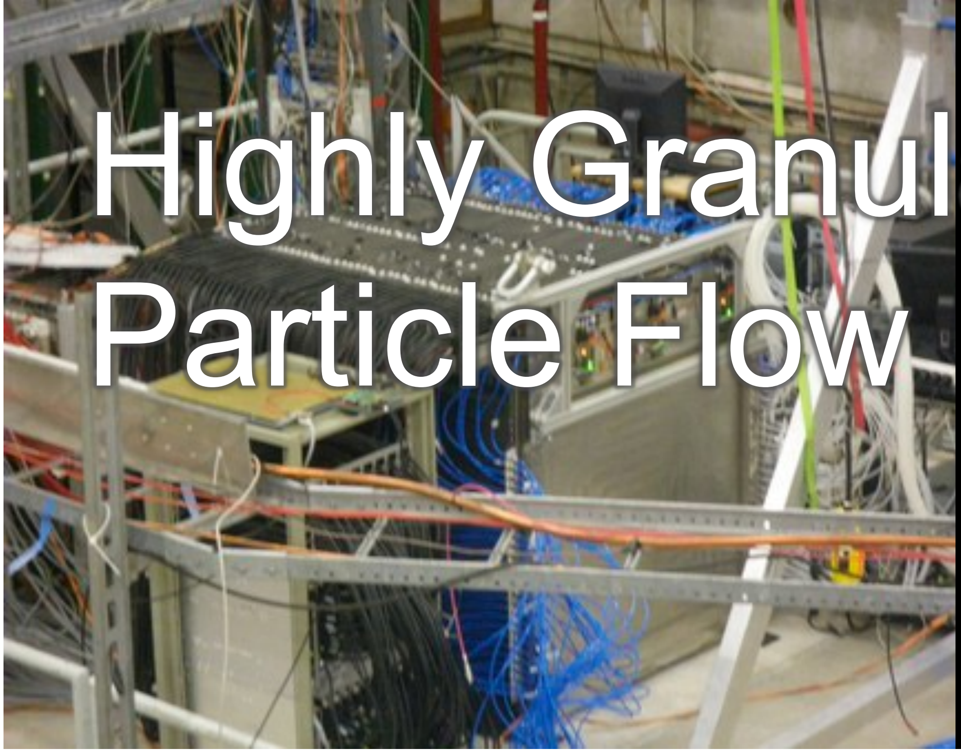
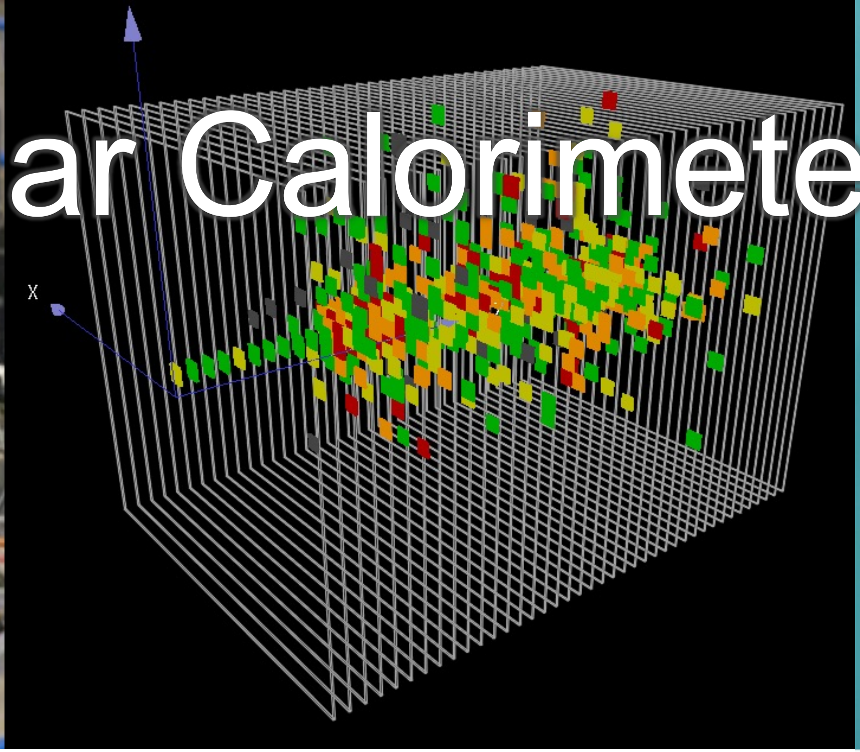


Highly Granular Calorimeters for Particle Flow

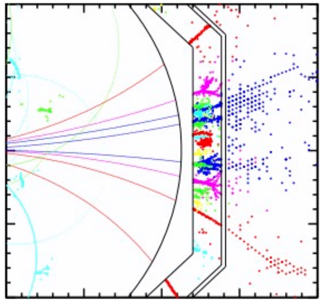
Katja Krüger (DESY)

TIPP 2021
28 May 2021

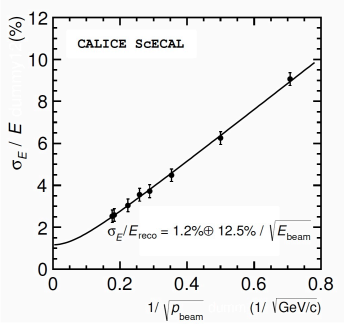
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

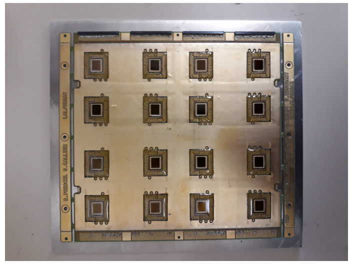
Outline



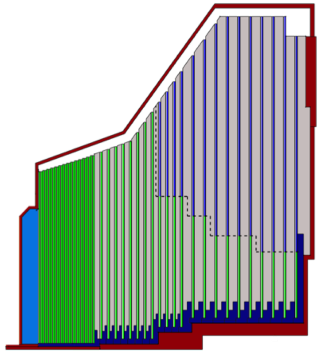
- Motivation



- Performance
  - Energy resolution
  - Shower Imaging



- Technological prototypes



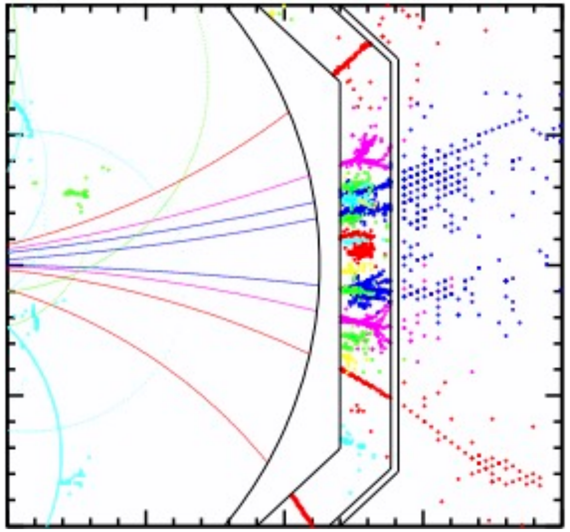
- Highly granular calorimeters beyond Higgs factories
- Summary

Motivation

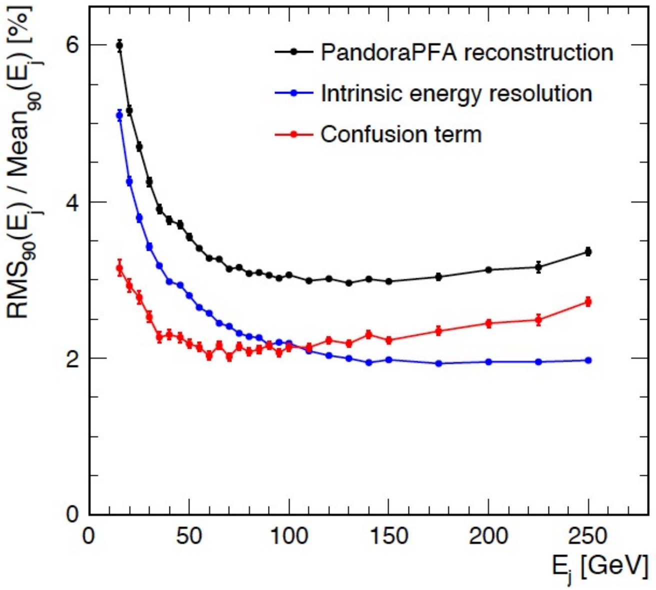
Calorimeters for Particle Flow Algorithms

Design considerations

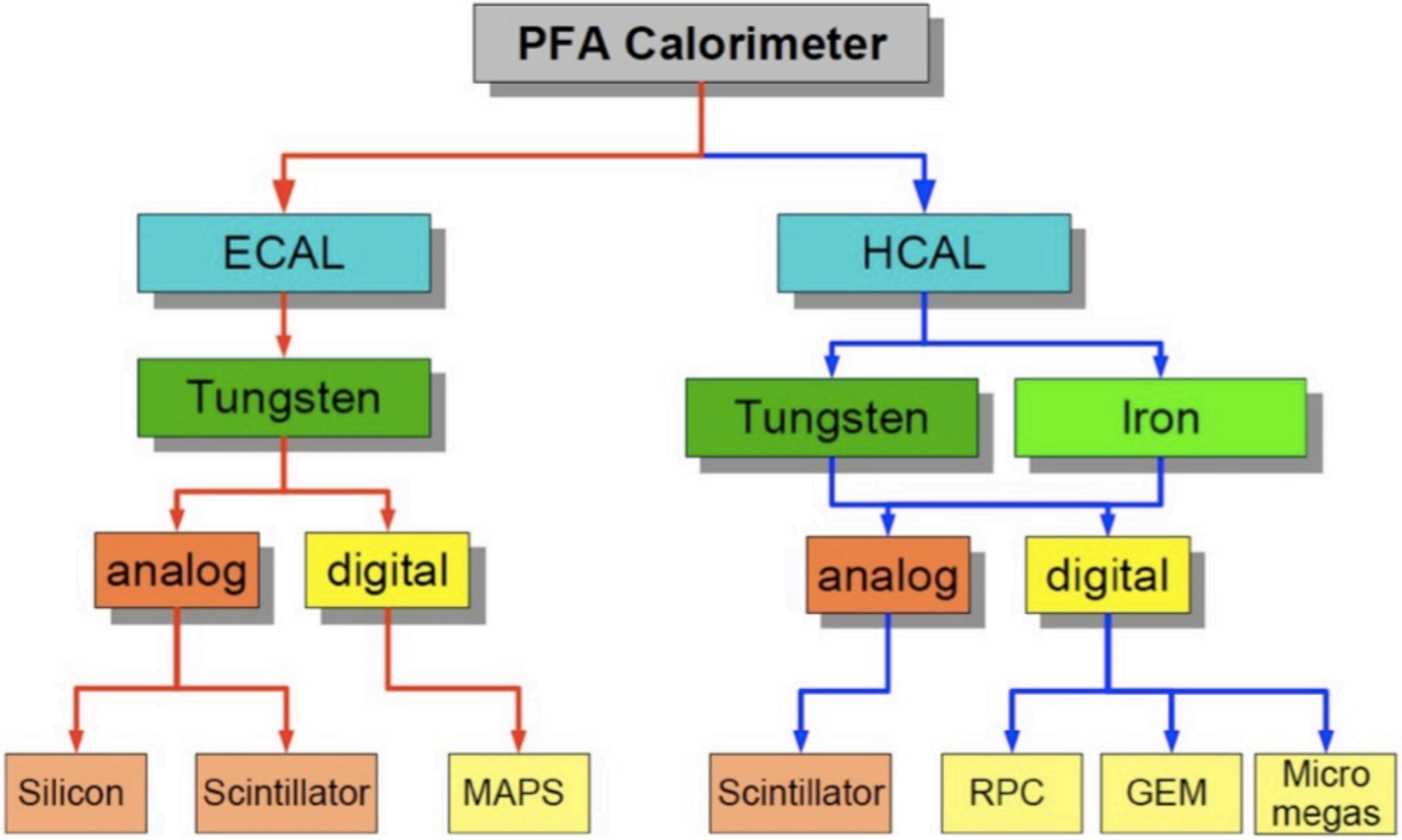
- Goal at Higgs Factories: want to distinguish Z → jet jet from W → jet jet
- Requires jet energy resolution of σ(E)/E ≈ 3-4%
- can be reached by particle flow algorithms (PFA)
  - for each particle within a jet: use the subdetector with optimal resolution
  - need to avoid double counting and wrong merging
- need an imaging calorimeter!



- requirements for the calorimeter:
  - highly granular
  - reconstruction of neutral particles: good energy resolution
  - calorimeter has to be within magnet coil: very compact



Technologies for Particle Flow Calorimeters



CALICE:
R&D Collaboration
For Highly Granular
PFA Calorimeters

Absorber material

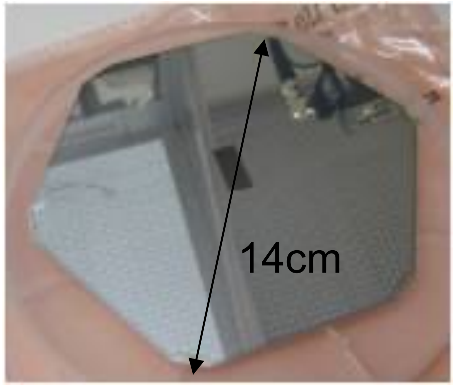
Readout method

Active technology

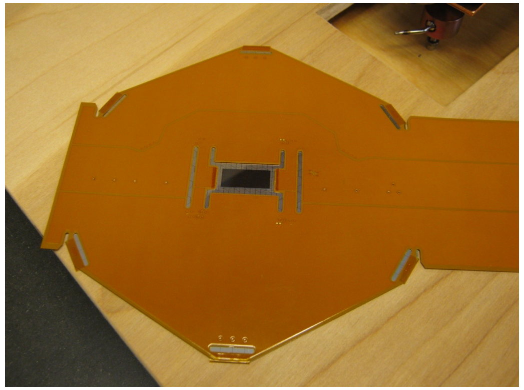
Electromagnetic Calorimeter Concepts

Technology Options

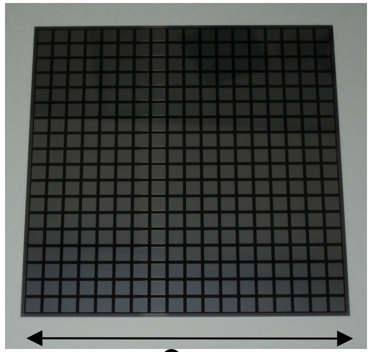
Silicon



1024 pixel

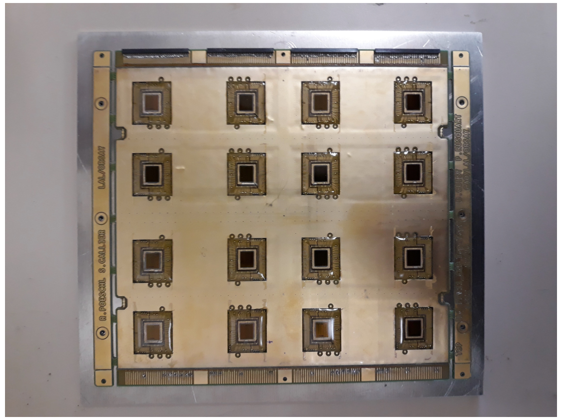


Silicon



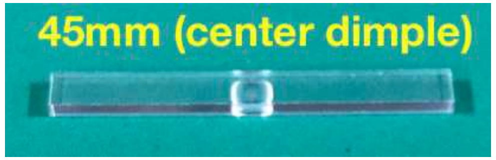
9cm

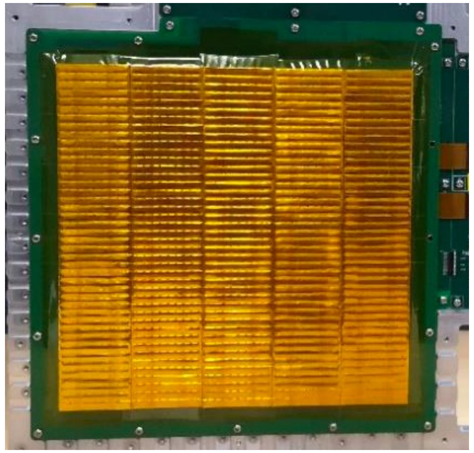
256 pixel



CALICE SiECAL

Scintillator

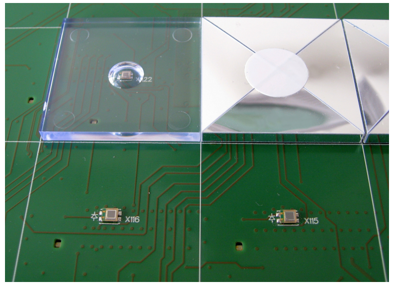


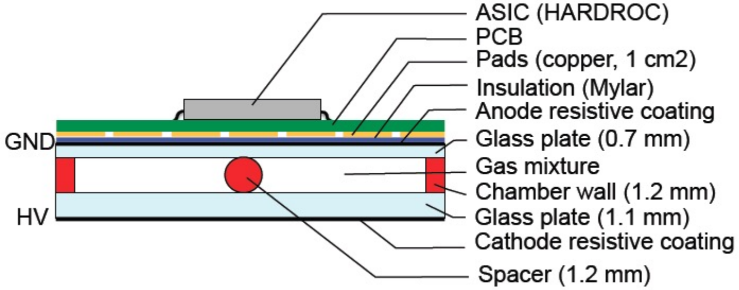


CALICE SciECAL

Hadronic Calorimeter Concepts

Technology Options





Scintillator tiles read out by SiPMs

3*3 cm^2 tiles

readout: 12 bit (analog)

CALICE AHCAL

Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage

1*1 cm^2 readout pads

readout: 1 bit (digital)

CALICE DHCAL

readout: 2 bit (semi-digital)

CALICE SDHCAL

Performance Measures

What can we measure? How can we measure it?

CALICE Strategy:

- Demonstrate performance with physics prototypes
- Demonstrate scalability with technological prototypes

Performance measurements in beam tests:

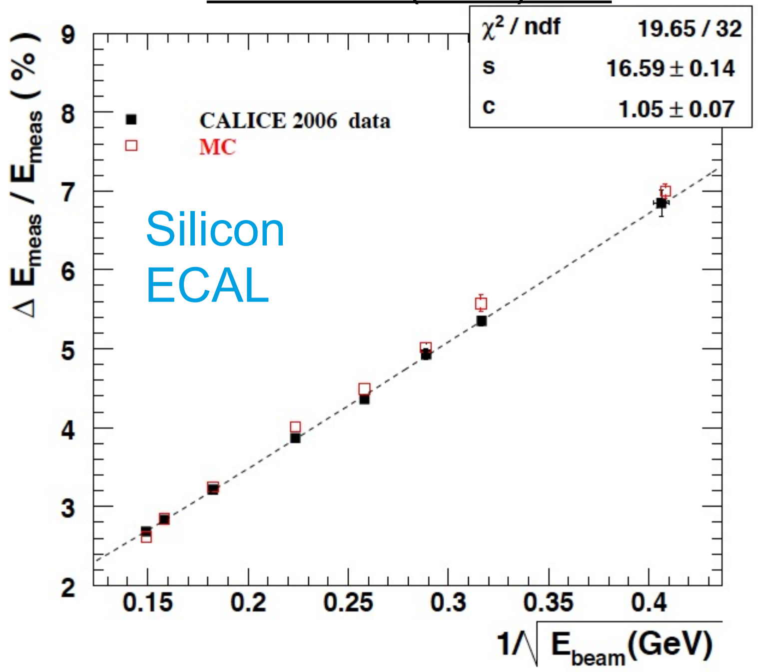
- In test beams you get only single particles, no jets → direct measurement of the jet energy resolution not possible
- Nevertheless, measurements in beam tests provide important information:
    - **energy resolution for single particles** → one important ingredient in the JER
    - **comparison of shower shapes in data and simulation** (Geant4) → important for realistic performance of Particle Flow Algorithms for jets in simulation
    - **tests of the Particle Flow Algorithms with overlayed showers**

Performance:
Energy resolution

Energy resolution for electrons

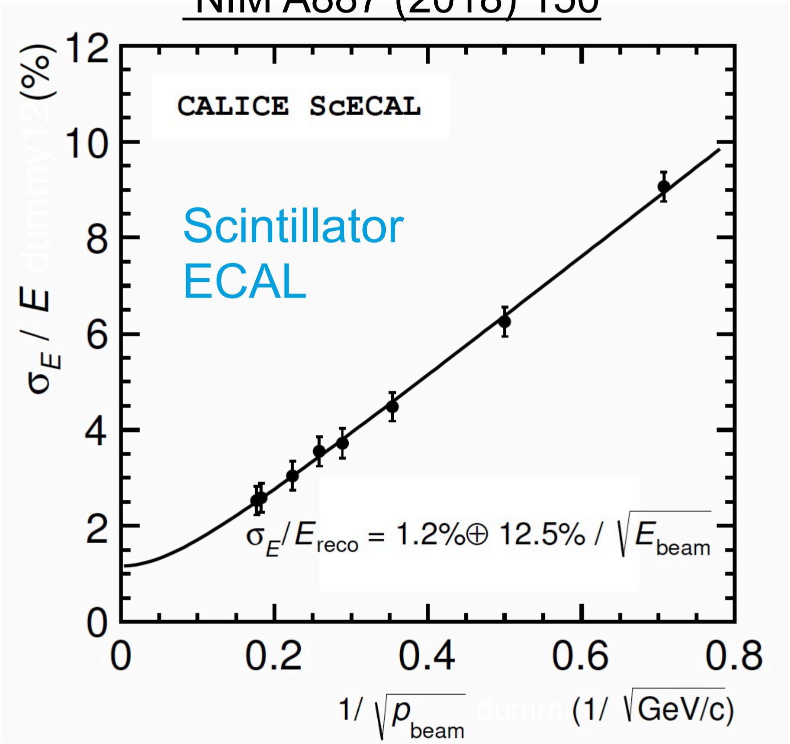
CALICE ECALs

NIM A608 (2009) 372



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

NIM A887 (2018) 150



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

reasonable energy resolution for electromagnetic showers

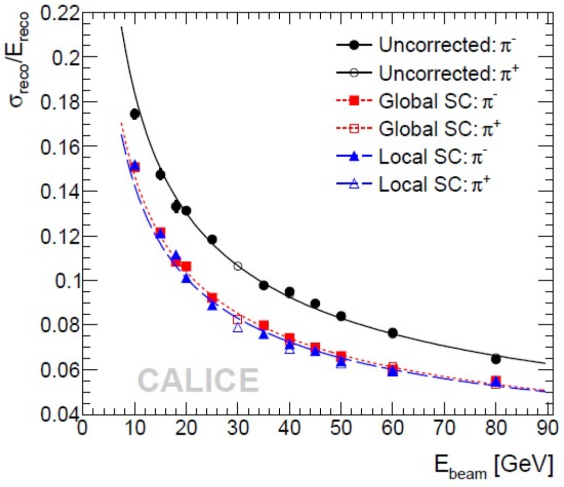
PFA ECALs are optimised for granularity, not single particle energy resolution

Energy resolution for charged pions

CALICE HCALs

JINST 7 (2012) P09017

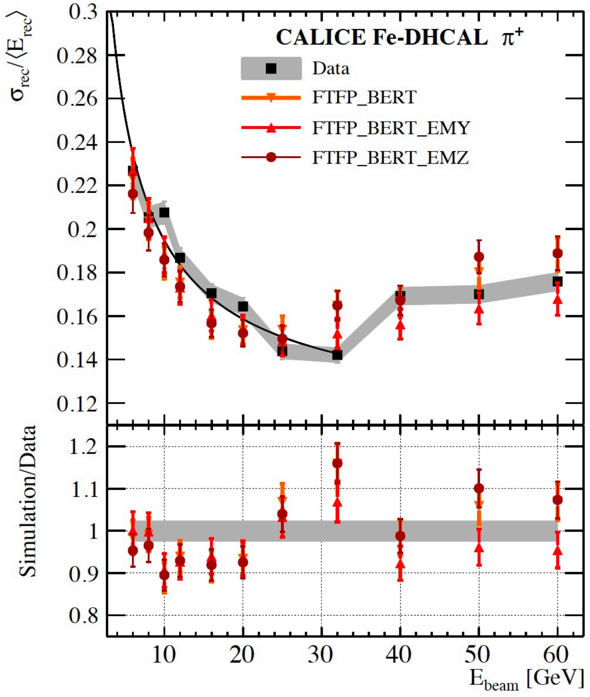
Analog HCAL



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

NIM A939 (2019) 89

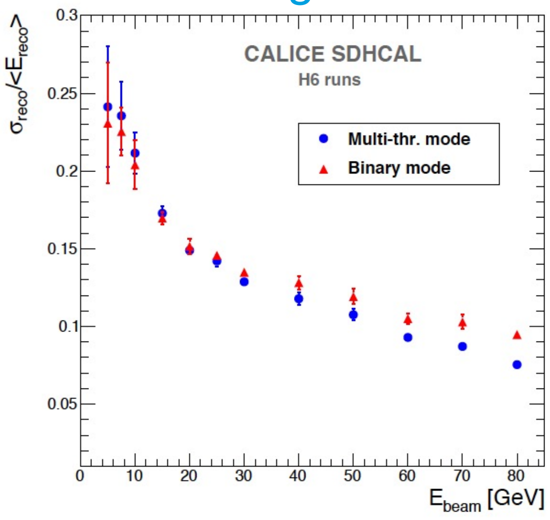
Digital HCAL



resolution doesn't improve beyond ~30 GeV

JINST 11 (2016) P04001

Semi-Digital HCAL



measurement with 1 or 3 thresholds

3 thresholds improve resolution at large energies

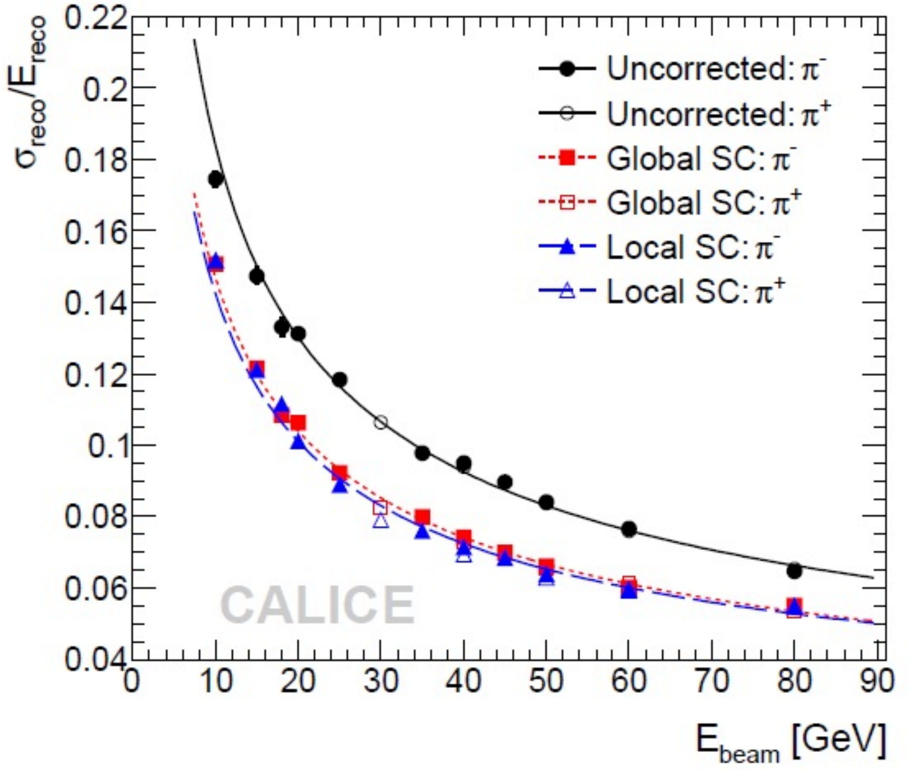
Energy resolution for charged pions

The power of high granularity

Software compensation (SC):

- non-compensating calorimeters show different signals for electromagnetic and hadronic showers
- hadronic showers include electromagnetic sub-showers
- in the reconstruction, use different weights for electromagnetic and hadronic sub-showers
- Significant improvement of energy resolution

JINST 7 (2012) P09017



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

Performance of combined scintillator calorimeter system

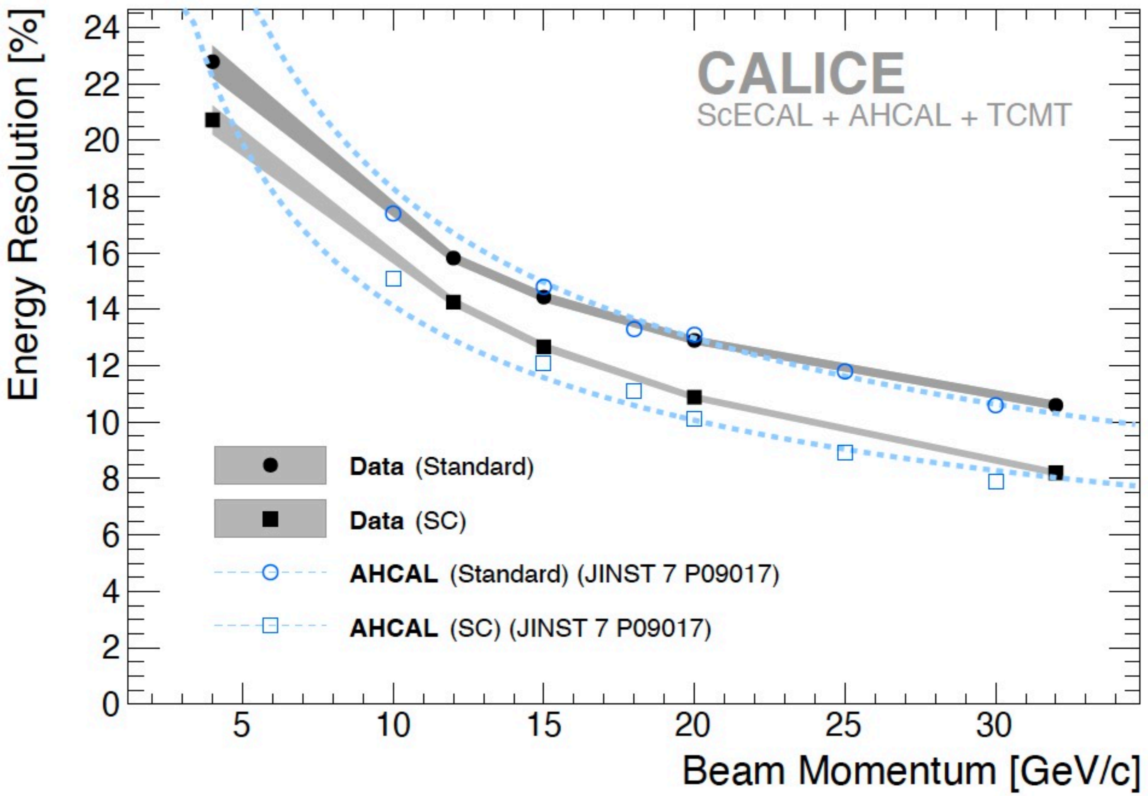
Energy reconstruction in a highly granular calorimeter system

in a real calorimeter system, hadrons are not measured purely in HCAL, but in ECAL + HCAL (+ tailcatcher)

ECAL and HCAL typically have different absorber, sampling ratio, active material

combined system of scintillator-tungsten ECAL + scintillator-steel AHCAL has **very similar performance** to AHCAL alone

JINST 13 (2018) P12022



Performance:
Shower Imaging

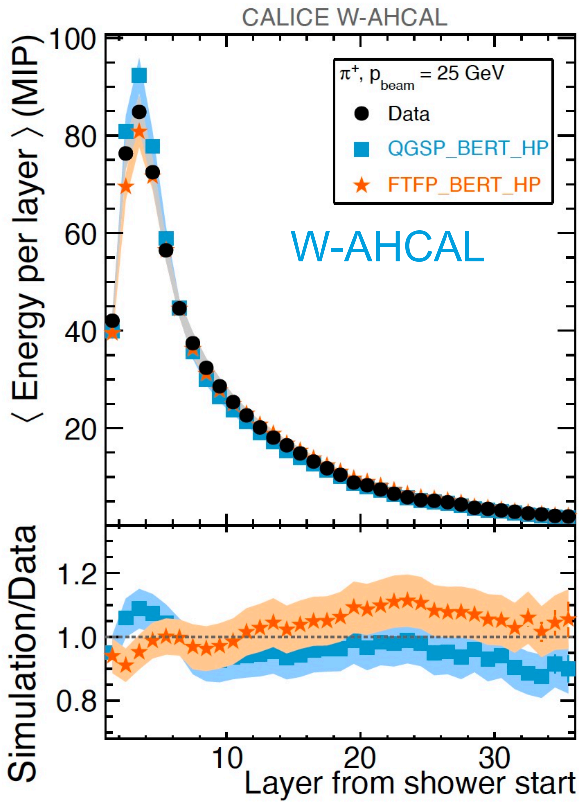
Shower Profiles

Examples: Pion showers in tungsten calorimeters

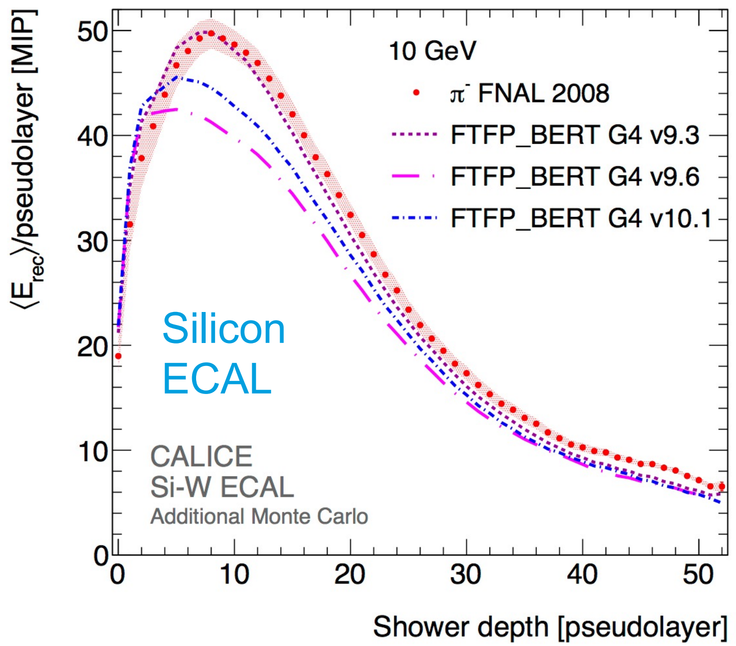
High granularity allows determination of shower start → measure detailed hadron shower profiles

Description by simulations typically within ~10% → important for Particle Flow performance

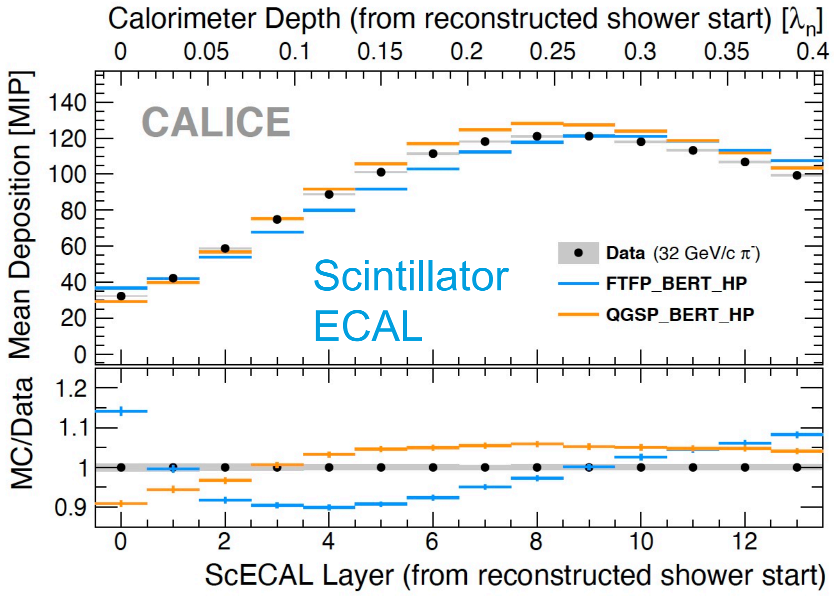
JINST 10 (2015) P12006



NIM A 794 (2015) 240



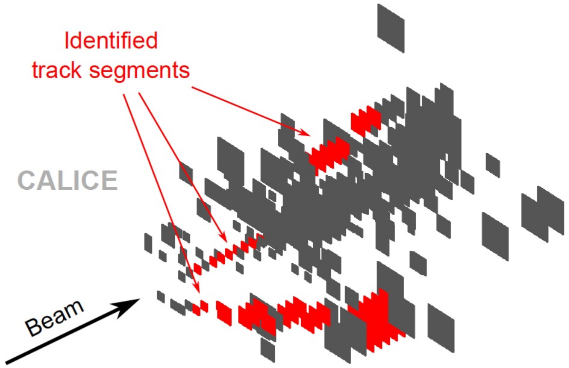
JINST 13 (2018) P12022



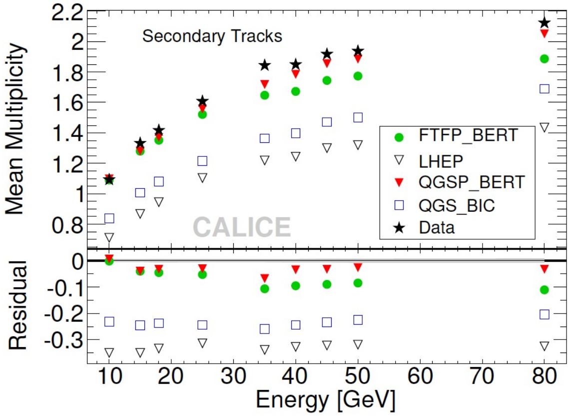
Track Segments within hadron showers

Substructure of hadron showers

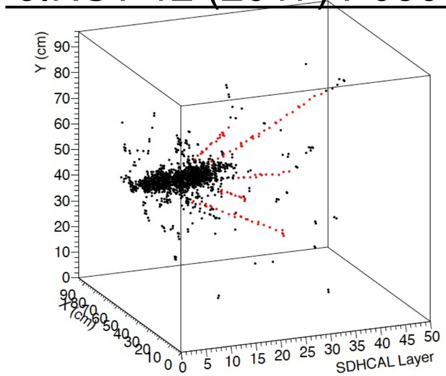
JINST 8 (2013) P09001

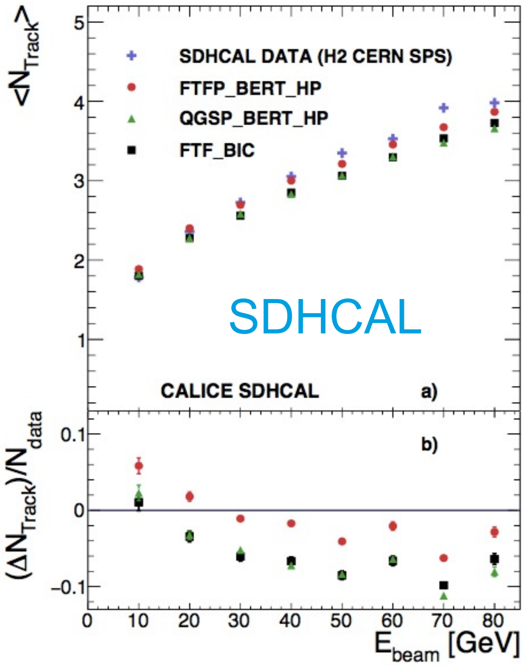


AHCAL

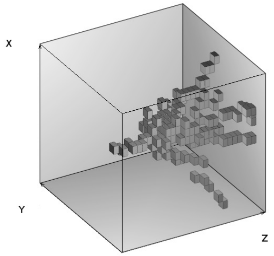


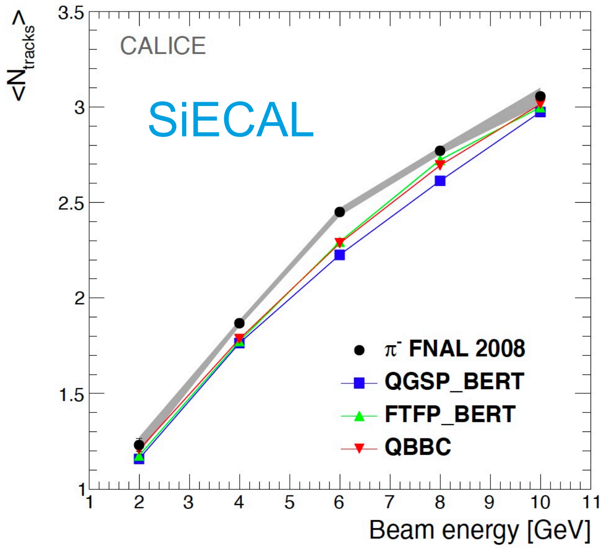
JINST 12 (2017) P05009





NIM A937 (2019) 41



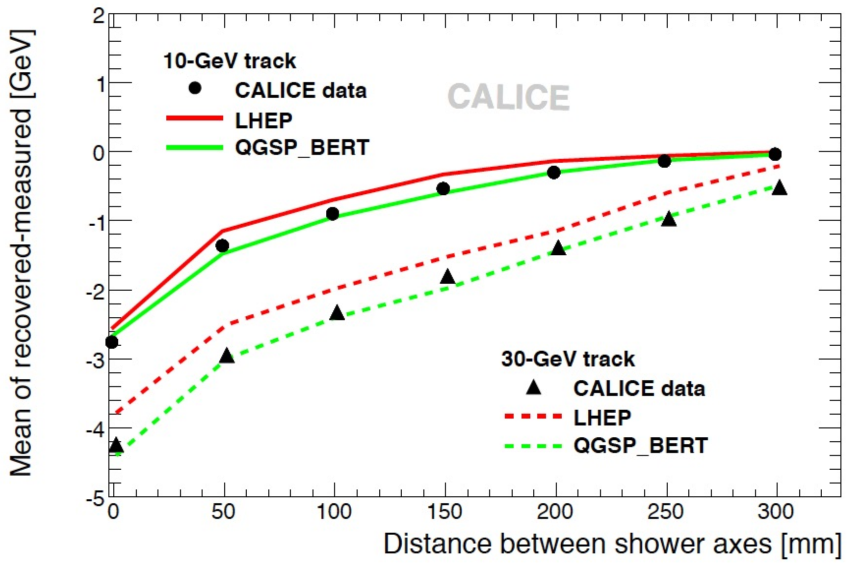


Shower Separation

Particle Flow Algorithms at work

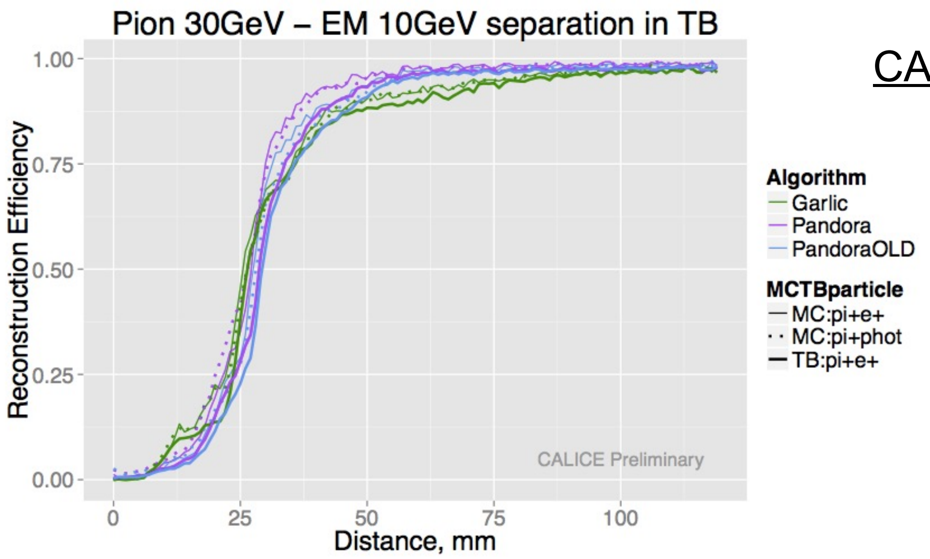
Overlay of showers in measured and simulated events

- Charged and neutral hadron showers
- Electromagnetic and charged hadron shower



JINST 6 (2011) P07005

Performance of Particle Flow Algorithms well described by simulation



CAN-057

Technological Prototypes

SDHCAL Technological Prototype

Recent developments

SDHCAL prototype has **integrated electronics** already

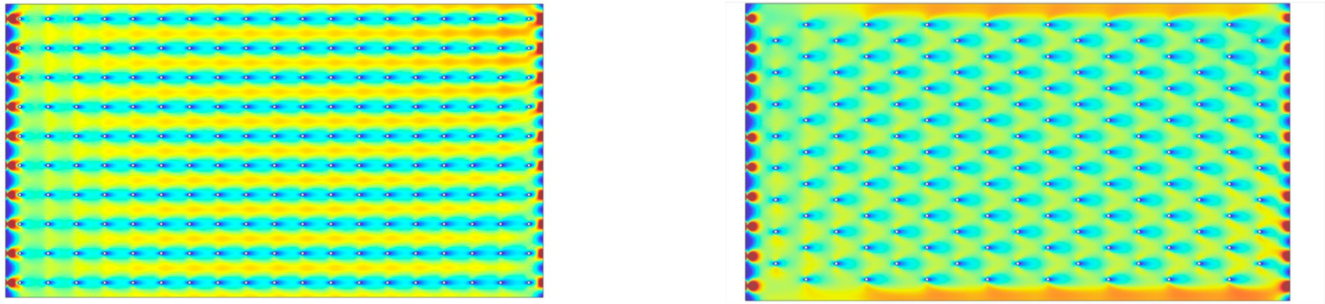
- 48 layers with ~440.000 channels

Aspects for **scalability** to collider detector

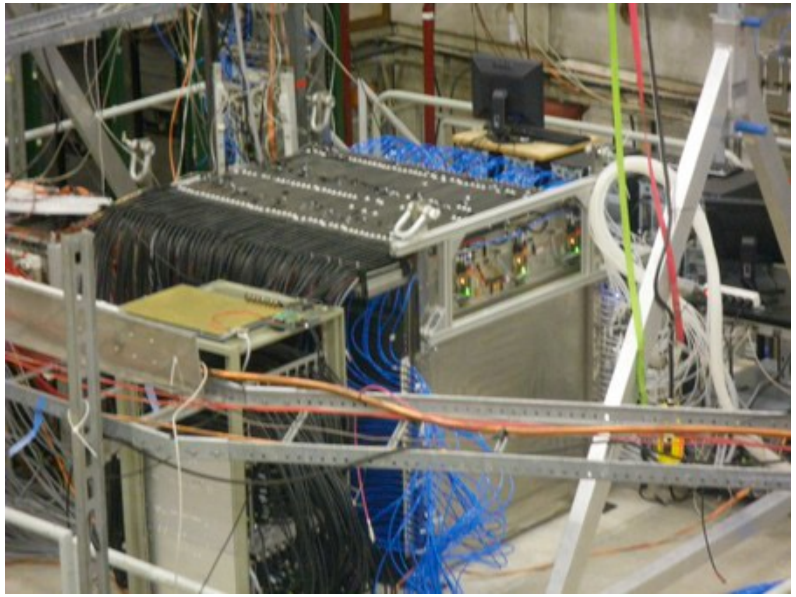
- Layer size will increase from 1*1 m^2 to up to 1*2 m^2
  → optimize gas flow and spacers
- Minimise size of interface electronics

Improved **time resolution**

- Multi-gap RPCs can reach ~100 ps
- Plan to build a timing layer and integrate it into SDHCAL prototype

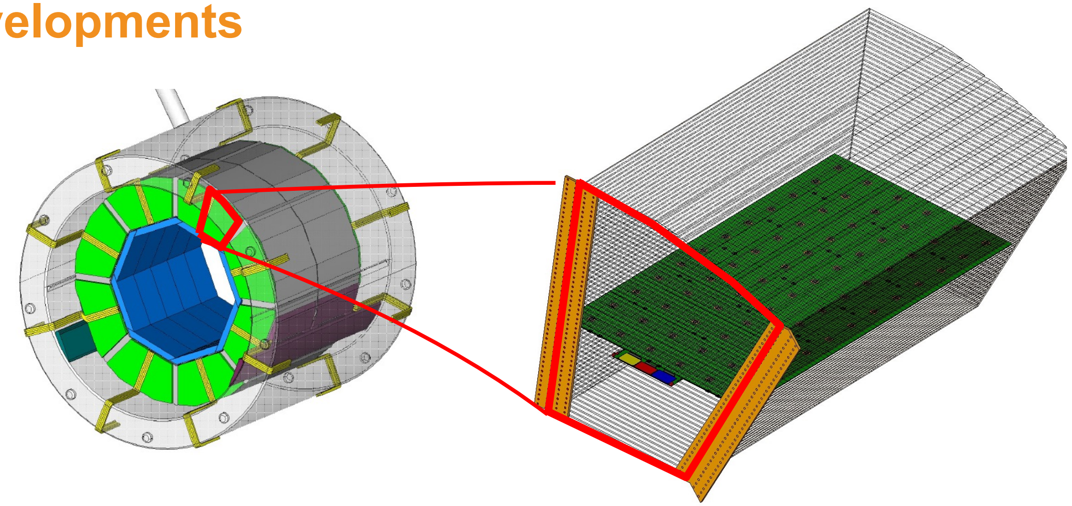


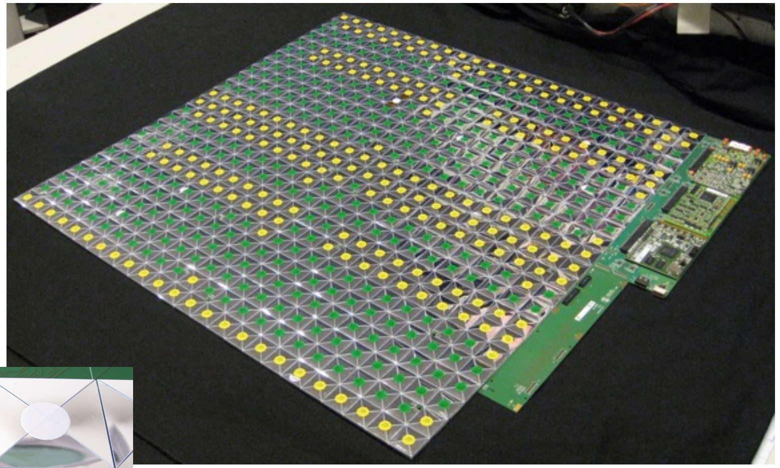
gas flow →

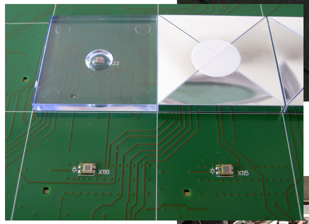


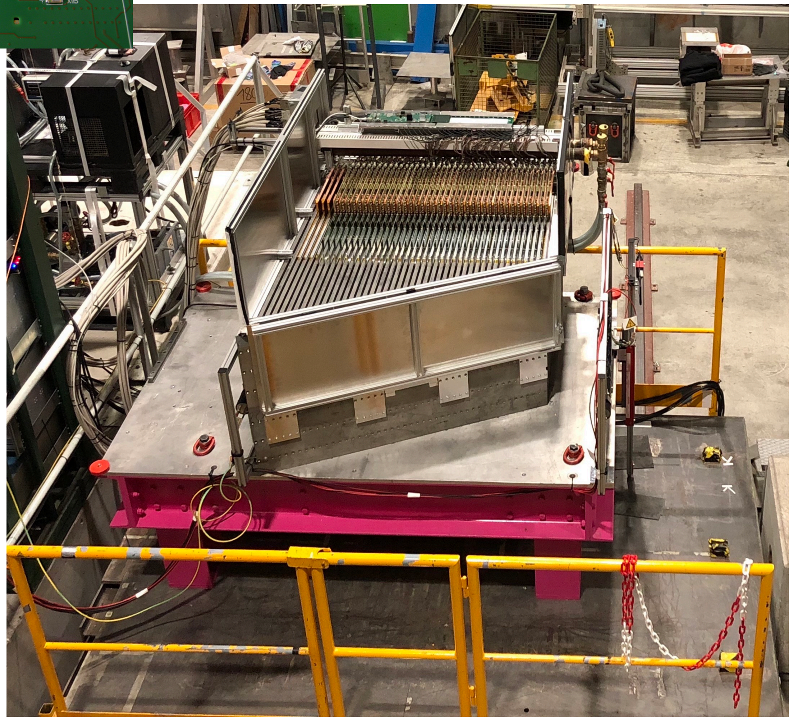
AHCAL Technological Prototype

Recent developments









Fully integrated design

- front-end electronics, readout
- voltage supply, LED system for calibration
- no cooling within active layers → **power pulsing**

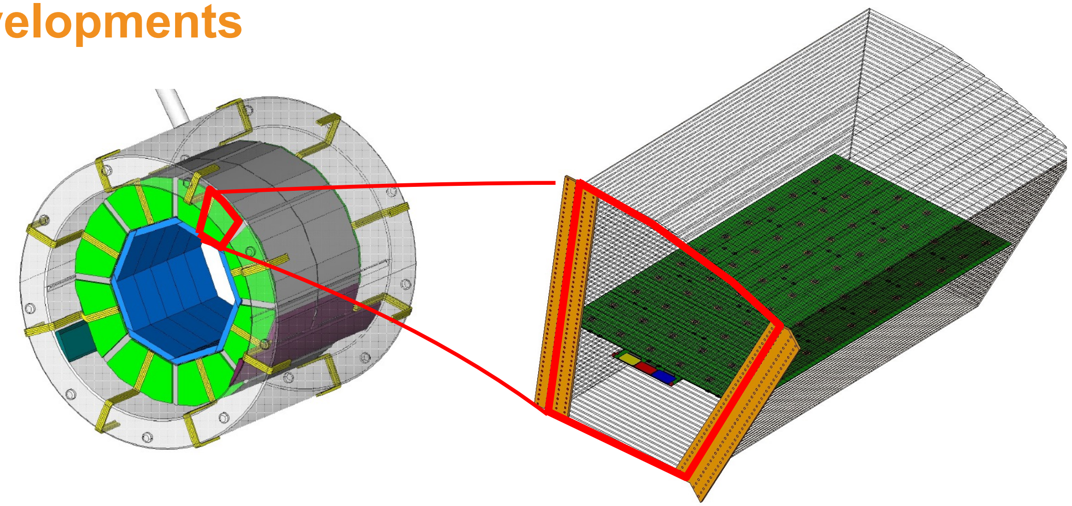
Scalable to full collider detector (~8 million channels)

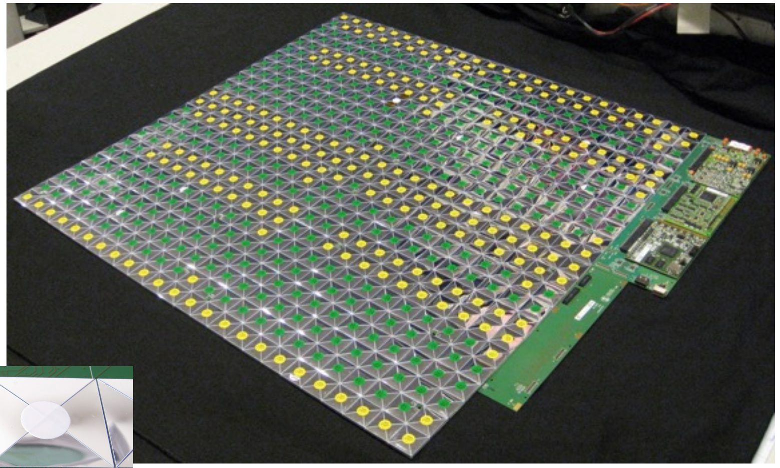
Prototype with 38 layers and ~22.000 channels operated in **testbeam**

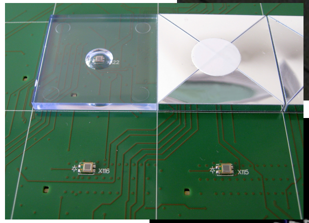
- Very stable running
- Nearly noise free
- < 1 per mille dead channels

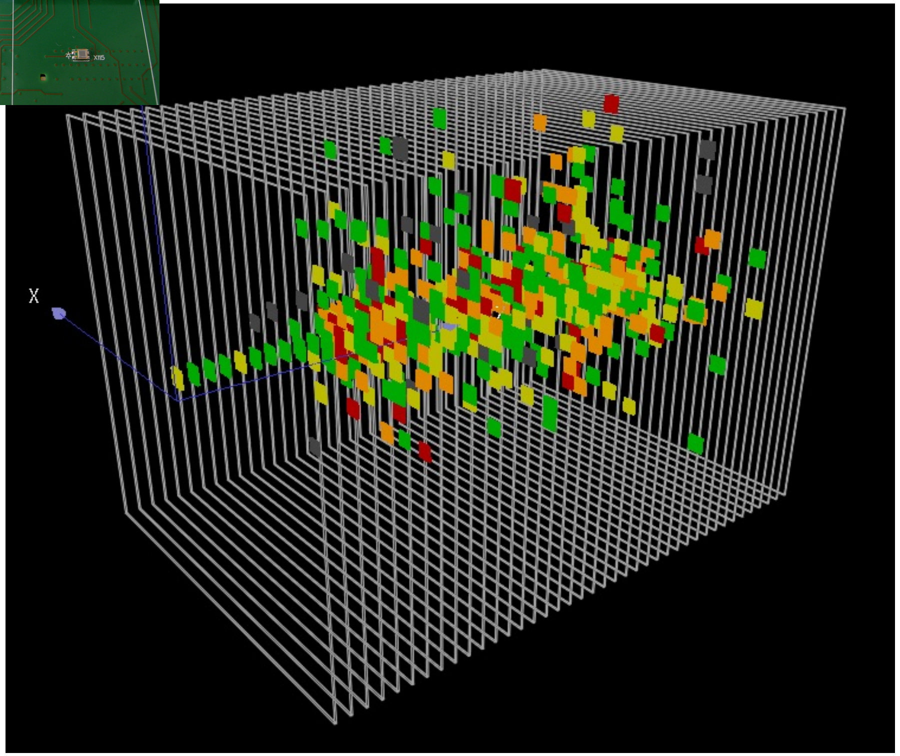
AHCAL Technological Prototype

Recent developments









Fully integrated design

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Scalable to full collider detector (~8 million channels)

Prototype with 38 layers and ~22.000 channels operated in **testbeam**

- Very stable running
- Nearly noise free
- < 1 per mille dead channels

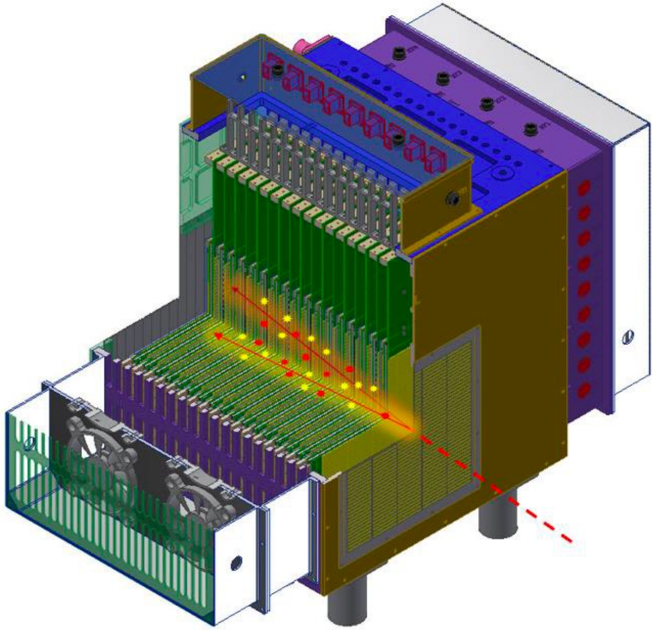
Scintillator ECAL Technological Prototype

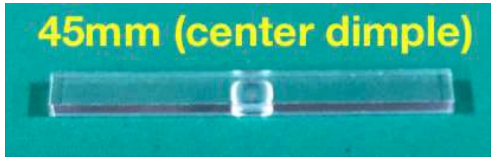
Recent developments

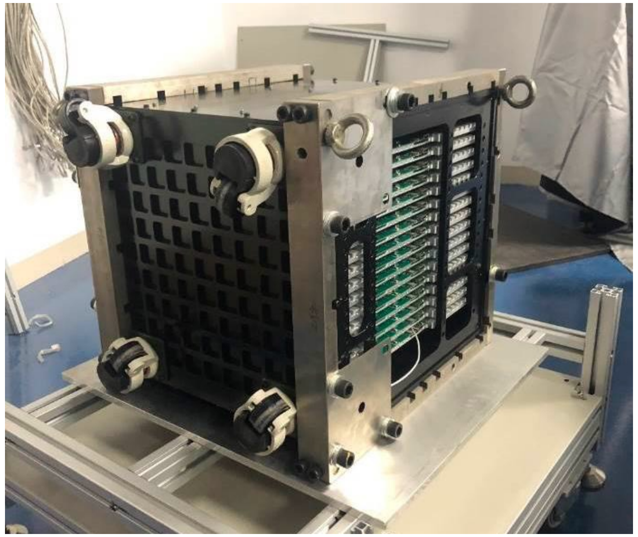
Fully integrated design

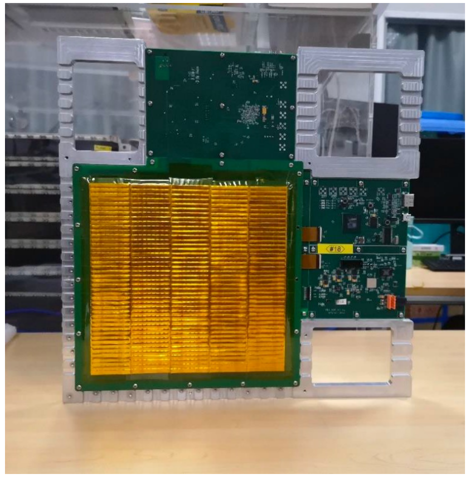
Testbeam prototype with 32 layers and ~7.000 channels built

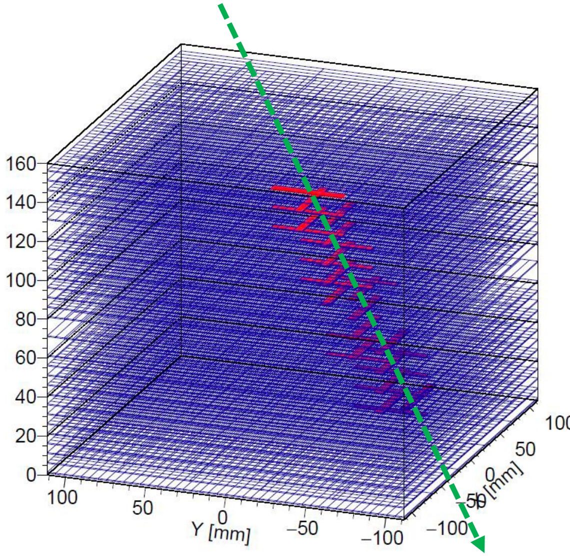
- Tested with cosmic muons
- Ready for beam tests (delayed due to Covid)

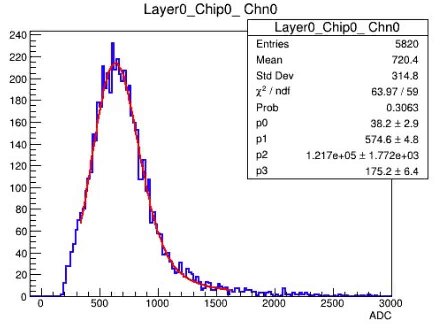












Silicon ECAL Technological Prototype

Recent developments

Space constraints for ECAL especially challenging

- Minimum thickness of integrated electronics to minimize total thickness
- Minimum size of electronics interfaces to minimize gaps in the coverage

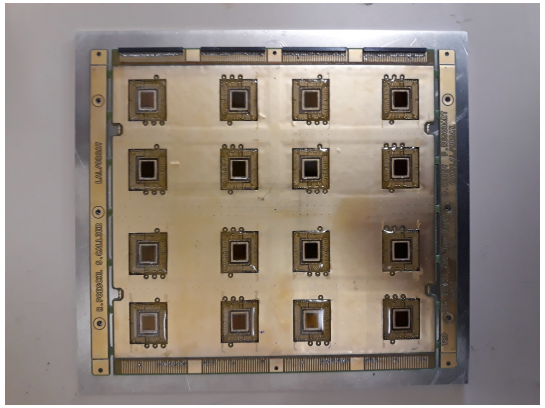
Fully integrated design

Scalable to full detector (~100 million channels)

Testbeam prototype under construction

- Up to 30 layers and ~30.000 channels

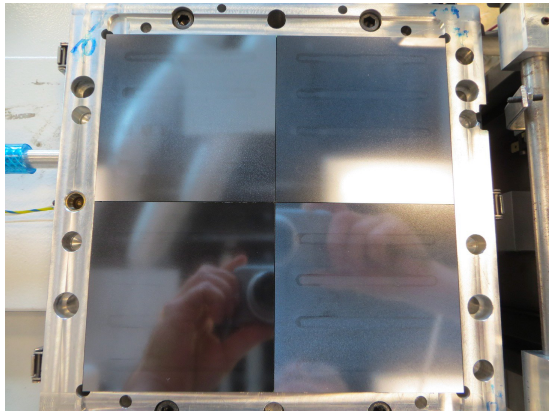
BGA-packaged ASICs

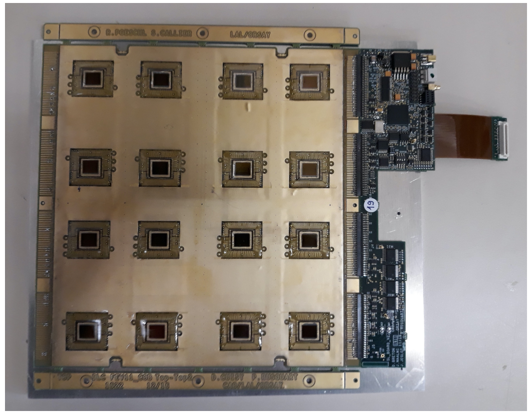


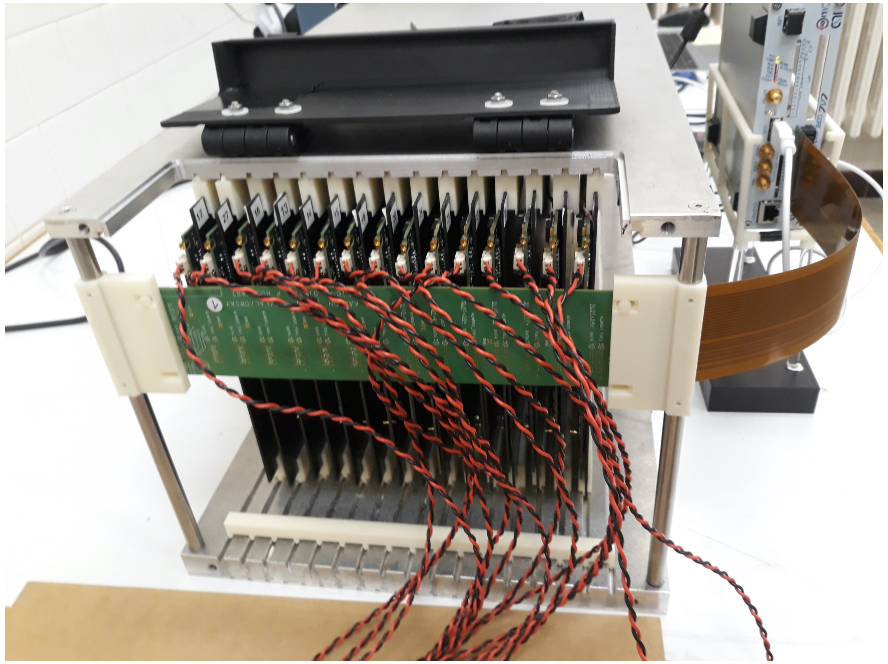
unpackaged ASICs

Silicon wafers glued onto PCB

Pixel size 5.5x5.5 mm^2







Highly granular calorimetry beyond Higgs Factories

CMS HGCAL

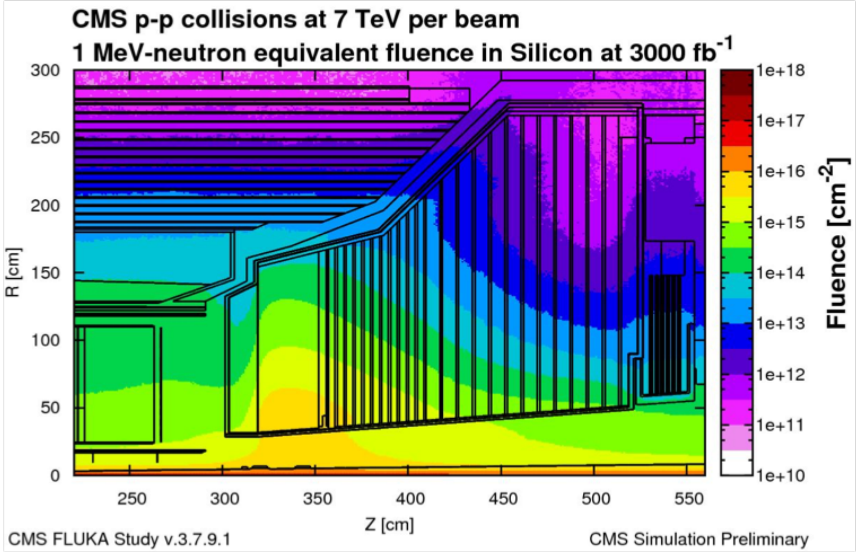
High granularity for HL-LHC

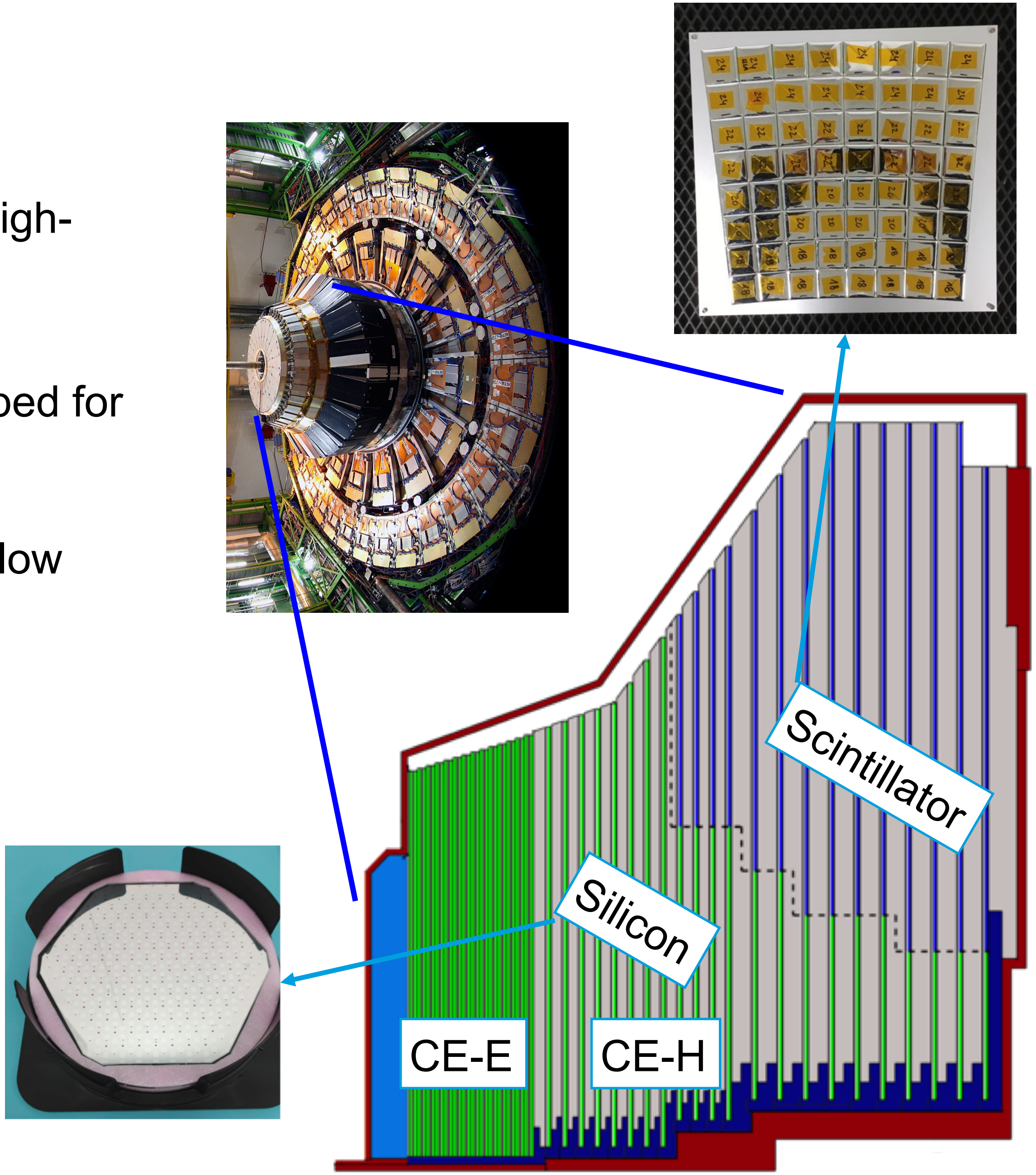
CMS calorimeter endcap will be replaced for HL-LHC by **H**igh-**G**ranularity **cal**orimeter

Granularity helps to suppress pile-up

Synergy with high granularity calorimeter concepts developed for electron-positron colliders

- Silicon in the CE-E and close to the beam pipe
- Scintillator tiles with SiPMs wherever radiation levels allow





CMS HGCAL

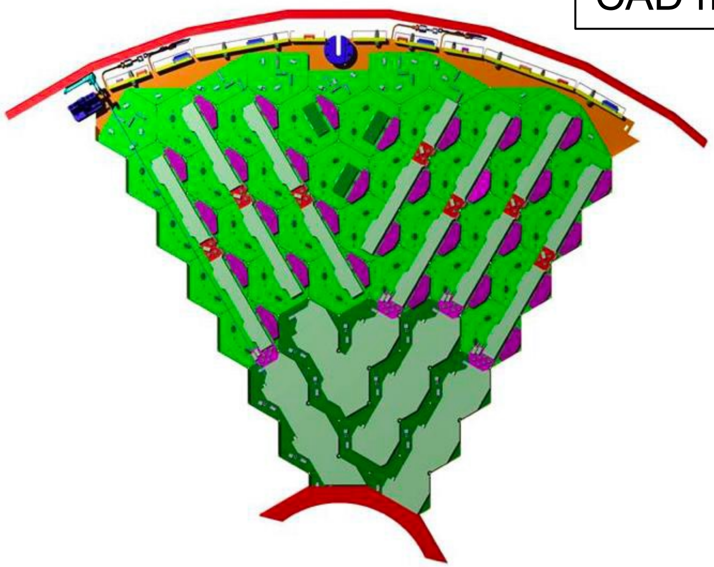
Towards construction

Moving towards fully-engineered design in 2021

Preparation for mass production of active modules

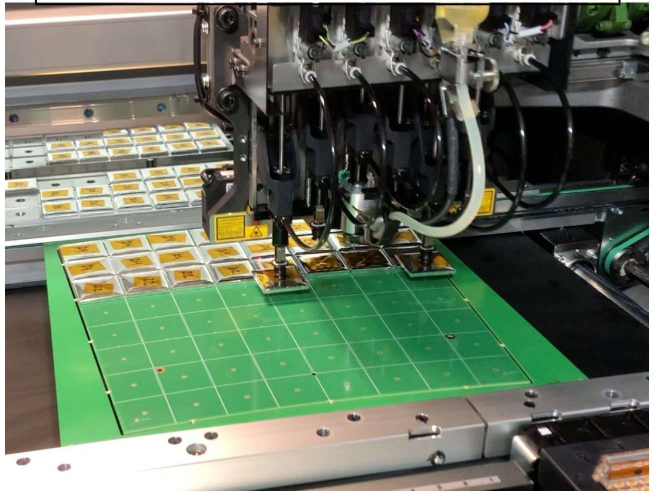
Will be the first large highly granular calorimeter in a collider detector!

CAD model

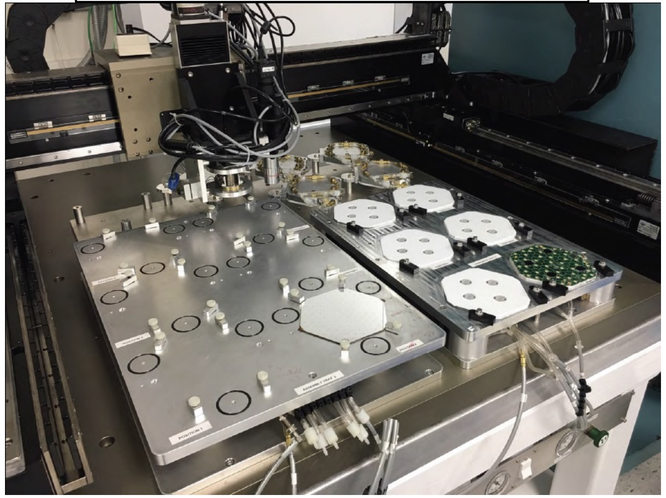


CE-E cassette

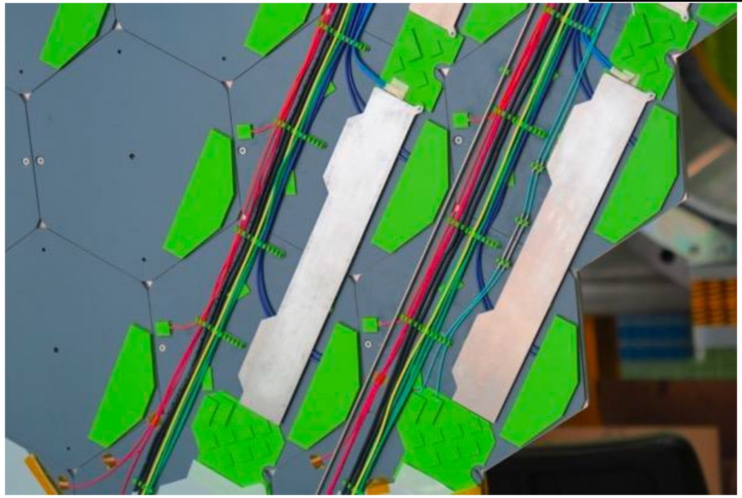
Scintillator module assembly



Silicon module assembly

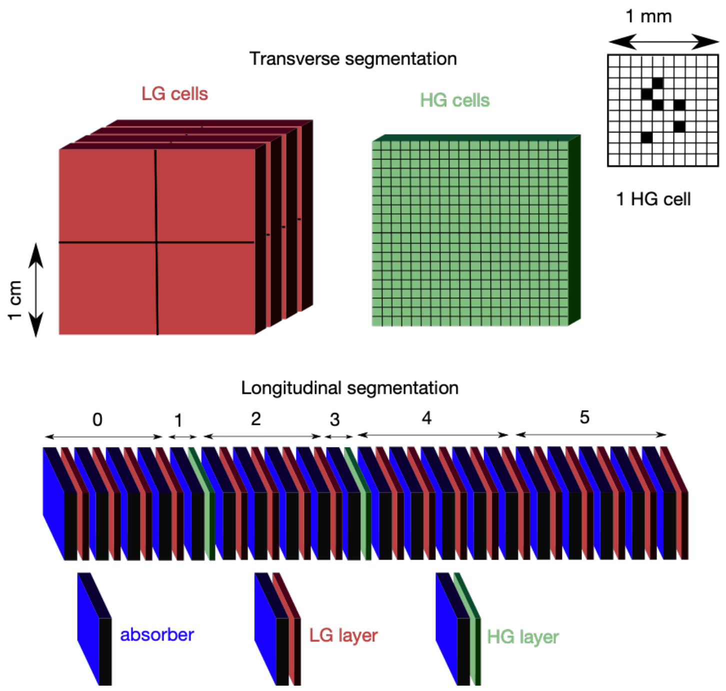


Mock-up



Digital Pixel Calorimeter

Ultimate granularity ECAL

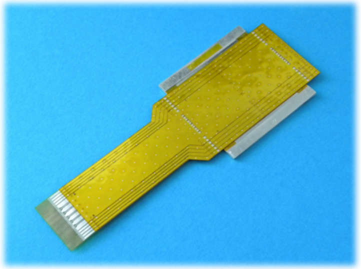


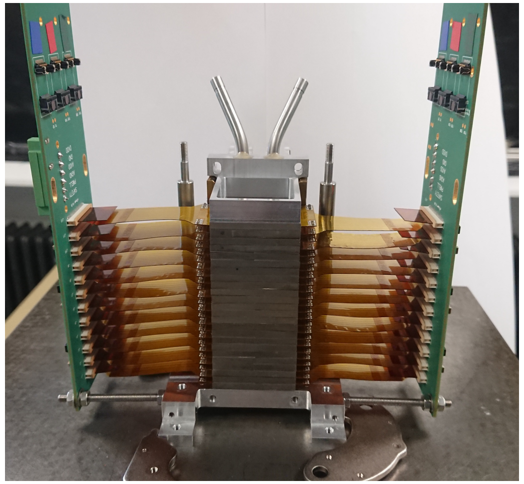
ALICE FoCal-E (Forward EM-Calorimeter)

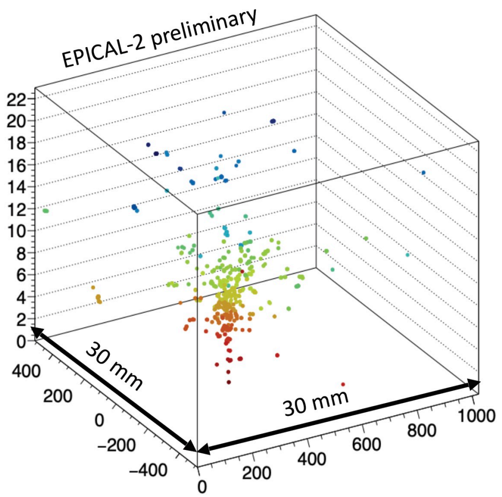
- W absorber + Si-sensors
- **Low-granularity layers** Si-pads (~1x1 cm^2) energy measurement
- **High-granularity layers** CMOS MAPS (~30x30 μm^2) two-shower separation

Digital Pixel Calorimeter prototype

- All layers consist of high-granularity MAPS sensors: ALPIDE
- 3x3 cm^2 cross section
- 24 layers
- Tested with electron beam







Deep Underground Neutrino Experiment

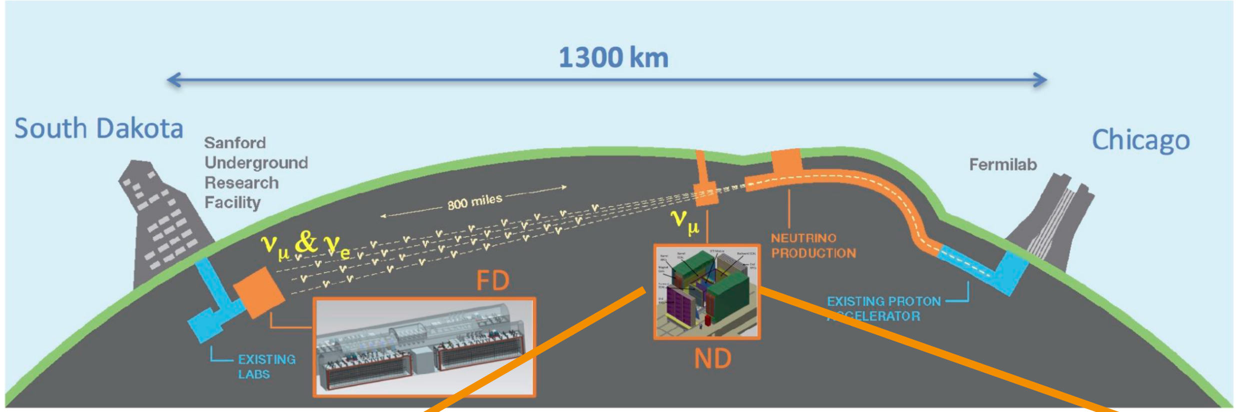
High granularity for neutrinos

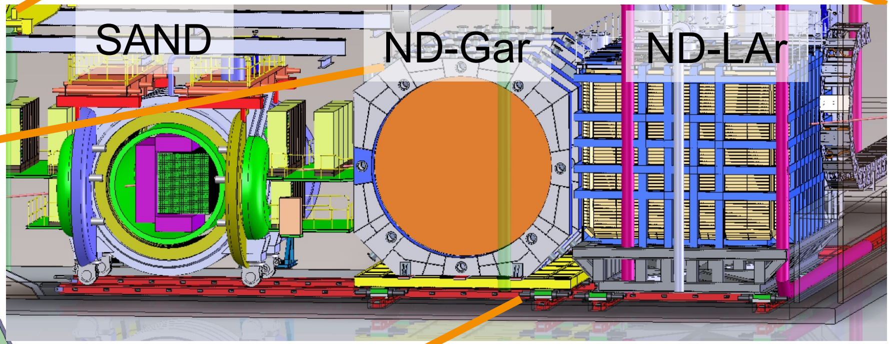
DUNE Far Detector: Study neutrino oscillations

- Large LAr TPCs

Near Detector (ND): measure beam before oscillation

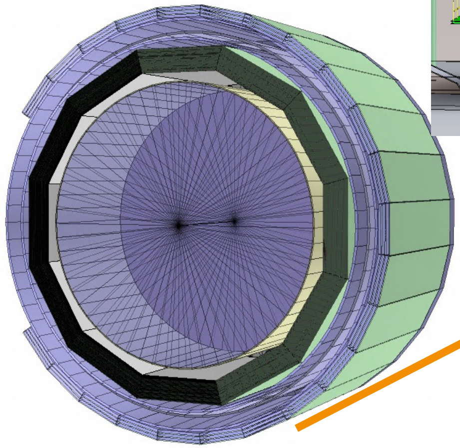
- DUNE PRISM: 3 detectors of which 2 can be moved off-axis
- ND-LAr: Liquid Argon TPC
- **ND-GAr: High Pressure GAr TPC, surrounded by ECAL and magnet**
- SAND: plastic scintillator target

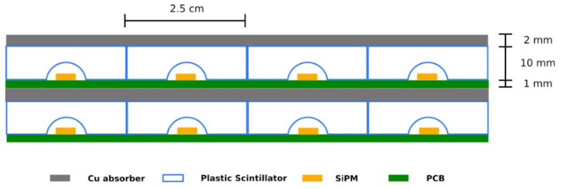




ND-GAr

- **Typical energies of a few 100 MeV**
- Angular resolution to distinguish π^0 and γ
- Key designs
  - Very thin absorber: 2 mm Copper
  - High granularity layers (similar to AHCAL)
  - Large strip layers in the back





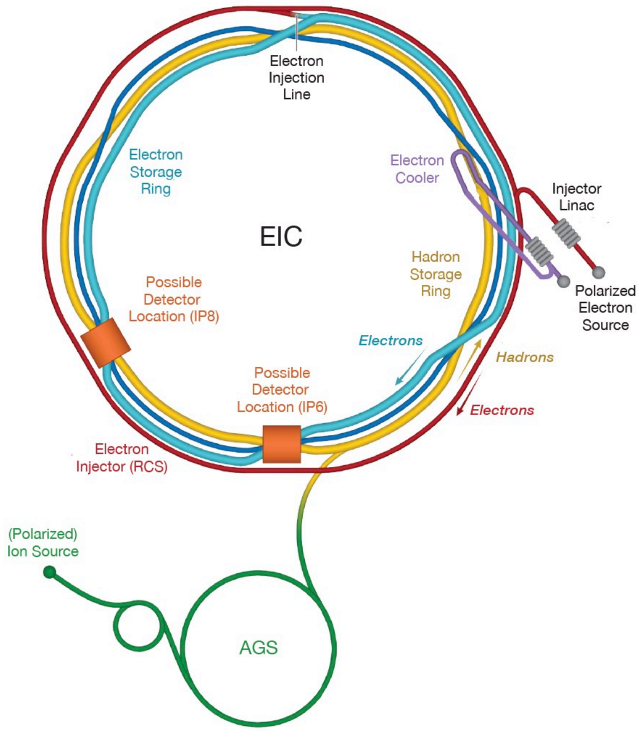
Electron-Ion Collider

High granularity for Deep Inelastic Scattering

EIC: High energy collider for electrons and protons or ions

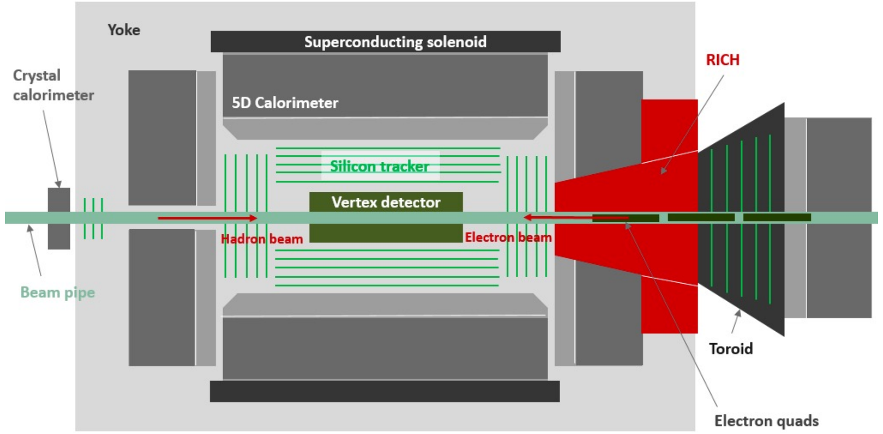
- Study nuclear structure
- $\sqrt{s}$ = 20 to 100 GeV
- Polarized beams
- 1 or 2 interaction regions

See talk by
E. Aschenauer



Several **detector concepts**

- Generic EIC concept detector
- TOPSiDE: **T**ime **Op**timized **Si**licon **D**etector for the **E**IC
  - All silicon tracker
  - Hermetic 5D calorimeter: high granularity & precise timing
    - Silicon tungsten ECAL with LGADs for timing
    - Scintillator tile or RPC HCAL



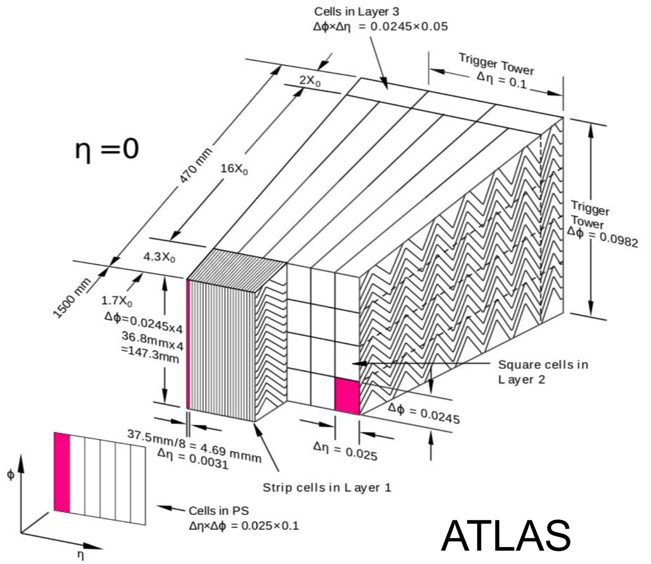
TOPSiDE

More High Granularity

What has not been mentioned so far

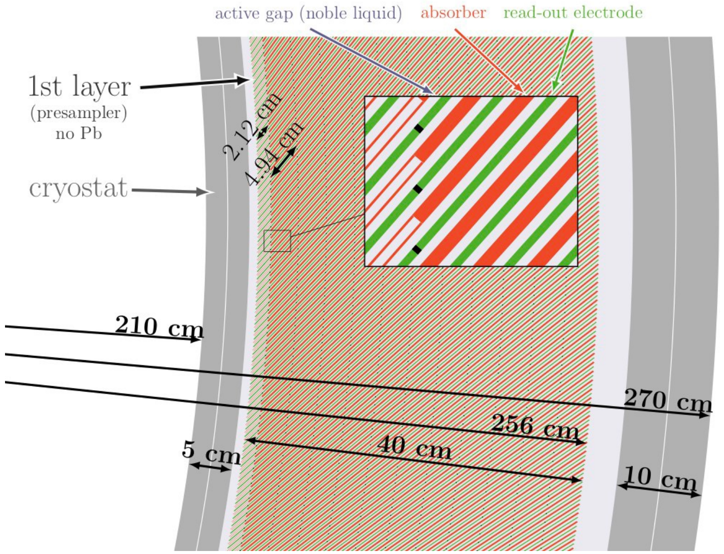
Higher granularity is being studied for many other technologies

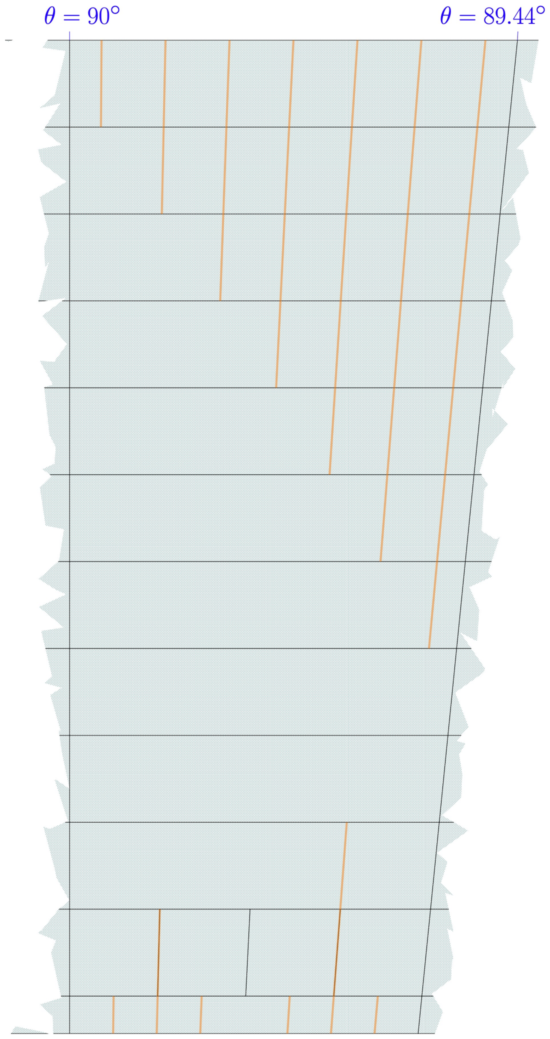
- LAr ECAL for FCC-ee and FCC-hh
- Granular Dual Readout calorimeters
- …



ATLAS

FCC-ee





Horizontal axis expanded by a factor 10

Summary

- Highly granular calorimeters are essential to reach the jet energy resolution needed for future Higgs factories
- Performance of several concepts has been demonstrated with prototypes in beam tests
- Scalability to collider detectors is being addressed
- Applications beyond Higgs factories
    - CMS HGCAL will be the first highly granular calorimeter in a collider detector

Thank you!