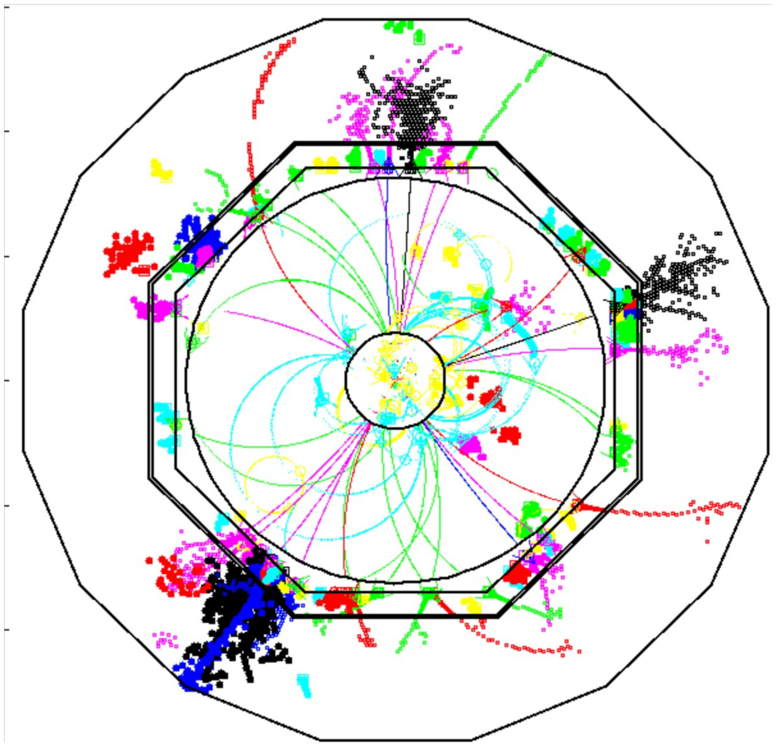
New developments in calorimetry



Katja Krüger (DESY)

HighRR Lecture Week

27. June 2022

HELMHOLTZ ASSOCIATION

Overview

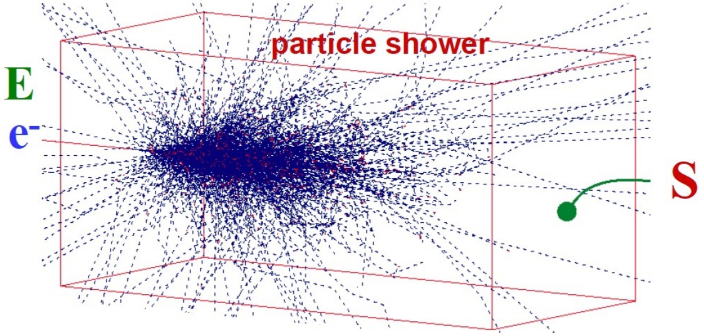
- Calorimeter Basics
- New Developments
  - Dual Readout
  - High Granularity
  - Timing

Calorimeter Basics

Why Calorimeters?

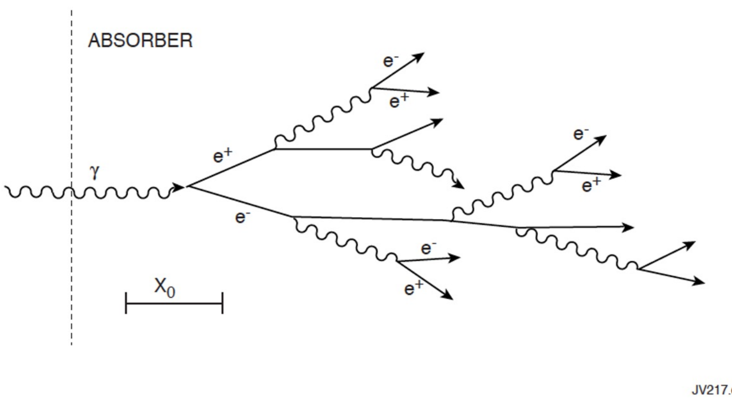
Energy measurement via total absorption of the incoming particles

- Principle of operation:
  - Incoming particle interacts with calorimeter material -> particle shower
  - Shower composition and dimension depend on particle type and detector material
  - Energy deposited in form of heat, ionization, excitation of atoms (e.g. scintillation), Cherenkov light…
  - Different calorimeter types use different kinds of these signals to measure total energy
- Basic assumption: Signal (S) is proportional to incoming energy (E)
- Calorimeters measure charged and neutral particles
- Calorimeters have a high rate capability and are fast and can therefore recognize and select interesting events in real time -> Trigger



Electromagnetic showers

- electromagnetic showers are simple:
  - electrons and positrons radiate photons
  - photons produce electron-positron pairs
- ~one step per **radiation length X_0**
- in each step
  - number of particles *2
  - mean particle energy *1/2
- at depth t (in X_0):
  - mean particle energy $E_0 * 2^{-t}$
- shower maximum t_{max} is reached when mean energy reaches critical energy E_C: $t_{max} = \log_2(E_0/E_C)$
- **logarithmic increase of shower depth with energy**



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

- radial development is described by Moliére radius
  - a cylinder with radius 1 R_M contains ~90% of the total energy

ECAL design

- consequences for ECAL design
  - want dense absorber material with small X_0 for compact showers
  - need sensitive material to detect particles in shower
  - granularity for ECAL energy resolution not so important, but relevant for position resolution, shower direction, 2-particle separation, ...

homogeneous calorimeter: sensitive material as absorber

- advantages
  - very good energy resolution
- disadvantages
  - limited granularity
  - expensive

sampling calorimeter: absorber interleaved with sensitive material

- advantages
  - compact
  - can be cheap
- disadvantages
  - limited energy resolution because of sampling fluctuations

Examples of ECAL energy resolutions

Technology (Experiment)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2\%/\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996

from PDG

homogeneous

sampling

Contributions to energy resolutions

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

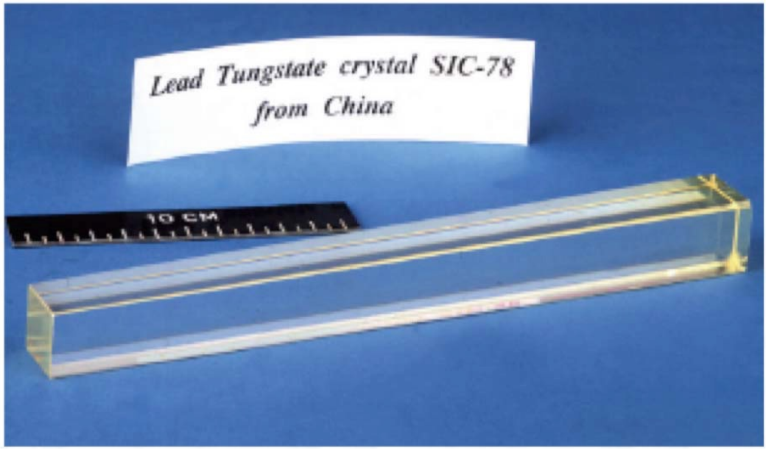
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- stochastic term
  - caused by fluctuations in the number of measured particles (intrinsic fluctuations, sampling fluctuations, statistical effects in detection, …)
- calibration term
  - caused mainly by non-uniformities, e.g. by calibration
- noise term
  - everything contributing energy independent of initial particle energy, e.g. noise
- size and relevance of these contributions are highly dependent on choice of calorimeter materials
- real calorimeters often have worsening of resolutions at high energies (containment)

Example ECALs: CMS vs. ATLAS

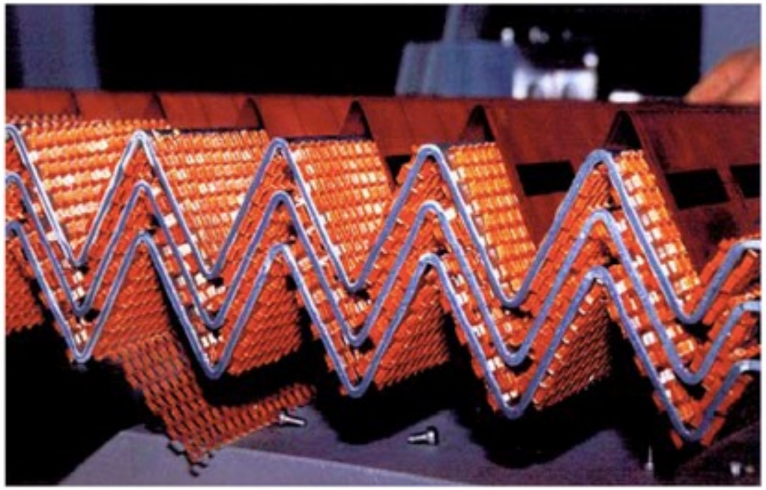
- CMS has chosen homogeneous crystal ECAL:

$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.2\ GeV}{E}$$



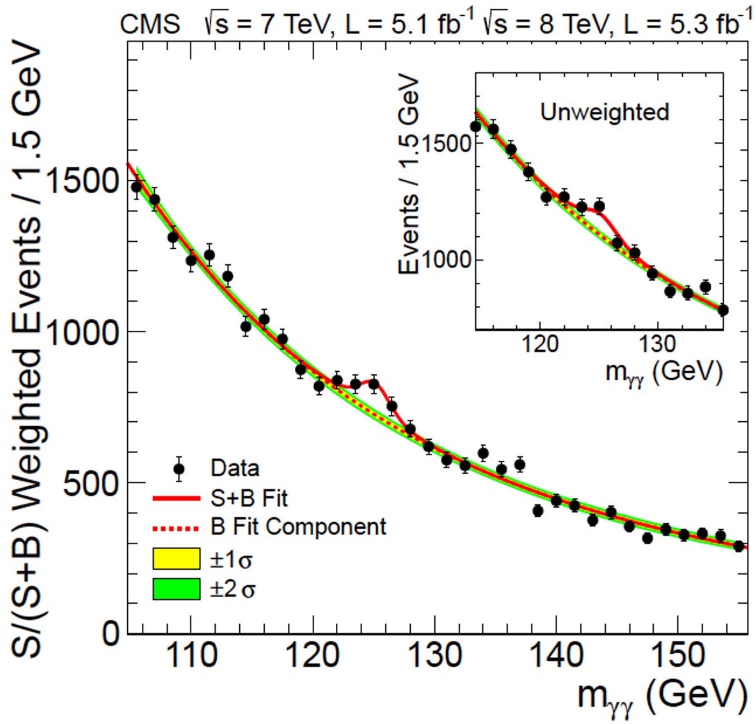
- ATLAS has chosen lead LAr accordion calorimeter:

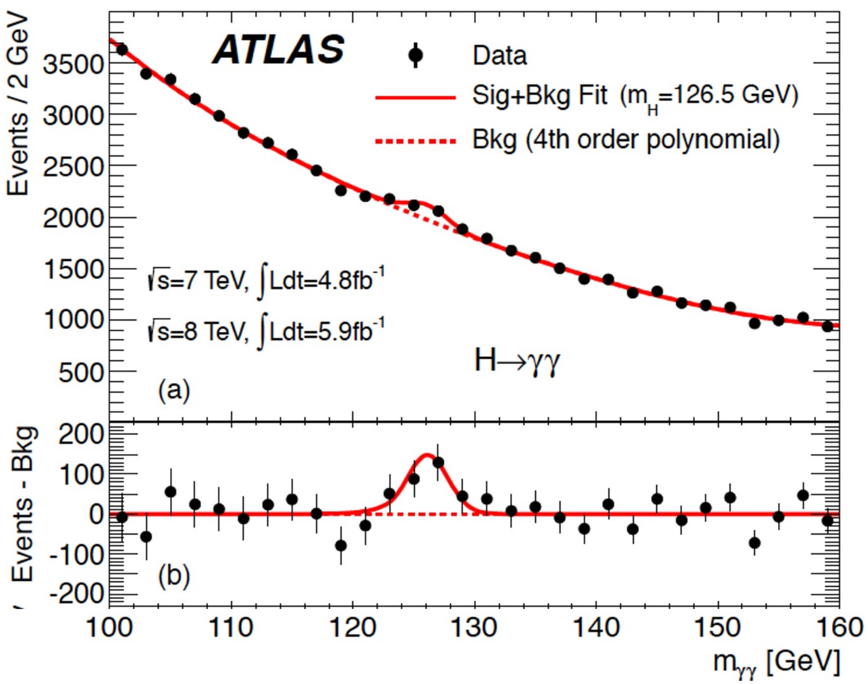
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.4\% \oplus \frac{0.3\ GeV}{E}$$



- so CMS should do much better in mass resolution for H $\rightarrow \gamma\gamma$, does it?

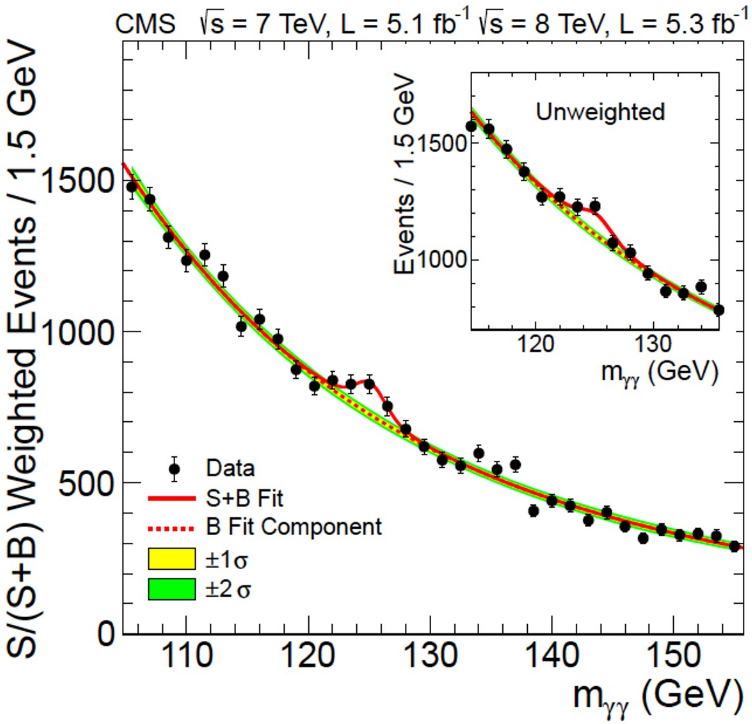
Example ECALs: CMS vs. ATLAS

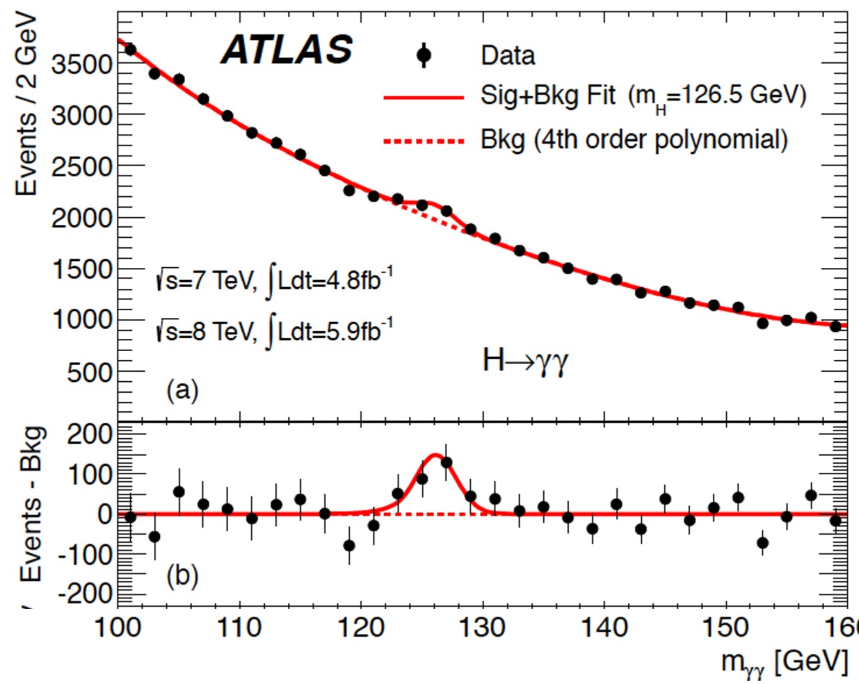




> CMS is not that much better than ATLAS! Why?

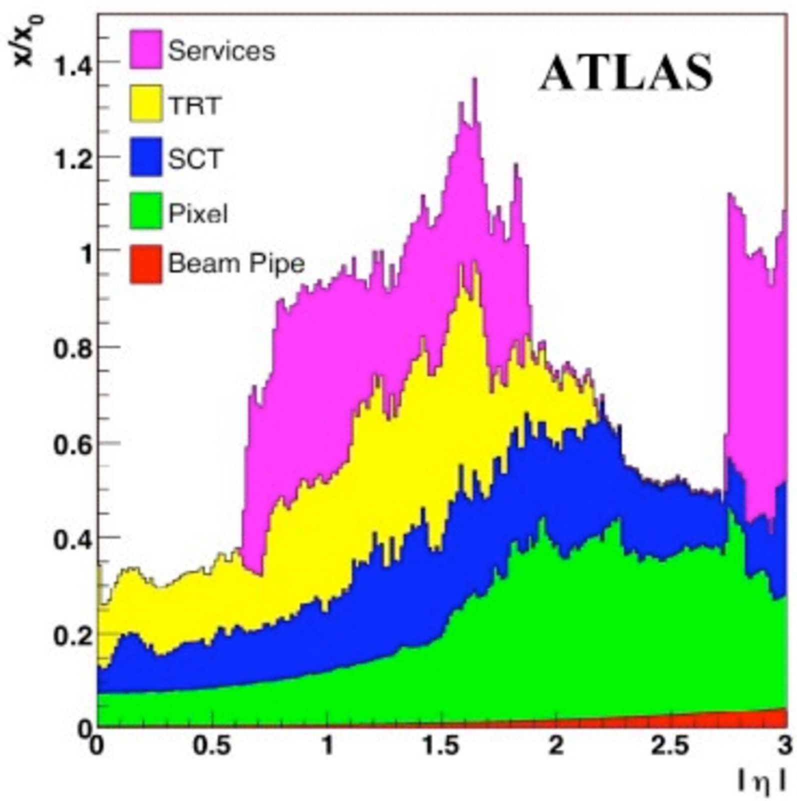
Example ECALs: CMS vs. ATLAS

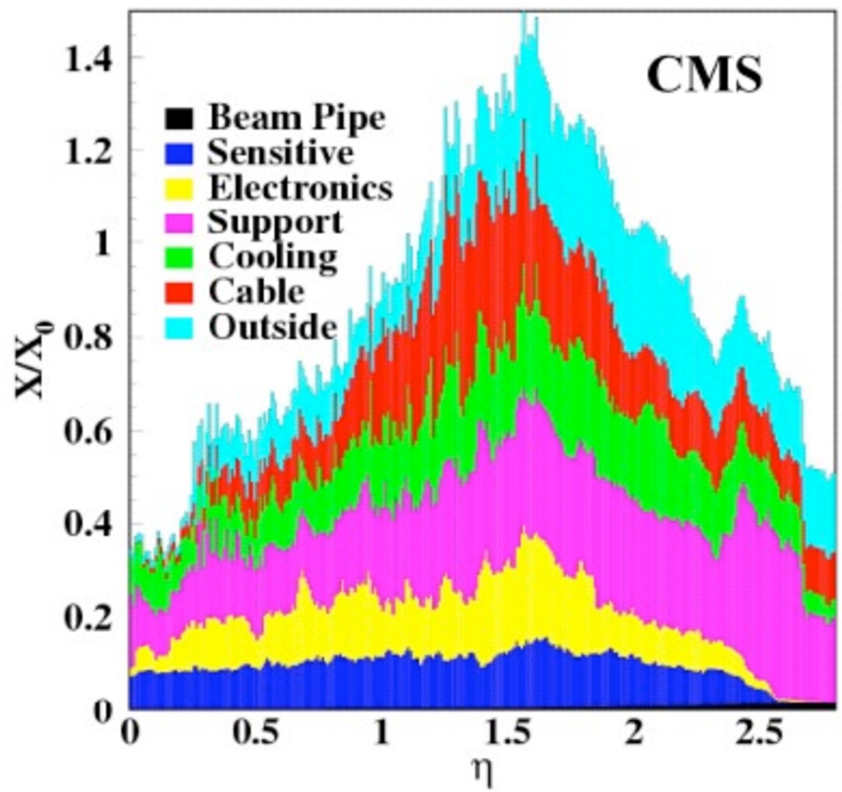




- CMS is not that much better than ATLAS! Why?
- energy resolution is not the only relevant quantity! ATLAS has finer granularity and therefore better position and angular resolution

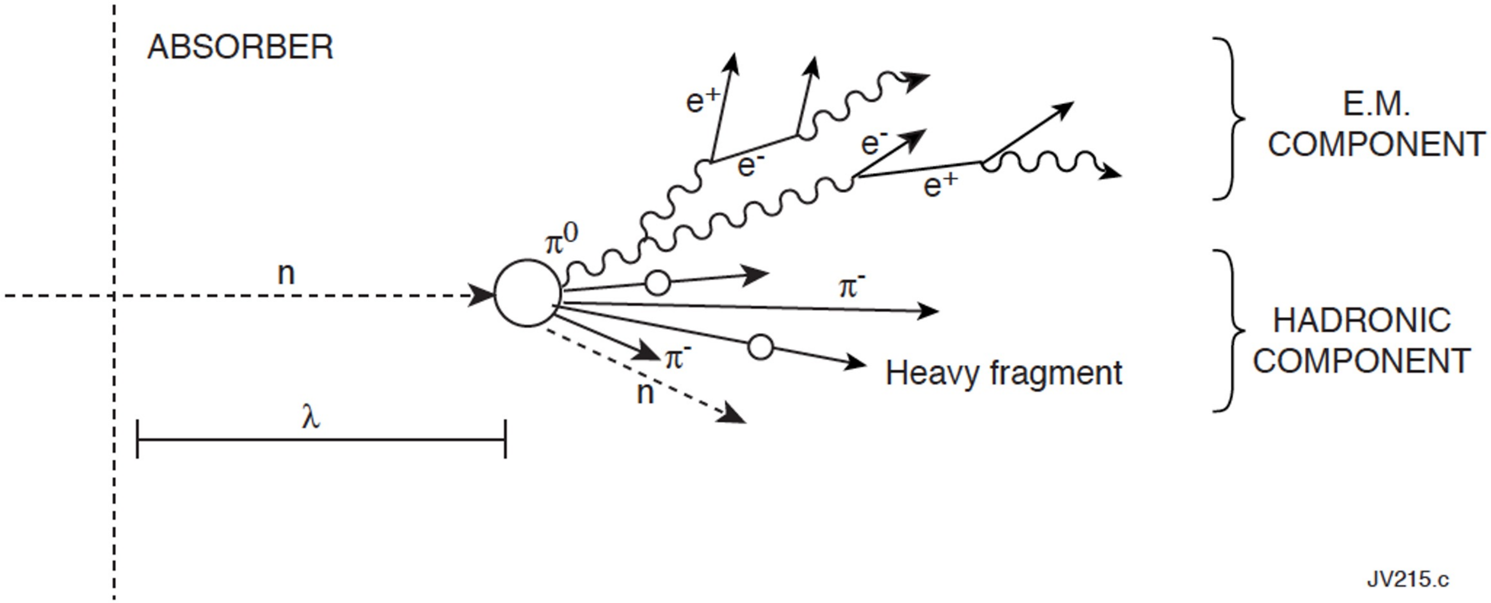
Example ECALs: CMS vs. ATLAS





> in addition: lots of material in front of calorimeters, so many photons convert to electron-positron pairs before reaching ECAL

Hadronic showers



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}**
- similar to EM showers: logarithmic increase of shower depth with energy

Examples of HCAL energy resolutions

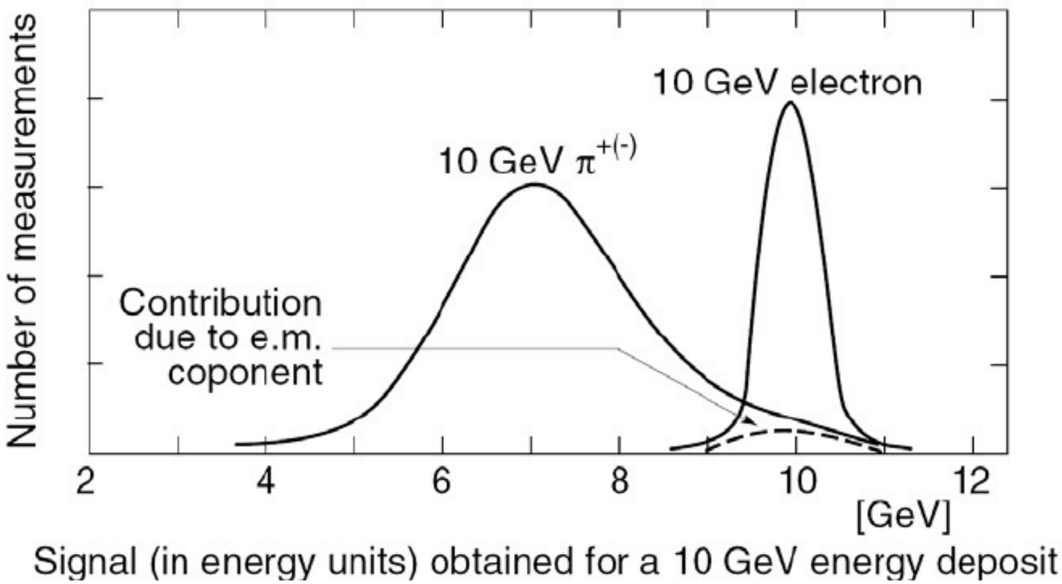
Experiment	technology	energy resolution
ALEPH	Fe / streamer tubes	$85\%/\sqrt{E}$
ZEUS	U / scintillator	$35\%/\sqrt{E} \oplus 2\%$
H1	Fe / liquid argon	$51\%/\sqrt{E} \oplus 1.6\% \oplus 0.9\ \mathrm{GeV}/E$
D0	U / liquid argon	$41\%/\sqrt{E} \oplus 3.2\% \oplus 1.4\ \mathrm{GeV}/E$
ATLAS (design)	Fe / scintilator	$50\%/\sqrt{E} \oplus 3\%$
CMS (design)	brass / scintillator	$100\%/\sqrt{E} \oplus 4.5\%$

All hadronic calorimeters are sampling calorimeters!

Why is Zeus so good?

Hadronic showers: energy resolution and compensation

- hadronic showers contain a large amount of “invisible” energy: nuclear binding energy, slow neutrons, neutrinos, ...
- calorimeter response to an electron and a pion of the same energy is usually not the same
  - $e/\pi > 1$: under-compensating (most calorimeters)
  - $e/\pi = 1$: compensating
  - $e/\pi < 1$: over-compensating



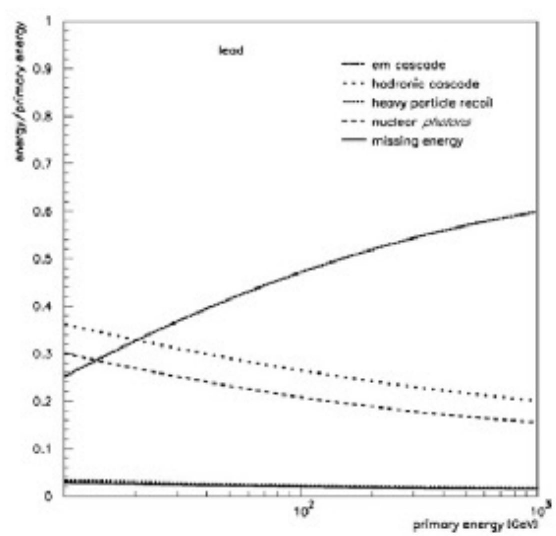
$$\pi = f_{EM}\, e + (1 - f_{EM})\, h$$

e: response to EM shower

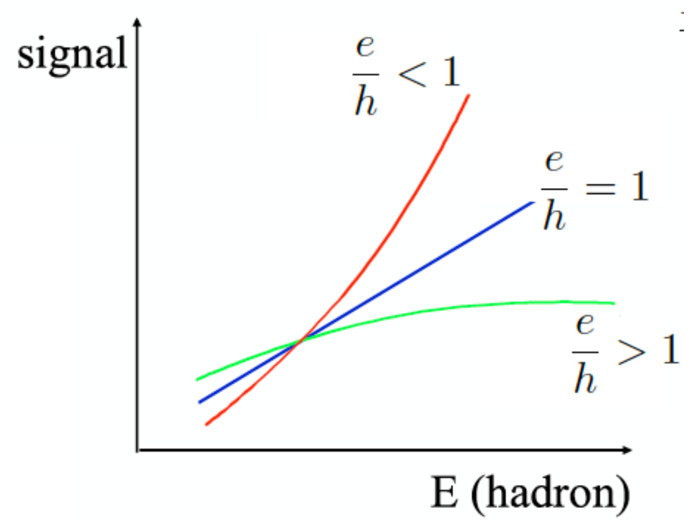
h: (hypothetical) response to purely HAD shower

Hadronic showers: energy resolution and compensation

- Why does $e/\pi \neq 1$ have an influence on the resolution?
  - the fraction of energy in the electromagnetic sub-shower (f_{EM}) varies from shower to shower
  - also the fraction of invisible energy varies from shower to shower
- **hadronic energy resolution much worse than electromagnetic!**
- In addition: the average f_{EM} increases with energy -> non-linearity



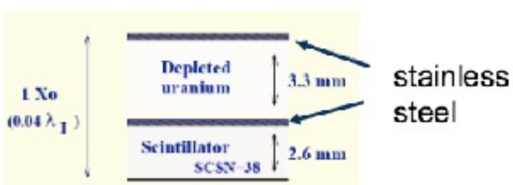
C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)



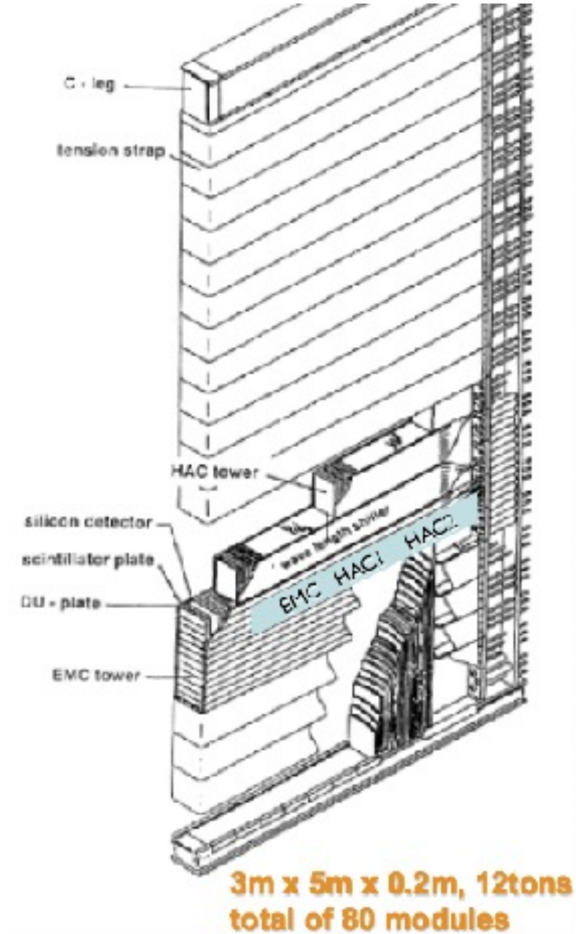
Hadronic showers: how to reach compensation?

Hardware

- design your HCAL such that e/π =1
  - Enhance response to HAD shower fraction (h)
  - Reduce response to EM shower fraction (e)
- challenges:
  - often deteriorates EM resolution



proper choice of active and passive thicknesses gives compensation



ZEUS: Highly-segmented, uranium scintillator sandwich calorimeter r/o by 12,000 photomultiplier tubes

Hadronic showers: how to reach compensation?

Hardware

- design your HCAL such that $e/\pi = 1$
  - Enhance response to HAD shower fraction (h)
  - Reduce response to EM shower fraction (e)
- challenges:
  - often deteriorates EM resolution

Software

- correct your energy measure-ment depending on f_{EM}
- challenges:
  - need to identify EM sub-shower and weight HAD and EM part differently
  - See later:
    - Dual readout
    - High granularity

New developments

- Dual readout
- High granularity
  - Motivation
  - Testbeam prototypes and measurements
  - Engineering prototypes
  - High granularity beyond electron-positron colliders
  - High granularity & timing

- Radiation hardness
  - Not really covered here
  - Very important for future hadron colliders (FCChh)
  - For highest fluence, mainly two technologies suitable
    - Liguid noble gas (Liquid Argon)
    - Silicon sensors

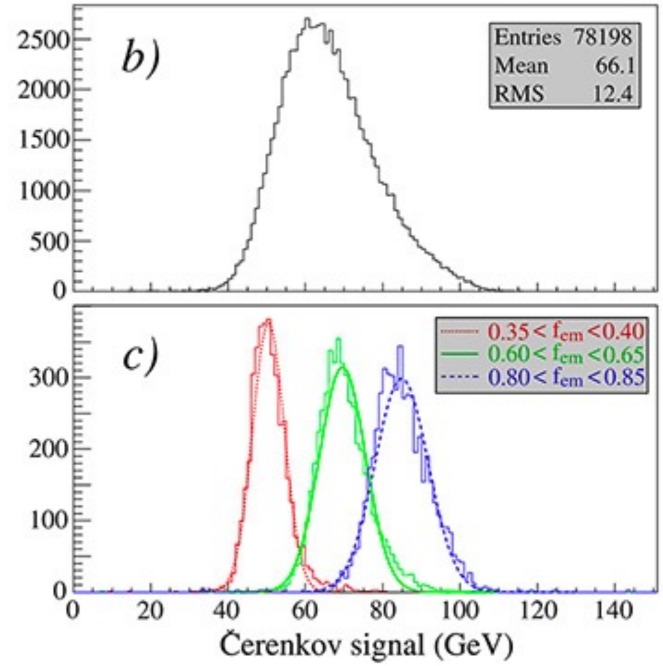
Dual Readout

Dual Readout: Idea

Measure f_{EM} for each shower directly by using scintillation & Cherenkov radiation

- Scintillation (S) is produced by all particles in a shower
- Cherenkov (C) radiation is produced only by “fast” particles (faster than the speed of light in the medium)
  - Mainly the electrons & positrons in the EM (sub-)shower
- By measuring both S and C for a hadronic shower, get a handle on f_{EM}
- Expectation: stochastic term of better than 30% should be reachable for single hadrons

100 GeV π^- DREAM

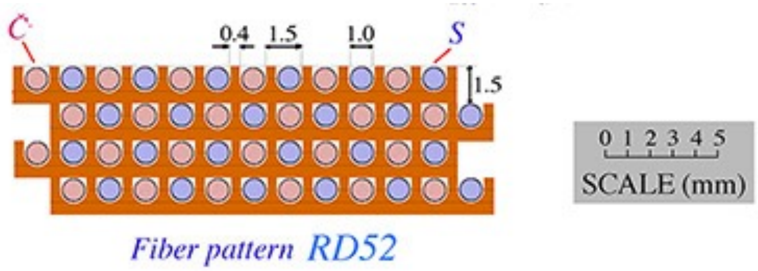


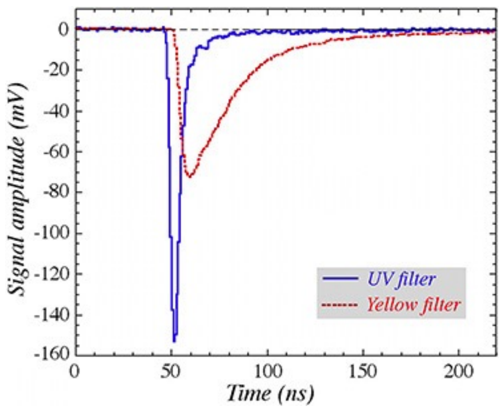
Plots from “DUAL-READOUT CALORIMETRY”, arXiv:1712.05494

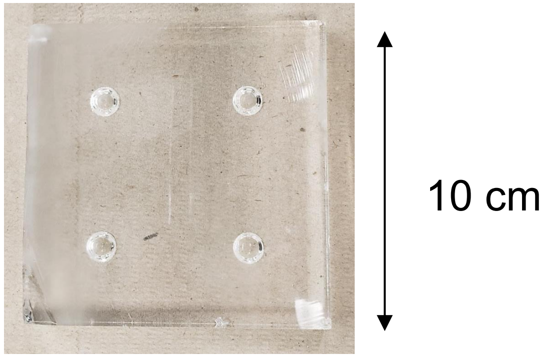
Dual Readout: Implementation

Several ideas have been explored

- Spaghetti fiber calorimeters with two sets of fibers (DREAM, RD52)
  - Scintillating fibers to detect S
  - Clear fibers (quartz or plastic) to detect C
- Distinguish S and C by their spectral and/or timing characteristic
  - C is (quasi-)instantaneous, small wave length (UV)
  - S is governed by scintillator characteristics
- Combination with high granularity: dual readout tiles (Adriano2)



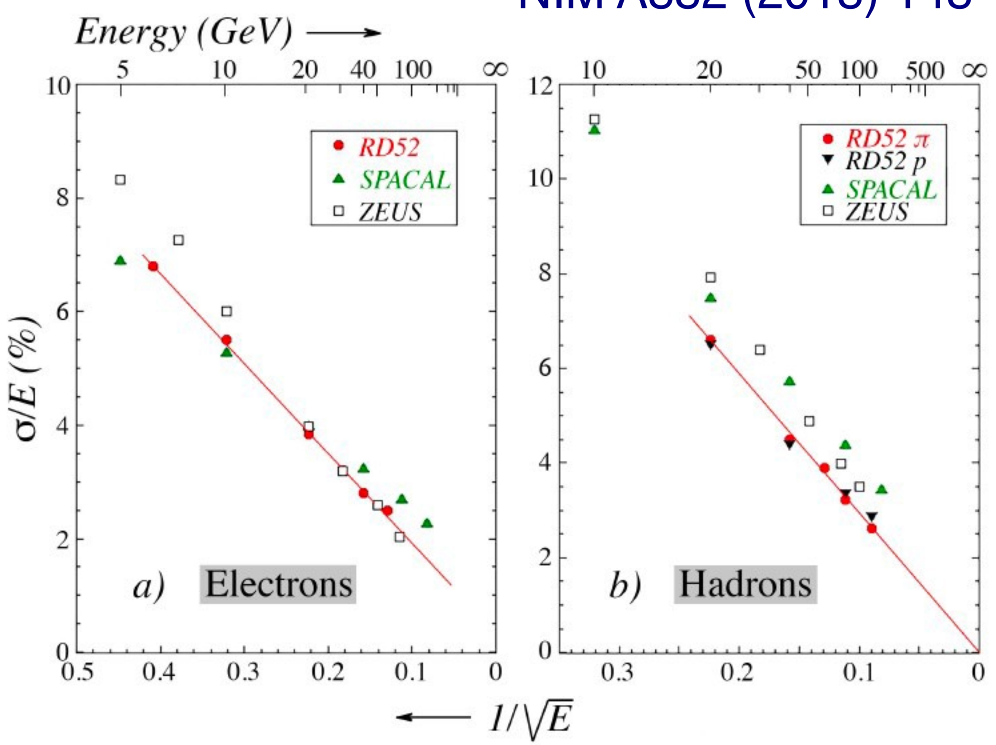




Dual Readout: Experimental challenge

- Yield of Cherenkov light is usually low (much less than scintillation)
- In order to demonstrate the performance, need to build a large prototype with very small leakage
  - Both lateral and longitudinal
- So far, ~30% / sqrt(E) has been shown for hadrons

NIM A882 (2018) 148



High Granularity

Motivation

- Highly granular calorimeter concepts originally developed for future electron-positron colliders
- main interest: measurement of jet energies in EW processes

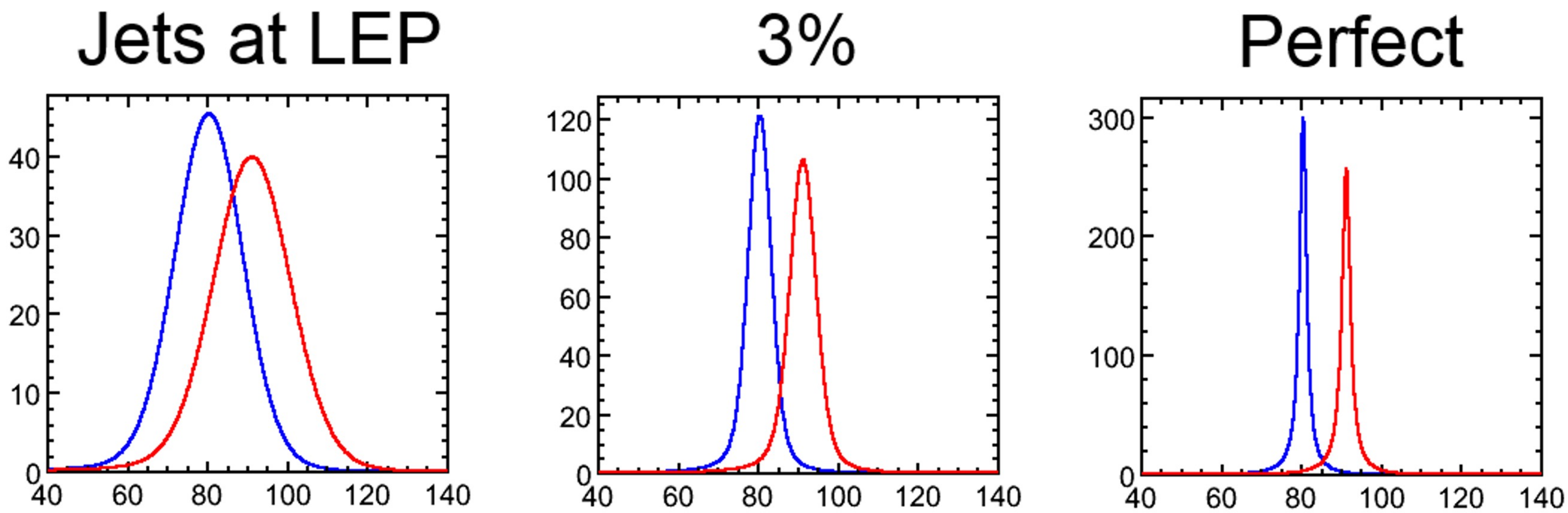
Physics Process	Measured Quantity	Critical System	Physical Magnitude	Required Performance
Zhh $Zh \to q\bar{q}b\bar{b}$ $Zh \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs coupling Higgs mass $B(h \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution $\Delta E/E$	3% to 4%

from ILC TDR

- other interesting processes with jets: everything with t quarks, SUSY, …
- don't forget single particles:
  - tau identification relies on ECAL
  - low energy muons don't reach the muon system → identify in calo!

Why 3-4% jet energy resolution?

- goal: distinguish the decays $W \rightarrow jet\ jet$ and $Z \rightarrow jet\ jet$ by their reconstructed mass

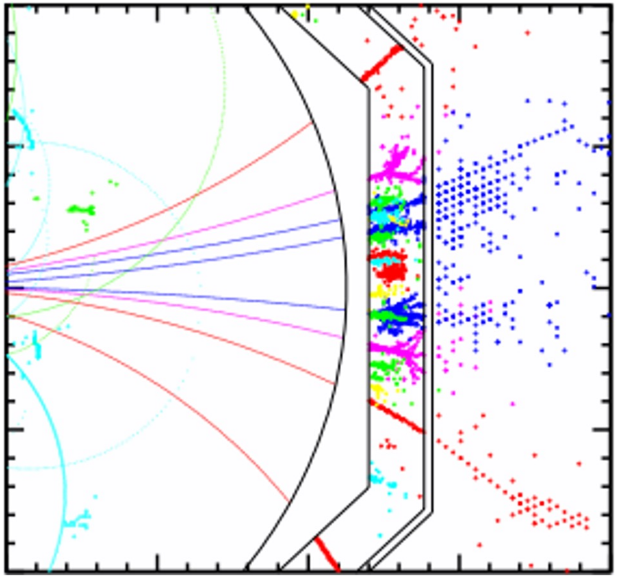


from Cambridge HEP group

- required resolution: $\sigma(E_{jet})/E_{jet} \approx$ 3-4%
- interesting jet energy range: $E_{jet} \approx$ 40 to 500 GeV
- not reachable with LEP (and existing collider) detectors!

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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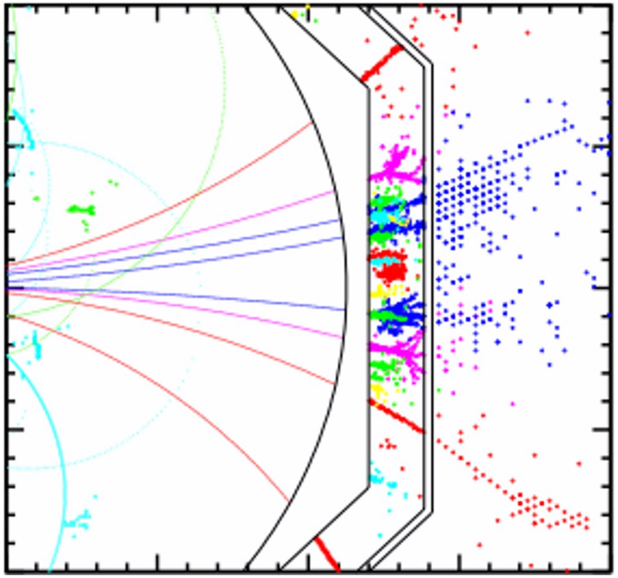


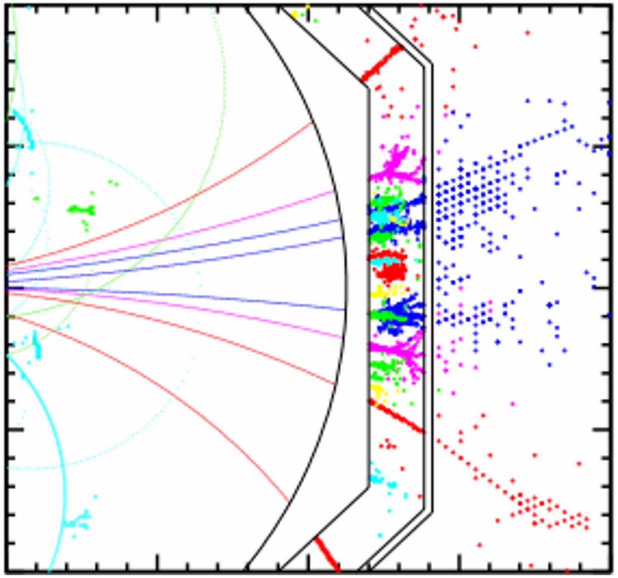
from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „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

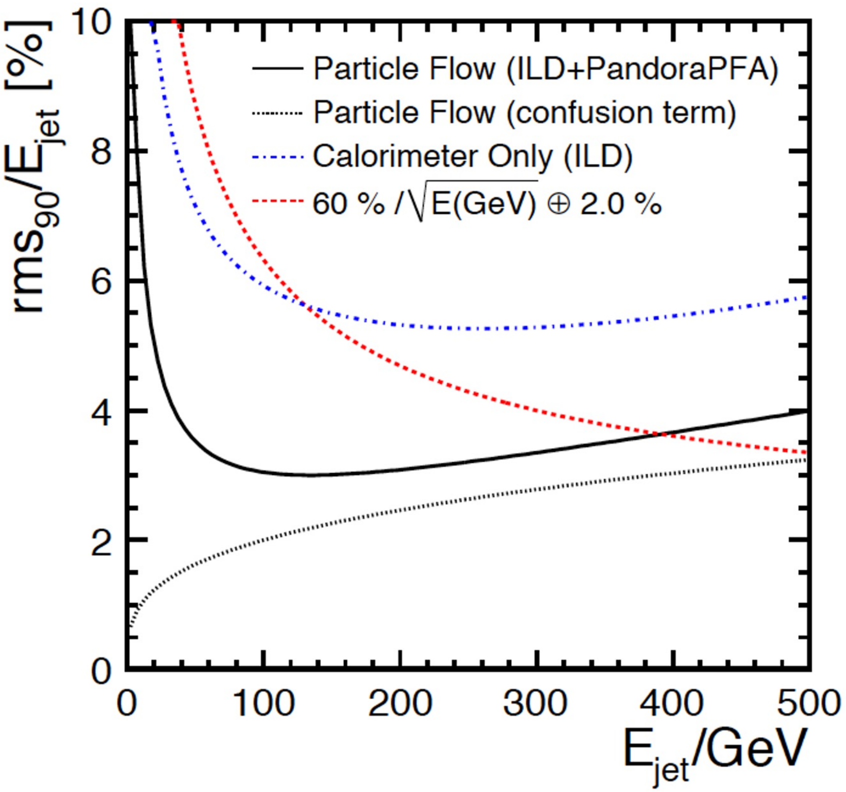


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

> „typical" jet:

		$(\sigma_{jet})^2$
~ 62% charged particles	tracking	$\approx\ 0.62\ (\sigma_{tracks})^2$
~ 27% photons	EM calorimeter	$+\ 0.27\ (\sigma_{EMCalo})^2$
~ 10% neutral hadrons	HAD calorimeter	$+\ 0.10\ (\sigma_{HADCalo})^2$
~~ 1% neutrinos~~		$+\ (\sigma_{loss})^2 + (\sigma_{confusion})^2$

Jet Energy Resolution with PFA



realistic ILC calorimeter (ILD)

PFA

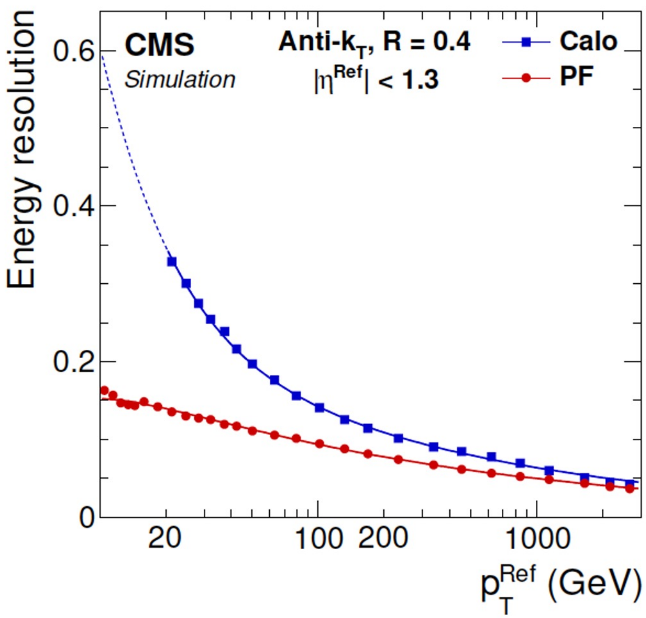
"ideal" traditional HAD calorimeter

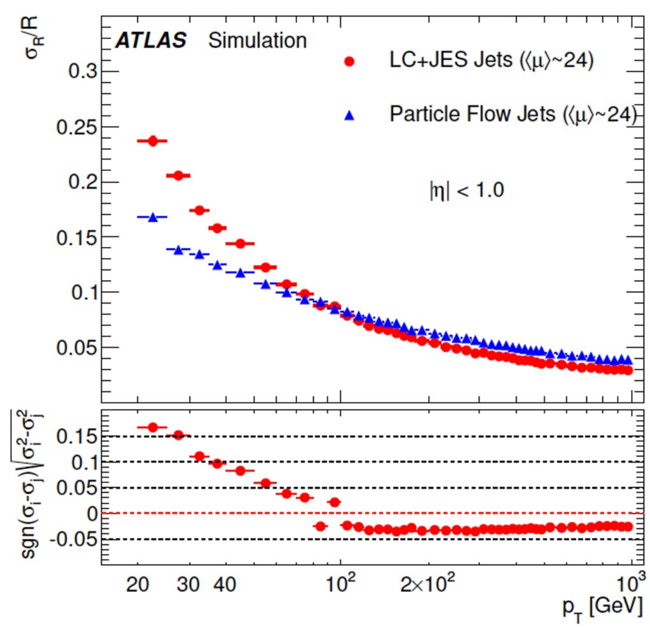
„Confusion": wrong association between tracks and calorimeter clusters

- 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 decent energy resolution

Particle Flow at Work

- Particle Flow (or similar) algorithms have been used for jet reconstruction in the past by several experiments (ALEPH, CDF, H1, ZEUS, ...)
- improvement in resolution relative to pure calorimeter algorithms depends a lot on the detector itself
  - CMS: HCAL with modest energy resolution → large gain
  - ATLAS: HCAL with good energy resolution, magnet coil between tracker and calorimeter → small gain
- none of these detectors were built for Particle Flow!





Particle Flow Detector

How should a detector look like that is optimized for Particle Flow?

> need good separation of particles entering the calorimeter

➔ large detector radius and length

➔ large magnetic field to separate charged from neutral particles

> need compact showers to minimize overlap

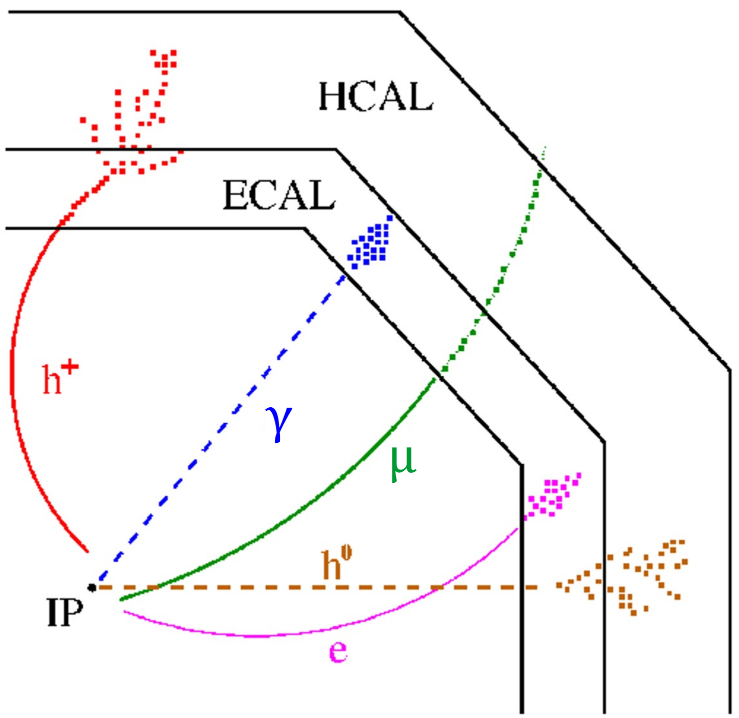
➔ **calorimeters** with small Molière radius

> need minimal amount of dead material between tracker and calorimeter

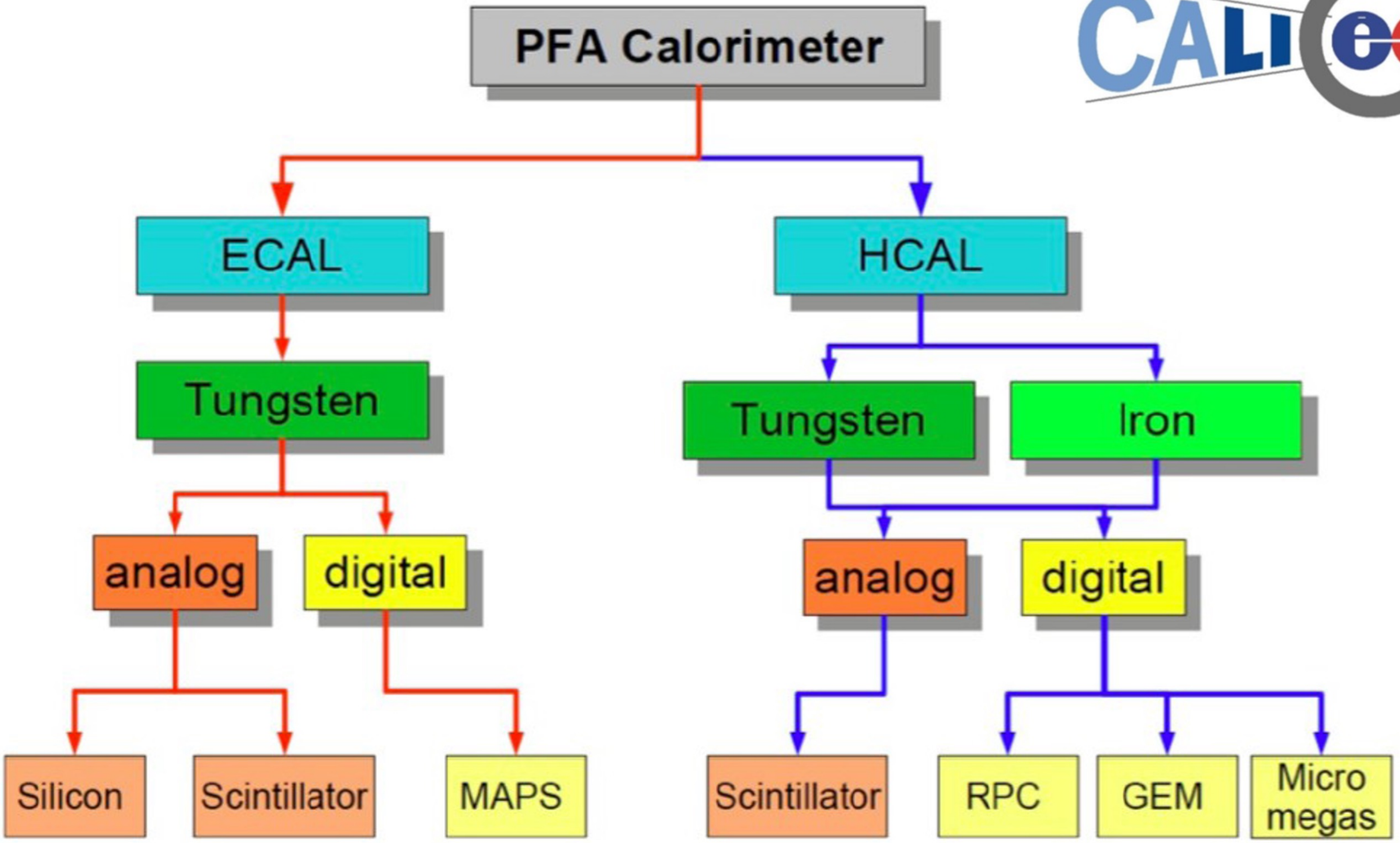
➔ **calorimeter** inside magnet coil

> need detailed information about shower position and shape

➔ **calorimeter** with very high granularity

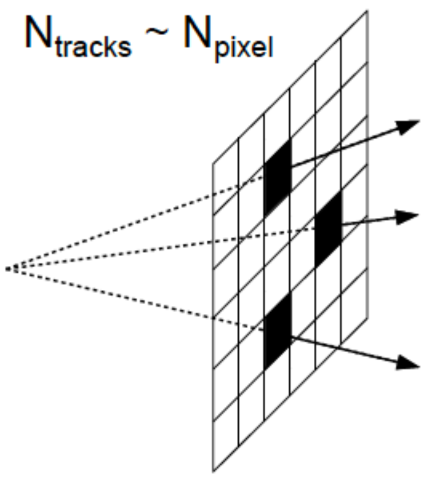


Calorimeter Technologies for Linear Collider detectors



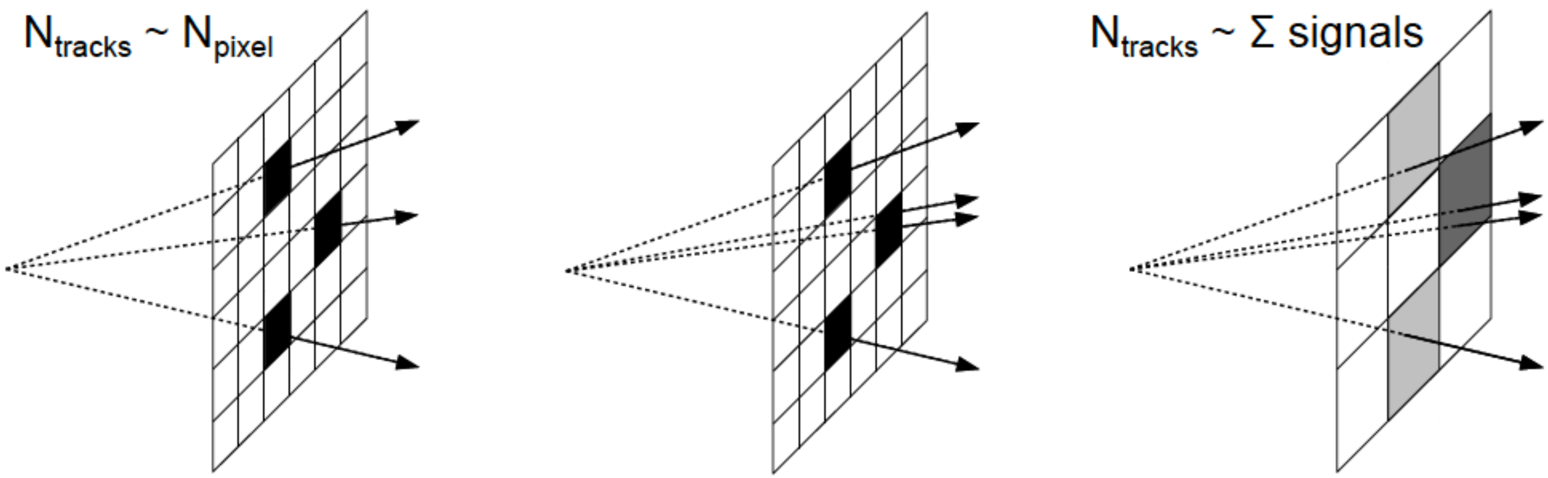
Calorimeter Readout Concepts

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



Calorimeter Readout Concepts

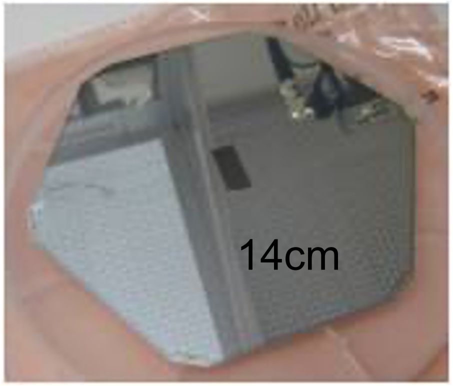
- digital CAL: count number of hit pixels (off/on)
- semi-digital CAL: additional information about number of particles within one pixel by using 3 thresholds (off/standard/large/very large)
- analog CAL: sum up signals in (larger) cells



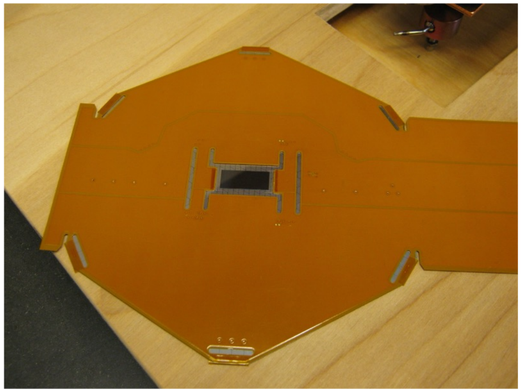
- for the hadronic calorimeter, all 3 concepts are studied and have shown their physics potential with "physics prototypes"

Electromagnetic Calorimeter: Active Material

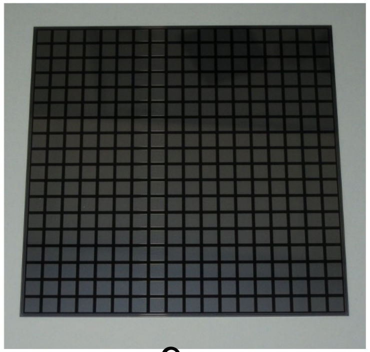
Silicon



1024 pixel

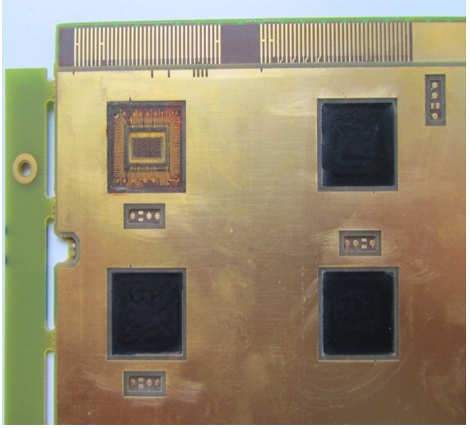


Silicon

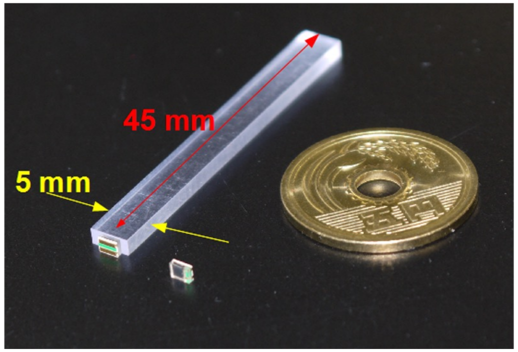


9cm

256 pixel

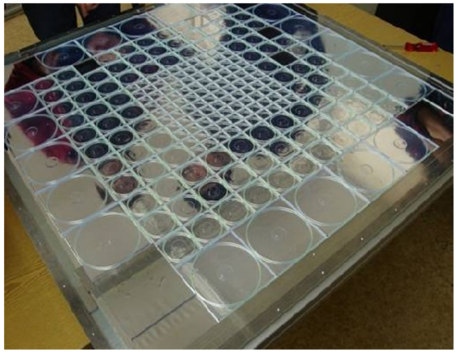


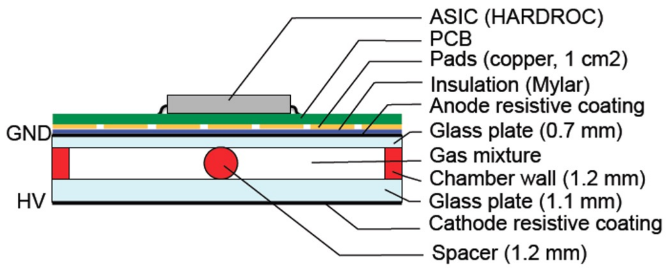
Scintillator

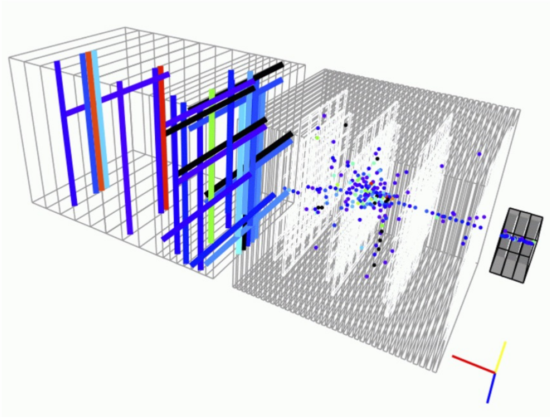


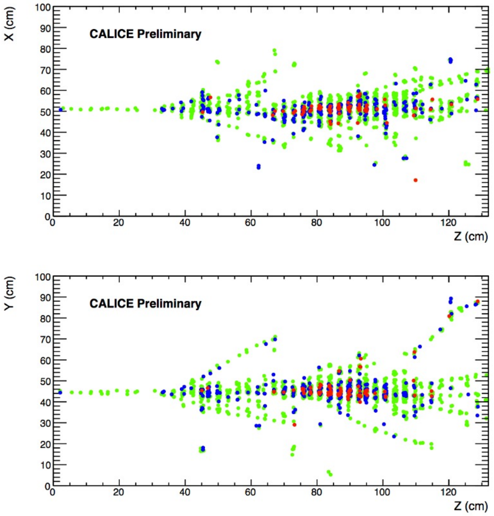
Highly Granular HCAL Concepts

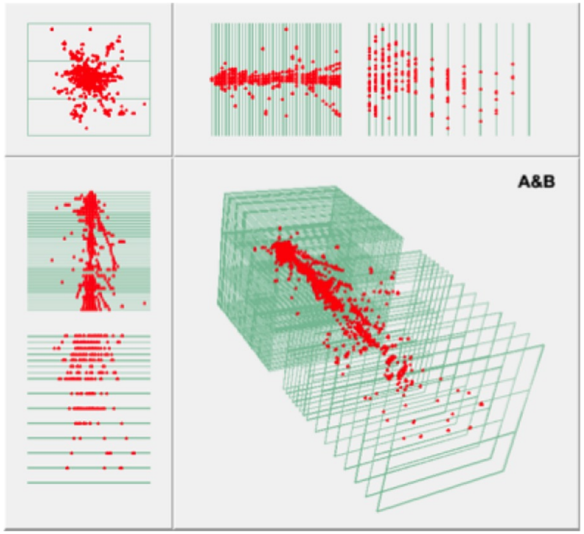
	analog	semi-digital	digital
granularity	3*3 cm^2	1*1 cm^2	1*1 cm^2
technology	scintillator tiles	RPCs (or µMegas)	RPCs (or GEMs)









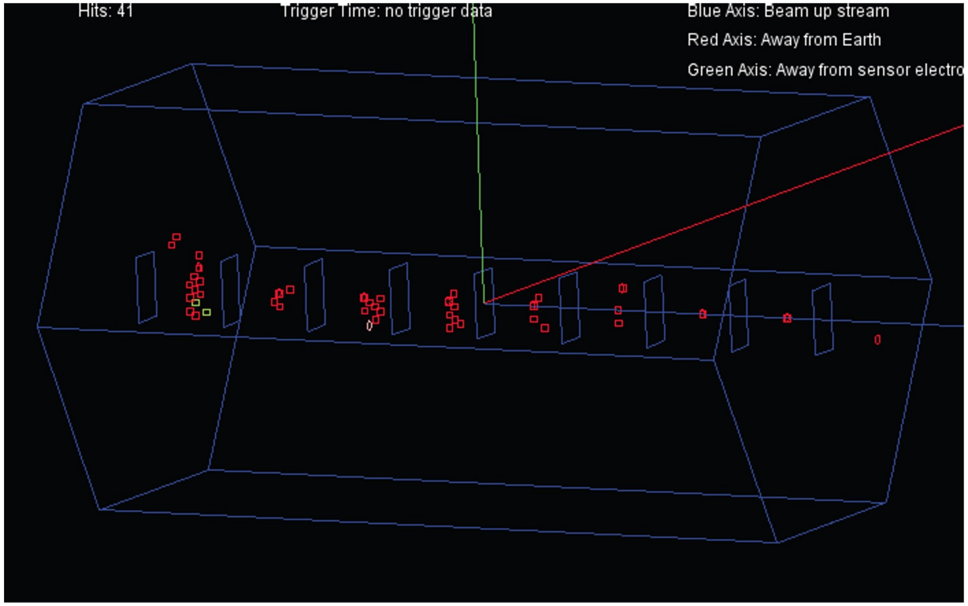


Measurements in Beam Tests

- In test beams you get only single particles, no jets
  ⇒ direct measurement of the jet energy resolution not possible
- Nevertheless, measurements in beam tests provide important information:
  - hands-on experience with (a small version of) the detector
  - calibration of the detector
  - energy resolution for single particles is one important ingredient in the jet energy resolution
  - comparison of hadron showers in data and simulation (Geant4)
    ⇒ studies of the substructure of showers
    ⇒ tests of the Particle Flow Algorithms with overlayed showers
    ⇒ realistic jet energy resolution in the simulation

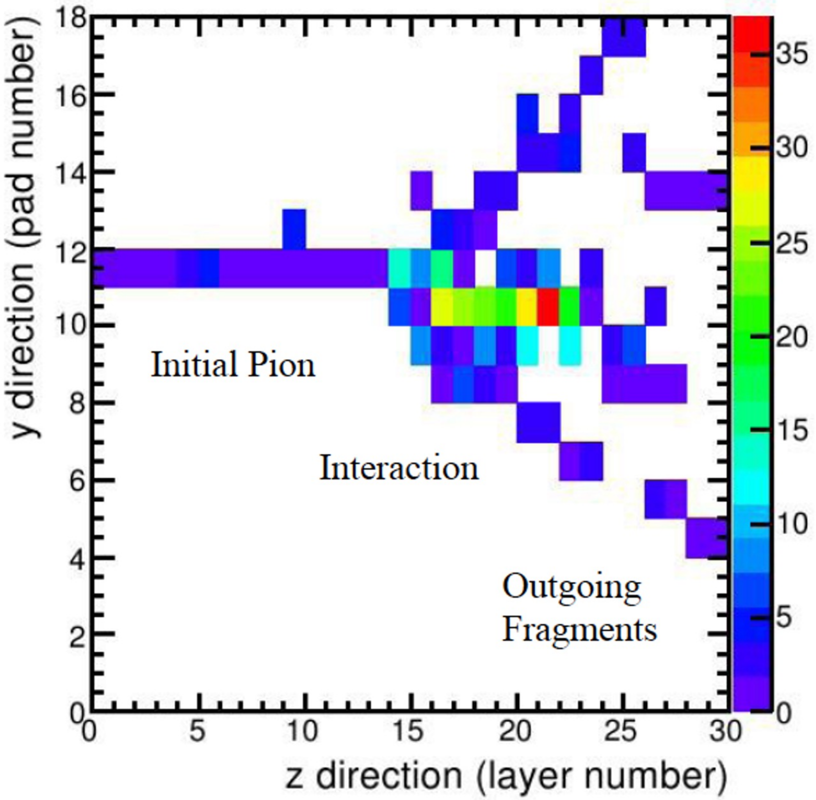
Disclaimer: the following results are a personal selection, many more measurements are available

Highly Granular ECALs

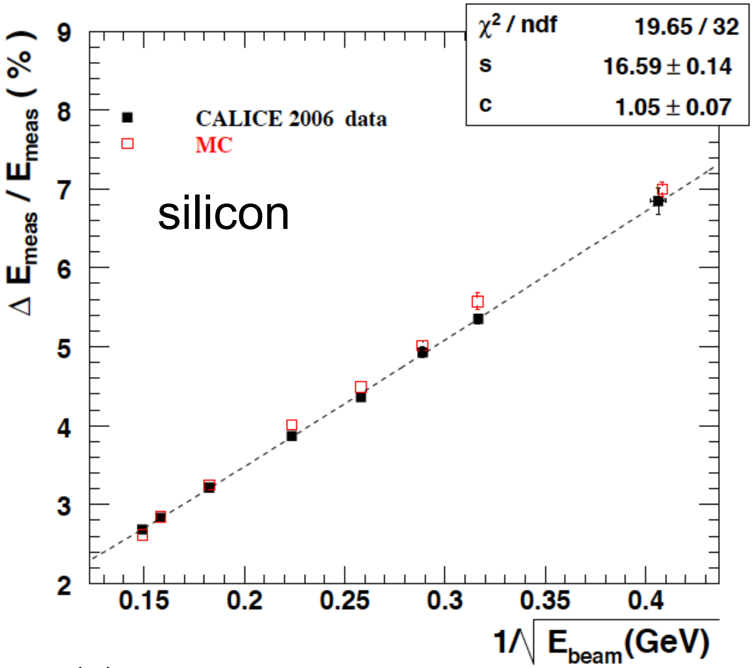


electron in silicon ECAL prototype with hexagonal sensors (6 X_0)

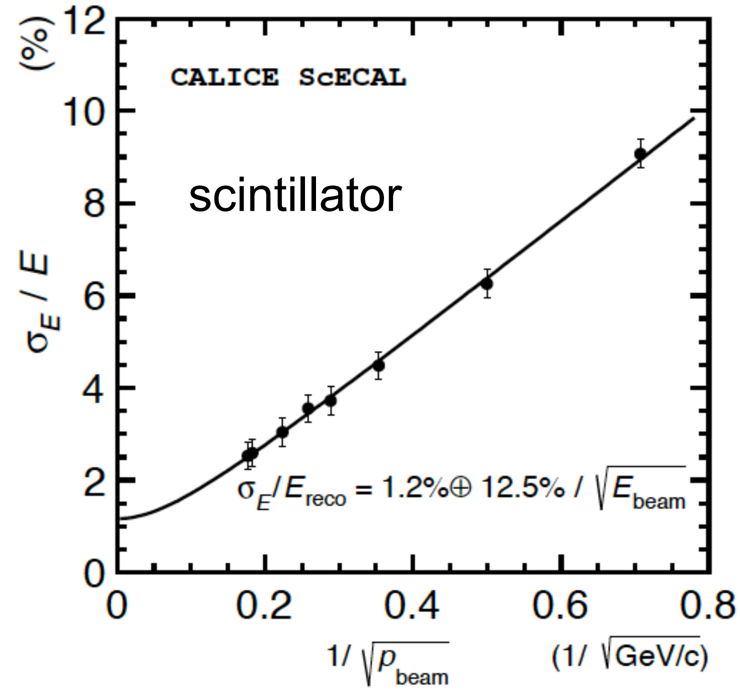
pion in silicon ECAL prototype with square sensors



ECAL resolutions

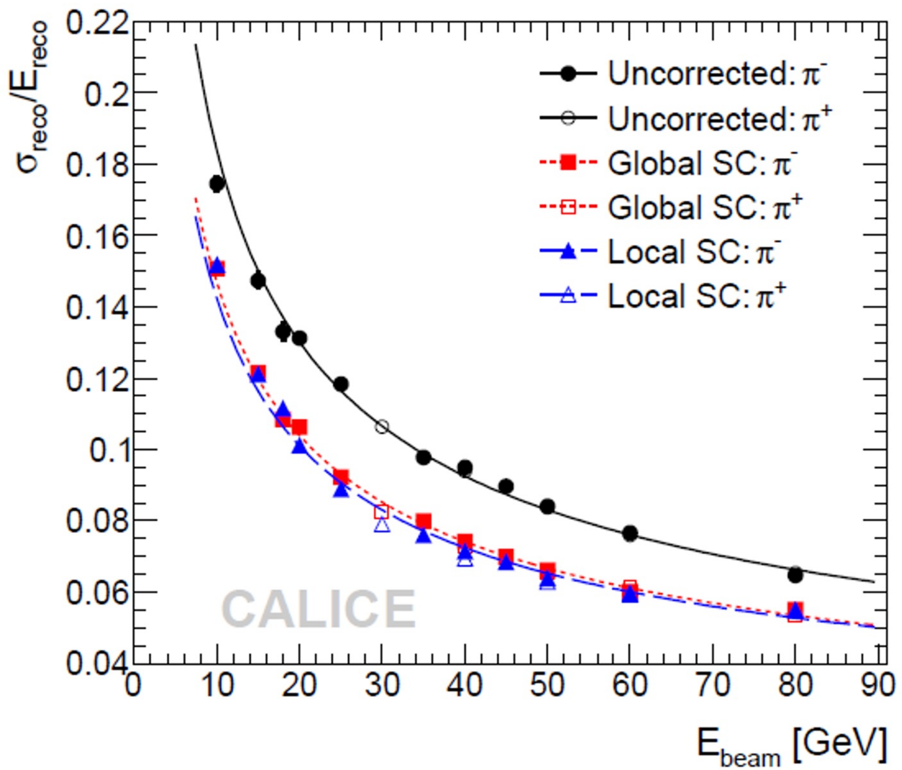


$$\frac{\sigma(E)}{E} = \frac{(16.6 \pm 0.1)\ \%}{\sqrt{E}} \oplus (1.1 \pm 0.1)\%$$



- reasonable energy resolution for electromagnetic showers (c.f. CMS ECAL: $3\%/\sqrt{E} \oplus 0.2/E \oplus 0.3\%$, ATLAS ECAL: $10\%/\sqrt{E} \oplus 0.2/E \oplus 0.2\%$)
- these ECALs are optimised for granularity, not single particle energy resolution

Energy Resolution for Single Hadrons: AHCAL



- Software compensation (SC):
  - in the reconstruction, use different weights for electro-magnetic and hadronic sub-showers (see next slide)

- 45%/√E reachable for the stochastic term *a*, constant term *b* of 1.8%

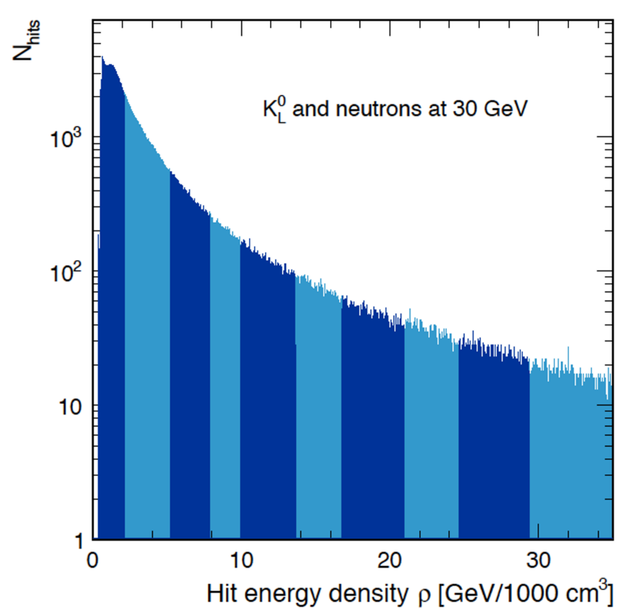
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

- Measurement of the energy resolution for charged pions at several beam energies with the AHCAL physics prototype

Software Compensation: Procedure

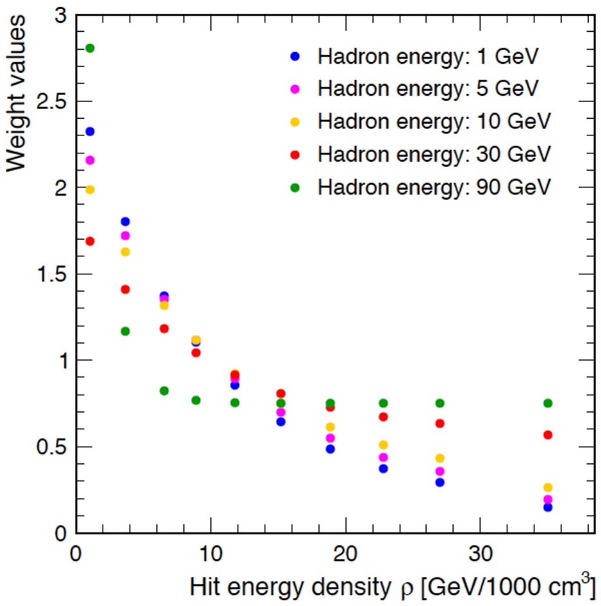
- “identify” the parts of the shower by their energy density
  - high energy-density (ρ) hits with EM sub-shower
  - low energy-density hits with hadronic shower component
- weight:
  - decrease weight for EM hits
  - increase weight for hadronic hits
  - weights depend on cluster energy, use simple energy sum as estimator (no prior knowledge from beam information)

$$E_{SC} = \sum_{\text{hits}} E_{ECAL} + \sum_{\text{bin } i} (E^i_{HCAL} \times \omega(\rho_i))$$



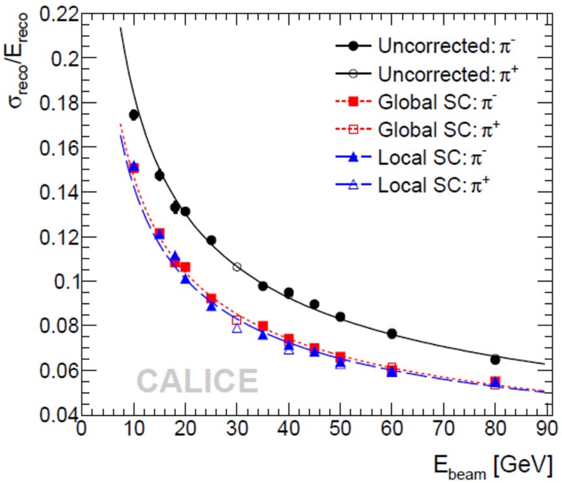
hadronic

EM



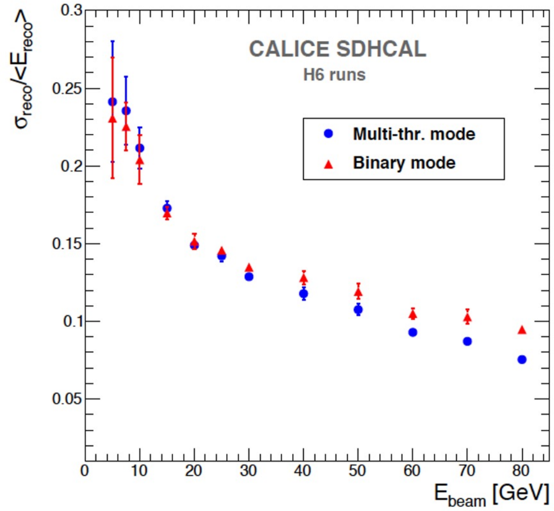
Energy Resolution for Single Hadrons: Comparison

AHCAL



software compensation improves stochastic term:
58%/√E → 45%/√E

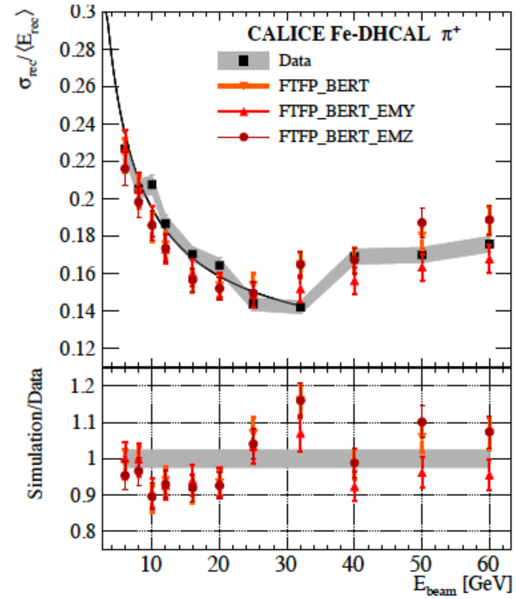
SDHCAL



measurement with
1 or **3** thresholds

3 thresholds improve resolution at large energies

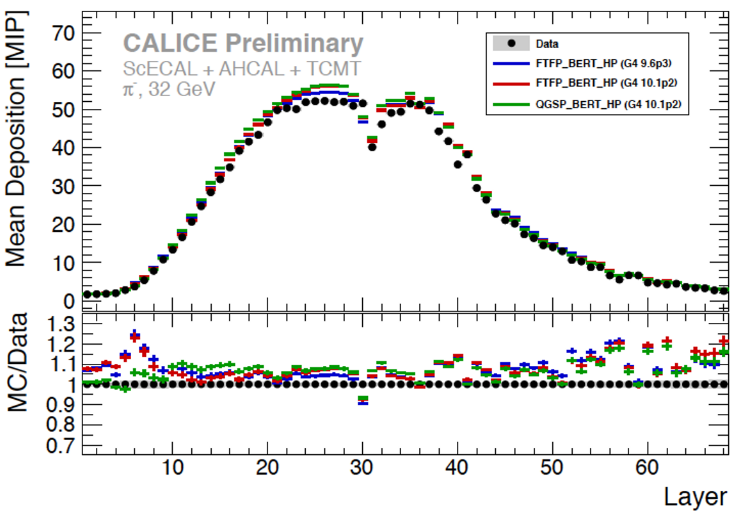
DHCAL



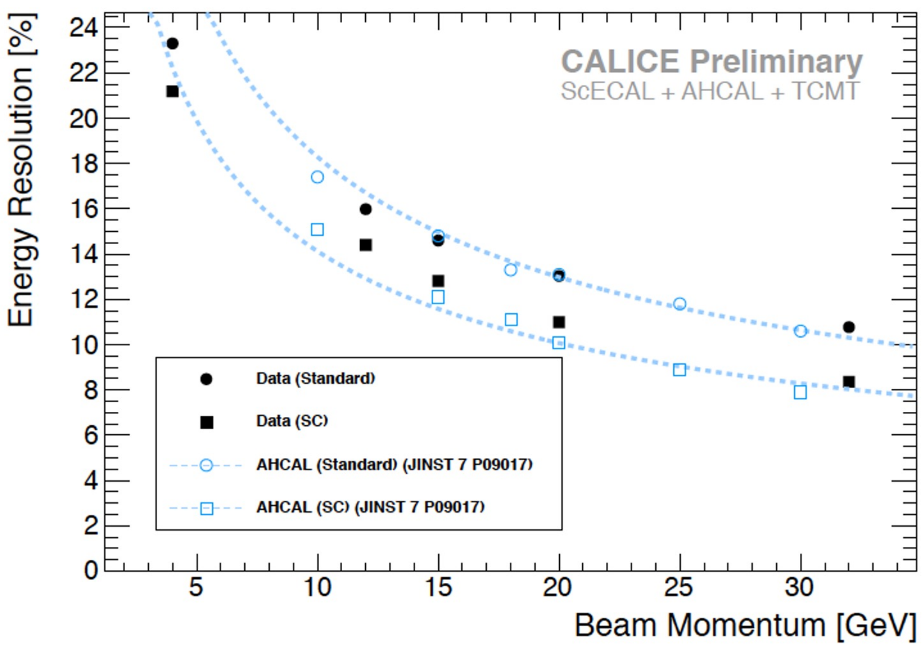
resolution degrades at large energies

Performance of a combined 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
- not obvious that combined system is as good as HCAL alone (actually for ATLAS it's significantly worse)

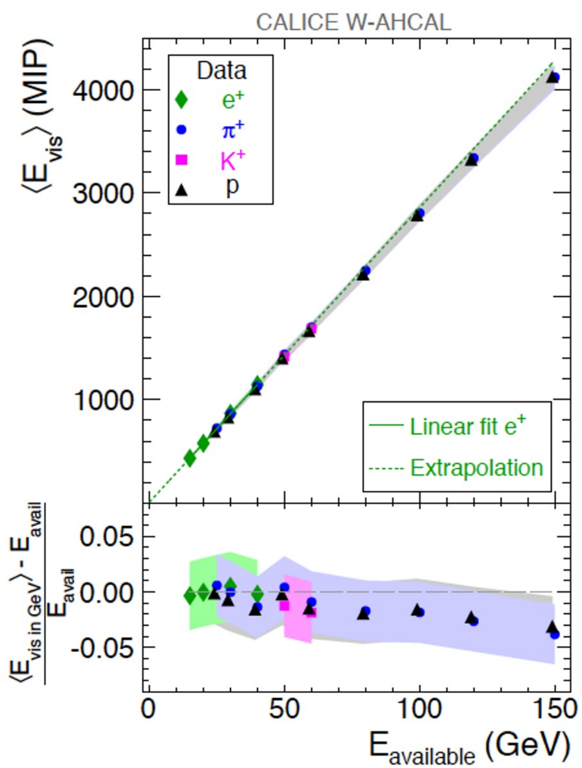


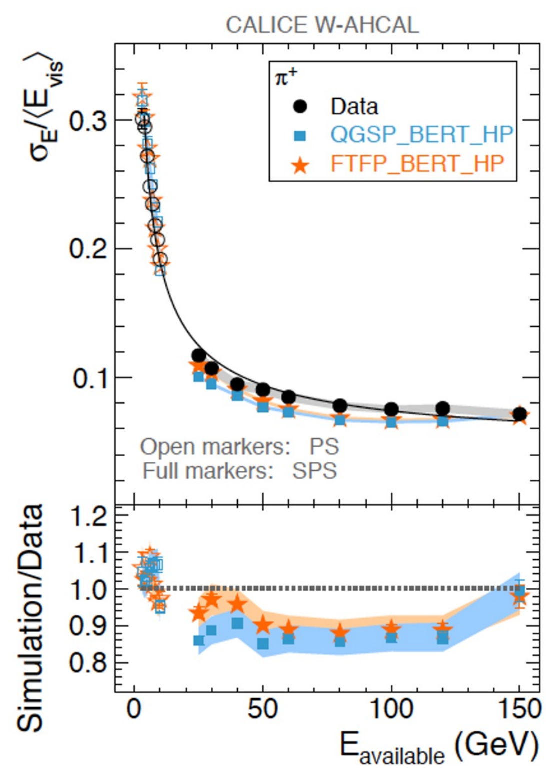
SciECAL AHCAL



Tungsten as HCAL Absorber

- tungsten absorber in HCAL allows for more compact HCAL
- study the impact of tungsten as absorber material in AHCAL

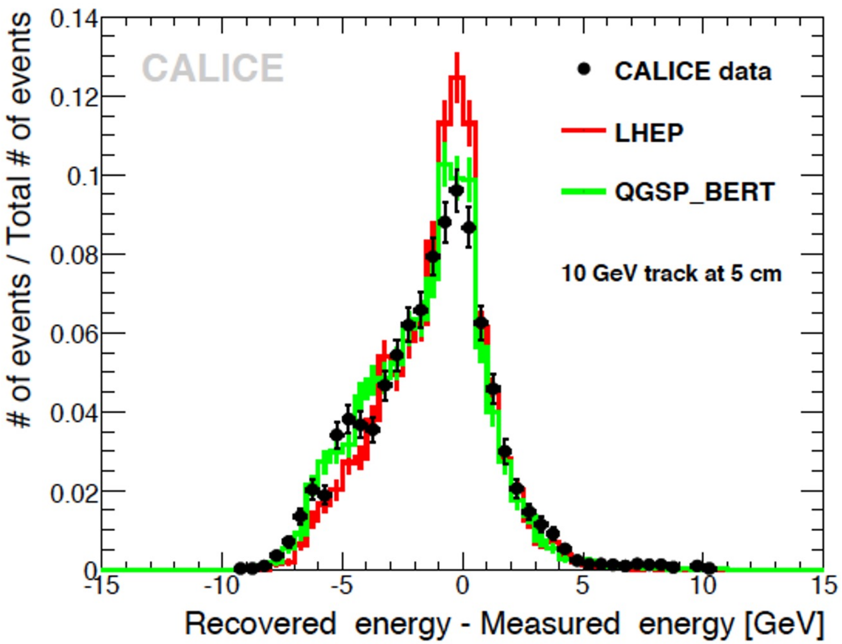


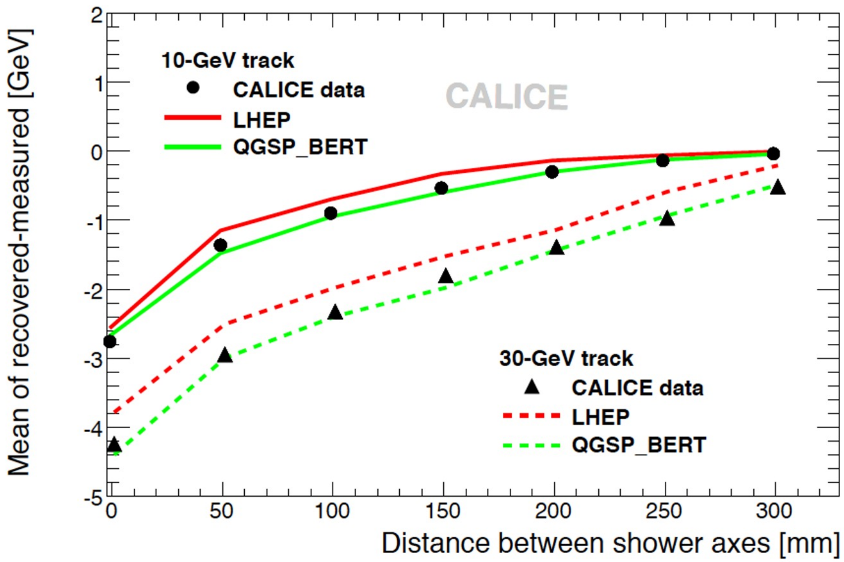


- nearly compensating at ~20-50 GeV for the used tungsten thickness
- resolution similar to iron absorber

Particle Flow Validation

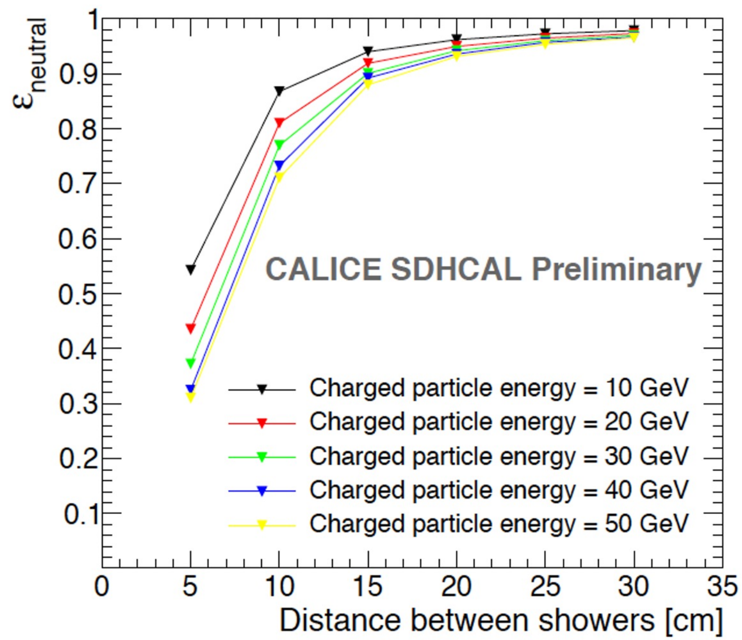
- for a direct test of the Particle Flow Algorithm a jet in a full detector slice (tracking, ECAL, HCAL, tailcatcher) with B field is needed
- beam test were done with ECAL, HCAL, tailcatcher without B field
- map measured AHCAL test beam showers onto ILD geometry, test distributions most relevant to PFA: shower separation of a “neutral” hadron of 10 GeV and a charged hadron of 10 or 30 GeV
- good description by modern physics list

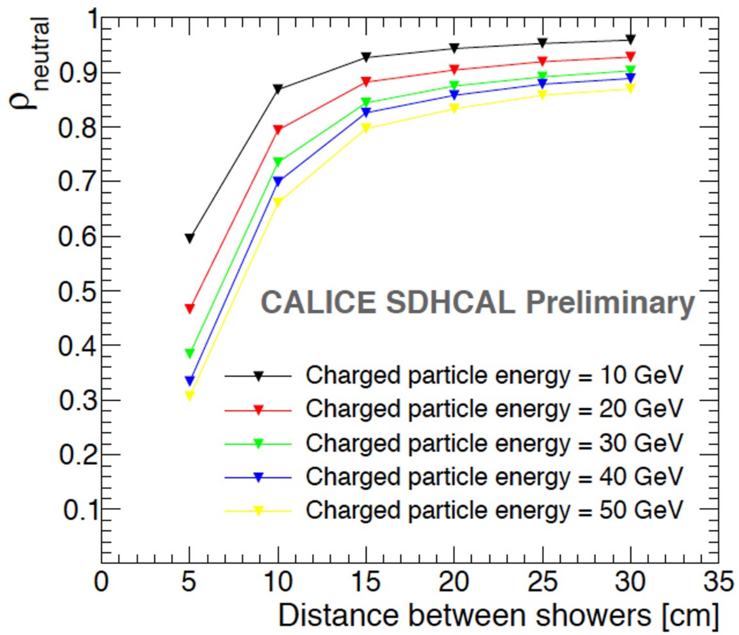




Particle Flow Validation: ARBOR

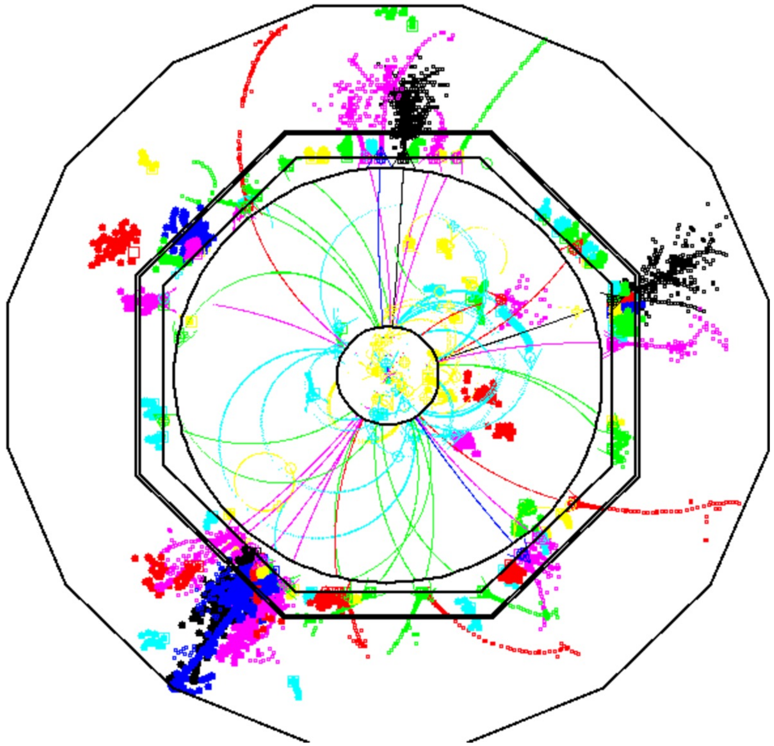
- ArborPFA:
  - particle flow algorithm using the tree-like structure of showers
  - energy information used in finalising clustering and track association
- test of cluster separation with SDHCAL pion shower data
  - overlay of 2 pion events: 10 GeV “neutral” particle (initial track segment removed) 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



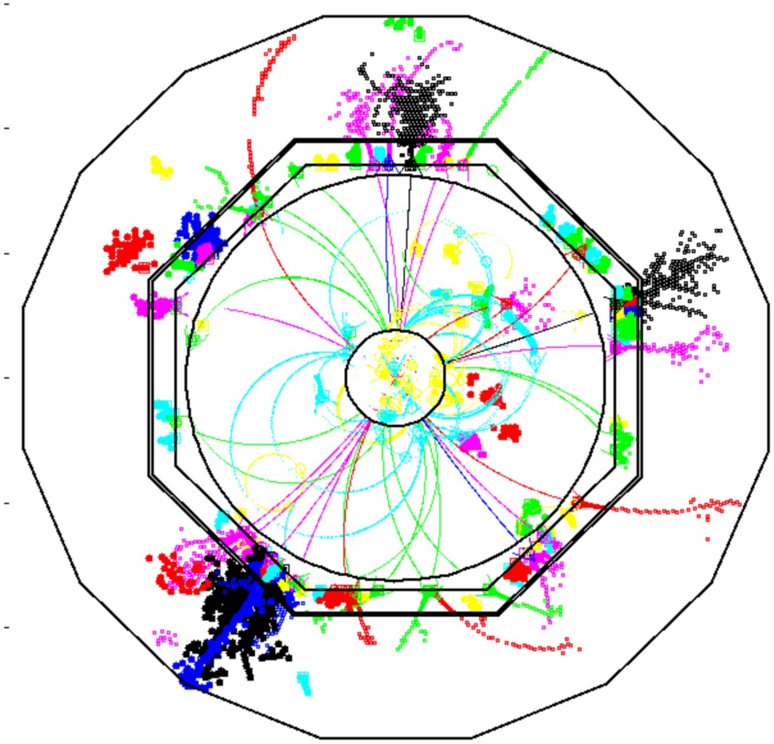


How small should the cells be?

1*1 cm^2 HCAL cell size

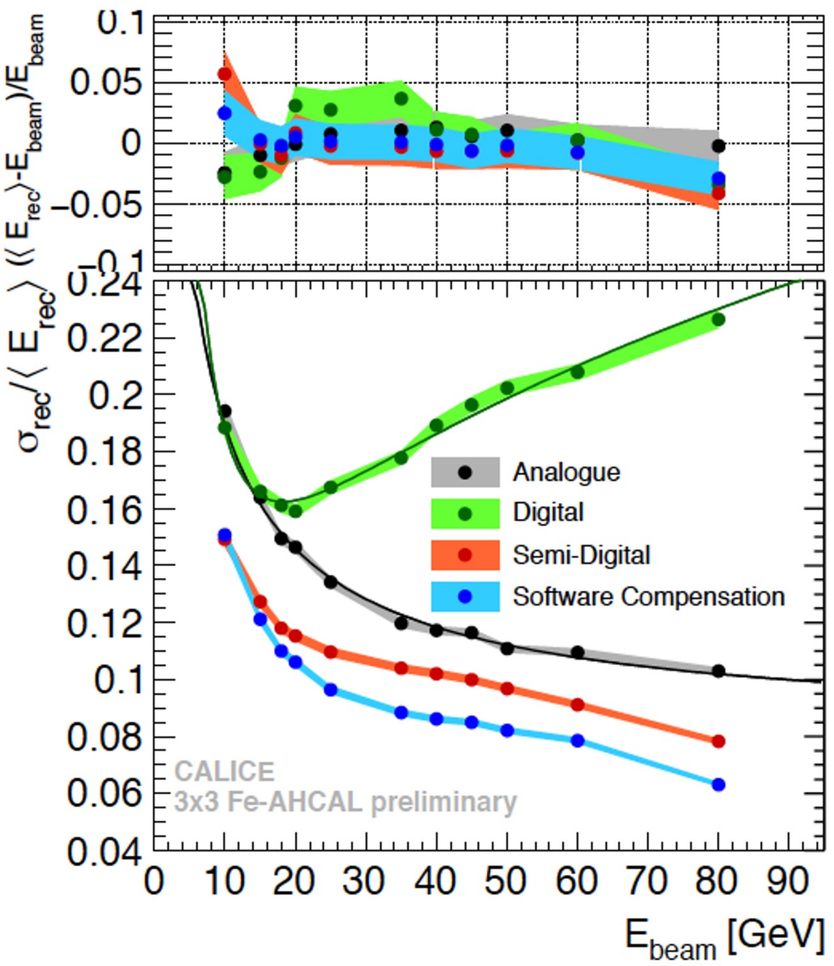


3*3 cm^2 HCAL cell size



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



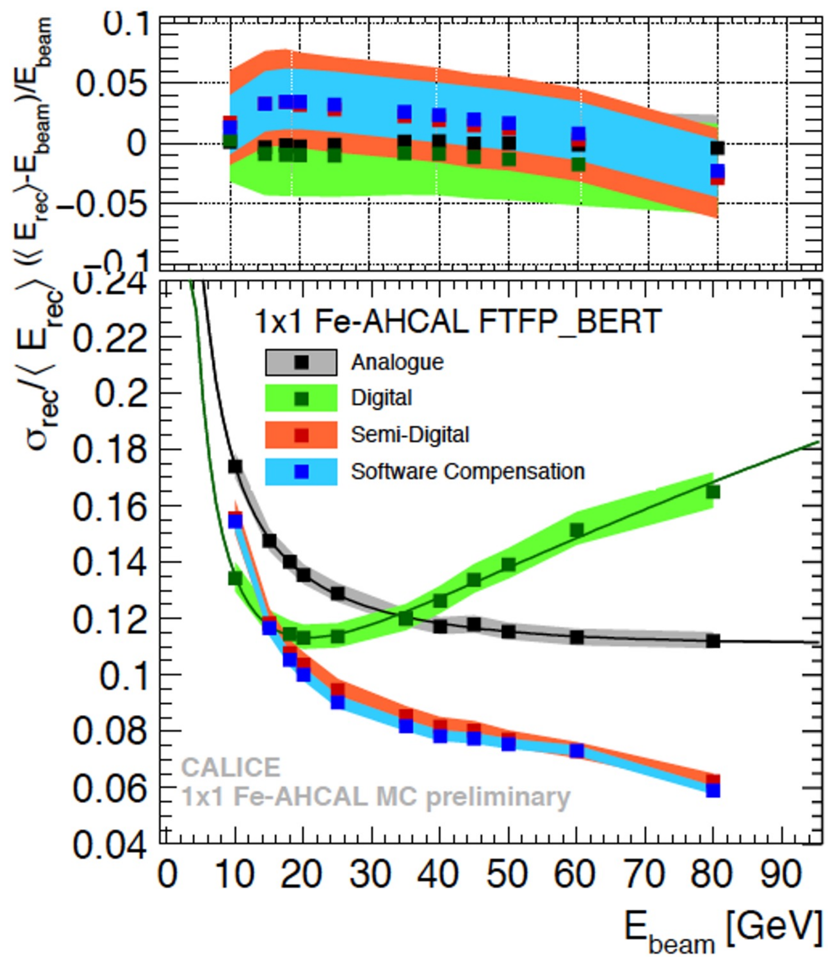
Cell size vs. Reconstruction Algorithm

> 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**



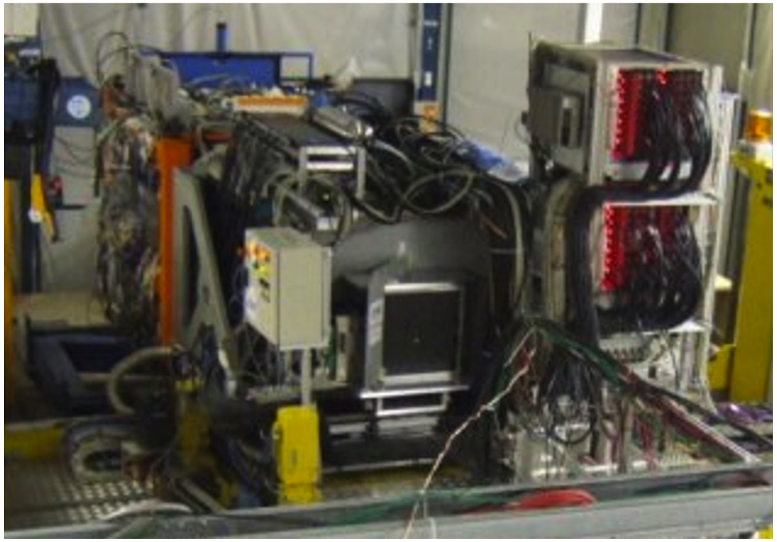
Engineering Prototypes

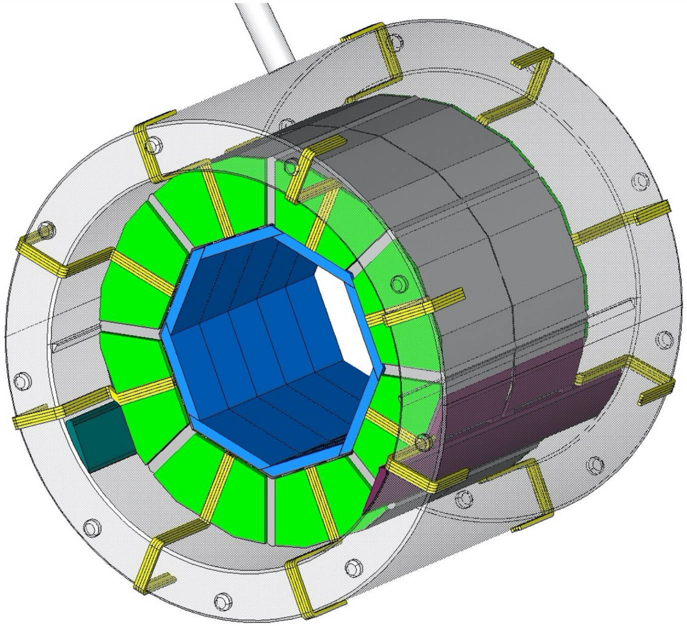
From physics prototypes to engineering prototypes

- capabilities of a highly granular calorimeters successfully demonstrated with the "physics prototypes"

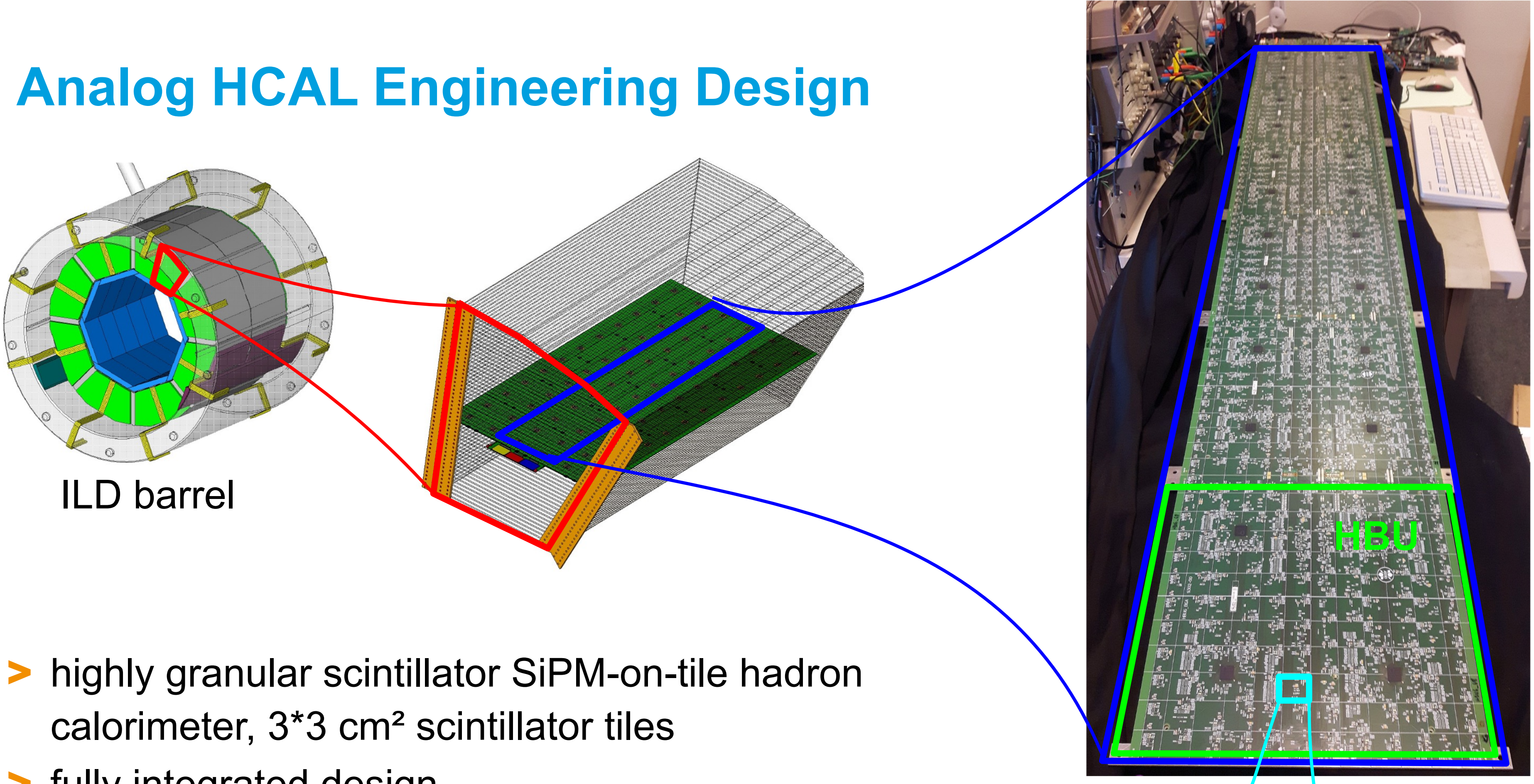
- but these were designed for beam tests, not really scalable to a collider detector

- goal for the "engineering prototype": develop, build and test a prototype scalable to the full collider detector layout
  - integration of electronics into layers
  - realistic infrastructure
  - easy mass assembly

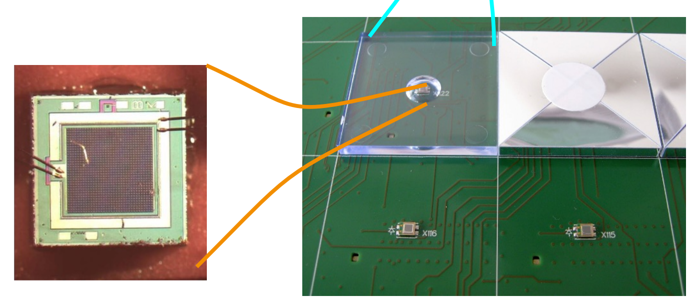




Analog HCAL Engineering Design



- highly granular scintillator SiPM-on-tile hadron calorimeter, 3*3 cm² scintillator tiles
- fully integrated design
  - front-end electronics, readout
  - voltage supply, LED system for calibration
  - no cooling within active layers
- scalable to full detector (~8 million channels)

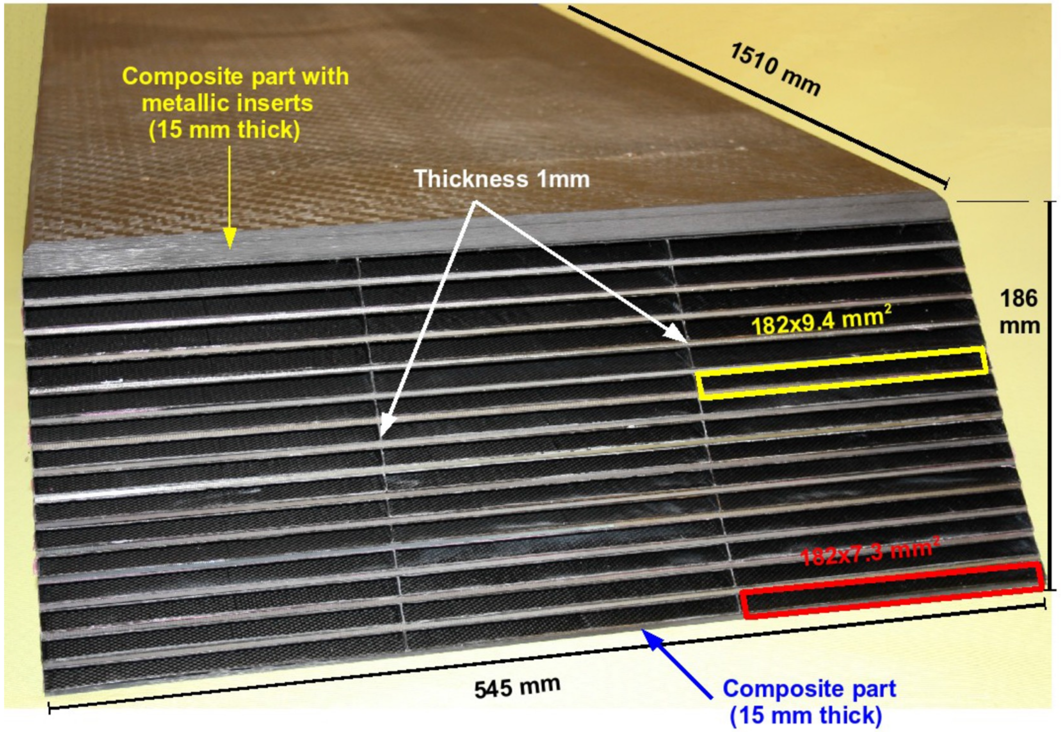


Silicon ECAL Engineering Prototype

- challenge: very compact structure with tungsten absorber
- alveolar structure: carbon fibre structure to hold the tungsten plates
- very thin gaps in absorber:
  - readout ASICs integrated in PCB

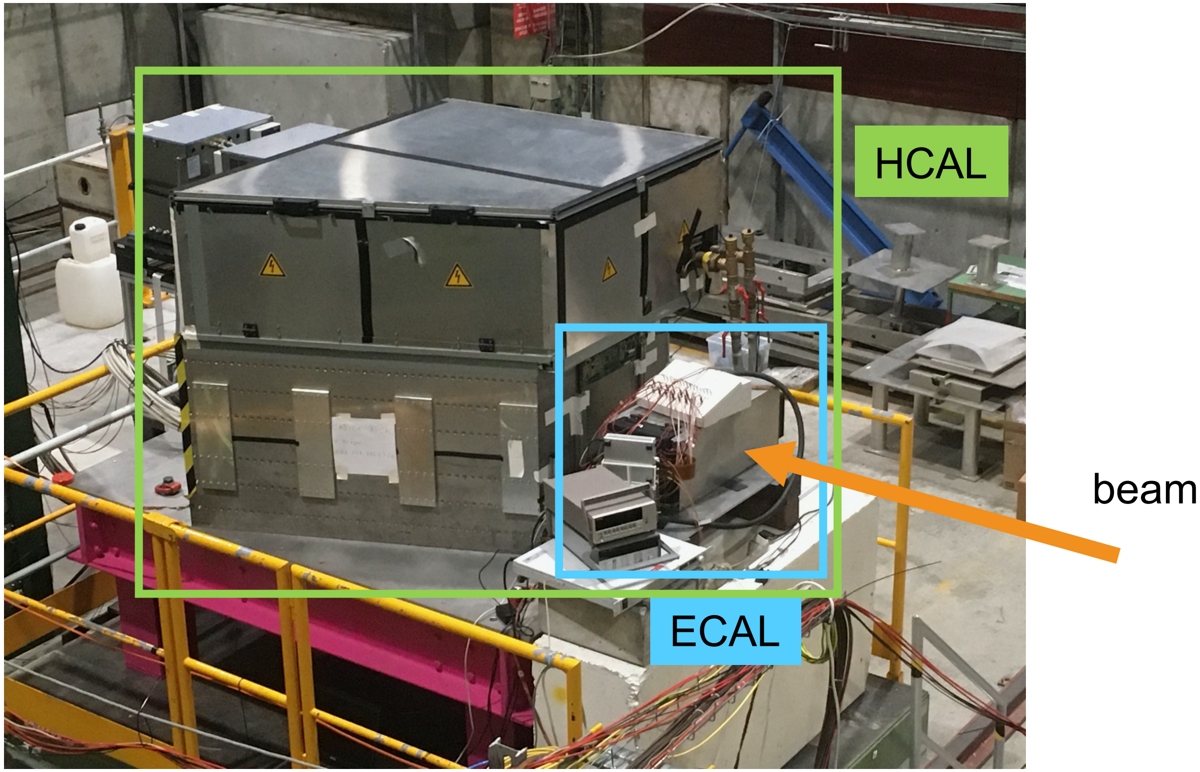
  or

  - readout ASICs directly connected to thin cables



Silicon ECAL + Analog HCAL in Testbeam

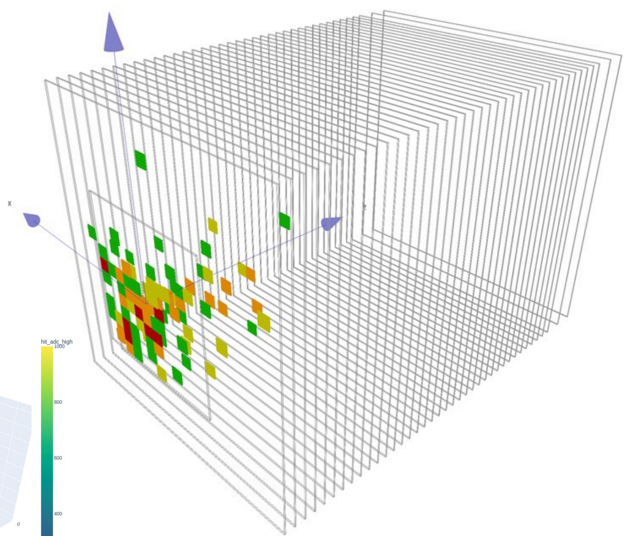
- Have just finished 2 weeks of testbeam at the CERN SPS with combined silicon ECAL + analog HCAL engineering prototypes



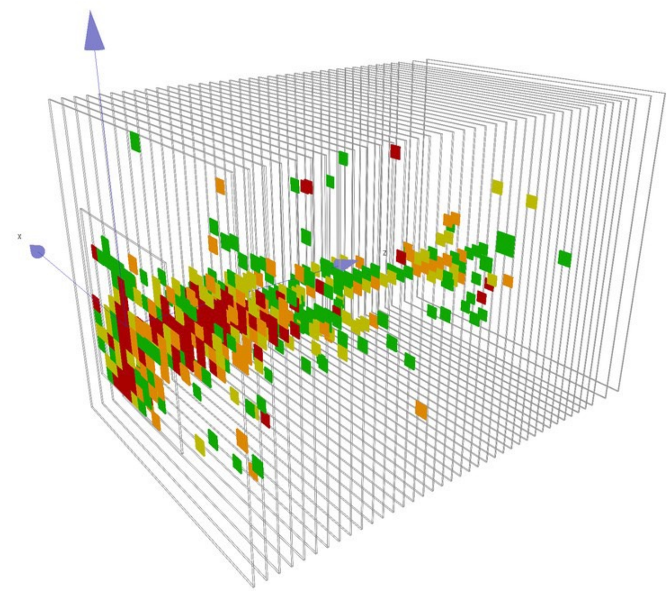
Silicon ECAL + Analog HCAL in Testbeam

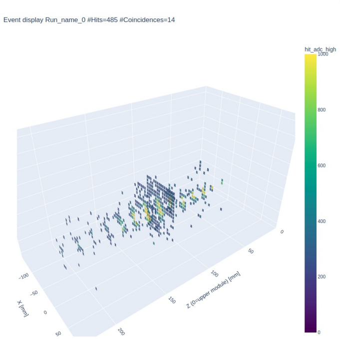
- Have just finished 2 weeks of testbeam at the CERN SPS with combined silicon ECAL + analog HCAL engineering prototypes

AHCAL: tail of an electron shower



AHCAL: pion shower, starting in ECAL



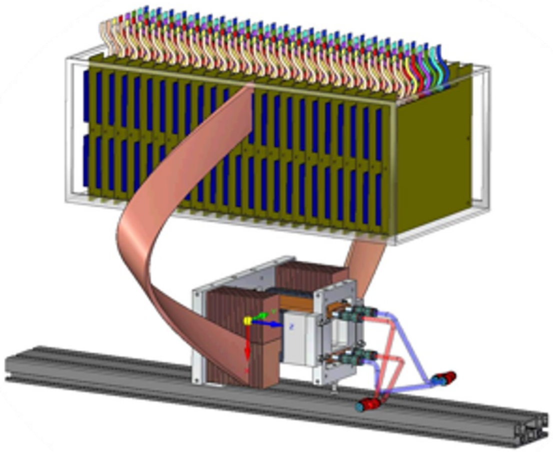


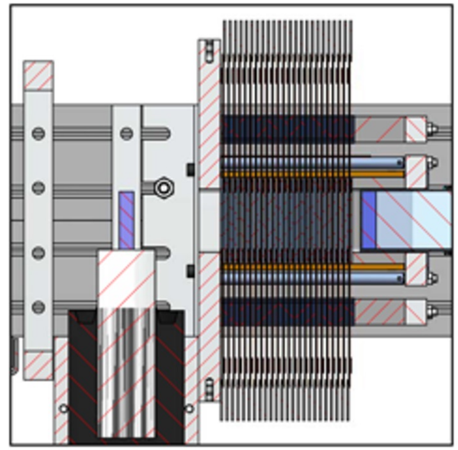
SiECAL: electron shower

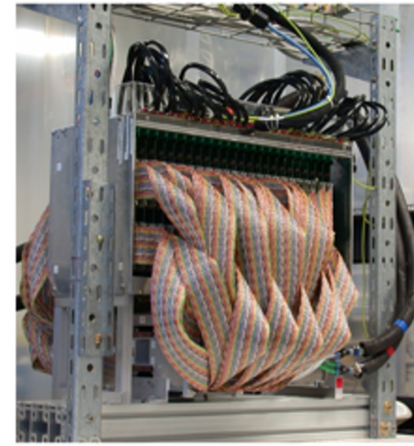
High Granularity beyond electron-positron colliders

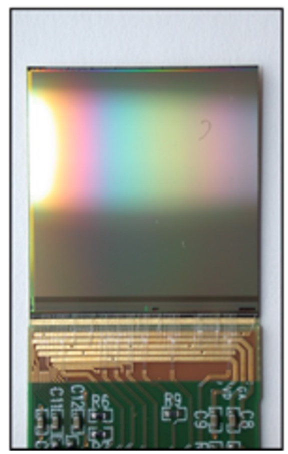
- recently also LHC detector collaborations adopted the idea of highly granular calorimeters
- granularity driven by pile-up mitigation, NOT particle flow

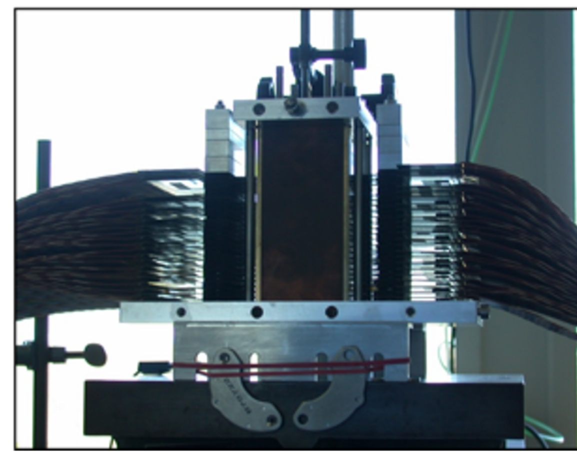
Digital ECAL: Pixel Calorimeter Prototype







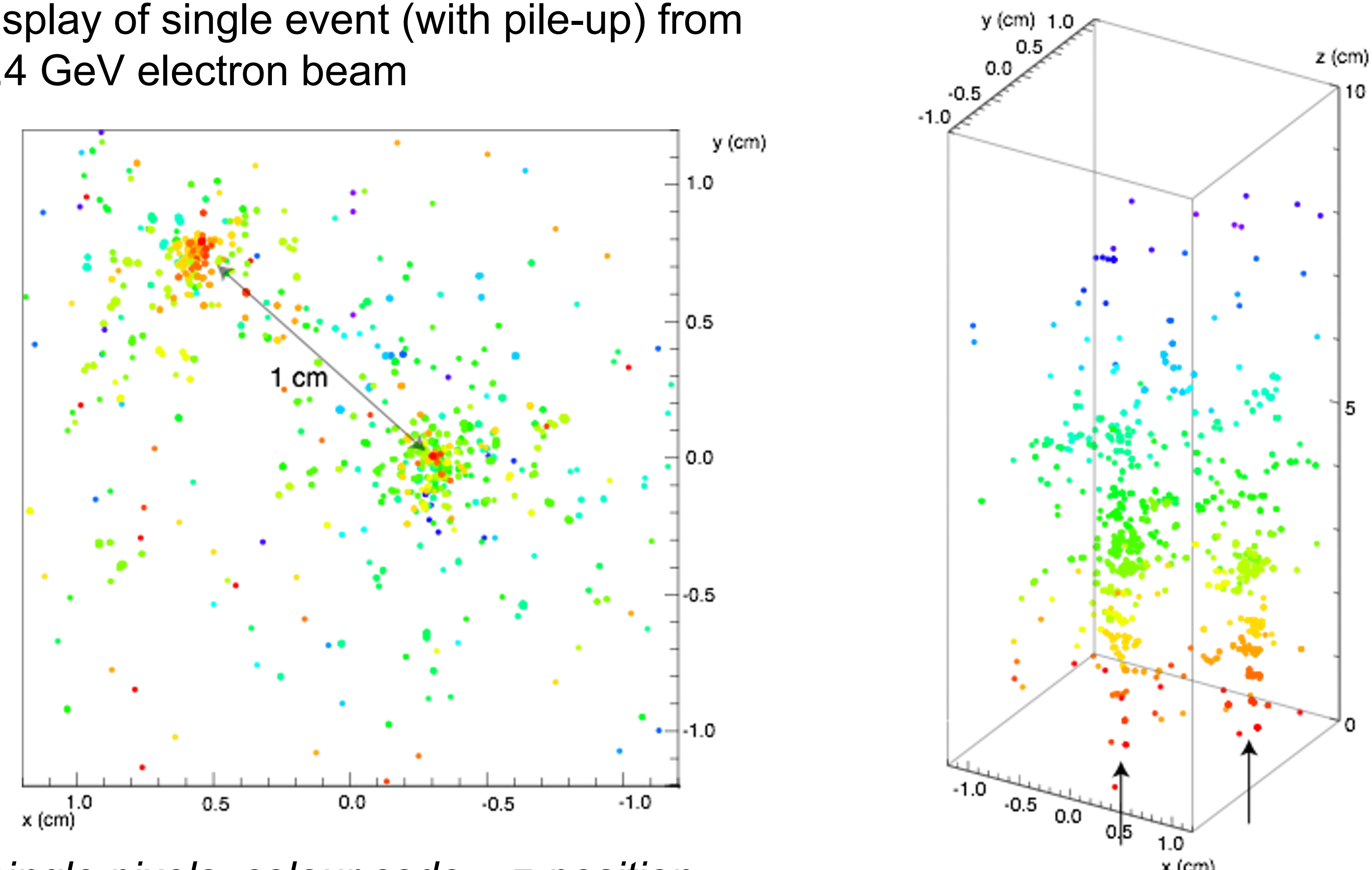




- R&D for ALICE FoCal upgrade
- full MAPS prototype, 24 layers
  - 3mm W
  - 1mm sensor layer
  - 120µm sensor (2x2 chips) + PCB, glue, air, …
- **39 M pixels in 4x4x10 cm^3 !**

Digital ECAL: Event Display

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

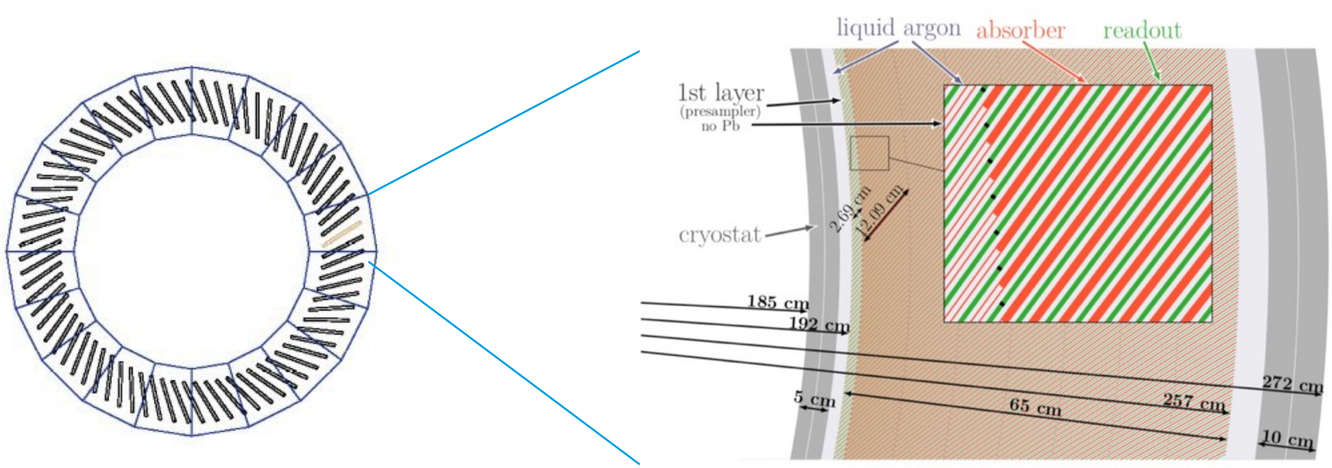


single pixels, colour code = z-position

FCC-hh: LAr with high(er) granularity

- Compared to ATLAS, FCC-hh Calo needs finer longitudinal and lateral granularity
  - Optimized for particle flow
  - 8 longitudinal compartments, fine lateral granularity
- Noble liquid (LAr) as active material
  - Radiation hardness, linearity, uniformity, stability
- EM Barrel: Absorbers 50° inclined with respect to radial direction
  - Sampling fraction changes with depth: ≈ 1/7 to 1/4
  - Longitudinal segmentation essential to be able to correct

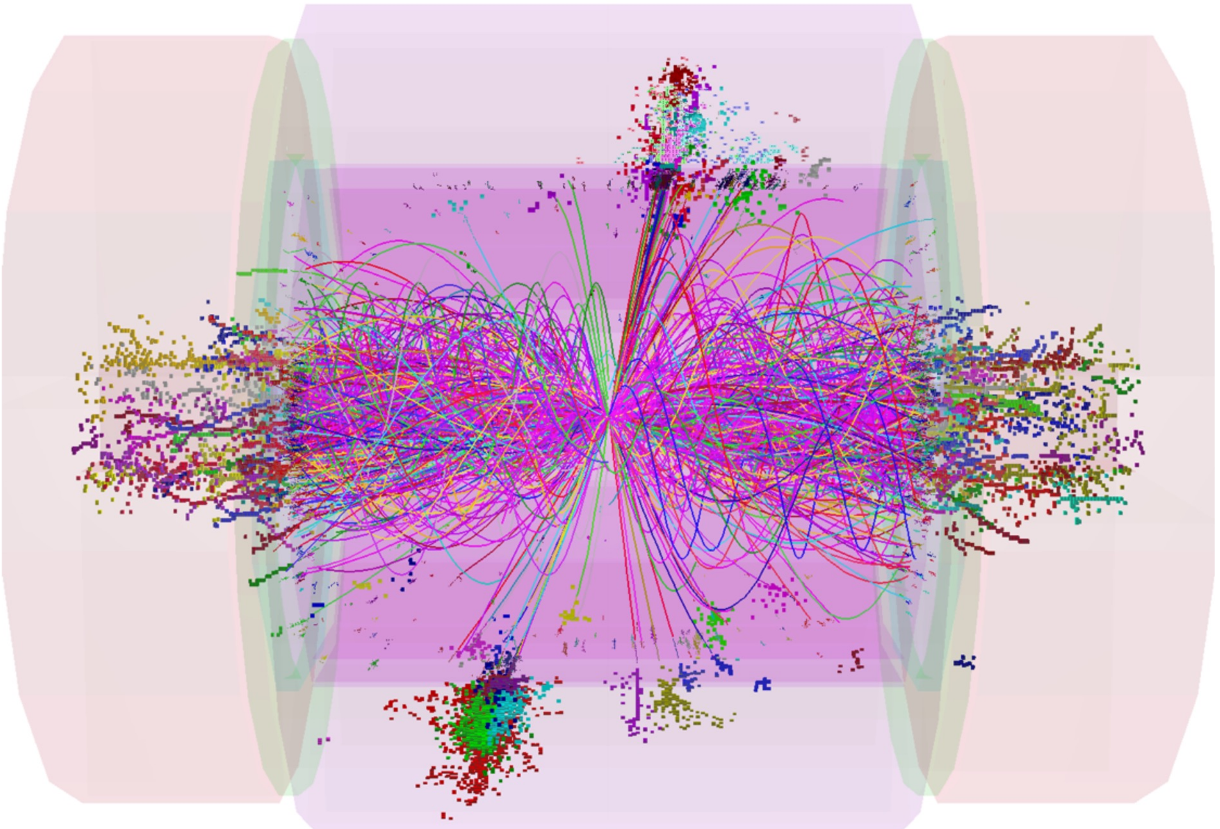
Electromagnetic calorimeter barrel



- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;

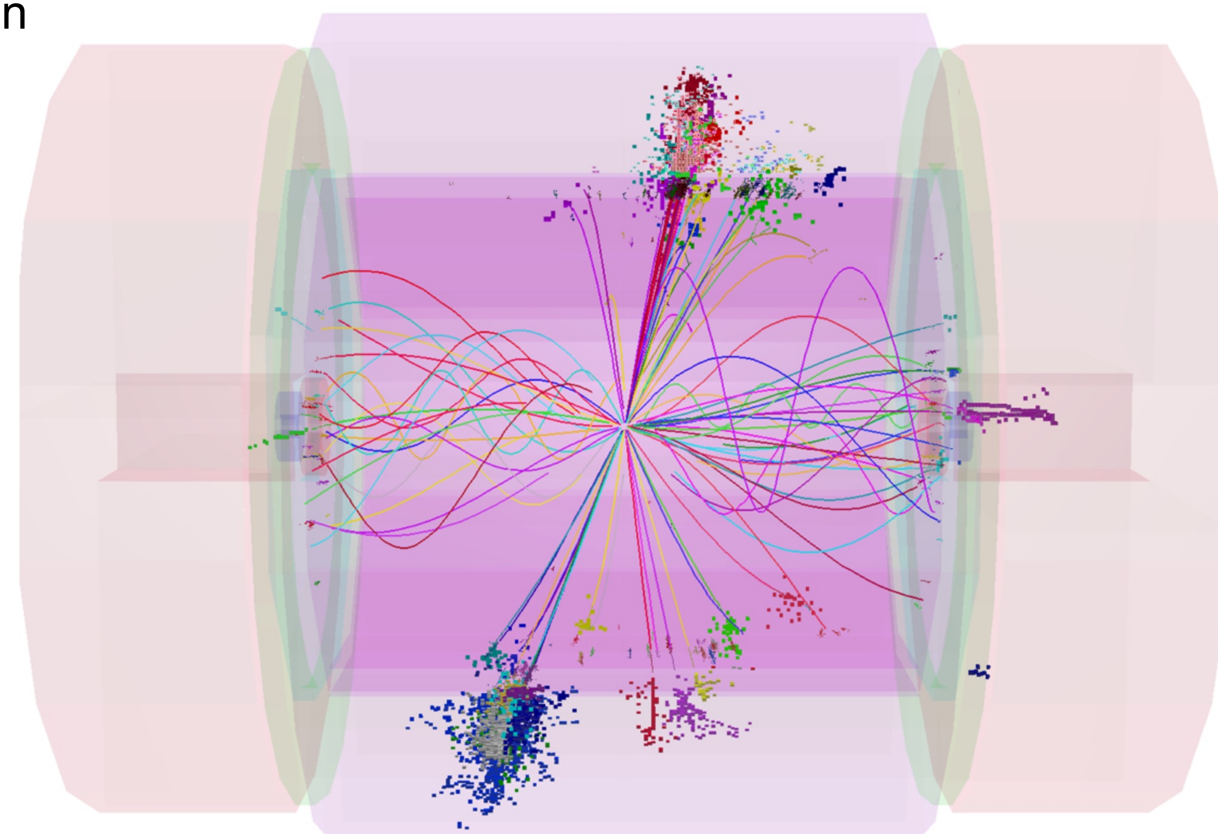
Granularity and Timing for Background (Pileup) Rejection

- CLIC: bunch trains with 0.5 ns bunch distance
  - simulated event $\sqrt{s}=1$ TeV with 60 bunch crossings overlay



Granularity and Timing for Background (Pileup) Rejection

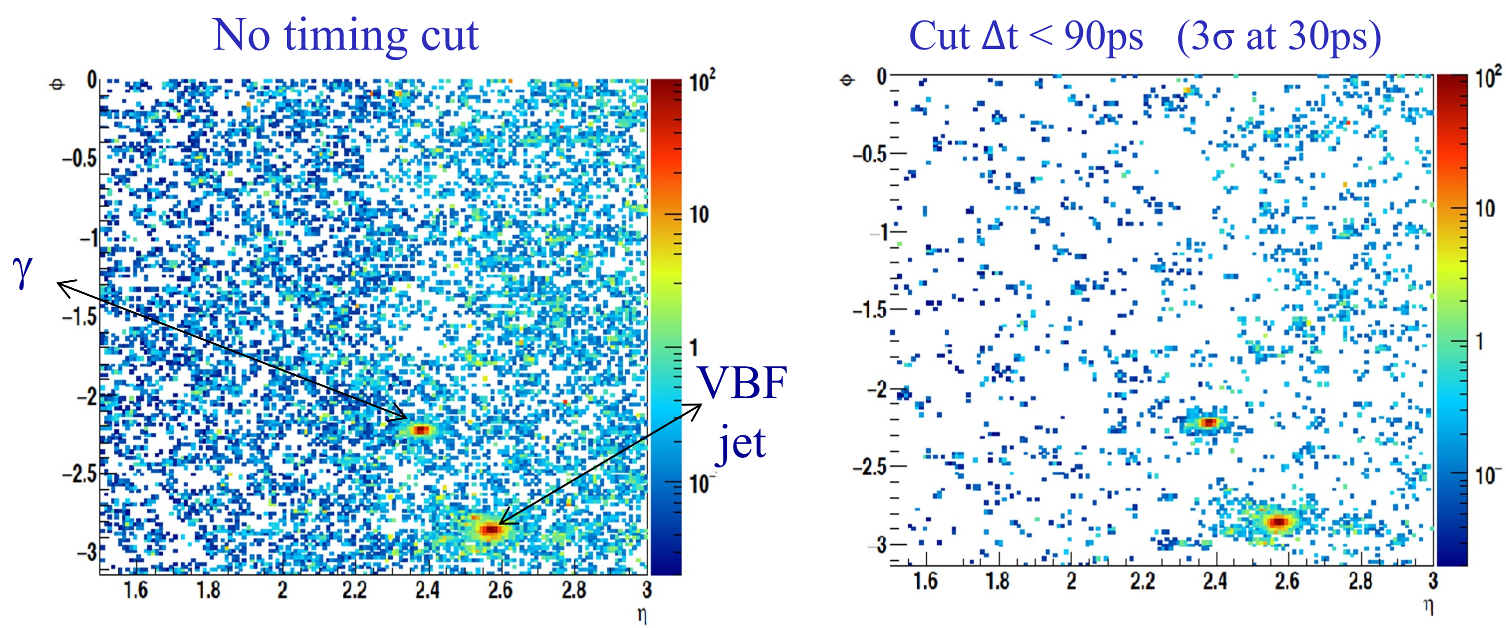
- CLIC: bunch trains with 0.5 ns bunch distance
  - simulated event $\sqrt{s}$=1 TeV with 60 bunch crossings overlay after tight timing selection



- Together with good time resolution, granularity enables efficient pileup rejection

Granularity and Timing for Background (Pileup) Rejection

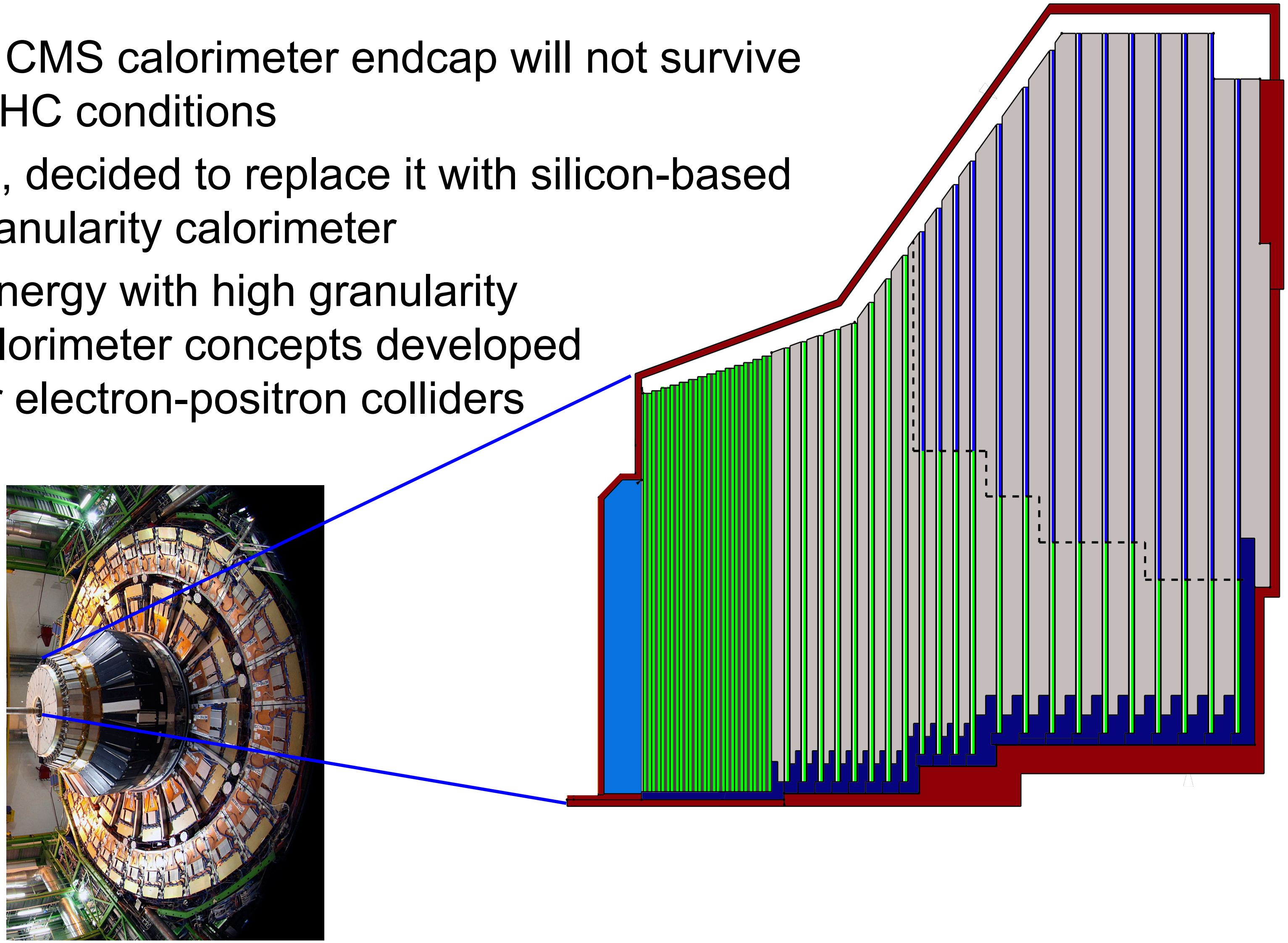
- CMS: expect up to 200 pileup events at HL-LHC
  - VBF (H→gg) event with one photon and one VBF jet in the same quadrant



Plots show cells with Q > 12fC (~3.5 MIPs @300µm - threshold for timing measurement) projected to the front face of the endcap calorimeter.
Concept: identify high-energy clusters, then make timing cut to retain hits of interest

CMS High Granularity Calorimeter Endcap Upgrade

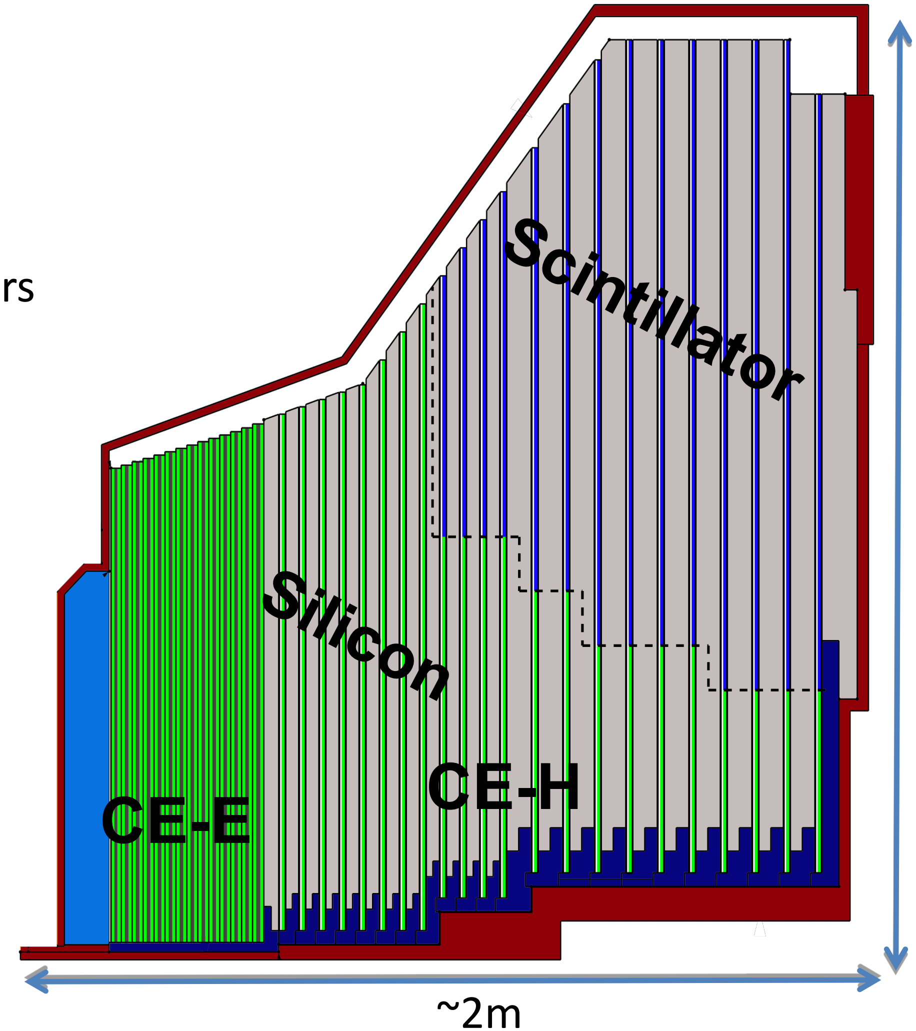
- current CMS calorimeter endcap will not survive in HL-LHC conditions
- in 2015, decided to replace it with silicon-based high-granularity calorimeter
  - synergy with high granularity calorimeter concepts developed for electron-positron colliders



CMS High Granularity CALorimeter

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H



Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
Full system maintained at -30°C
~620m² Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm² cell size
~400m² of scintillators in ~4000 boards
~240k scint. channels, 4-30cm² cell size

Electromagn. calo (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calo (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8.5λ

CMS High Granularity CALorimeter

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- “Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
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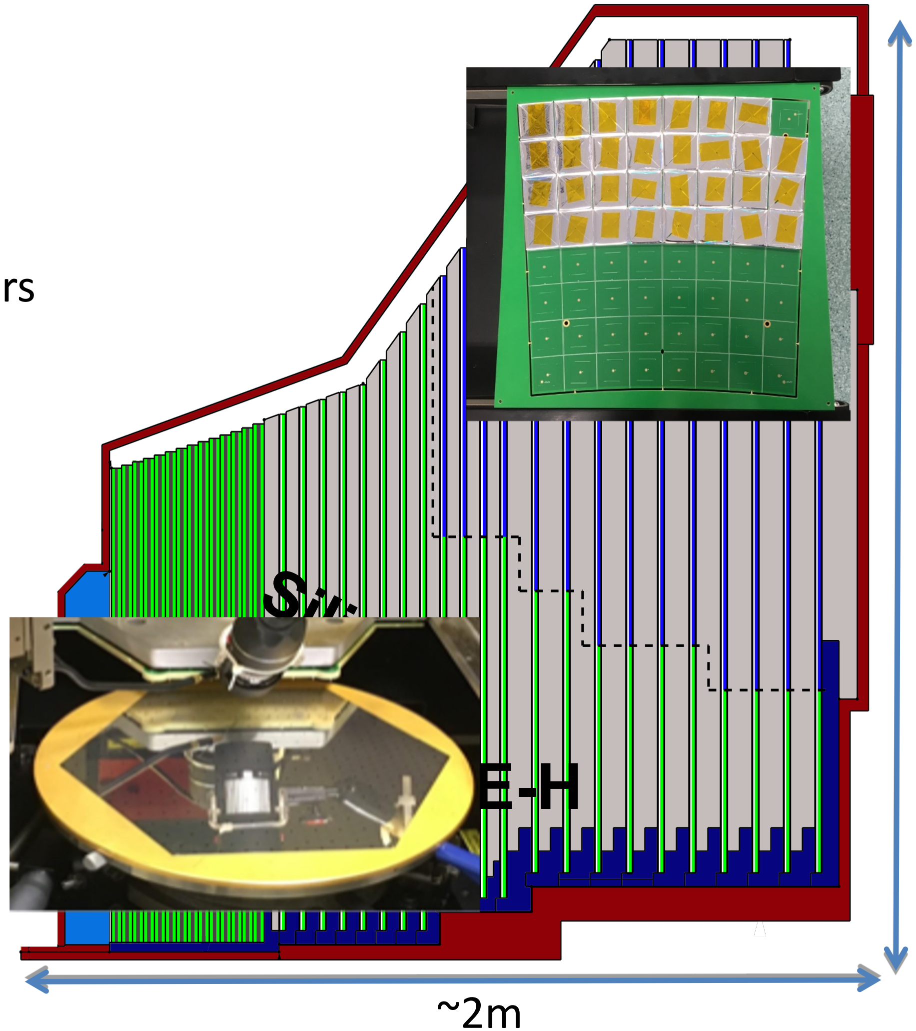
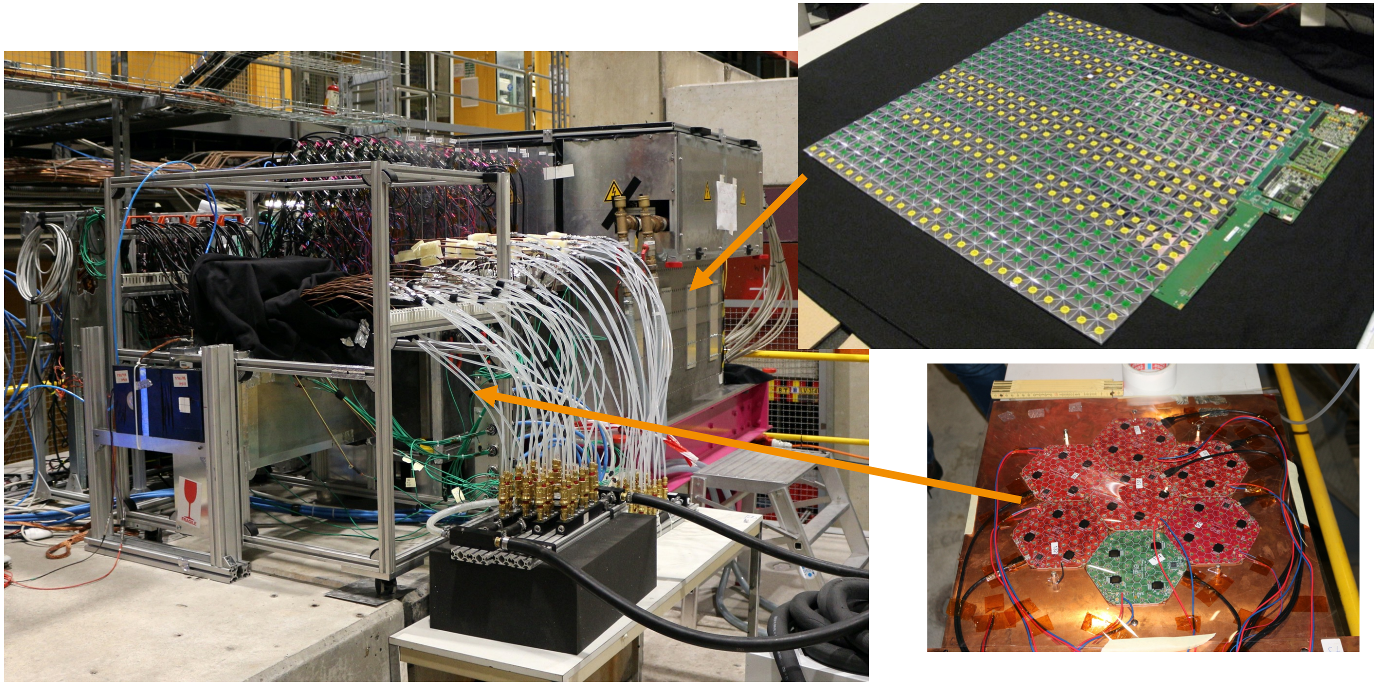


Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
Full system maintained at -30°C
~620m² Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm² cell size
~400m² of scintillators in ~4000 boards
~240k scint. channels, 4-30cm² cell size

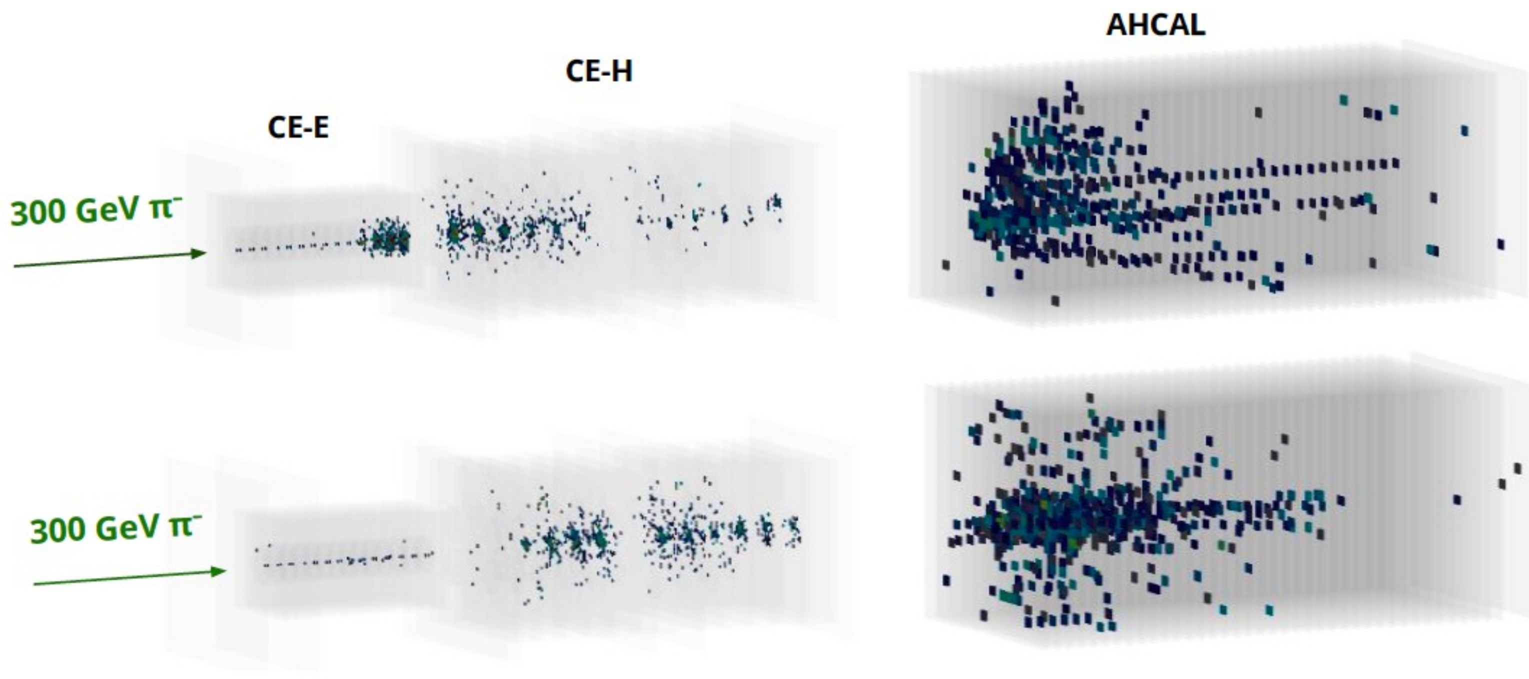
Electromagn. calo (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calo (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8.5λ

Common Running of AHCAL & HGCAL silicon prototype



- In October 2018, collected hadron data with HGCAL silicon module prototypes and the AHCAL prototype
  - 28 layers HGCAL EE (silicon/lead), 12 layers HGCAL FH (silicon/steel), 39 layers AHCAL (scintillator/steel)

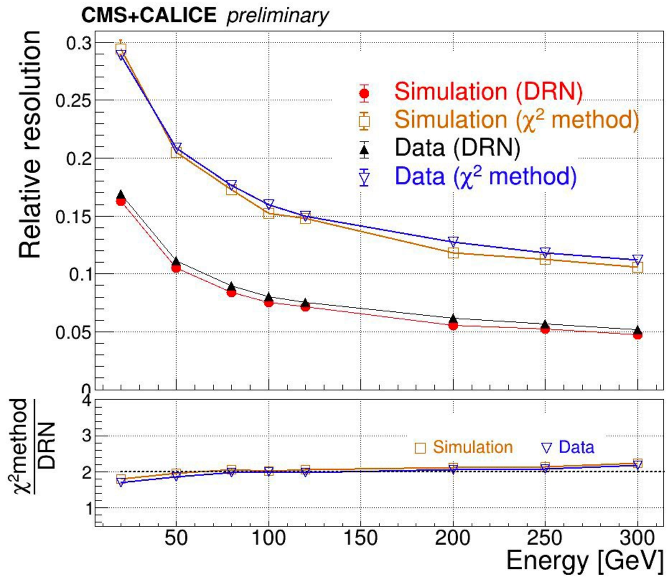
Common Running of AHCAL & HGCAL silicon prototype

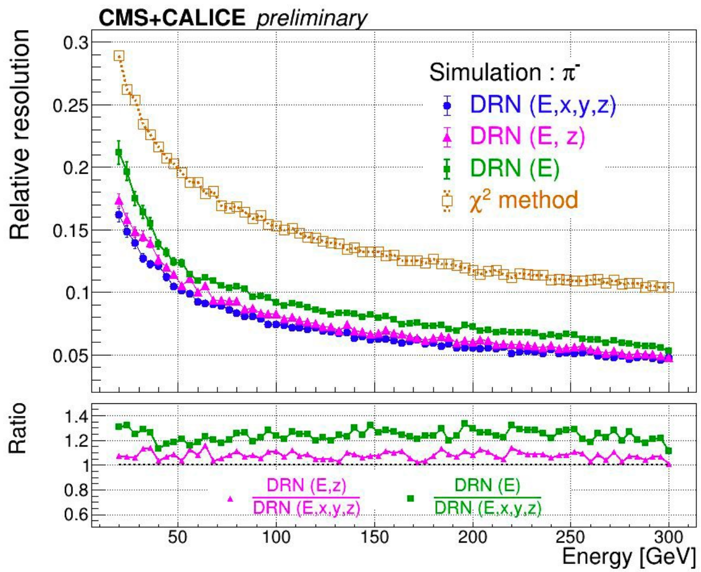


- In October 2018, collected hadron data with HGCAL silicon module prototypes and the AHCAL prototype
  - 28 layers HGCAL EE (silicon/lead), 12 layers HGCAL FH (silicon/steel), 39 layers AHCAL (scintillator/steel)

HGCAL prototype: GNN reconstruction

- High granularity allows sophisticated reconstruction algorithms
  - Physicist's knowledge: software compensation
  - Machine learning: train a Graph Neural Network
    - With hit energies alone (E) already better than "classical" energy sum
    - Adding position information (E,z) and (E,x,y,z) even better
      - Can also correct for leakage



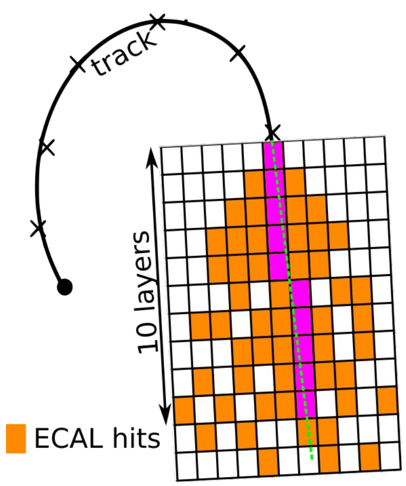


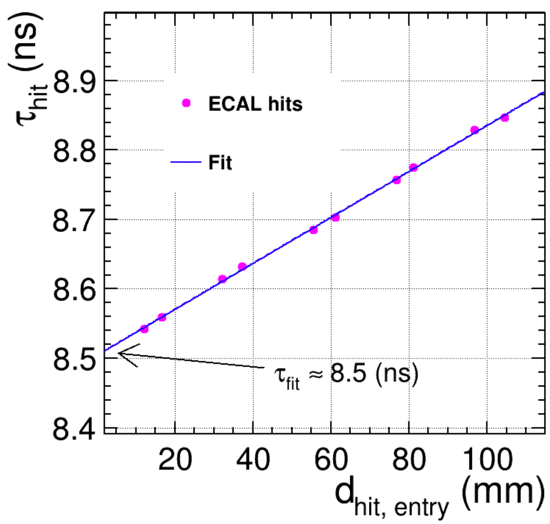
Other uses of timing

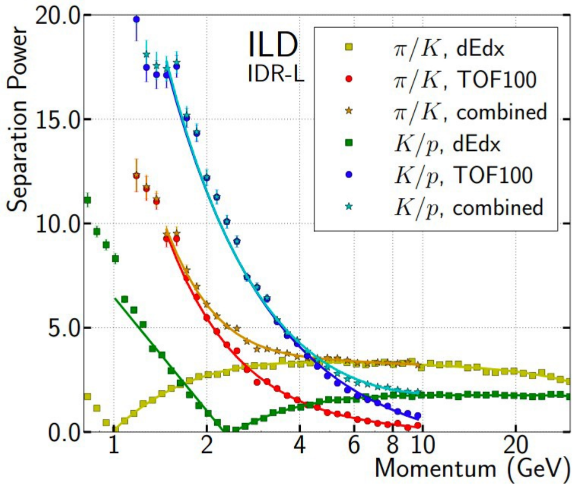
> Precise time information for each hit is interesting also for other applications

> Opens the possibility for full 4-dimensional shower reconstruction
  - More detailed information how hadron showers evolve
  - Could be used in software compensation
  - Could be used for improvements in separation of close-by showers in Particle Flow Algorithms

> Could be used for particle identification by time-of-flight
  - Needs time resolution of ~100ps or better







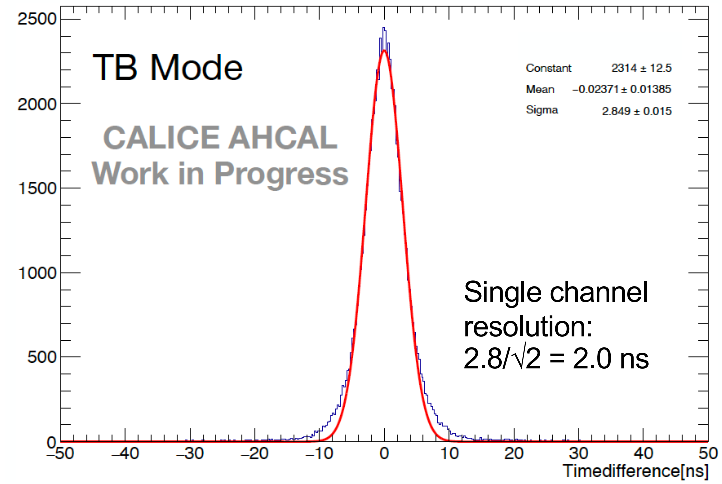
AHCAL Prototype: Hit Time Measurement

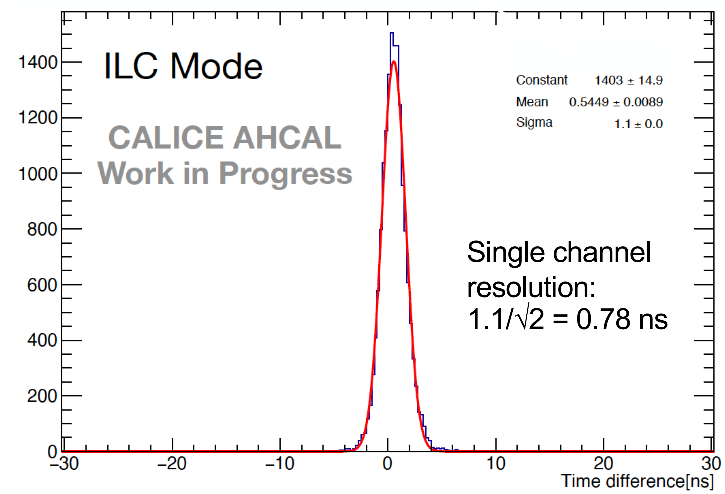
New feature in AHCAL technological prototype: time measurement for individual hits

- Design resolution: ~1 ns
- SPIROC2E readout ASIC supports 2 bunch clock speeds
  - Testbeam mode: 250 kHz clock
    - More efficient for data taking in testbeams
    - Worse hit time resolution: ~2ns
  - ILC mode: 5 MHz
    - Adapted to ILC bunch structure
    - Better hit time resolution: ~0.8 ns

- Full exploitation in data analysis just started

- Most testbeam data so far taken in testbeam mode

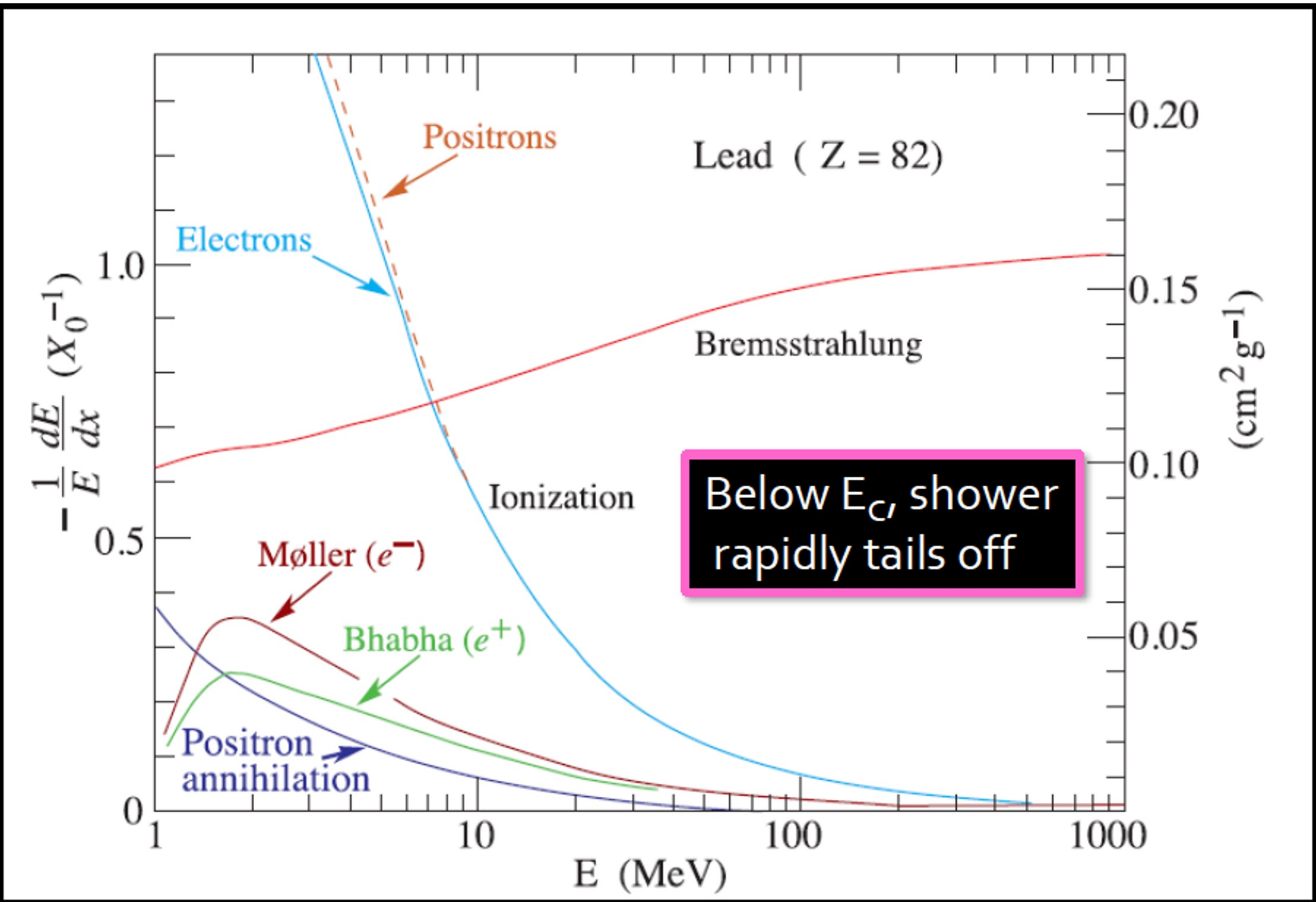




Conclusions

- Calorimeters are an essential part of particle physics detectors
  - Energy measurement of neutral (and charged) particles
- High granularity calorimeters together with Particle Flow Algorithms can provide unprecedented jet energy resolution
  - Granularity also very interesting also for background rejection (HL-LHC, FCC-hh)
- On the horizon: integration of timing information for every hit

Backup



Below E_c, shower rapidly tails off

Nigel Watson / Birmingham Univ. Frauenchiemsee / 12 Aug 2014

Material choices

Material	X_0 / cm	λ_{Int} / cm	R_M / cm	λ_{Int} / X_0
W	0.35	9.9	0.93	28.3
Pb	0.56	17.6	1.6	31.4
Fe	1.8	16.7	1.7	9.3
Cu	1.4	15.3	1.6	10.9

> important for good and compact ECAL
- small X_0
- small R_M

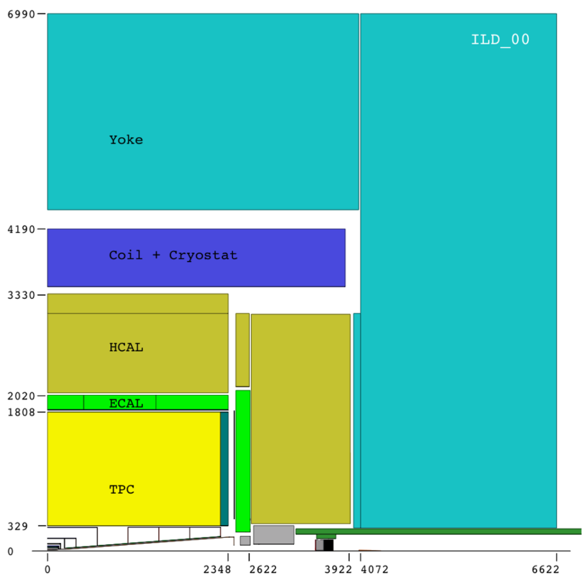
> important for good and compact HCAL
- small λ
- large λ/X_0

> other aspects
- price: W is very expensive
- mechanics:
  - Fe is easy to handle
  - Pb is not very rigid
  - W is very brittle

General Considerations for a Particle Flow Calorimeter

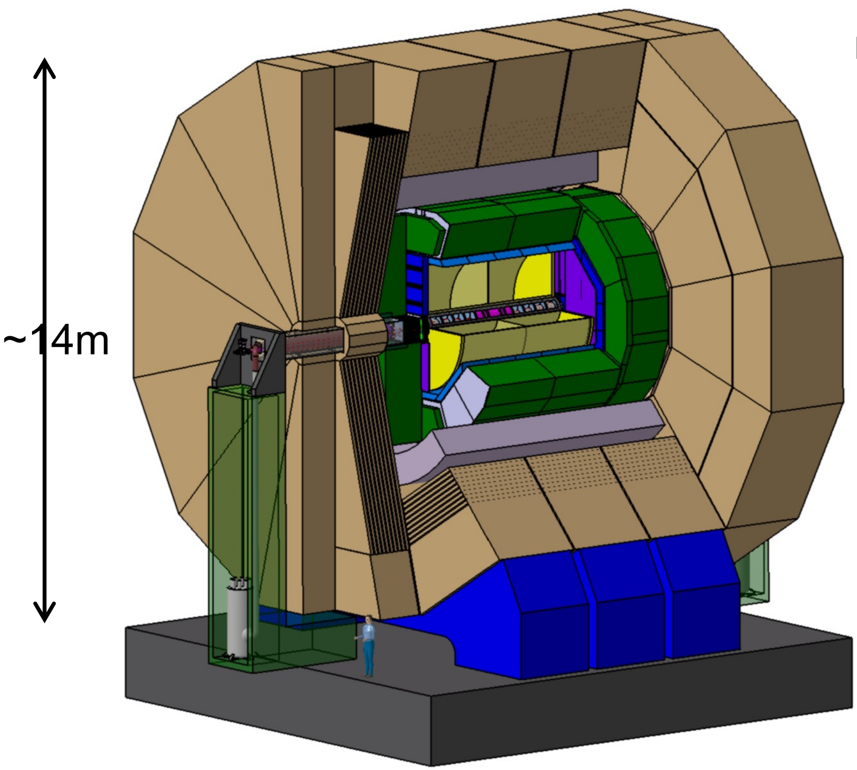
> **ECAL:**
- rather small → more expensive material affordable
- absorber: tungsten
- several concepts for the active layers

> **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



ILC Detectors

- 2 detector concepts for ILC: ILD and SiD

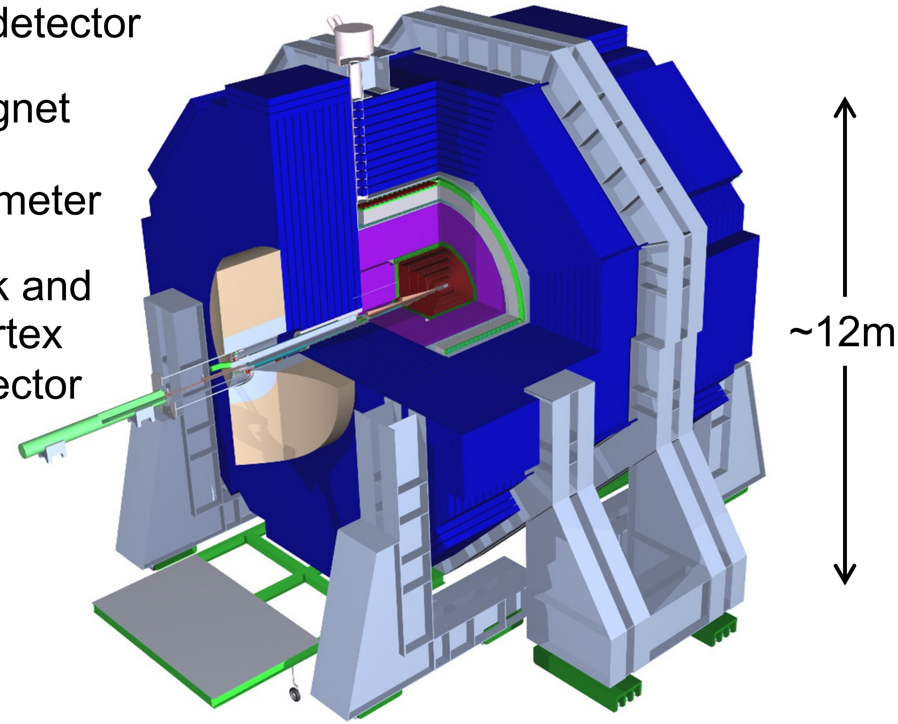


myon detector

magnet

calorimeter

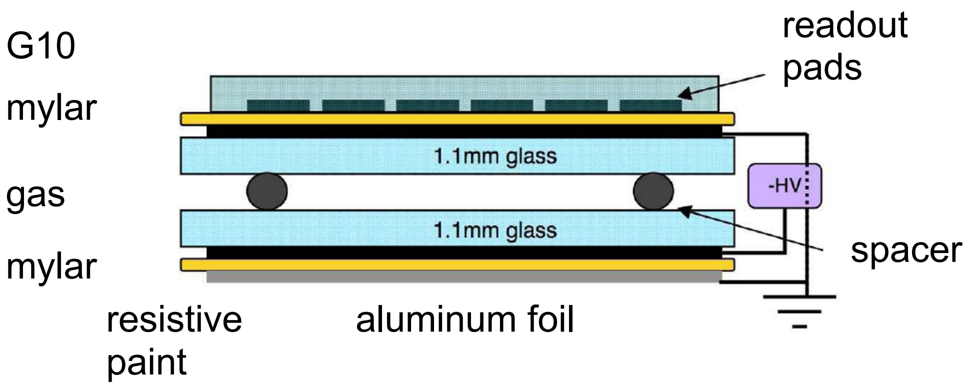
track and vertex detector



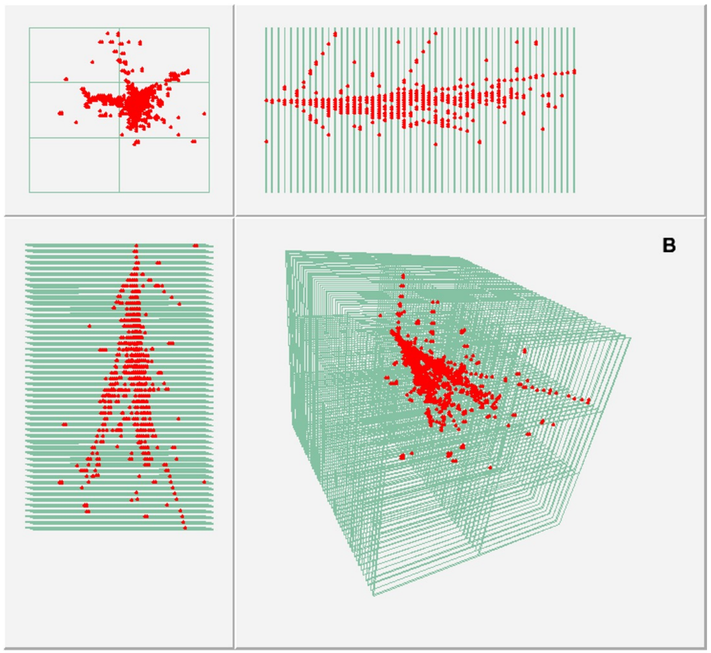
International **L**arge **D**etector

Silicon **D**etector

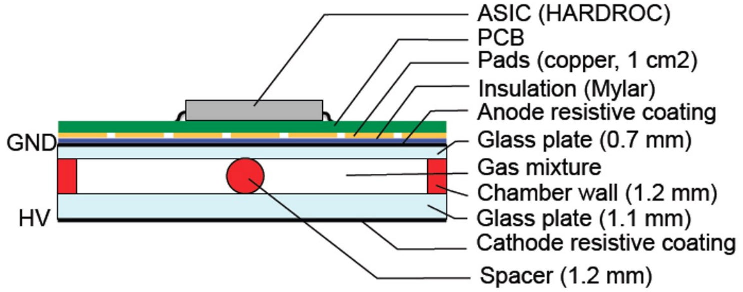
Digital HCAL



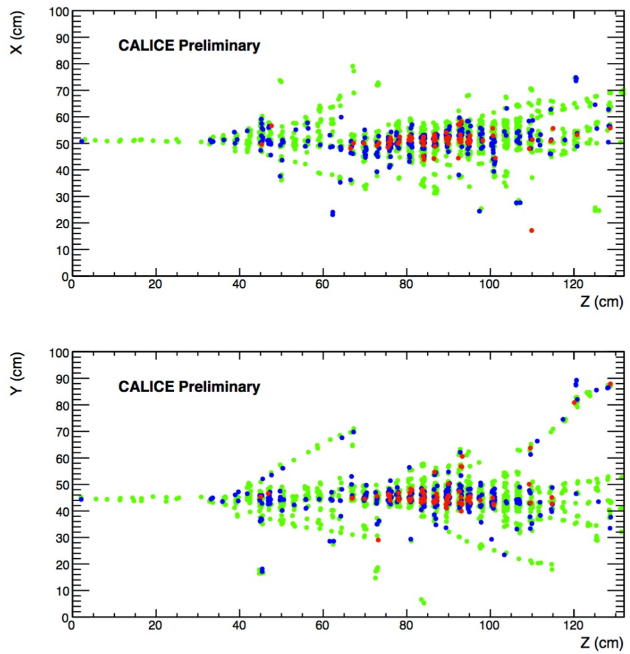
- Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage
- 1*1 cm^2 readout pads
- readout: 1 bit (digital)

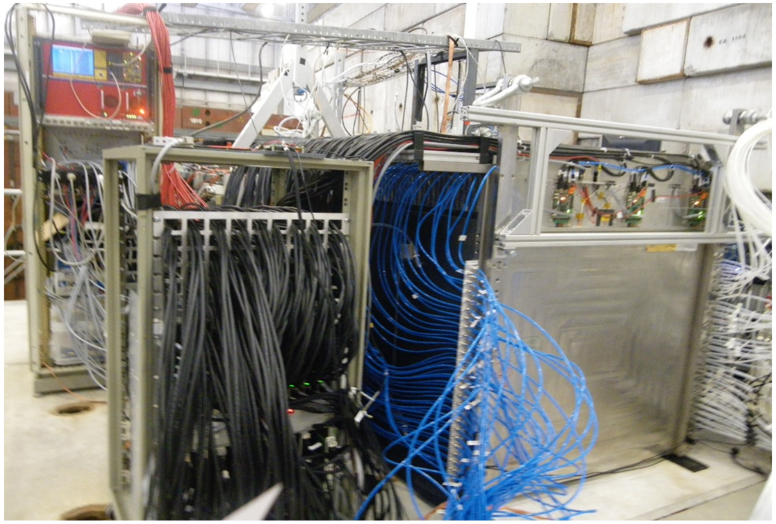


Semi-Digital HCAL

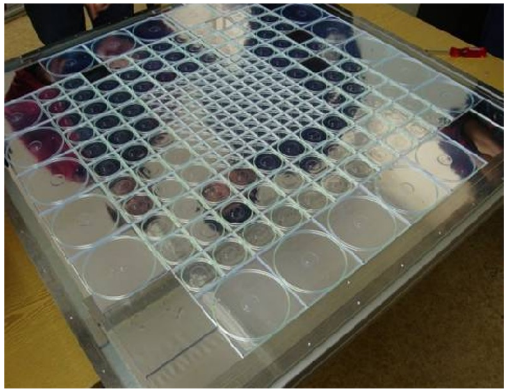


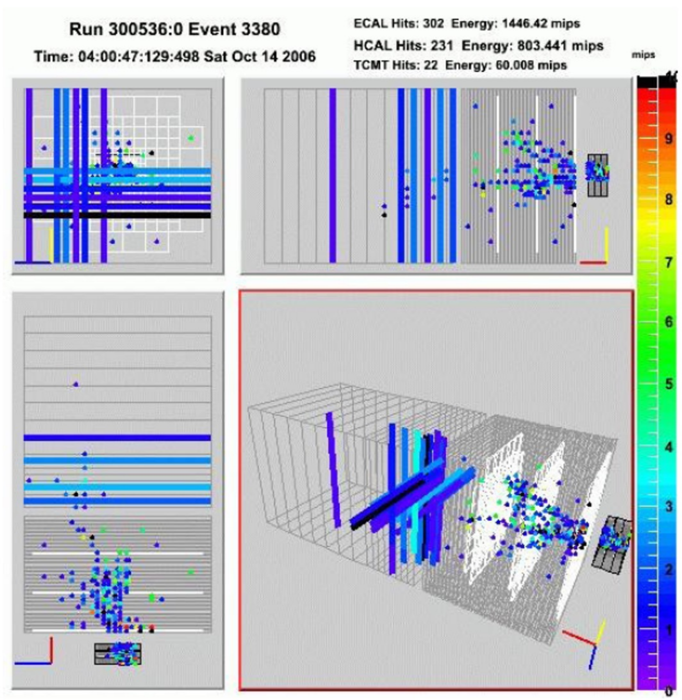
- Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage
- 1*1 cm^2 readout pads
- readout: 2 bit (semi-digital)



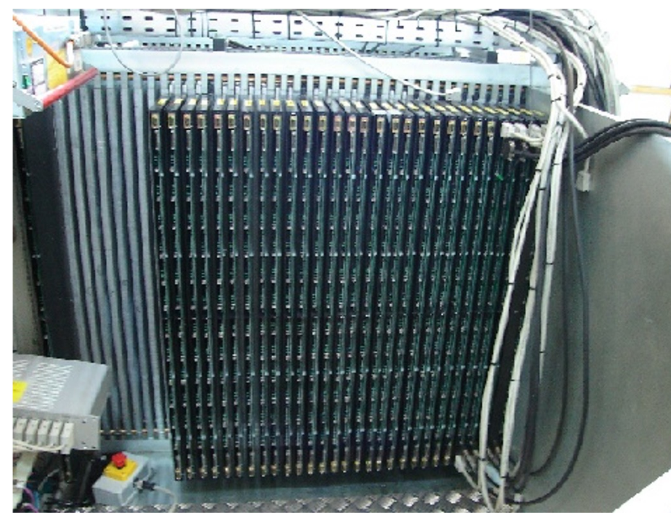


Analog HCAL





- Scintillator tiles with wave length shifting fibers, read out by SiPMs
- 3*3 cm^2 - 12*12 cm^2 tiles
- readout: 12 bit (analog)



CALICE

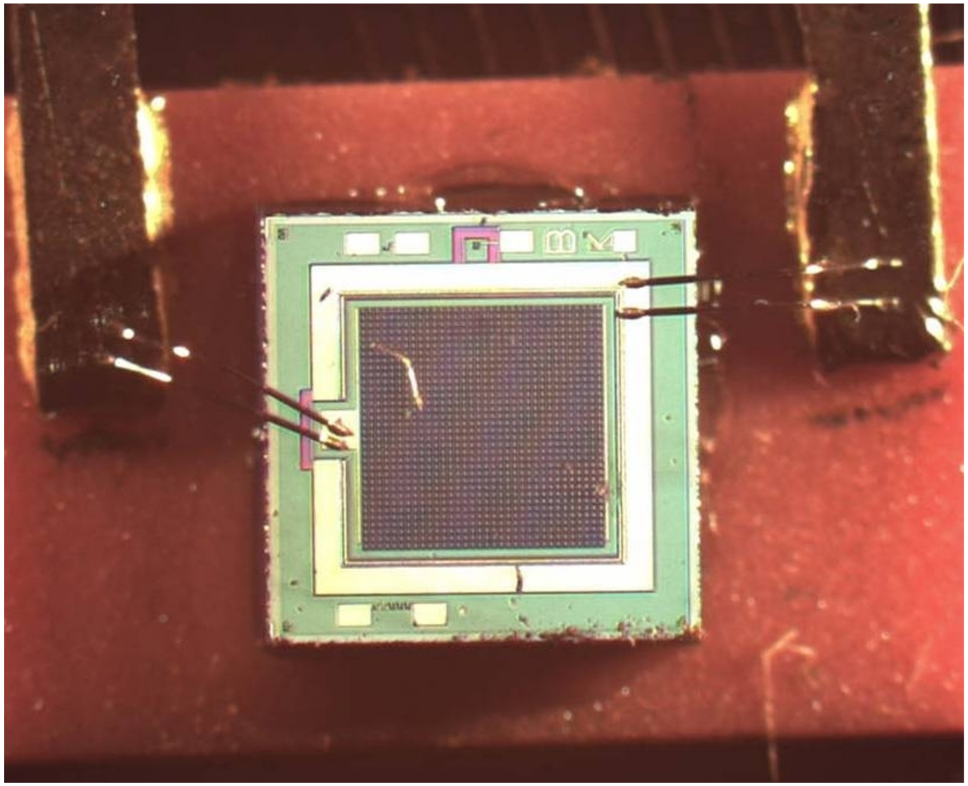
Calorimeter R&D for the … and beyond

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

- Integrated R&D effort

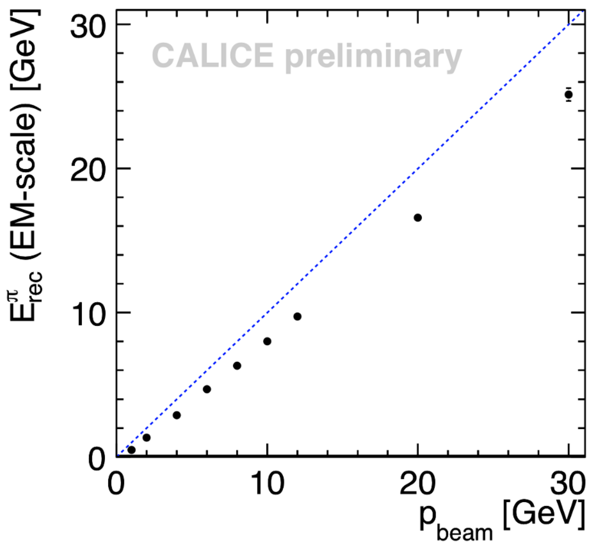
- Benefit/Accelerate detector development due to *common* approach

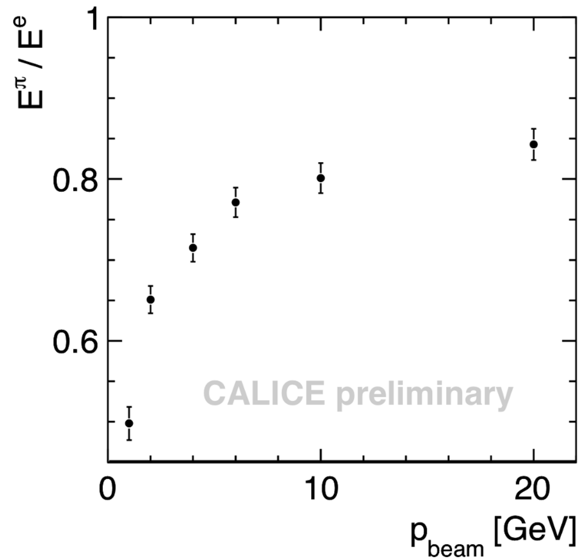
SiPMs: Silicon PhotoMultipliers

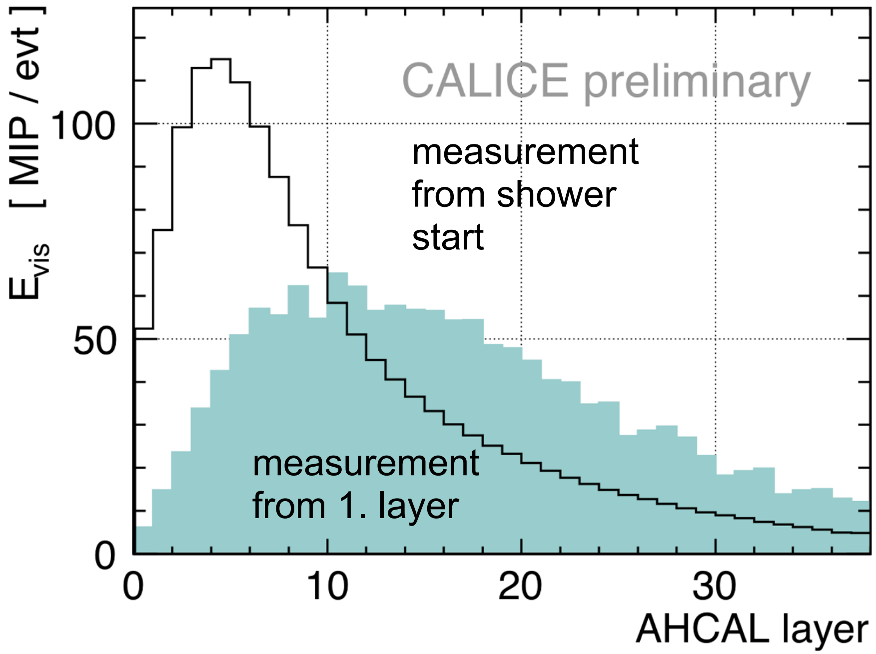


- pixelated
- avalanche photodiodes operated in Geiger mode
- sensitive to single photons
- gain of about 10^6
- insensitive to magnetic fields
- recently many developments in industry, e.g. reduced noise rates, more pixels, sensitivity to UV
- used e.g. in HCAL outer upgrade of CMS

AHCAL Characteristics





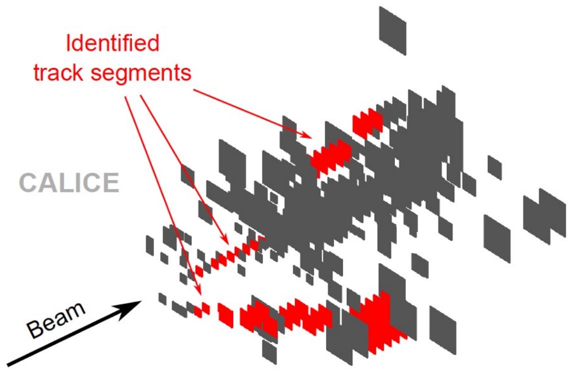


- non-compensating calorimeter: measured energy for hadrons smaller than for electrons of the same energy
- high granularity allows for detailed studies of shower shapes

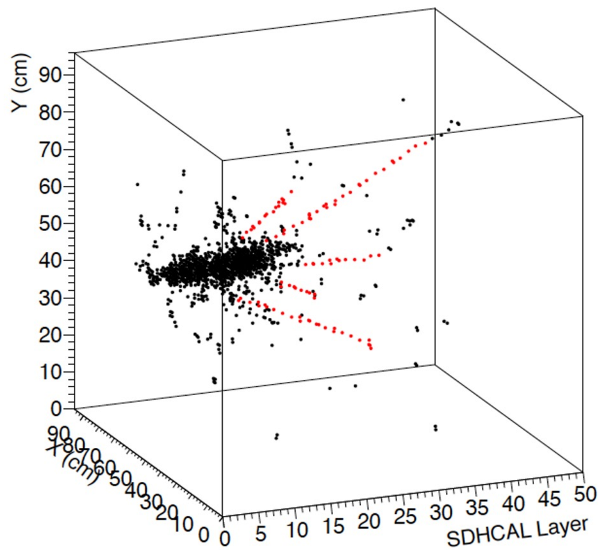
Imaging validation

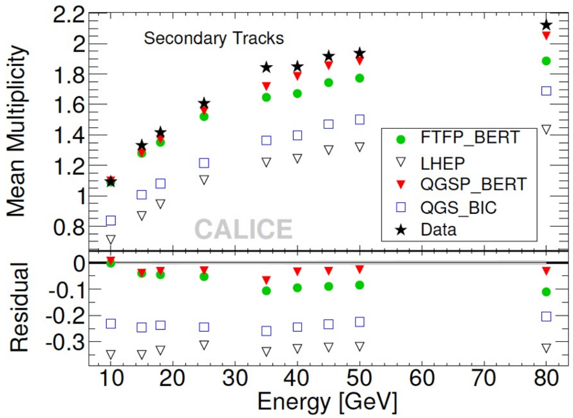
look at track segment within a shower

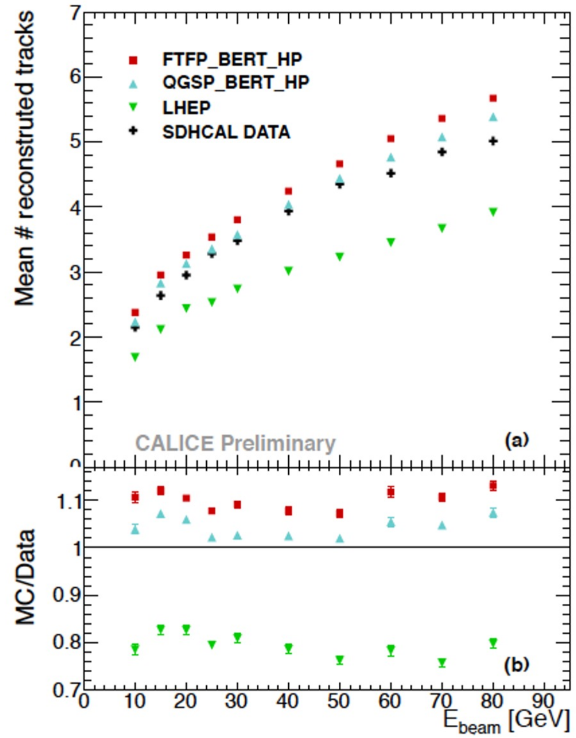
AHCAL



SDHCAL

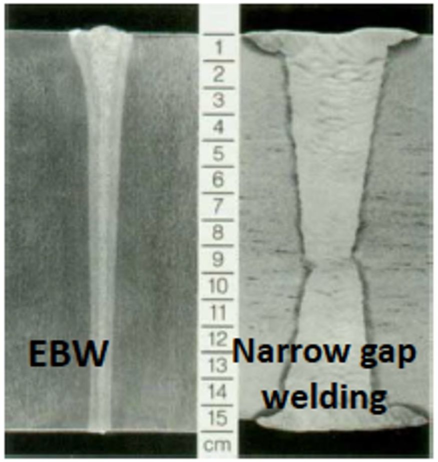


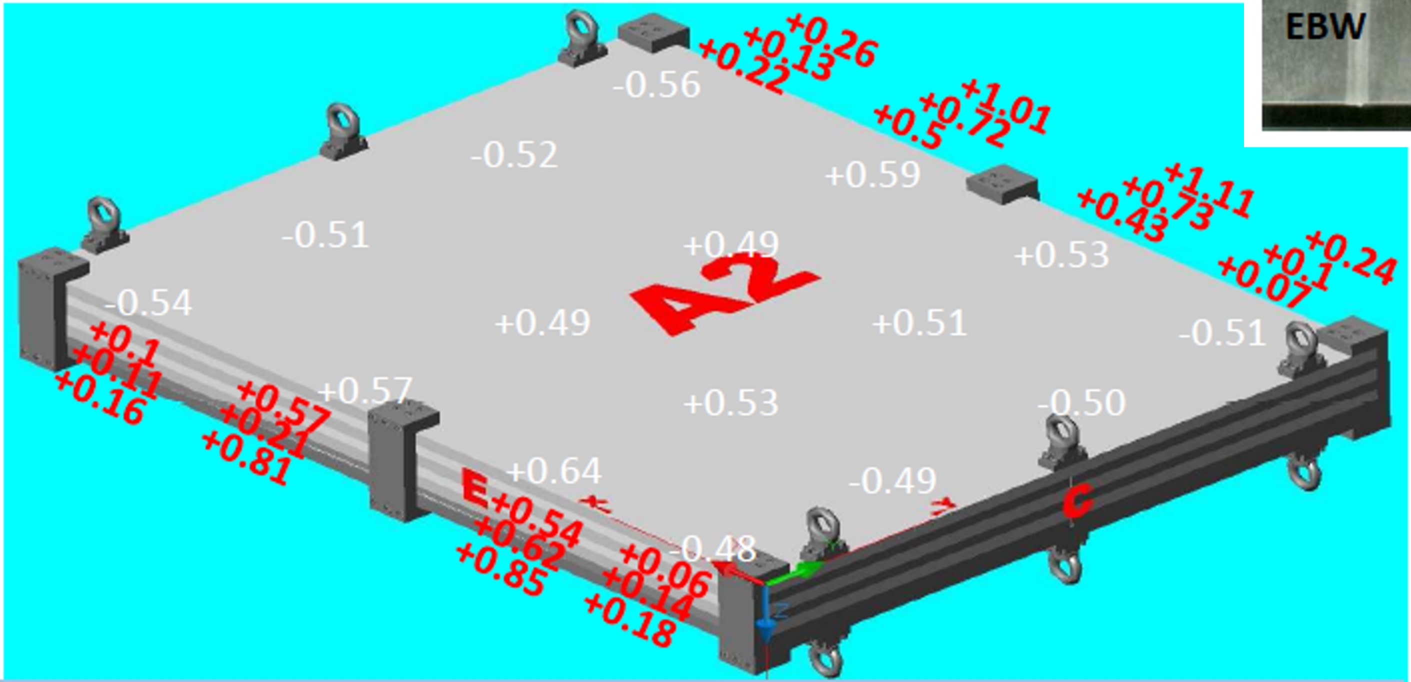




Hardware R&D for next generation of SDHCAL: Mechanics

- electron beam welding allows very narrow welding which should lead to only small deformations
- first test with 1m² plates showed deformations bigger than expected (up to ~1mm)
- working on improving the welding sequence





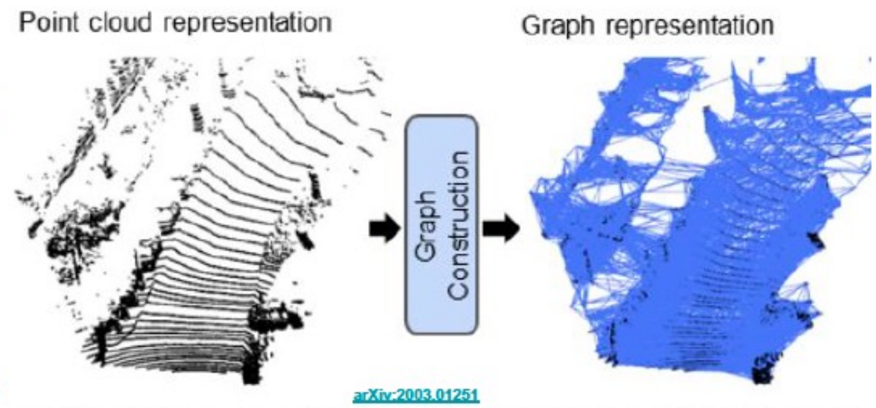
Differences with respect to the initial status of the plate in Z.

Differences with respect to the initial status of the distance between plates

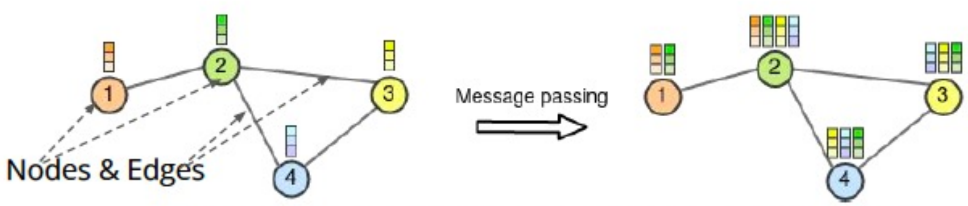
DESY

Graph Neural Networks

- Pion showers are reconstructed as large point clouds,
  - Variable in number of hits and in how the hits are distributed.
  - Such highly irregular input data can be represented by graphs.



- Graphs are formed by drawing edges in between k nearest rechits.
- Each node learns about its neighbor & about itself using the message passing layer called the graph convolutions.



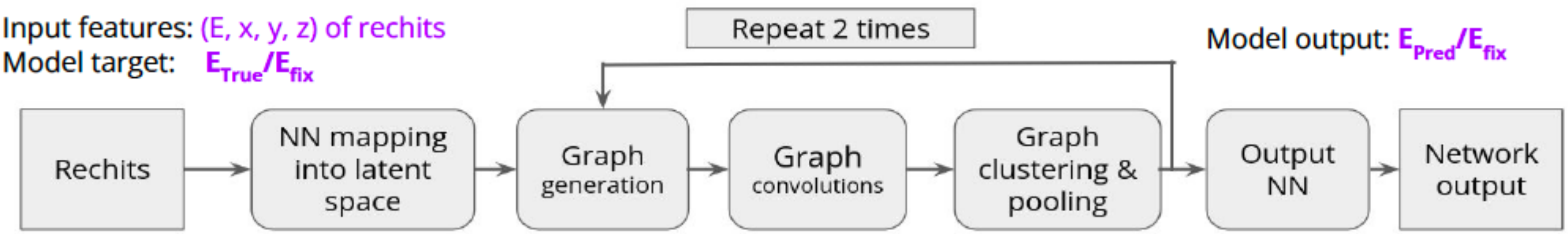
https://uvadlc-notebooks.readthedocs.io/en/latest/tutorial_notebooks/tutorial7/GNN_overview.html

- Advantages of graph approach:
  - Preserves permutation-invariance of input data (the order in which rechit are fed to the network does not matter).
  - No padding or truncation necessary like it is needed in case of convolutional NNs.

Dynamic Reduction Network (DRN)

- Based on Dynamic Graph Neural Networks (1801.07829), a model is defined with the following differences(2003.08013v1),,
  - Input features are mapped onto a higher dimensional latent space
  - Add clustering & pooling step to learn high level information iteratively.

Input features: (E, x, y, z) of rechits
Model target: E_{True}/E_{fix}



E_{True} is the true energy of particle & E_{fix} is reconstructed energy using detector level calibration
E_{Pred} is the energy reconstruction using DRN weights.

- The model is trained on a flat energy sample of 10-350 GeV with a total of 4.1M events simulated using GEANT4.10.4.p03 and FTFP BERT EMN hadronic physics list.
- AdamW optimizer with a constant learning rate of 10^{-4} is used while training the model & a total of 63k parameters to learn in the model.
- The most expensive step is the graph convolutions, followed by construction of the nearest neighbors graph.