Basics of calorimetry in test beams

Katja Krüger (DESY)

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Overview

- Calorimeter basics & Current developments in calorimetry
  - developments for electron-positron colliders
  - (HL-)LHC detector upgrades
- Calorimeters in testbeams

Calorimeter basics &
Current developments in calorimetry

General Considerations for Calorimetry

- want to measure particle energy, so main quality criterion is the energy resolution

- usually, energy resolution of a calorimeter can be parameterised as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

  - stochastic term: caused by fluctuations in the number of measured shower particles
  - calibration term: caused mainly by non-uniformities, e.g. by calibration
  - noise term: everything contributing energy independent of initial particle energy, e.g. noise

- need wide range of energies to characterize system performance

ECAL and HCAL

- differences between hadronic and electromagnetic showers:
  - hadronic showers much larger: $\lambda_{Int} \gg X_0$
  - much larger variety of hadronic processes
  - some fraction of energy in hadronic showers not measurable ("invisible")

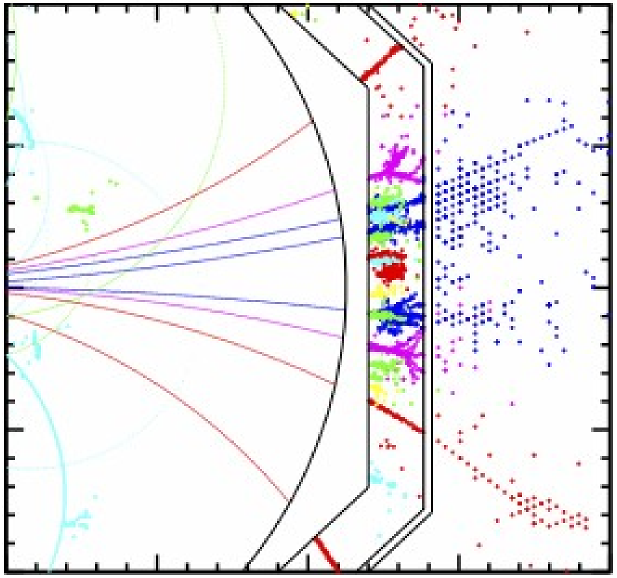
- usually dedicated electromagnetic and hadronic calorimeters
  - ECAL: more compact; homogeneous or fine sampling
    - ATLAS: sampling, lead / LAr $\frac{\sigma(E)}{E} = \frac{10\,\%}{\sqrt{E}} \oplus 0.4\,\% \oplus \frac{0.3\,\mathrm{GeV}}{E}$
    - CMS: homogeneous, crystals $\frac{\sigma(E)}{E} = \frac{3\,\%}{\sqrt{E}} \oplus 0.5\,\% \oplus \frac{0.2\,\mathrm{GeV}}{E}$
  - HCAL: large, coarser sampling
    - ATLAS: iron / scintillator $\frac{\sigma(E)}{E} = \frac{50\,\%}{\sqrt{E}} \oplus 3\,\%$
    - CMS: brass / scintillator $\frac{\sigma(E)}{E} = \frac{100\,\%}{\sqrt{E}} \oplus 4.5\,\%$

Current developments

- developments of detectors for future electron-positron colliders
  - main challenge: unprecedented jet energy resolution
  - method: high granularity for Particle Flow Algorithms (PFA)
- upgrades of LHC detectors (focus on HL-LHC)
  - main challenges
    - very high radiation dose
    - high pile-up
  - methods
    - higher granularity
    - improved time resolution
- calorimeters also play an important role in many other areas (not covered here)
  - space experiments
  - calorimeters for ultimate single-hadron resolution (dual readout)
  - ...

Particle Flow Algorithm

- Idea:
  for each individual particle in a jet, use the detector part with the best energy resolution



from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „typical“ jet:
  ~ 62% charged particles
  ~ 27% photons
  ~ 10% neutral hadrons
  ~ 1% neutrinos

Particle Flow Algorithm

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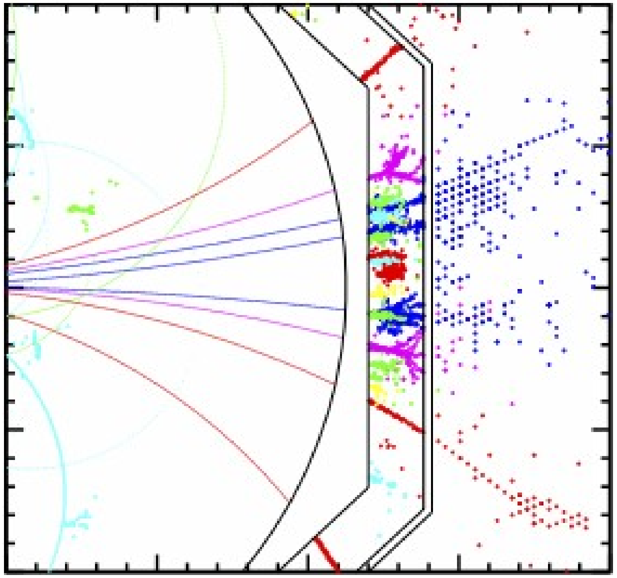


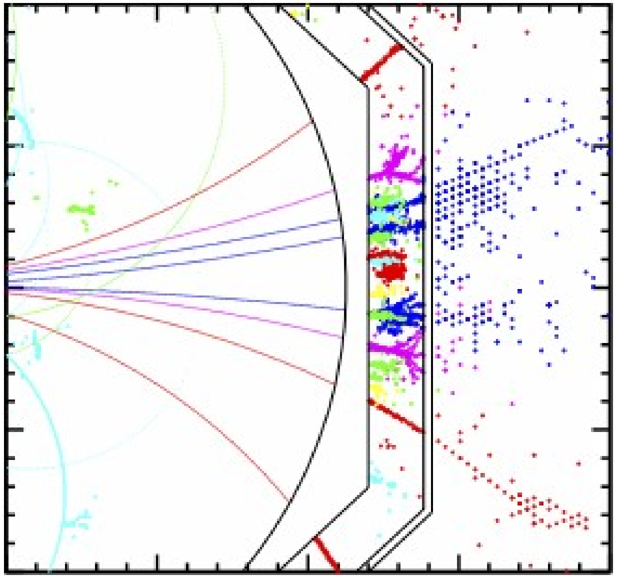
from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

> „typical" jet:

~ 62% charged particles	tracking
~ 27% photons	EM calorimeter
~ 10% neutral hadrons	HAD calorimeter
~~ 1% neutrinos~~	

Particle Flow Algorithm

- Idea:
  for each individual particle in a jet, use the detector part with the best energy resolution

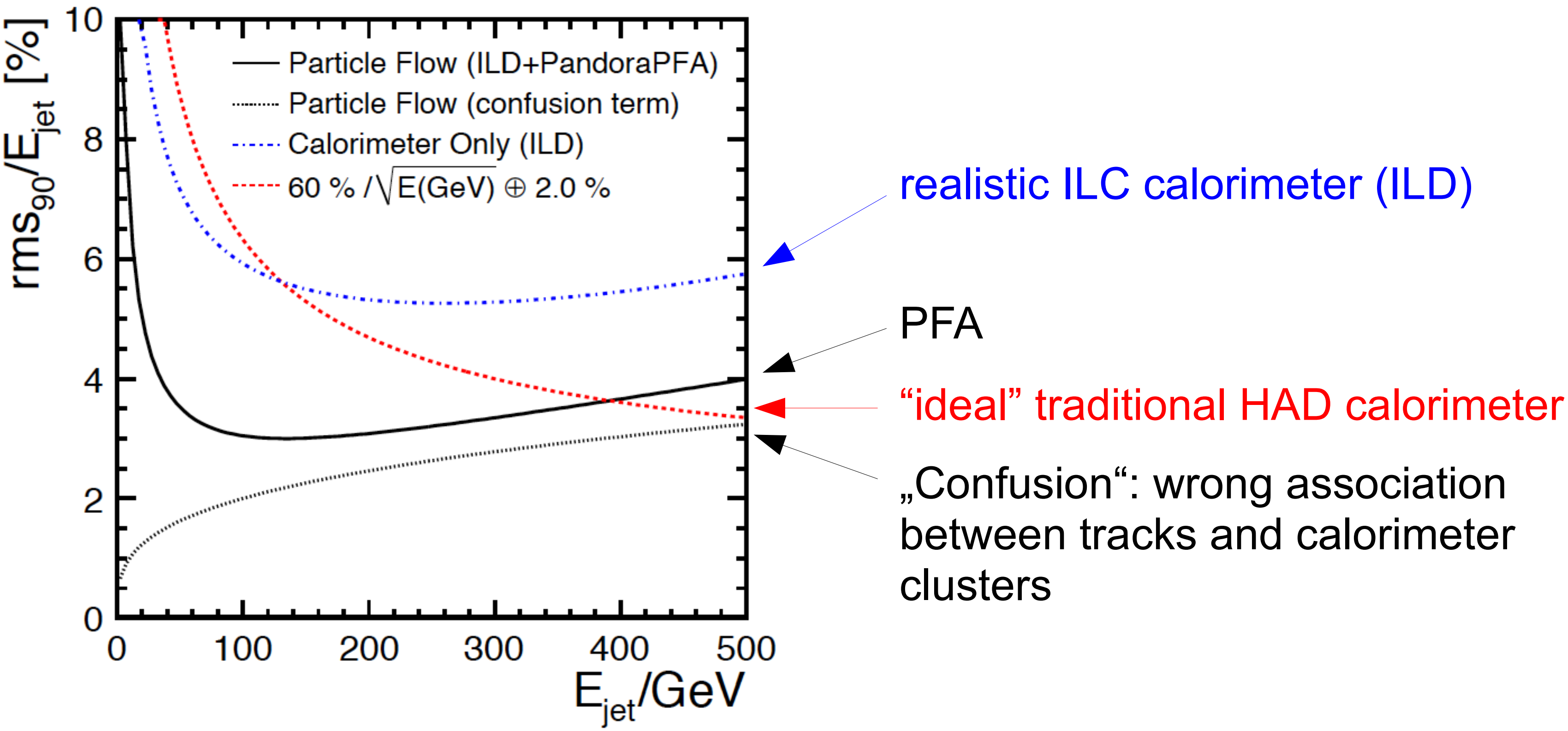


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „typical“ jet:

		$(\sigma_{jet})^2$
~ 62% charged particles	tracking	$\approx (\sigma_{tracks})^2$
~ 27% photons	EM calorimeter	$+ (\sigma_{EMCalo})^2$
~ 10% neutral hadrons	HAD calorimeter	$+ (\sigma_{HADCalo})^2$
~ 1% neutrinos		$+ (\sigma_{loss})^2 + (\sigma_{confusion})^2$

Jet Energy Resolution



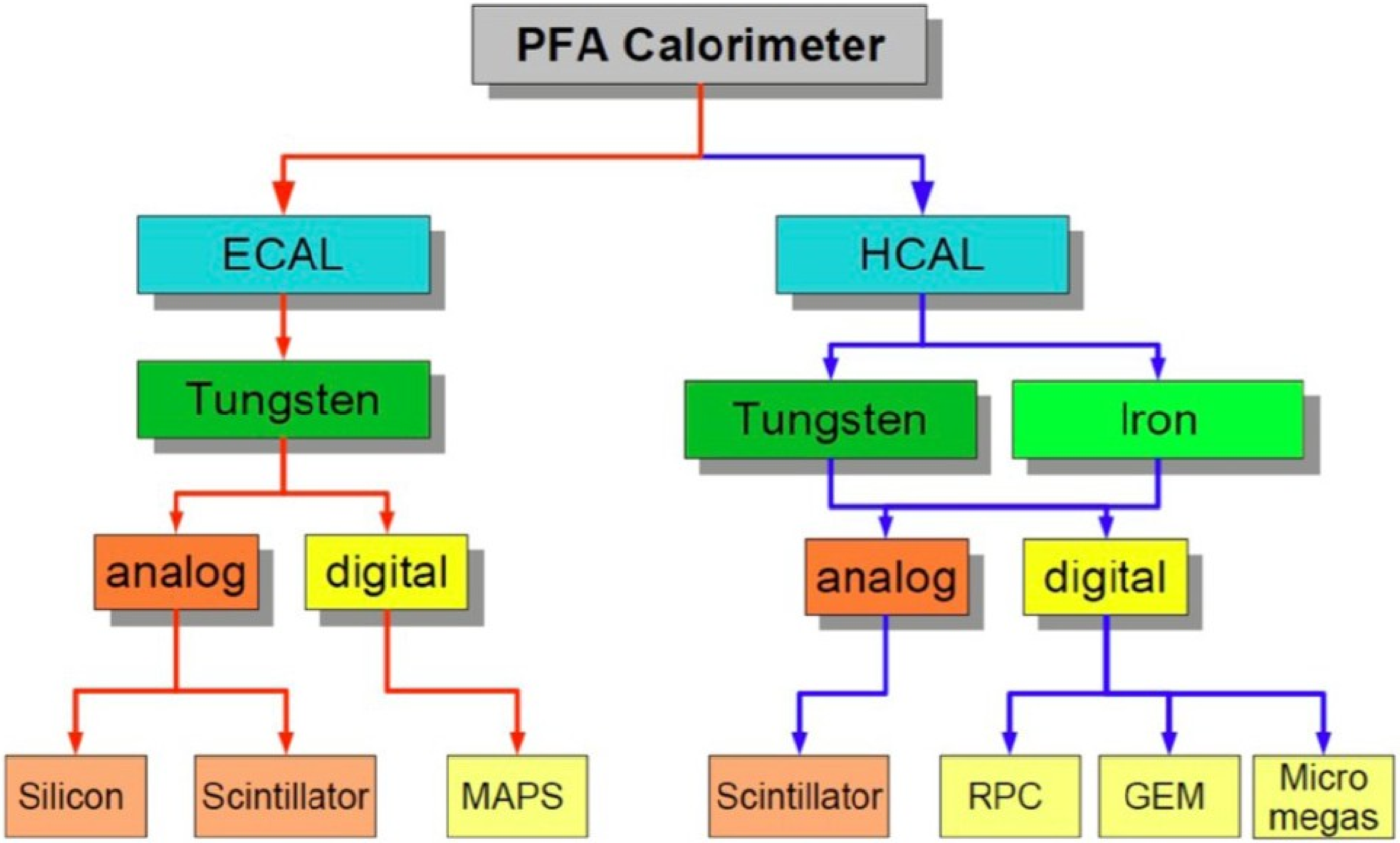
- PFA resolution is clearly better than calorimeter alone
- at high jet energy: correct association between tracks and calorimeter clusters is very important ⇒ calorimeter with **very high granularity**
- at low jet energy: dominated by "classical" calorimeter energy resolution ⇒ hadronic calorimeter with **good energy resolution**

Calorimeter Technologies for PFA

absorber

readout
scheme

active
technology



CALICE: R&D collaboration for highly granular calorimeters

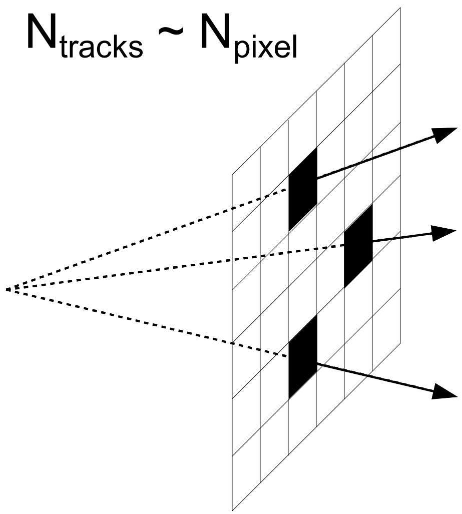
Calorimeter R&D for the ... and beyond

~360 physicists/engineers from 60 institutes and 19 countries from 4 continents

- Integrated R&D effort
- Benefit/Accelerate detector development due to *common* approach

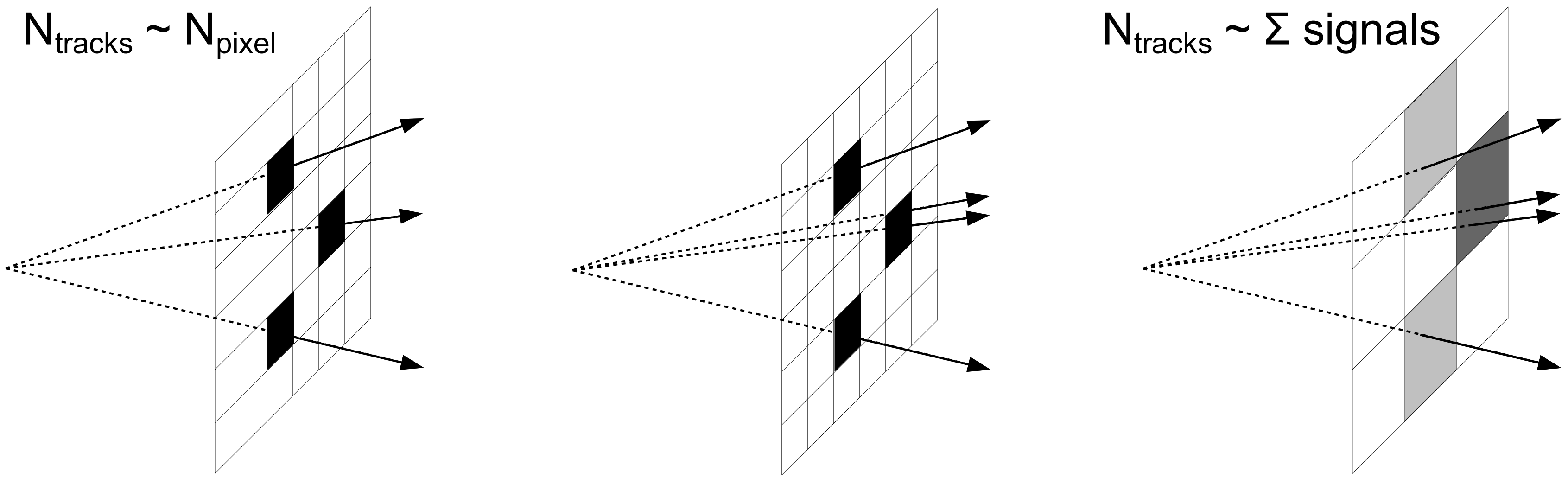
Calorimeter Readout Concepts

- digital CAL: count number of hit pixels (off/on)



Calorimeter Readout Concepts

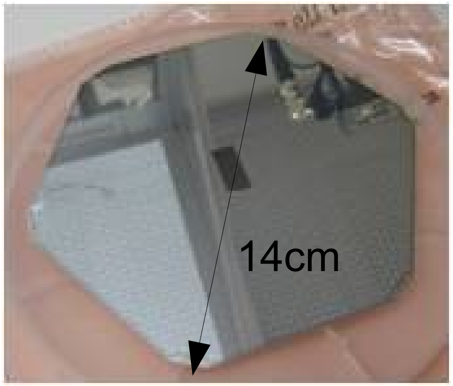
- digital CAL: count number of hit pixels (off/on)
- semi-digital CAL: additional information about number of particles within one pixel by using 3 thresholds (off/standard/large/very large)
- analog CAL: sum up signals in (larger) cells



- granularity required for a good energy resolution depends on readout concept

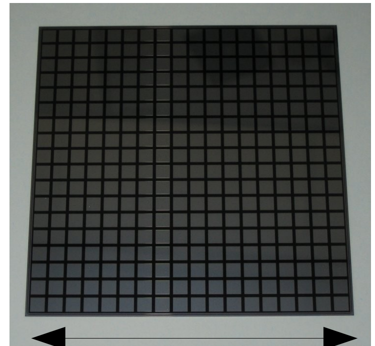
Analog ECAL: Active Material

Silicon



1024 pixel

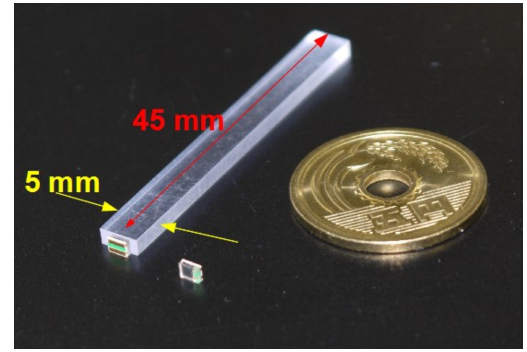
Silicon

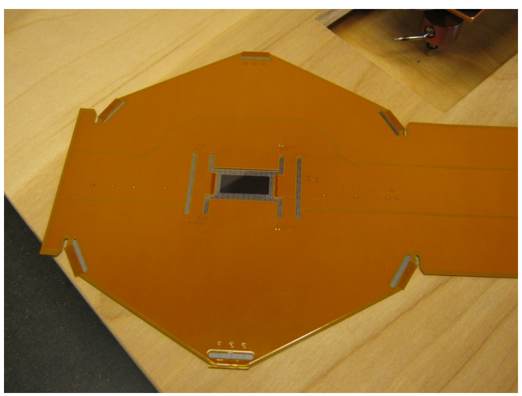


9cm

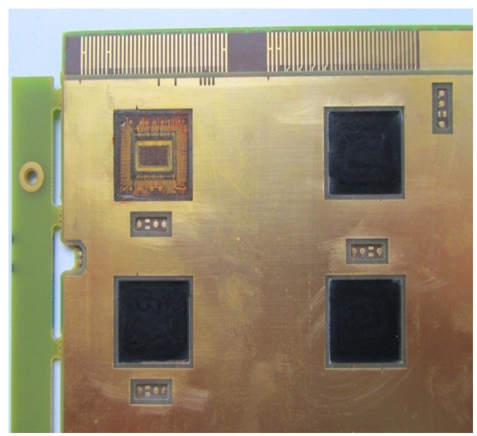
256 pixel

Scintillator





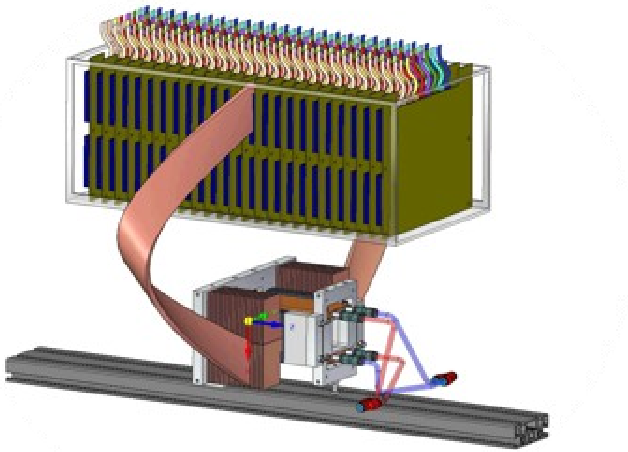
SiD



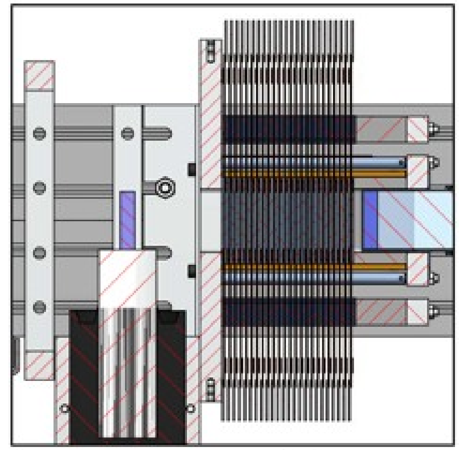
ILD option

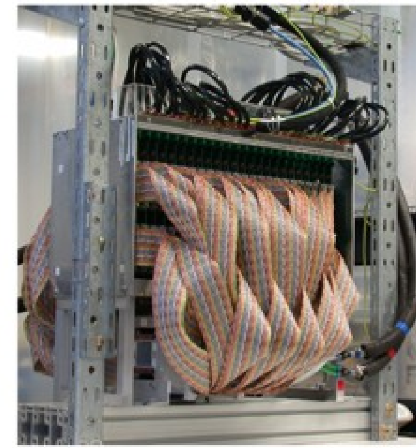
ILD option

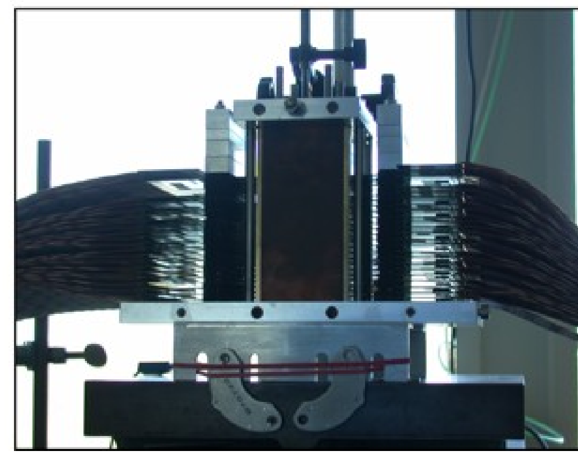
Digital ECAL: Pixel Calorimeter Prototype



- R&D for ALICE FoCal upgrade (Utrecht/Nikhef, Bergen)
- full MAPS prototype, 24 layers
  - 3mm W
  - 1mm sensor layer
    - 120µm sensor (2x2 chips) + PCB, glue, air, …
- **39 M pixels in 4x4x10 cm³ !**



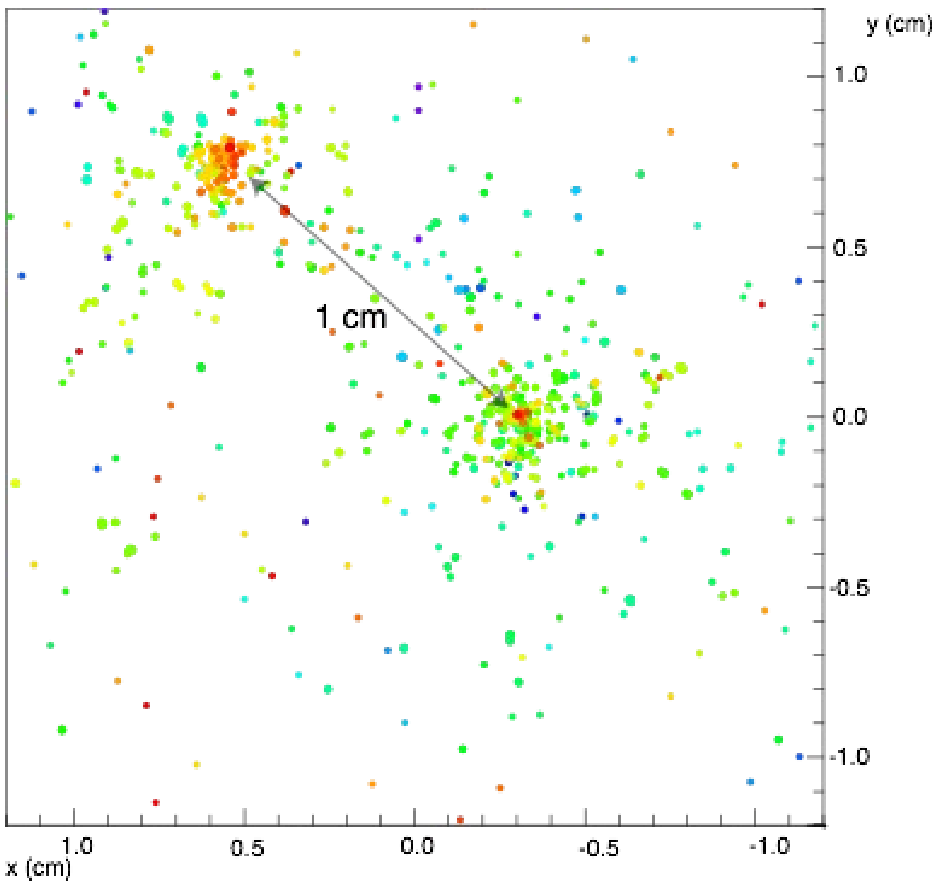


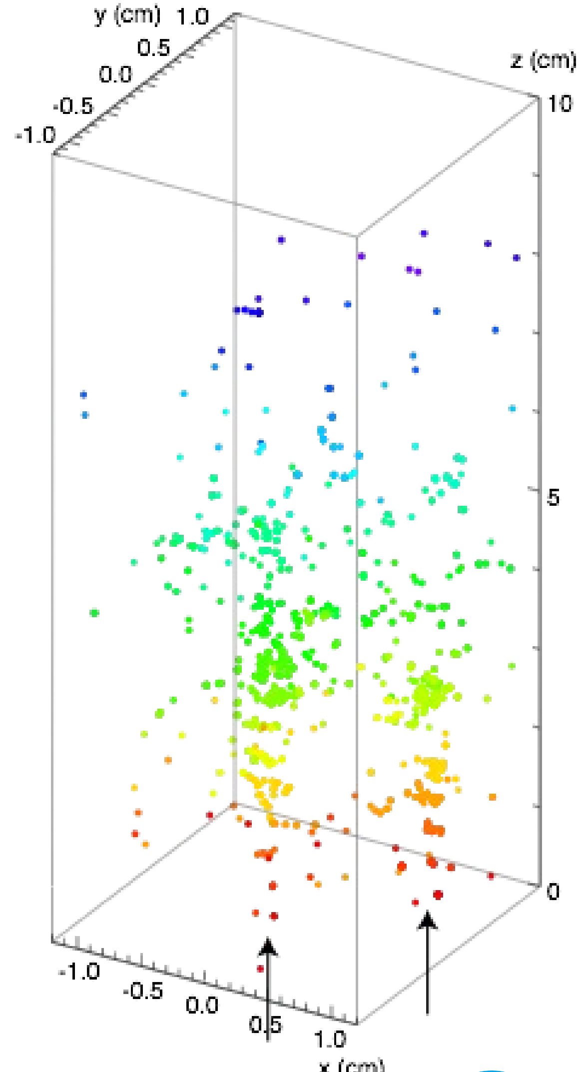


other R&D with prototypes ongoing at Tokyo, ORNL, Kolkata, Prague, ...

Digital ECAL: Event Display

display of single event (with pile-up) from 5.4 GeV electron beam

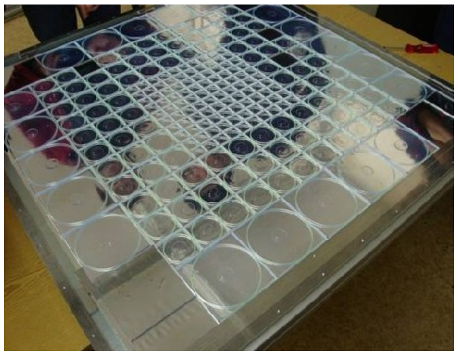


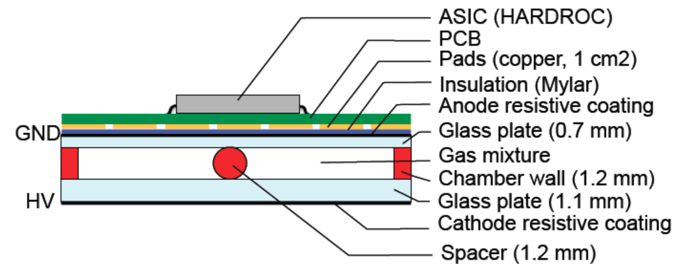


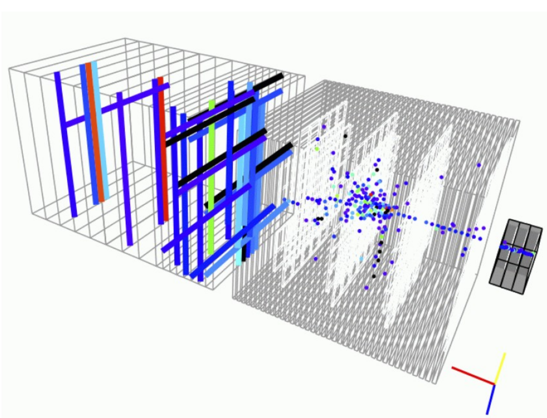
single pixels, colour code = z-position

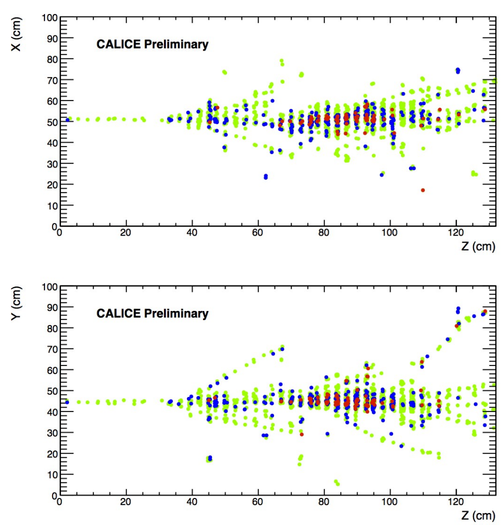
CALICE HCAL Concepts

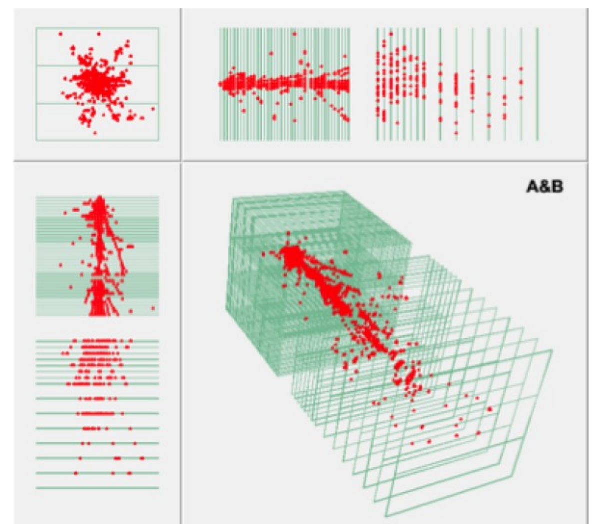
	analog	semi-digital	digital
granularity	3*3 cm^2	1*1 cm^2	1*1 cm^2
technology	scintillator tiles	RPCs (or μMegas)	RPCs (or GEMs)







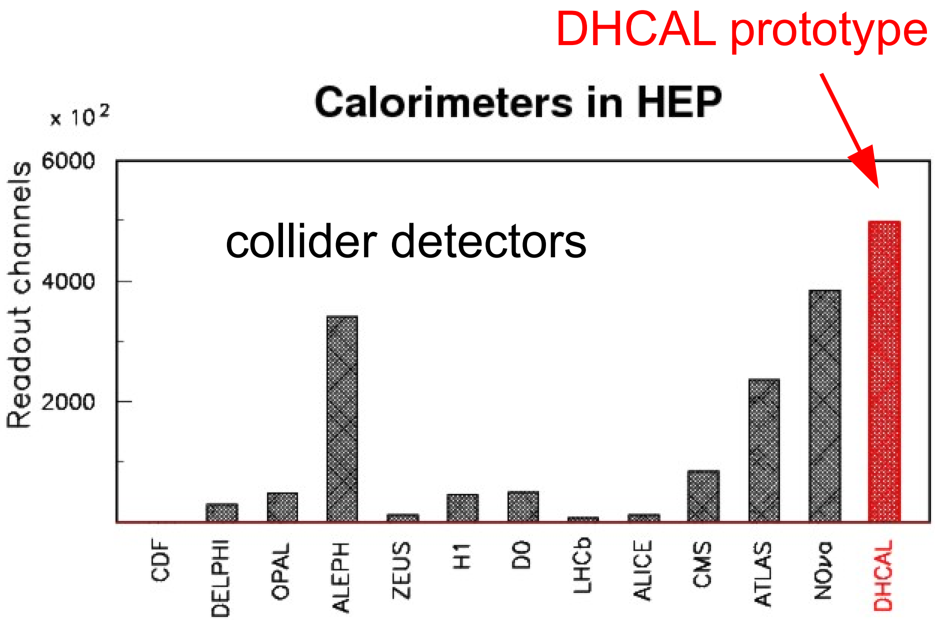




PFA calorimeters: Technical Challenges

high granularity → high channel count

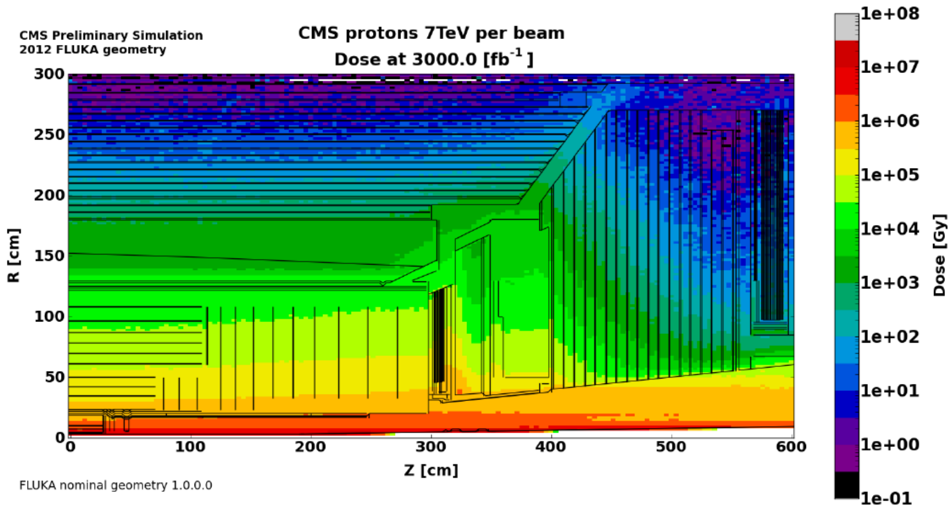
- detector uniformity (active elements and absorber!)
  - avoid cooling inside detector volume
- integrated readout electronics: stringent constraints on space and power consumption
- data reduction and concentration as early as possible
  - digitisation in integrated electronics
  - auto-trigger, zero suppression on/in detector
- mass assembly

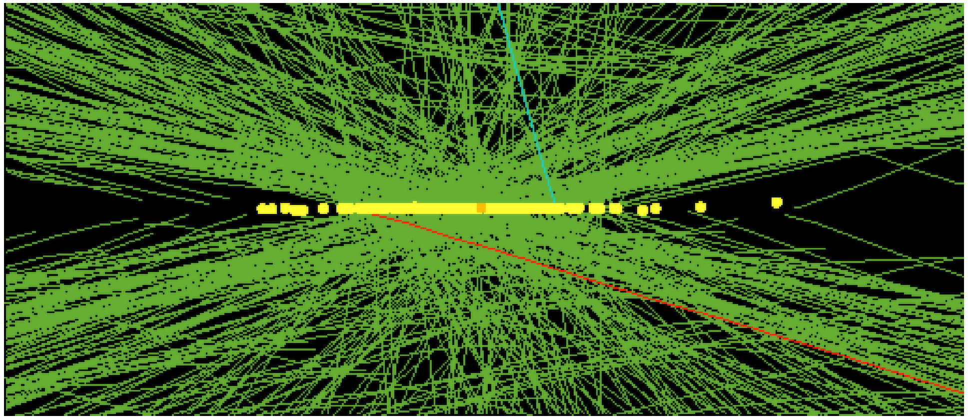


- easy (compared to LHC) at electron positron colliders
  - radiation
  - pile-up
  - event rates

HL-LHC Detector Upgrades

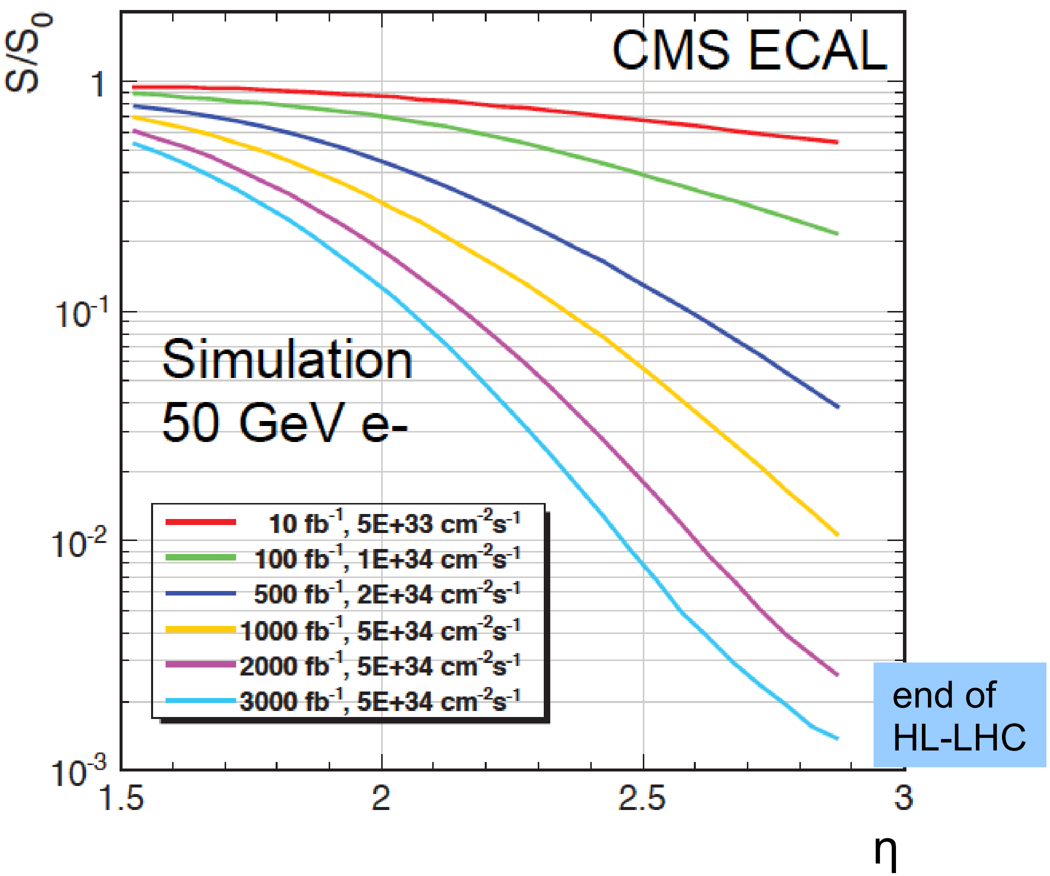
- why
  - huge radiation dose
  - pileup: 25 → 140 to 200
  - event rates: factor ~5-7 to nominal inst. luminosity
- how
  - radiation hard materials
  - higher granularity: allows separation of interesting particles from pile-up
  - better timing resolution: aim for ~30ps resolution
- leads to challenging require-ments for electronics, trigger and DAQ (not covered here)
- need to be installed by 2026!



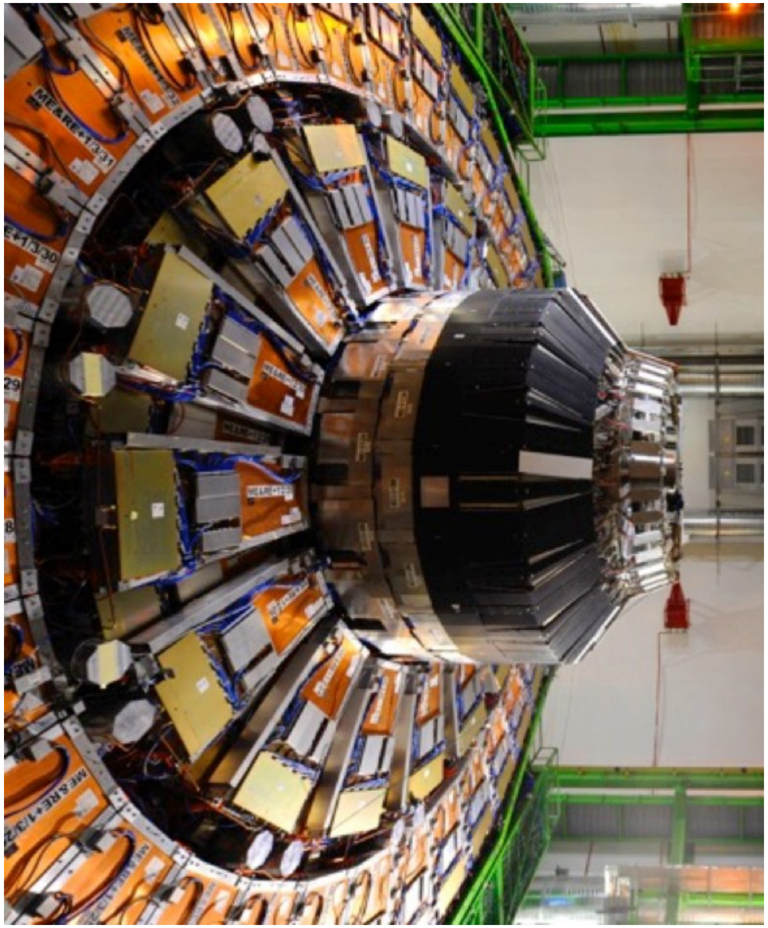


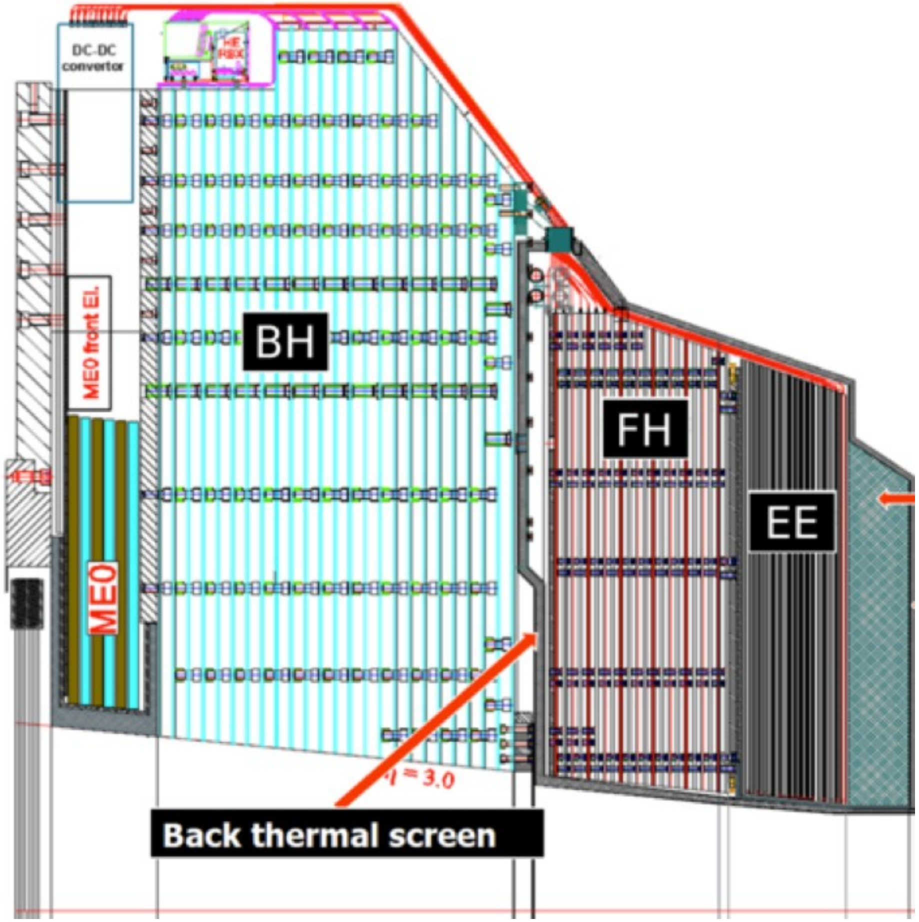
CMS Endcap Calorimeter Upgrade: Motivation

- current CMS calorimeter endcap will not survive in HL-LHC conditions
- in 2015, decided to replace it with silicon-based high-granularity calorimeter
  - profit from extensive R&D on radiation hardness of silicon detectors for pixel and track detectors
  - synergy with high granularity calorimeter concepts developed for electron-positron colliders

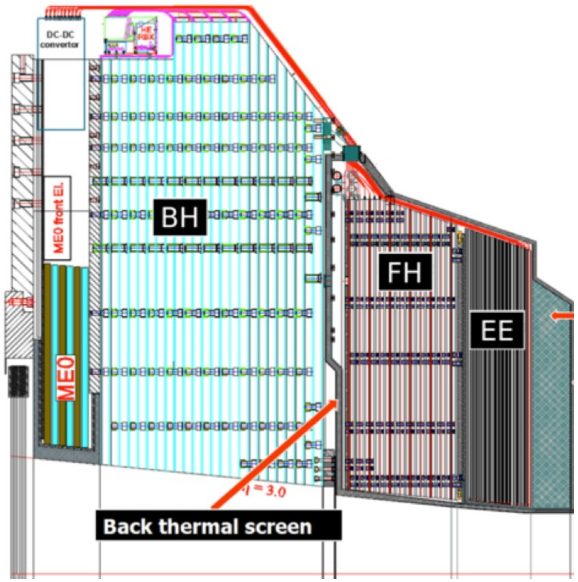


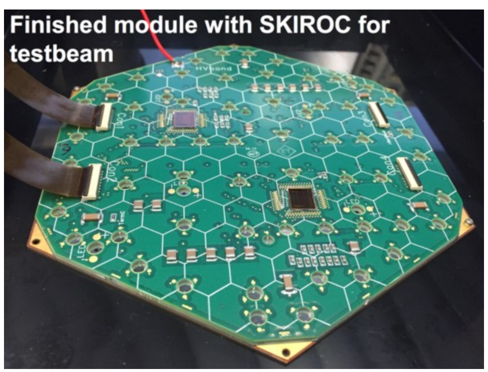
CMS Endcap Calorimeter Upgrade





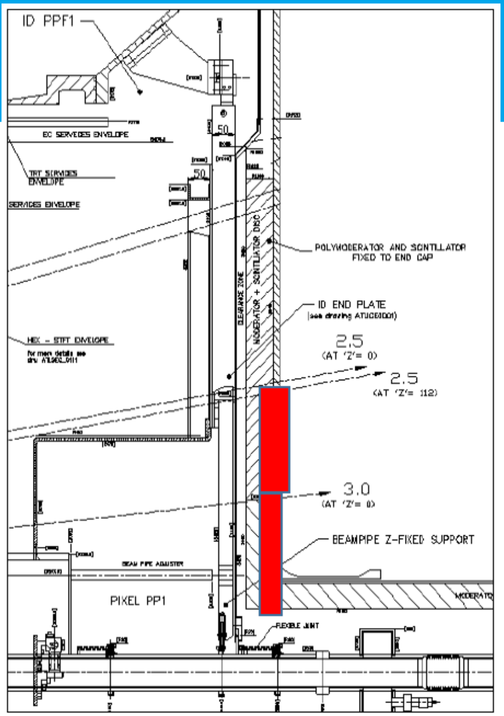
CMS High Granularity Calorimeter: HGCAL



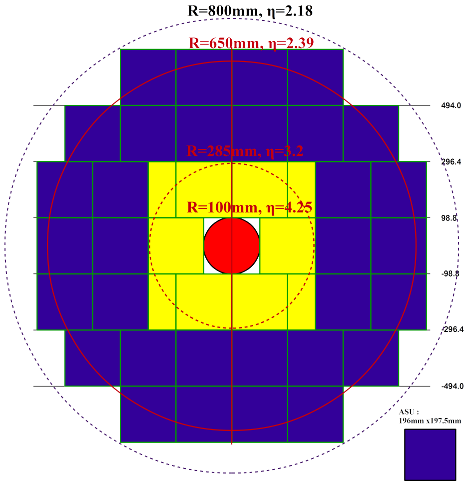


- three sections
  - EE: silicon with tungsten absorber, 28 layers, 25 X_0 (~1.3 λ)
  - FH: silicon with stainless steel absorber, 12 layers, 3.5 λ
  - BH: scintillator with brass absorber, 11 layers, 5.5 λ
- silicon parts need to be maintained at -30°C
- key parameters
  - nearly 600 m^2 of silicon
  - 6 M readout channels
  - >20.000 modules, >90.000 readout ASICs
- TDR to be submitted by November 2017 → expect a lot of activity in the coming months

ATLAS calorimeter upgrades



- current ATLAS calorimeters can survive HL-LHC radiation
  - plan extensive electronics upgrades
- two calorimeter upgrades considered:
  - high granularity LAr sFCAL not followed up because of risk of opening the cryostat
  - High Granularity Timing Device (HGTD)
    - in small gap between tracker and LAr calorimeter
    - coverage: $2.4 < \eta < 4.2$
    - LGAD silicon sensors
    - 4 silicon sensor layers, design based on ILD silicon-tungsten ECAL
    - 2 options considered: with and without tungsten absorber layers
    - 3.4 M readout channels



Calorimeters in Testbeam

Measurements in Beam Tests

- tests of components
  - sensors / active layers
    - MIP response, time resolution, radiation tolerance, …
- system tests
  - absolutely essential because most relevant performance measures for calorimeters depend on the whole system
    - single particle energy linearity and resolution
      - electrons
      - different hadron species: pions, protons, kaons
    - particle ID based on shower shapes
    - two-particle separation
    - uniformity of the response
    - position resolution
  - jet energy resolution not directly accessible in beam tests
  - comparison of hadron showers in data and simulation

Muons, electron and hadrons in calorimeter beam test

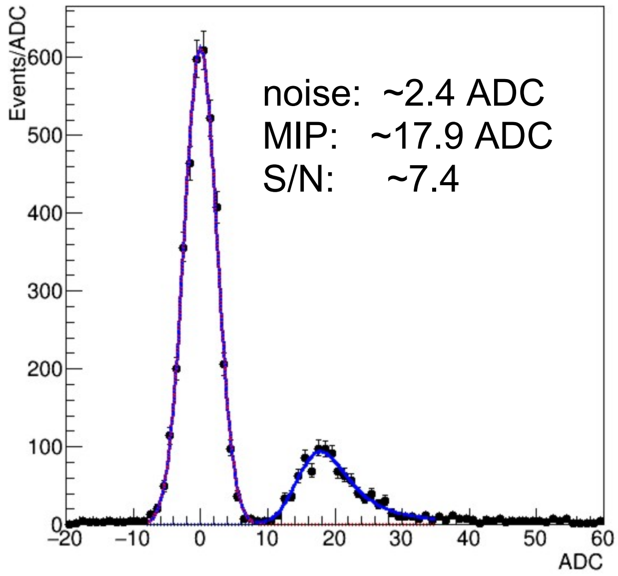
particle species have different roles in beam tests

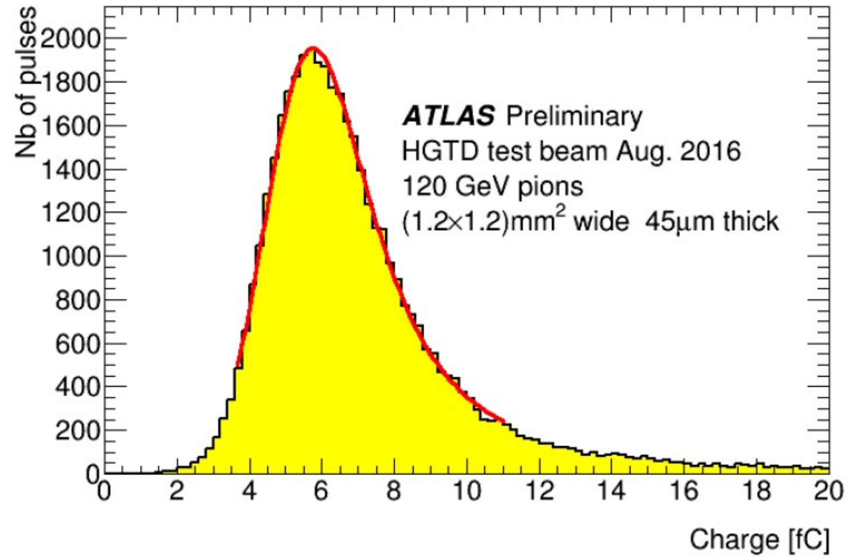
- muons/MIPs
  - detector response to one charged particle
  - detector equalization / uniformity
- electrons
  - simple well-known showers
  - linearity and resolution for electromagnetic showers
  - modeling of detector setup in simulation
- hadrons
  - complex much less well-known showers
  - linearity and resolution for hadronic showers
  - modeling of evolution of hadronic showers in simulation

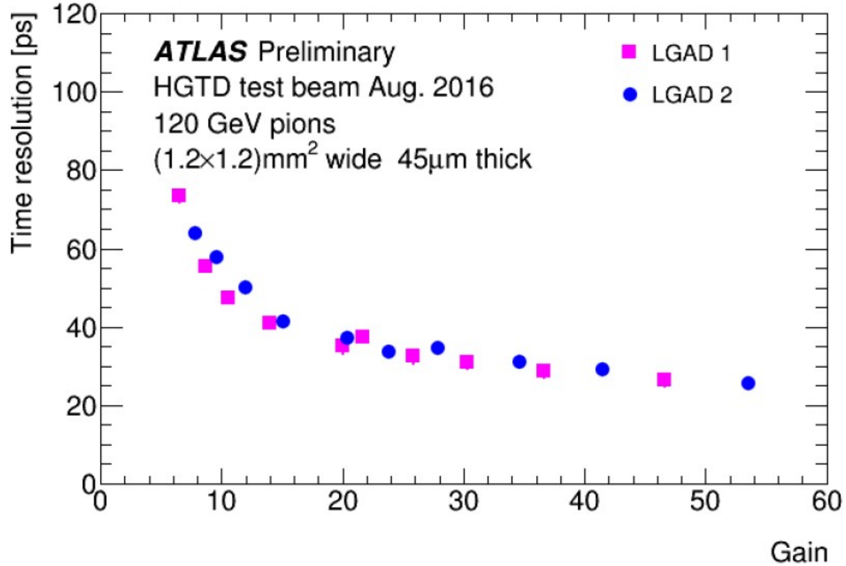
Component tests

CMS HGCAL silicon sensor

Z. Gecse, High Luminosity LHC experiments workshop 2016







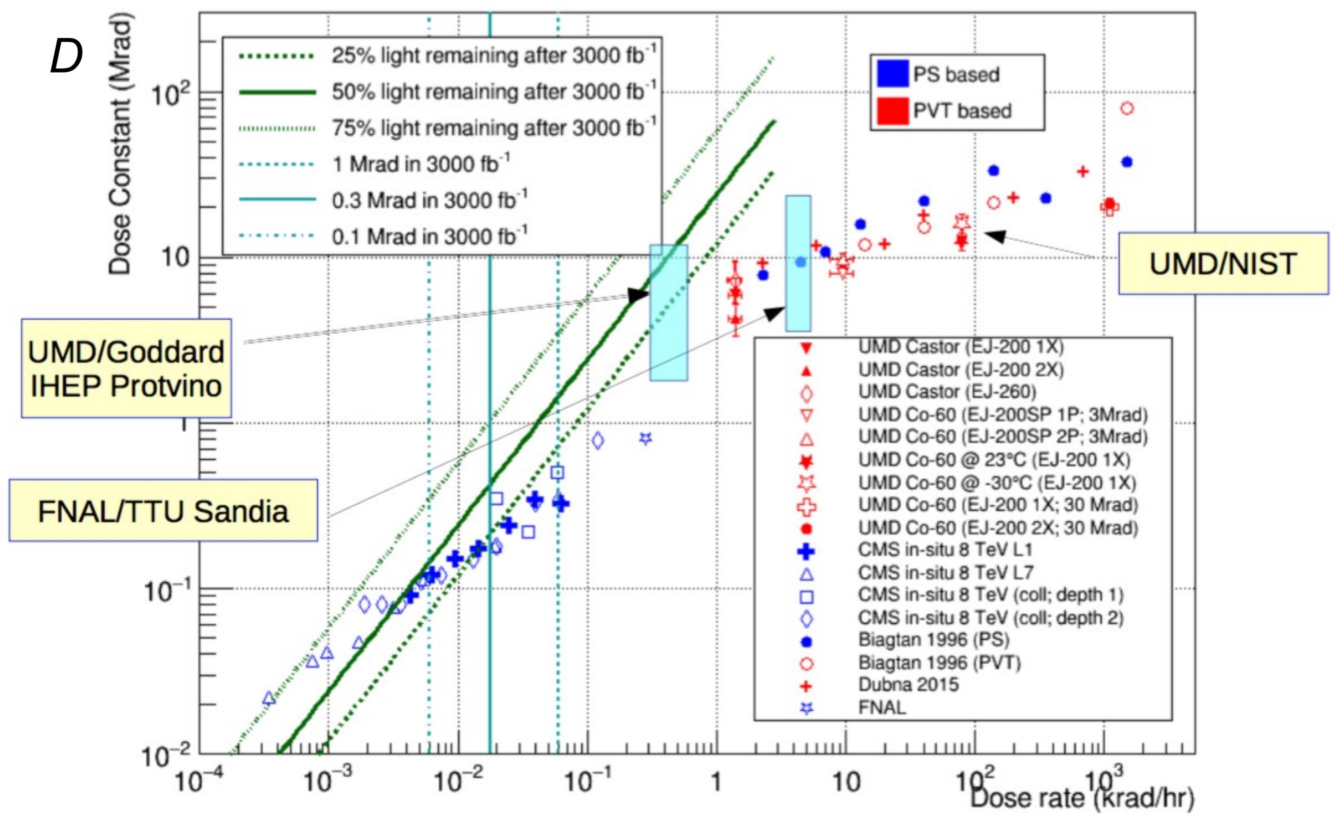
- signals
  - size of MIP signal
  - signal to noise ratio
- hit time resolution

Component tests

- radiation tolerance
  - well known and understood for “standard” silicon sensors
  - different for silicon sensors with intrinsic gain (LGAD, SiPM)
  - extensive research for scintillator ongoing: damage depends on dose rate!

$$L(d) = L_0 \, e^{-d/D}$$

D



P. Bloch, High Luminosity LHC experiments workshop 2016

System tests

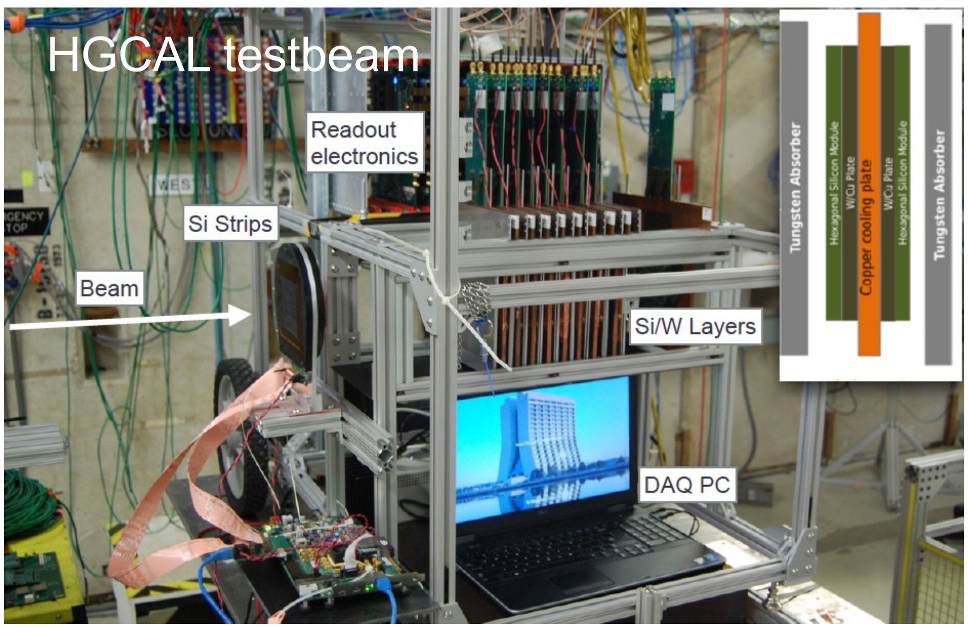
strategy

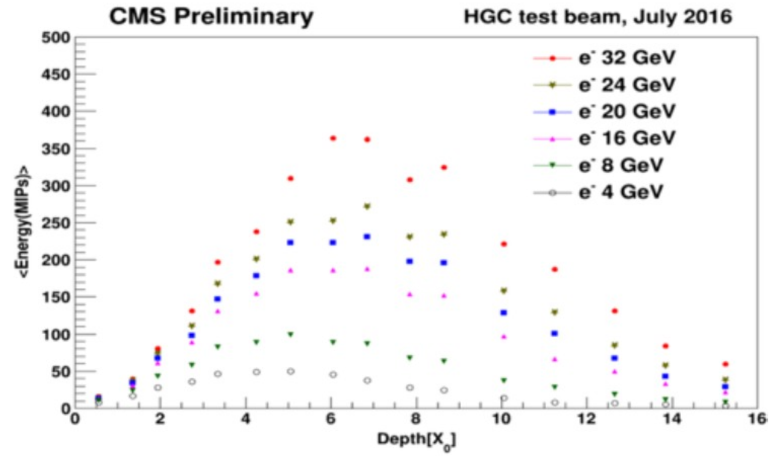
- calibrate/equalize with MIPs (one energy)
- linearity and response for electrons (energy scan, usually ~5 – 100 GeV)
- hadron calorimeter: linearity and response for hadrons (energy scan, usually ~10 – 200 GeV)
  - pions, protons, if possible kaons → beam particle ID
  - both negative and positive beam particles (clean pions/kaons vs. protons)
- in the real detector, hadron energy linearity and resolution will depend on ECAL+HCAL system → test the combined system
- detector uniformity:
  - scan large areas (HAD calorimeter: ~1 m^2)
  - measure at several tilt angles
- shower shapes, two-particle separation: essential for PFA performance → comparison to simulation

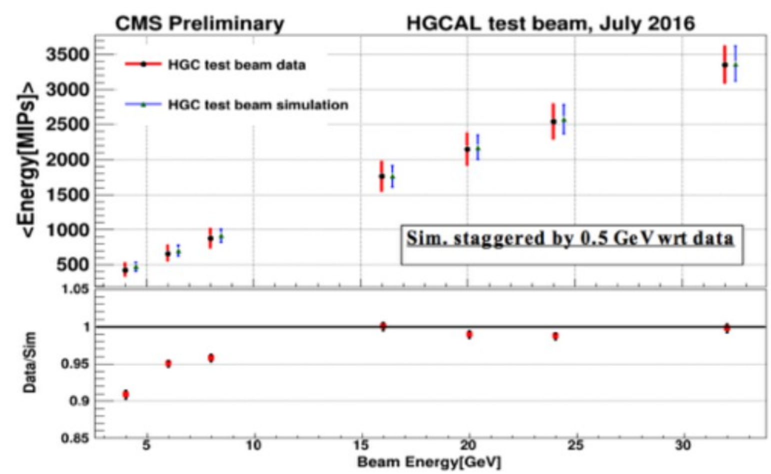
to fully characterize a calorimeter in testbeam, need many energies for several particle species → long measurement times

System tests: smaller setups

- smaller setups (reduced number of layers, reduced thickness) can be important step:
  - interplay of the whole system
  - linearity
  - comparison to simulation
- cannot determine final resolution!



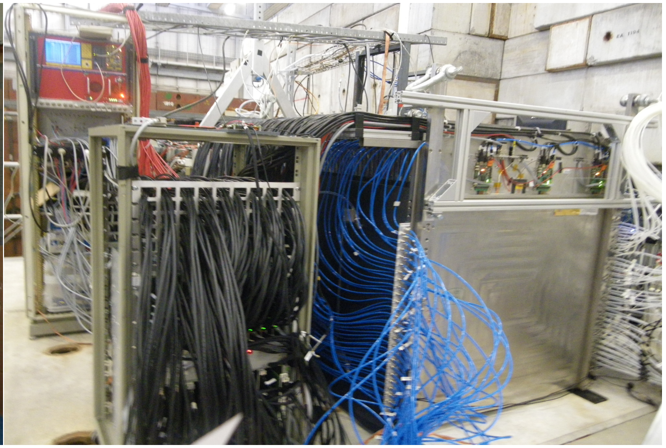


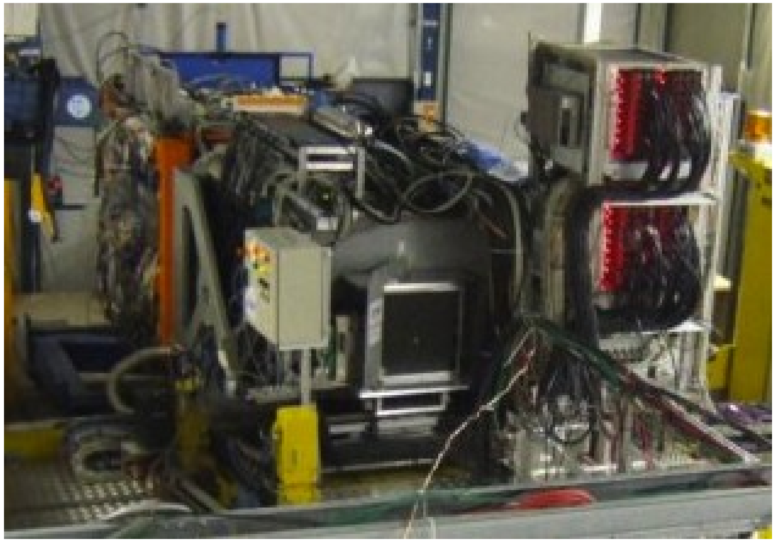


Z. Gecse, High Luminosity LHC experiments workshop 2016

System tests: large setups

CALICE HCALs in testbeam: active volume ~1 m^3

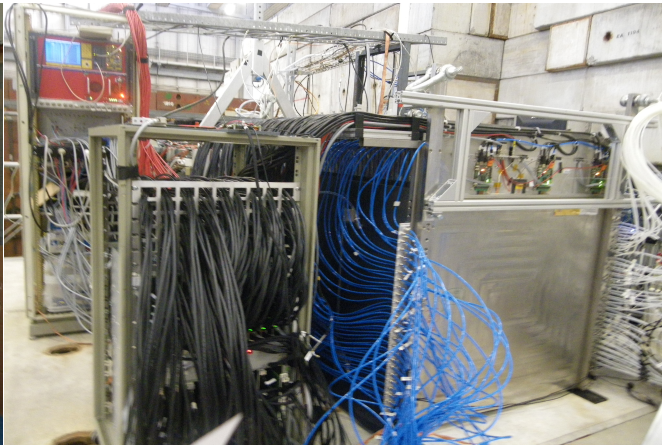



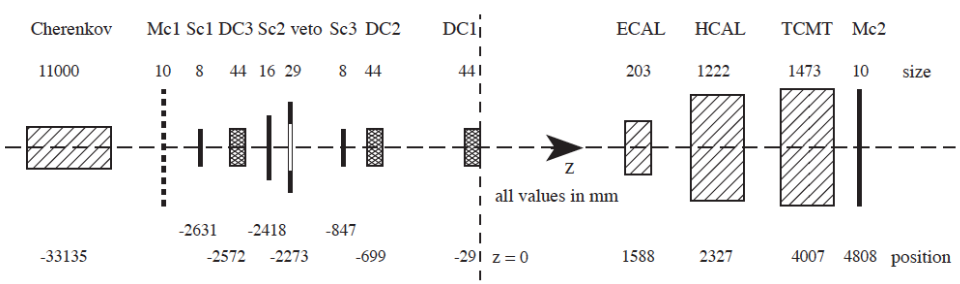
complete CALICE calorimeter system setup:

- ECAL
- HCAL
- tailcatcher
- electronics, cables, cooling, ...
- beam instrumentation: trigger, tracking, particle ID

System tests: large setups

CALICE HCALs in testbeam: active volume ~1 m^3

complete CALICE calorimeter system setup:

- ECAL
- HCAL
- tailcatcher
- electronics, cables, cooling, ...
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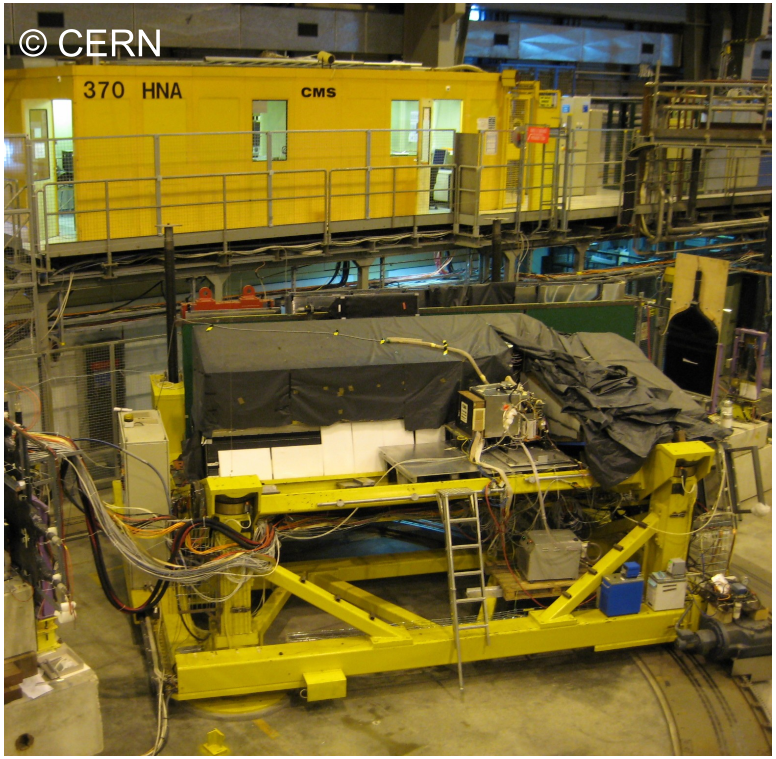
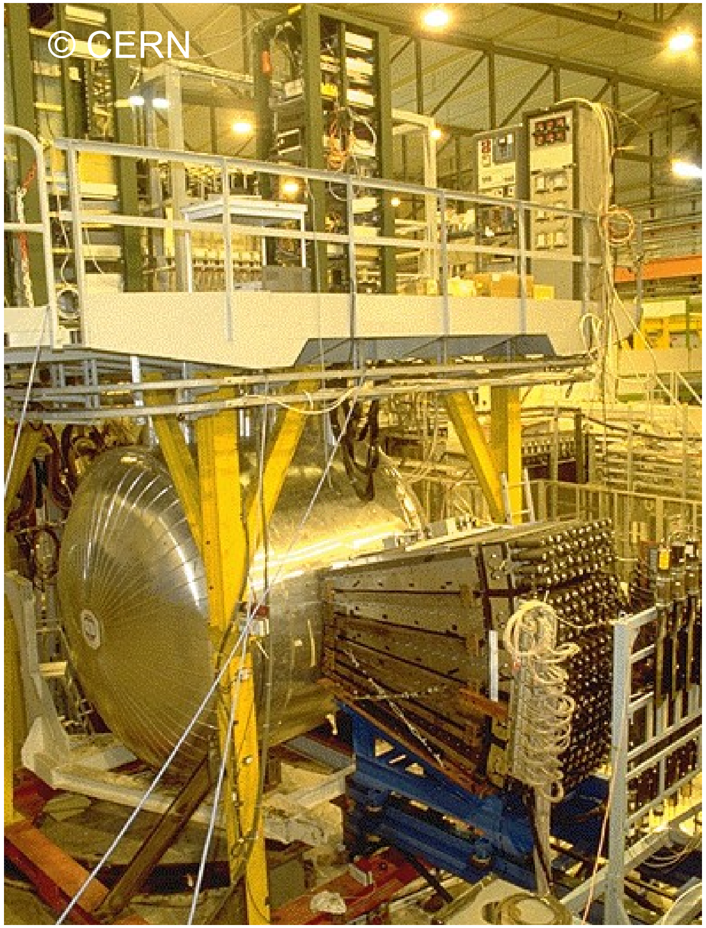
System test: CMS and ATLAS setups



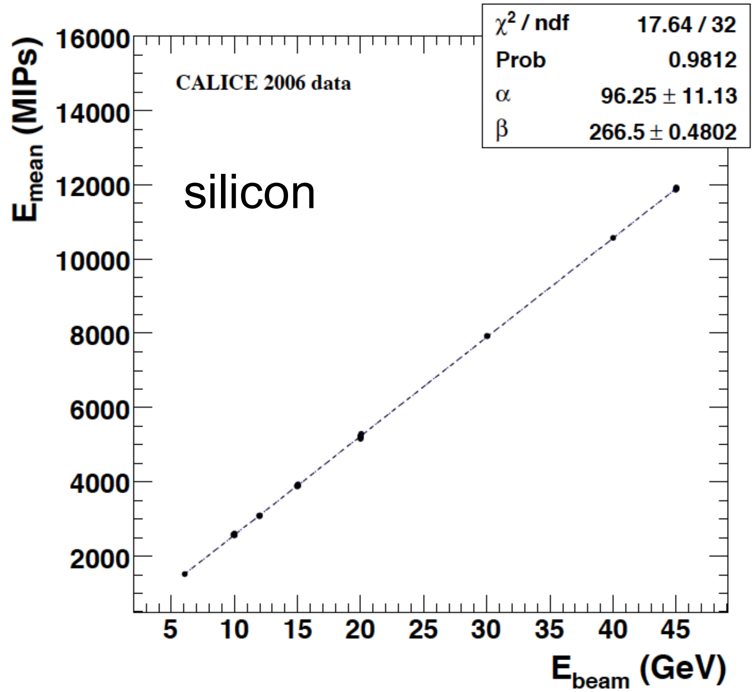
CMS combined calo beam test



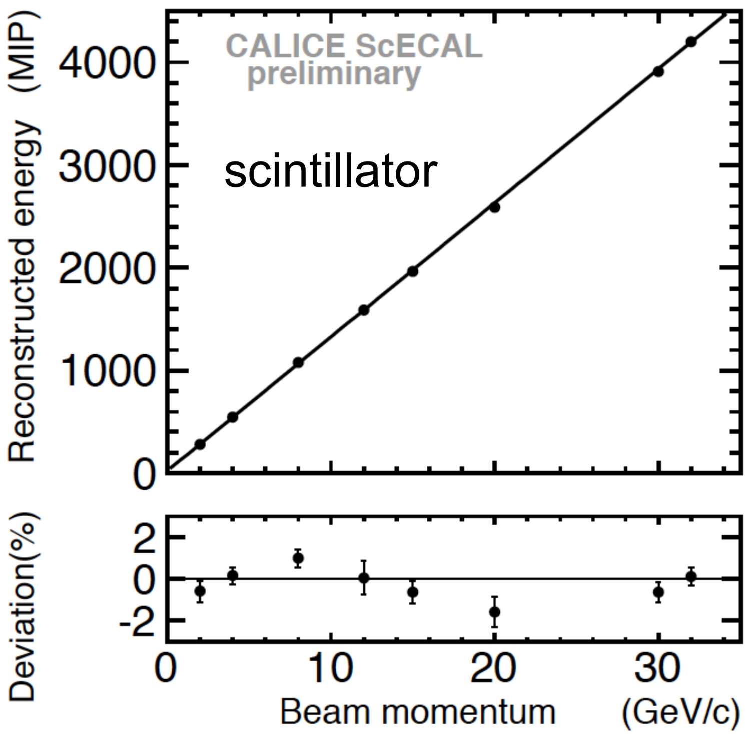
ATLAS combined calo beam test

CALICE ECALs: energy linearity

NIM A608 (2009) 372

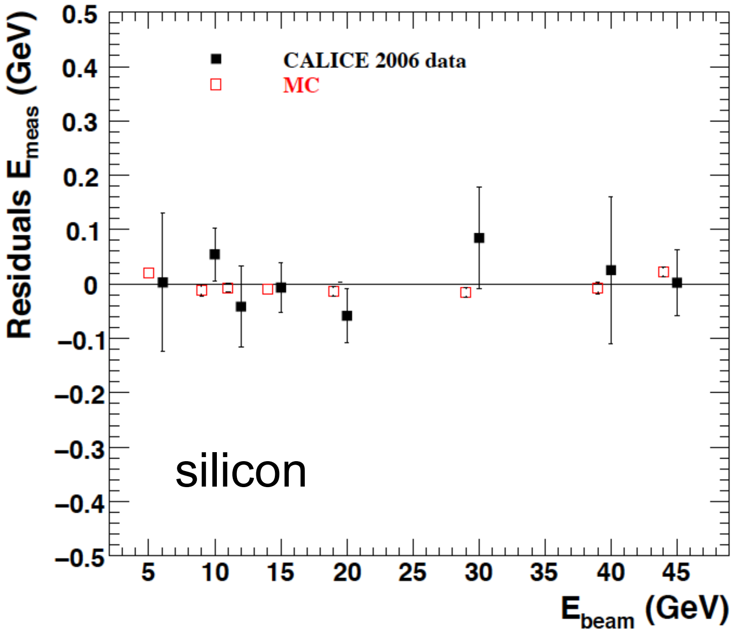


CAN-016c

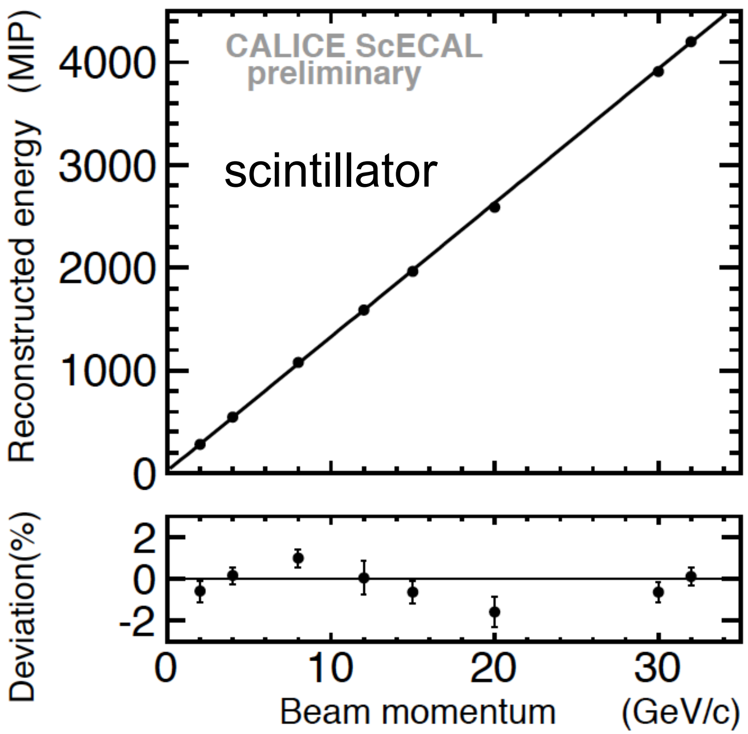


CALICE ECALs: energy linearity

NIM A608 (2009) 372



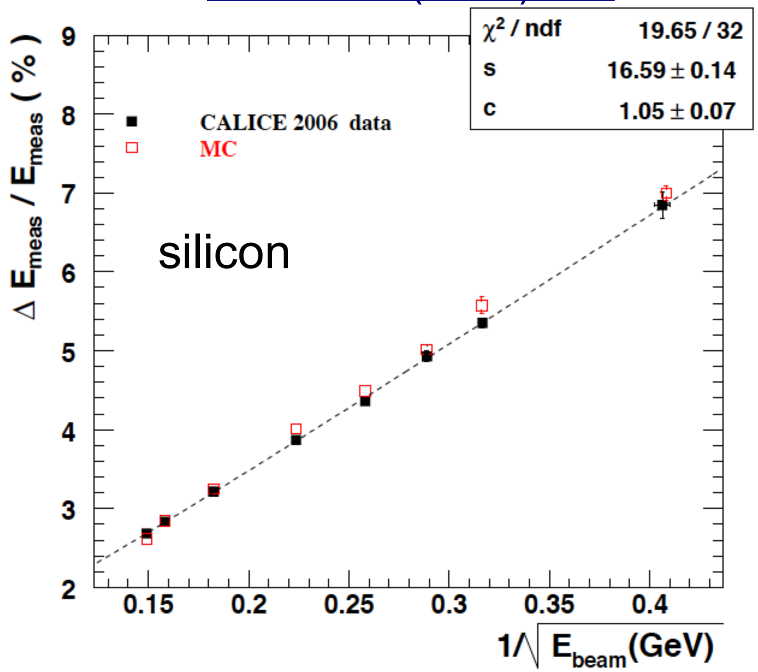
CAN-016c



- energy linearity for electrons better than 100 MeV / 1%
- need enough statistics to reach this precision (≳10000 events/energy)

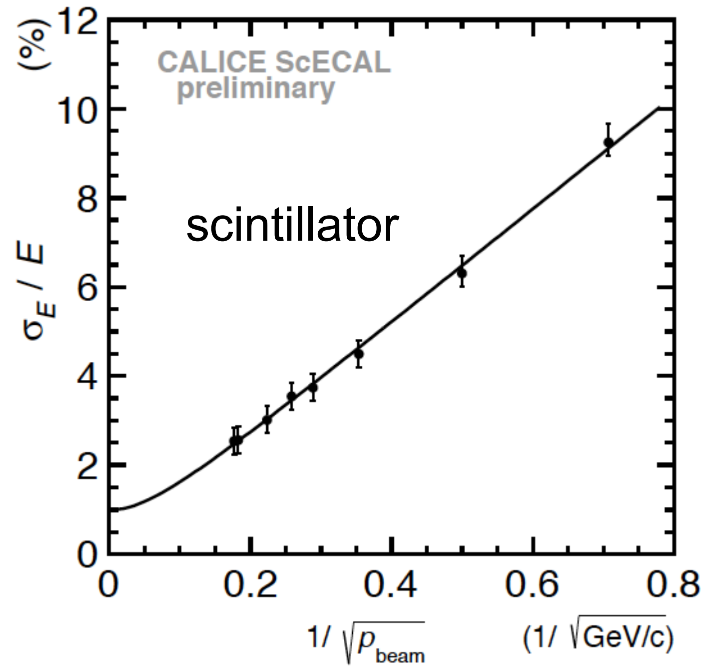
CALICE ECALs: energy resolution

NIM A608 (2009) 372



$$\frac{\sigma(E)}{E} = \left(\frac{16.6 \pm 0.1}{\sqrt{E}} \oplus (1.1 \pm 0.1)\right)\%$$

CAN-016c



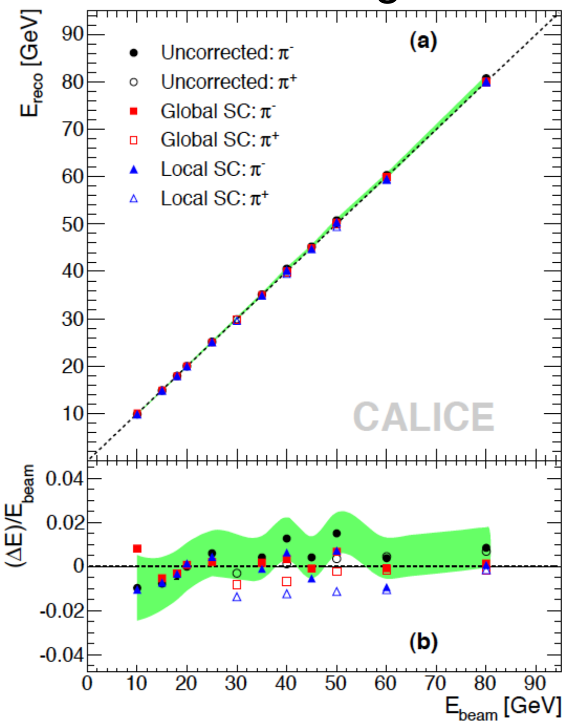
$$\frac{\sigma(E)}{E} = \left(\frac{12.8 \pm 0.4}{\sqrt{E}} \oplus (1.0 {}^{+0.5}_{-1.0})\right)\%$$

- reasonable energy resolution for electromagnetic showers
- CALICE ECALs are optimised for granularity, not single particle energy resolution

CALICE HCALs: energy linearity (pions)

JINST 7 (2012) P09017

Analog HCAL

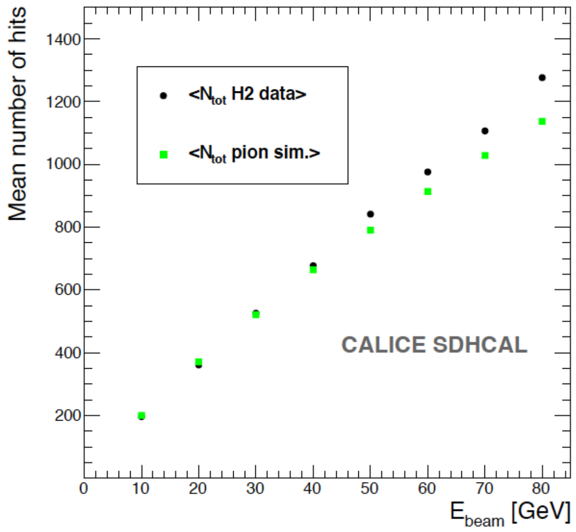


linear response to hadrons

at the 1-2% level

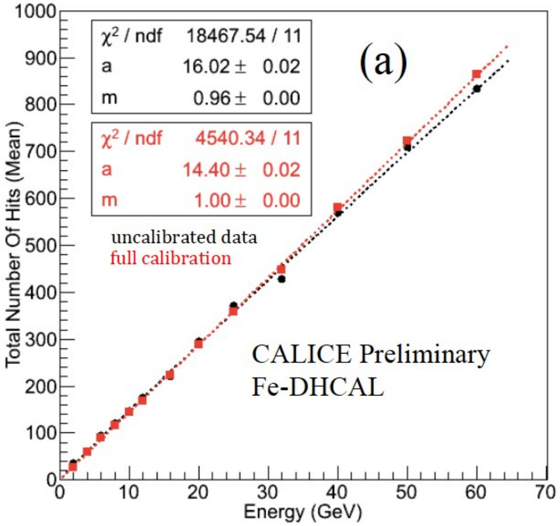
JINST 11 (2016) P04001

Semi-Digital HCAL



CAN-042

Digital HCAL



non-linear response

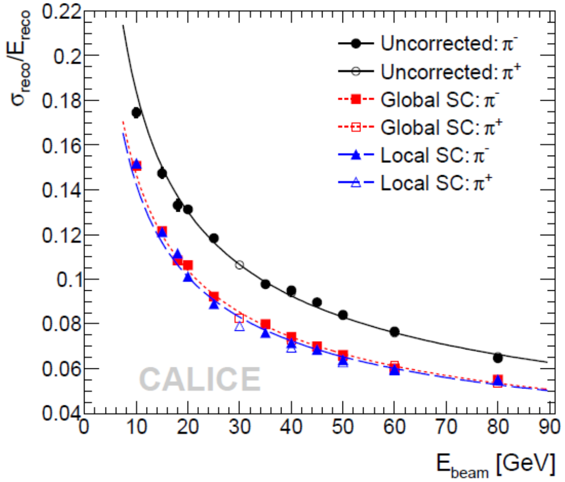
deviations from linearity due to finite readout pad size

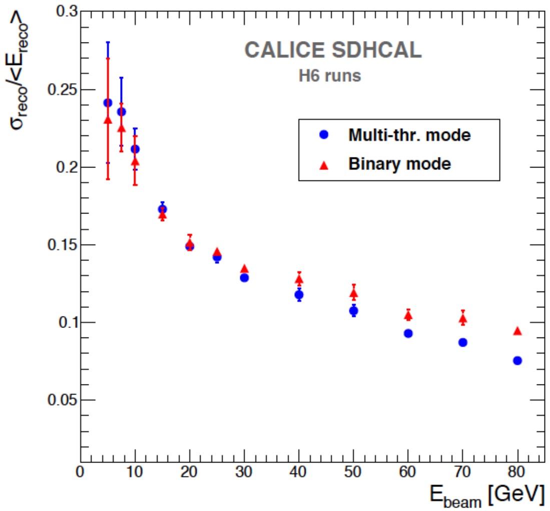
needs to be taken into account in energy reconstruction

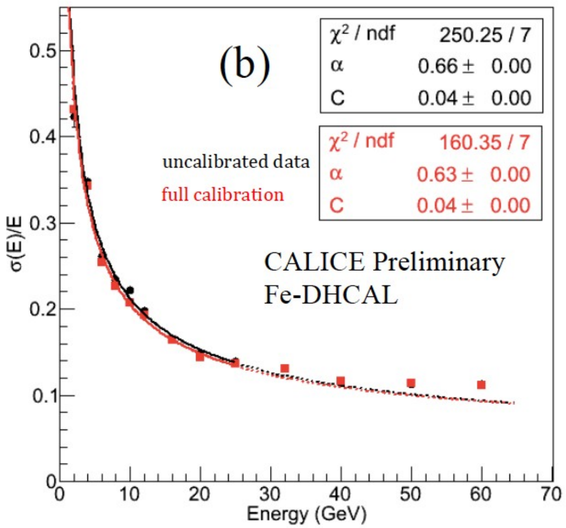
non-compensating HCAL intrinsically non-linear → check for linearity is important

Energy Resolution for Single Hadrons: Comparison

JINST 7 (2012) P09017	JINST 11 (2016) P04001	CAN-042
Analog HCAL	Semi-Digital HCAL	Digital HCAL







software compensation improves stochastic term:
$58\%/\sqrt{E} \rightarrow 45\%/\sqrt{E}$

measurement with
1 or 3 thresholds

3 thresholds improve resolution at large energies

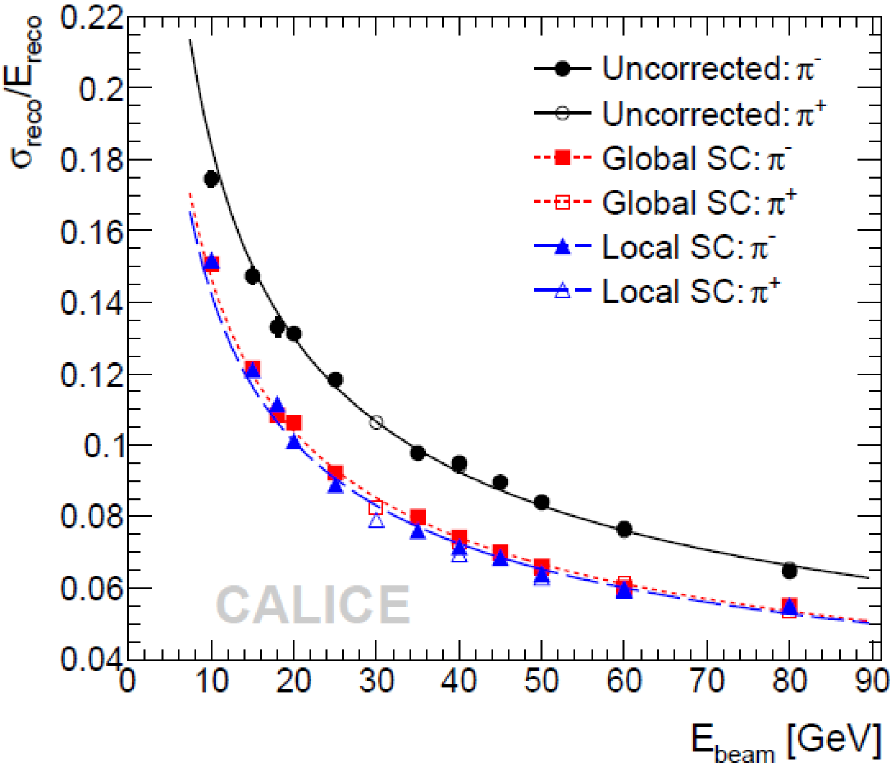
before and **after** calibration

stochastic term $63\%/\sqrt{E}$

constant term 4%

Energy Resolution for Single Hadrons: AHCAL

JINST 7 (2012) P09017



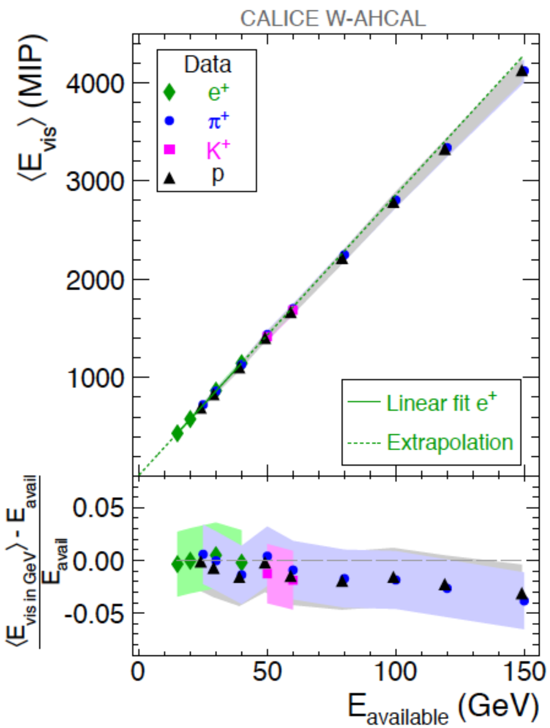
$$\frac{\sigma(E)}{E} = \frac{44.3 \pm 0.3\,\%}{\sqrt{E}} \oplus 1.8 \pm 0.3\,\% \oplus \frac{0.18\,\mathrm{GeV}}{E}$$

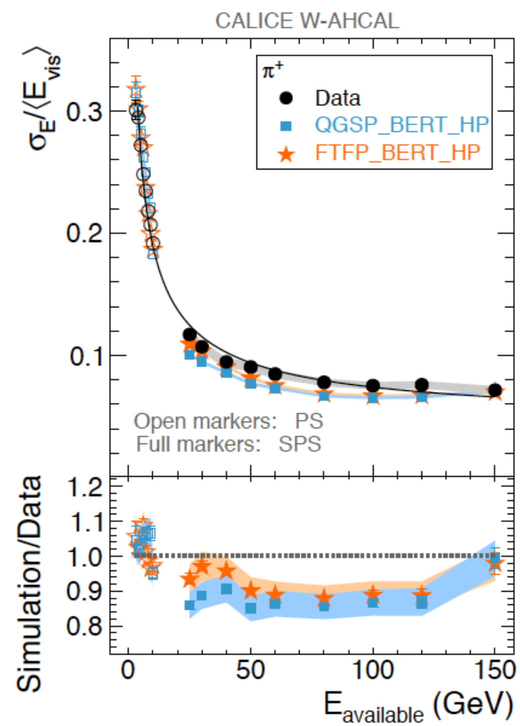
- Software compensation (SC):
  - non-compensating calorimeters show different signals for electromagnetic and hadronic showers
  - hadronic showers include electromagnetic sub-showers
  - in the reconstruction, use different weights for electro-magnetic and hadronic sub-showers

Tungsten as HCAL Absorber

- tungsten as absorber allows very compact calorimeters
- disadvantages: expensive, mechanics is a challenge
- usually used for ECALs, but also studied for CALICE AHCAL (in view of possible application at CLIC)

JINST 10 (2015) P12006

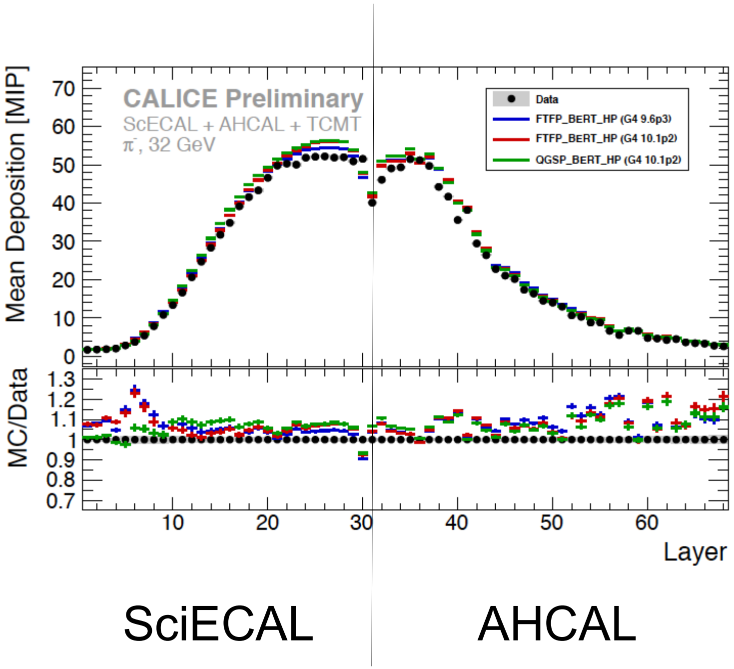


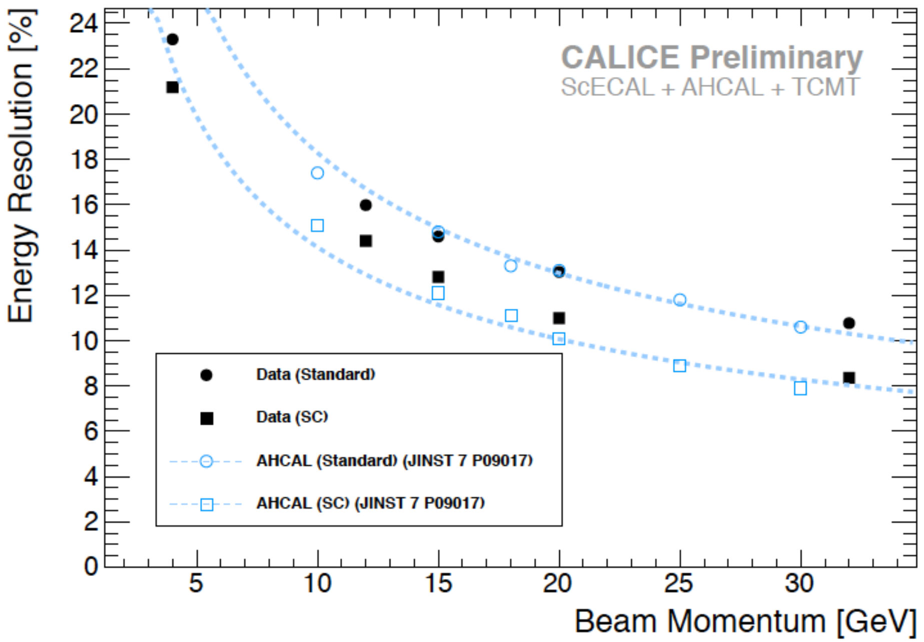


- nearly compensating at ~20-50 GeV for the used tungsten thickness
- resolution similar to iron absorber

Performance of combined scintillator calorimeter system

- in a real calorimeter system, hadrons are not measured purely in HCAL, but in ECAL + HCAL (+tailcatcher)
- ECAL and HCAL typically have different absorber, sampling ratio, active material
- combined system of scintillator-tungsten ECAL + scintillator-steel AHCAL has very similar performance to AHCAL alone





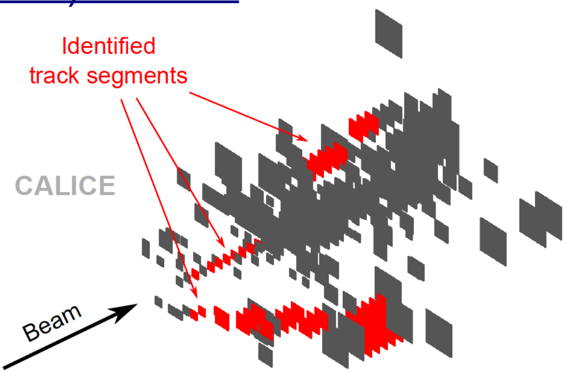
CAN-056

Comparison with simulation: shower sub-structure

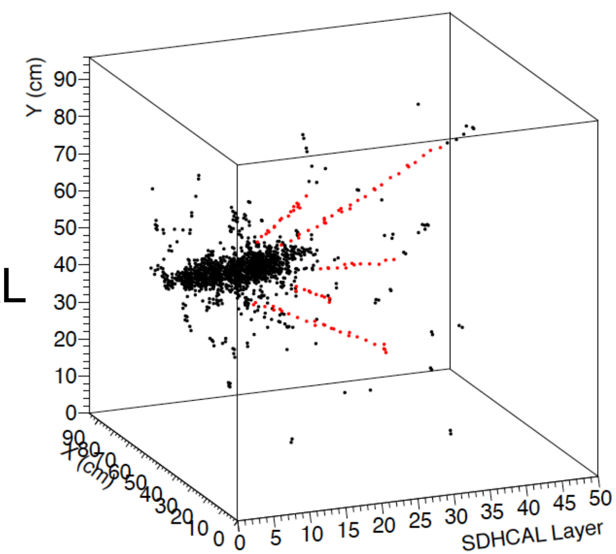
- track segments within hadron showers

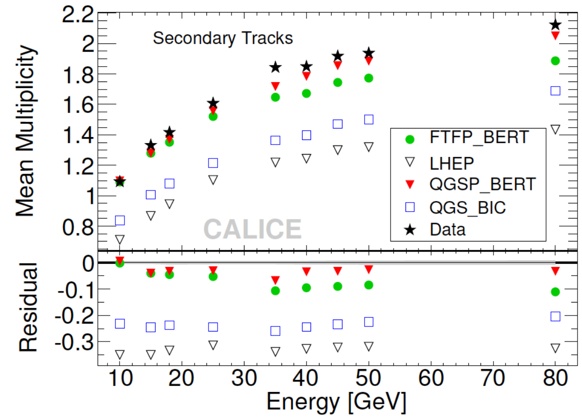
JINST 8 (2013) P09001

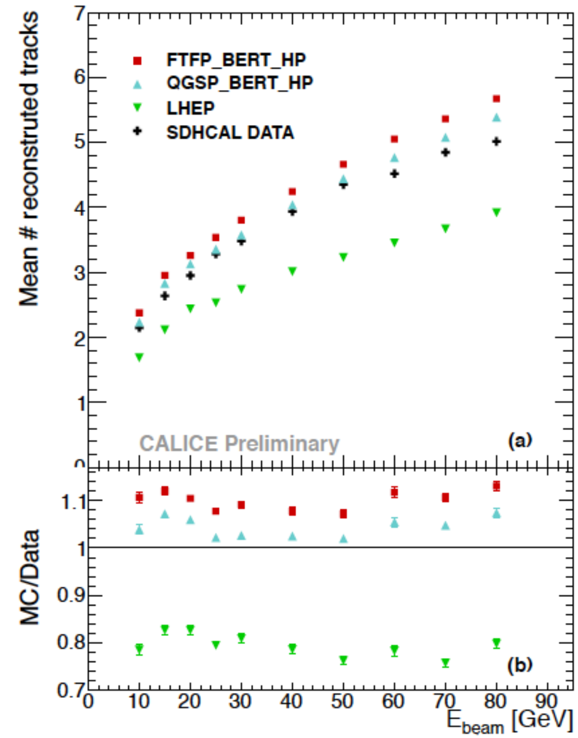
AHCAL



SDHCAL





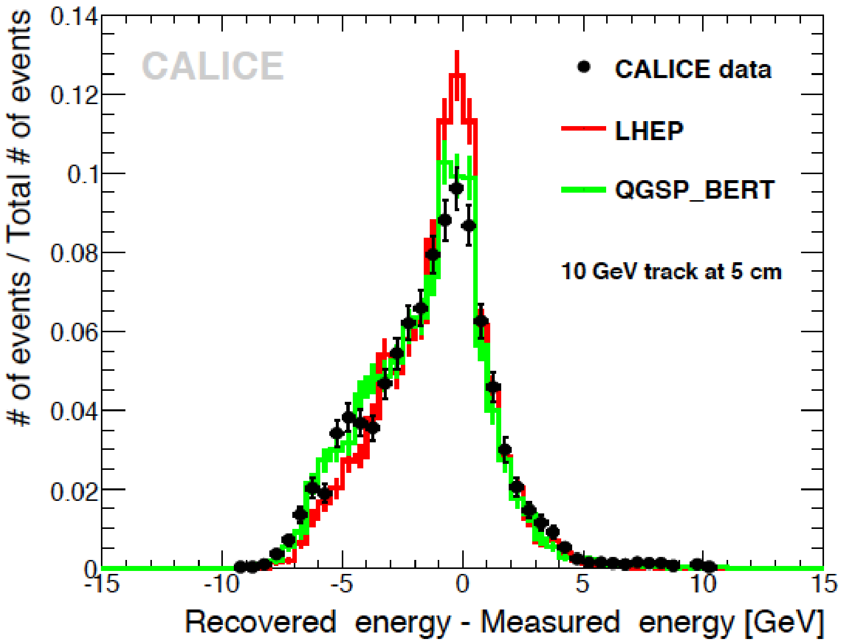


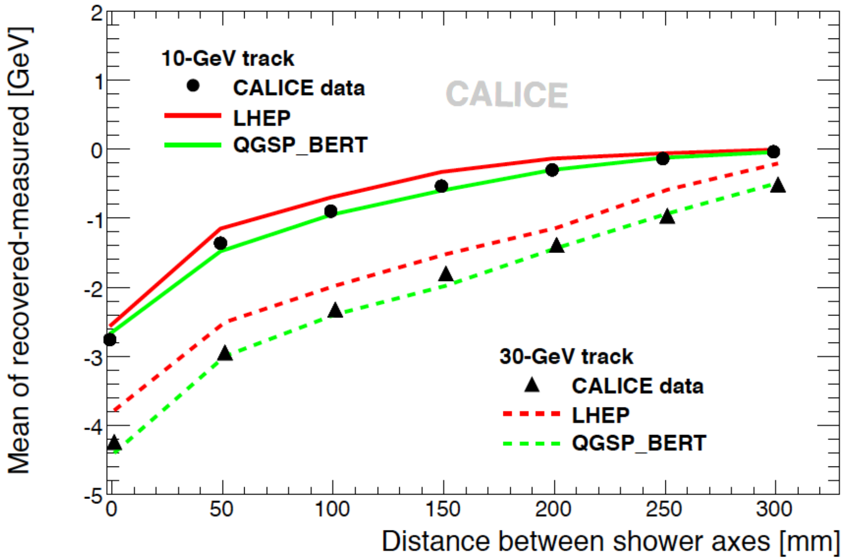
CAN-047

Comparison with simulation: shower separation

- PandoraPFA: PFA algorithm used to optimise design of ILC detectors
- test of cluster separation with AHCAL pion shower data:
  - map measured AHCAL test beam pion showers onto ILD geometry
  - test shower separation of a “neutral” hadron (initial track segment removed) of 10 GeV and a charged hadron of 10 or 30 GeV
- good shower energy reconstruction for distances larger than 10 cm
- good description by up-to-date physics list

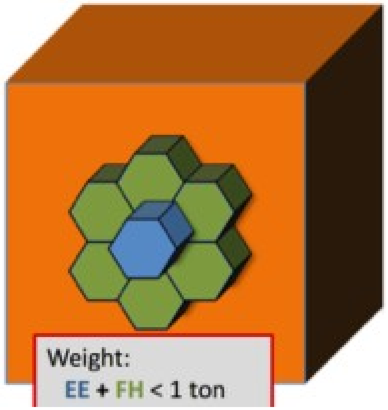
JINST 6 (2011) P07005



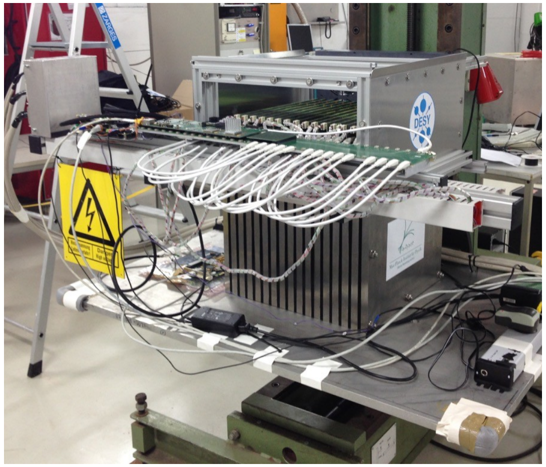


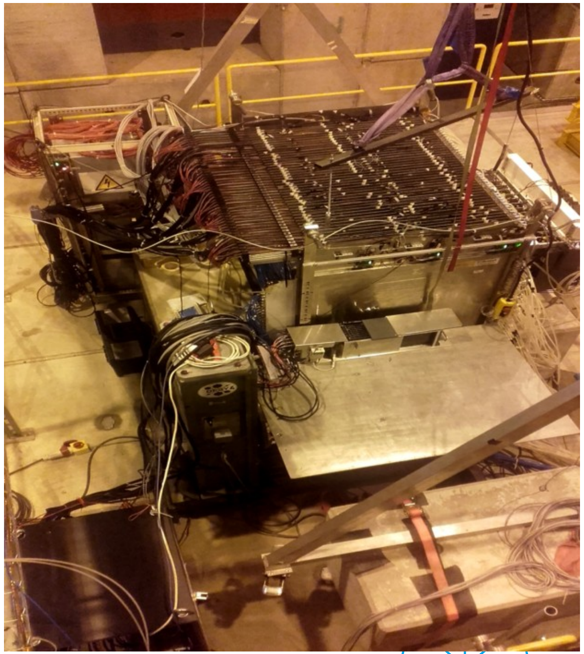
Calorimeter beam tests in the coming year(s)

> HL-LHC detector upgrades:
  - designs to be frozen, important documents to be written in 2017
  - input from beam tests will be crucial
    - continued sensor tests
    - HGCAL: full system test



> CALICE calorimeter prototypes:
  - demonstrate that the concepts are scalable to a full collider detector
  - tests of ECAL, HCAL and ECAL+HCAL planned





Conclusions

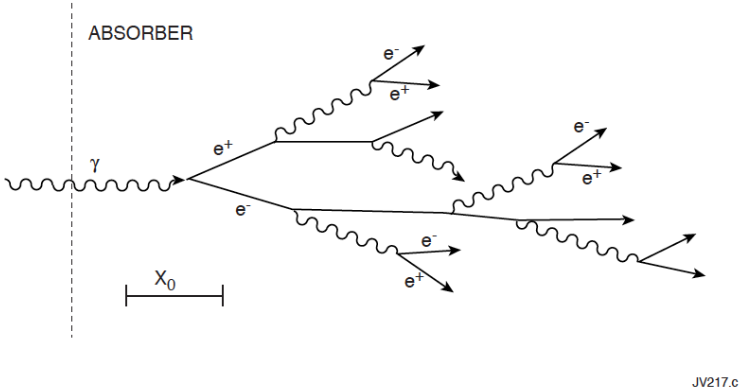
- most important performance measures for calorimeters depend on system performance
- ongoing efforts to address challenges at future colliders: radiation hardness, high granularity, timing
- calorimeters need dedicated and complex testbeams
  - different particle species: MIPs, electrons, pions, protons, ideally also kaons; both beam polarities
  - large energy ranges
  - full calorimeter system: ECAL, HCAL, tailcatcher
  - trigger, tracking, particle ID

  ➔ nearly a complete collider detector experiment
- interesting and important calorimeter testbeams in the coming year(s)

Backup

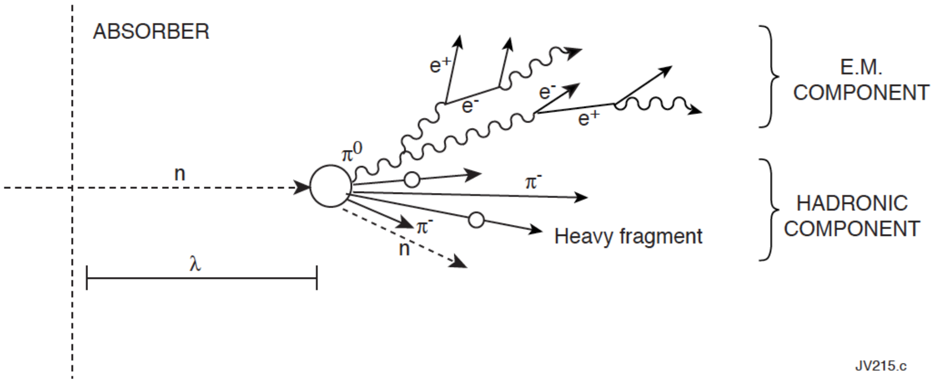
General Considerations for Calorimetry

- want to measure particle energy, so showers of charged and neutral particles should be contained
- electromagnetic showers are simple:
  - electrons and positrons radiate photons
  - photons produce electron-positron pairs
  - ~one step per **radiation length X_0**
  - radial development is described by Moliére radius



from T.S. Virdee, CERN-OPEN-2000-261

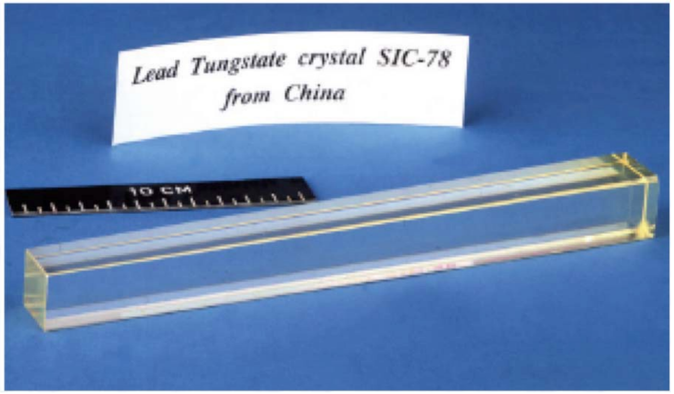
- hadronic showers much less well understood, much more variations!
  - many processes: quasi-elastic scattering … nuclear break up
  - usually have electromagnetic sub-shower
  - relevant length scale: **interaction length λ_{Int}**

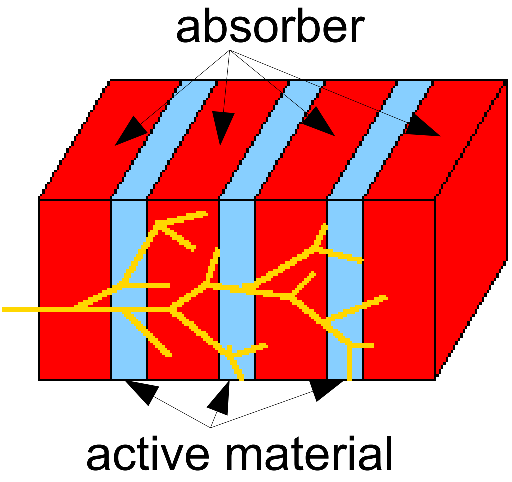


DESY

General Considerations for Calorimetry

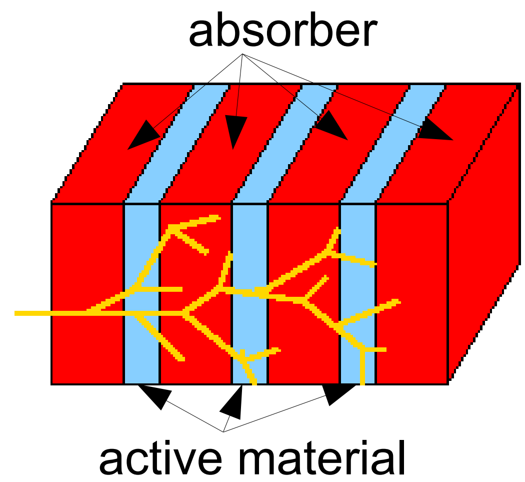
- showers of charged and neutral particles should be contained
  - absorber: dense material, short radiation length X_0 or nuclear interaction length λ_I
  - active material: detect the (charged) particles in the shower
  - homogeneous calorimeter: absorber is active
  - sampling calorimeter: different materials



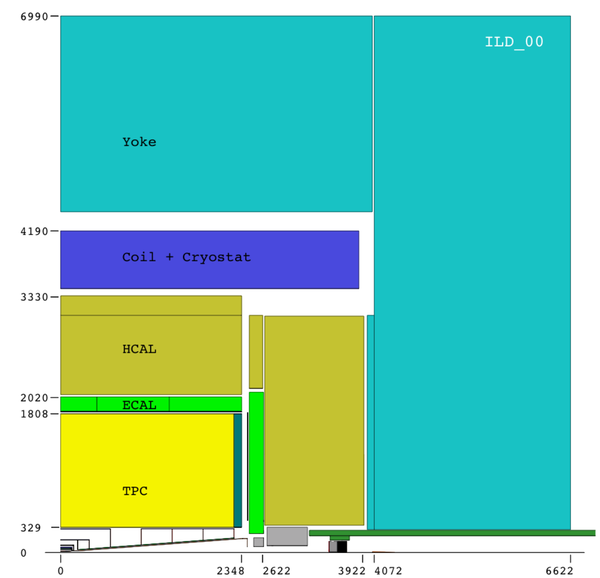


General Considerations for a (Particle Flow) Calorimeter

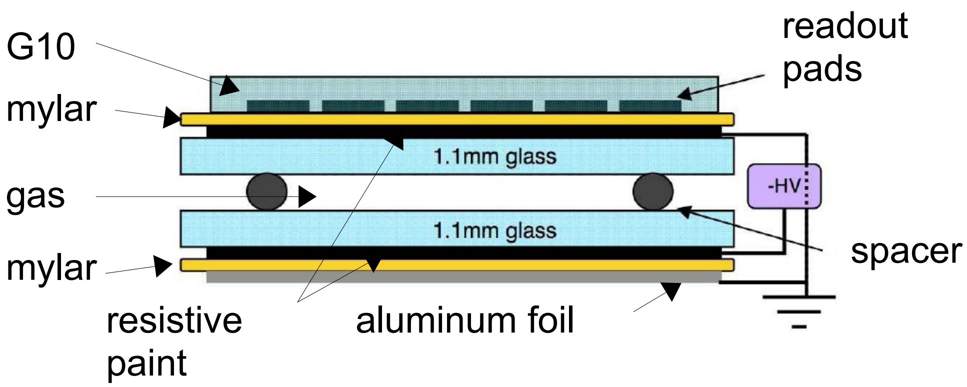
- Sandwich calorimeter
  - absorber: dense material, small Molière radius, small radiation length X_0 or nuclear interaction length λ_I
  - active layers: "count" the particles in the shower

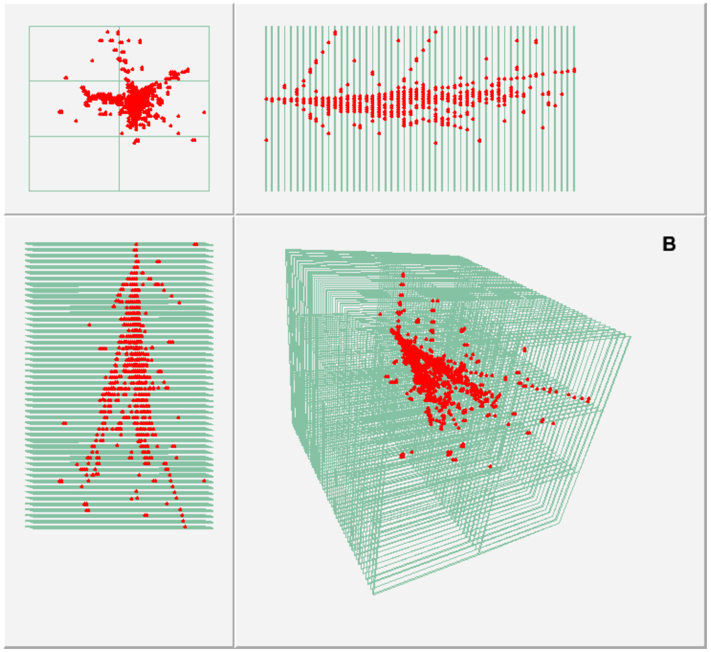


- ECAL:
  - rather small → more expensive material affordable
  - absorber: tungsten
  - several concepts for the active layers
- HCAL:
  - rather large volume, but total detector cost includes also magnet and iron yoke:
    - compact calorimeter (expensive material) → smaller (cheaper) magnet
    - larger calorimeter (cheaper material) → larger (more expensive) Magnet
    - ➔ Basic solution: steel as absorber material, tungsten as possible alternative
  - several concepts for the active layers



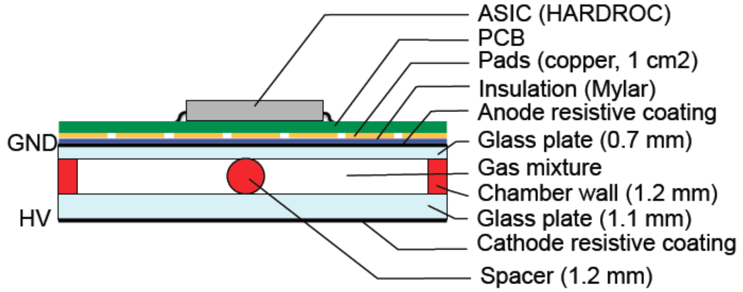
Digital HCAL

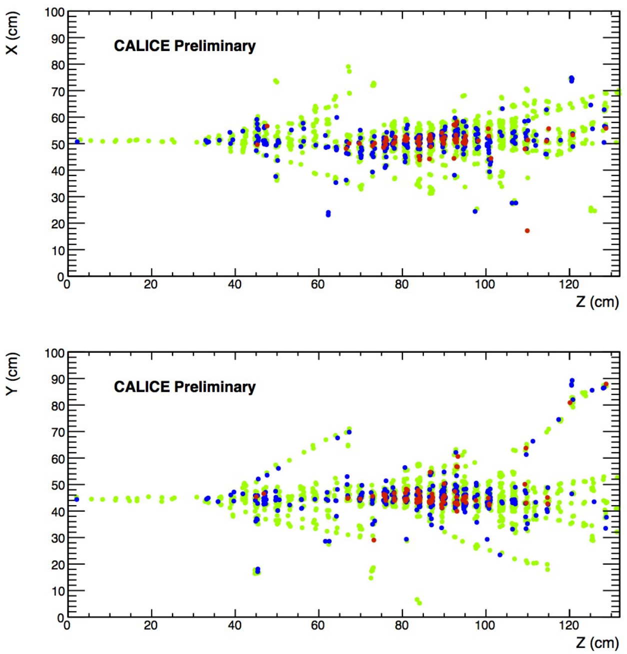




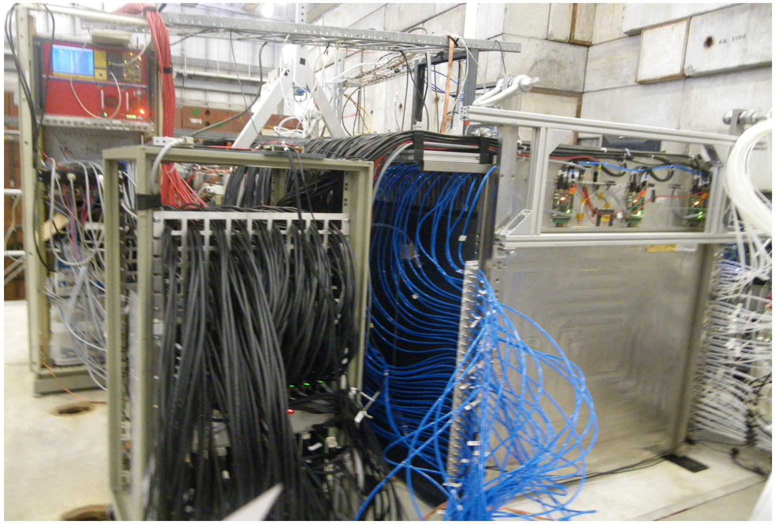
- Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage
- $1*1\ cm^2$ readout pads
- readout: 1 bit (digital)
- **SiD alternative**

Semi-Digital HCAL

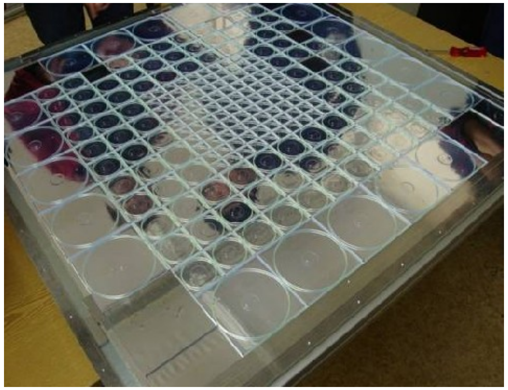




- Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage
- 1*1 cm^2 readout pads
- readout: 2 bit (semi-digital)
- **ILD option**



Analog HCAL

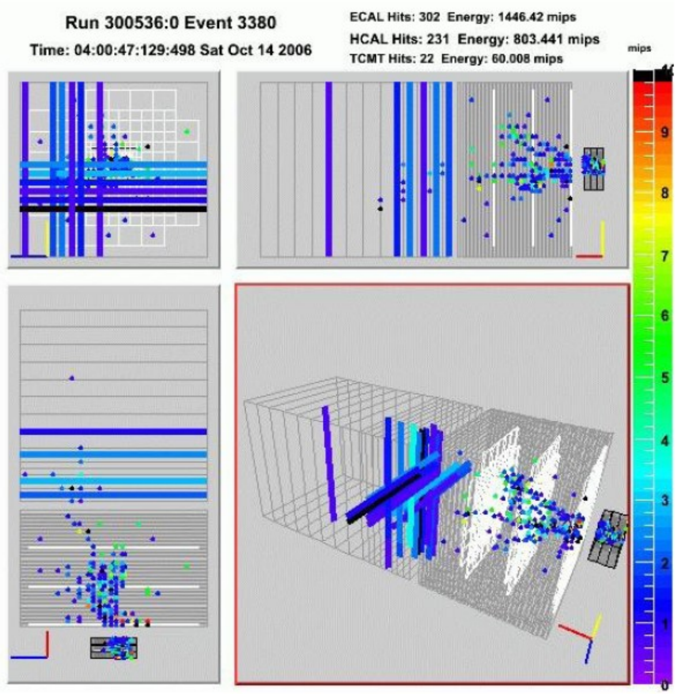


> Scintillator tiles with wave length shifting fibers, read out by SiPMs

> 3*3 cm^2 - 12*12 cm^2 tiles

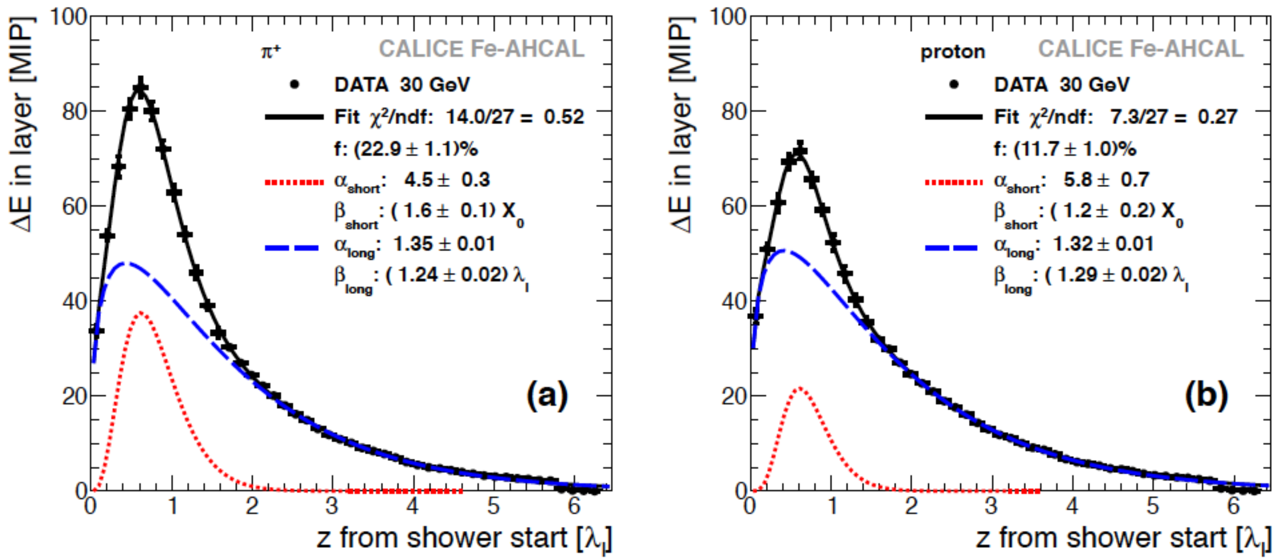
> readout: 12 bit (analog)

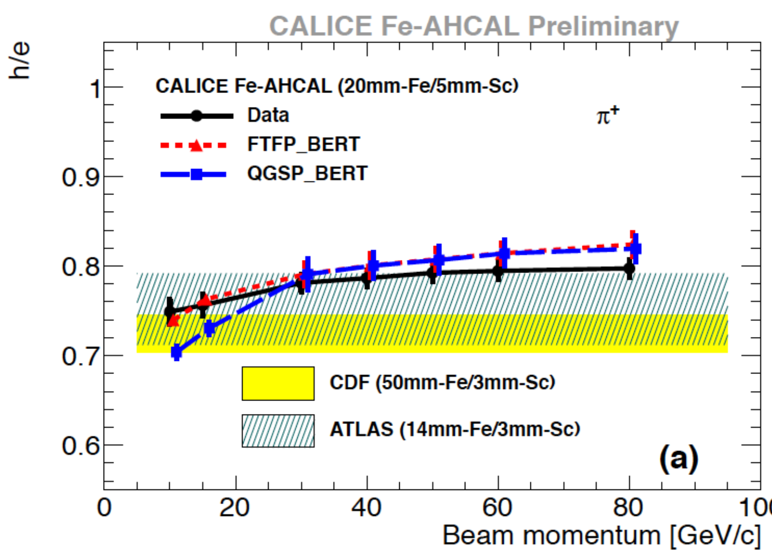
> **ILD option and SiD base design**



Pion and Proton showers in the AHCAL

JINST 11 (2016) P06013





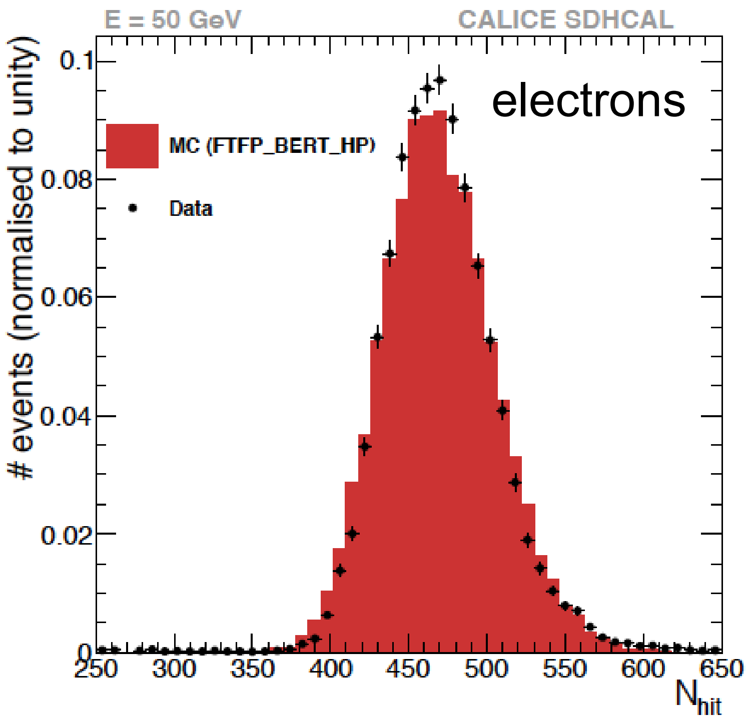
CAN-051

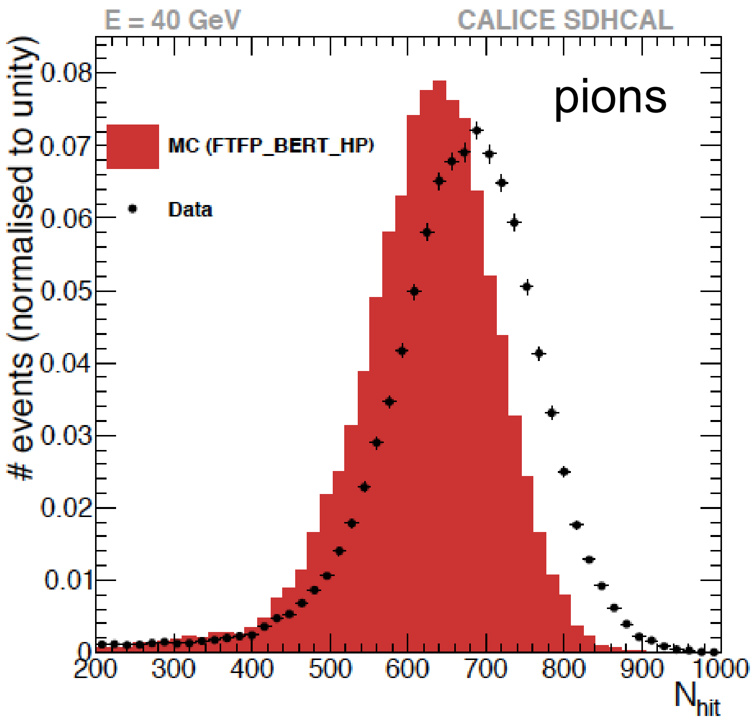
- high granularity allows separation of “short” and “long” shower component in longitudinal profiles
- extraction of h/e, ratio of calorimeter response to non-electromagnetic and electromagnetic shower component

SDHCAL comparison to simulation

- RPCs are not sensitive to average dE/dx, but to the number of points of ionisation → tests different aspect of simulation than scintillator
- tune simulation to muons and electrons
- get reasonable description of pion showers

JINST 11 (2016) P06014

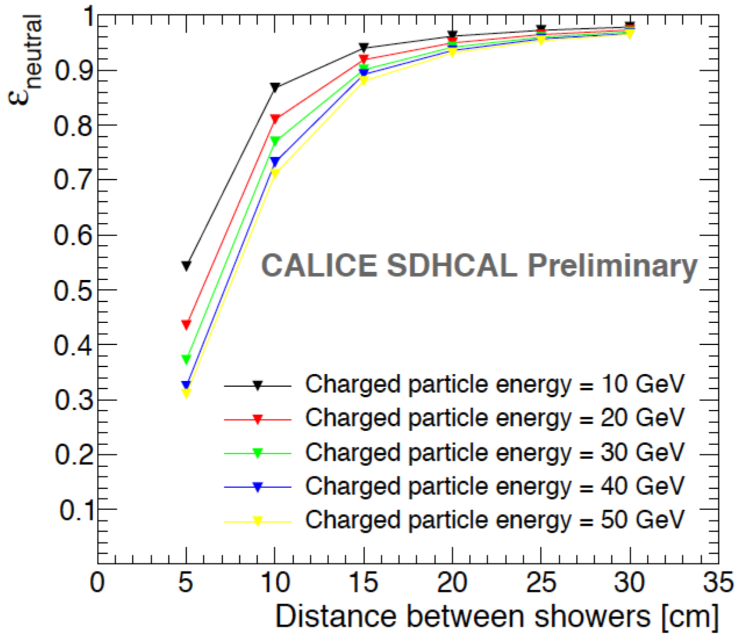


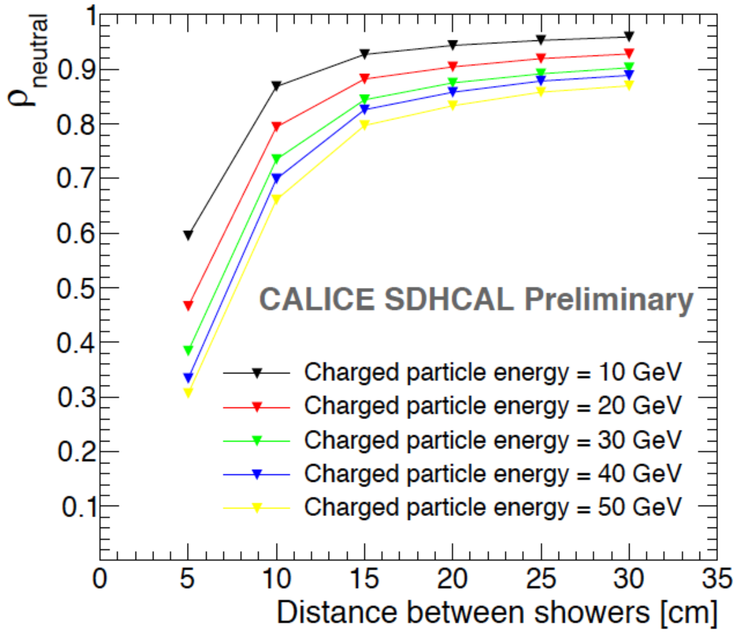


Particle Flow Validation: SDHCAL with ArborPFA

- ArborPFA: particle flow algorithm using the tree-like structure of showers
- test of cluster separation with SDHCAL pion shower data
  - overlay of 2 pion events: 10 GeV “neutral” particle (initial track segment removed) and charged hadron with 10 – 50 GeV at 5 – 30 cm distance
- good efficiency and purity to assign hits to the neutral cluster for distances of 10 cm or more

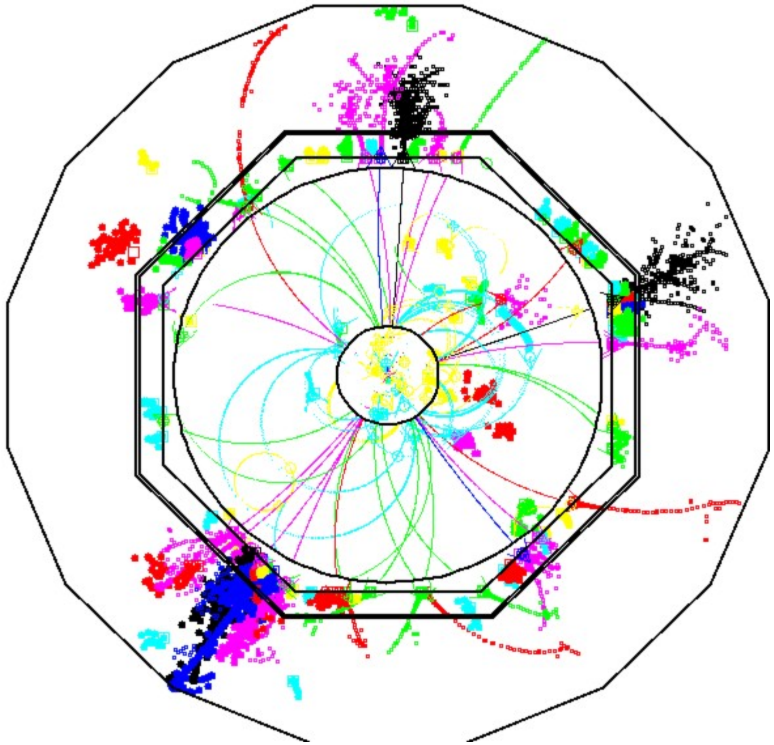
CAN-054



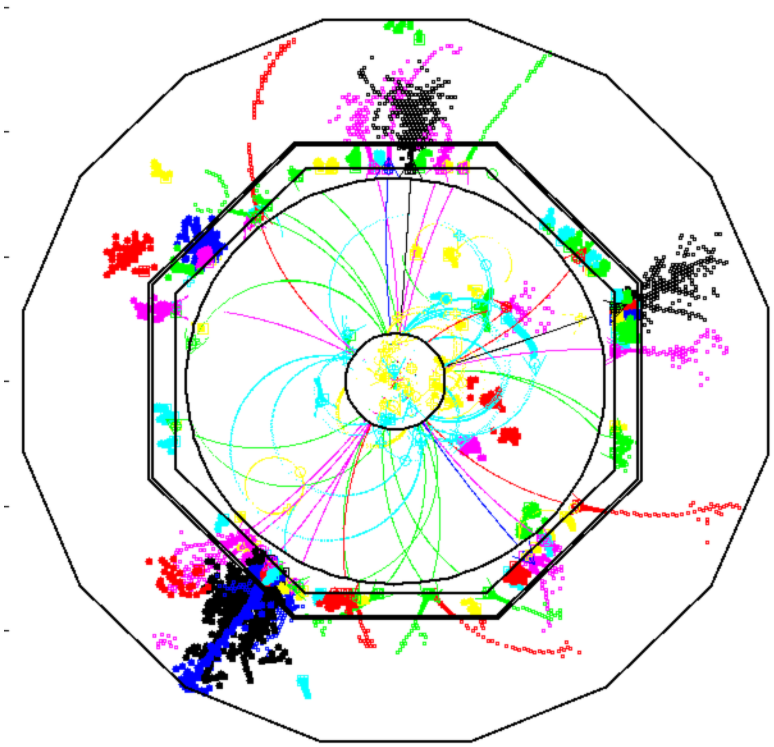


How small should the cells be?

1*1 cm^2 HCAL cell size

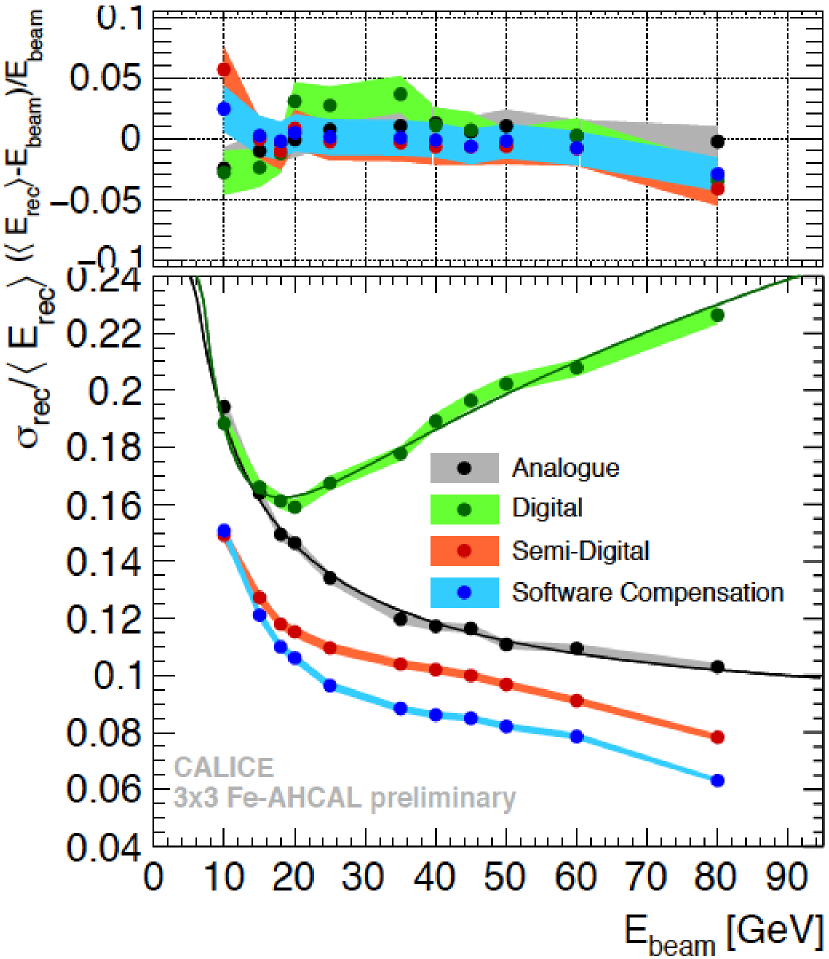


3*3 cm^2 HCAL cell size



Cell size vs. Reconstruction Algorithm

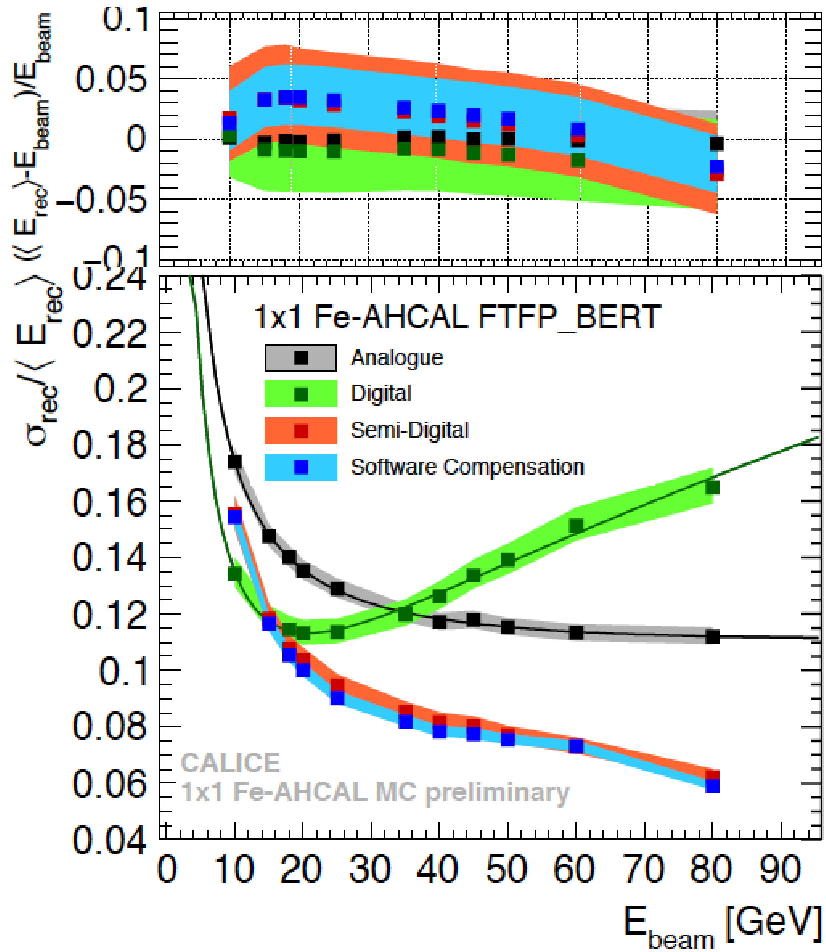
- the 3 HCAL concepts differ in several aspects
  - granularity
  - energy reconstruction method
  - active medium
- all of them influence the energy resolution for single particles and jets
- disentangle with data and validated simulation
  - 3*3 cm² AHCAL data with different reconstruction methods



Cell size vs. Reconstruction Algorithm

- the 3 HCAL concepts differ in several aspects
  - granularity
  - energy reconstruction method
  - active medium
- all of them influence the energy resolution for single particles and jets
- disentangle with data and validated simulation
  - 3*3 cm² AHCAL data with different reconstruction methods
  - 1*1 cm² AHCAL simulation with different reconstruction methods

➔ **optimal cell size depends on energy reconstruction method**



ARBOR

- ArborPFA:
  - particle flow algorithm using the tree-like structure of showers
  - energy information used in finalising clustering and track association
  - modular architecture: uses PandoraSDK toolkit and Marlin framework, available at https://github.com/SDHCAL/ArborPFA
- test of cluster separation with SDHCAL pion shower data
  - overlay of 2 pion events: 10 GeV “neutral” particle (initial track segment removed) and charged hadron with 10 – 50 GeV at 5 – 30 cm distance
  - good efficiency and purity to assign hits to the neutral cluster for distances of 10 cm or more