Highly Granular Calorimeters for Colliders and Beyond

DESY
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Developing Technologies for HEP (and other fields)

- A combination of incremental improvement and transformative steps
    - Sometimes you have to improve already existing concepts, sometimes you have to take a brave leap

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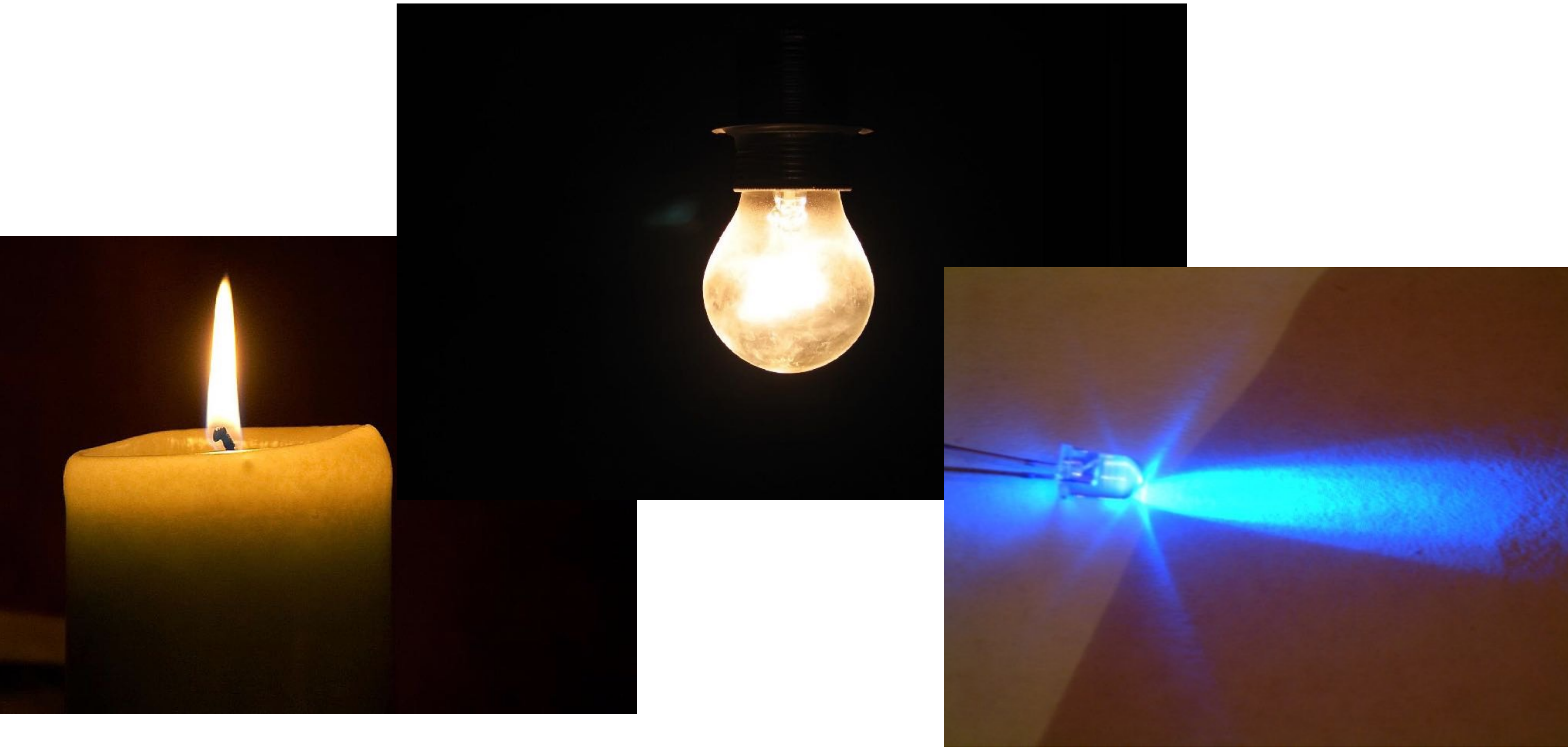

(Far) Future Projects - A Blessing and a Curse

- Running or imminent projects force to stay close to “real axis” - favors further development of existing technologies and concepts
- For future projects: The long time scales allow to try out new concepts
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Successful developments result in adoption by other experiments - making LC - inspired R&D universally valuable for experimental science as a whole

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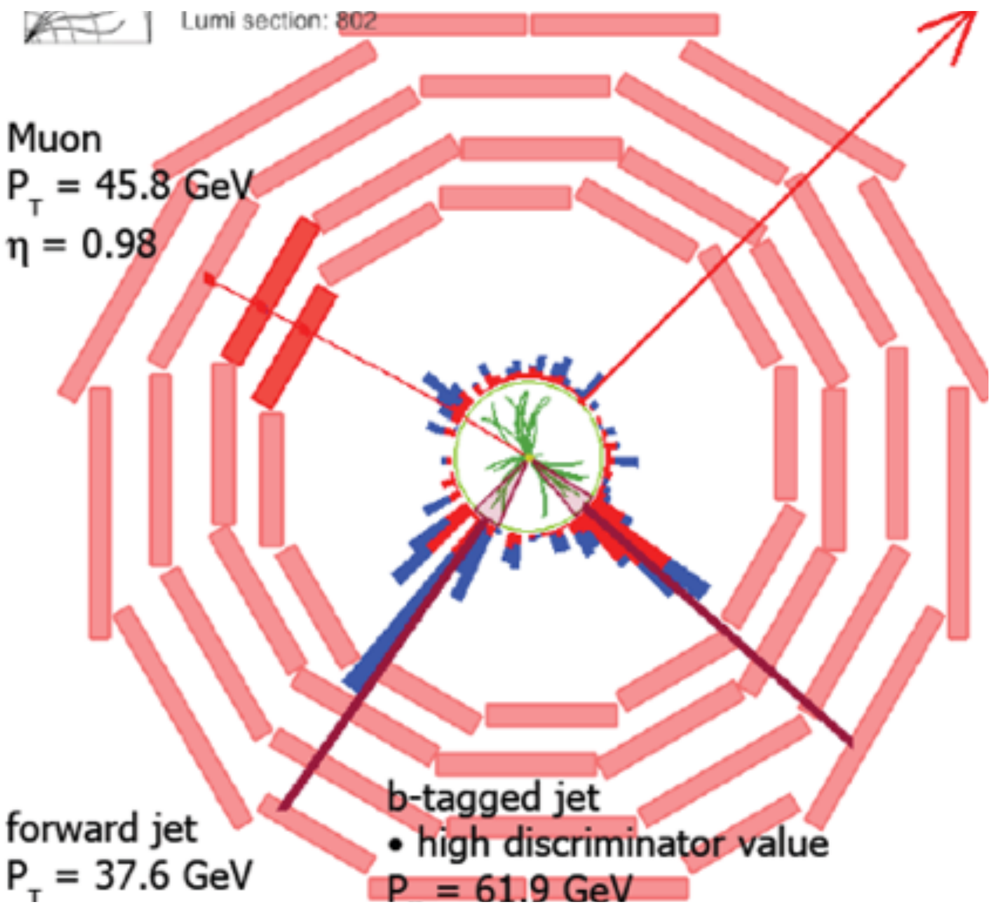

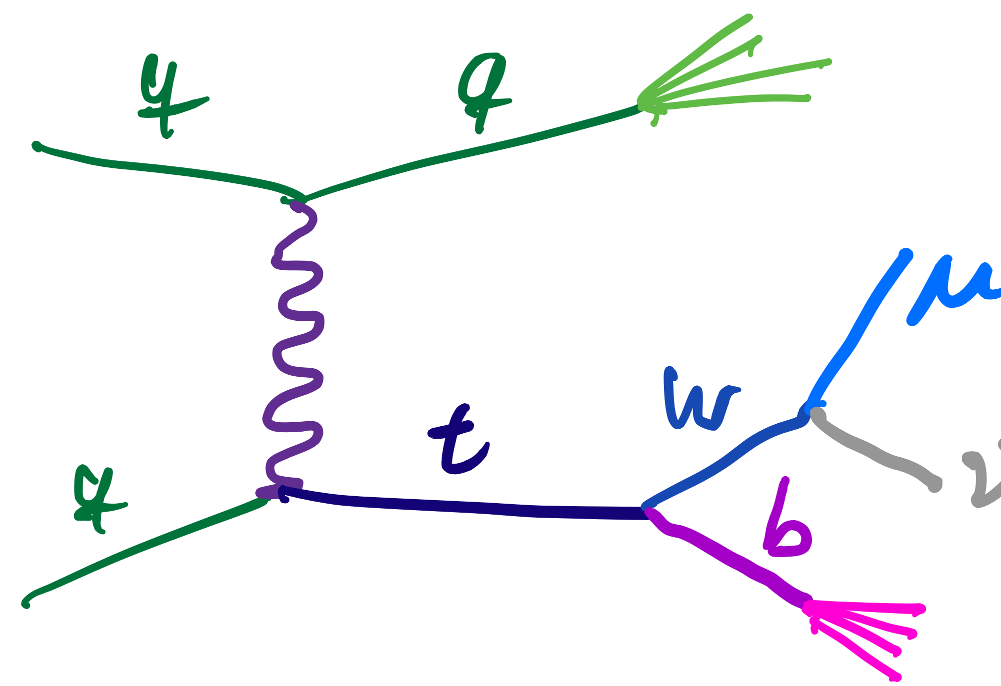

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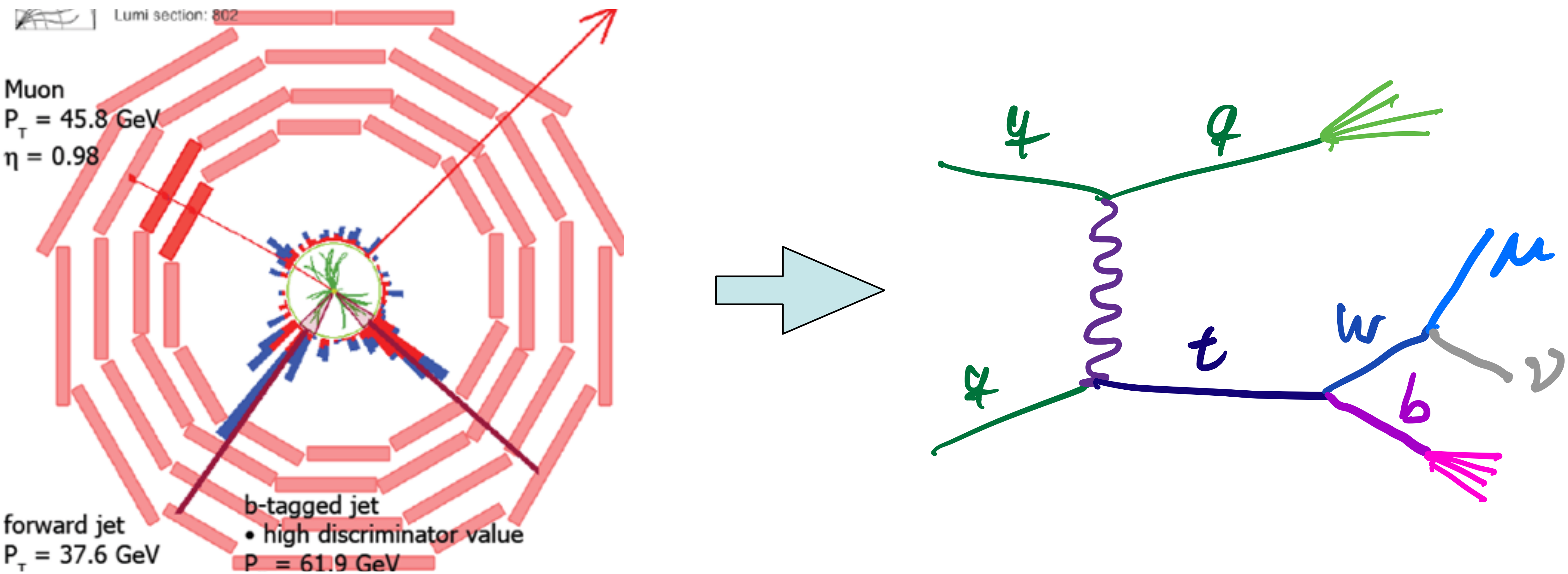
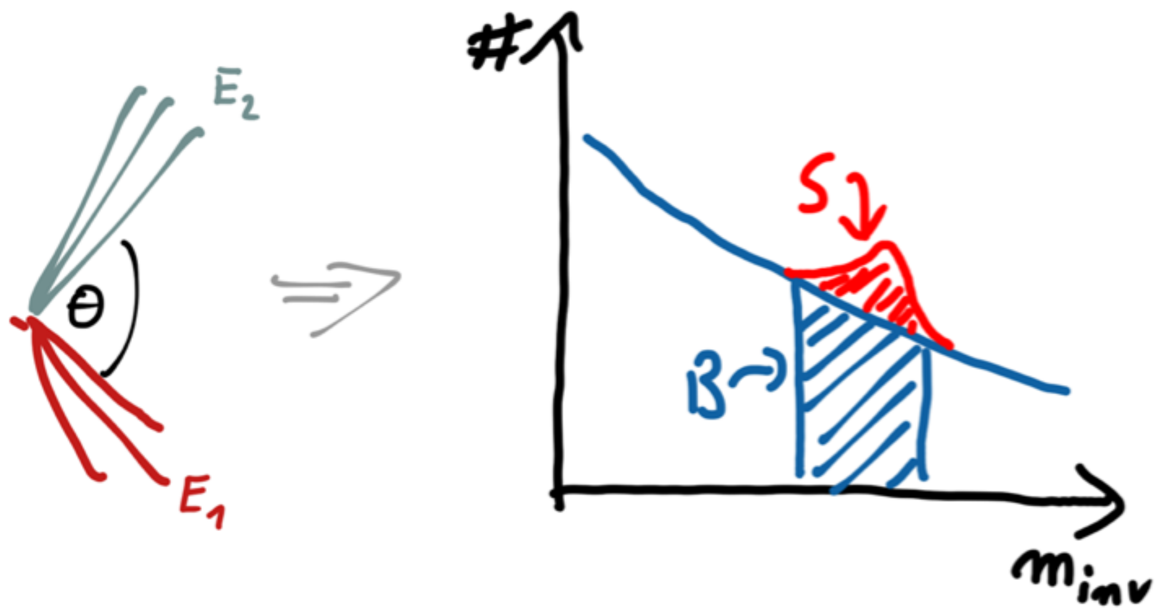


- Ideally: Reconstruct every single particle in the event - not just leptons + “cones of energy” - Modern experiments are already “on the way” to this: ***“Particle Flow”***
  - NB: This does not mean perfect assignment: Jet reconstruction comes “on top”

… and from a more practical Perspective:

- Reconstruction of hadronic final states at future e+e- colliders



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A narrow resonance
decaying into quark pairs

significance:

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

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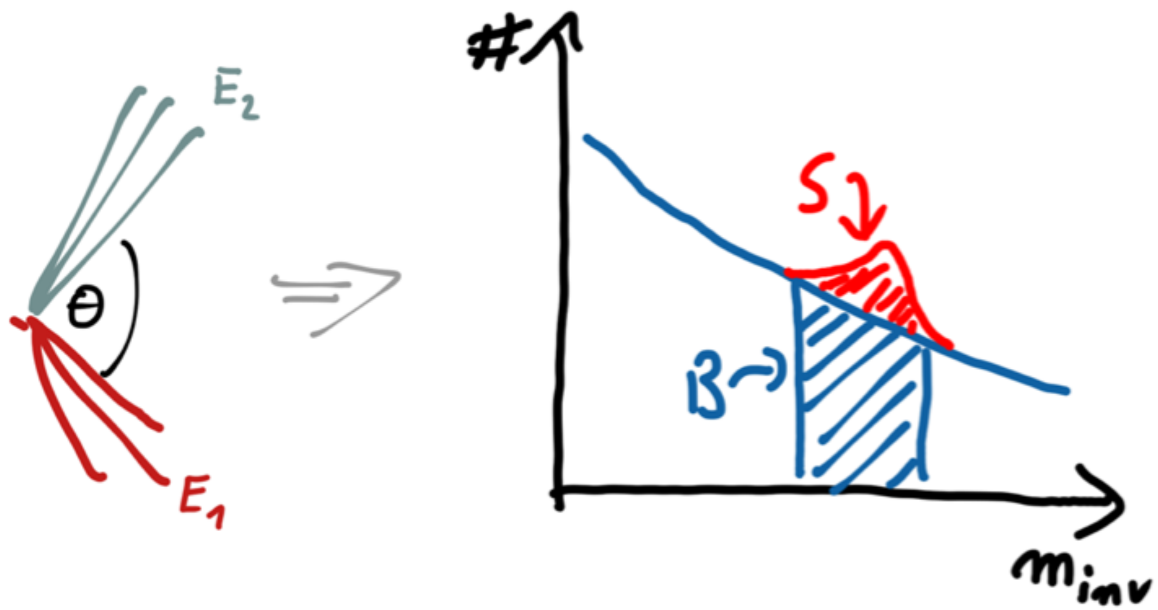

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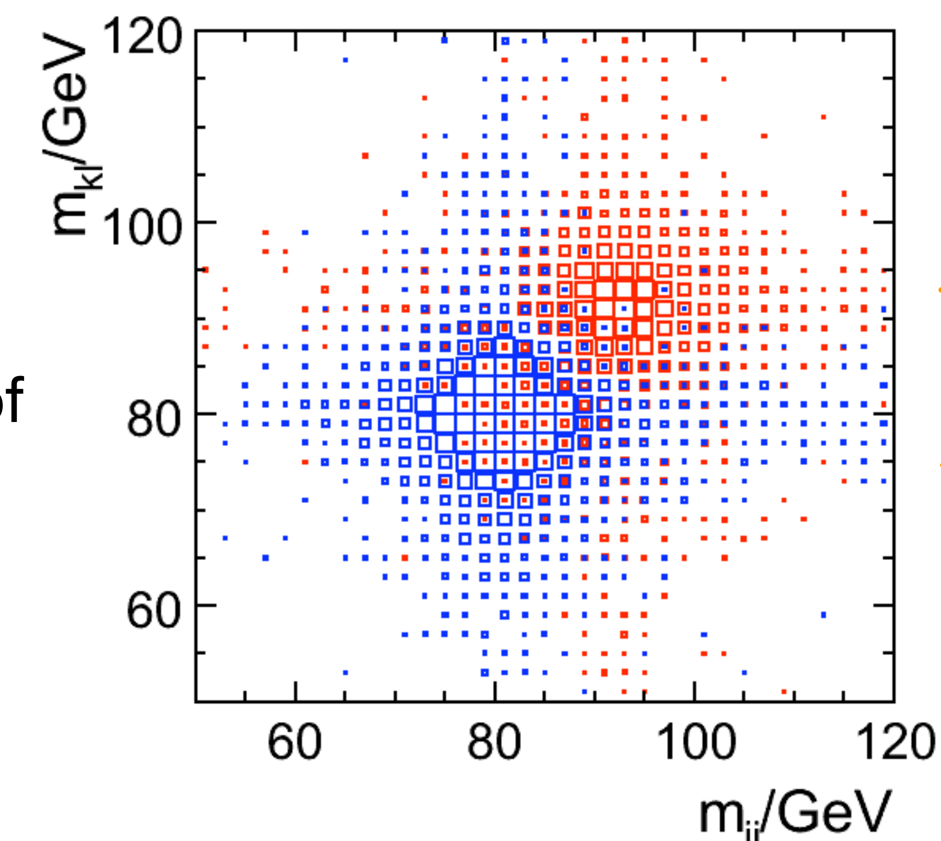
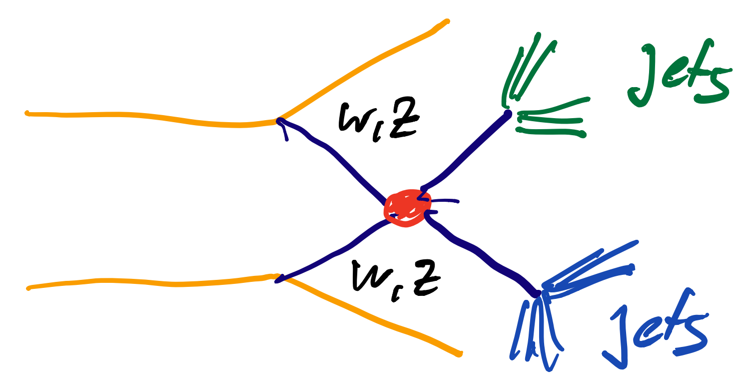
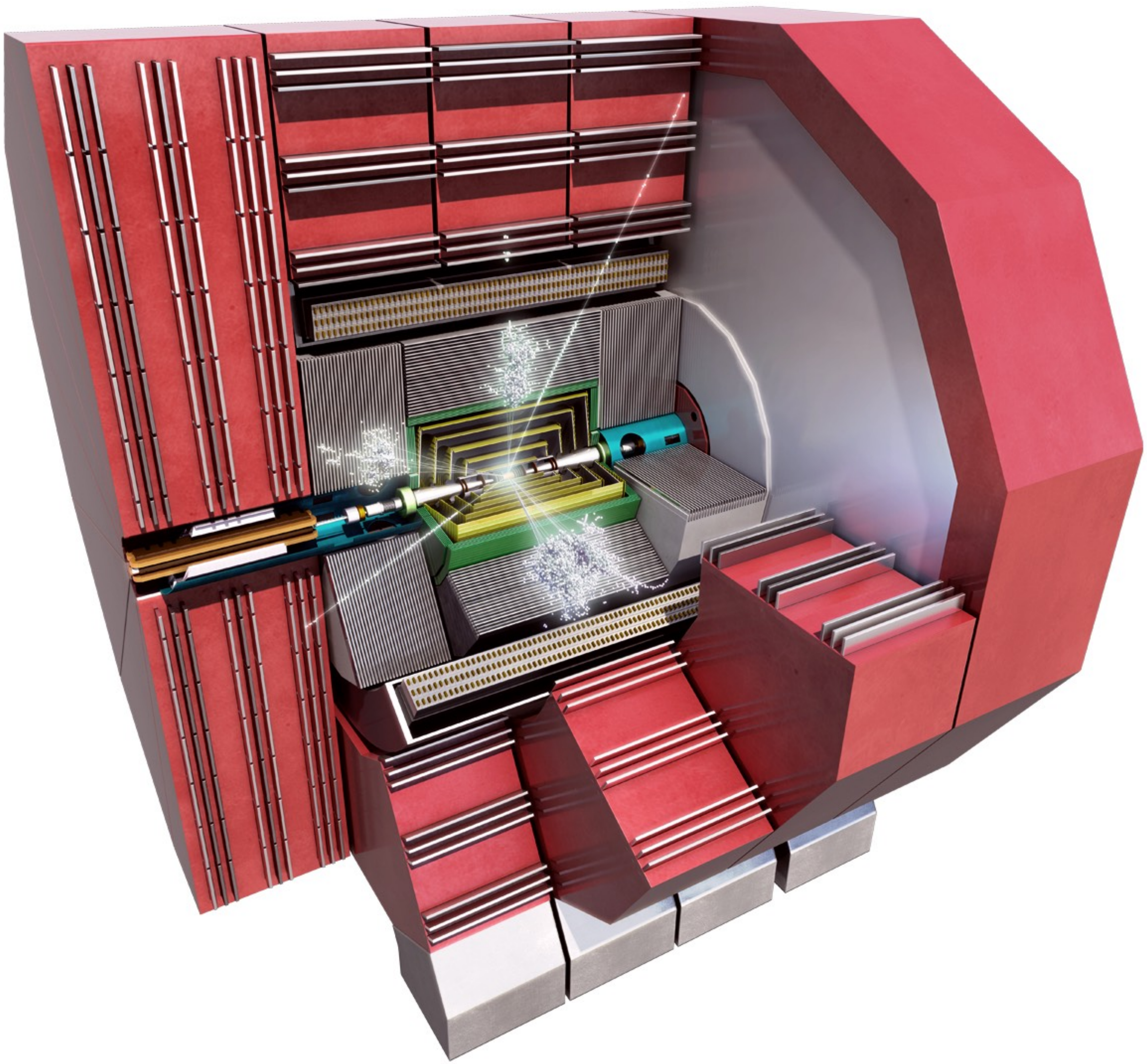
- With a typical "PR" example of separation of hadronic final states of heavy bosons: Requires jet energy resolution of ~ 3.5% over a wide energy range





The Basic Hardware to work with: A Collider Detector



Muon system: ID and momentum measurement

Calorimeters: Energy measurement of charged and neutral particles

Tracker: Momentum measurement of charged particles

Dreams to Software: Particle Flow Algorithms

- Jets consist of a mix of particles
  - typically 60% charged hadrons, 30% photons, 10% neutral hadrons
  - ➯ “classical” calorimeter-only reconstruction is driven by calorimeter resolution for hadrons

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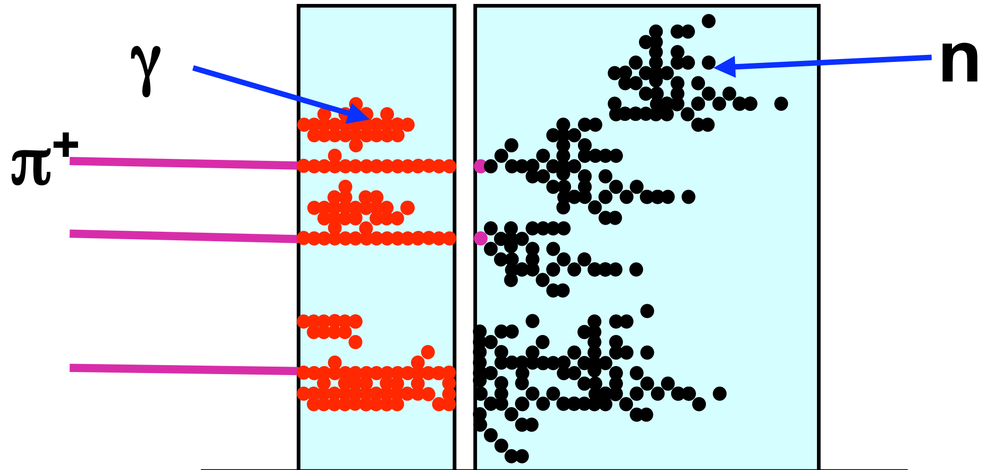
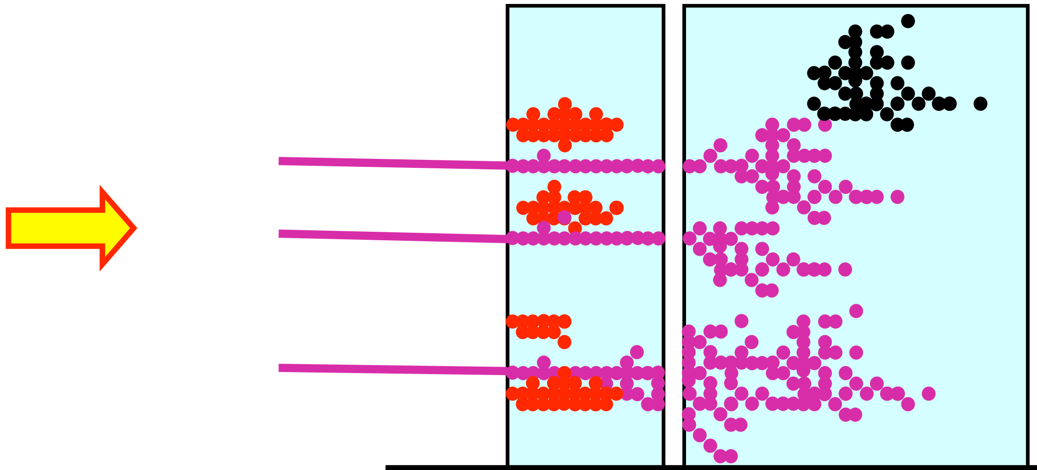


$E_{JET} = E_{ECAL} + E_{HCAL}$



$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

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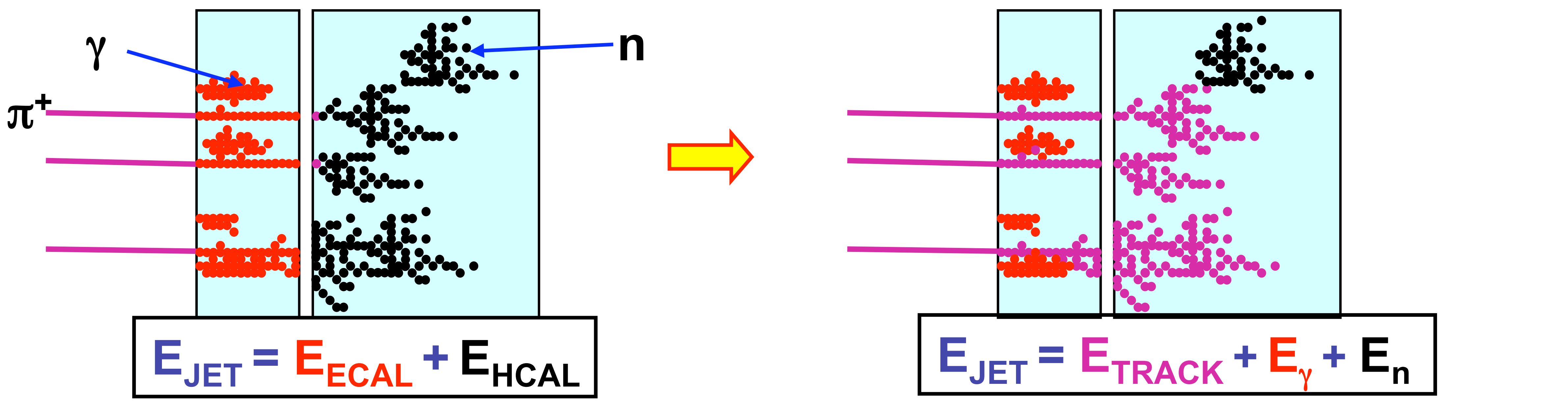

For best results: high granularity in the calorimeters to correctly separate showers

The level of mistakes, “***confusion***”, determines the achievable jet energy resolution, not the intrinsic resolution of the calorimeters!

Making PFA Happen: Granularity!

- Sophisticated pattern recognition in calorimeters to correctly assign calorimeter energy to particles seen in tracker: ***Imaging calorimeters***

➪ Granularity goals defined by hadronic shower physics: Segmentation finer than the typical structures in particle showers

- ➪ 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

➯ *O* 10^{7-8} cells in HCAL, 10^8 cells in ECAL for typical detector systems!

Overview

- Technology of Highly Granular Calorimeters
  - Validation of the Concept
  - Towards Technical Realization

- Performance: Energy Reconstruction - also beyond Prototypes

- Beyond Linear Colliders

Technology of Imaging Calorimeters

- Validation of the Concept -

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- The (obvious?) possibilities:
  - Plastic scintillators - a classic solution for calorimeters
  - Silicon - easily segmentable, high density
  - Gas detectors - low cost per unit area

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Plastic scintillators - a classic solution for calorimeters	Need ultra-compact, low cost photon sensors
Silicon - easily segmentable, high density	Price per area
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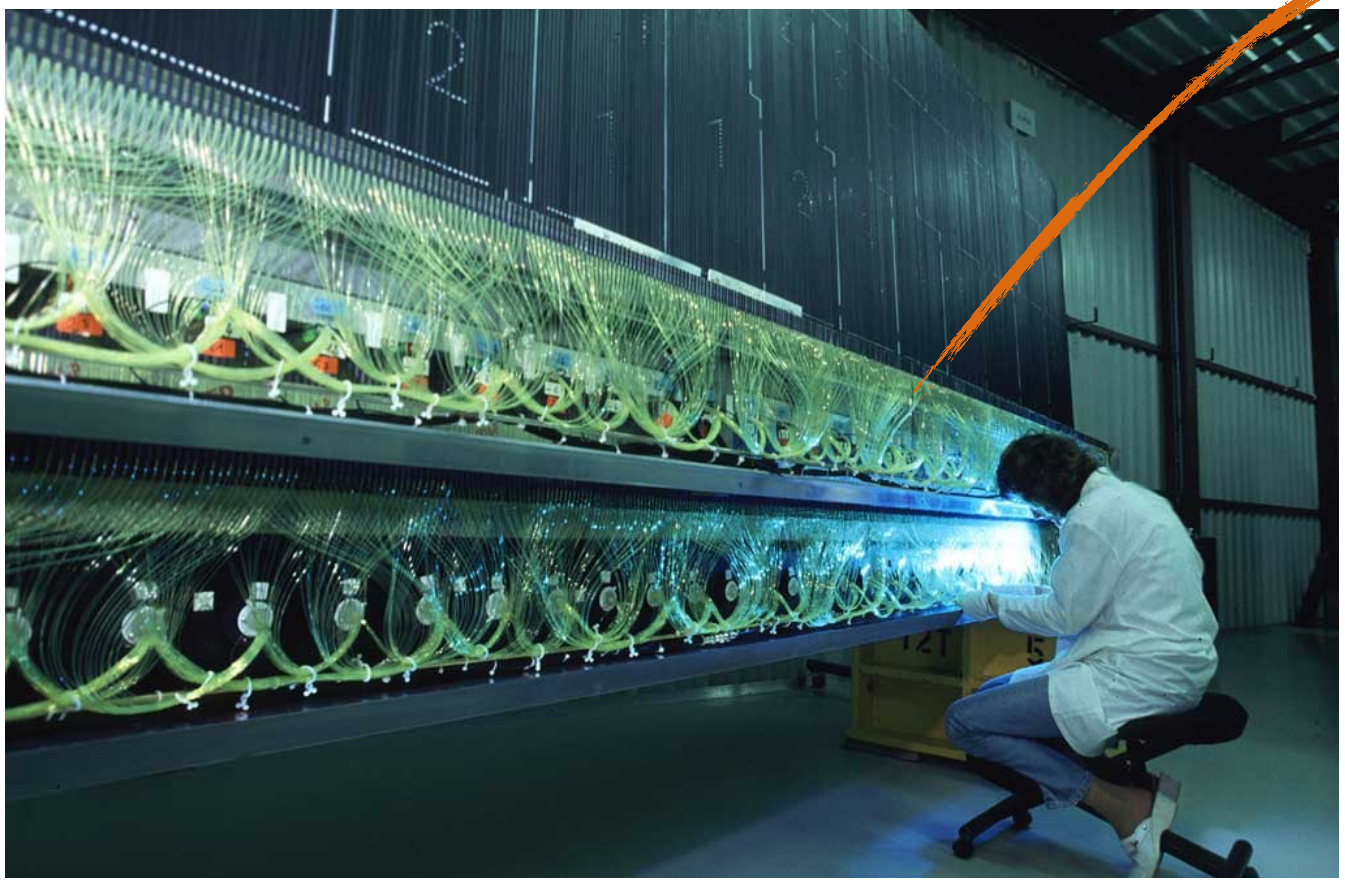
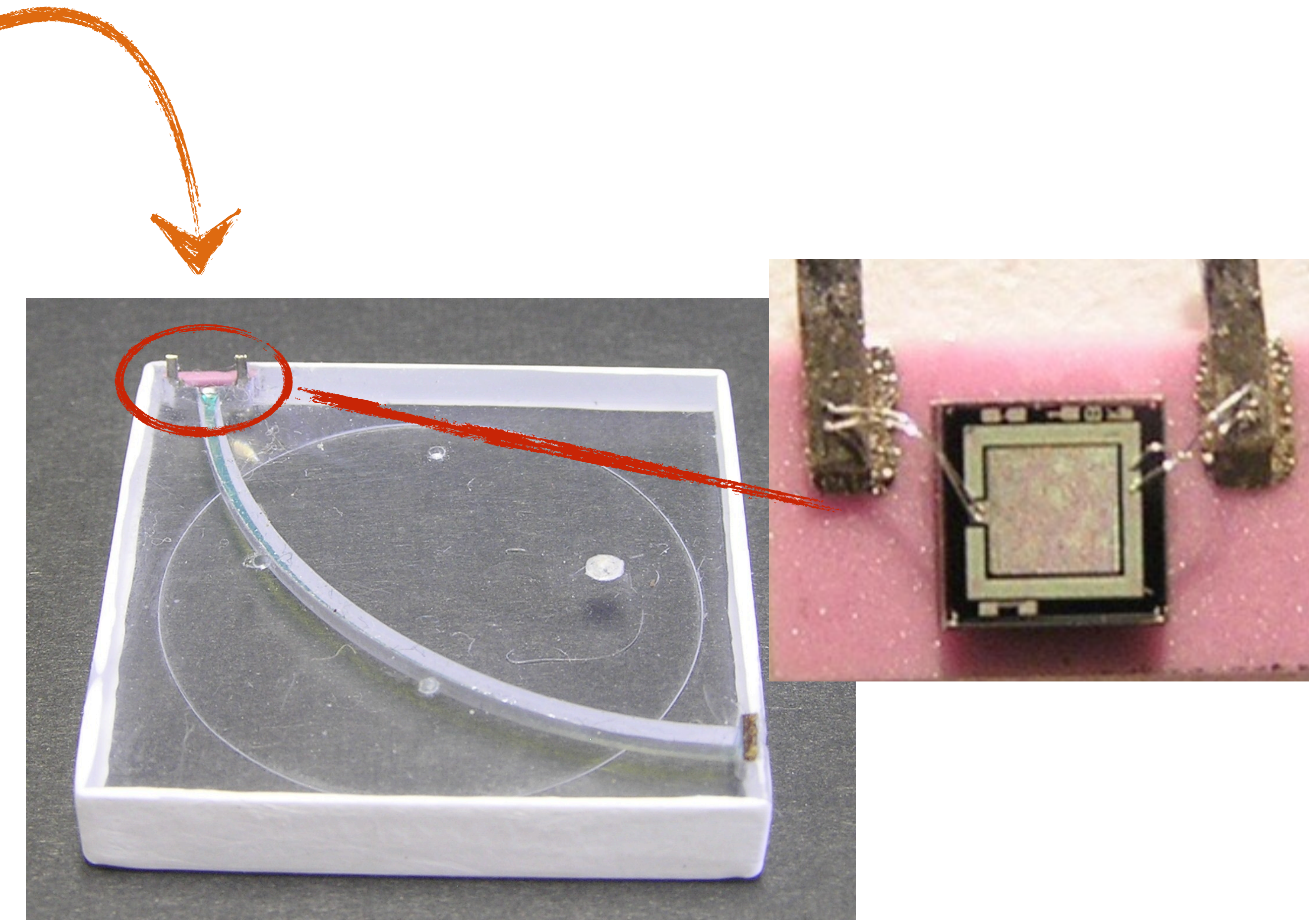
Universal challenges: highly integrated, fully embedded electronics, techniques for mass assembly of large areas, …

Paving the Way for Highly Granular Calorimeters

- The invention of SiPMs made scintillator-based calorimeters with very large channel counts possible





- Advances in microelectronics
- Large area silicon systems

CALICE: Making Highly Granular Calorimetry happen

- Particle Flow event reconstruction was seen as the most promising technology to achieve the physics goals of a future linear e^+e^- collider - but the corresponding calorimeter technology was not available. Required a radical change of the paradigms of HEP calorimetry

➯ Dedicated R&D program started to address this issue in 2001 - initially as DESY PRC R&D 01/02 in the context of TESLA

- Completion of the formal founding of the CALICE collaboration in 2005

CALICE today:
- 55 institutes in 19 countries (4 continents)
- ~ 350 members

- not exclusive to linear colliders: Also groups from ALICE and with generic calorimetry interest

CALICE Goals

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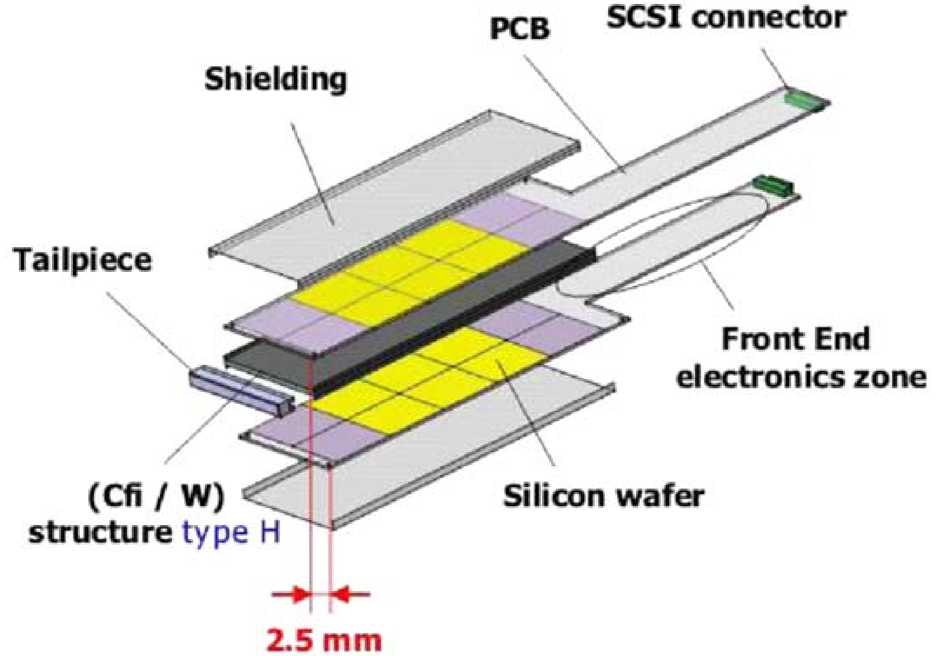
- ***Application*** of CALICE technology in running experiments:
  - Use of CALICE detector elements
  - Full detector systems based on CALICE technology

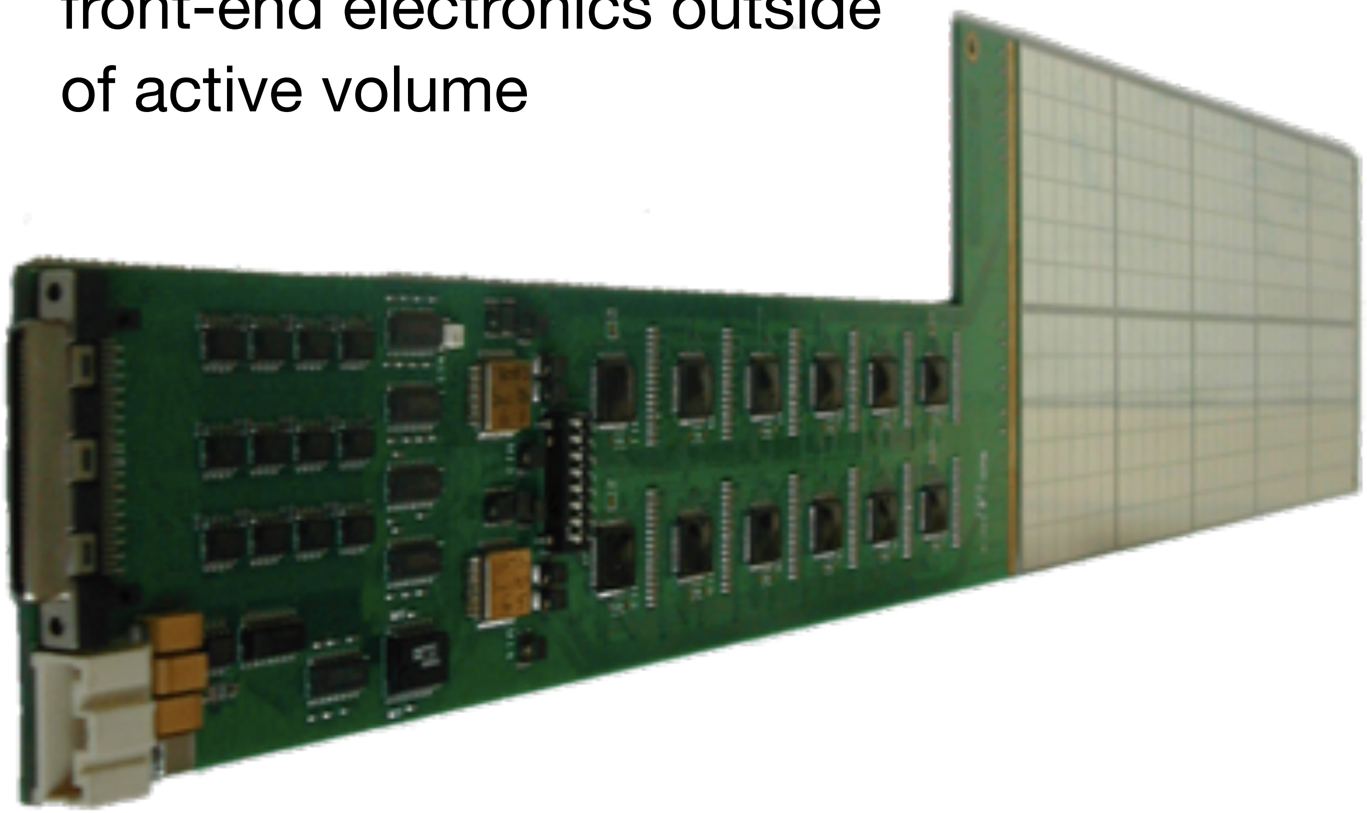
Technologies: Silicon

- Key features:
  - (relatively) high density, low required energy per e$^-$/hole pair: large sampling fraction also for thin active layers, large signals
  - Easily segmentable, stable against changing environmental parameters



Used in electromagnetic calorimeters

In physics prototype: 6 x 6 cm wafers, front-end electronics outside of active volume



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5.5 x 5.5 mm^2 cells for technological prototype

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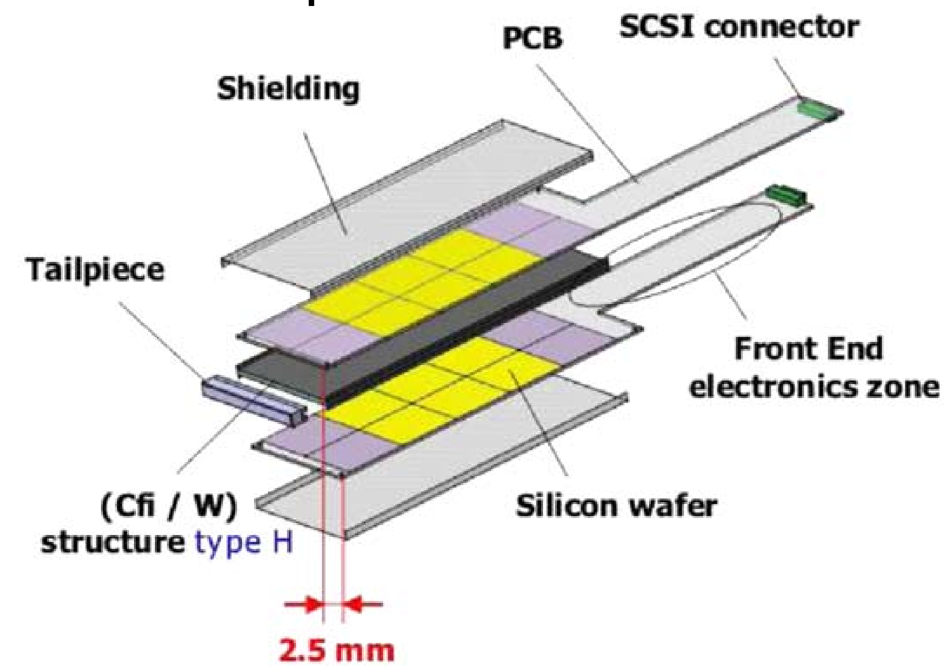

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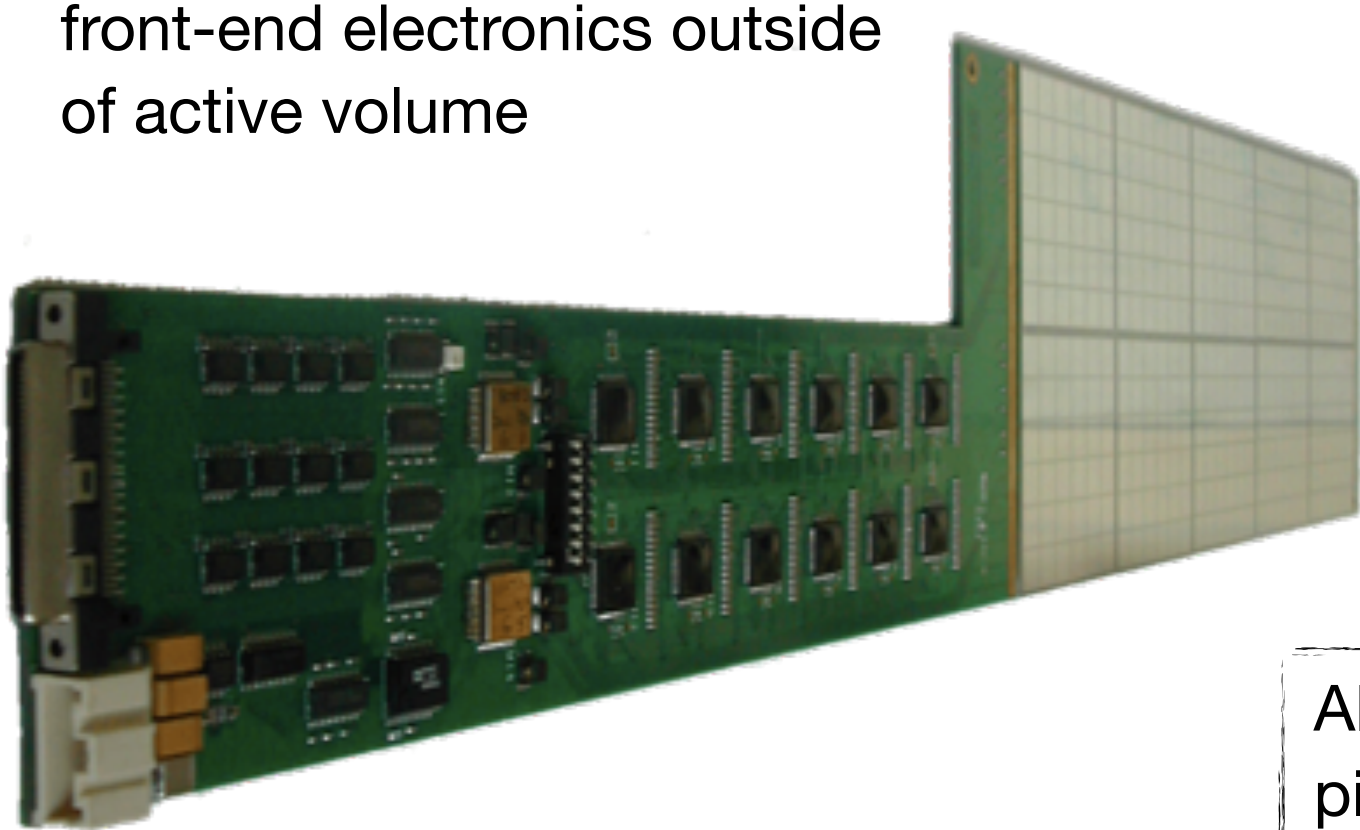

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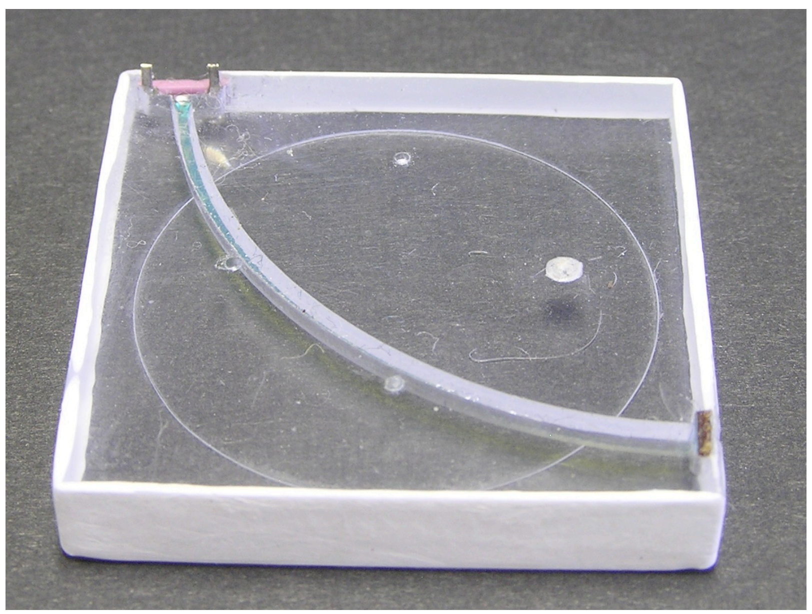
Also under study: MAPS with very small pixels (typically 25 x 25 μm²) “Digital ECAL”

Technologies: Scintillator

- Key features
  - highly segmentable when combined with SiPM readout
  - large dynamic range

Used in electromagnetic and analog hadronic calorimeters



AHCAL physics prototype:
3 x 3 x 0.5 cm^3 cells
first large-scale use of SiPMs:
~ 8000 in prototype, started
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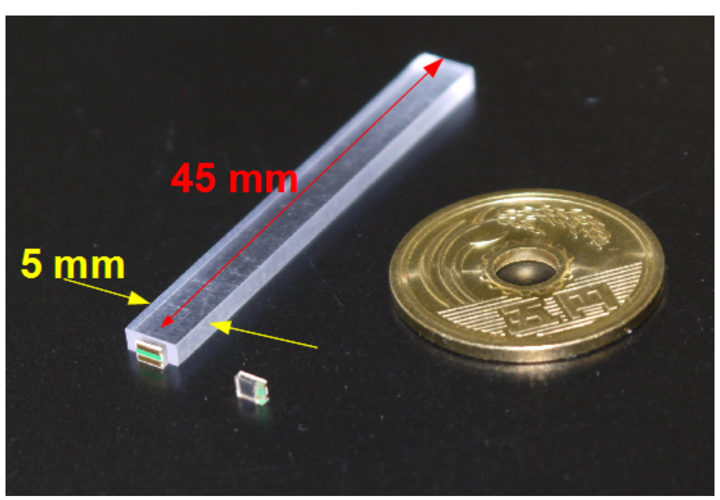

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45 x 5 x 2 mm^3 strips
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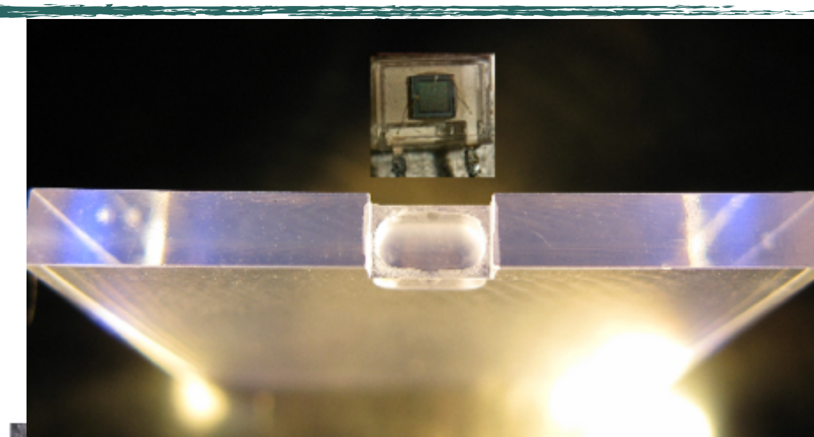

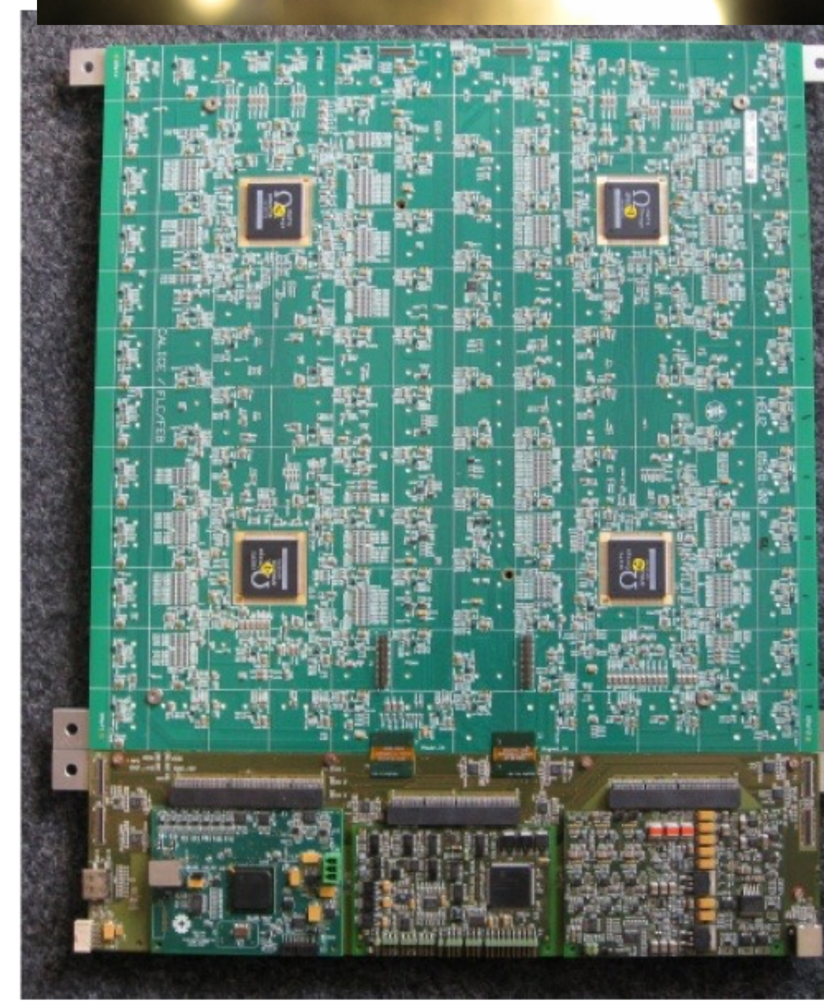

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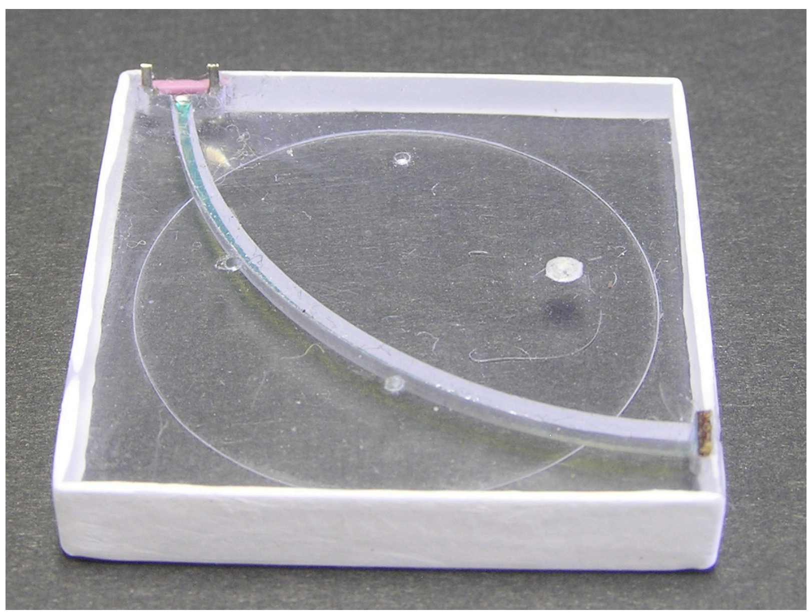

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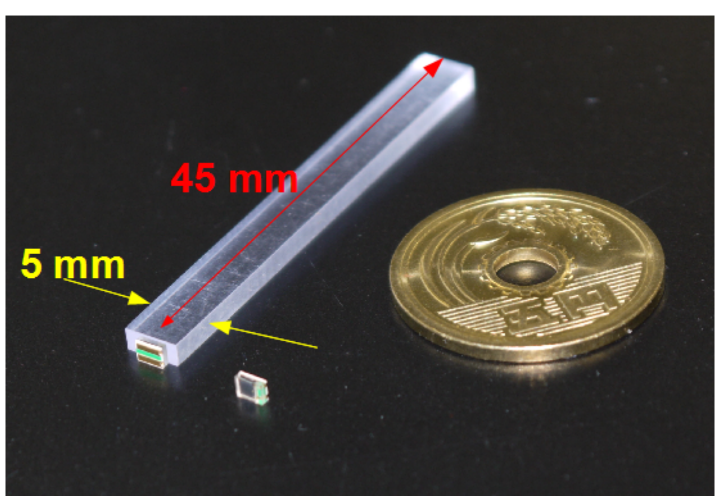


3 mm thick scintillator for technological PT, fiberless coupling, fully integrated electronics

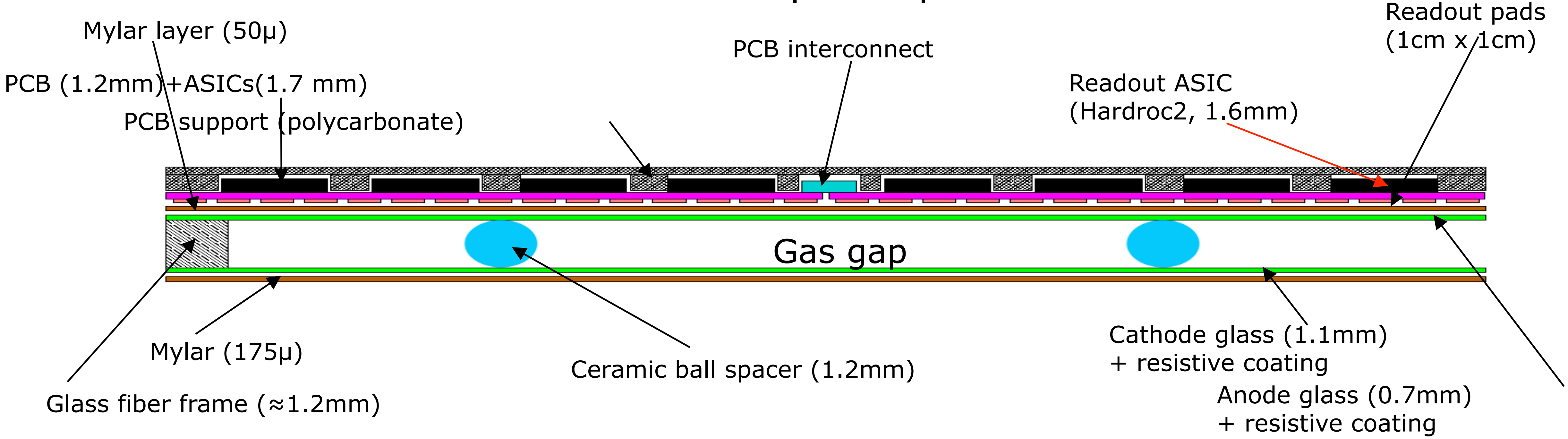
Technologies: Gas

- Key features
  - Very high segmentation possible
  - Low cost of active elements

Used in digital and semi-digital hadronic calorimeters

Main active elements:
Glass RPCs

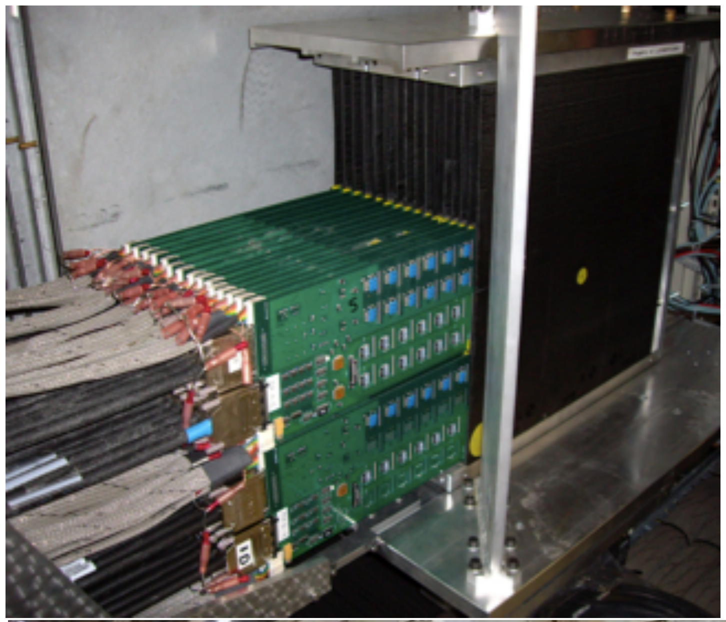
For SD-HCAL: Already equipped (and tested) with power-pulsed electronics

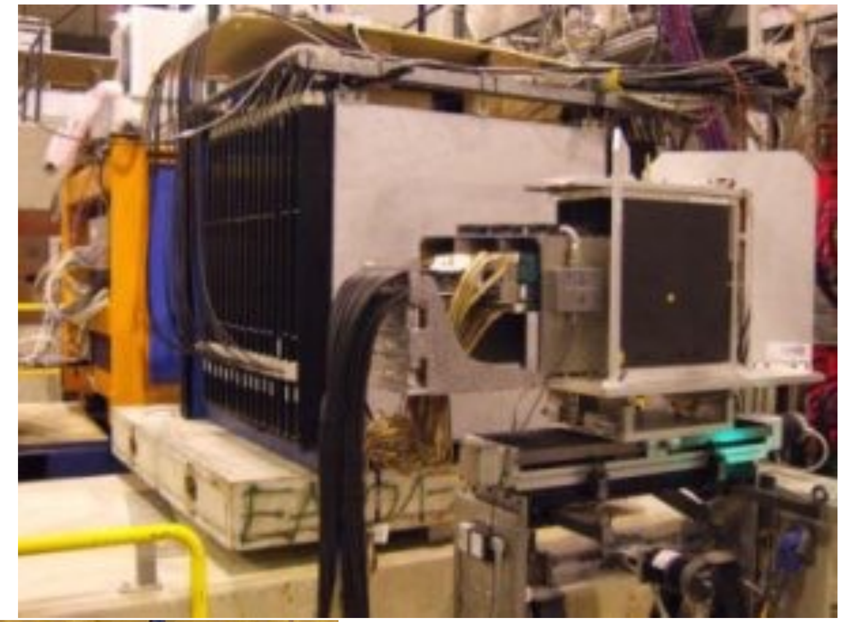


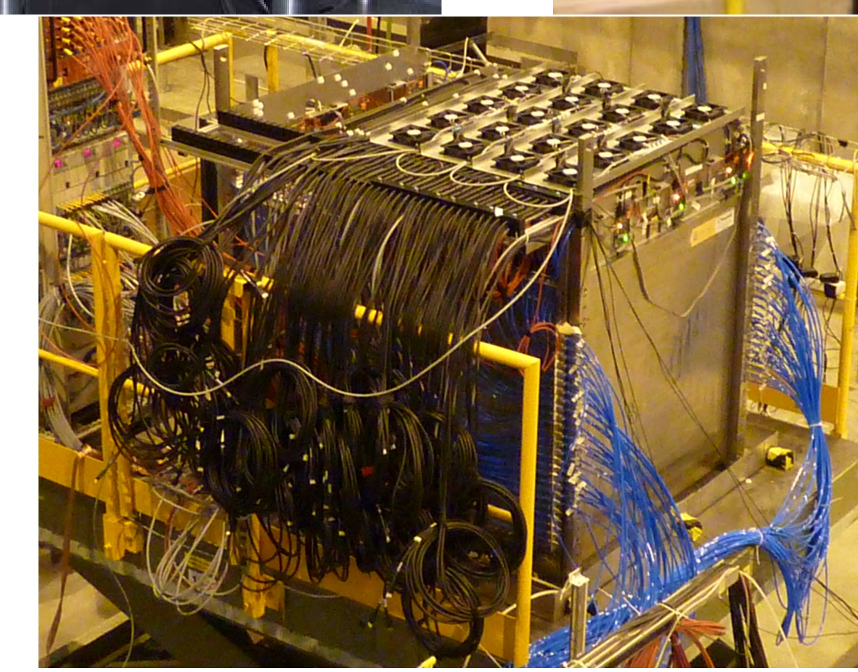
- Alternatives being explored: Micromegas, GEMs

Proving the Technology: Beam Tests

- Extensive test beam program with all technologies, also combining different ECAL and HCAL options - using beams at DESY, CERN, FNAL







Complex projects:

- up to 500k electronics channels
- use of remote control room / remote shifting since 2008

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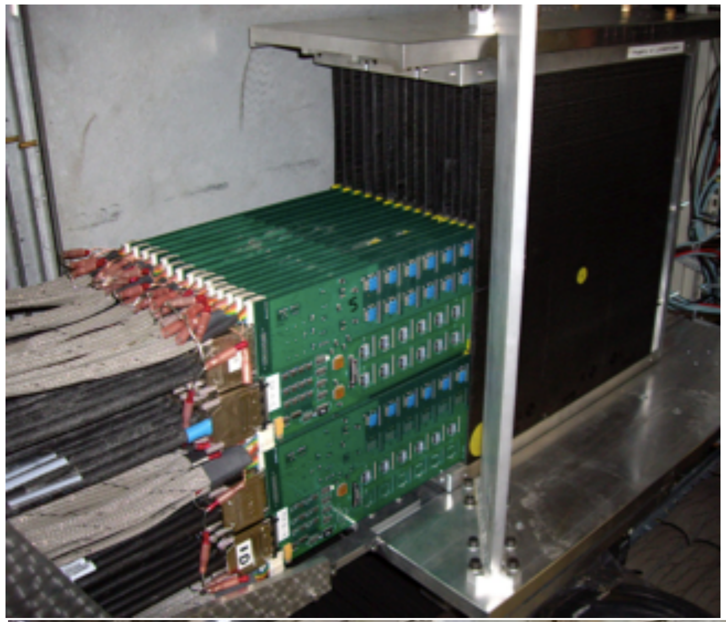
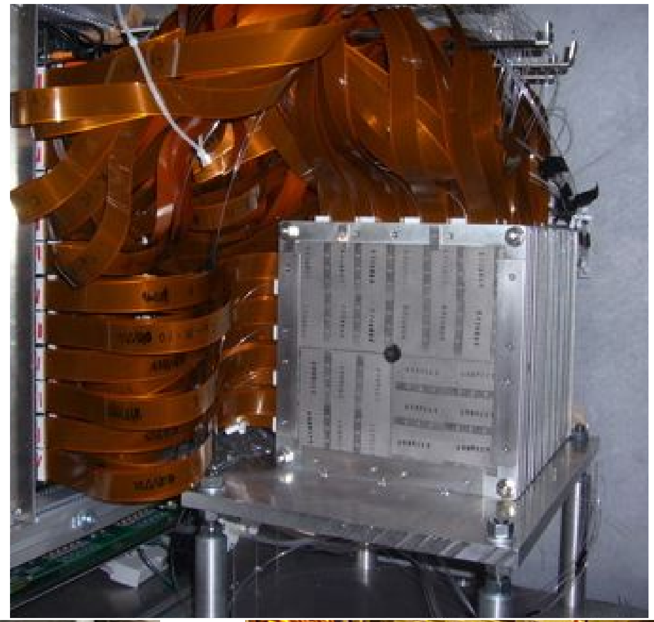
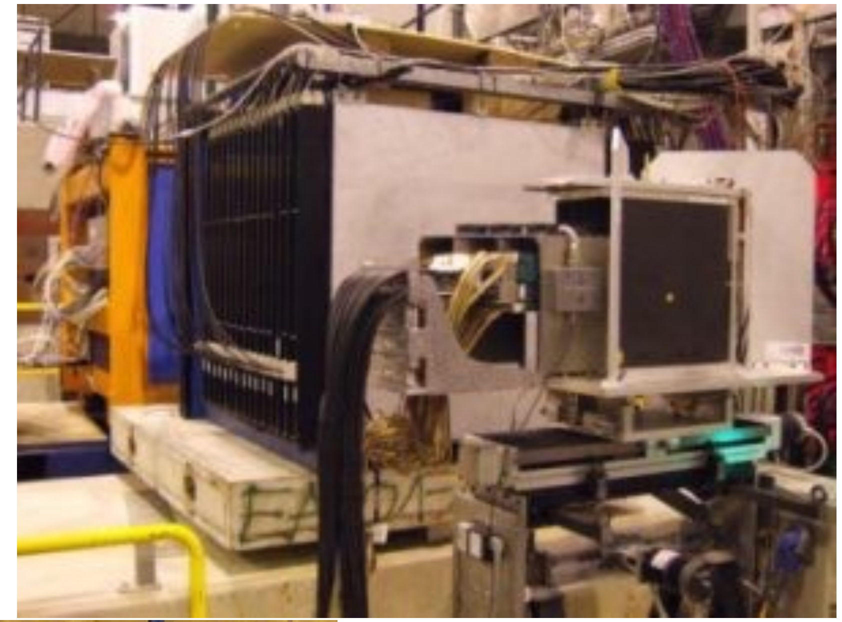

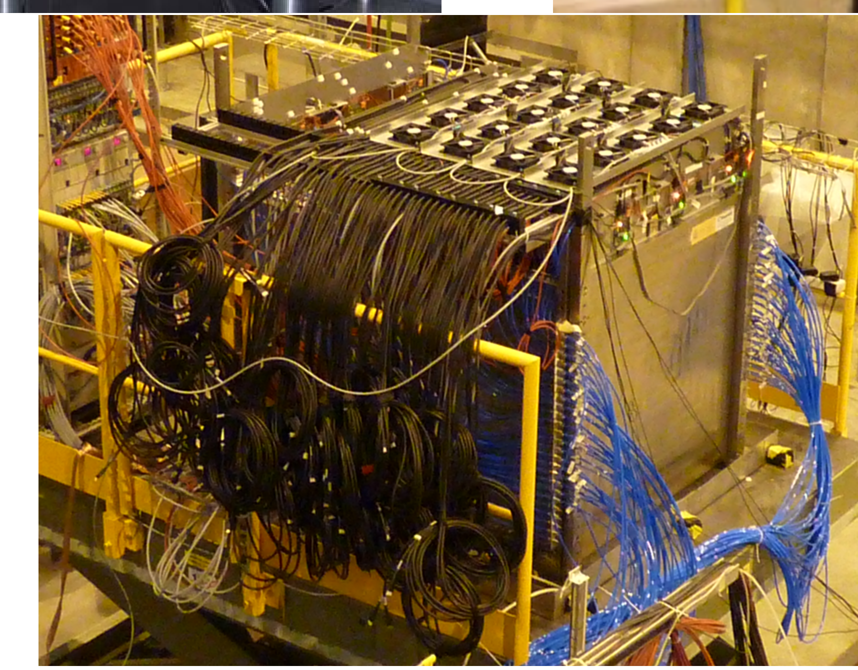

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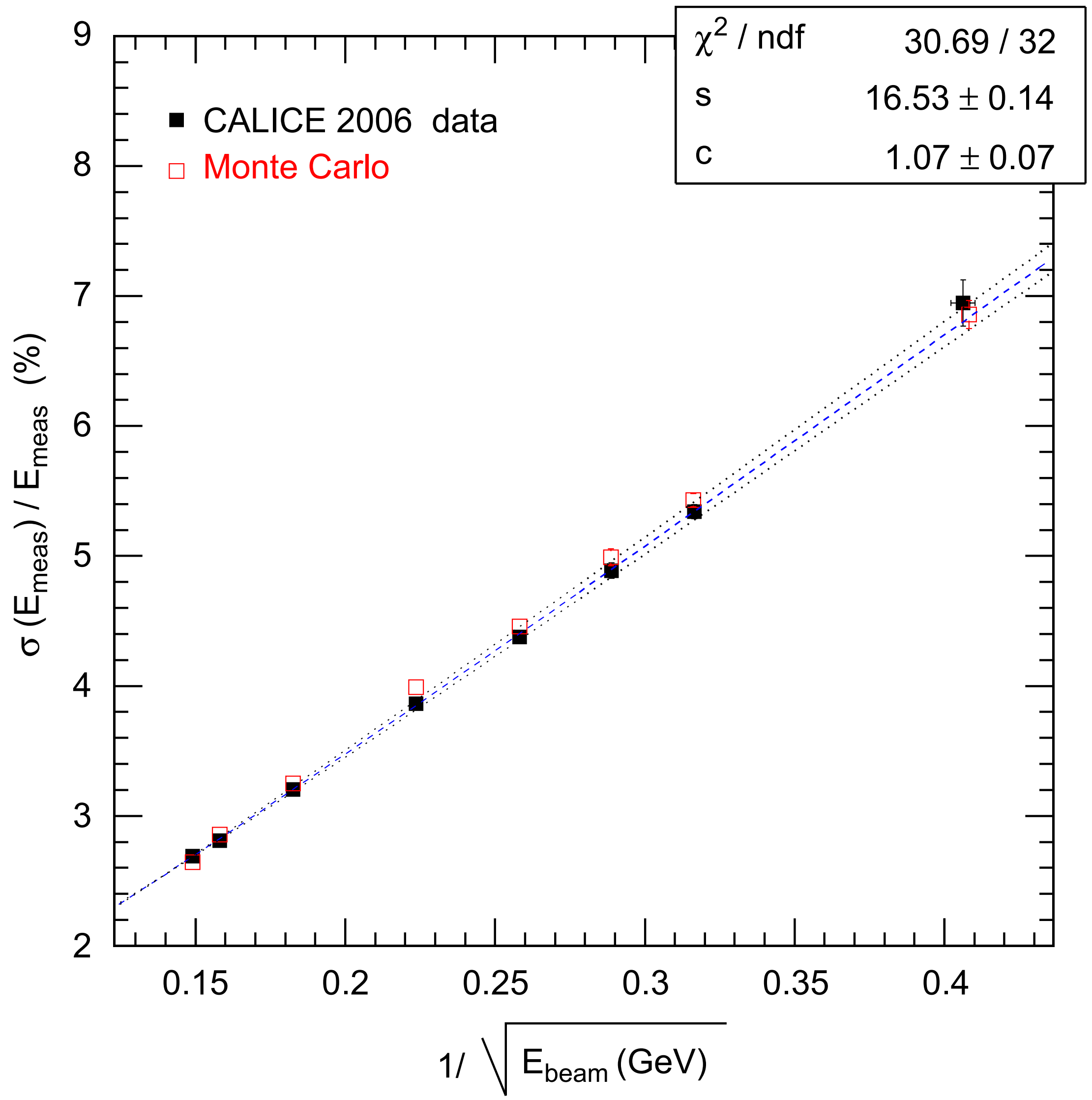
➯ A large data set to demonstrate calibration, stability & performance, and to study showers

Validation: Performance - Resolution

- Demonstrated key performance aspects - three examples:

- Electromagnetic resolution



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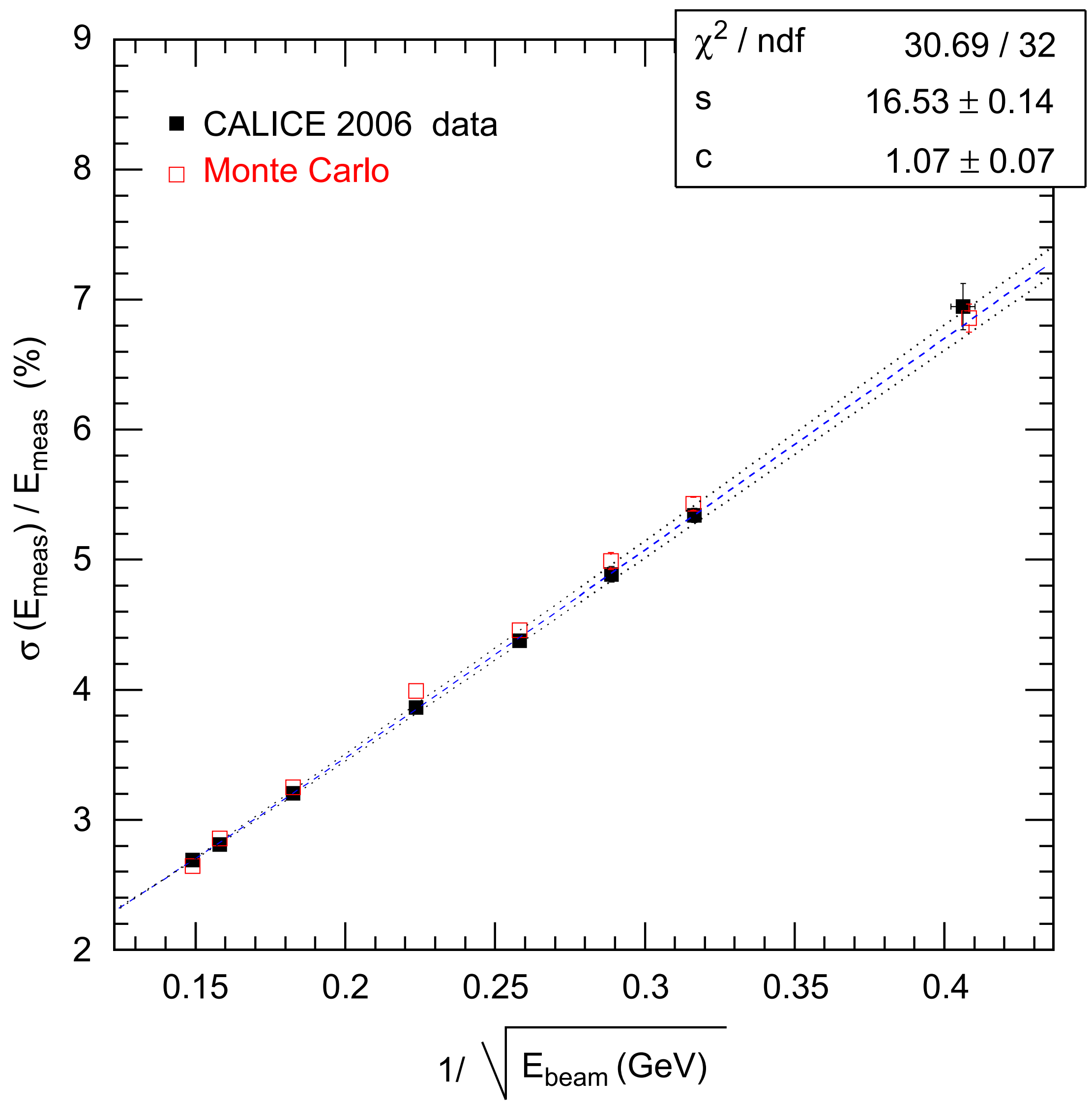
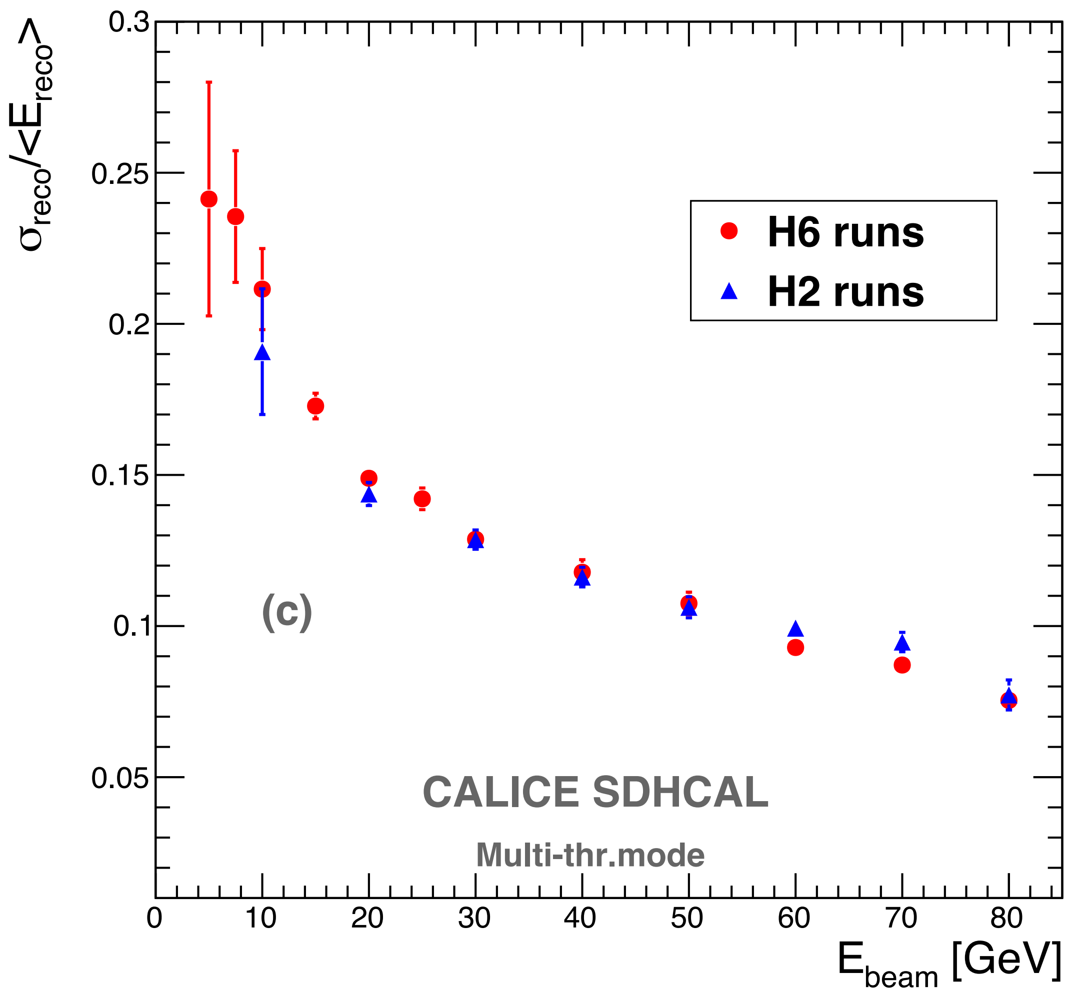


- Hadronic resolution in gaseous calorimeters



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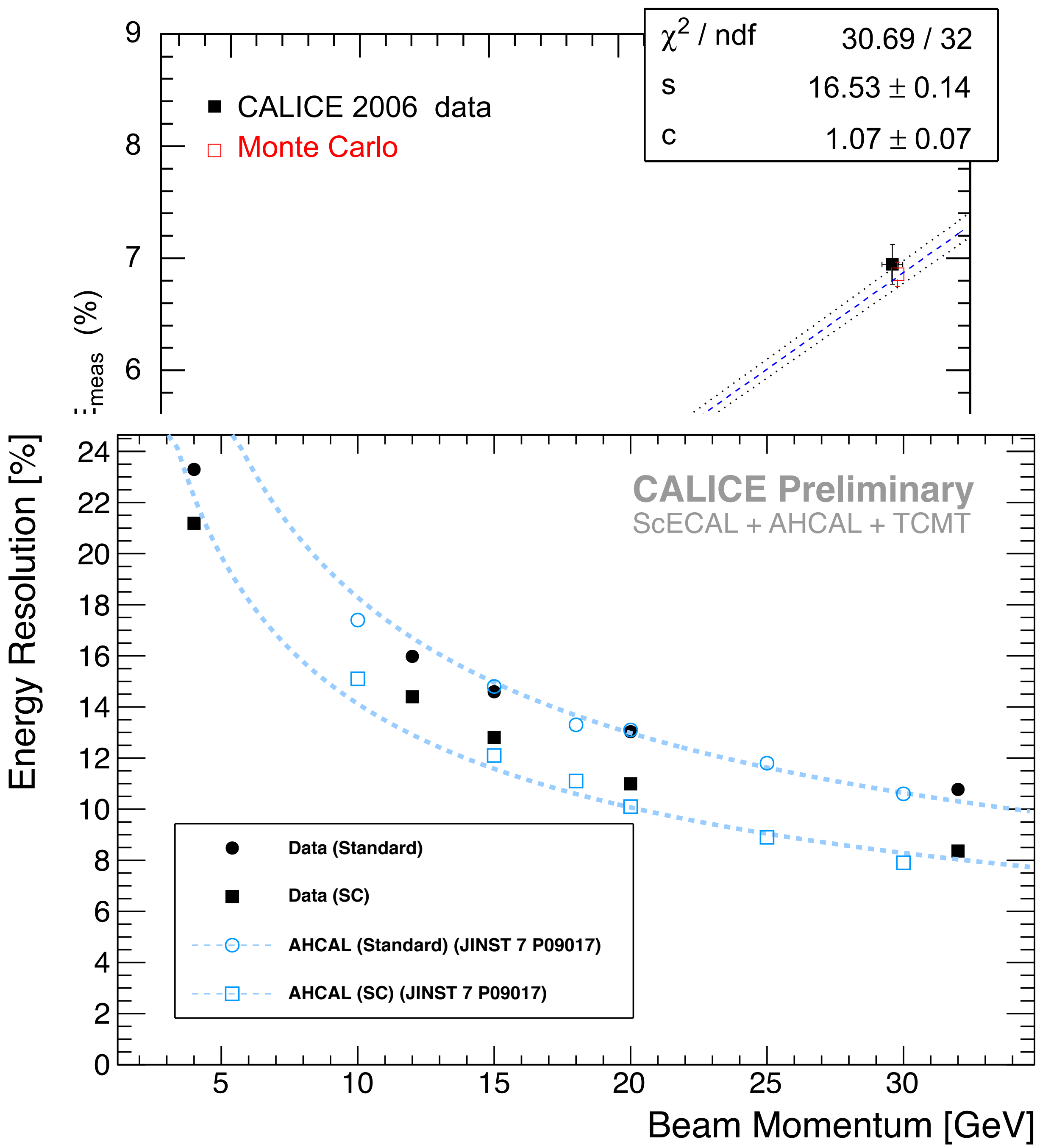

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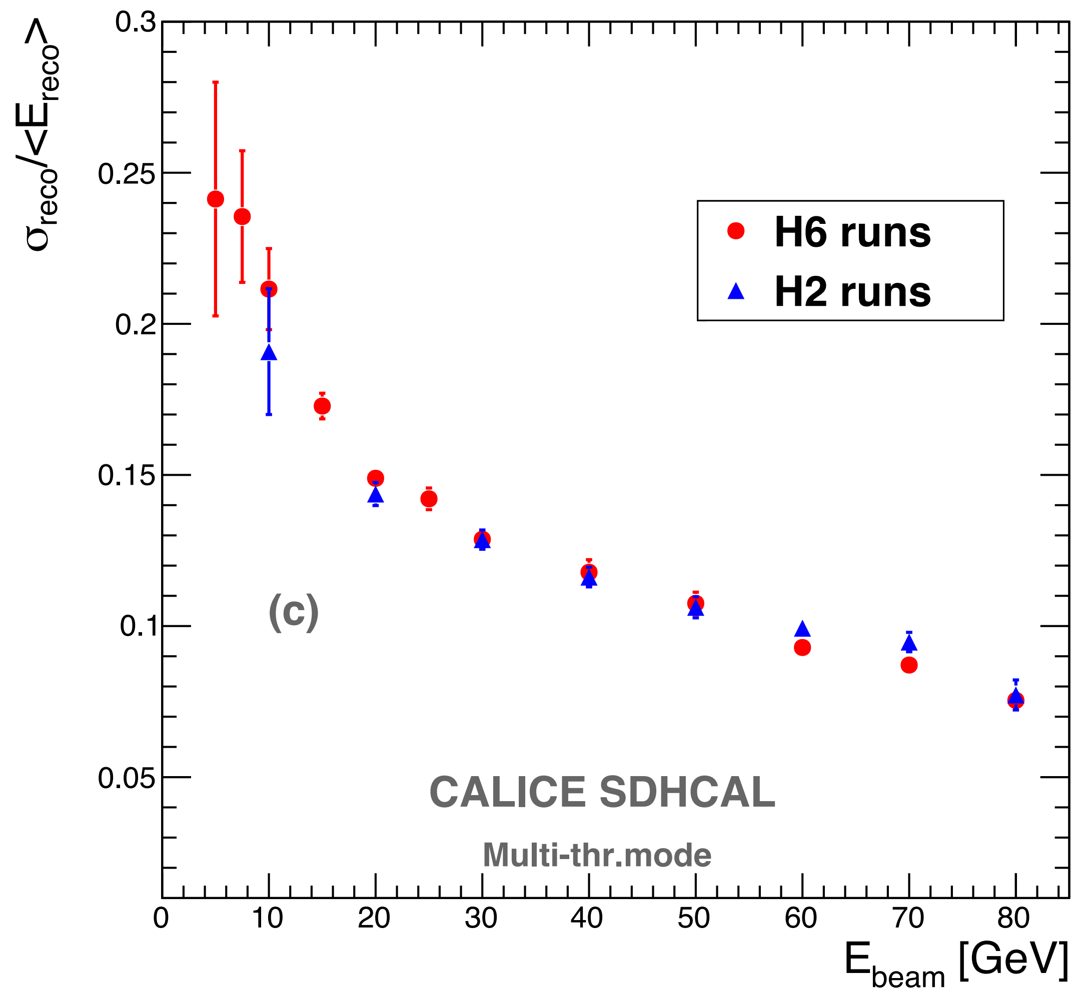
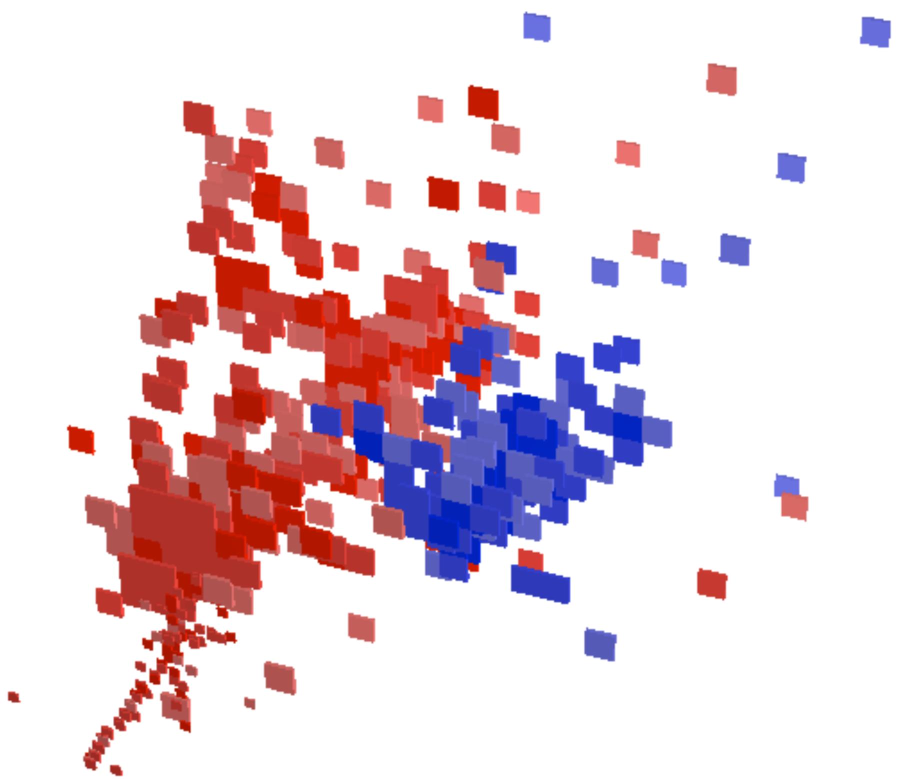


- Hadronic resolution in combined systems with software compensation

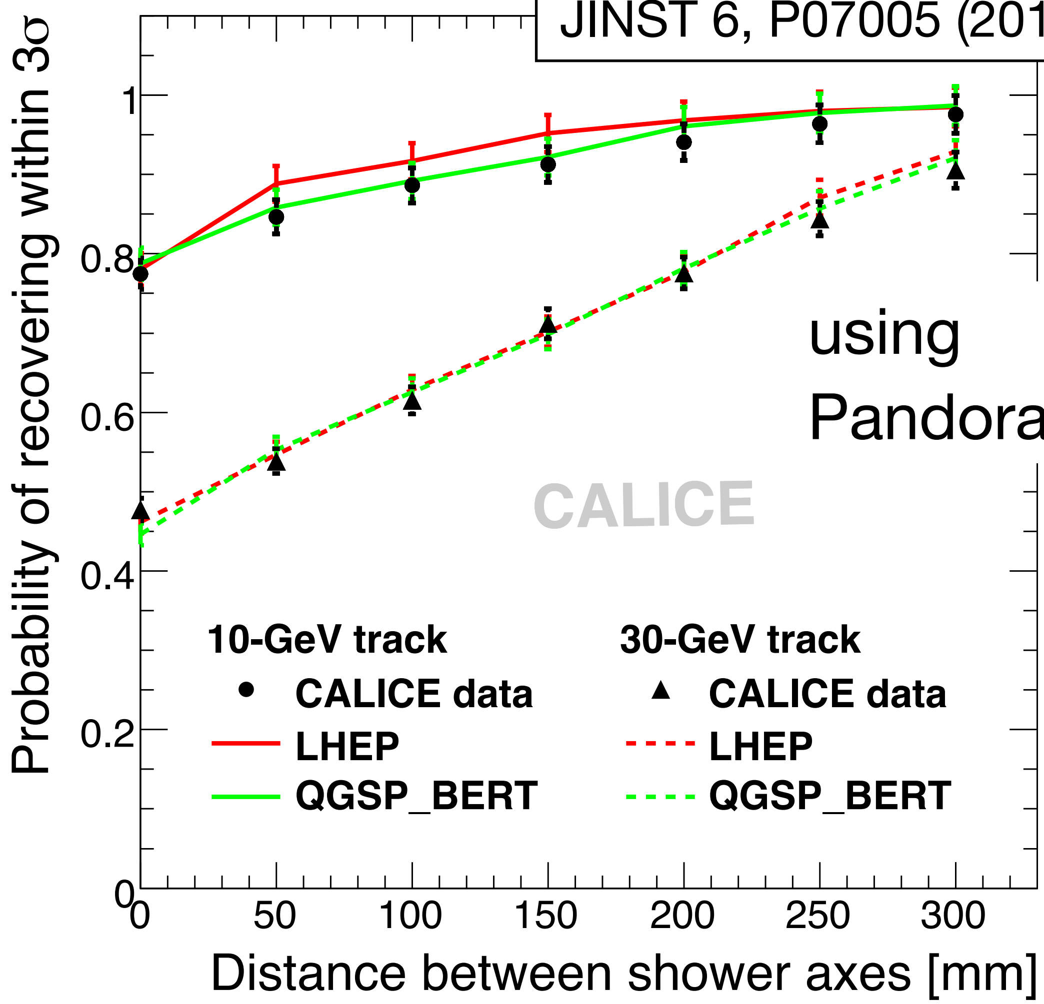
Validation: Performance - Separation

- CALICE calorimeters are not (just) about single particle resolution, but PFA performance - which requires particle separation in a jet environment

Studied via overlayed CALICE events (SiW ECAL + AHCAL) fed into particle flow algorithms



JINST 6, P07005 (2011)



using PandoraPFA

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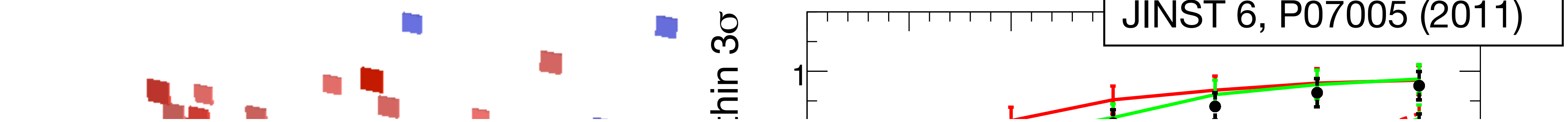
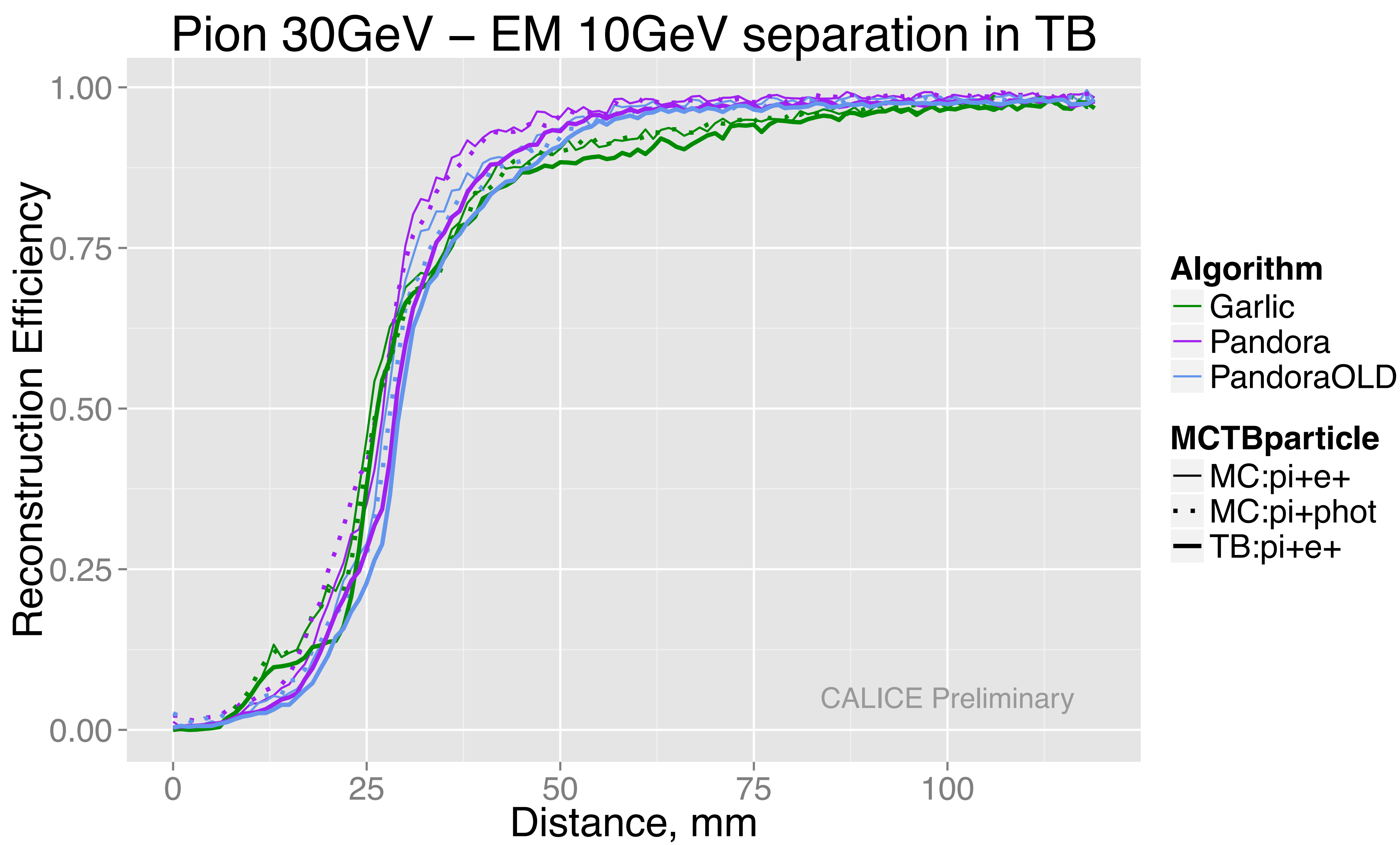
JINST 6, P07005 (2011)





Technology of Imaging Calorimeters

- Towards technological realisation -

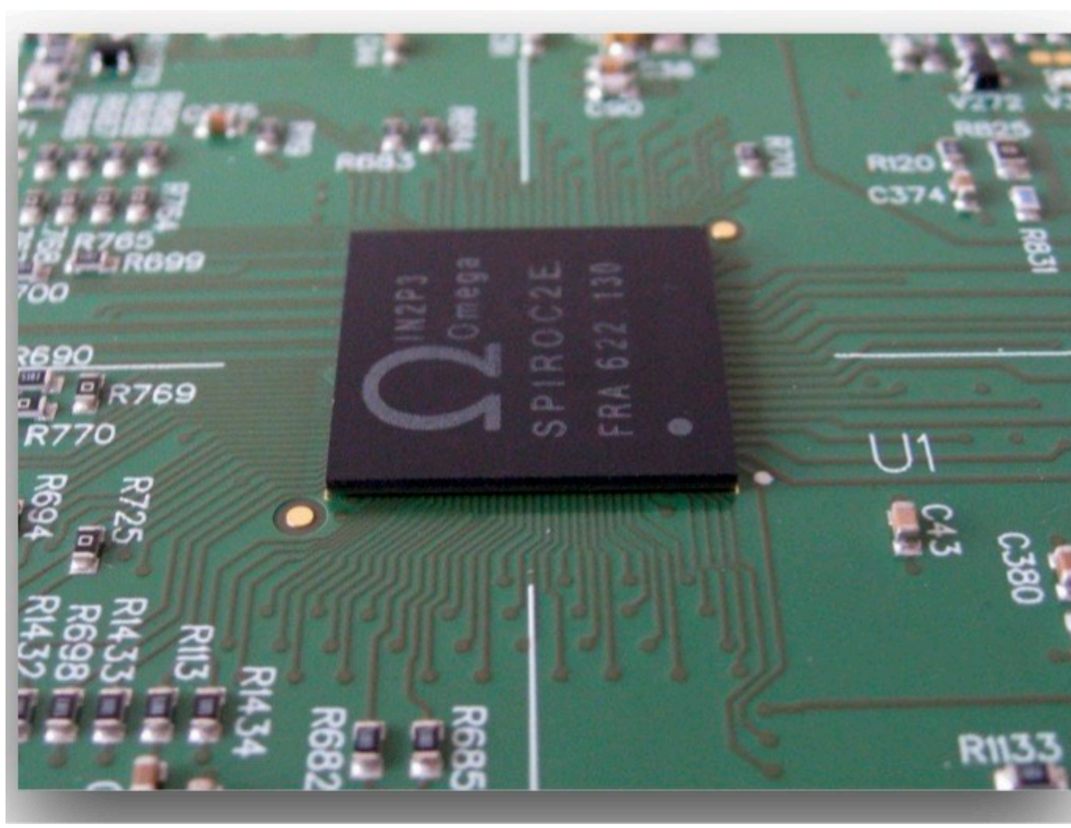
… with a mild bias towards the project pursued in Germany

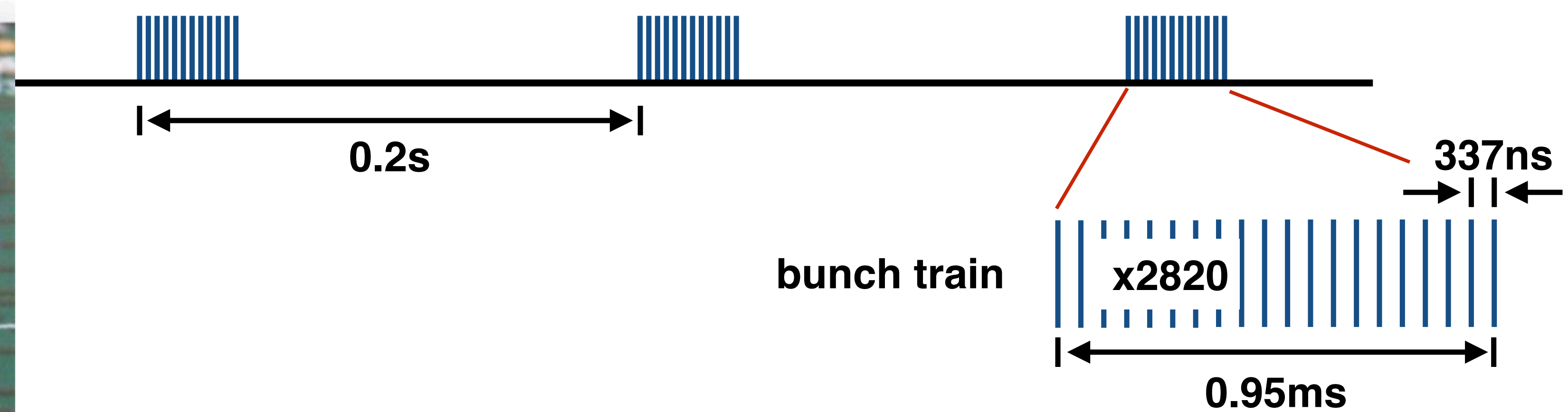
Common to all Technologies: Embedded Electronics

- A highly granular ECAL system at a collider detector will have ~ 100 M channels (or much more, if working with CMOS pixels), for the HCAL the number is also in the range from 10 M - 100 M
  - N.B.: This is comparable to the channel count in present-day pixel detector systems at LHC

➯ Requires electronics embedded in the active layers, autotrigger, zero-suppression

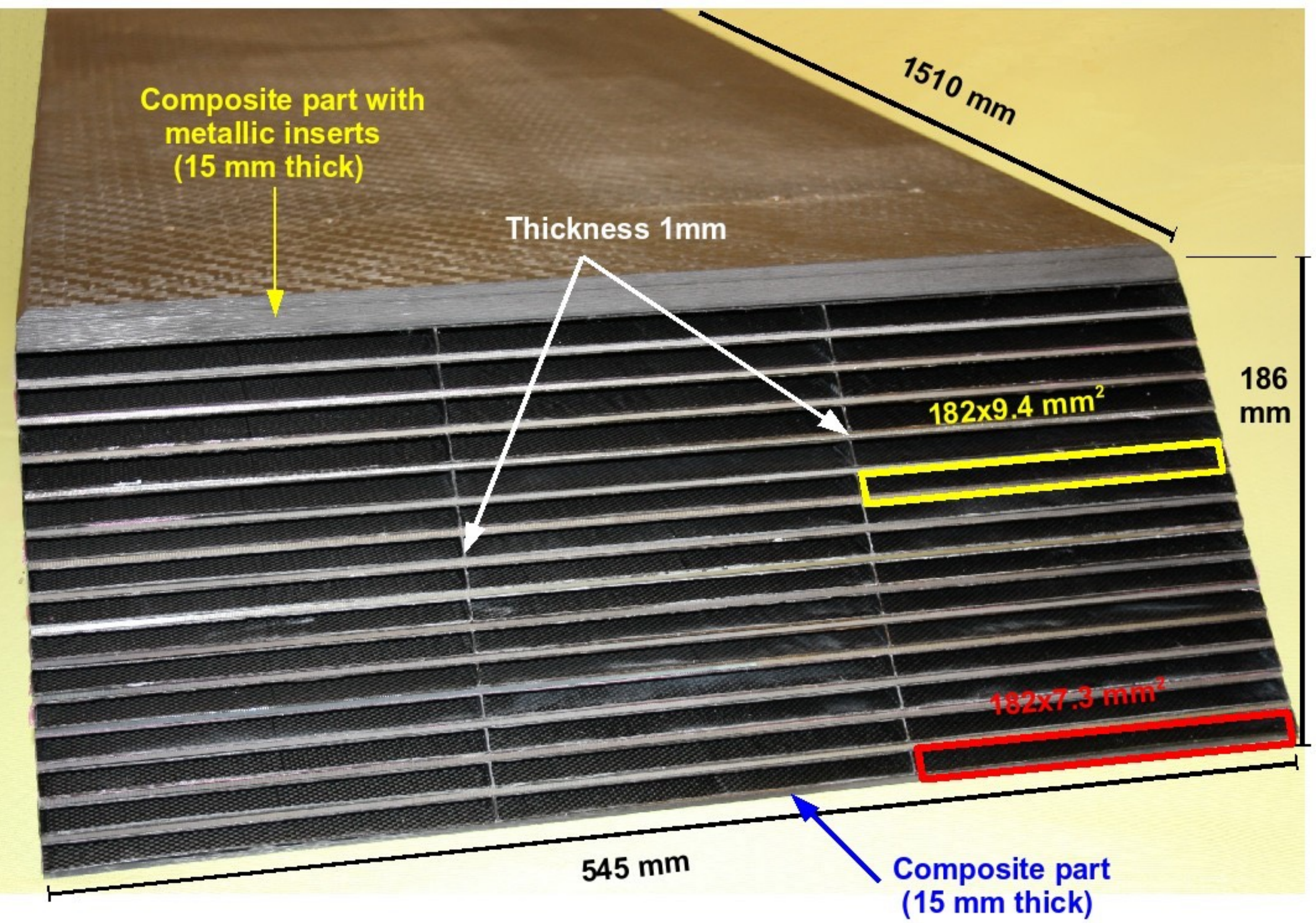
➯ For maximum compactness avoid cooling (too low mass…): Power pulsing!

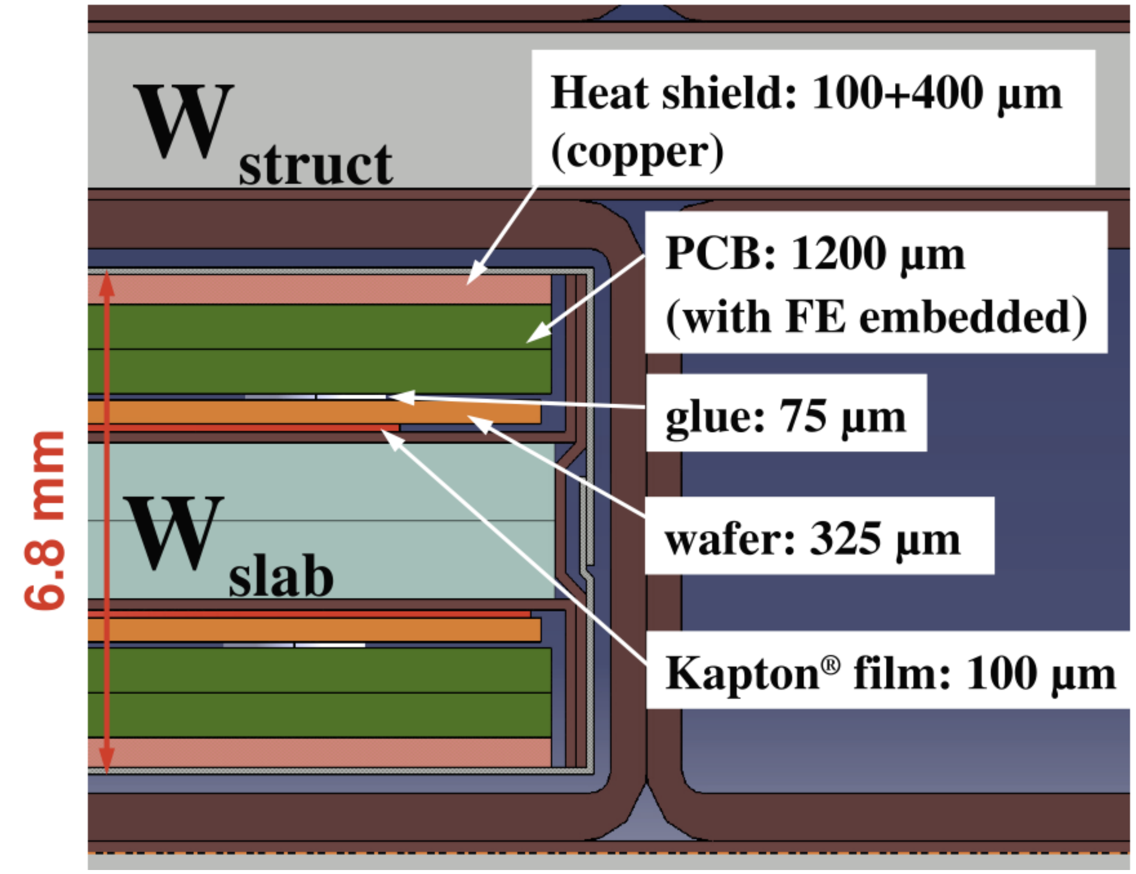




Technological Prototypes: The SiW ECAL

- The goal: ~ 25 X_0 in less than 20 cm, with 5 x 5 mm^2 granularity

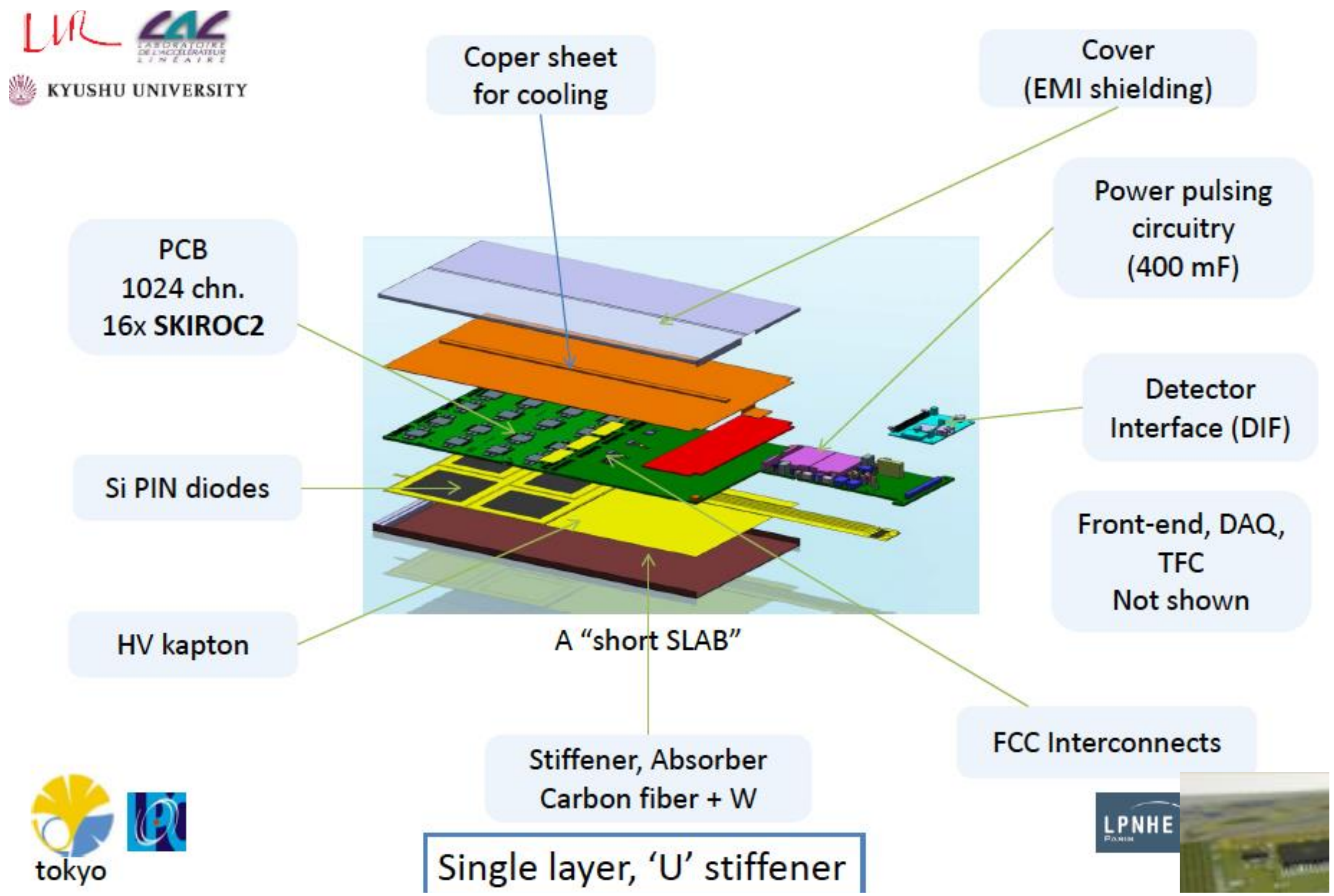




- Tungsten absorber structure (with carbon fiber coating)
  - provides mechanical rigidity
- Detector elements with integrated W absorber, two silicon layers

SiW ECAL: Towards the Next Prototype

- Complex design of active elements:



- sensitive area of "short slab" 16 x 16 cm^2 (4 Si sensor) - long slabs with up to 2 m length in development

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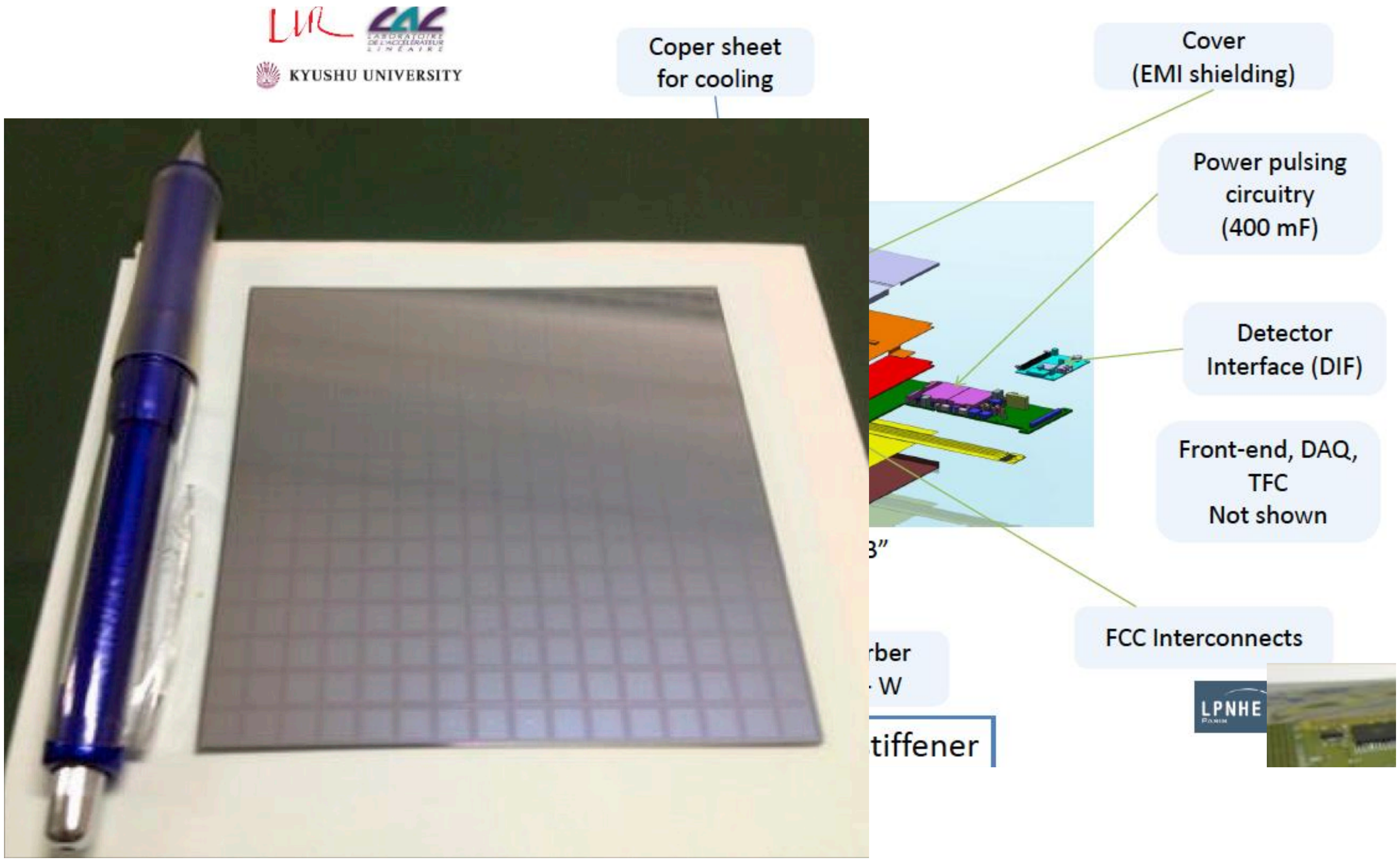

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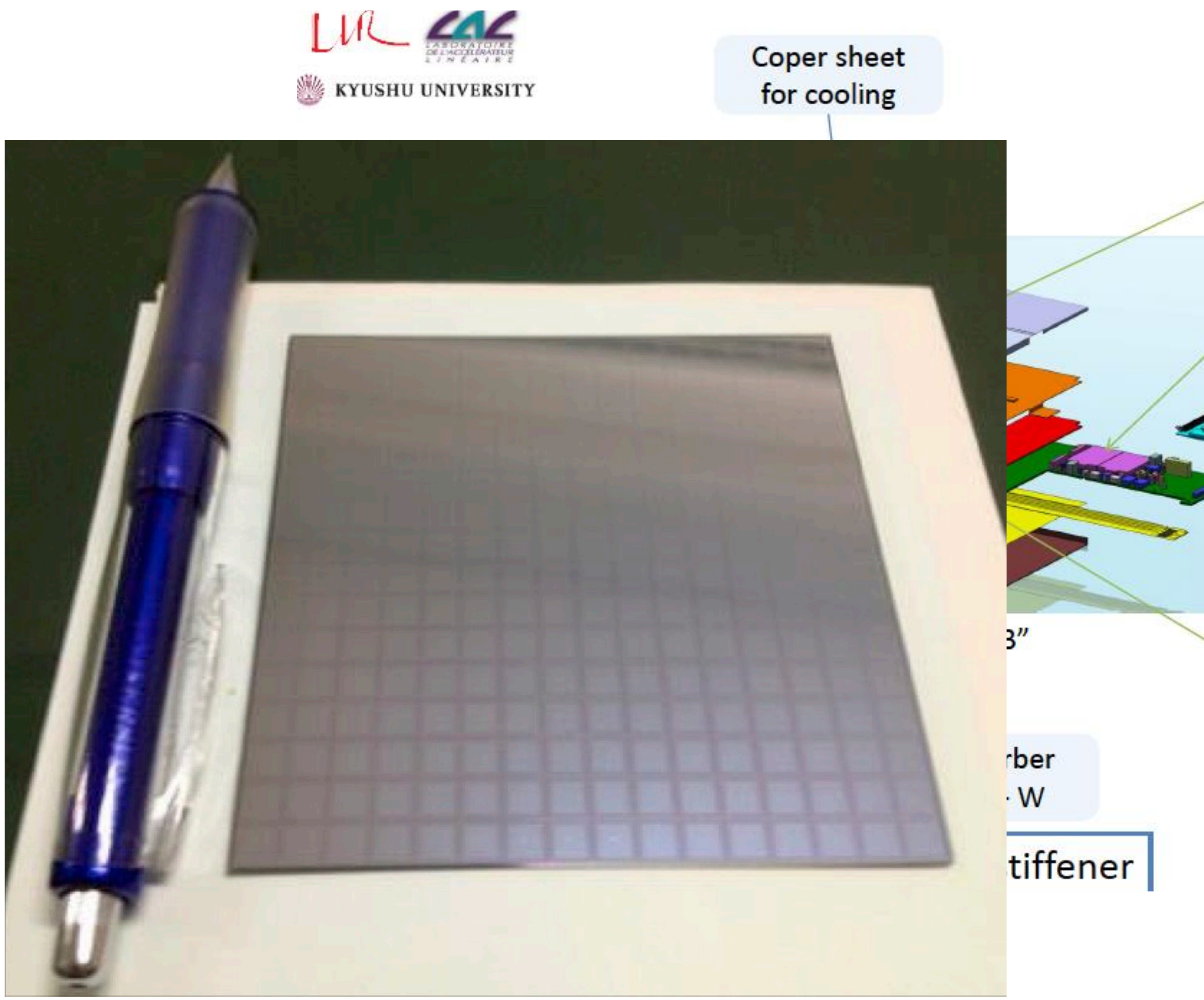

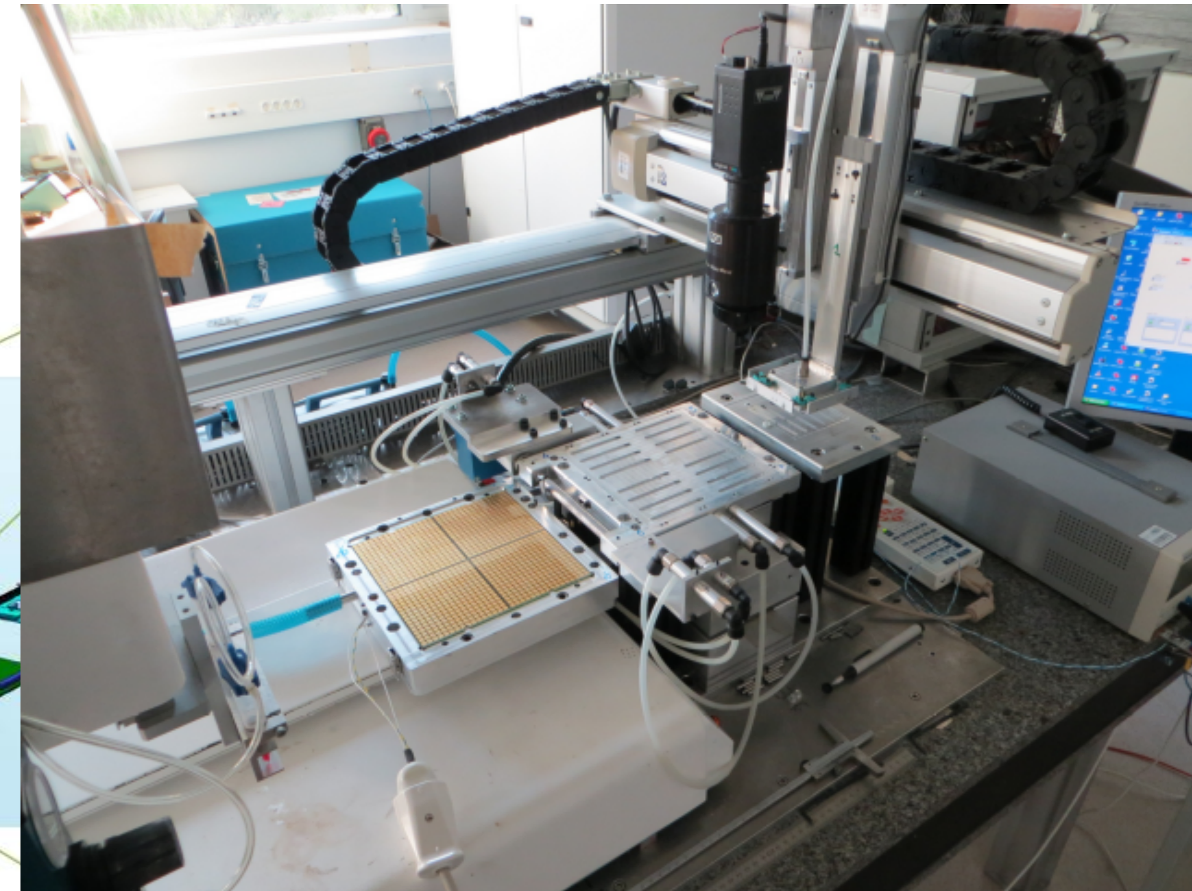

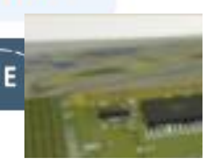

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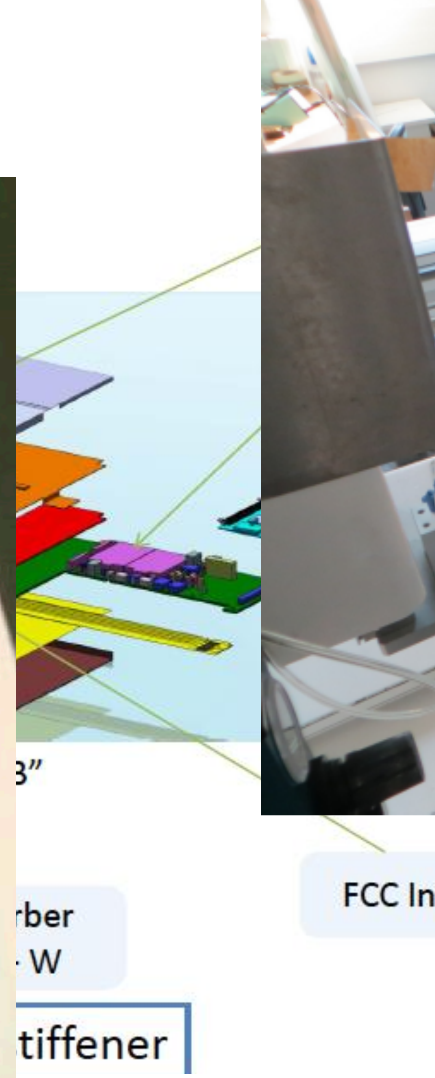
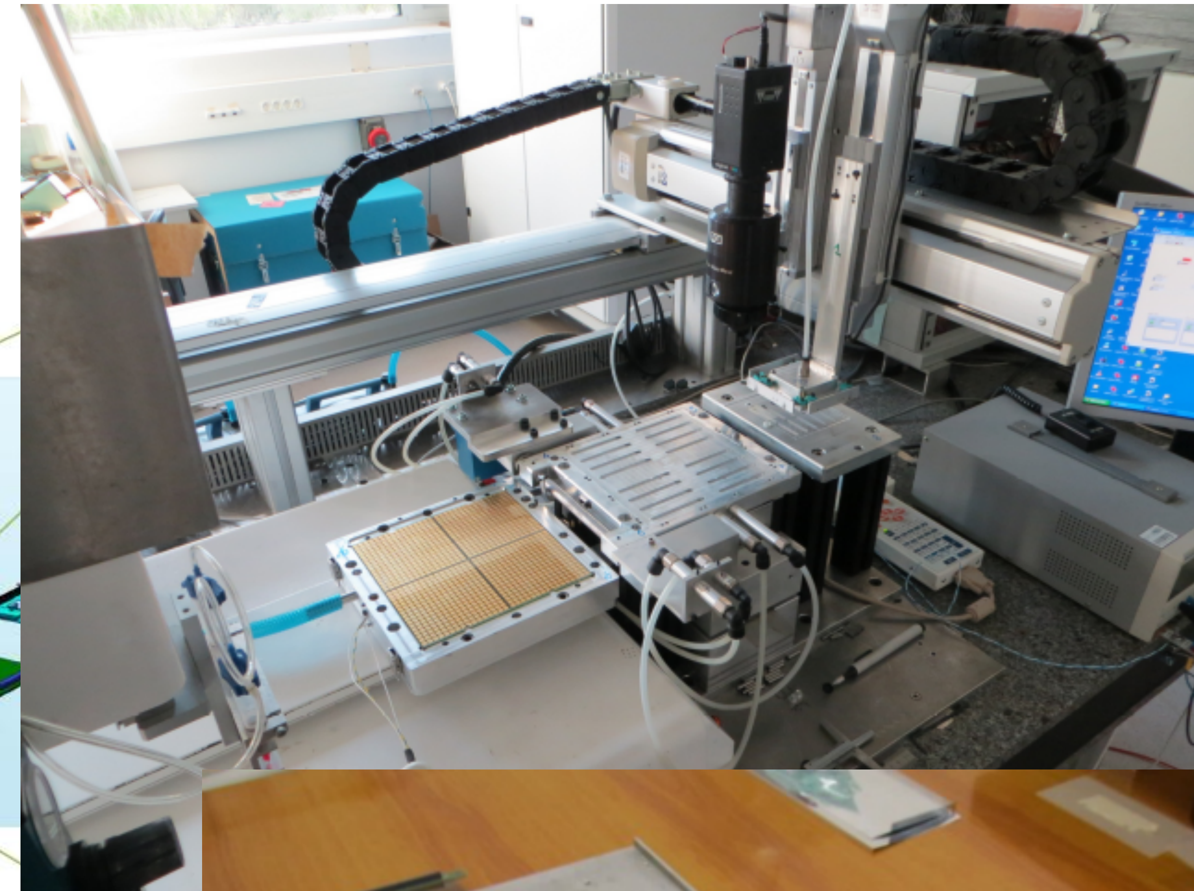
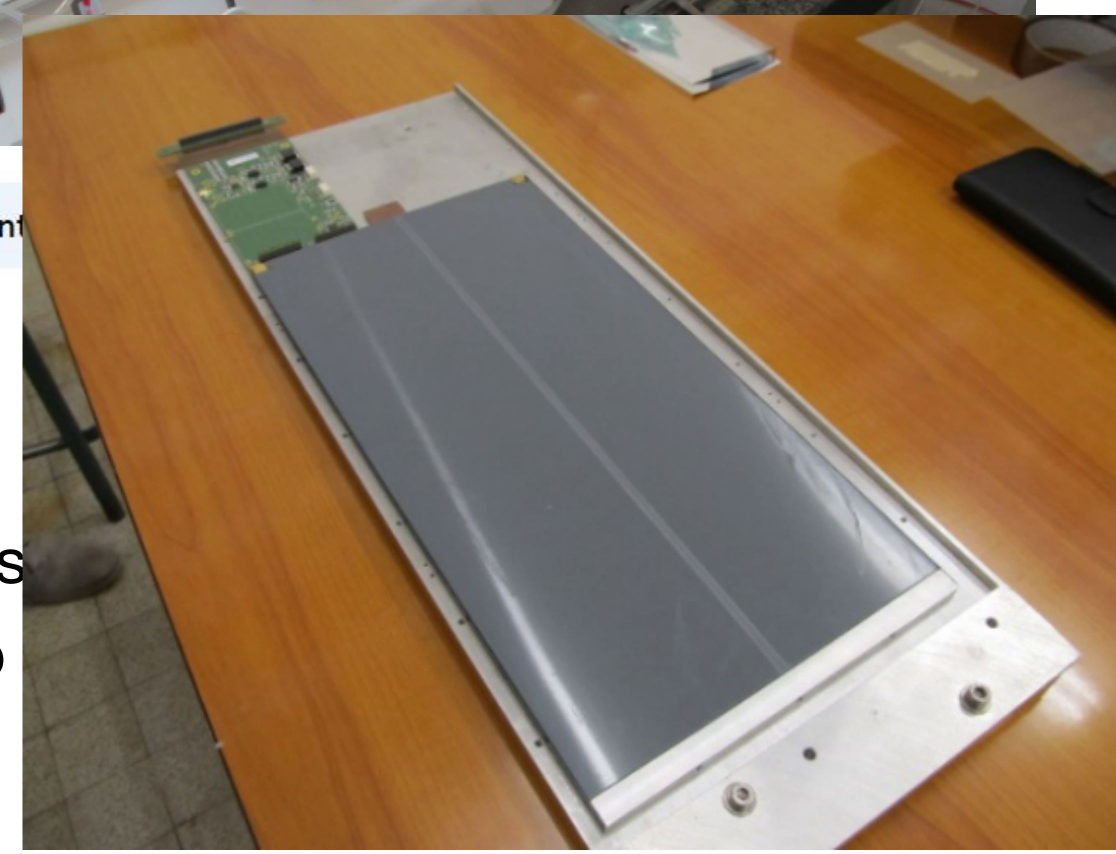


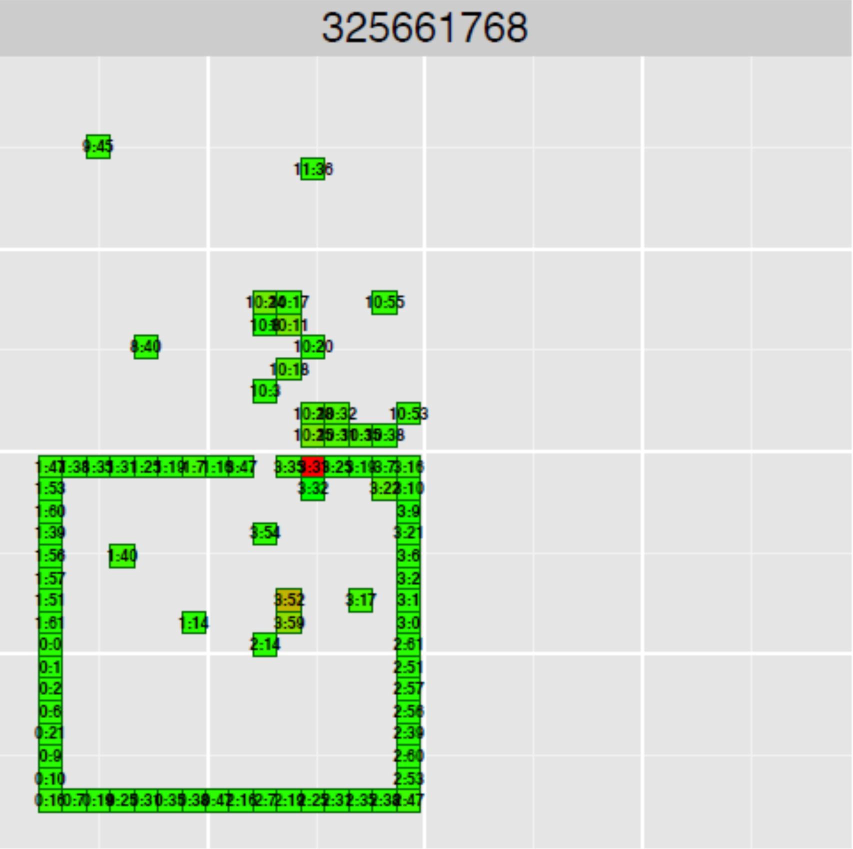




- sensitive area of “s
  long slabs with up

SiW ECAL - First Prototype Test

- An issue to watch out for: “square events”
  - Observed also in physics prototype - connected to high energy deposition in guard ring region of sensor - can be mitigated / eliminated when using sensors w/o guard ring or specialized guard ring design



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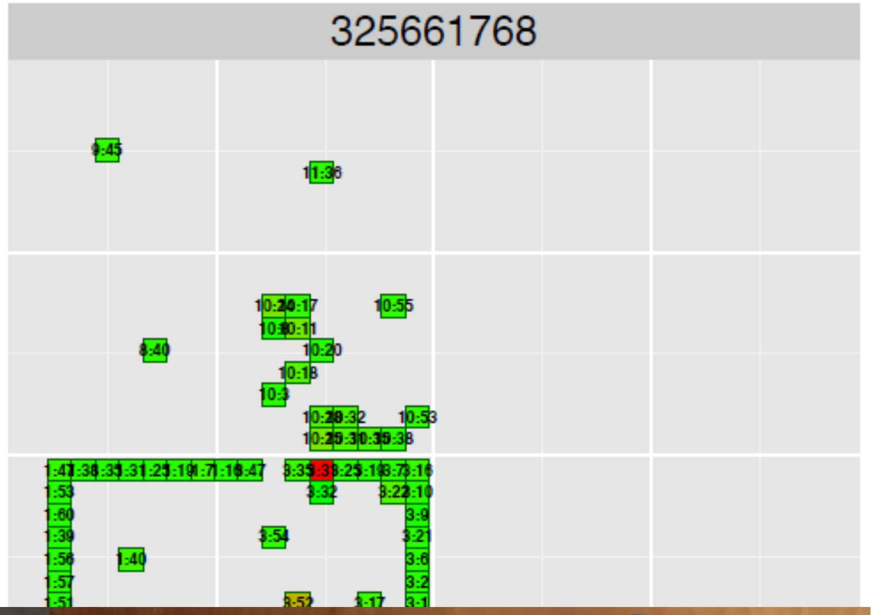
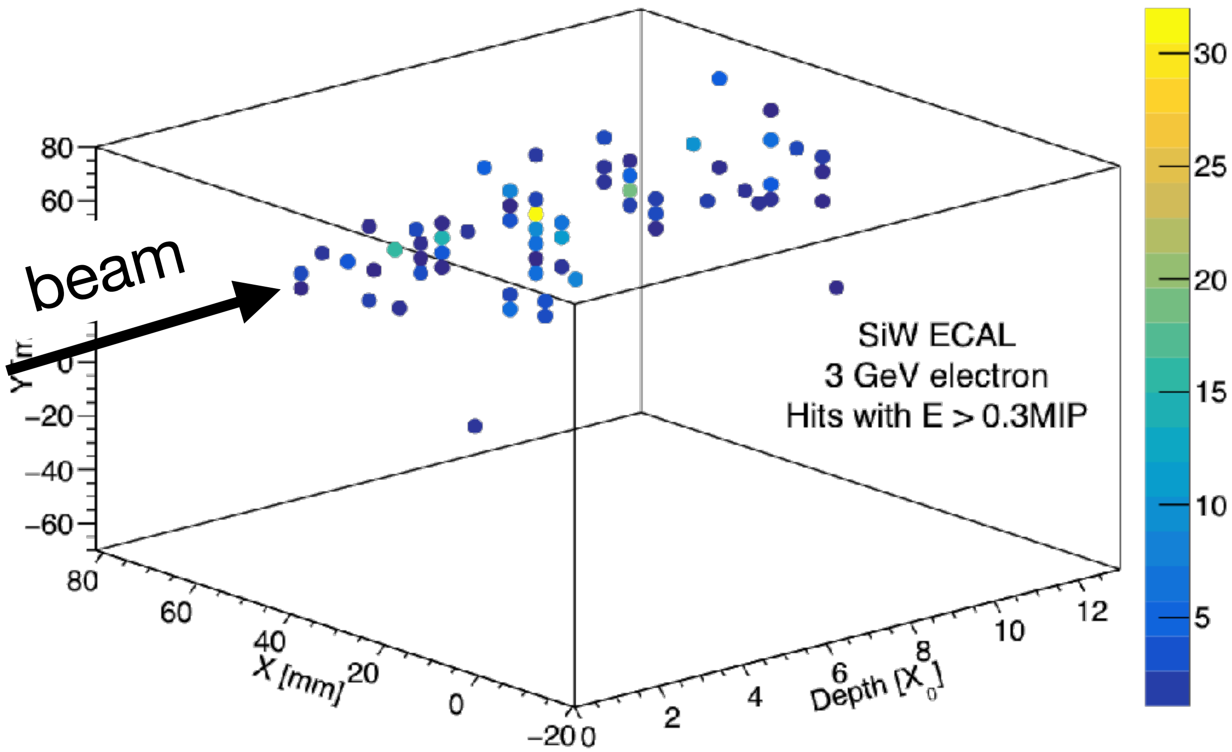
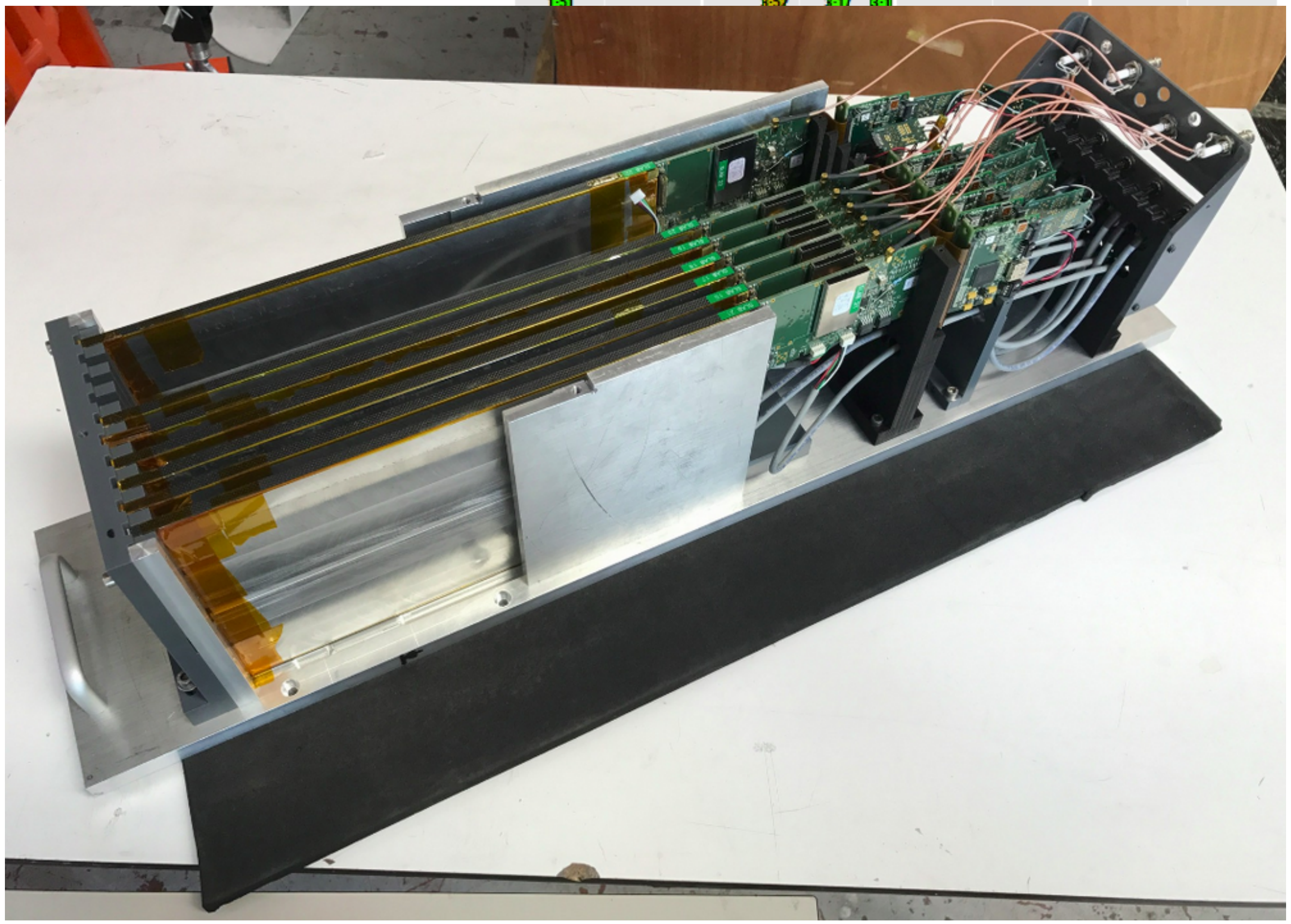


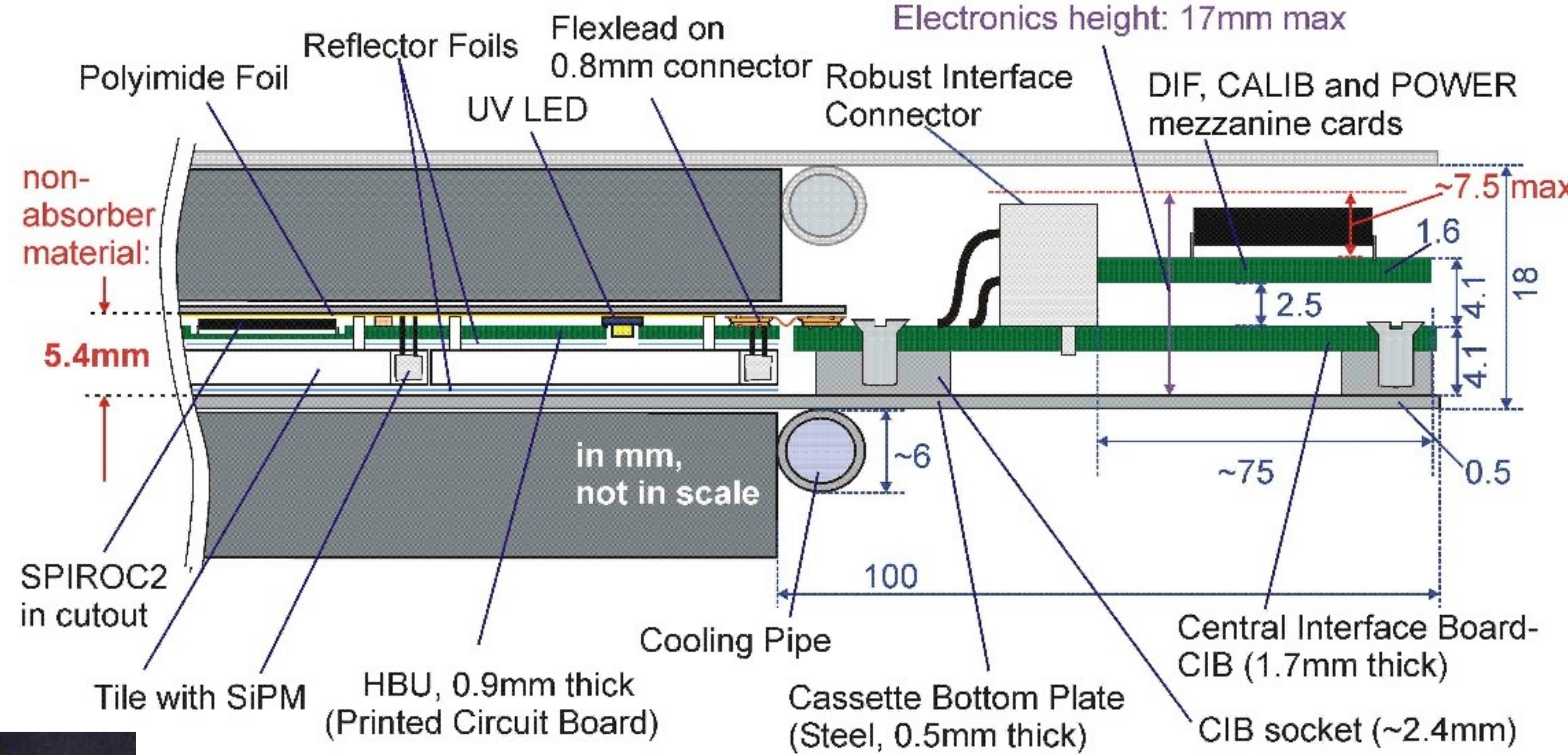
- Successful tests in beam at DESY : 7 layers with different absorber configurations to sample shower

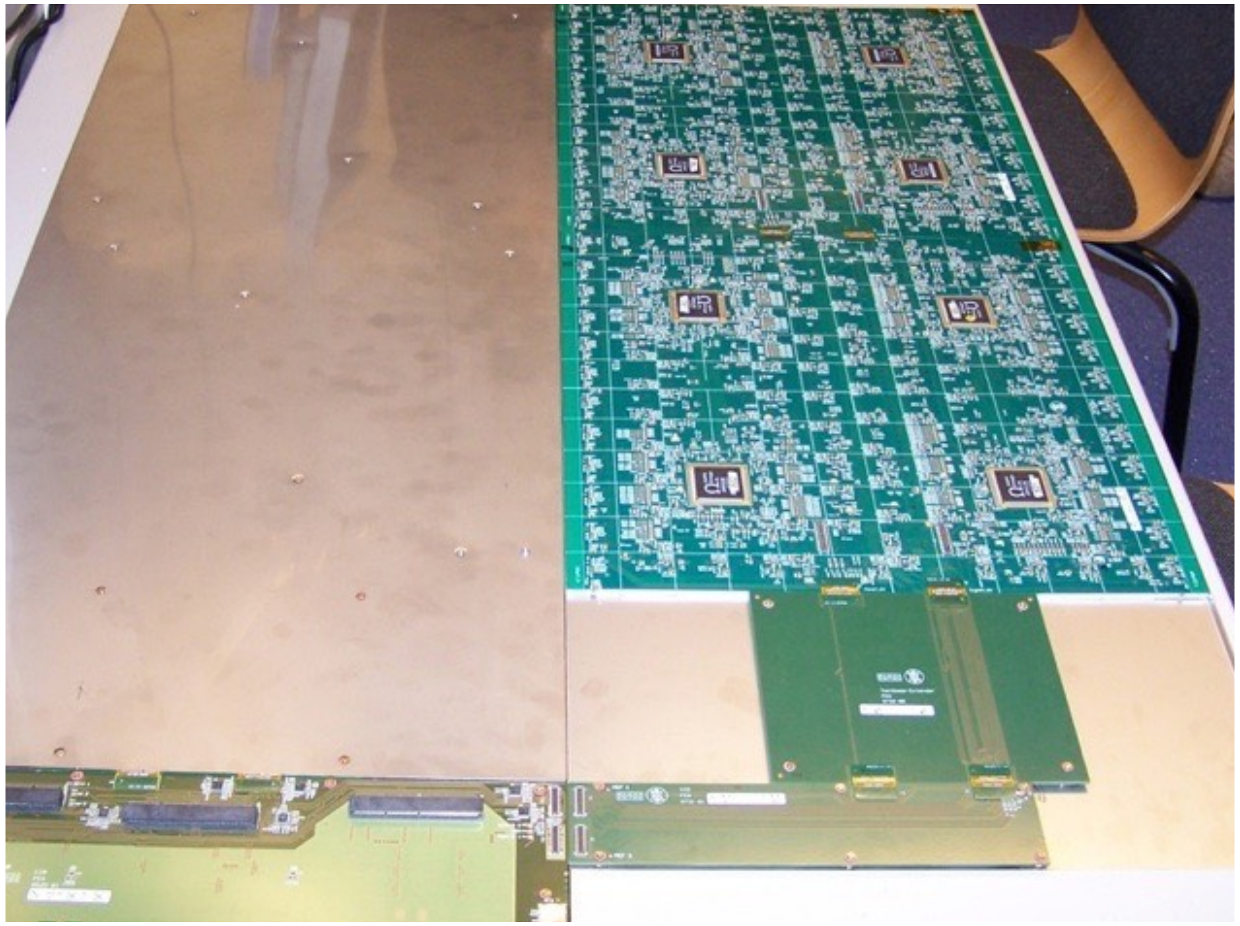




Technological Prototypes: The Analog HCAL

- Optimised for highest possible compactness - 5.4 mm non-absorber material per layer (+ 1 mm tolerance for test beam prototypes)

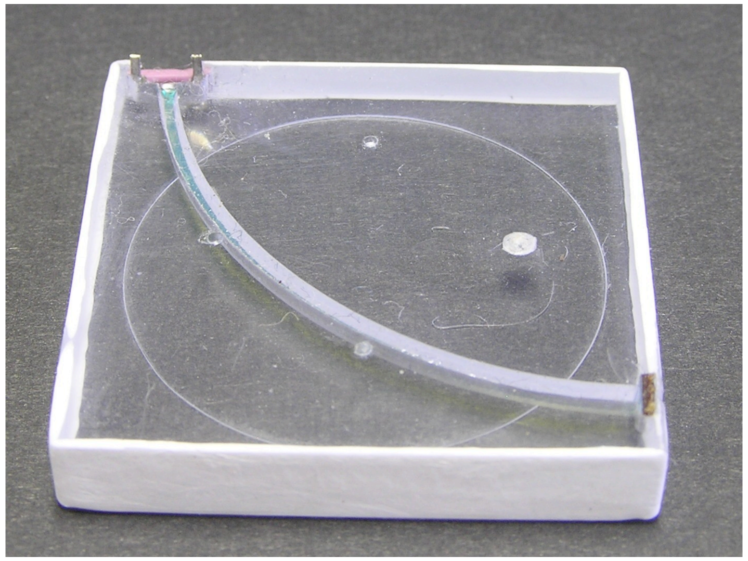




- Embedded electronics, compact mechanics

CALICE AHCAL: Key Innovation Steps

If you have 10 million scintillator tiles with SiPMs, they need to be ***simple***, ***robust*** and ***reproducible***!



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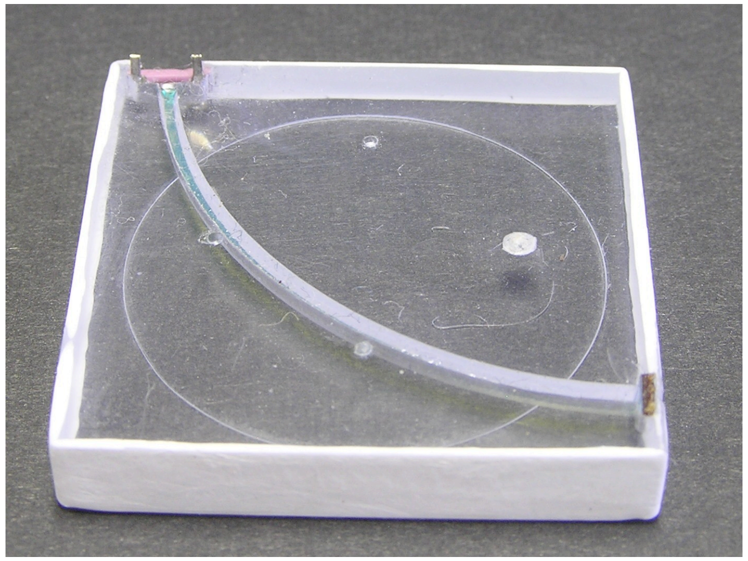
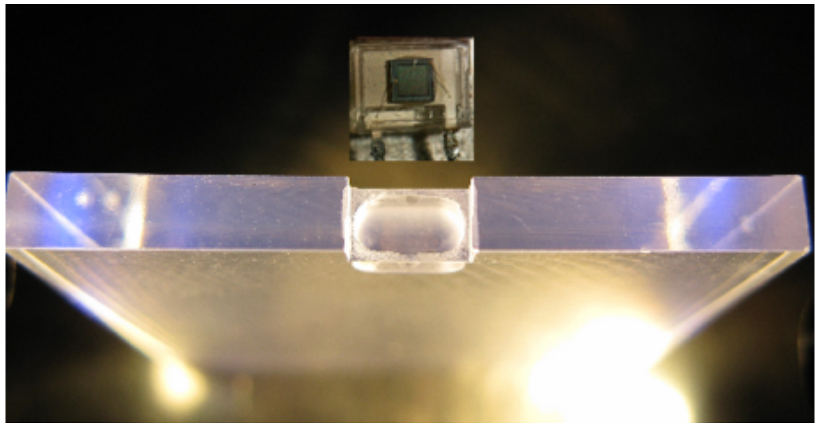
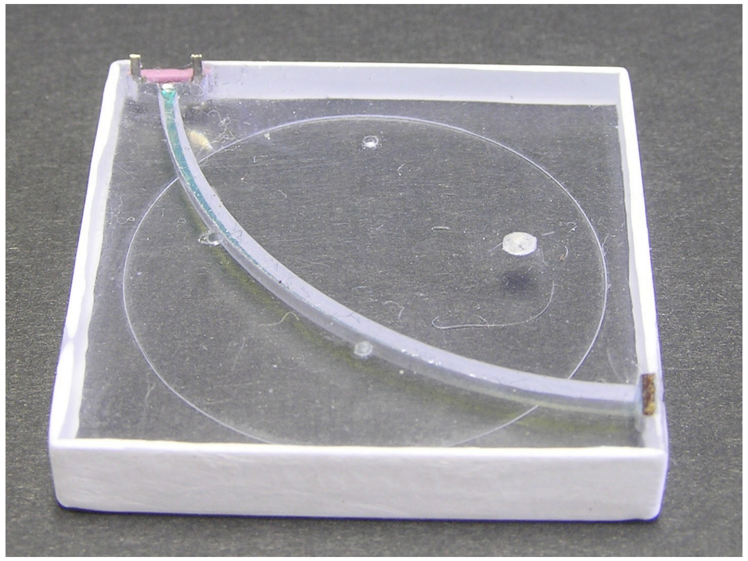




A first simplification of the scintillator tiles: Blue-sensitivity of current SiPMs enables fiberless coupling, combined with specialized tile geometries

CALICE AHCAL: Key Innovation Steps



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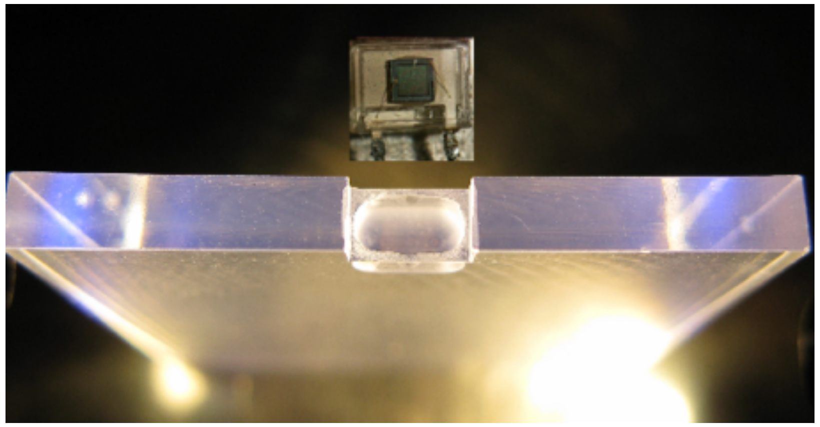

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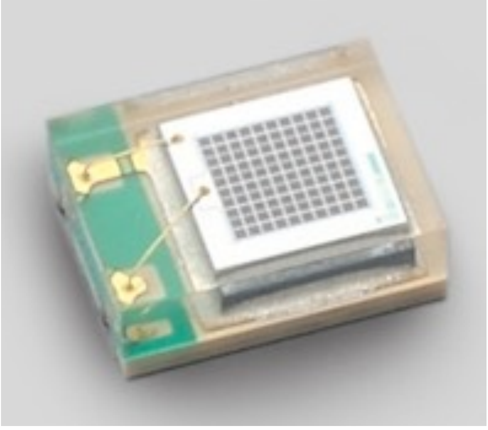

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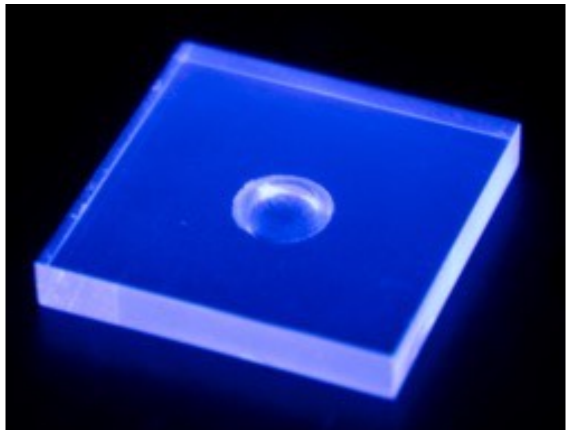
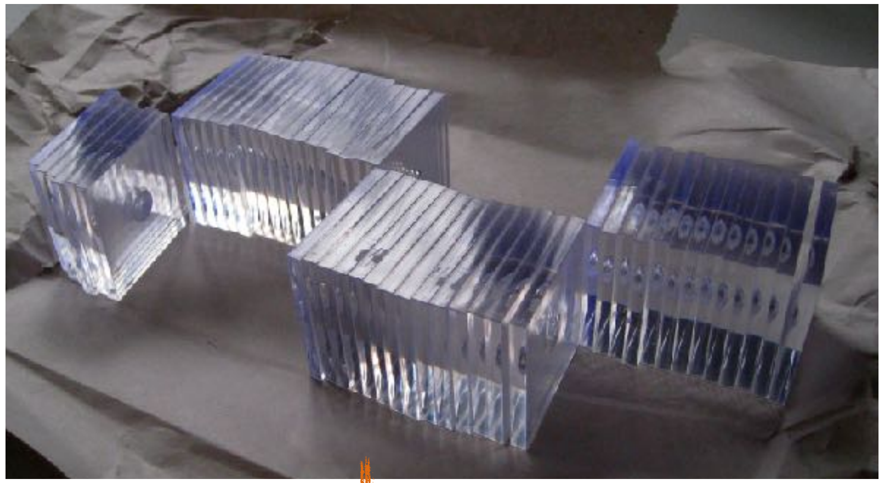
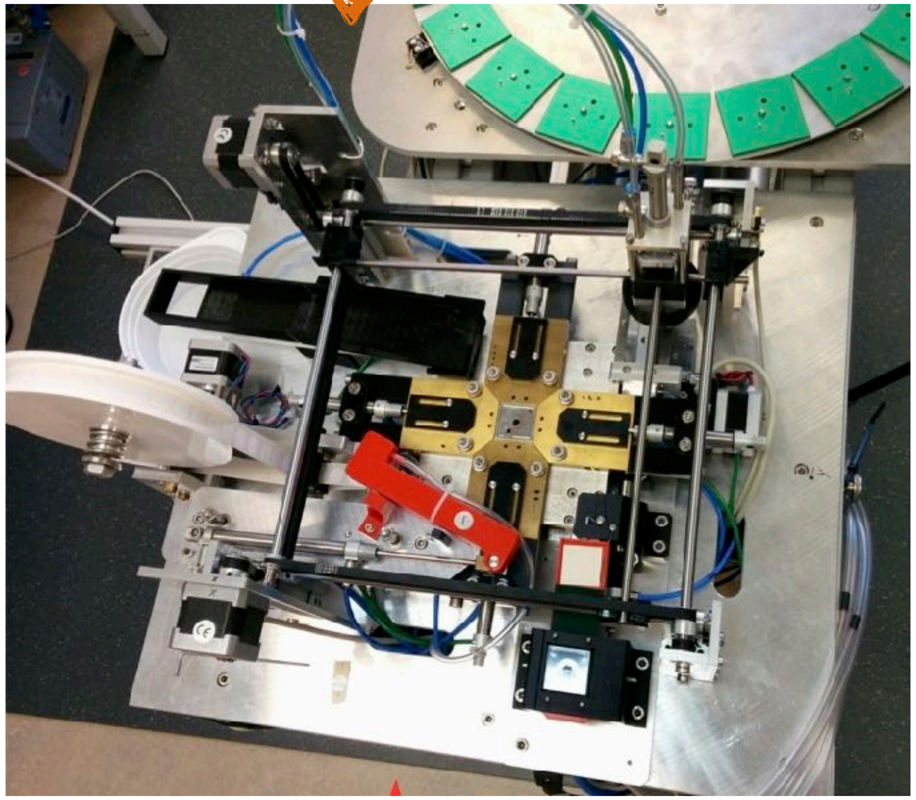


SiPMs in surface-mount packages for pick-and-place machines, together with fiberless tiles, pave the way towards automatic assembly of active layers

CALICE AHCAL: Building the Next Prototype

- Automatic wrapping of scintillator tiles





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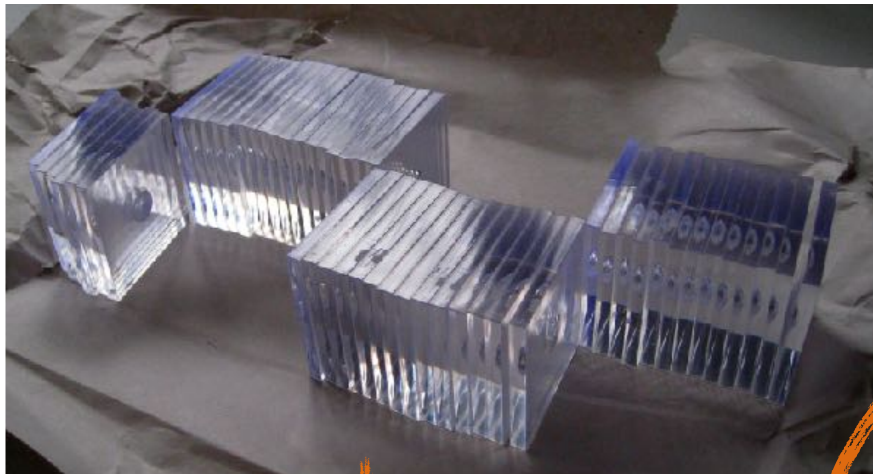

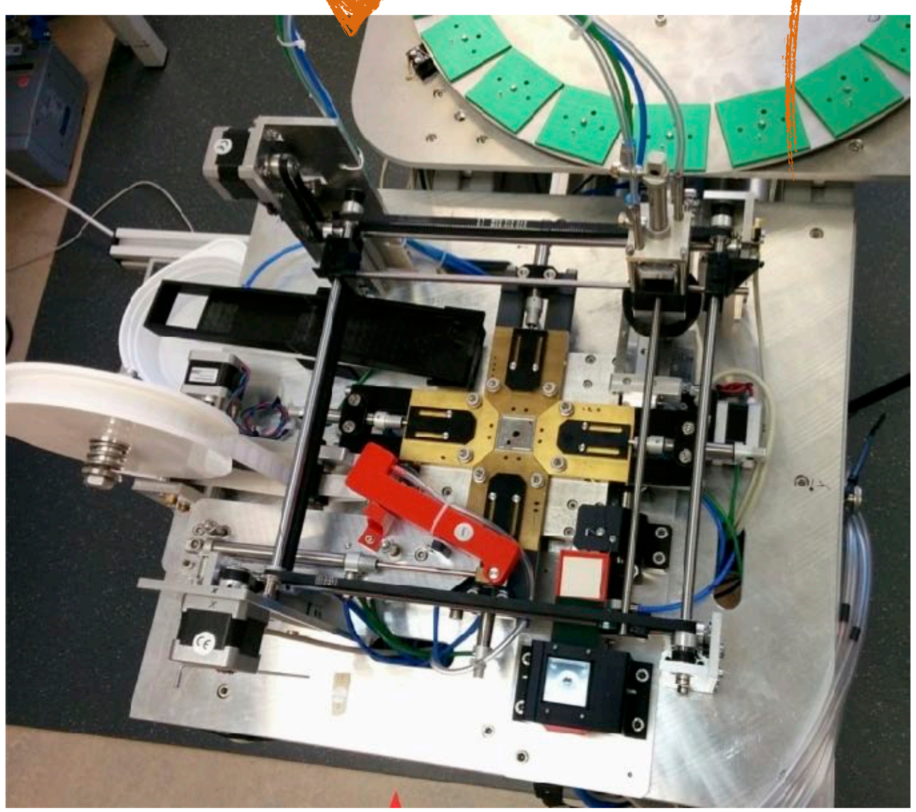

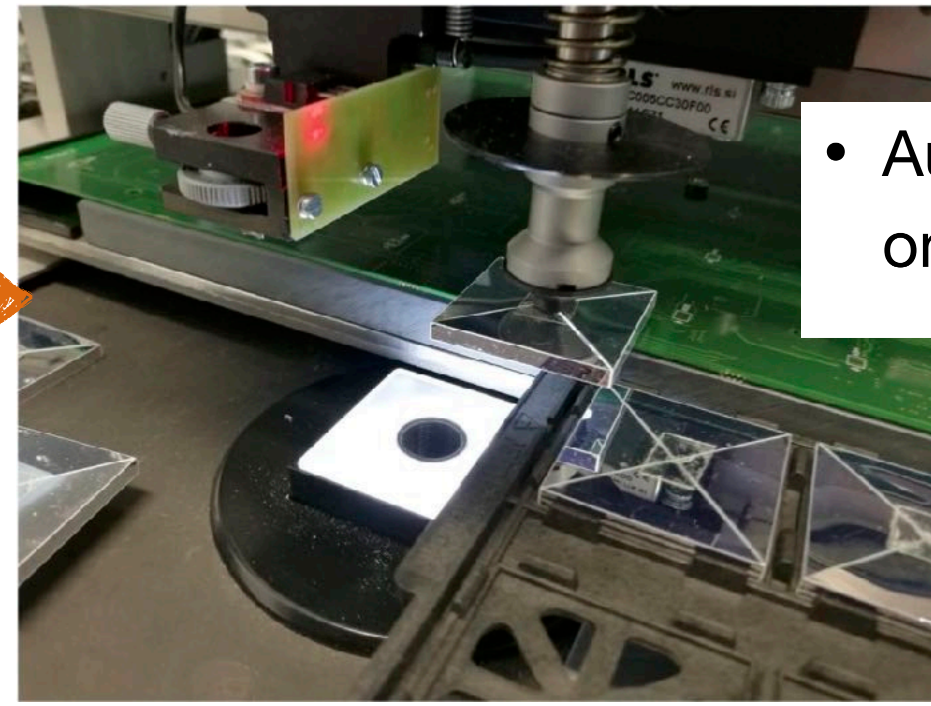

- Automatic placement on electronics boards

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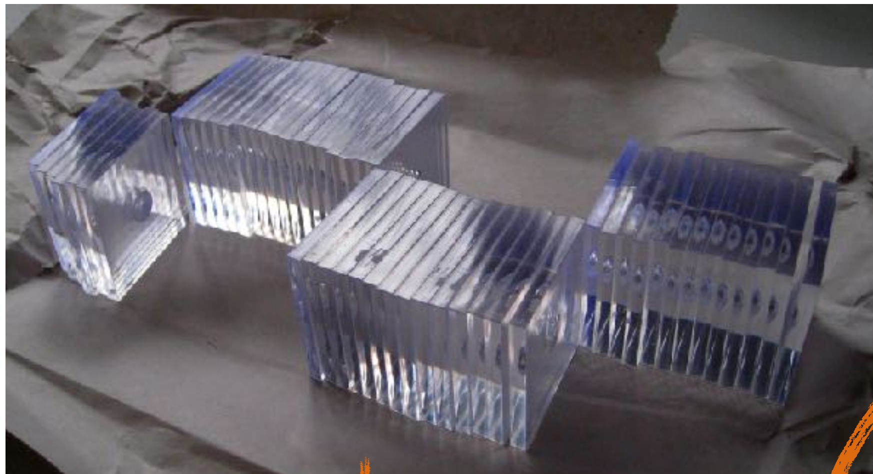
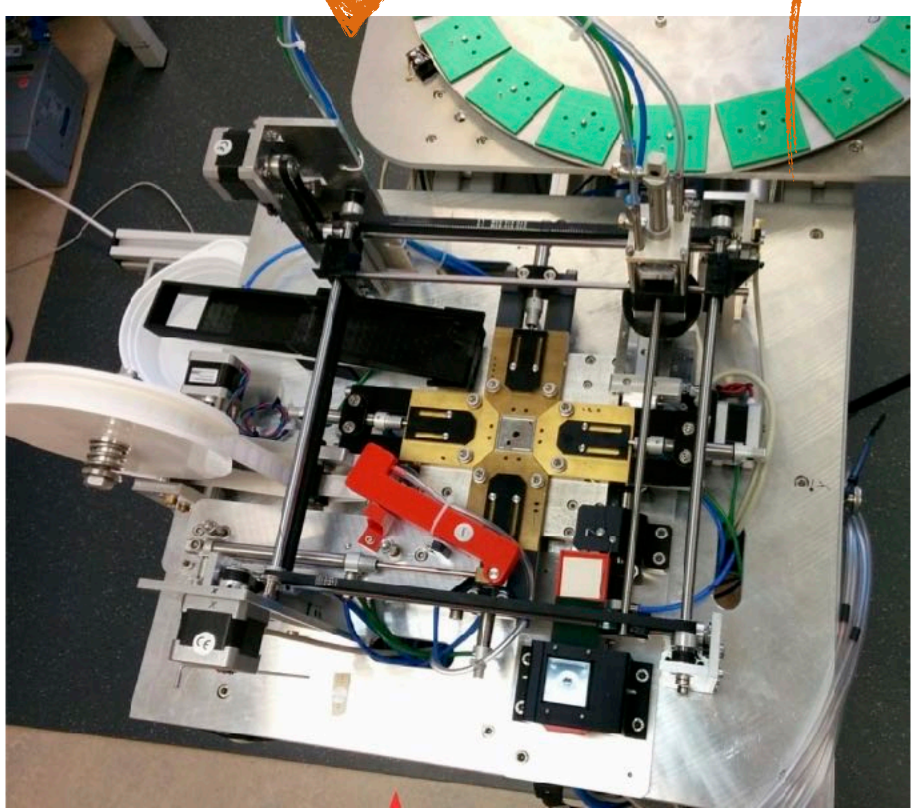
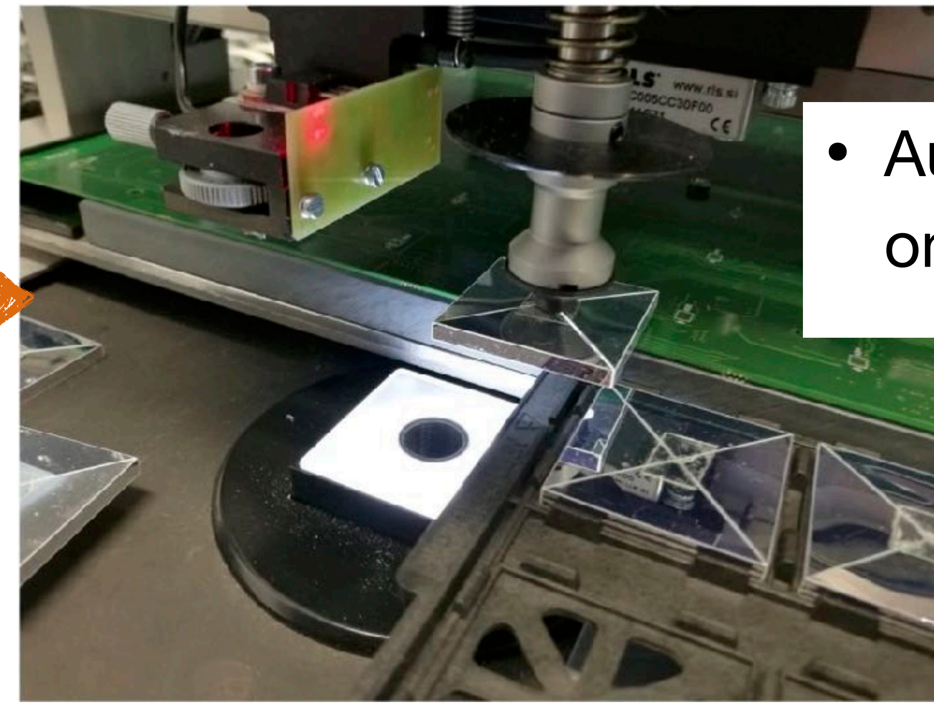


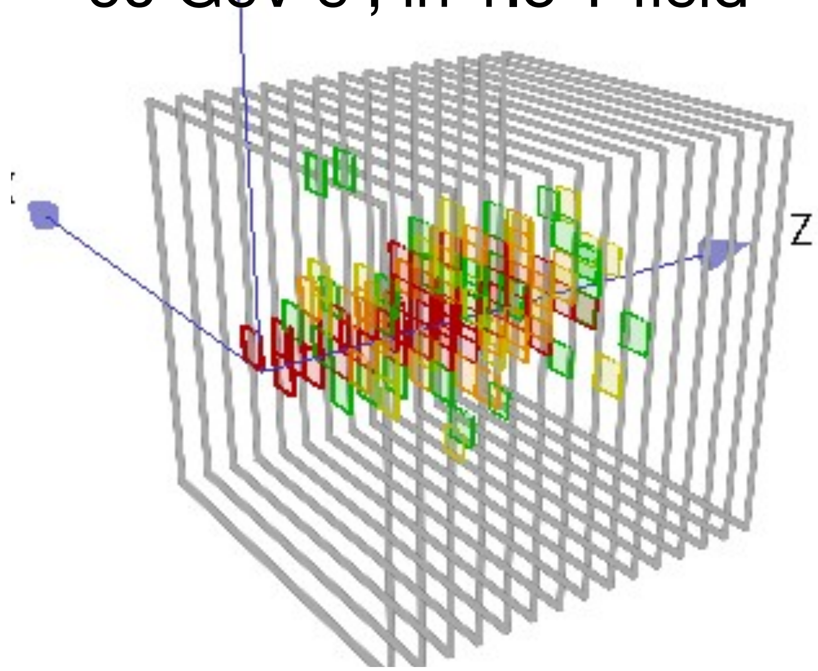




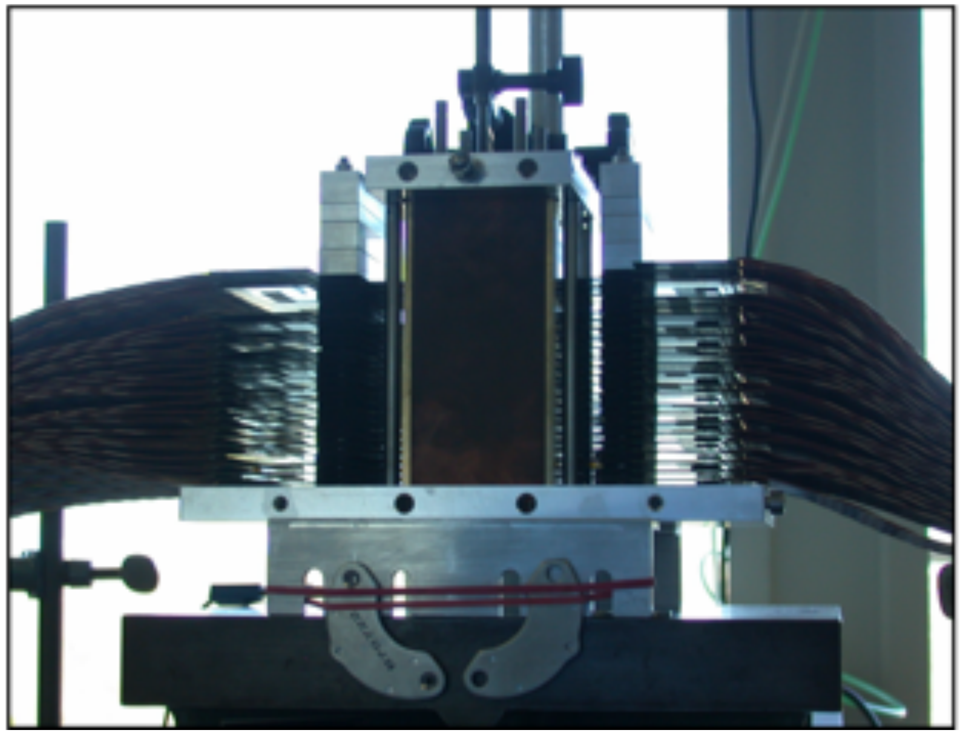
- Automatic placement on electronics boards

first test with smaller prototype successful

60 GeV e$^-$, in 1.5 T field

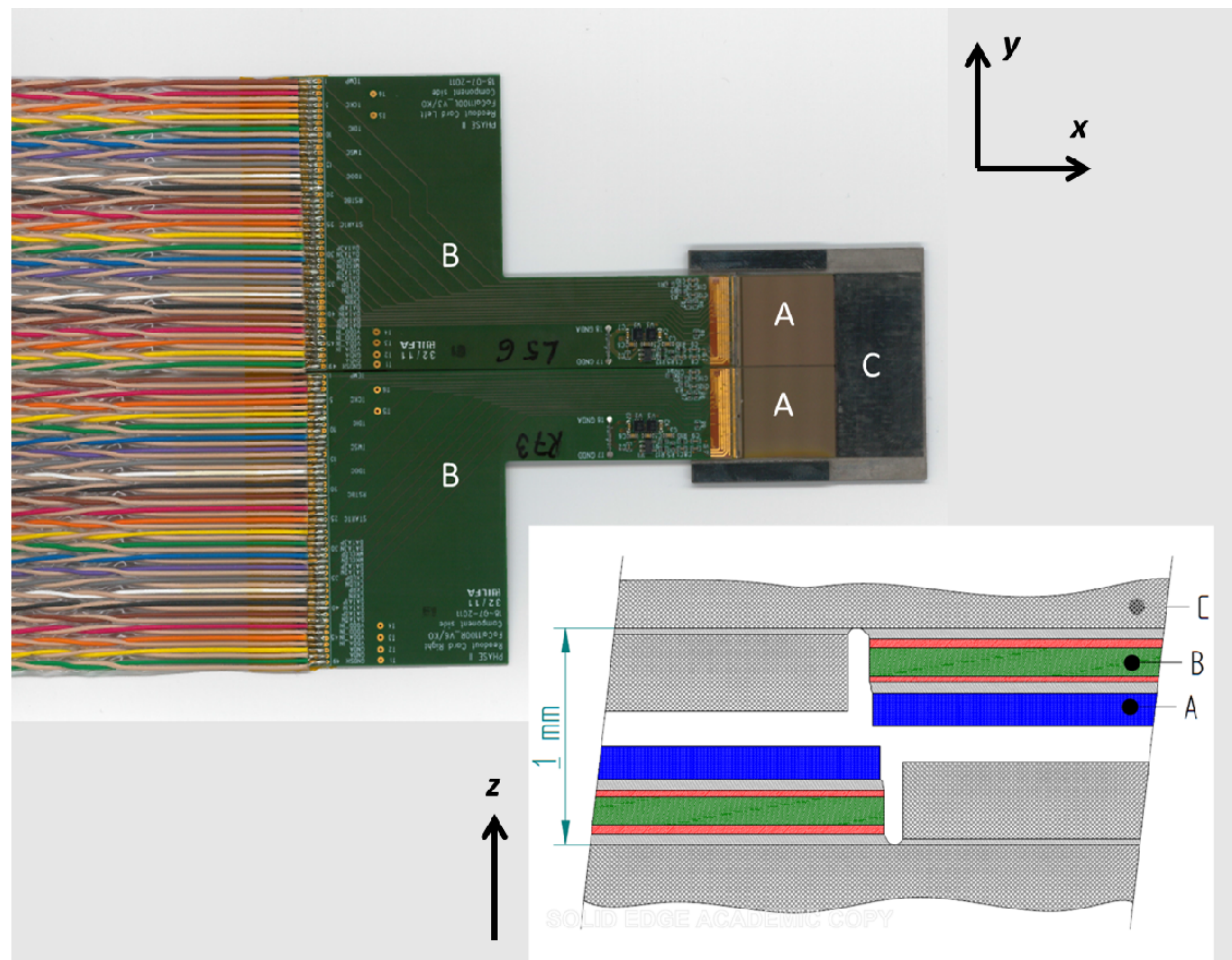


Pushing Granularity: MAPS ECAL



- 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)



A) MIMOSA sensor, 30 μm pixel pitch

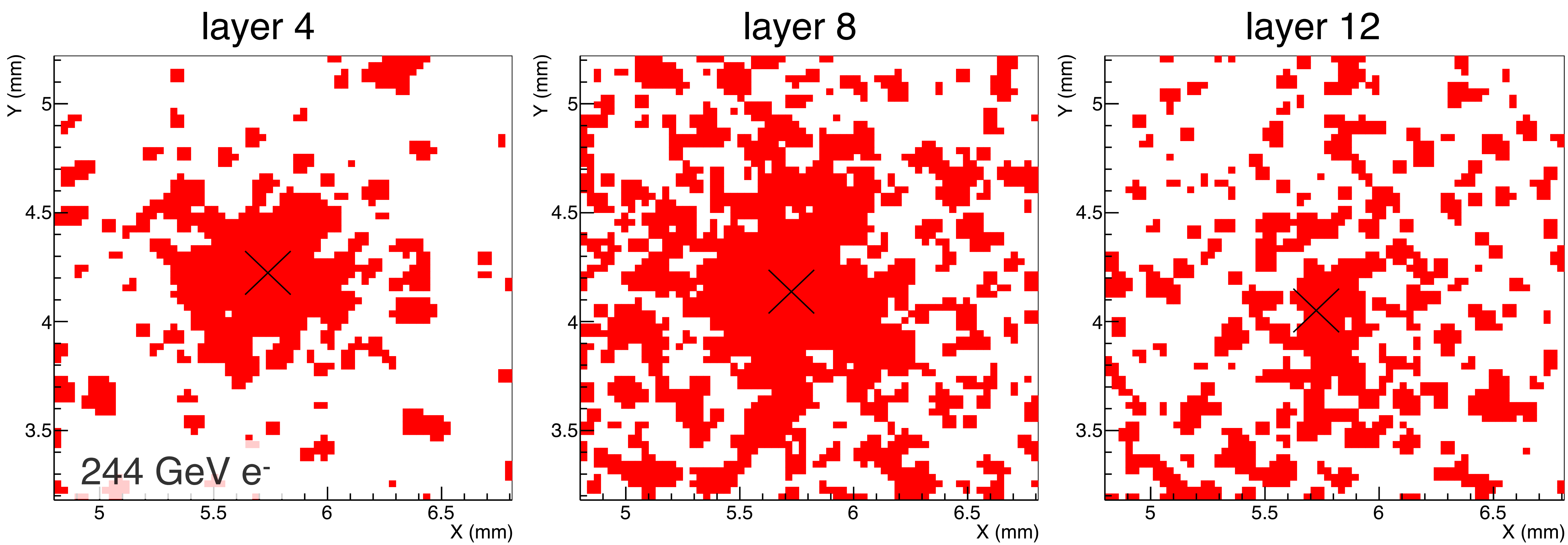
B) PCB

C) Tungsten (1.5 mm in half layer)

total thickness ~ 24 X_0

Pushing Granularity: MAPS ECAL

- A look into electromagnetic showers with unprecedented detail
- Slow readout - and enormous data volume
  - Realistic solution in ALICE: A combination of pixel and pad layers



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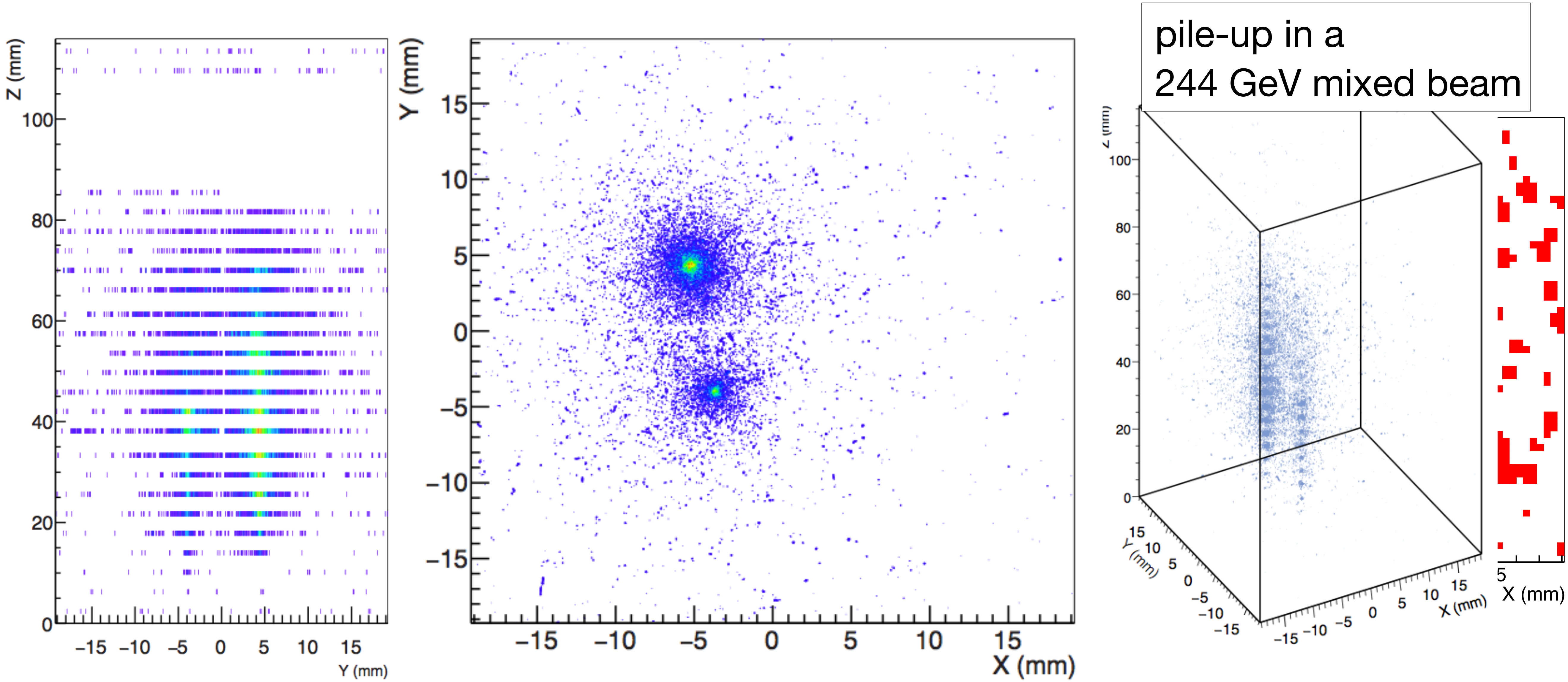
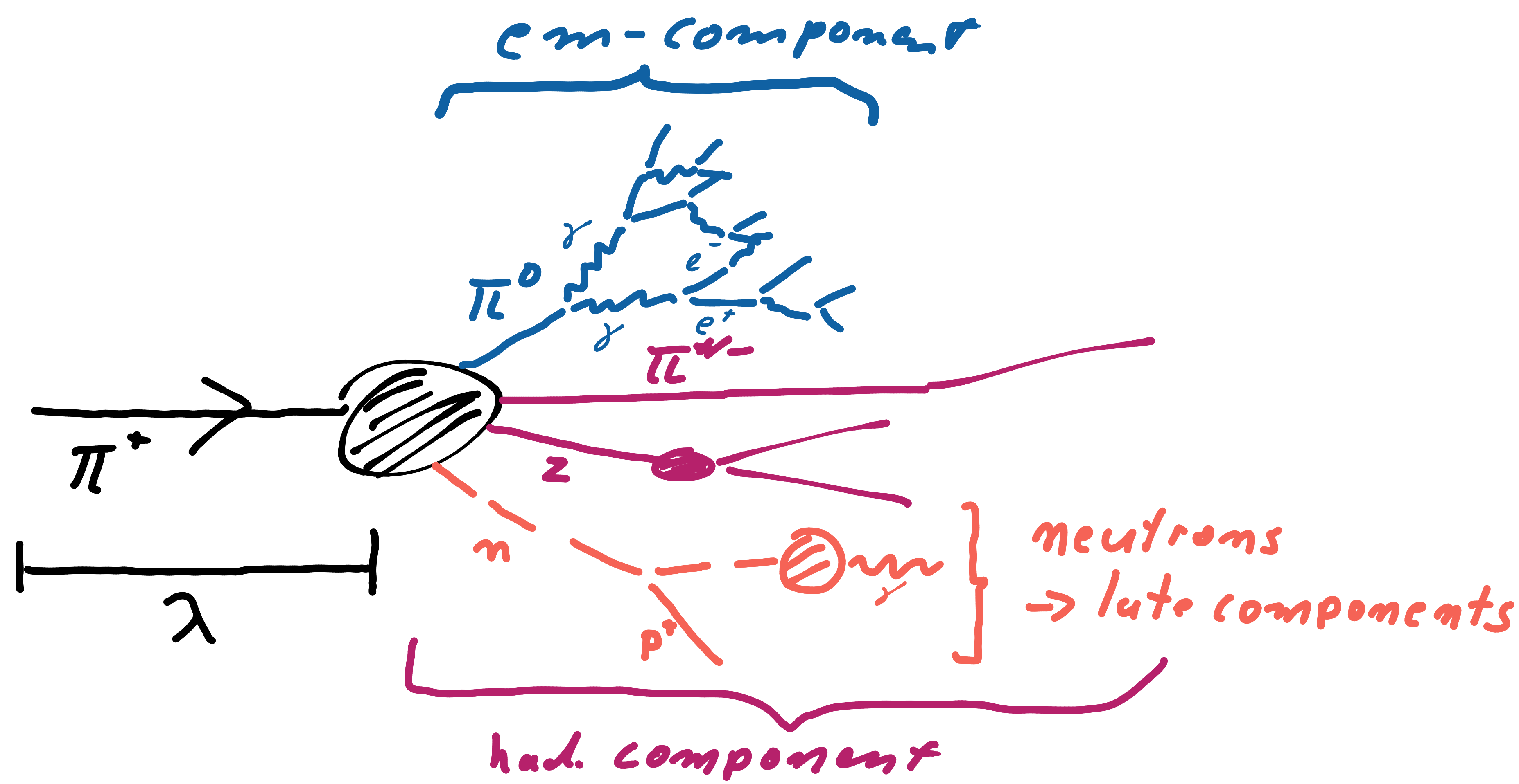


Performance: Energy Reconstruction

… also beyond prototypes

Intricacies of Hadronic Energy Reconstruction

- Still a key performance criterion: energy resolution
- For hadrons: challenges imposed by shower physics



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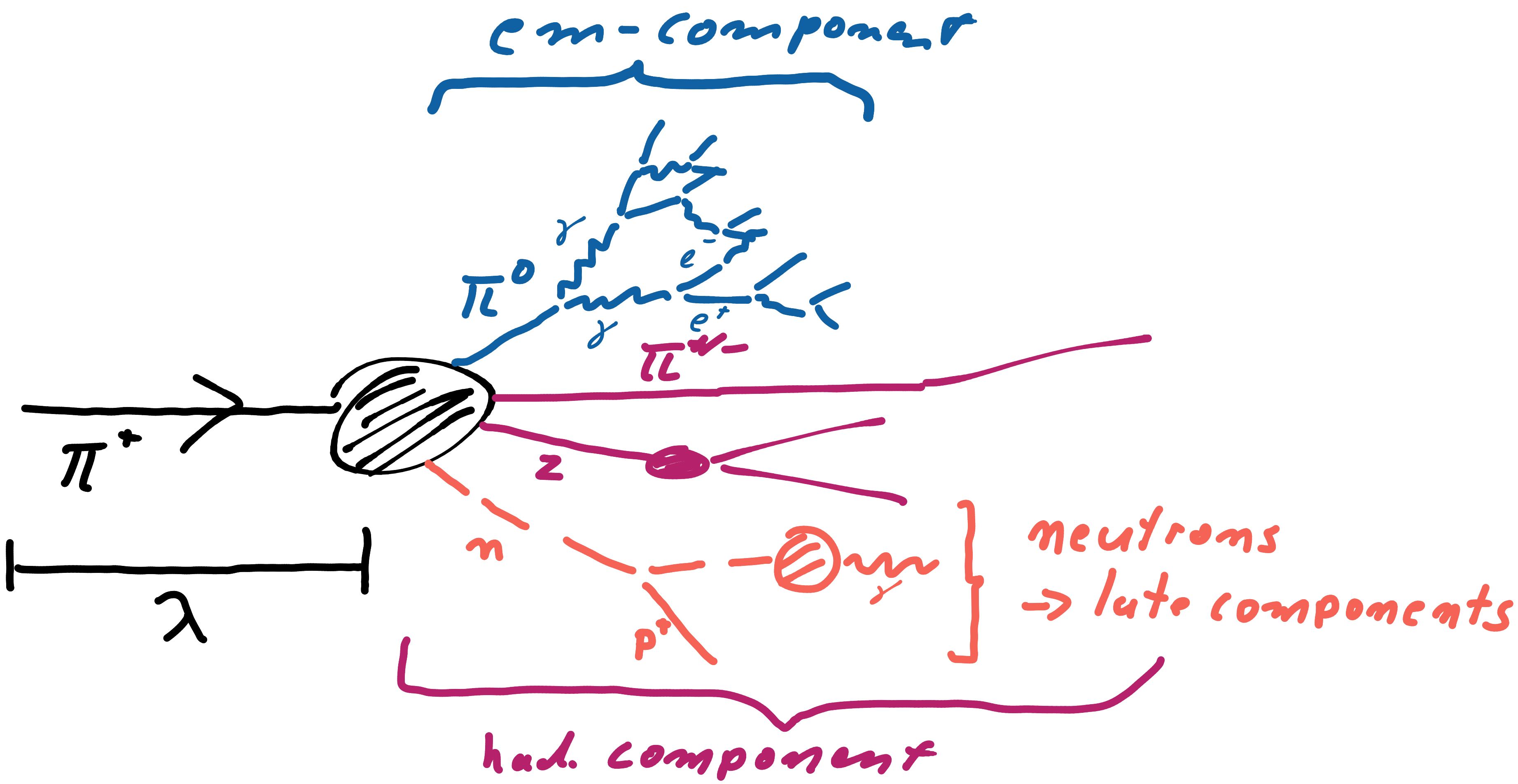
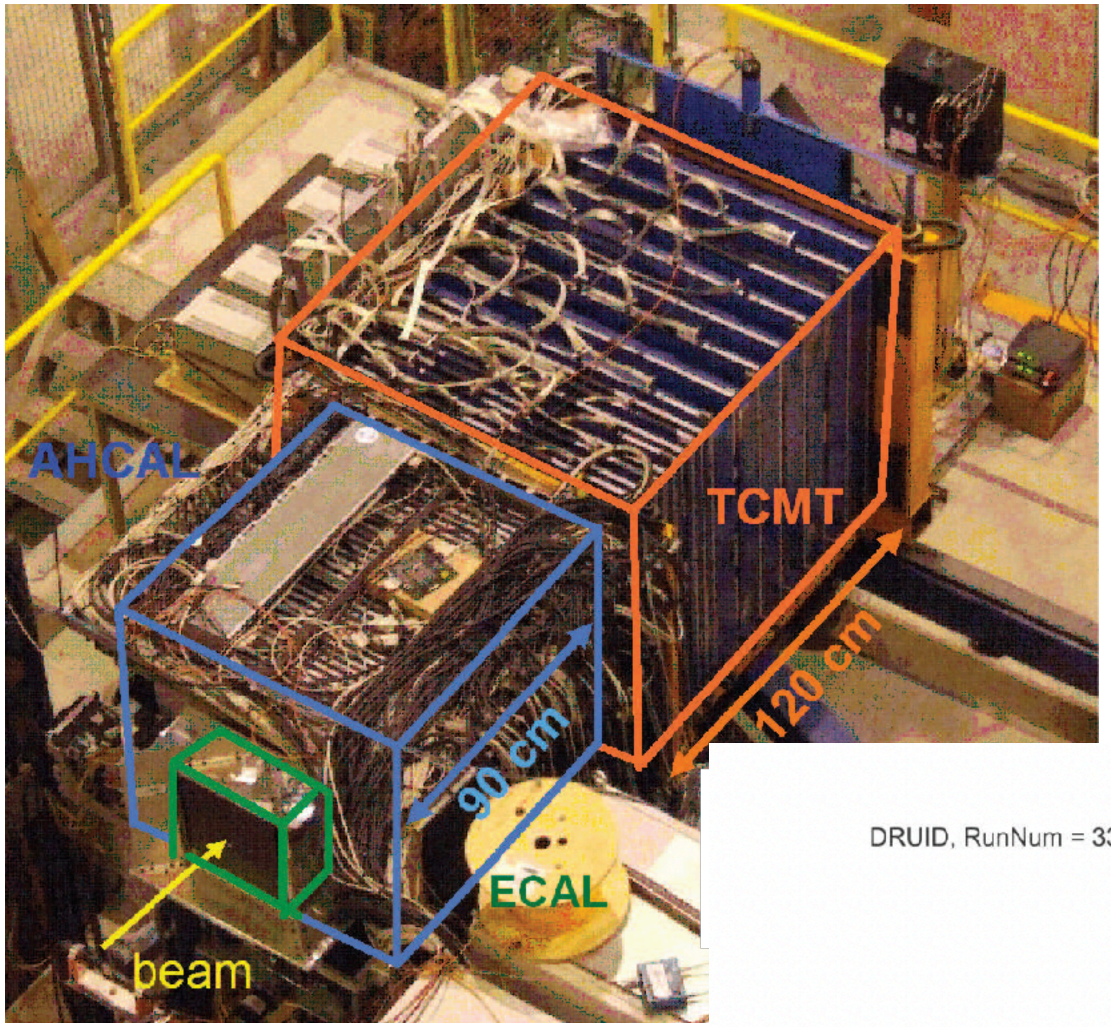
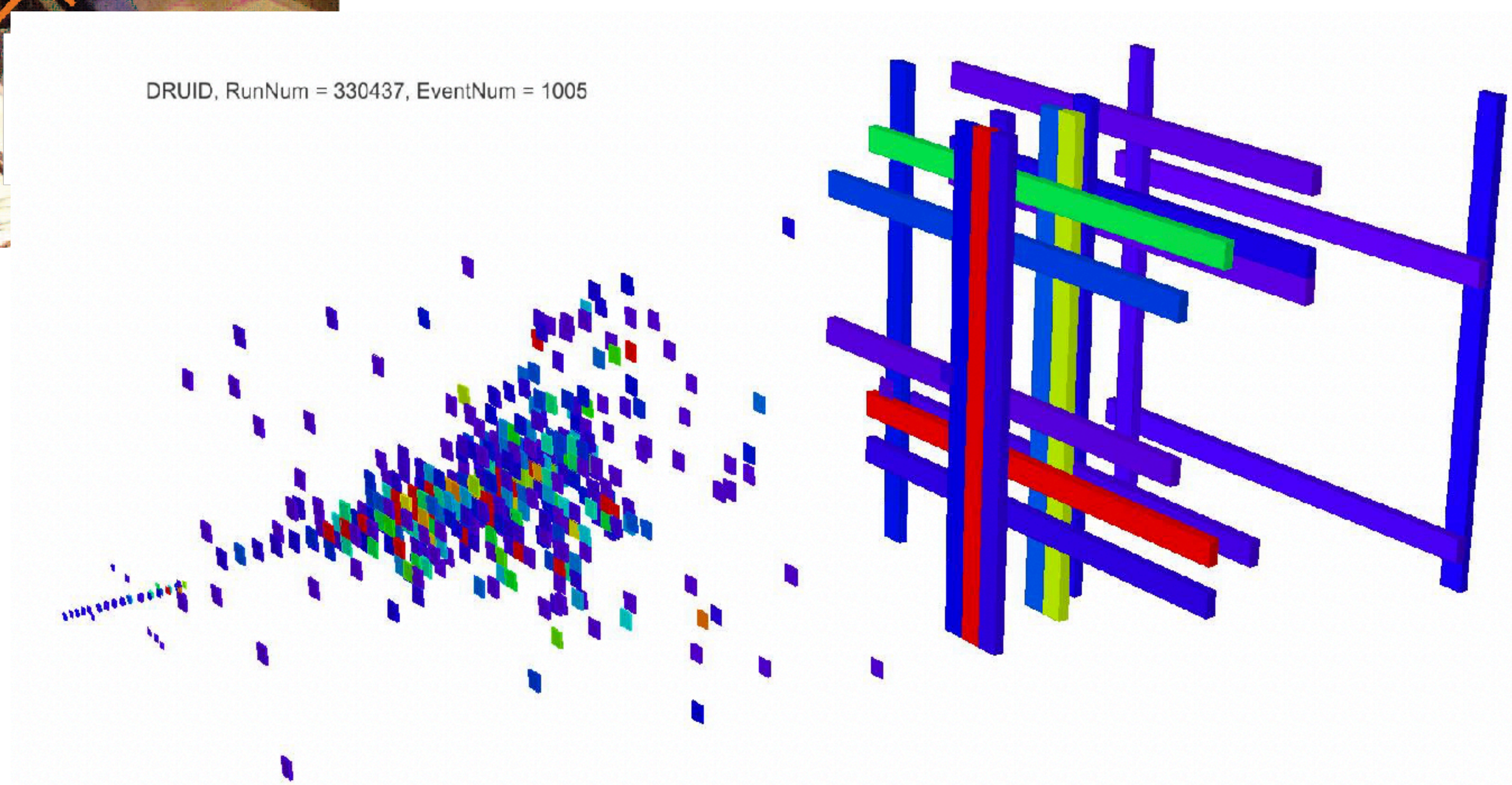


➫ Granularity finer than typical shower structure can be exploited to improve the energy resolution

Energy Reconstruction in a Combined System



- Studying energy resolution in a "real-world" setting: A combined system of SiW ECAL, Scintillator/FE HCAL, Tail Catcher
- Exploiting granularity: Local energy density can be used to improve energy resolution with software compensation methods



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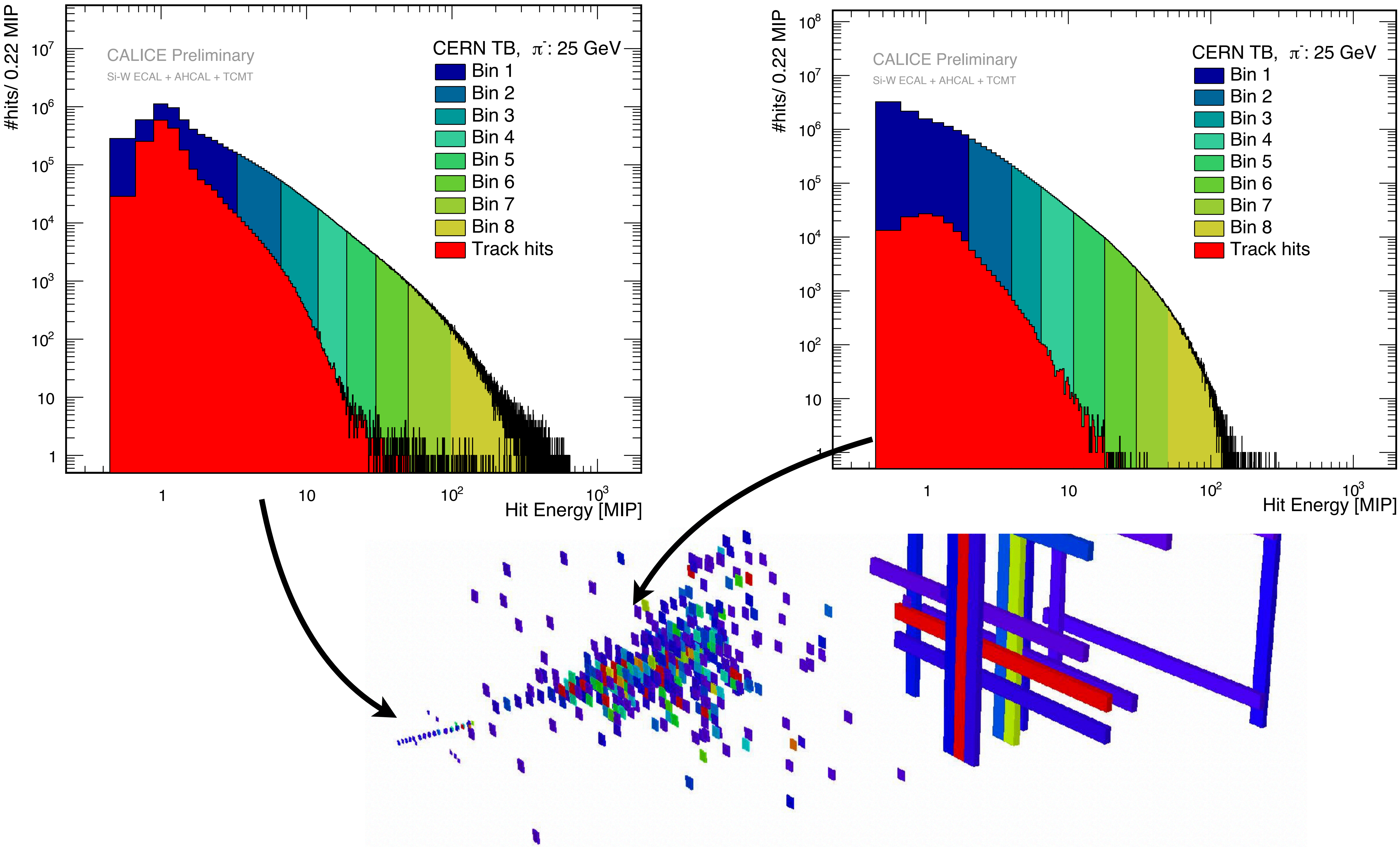
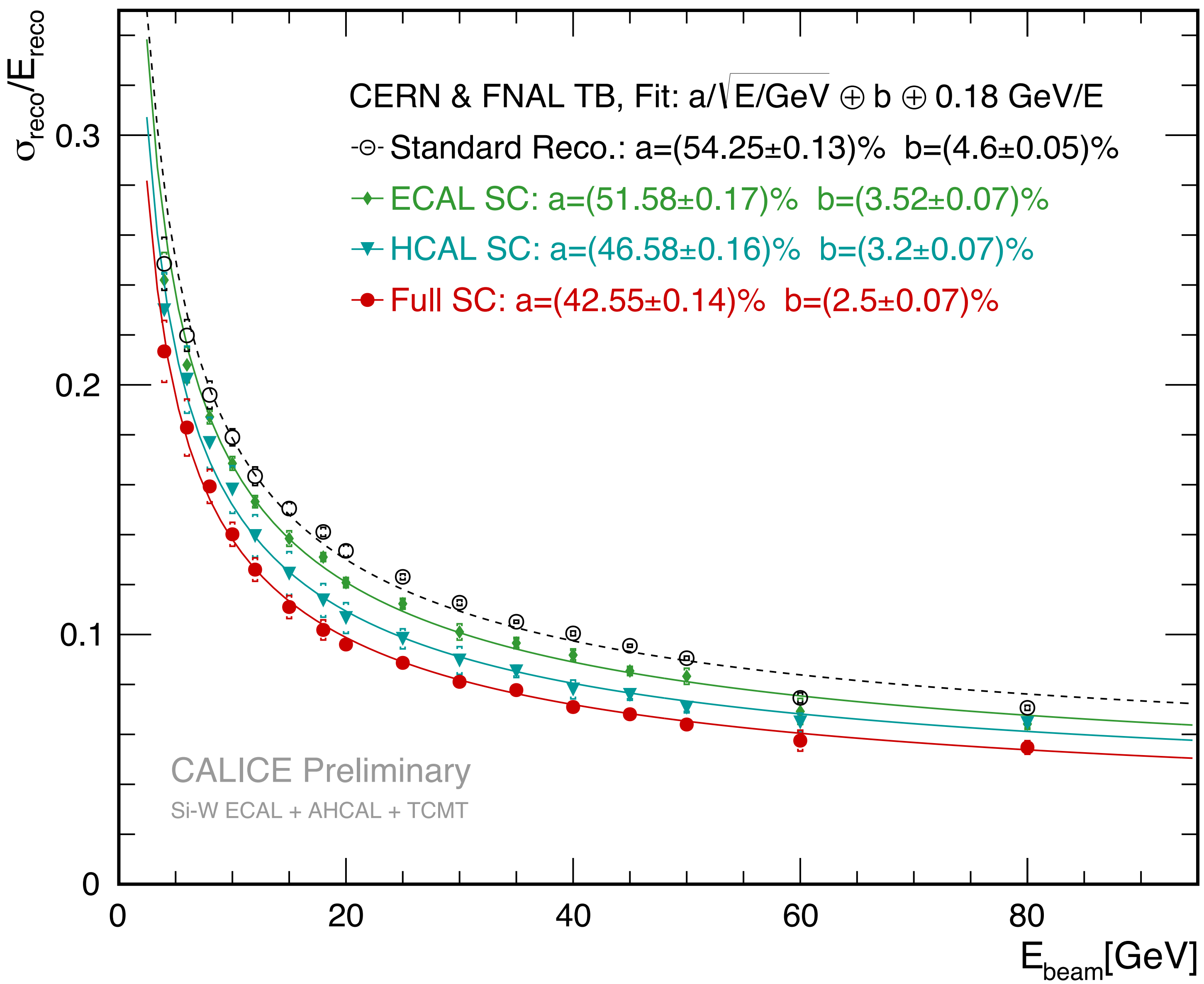


Software Compensation in a Combined System

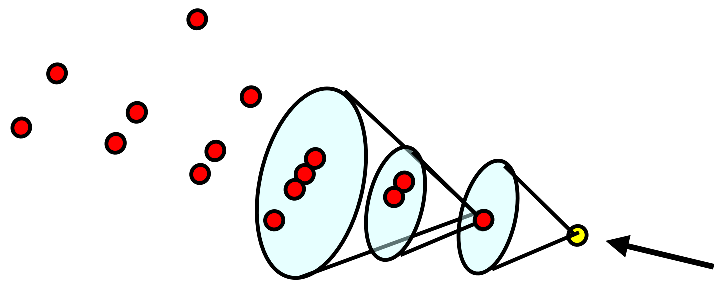
- Local software compensation: each "hit" is weighted according to its amplitude
  - weights are energy dependent: Needs first estimate of cluster energy determined w/o SC methods

JINST 7 P09017 (2009)



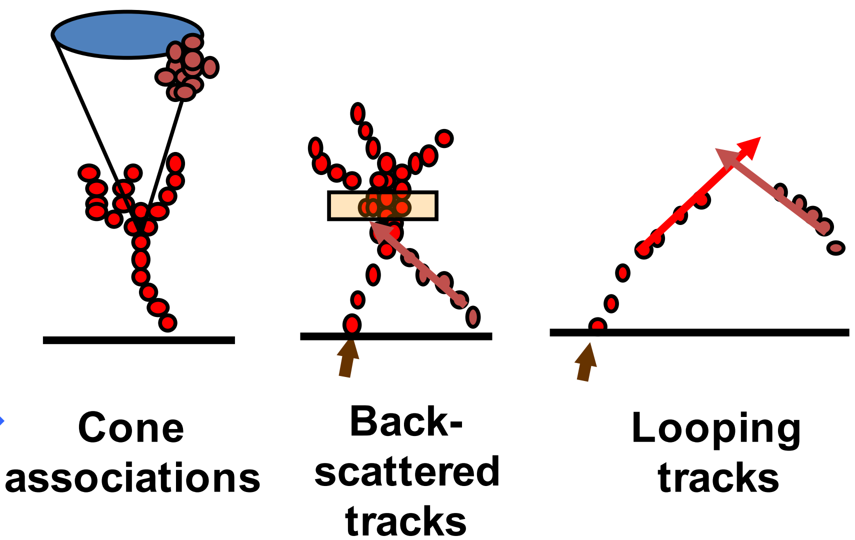
- New study with full detector system (SiW ECAL + AHCAL + TCMT)
  - SC in ECAL alone up to 8% improvement
  - SC in HCAL alone up to 23% improvement
  - Full SC up to 30% improvement, for a stochastic term of 42.5% and a constant term of 2.5%

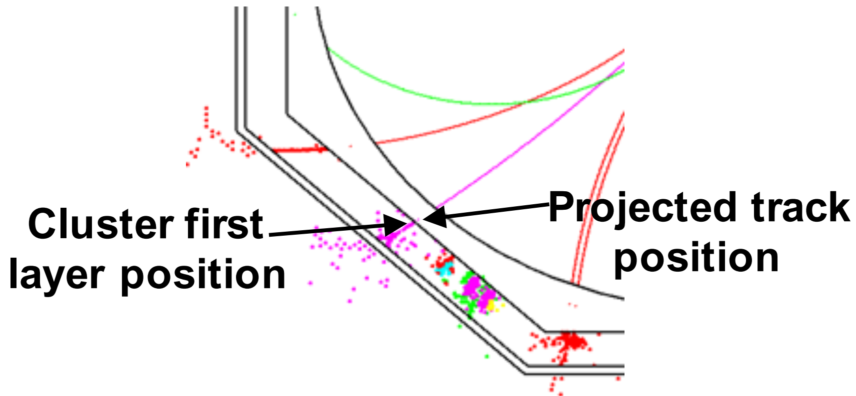
Connecting Prototypes and PFA



ConeClustering Algorithm

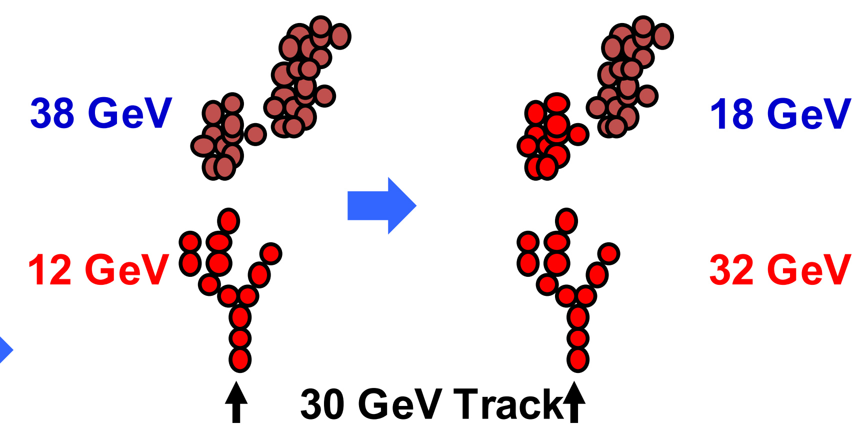
Topological Association Algorithms

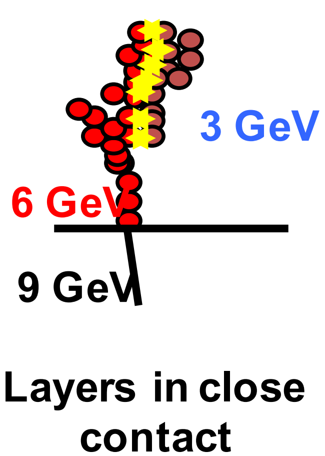


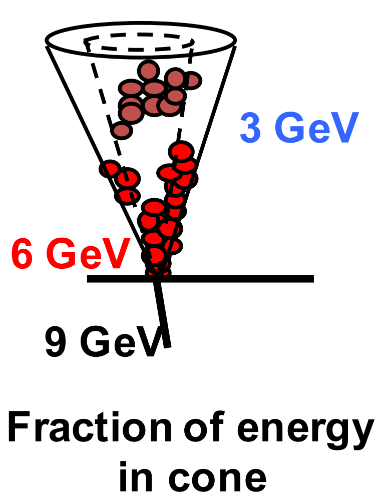


Track-Cluster Association Algorithms

Reclustering Algorithms

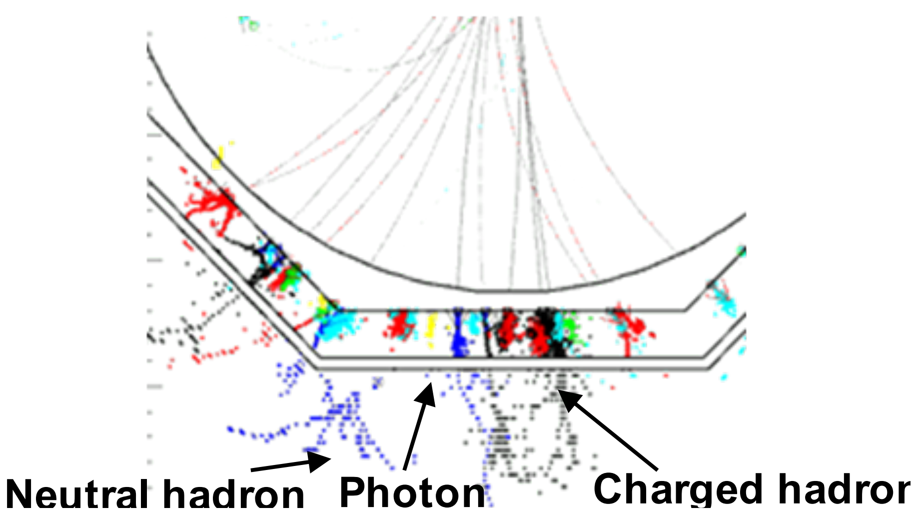




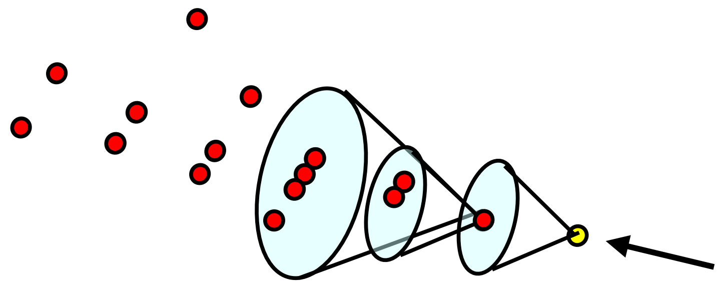


Fragment Removal Algorithms

PFO Construction Algorithms



Connecting Prototypes and PFA



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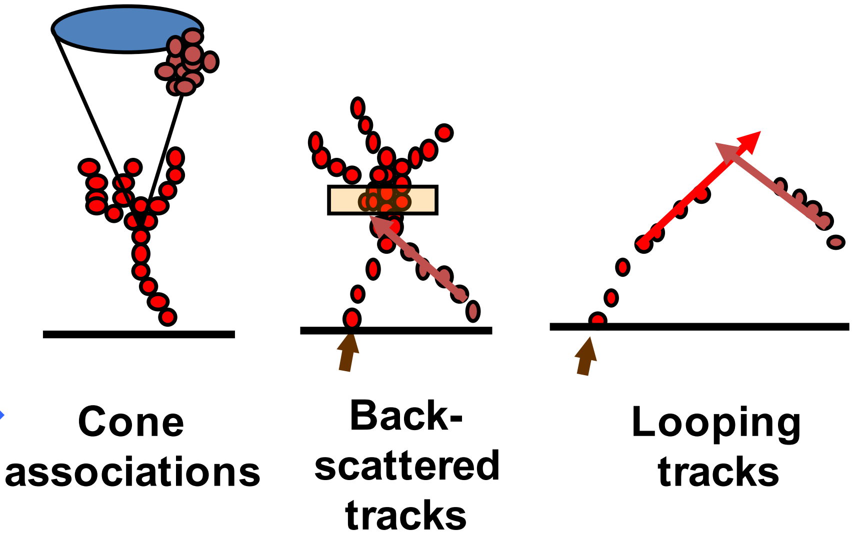

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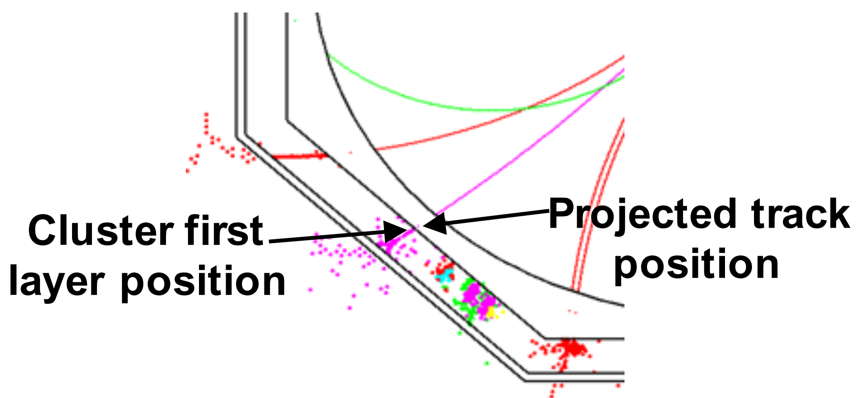

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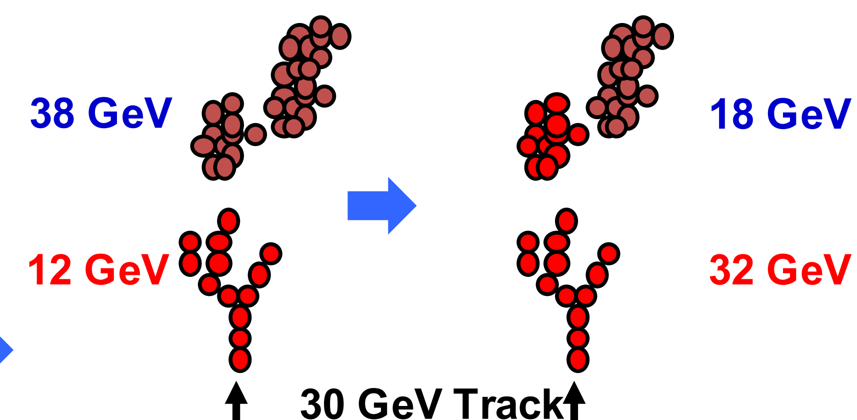
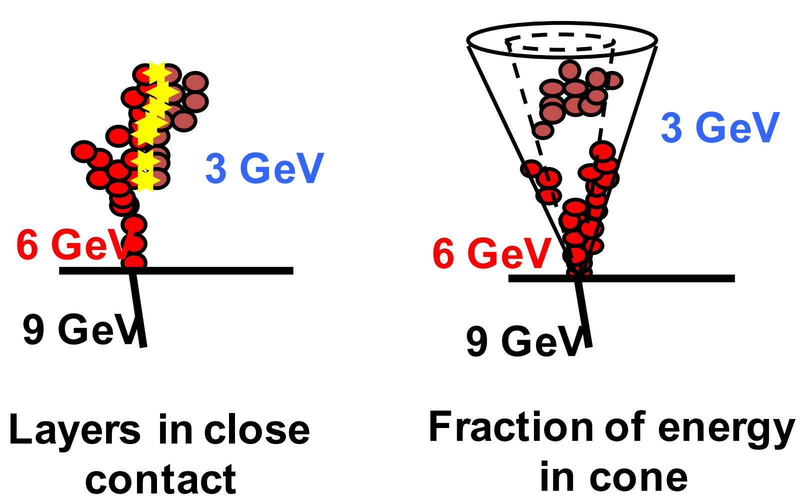


Energy resolution relevant

Fragment Removal Algorithms



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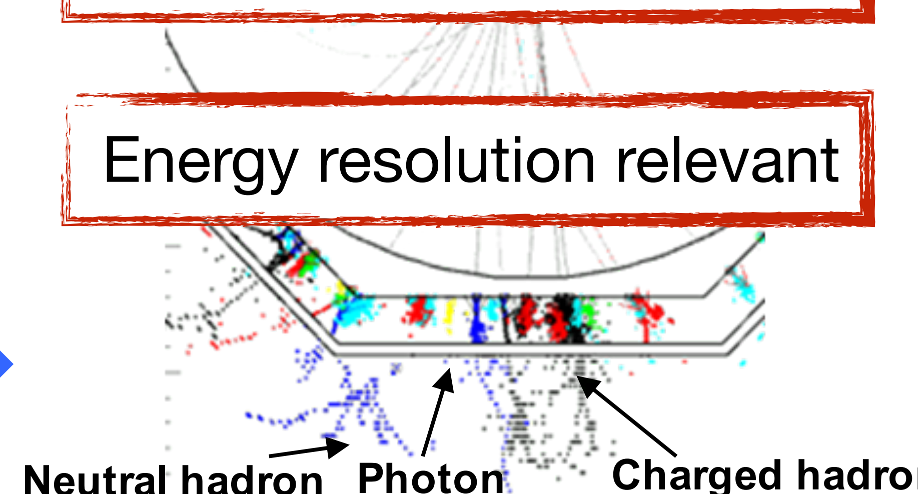
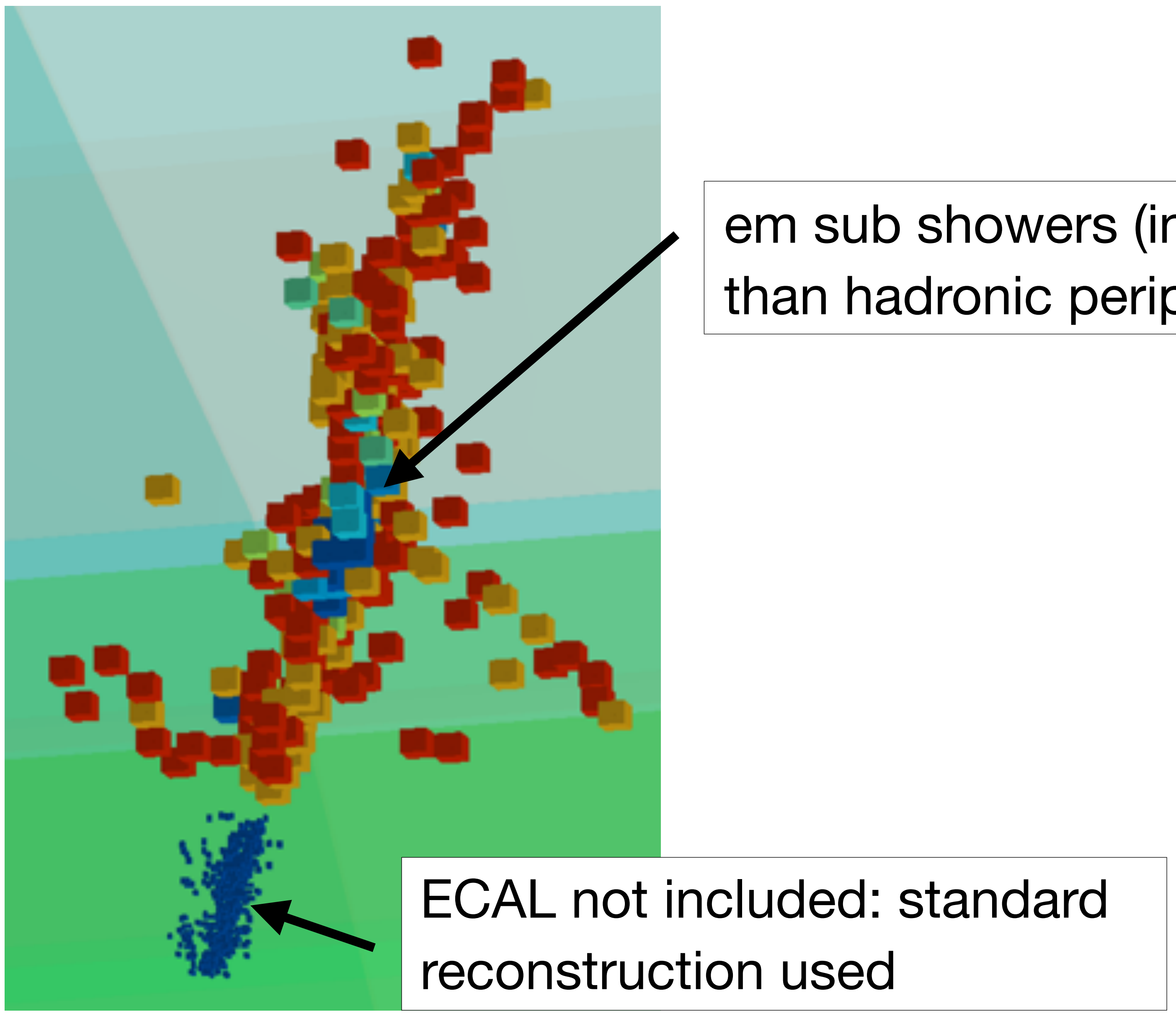


Connecting Prototypes and PFA

- Integrated algorithm developed on CALICE AHCAL prototype data into Particle Flow reconstruction used for physics study
  - Simulation validated against test beam data



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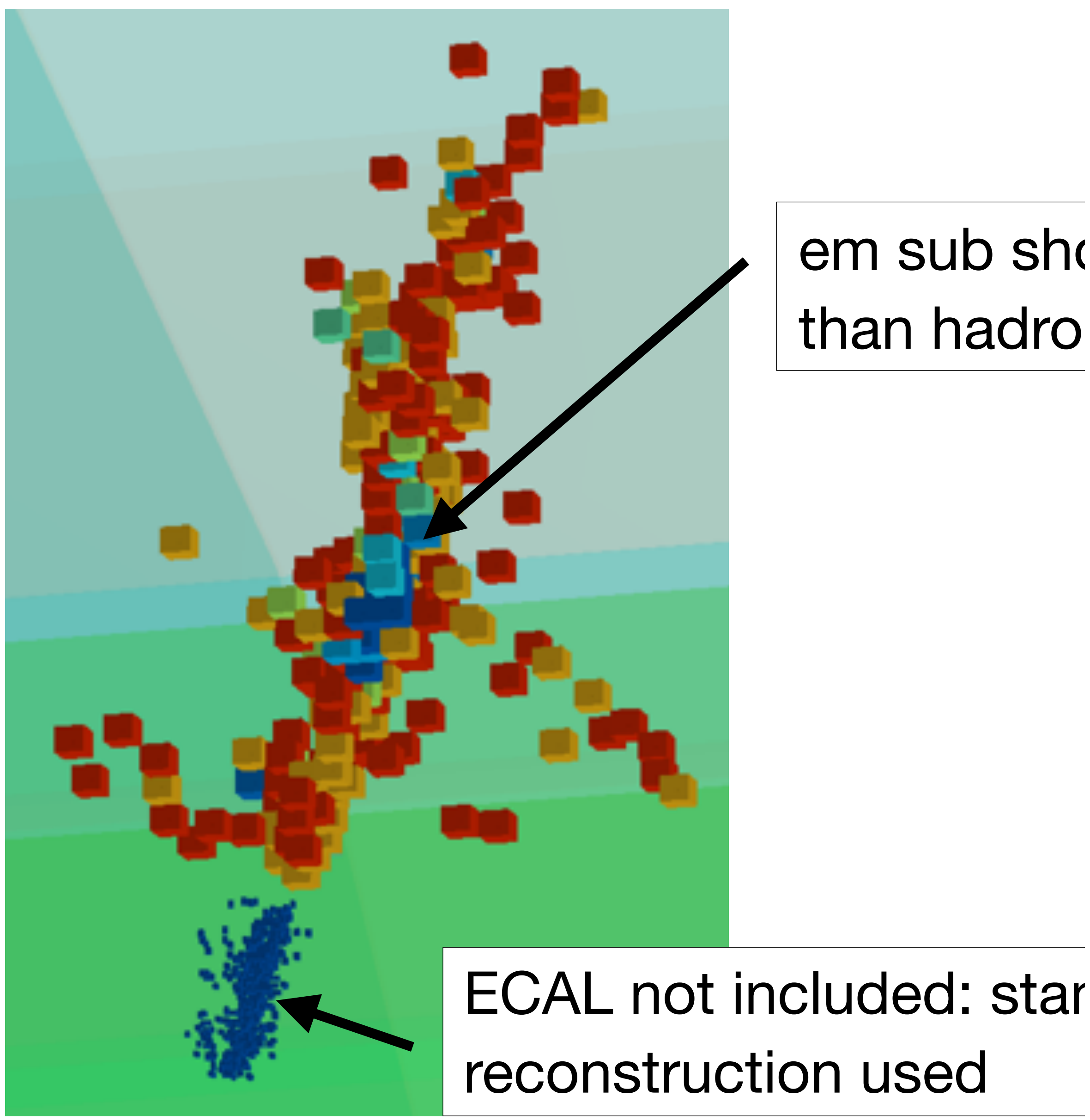
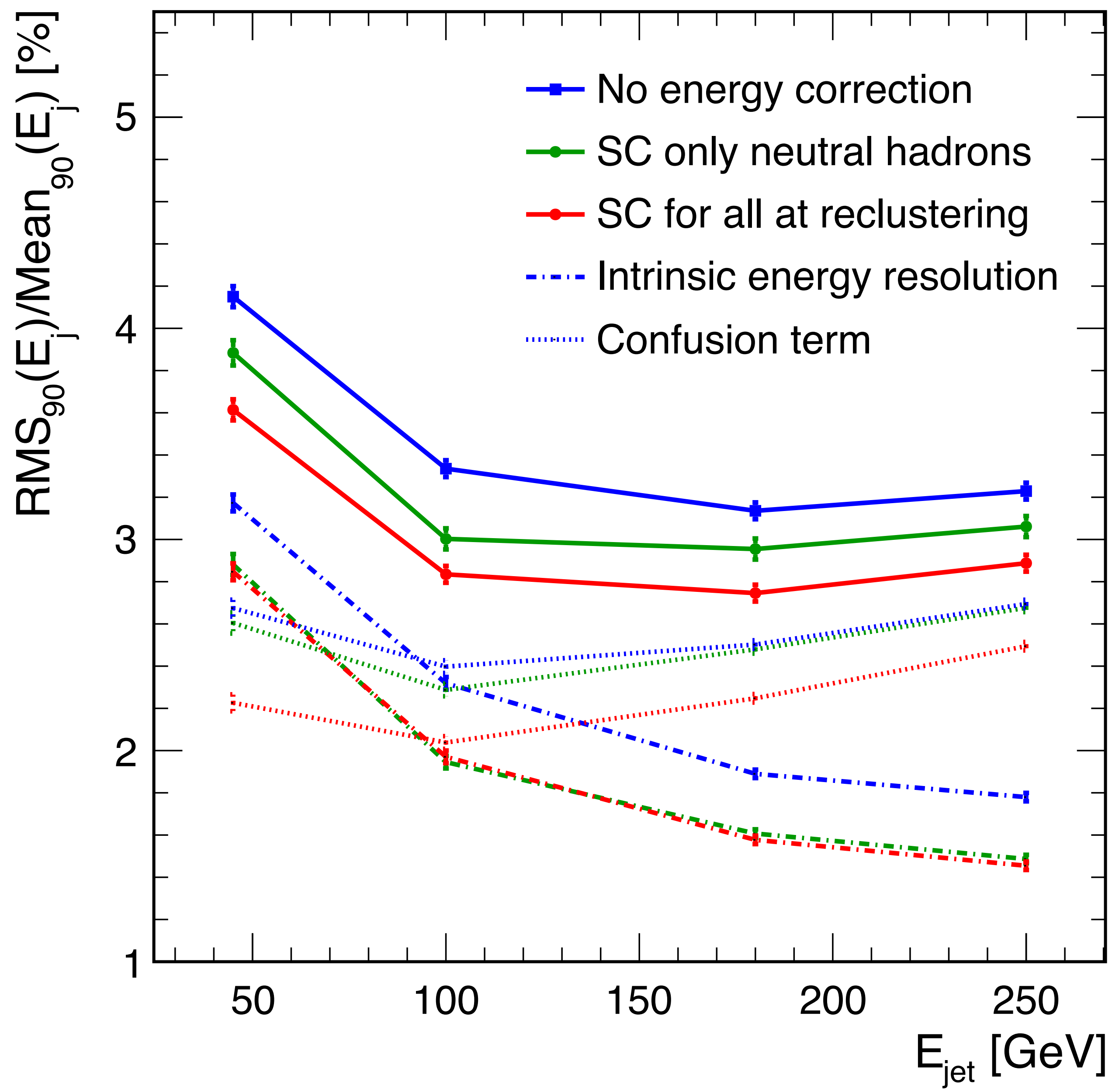




EPJ C77, 698 (2017)

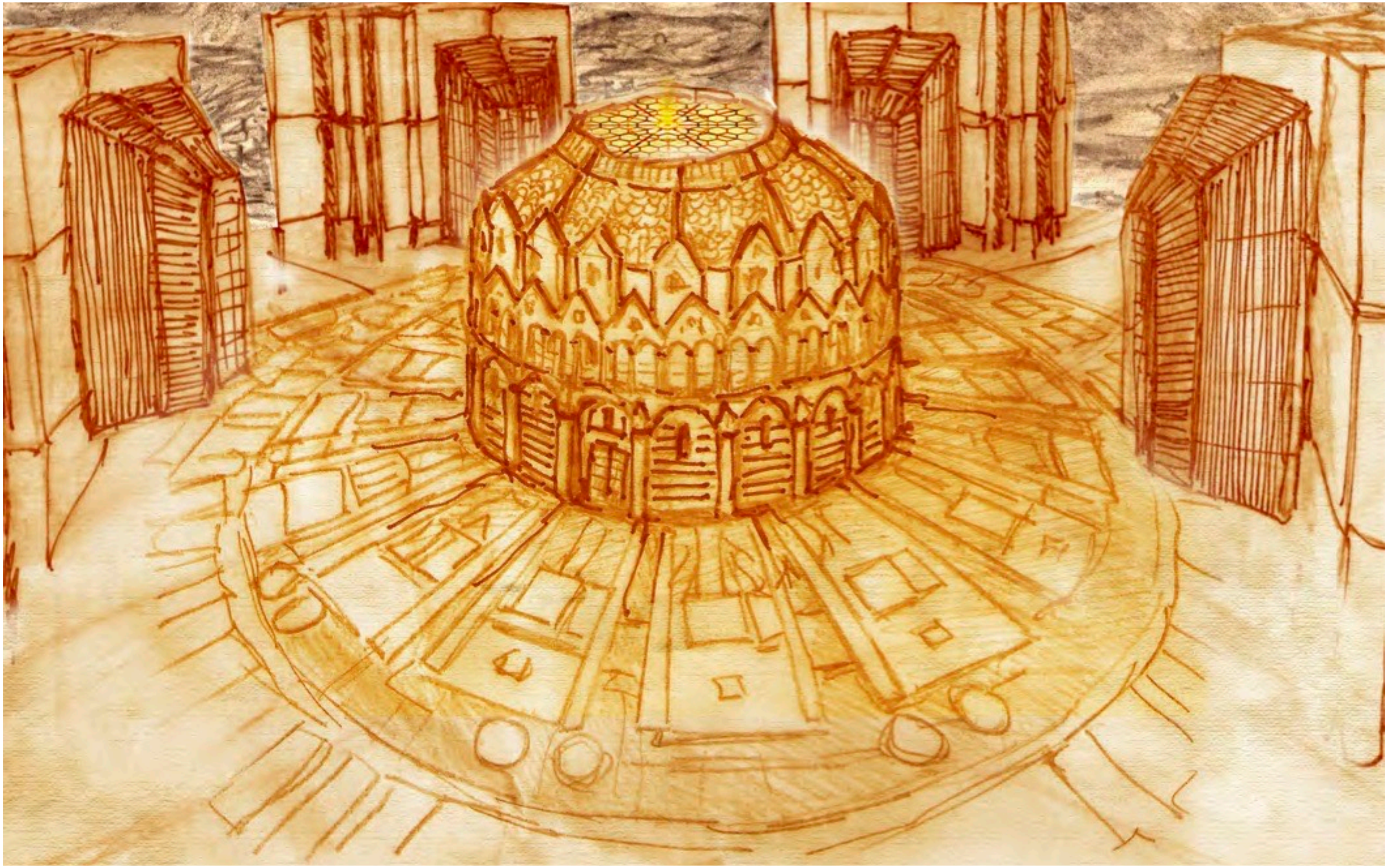
Beyond Linear Colliders

- Applications of CALICE Technology-

… with a strong bias towards projects I am involved in.

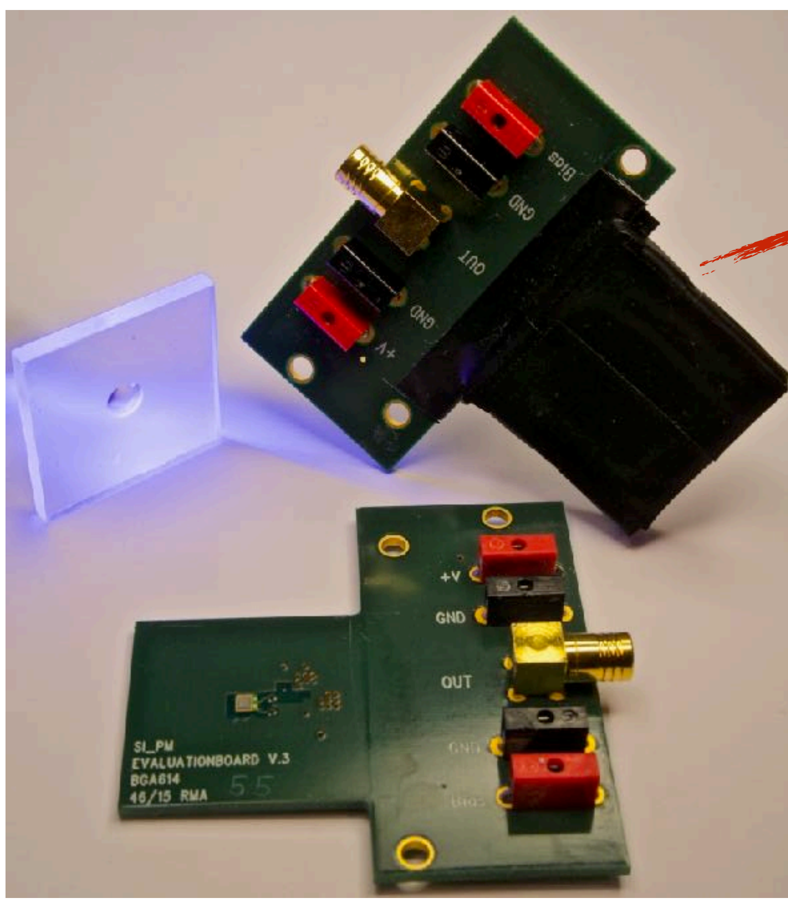
Most Prominent: The CMS HGCAL

- “A Child of CALICE”: A highly granular calorimeter with silicon and scintillator + SiPM active elements to address the challenges of HL-LHC conditions in the forward region



Application: CALICE Detector Elements

- Detector technologies developed in CALICE have many applications outside of collider calorimetry - a ***small-scale*** example:
- Beam background time structure during SuperKEKB commissioning: Using scintillator tiles with SiPM readout and sub-ns sampling with ms buffers
  - Based on CALICE-T3B



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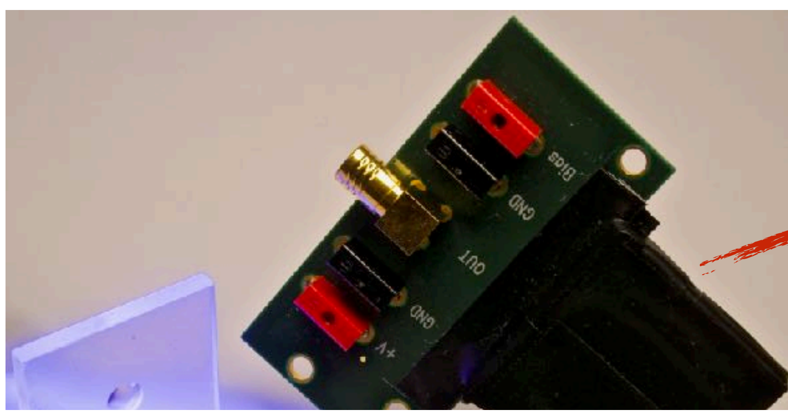
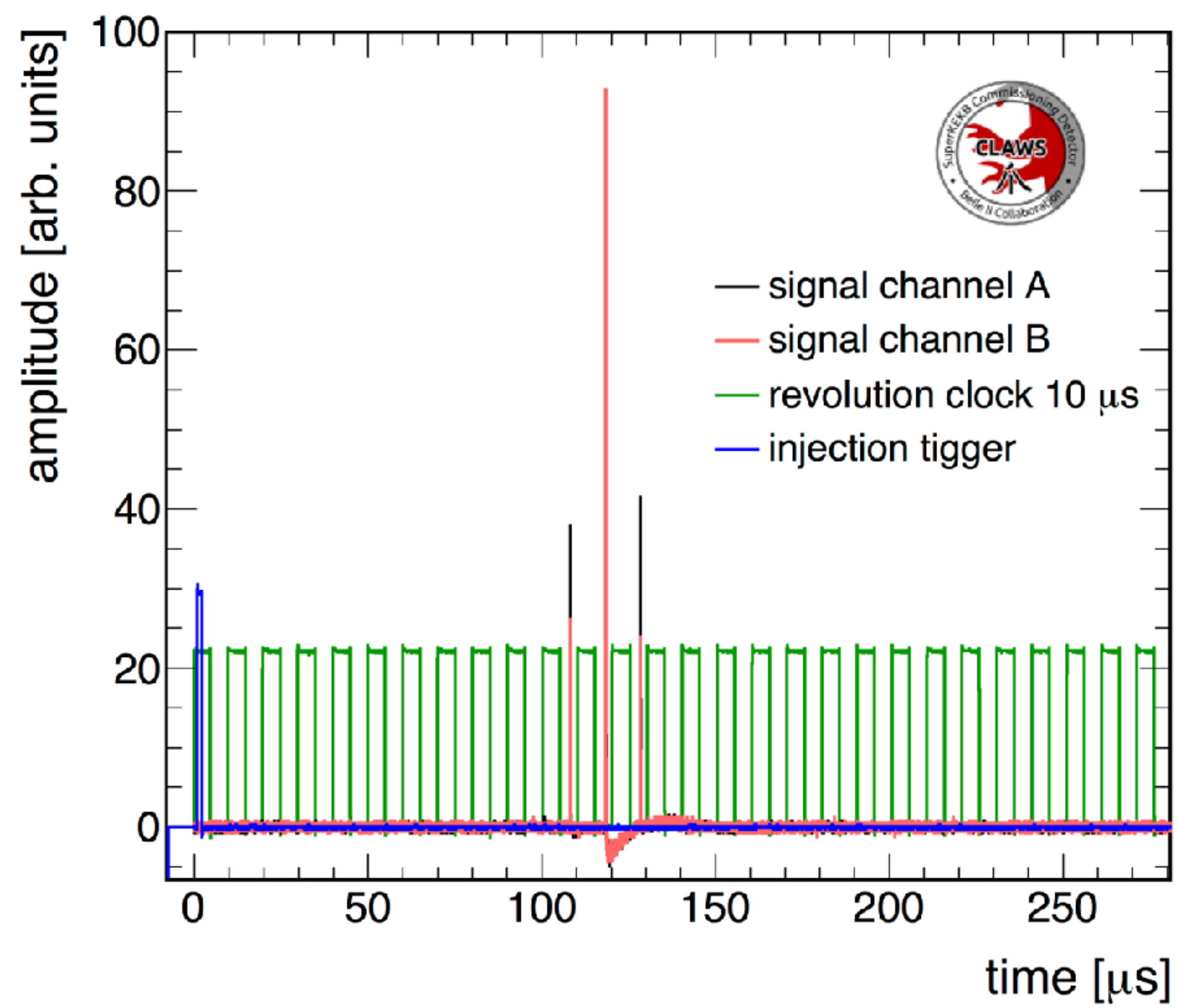
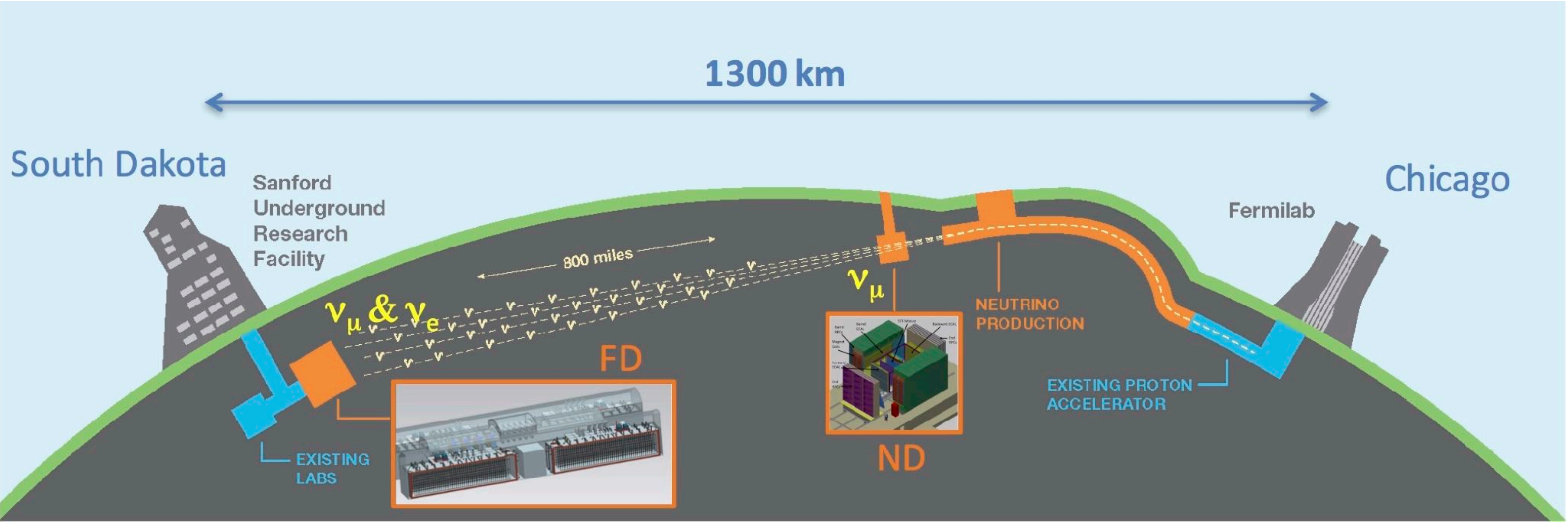




- The first detector to see particles from the accelerator during “first turns” on February 8, 2016

Beyond Colliders: Neutrino Near Detectors

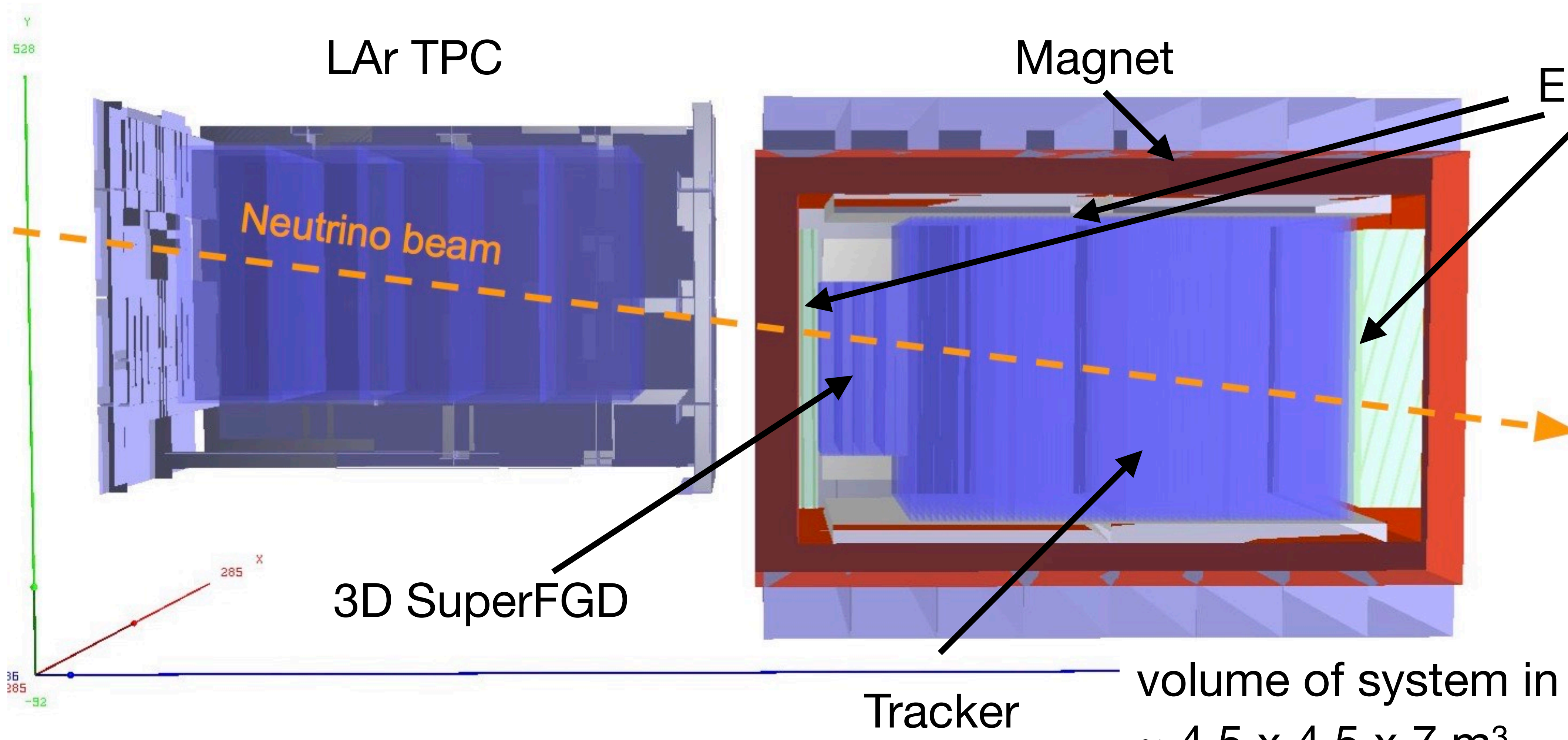
- ***DUNE/LBNF***: Recently started construction at Fermilab / SURF



- Primary goals: Measure the neutrino mass hierarchy, discover and study leptonic CP violation, search for proton decay, enable supernova measurements
- Two distinct detector systems:
  - Far detector: Four 10 kT fiducial mass LAr TPCs
  - Near detector: Multi-component detector system

DUNE ND: The Case for High Granularity

- A ***Near Detector*** system to determine the properties of the neutrino beam, and to perform high-statistics measurements of neutrino interactions



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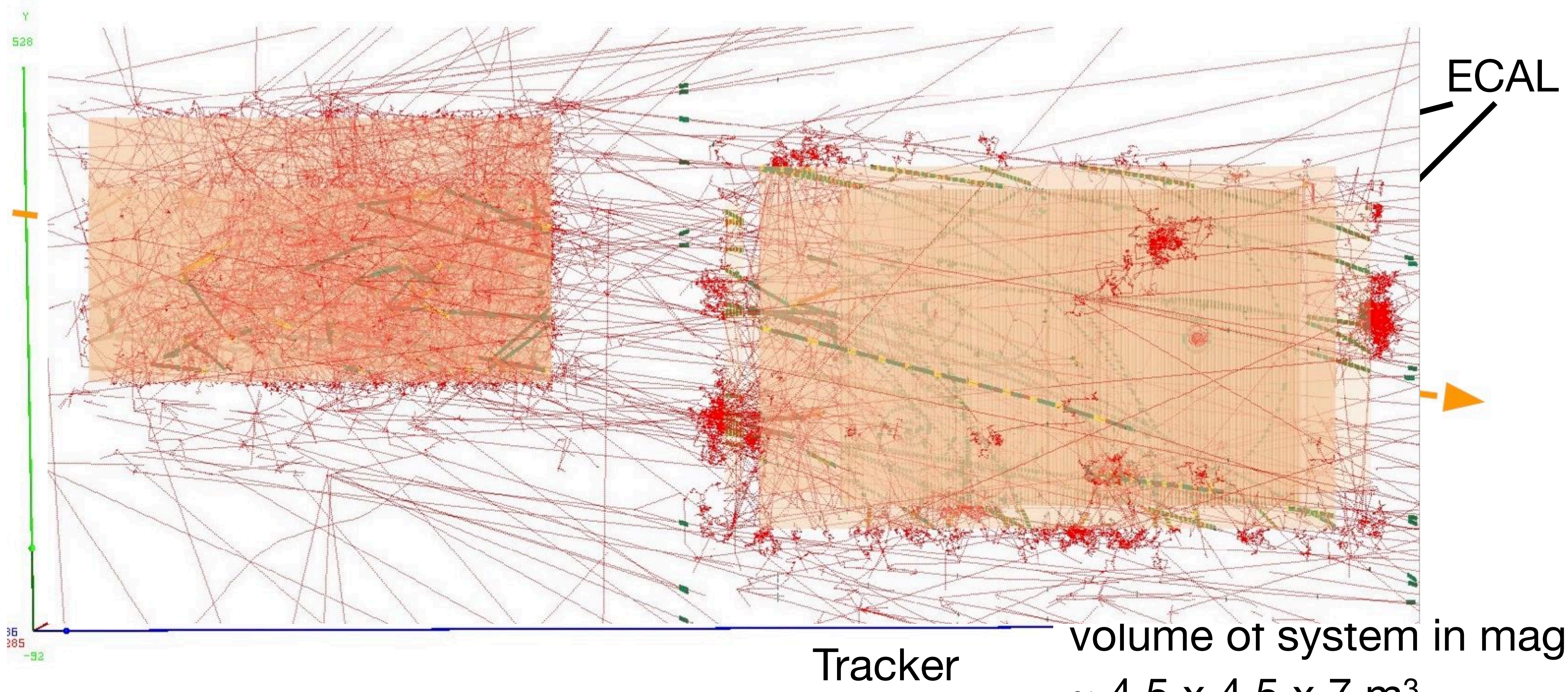

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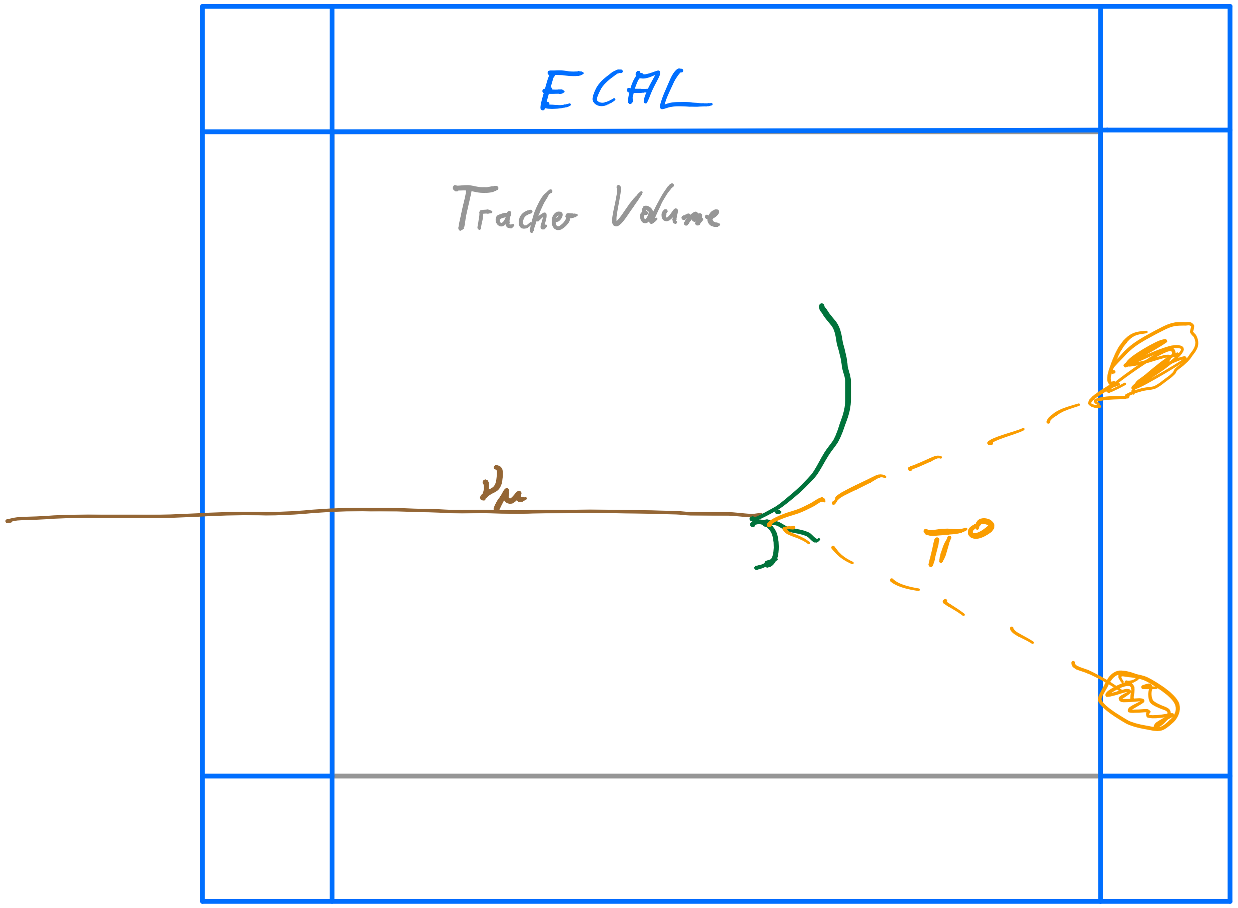
- One spill (~ 10 μs), here without dirt / rock interactions, interactions in hall or detector infrastructure: high interaction rate, creates a pile-up challenge for slow detectors

A Highly Granular ECAL for DUNE?



- Understanding neutral pion production is critical for oscillation physics:
  - important background source for oscillation signal
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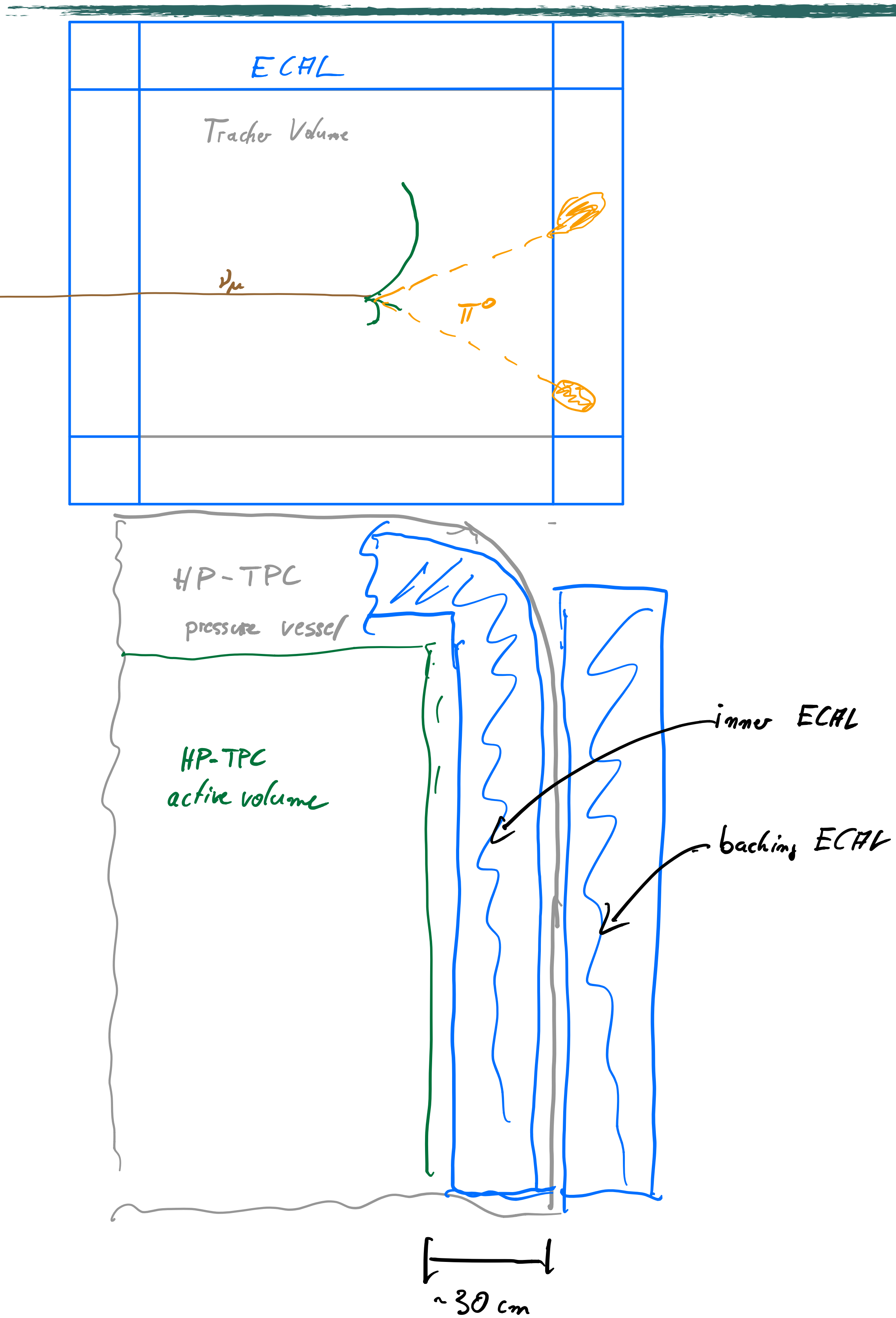

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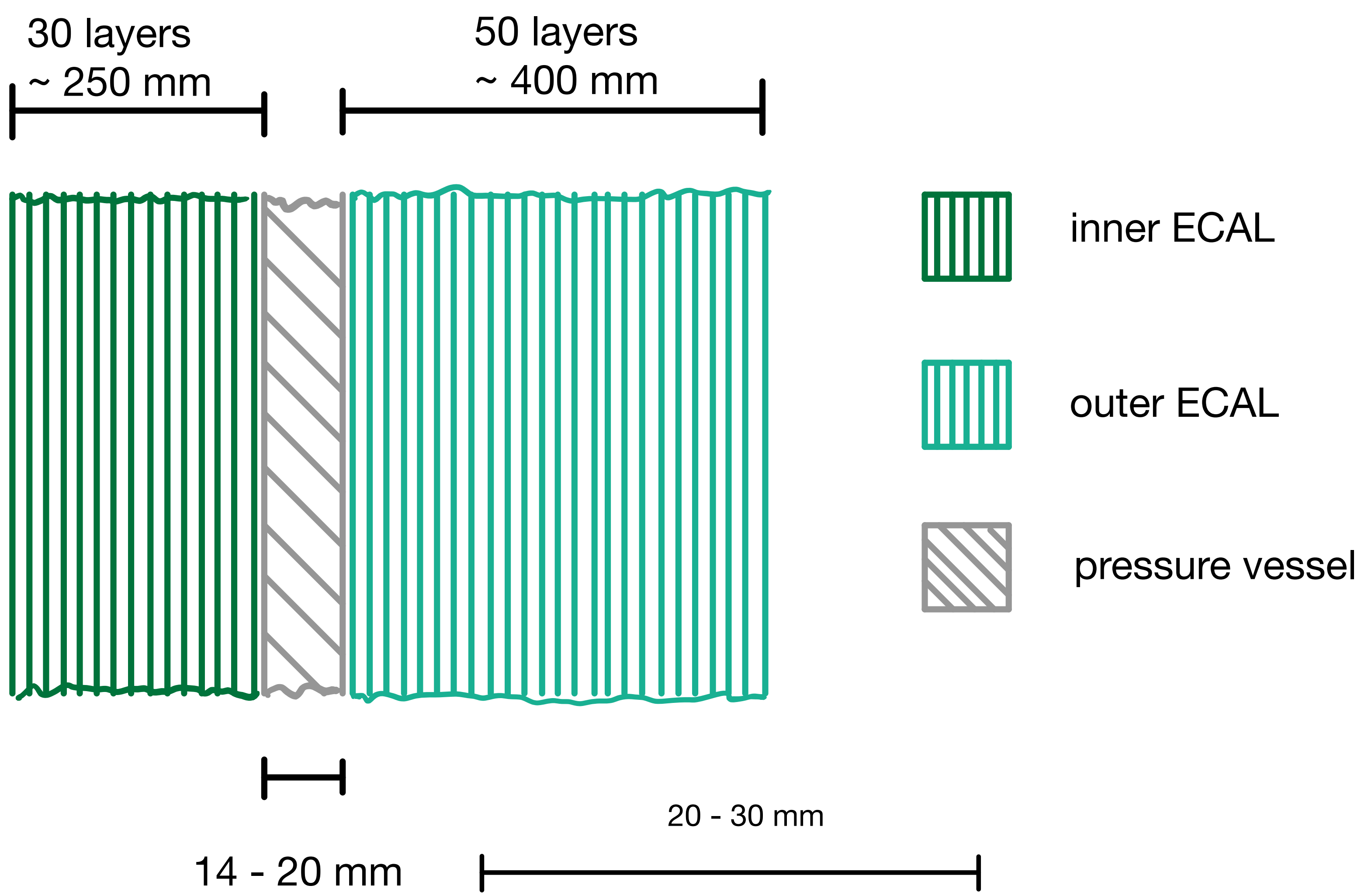
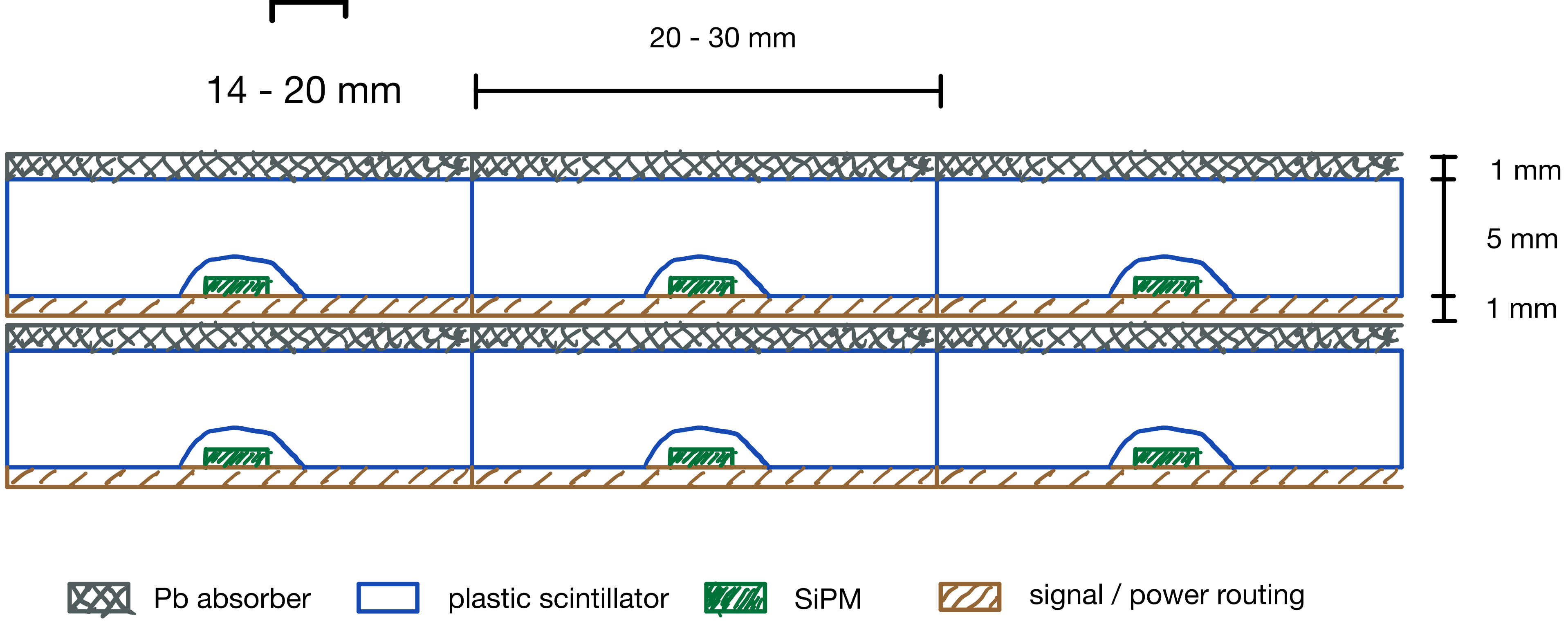
- Particularly relevant in scenarios with a high pressure TPC: No π^0 detection capability in the TPC itself

DUNE ECAL: Straw-Man Detector Concept



- Developed for the case of a HP-TPC
- Assumes a granularity of 20 x 20 - 30 x 30 mm²
  - realistically not in the form of cells in all layers - crossed strips in larger part of the detector a viable option



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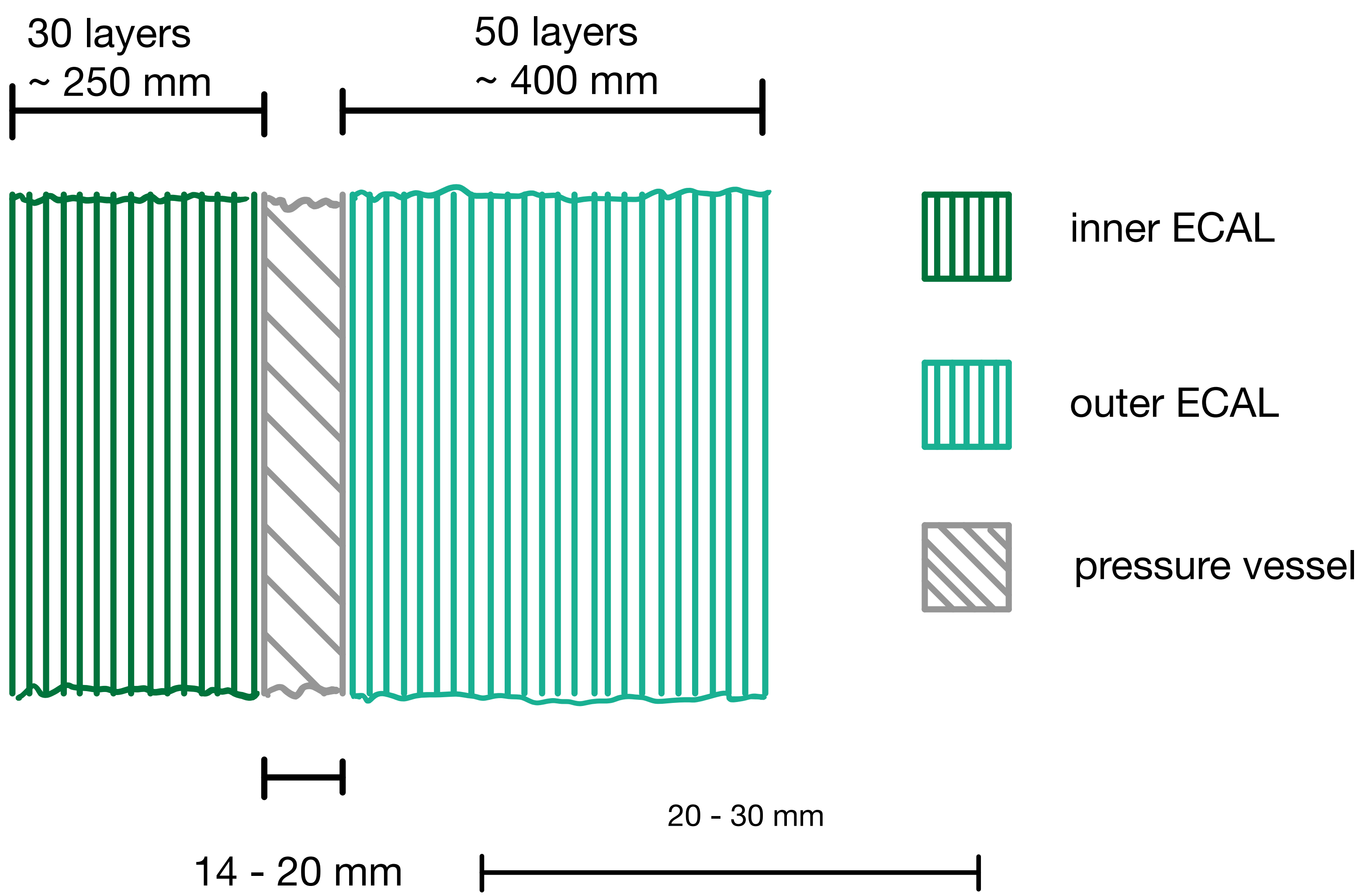

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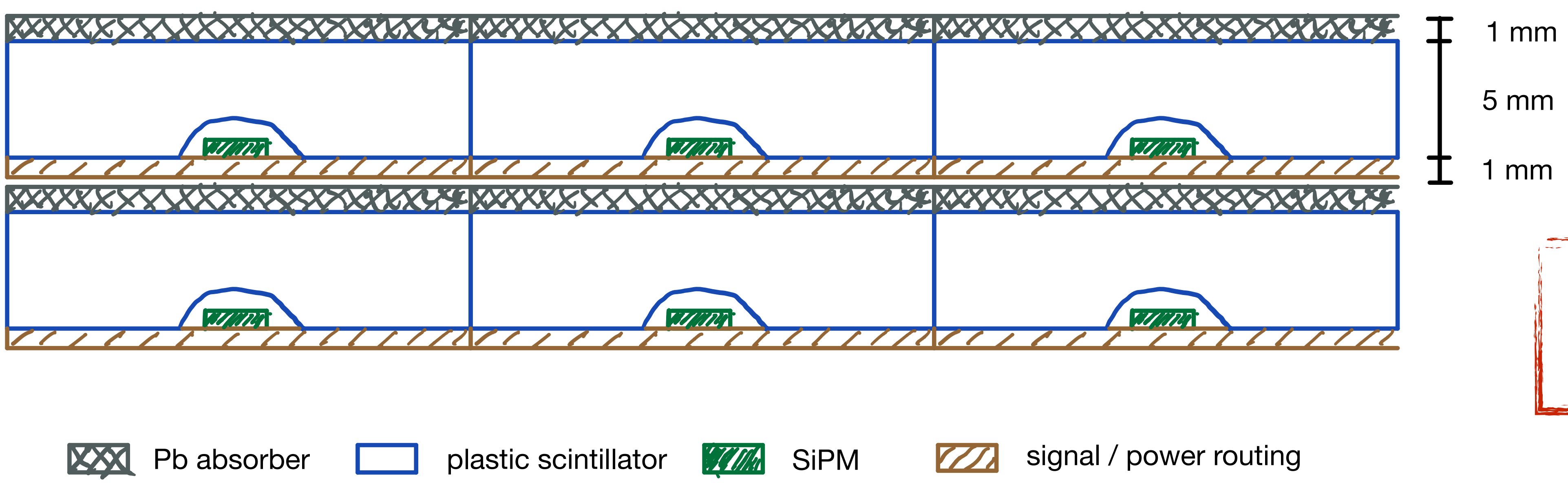
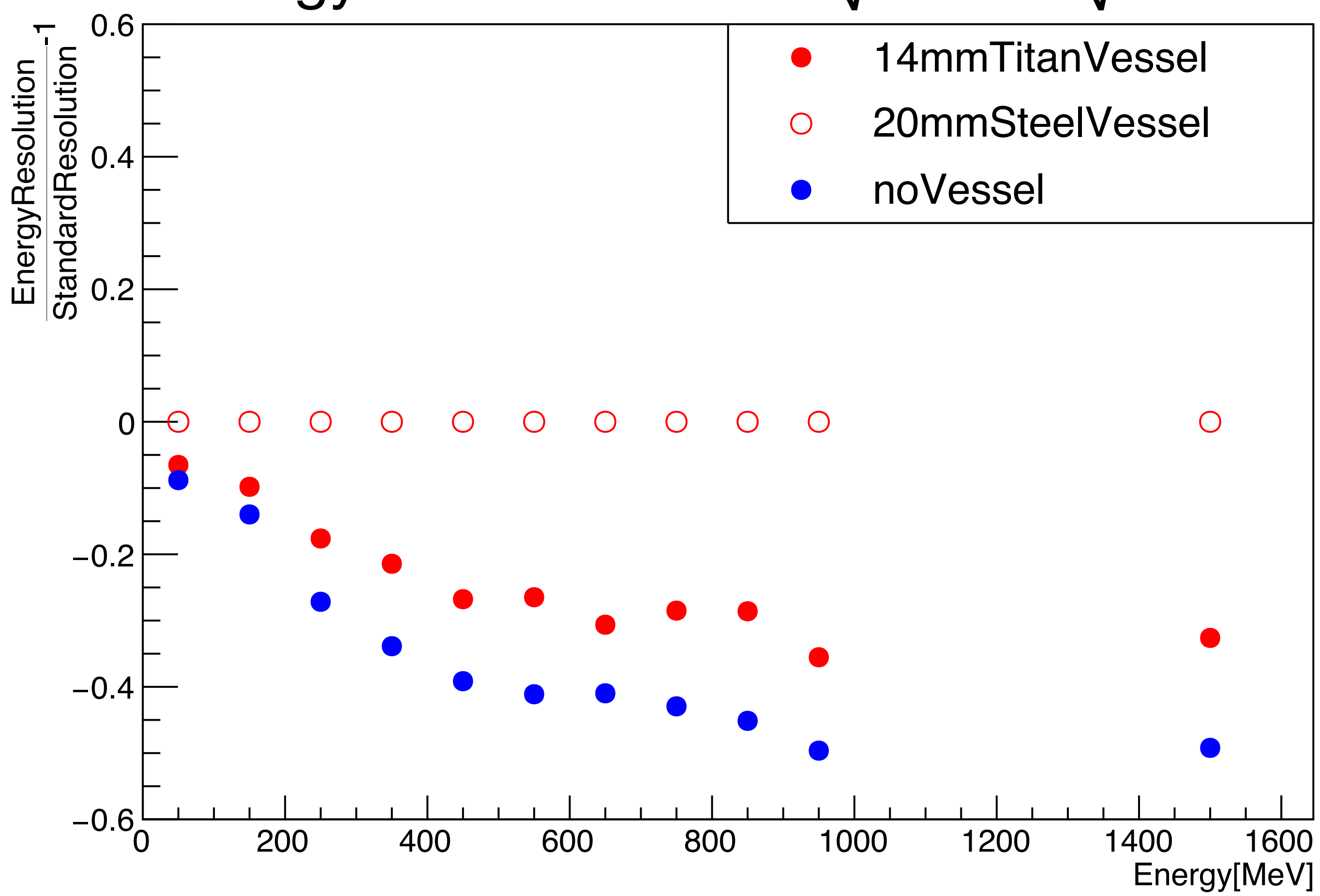
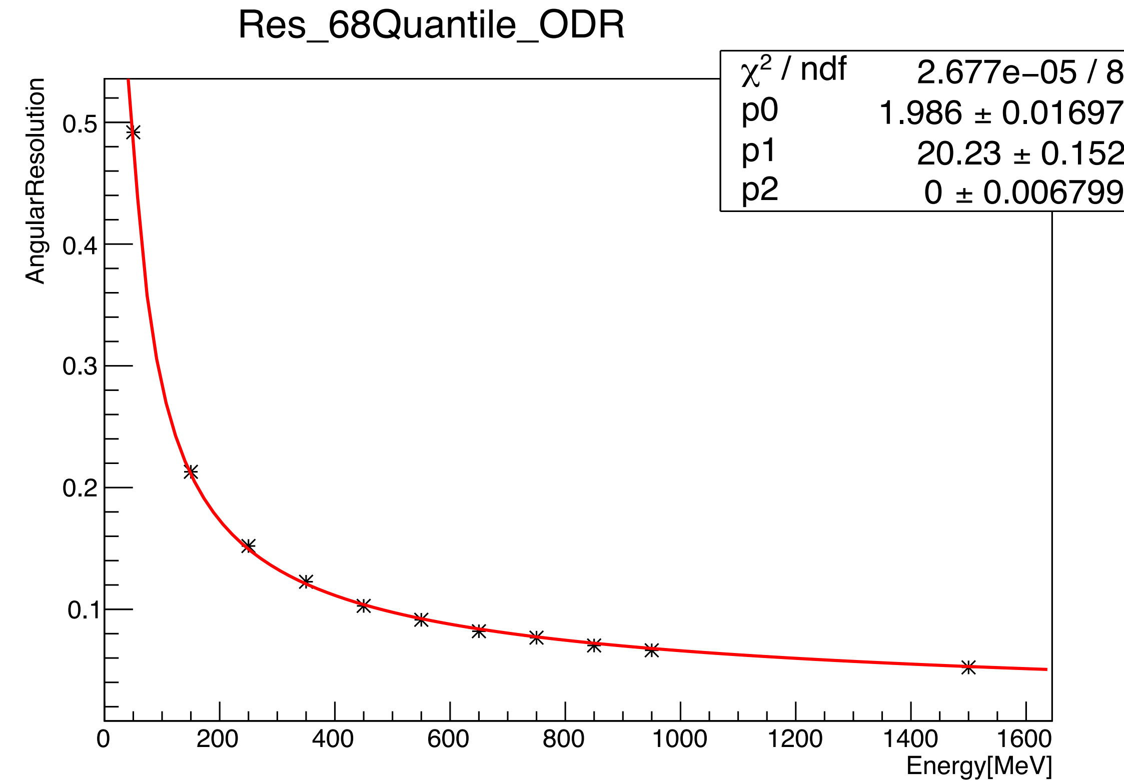


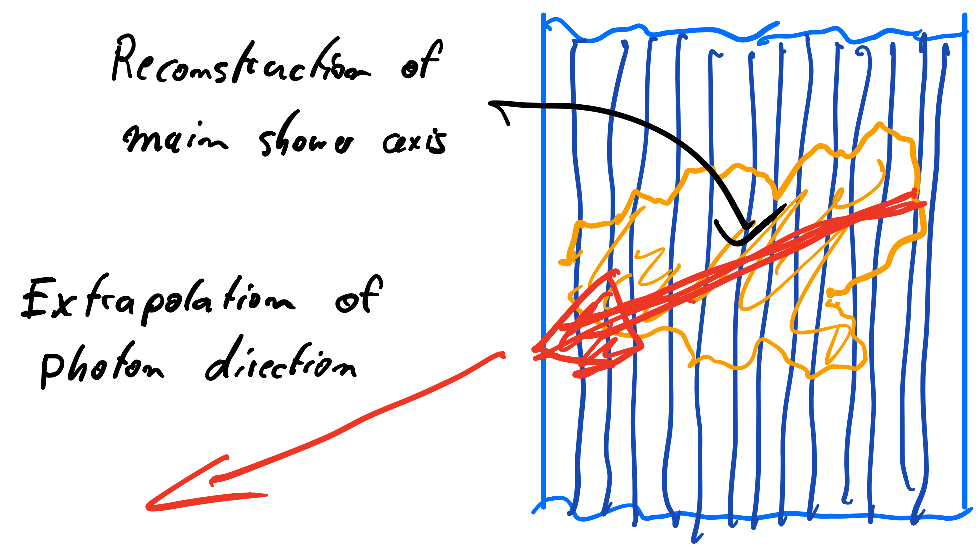
R&D on scintillator options started at MPP

DUNE ECAL: First Steps

- Simulation studies:
  - Photon pointing, and π^0 reconstruction within 5 - 10 cm in the detector volume appears possible
  - Energy resolution ~ $6\%/\sqrt{E}$ - $9\%/\sqrt{E}$ feasible







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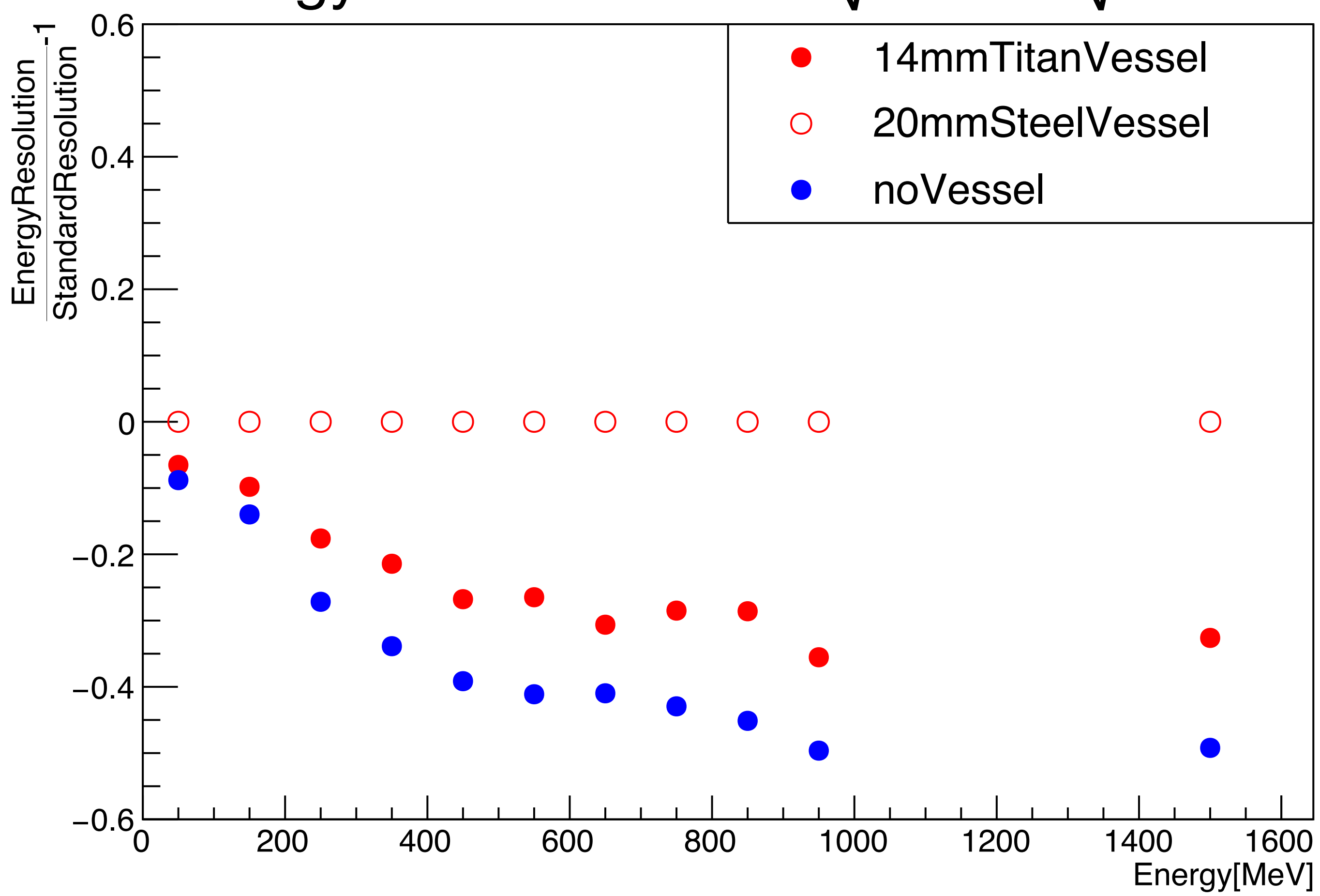

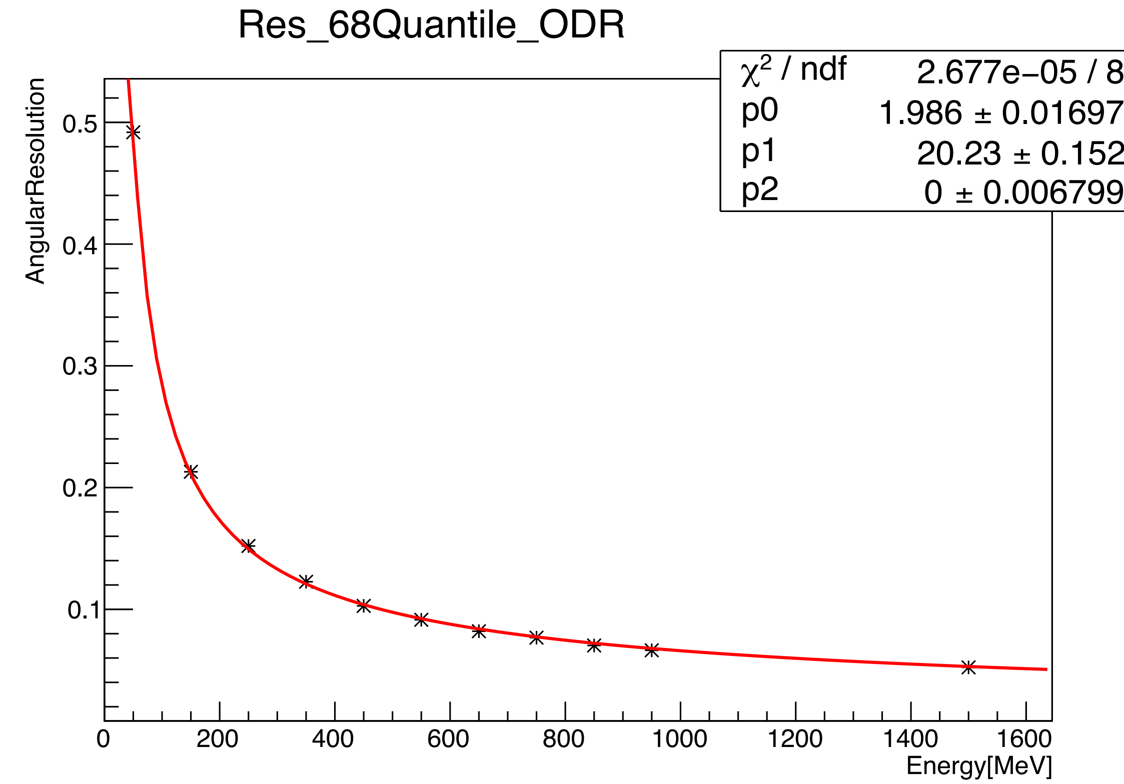

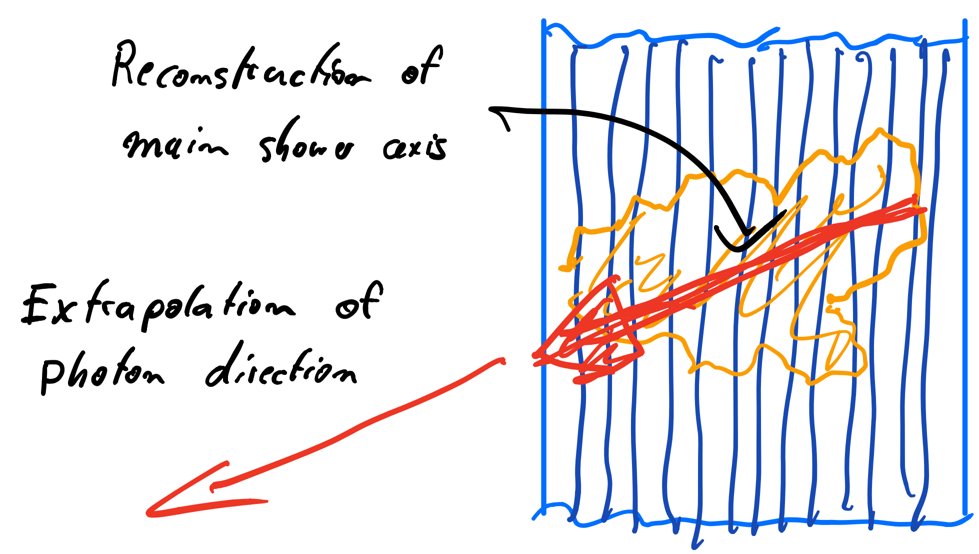

➩ Input to the technology decisions on the tracking technology within DUNE - to be taken in the coming months

Conclusions

What We've Learned

- Highly granular calorimeters work - both for electromagnetic and hadronic systems, with different technologies: Silicon, Scintillator + SiPMs, Gas
- The behavior of the systems is well understood - also in simulations:
  - Validated with electromagnetic showers for all technologies
  - Particle separation as a key performance measure of particle flow algorithms validated with test beam data; matching GEANT4 simulations
  - *Not shown today:*
    - CALICE data contributes to further development of GEANT4 hadronic shower models - includes detailed substructure and shower time structure
- Excellent performance for hadrons possible using detailed spatial information for software compensation algorithms - successfully transferred to PFAs

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Requirements for future Linear Collider Experiments can be fulfilled by imaging calorimeters

It does not end there…

- Currently building the next generation of prototypes: proving scalability and potential for automatisation for the construction of highly granular calorimeters
  - Not just a “construction exercise” - the new prototypes will also provide a new quality of hadronic shower data, with cell-by-cell timing on the ns level throughout the full detector volume
- Pushing granularity to a new level: A first prototype of a digital ECAL based on MAPS large enough to contain high-energy electromagnetic showers

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- Pushing granularity to a new level: A first prototype of a digital ECAL based on MAPS large enough to contain high-energy electromagnetic showers
- CALICE technologies are now finding applications in other experiments
  - LHC Phase II upgrades
  - Smaller detectors - such as commissioning of SuperKEKB
  - Possibly for the Near Detector of DUNE: A highly granular scintillator / SiPM - based ECAL