Calorimeters for Upgrades & Future Colliders

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

Disclaimer

This presentation does not claim or attempt completeness - the selection of topics reflects my personal bias towards highly granular calorimeters.

Outline

- Calorimetry Basics
  - Present Systems at the LHC
- New(er) Concepts:
  - Dual Readout
  - Highly Granular Calorimeters
- Upgrades for HL-LHC
- Other Future Concepts
- A few thoughts on Test Beams

Calorimetry Basics

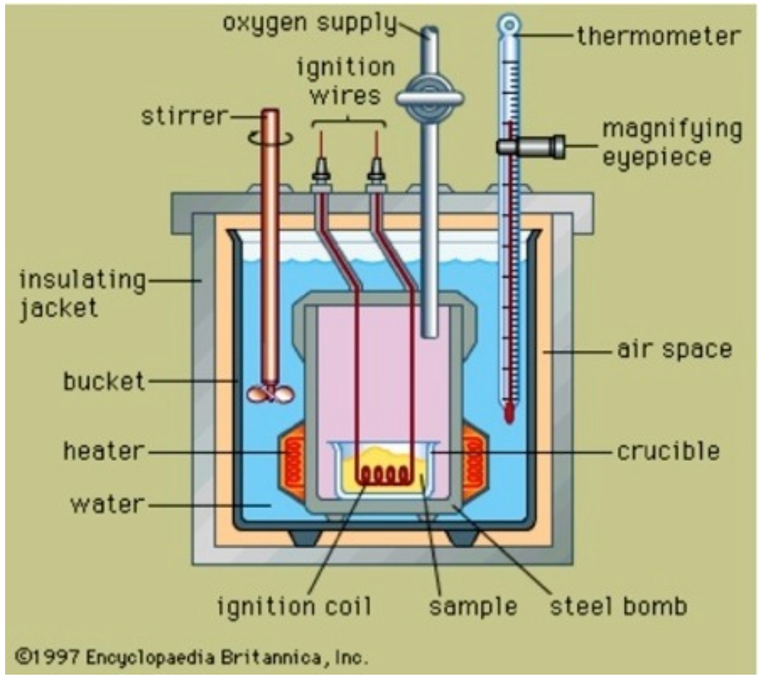
Calorimetry

The Basic Concept

- Originally from chemistry: Measurement of the released heat by a chemical reaction: Here increase of temperature of a well-known amount of water

- For elementary particles:
  Measurement of the energy of a particle by total absorption
  - 1 cal = 10^7 TeV: Very small energies, (almost) no temperature increase! *

  ➪ Somewhat more sophisticated strategy for energy measurement needed



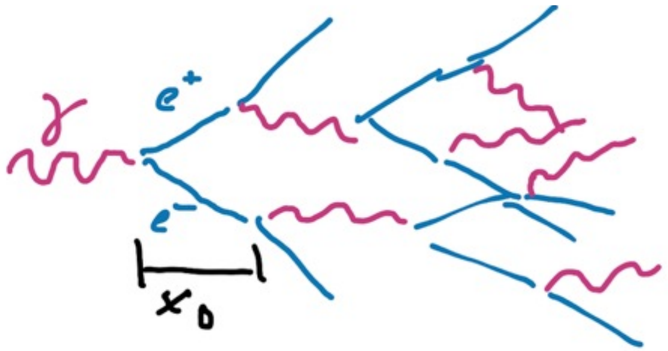
"bomb calorimeter"

* there are specialized applications where temperature increase is used also for the energy measurement in particle physics, for example the CRESST dark matter experiment - not covered here

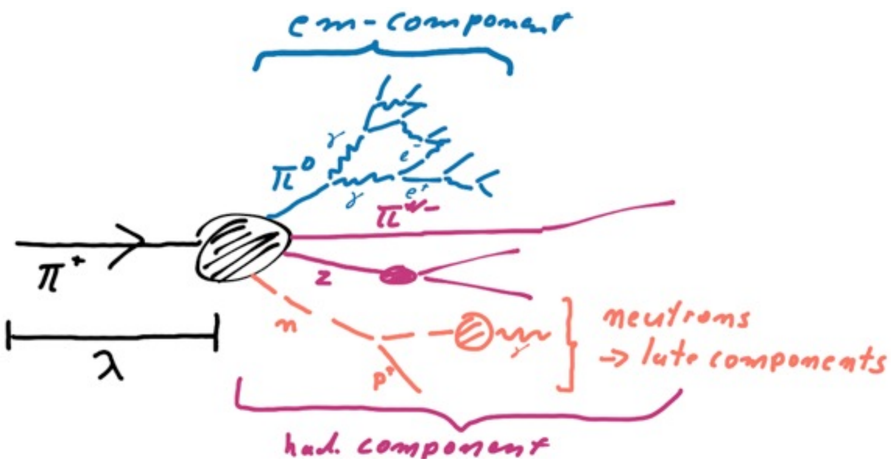
Calorimetry in HEP

The basic physics process: Showers

- Highly energetic particles deposit their energy in material via particle showers:



electromagnetic



hadronic

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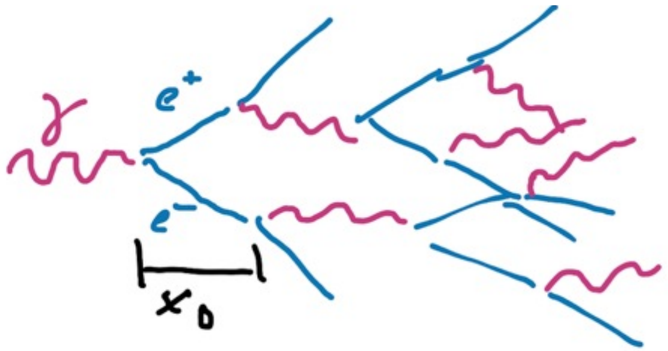

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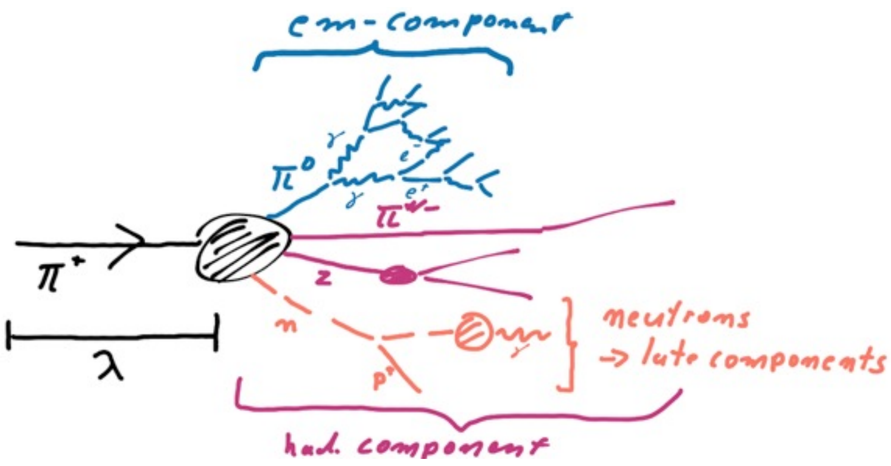


hadronic

➪ A calorimeter has to

- contain material that promotes shower formation
- contain material sensitive to secondary particles created in the showers
- be “deep” enough to contain (most) particles created in the showers

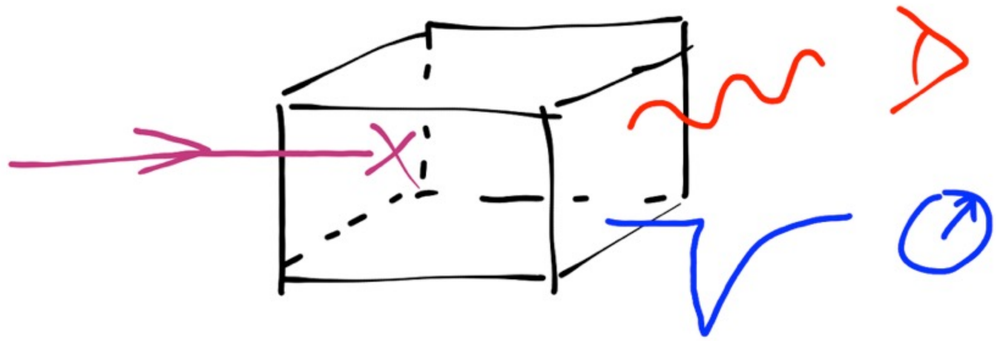
Calorimetry in HEP

Transforming Energy into a Signal

- A key part of the energy measurement process: Converting the energy of the incident particle to a detector response

➪ Choose something that is easily detectable also for “small” energies

  - Electric charge
  - Photons (in or close to visible range)



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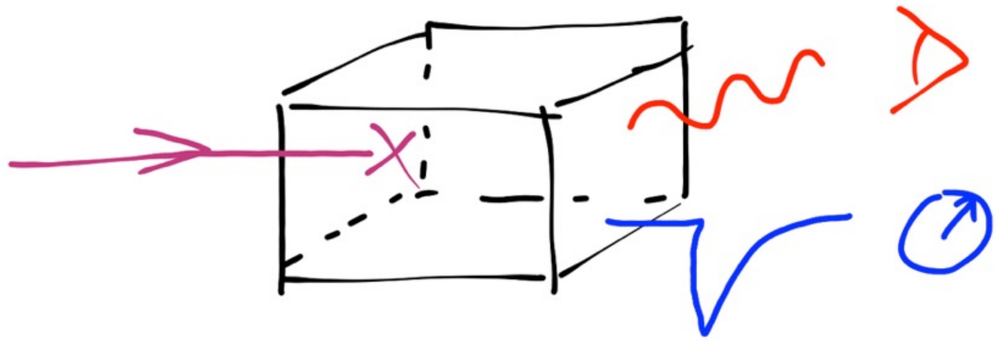

- Mostly: Detection of ionization energy loss of charged particles produced in the showers

➪ Direct detection of the produced charge:
  - Semiconductor detectors
  - Noble liquids
  - Gaseous detectors

➪ Detection of scintillation light - ionization converted to light in scintillator

- Also: Detection of Cherenkov light emitted by charged particles

Performance Measures for Calorimeters

The main one: Energy Resolution

- Calorimetric processes are stochastic:
  - Counting of photons / created charge carriers
  - Number of secondary particles in showers induced by high-energy particles

Energy resolution often well-described by $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

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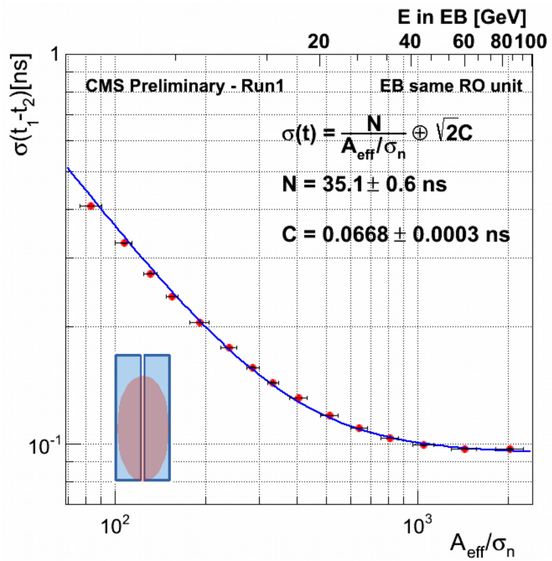
Energy resolution often well-described by $$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

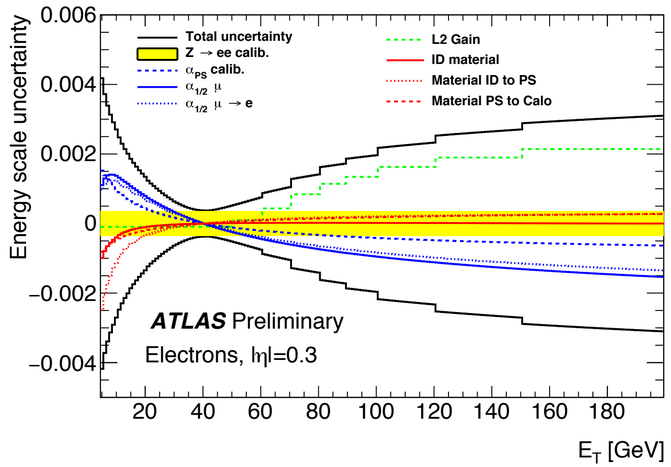
- Three components:
  - *a*: The **stochastic** term: The counting aspect of the measurement: Simple statistical error: scales with the square root of the number of particles
    ➪ Resolution term scales with 1/√E
  - *b*: The **noise** term: Constant, energy-independent noise contribution to the signal -
    ➪ Resolution term scales with 1/E
  - *c*: The **constant** term: Contributions that scale with energy: Influence of inhomogeneities in the detector material, un-instrumented or dead regions, ...
    ➪ Resolution term is independent of energy

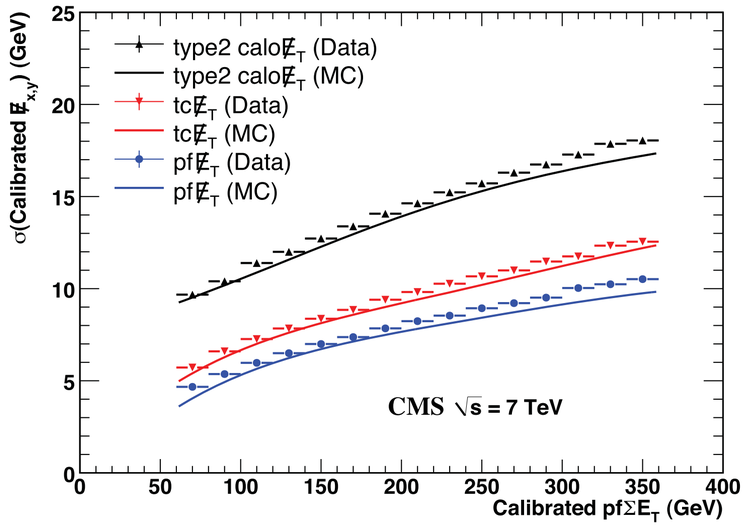
Performance Measures for Calorimeters

Other Parameters to Consider

- Energy resolution may be the most prominent metric, but there are other parameters that are highly relevant as well:
  - Calibration accuracy and stability over time
  - Particle separation and pattern recognition
  - Time resolution
  - For full systems: MET resolution, JER, JES







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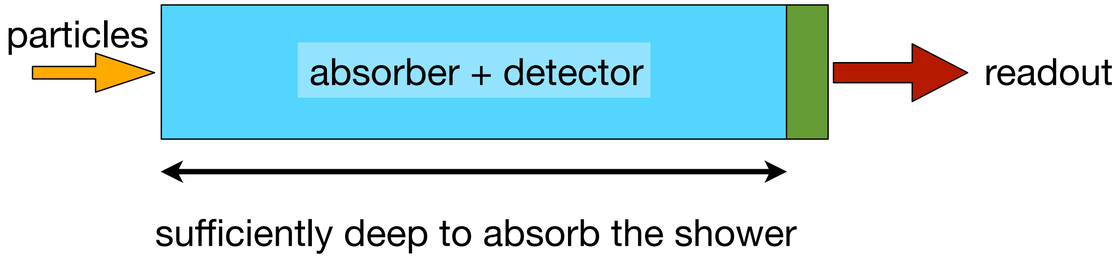
Calorimetry in HEP

Basic Calorimeter Types

- The dream: Contain the full energy of one particle, convert all energy into a measurable signal which is linear to the deposited energy

➪ Reality is often different, in particular when measuring hadrons

Two types: ***homogeneous calorimeters*** and ***sampling calorimeters***



- The shower develops in the sensitive medium
  - Potentially optimal energy resolution: Complete energy deposit is measured
  - Challenging readout: No passive readout structures in detector volume

➪ Scintillating crystals as active medium

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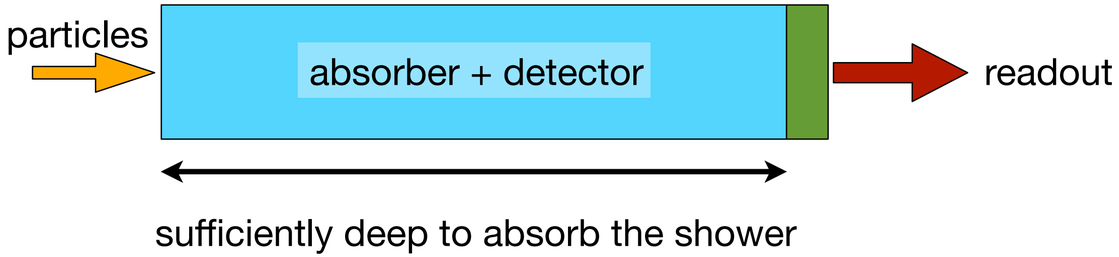

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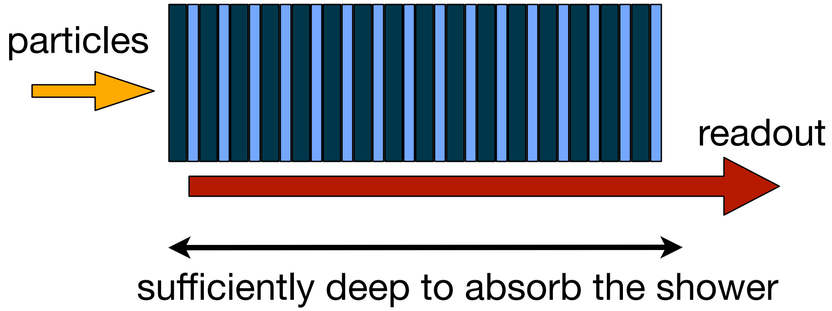


- The shower develops (mostly) in dense absorber medium, particles are detected in interleaved active structures
  - Potentially reduced energy resolution: Only a fraction of the deposited energy is detected

➪ highly flexible in choice of absorbers and active medium

Calorimeter Systems in HEP

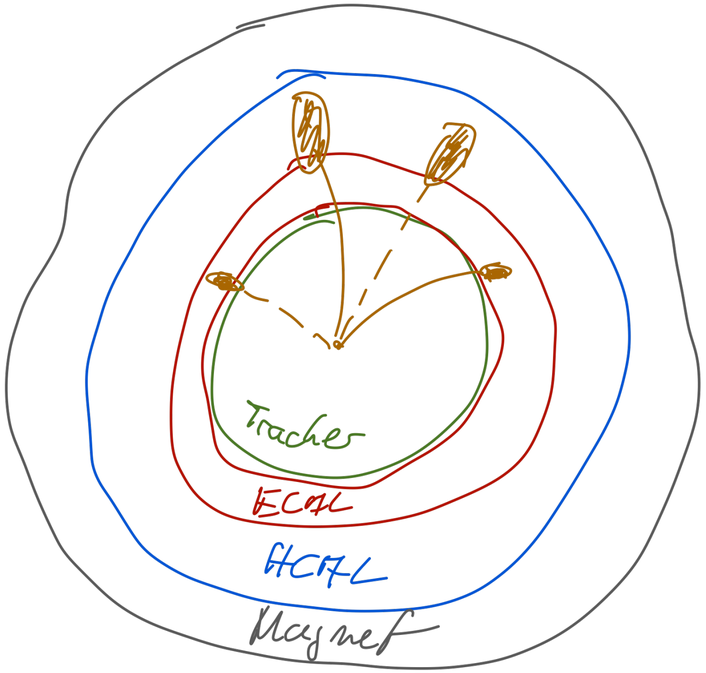
General Philosophy

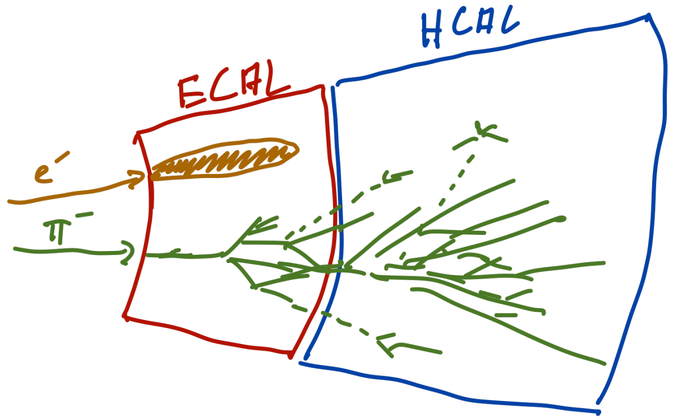
- Calorimeter systems at colliders need to measure the energy of electromagnetic particles and of hadrons, both charged and neutral - and the energy of jets

- Subdivided into ECAL and HCAL, reflecting differences in shower evolution

General requirements:

- Good energy resolution for electromagnetic and hadronic particles
- Large depth: absorb high-energetic particles
- Good timing: Reduce pile-up
- Operate inside magnetic fields
- Radiation hardness





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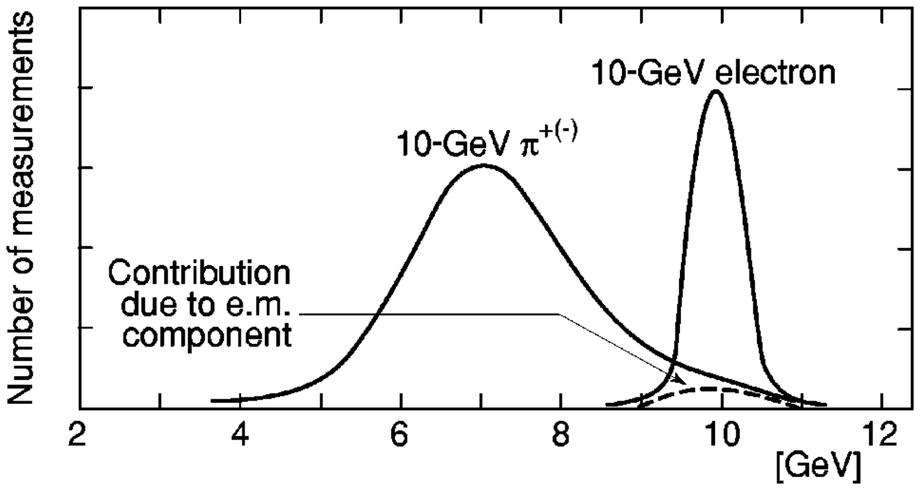
- Shower Physics - a challenge:

  Detectors often show a different response to electromagnetic and hadronic showers

  - Hadronic showers have “invisible” energy - binding energy loss etc
  - Complex time structure: Integration time matters
  - Energy loss can be (over-) compensated by sensitivity to neutrons

  ➪ Typically: Higher response to electrons than pions - e/pi > 1

  - Results in non-linearities, calibration challenges when using different electromagnetic and hadronic calorimeters



Signal (in energy units) obtained for a 10 GeV energy deposit

Calorimeter Systems in HEP

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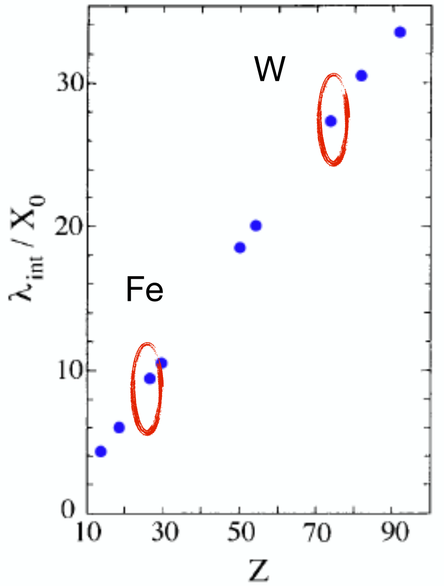
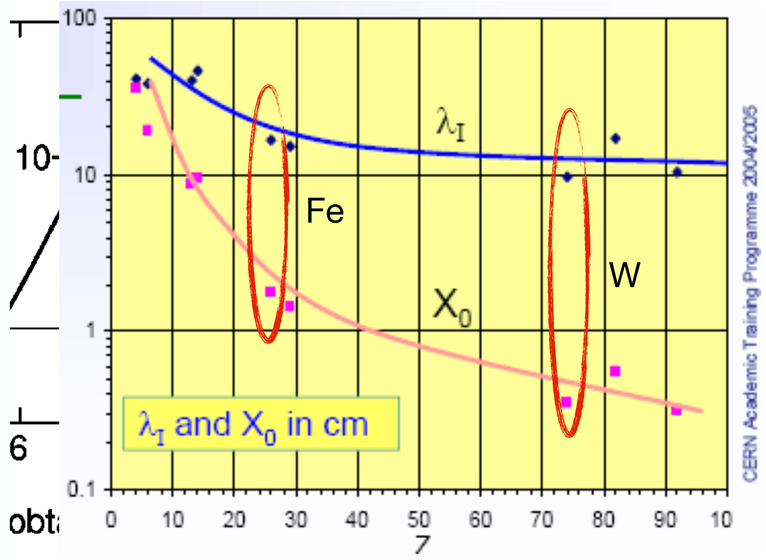
- Hadrons don’t care about the separation into em and hadronic calorimetry: 30% - 60% of all hadronic showers start already in the em section of a HEP calorimeter system





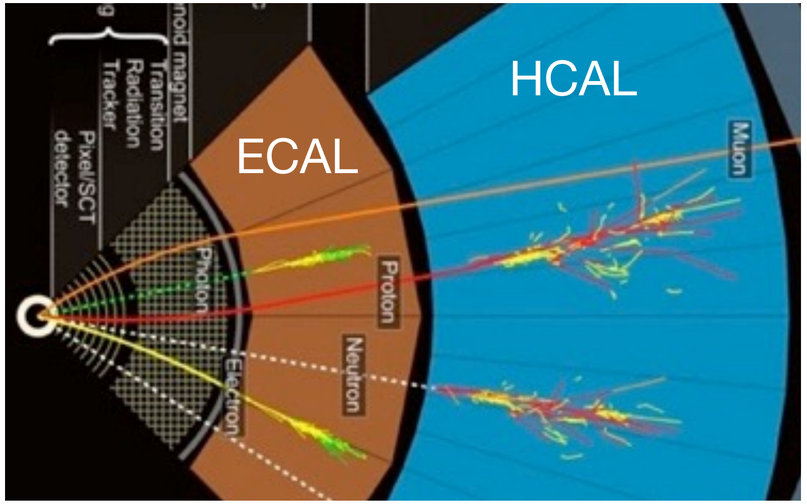
- The choice of the absorber strongly influences the relative sensitivity to em and hadronic shower components

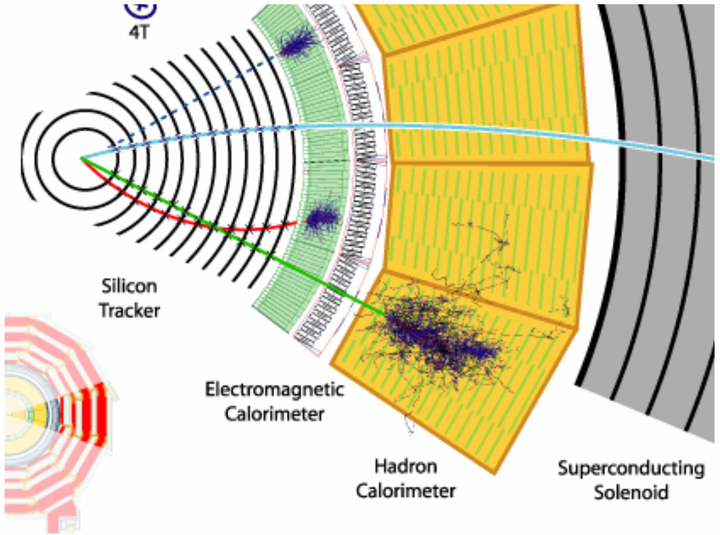
➪ Need to make compromises / set priorities

Calorimeter Systems in HEP

Present-day LHC

- ATLAS & CMS: Two different philosophies (here: barrel calorimeter systems)





ATLAS:

- sampling ECAL: Pb / liquid Argon $\sigma(E)/E \sim 10\%/\sqrt{E} \oplus 0.4\%$
- sampling HCAL: Steel / plastic scintillator $\sigma(E)/E \sim 50\%/\sqrt{E} \oplus 3\%$
- combined system pions $\sigma(E)/E \sim 52\%/\sqrt{E} \oplus 3\%$

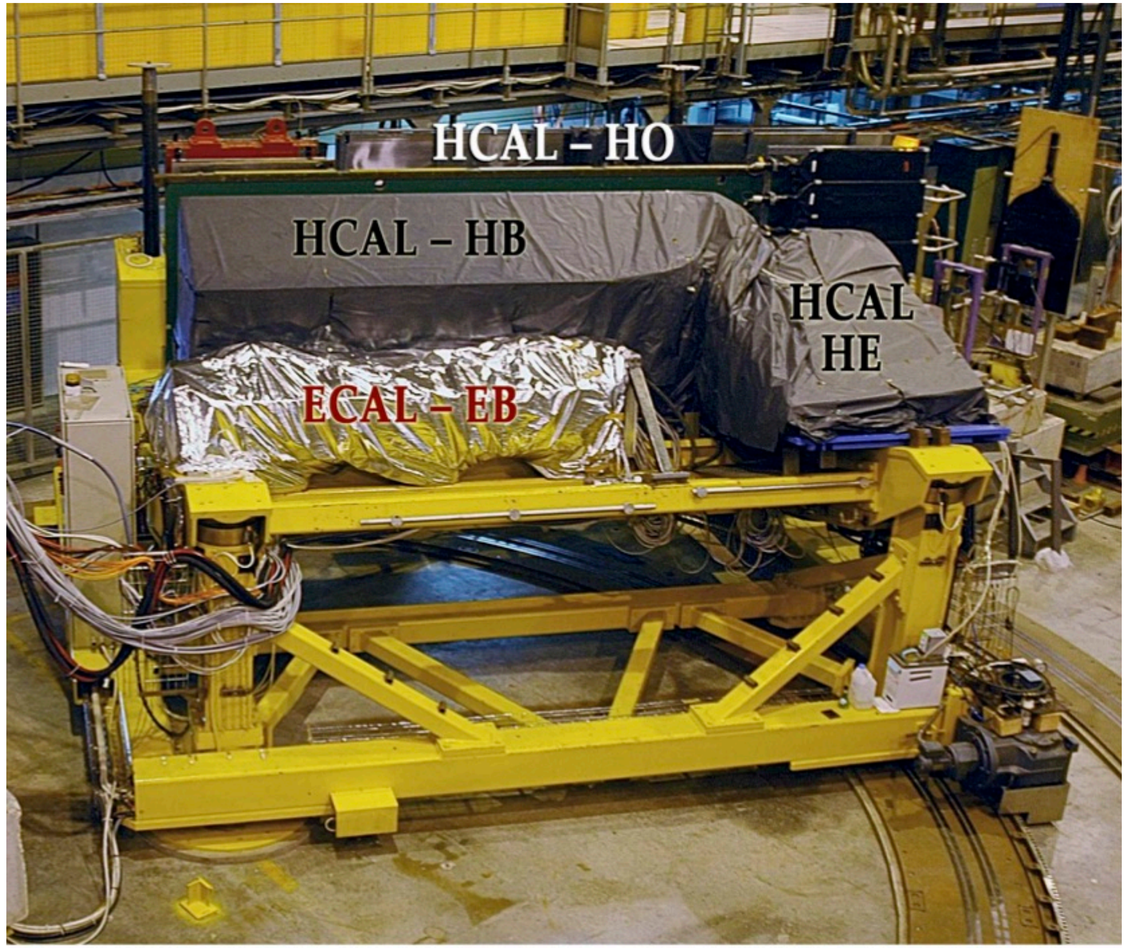
CMS:

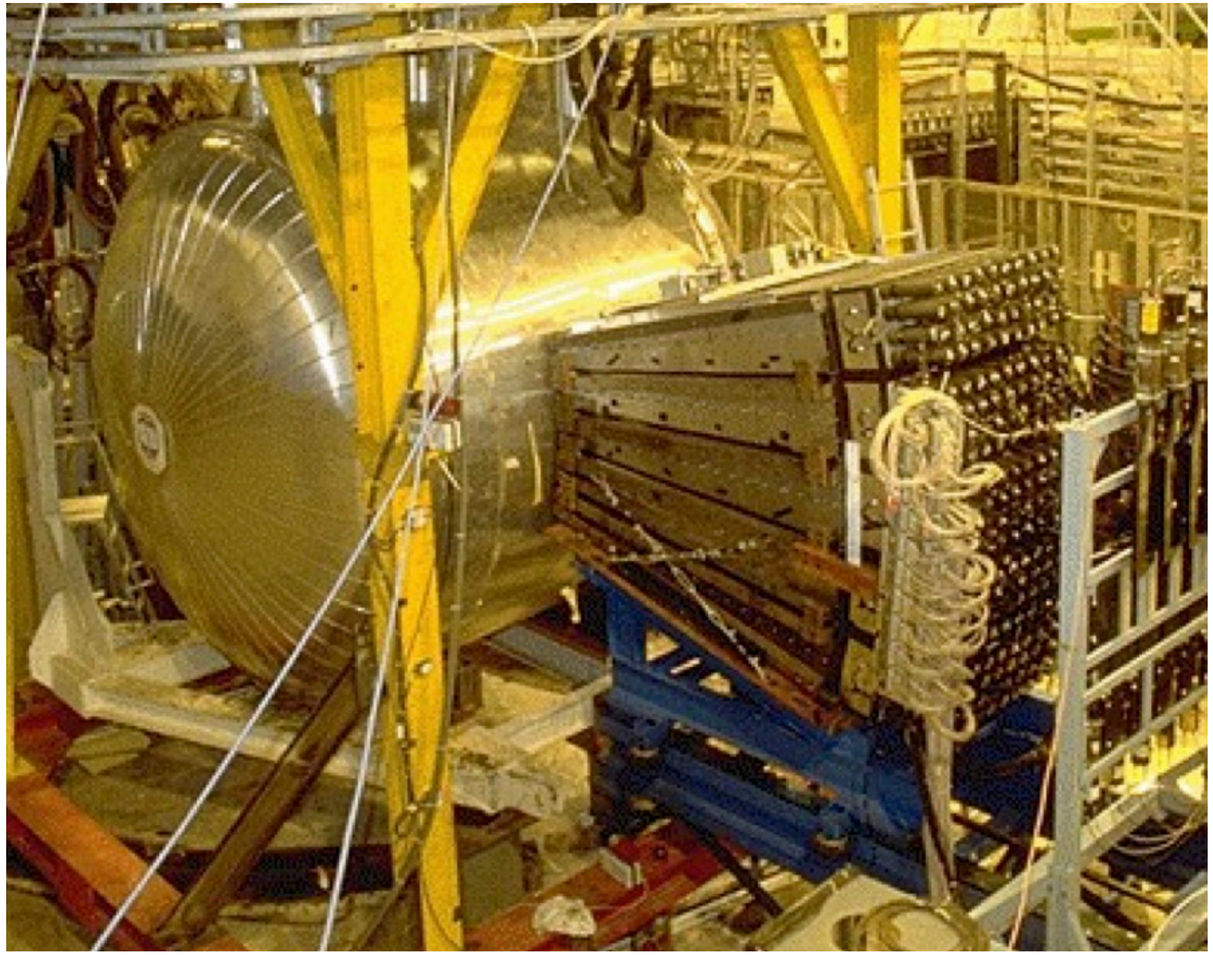
- homogeneous ECAL: $PbWO_4$ crystals $\sigma(E)/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
- sampling HCAL: Brass / plastic scintillator $\sigma(E)/E \sim 100\%/\sqrt{E} \oplus 4.5\%$
- combined system pions (optimised) $\sigma(E)/E \sim 85\%/\sqrt{E} \oplus 7.5\%$

Calorimeter Systems in HEP

Present-day LHC - Performance established in Test Beam prior to installation

- Extensive beam tests at SPS to study performance of combined ECAL and HCAL systems (as well as stand-alone): Very large installations!



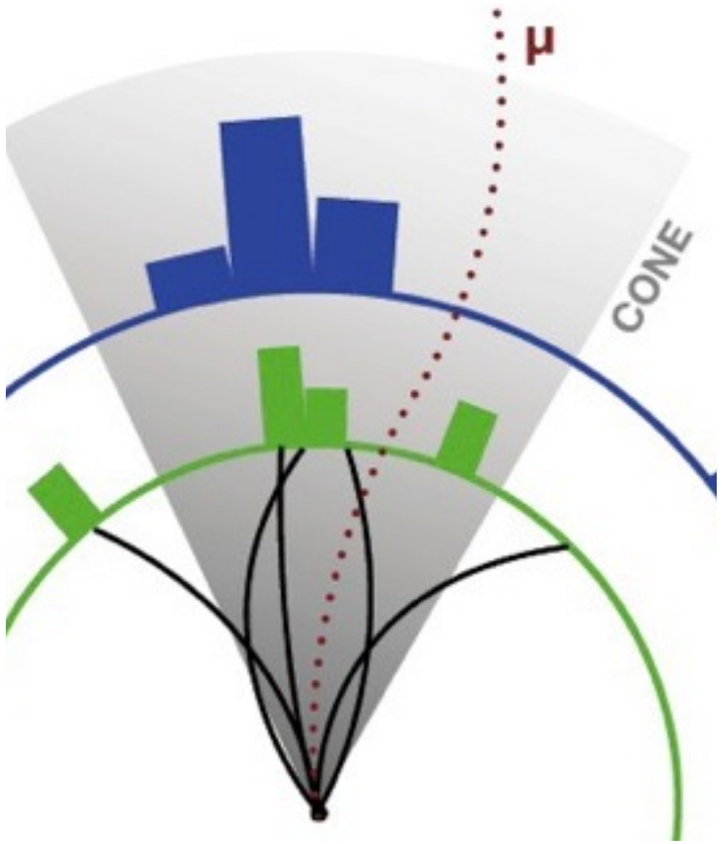


New(er) Ideas

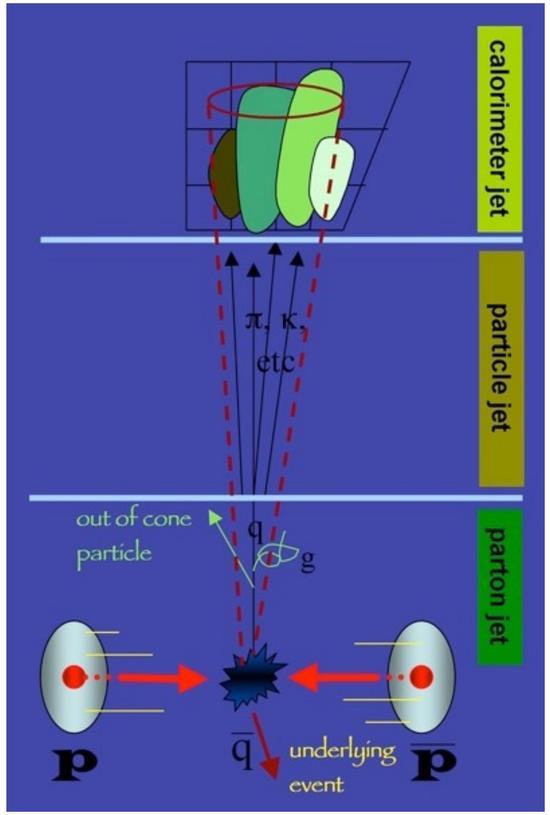
Primarily developed in the context of a linear e^+e^- collider

Jet Energy Resolution

An important, but difficult parameter



- A (the?) key task for calorimetry in collider experiments: Measuring ***Jets***
- The challenge: Jets consist of charged and neutral particles - electromagnetic and hadronic
  Typical jet composition:
  - 60% charged hadrons
  - 30% photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10% neutral hadrons (mainly n, K_L)
- Classical jet reconstruction relies exclusively on calorimetry: 70% of jet energy measured in the hadron calorimeter, with a rather limited resolution



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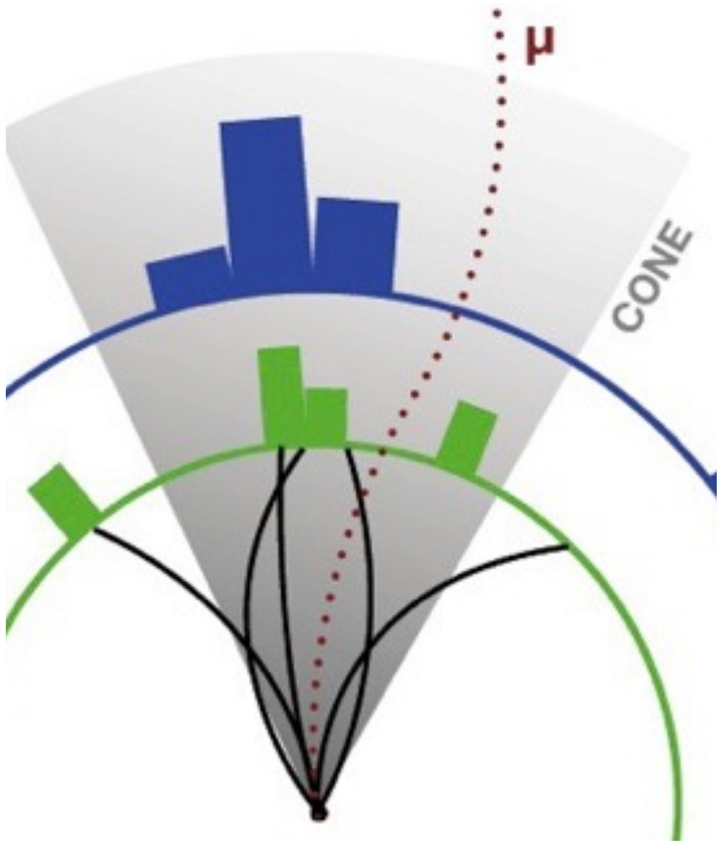

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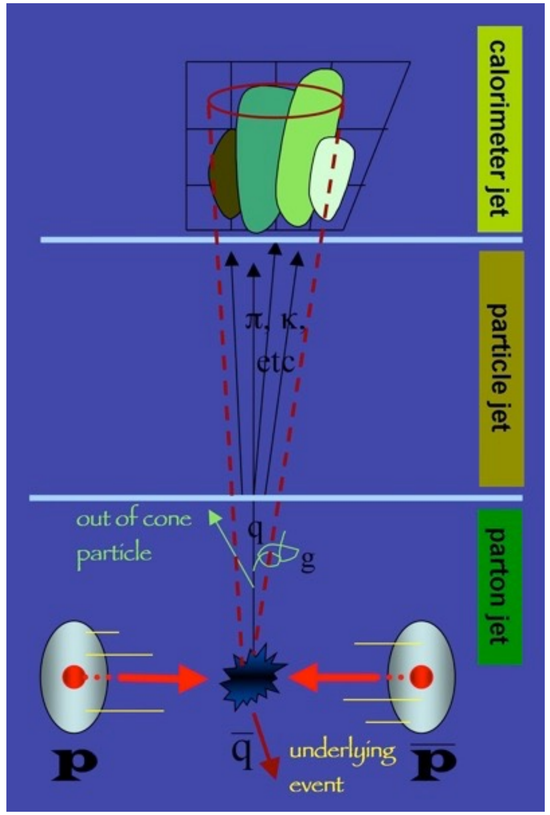

For future e^+e^- linear colliders:
Precision physics requires a jet energy resolution of 3%- 4% - new concepts needed!

Improving Jet Energy Resolution

Two different approaches

- Improve energy resolution for hadrons
- Make hadronic energy resolution less relevant

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  Requires using tracker measurements for as many particles as possible to reduce need for calorimetric energy resolution for hadrons

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  Dual Readout:

  - Measure the different shower components event-by-event
  - Exploit Cherenkov light emission by electrons and positrons (em showers):
    - Scintillation elements (all charged particles)
    - Cherenkov elements (em only)

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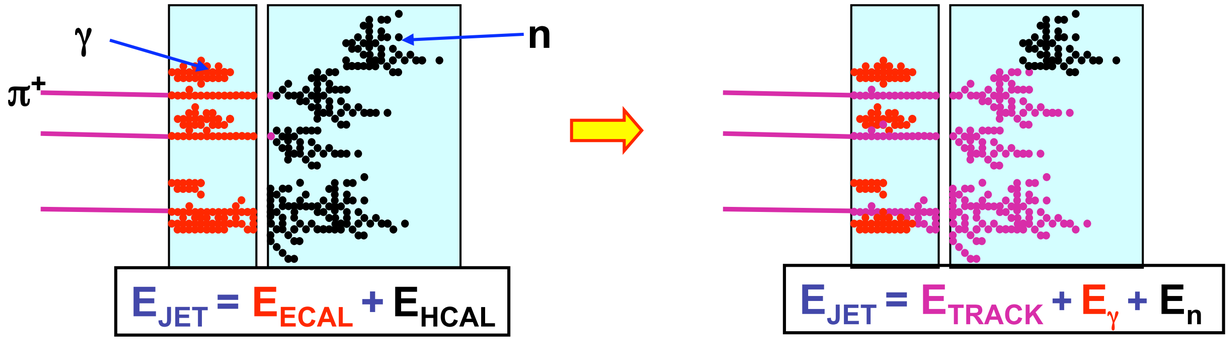

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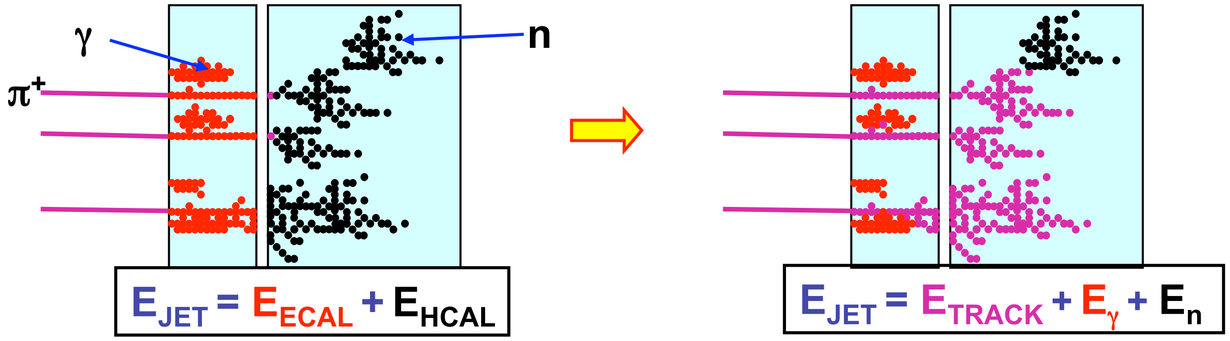


➪ Imaging capabilities in calorimeters to enable shower - track connections & avoid double-counting

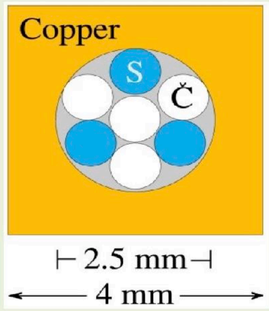
➪ Proof of detector technologies for both concepts require extensive test beam programs!

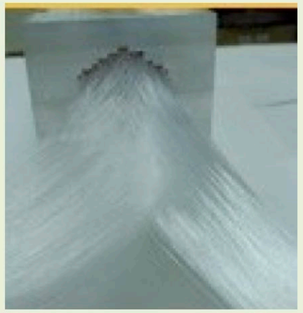
Dual Readout

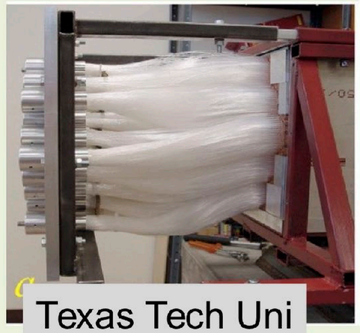
The Concept

2003 DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%



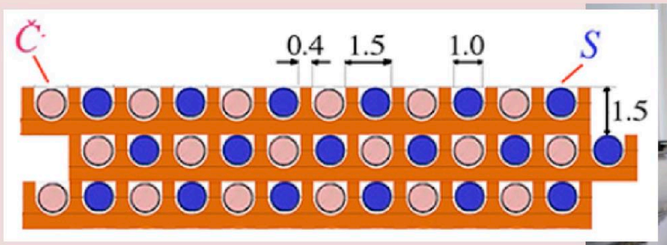




2012 RD52

Copper, 2 modules

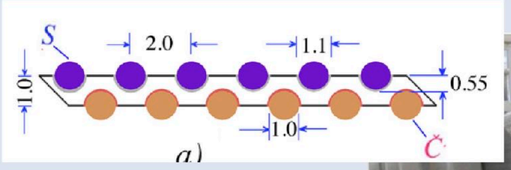
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}

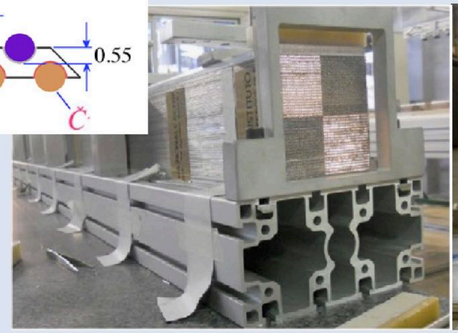


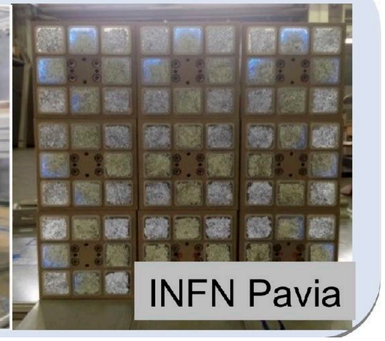
2012 RD52

Lead, 9 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}





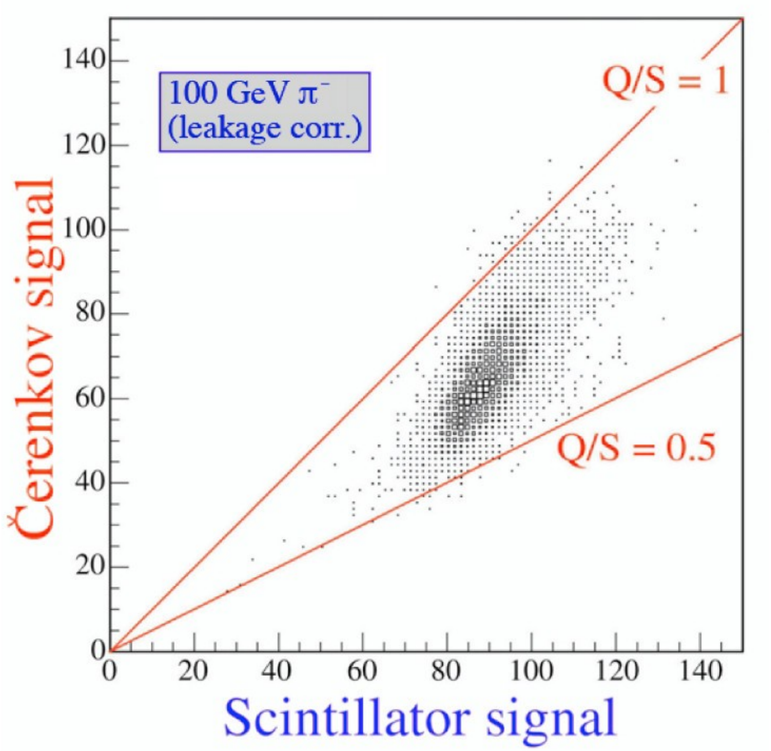


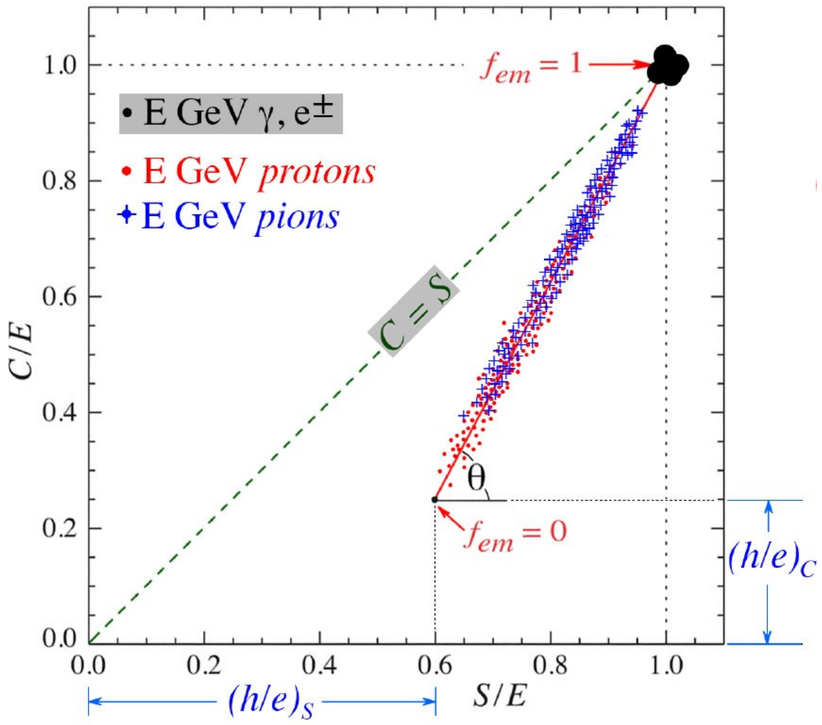
- A series of prototypes, demonstrating the concept and using it to study principles of calorimetry
- Recently demonstrated the possibility to use SiPMs to read out fibers - substantial increase in granularity, eliminates need for “fiber bundles” at calorimeter back

R. Ferrari, CHEF 2017

Dual Readout

The Concept

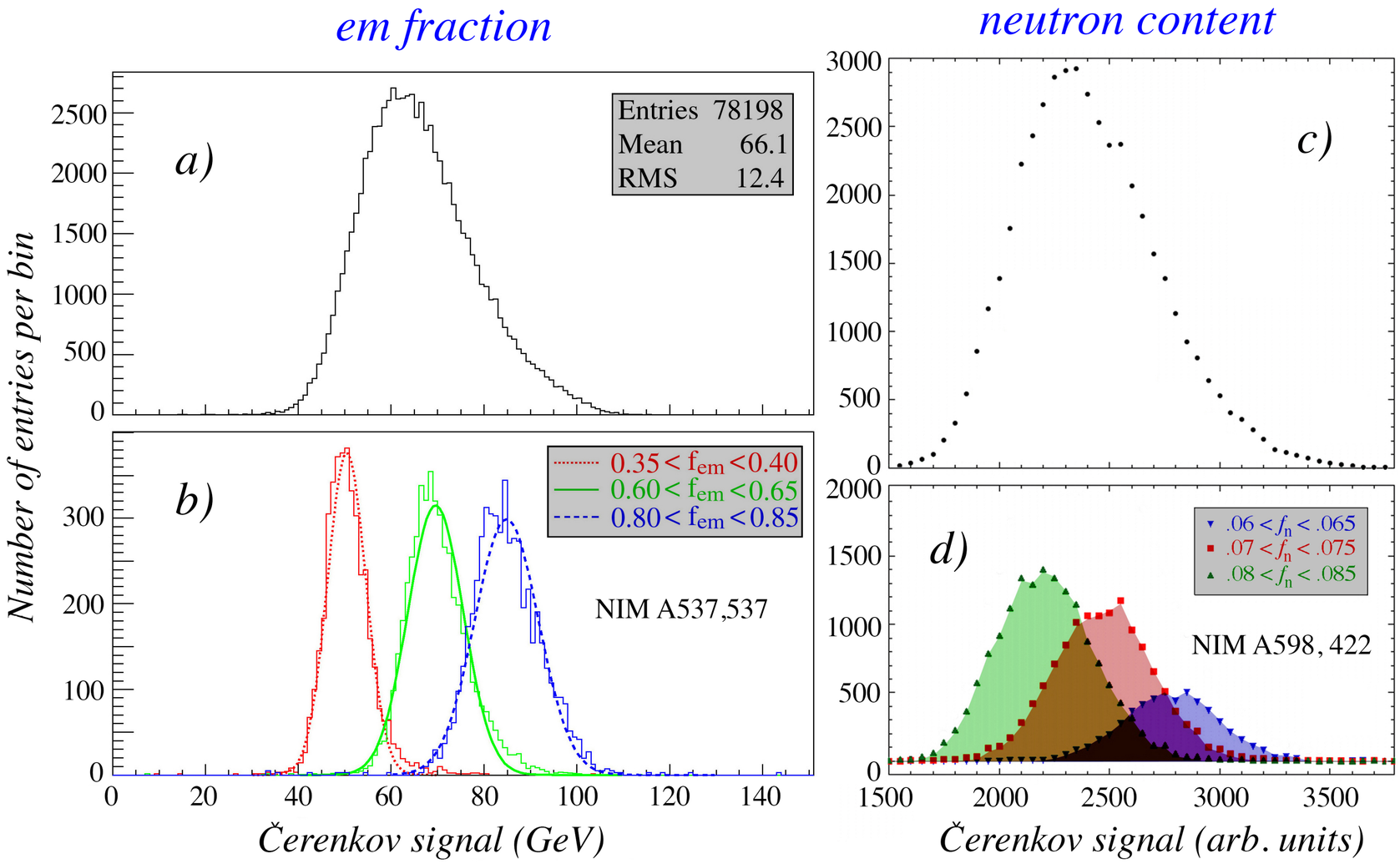




- Exploit the ratio of the Cherenkov signal (em only) and the scintillation signal (all charged particles in shower) to correct reconstructed energy event-by-event

Dual Readout

The Concept



R. Wigmans, CHEF 2017

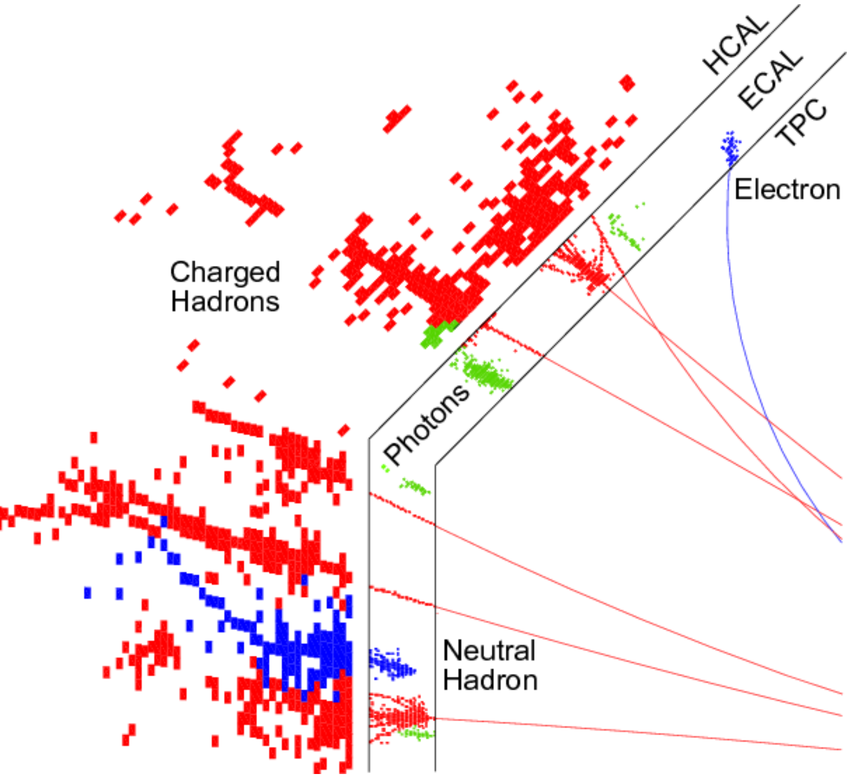
- Exploit the ratio of the Cherenkov signal (em only) and the scintillation signal (all charged particles in shower) to correct reconstructed energy event-by-event
- Studies (MC + test beam data) demonstrate that dual readout provides larger resolution improvement potential than hardware compensation

Simulation studies for FCCee: ~ 27%/√E, with additional "tricks" getting close to 20%√E - the ultimate hadron resolution

Particle Flow

The Concept

- Combining tracking and calorimetry - measure each particle in the event with the best possible precision
- Uses powerful pattern recognition in calorimeters to match tracks to clusters



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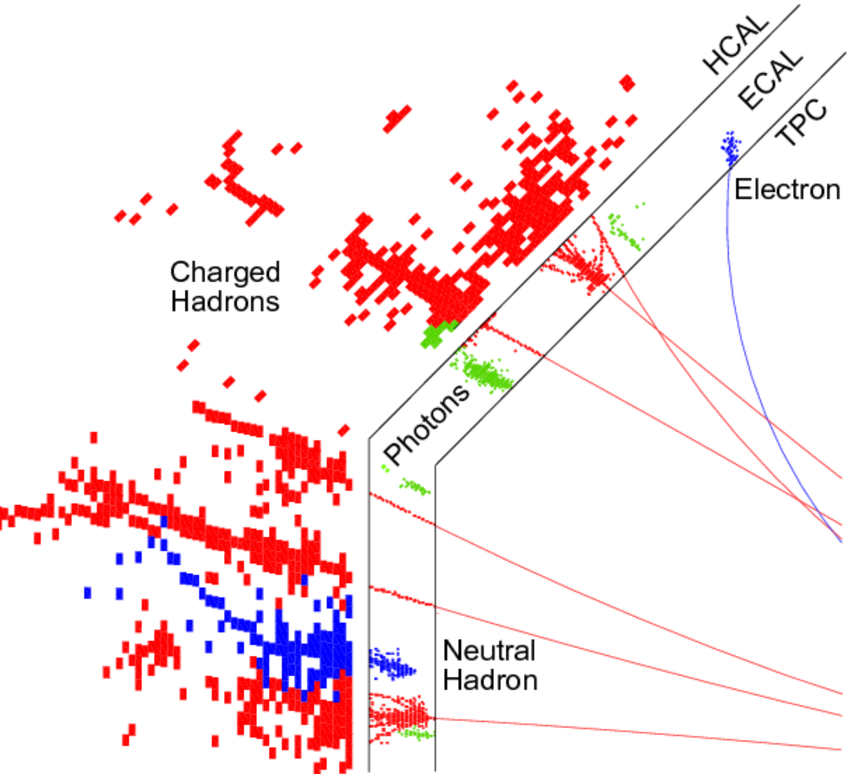

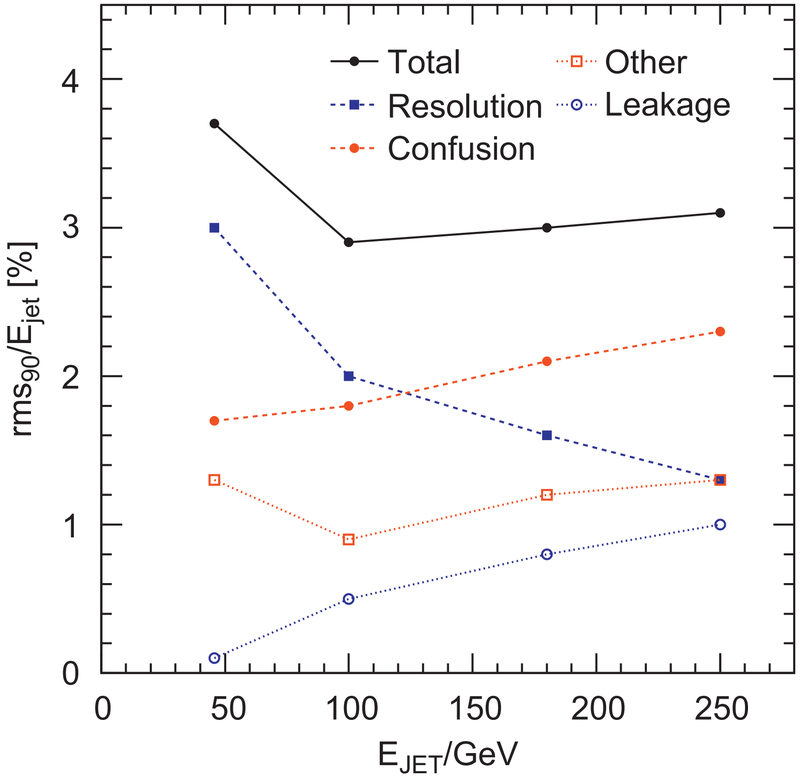

- Level of mistakes in associating calorimeter energy to particles ("confusion") is a driving factor in the overall performance

➪ High granularity in calorimeters for best pattern recognition

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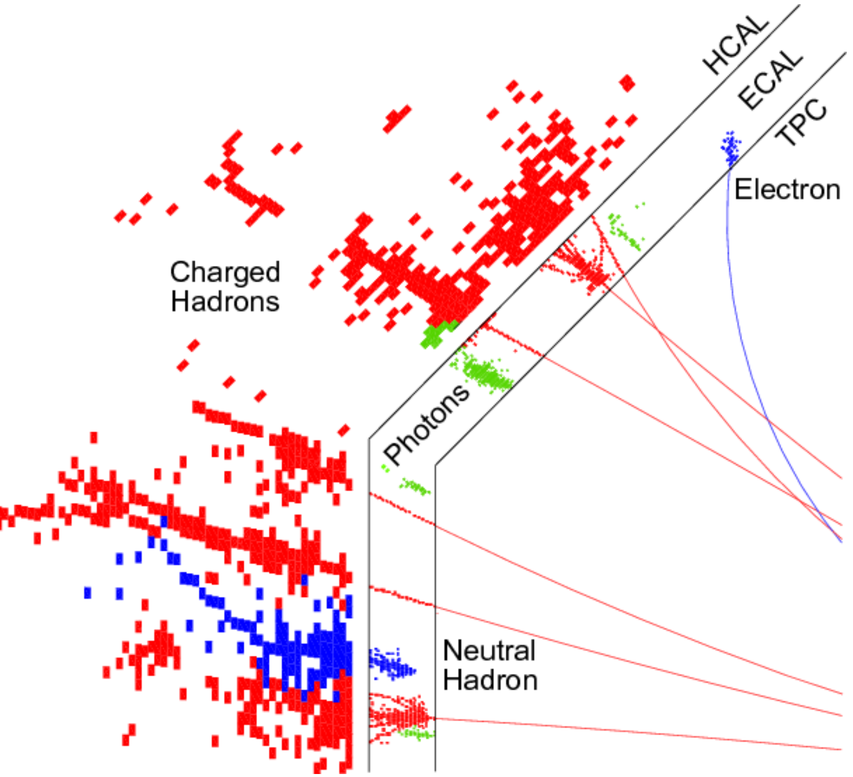

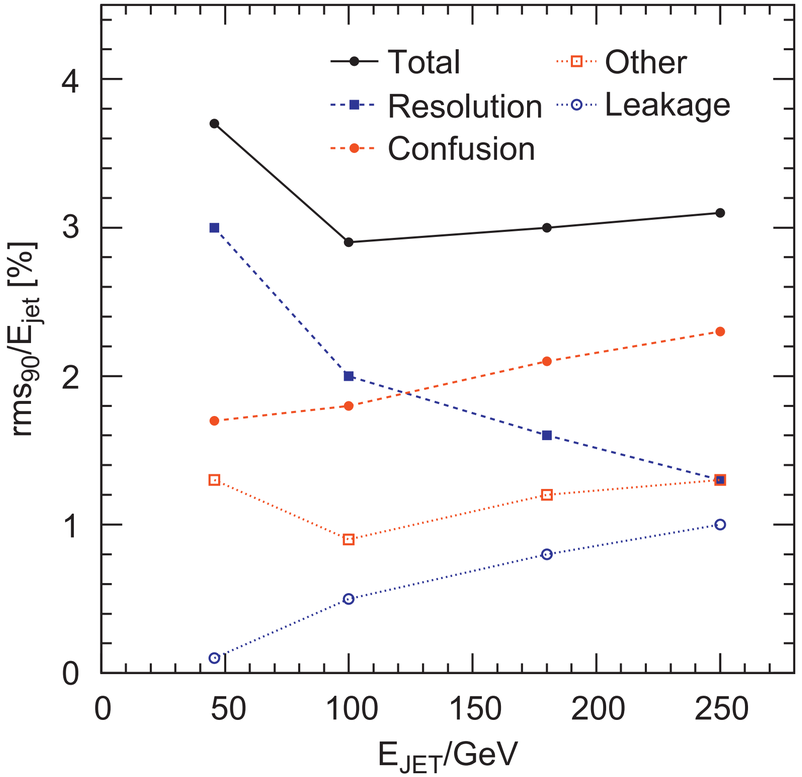

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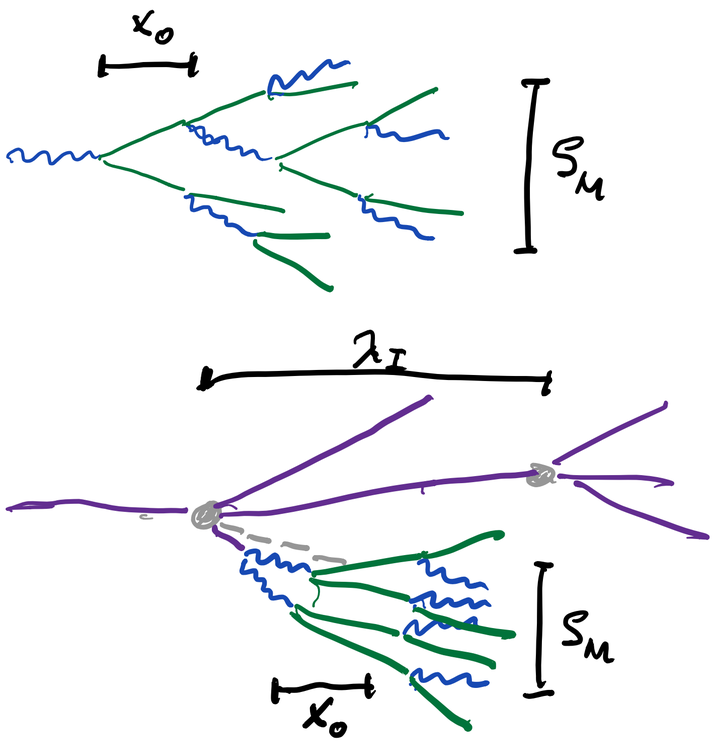
Successfully used in CMS

Highly Granular Calorimeters

Physics-driven Concept & Practical Constraints

- 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)

X_0, ρ_M => ~ *(5 mm)^3 - (30 mm)^3*

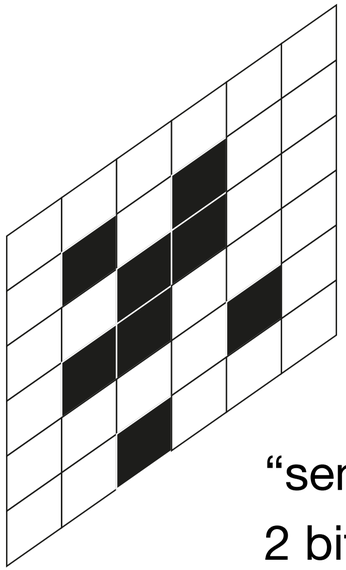


- ➪ *O* $10^{7\text{-}8}$ cells in HCAL, 10^8 cells in ECAL for typical detector systems! (compared to a few 10k - 100k for current LHC detectors)
- ➪ fully integrated electronics needed
- ➪ requires active elements that support high granularity and large channel counts
- ➪ need technical solutions amenable to mass production & automatisation

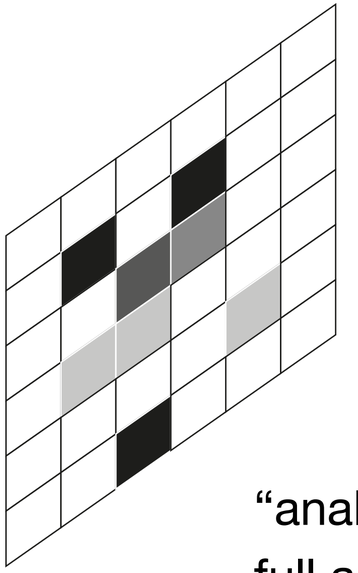
Highly Granular Calorimeters

Readout Schemes

- Different readout concepts to convert shower information into data



“digital”
counting hit cells



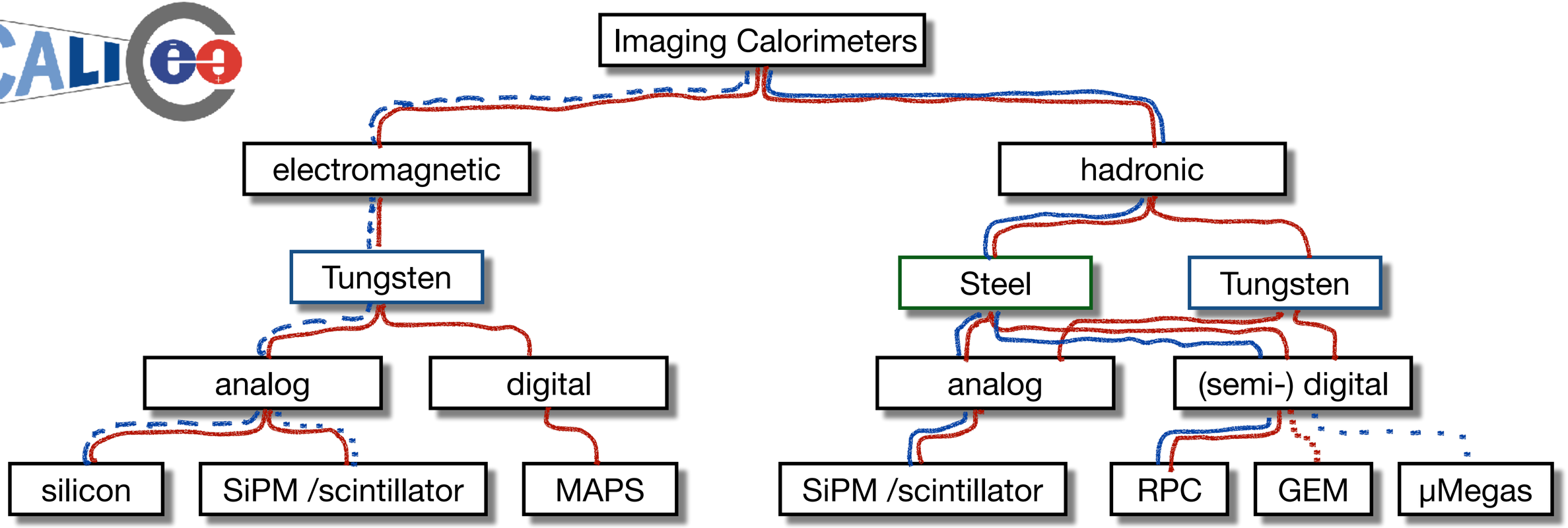
“semi-digital”
2 bits per cell:
one, a few, many particles

“analog”
full analog information
typically 14+ bits

Active elements:	gas detectors	gas detectors	Plastic scintillator elements
	Silicon pixel detectors		Silicon pad detectors

CALICE: Developing Highly Granular Calorimeters

An extensive R&D Program since 2001



physics prototype — full technological prototype — multiple layers — single / few layers

- Mapping out the “phase space” of highly granular calorimeters

Test Beams: Absolutely Crucial

CALICE Prototypes tested in Beams around the World

- Electromagnetic and hadronic calorimeter prototypes of CALICE in beams at
  - DESY (electrons)
  - CERN (muons, electrons, hadrons)
  - FNAL (muons, electrons, hadrons)
  - In addition: tests of smaller elements also at other locations:
    - ELPH (electrons)

Energies from 1 GeV up to 300 GeV

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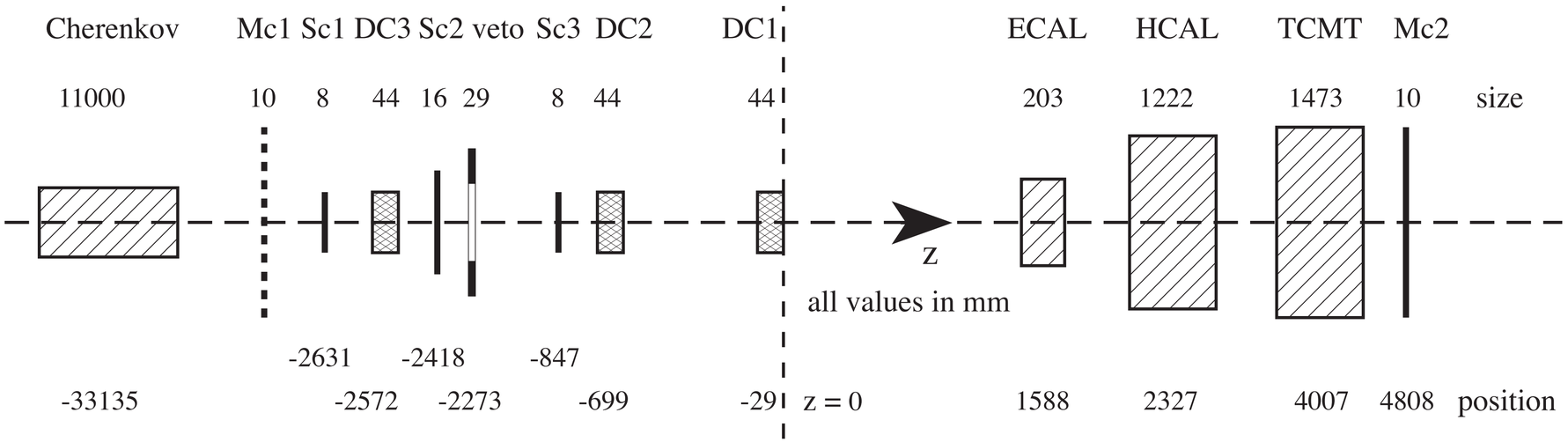
Energies from 1 GeV up to 300 GeV

very complex,
large-scale installations!



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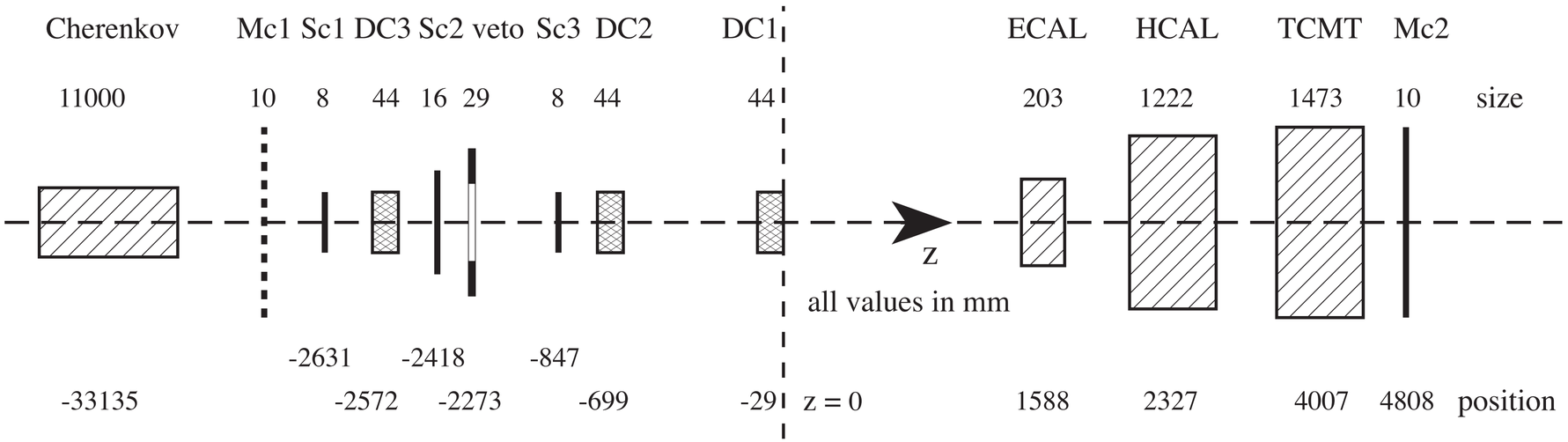


Provided an unprecedented dataset - used to validate the concepts, establish the performance, develop reconstruction techniques, study the structure of hadronic showers, …

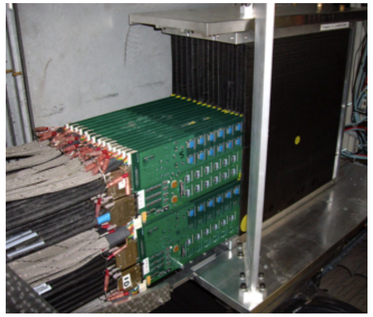
Evolving Prototypes

From Demonstration & Validation to Technical Solutions

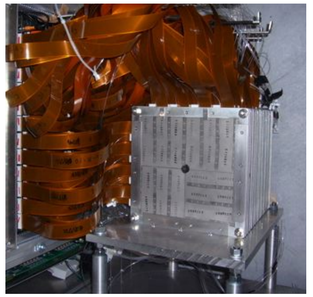
Physics Prototypes

Technological Prototypes

SiW ECAL

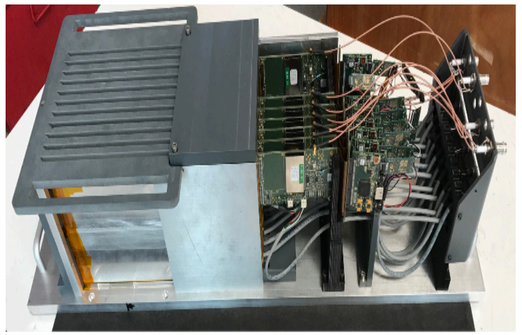


ScintW ECAL



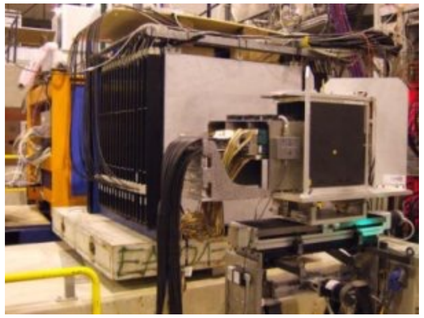
SDHCAL

SiW ECAL



2005 — 2006 — 2007 — 2008 — 2010 — 2012 — 2018 — year of (first) TB

AHCAL



DHCAL

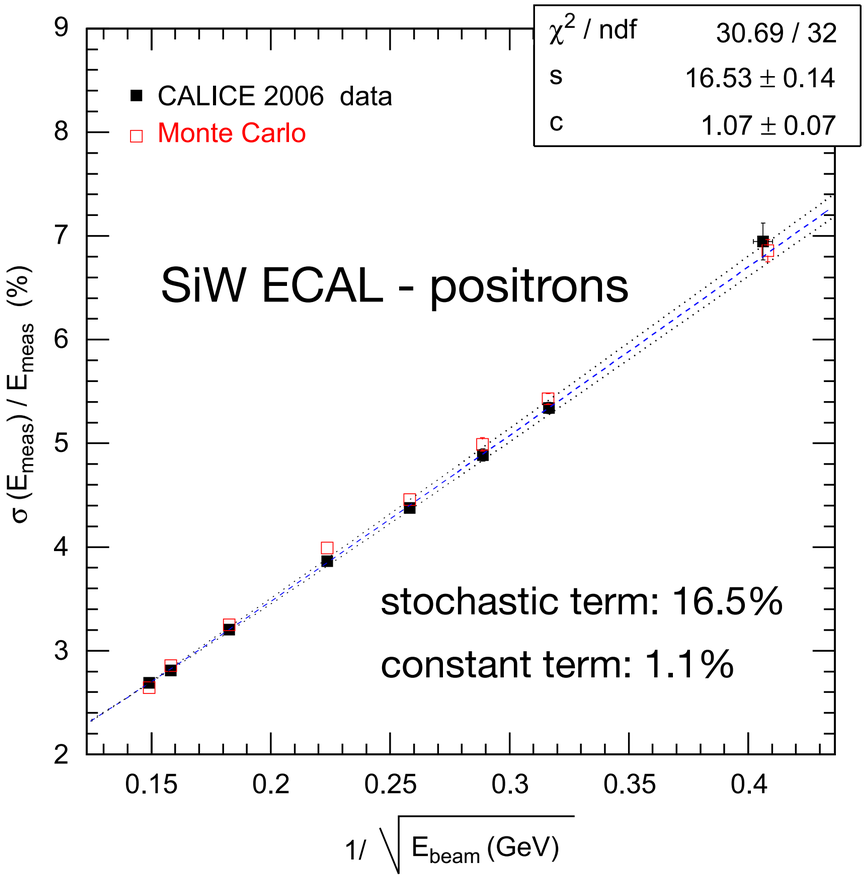
AHCAL

also: W-AHCAL also: W-DHCAL

CALICE Detectors: Performance

Selected Examples - All from Test Beams

- Energy resolution



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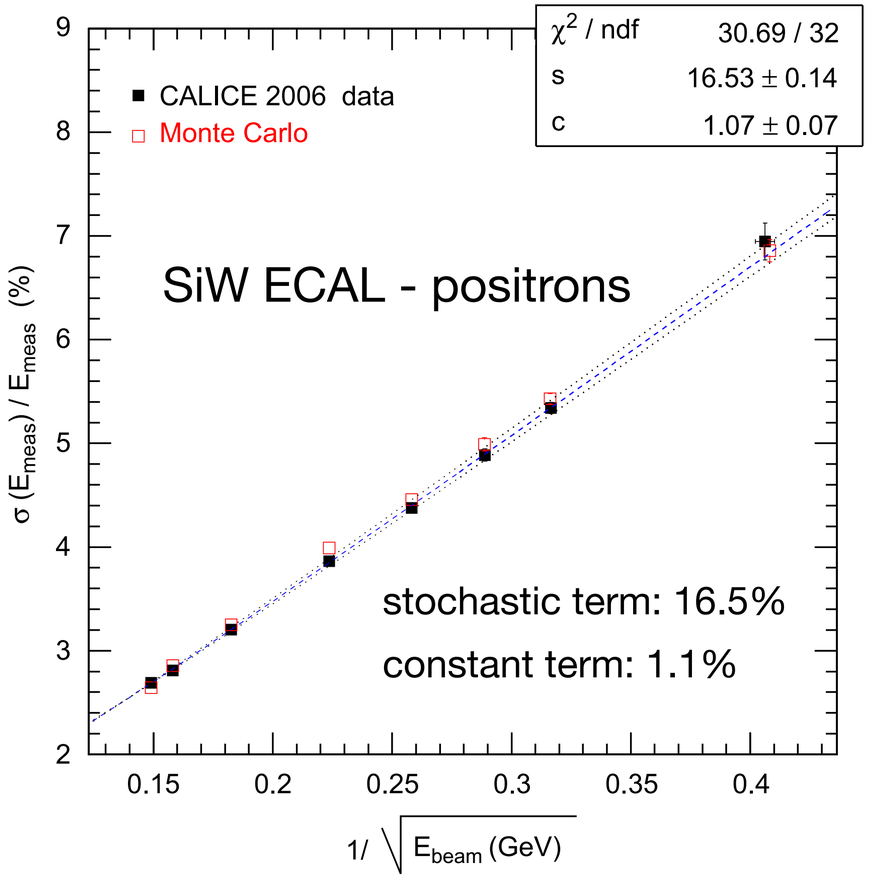
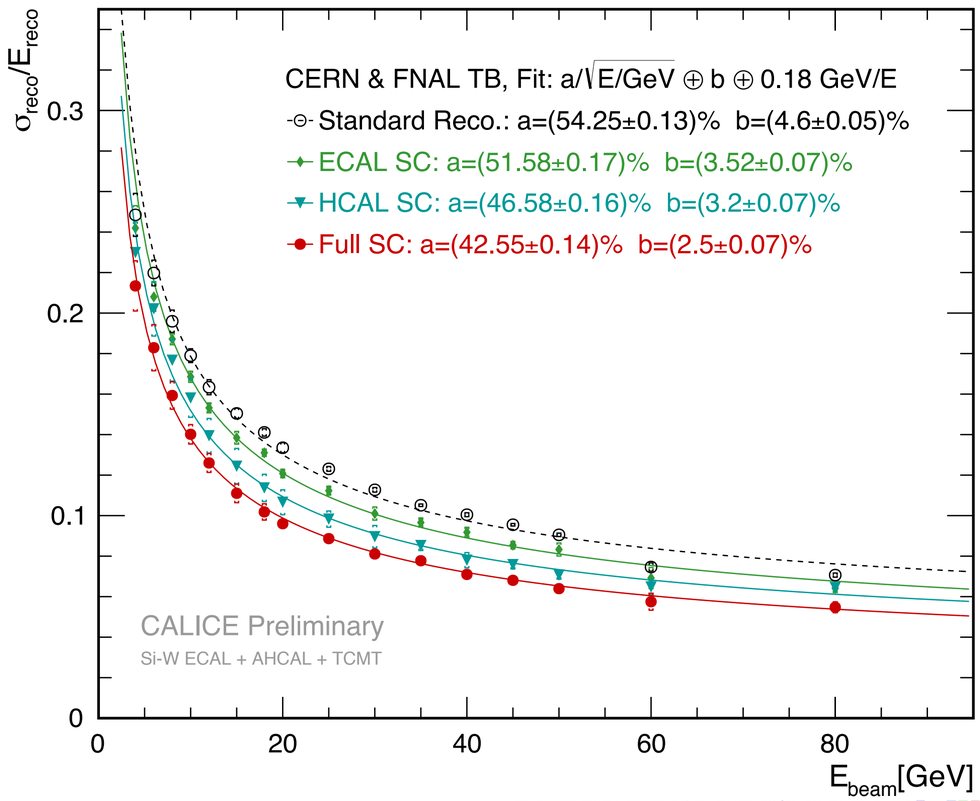
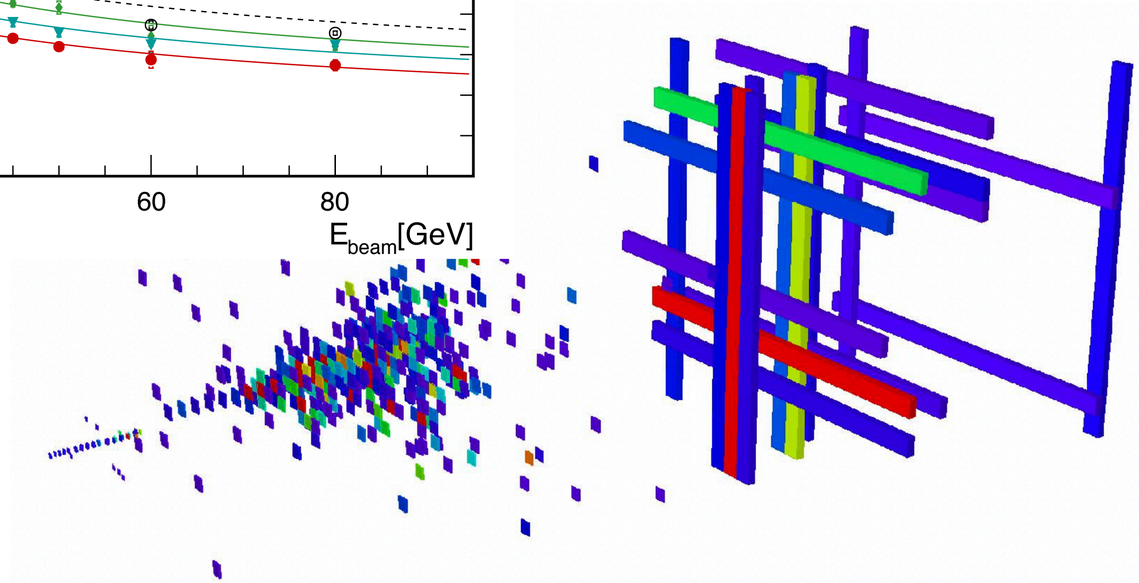




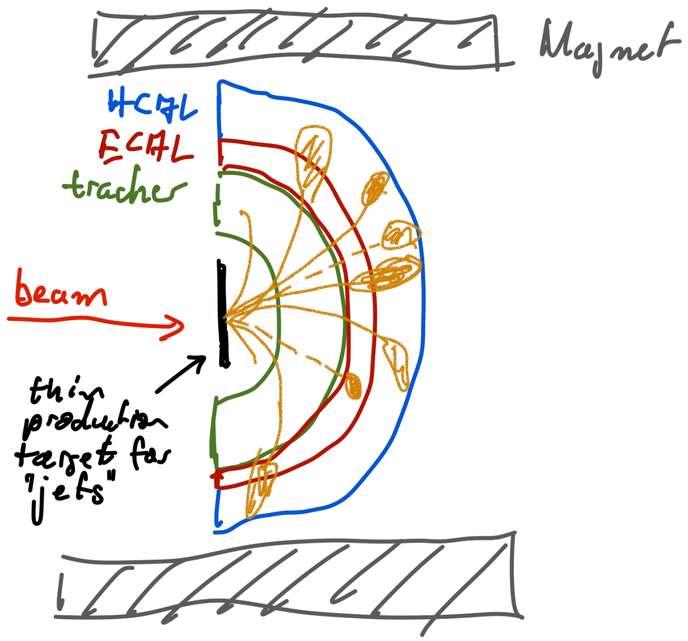
SiW ECAL + AHCAL - pions
local software compensation
using energy density to
improve resolution



CALICE Detectors: Performance

Establishing PFA Performance

- A fully realistic test of PFA in a test beam is (close to) impossible
  - requires “jets”, tracking and momentum measurement & calorimetry covering all particles



… and even with such a setup there are limitations:
jet energy not very well defined, particle composition, …

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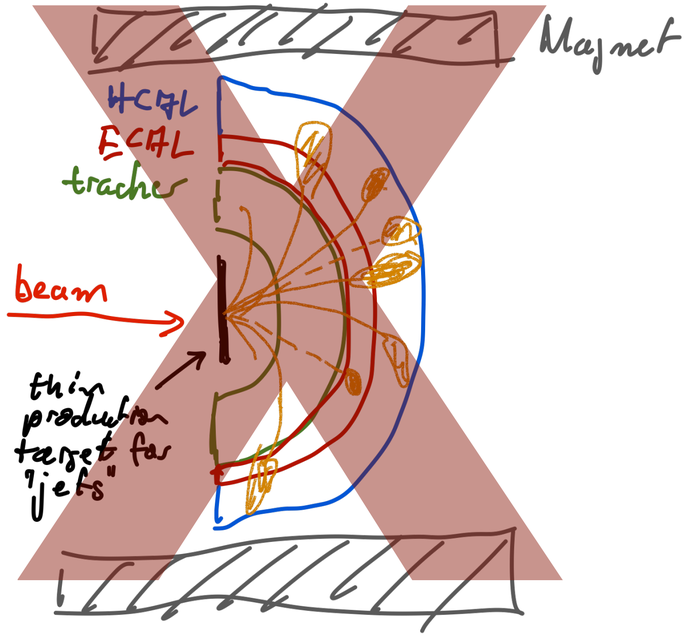
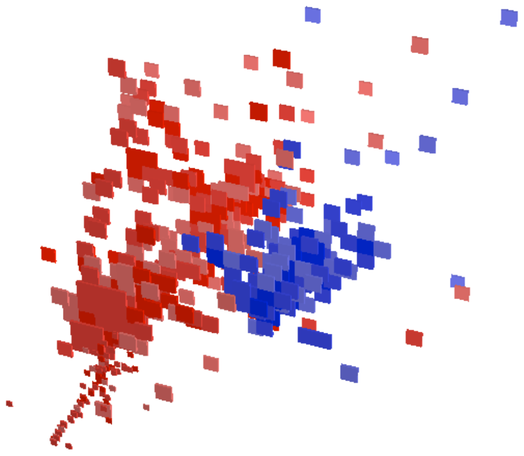
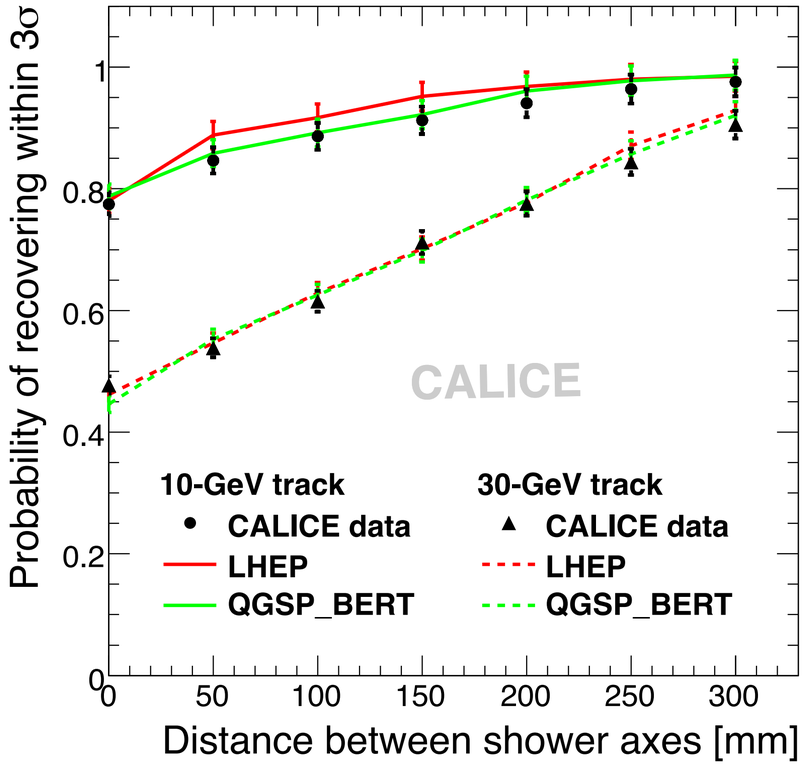


… and even with such a setup there are limitations:
jet energy not very well defined, particle composition, …

➪ Factorize the problem: Full PFA in simulations, test individual ingredients in beams





For calorimeters: Energy reconstruction, resolution and two-particle separation

Towards Technical Realization

Focusing on the CALICE AHCAL

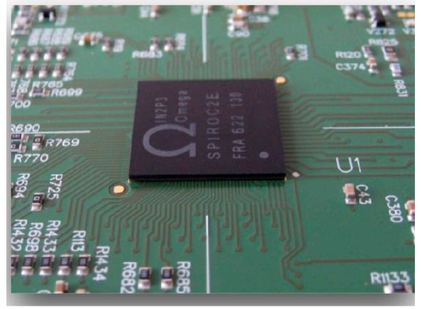
Technical Realisation

Need to establish suitability of technology for real-life constraints

Physics prototypes

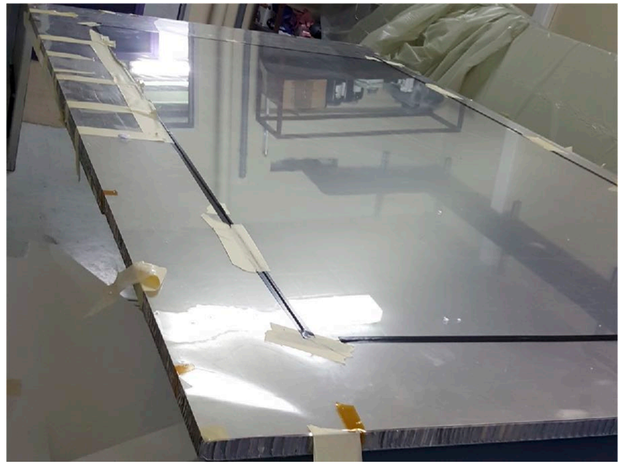
integration

scalability to large areas, automatisation



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

Large RPCs
SDHCAL prototype



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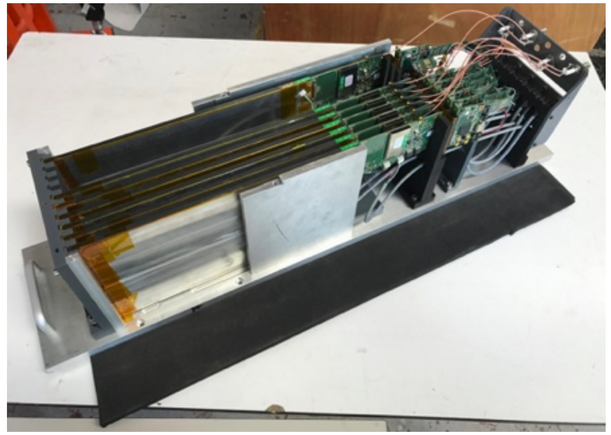
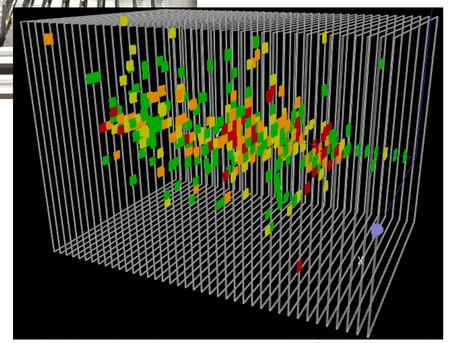


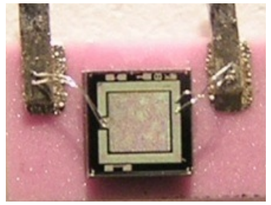
AHCAL prototype

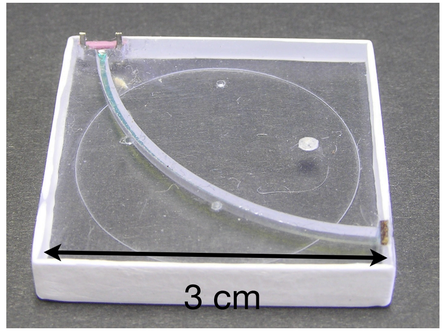


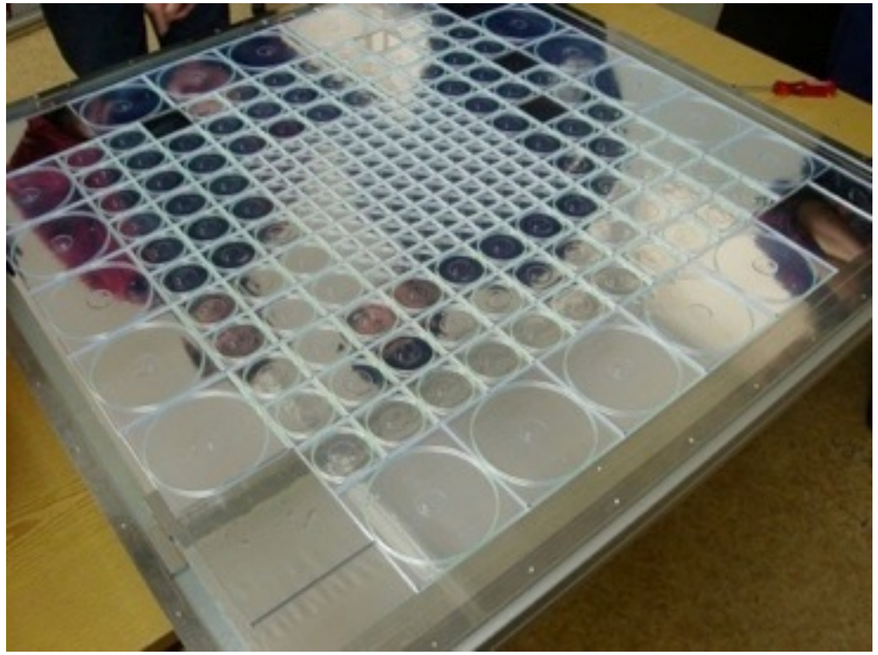
Evolution of the Analog HCAL

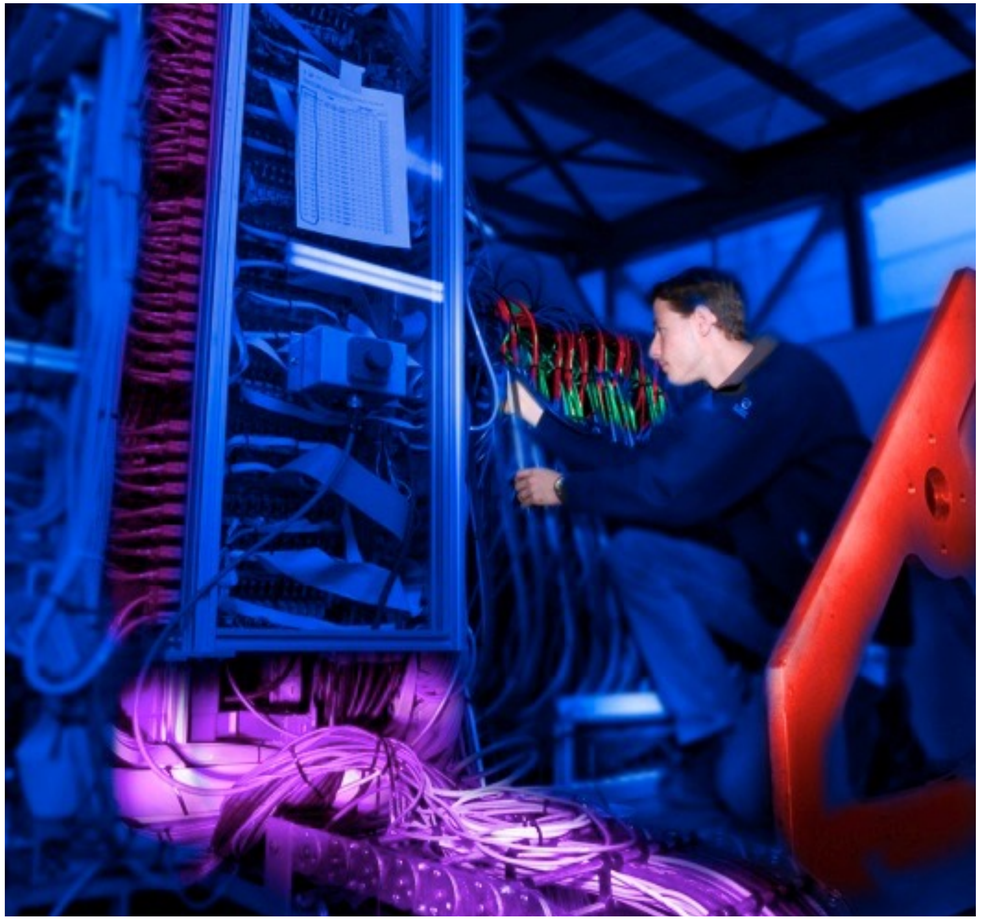
A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- The starting point: The Analog HCAL physics prototype
  - The first large-scale use of SiPMs in HEP: ~ 8000 SiPMs in detector









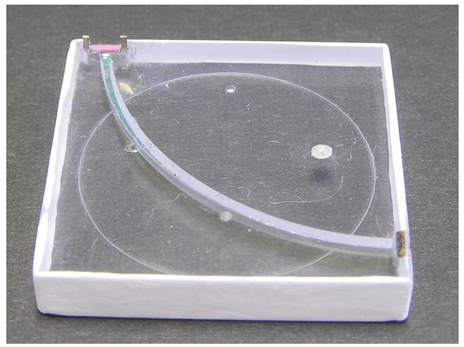
- A scintillator - steel sampling calorimeter
- Developed for experiments at Linear Colliders

Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

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

2008 - 2016



Physics Prototype

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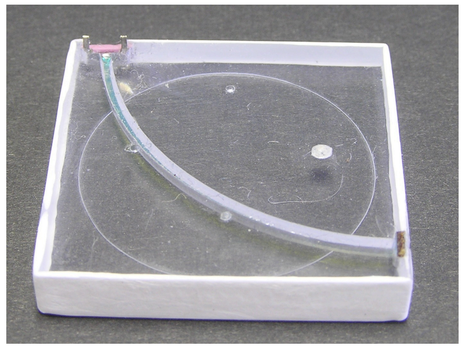

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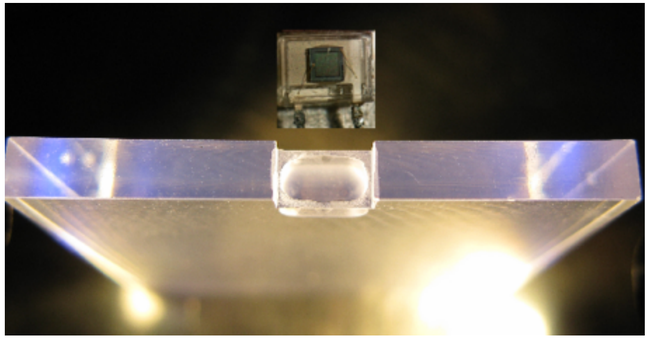

Direct coupling of tiles and photon sensors

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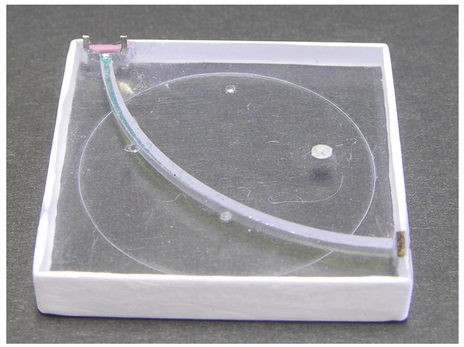

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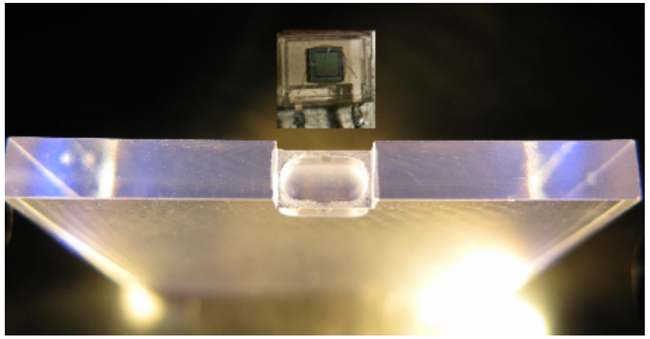

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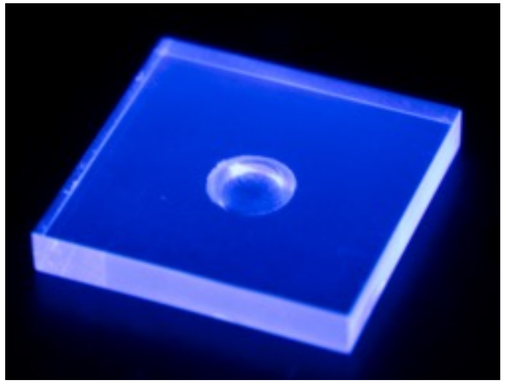

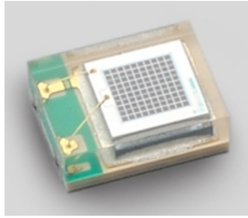

SMD SiPMs, modification of direct coupling

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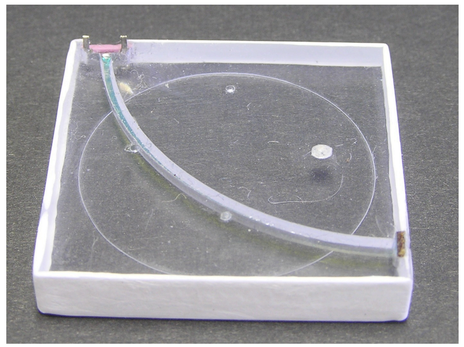

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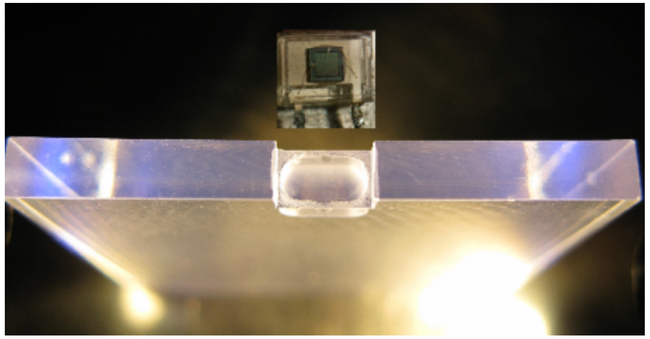

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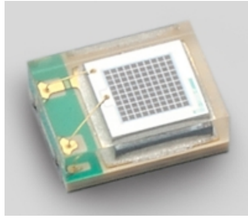

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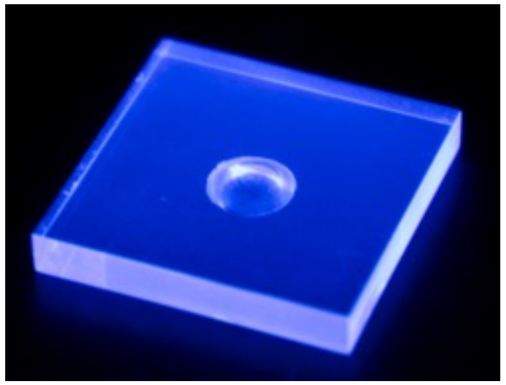
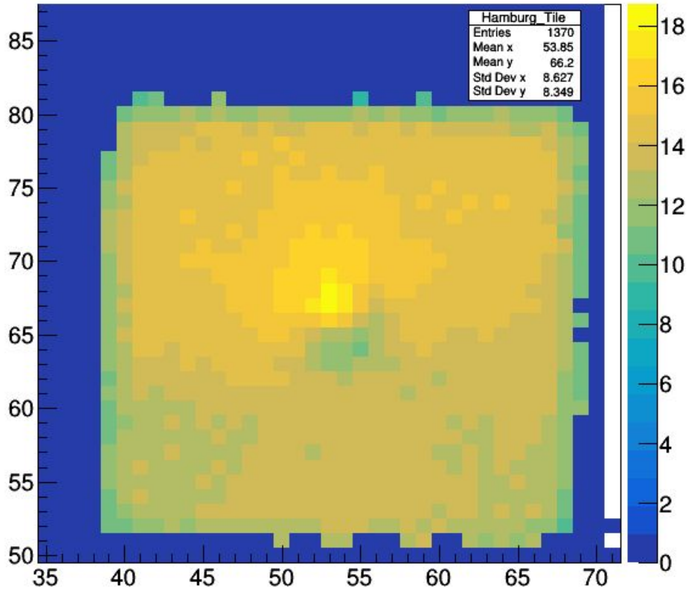


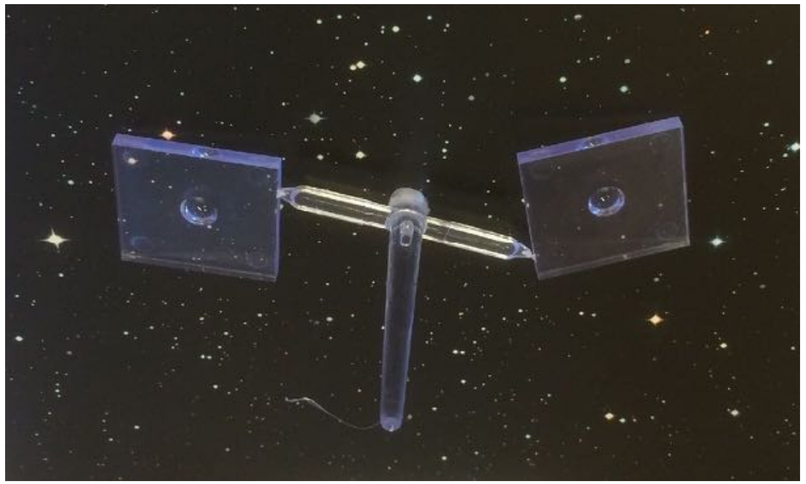


verification of tile performance in the lab

Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- Mass production for a new 0.5 m^3, 22k channel prototype
  - 24k tiles produced & wrapped



injection molding of PS based scintillator tiles

09/2017

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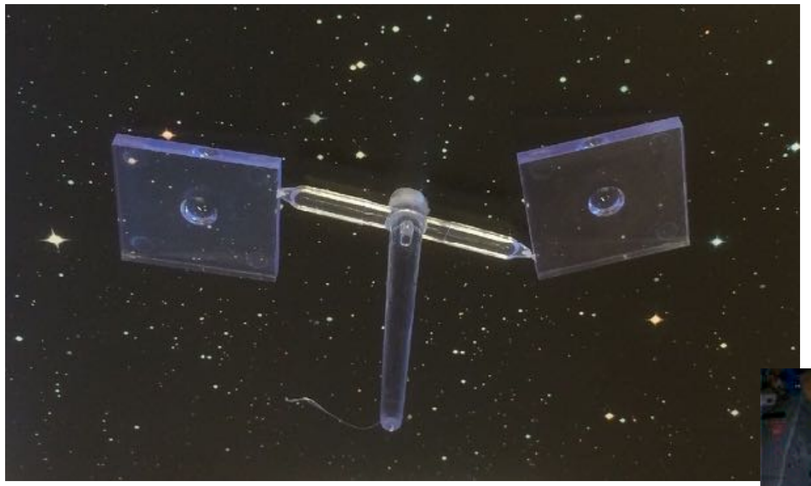

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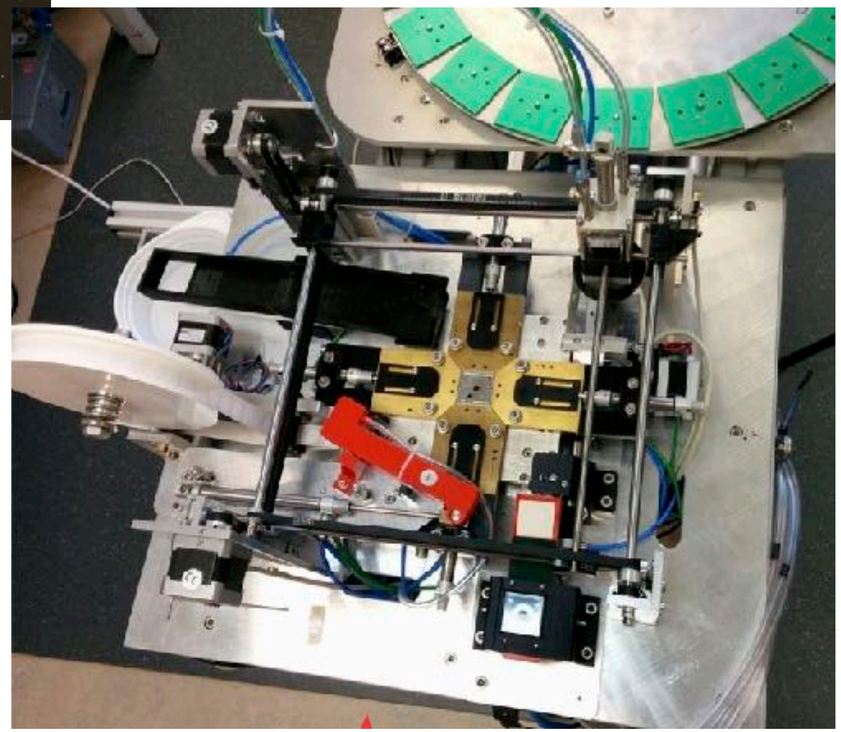


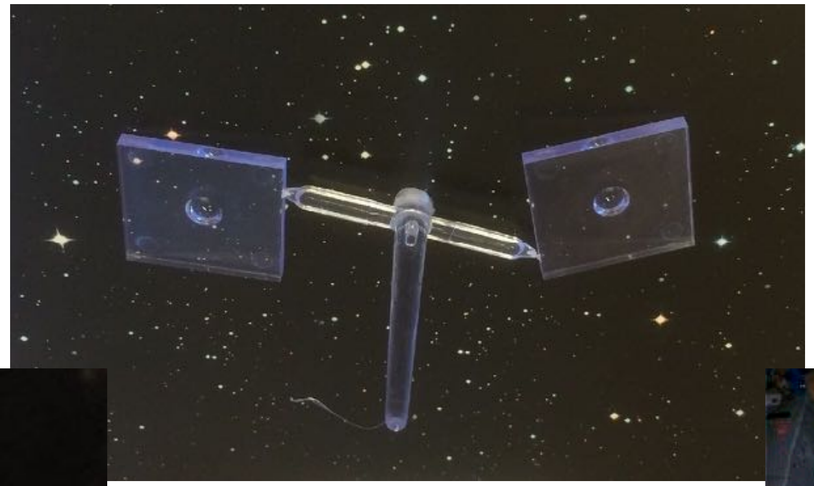
10/2017 - 01/2018

semi-automatic wrapping of scintillator tiles

Evolution of the Analog HCAL

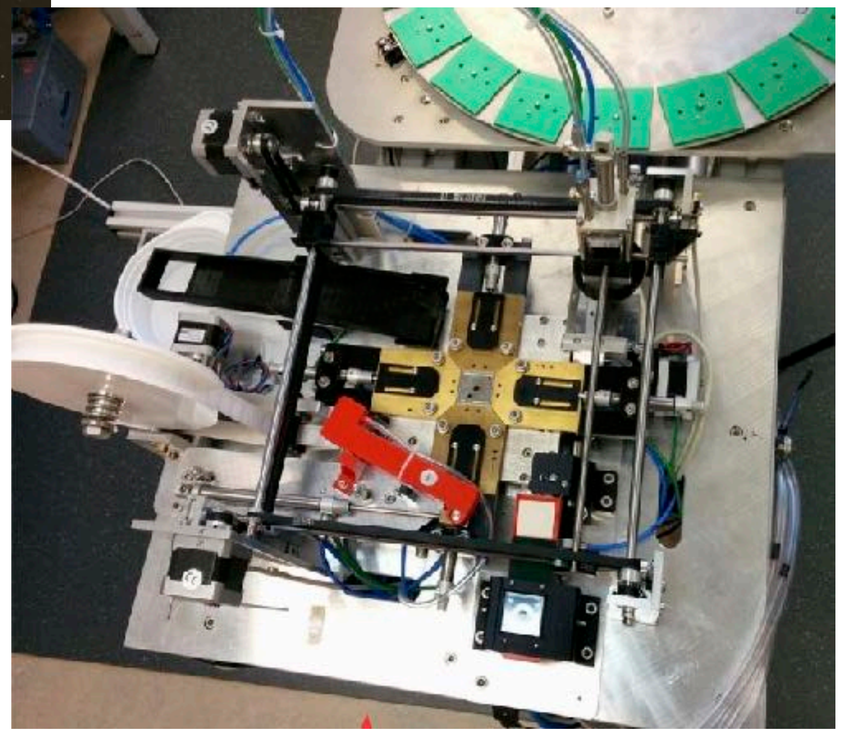
A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- Mass production for a new 0.5 m^3, 22k channel prototype
  - 24k tiles produced & wrapped



injection molding of PS based scintillator tiles

09/2017



10/2017 - 01/2018

semi-automatic wrapping of scintillator tiles

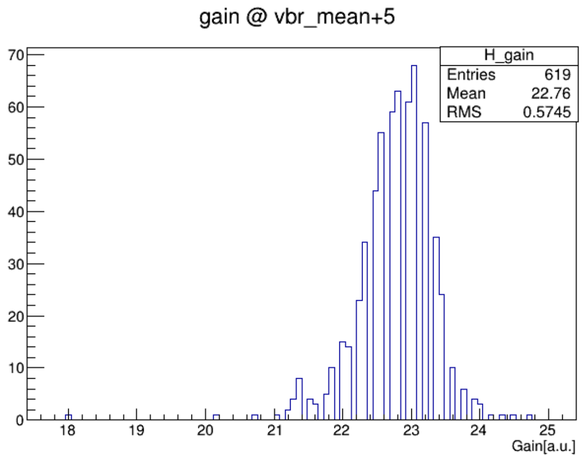
automatic placement of tiles on electronics board (HBU), fully assembled with SiPMs and ASICs

11/2017 - 02/2018

Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- A multi-step QA procedure



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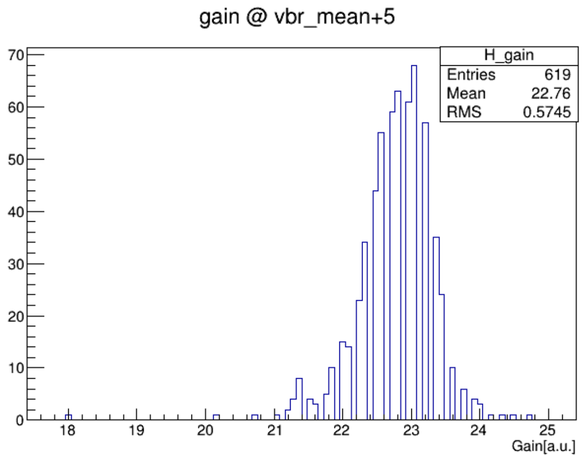

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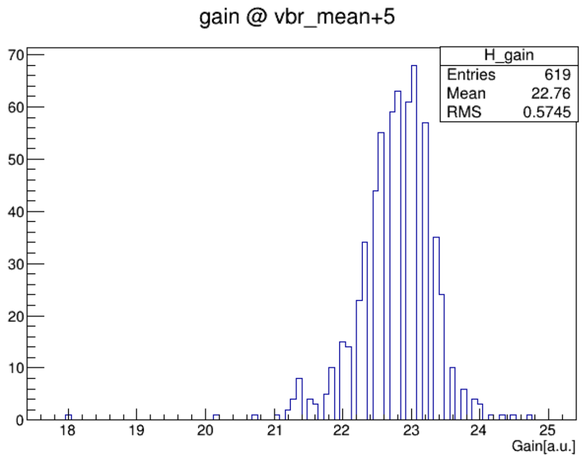

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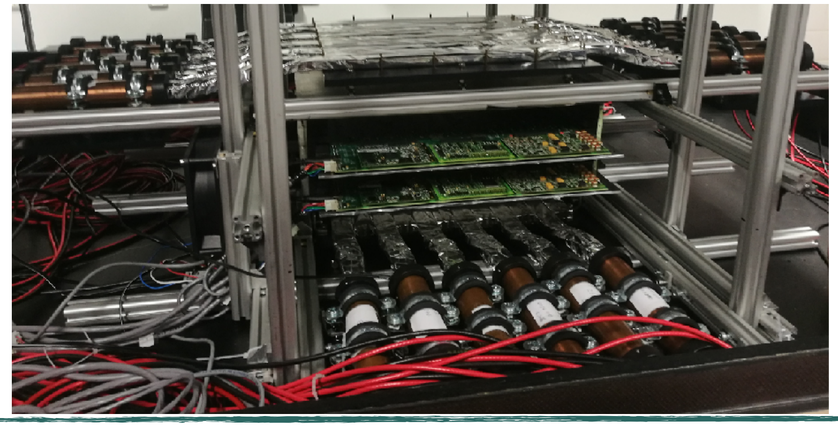


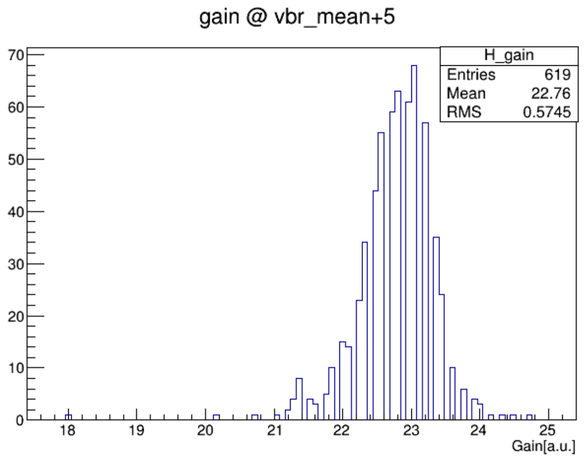
test and calibration of all channels with cosmics

Evolution of the Analog HCAL

A Demonstration of the Scalability of Highly Granular Calorimeter Technologies

- A multi-step QA procedure

integration of layers & interfaces,
test & calibration ***in beam at DESY***



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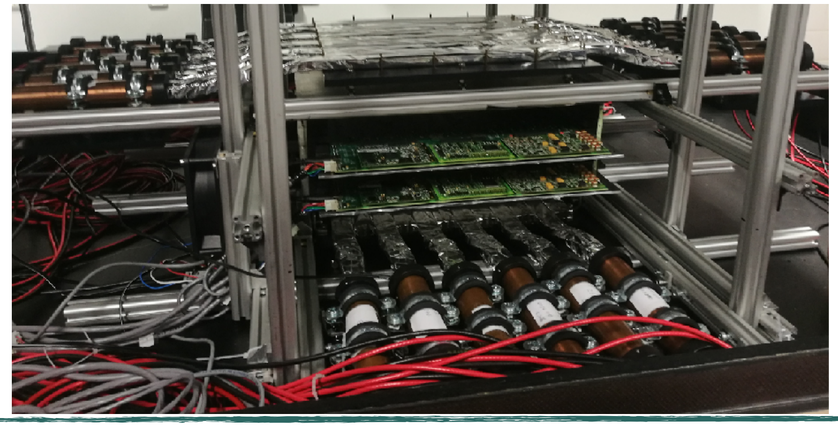

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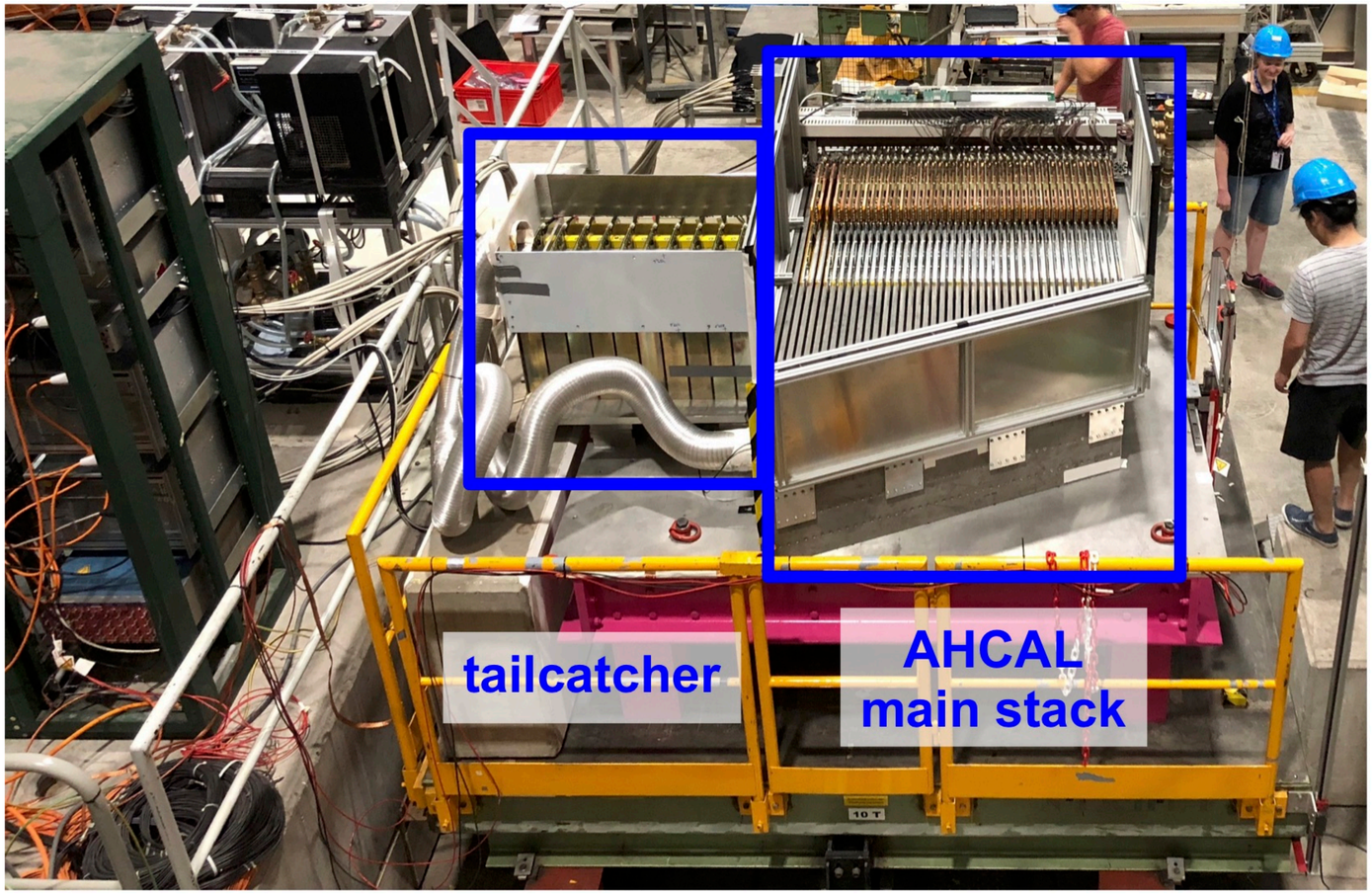
The CALICE AHCAL Prototype

Successful Test Beams

- In May and June 2018: Test beam at CERN SPS - the smoothest CALICE test beams ever.



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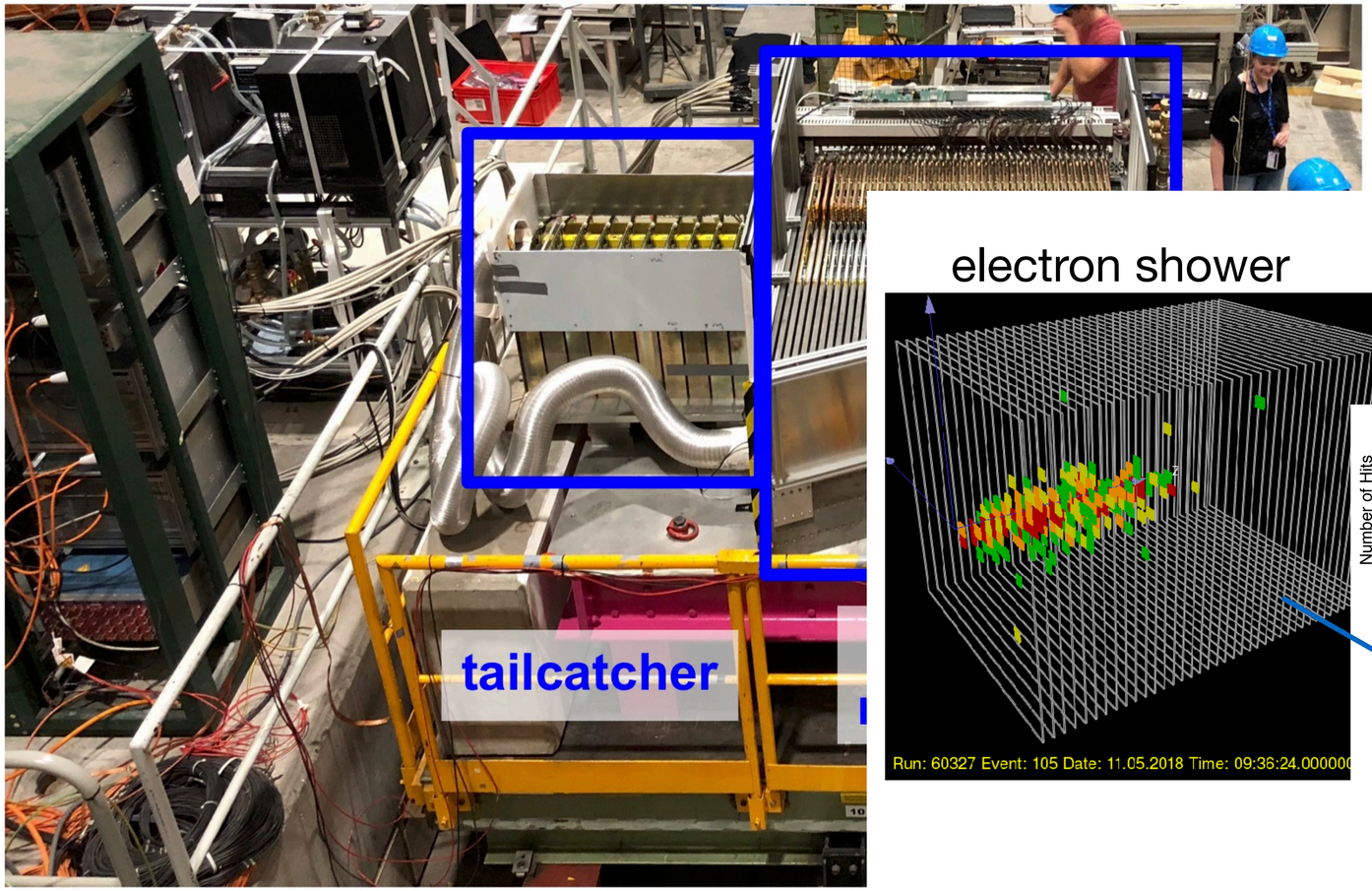
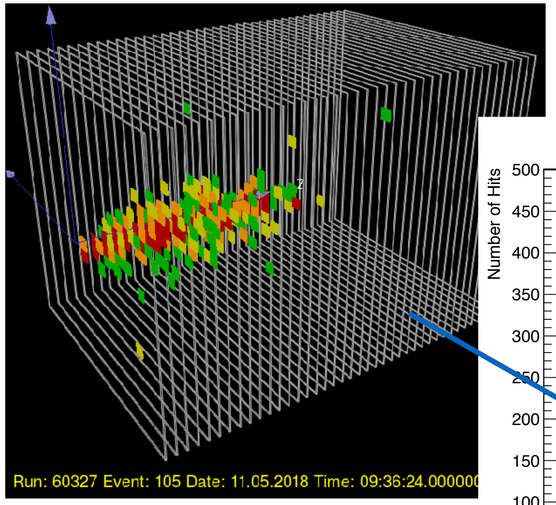
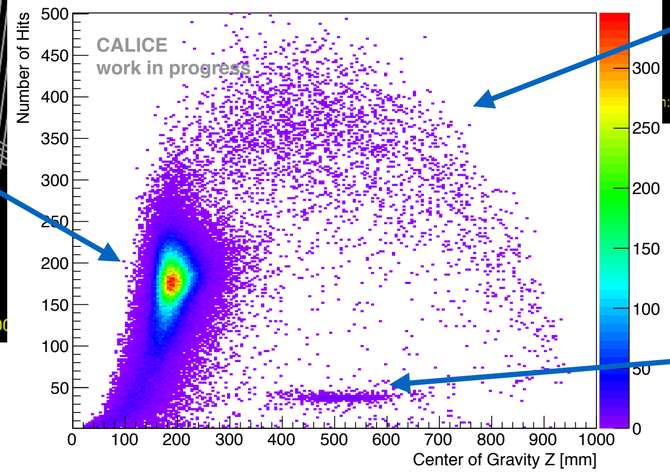


electron shower

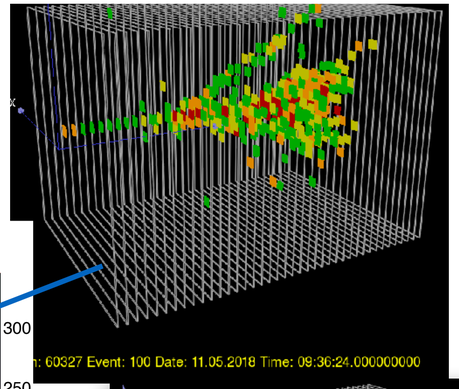


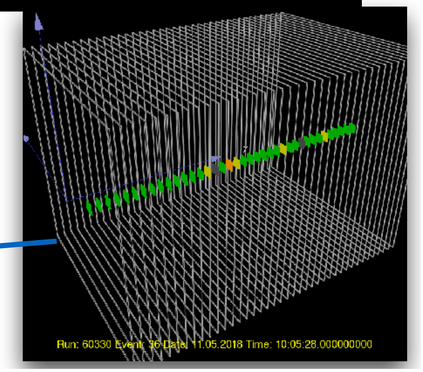
online data

50 GeV electron beam with pion and muon contamination



pion shower





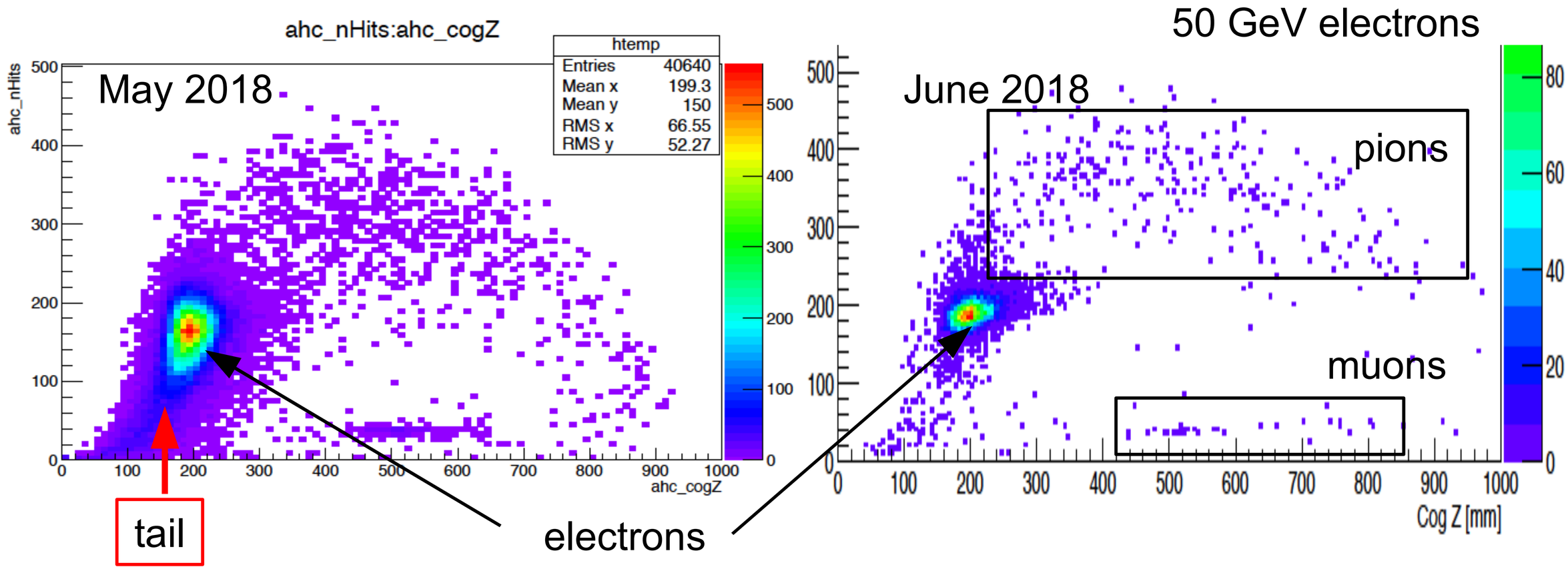
muon track

- Analysis ongoing - first results soon

Test Beams: Care Needed!

Quality of the Results depends on Quality of Beam

- A lesson from the AHCAL test beam: electron shower distributions looked “weird” in May 2018



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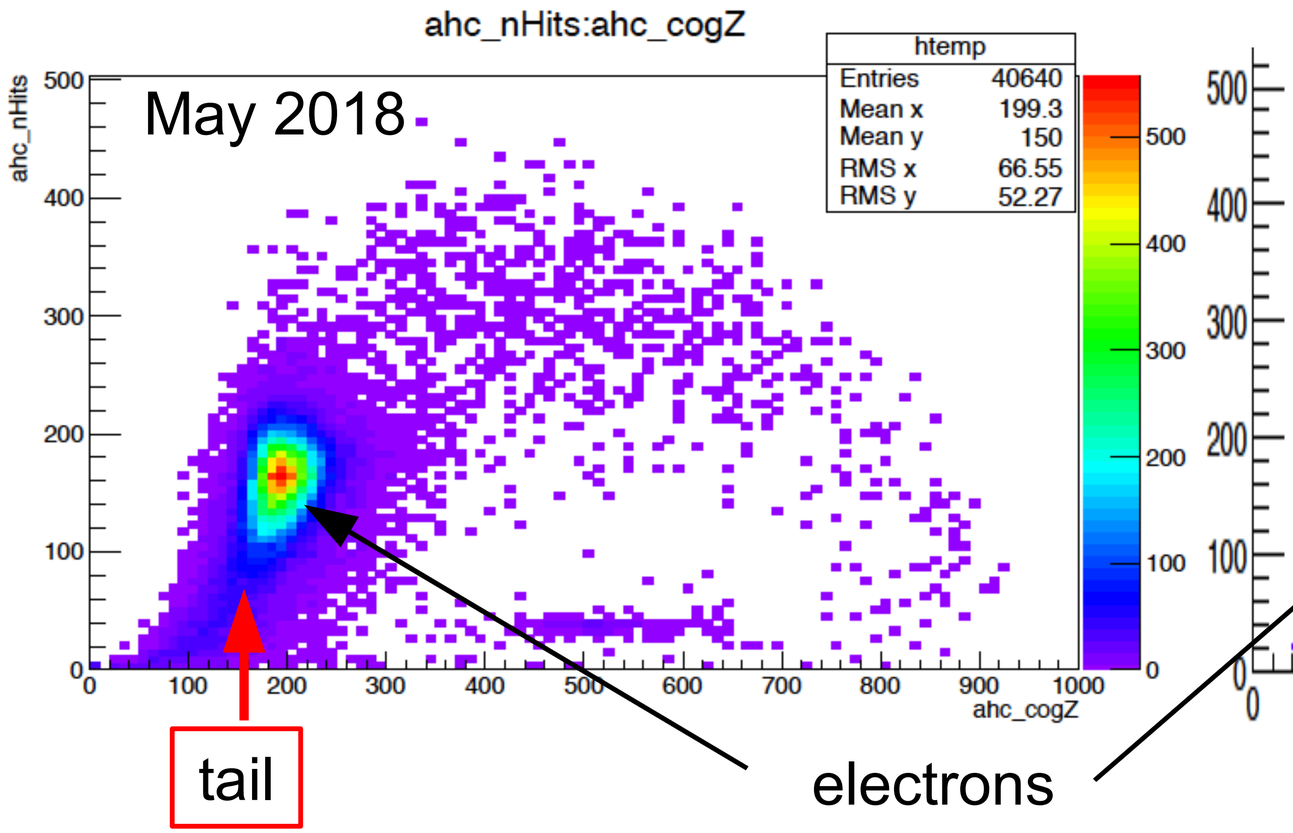

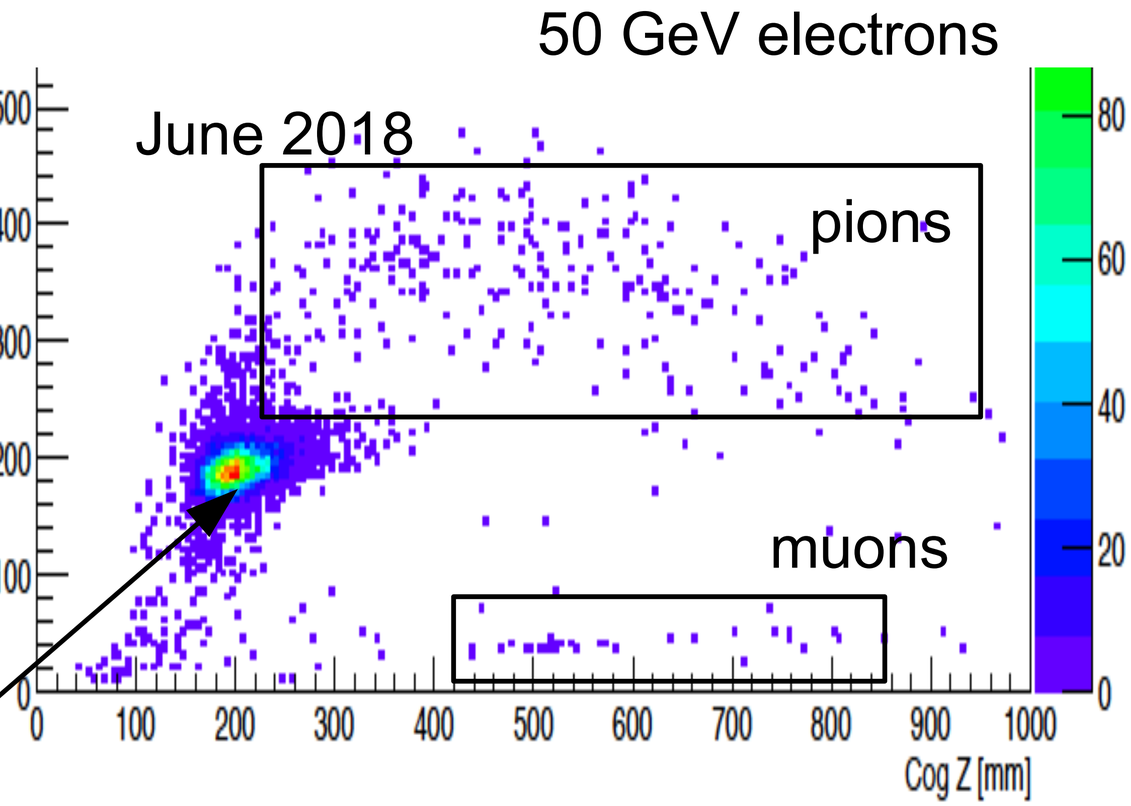

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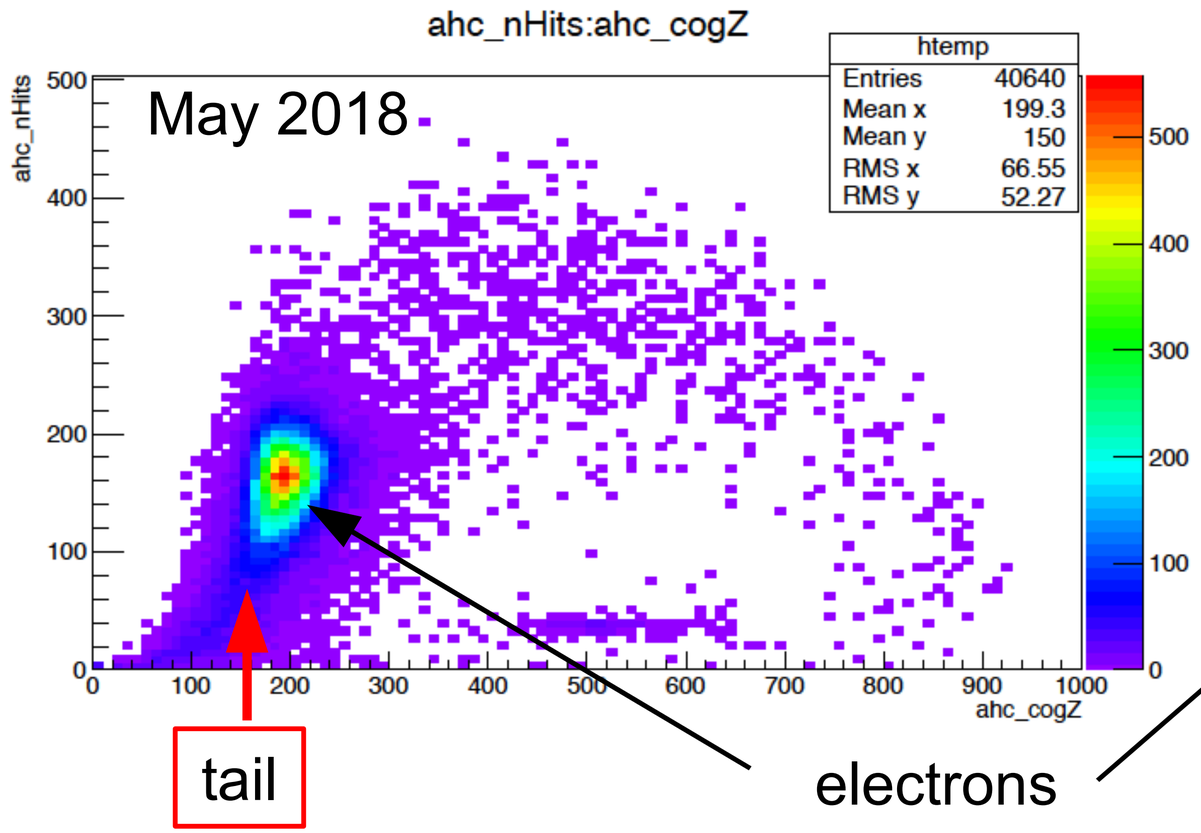

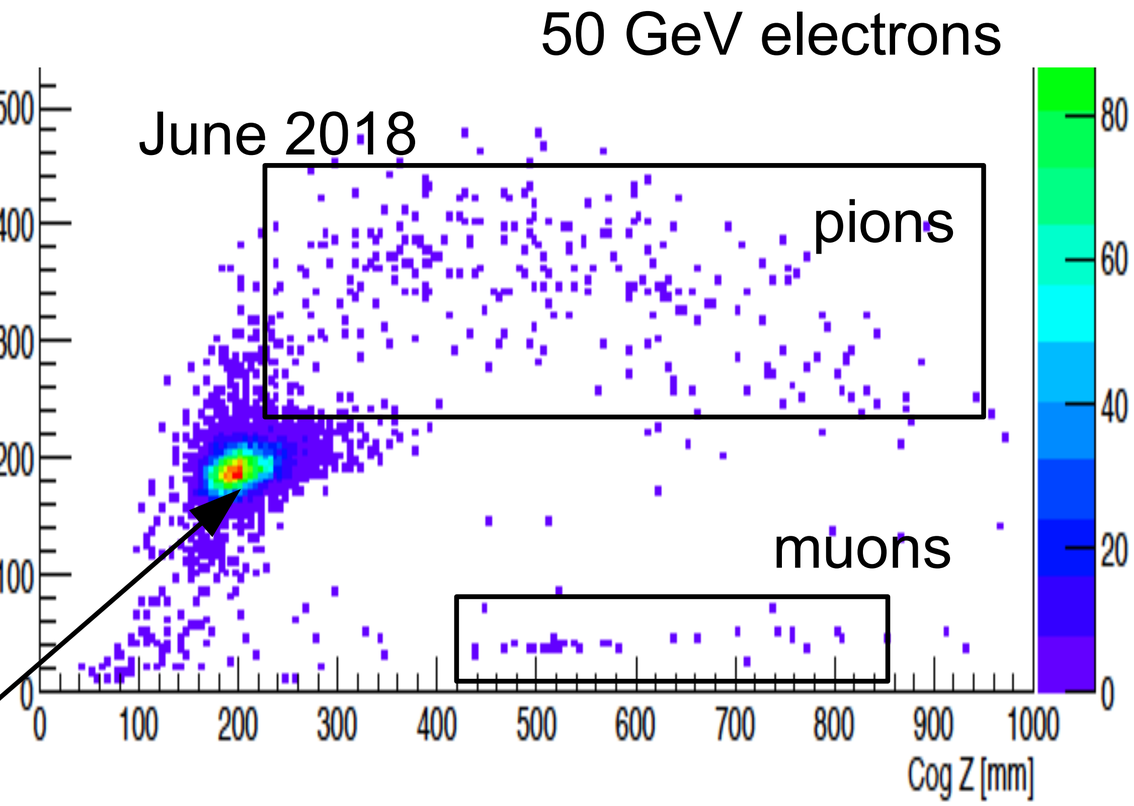

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Lessons: Online or fast offline analysis crucial! Also question the quality of the beam!

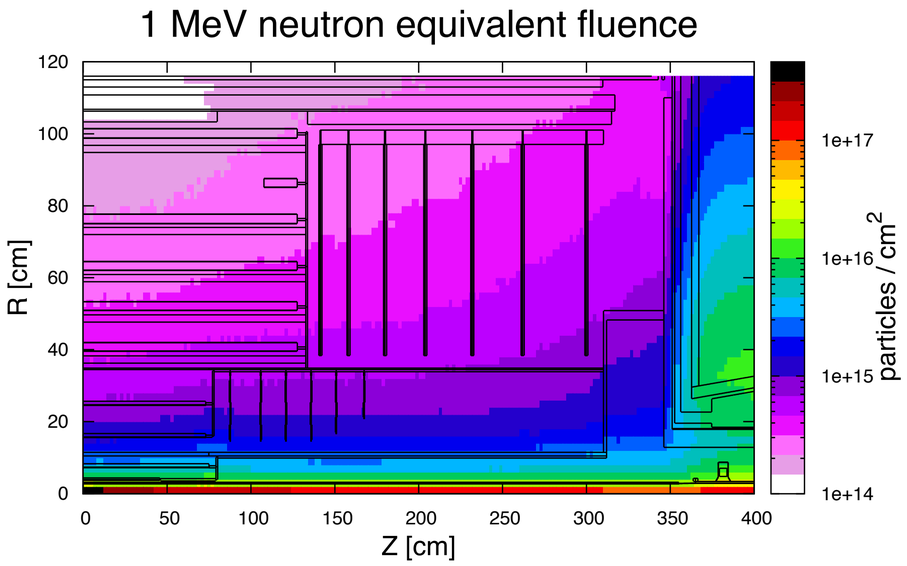
Calorimeter Upgrades for HL-LHC

Focusing on: The CMS HGCAL

Calorimetry at the HL-LHC

Main Challenges

- The radiation environment



- High pileup & high particle multiplicity

- The goal of Phase II upgrades: (at least) retain the present performance in the HL-LHC phase

But: calorimeters are very large items in the overall experiments, difficult (or almost impossible in case of LAr) to access, costly to exchange

➪ Where possible leave detector hardware unchanged, replace electronics to increase speed, granularity, …

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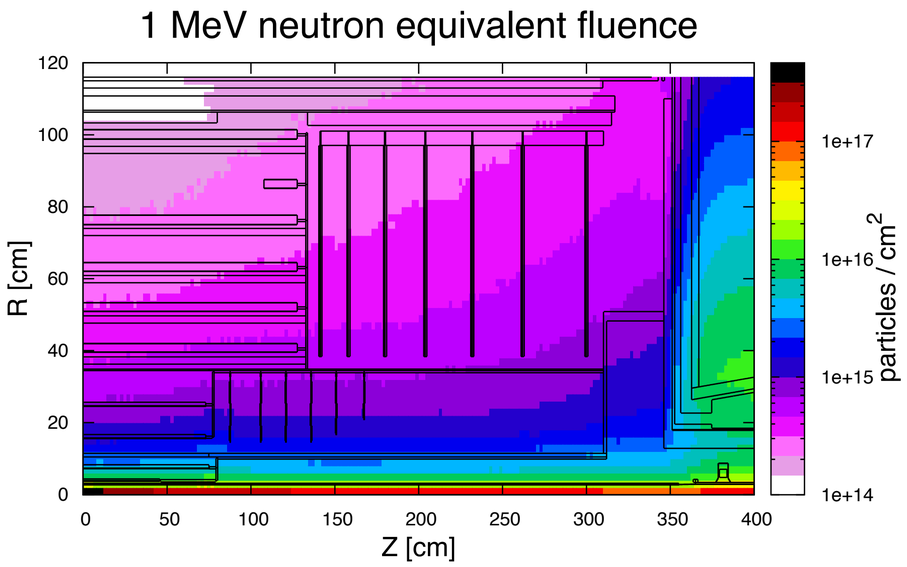

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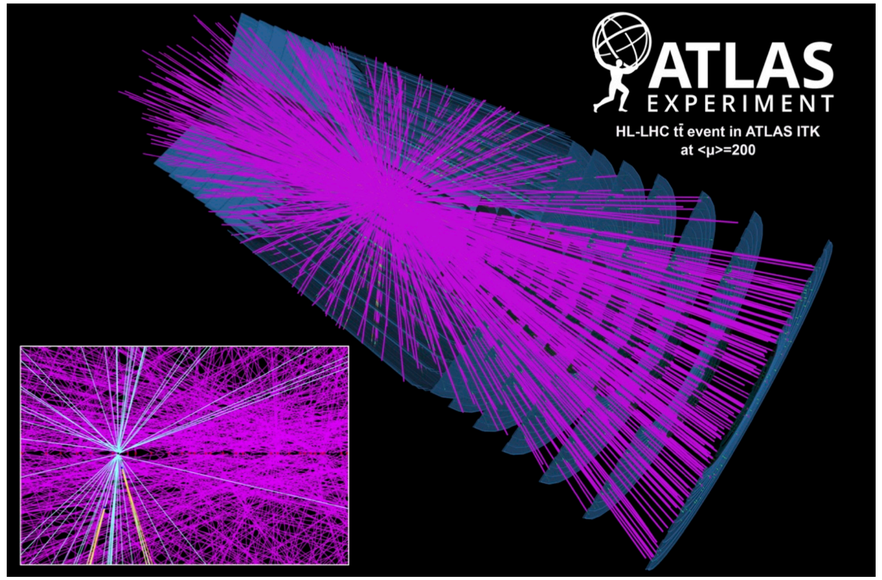

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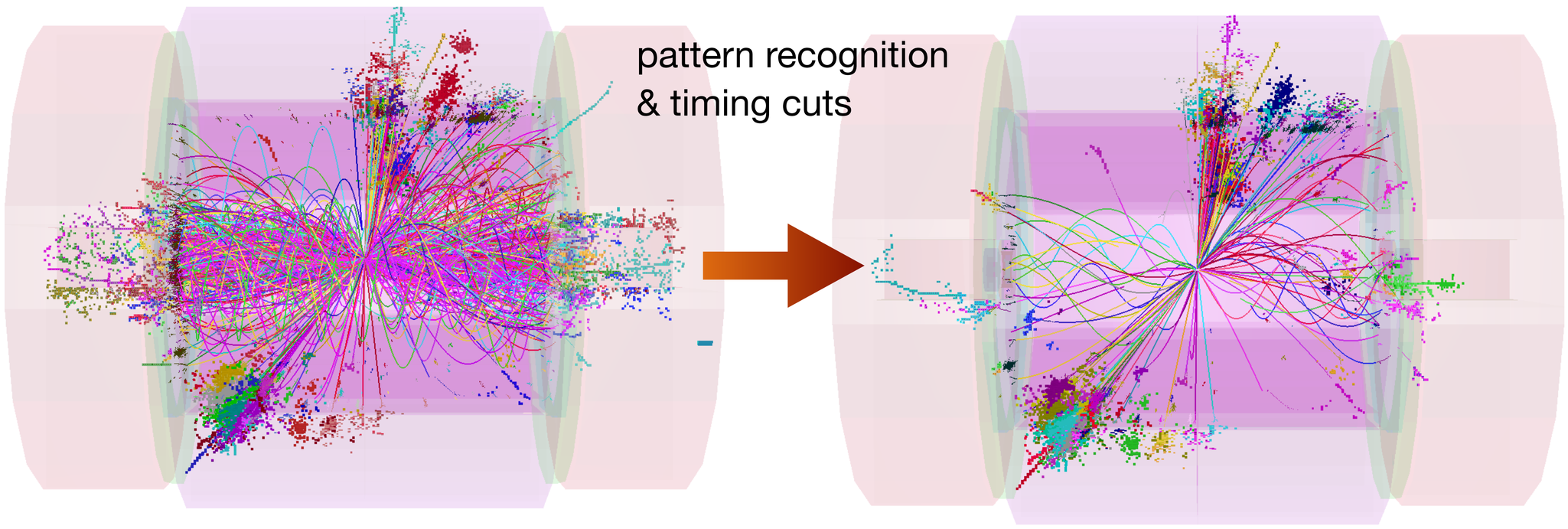
Imaging Calorimeters as “Pile-up Killers”

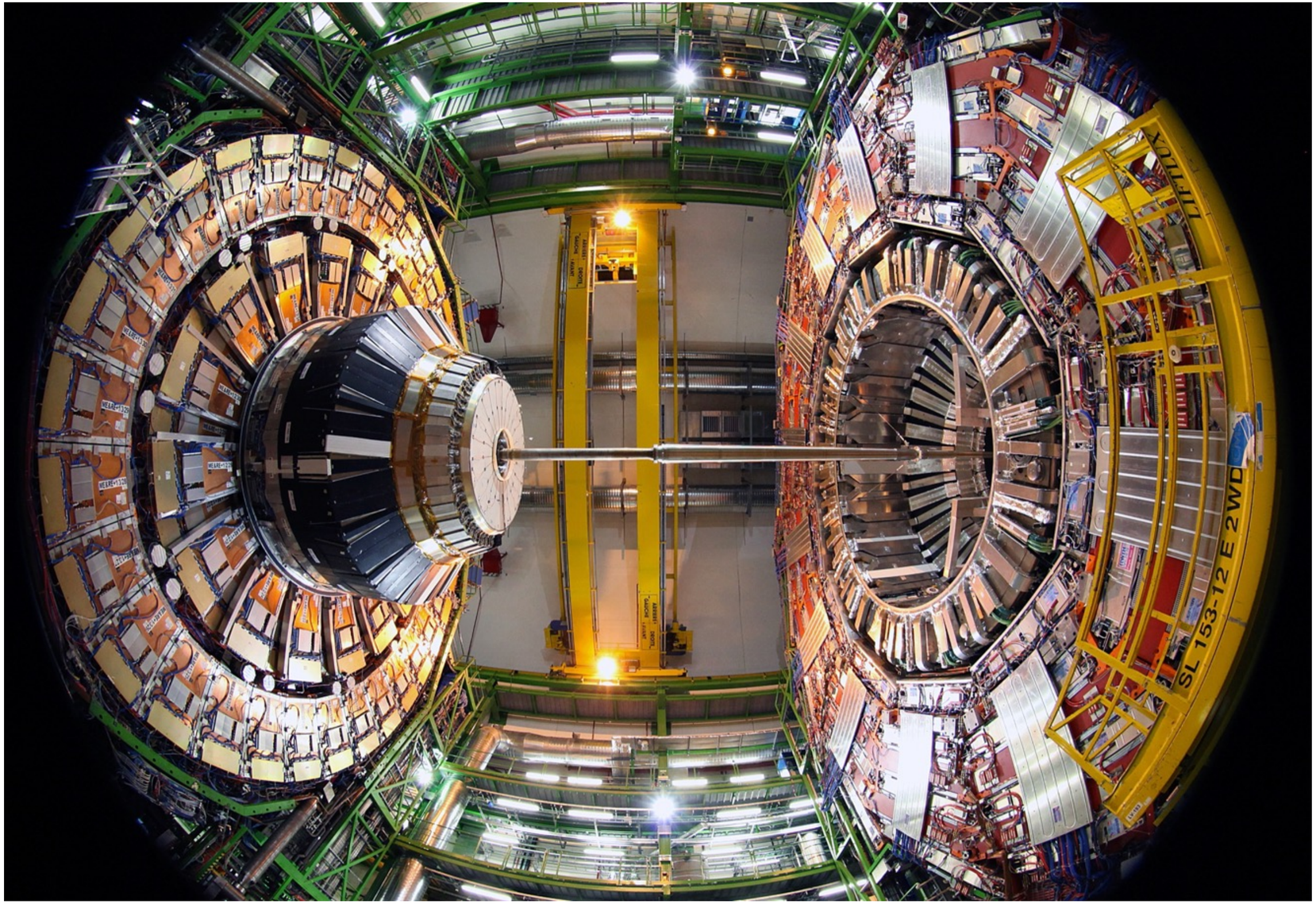
First studied in the Context of CLIC

- High granularity enables detectors to deal with high particle rates & high density
  Extensively studied for CLIC: Here “pile-up” of γγ-> hadrons background, both in time and with 2 GHz bunch crossing frequency from neighboring bunches
  - Combine PFA pattern recognition and (moderate) timing cuts on the ns level



The CMS HGCAL

Replacing the current Endcap Calorimeters in CMS



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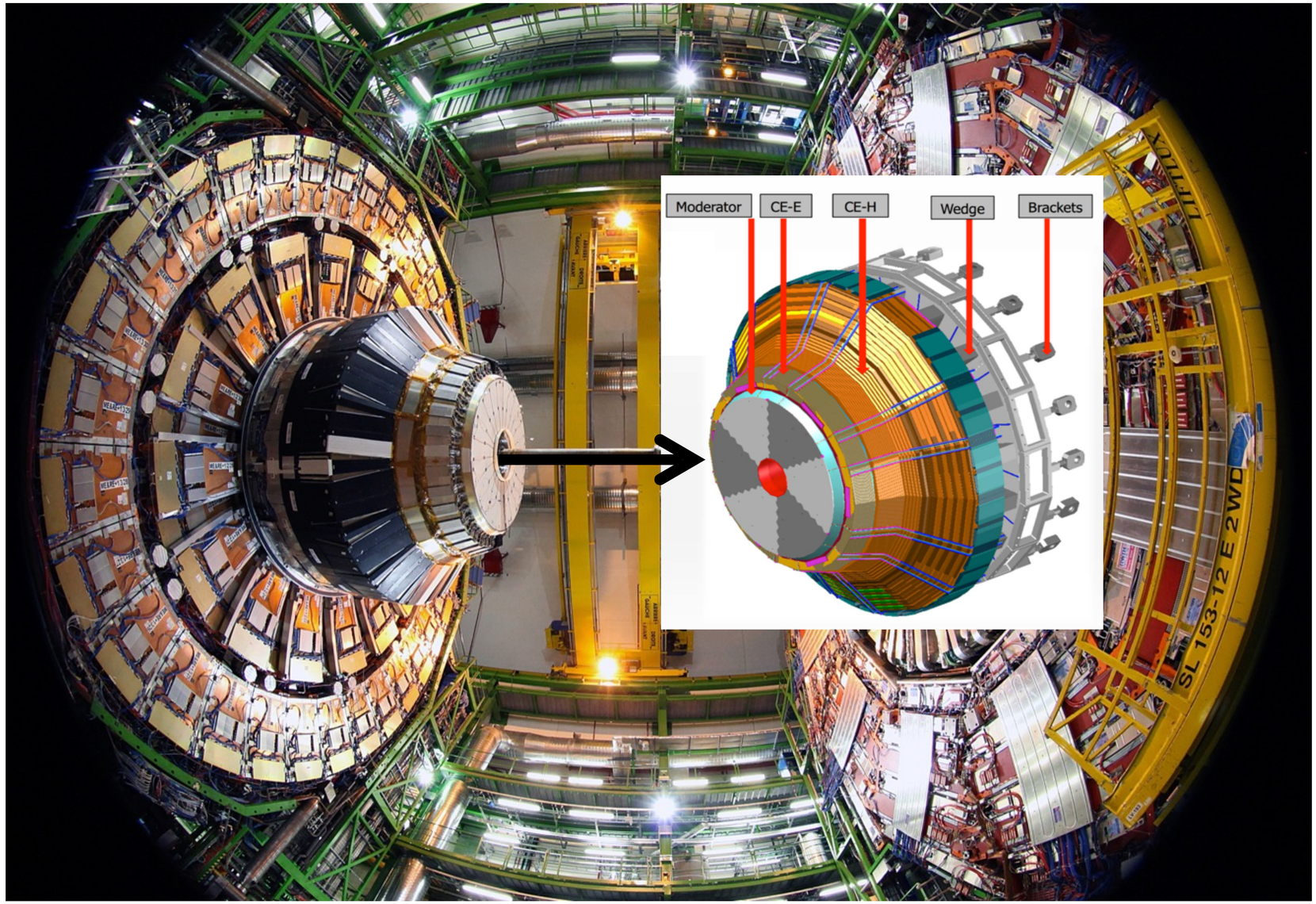

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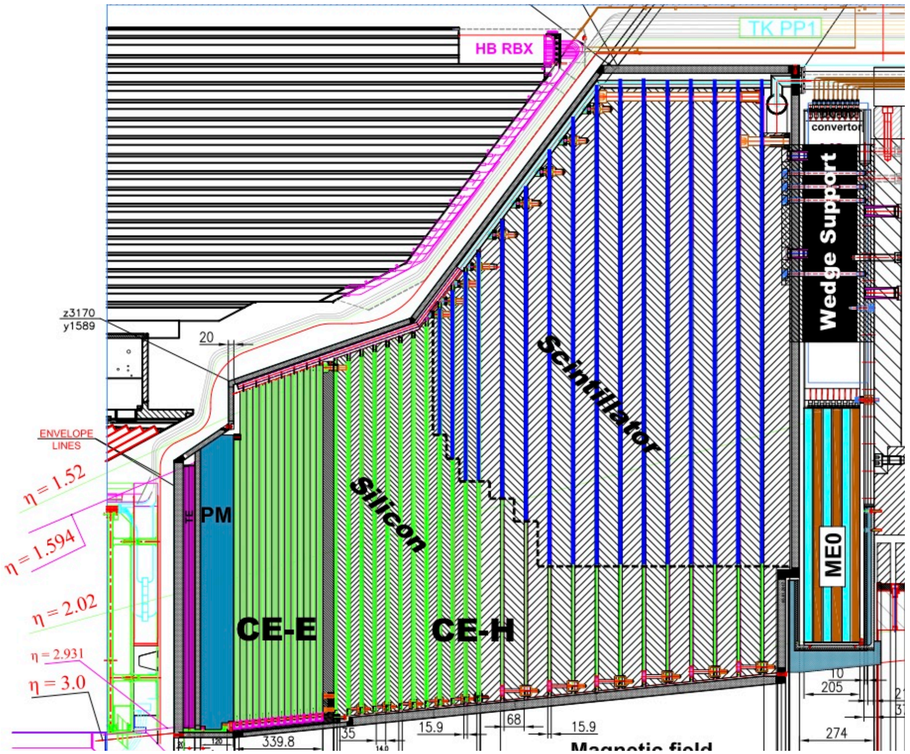
➪ Upgrade with a radiation hard technology that is capable of reconstructing showers in the high-density environment

The HGCAL: 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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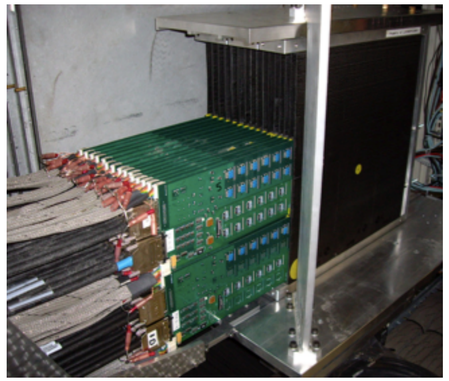

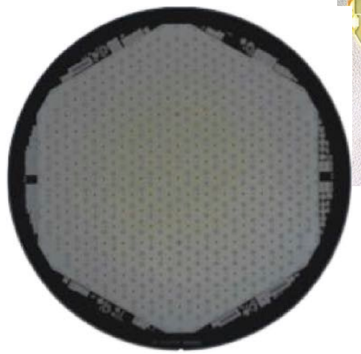

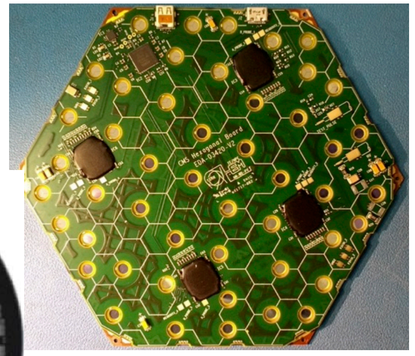

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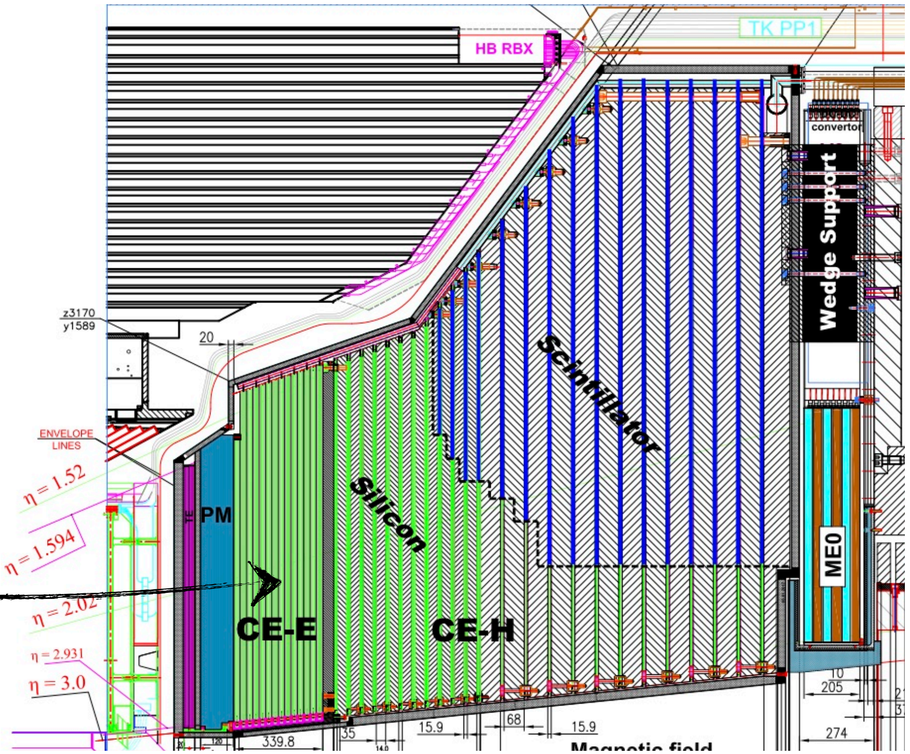

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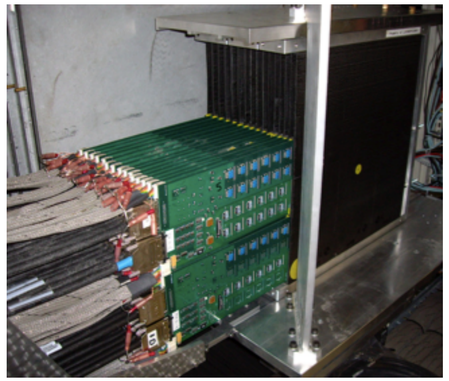

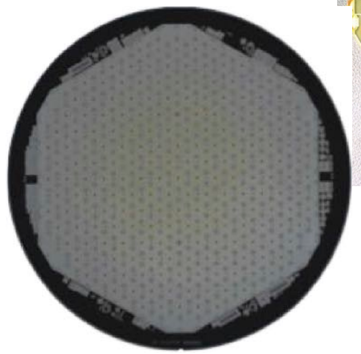

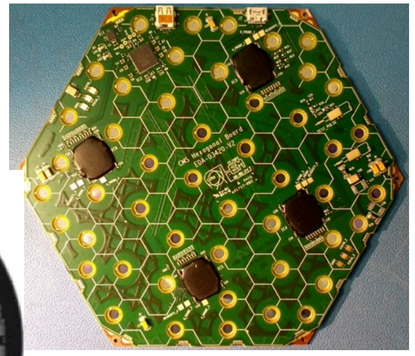

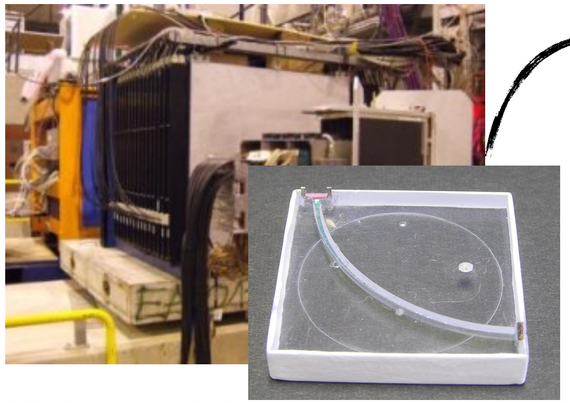

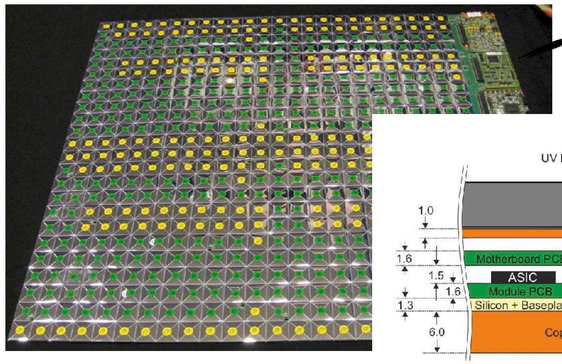

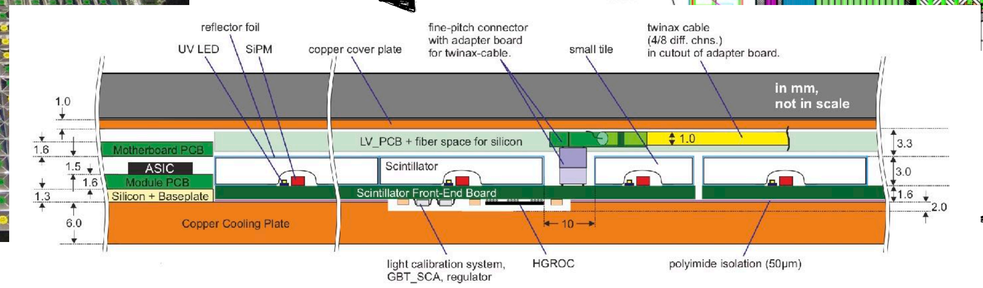

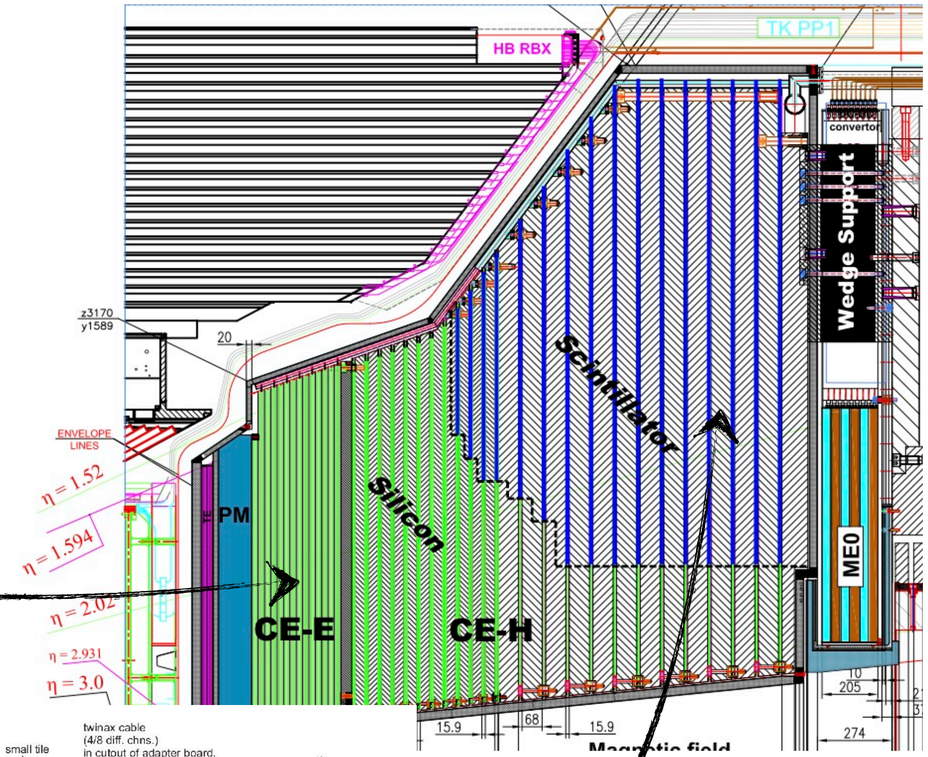

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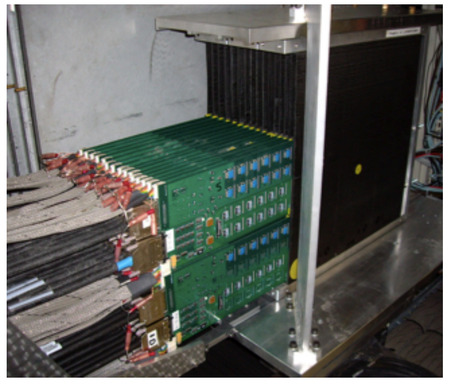
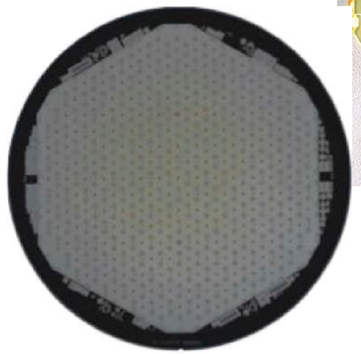
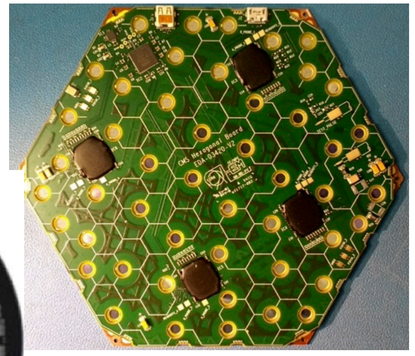
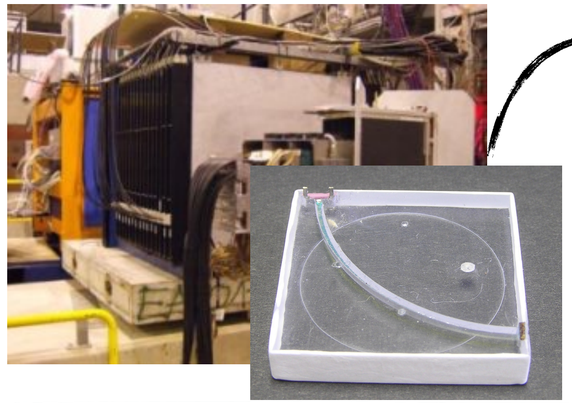
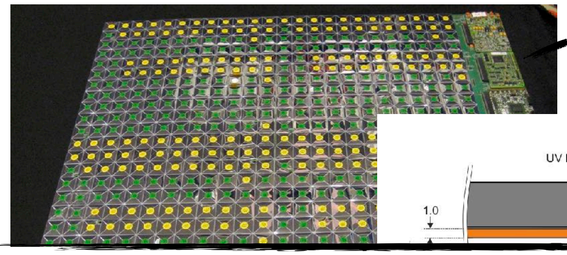
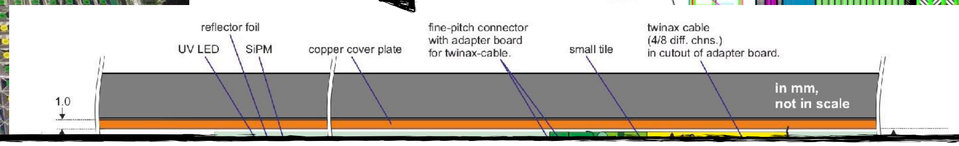


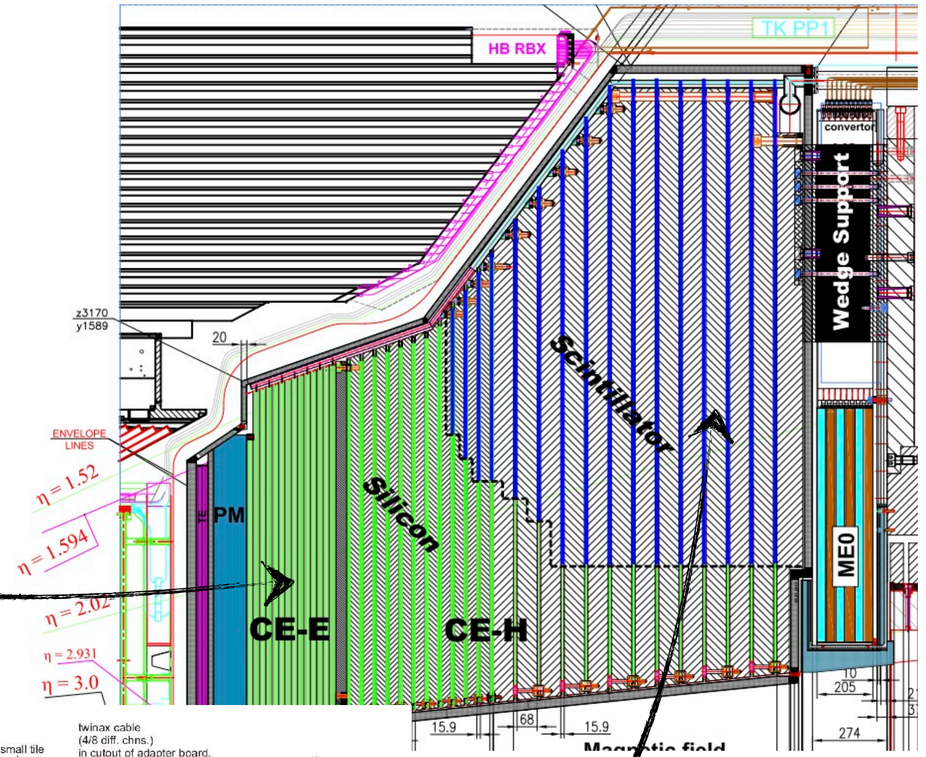










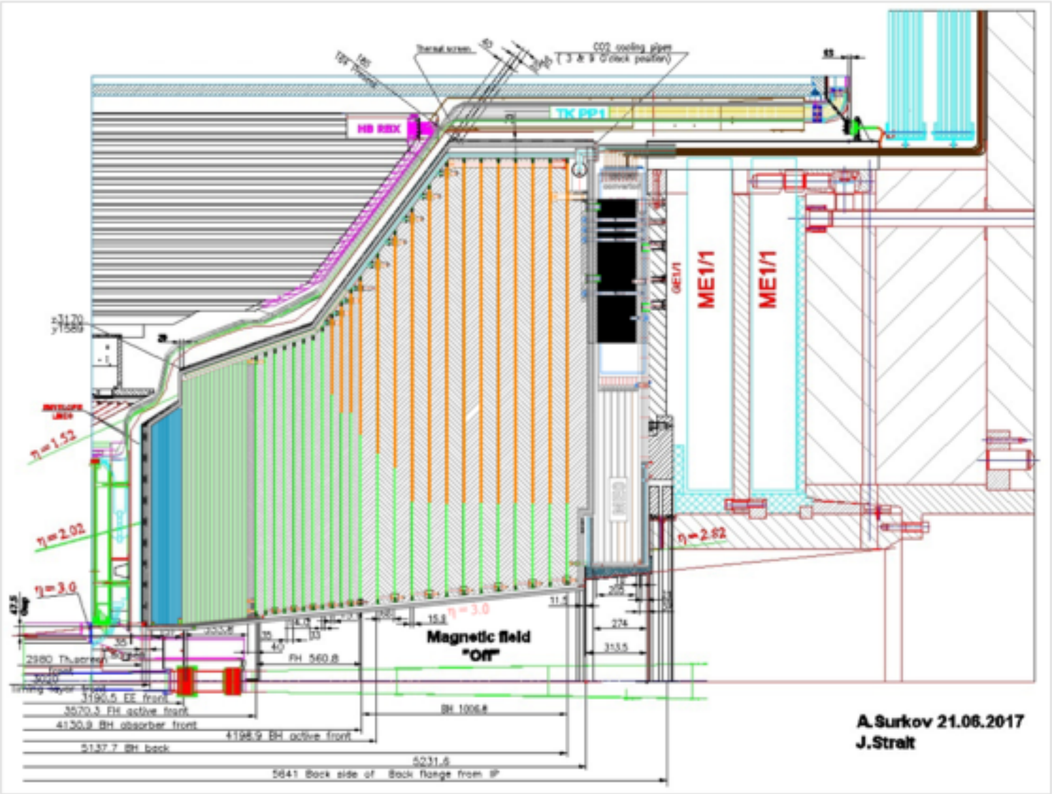


Key differences to the CALICE concept: Radiation hardness crucial, continuous readout and very high data rates

The CMS HGCAL

The Project in Numbers

All the calorimeter is maintained at –30°C



Construction:

- Hexagonal Si-sensors built into modules with a W/Cu backing plate and PCB readout board
- SiPM on tile scintillator assemblies, built into modules with a PCB readout board
- Modules mounted on copper cooling plates to make wedge-shaped cassettes.
- Cassettes integrated into absorber structures

Key parameters:

- 600 m^2 of silicon
- 6M ch, 0.5 or 1 cm^2 cell-size
- 25'000 modules (8" sensors)
- 520m^2 of SiPM on tile plastic scintillator
- ~400k ch, 2x2cm^2 -> 5x5cm^2 tiles
- Total power at end of life 160~180 kW @-30C

System Divided into three separate parts:

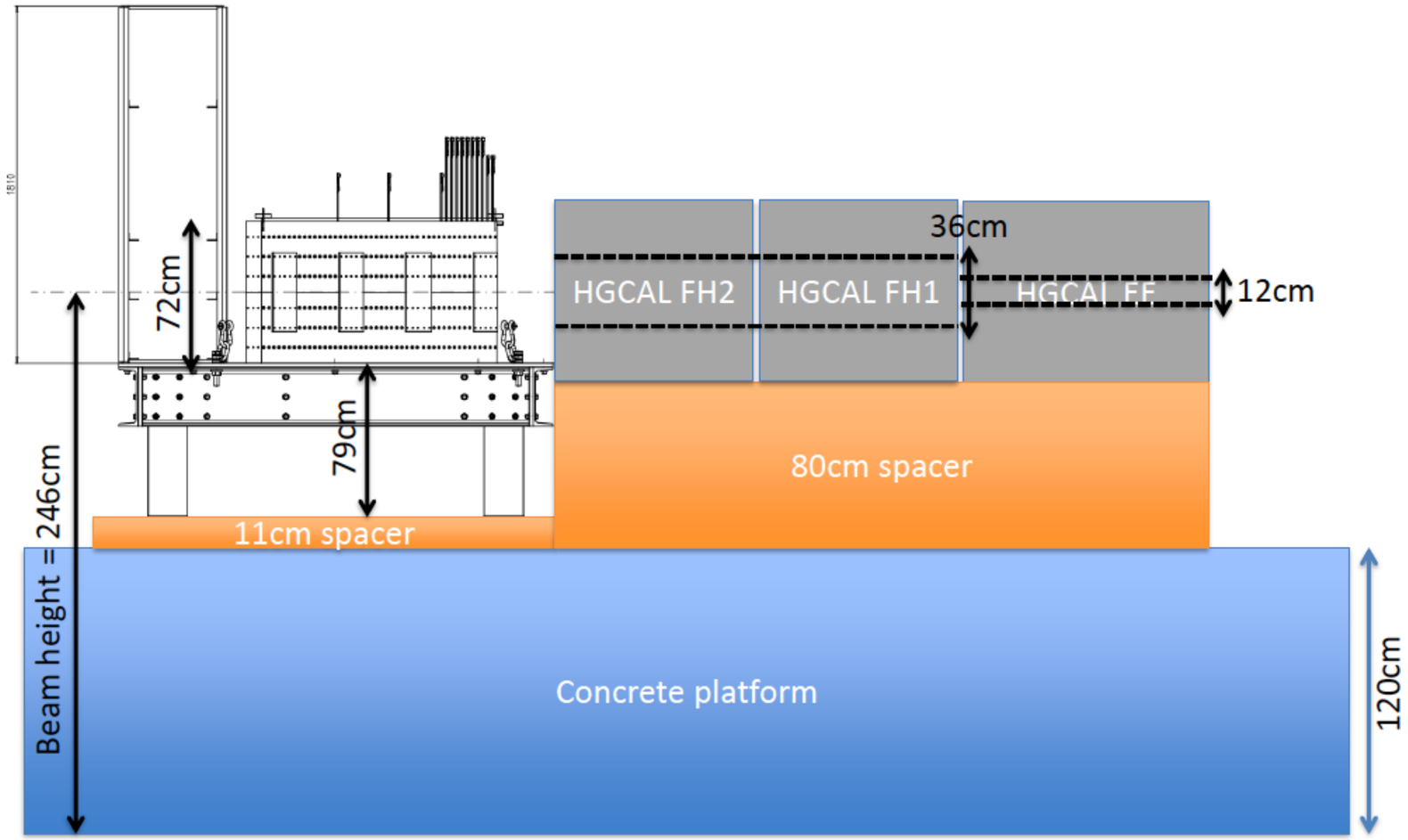
EE – Silicon with tungsten/Pb absorber – 28 sampling layers – 25 X_0 + ~1.3 λ

FH, BH – planes of Silicon OR silicon and SiPM on tile plastic scintillator, sandwiched between SS absorber plates – 24 sampling layers – 9 λ

The CMS HGCAL & CALICE AHCAL

Combined Test Beams - Bridging the LHC and the LC Worlds

- Using the CALICE AHCAL as a BH prototype, together EE and FH Hexaboard-based modules



Demonstrates the size and complexity of calorimeter test beams

28 layers HGCAL EE (Si/Pb)

12 layers HGCAL FH (Si/Fe)

38 layers AHCAL (Sc/Fe)

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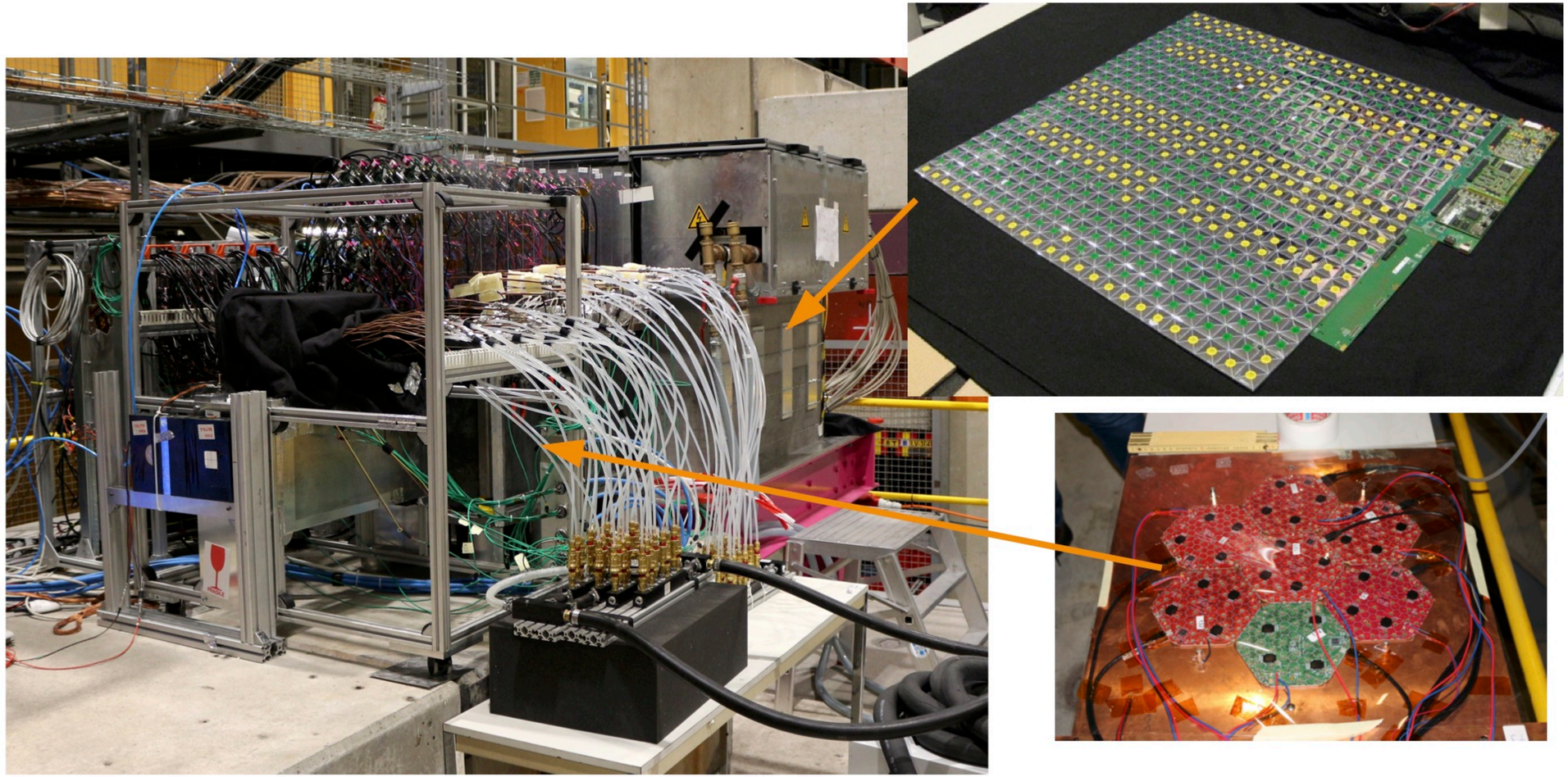

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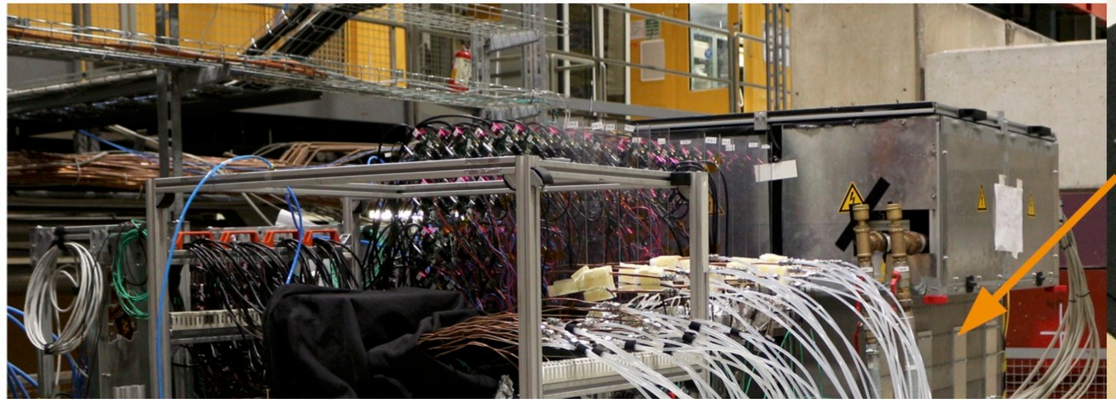
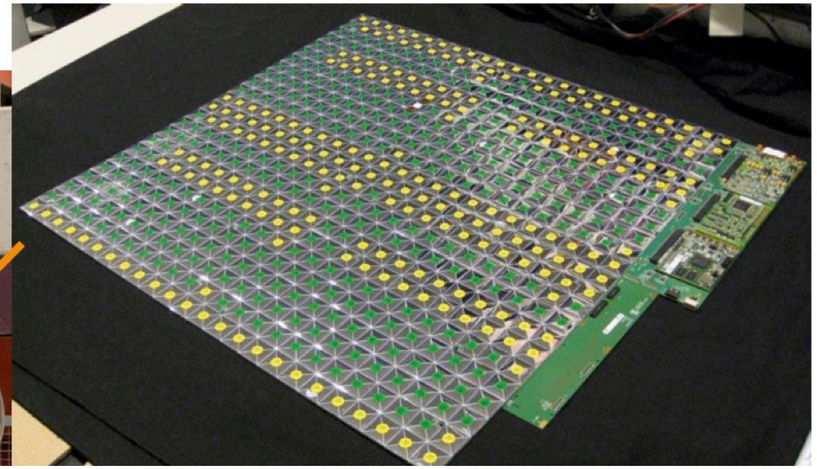




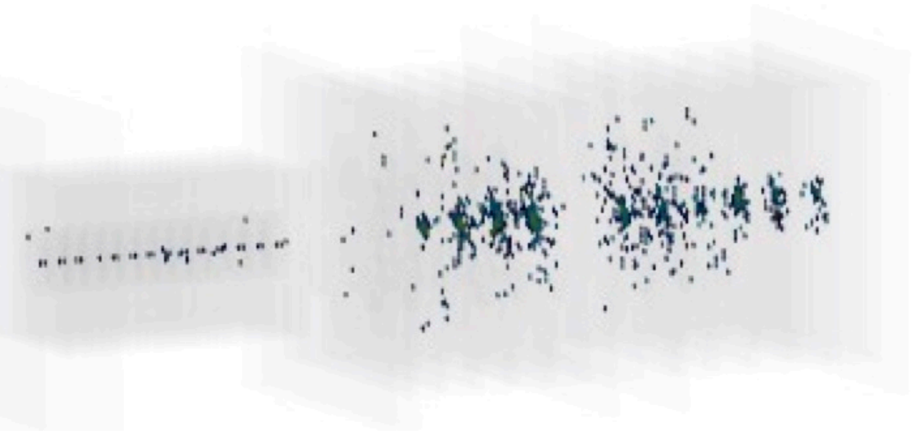
Demonstrates the size and complexity of calorimeter test beams

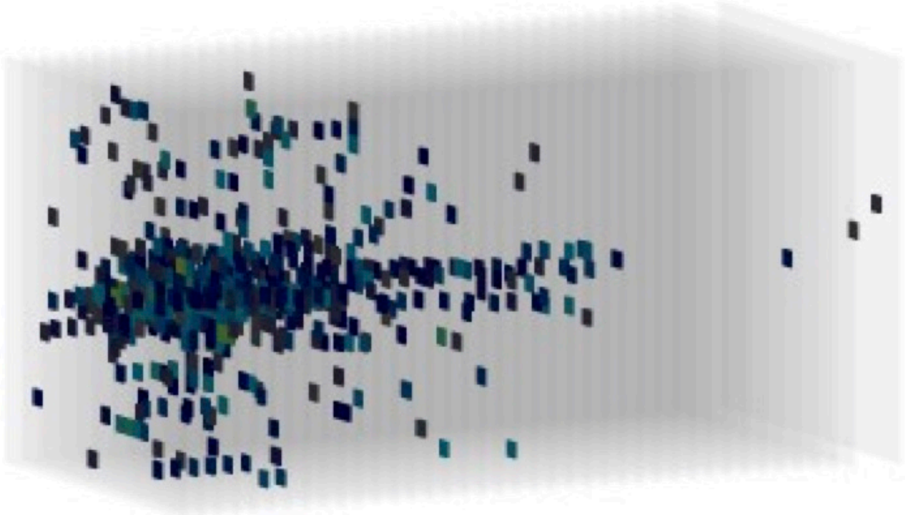
28 layers HGCAL EE (Si/Pb)

12 layers HGCAL FH (Si/Fe)

38 layers AHCAL (Sc/Fe)

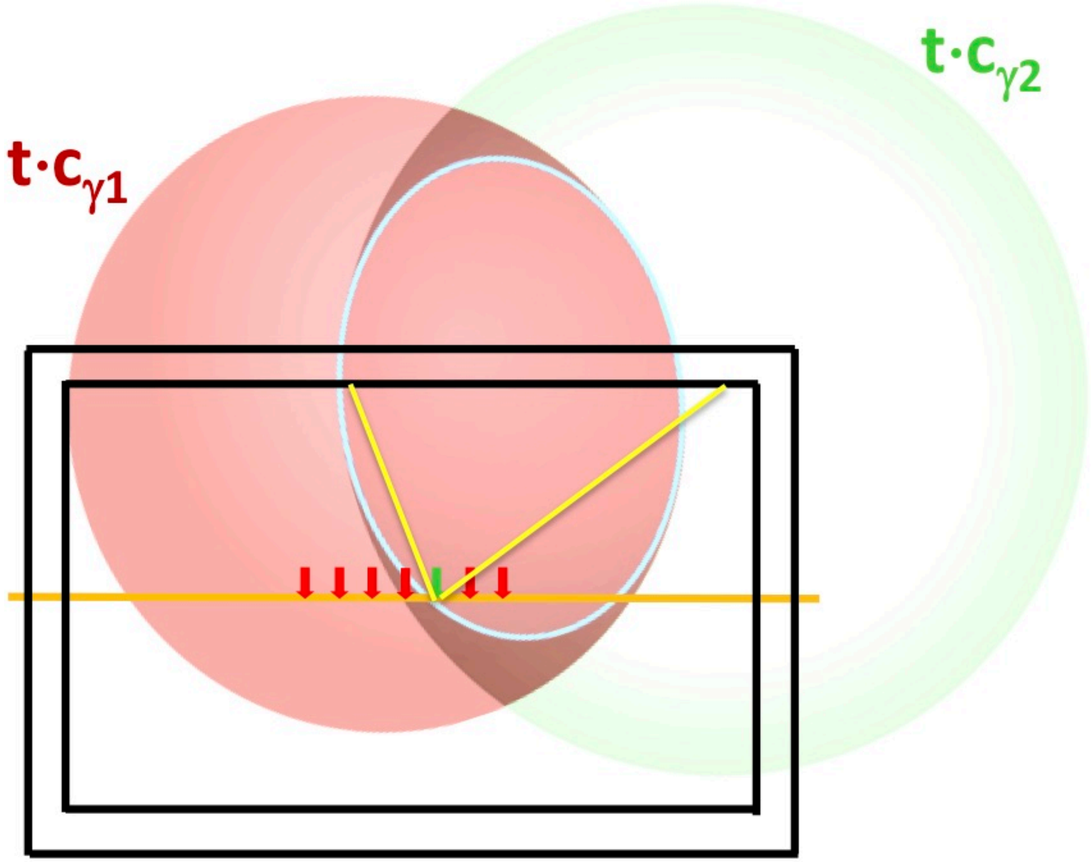
combined readout using EUDAQ 2



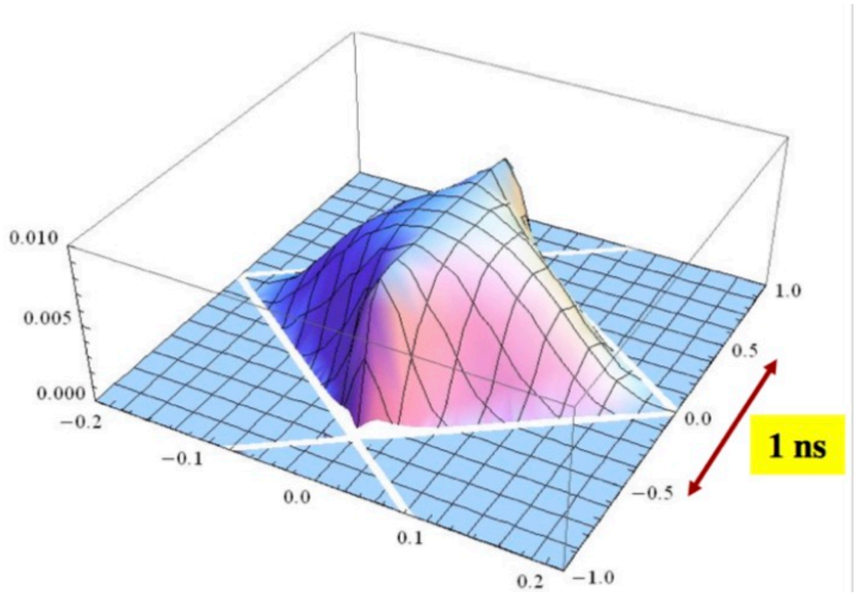


Timing: A New Trend in Calorimetry - and Beyond

Towards 10 ps level timing



- Timing can enable the association of neutrals to vertices



beamspot in time:

RMS ~ 200 ps

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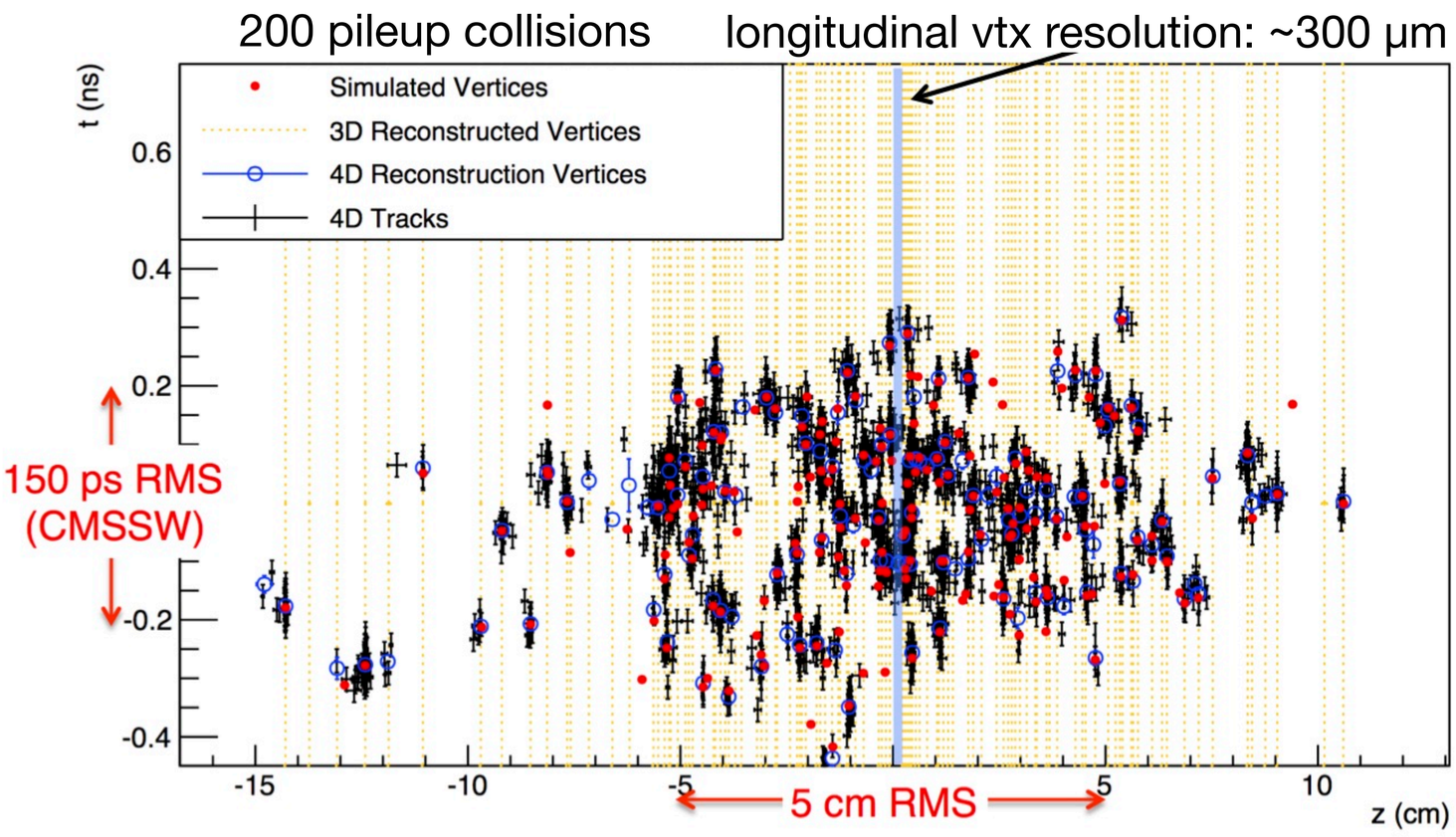

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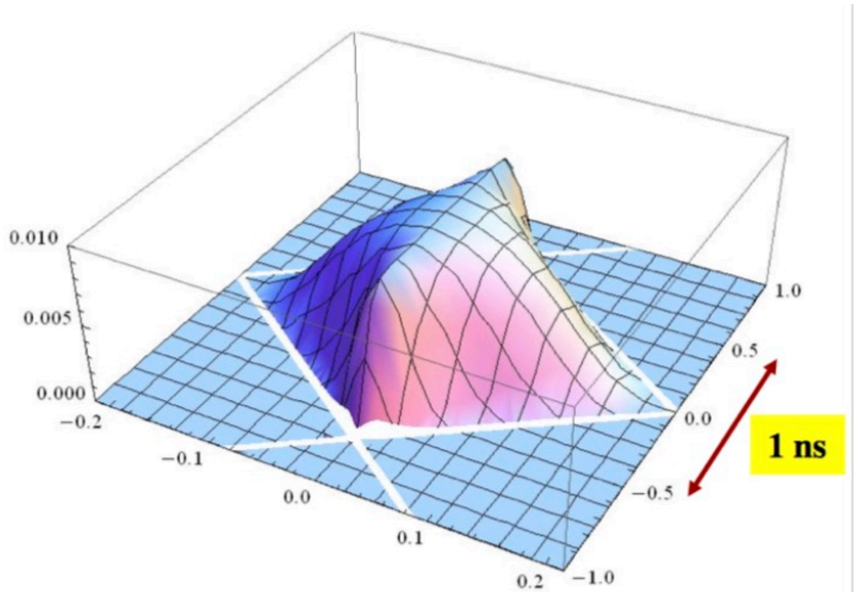

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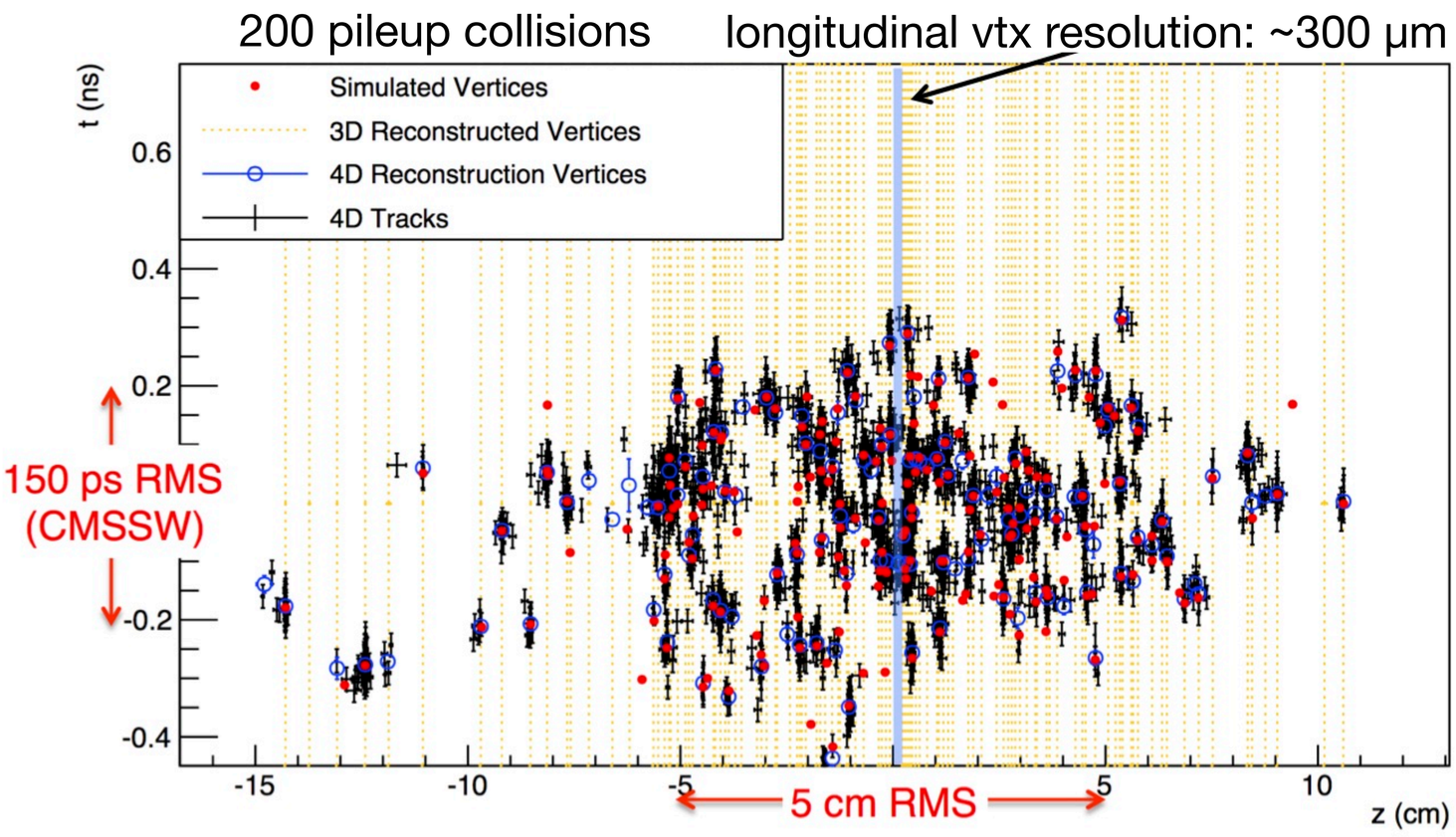

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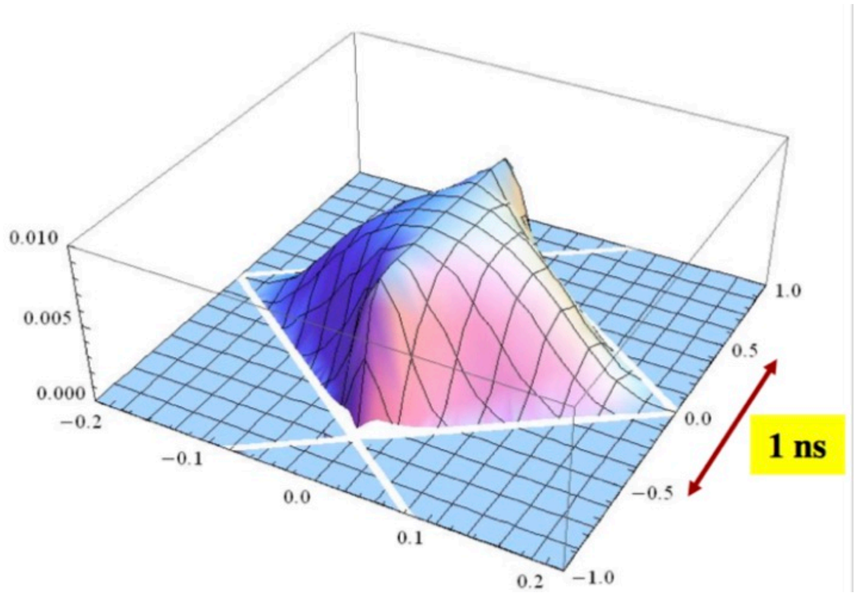


beamspot in time: RMS ~ 200 ps

- Also improved vertex association for charged particles

➪ few 10 ps time resolution provided for showers in upgraded CMS ECAL, HGCAL; additional dedicated MIP timing detectors

Other Future Concepts

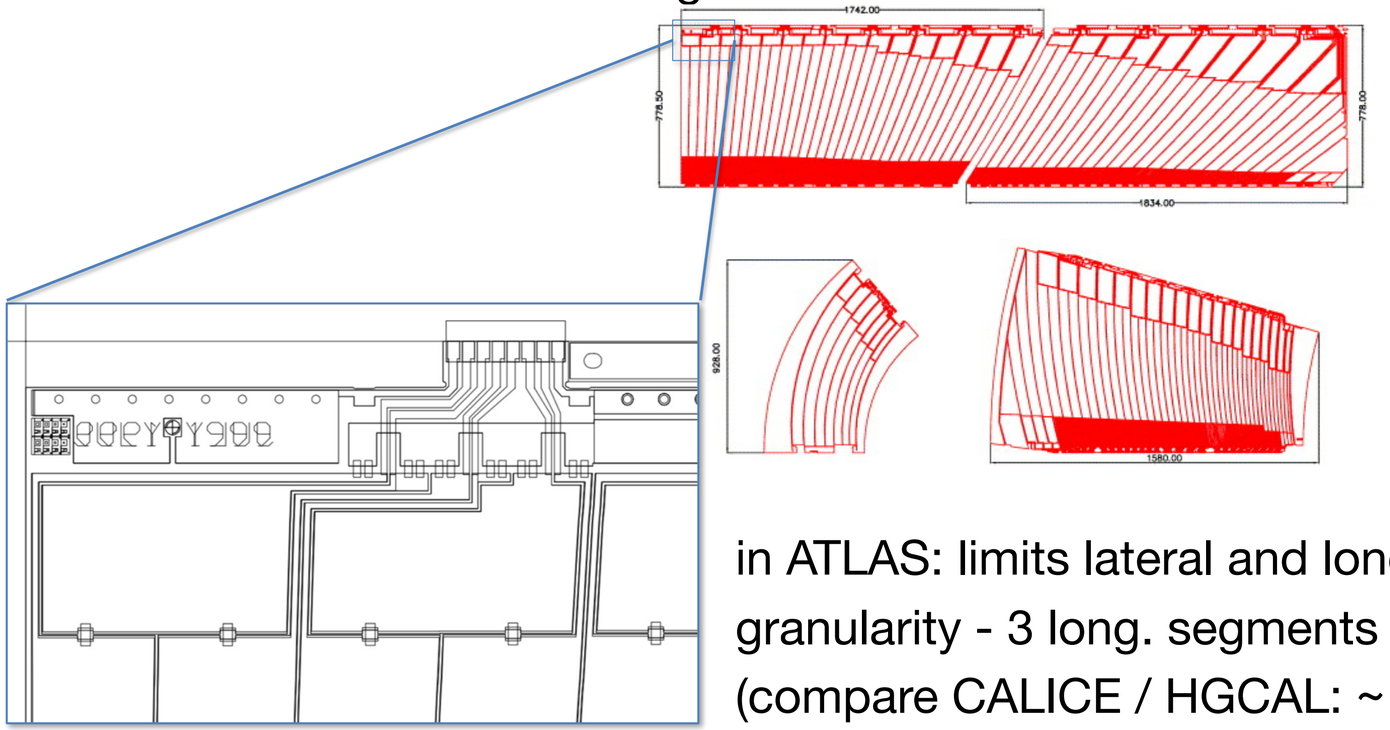
Granularity as a main theme

Bringing Granularity to LAr

Current Limitations

- Liquid argon calorimeters are fantastically radiation hard, and haven proven to have excellent long-term stability - but granularity is a challenge

The issue: charge signals brought out on the back of the calorimeter - routing limitations for electrodes



in ATLAS: limits lateral and longitudinal granularity - 3 long. segments max (compare CALICE / HGCAL: ~ 30 individual longitudinal samplings in ECAL)

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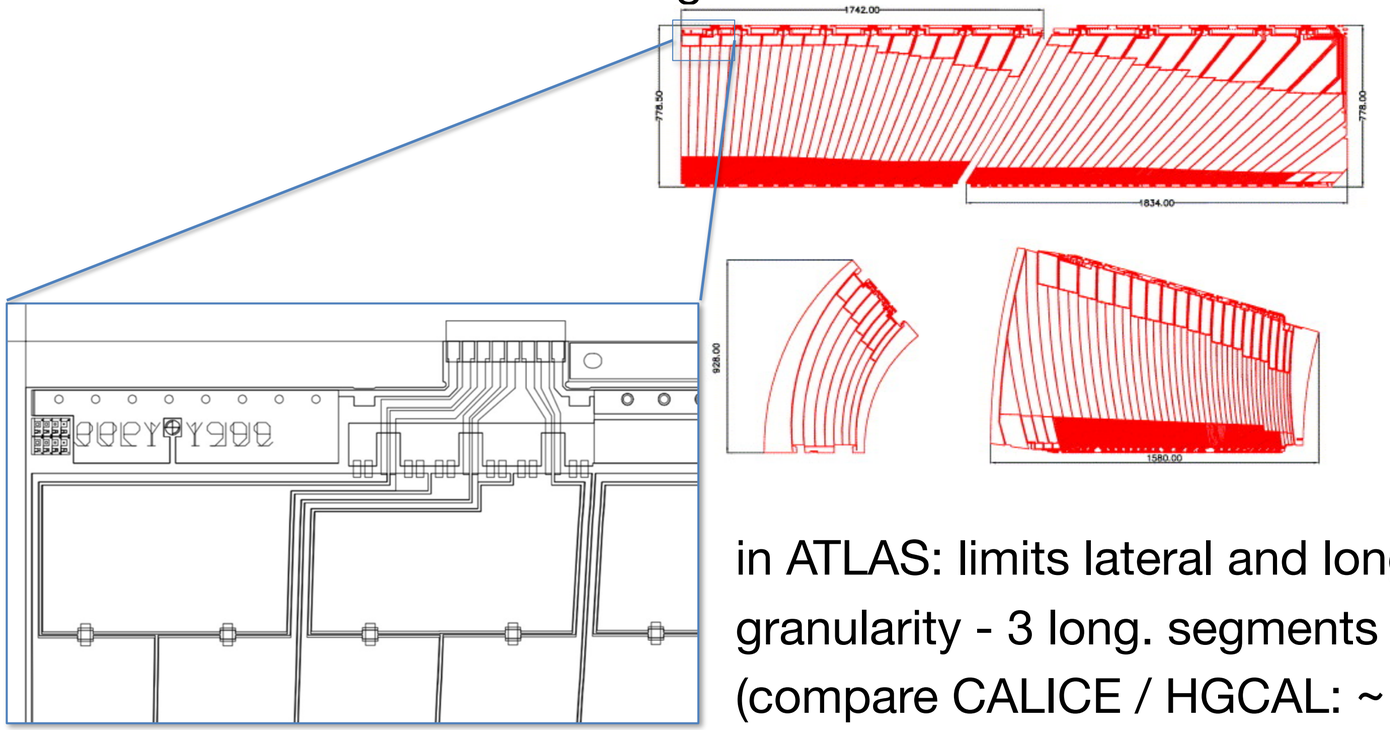
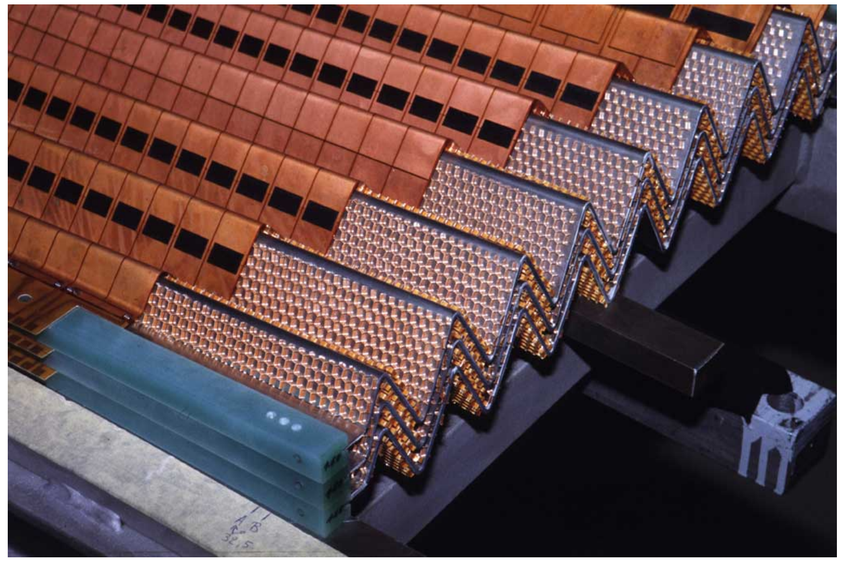


cannot be solved with accordion geometry: requires routing of electrons, cannot use multi-layer PCBs



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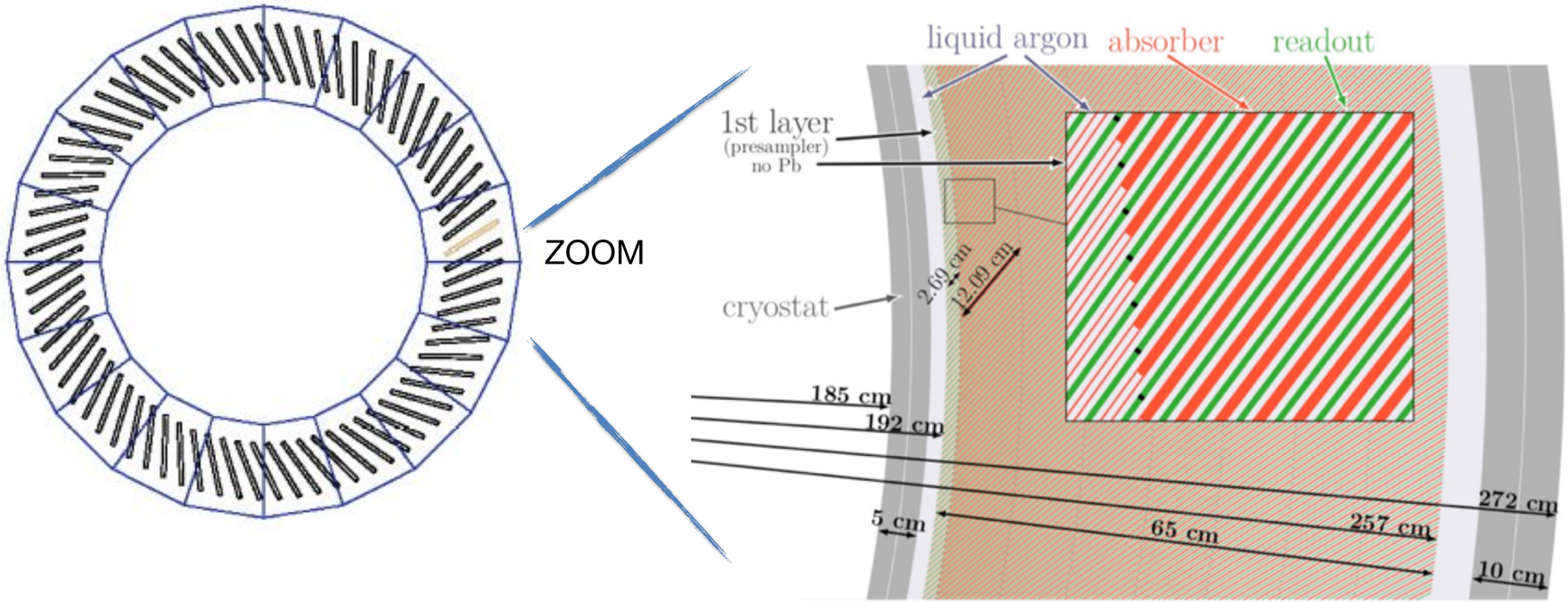
Bringing Granularity to LAr

Ideas in the Context of FCC

- Moving to multi-layer PCBs for electrode layers:

electronics outside of cryostat



With a 7 - layer PCB:
8 longitudinal segments,
high lateral segmentation in first segment:
~ 2.5 M channels total

- fan-like geometry implies changing sampling structure with radius

➪ Intercalibration based on longitudinal segmentation

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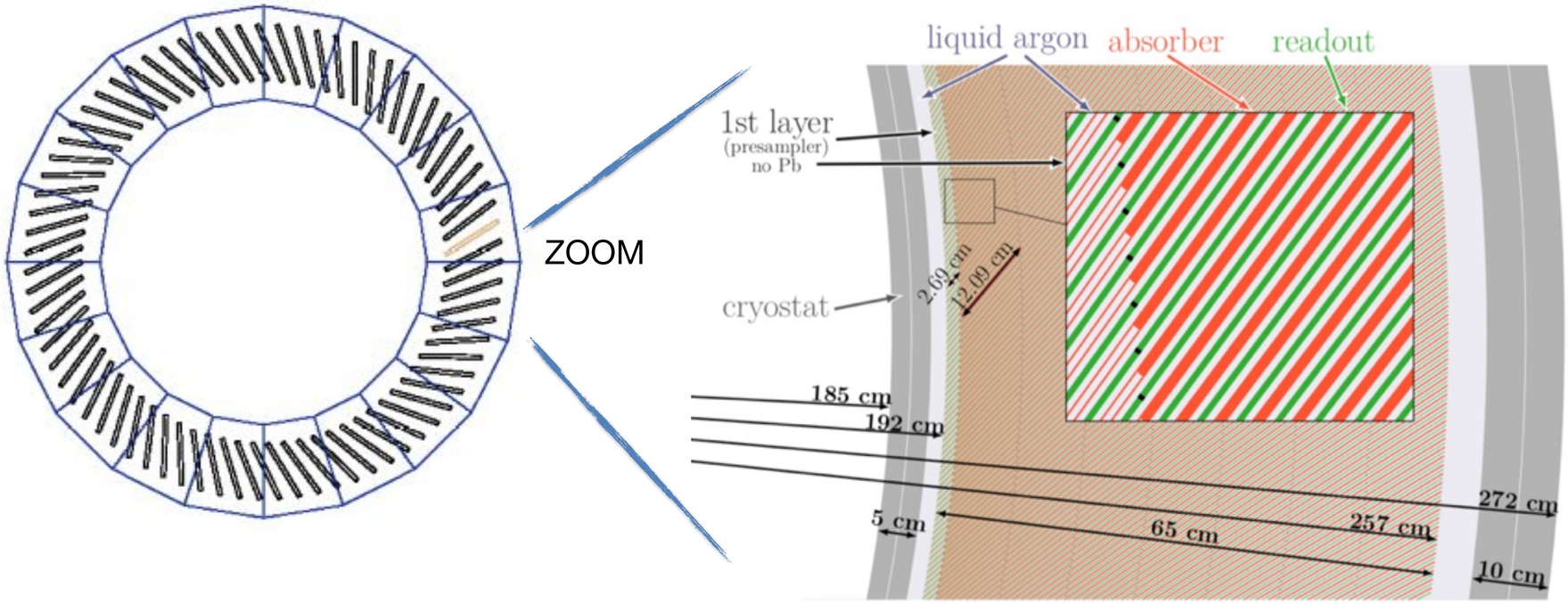

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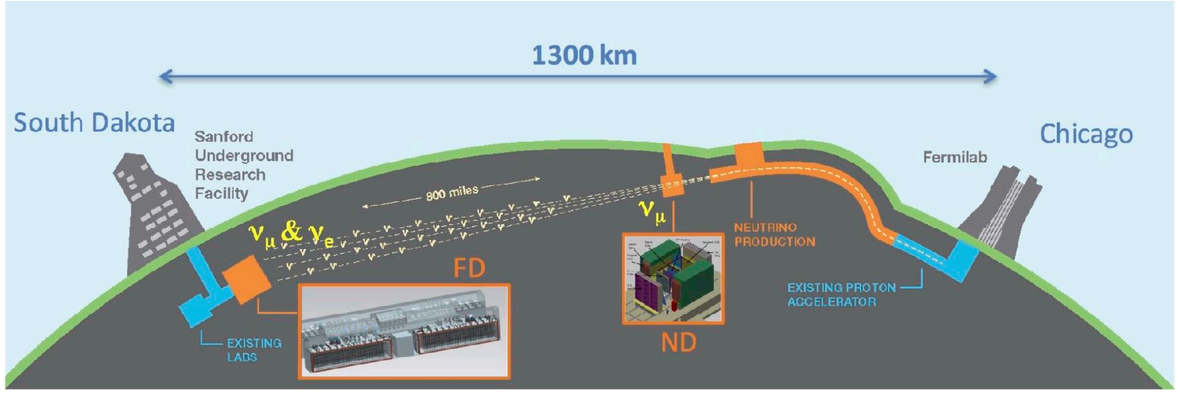
studies only just beginning:
Will result in complex test beam setups!

Calorimeters for Neutrino Experiments

Ideas beyond Colliders

- The near detector systems at long baseline neutrino experiments (T2K, DUNE, T2HK,…) are complex systems including (highly) granular electromagnetic calorimetry

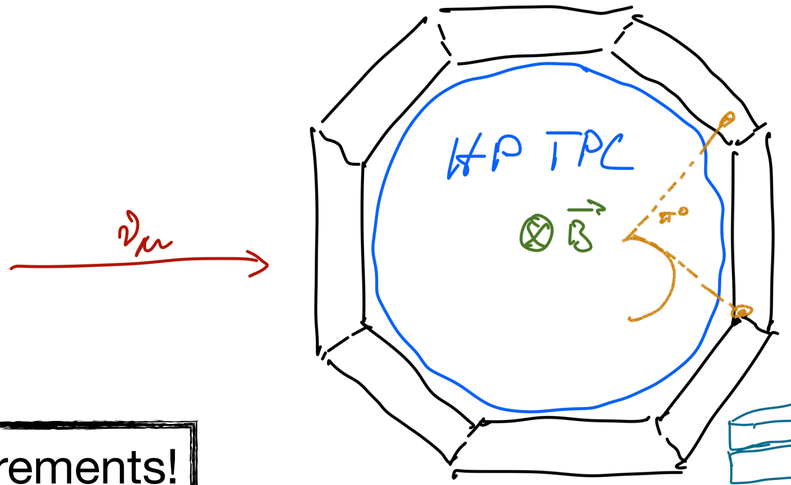


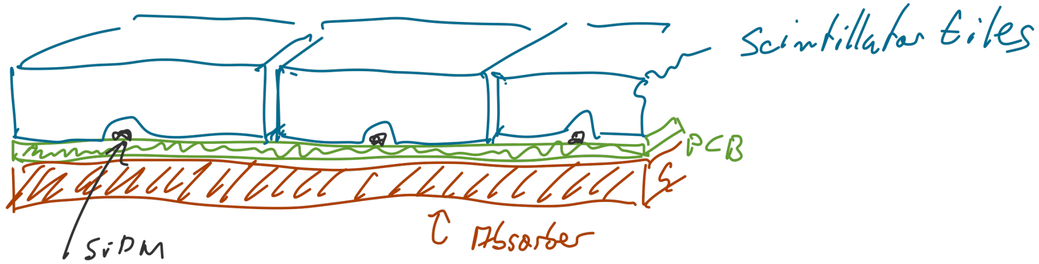
A possible concept for DUNE:
A highly granular ECAL

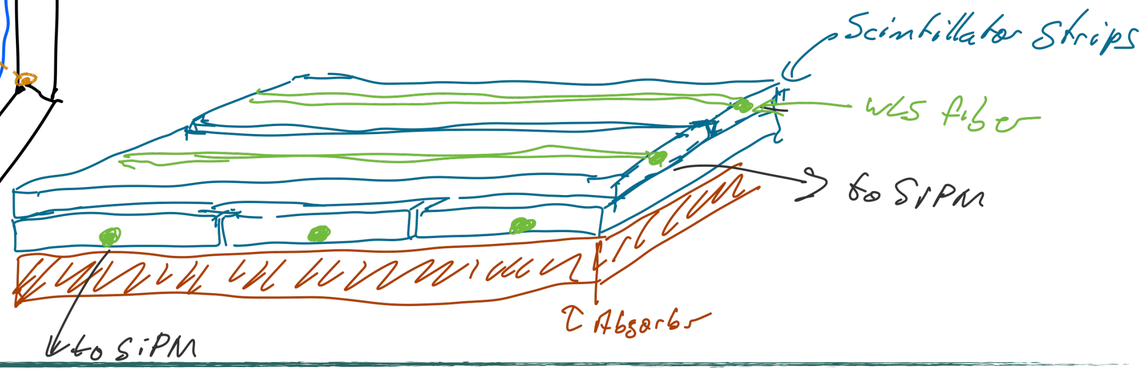
A ***Strawman Concept***

very different requirements:

low-energy photons - a few 10 MeV to a few GeV







Interesting test-beam requirements!

Wrapping Up: The Role of Test Beams

Test Beams for Calorimetry

Establishing Performance & Beyond

- Beam tests are indispensable in the development cycle of calorimeters to test the functionality of new concepts and to establish performance - energy reconstruction, resolution, …
- Crucial for the validation of detector simulations - which are required for physics performance studies of experimental concepts
- Calibration of detector elements prior to installation - will further gain in importance with increasing granularity of detectors

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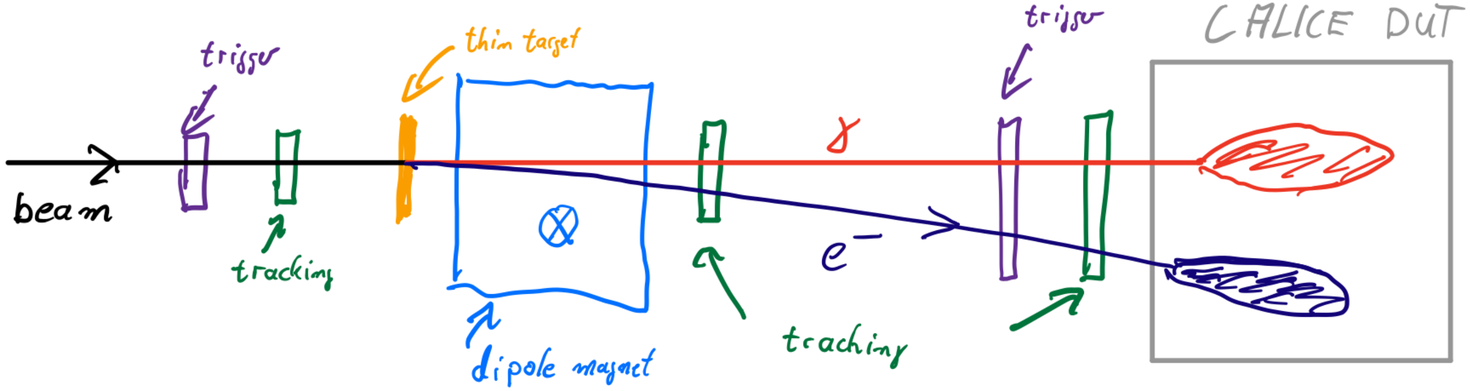
- Requirements go beyond single particles “directly from the source”
  - One example: Tagged photons - interesting for (highly granular) ECALs in various contexts, also for calorimeters in neutrino beams



… has for example been used to study a very compact SiW ECAL for luminosity measurements at Linear Colliders

Test Beams for Calorimetry: Calibrating Calorimeters

A few Thoughts, comparing non-segmented and Highly Granular Calorimeters

- Calibration is crucial - based on test beams before installation, and in-situ calibration
- Often based on electromagnetic showers
  - Global calibration
  - Inter-calibration of modules, cells / towers

➪ First calibration in beam tests
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- For highly granular calorimeters: Very large number of cells, fine longitudinal segmentation makes calibration with showers only not possible

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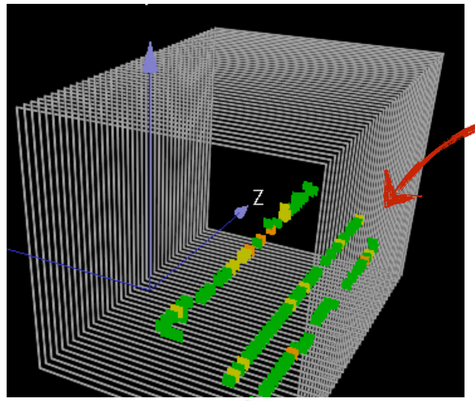
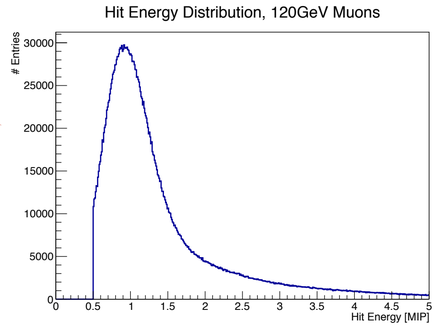
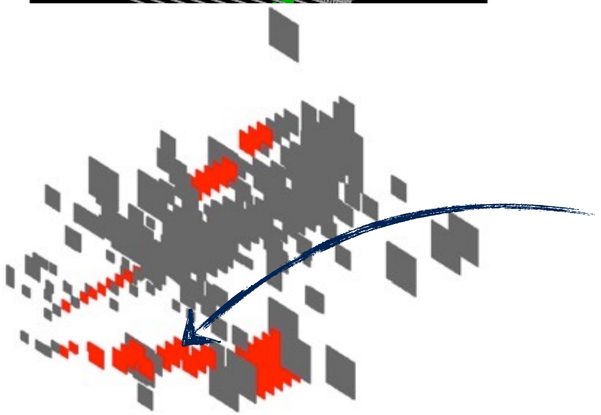
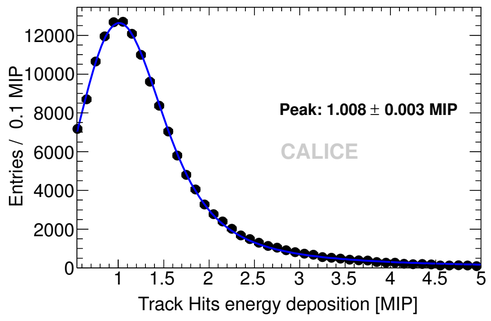
- Muons in test beam, in-situ
- But also: Track segments in hadronic showers









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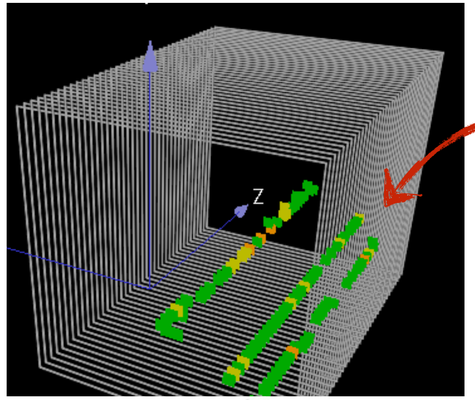

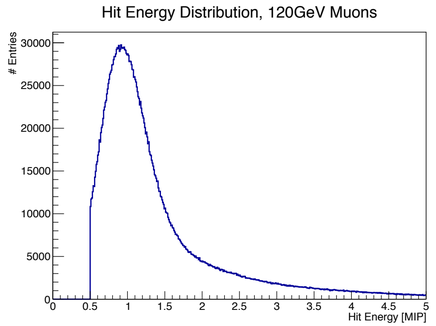

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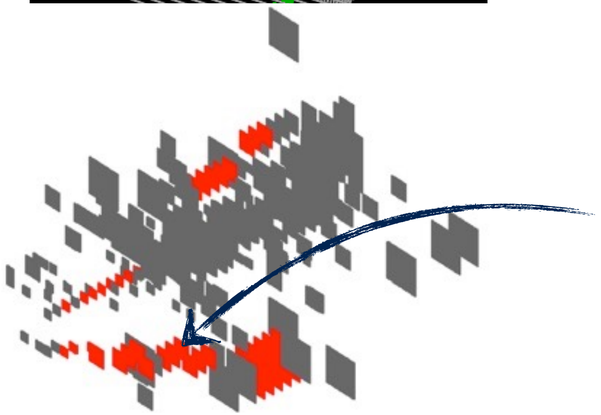
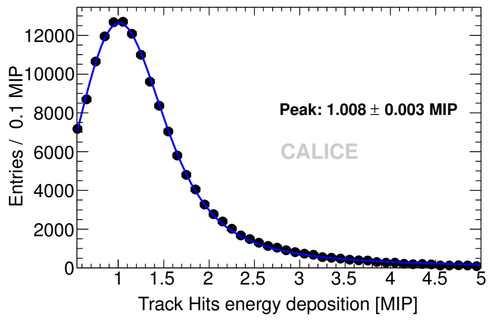


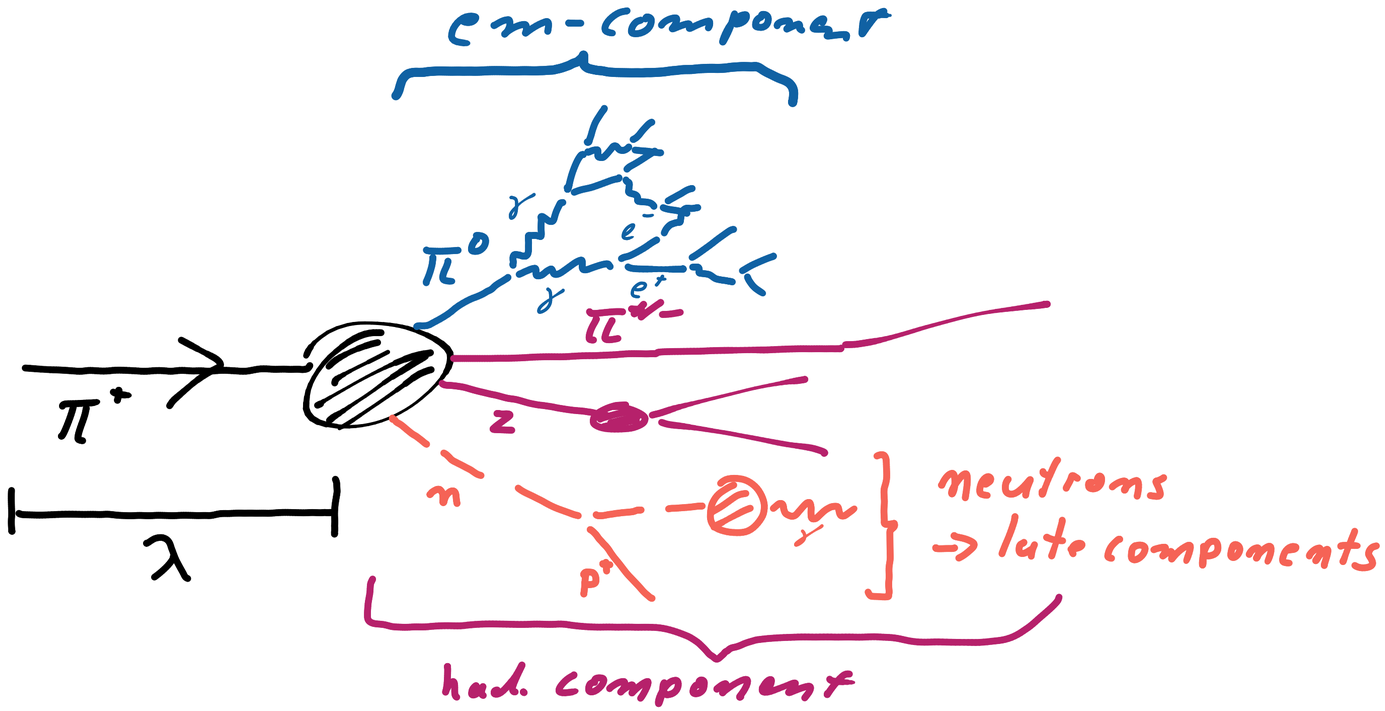


➪ Requires MIP detection capability in each cell throughout full life cycle of detector!

Test Beams for Calorimeters: Also a Physics Progam

Understanding Hadronic Showers

- Hadronic showers are complex:



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

extended in time:

- few 10 ns from travel time of MeV-scale neutrons
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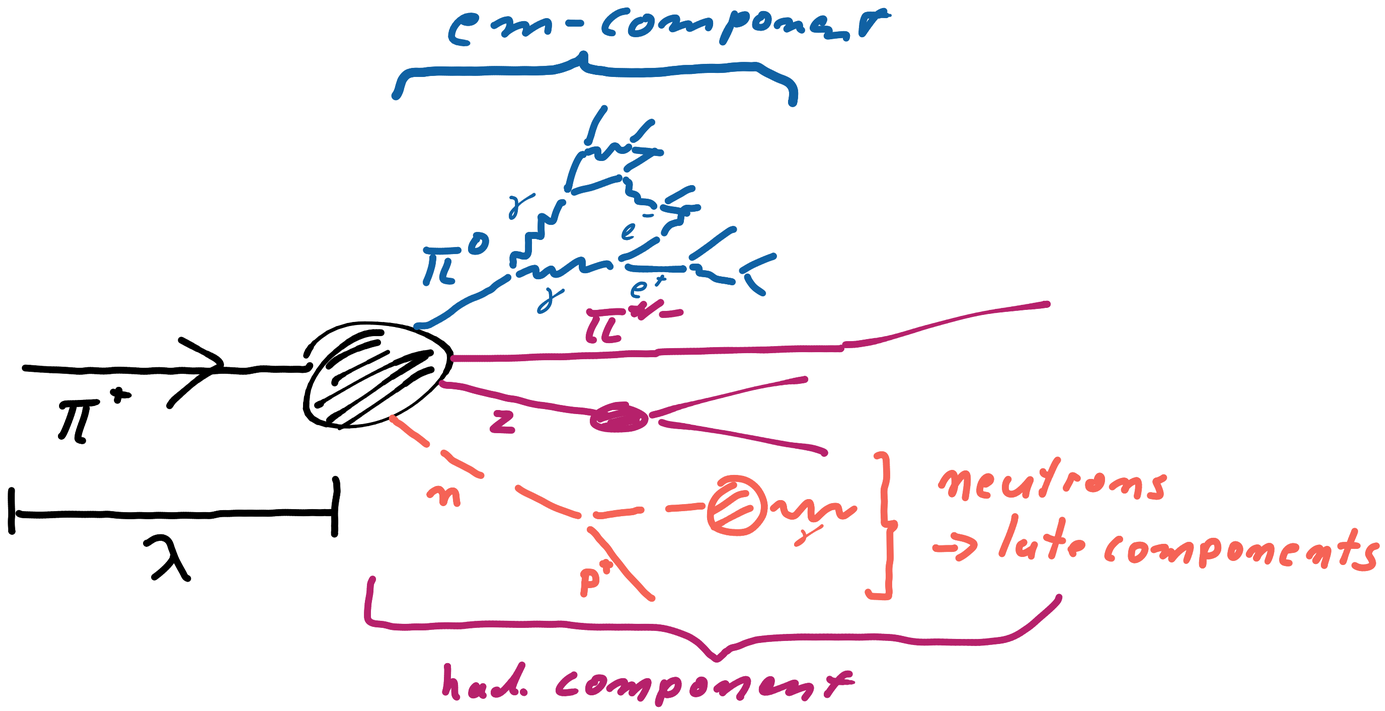

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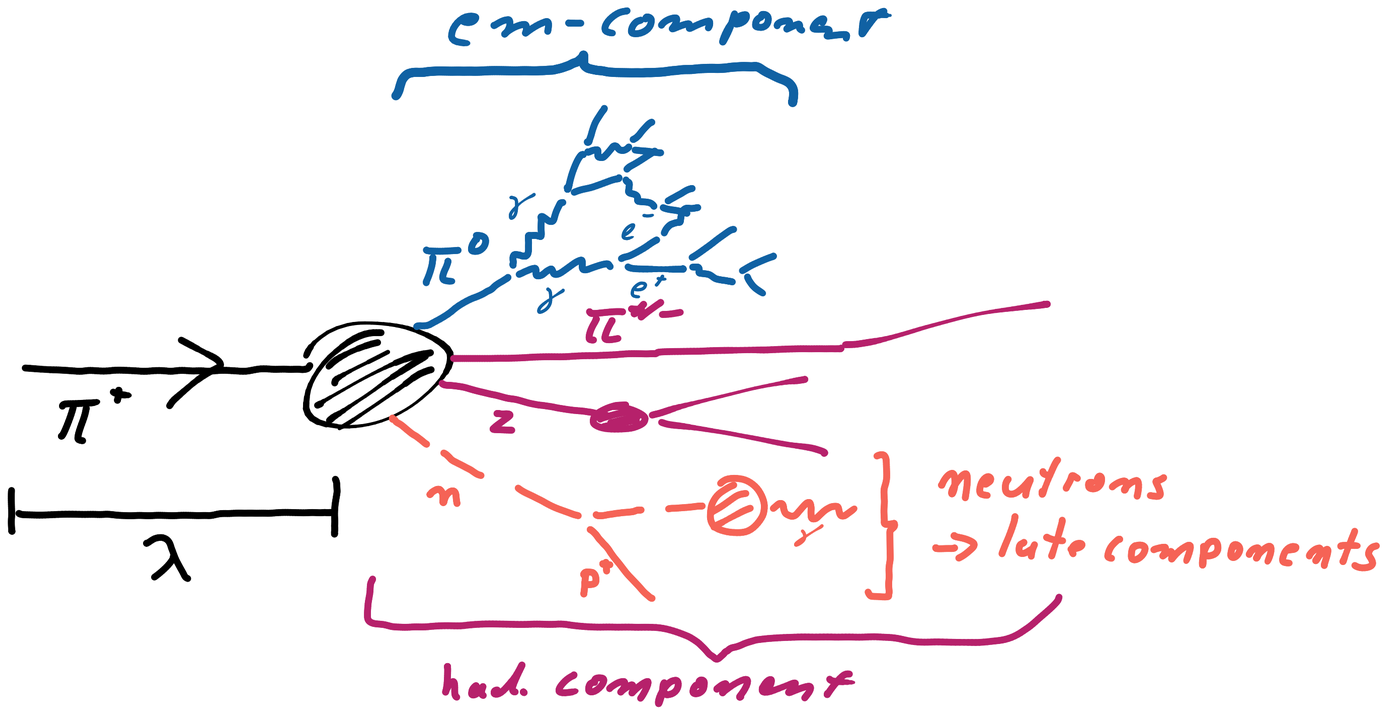

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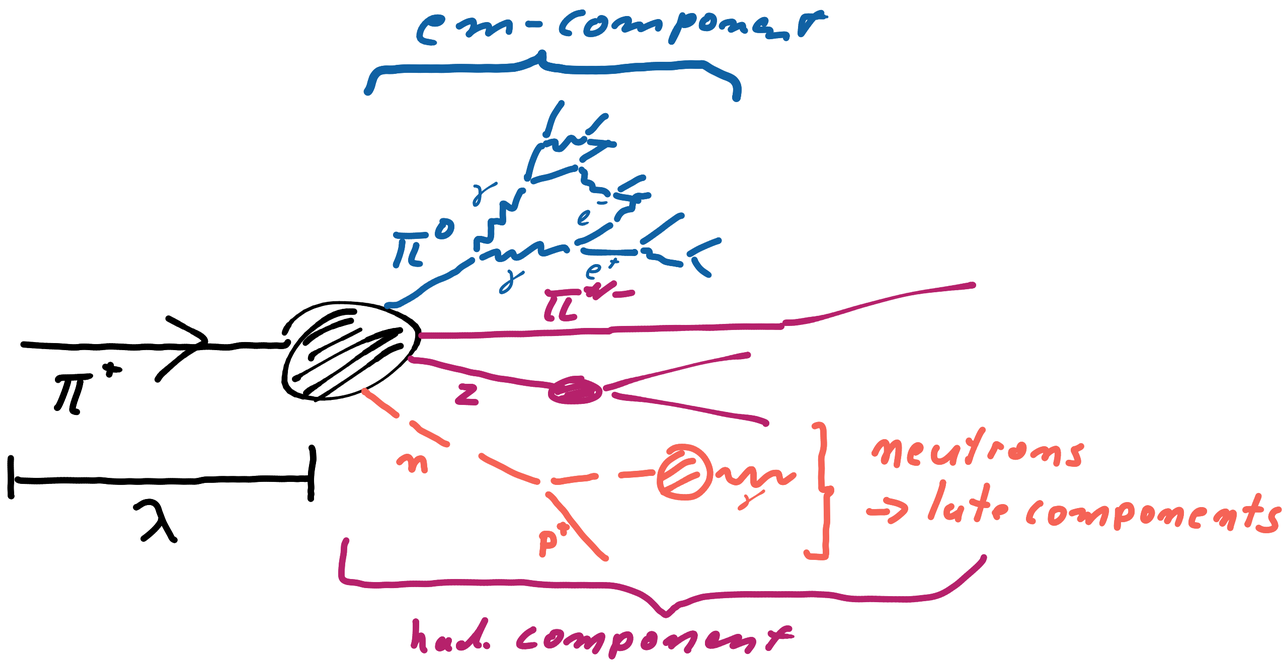
Perform a wide range of measurements, with different active and passive elements, particles, …

Understanding Hadronic Showers

Selected Results on Spatial Structure



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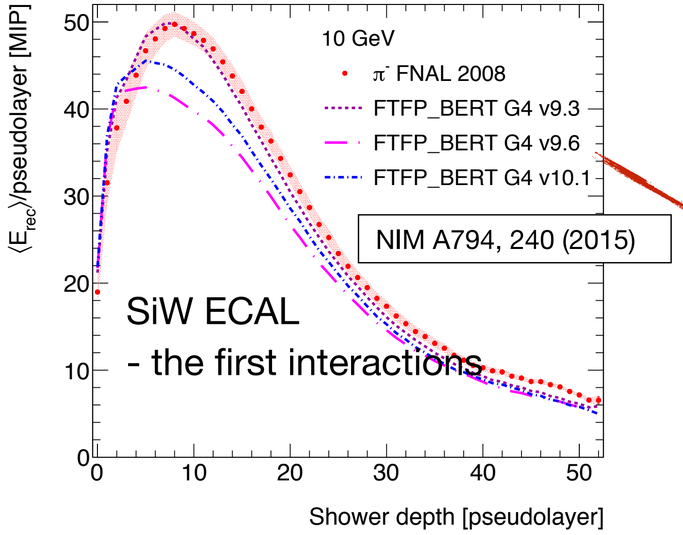

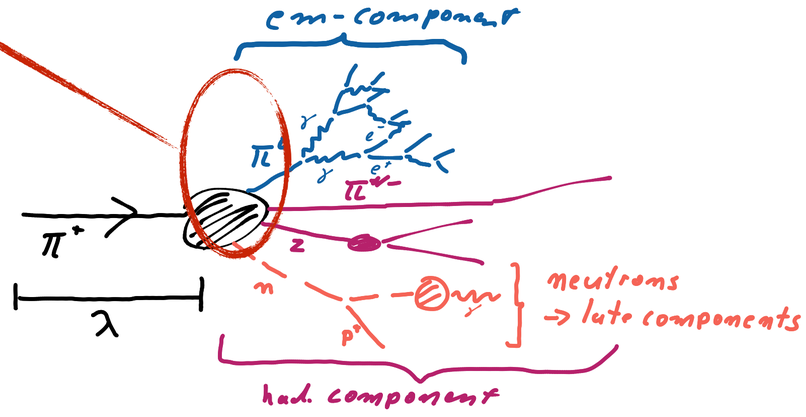

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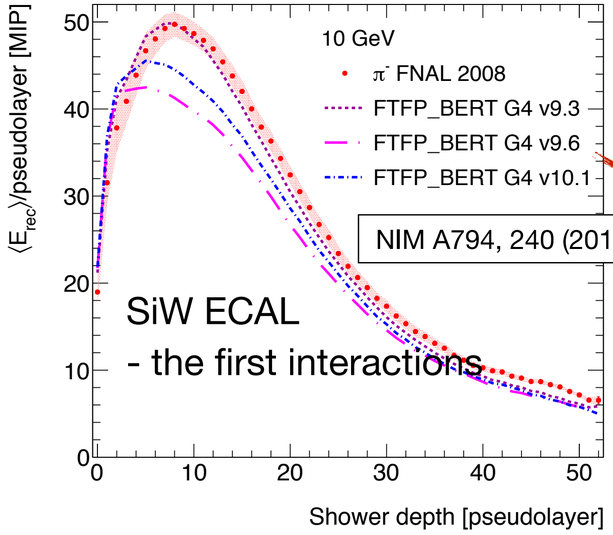

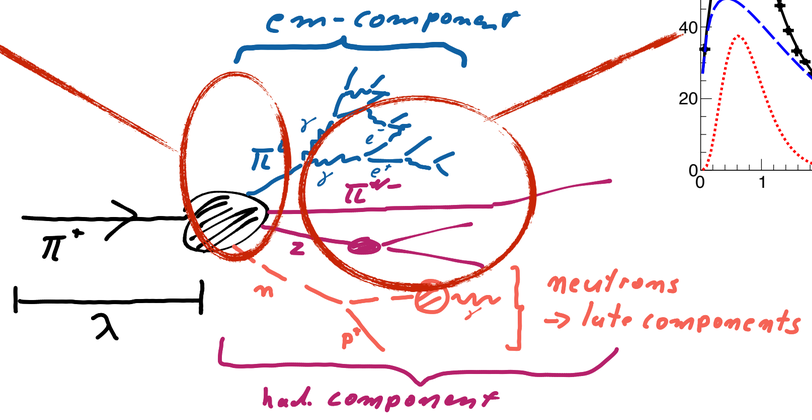

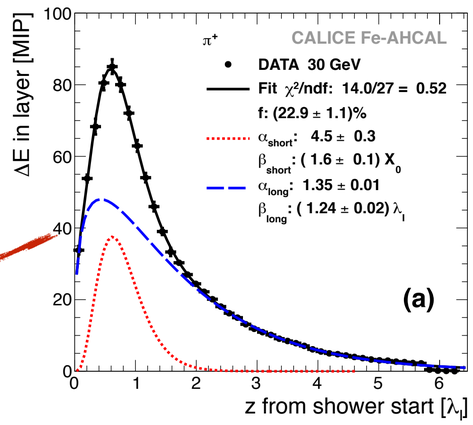

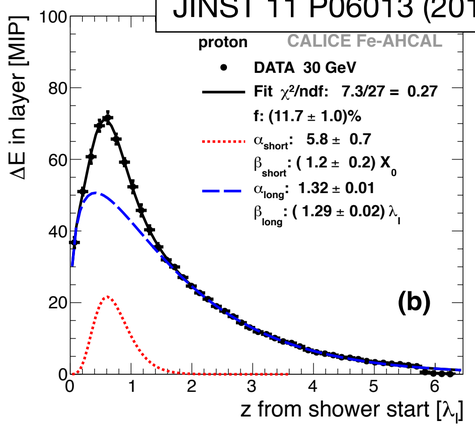

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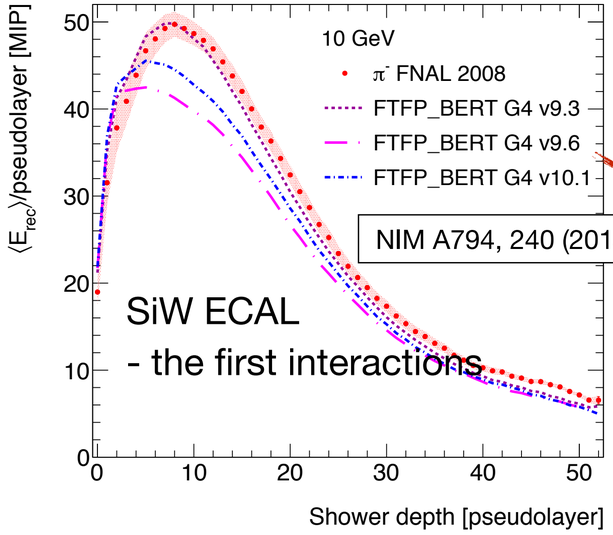
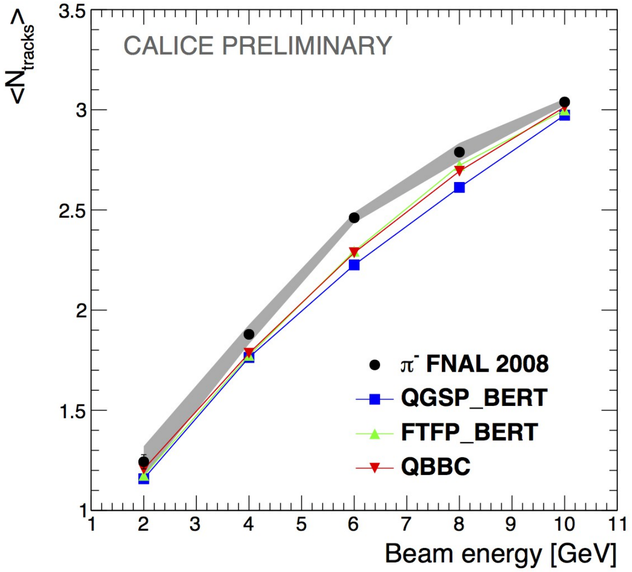
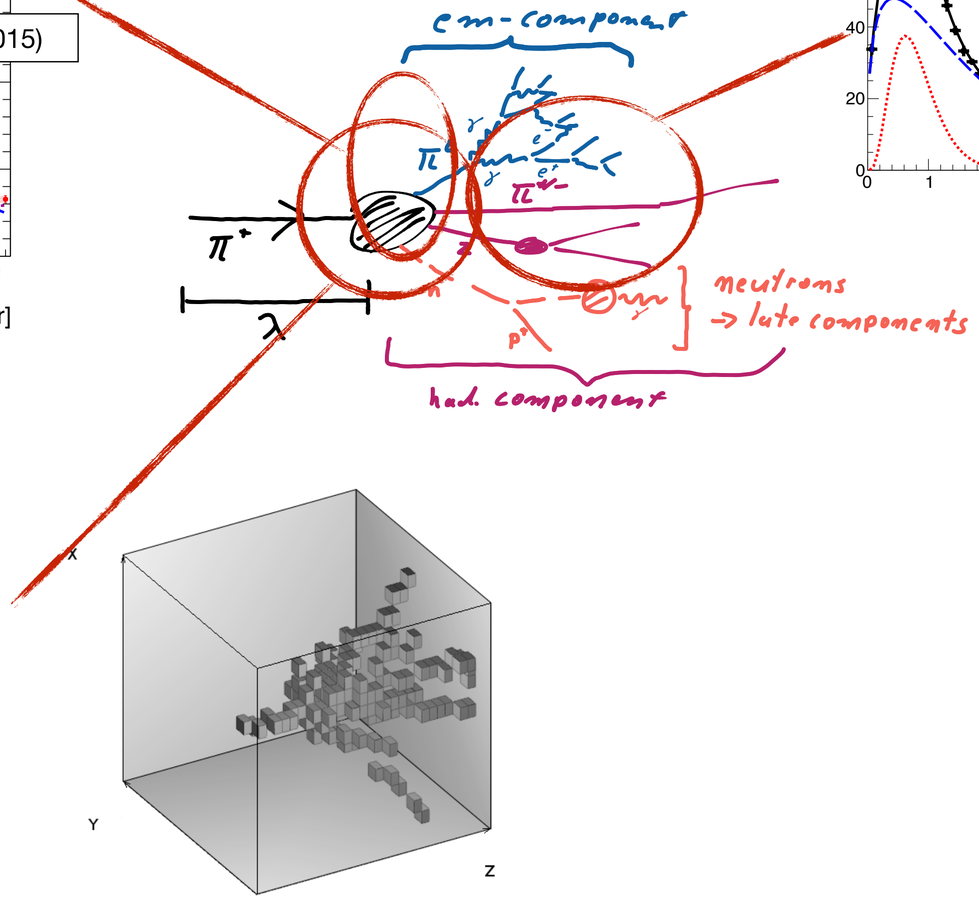
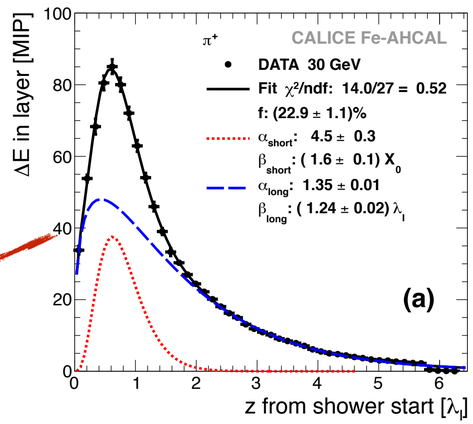


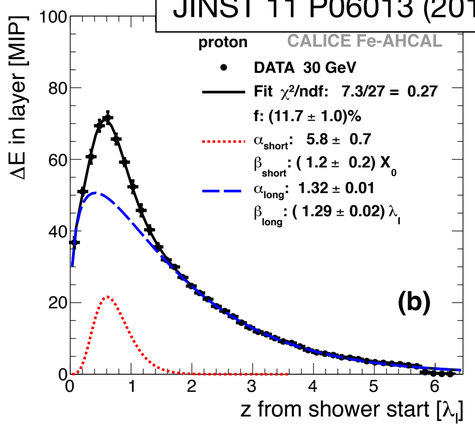
NIM A794, 240 (2015)







JINST 11 P06013 (2016)



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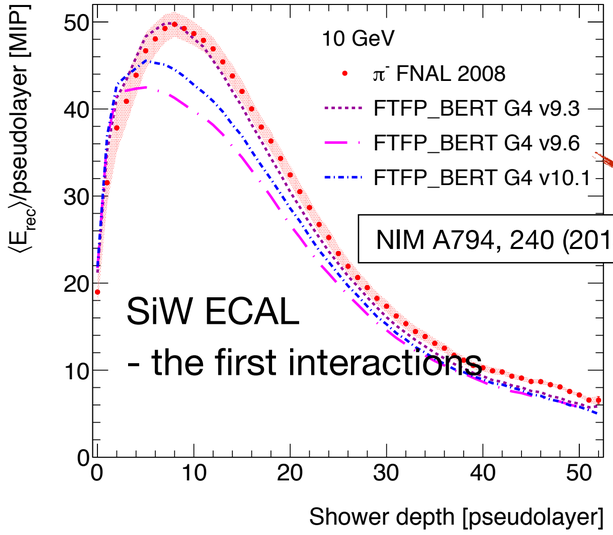
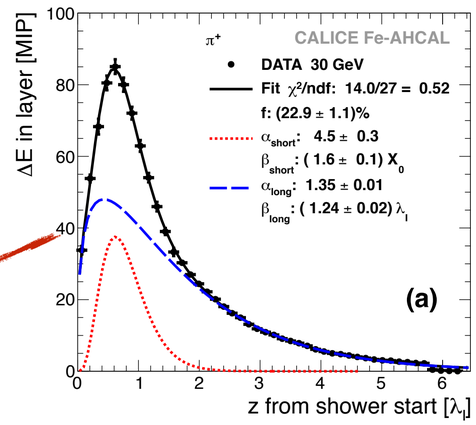
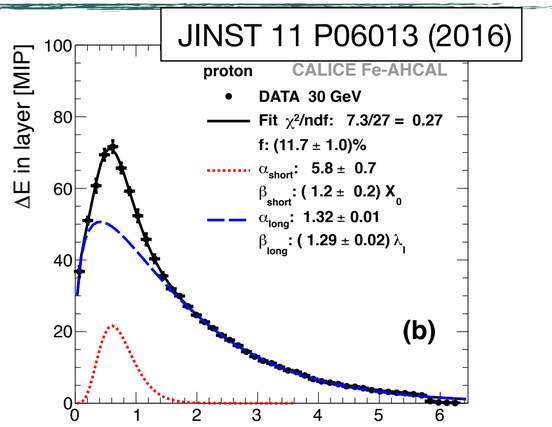
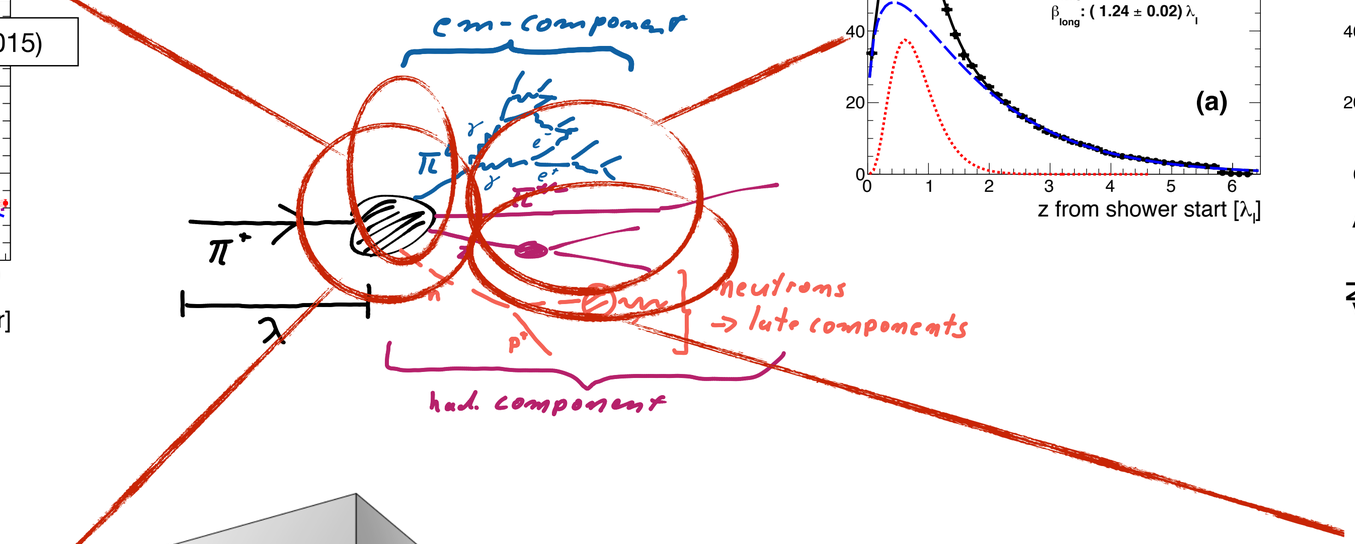
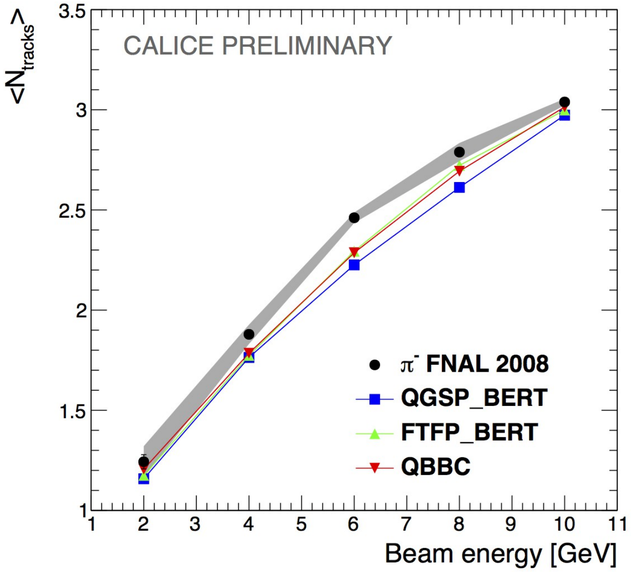
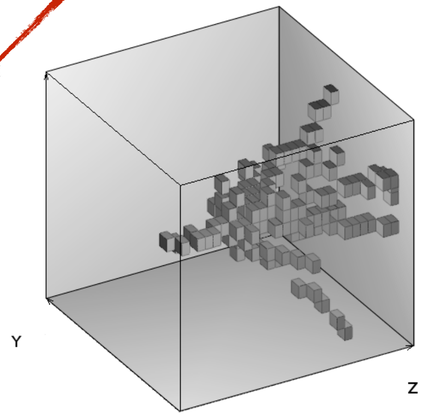


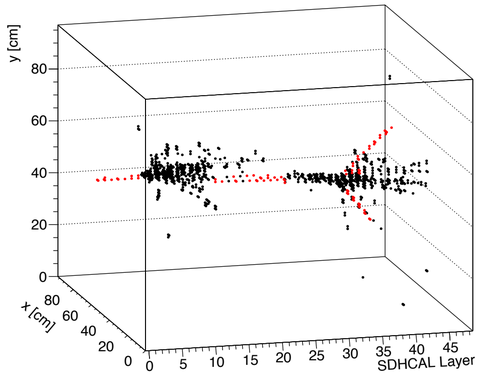


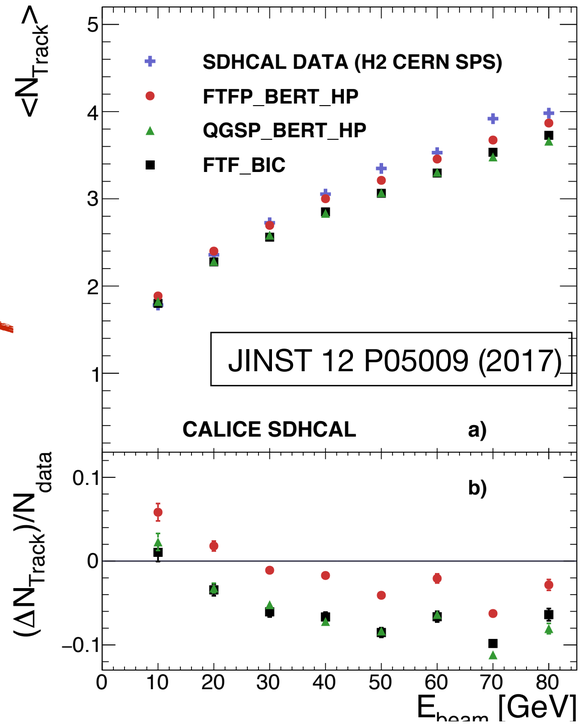








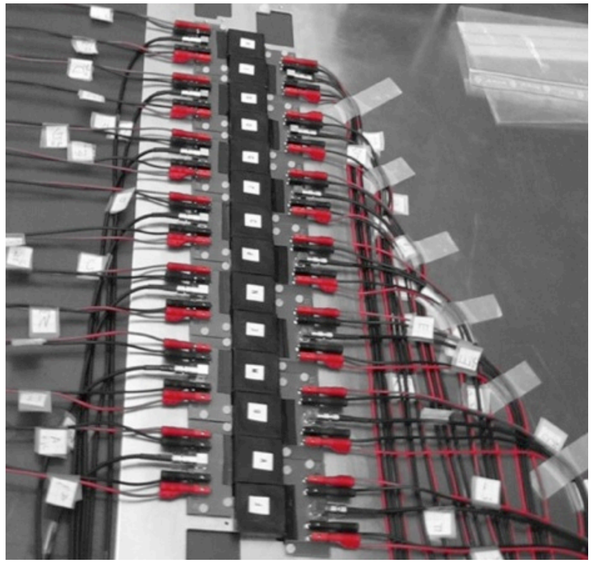




Understanding Hadronic Showers

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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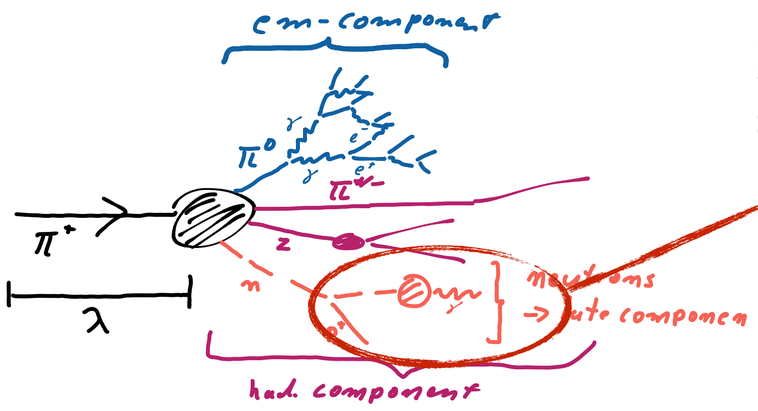

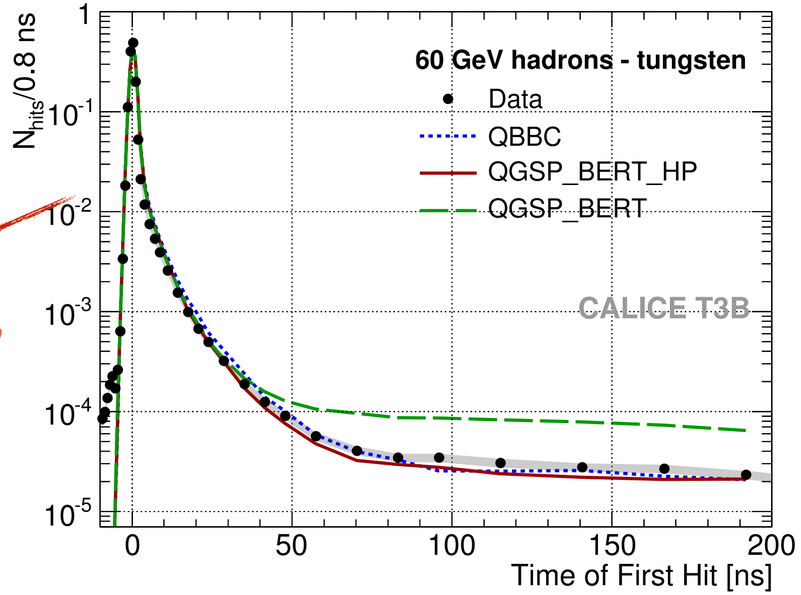

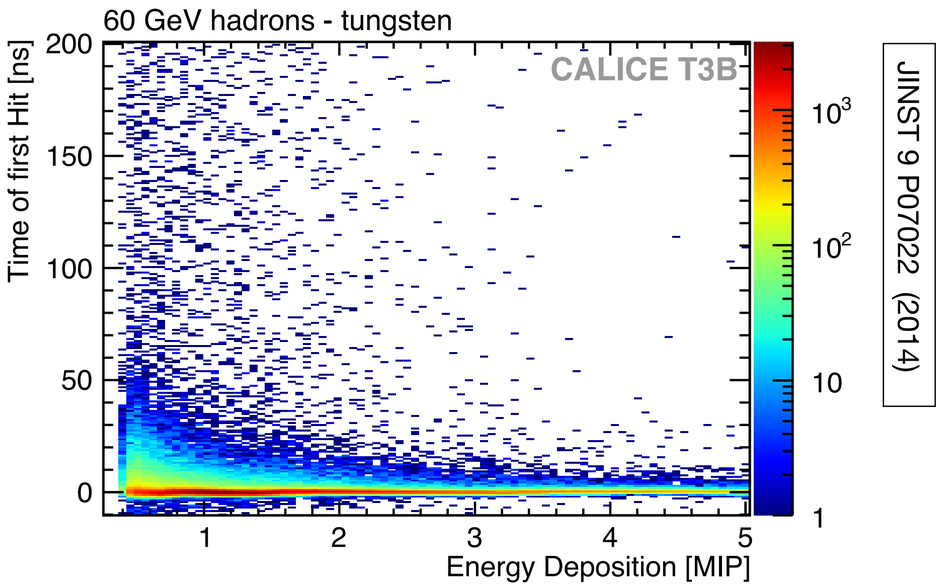

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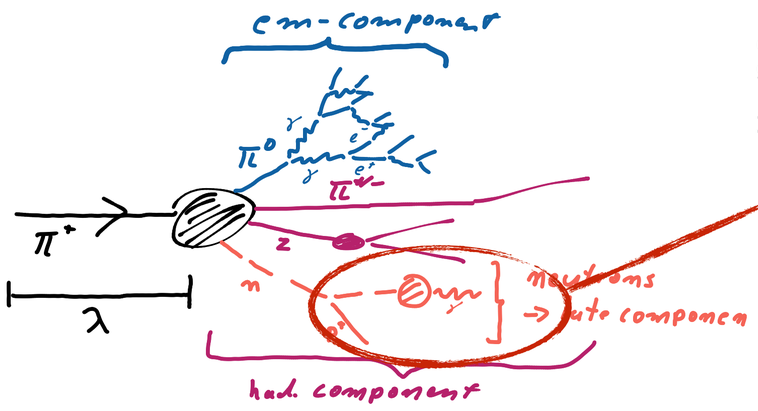
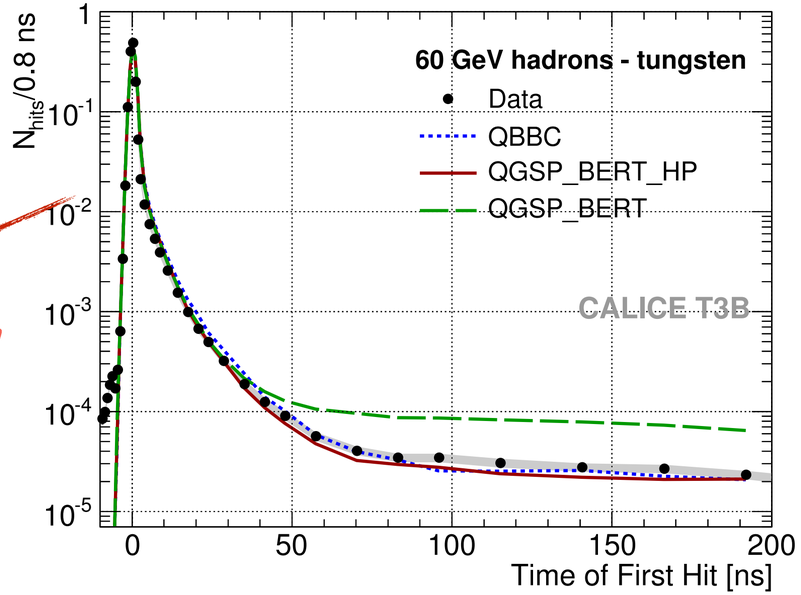
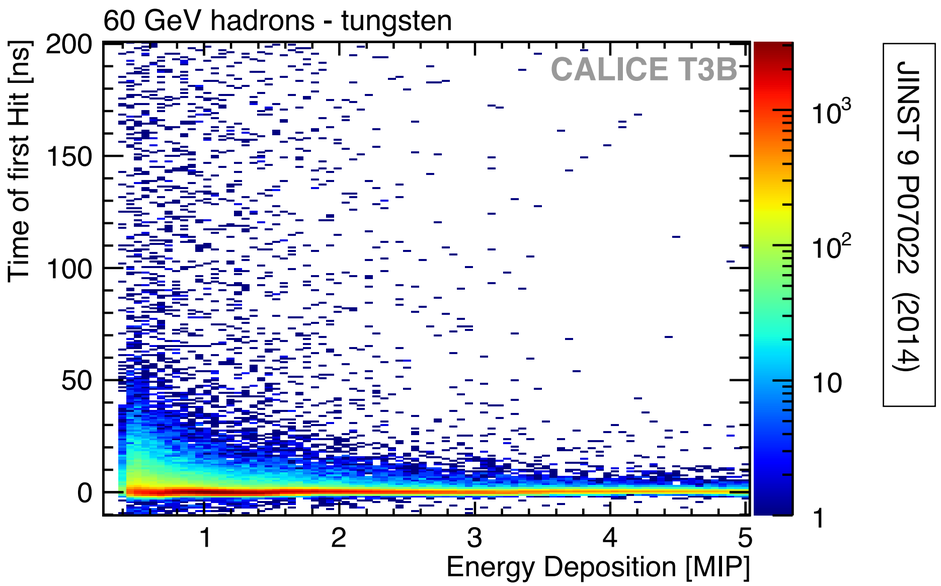






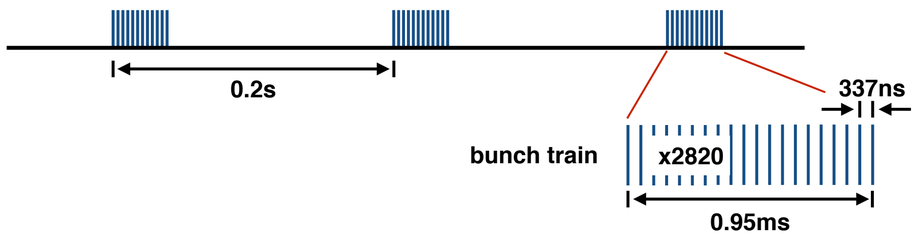
- With more data: Scaling this up from a single strip of cells to a fully instrumented volumes - with both scintillator / SiPM and silicon

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

Test Beams for Calorimetry

New Challenges

- Calorimeters for Linear Colliders rely on power pulsing: For tests under optimal conditions need LC - like time structure of beams



- Future hadron colliders (and high-energy colliders in general) will result in very high energies and particle densities - beyond the reach of available test beams
  - Extreme particle rates can (partially) serve as a proxy for high energy showers: High particle densities

- Highly granular calorimeters for a future e^+e^- collider will require extensive beam times for calibration and commissioning during construction - Need to (inter-) calibrate 10s or 100s of millions of detector cells

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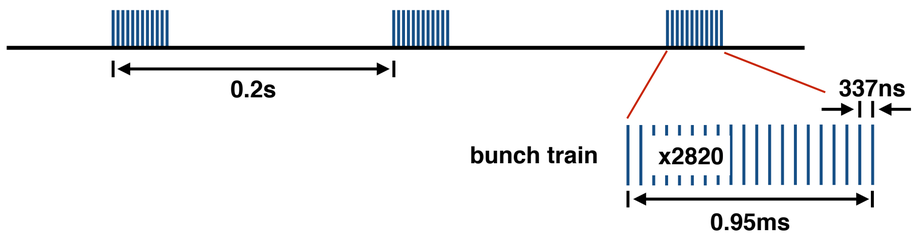

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➪ Calorimetry will remain an excellent and interesting customer for test beams!

Summary & Outlook

- Calorimeters are developing rapidly at the moment, with new concepts developed over the last decades now moving towards applications

- 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
  - With further potential: Bringing granularity to other active technologies, including LAr and dual readout

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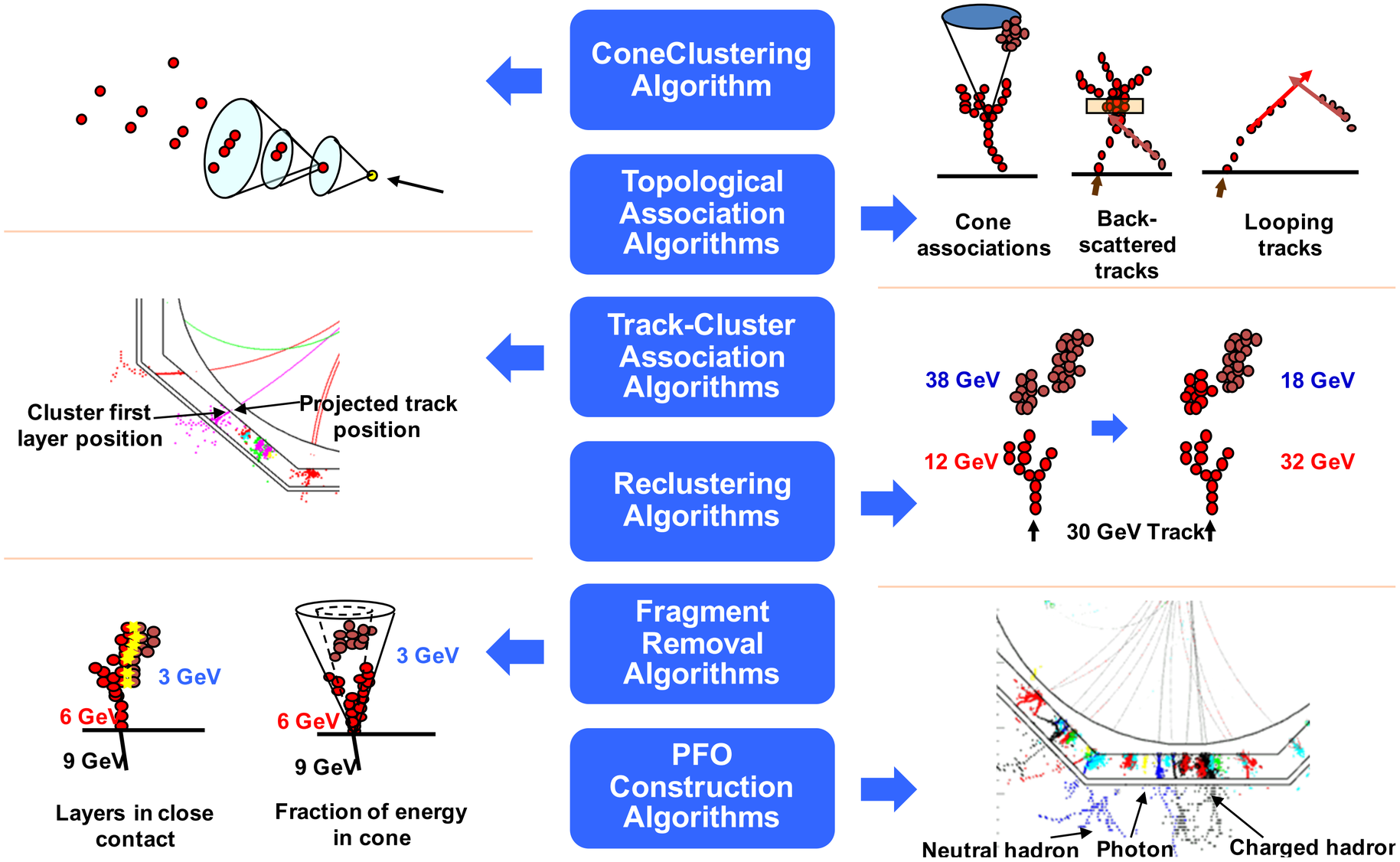
… with interesting challenges provided by the next generation of detectors!

Extras

Particle Flow Algorithms

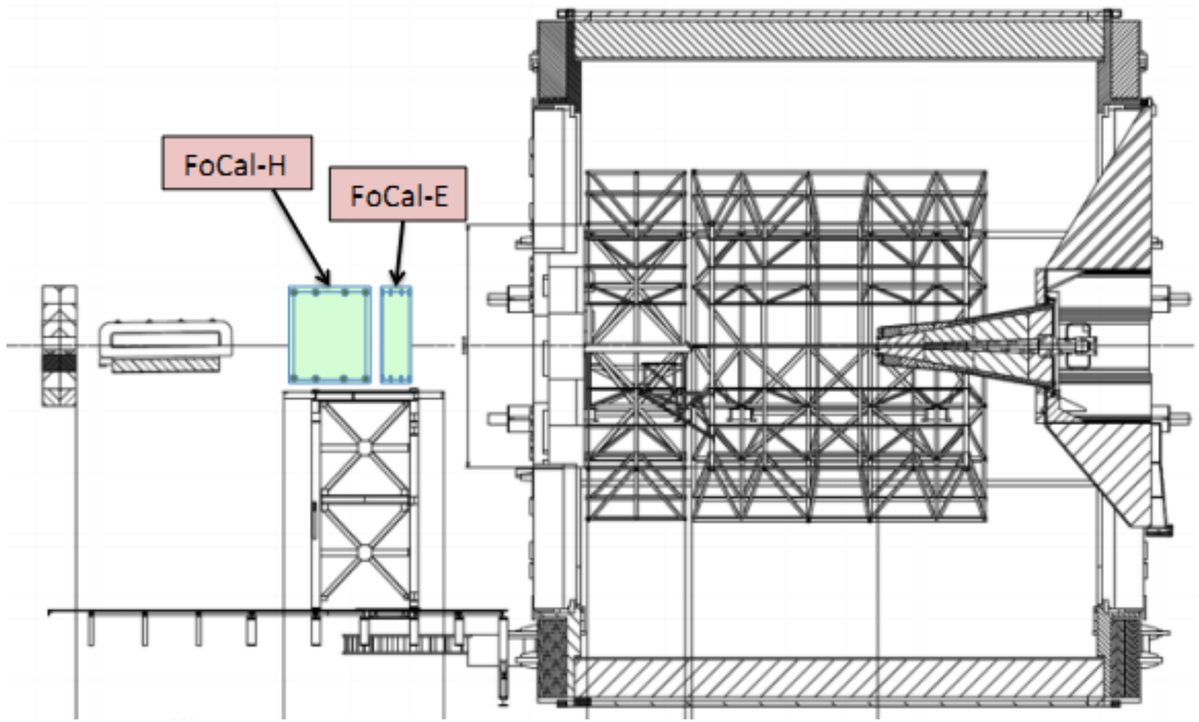
Under The Hood



Extremes in Granularity

The ALICE FOCAL Prototype

- A highly granular forward electromagnetic calorimeter for direct photon measurements at ALICE
- Technological development carried out in ALICE groups; connected to CALICE for shower studies



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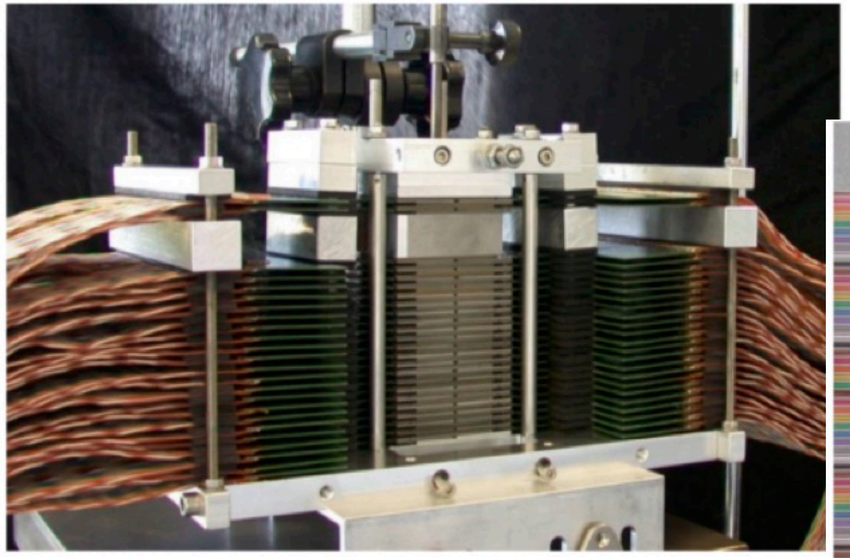

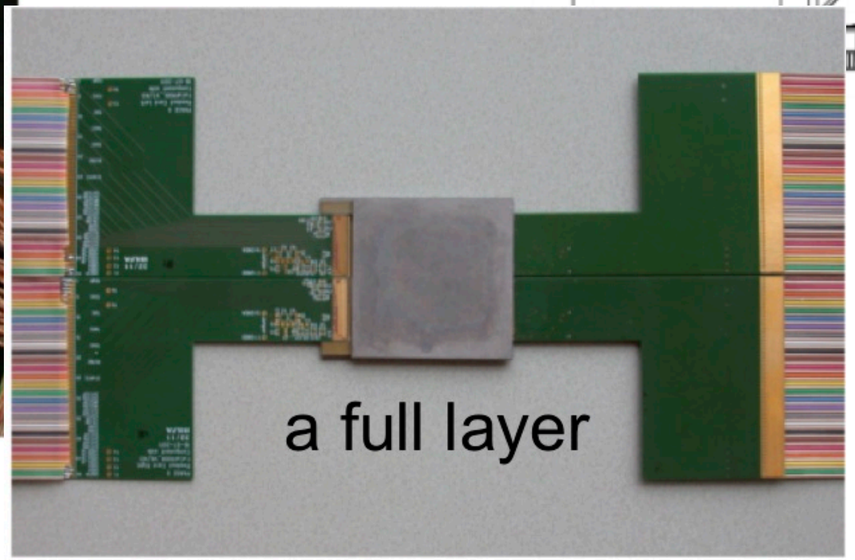

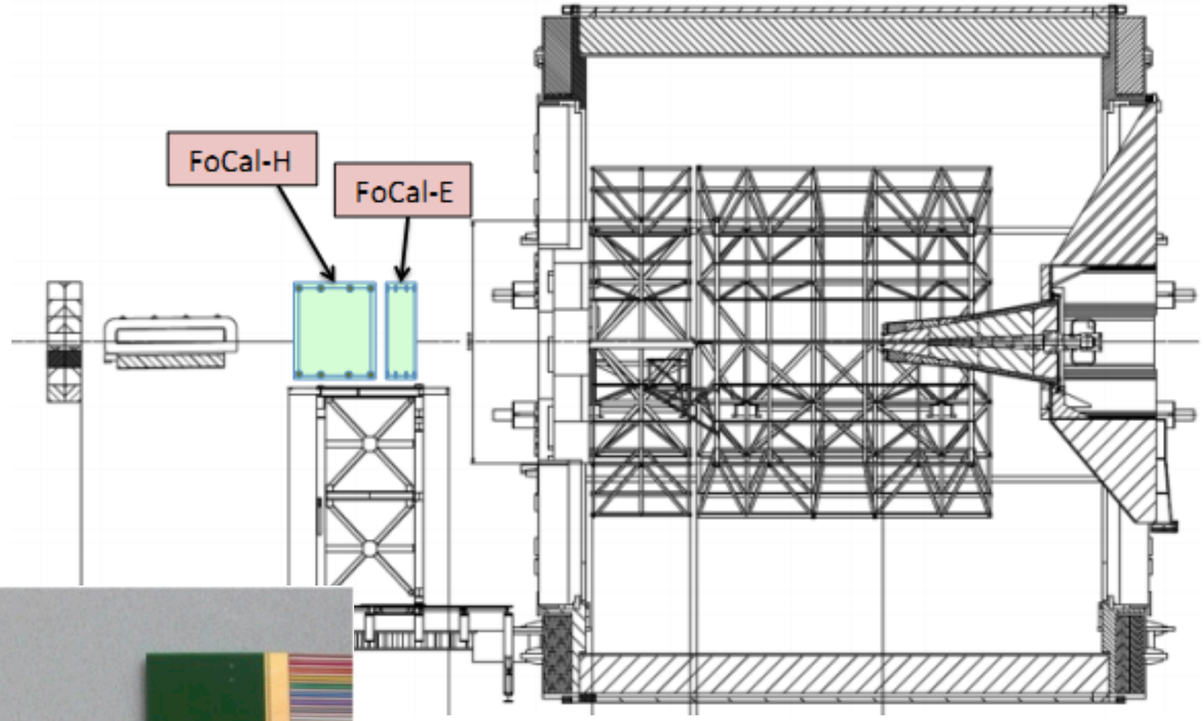

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28 X_0 in 11 cm

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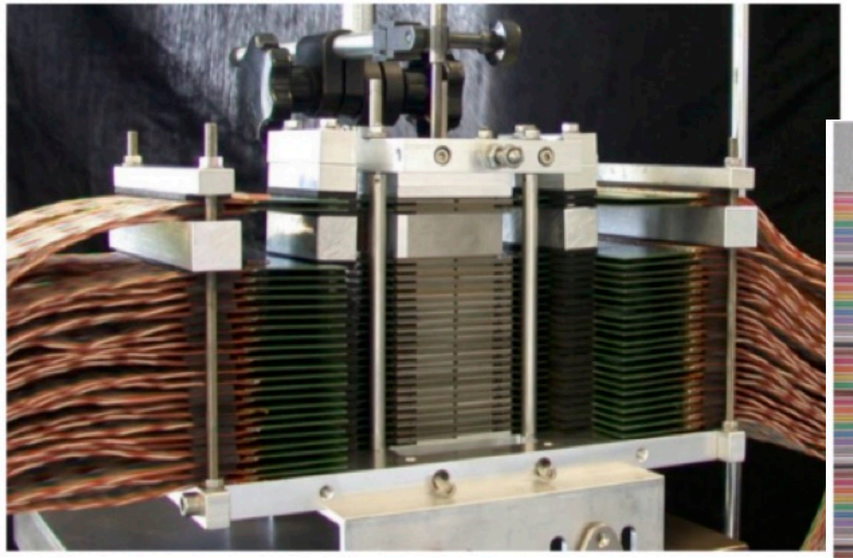
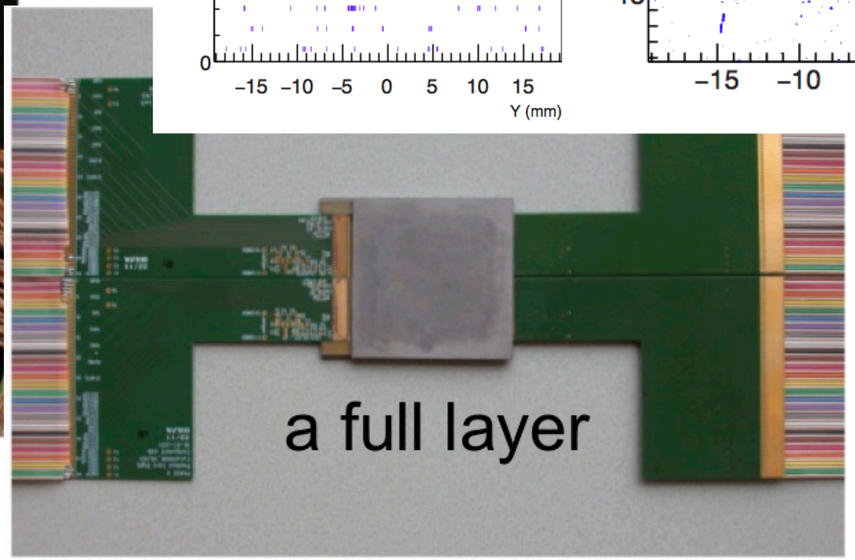
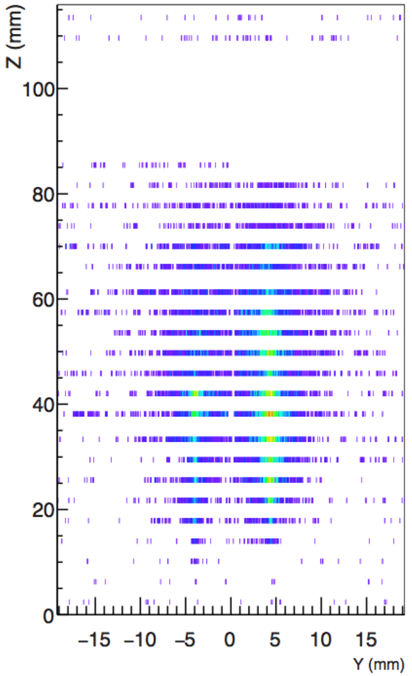
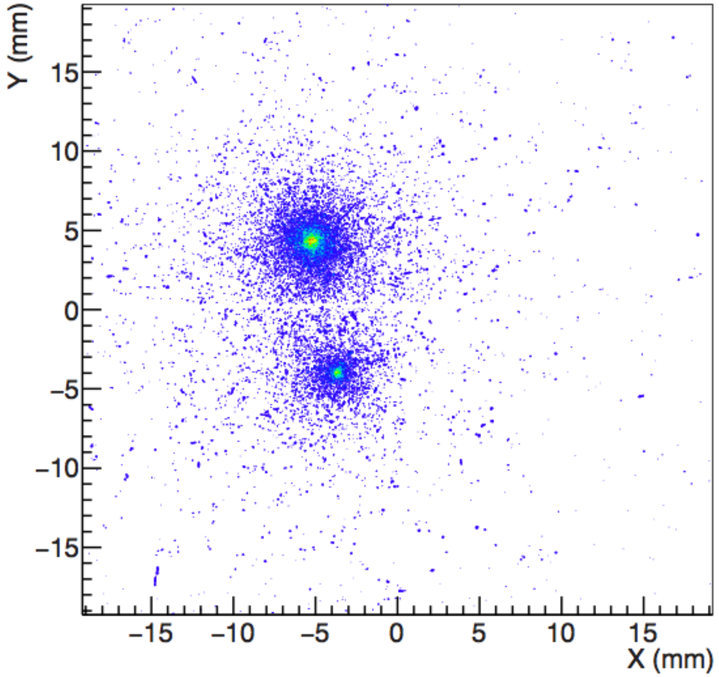
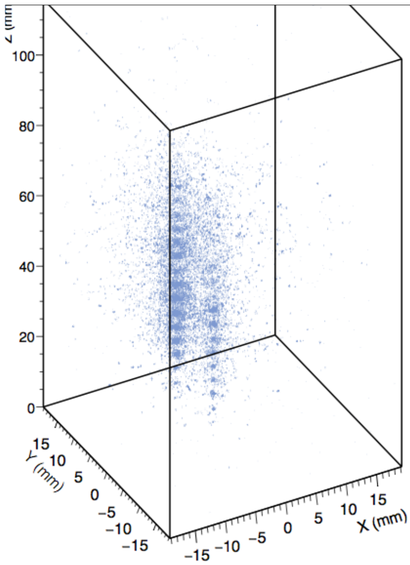








pile-up in a 244 GeV mixed beam



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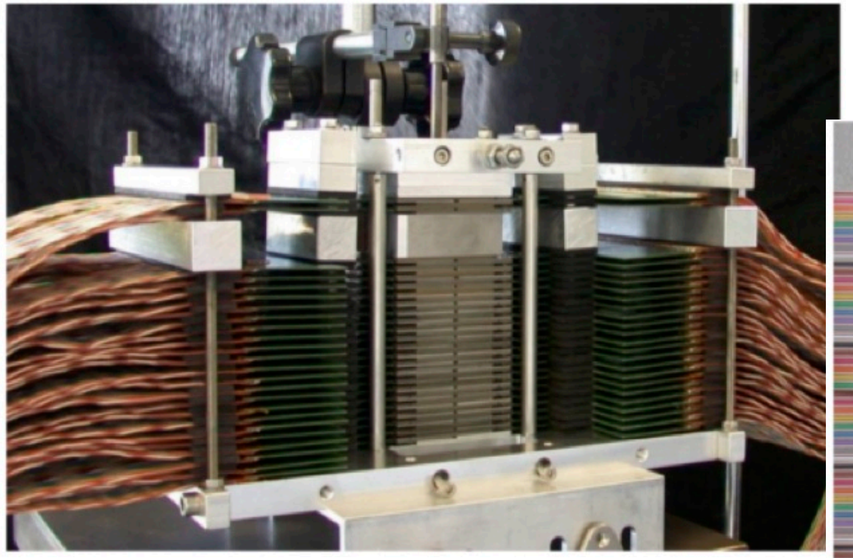

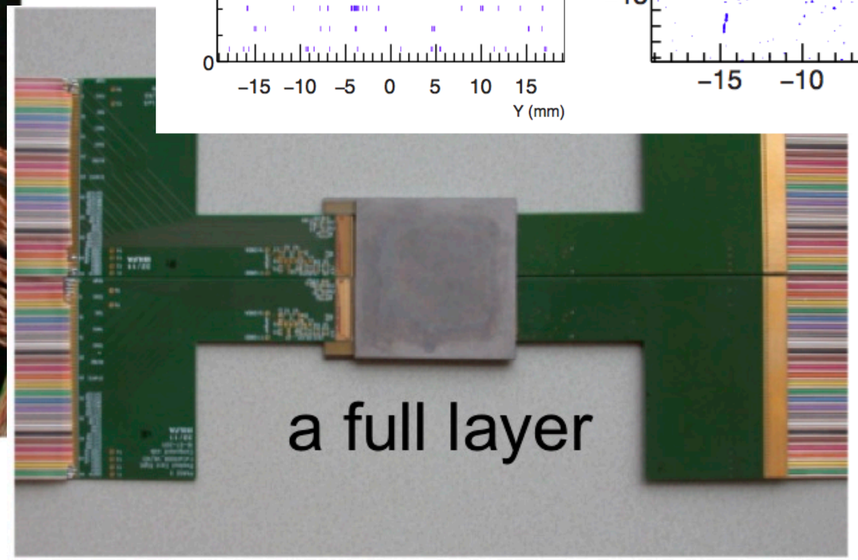

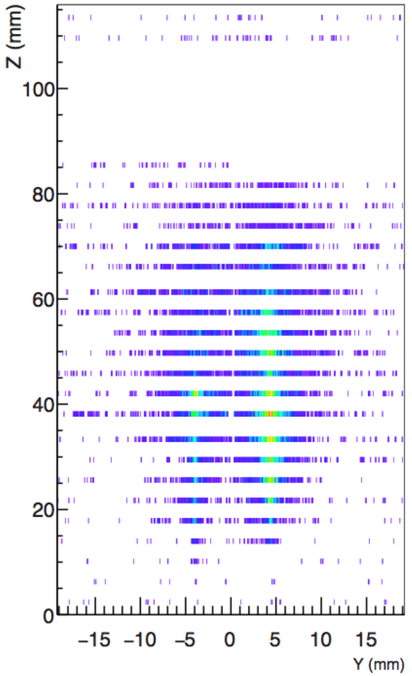

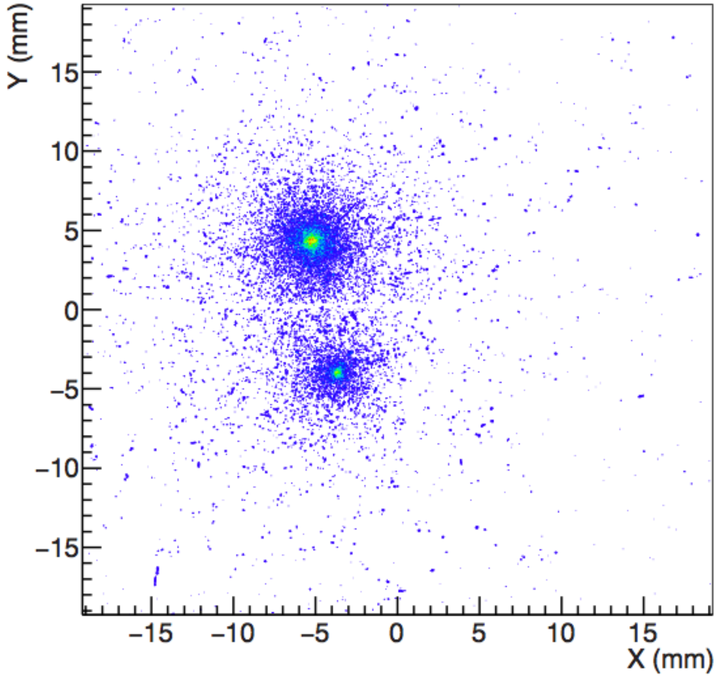

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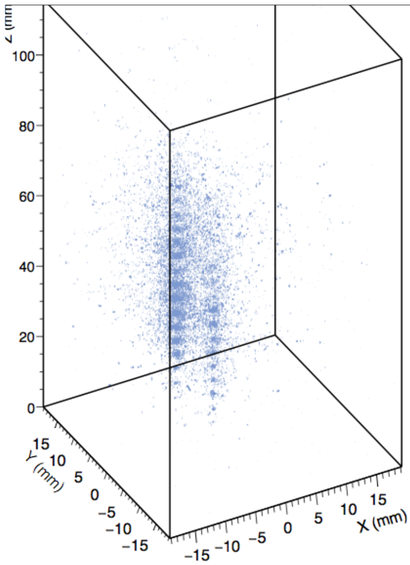

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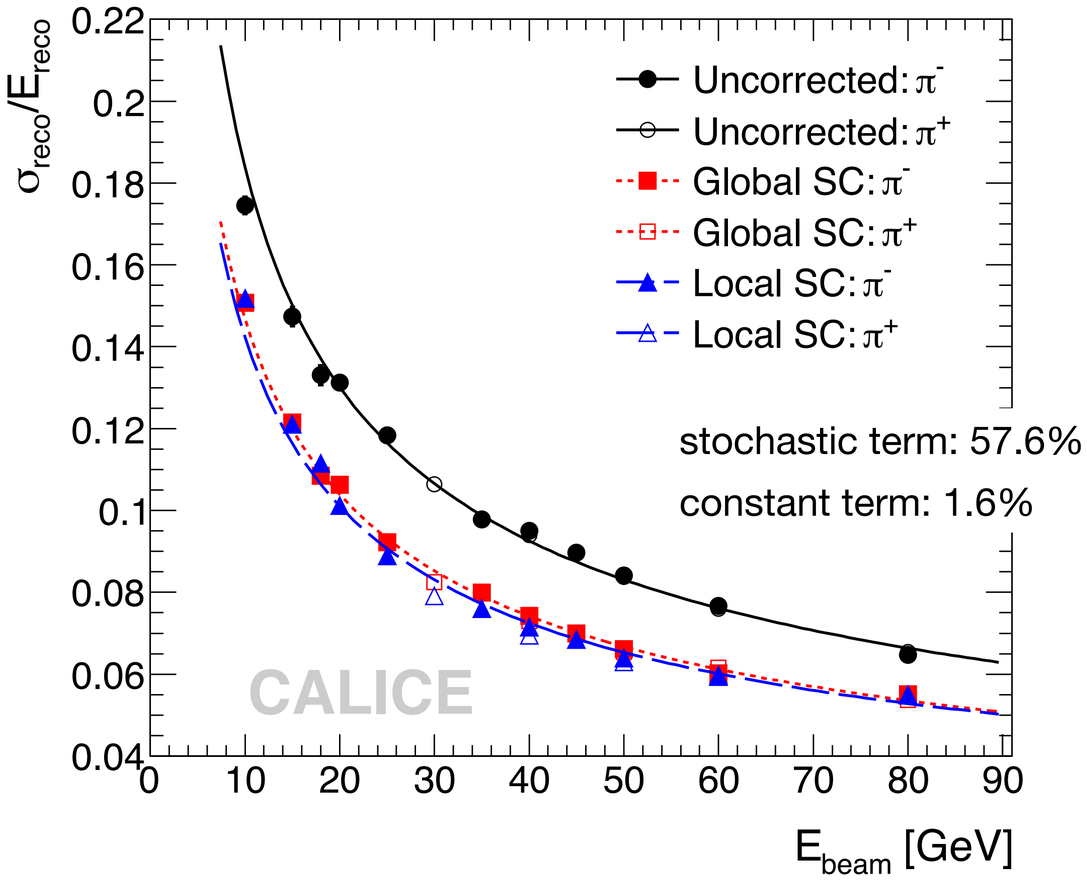
New prototype based on ALPIDE chip in construction: 24 layers, even higher compactness

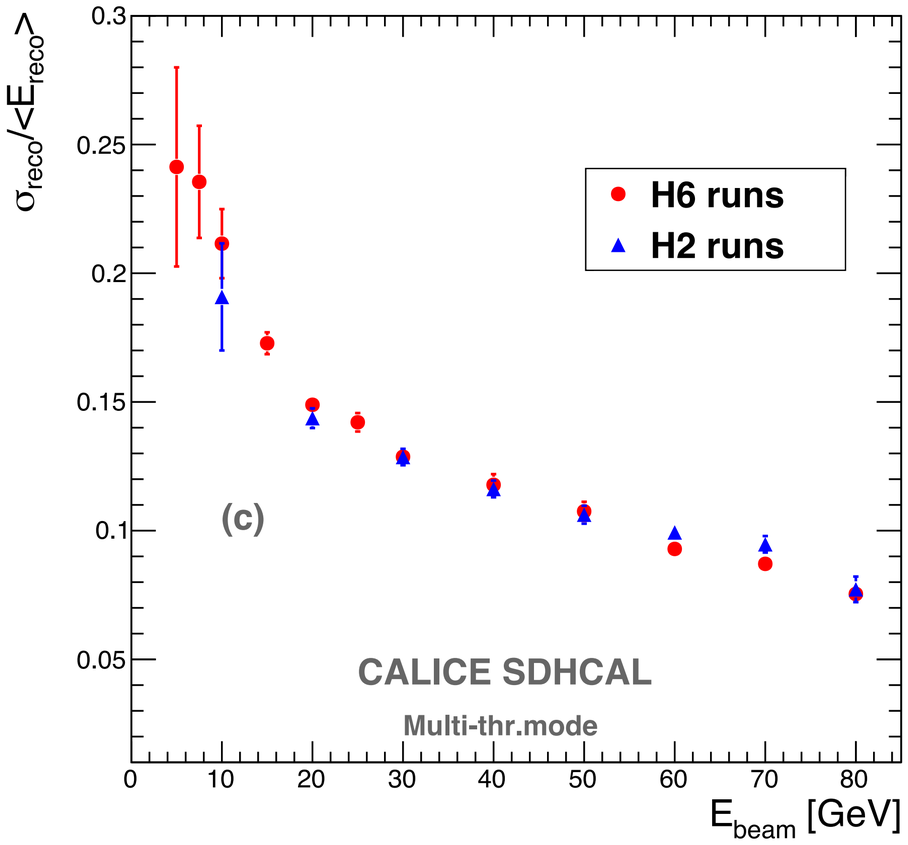
Performance of Highly Granular Calorimeters

Energy resolution -Hadronic

Analog (Scintillator + SiPM)



semi-digital (RPCs)

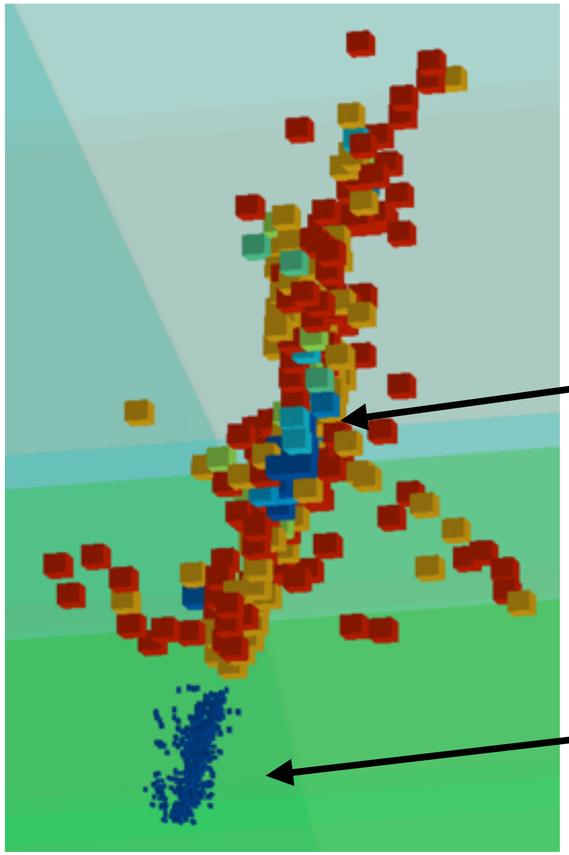


Software compensation (SC) and semi-digital reconstruction use weighting factors to optimise energy resolution

Energy Reconstruction with Software Compensation

Exploitation: Algorithms - Transfer to 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

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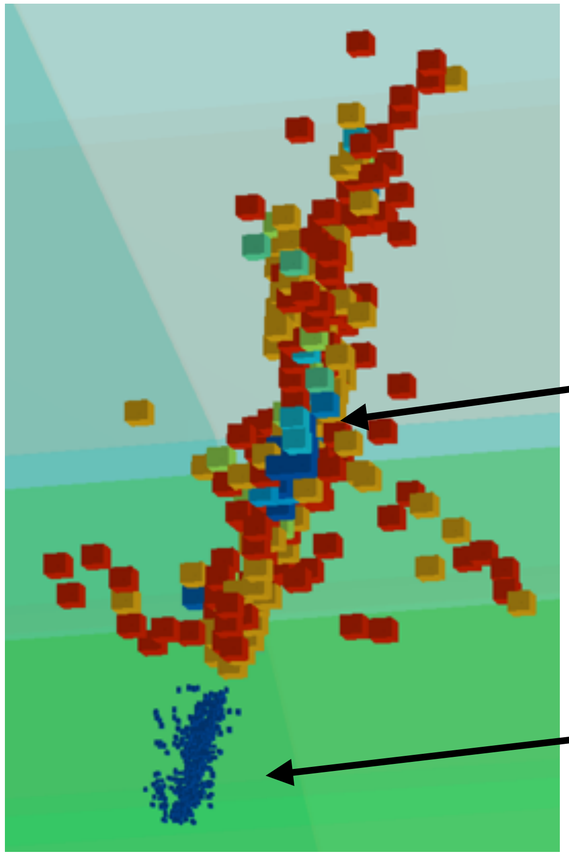

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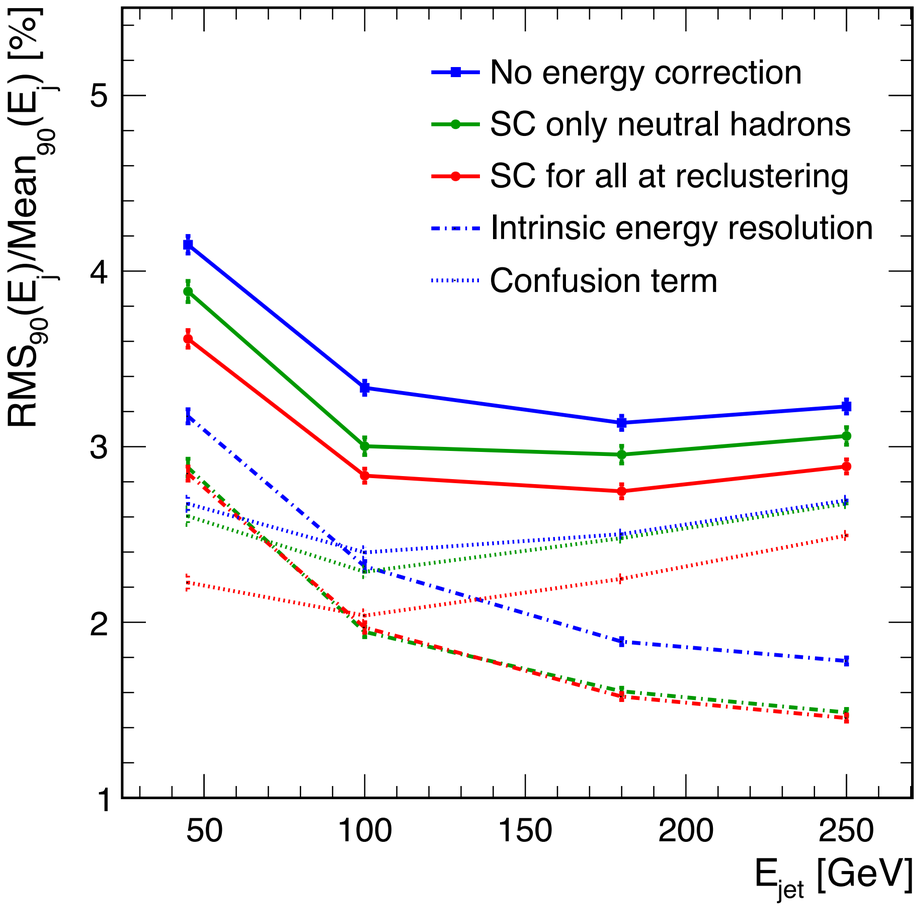

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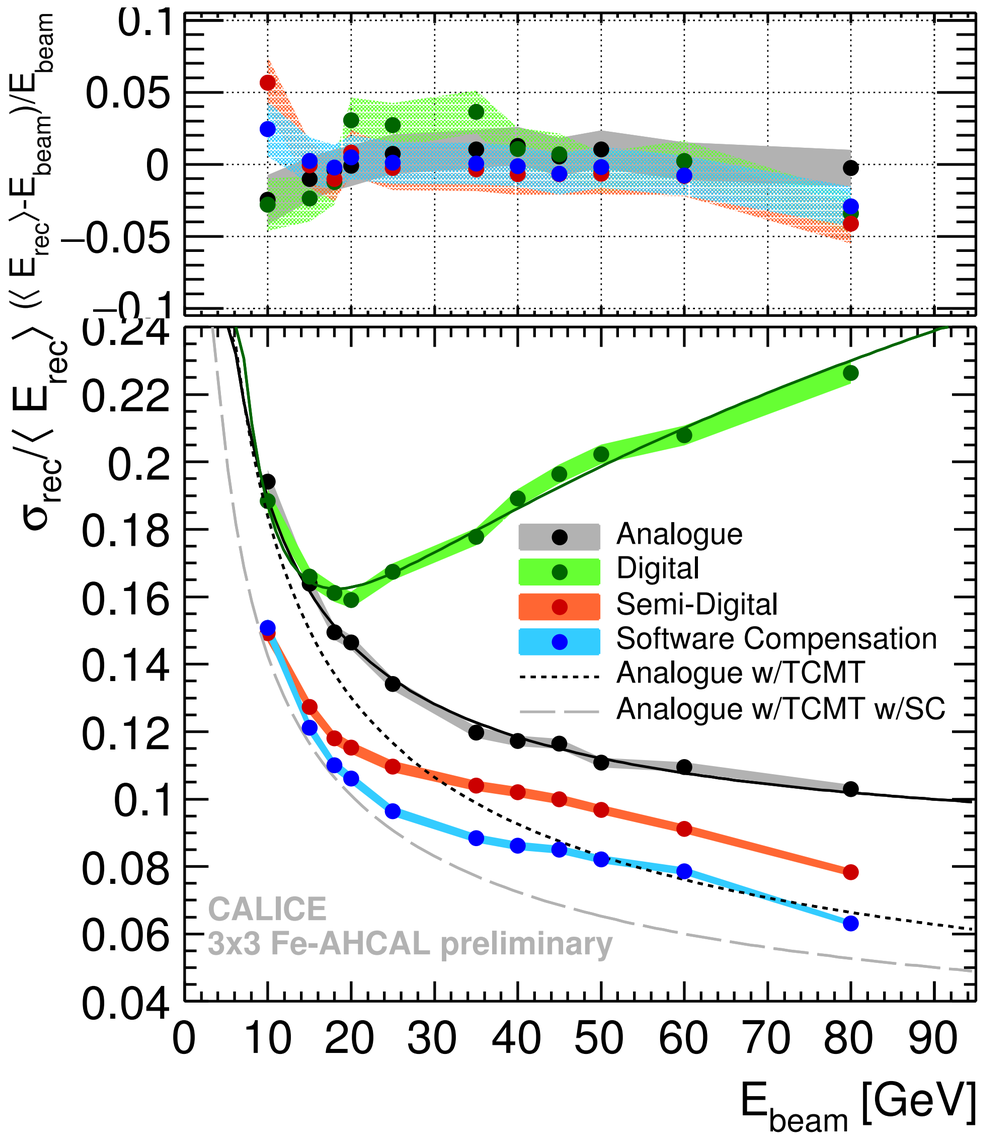
Different Schemes of Hadronic Energy Reconstruction

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 cm^2 granularity)



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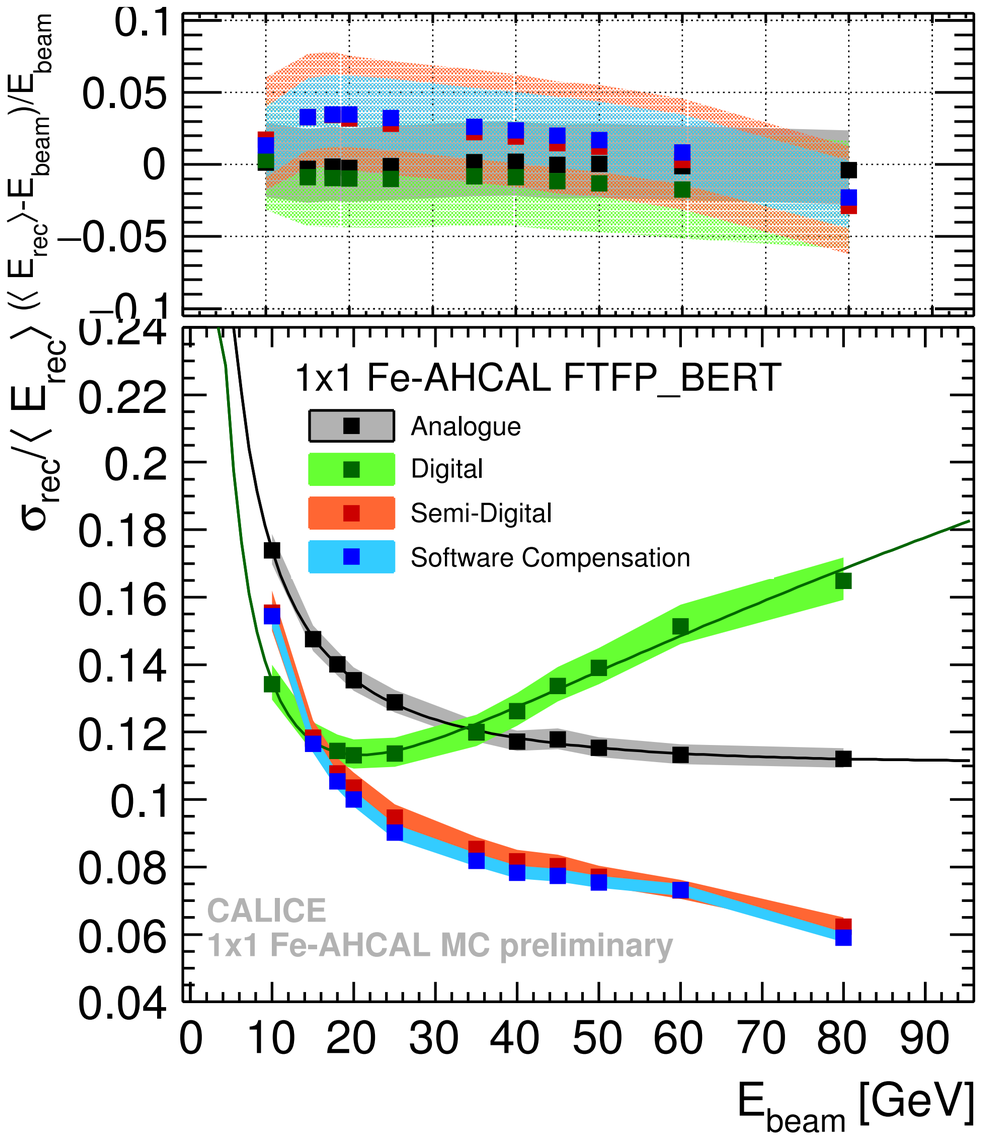
- Different schemes tested on AHCAL data (3 x 3 cm^2 granularity)
- Simulations used to study 1 x 1 cm^2 granularity (scintillator)
  - Digital & fine granularity best at low energy: Suppression of fluctuations
  - SC & semi-digital comparable
    NB: Sampling fraction matters: Semi-digital reconstruction in RPCs does not reach the same resolution



Evolution of the SiW ECAL

Towards large-scale systems

- For a future linear collider detector, “slabs” with an active length of ~ 1.5 m are required
  - Development ongoing, based on established assembly & QA procedures - making use of low-profile ASU - to - ASU interconnections
- Active elements with 2 silicon layers, integrated absorber, to be inserted in precision absorber frame - prototype available