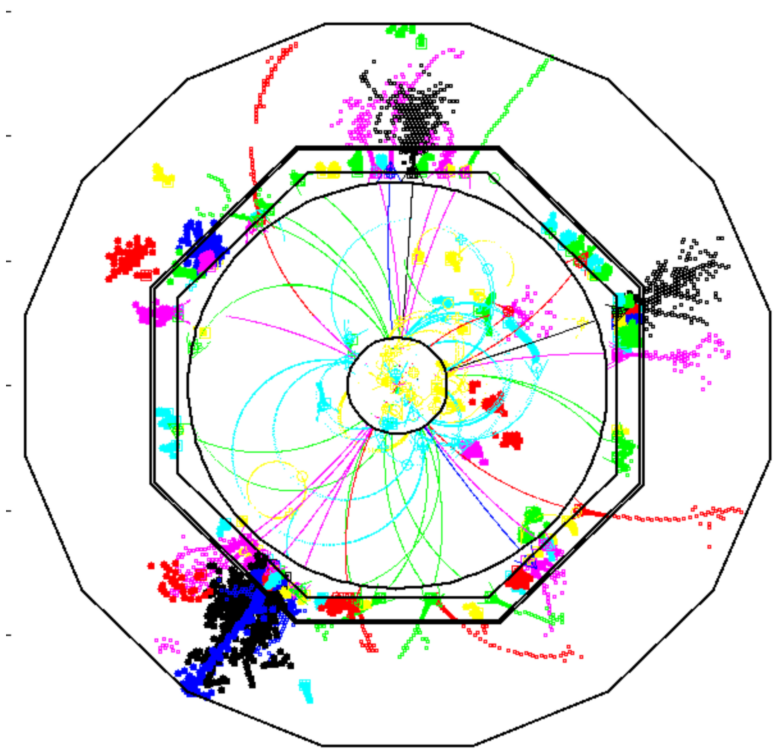
Calorimetry III: Particle Flow Calorimeters



Katja Krüger (DESY)

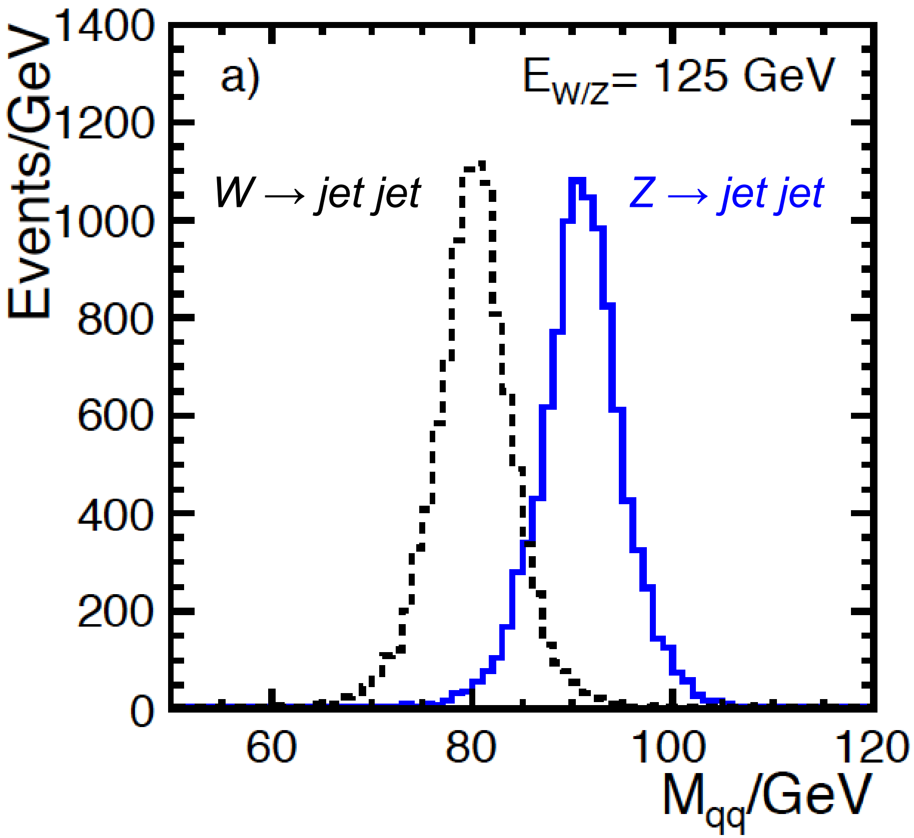
EDIT 2020

DESY, 26. February 2020

Overview

- Introduction
  - Jet Energy Challenge
  - Particle Flow Algorithm
- Highly Granular Calorimeters
  - Concepts
  - Performance in Testbeam
- High Granularity beyond Particle Flow
  - Software Compensation
  - Pileup Rejection

The Jet Energy Challenge



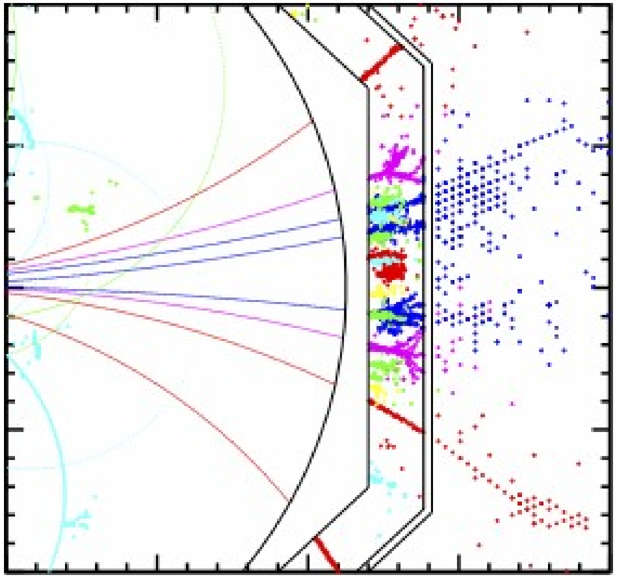
from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- many interesting physics processes involve W or Z bosons
  - predominantly decay into jets
- goal: distinguish the decays $Z \rightarrow jet\ jet$ and $W \rightarrow jet\ jet$ by their reconstructed mass
- Required resolution:
  $\sigma(E_{jet})/E_{jet} \approx 3\text{-}4\%$
  for $E_{jet} \approx 40$ to 500 GeV
- "typical" calorimeter:
  $\sigma(E_{jet})/E_{jet} \approx 60\%/\sqrt{E(\text{GeV})} \oplus 2\%$
  $\Rightarrow \sigma(E_{jet})/E_{jet} \approx 10\%$ at E_{jet} = 50 GeV
- promising solution:

Particle
Flow
Algorithms

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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  for each individual particle in a jet,
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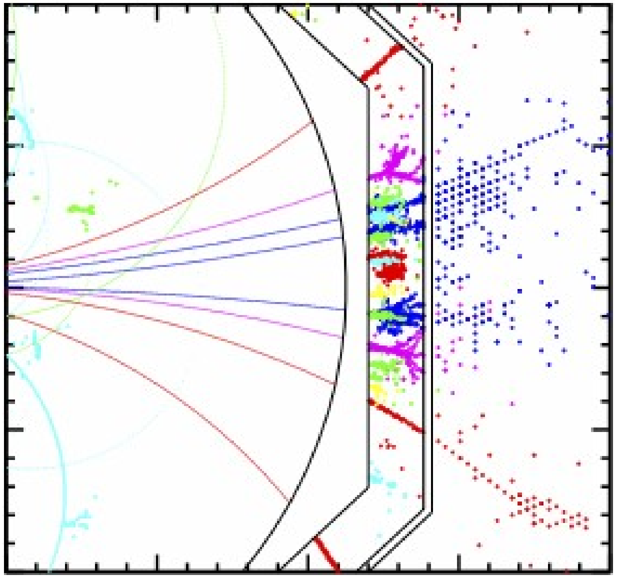


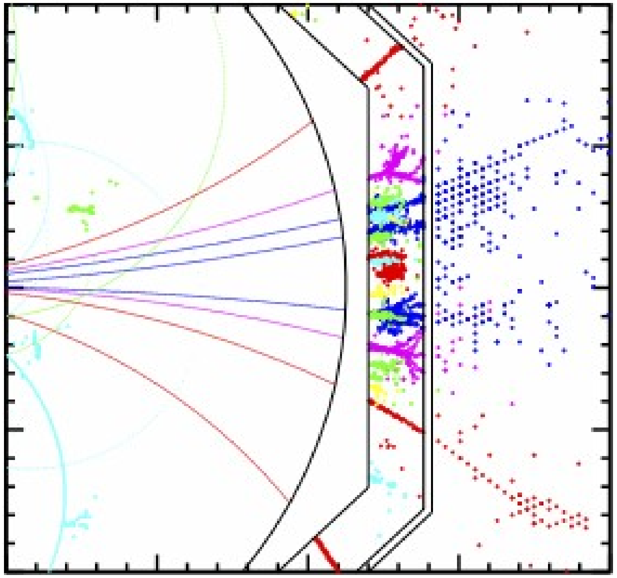
from: M.A. Thomson,
Nucl.Instrum.Meth. A611 (2009) 25

- „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

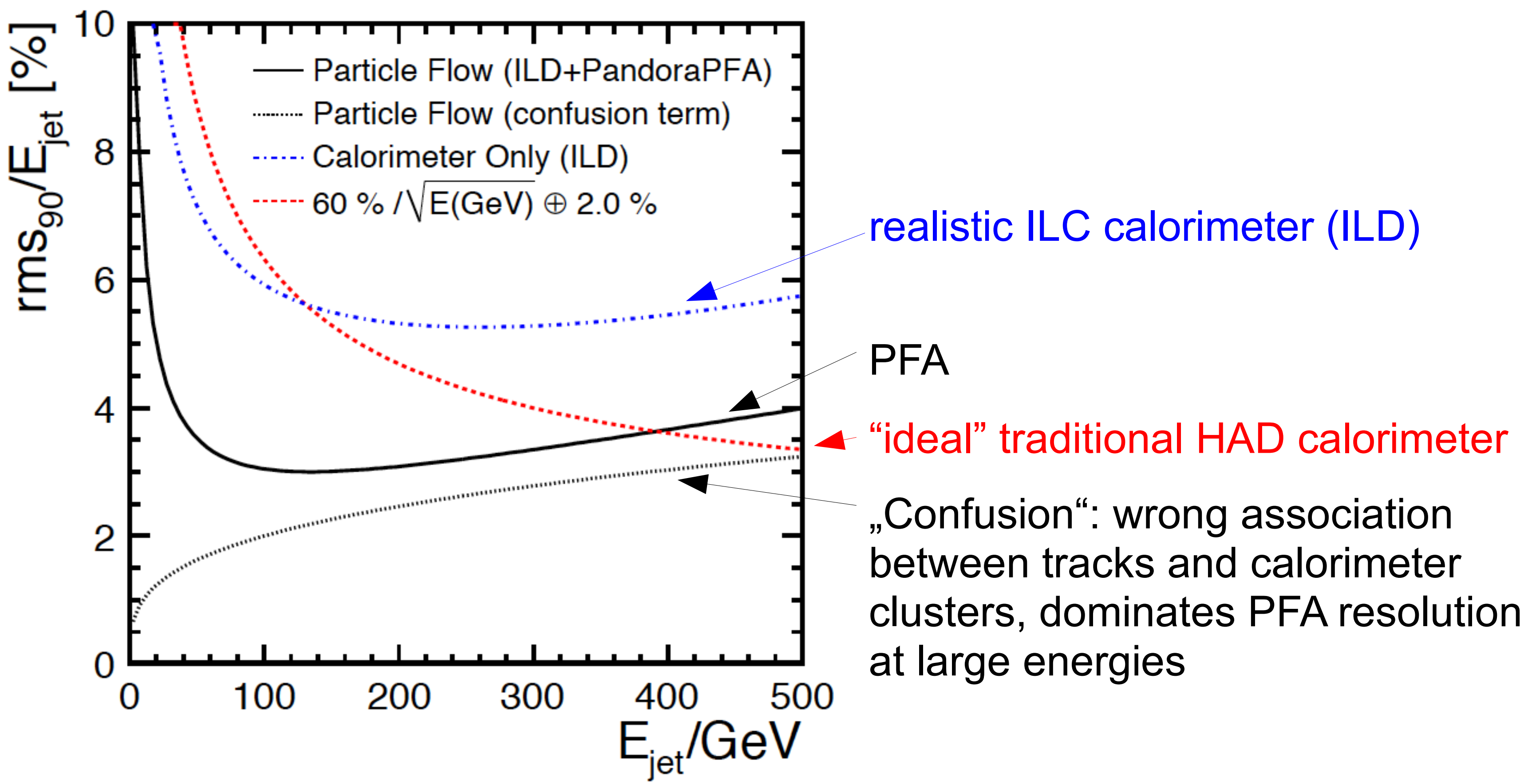


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „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~~		$+\ (\sigma_{loss})^2 + (\sigma_{confusion})^2$

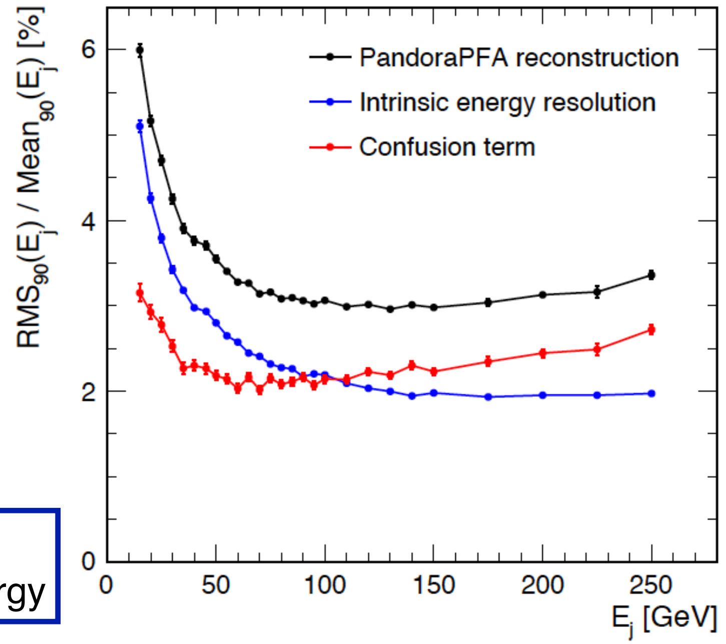
Jet Energy Resolution



- PFA resolution is clearly better than calorimeter alone
- correct association between tracks and calorimeter clusters is very important ⇒ "imaging" calorimeter with very high granularity

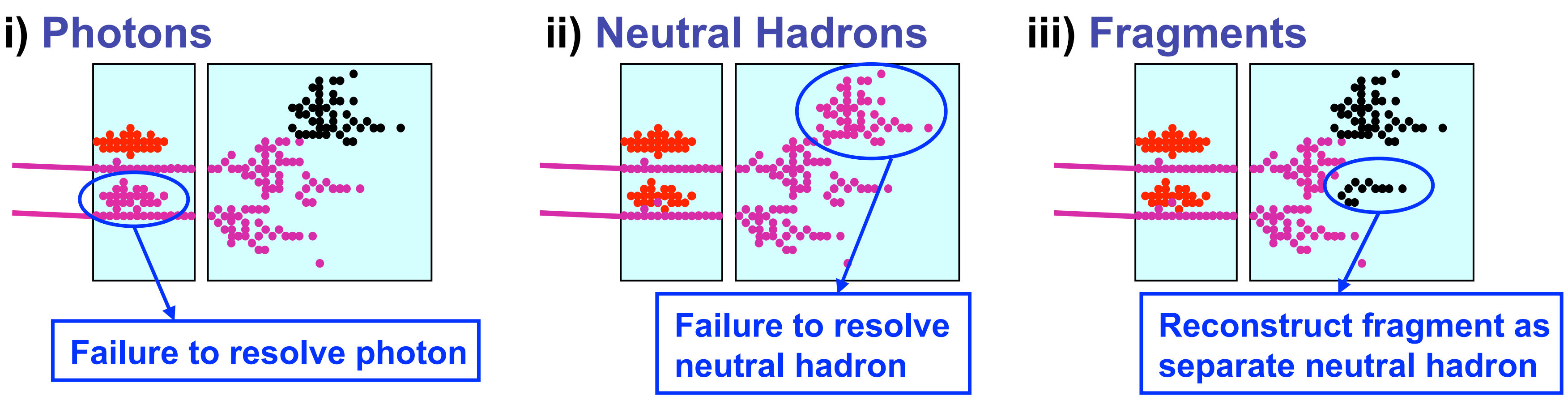
Particle Flow Performance with PandoraPFA

- separating the energy depositions of individual particles requires high granularity
- calorimeter energy resolution is still important
  - dominates for jets up to 100 GeV
  - contributes to resolving confusion



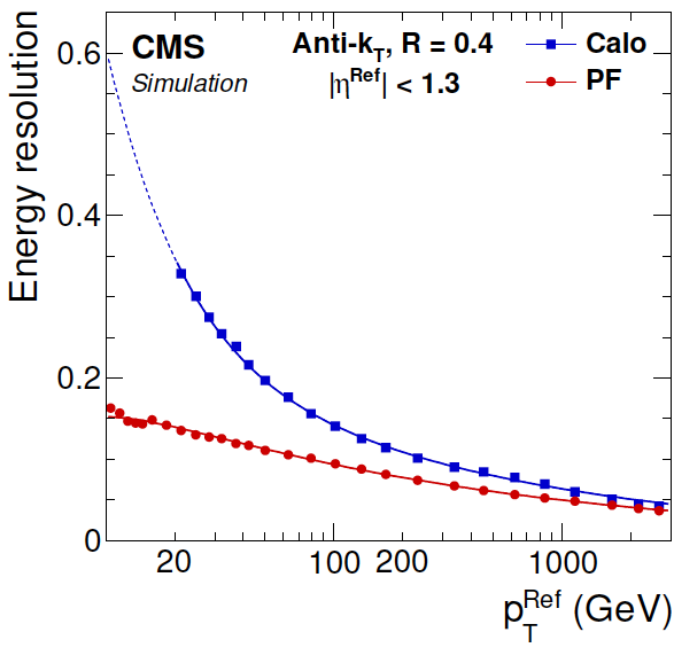
Pattern recognition based on topology and energy

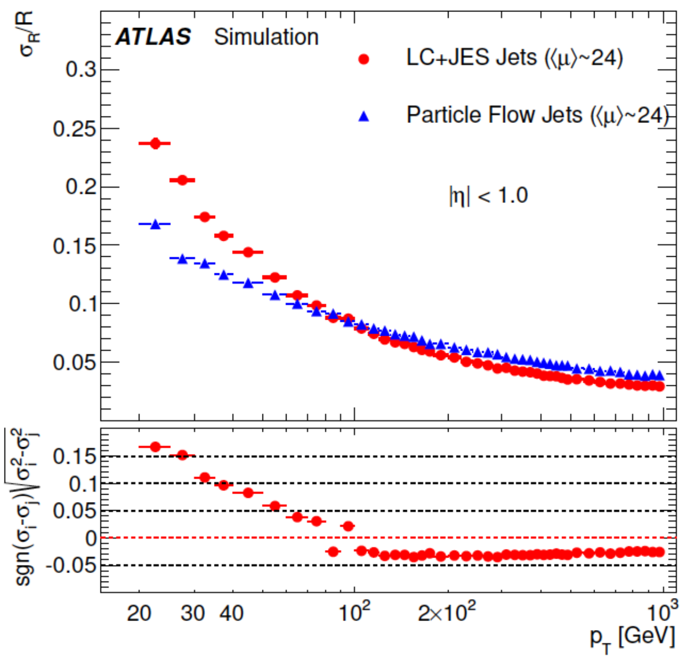
Types of confusion:



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

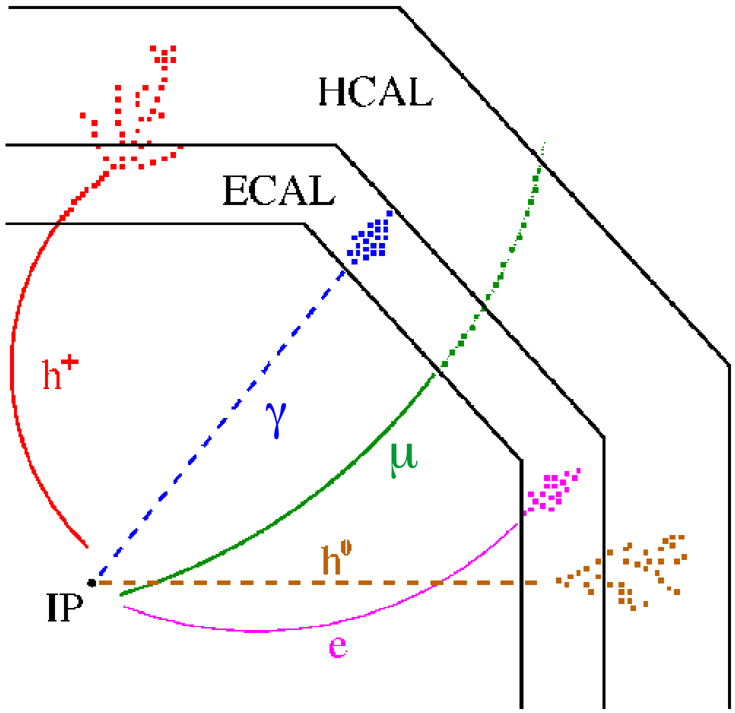




Particle Flow Detector

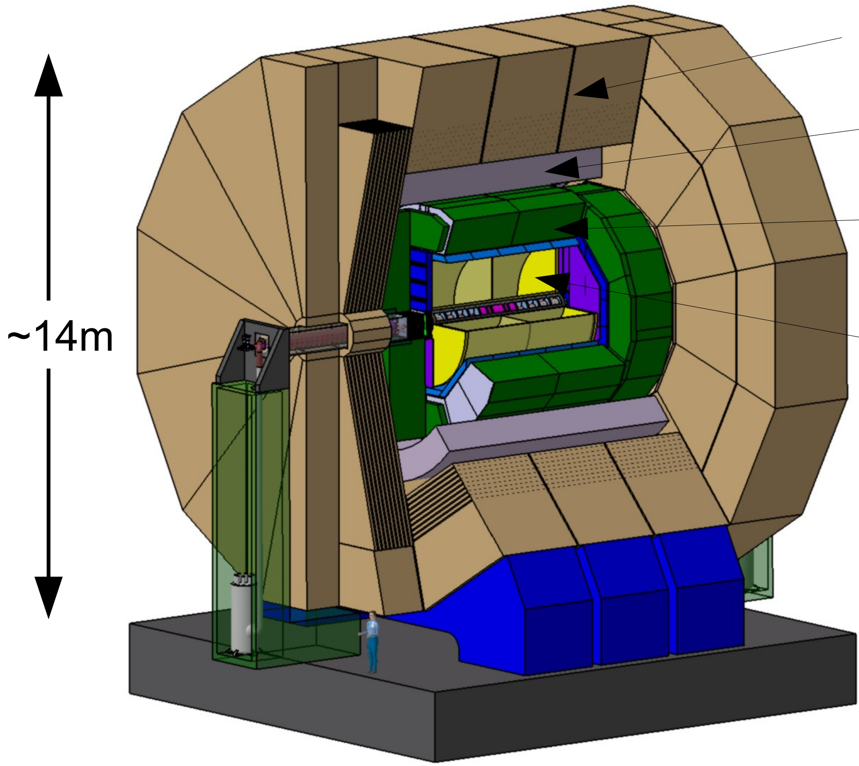
How should a detector look like that is optimized for Particle Flow?

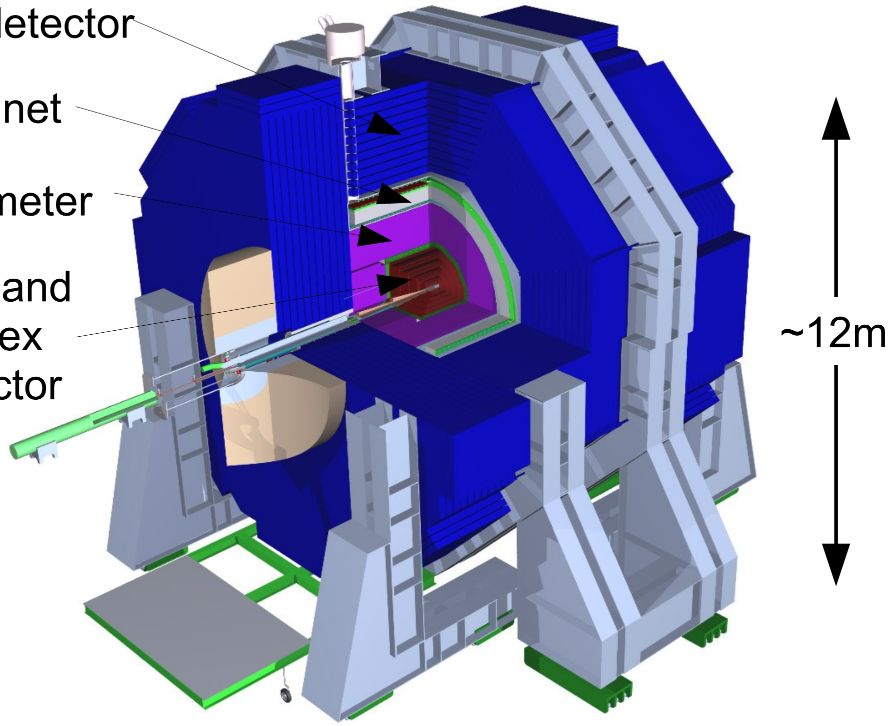
- need good separation of particles entering the calorimeter
  - ➔ large detector radius and length
  - ➔ large magnetic field to separate charged from neutral particles
- need compact showers to minimize overlap
  - ➔ calorimeters with small Molière radius
- need minimal amount of dead material between tracker and calorimeter
  - ➔ calorimeter inside magnet coil
- need detailed information about shower position and shape
  - ➔ calorimeter with very high granularity



Detectors Designed for Particle Flow: ILD and SiD

- 2 detector concepts for ILC (e+e- at √s of 250 to 500 GeV)



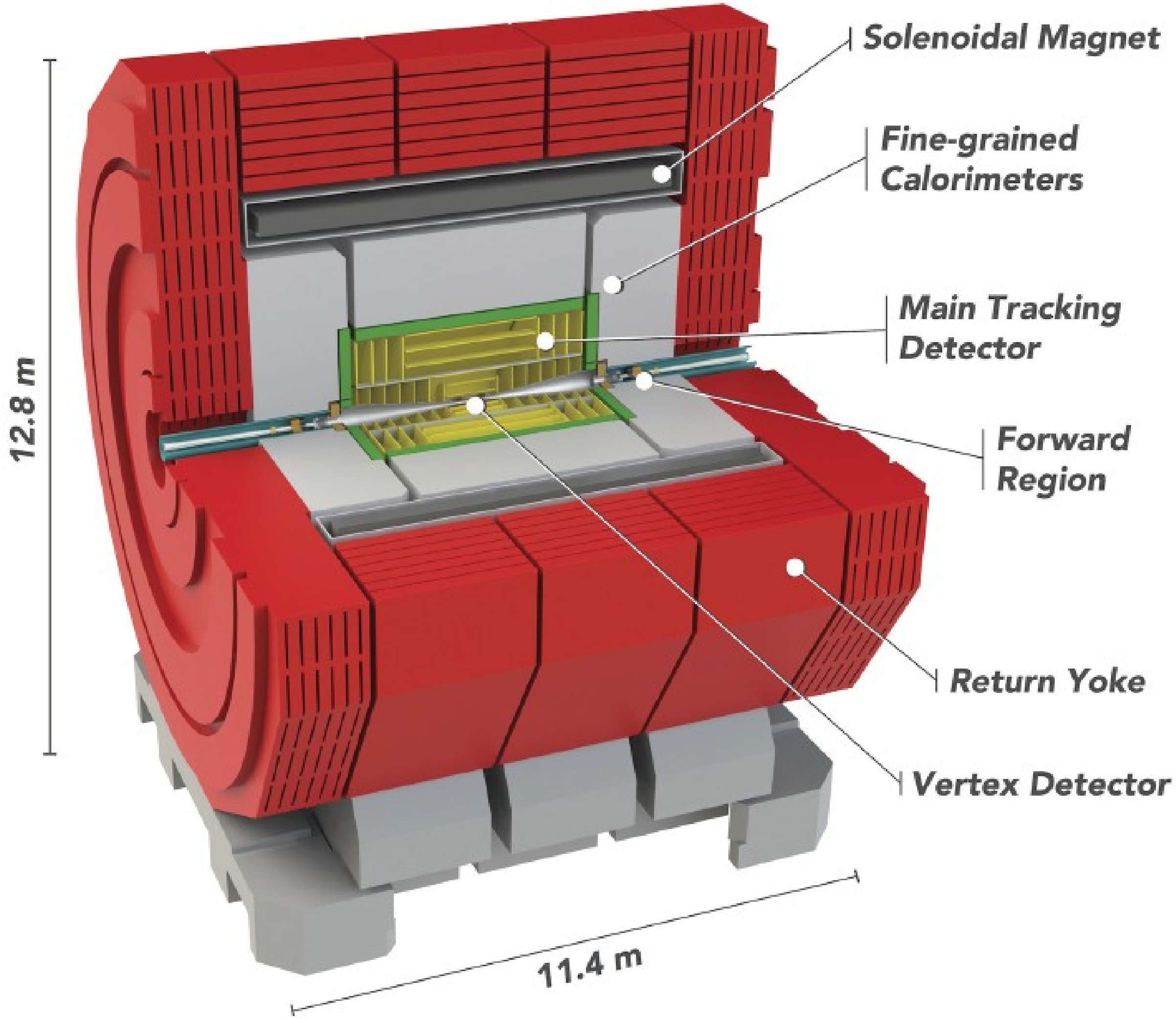


International **L**arge **D**etector

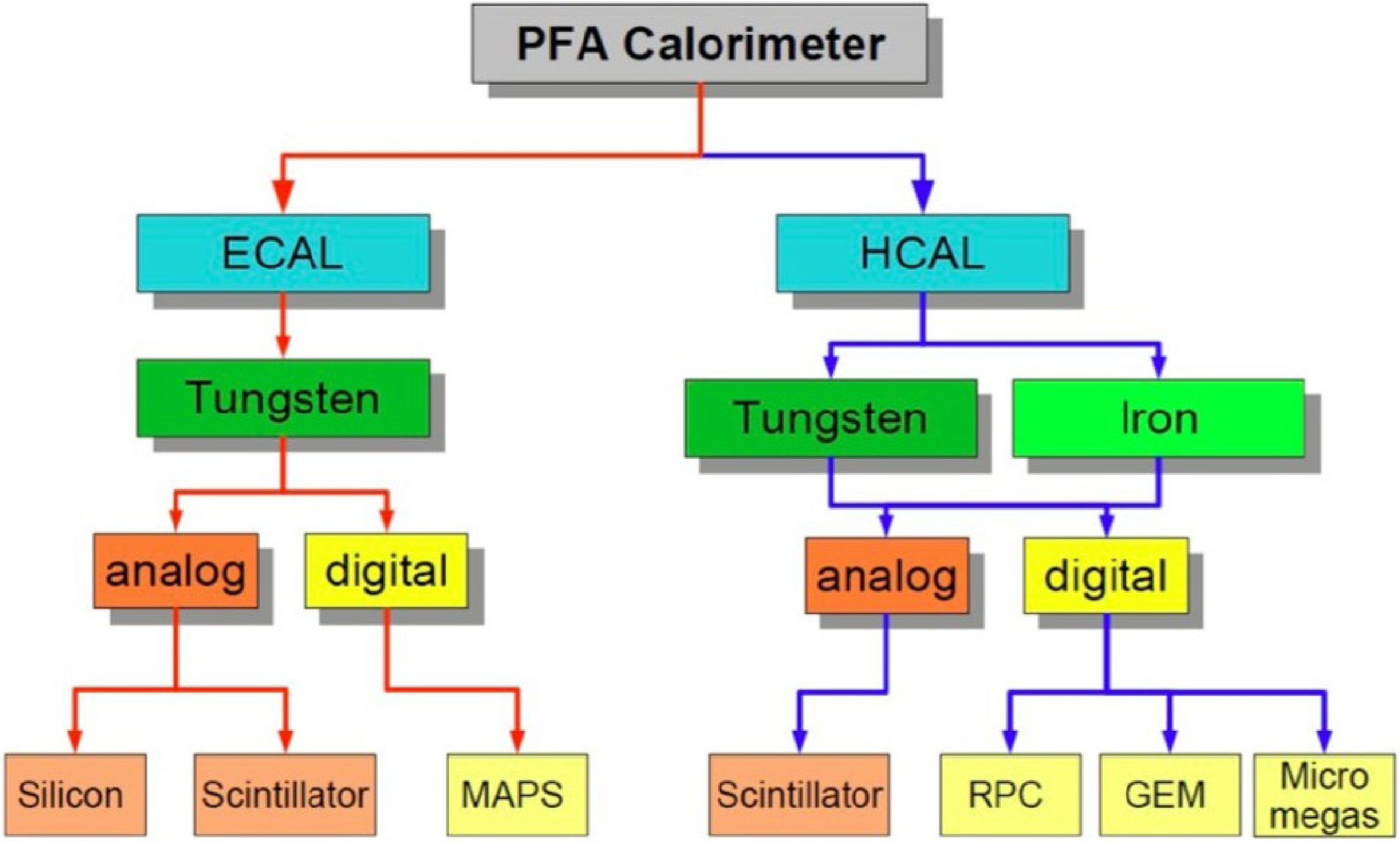
Silicon **D**etector

Detectors Designed for Particle Flow: CLICdet

> CLICdet: optimised for higher $\sqrt{s}$ (3 TeV)

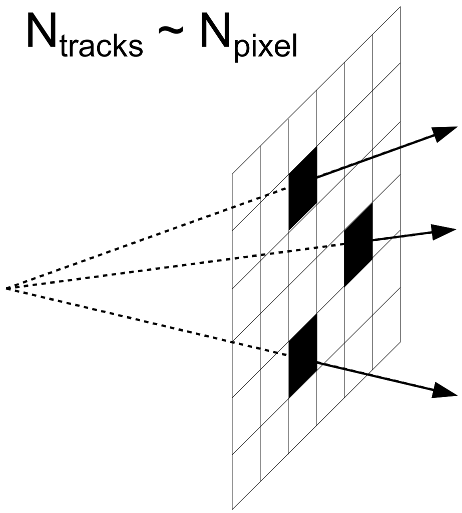


Technologies for Particle Flow Calorimeters



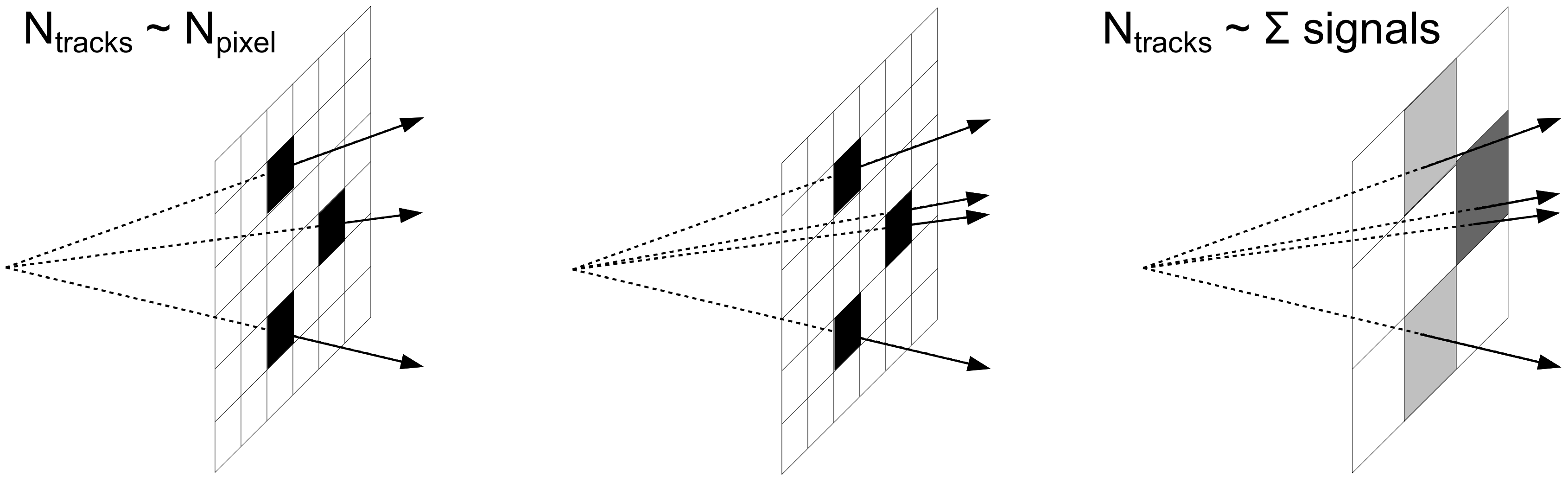
Calorimeter Readout Concepts

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



Calorimeter Readout Concepts

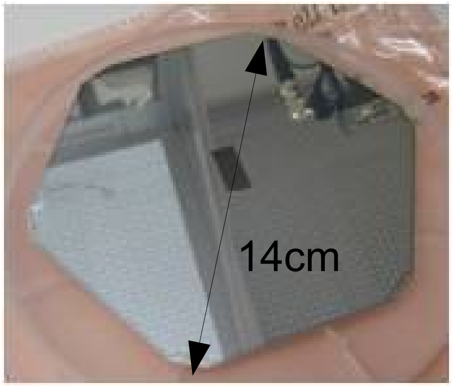
- digital CAL: count number of hit pixels (off/on)
- semi-digital CAL: additional information about number of particles within one pixel by using 3 thresholds (off/standard/large/very large)
- analog CAL: sum up signals in (larger) cells ("classical" calo reconstruction)



- for the hadronic calorimeter, all 3 concepts are studied

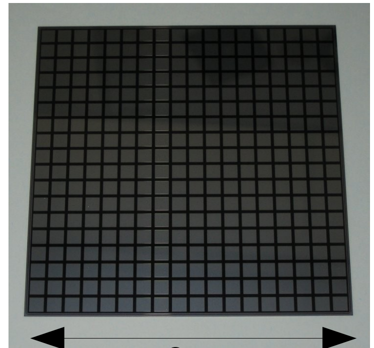
Analog ECAL: Active Material

Silicon



1024 pixel

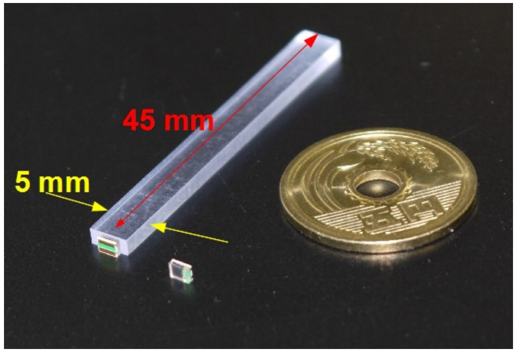
Silicon

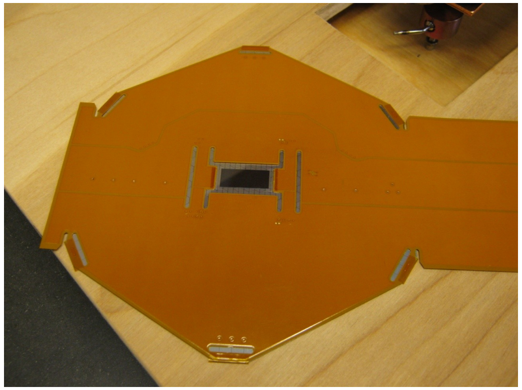


9cm

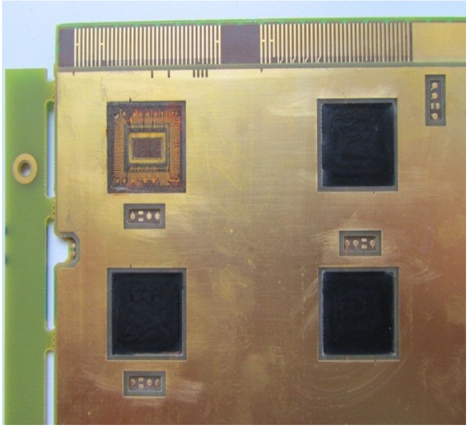
256 pixel

Scintillator





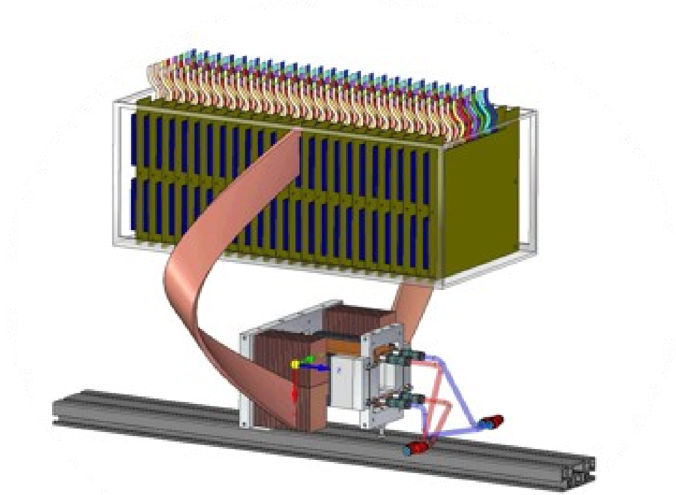
SiD

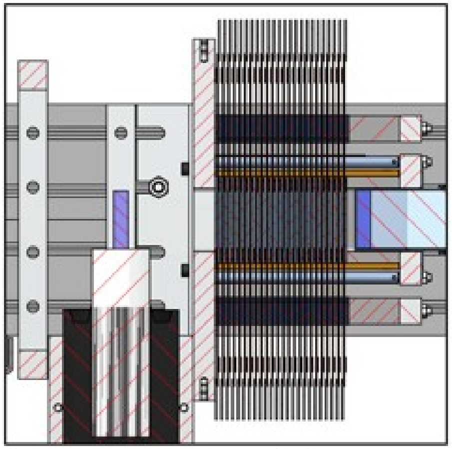


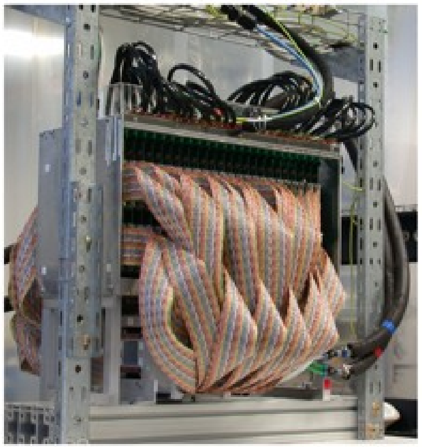
ILD

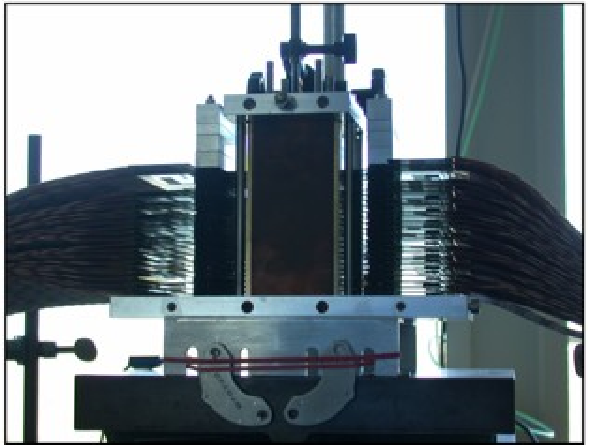
ILD
alternative

Digital ECAL: Pixel Calorimeter Prototype





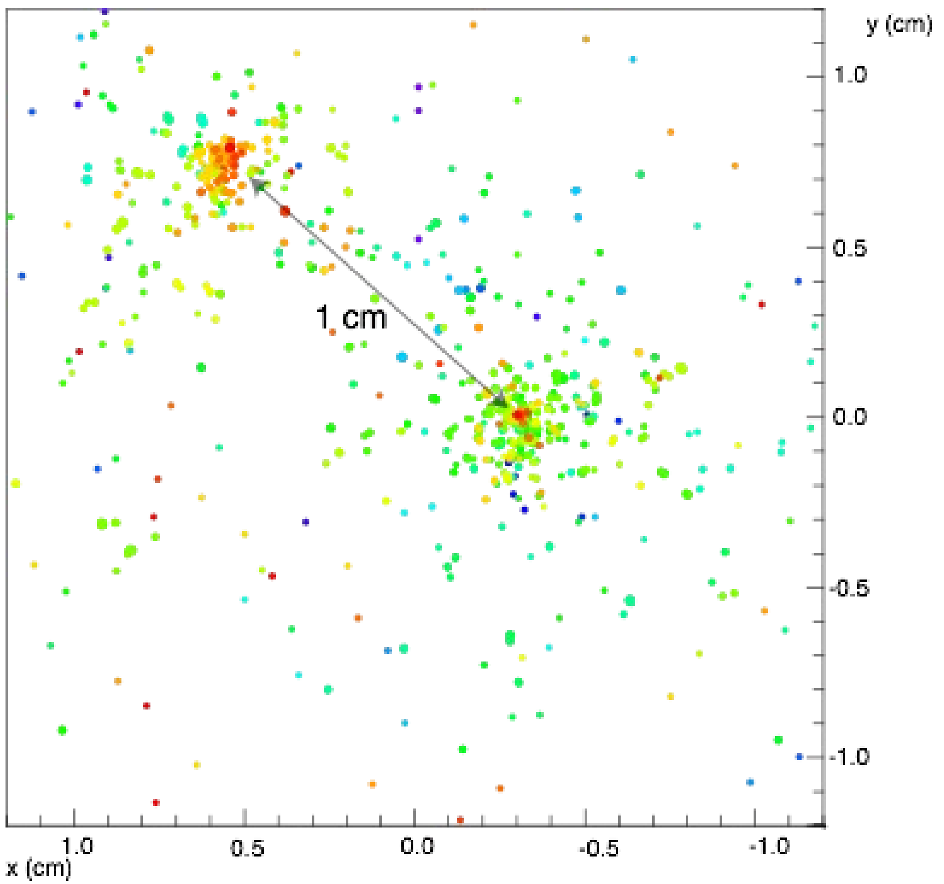


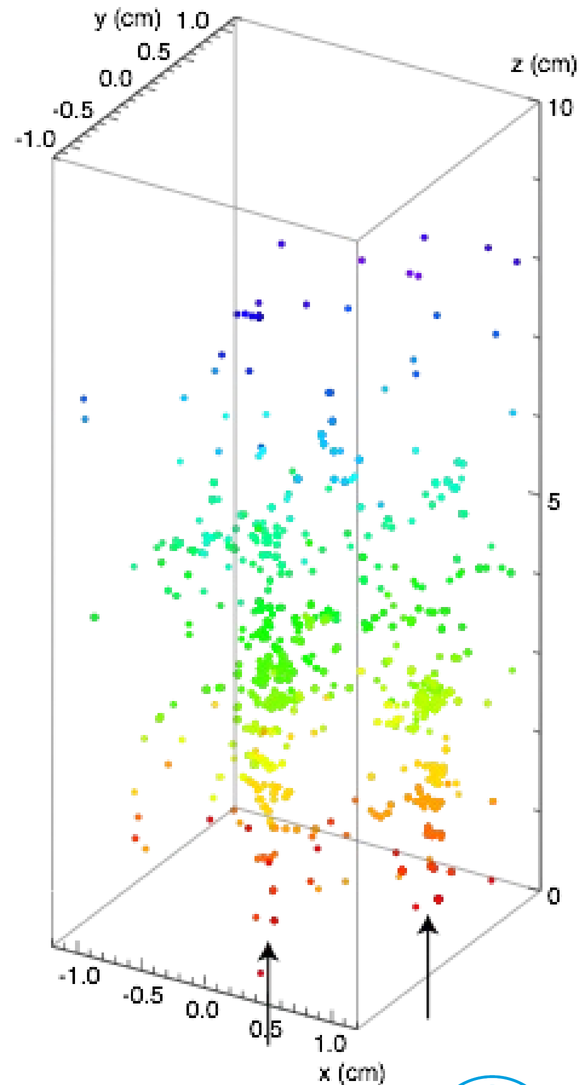


- R&D for ALICE FoCal upgrade
- full MAPS prototype, 24 layers
  - 3mm W
  - 1mm sensor layer
    - 120µm sensor (2x2 chips) + PCB, glue, air, …
- **39 M pixels in 4x4x10 cm^3 !**

Digital ECAL: Event Display

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

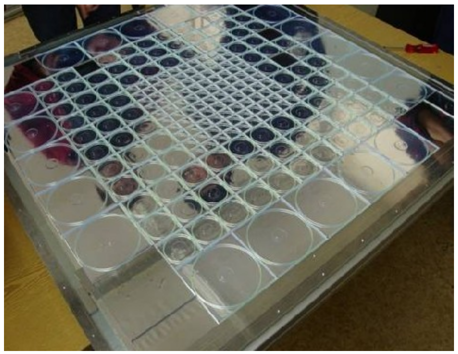


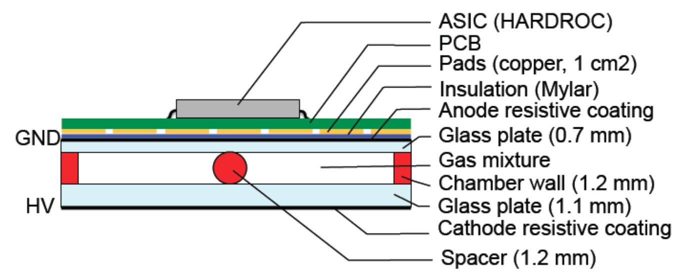


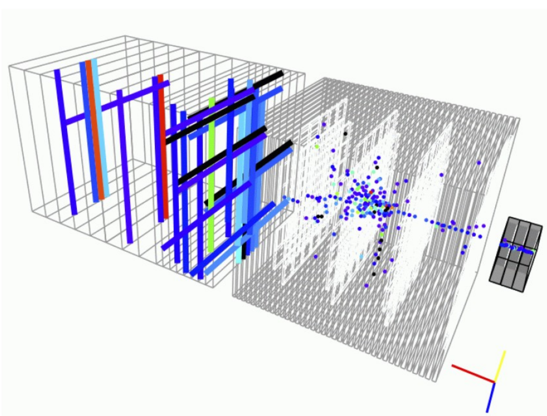
single pixels, colour code = z-position

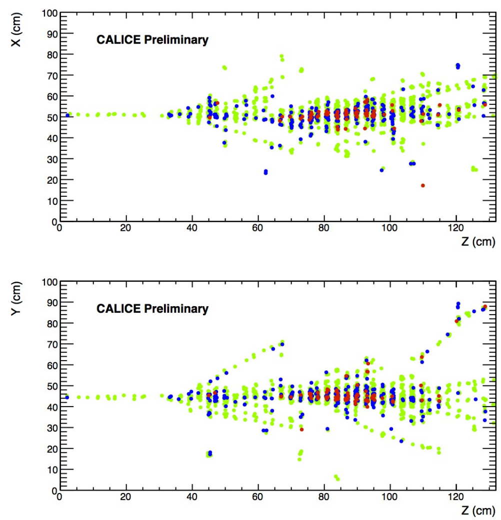
Highly Granular HCAL Concepts

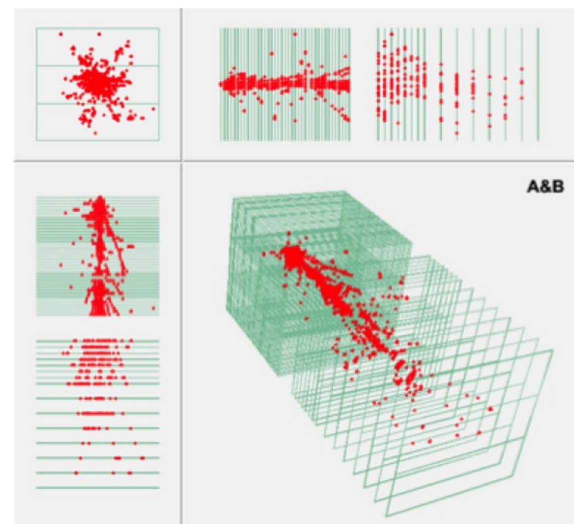
	analog	semi-digital	digital
granularity	3*3 cm^2	1*1 cm^2	1*1 cm^2
technology	scintillator tiles	RPCs (or µMegas)	RPCs (or GEMs)



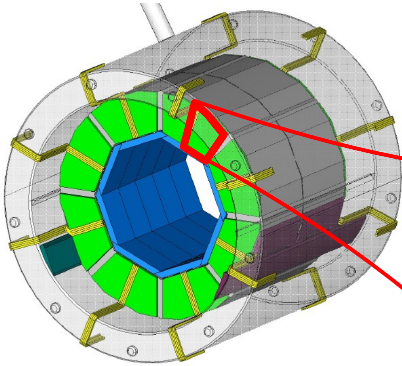




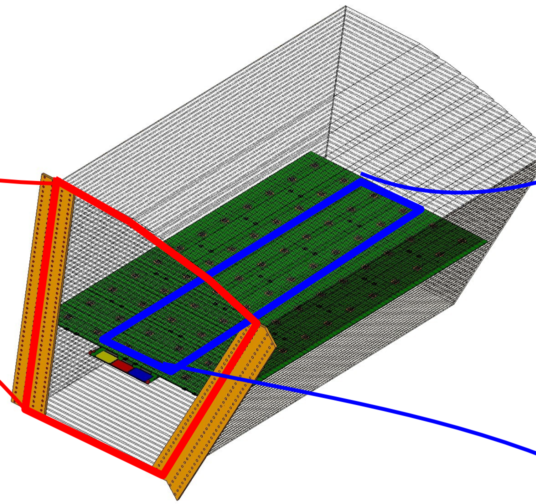


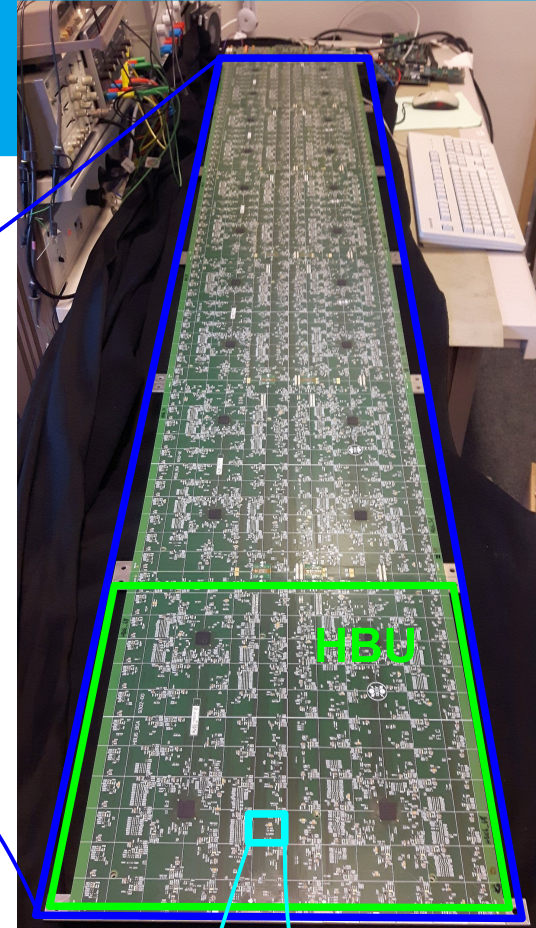


Analog HCAL engineering design

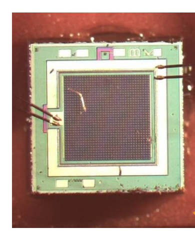


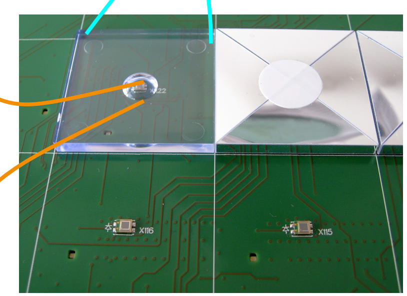
ILD barrel





- 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)



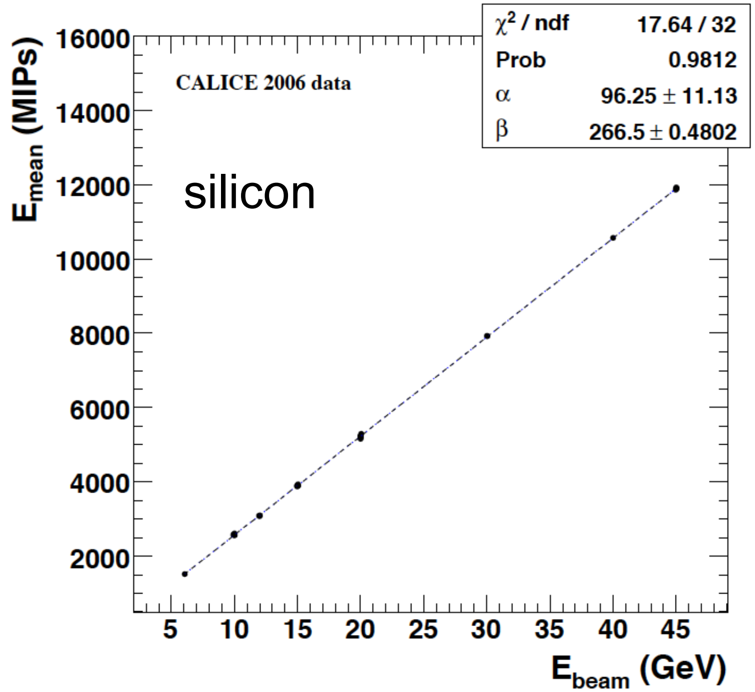


Measurements with Prototypes

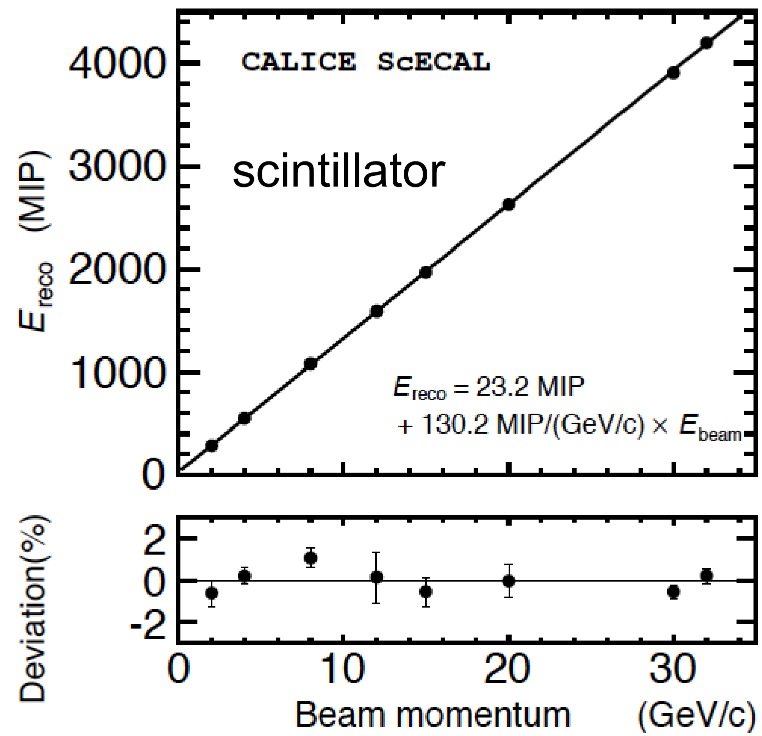
- In test beams you get only single particles, no jets
  ⇒ direct measurement of the jet energy resolution not possible
- Nevertheless, measurements in beam tests provide important information:
  - hands-on experience with (a small version of) the detector
  - calibration of the detector
  - energy resolution 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

Highly Granular ECALs: energy linearity

NIM A608 (2009) 372



NIM A887 (2018), 150



Highly Granular ECALs: energy linearity

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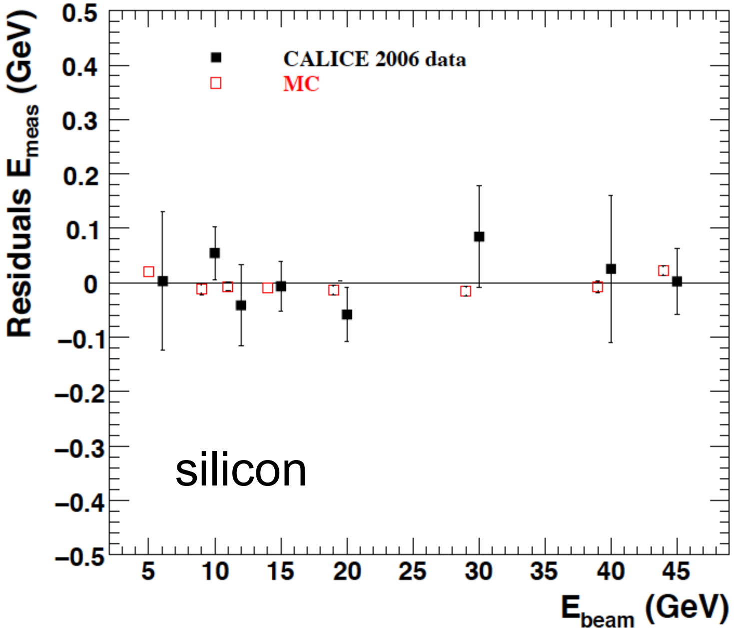
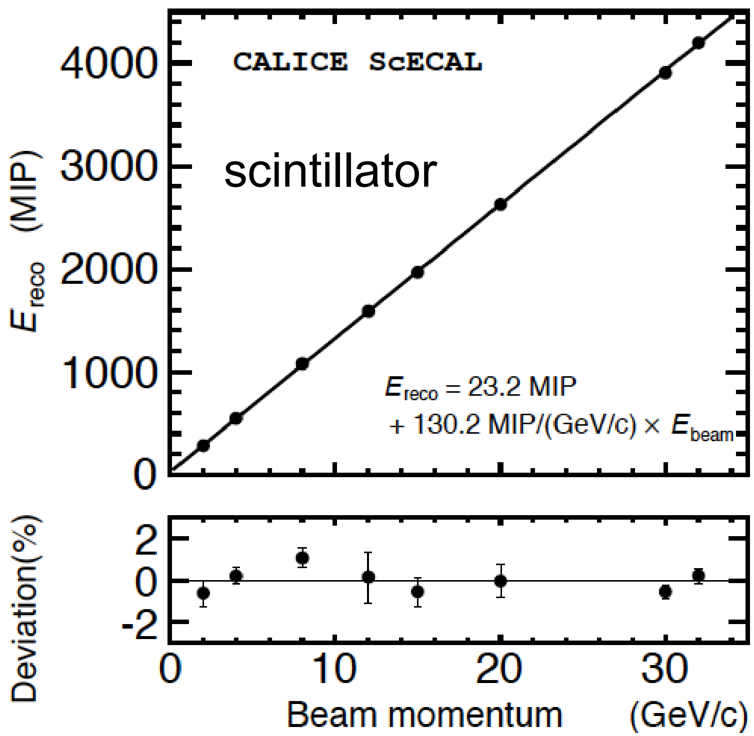


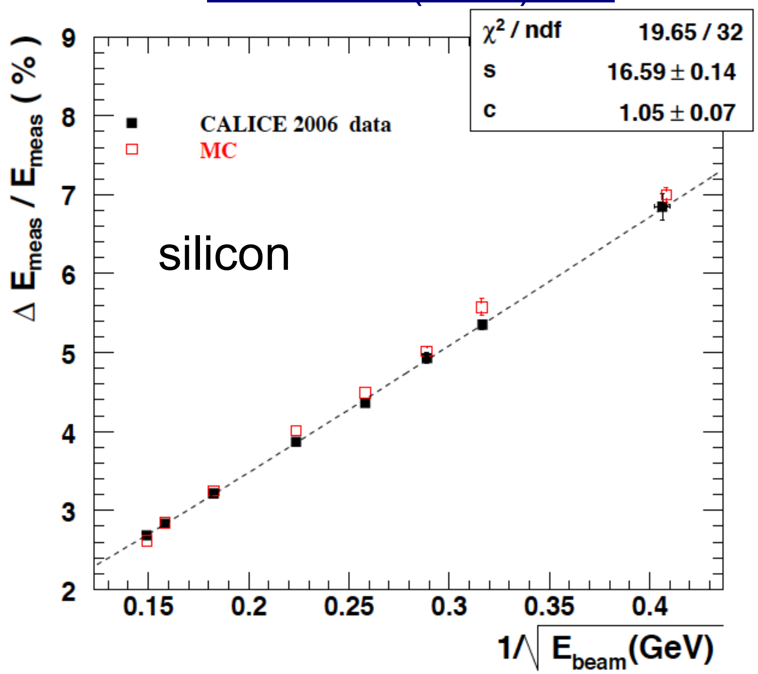
NIM A887 (2018), 150



> energy linearity for electrons better than 100 MeV / 1%

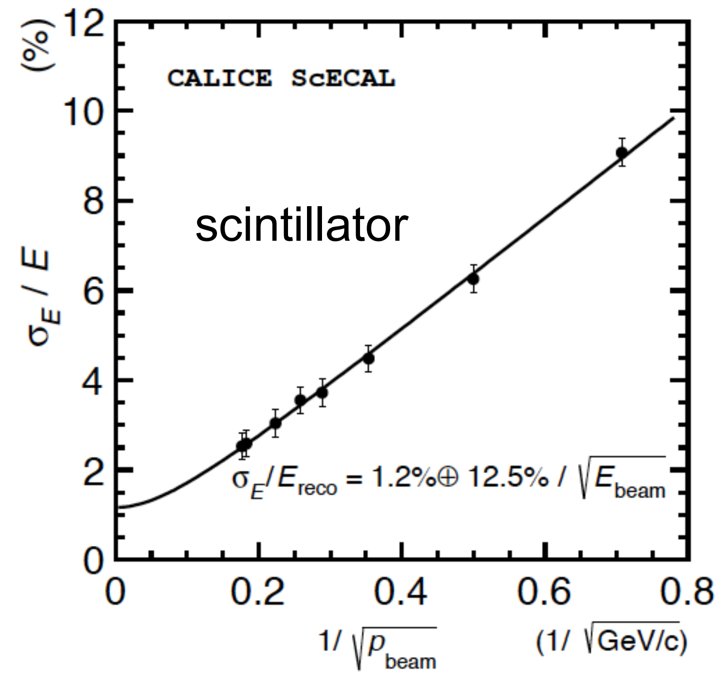
Highly Granular ECALs: energy resolution

NIM A608 (2009) 372



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

NIM A887 (2018), 150



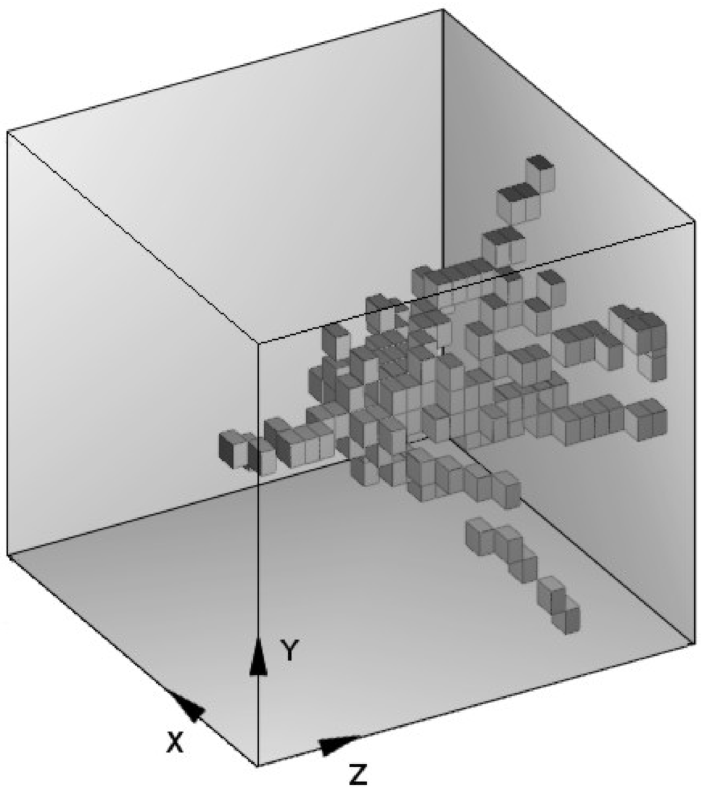
$$\frac{\sigma(E)}{E} = \left(\frac{12.5 \pm 0.4}{\sqrt{E}} \oplus (1.2 {}^{+0.6}_{-0.7})\right)\%$$

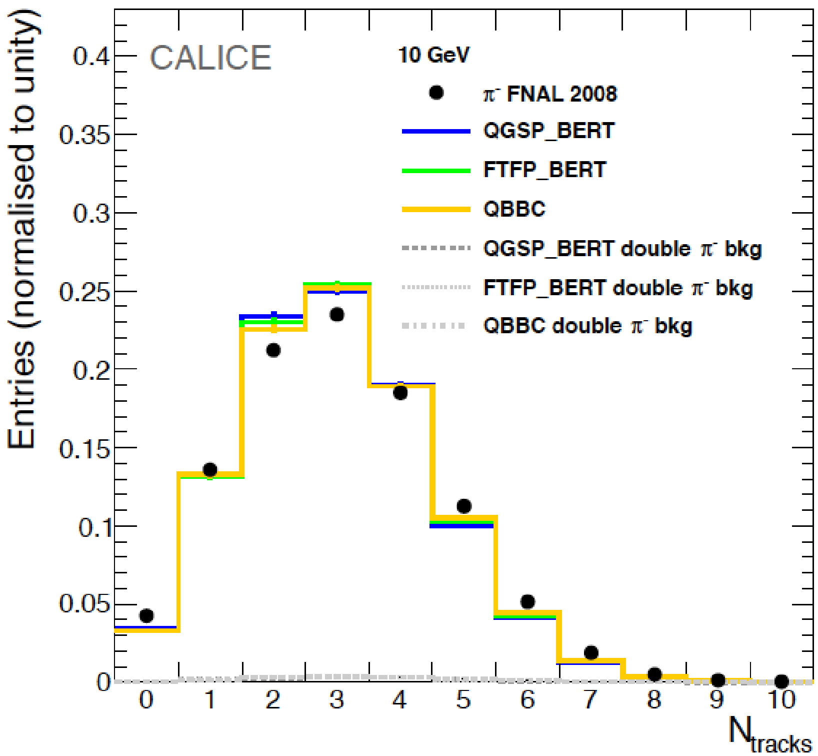
- reasonable energy resolution for electromagnetic showers (c.f. CMS ECAL: $3\%/\sqrt{E} \oplus 0.2/E \oplus 0.3\%$, ATLAS ECAL: $10\%/\sqrt{E} \oplus 0.2/E \oplus 0.2\%$)
- these ECALs are optimised for granularity, not single particle energy resolution

Hadrons in a Highly Granular ECAL

- high granularity in ECAL is also important for the measurement of hadrons

NIM A937 (2019) 41

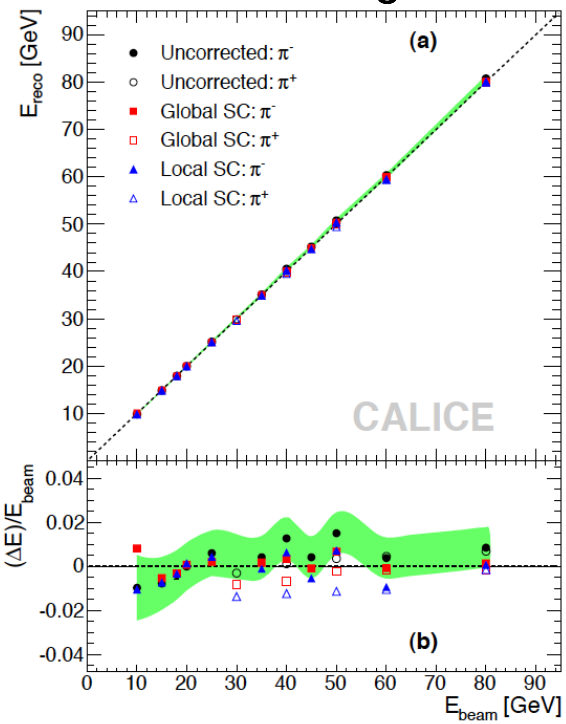




Highly Granular HCALs: energy linearity (pions)

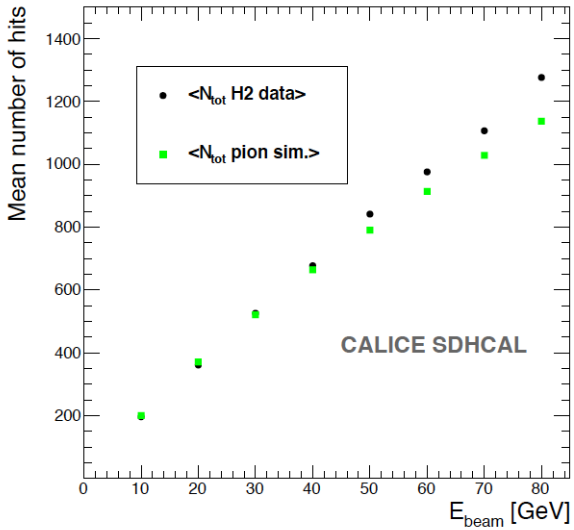
JINST 7 (2012) P09017

Analog HCAL



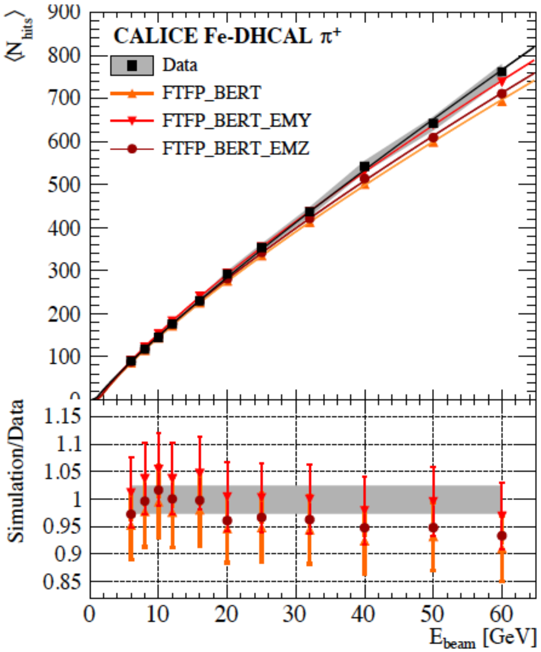
JINST 11 (2016) P04001

Semi-Digital HCAL



NIM A937 (2019) 41-52

Digital HCAL



linear response to hadrons

at the 1-2% level

non-linear response

deviations from linearity due to finite readout pad size

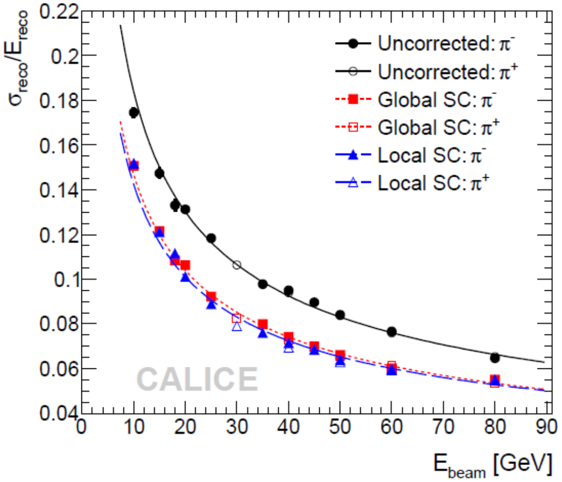
needs to be taken into account in energy reconstruction

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

Highly Granular HCALs: energy resolution (pions)

[JINST 7 (2012) P09017](#) | [JINST 11 (2016) P04001](#) | [NIM A937 (2019) 41-52](#)

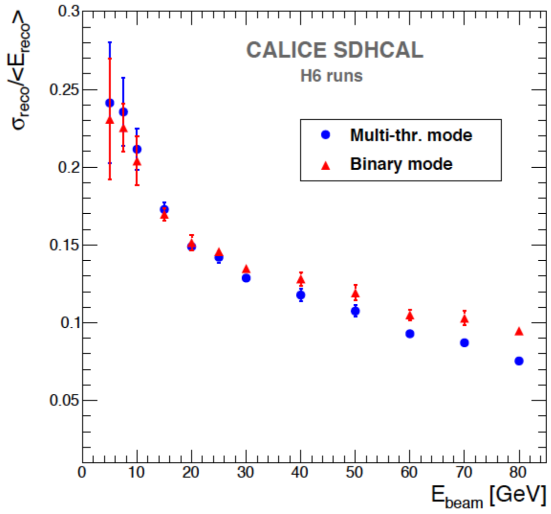
Analog HCAL



"classical" energy sum:

$$\frac{\sigma(E)}{E} = \left(\frac{57.6}{\sqrt{E}} \oplus (1.6)\right)\%$$

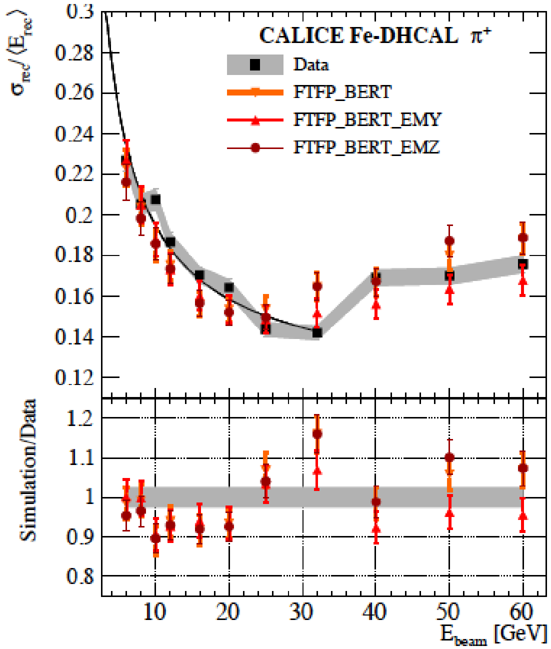
Semi-Digital HCAL



measurement with
1 or **3** thresholds

3 thresholds improve resolution at large energies

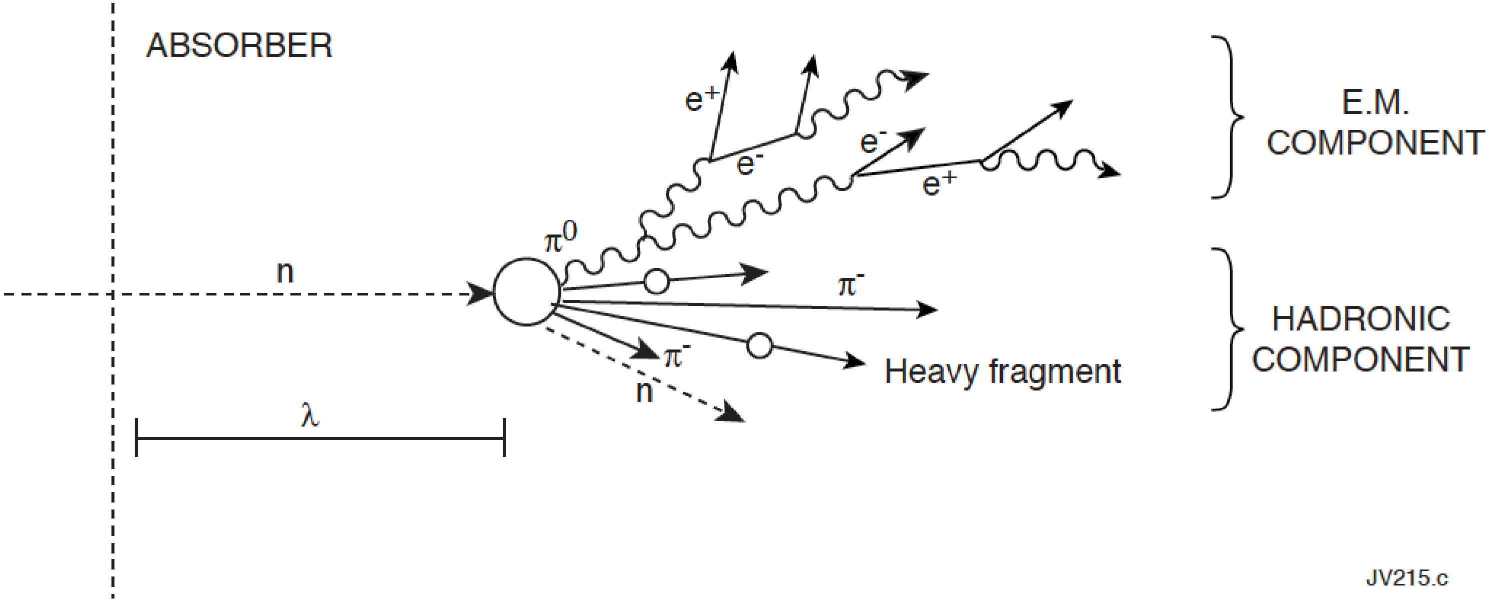
Digital HCAL



resolution degrades at large energies

Software Compensation: Idea

- non-compensating calorimeters show different signals for electromagnetic and hadronic showers
- hadronic showers include electromagnetic sub-showers, and the electromagnetic fraction varies strongly from shower to shower
  - the different response to the electromagnetic and hadronic part of the shower lead to a significantly worse energy resolution
- idea: in the reconstruction, use different weights for electromagnetic and hadronic sub-showers

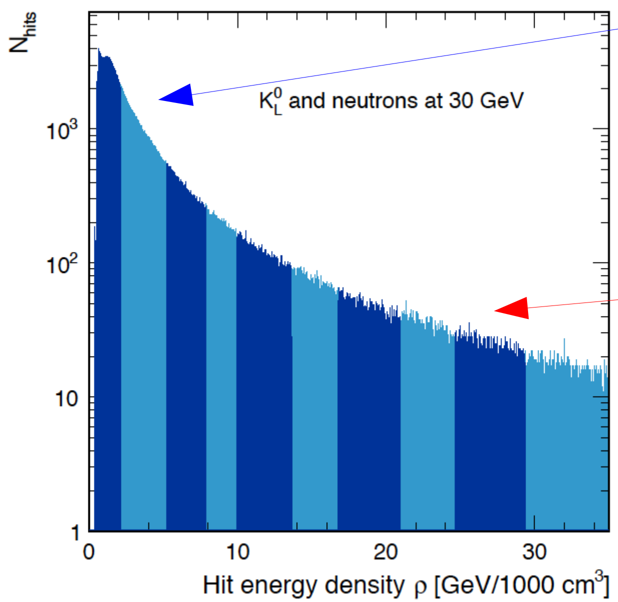


from T.S. Virdee, CERN-OPEN-2000-261

Software Compensation: Procedure

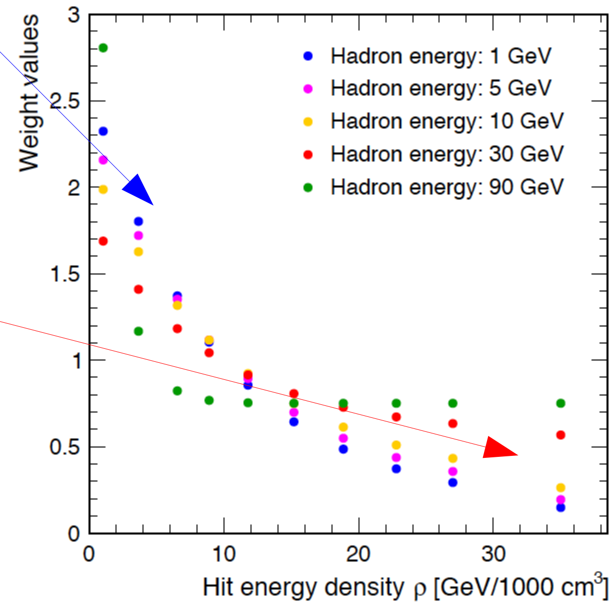
- “identify” the parts of the shower by their energy density
  - high energy-density (ρ) hits with EM sub-shower
  - low energy-density hits with hadronic shower component
- weight:
  - decrease weight for EM hits
  - increase weight for hadronic hits
  - weights depend on cluster energy, use simple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

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



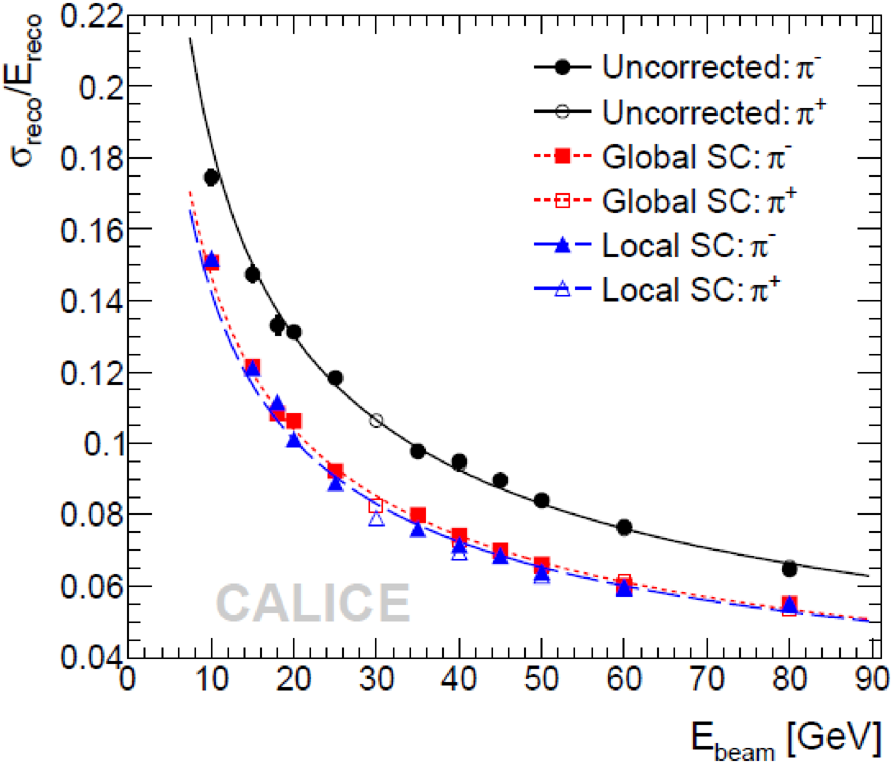
hadronic

EM



Software Compensation for Single Particles

JINST 7 (2012) P09017

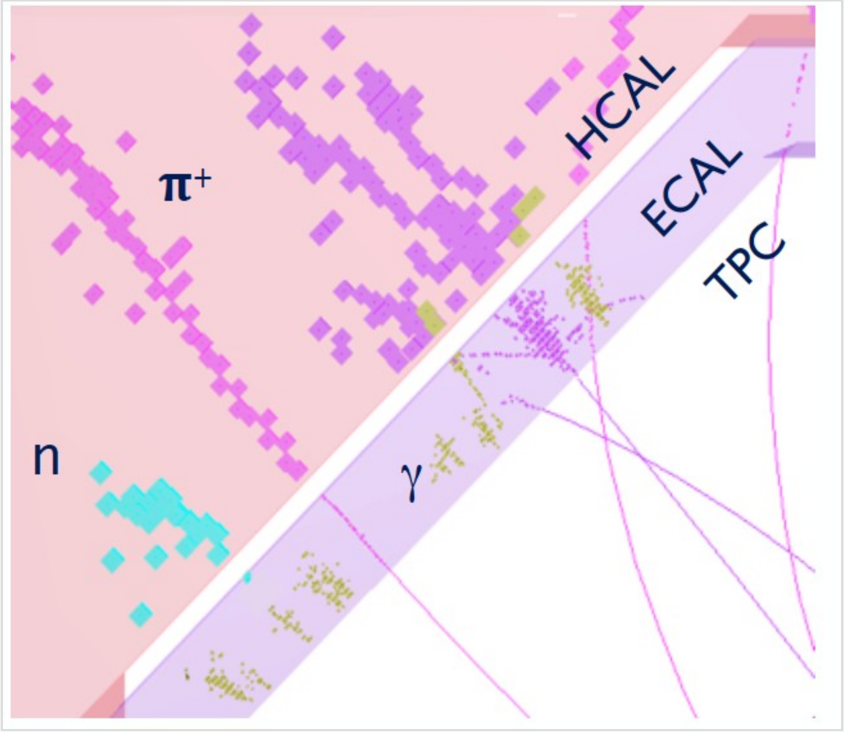


$$\frac{\sigma(E)}{E} = \frac{44.3 \pm 0.3\,\%}{\sqrt{E}} \oplus 1.8 \pm 0.3\,\% \oplus \frac{0.18\,\mathrm{GeV}}{E}$$

- Software compensation can improve single particle energy resolution significantly
- Software compensation is only possible if detailed (highly granular) information is available to distinguish the shower parts

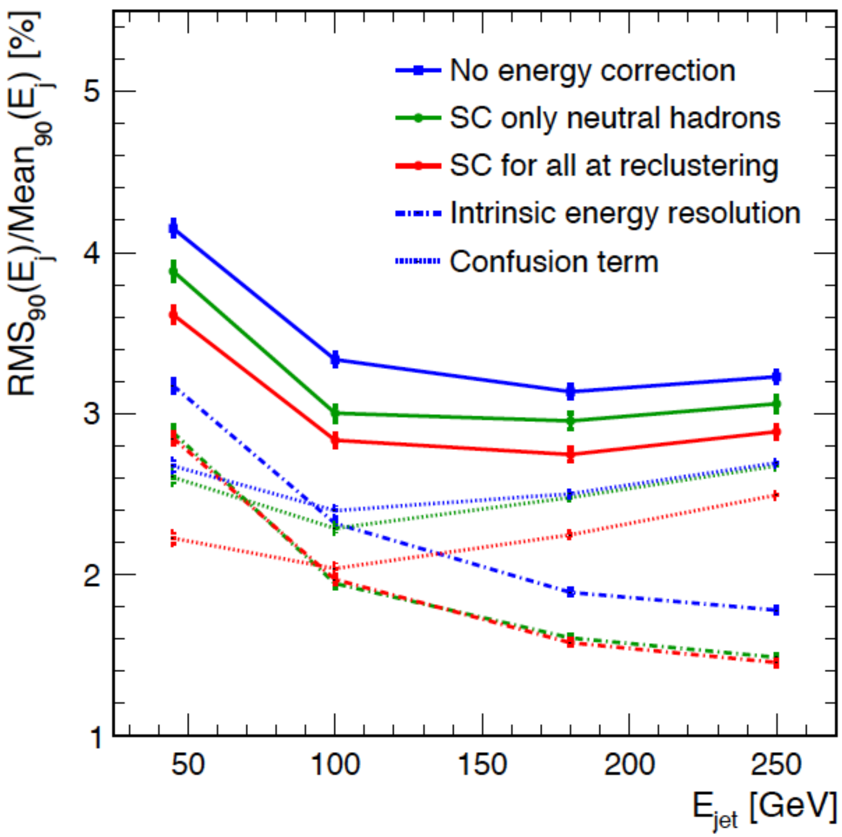
Software Compensation in Particle Flow Reconstruction

- software compensation successfully tested for single hadrons in testbeam data
- possible improvements due to software compensation in particle flow reconstruction
  1) better single neutral hadron energy reconstruction
  2) better track – cluster matching leading to less confusion
- implementation in PandoraPFA particle flow reconstruction
  - in the cluster energy estimation: 1)
  - in the pattern recognition reconstruction: 1) and 2)
- studies shown are done with simulation of (generic) ILD detector



Software Compensation in PandoraPFA: Jets

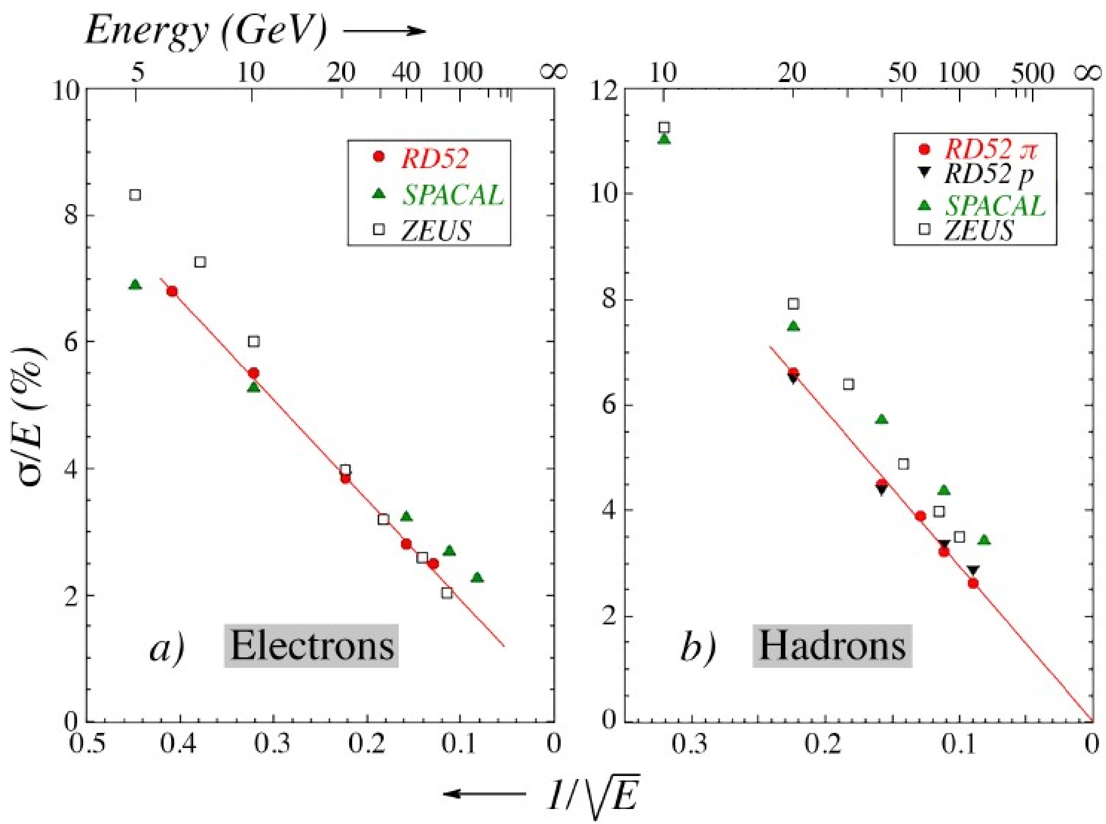
EPJ C77 (2017) 698



- application of software compensation in PandoraPFA to simulated *uds* jets
- significant improvement in the jet energy resolution (JER)
  - contribution of the intrinsic energy resolution to the JER: effect similar to single hadrons
  - confusion term only affected by application of software compensation in pattern recognition
  - total JER: application in pattern recognition clearly better than application in cluster energy estimation only

Comparison to Compensating and Dual Readout Calos

- Could we do better with a compensating or a Dual Reaodut calorimeter?
  - ZEUS, SPACAL: calorimeters designed to be compensating
  - RD52: dual readout calorimeter that uses Cerenkov and Scintillating fibres to measure (and correct for) electromagnetic fraction event-by-event



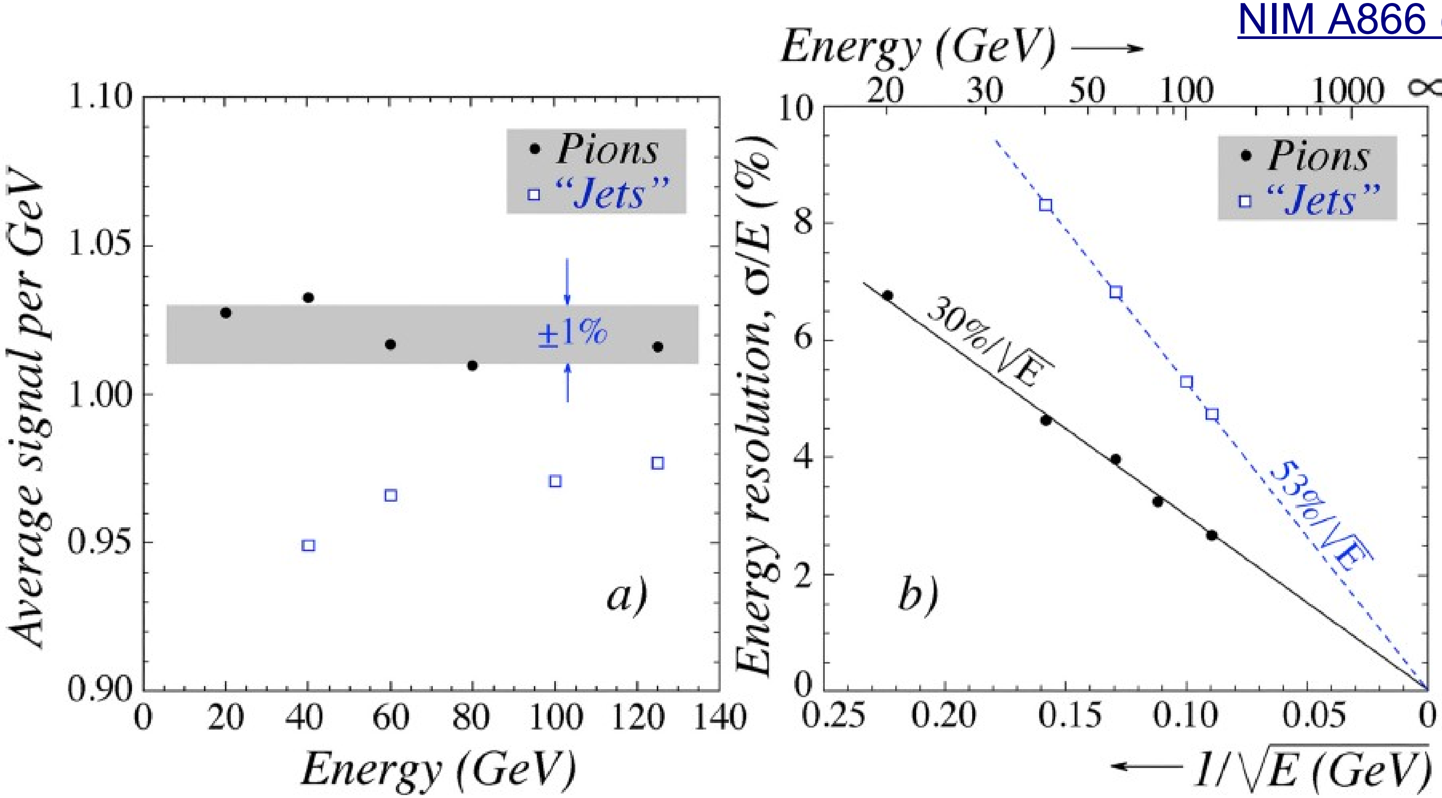
With Dual Readout, reach single particle energy resolution of ca. 30%/√E

NIM A882 (2018) 148

Dual Readout Calorimetry for Jets

- Cannot produce jets in testbeam, but can use particles interacting before the main calorimeter to mimic “jets”

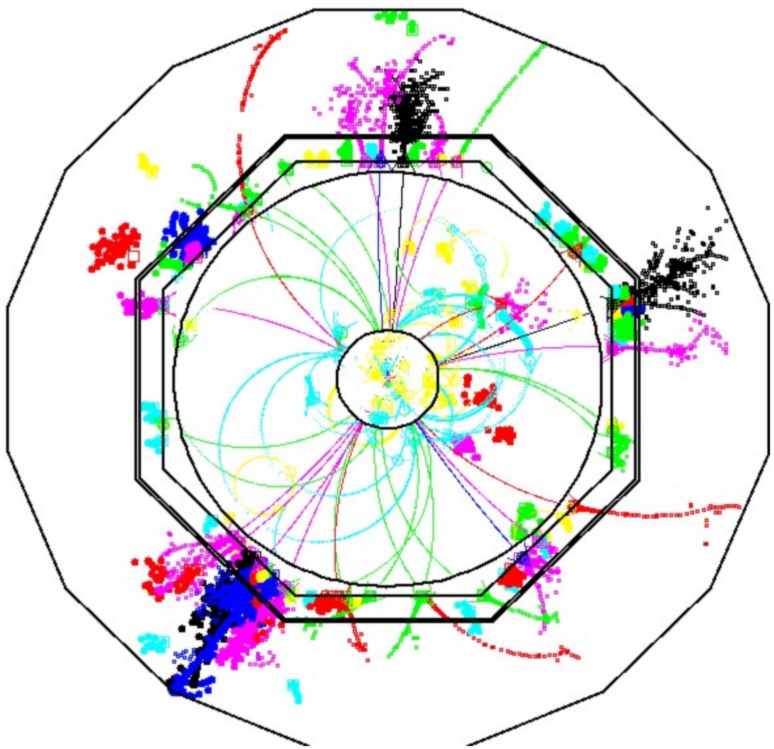
NIM A866 (2017) 76



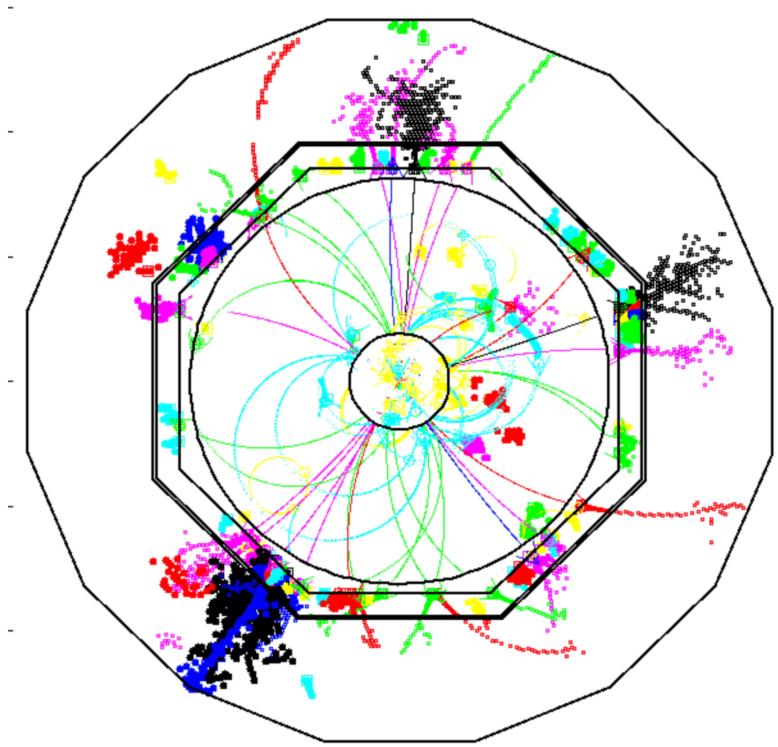
- Dual Readout energy resolution significantly worse for “jets”, not compatible with separation of hadronic W and Z decays

High Granularity: How small should the cells be?

1*1 cm^2 HCAL cell size

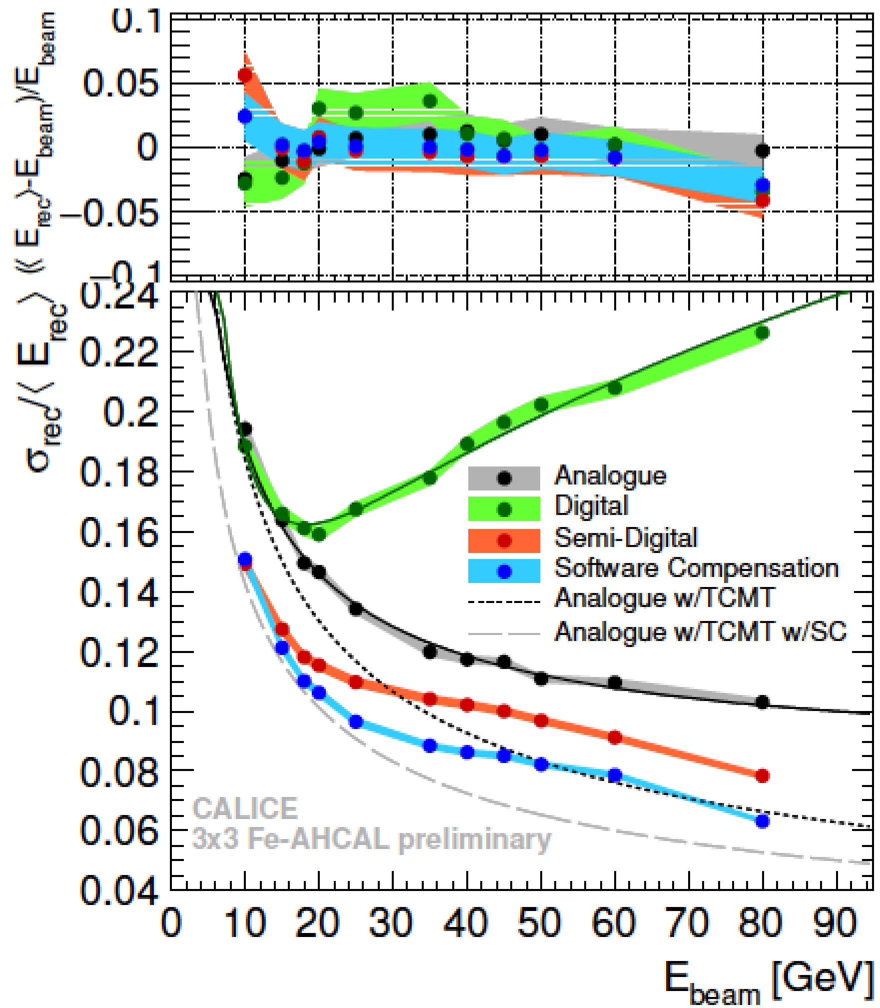


3*3 cm^2 HCAL cell size



Cell size vs. Reconstruction Algorithm

- the HCAL concepts differ in several aspects
  - active medium
  - granularity
  - energy reconstruction method
- 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



CAN-049a

Cell size vs. Reconstruction Algorithm

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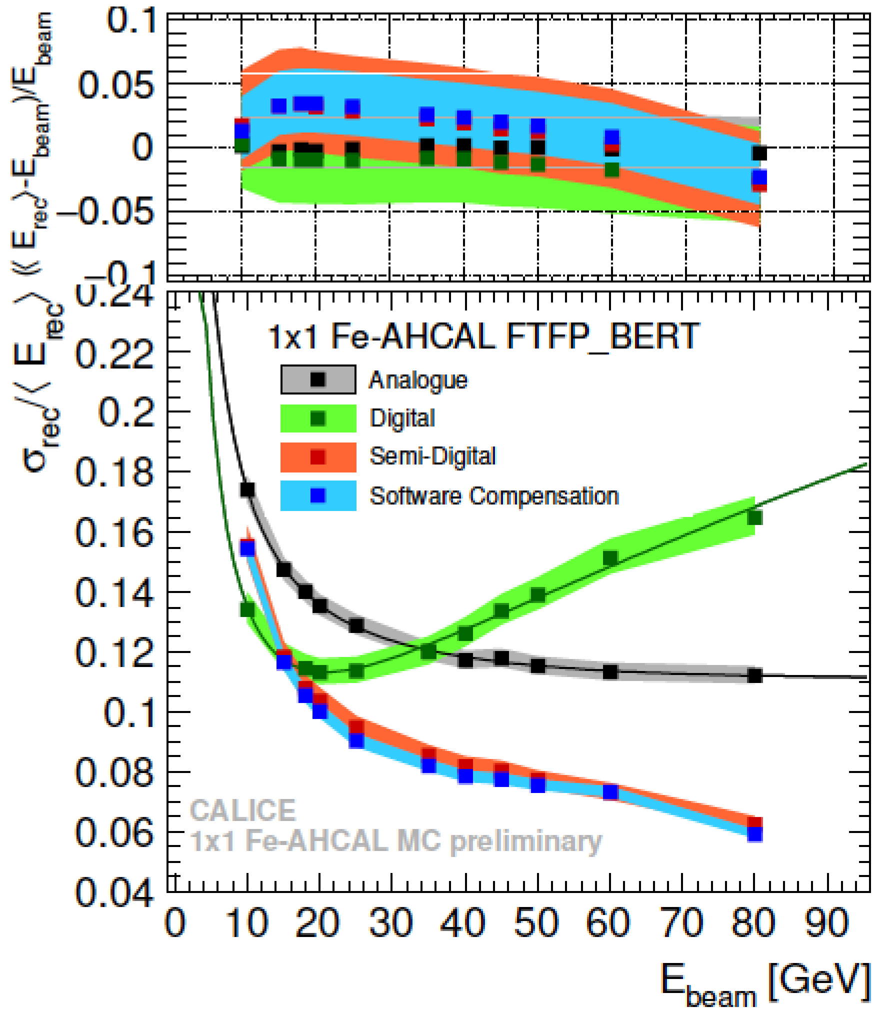
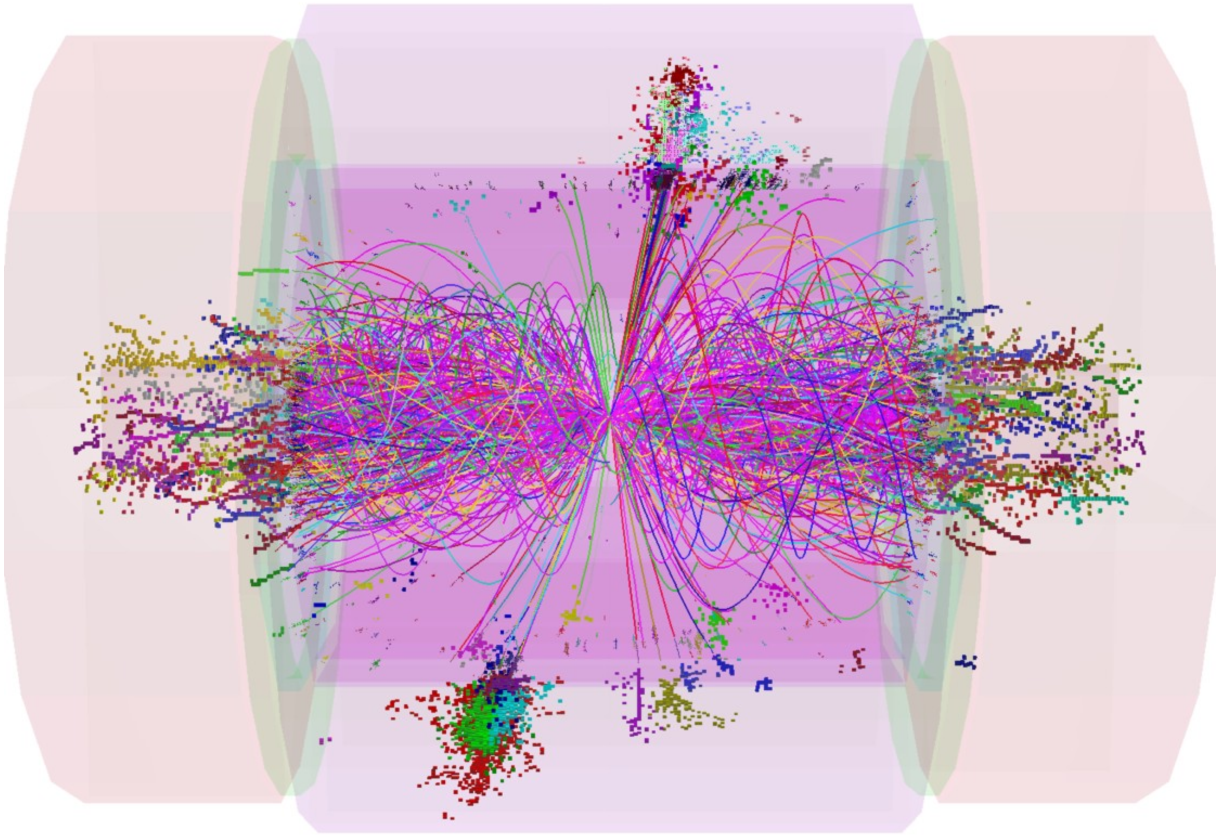
  - 3*3 cm² AHCAL data with different reconstruction methods
  - 1*1 cm² AHCAL simulation with different reconstruction methods

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



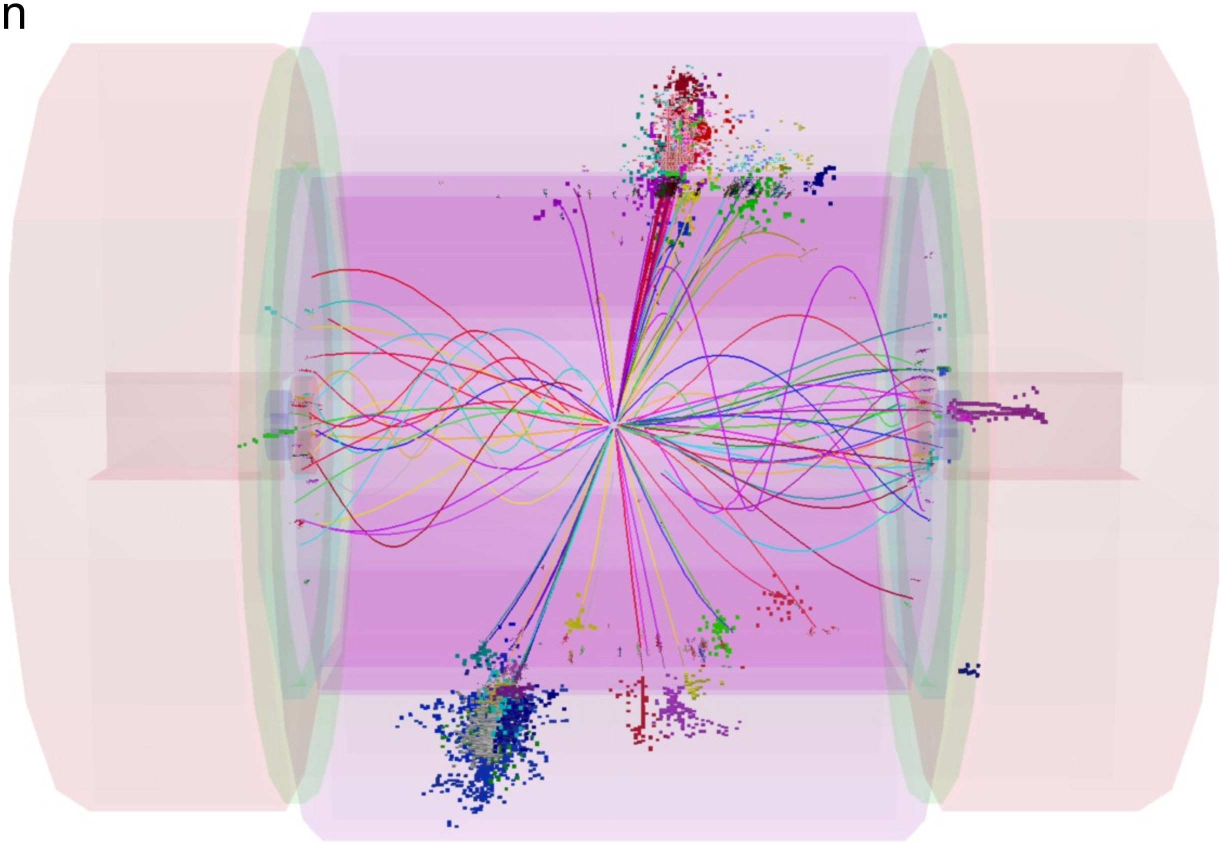
Granularity and Timing for Background (Pileup) Rejection

- CLIC: bunch trains with 0.5 ns bunch distance
  - simulated event √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

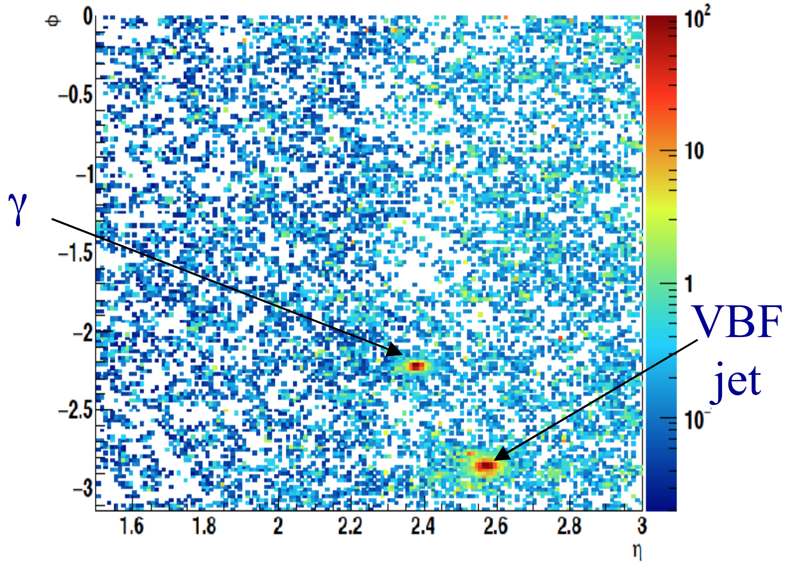


- Together with good time resolution, granularity enables efficient pileup rejection

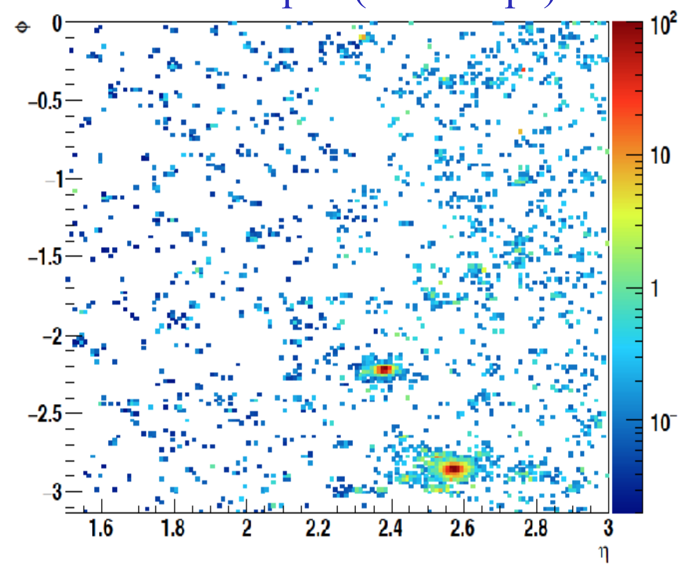
Granularity and Timing for Background (Pileup) Rejection

- 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

No timing cut



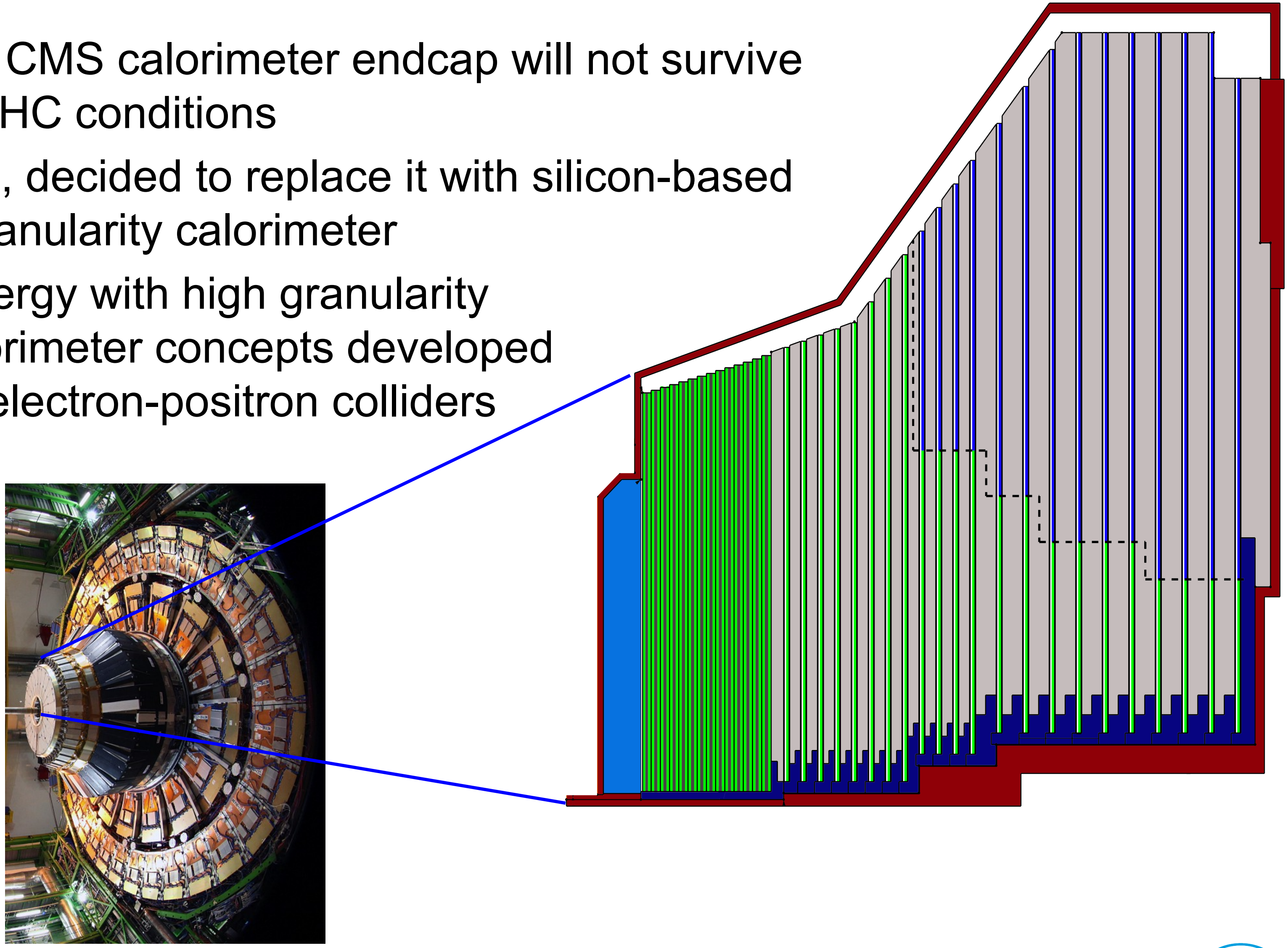
Cut $\Delta t < 90$ps (3σ at 30ps)



Plots show cells with Q > 12fC (~3.5 MIPs @300mm - 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: $1.5 < |\eta| < 3.0$

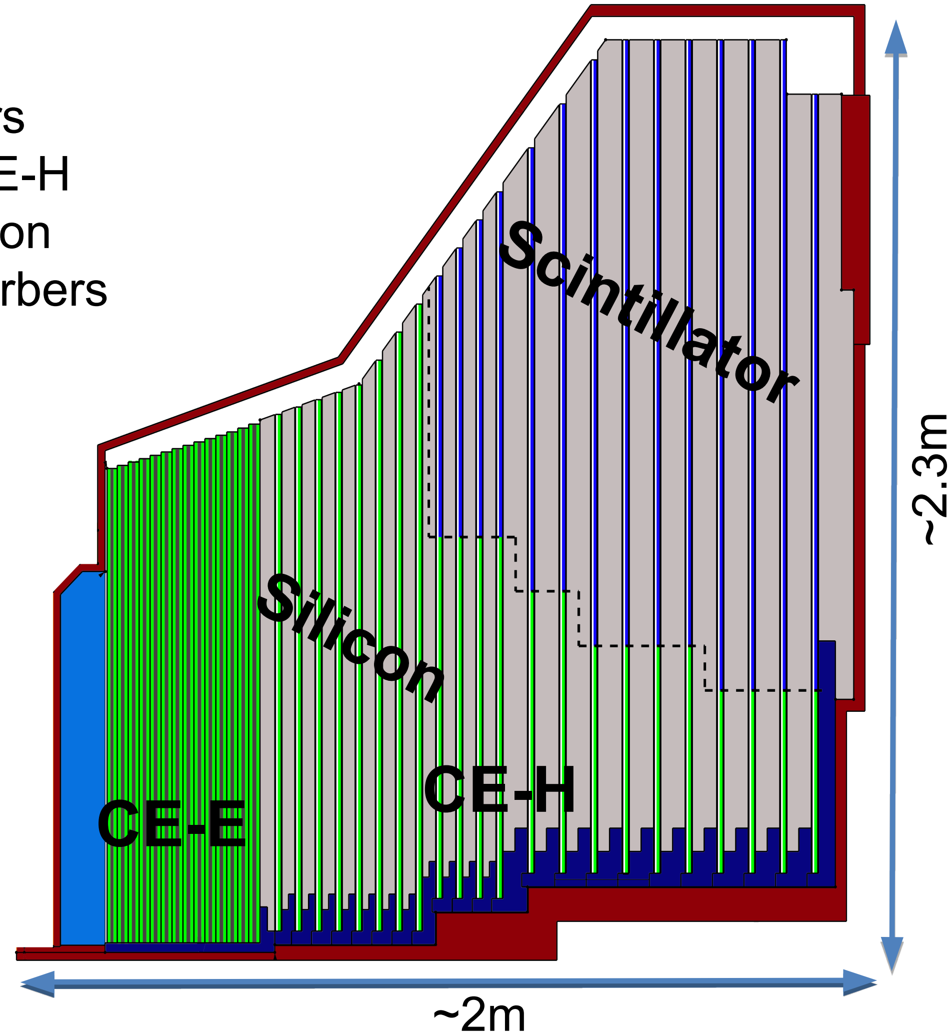
Full system maintained at -35°C

~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

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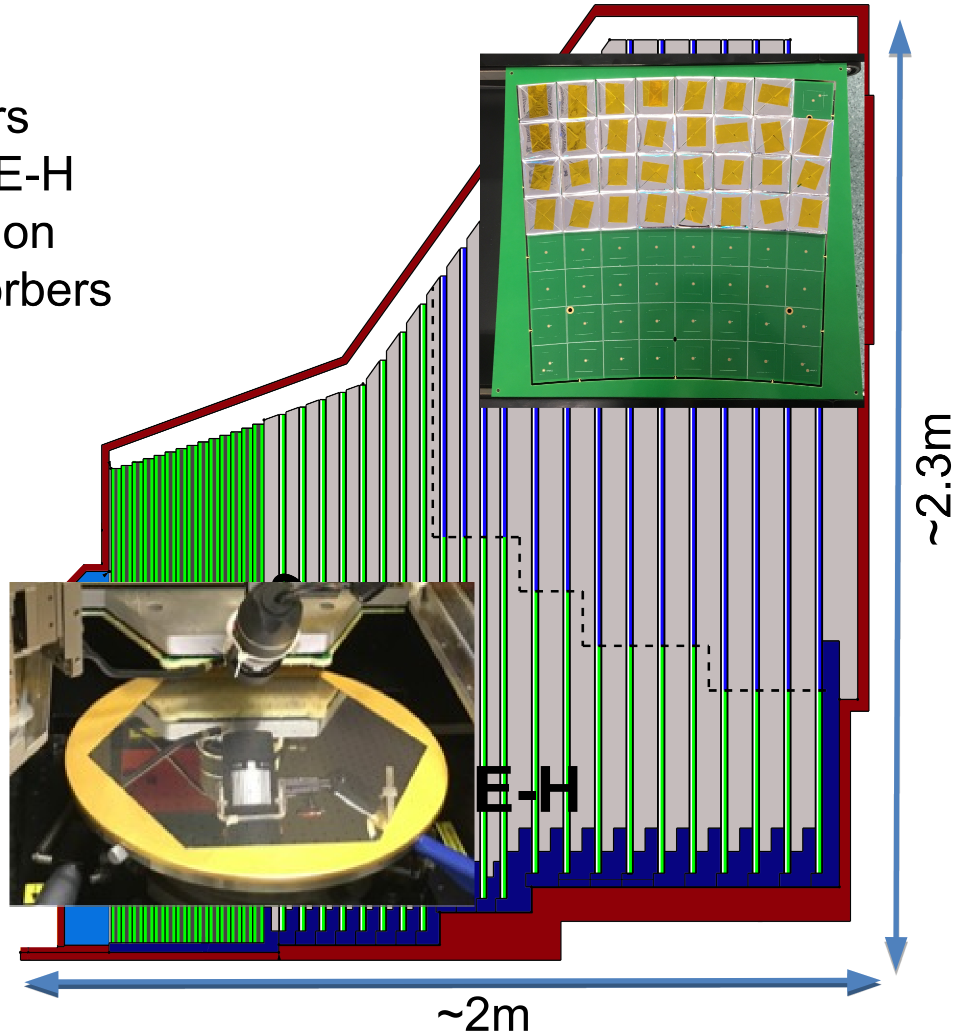

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Comparison "Classic" Calo vs. PFA Calo

- few large cells
  - few readout channels
  - large dynamic range
  - precise calibration of each cell needed
- (typically) better single particle resolution
- average pileup subtraction

- many small cells
  - complex (integrated) readout
  - smaller dynamic range
  - precise calibration only of averages needed
- (typically) worse single particle energy resolution
- event-by-event pileup rejection
- sophisticated shower reconstruction algorithms possible

optimal calorimeter depends on the purpose

highly granular calorimeters pose different challenges

Summary

- very good jet energy resolution cannot be reached by calorimeters alone
- Particle Flow Algorithms can help
  - improvements for existing detectors
  - full power when detector design is optimised, requiring highly granular calorimeters
- highly granular calorimeters offer further advantages
  - software compensation
  - pileup rejection

Summary

- very good jet energy resolution cannot be reached by calorimeters alone
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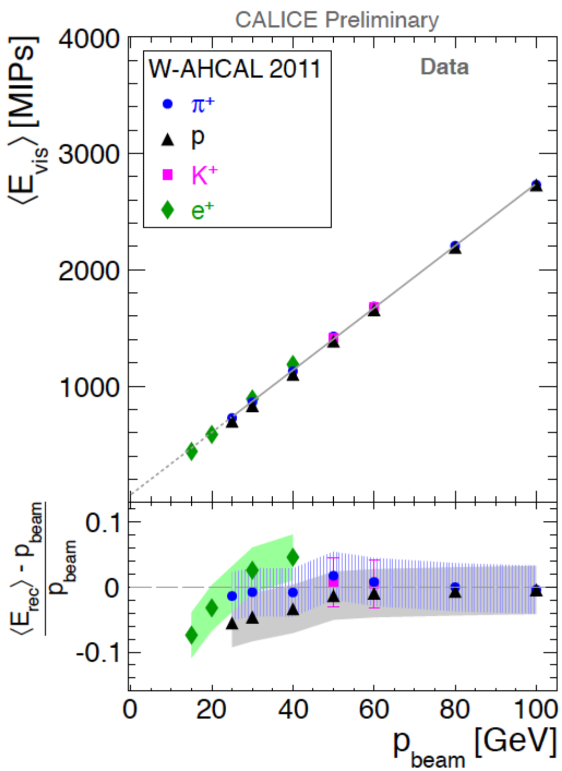
- highly granular calorimeters offer further advantages
  - software compensation
  - pileup rejection

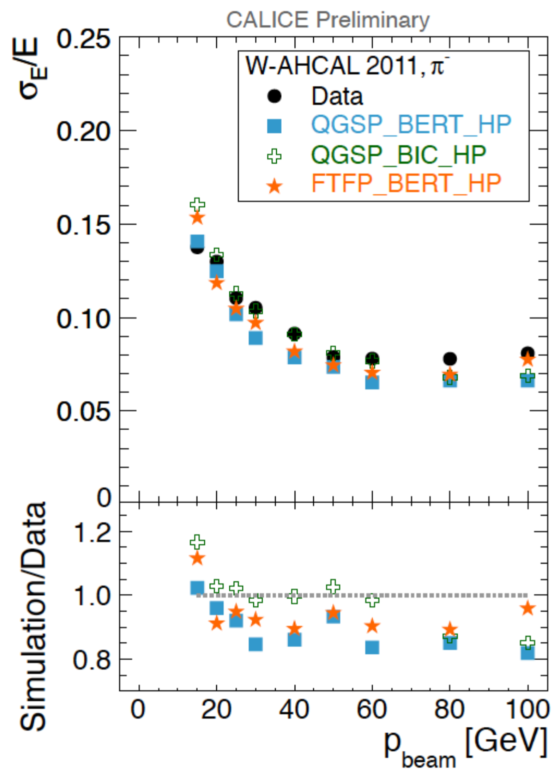
Thank You for Your Attention!

Backup

Tungsten as HCAL Absorber

- for CLIC, jet energies up to 1.5 TeV are expected
- tungsten absorber in HCAL allows for more compact HCAL
- study the impact of tungsten as absorber material in AHCAL

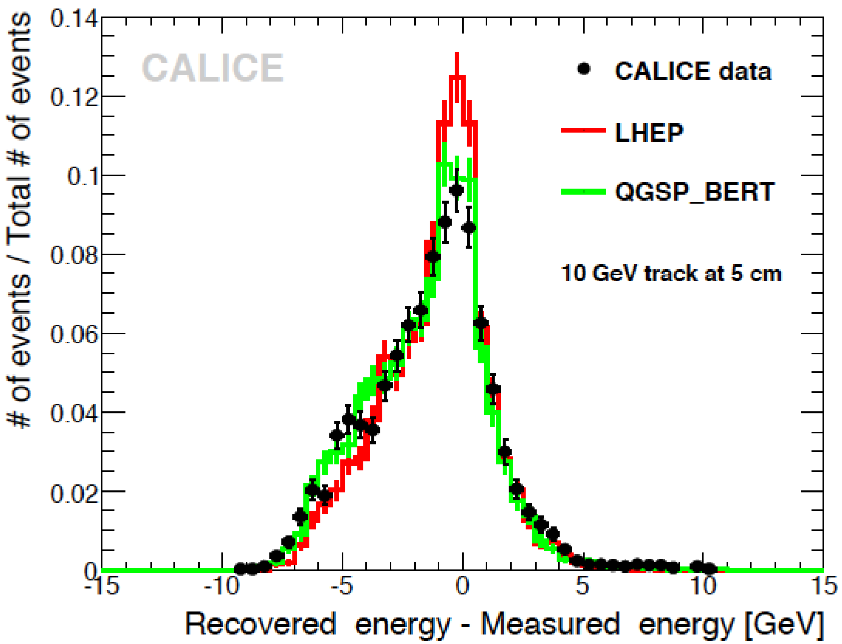


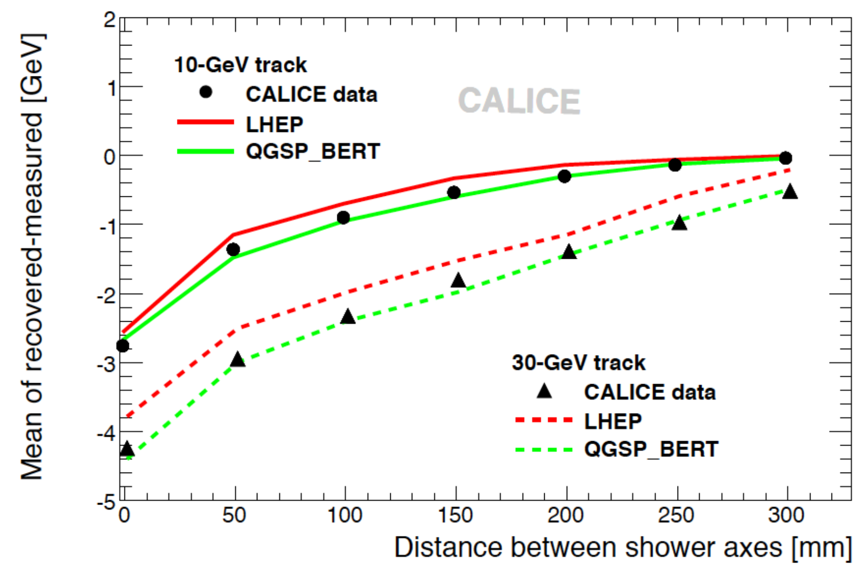


- nearly compensating at ~20-40 GeV for the used tungsten thickness
- resolution similar to iron absorber

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 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 up-to-date physics list



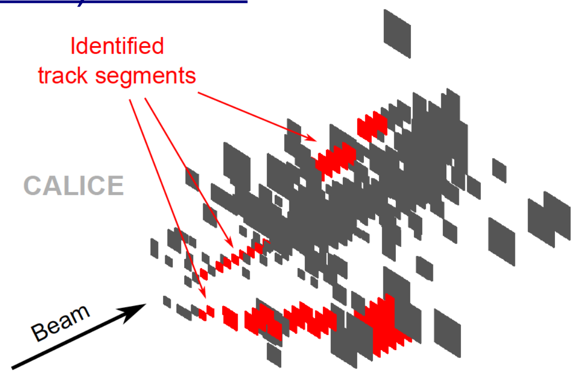


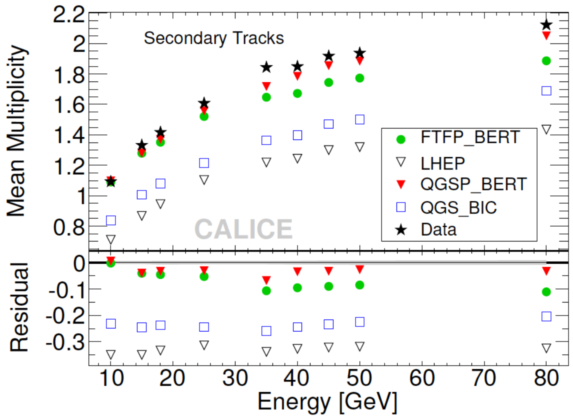
Comparison with simulation: shower sub-structure

- track segments within hadron showers

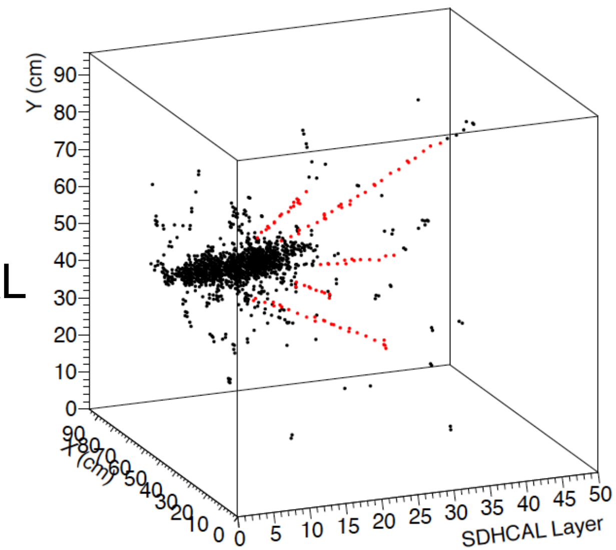
[JINST 8 (2013) P09001]

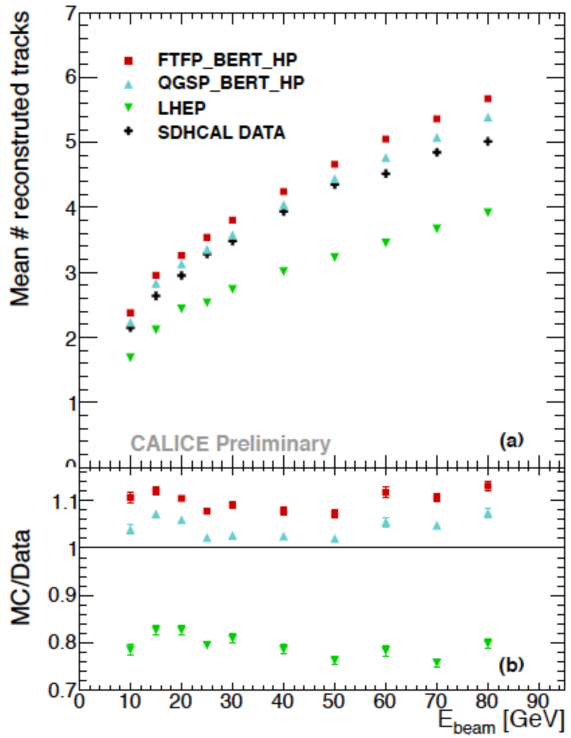
AHCAL





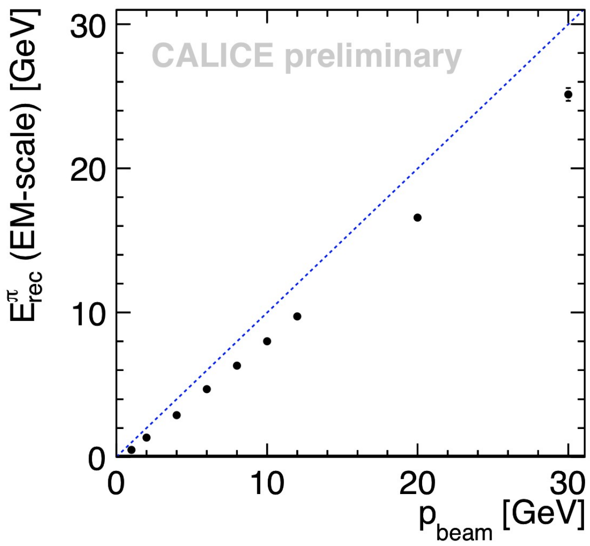
SDHCAL

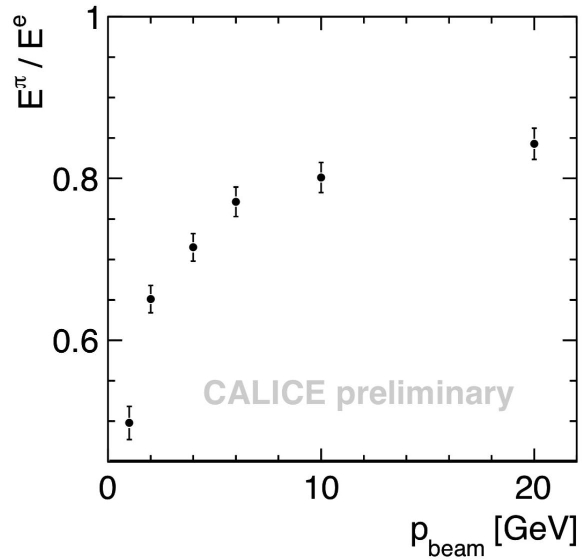


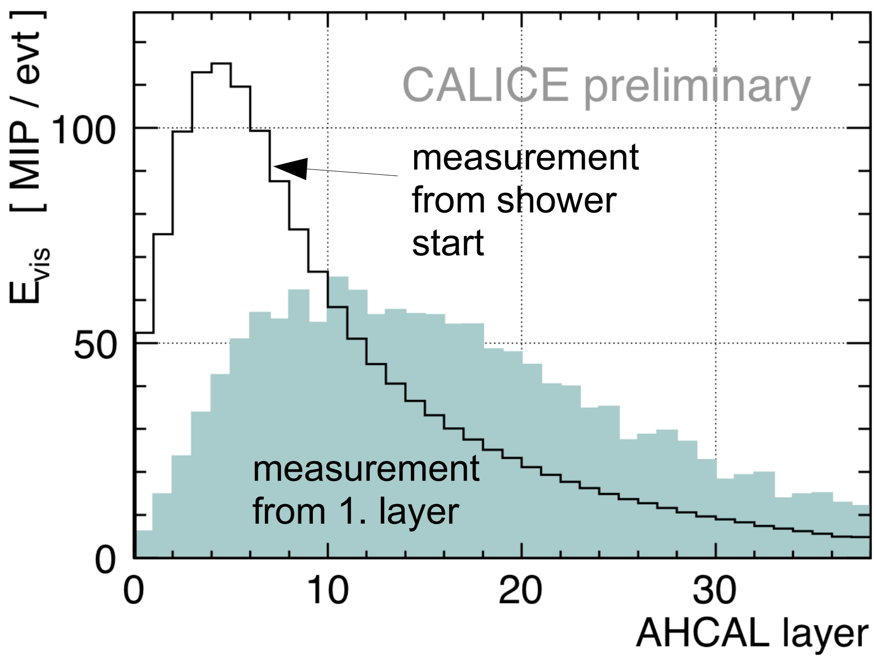


CAN-047

AHCAL Characteristics

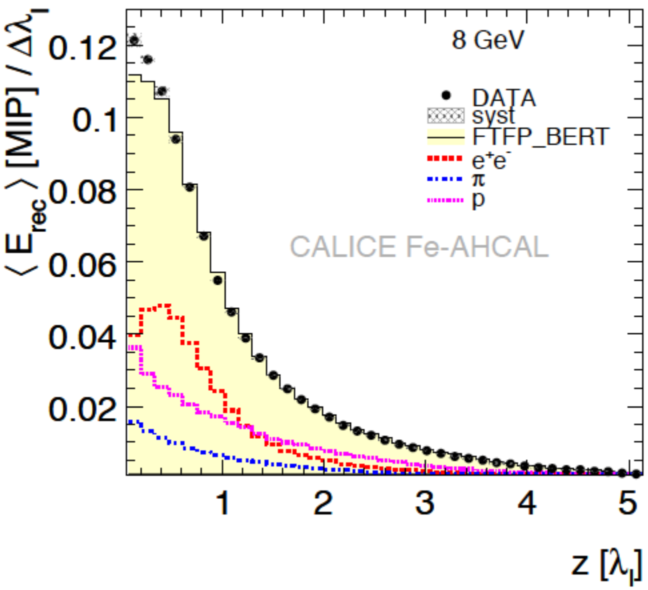


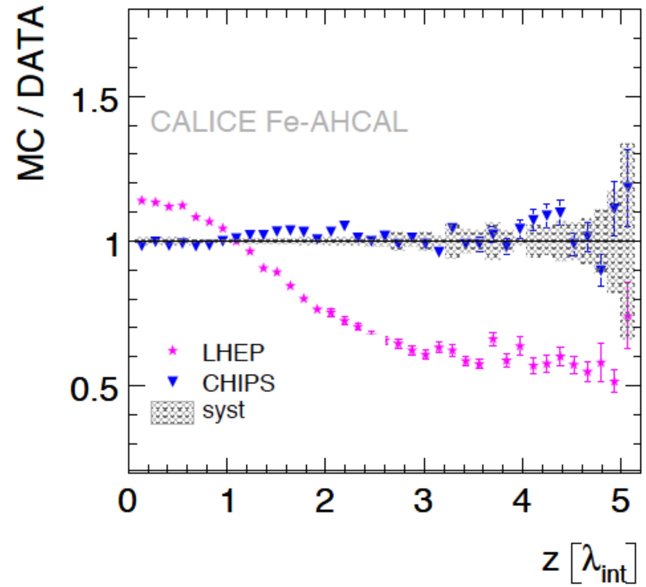


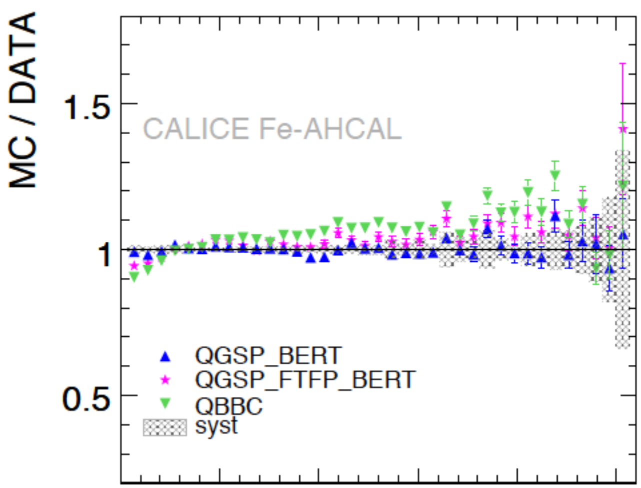


- non-compensating calorimeter: measured energy for hadrons smaller than for electrons of the same energy
- high granularity allows for detailed studies of shower shapes

Comparison of Hadron Showers in Data and Simulation



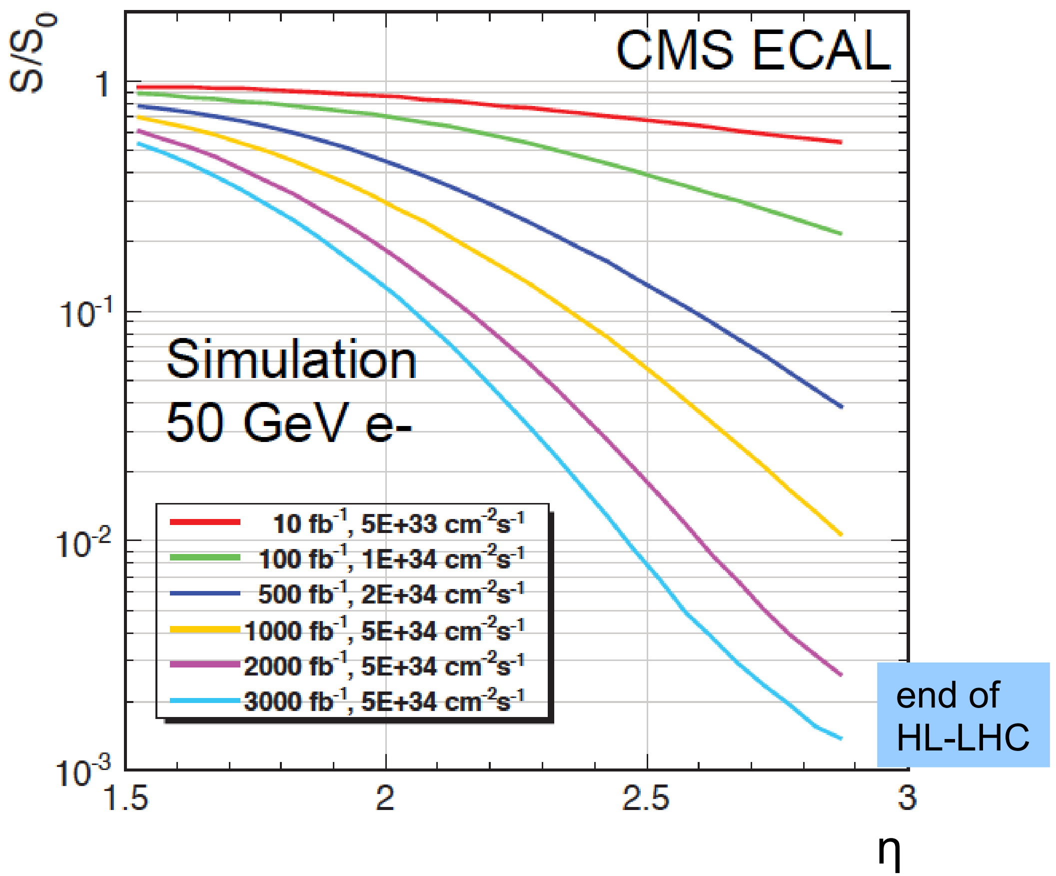




- longitudinal shower development for 8 GeV π^-
- various 'physics lists' in GEANT4, e.g.:
  - LHEP: parameterization of old measurements
  - FTFP_BERT, QGSP_BERT: combination of physics motivated models
- good description by up-to-date models

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



CALICE

Calorimeter R&D for the ... and beyond

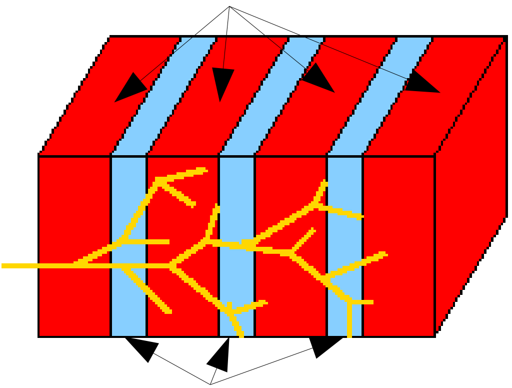
~360 physicists/engineers from 60 institutes and 19 countries from 4 continents

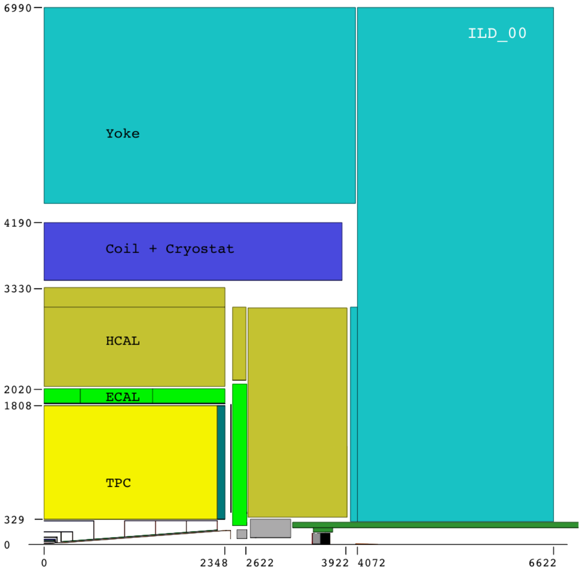
- Integrated R&D effort

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

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





The International Linear Collider

- e^+e^- Collider with center of mass energy up to $\sqrt{s}$ = 500 GeV possible upgrade to $\sqrt{s}$ = 1 TeV
- 31 km long, superconducting cavities for acceleration
- mature technology

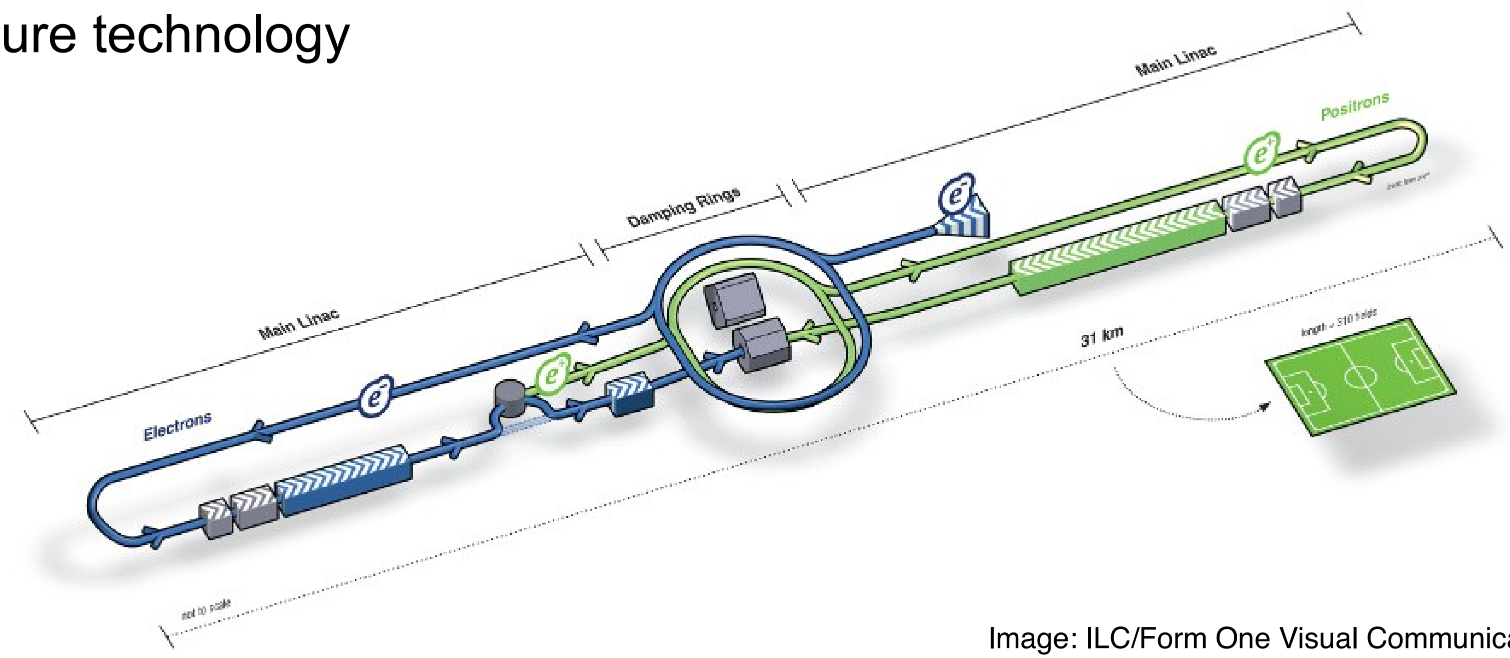
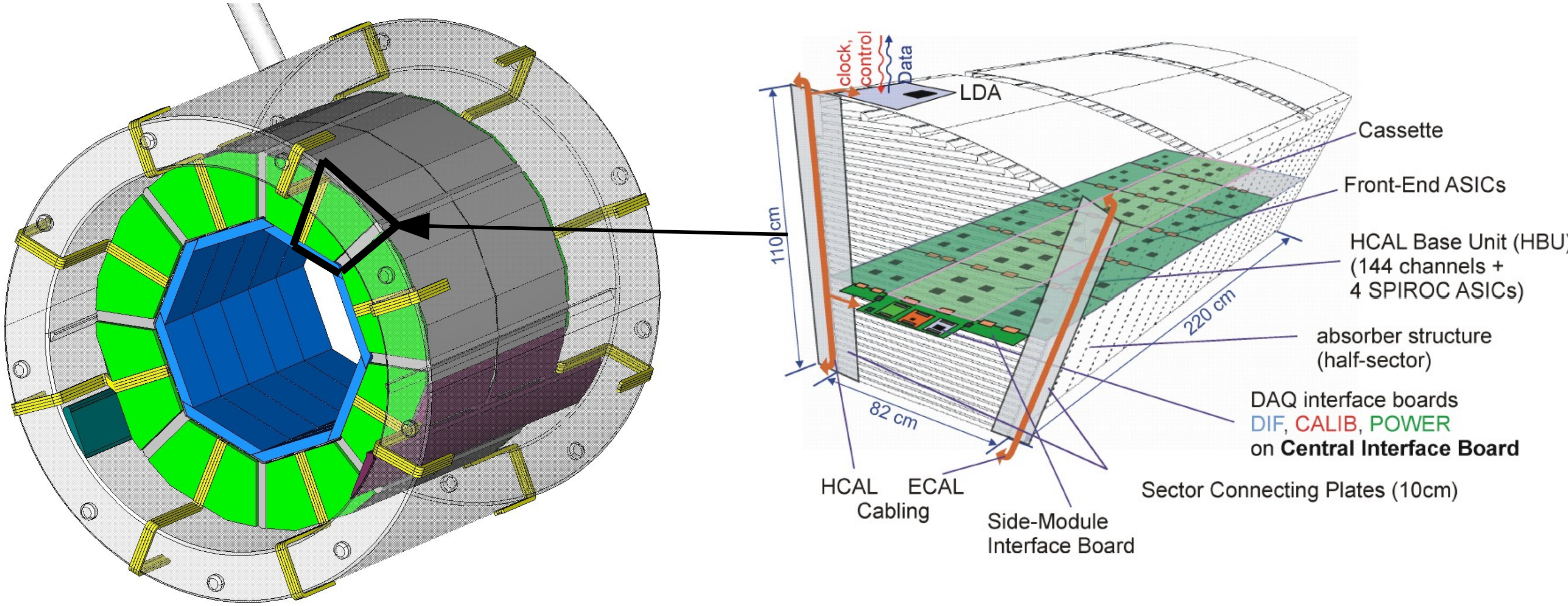


Image: ILC/Form One Visual Communication

- alternative concept: CLIC, novel technology, up to $\sqrt{s}$ = 3 TeV

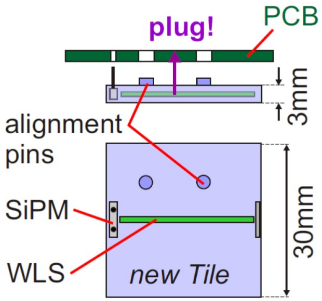
AHCAL: From Physics Prototype to Engineering Prototype

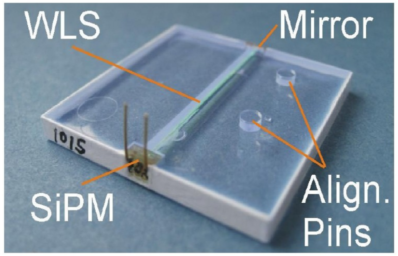
- goal: development of a prototype that could be (part of) the calorimeter of an ILC detector („engineering prototype“)

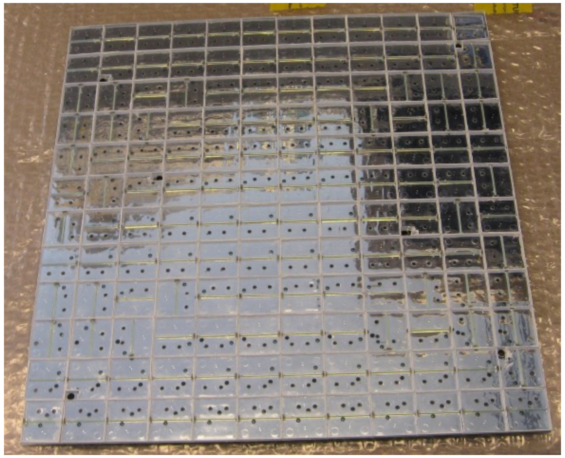


- geometry: octagonal shape, 2 rings along beam axis
- barrel + endcaps: 8 million readout channels
- as compact as possible, minimal regions without instrumentation:
  - electronics integrated into the active layers
  - no active cooling within the layers

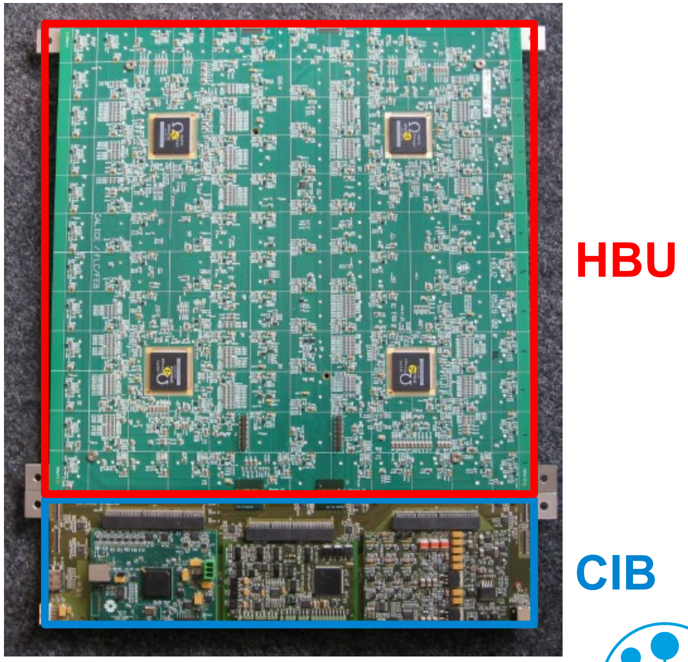
AHCAL: Towards the Engineering Prototype



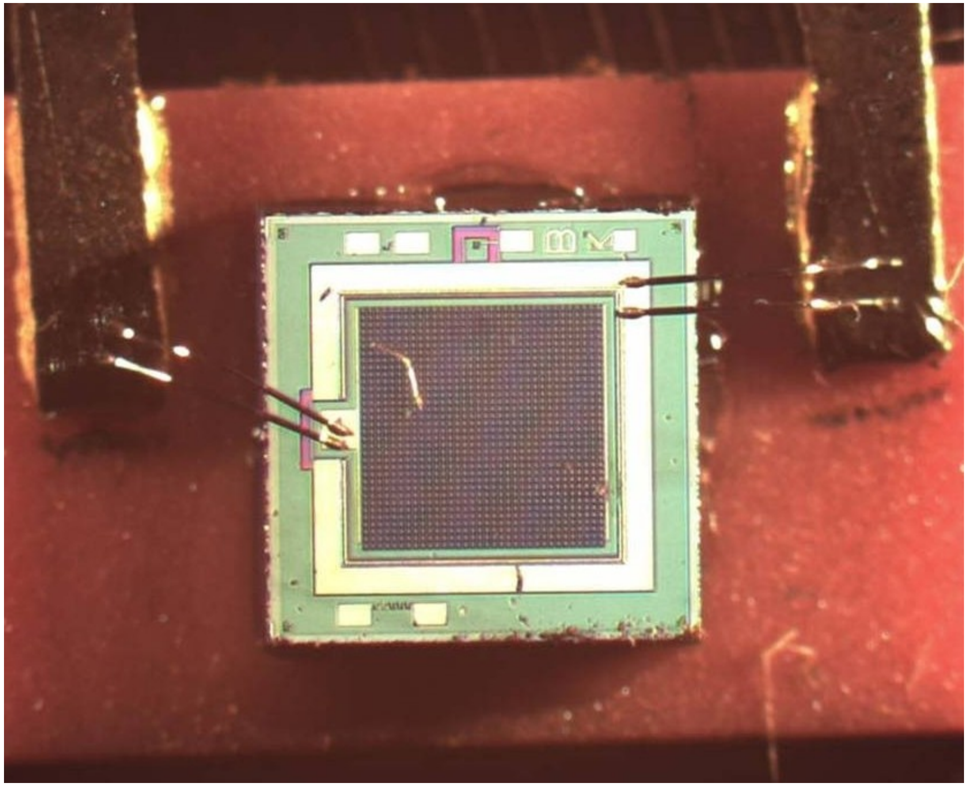




- 3*3*0.3 cm^3 scintillator tiles with wave length shifting fibers, read out by SiPMs
- **H**CAL **B**ase **U**nit: 36*36 cm^2, 144 tiles, 4 readout chips
- **C**entral **I**nterface **B**oard: HV and LV supply, readout and calibration for a full layer (up to 18 HBUs)



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: Optimization of the Power Consumption

- goal: construction of a calorimeter with integrated electronics, but without active cooling
- electronics with very low power consumption: maximum consumption of 40 µW/channel
  - specially designed readout electronics, e.g. readout ASICs
  - taking advantage of the planned time structure of the ILC beams („power pulsing“)