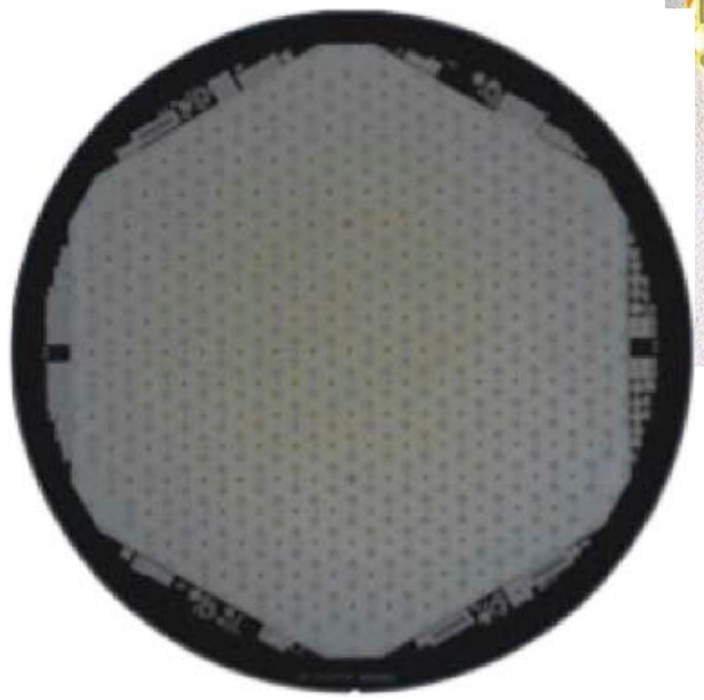

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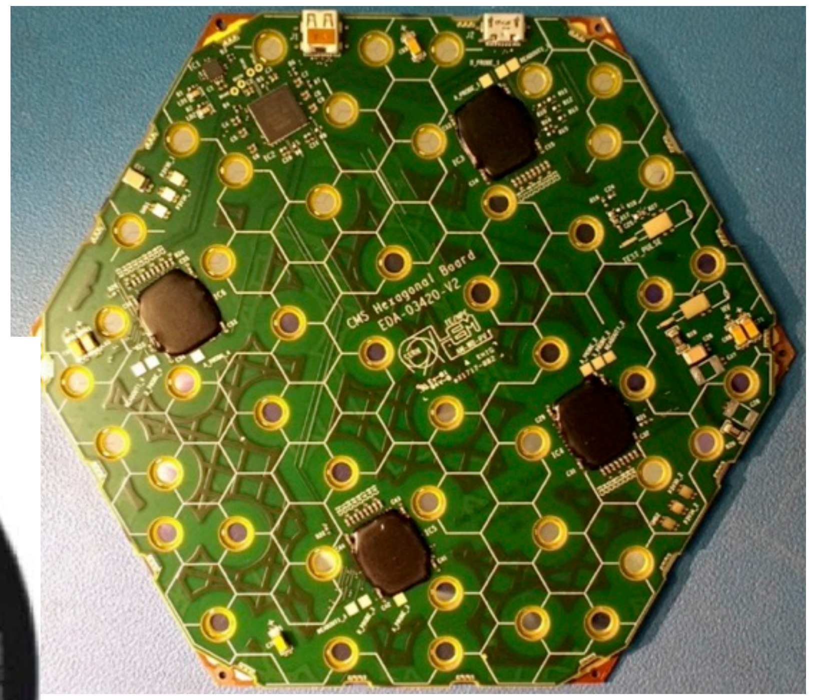

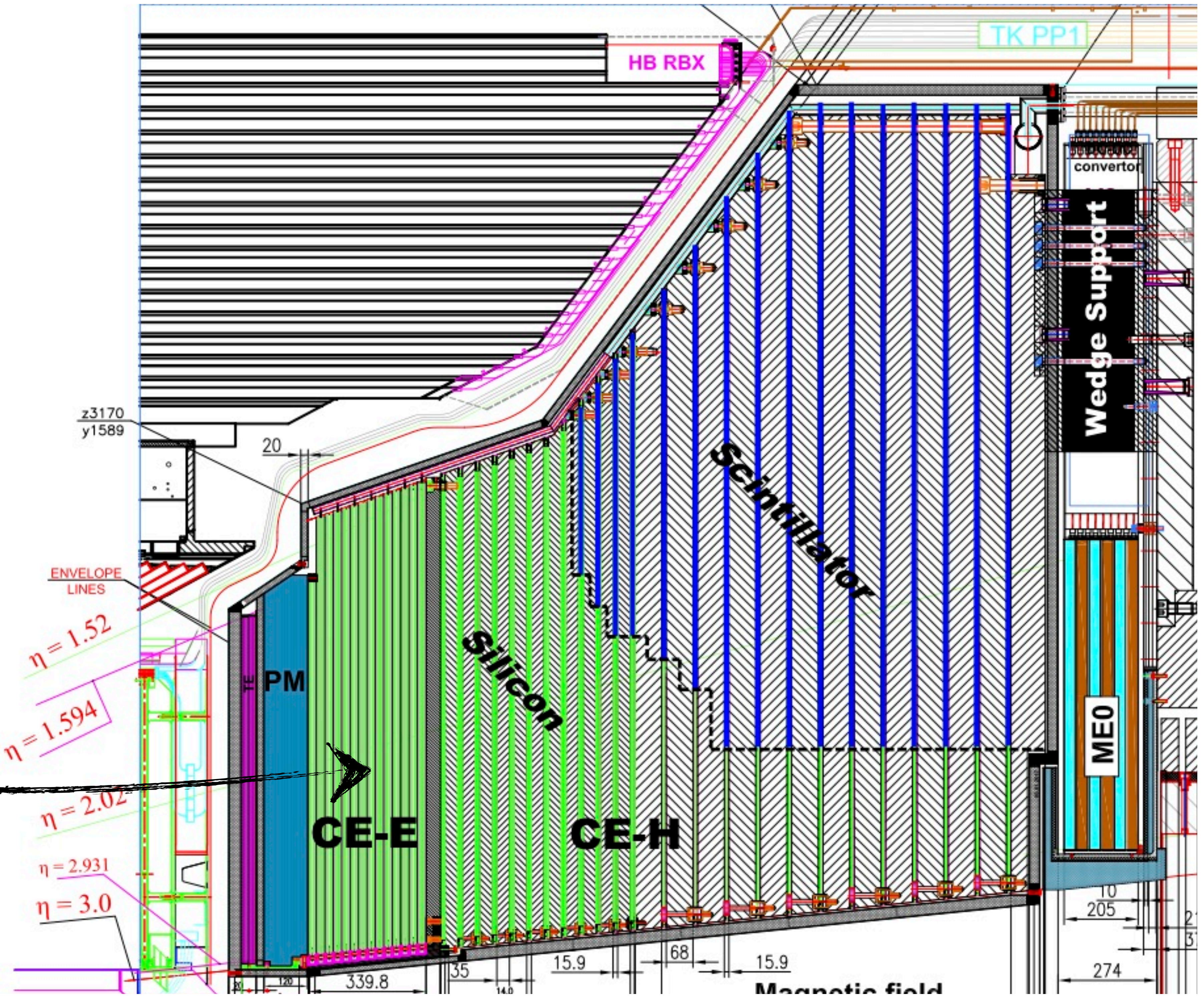

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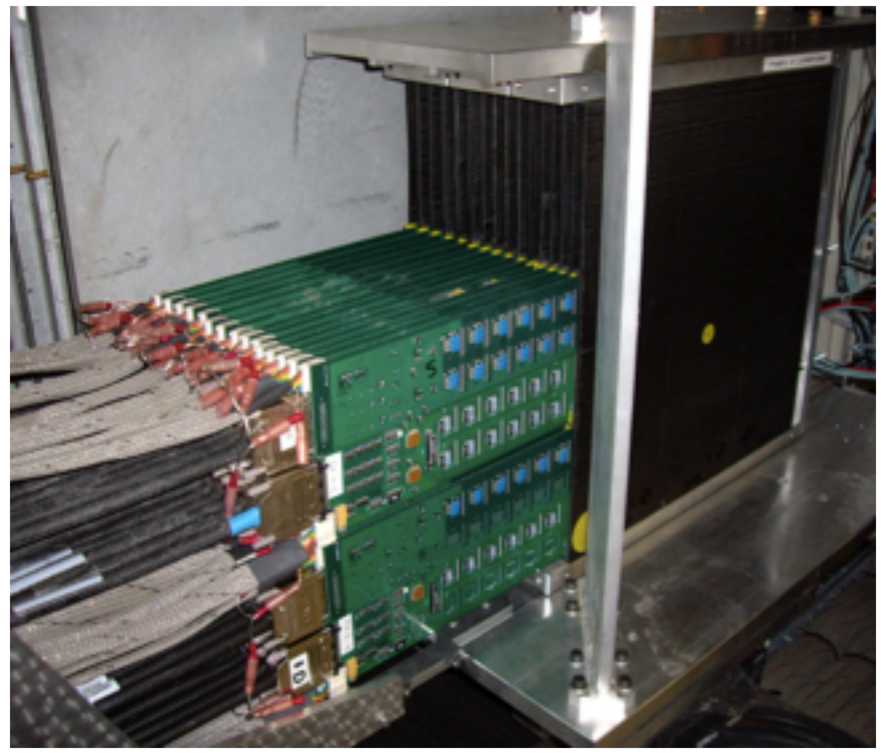

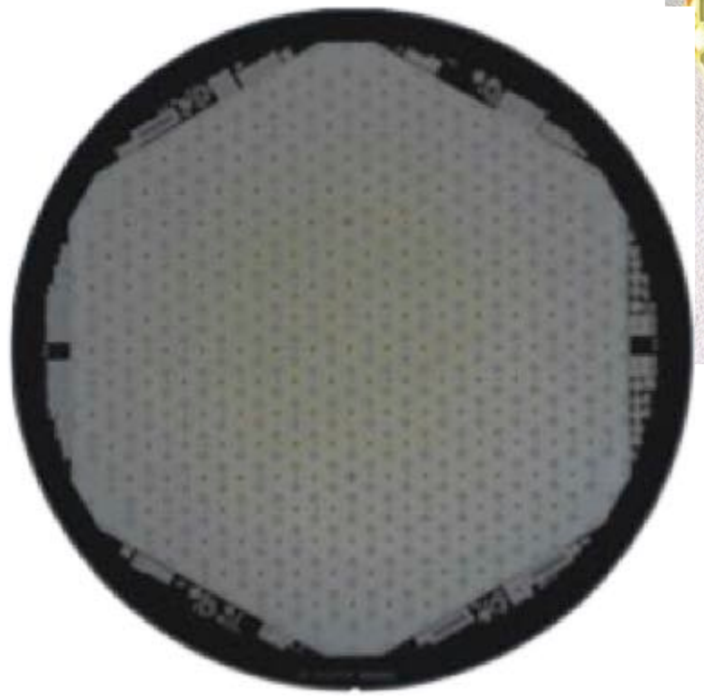

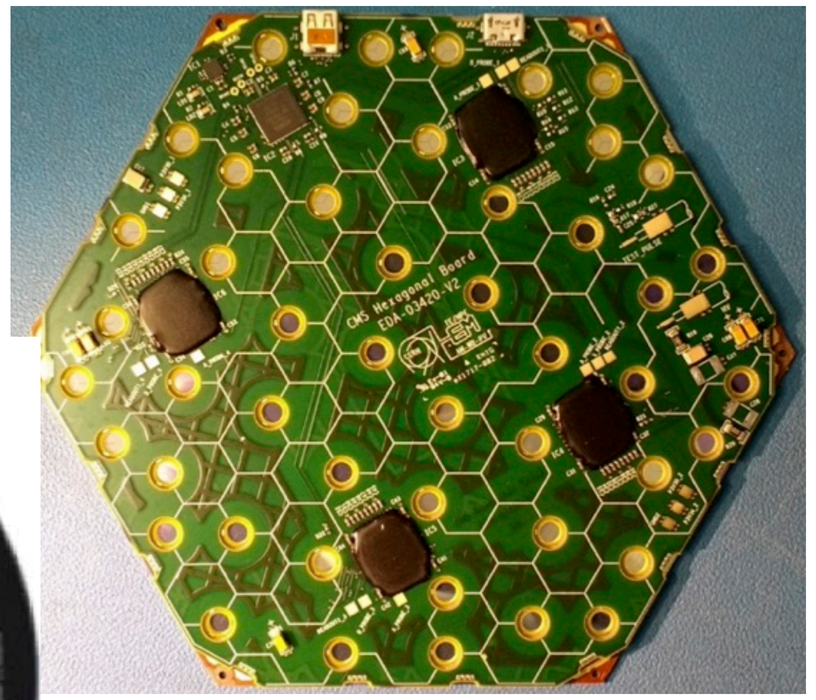

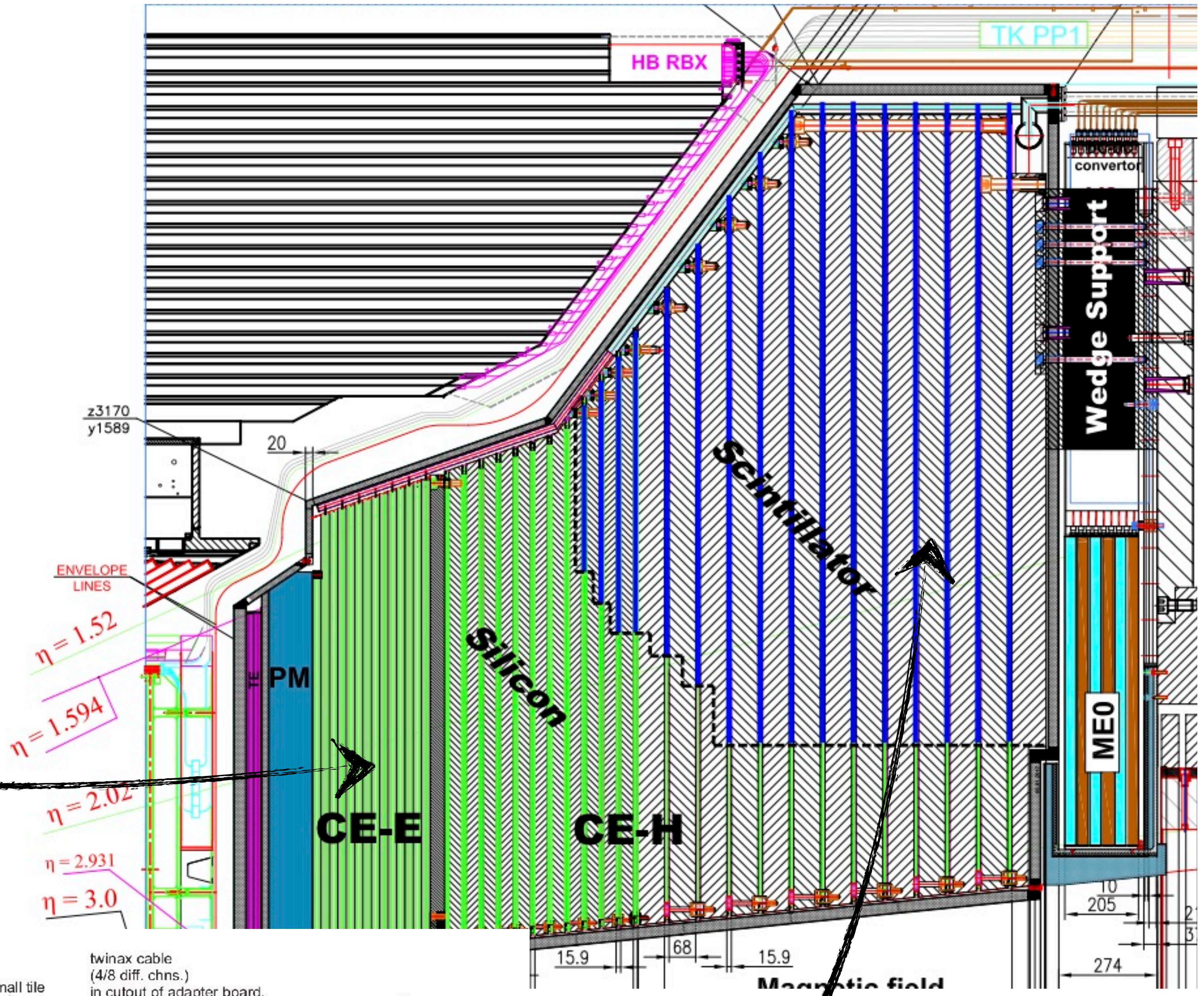

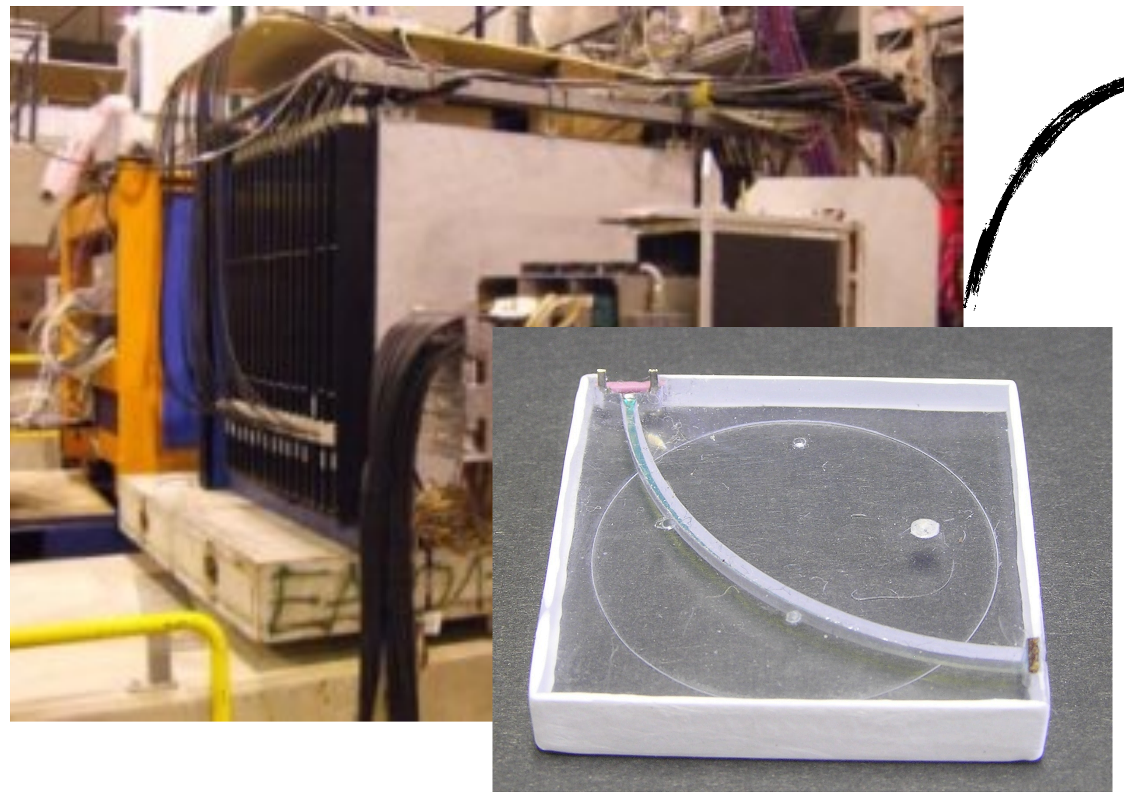

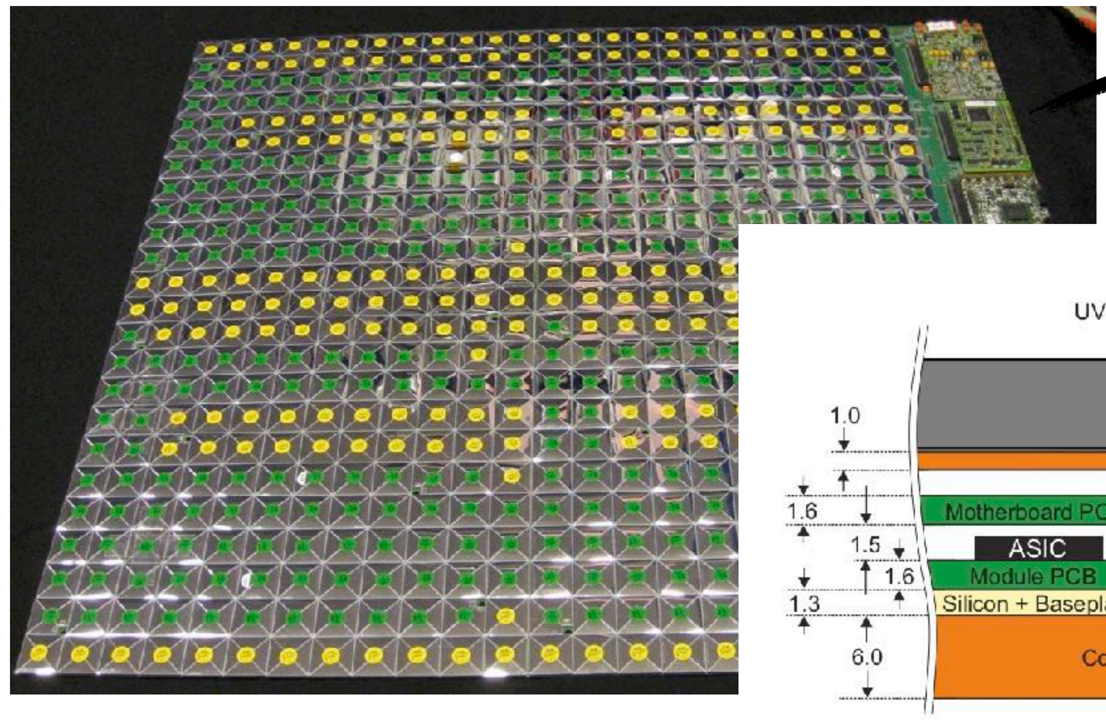

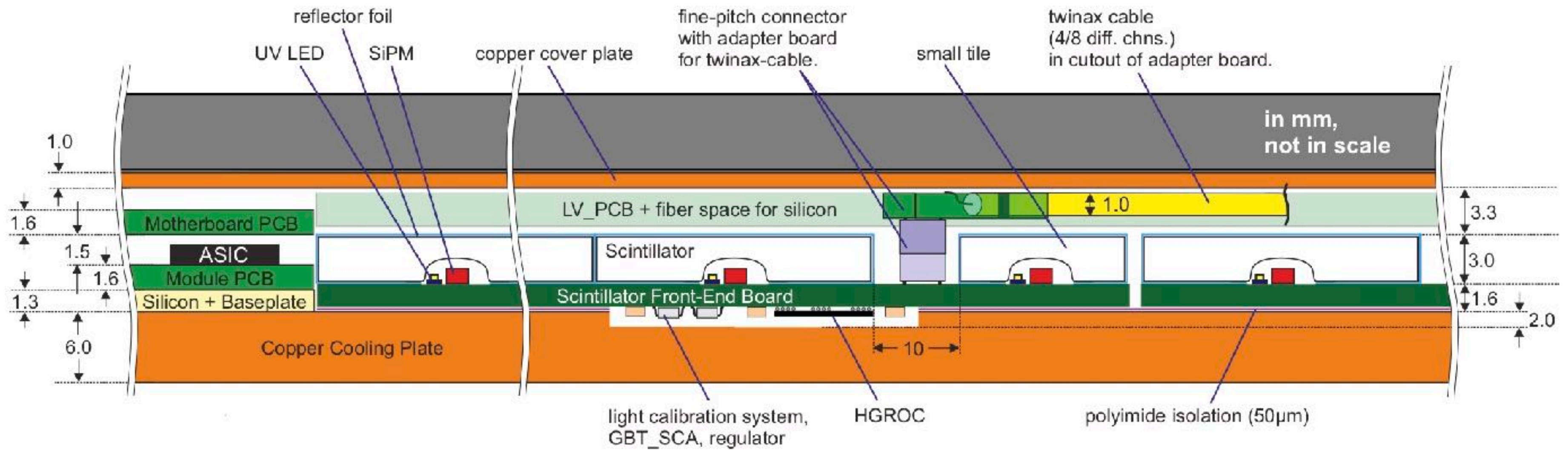

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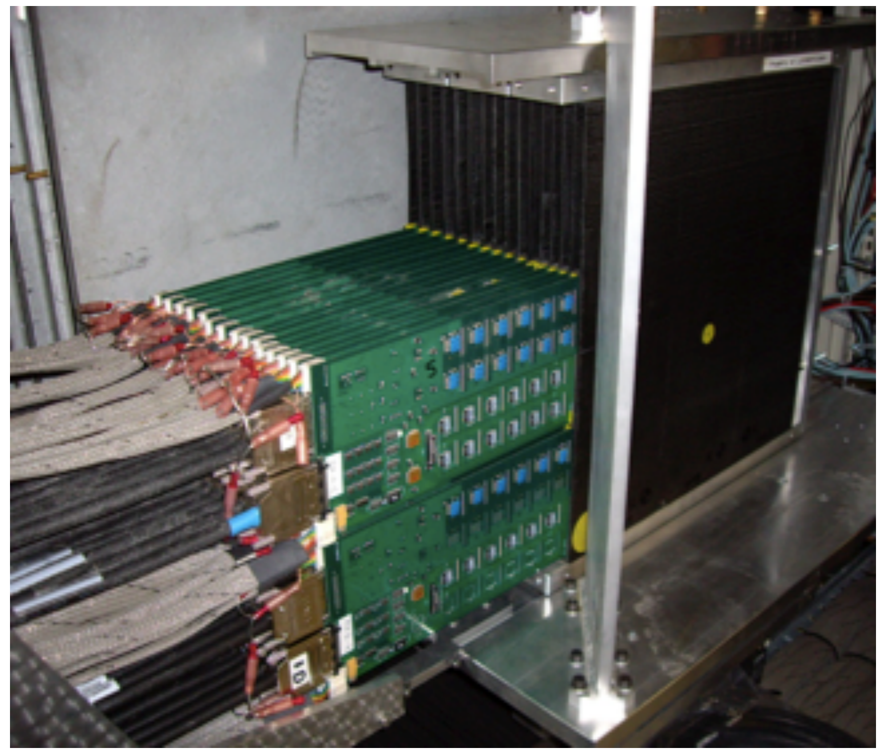

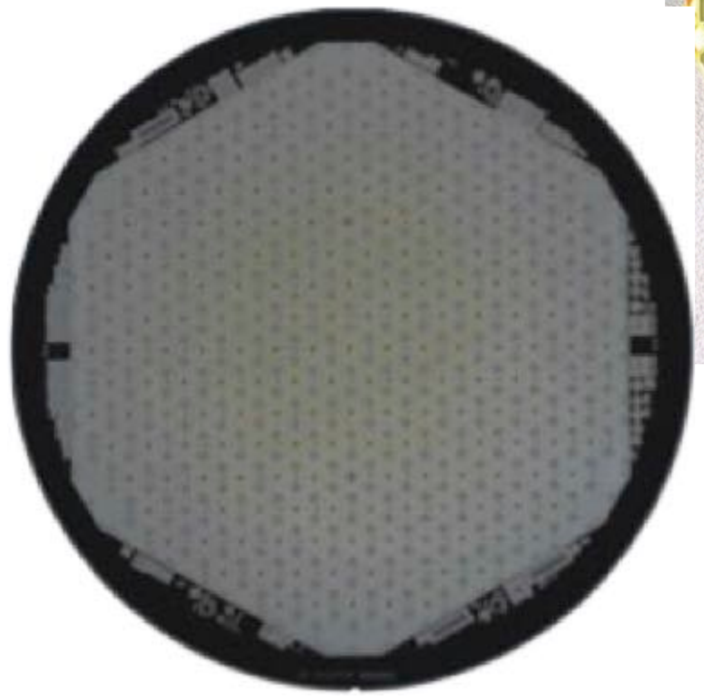

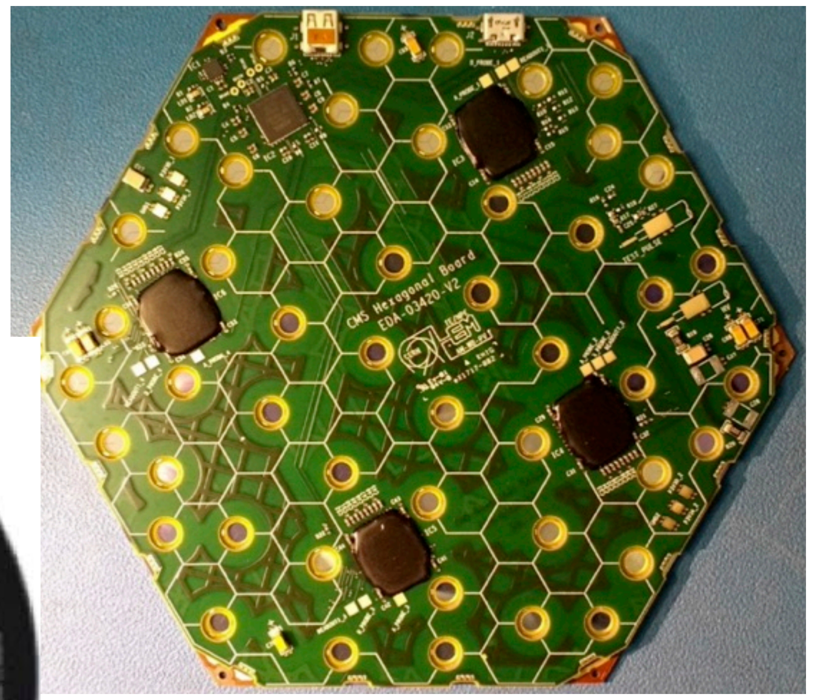

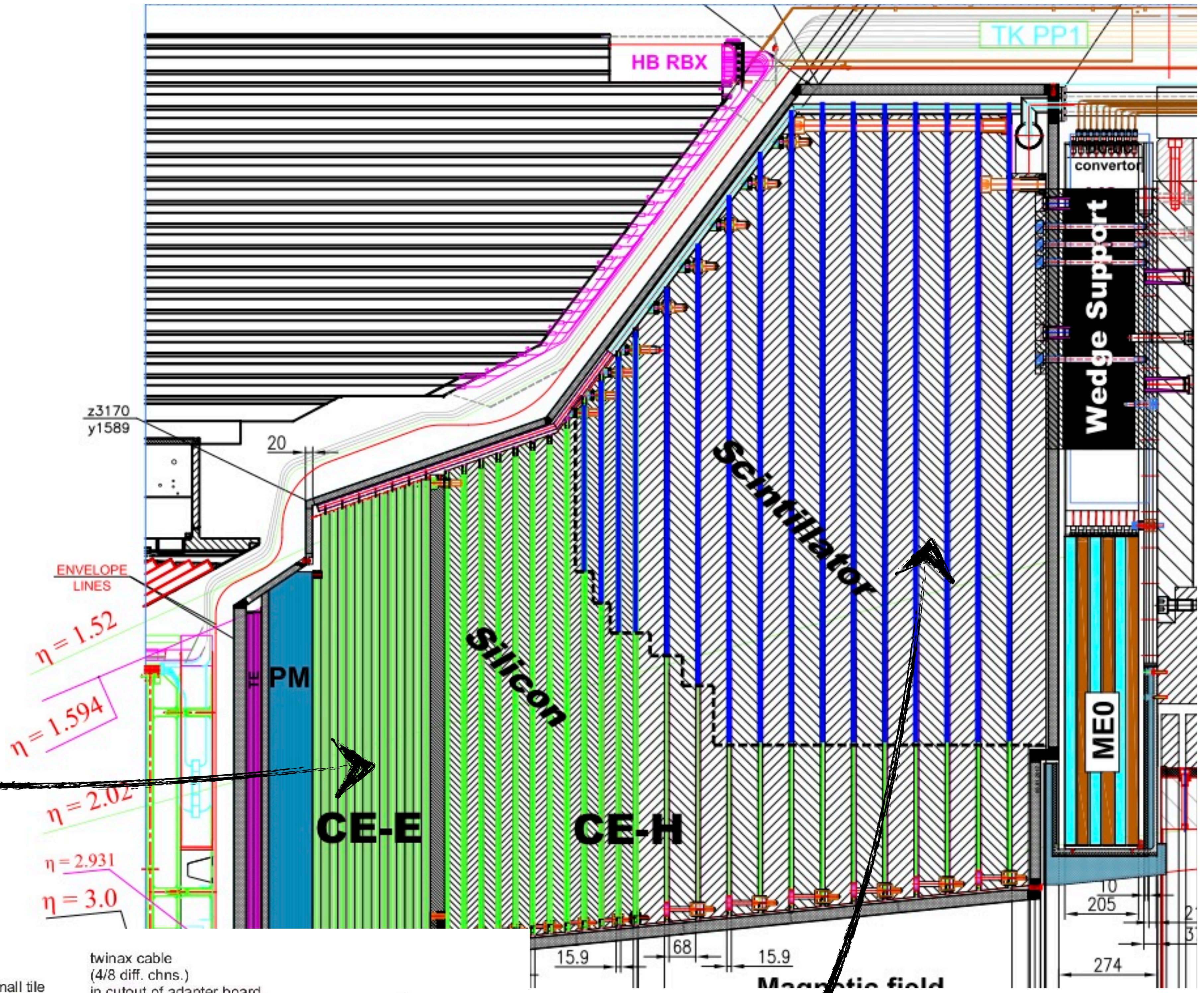

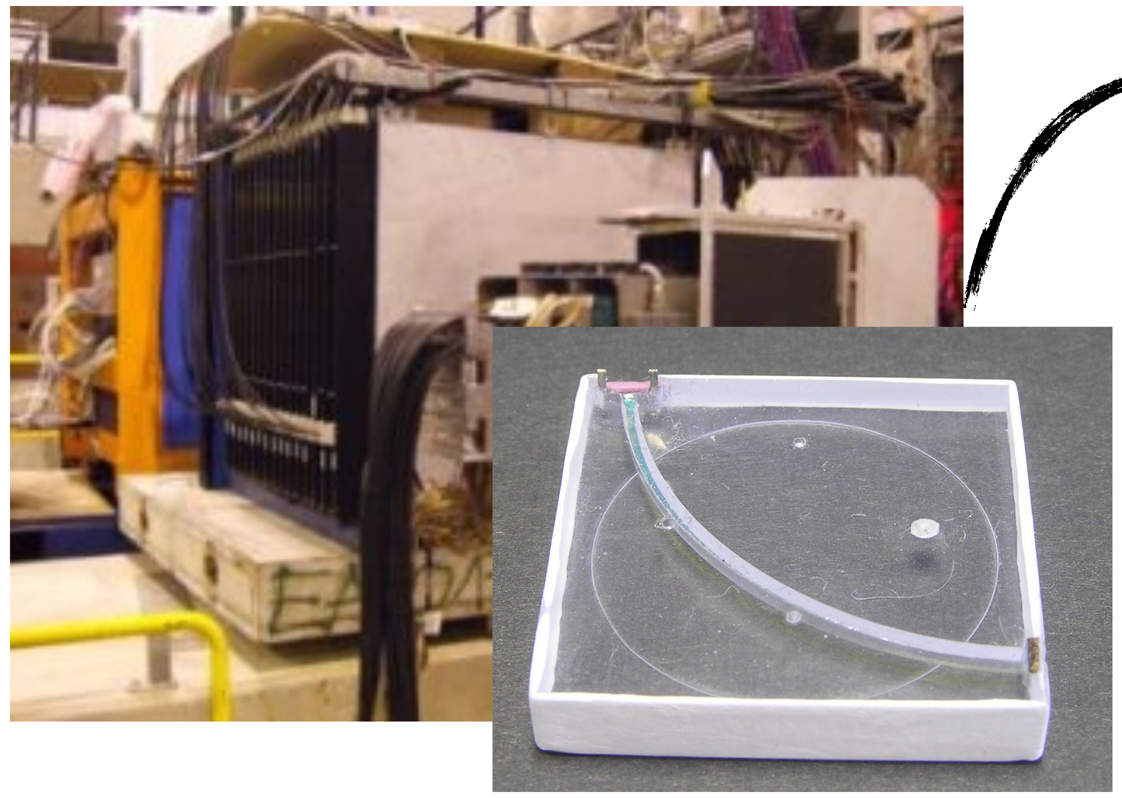

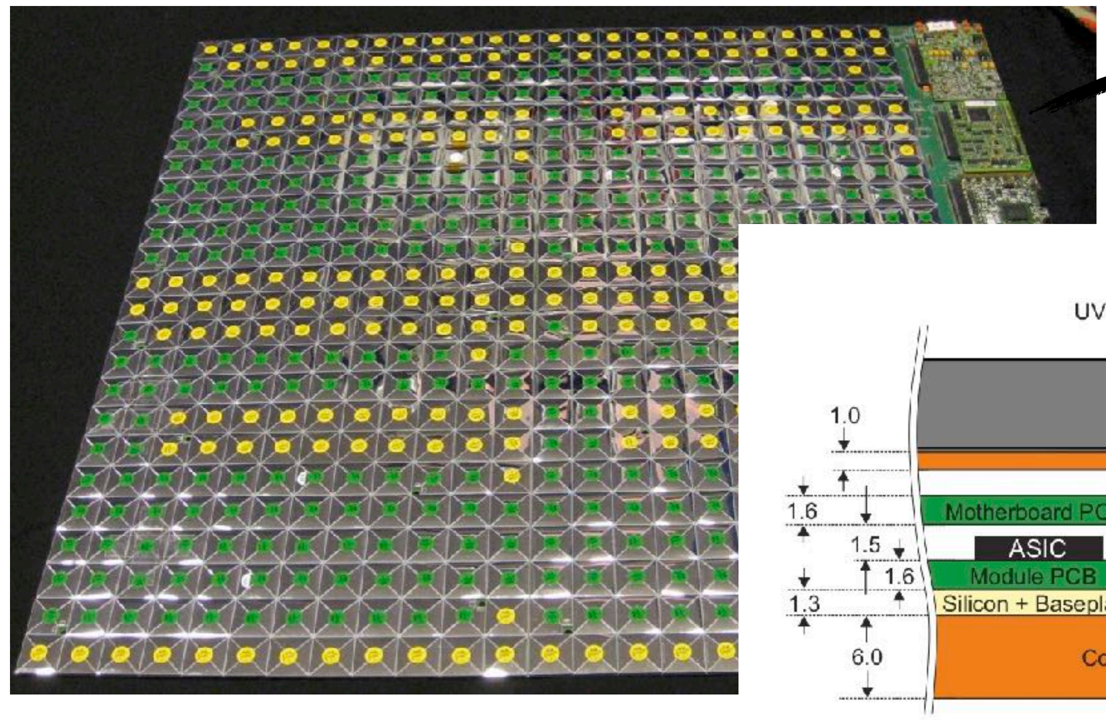

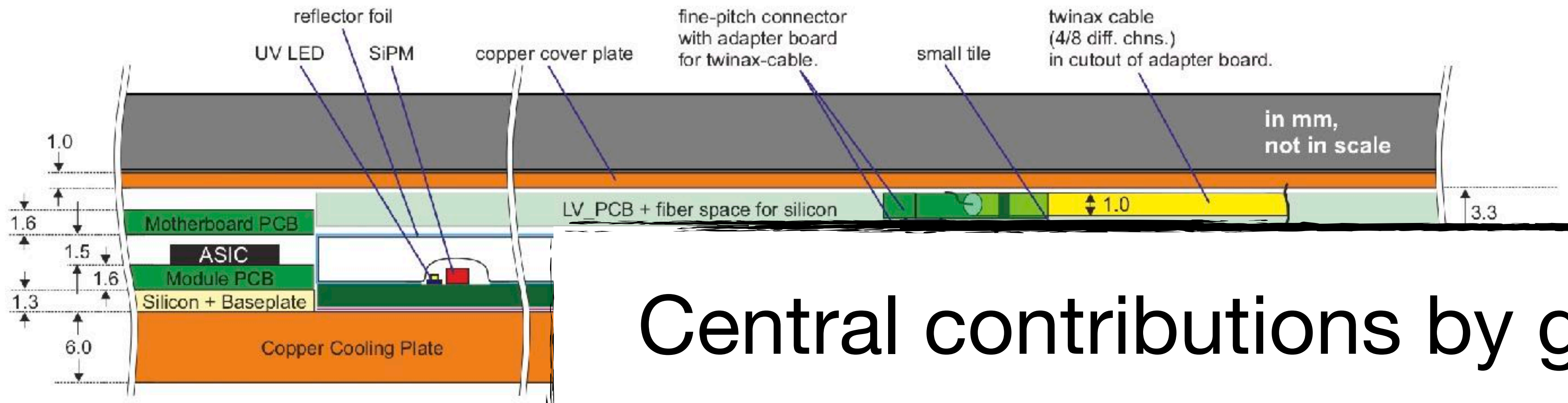

Central contributions by groups very active in CALICE, including CERN, DESY, LLR, OMEGA.

Common Test Beams

A key feature of CALICE - and extending to other Collaborations

- SiW ECAL / SDHCAL (2018)

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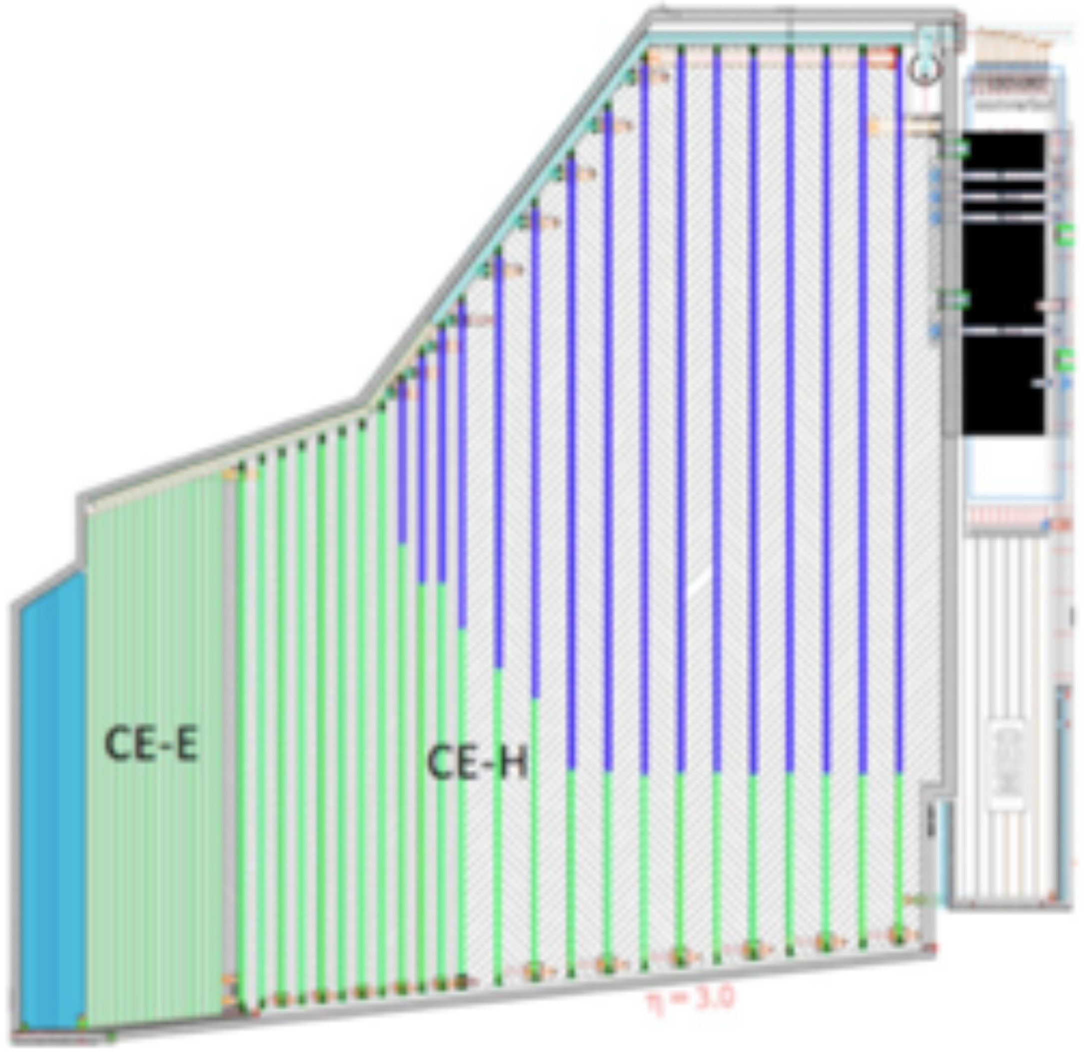
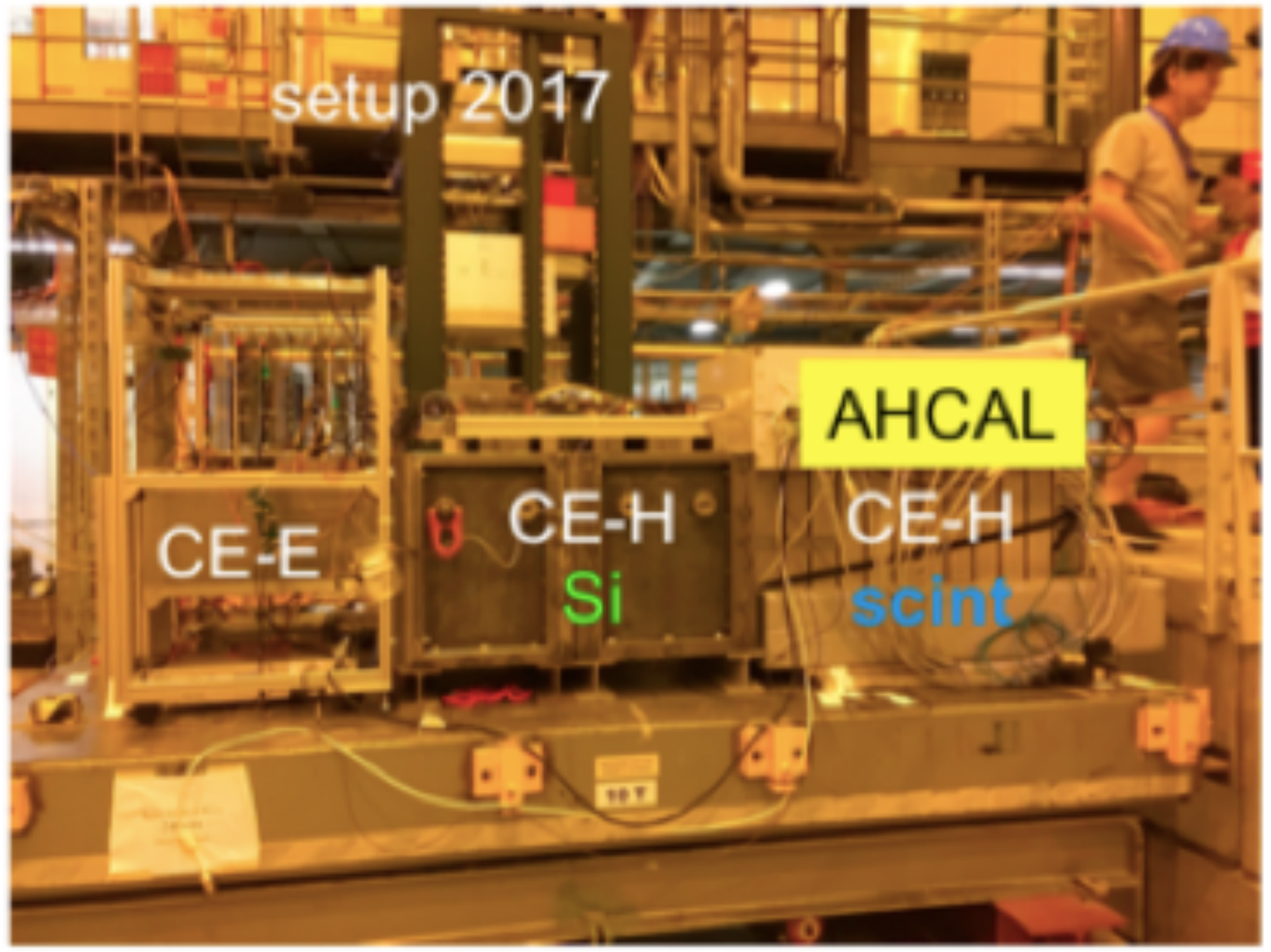
- CALICE and CMS: HGCAL + AHCAL, common tests since 2017





- Common beam tests benefit from common approach within CALICE, and from wider networking activities such as EUDAQ2 of AIDA2020
- More common beam tests to come after LS2

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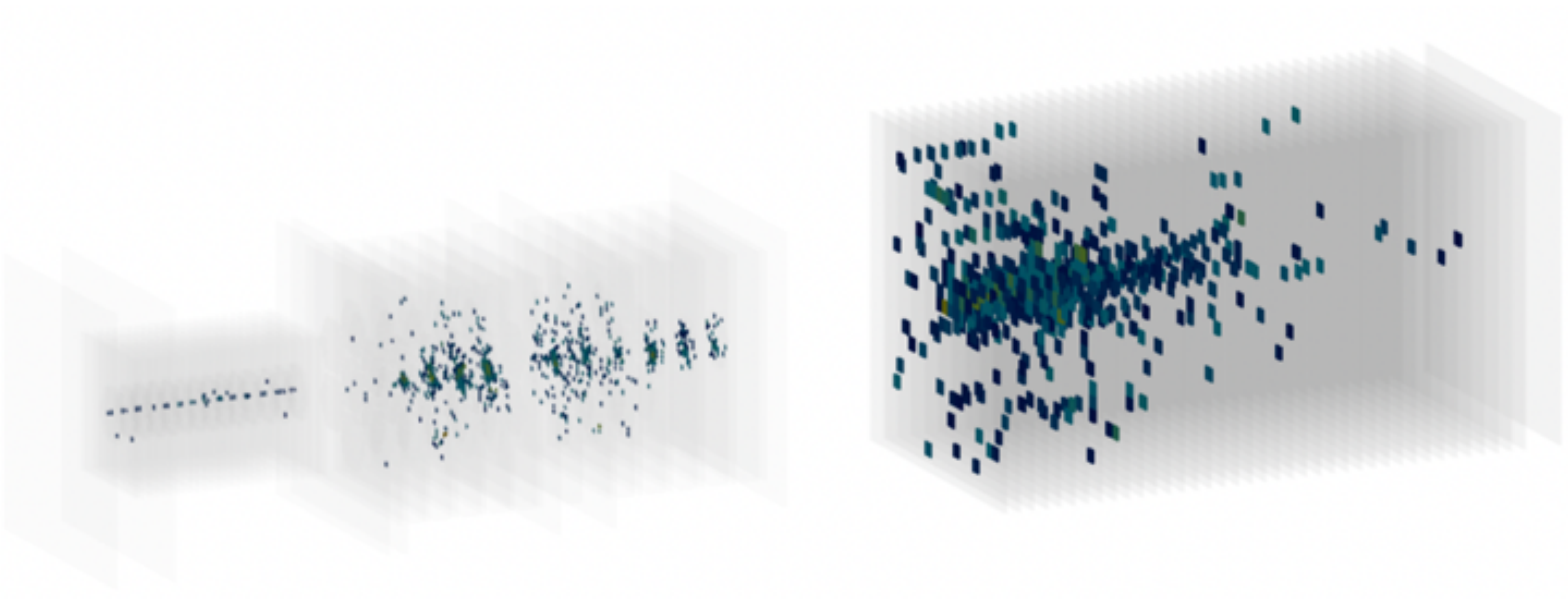

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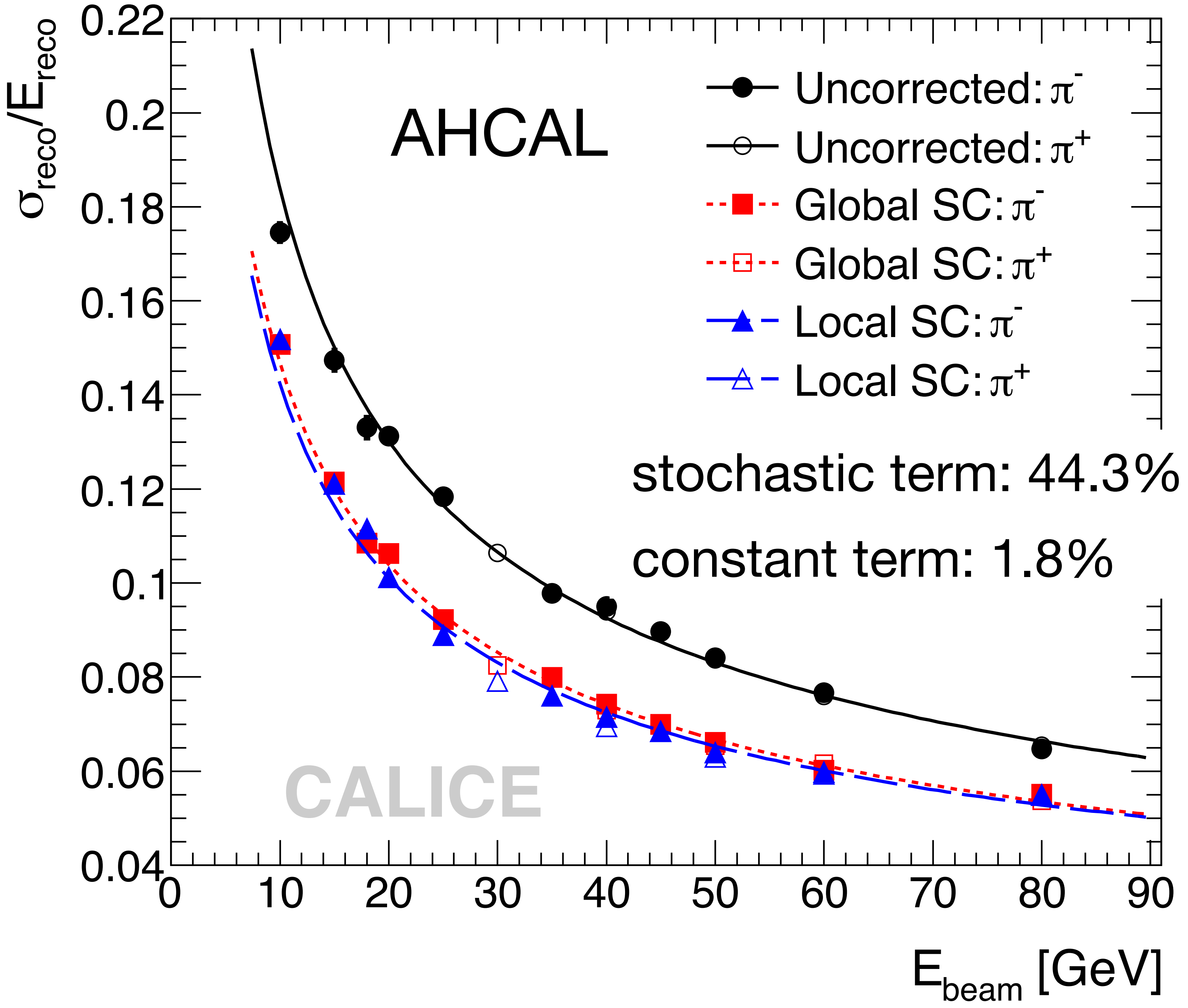
Performance

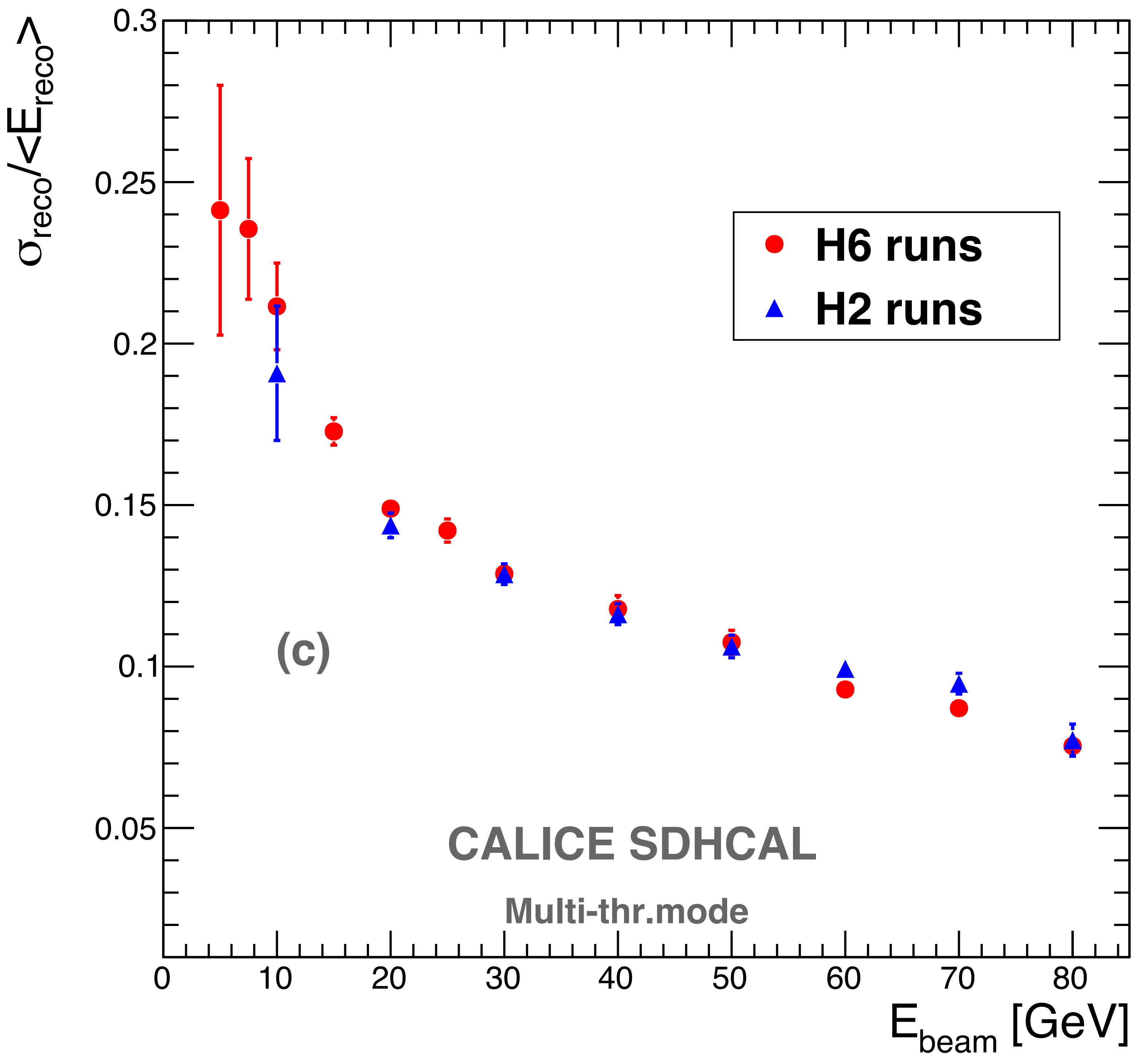
A very small selection

Energy Resolution

for Hadrons

- In hadronic calorimeters





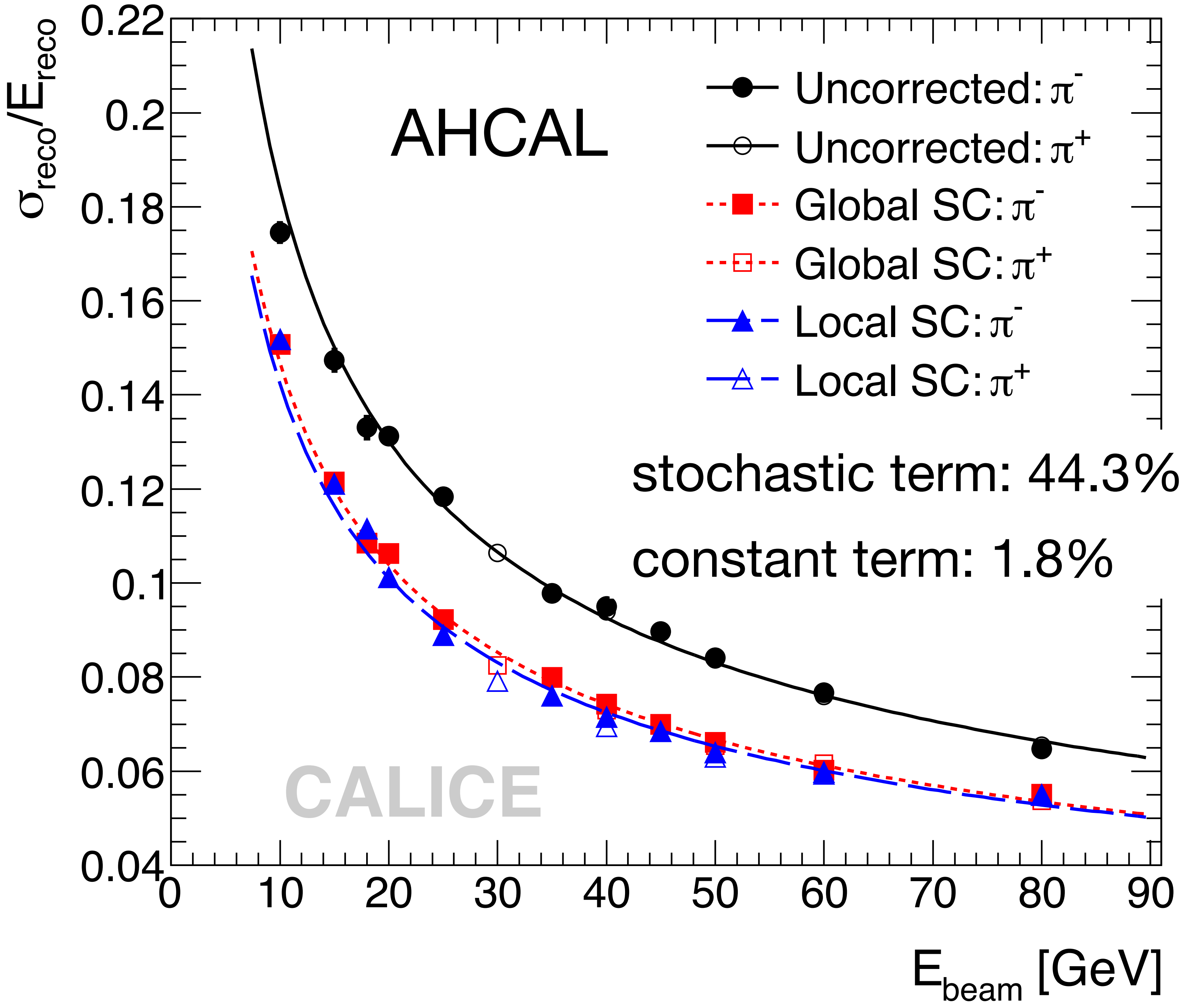
Software compensation (SC) and semi-digital reconstruction use weighting factors to optimise energy resolution

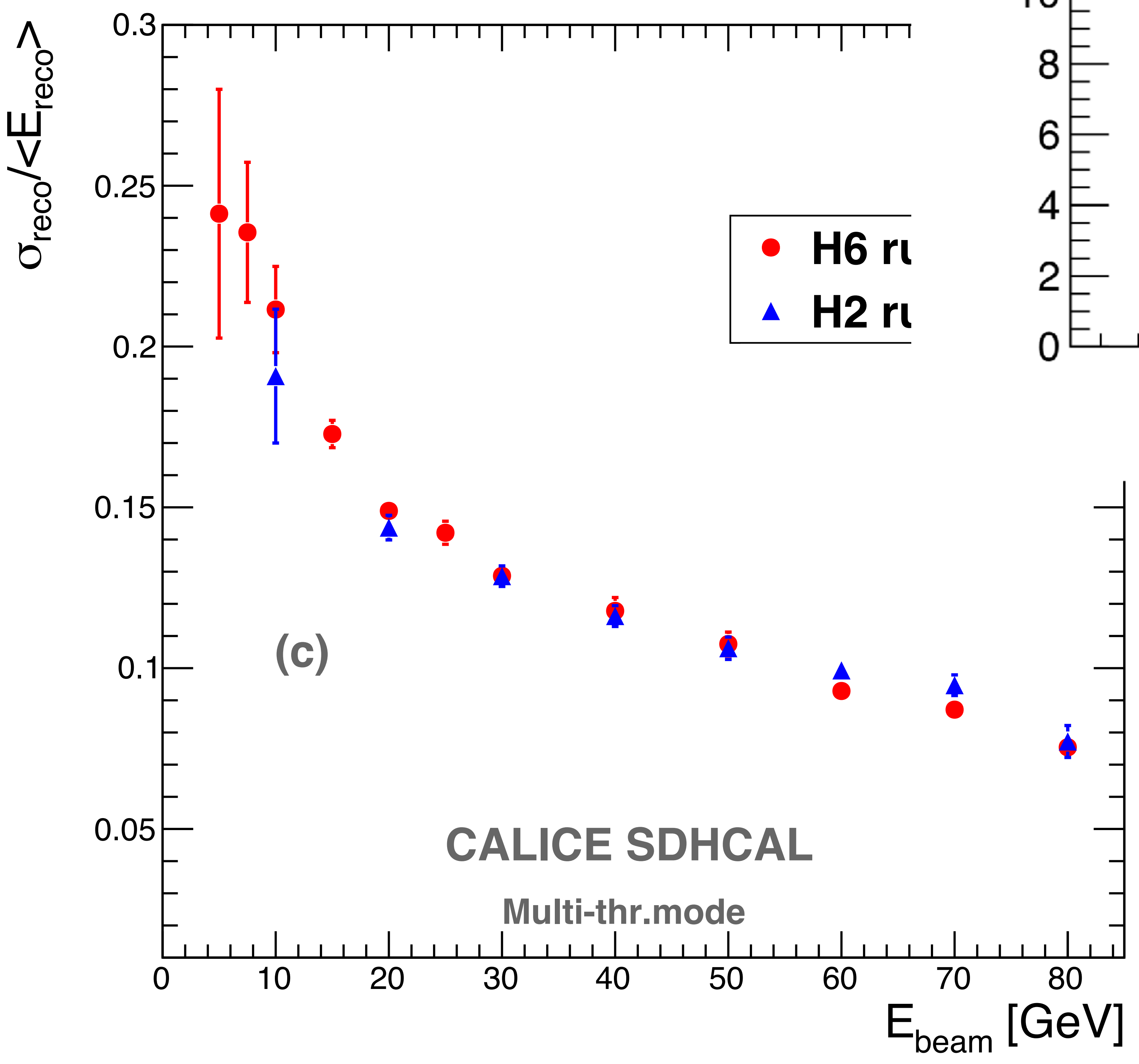
Energy Resolution

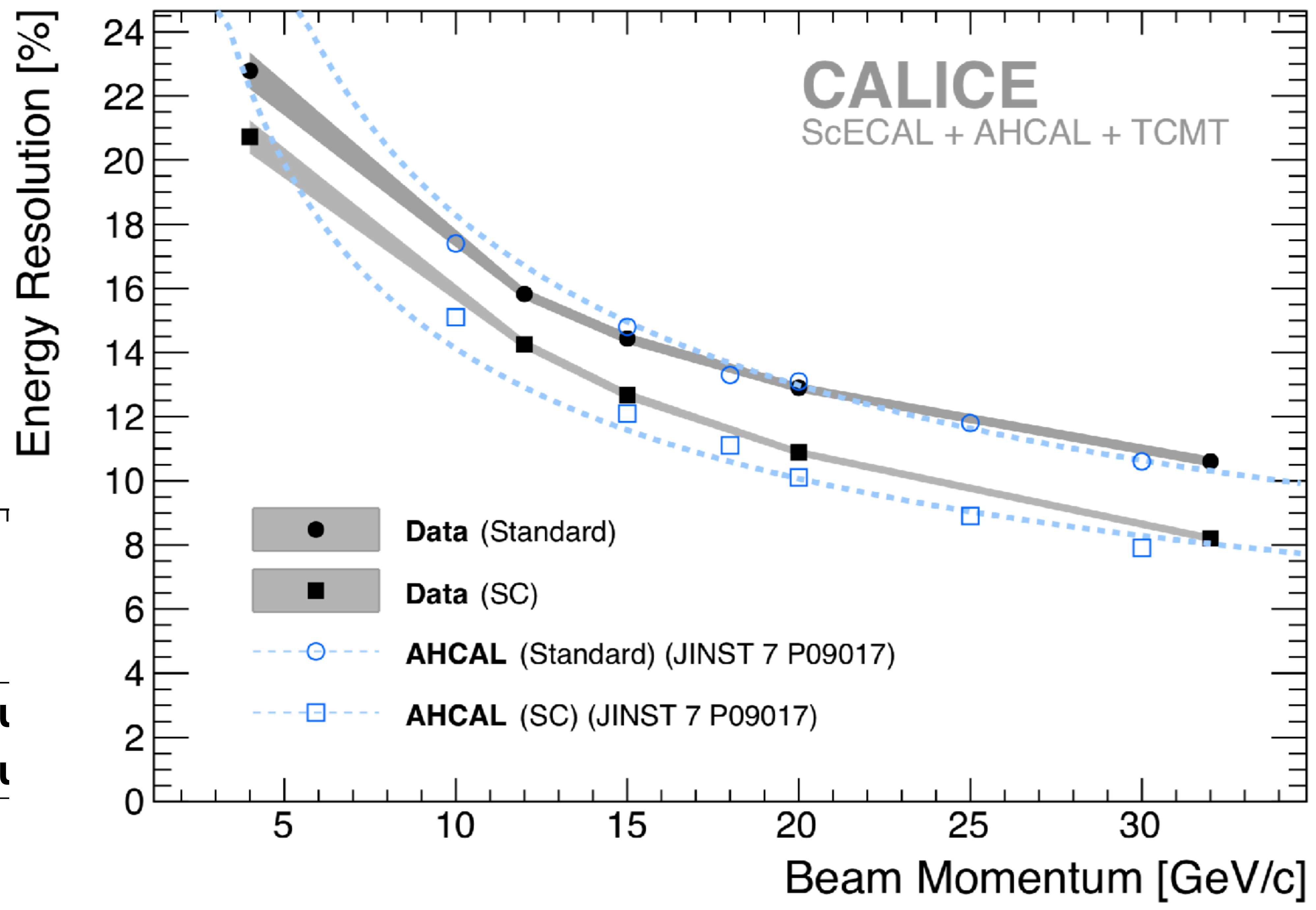
for Hadrons

- In hadronic calorimeters

… and combined systems.







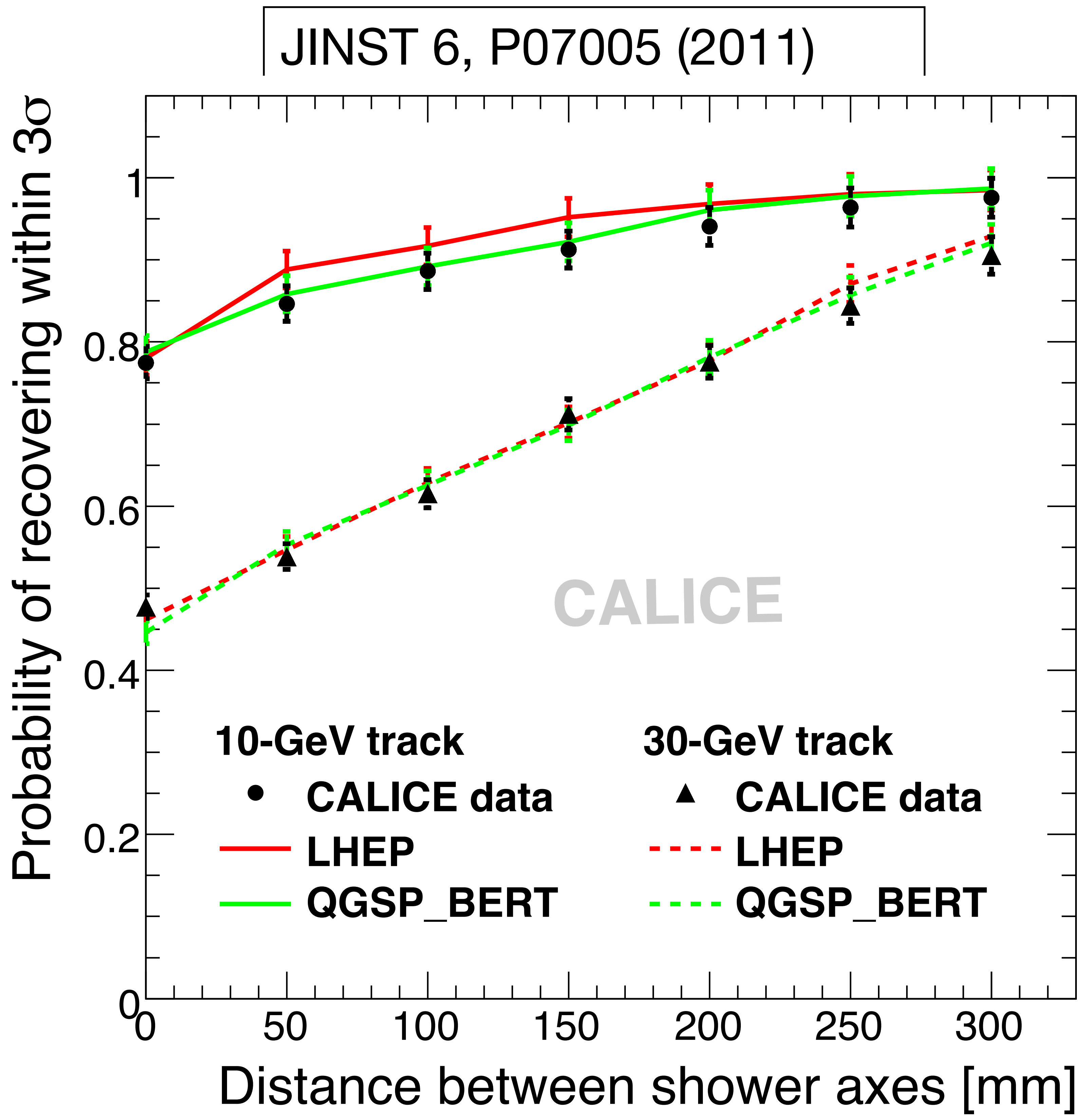
Here: ScintW ECAL, AHCAL

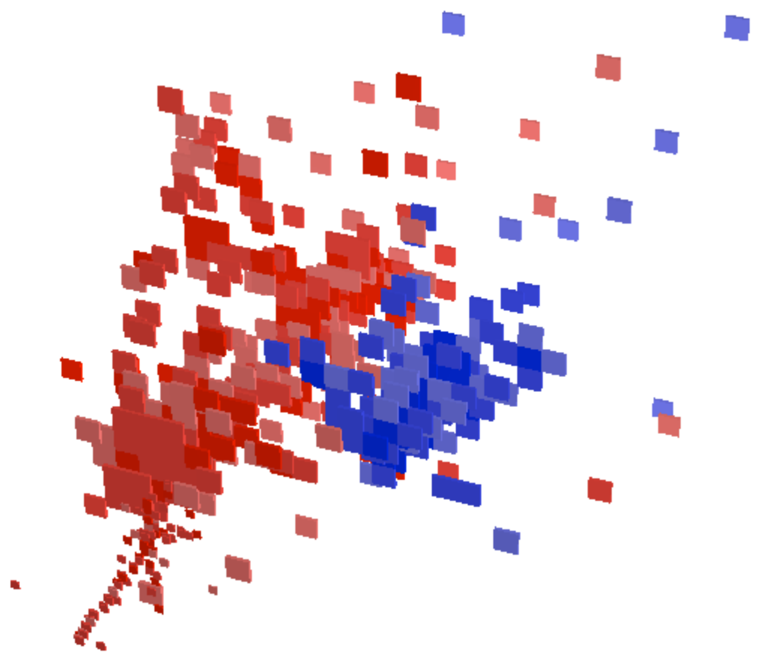
Software compensation (SC) and semi-digital reconstruction use weighting factors to optimise energy resolution

Particle Separation

With PFAs, reproduced by Simulations

- A key figure of merit for PFA performance
  - studied with overlaid test-beam events for SiW ECAL + AHCAL





Particle Separation

With PFAs, reproduced by Simulations

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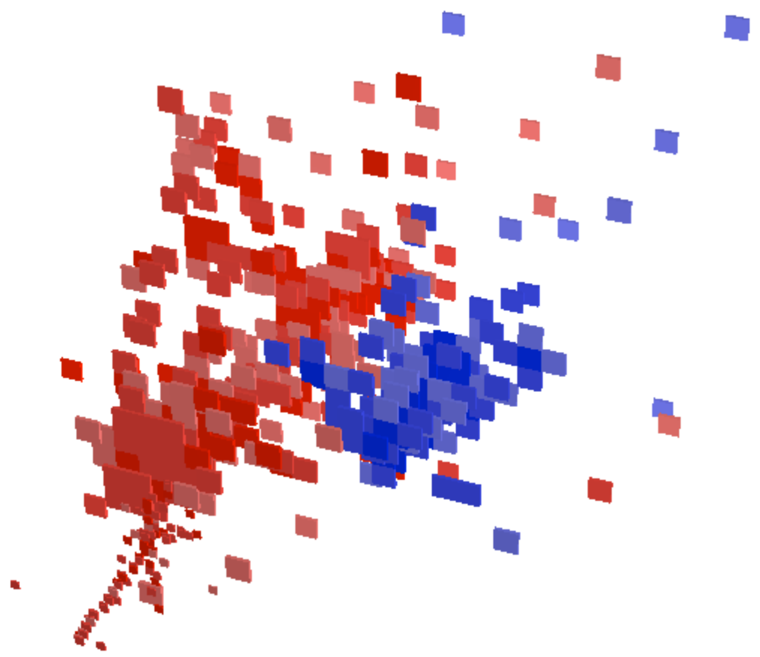
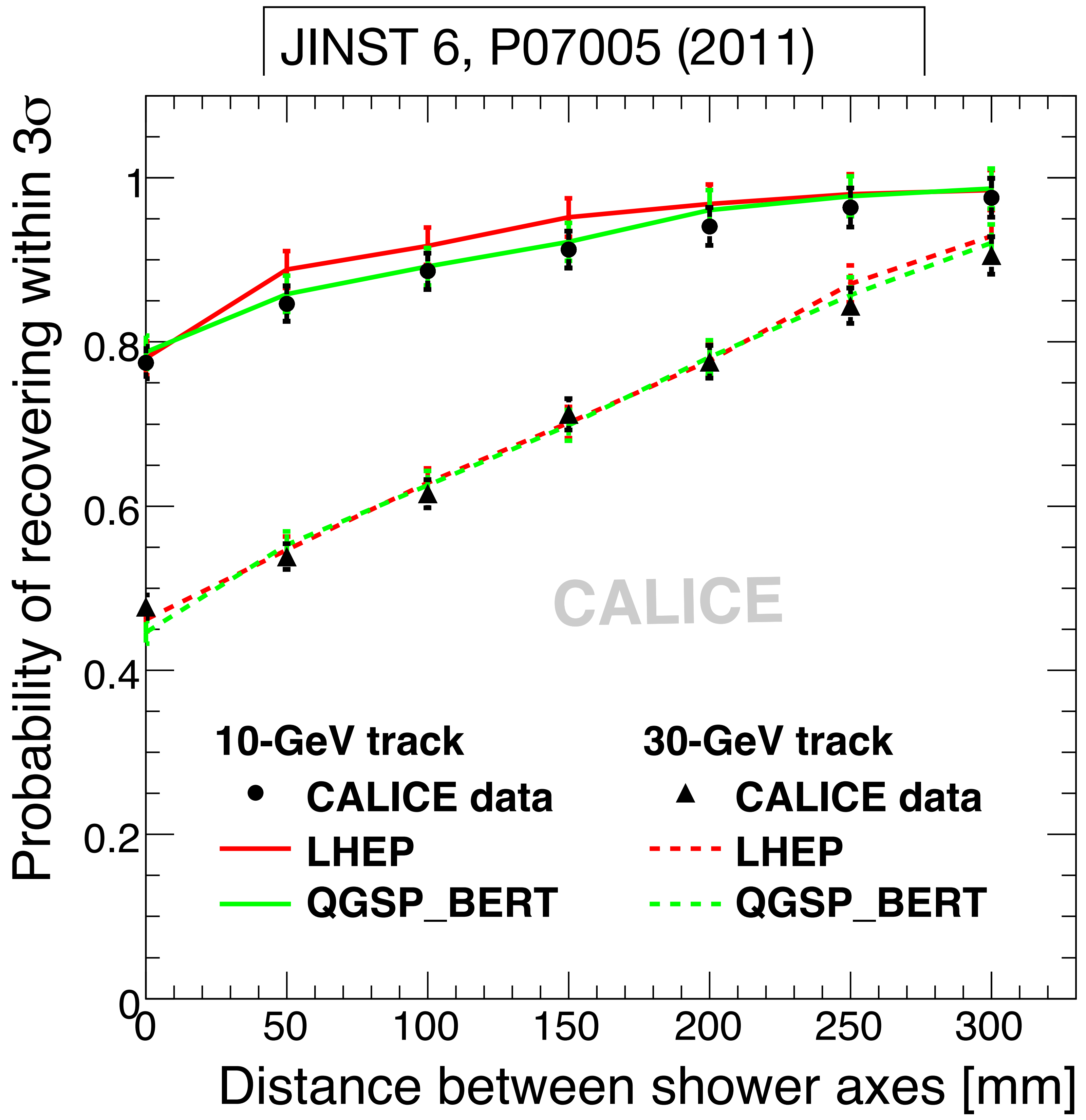
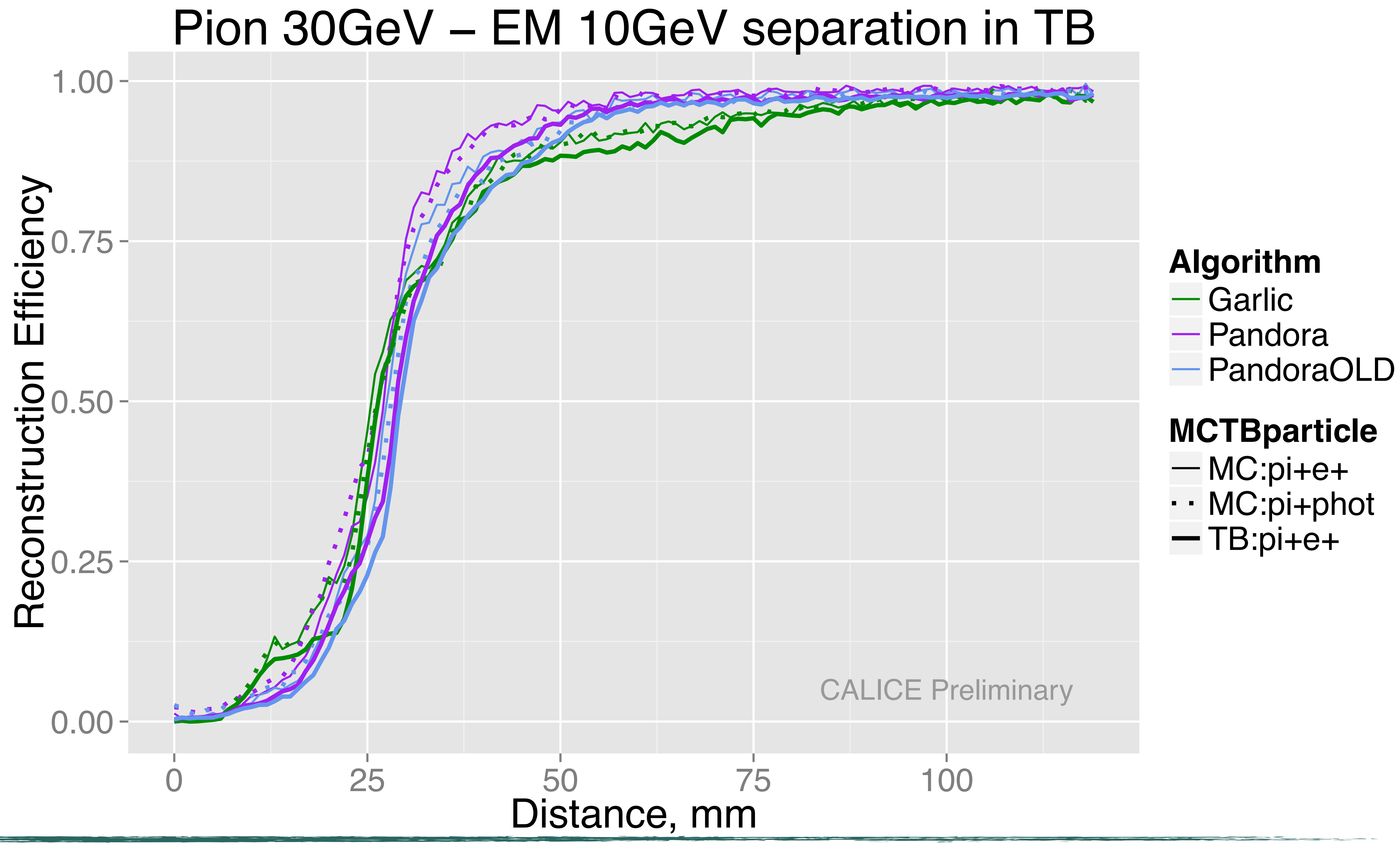


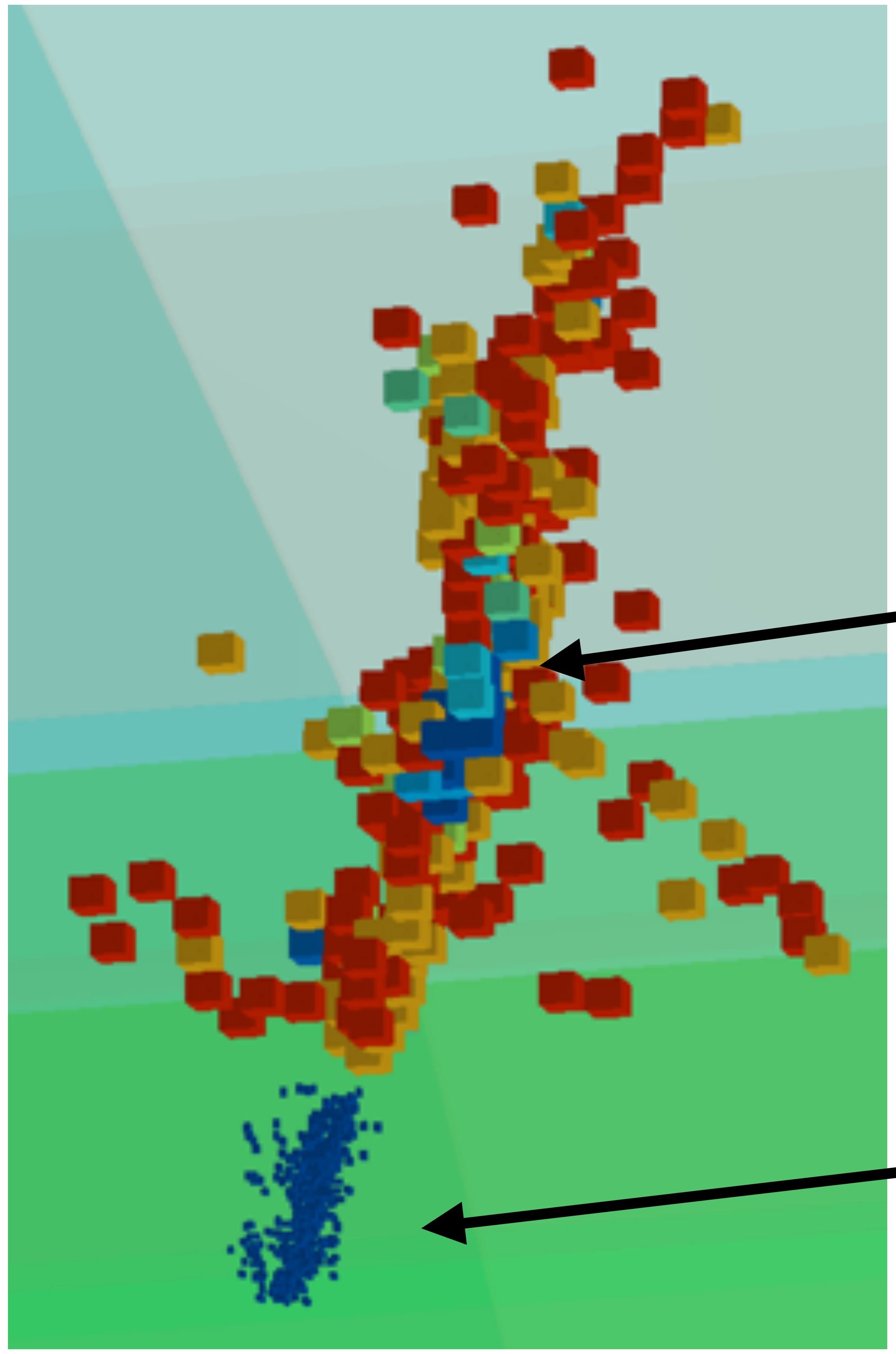




Transfer to full Detector Simulations - Here ILD

Software Compensation in Particle Flow

- Particle flow algorithms make use of calorimeter energy at two main points
  - Track - calorimeter cluster matching, and iterative reclustering
  - Energy of neutral particles



transfer software compensation algorithm and training strategies from CALICE to full ILD detector simulations

em sub showers (in shower core) weighted less than hadronic periphery

ECAL not yet included: standard reconstruction used

Transfer to full Detector Simulations - Here ILD

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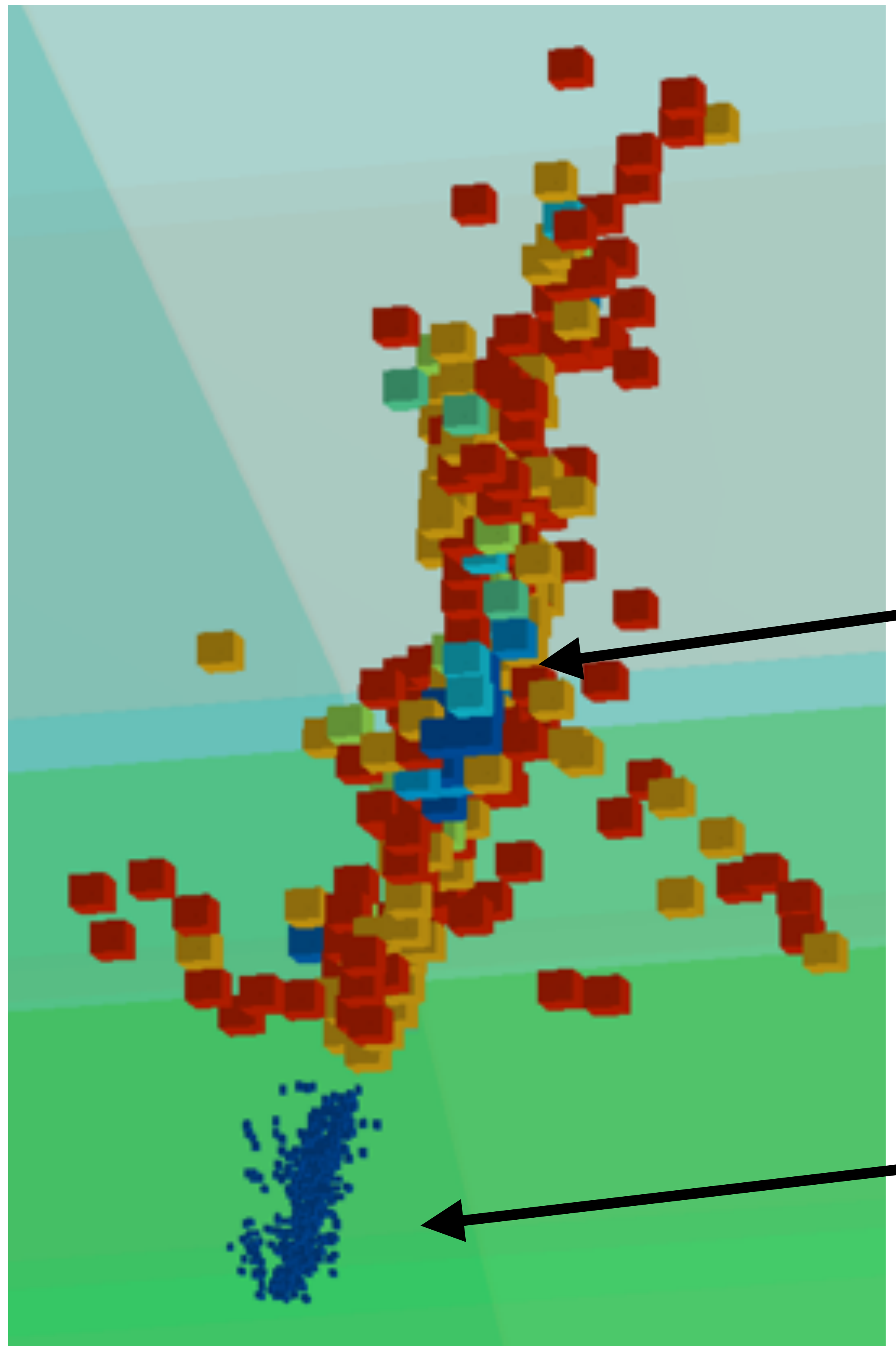

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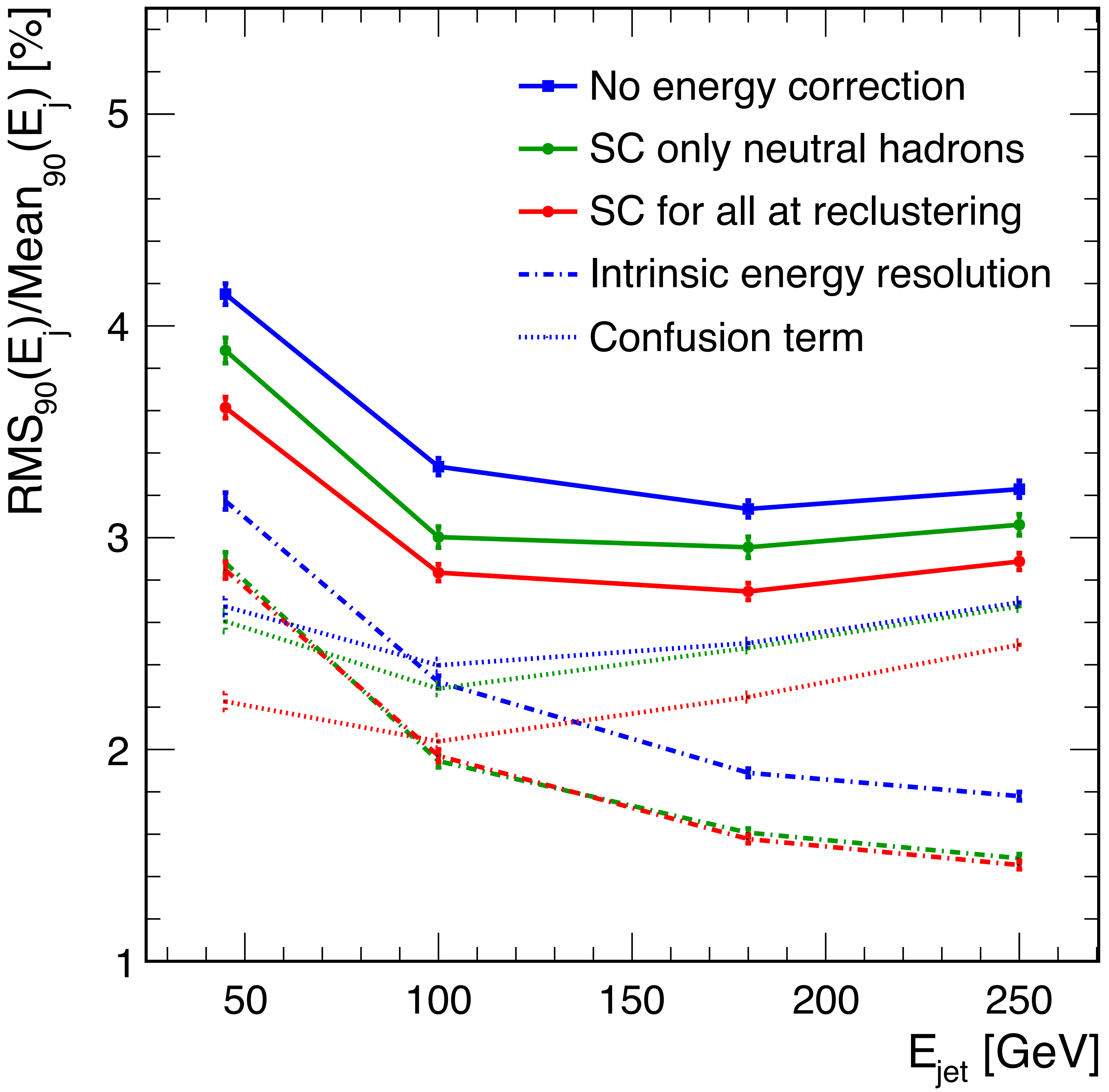
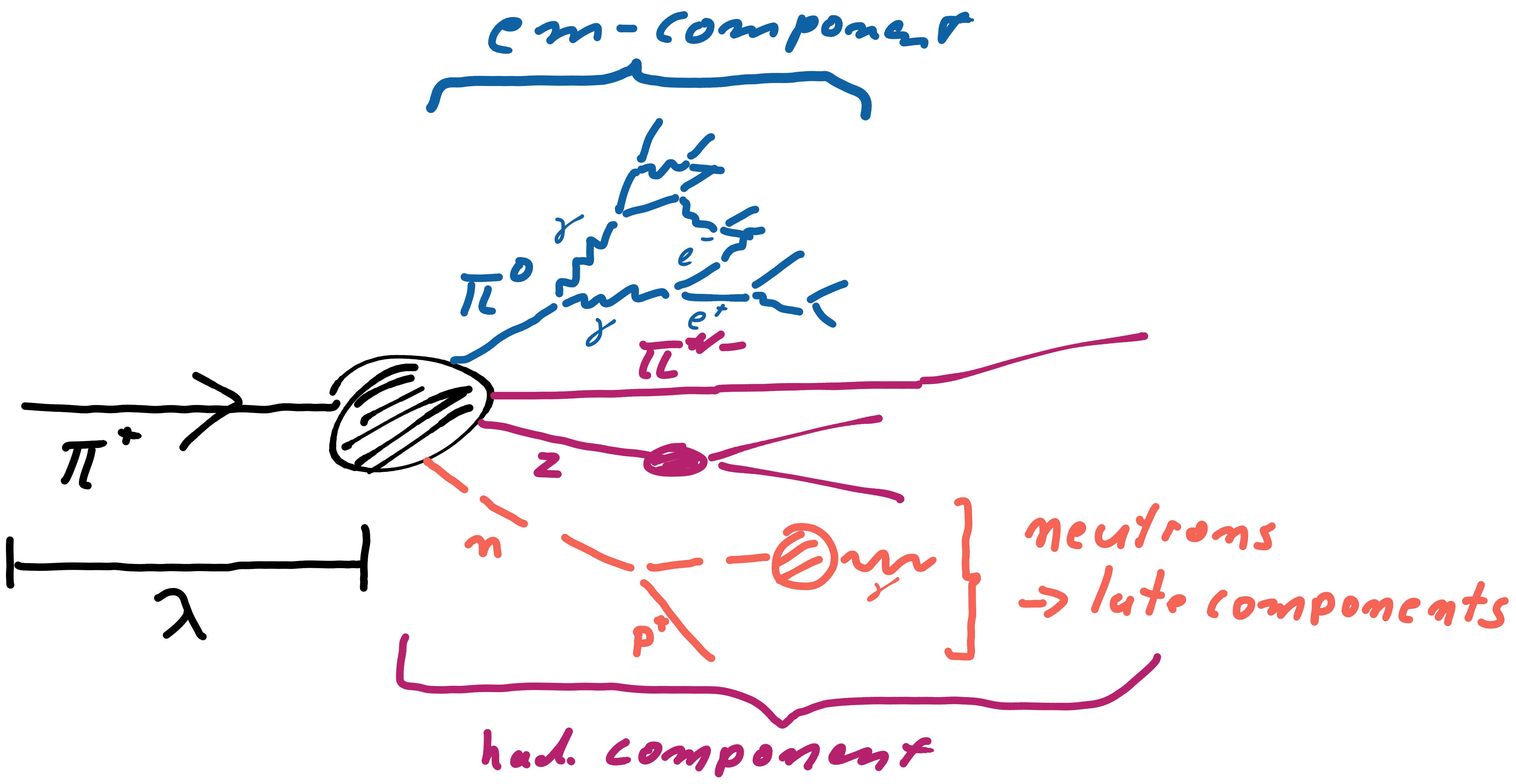


EPJ C77, 698 (2017)

Understanding Hadronic Showers

Exploring the spatial (sub-) Structure



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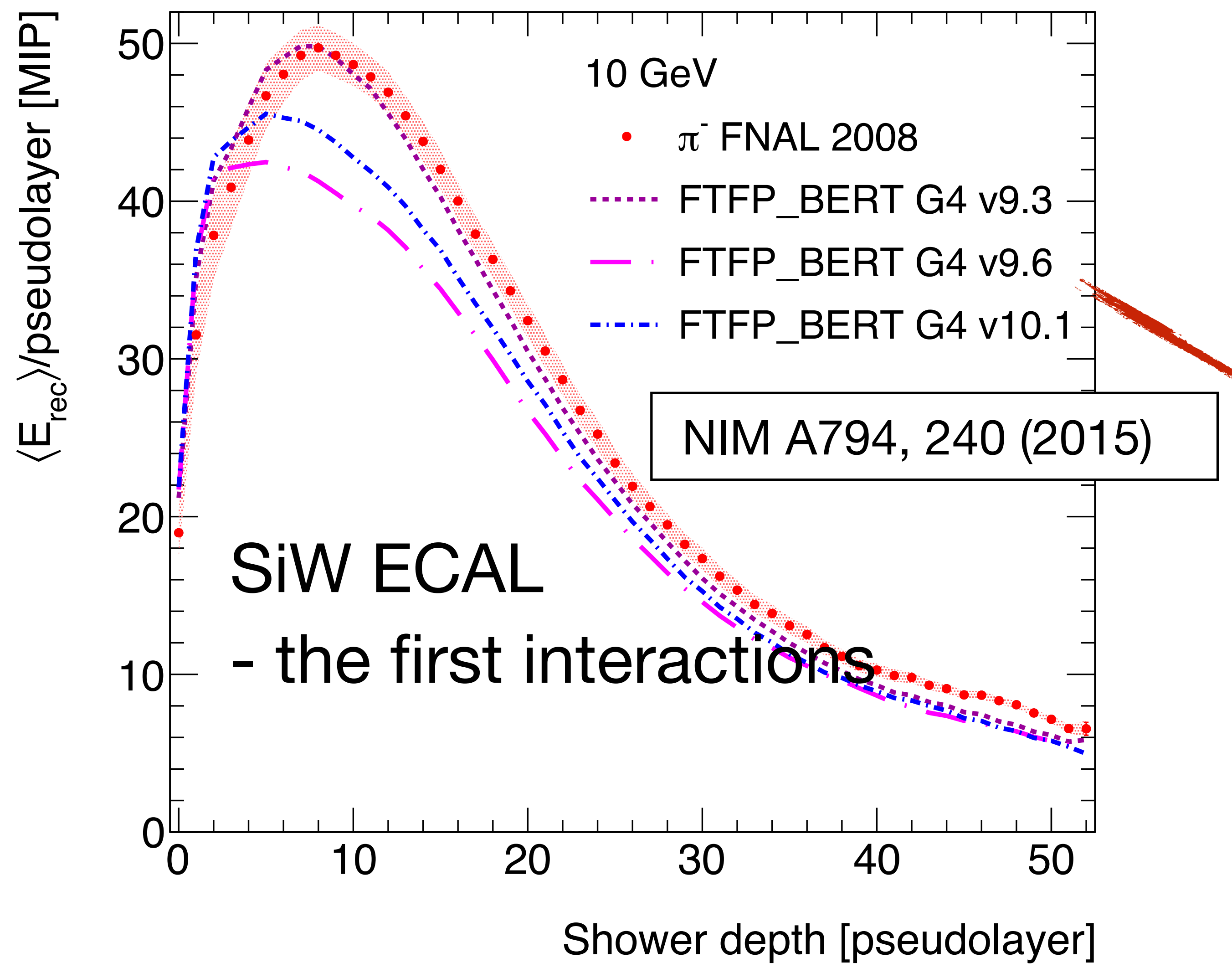

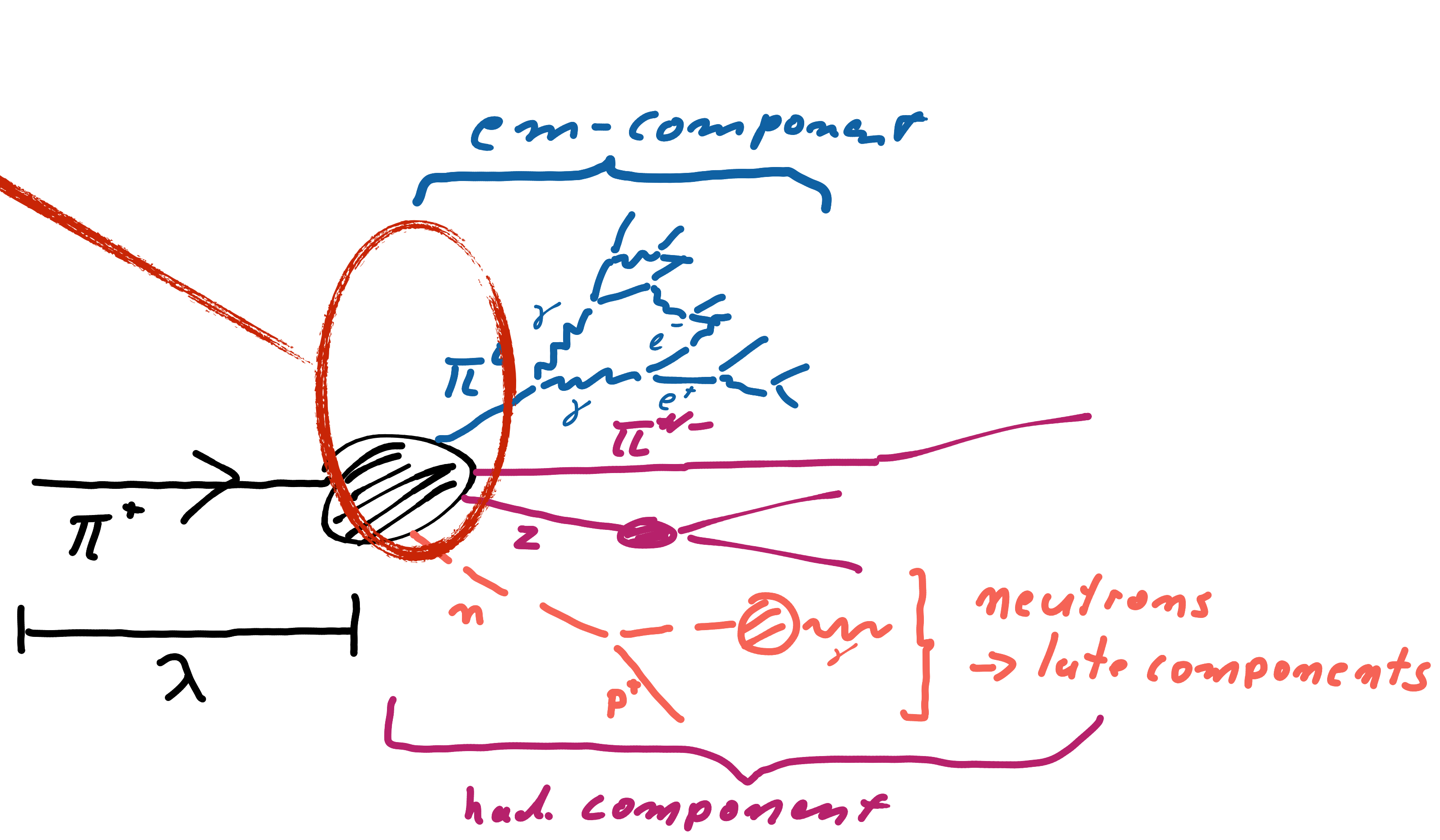

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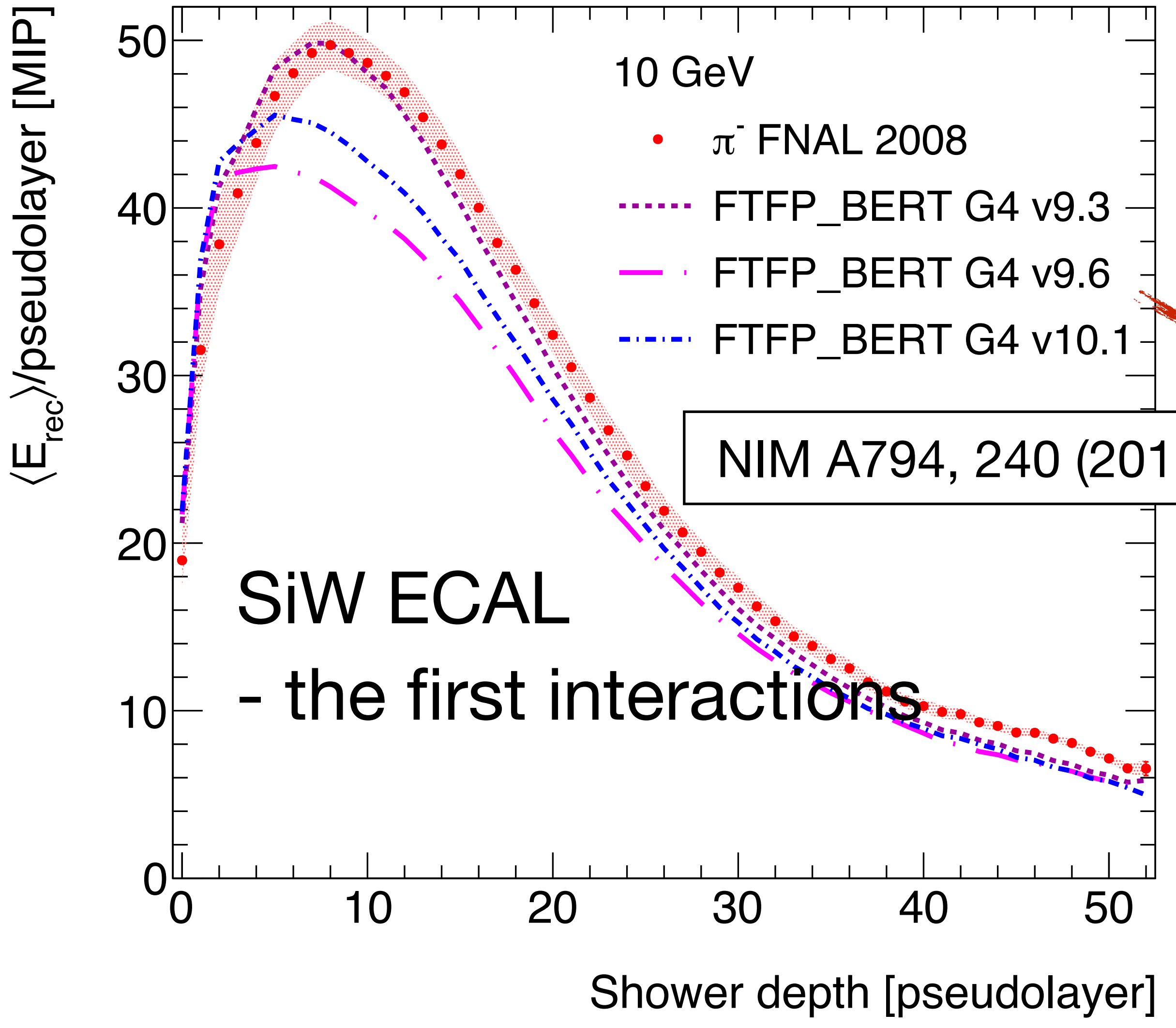
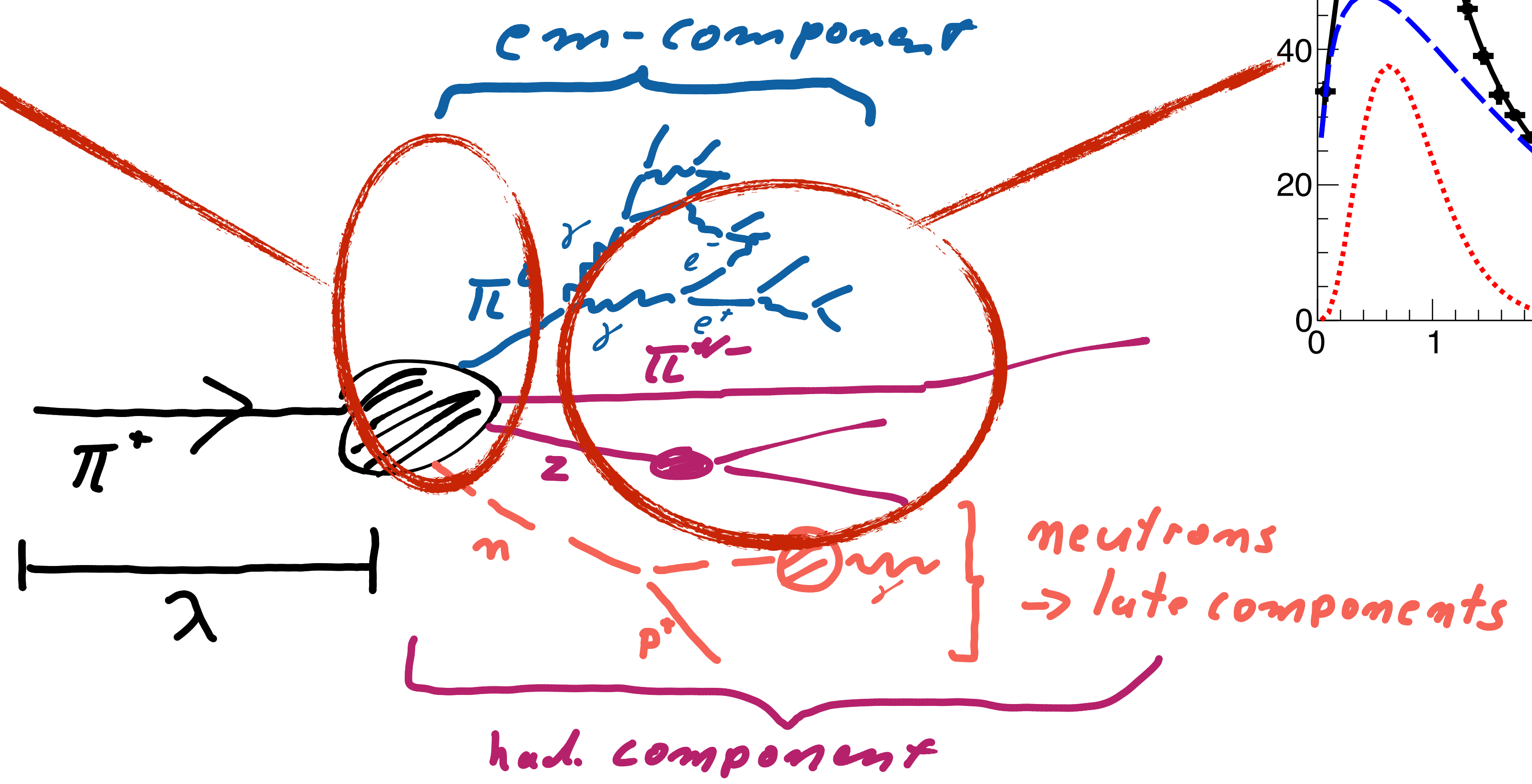
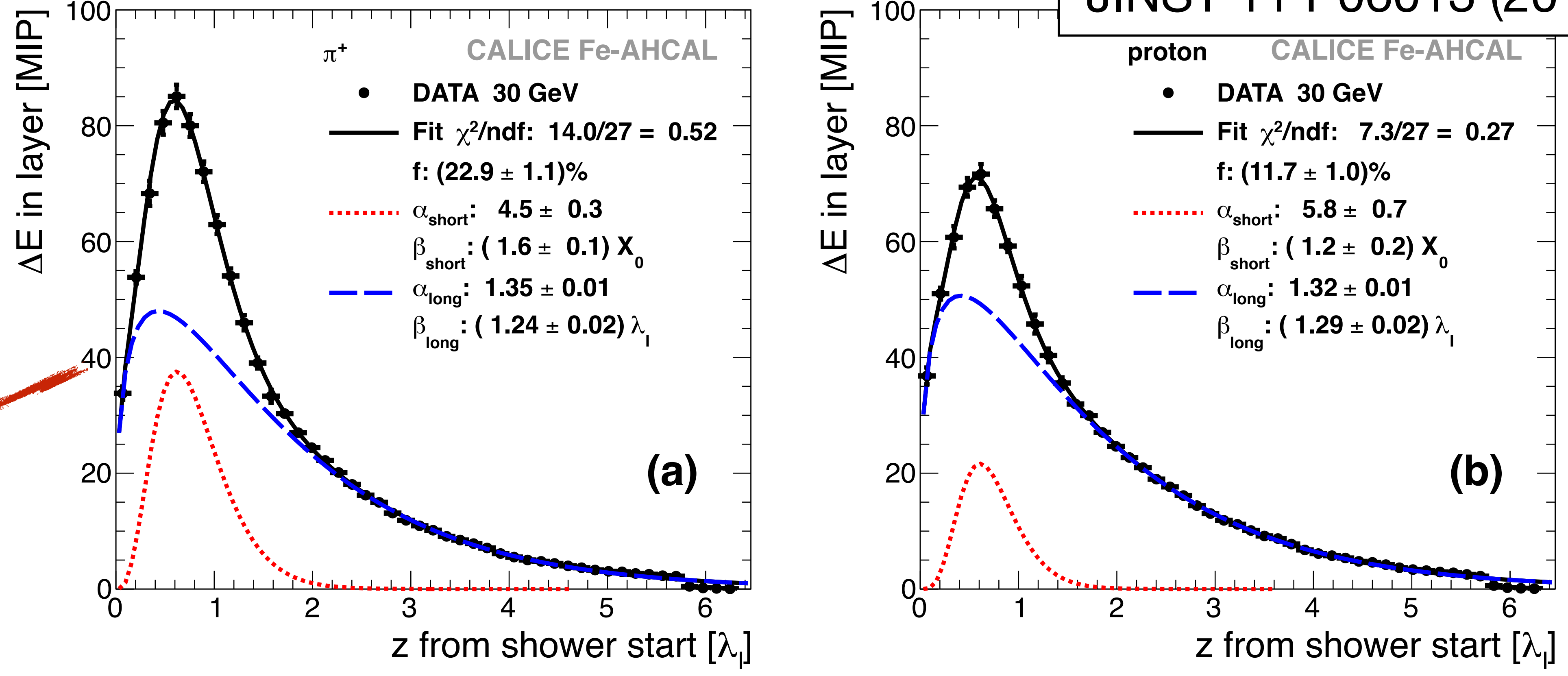


NIM A794, 240 (2015)



JINST 11 P06013 (2016)



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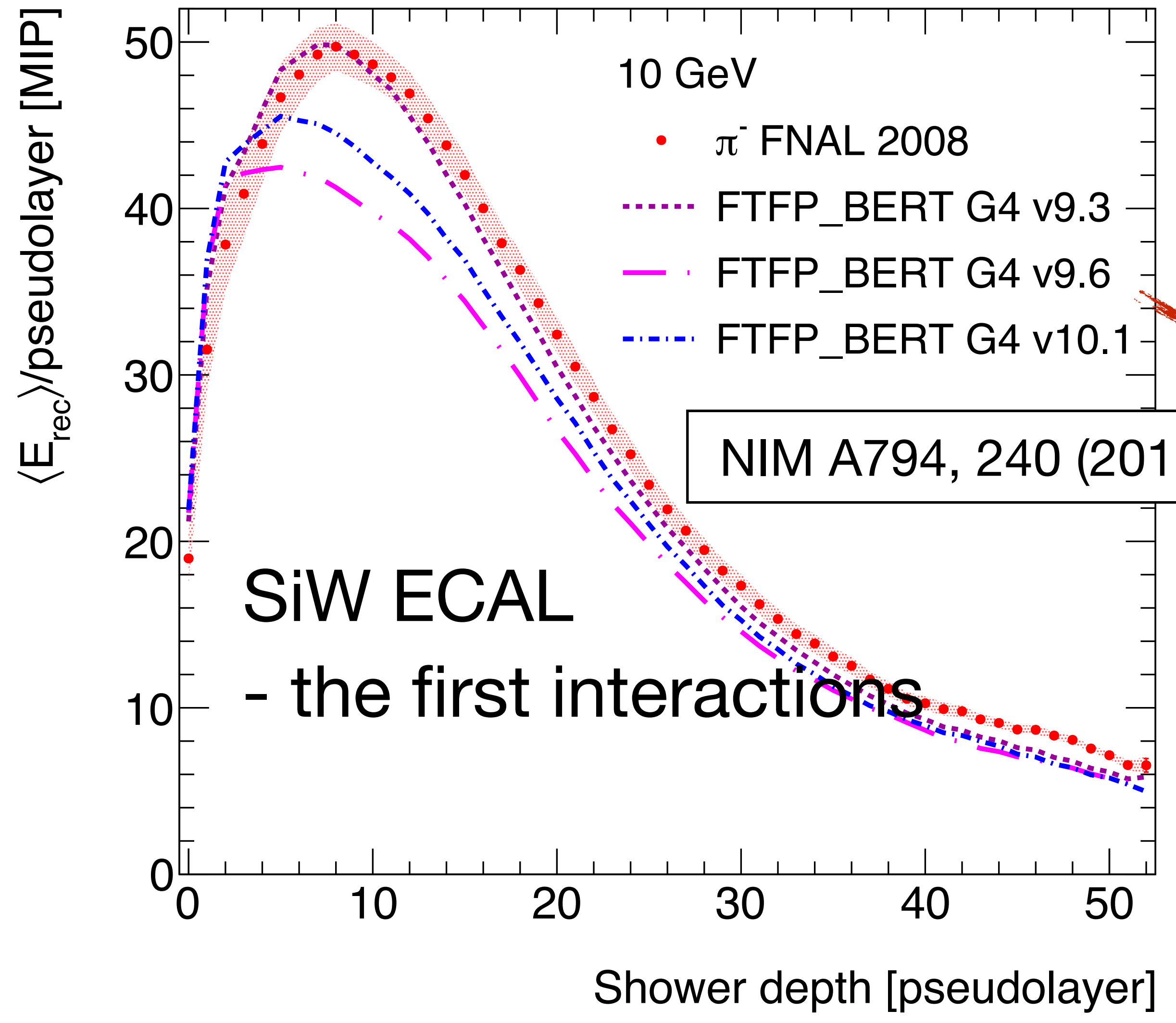

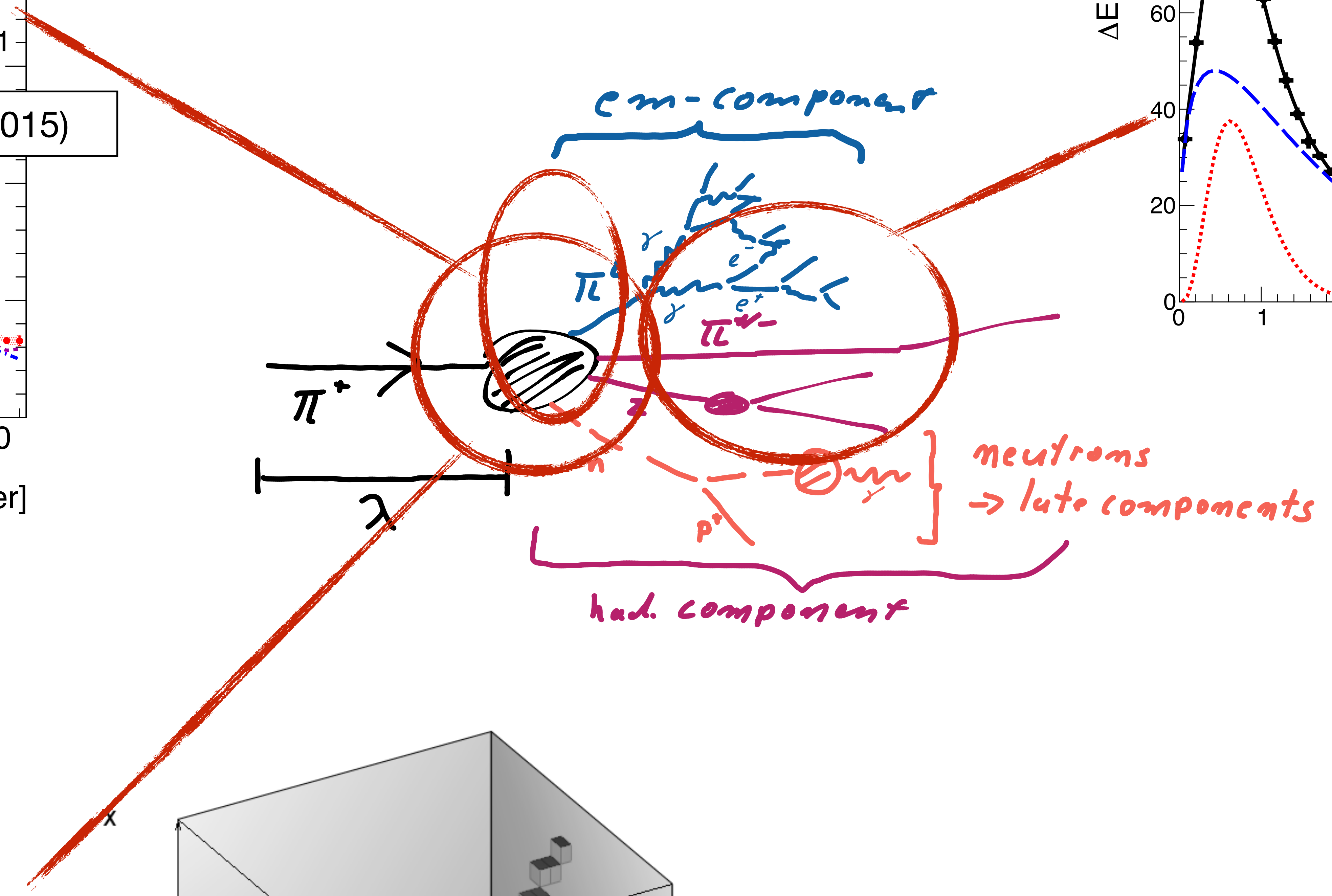

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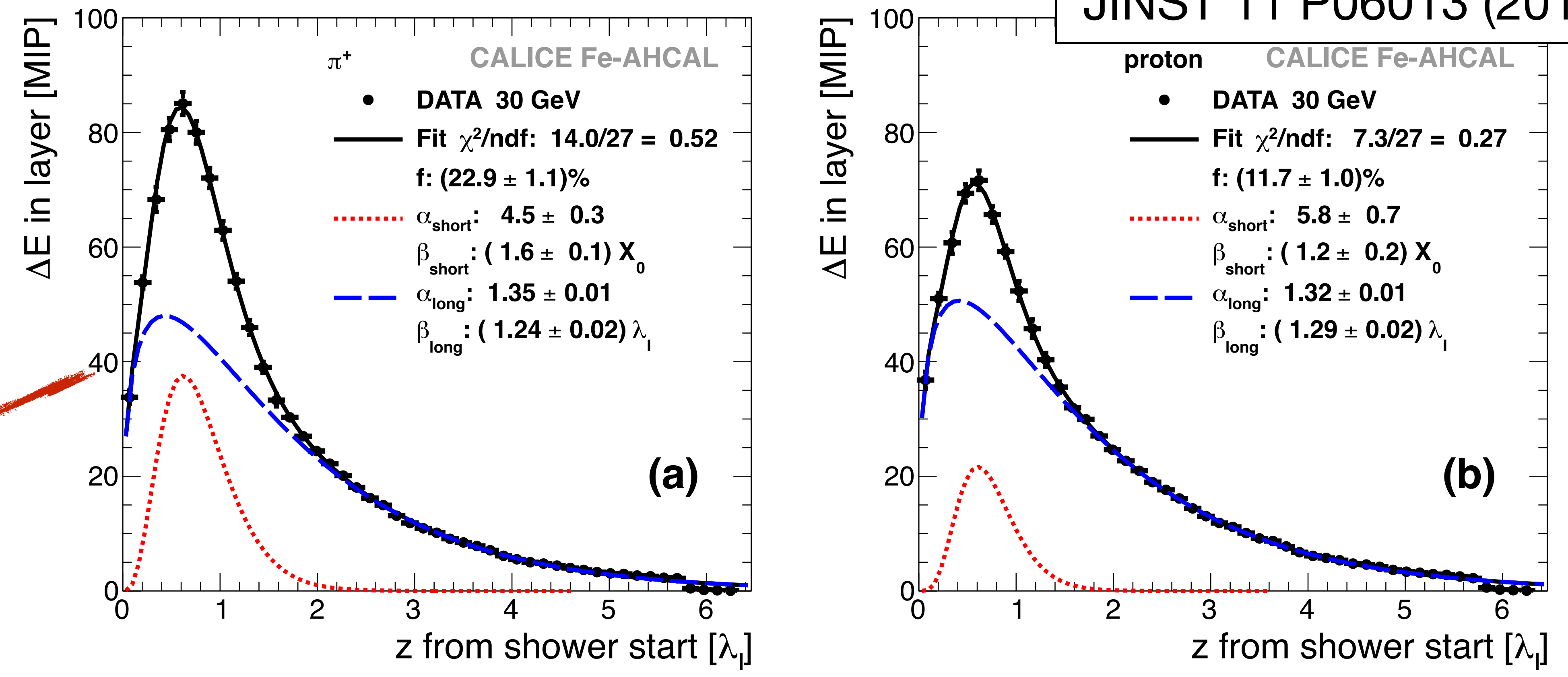

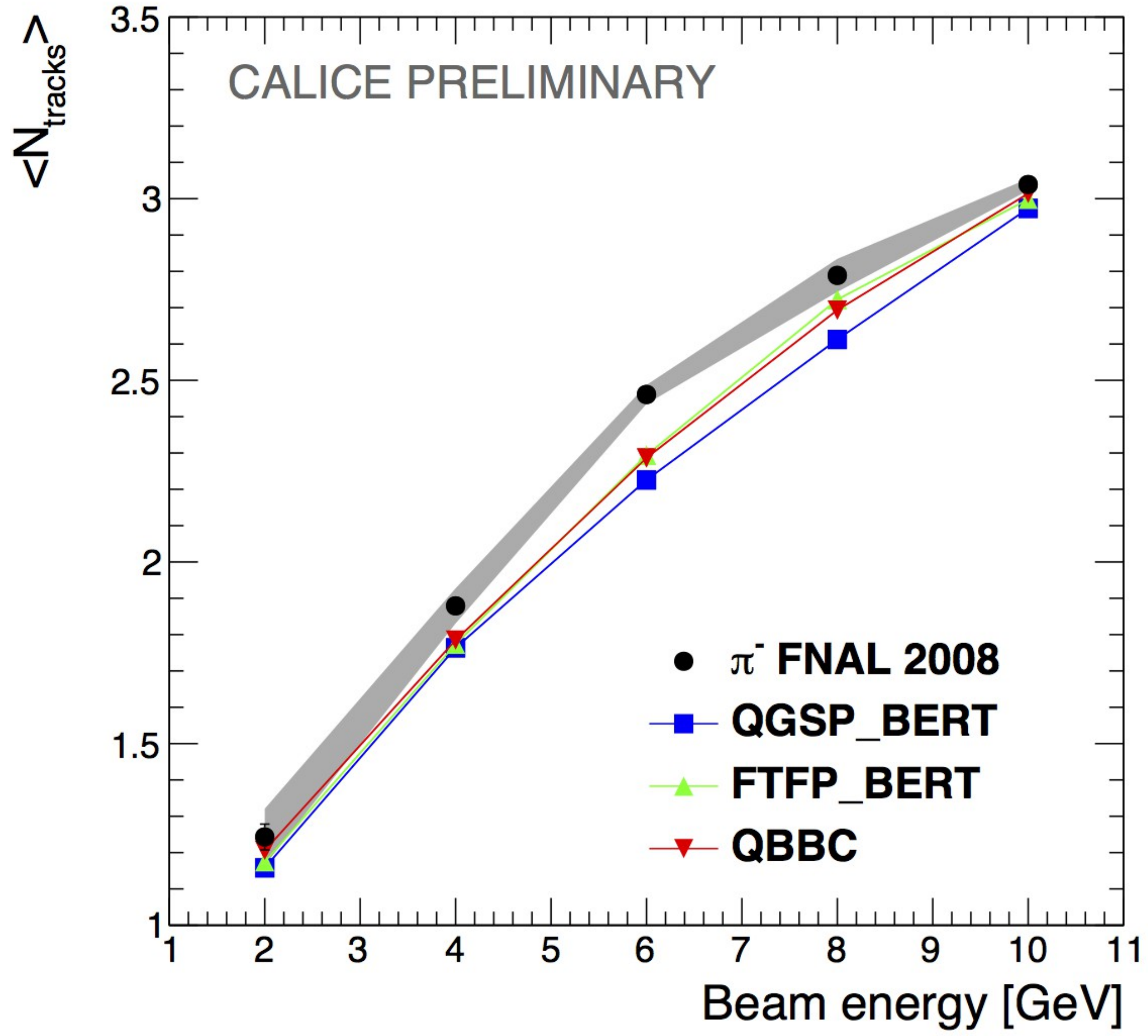

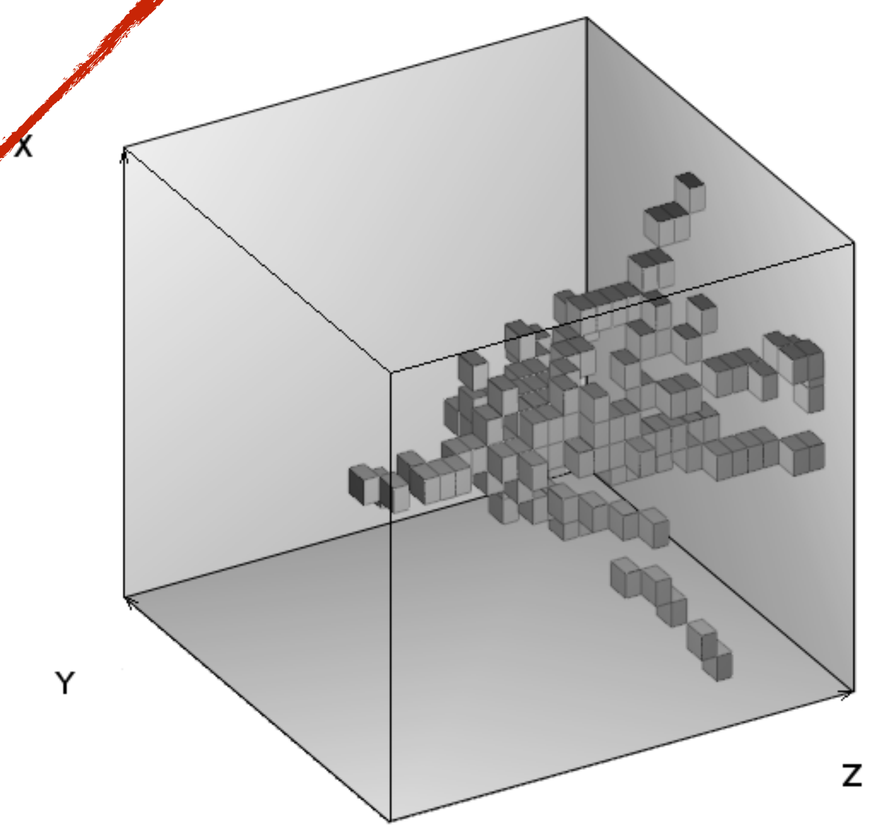

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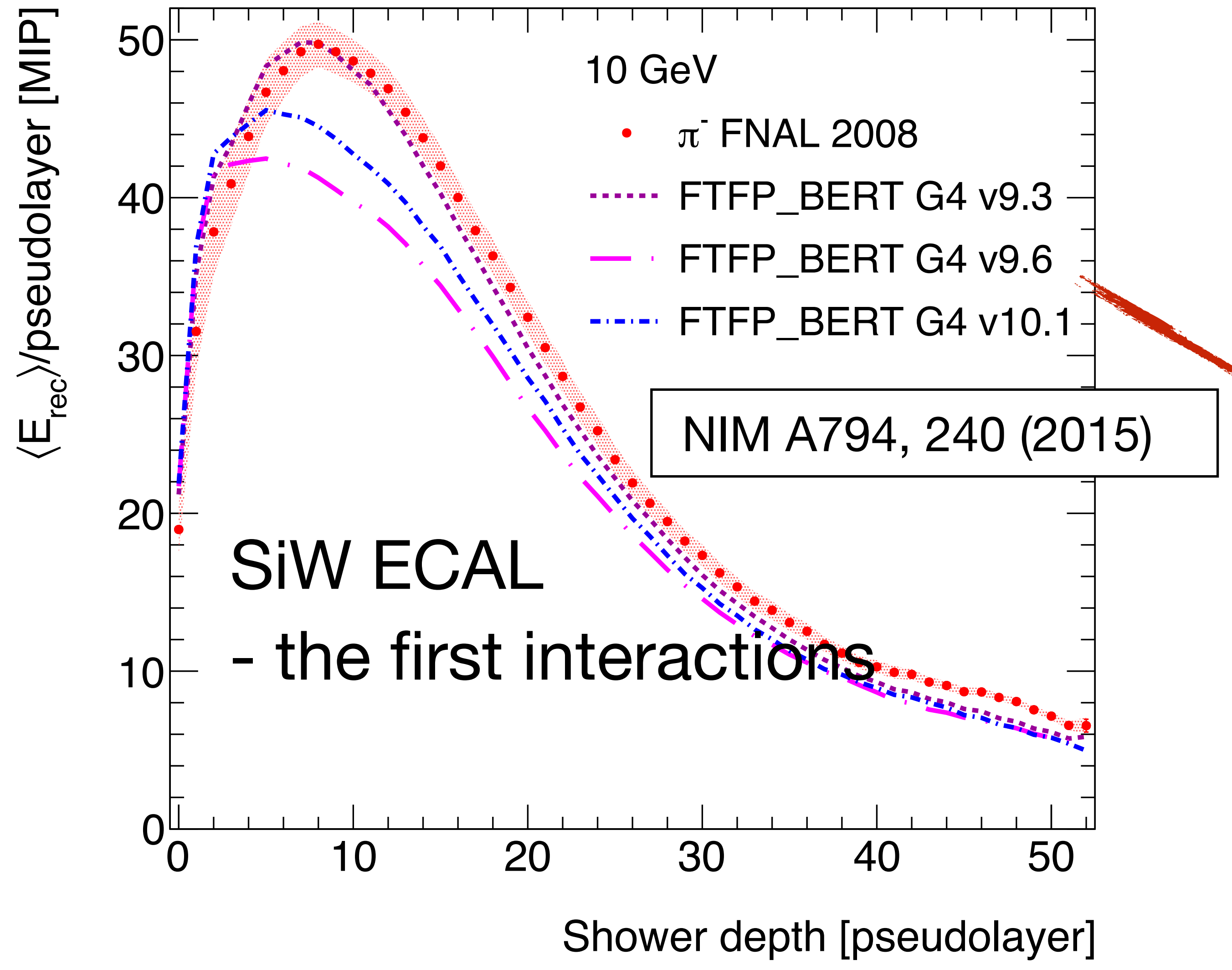
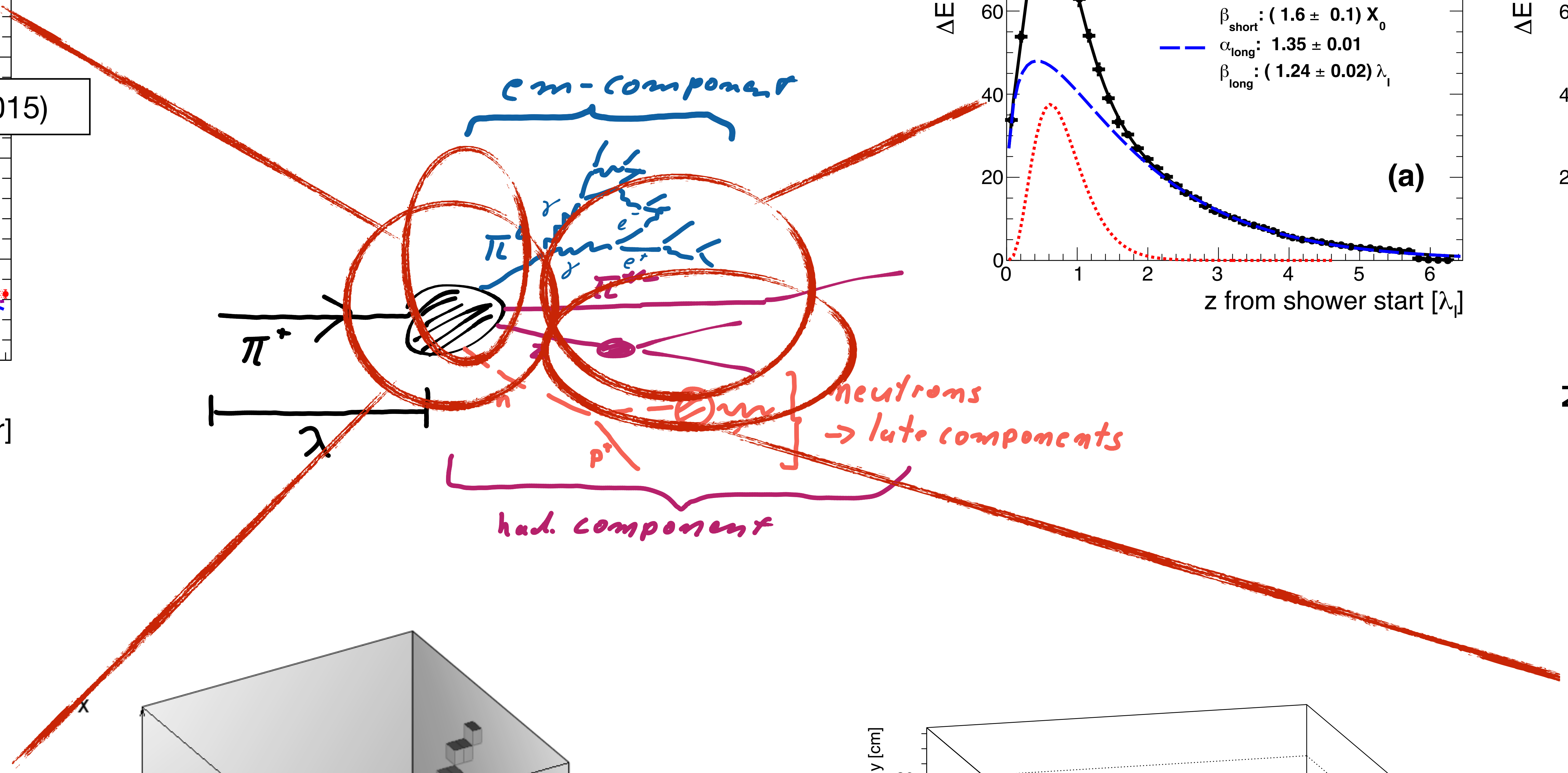
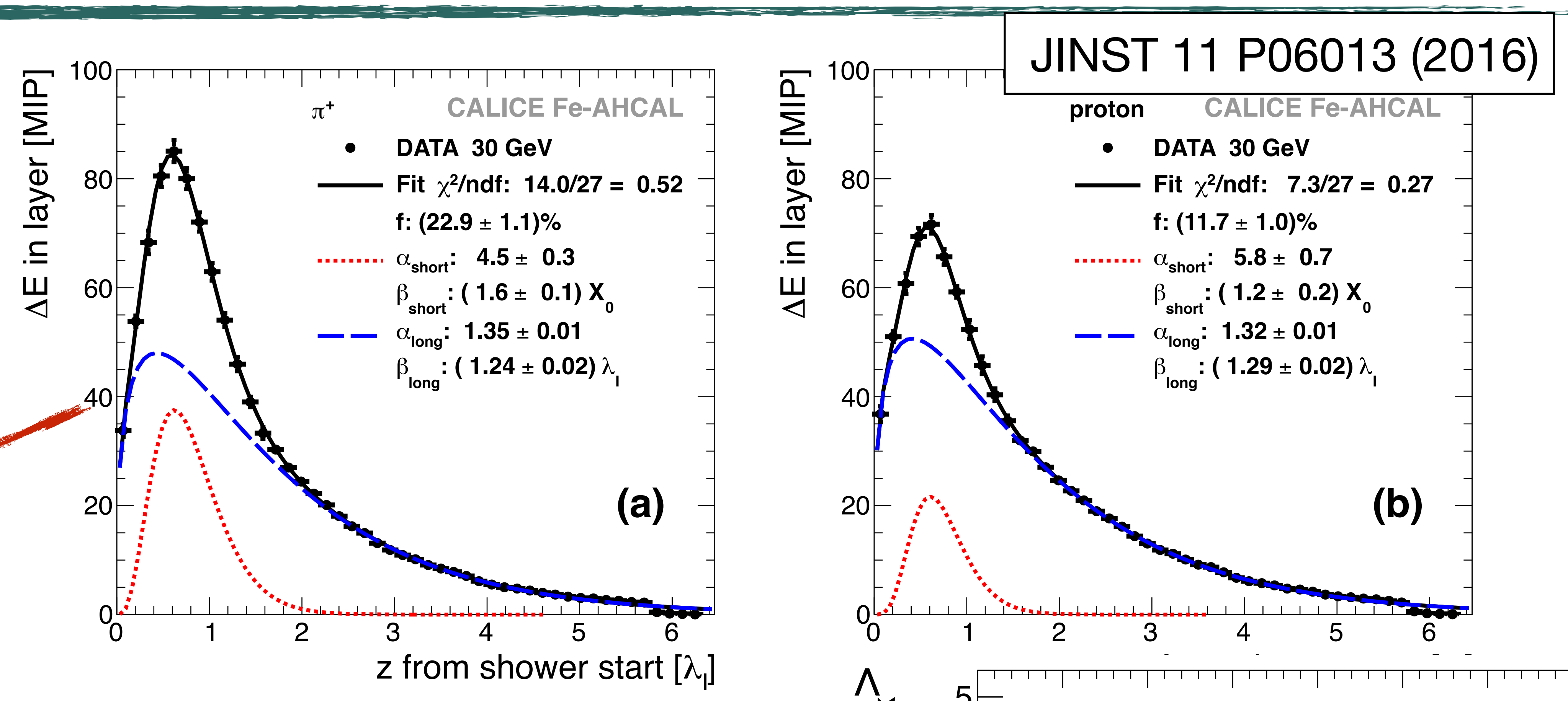
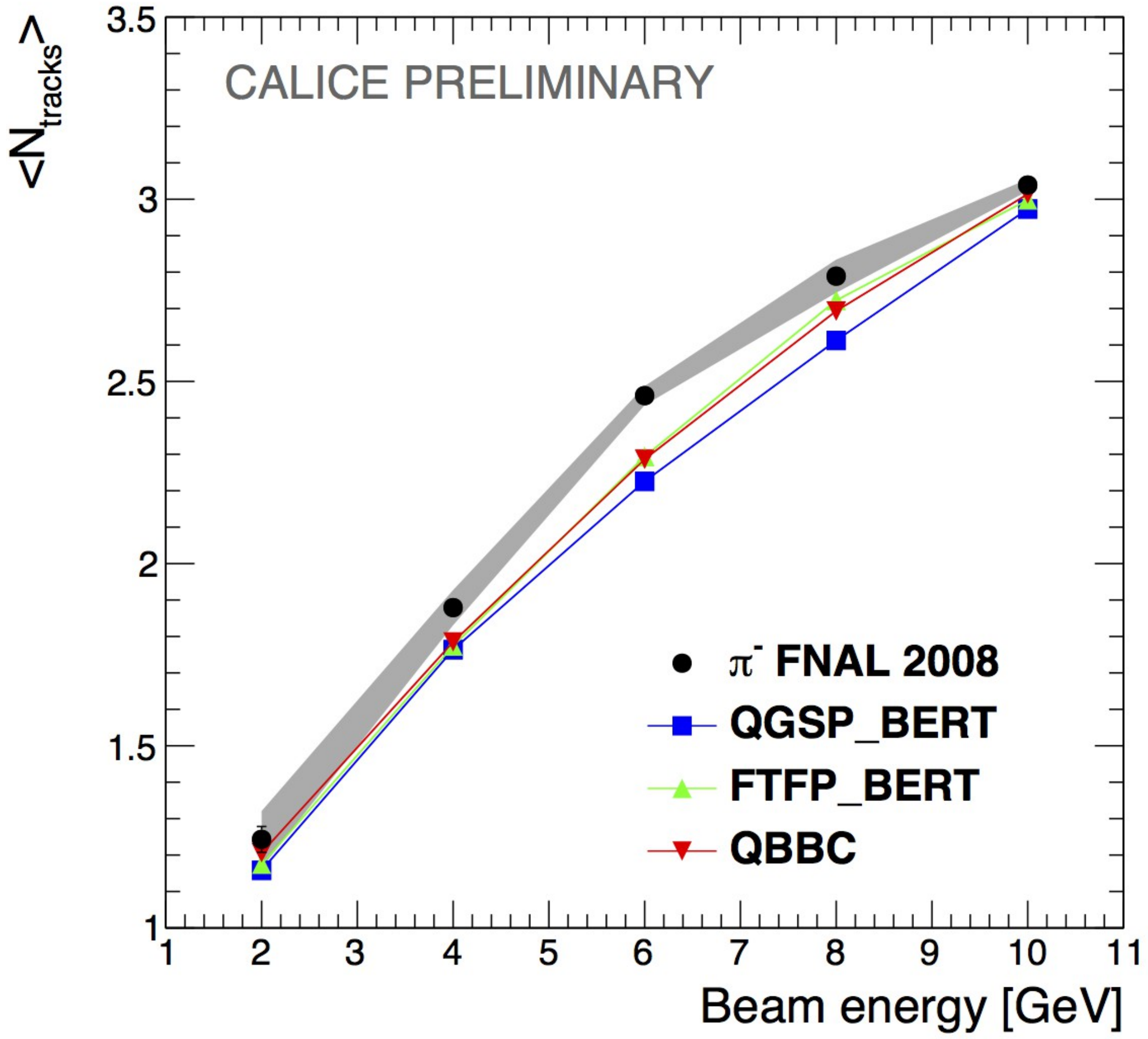
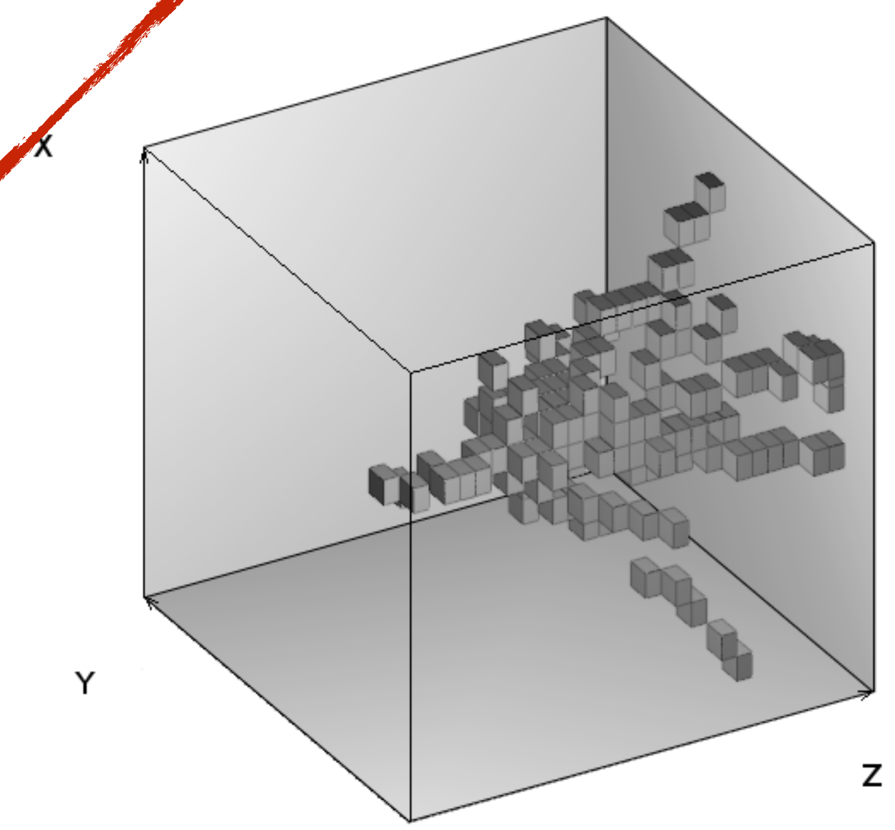
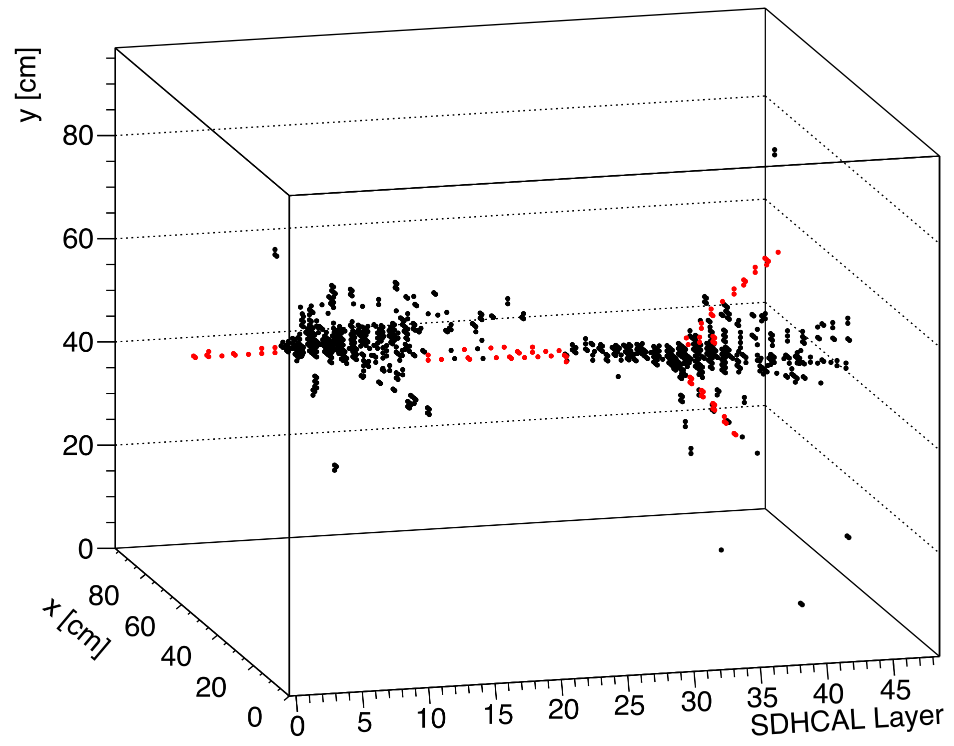


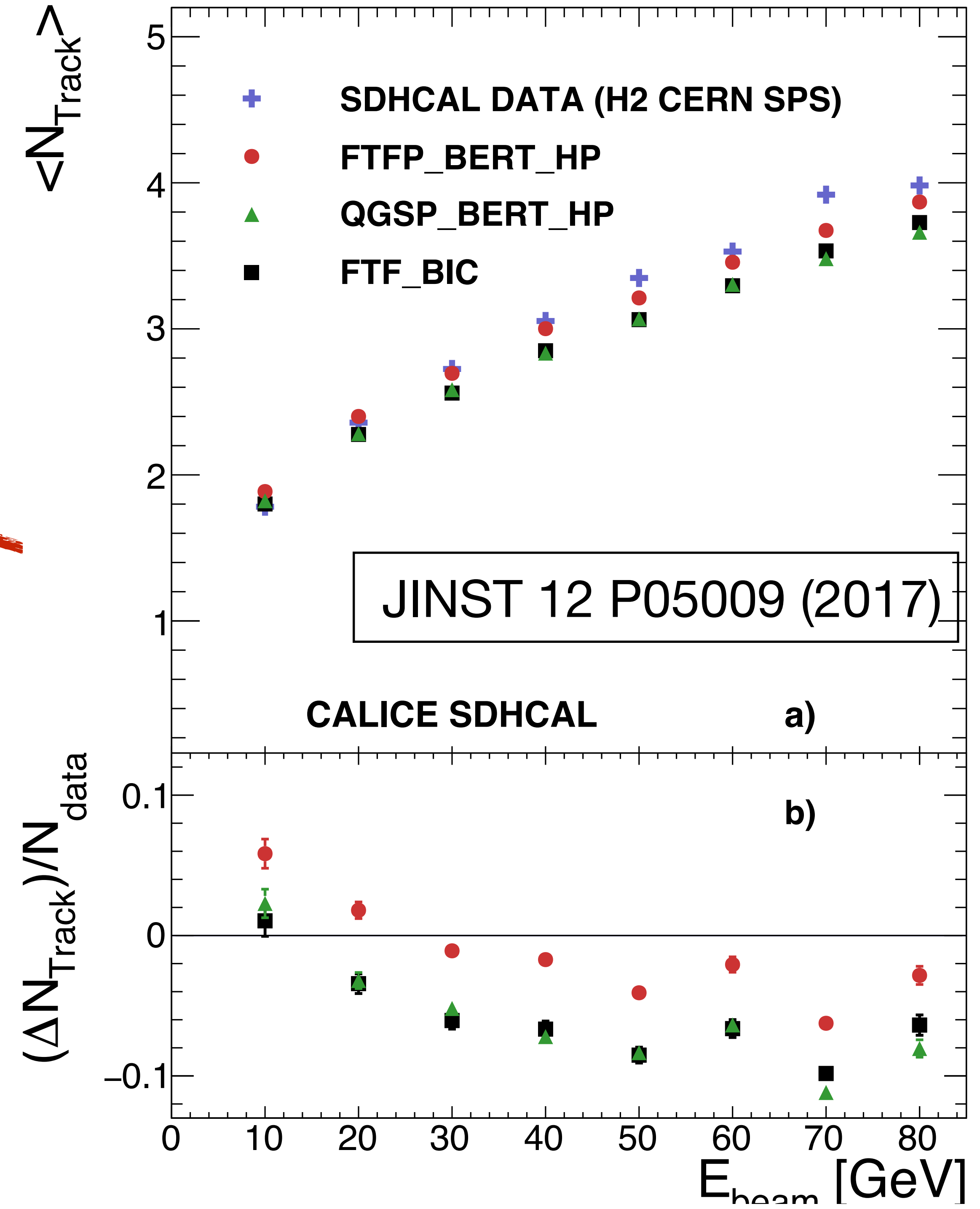












Finally: Next Steps & New Ideas

Just a few thoughts

- Incomplete collection of ideas - some of those are already being pursued or are on the agenda, others are speculative ideas that may or may not be picked up

  Plenty of opportunities!

Exploiting Prototypes and Datasets

Existing and Upcoming

- Fully exploit the capabilities of technological prototypes
  - Timing in hadronic showers
  - Hadronic showers in different absorbers: Steel and Tungsten
  - Combined ECAL + HCAL: Full system performance - resolution and topological reconstruction

➫ Continuing test beam program with a variety of different detectors

Further Developing CALICE Technology

Sensors, Electronics, Absorber Structures

- Novel sensors for ultra-high granularity - pixel sensors for digital ECALs
- Scalability of well-established solutions: silicon, scintillator, RPCs
- Additional twists: Megatiles as scintillator elements, novel materials for improved timing or enhanced neutron sensitivity

- Development of compact, low power interfaces - further miniaturization
- Solutions for circular colliders with continuous readout - w/o power pulsing
- Integration of interfaces, signals and services

- Highly precise, compact absorber structures
- Geometrical solutions for endcaps, module segmentation

Novel Technologies

Going beyond the current CALICE Portfolio

- Integration of timing layers (~ 30ps for MIPs) in the calorimeter volume
  - Understanding the benefits
  - Sensor options
  - Integration solutions

- Adding new materials:
  - highly segmented crystal calorimeters as options for imaging electromagnetic calorimeters
  - dual readout: scintillation and Cherenkov materials with highly granular readout

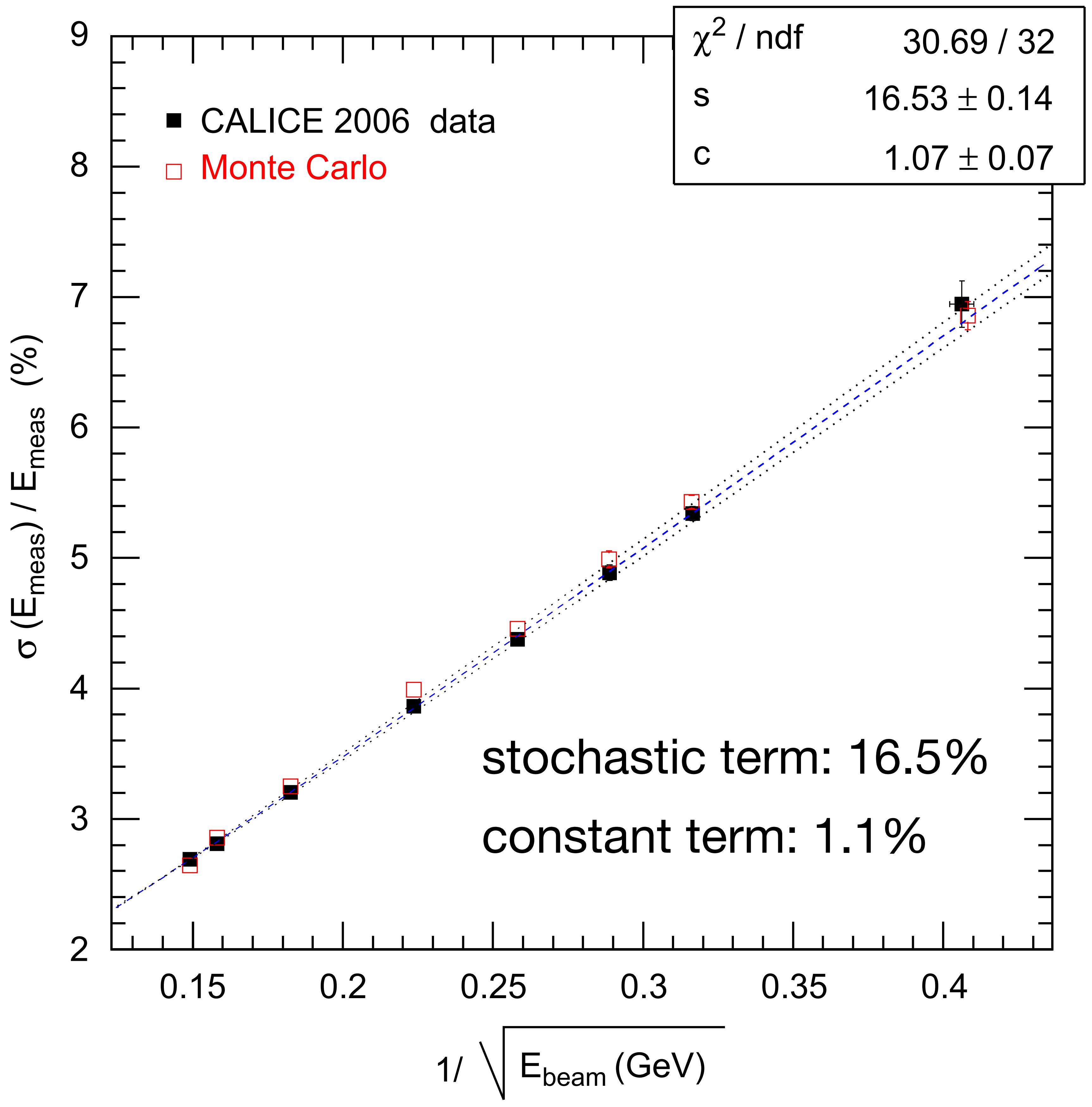
Summary

- Highly granular calorimeters are motivated by PFA - based event reconstruction - to allow optimal combination of calorimetry and tracking
  - In terms of possibilities, we have most likely only looked at the tip of the iceberg: Enormous potential for advanced reconstruction techniques making full use of the 4D or 5D information provided by such detectors
- CALICE has developed imaging calorimetry from an idea to a well-proven concept with established technological solutions suited for full experiments, also addressing integration and production challenges
  - The CMS HGCAL will take this one step further - in the extreme environment of the HL-LHC
- Interesting further R&D topics remain in many areas - and new collaborators from the US and elsewhere are highly welcome!

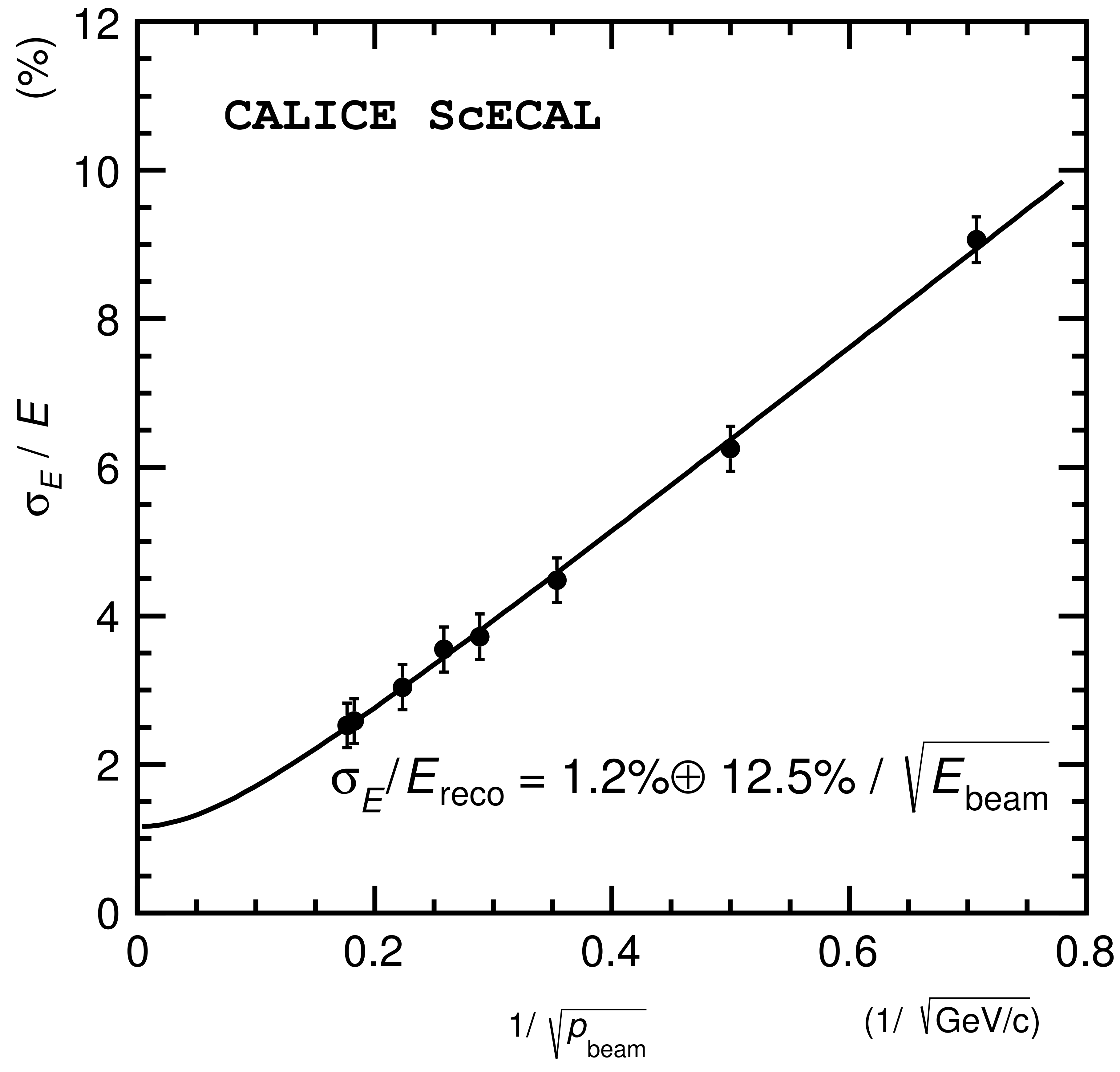
Extras

[N.B. Detector optimized for particle separation, not single particle resolution]

Silicon-Tungsten ECAL:



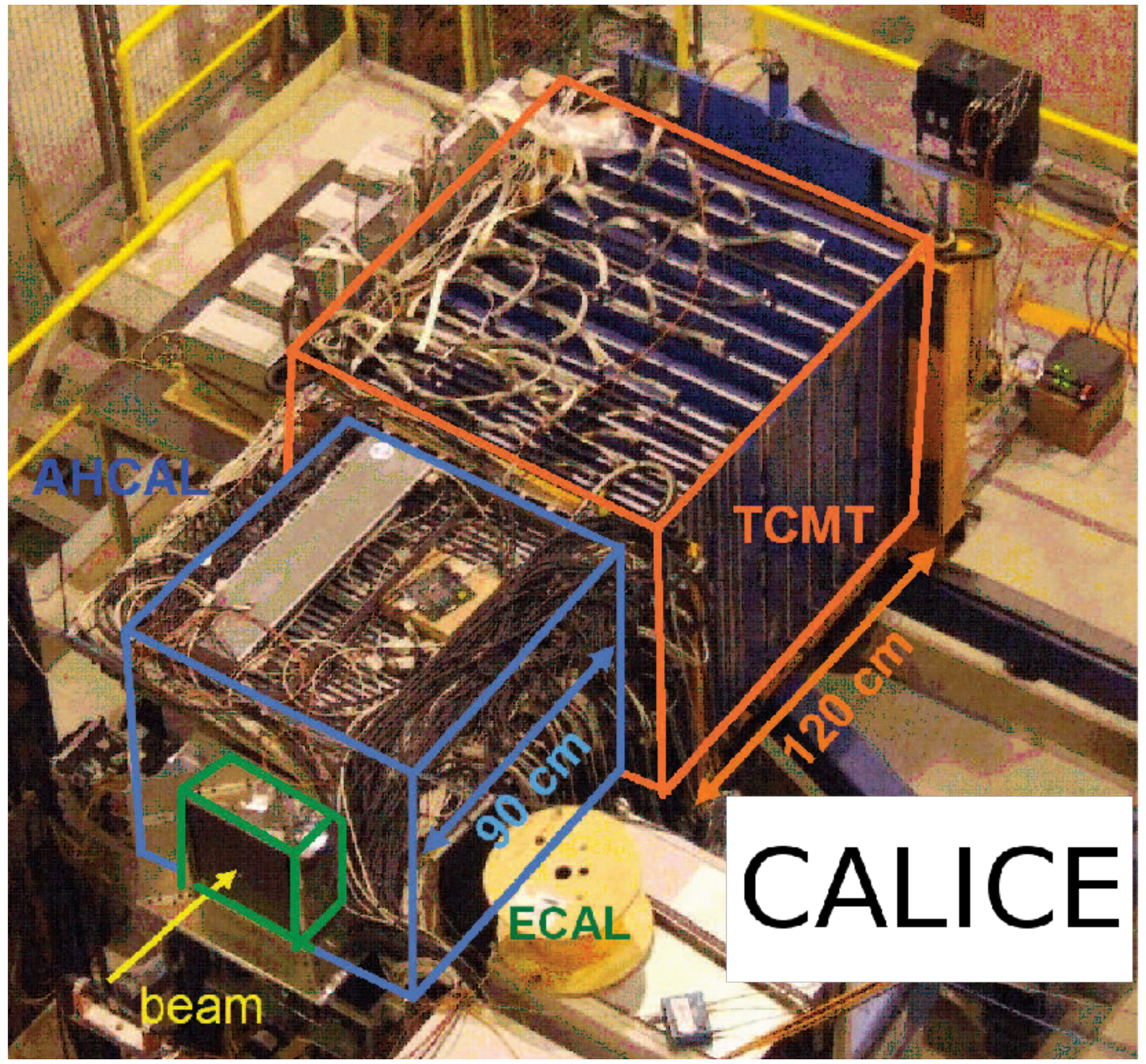
Scintillator-Tungsten ECAL:



Scintillator provides better energy resolution due to larger sampling fraction, with a reduced compactness

Energy Reconstruction with Software Compensation

Exploitation: Algorithms



- Studying energy resolution in a “real-world” setting: A combined system of SiW ECAL, Scintillator/FE HCAL, Tail Catcher
  - A combination of non-compensating systems with different active and absorber materials and varying longitudinal sampling
- Exploiting granularity: Local energy density can be used to improve energy resolution with software compensation methods

ECAL (30 layers):

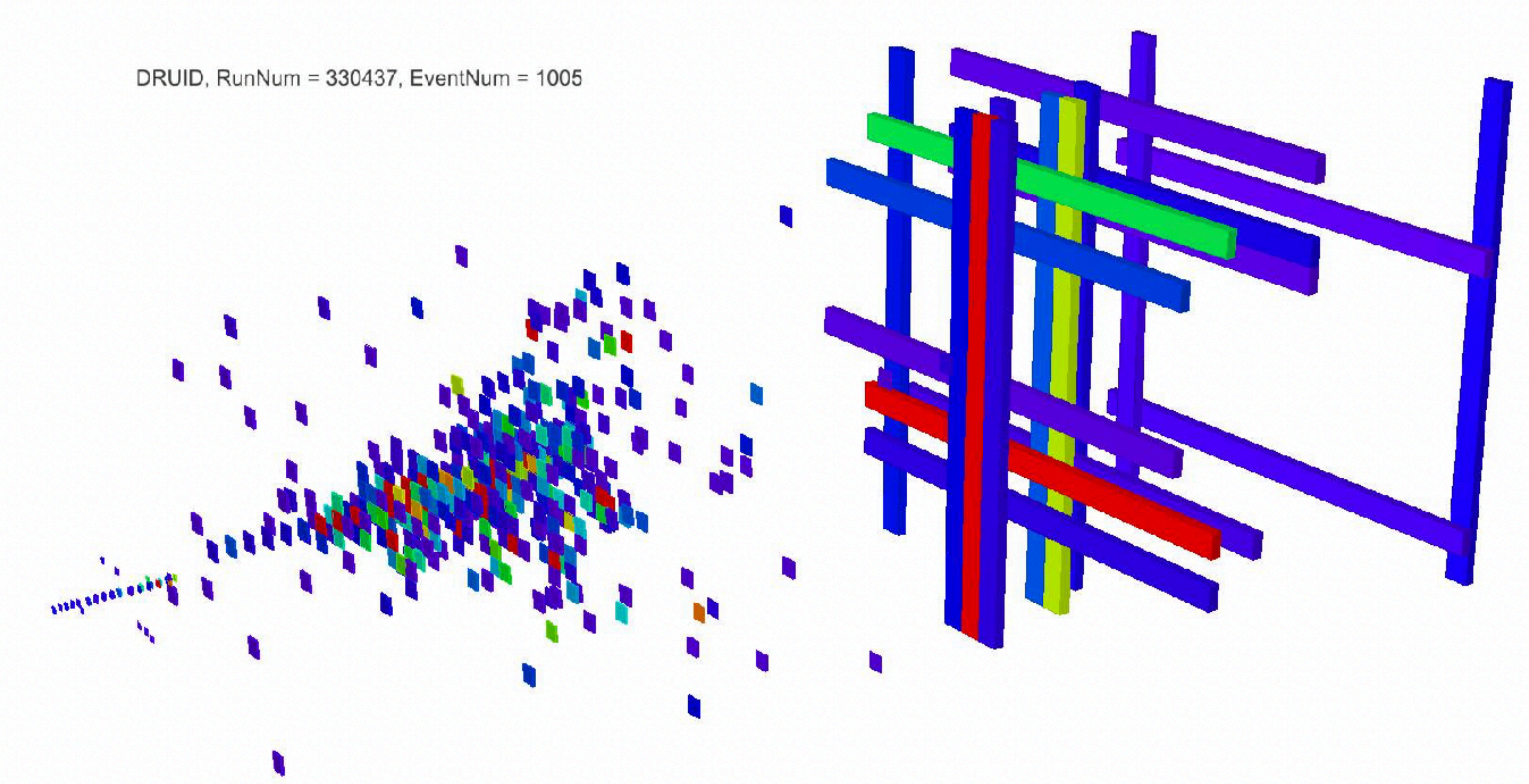
Absorber: W; 1.4 mm, 2.8 mm, 4.2 mm

Active: Si; 525 µm

HCAL (38 layers) / TCMT (8+8 layers):

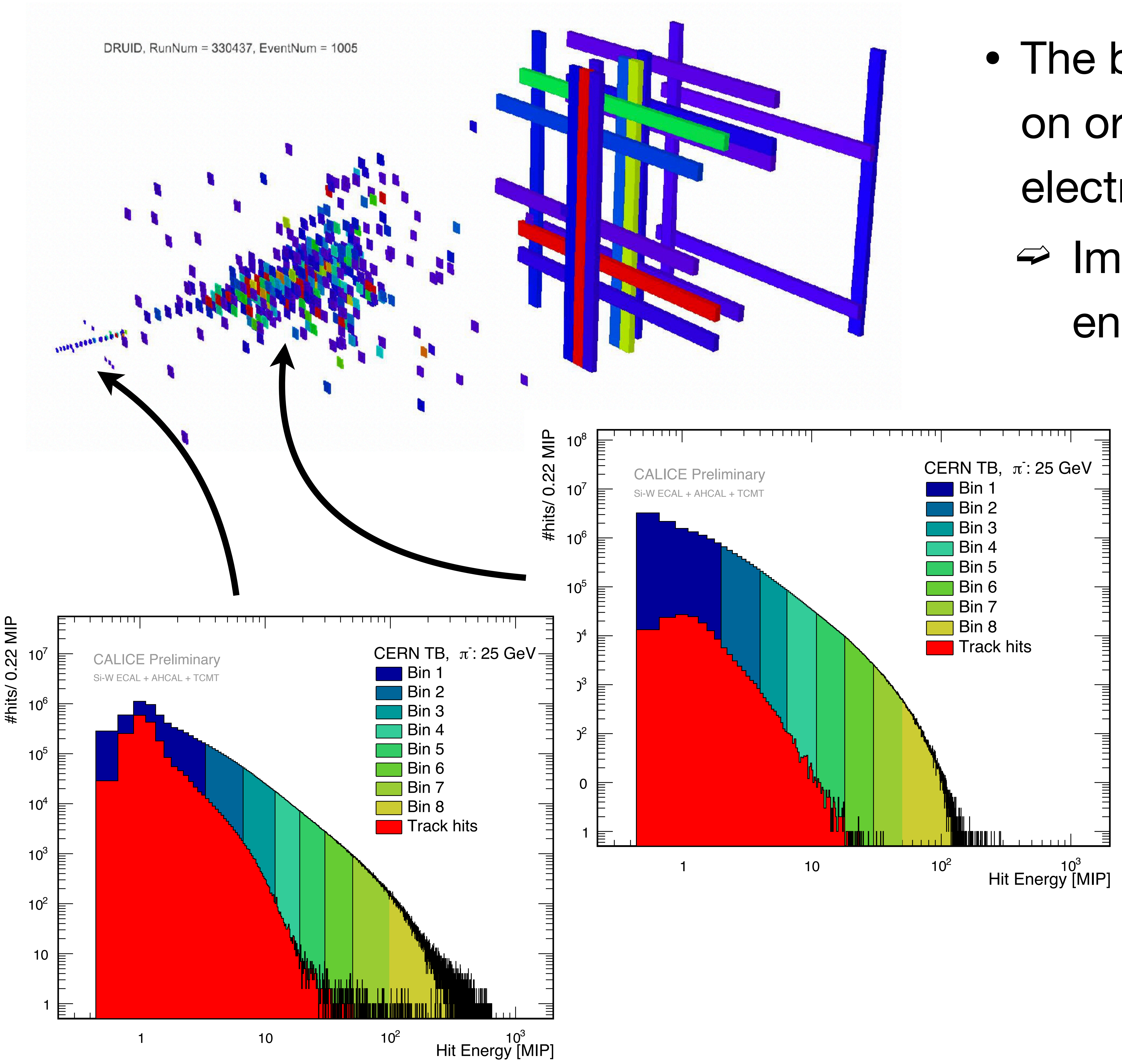
Absorber: Steel; ~ 21 mm (including cassettes)

Active: Plastic scintillator; 5 mm



Energy Reconstruction with Software Compensation

The Principle



- The basis of the technique: Local shower density depends on origin of energy deposits: higher density for electromagnetic subshowers
  - ➩ Impact of non-unity e/h can be reduced by assigning energy-dependent weights to hits in global energy sum

Energy Reconstruction with Software Compensation

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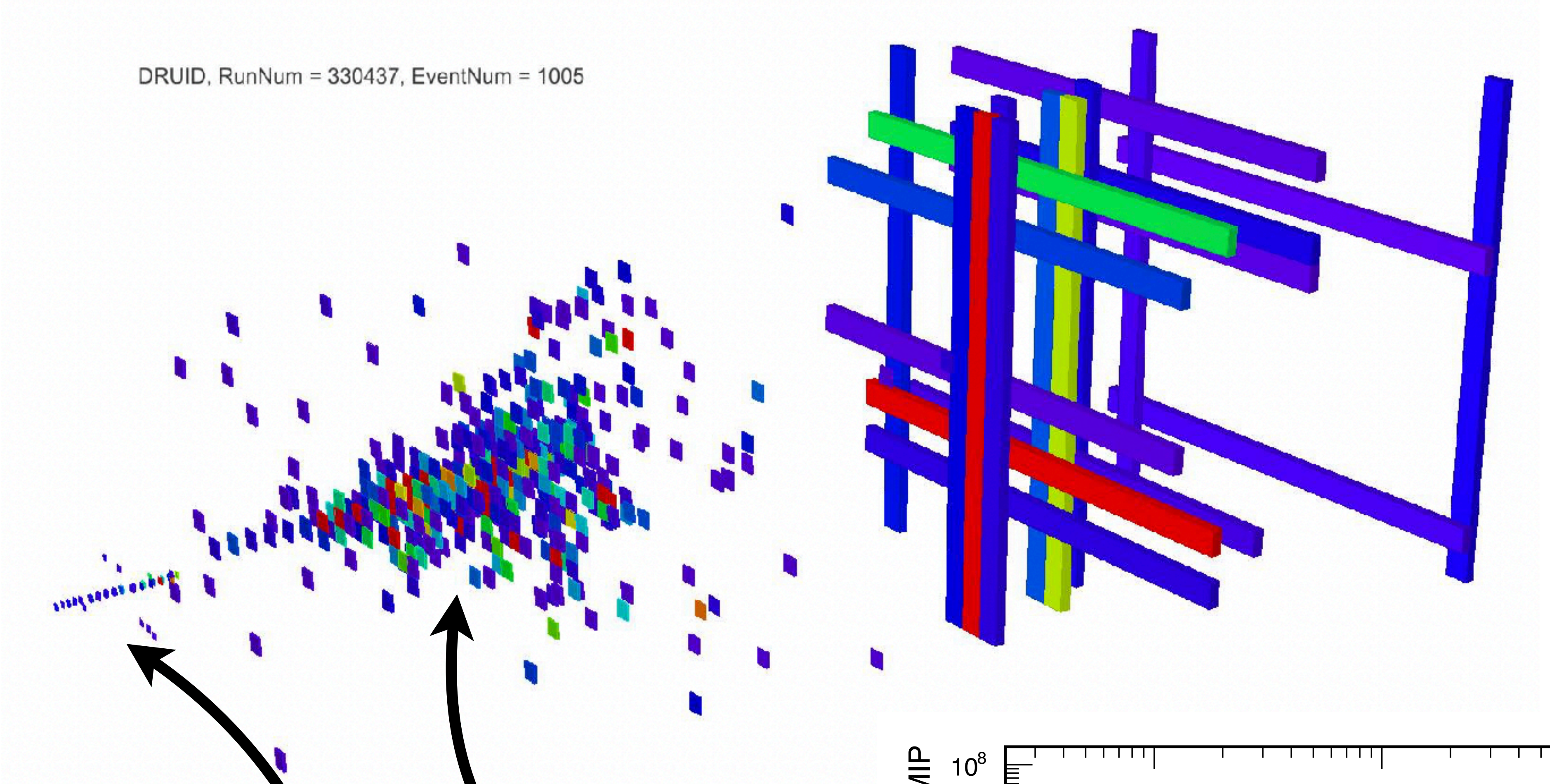

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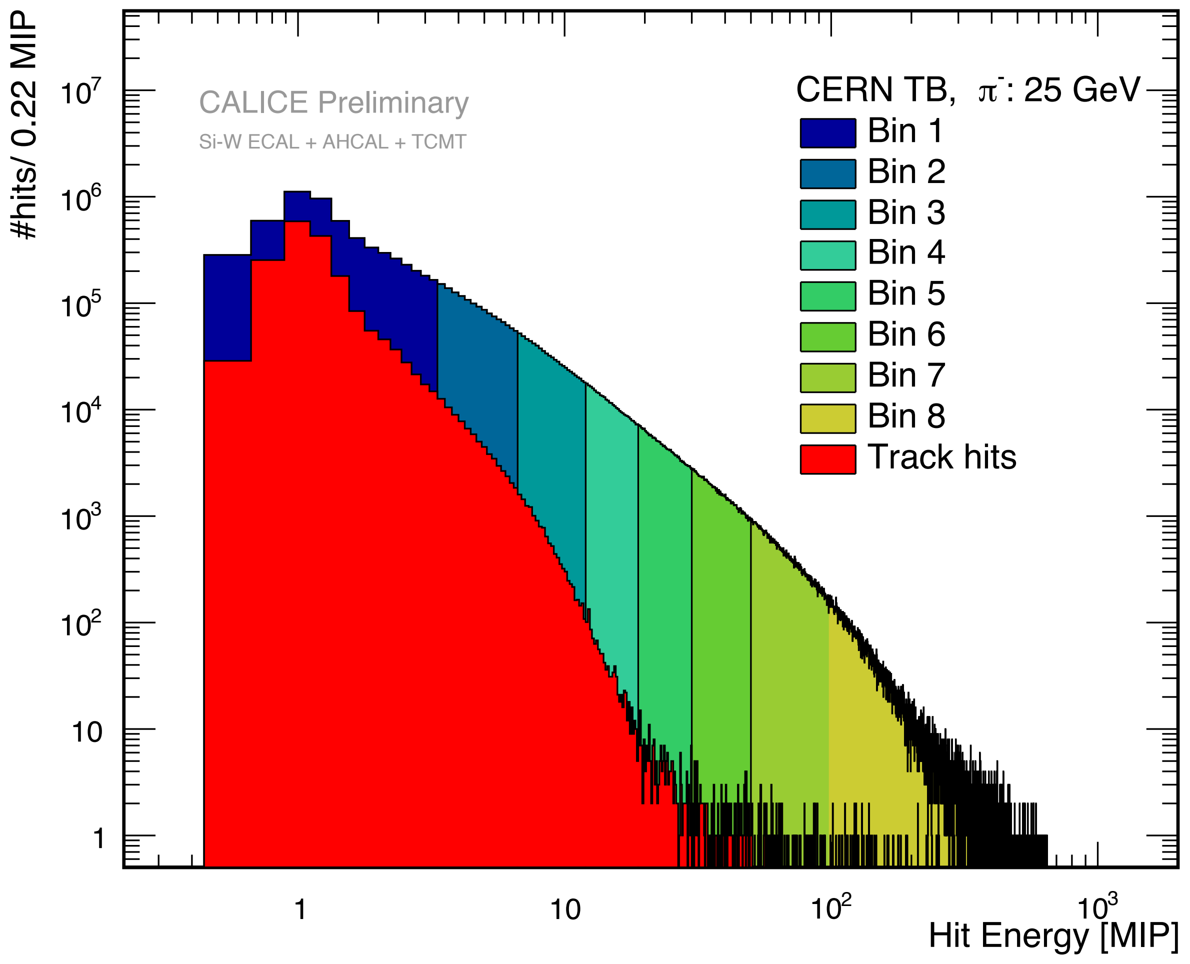
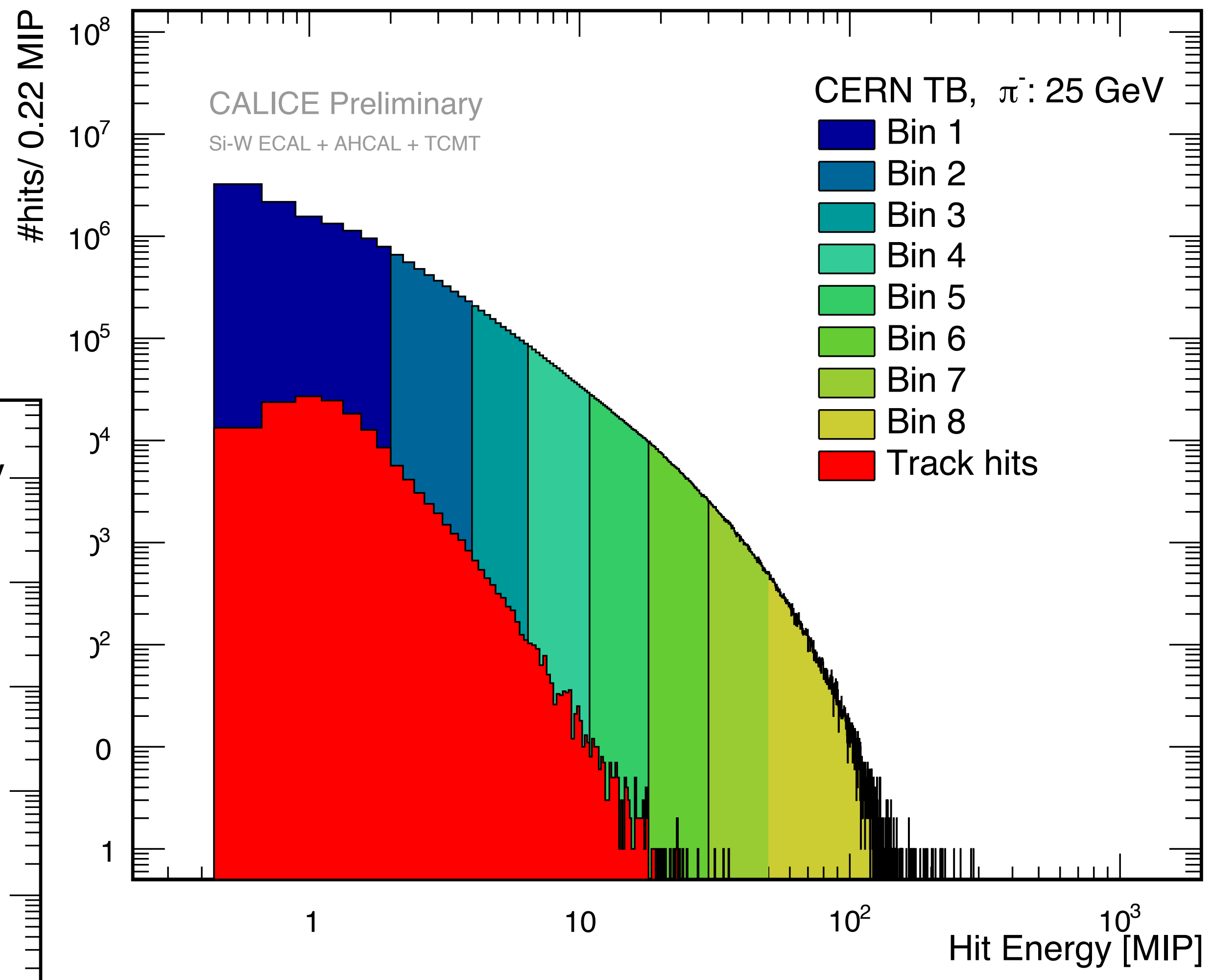
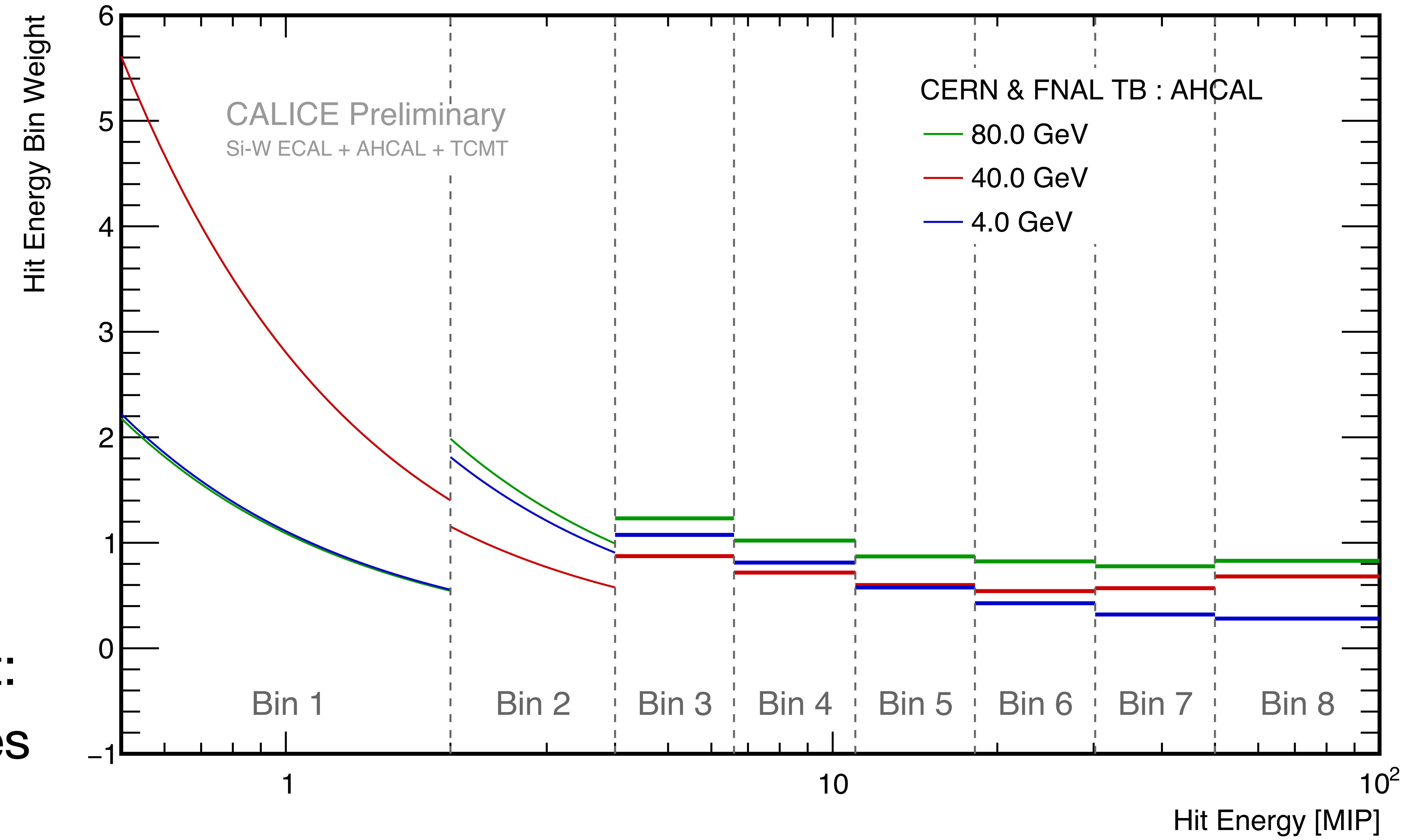




weights are energy dependent: overall shower density changes with energy!



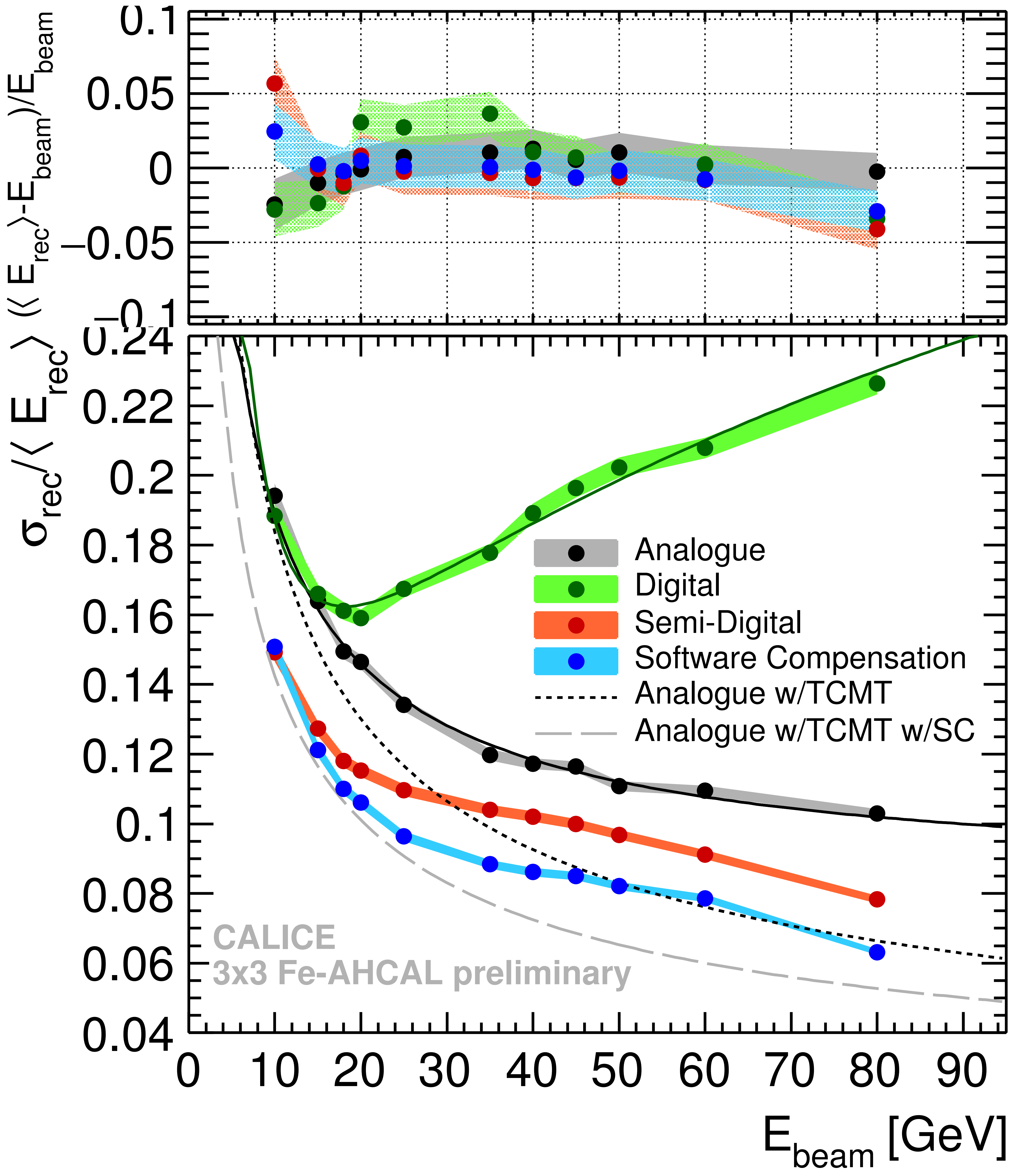
Different Schemes of Hadronic Energy Reconstruction

Understanding the Performance of Highly Granular Calorimeters

- CALICE hadron calorimeters use different schemes for energy reconstruction - depending on readout technology:
  - *scintillator*: analog & software compensation
  - *gas*: digital (1 bit), semi-digital (2 bit)

N.B.: Semi-digital reconstruction and software compensation are related: both use optimised hit or energy dependent weighting factors

- Different schemes tested on AHCAL data (3 x 3 cm² granularity)



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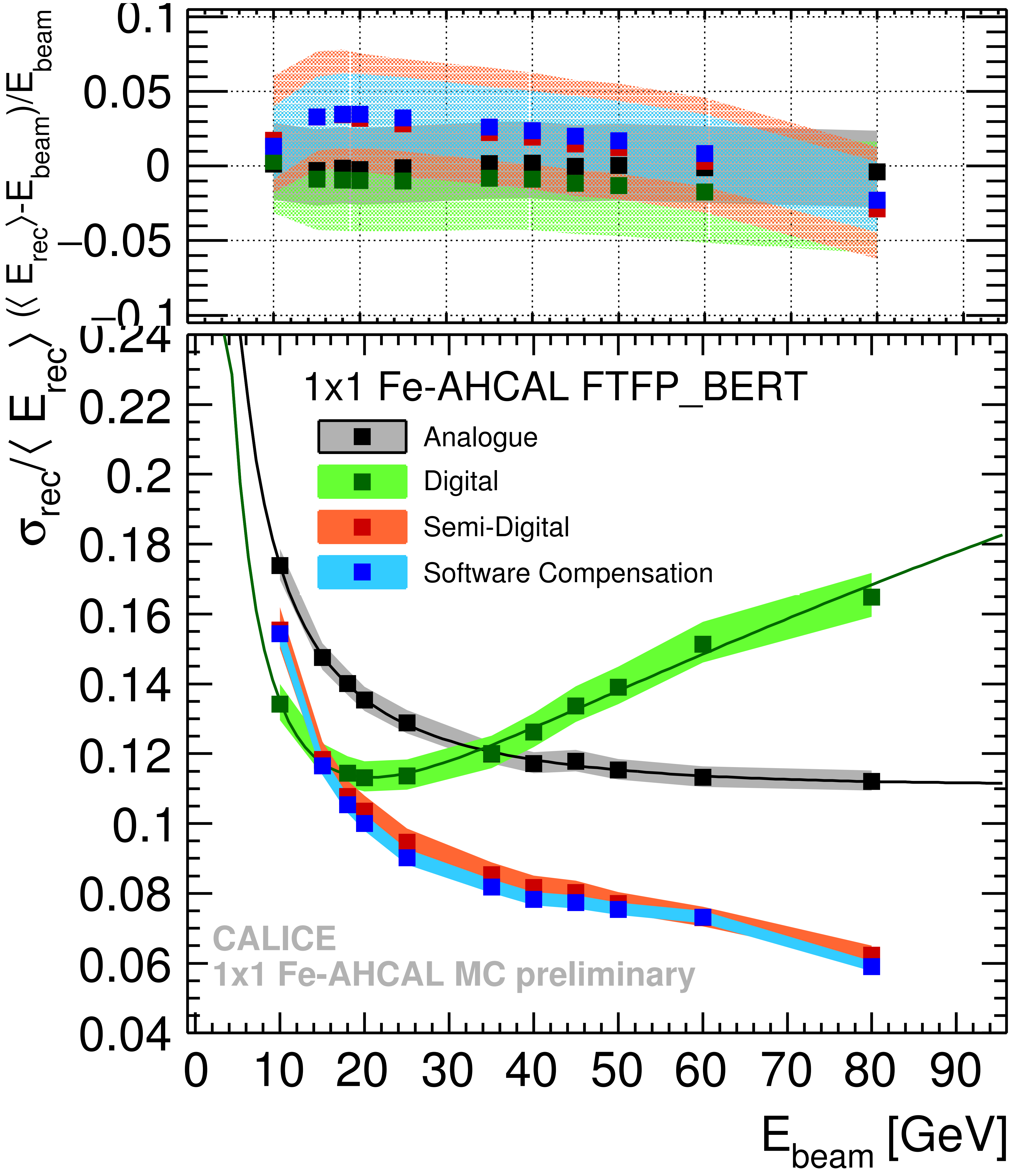
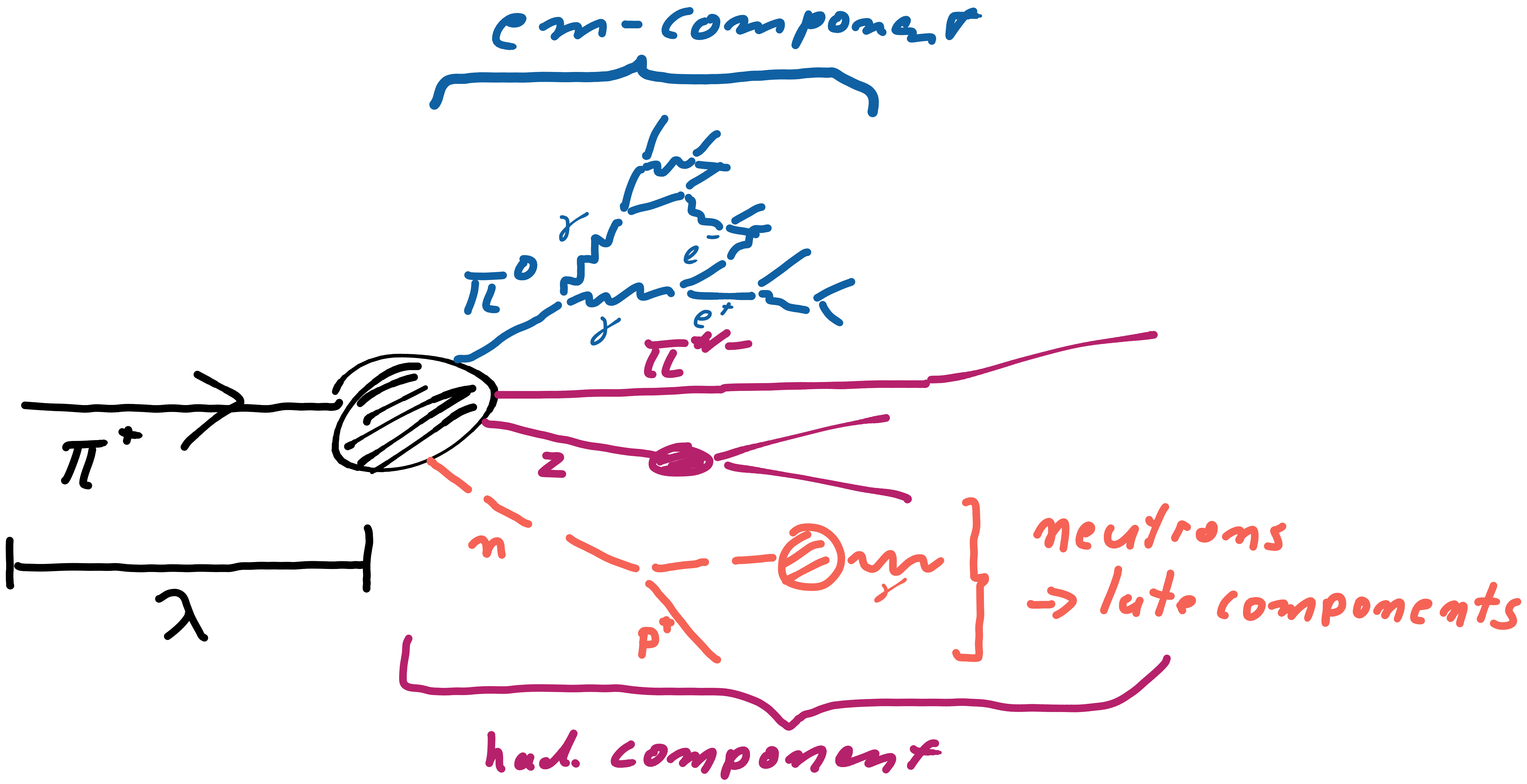
- Different schemes tested on AHCAL data (3 x 3 cm² granularity)
- Simulations used to study 1 x 1 cm² granularity (scintillator)
  - Digital & fine granularity best at low energy: Suppression of fluctuations
  - SC & semi-digital comparable
    NB: Sampling fraction matters: Semi-digital reconstruction in RPCs does not reach the same resolution



- Hadronic showers are complex:



compact - characterizes regions close to inelastic interactions

sparse - results in MIP-like particles connecting regions of higher activity

extended in time:

- few 10 ns from travel time of MeV-scale neutrons
- longer delays up to μs (and more) from thermal neutron capture and subsequent photon emission

Understanding Hadronic Showers

Highlights and Expectations

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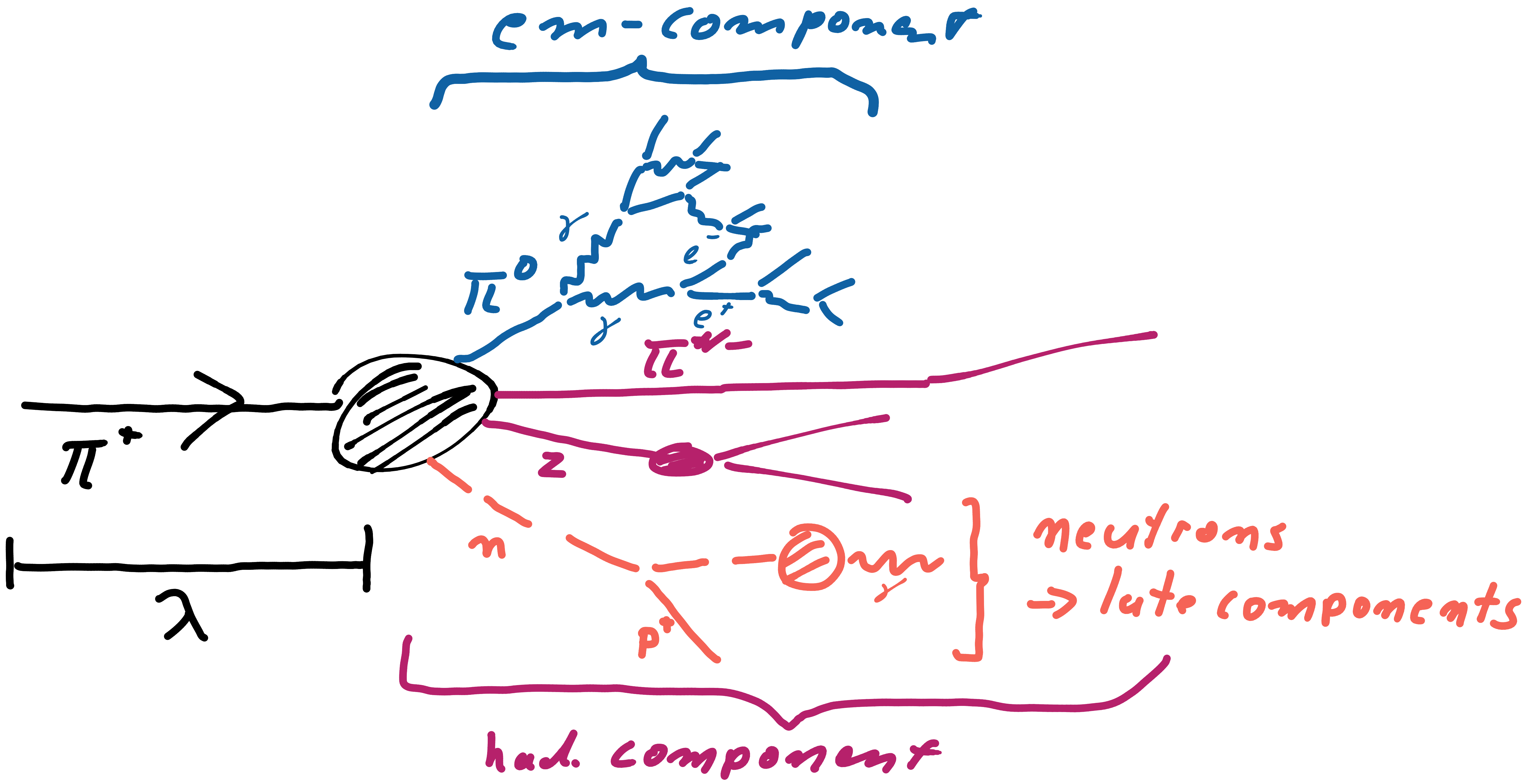

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extended in time:
- few 10 ns from travel time of MeV-scale neutrons
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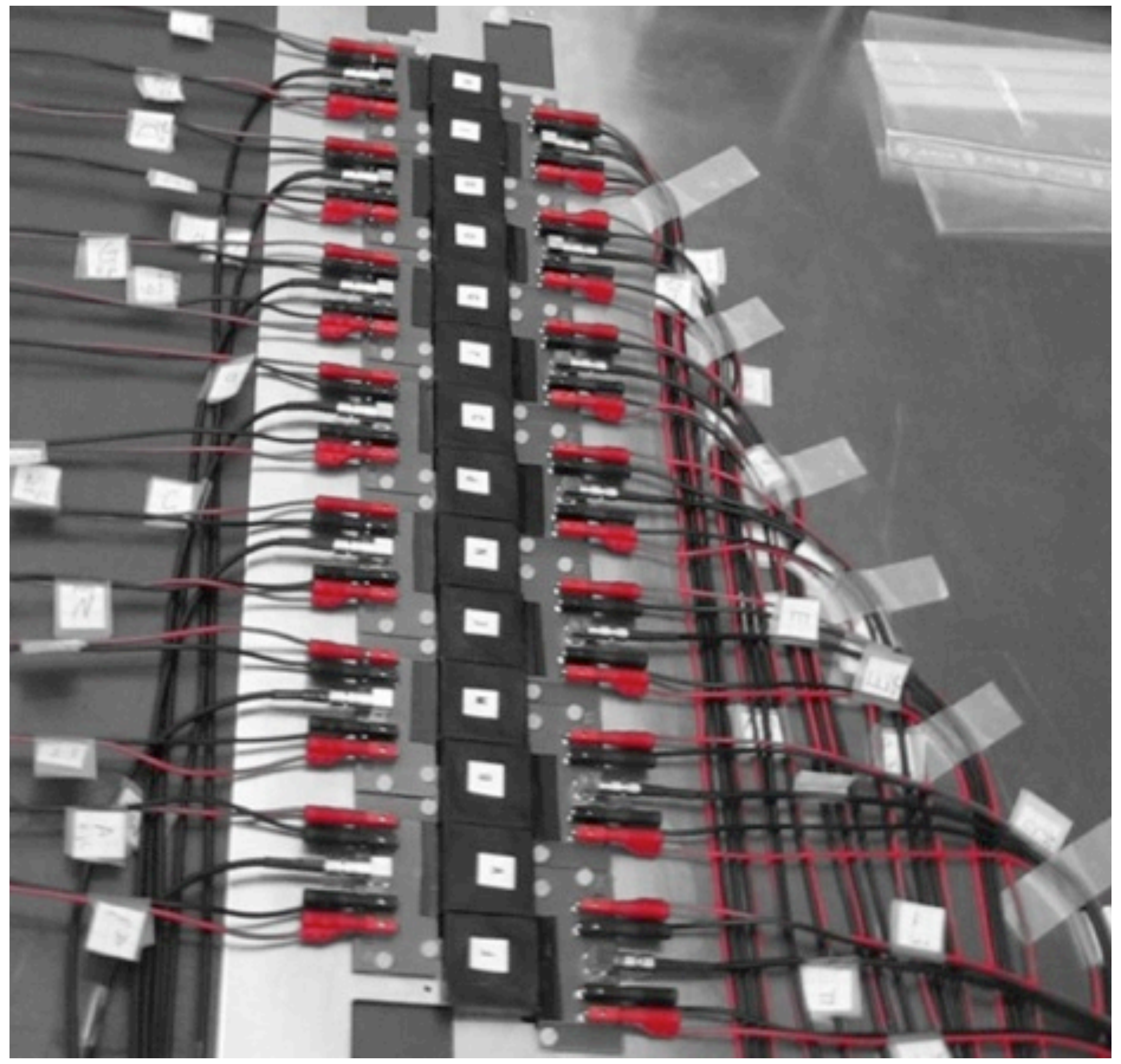
- Simulation is crucial to optimise detectors and to analyse data

➩ CALICE data with unprecedented granularity provides a new level of information to improve modeling of showers in GEANT4

Understanding Hadronic Showers

From 4D to 5D

- New technological prototypes (SiW ECAL, AHCAL) will provide cell-by-cell nanosecond-level timing: Studies of hadronic showers in space, amplitude and time
  - Builds on first studies with a single strip of scintillator tiles



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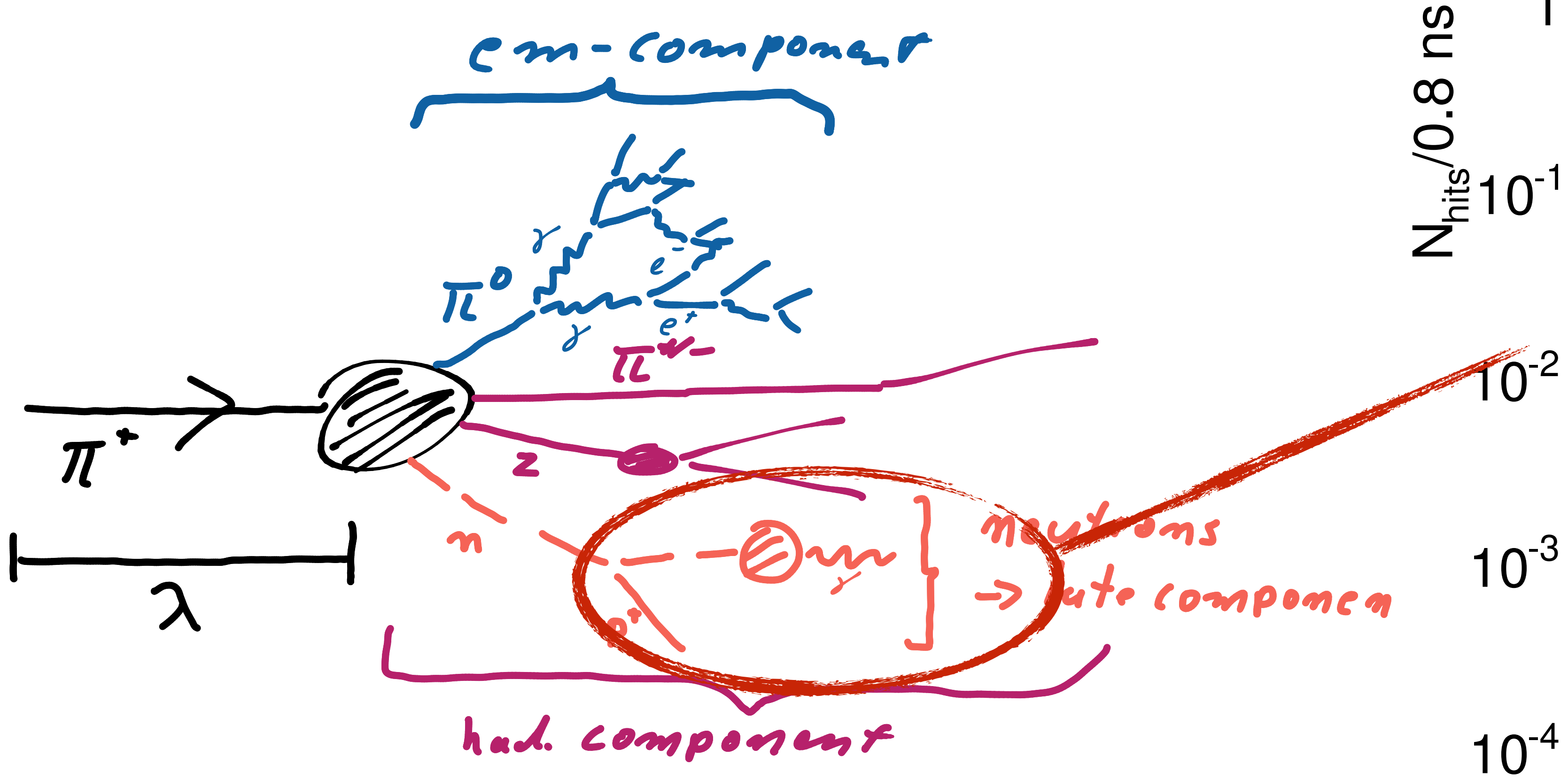

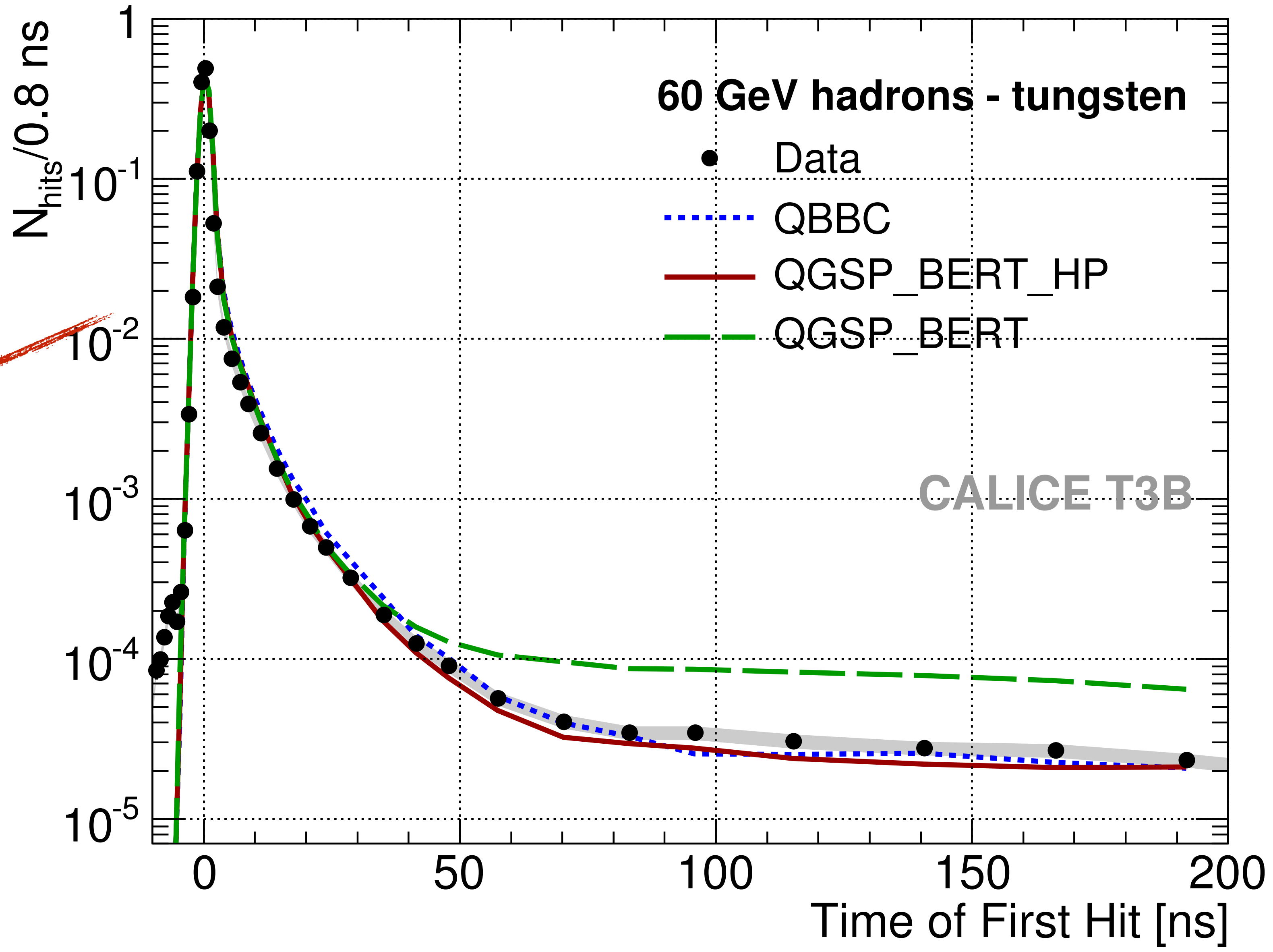

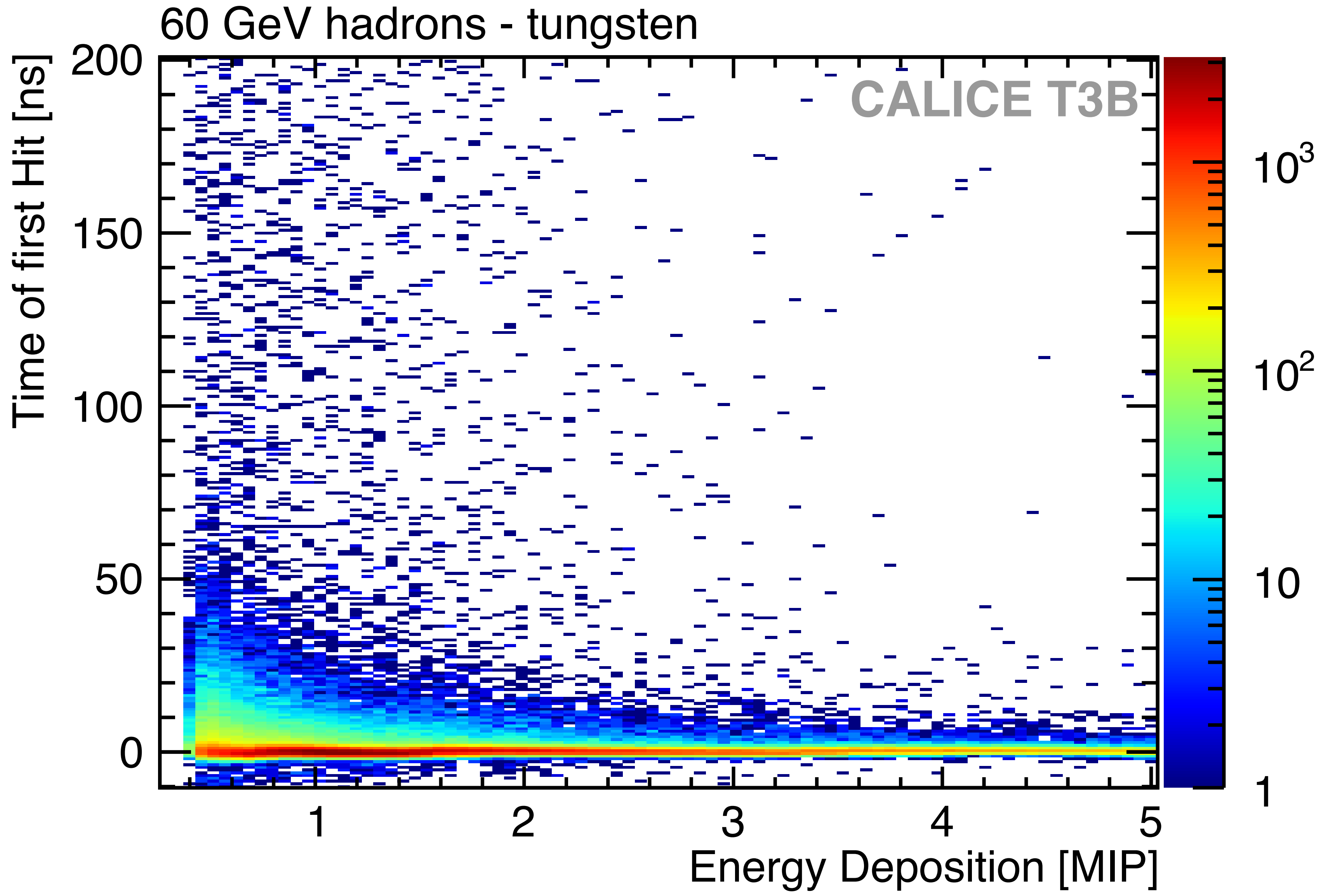

JINST 9 P07022 (2014)

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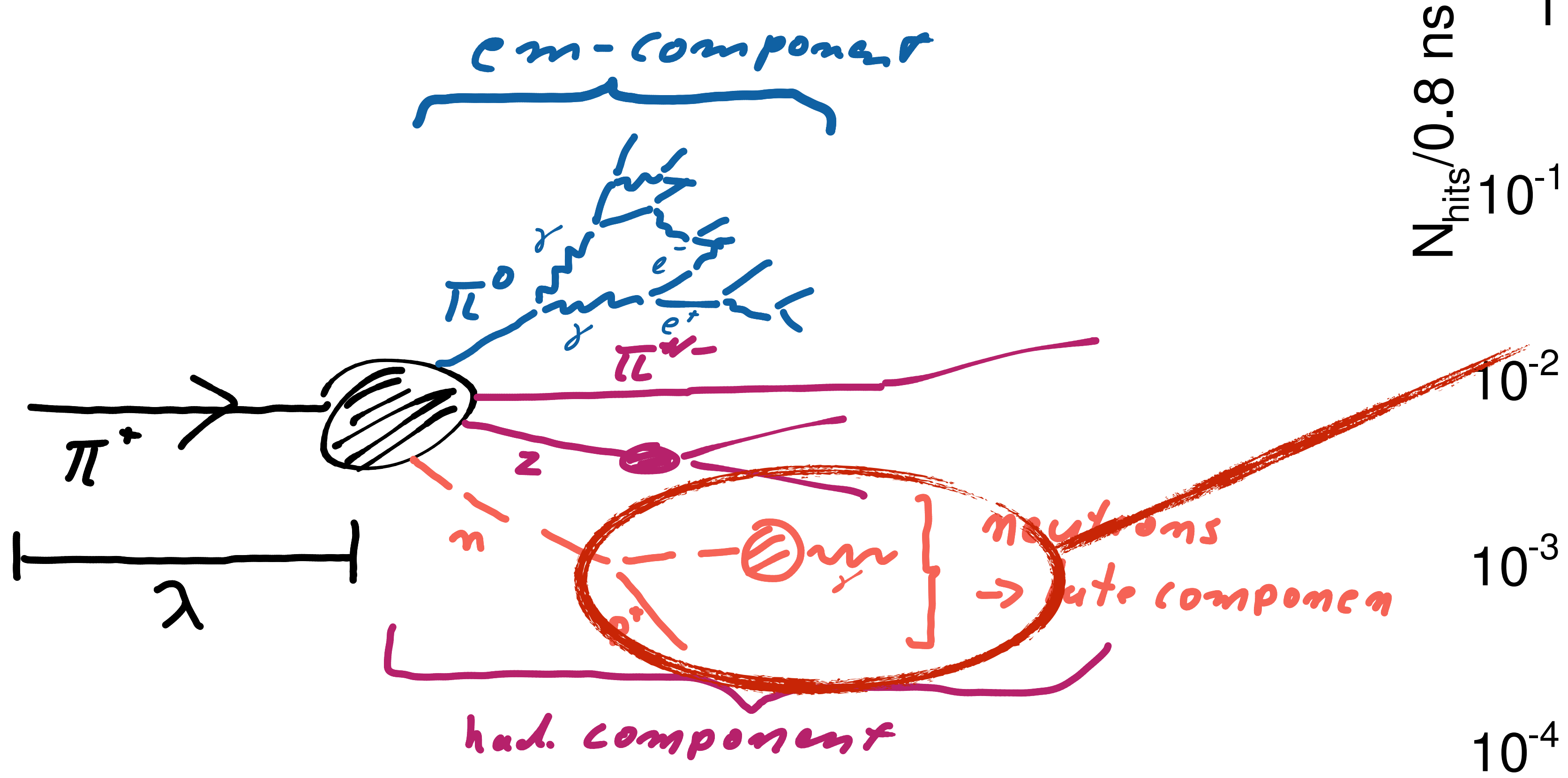
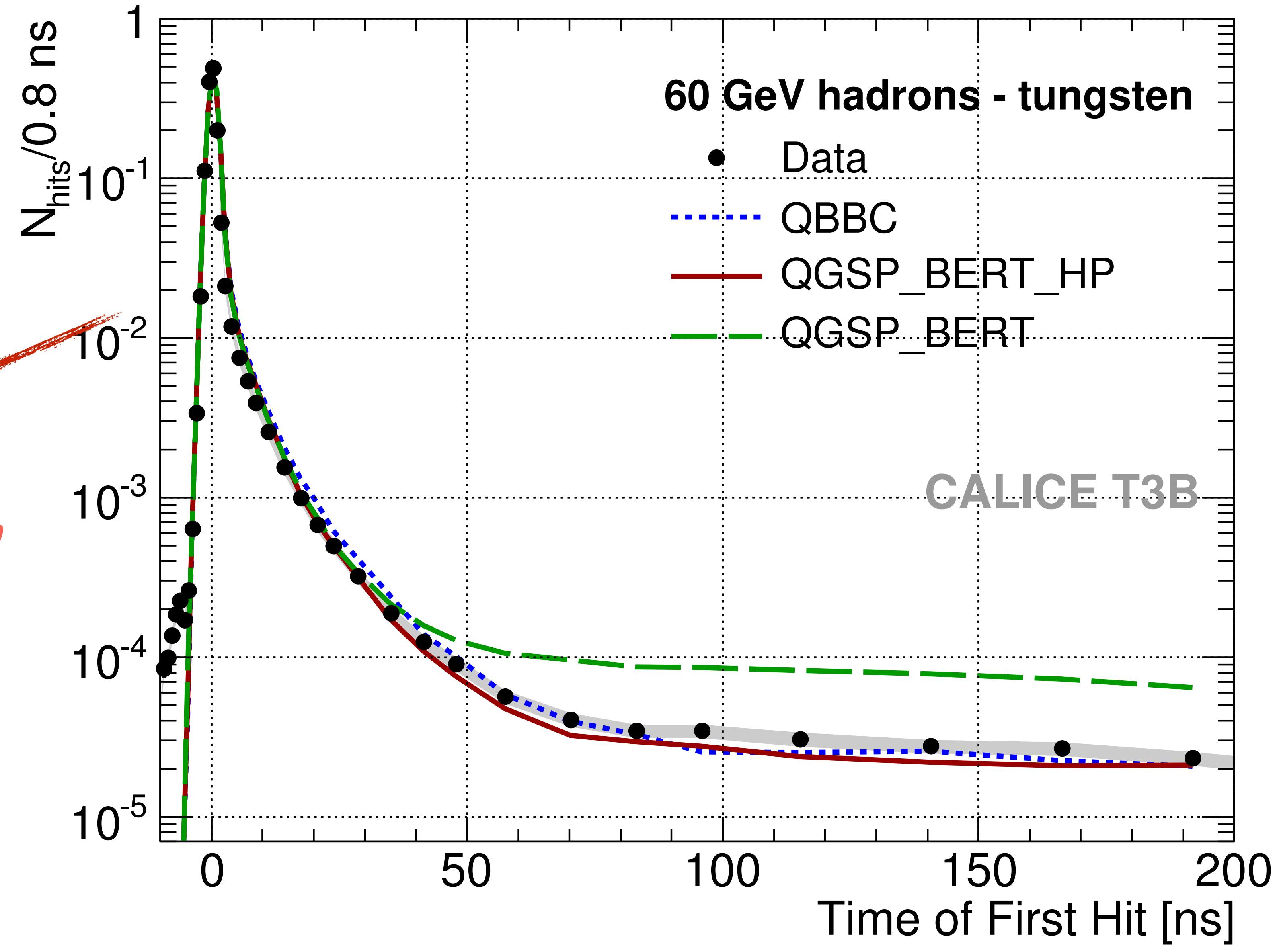
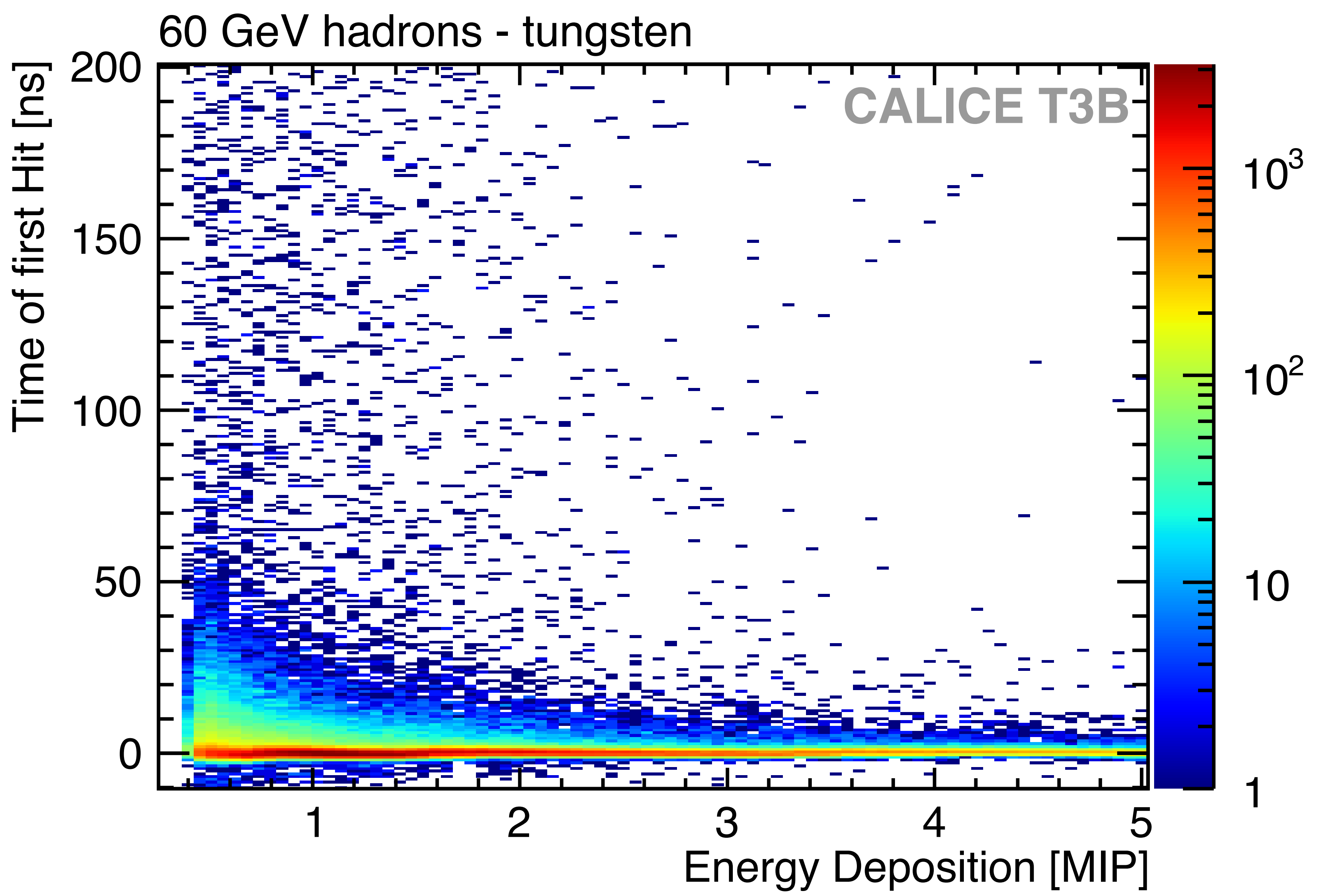






JINST 9 P07022 (2014)

- With the data taken this year and in the coming years: Scaling this up from a single strip of cells to a fully instrumented volumes - with both scintillator / SiPM and silicon

➩ Will further improve understanding of shower structure, and may provide interesting possibilities for improved reconstruction techniques

Imaging Calorimeters for Circular Colliders

Modifications from the CALICE Concept

- On the technological side: Continuous readout, rather than bunch trains as for linear colliders
  - ➯ Does not allow to use power pulsing to reduce power budget: Cooling in the active volume?
  - ➯ Different ASICS?
    - Amenable to continuous readout
    - Different power optimisation

- A different detector optimisation: More focus on lower energies
  - What is the right granularity in ECAL and HCAL?
  - What is the right trade-off between granularity and electromagnetic energy resolution?
  - What is the right sampling in ECAL and HCAL, and where should the transition be?

…

➯ Many interesting questions to study - and lots of room for new contributions!

Summary & Conclusions

- Highly granular calorimetry is now widely accepted in HEP - as the solution of choice for optimal event reconstruction with particle flow, and to control backgrounds and pile-up

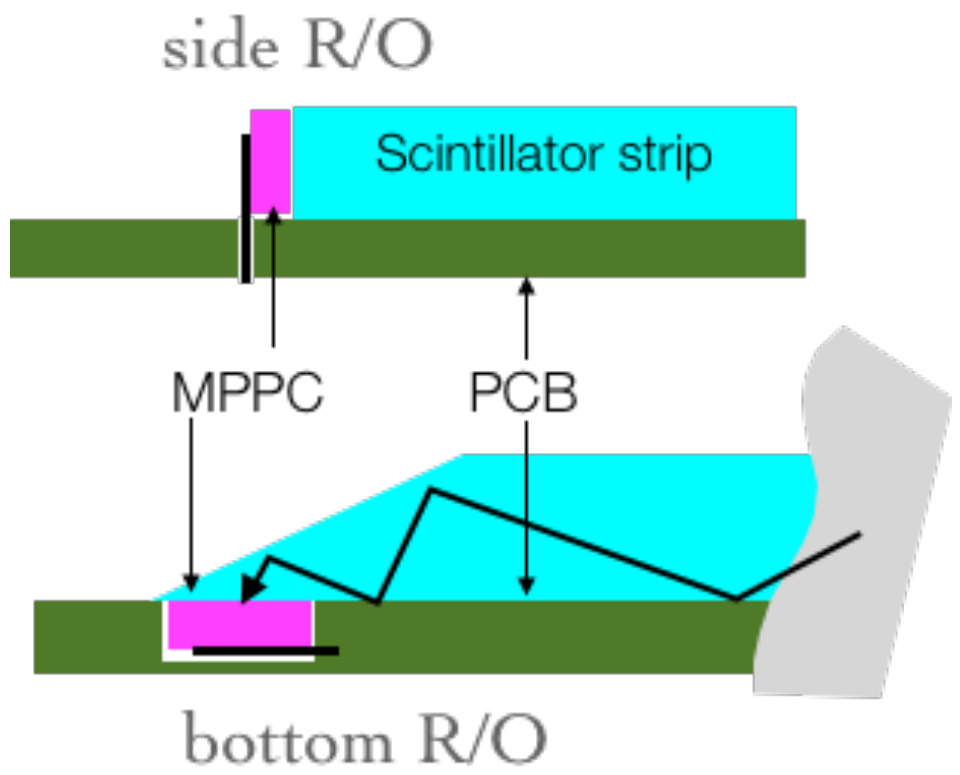
- CALICE has successfully demonstrated different technologies - the results from the beam tests provide important input for the development of reconstruction algorithms and for the validation and further development of GEANT4 shower simulations

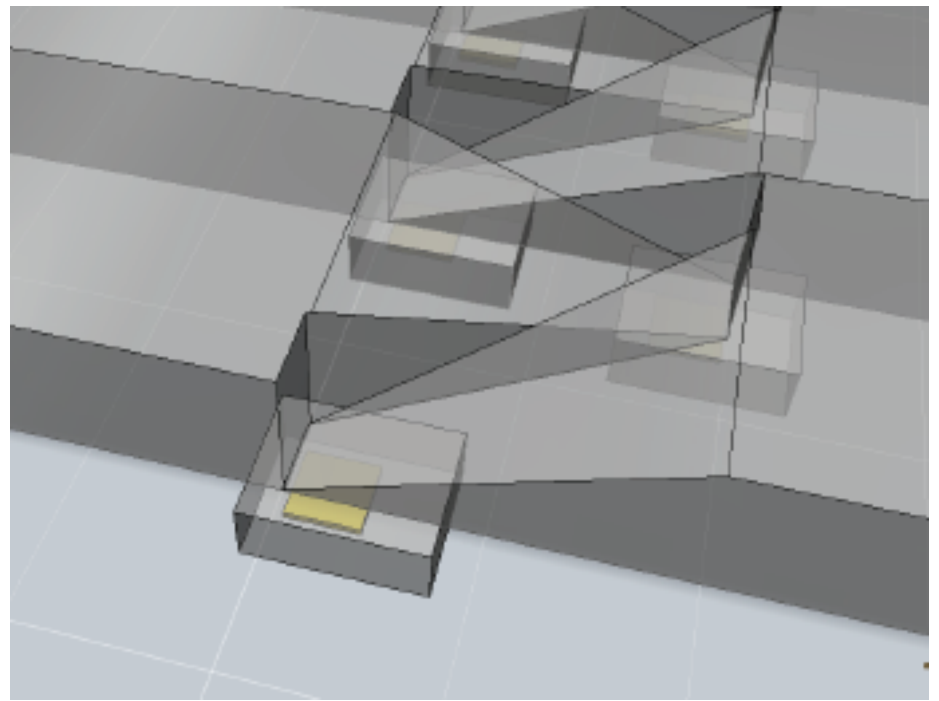
- It does not end there: further development to address issues of scalability and realistic constraints in collider environments;
  - Fully embedded electronics with auto-triggering and time stamping
  - Larger active elements
  - Automatic assembly and testing

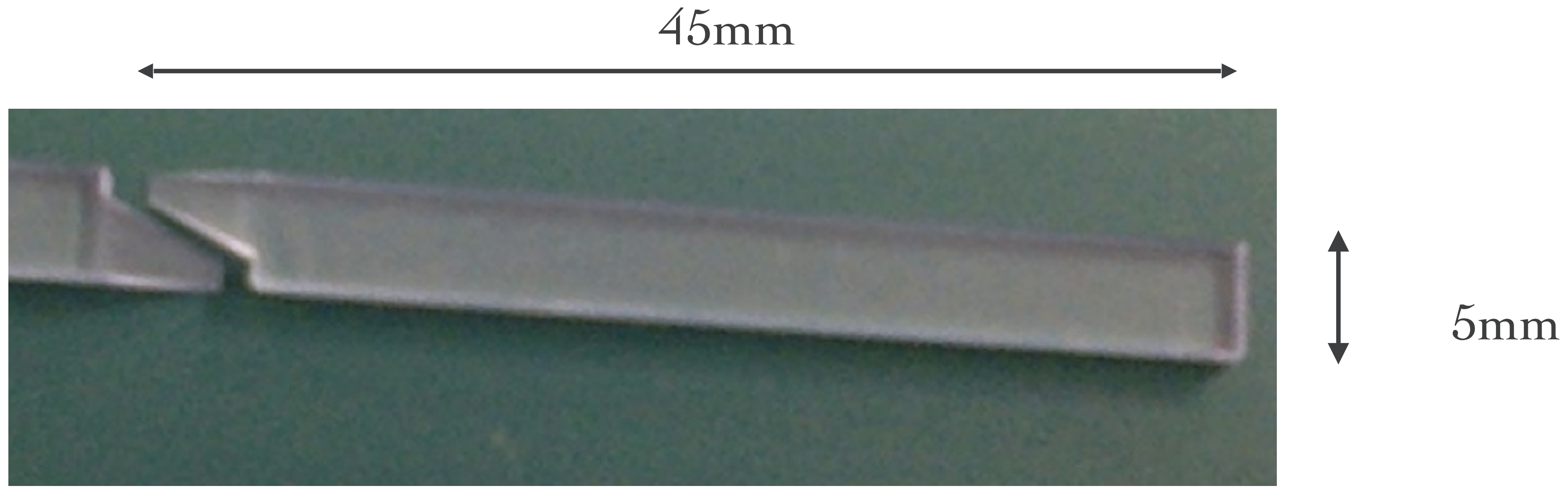
- And: Interesting challenges specific to circular colliders, still to be addressed!

Scintillator ECAL

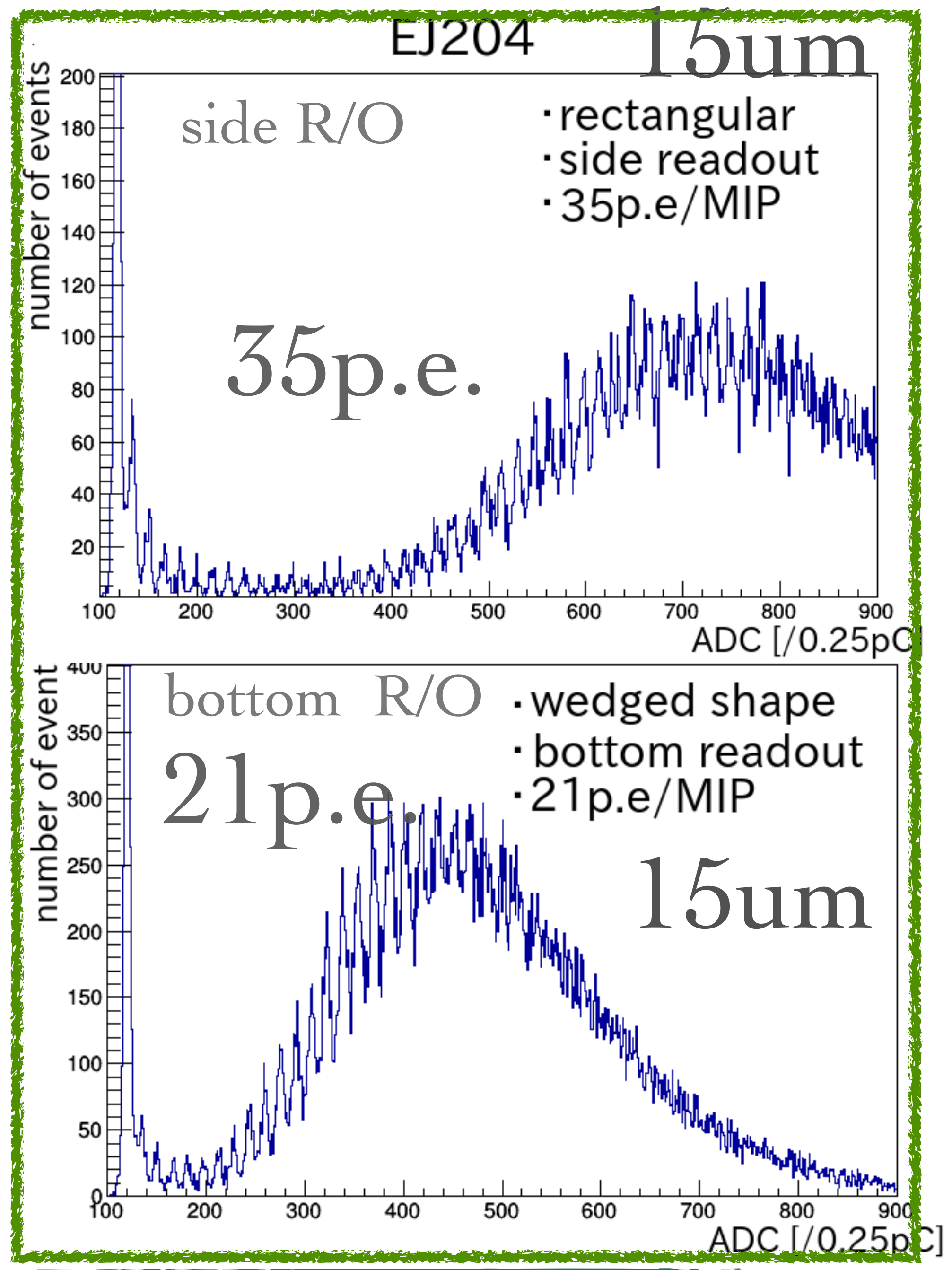
Scintillator Strips, SiPMs



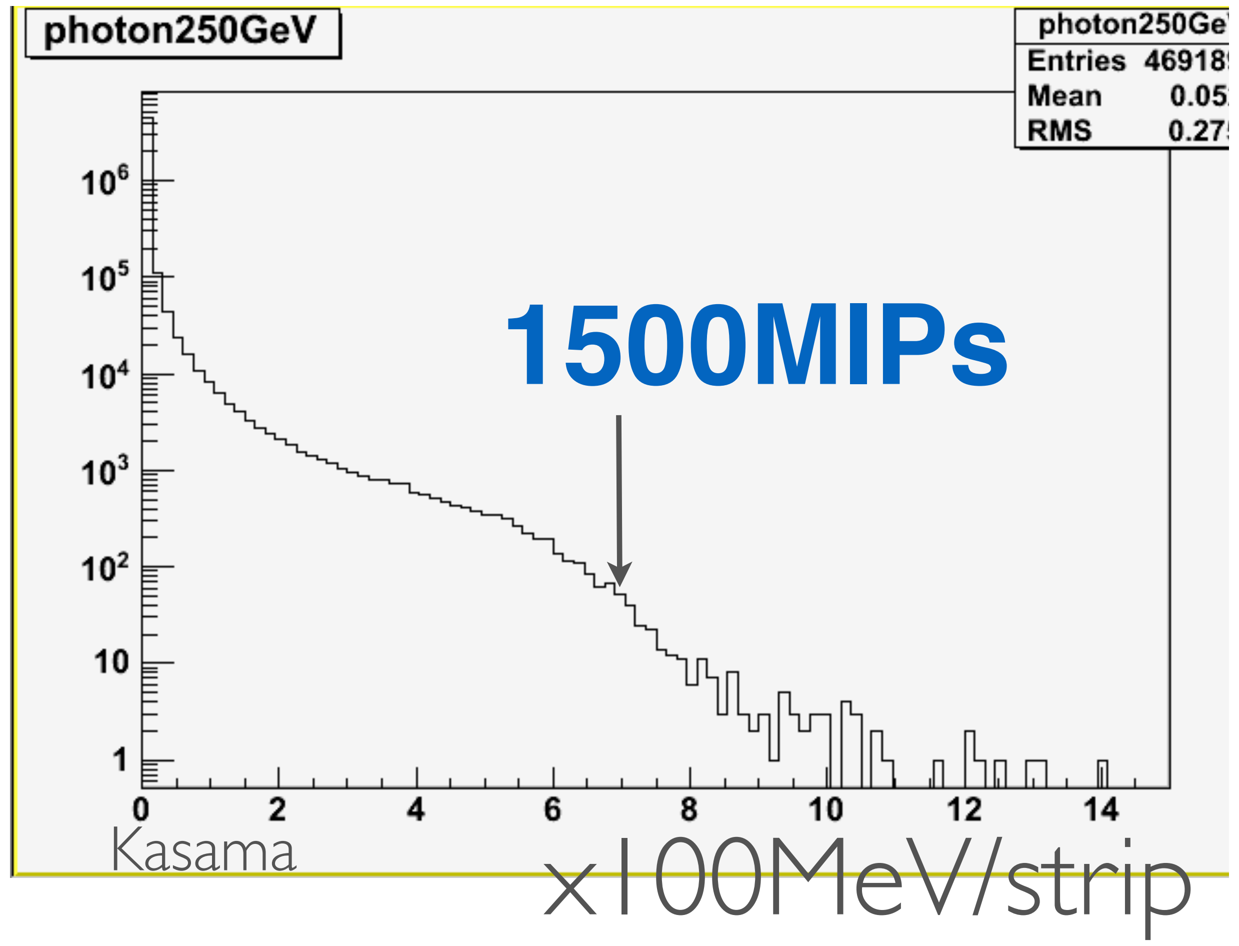


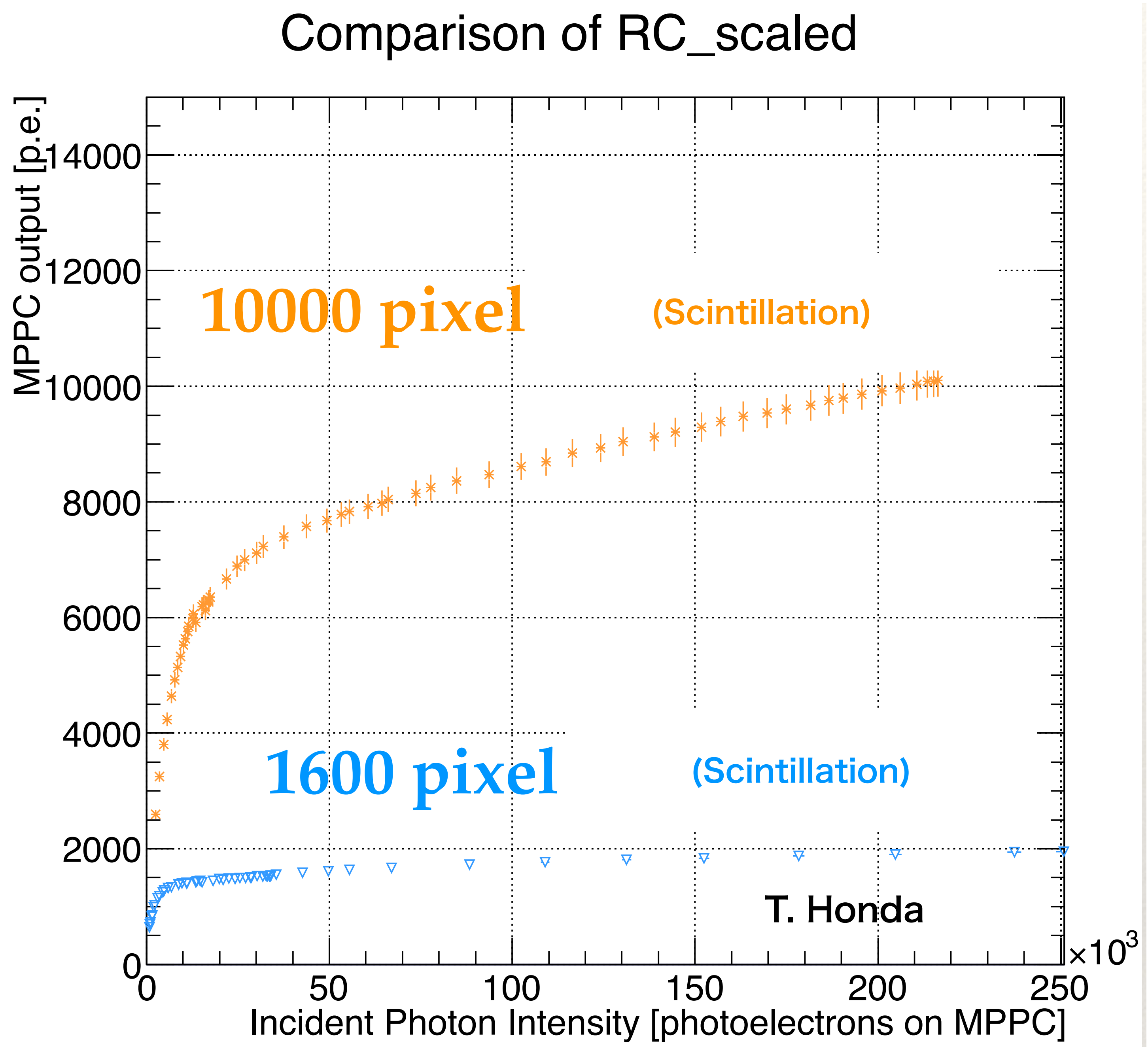


scintillator strip for bottom read out



- Dynamic range is crucial for an ECAL: use small-pixel SiPMs

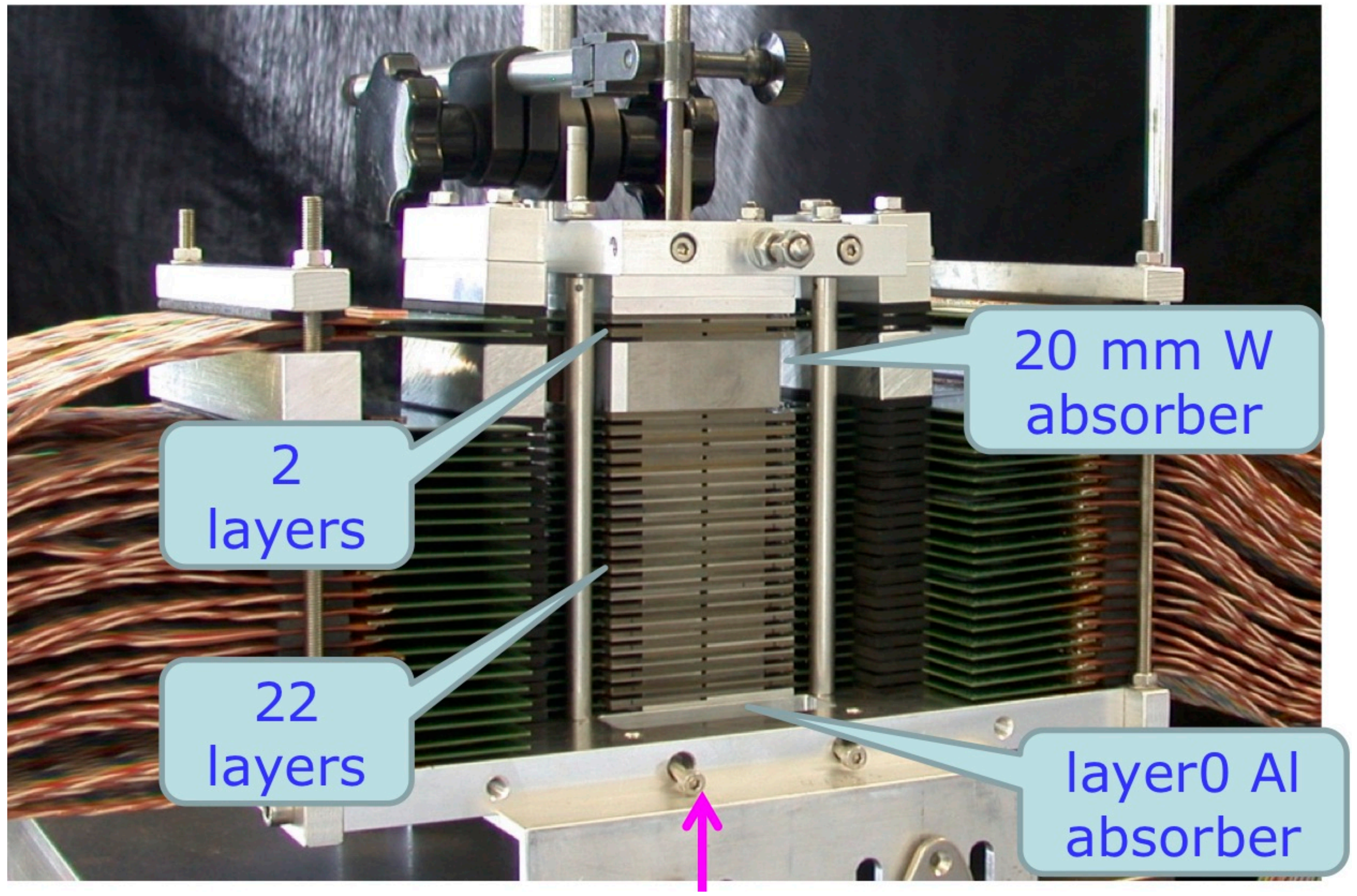




- Will profit from new HDR generation of MPPCs that are now becoming available

Extremes in Granularity

A MAPS based SiW ECAL



- In the context of the FoCAL upgrade of ALICE - identification and separation of very close-by photons in a dense environment

A 24 layer prototype built and tested in beam (39 Mpixel, 30 x 30 μm^2)

- 28 X_0, 11 cm deep (3 mm W / layer), 40 x 40 mm^2 active area, total thickness / layer 4 mm

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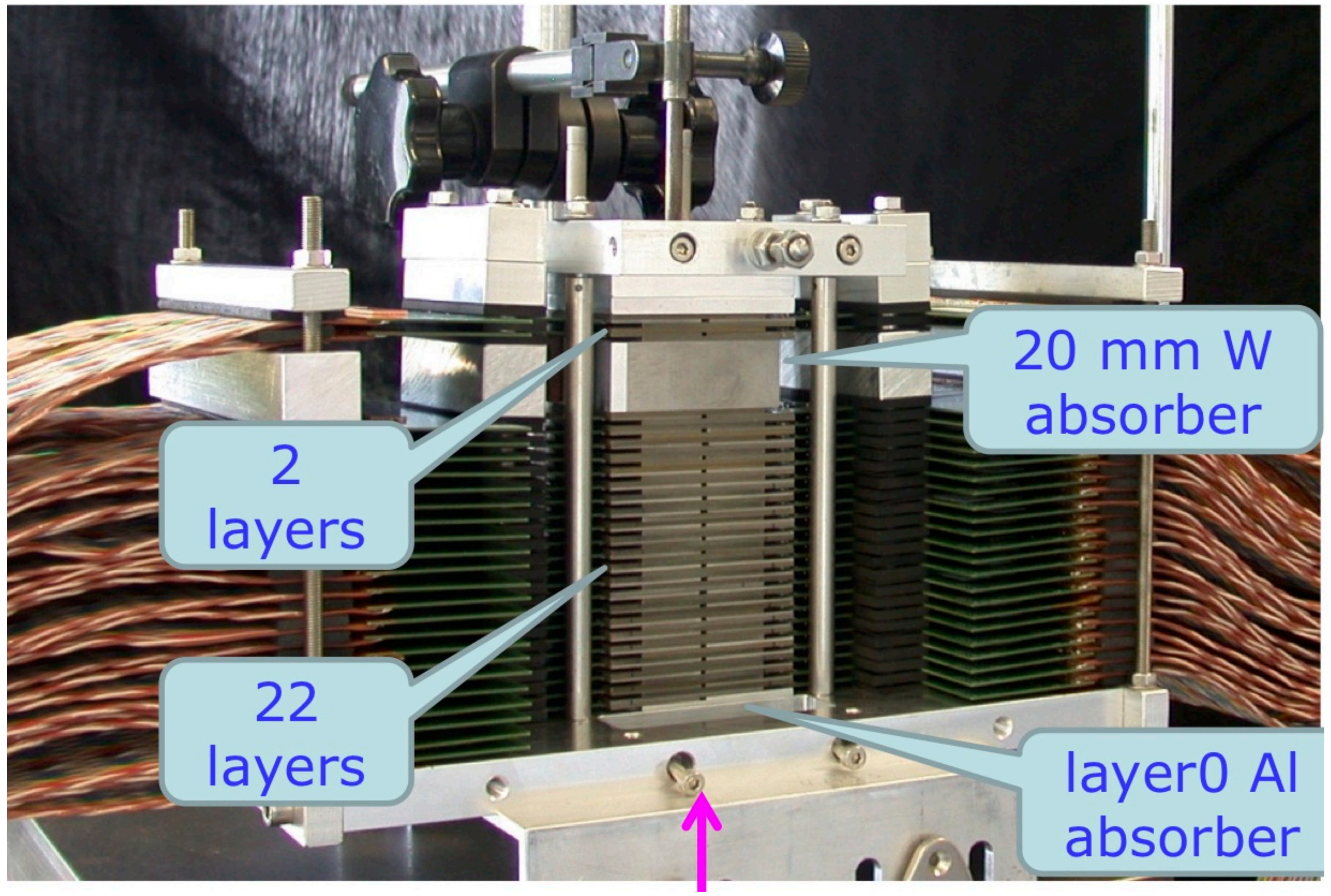

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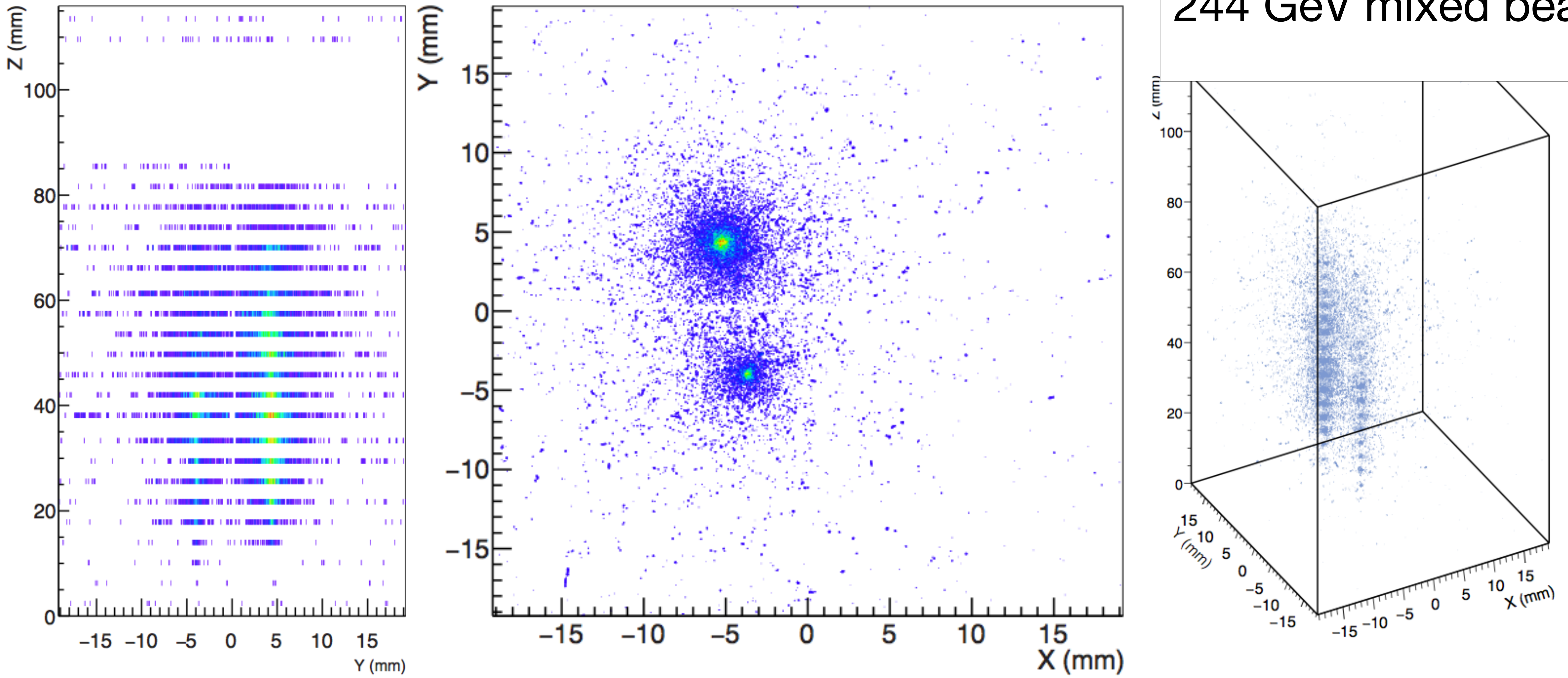
pile-up in a 244 GeV mixed beam



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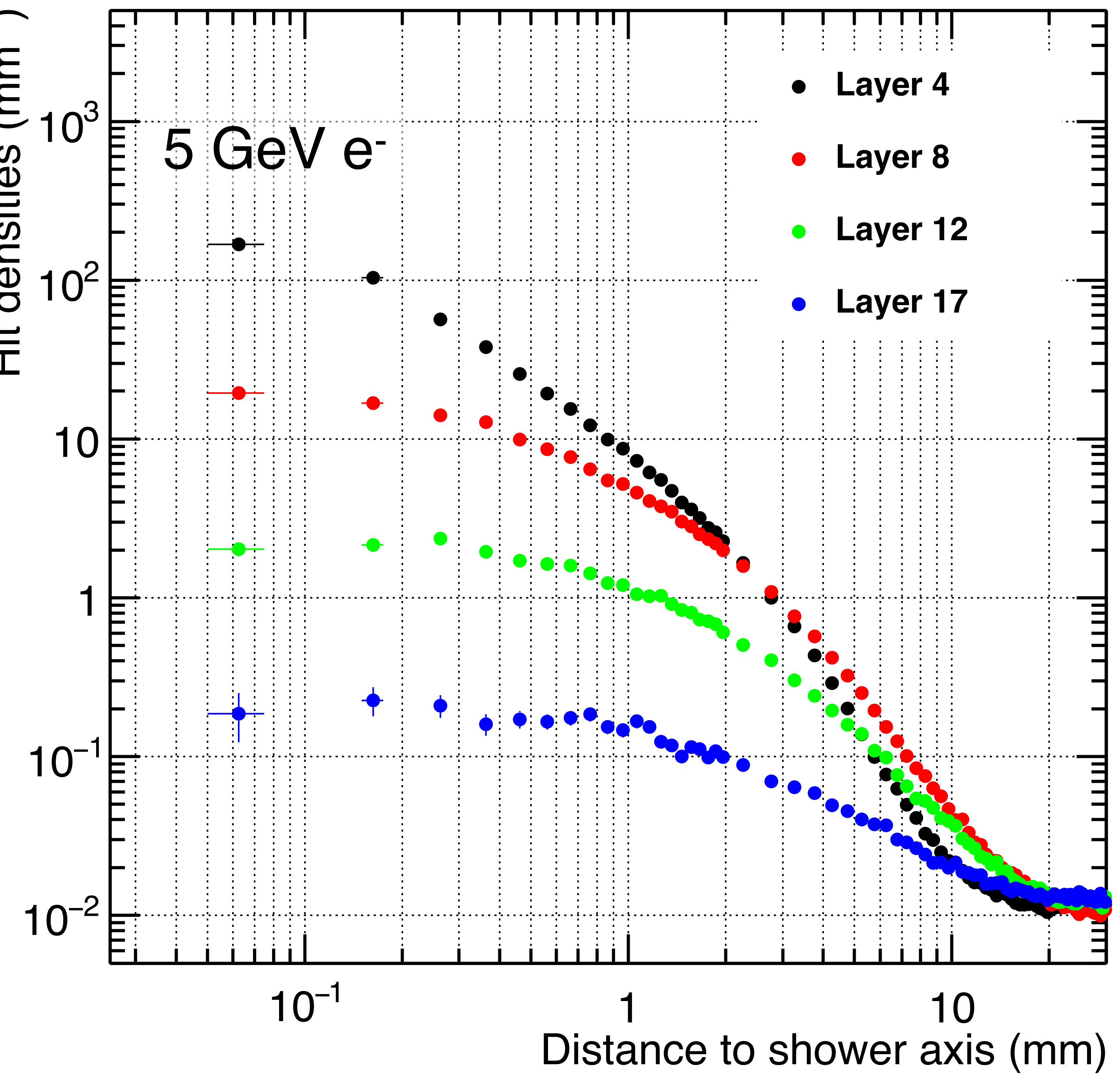

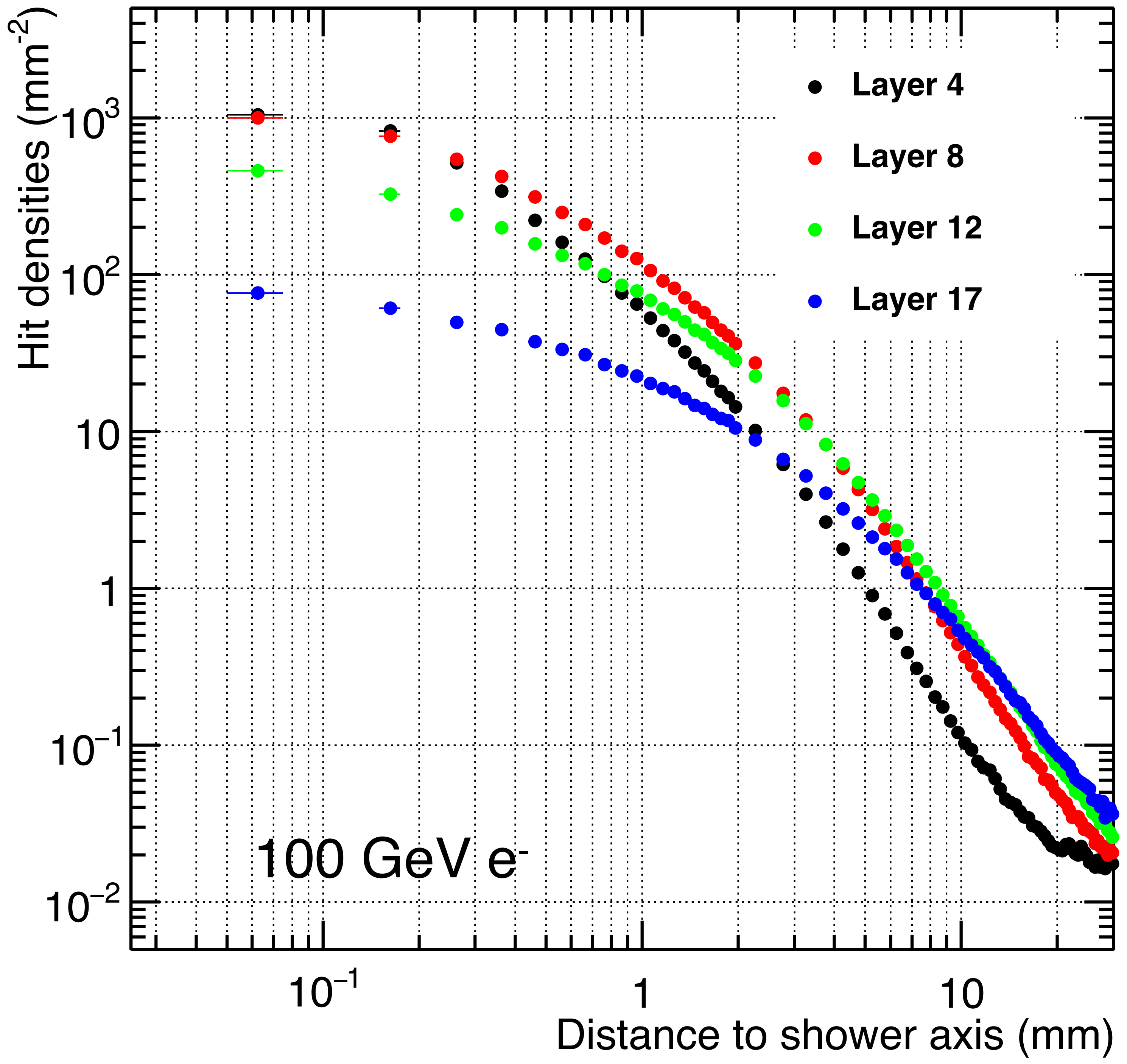

CAL upgrade of ALICE - identification and
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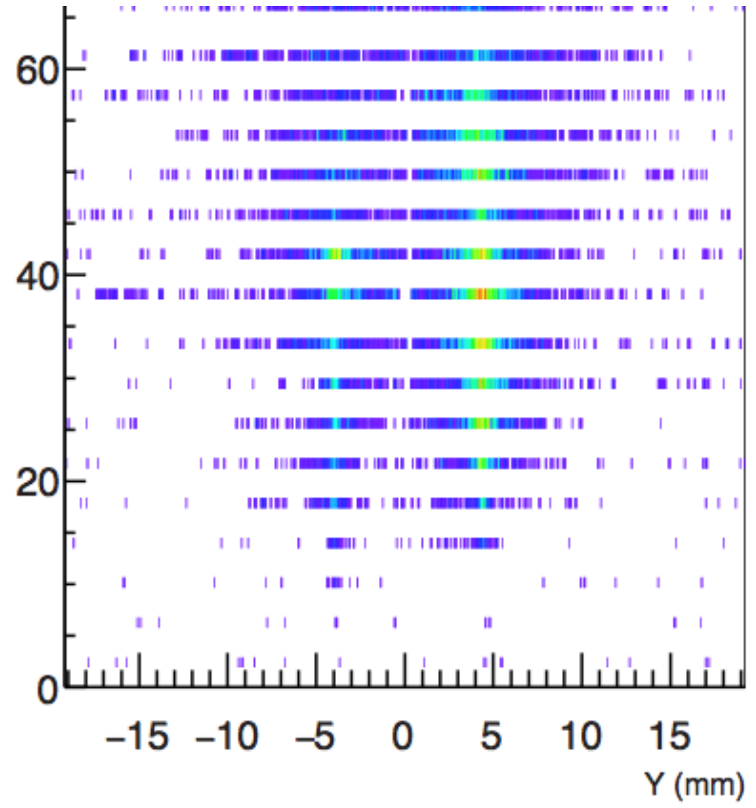

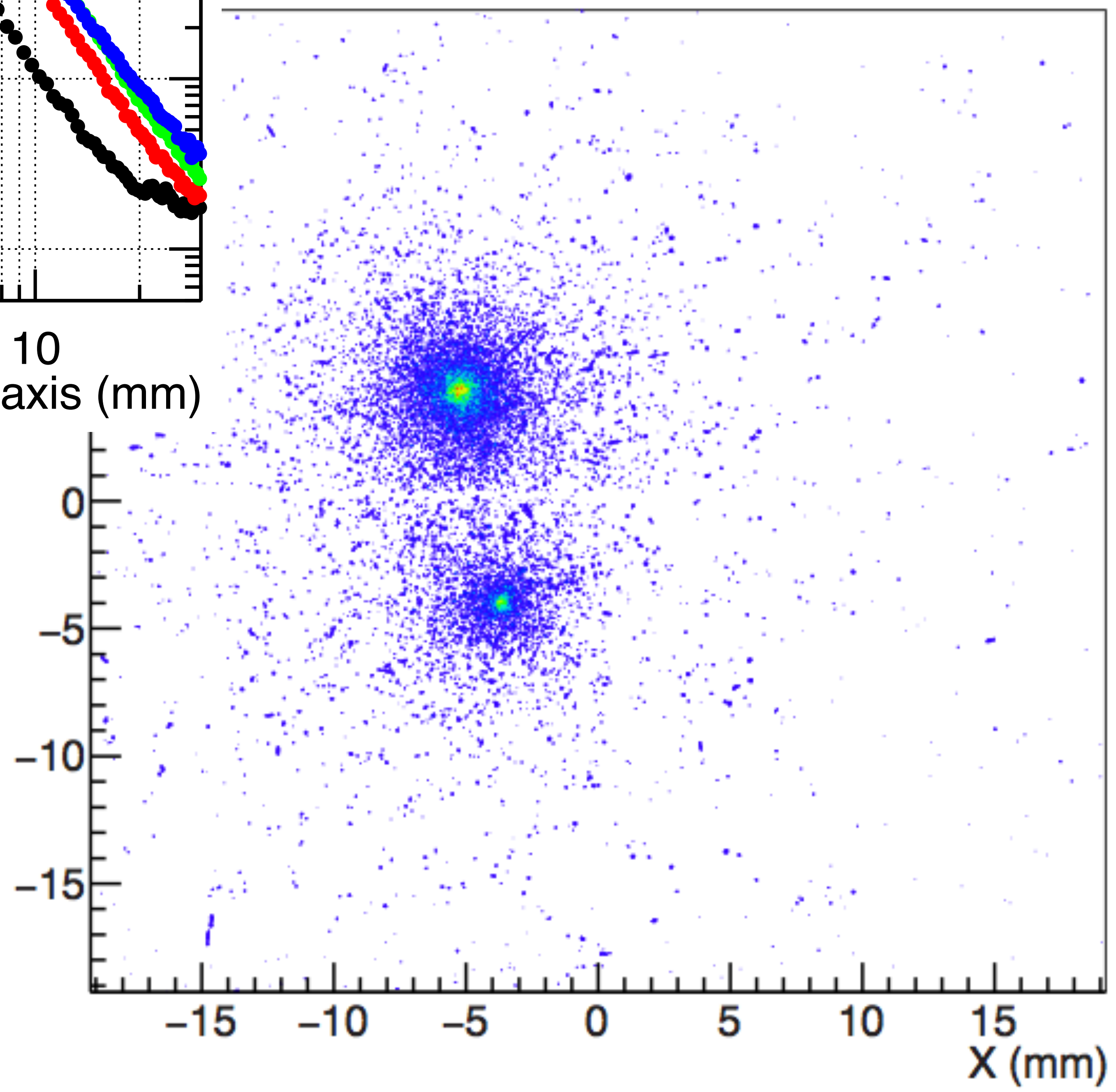

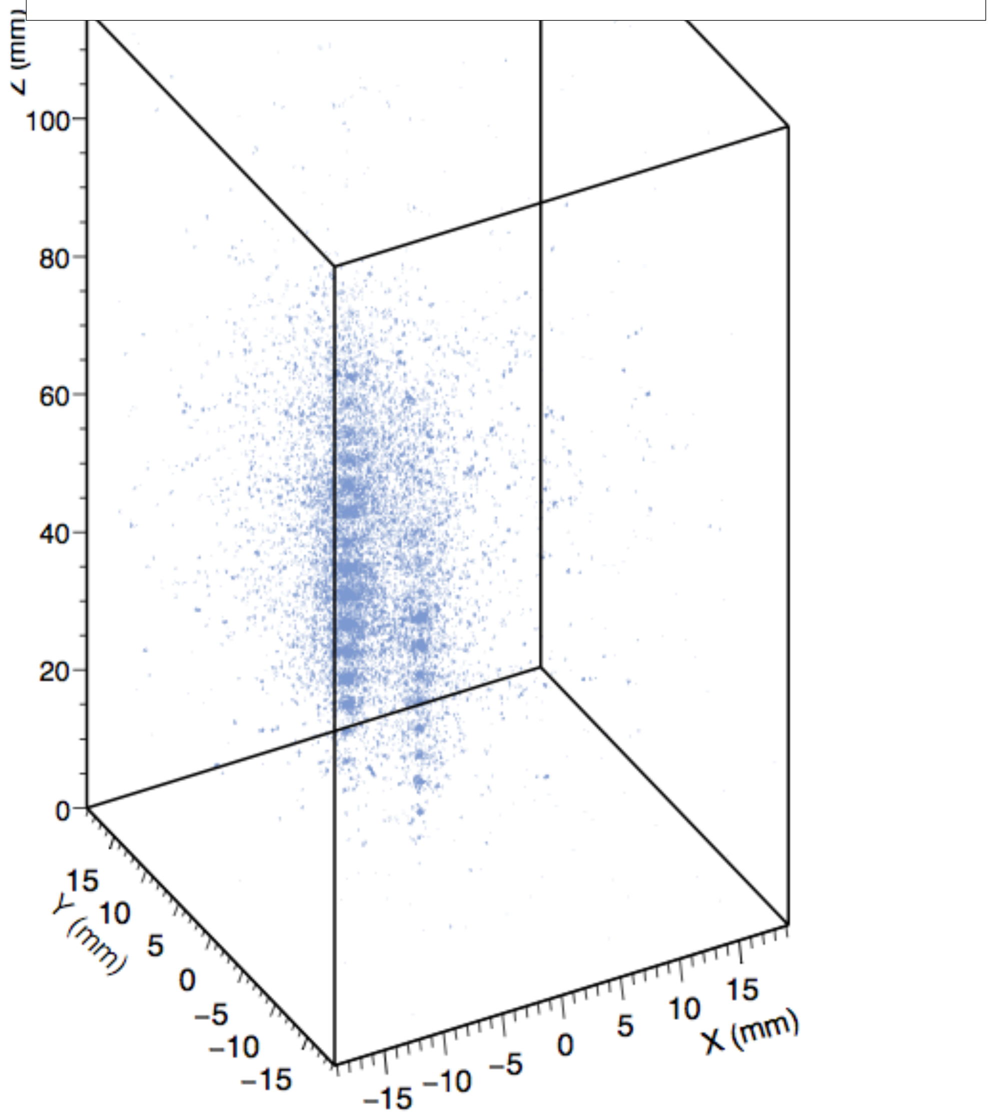

radial shower profiles in HD:

- low energy: early shower maximum, profiles broaden and decay with depth
- high energy: profiles broaden with depth, increase up to shower maximum