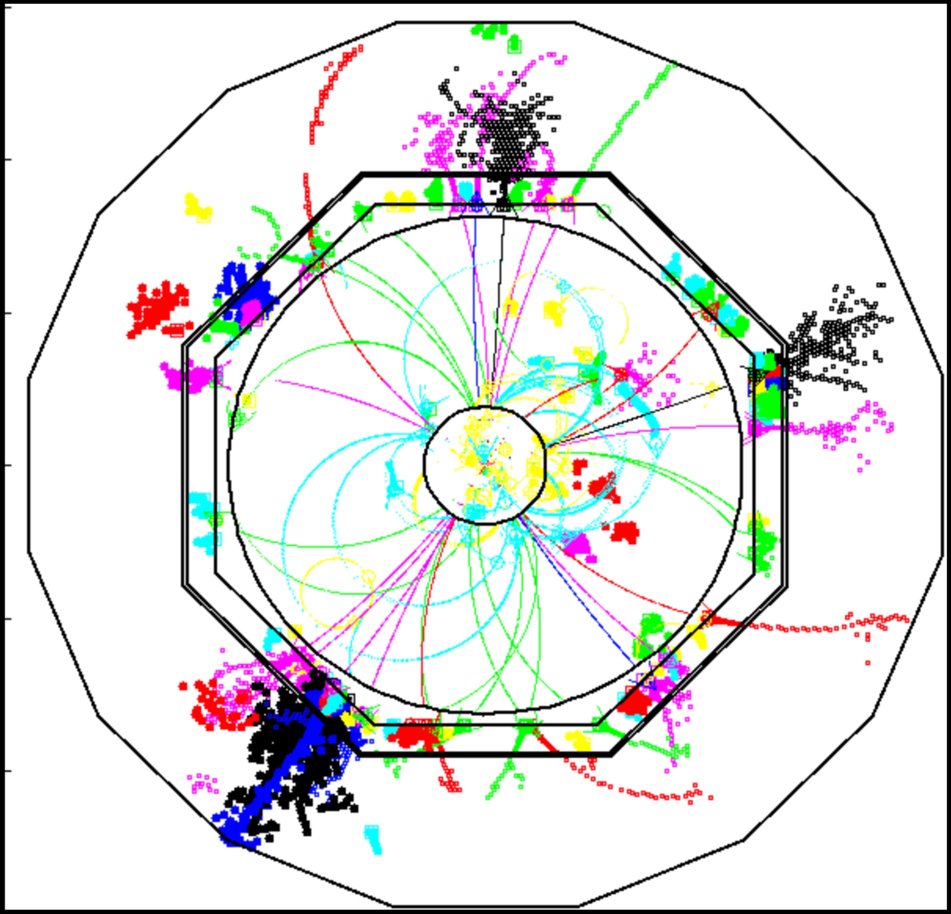
# Calorimetry



Ian Shipsey

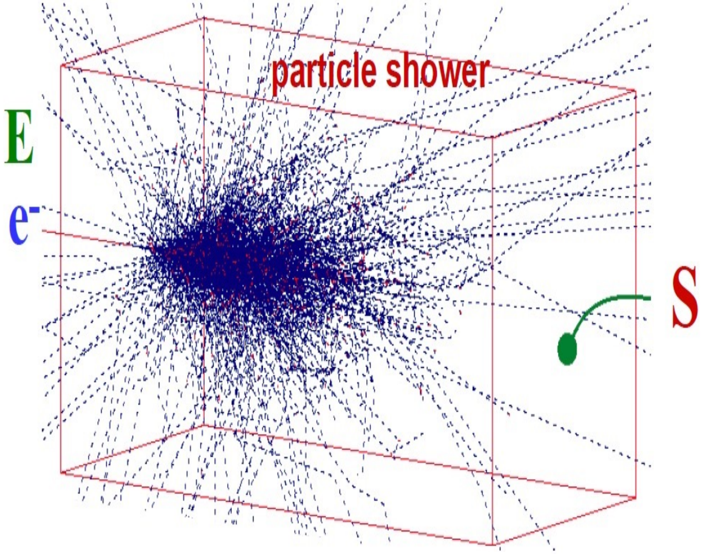
# Overview

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

# Why Calorimeters?

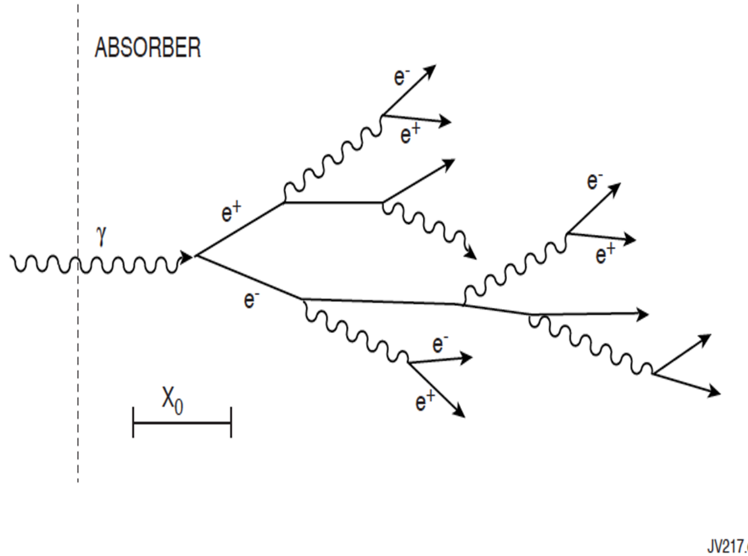
Energy measurement via total absorption of the incoming particles

- 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

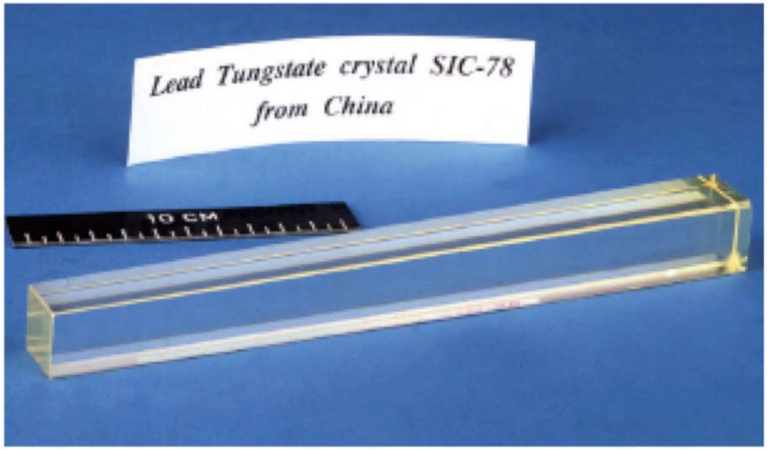
- CMS homogeneous crystal ECAL:

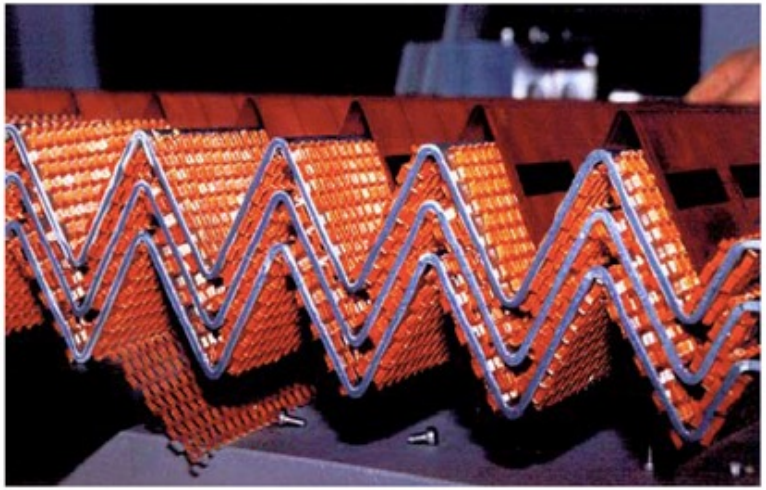
$$\frac{\sigma(E)}{E} = \frac{3\%}{\sqrt{E}} \oplus 0.5\% \oplus \frac{0.2\ GeV}{E}$$

- ATLAS lead LAr accordion calorimeter:

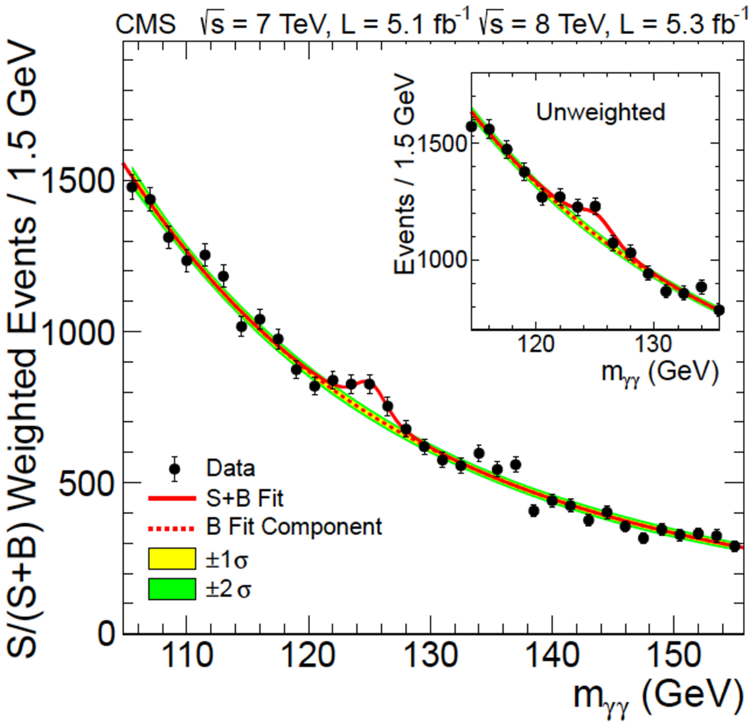
$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.4\% \oplus \frac{0.3\ GeV}{E}$$

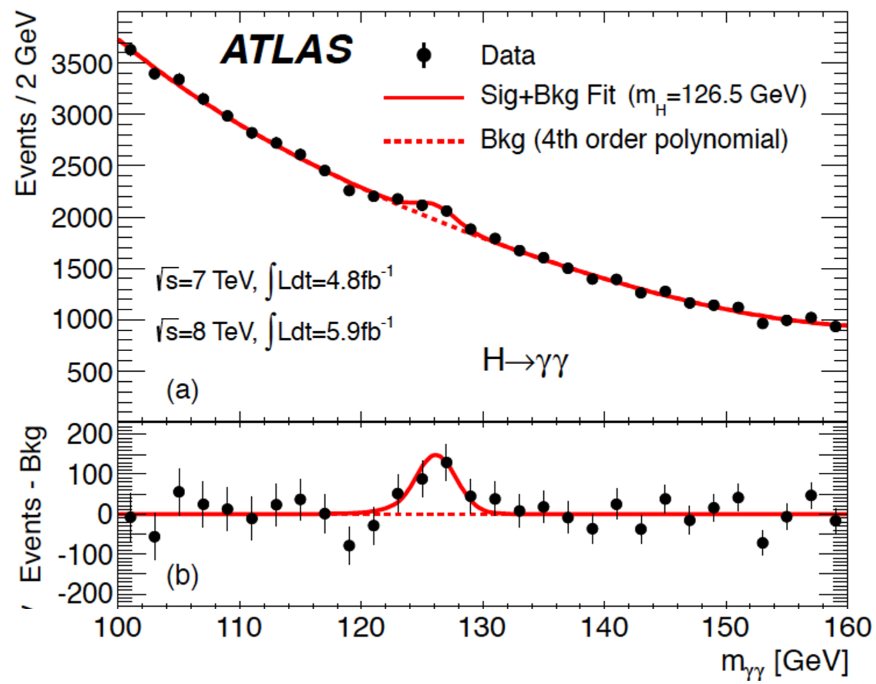
- so CMS should do much better in mass resolution for H $\rightarrow \gamma\gamma$, does it?



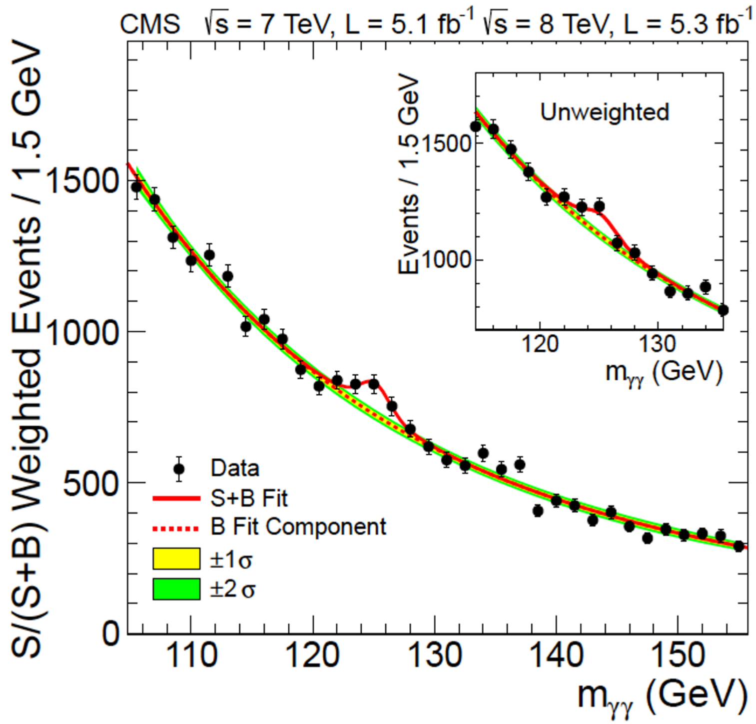
# Example ECALs: CMS vs. ATLAS

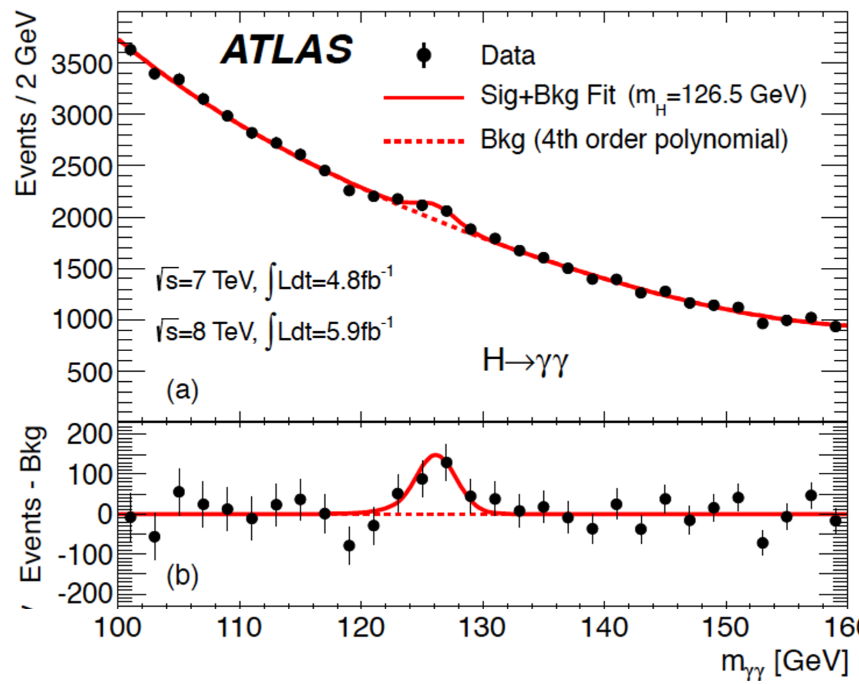



- CMS is not that much better than ATLAS! Why?

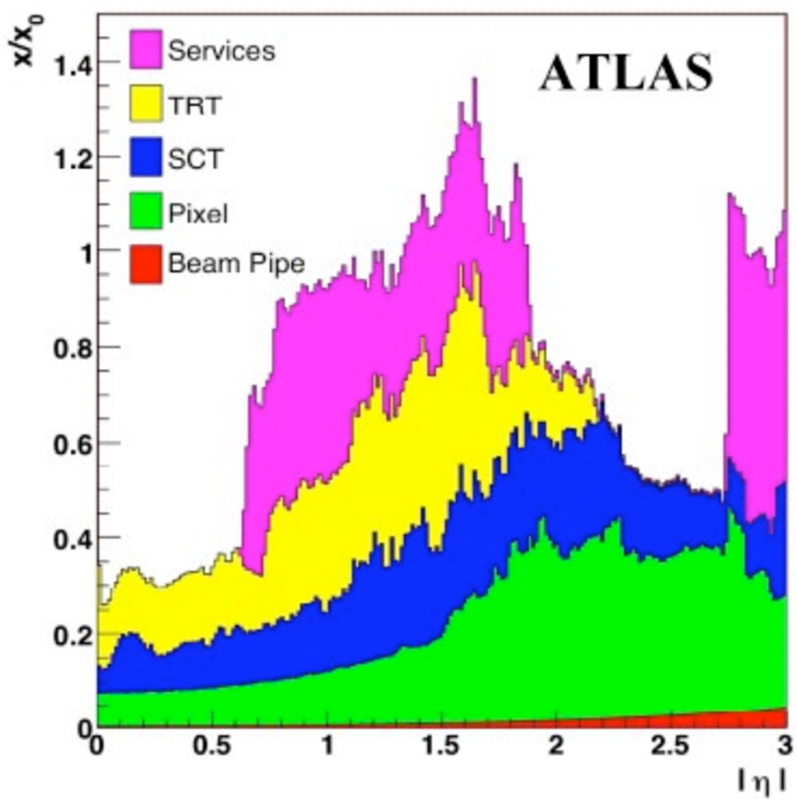
# Example ECALs: CMS vs. ATLAS

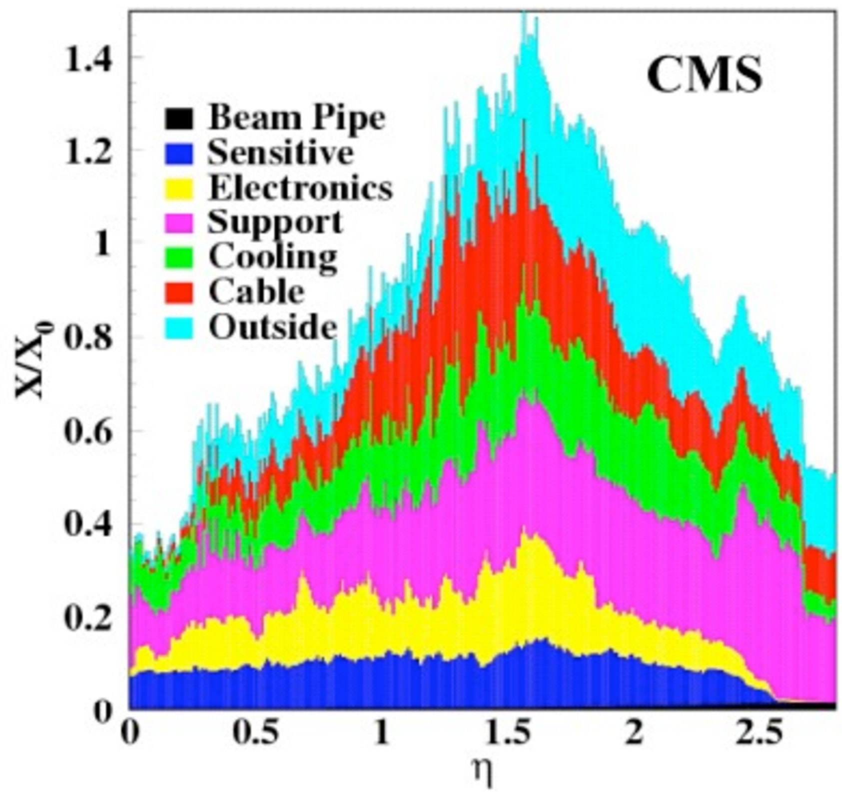



- CMS is not that much better than ATLAS! Why?
- energy resolution is not the only relevant quantity! ATLAS has finer granularity and therefore better position and angular resolution

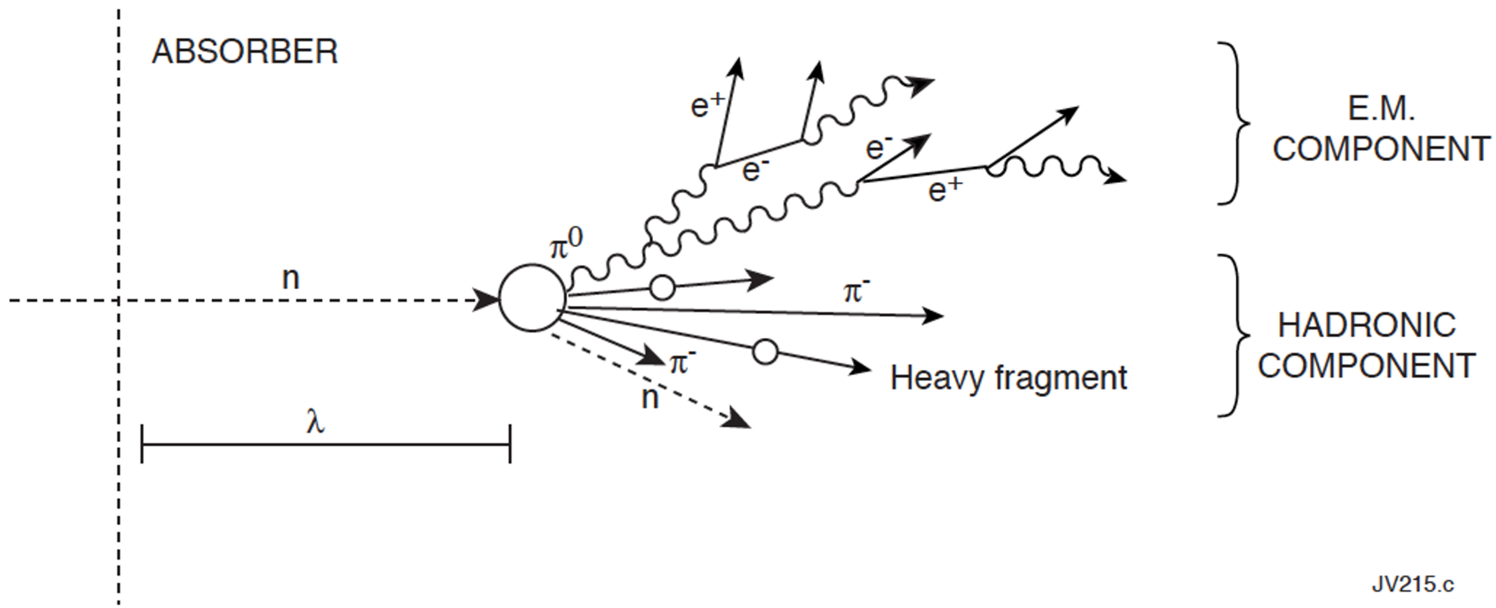
# Example ECALs: CMS vs. ATLAS




- 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, and much larger intrinsic variation
  - many processes: quasi-elastic scattering … nuclear break up
  - usually have electromagnetic sub-shower
- relevant length scale: **interaction length $\lambda_{Int}$**
- similar to EM showers: logarithmic increase of shower depth with energy

# Examples of HCAL energy resolutions

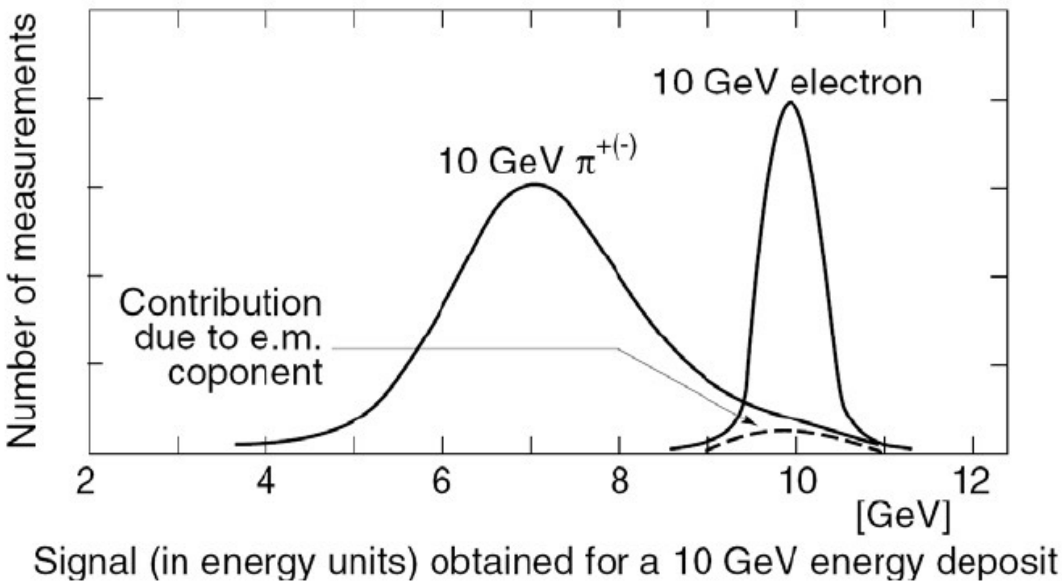
| **Experiment** | **technology** | **energy resolution** |
|---|---|---|
| ALEPH | Fe / streamer tubes | $85\%/\sqrt{E}$ |
| ZEUS | U / scintillator | $35\%/\sqrt{E} \oplus 2\%$ |
| H1 | Fe / liquid argon | $51\%/\sqrt{E} \oplus 1.6\% \oplus 0.9$ GeV/E |
| D0 | U / liquid argon | $41\%/\sqrt{E} \oplus 3.2\% \oplus 1.4$ 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



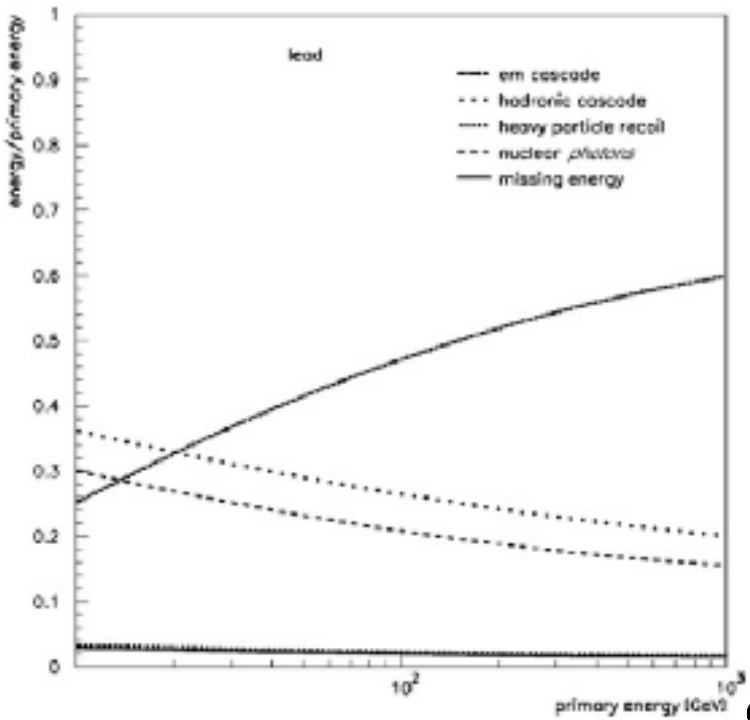

$$\pi = f_{EM}\, e + (1 - f_{EM})\, h$$

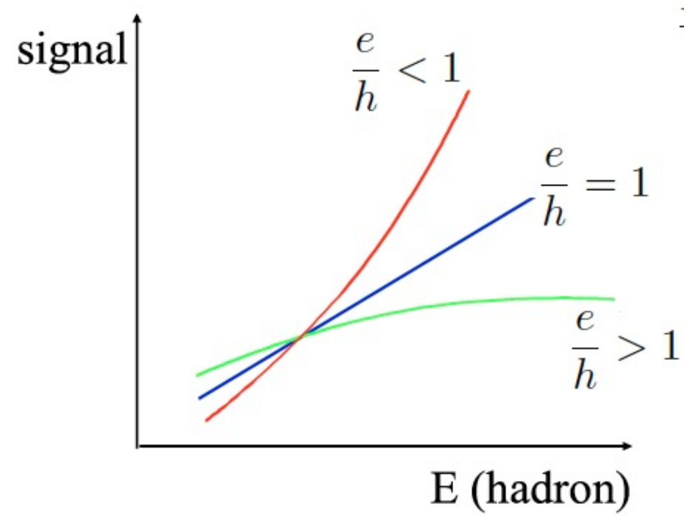
e: response to EM shower

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



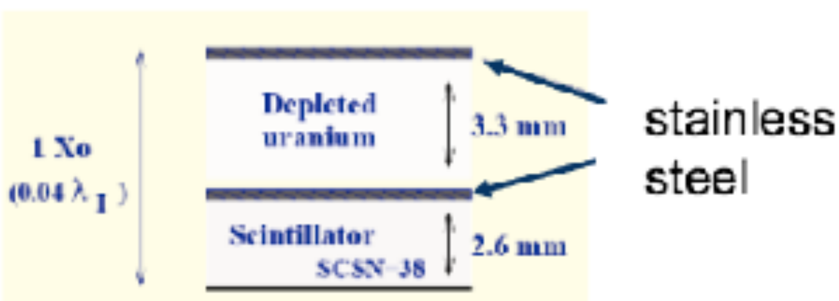




C. Fabjan, F. Gianotti, Rev. Mod. Phys. 75, 1243 (2003)

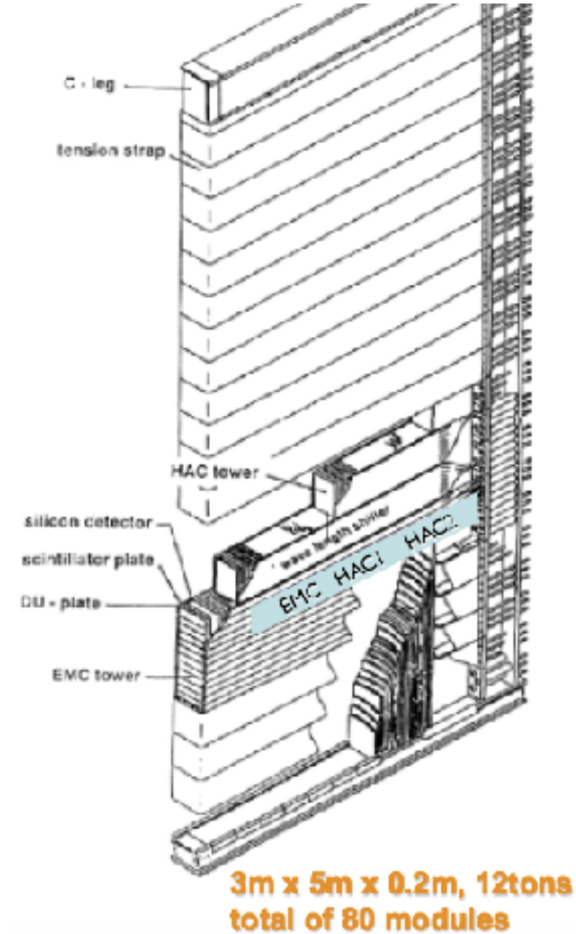
# Hadronic showers: how to reach compensation?

Hardware

- design 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 energy measurement 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

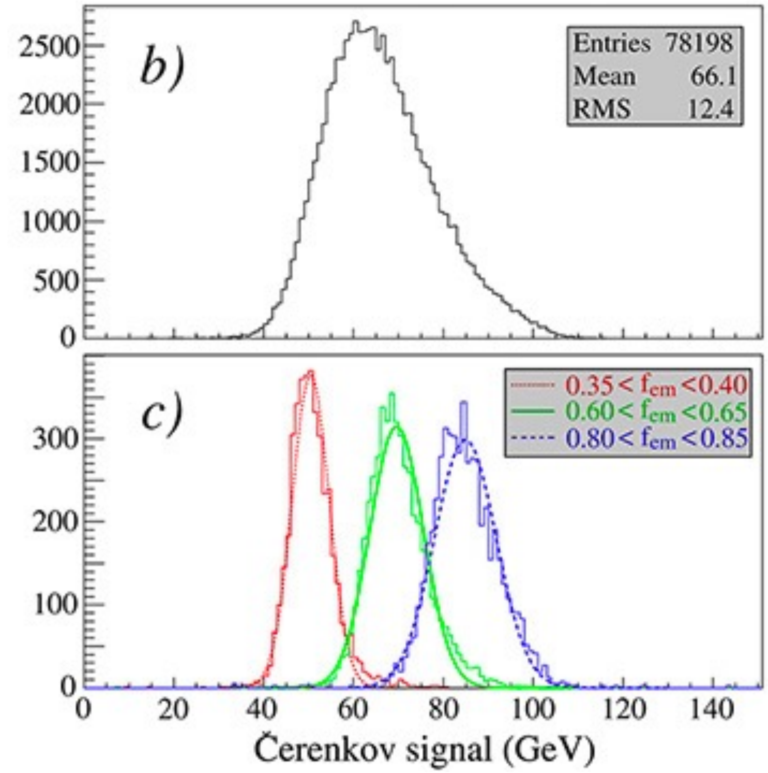
- Radiation hardness
  - Not really covered here
  - Very important for future hadron colliders (FCChh)
  - For highest fluence, mainly two technologies suitable
    - Liguid noble gas (Liquid Argon)
    - Silicon sensors

# Dual Readout: 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 $\pi-$ DREAM

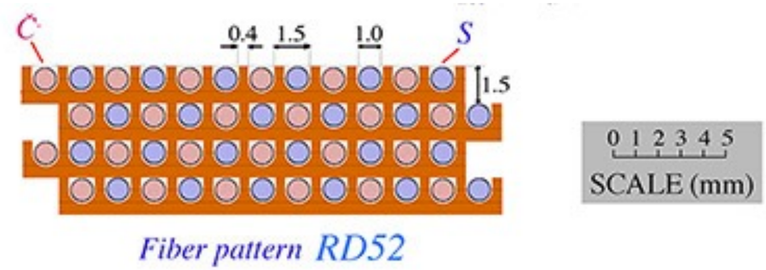


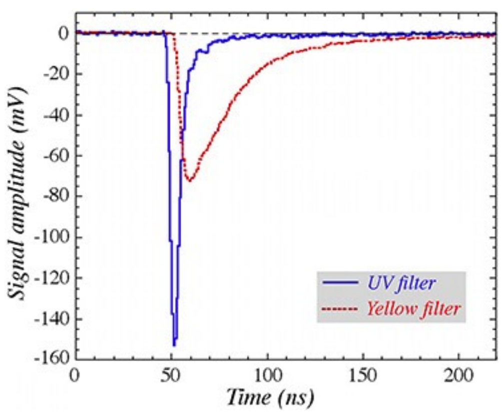

Plots from “DUAL-READOUT CALORIMETRY”, arXiv:1712.05494

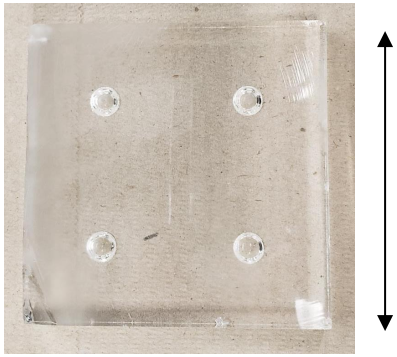
# Dual Readout: Implementation

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



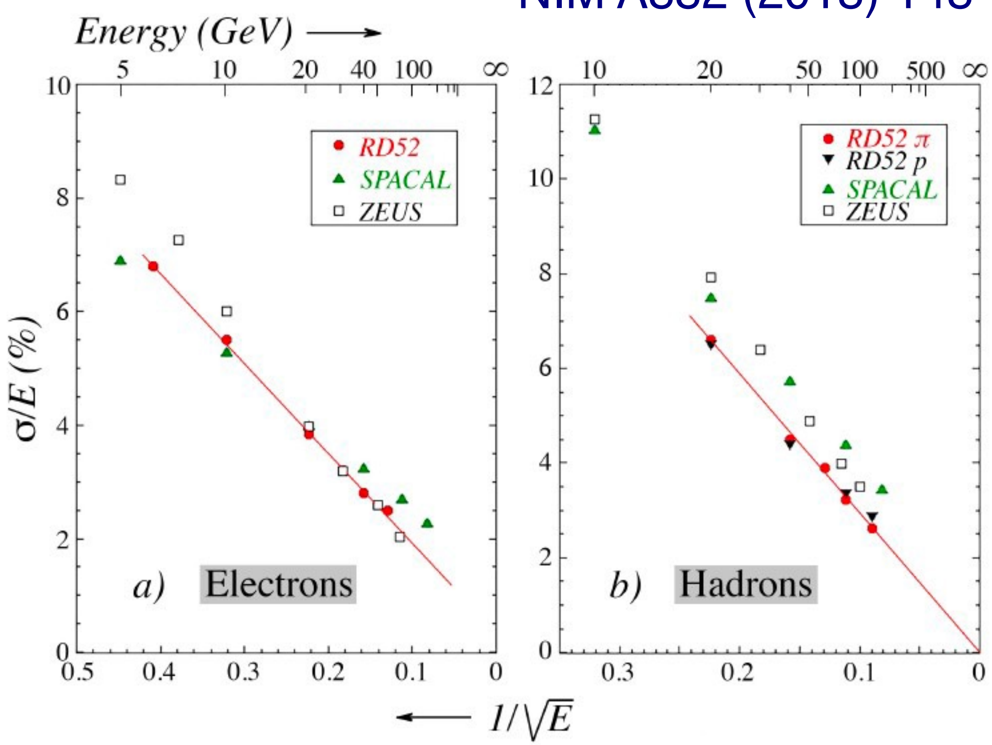



10 cm

# 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



# Motivation

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

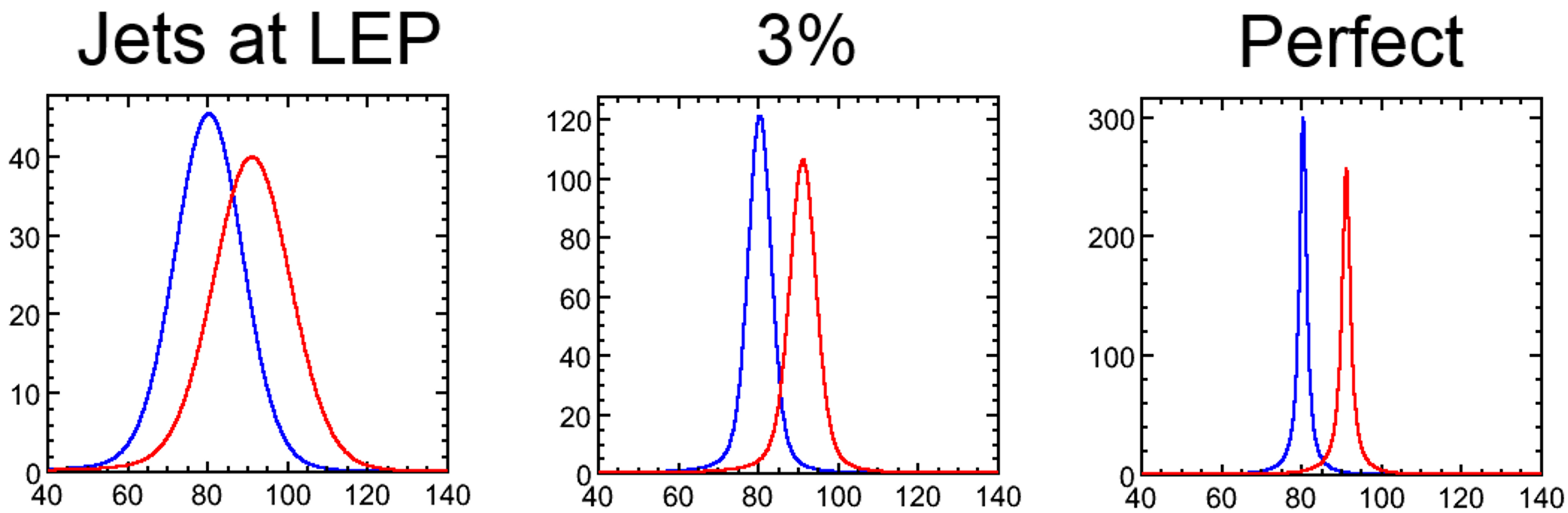
| Physics Process | Measured Quantity | Critical System | Physical Magnitude | Required Performance |
|---|---|---|---|---|
| $Zhh$ | Triple Higgs coupling | Tracker | Jet Energy | |
| $Zh \to q\bar{q}b\bar{b}$ | Higgs mass | and | Resolution | |
| $Zh \to ZWW^*$ | $B(h \to WW^*)$ | Calorimeter | $\Delta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

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?

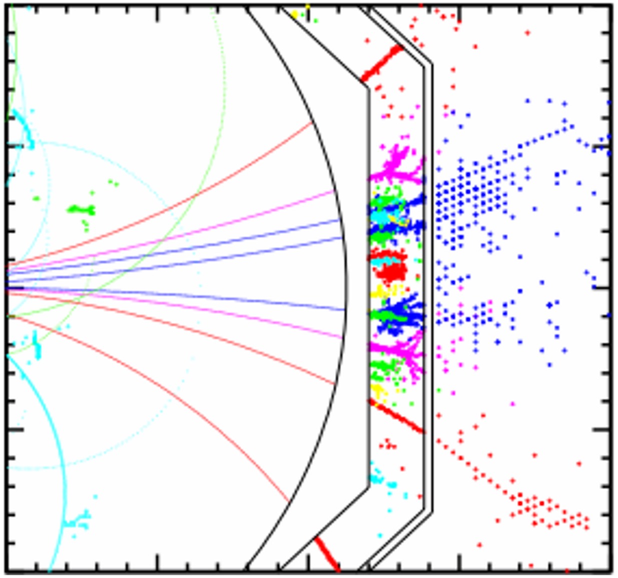
- goal: distinguish the decays *W → jet jet* and *Z → jet jet* by their reconstructed mass




from Cambridge HEP group

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

# Particle Flow Algorithm



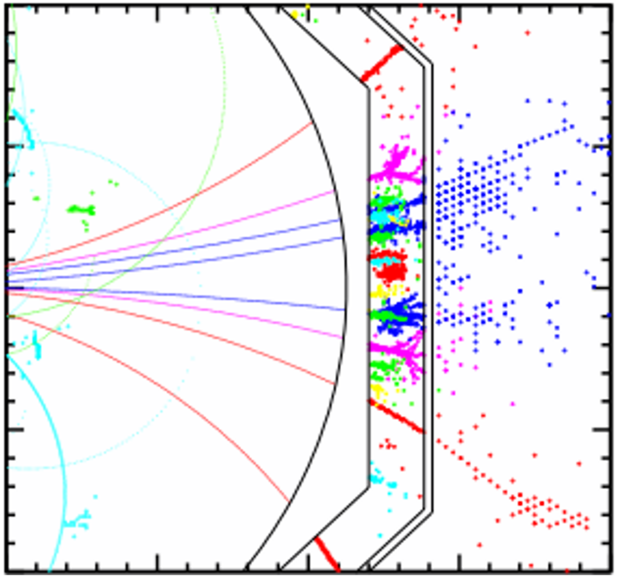
from: M.A. Thomson,
Nucl.Instrum.Meth. A611 (2009) 25

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

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

# Particle Flow Algorithm

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



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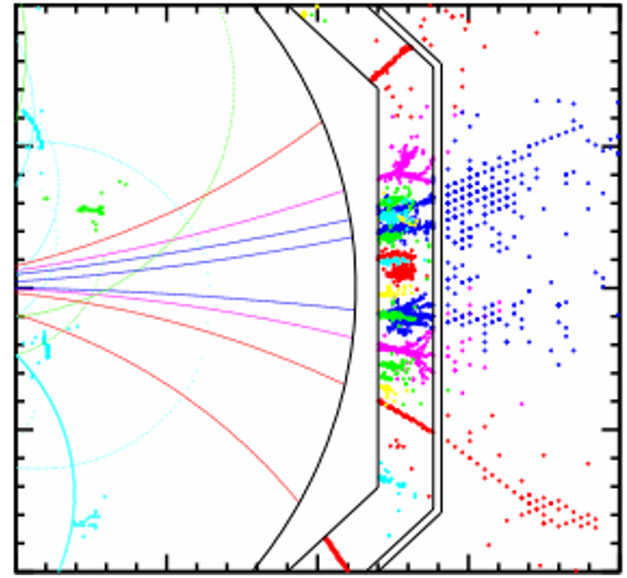
> „typical“ jet:

| | |
|---|---|
| ~ 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

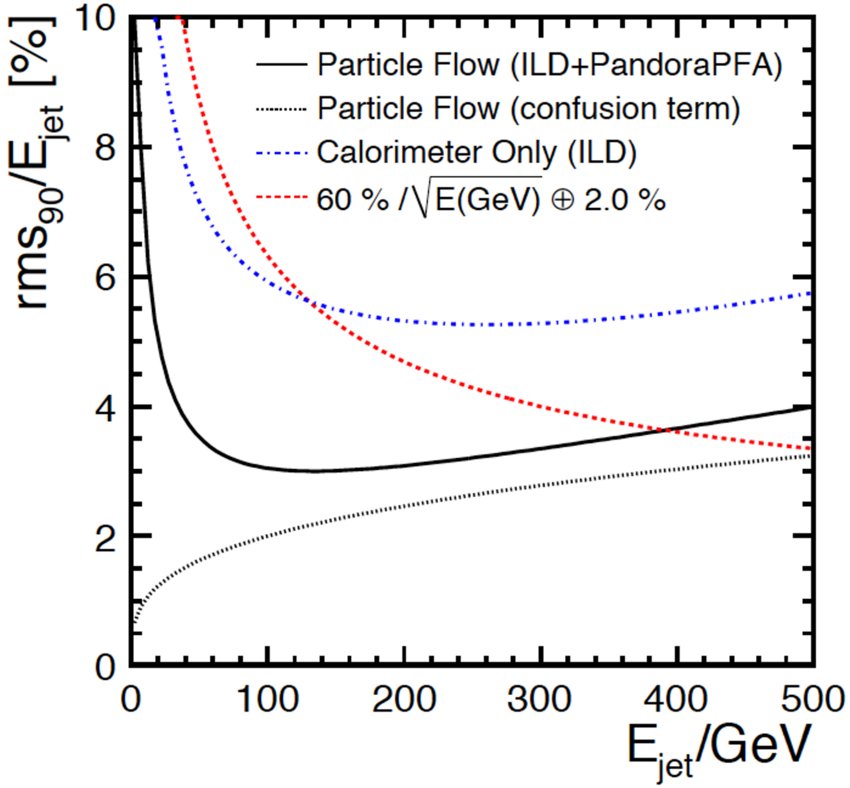


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „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

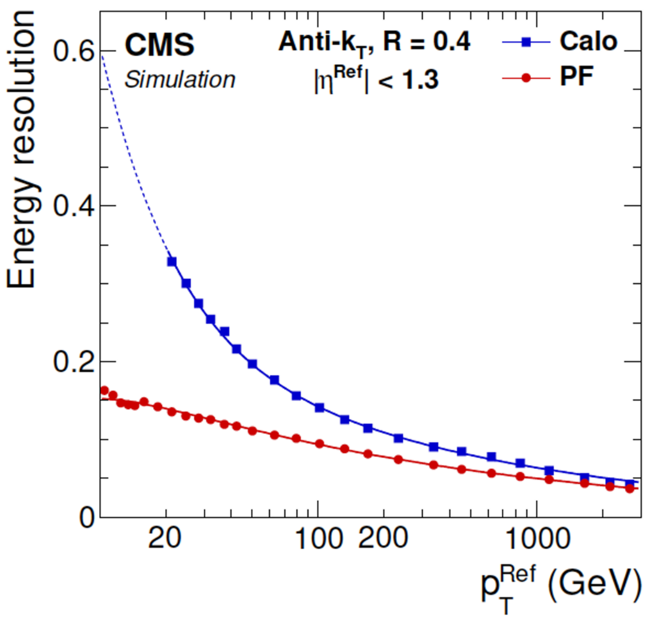
“ideal” traditional HAD calorimeter

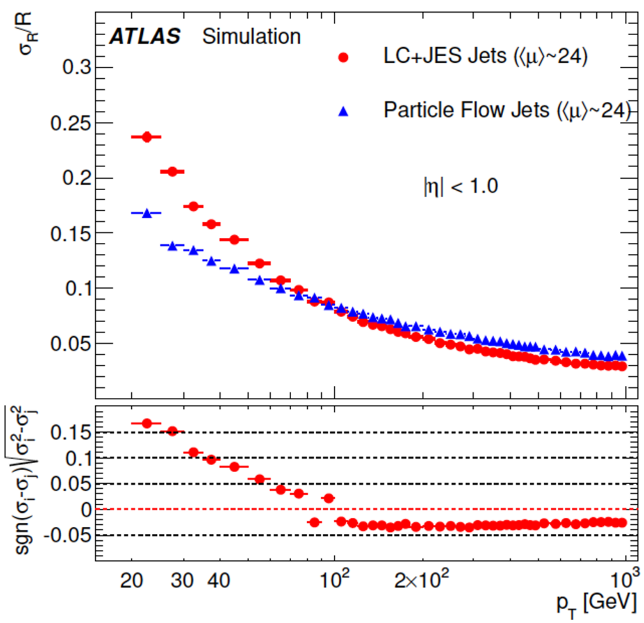
„Confusion“: wrong association between tracks and calorimeter clusters

- 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

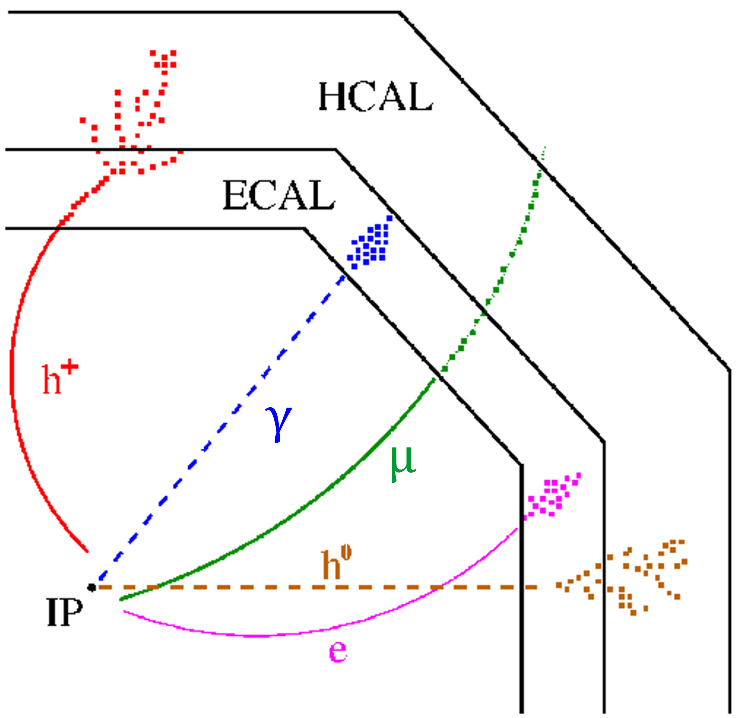
What featires should a detector possess so that it is optimized for Particle Flow?

- > need good separation of particles entering the calorimeter
- ➔ large detector radius and length
- ➔ large magnetic field to separate charged from neutral particles

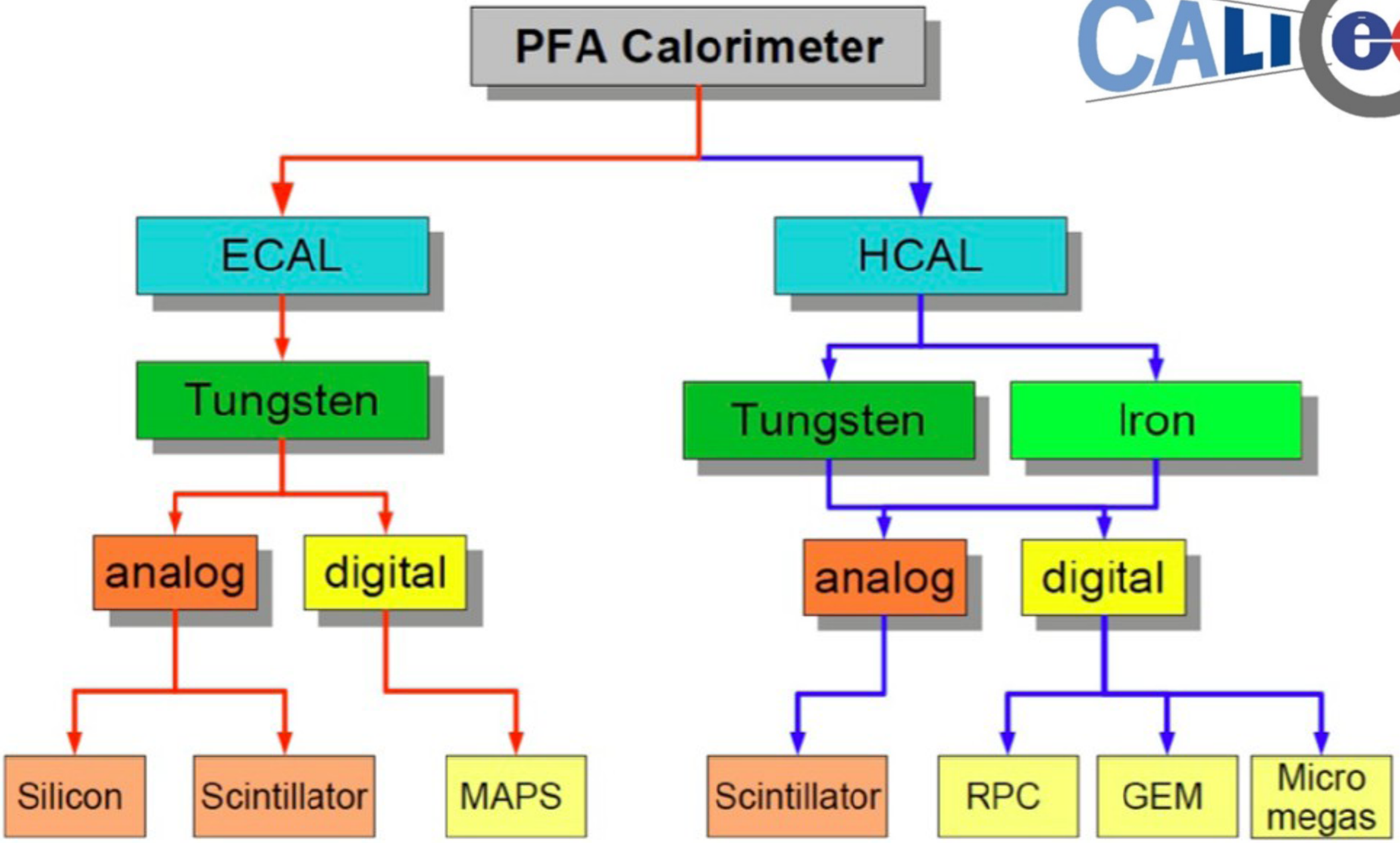
- > need compact showers to minimize overlap
- ➔ **calorimeters** with small Molière radius

- > 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

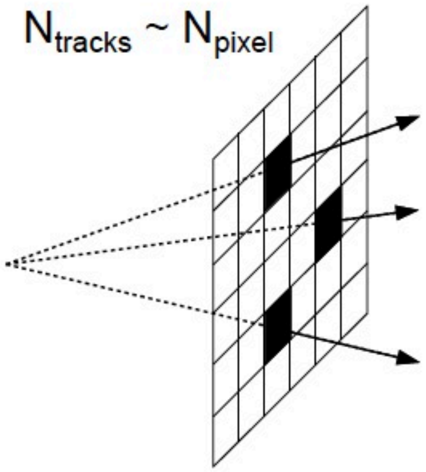


# Calorimeter Technologies for Linear Collider detectors



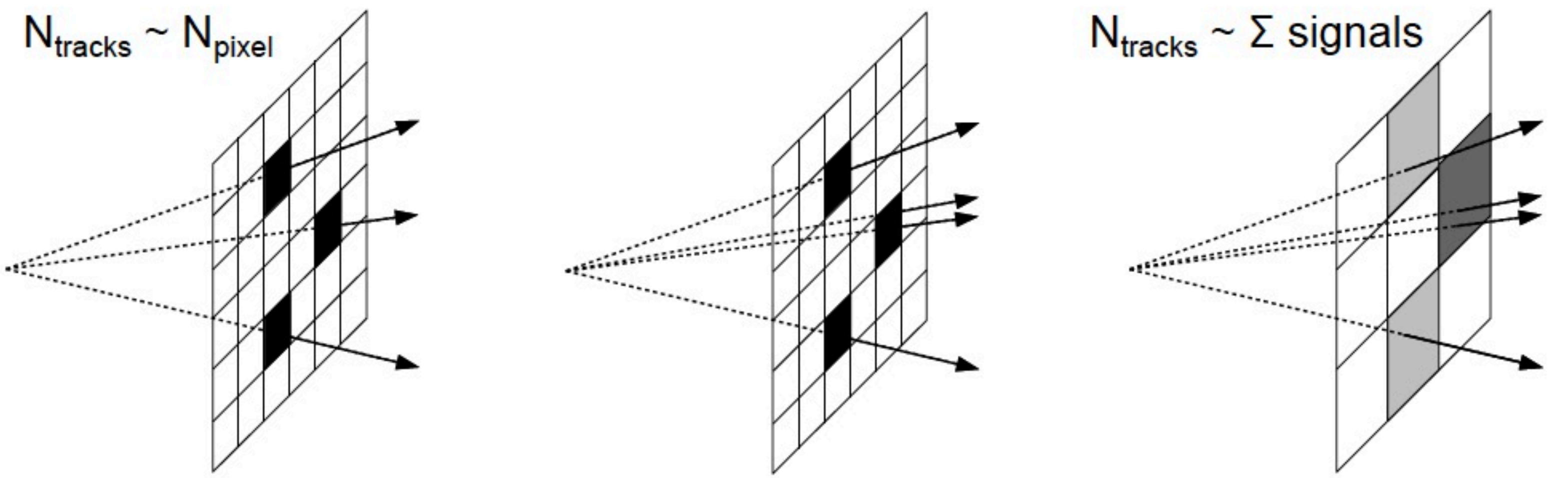
# Calorimeter Readout Concepts

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



# Calorimeter Readout Concepts

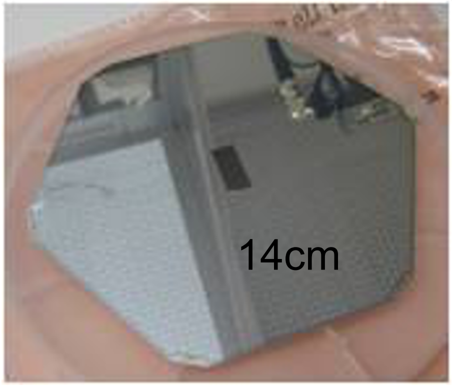
- digital CAL: count number of hit pixels (off/on)
- semi-digital CAL: additional information about number of particles within one pixel by using 3 thresholds (off/standard/large/very large)
- analog CAL: sum up signals in (larger) cells




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

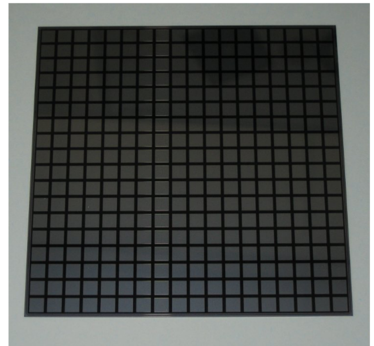
# Electromagnetic Calorimeter: Active Material

Silicon




1024 pixel

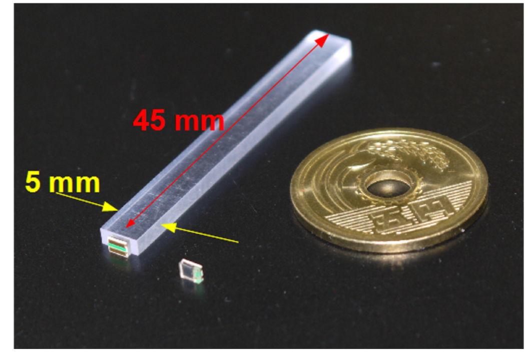
Silicon

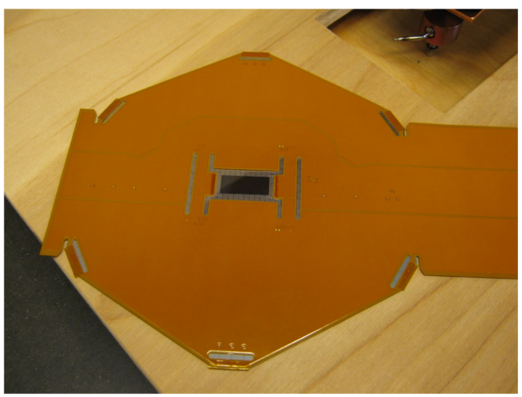


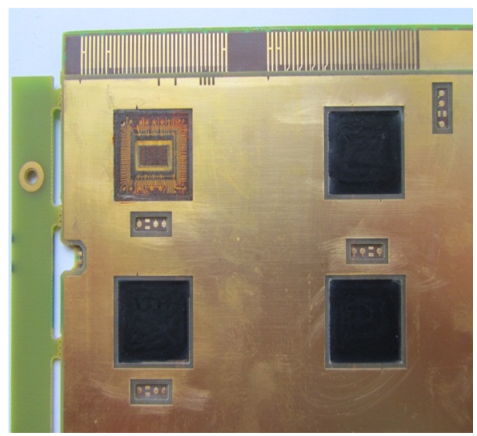
9cm

256 pixel

Scintillator

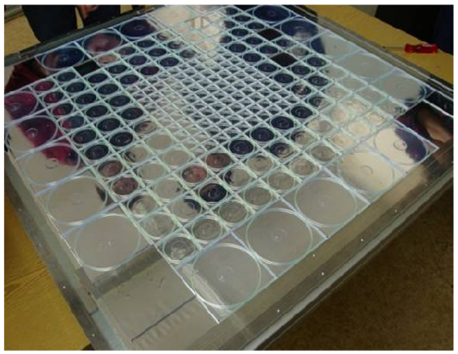


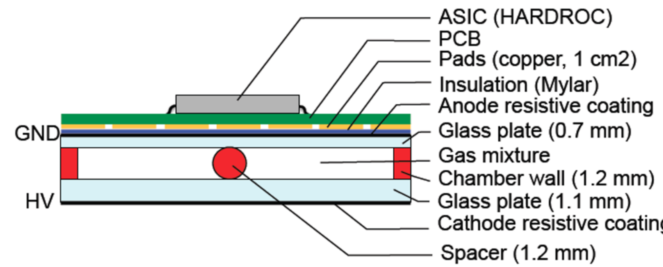



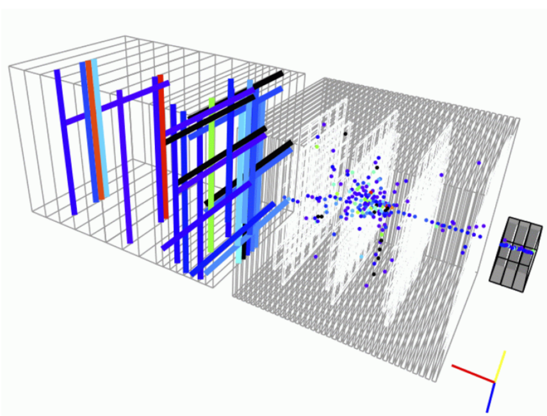


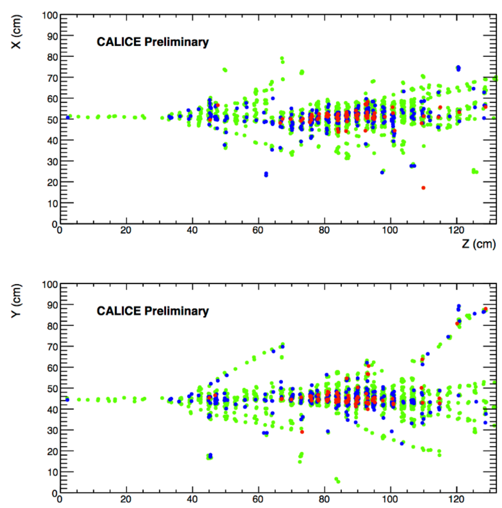
# Highly Granular HCAL Concepts

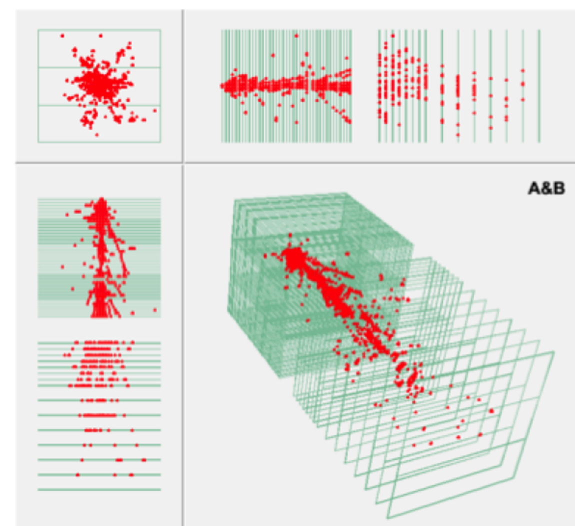
| | analog | semi-digital | digital |
|---|---|---|---|
| granularity | 3*3 $cm^2$ | 1*1 $cm^2$ | 1*1 $cm^2$ |
| technology | scintillator tiles | RPCs (or µMegas) | RPCs (or GEMs) |





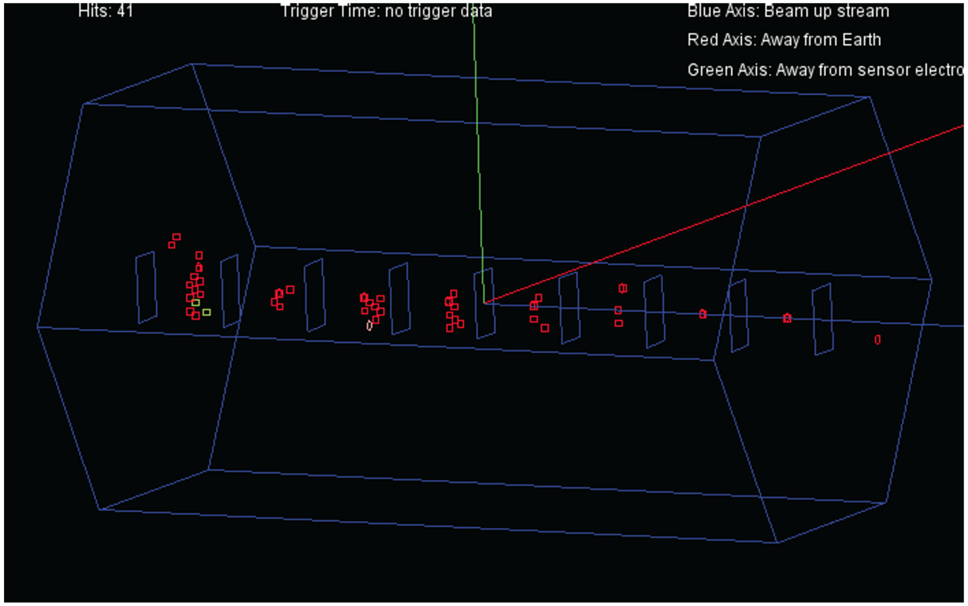


# Measurements in Beam Tests

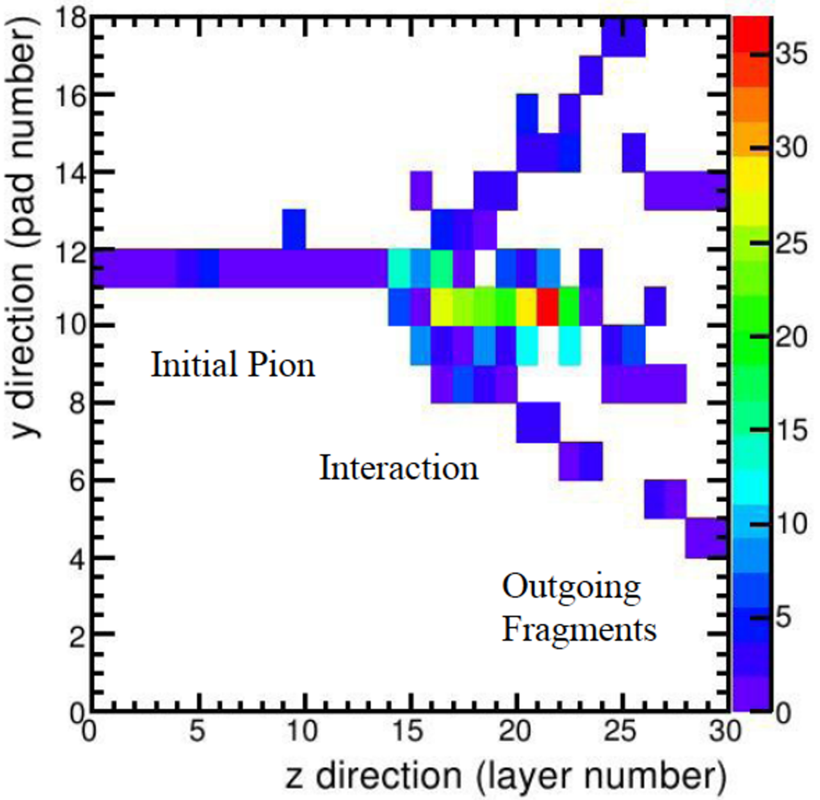
- In test beams you get only single particles, no jets
  ⇒ direct measurement of the jet energy resolution not possible
- Nevertheless, measurements in beam tests provide important information:
  - hands-on experience with (a small version of) the detector
  - calibration of the detector
  - energy resolution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

# Highly Granular ECALs



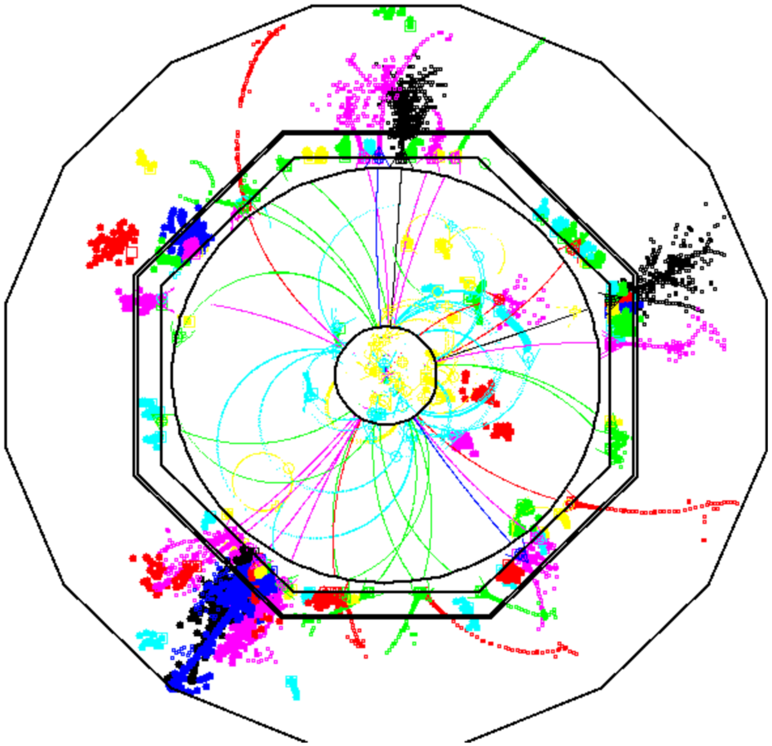

electron in silicon ECAL prototype with hexagonal sensors (6 $X_0$)

pion in silicon ECAL prototype with square sensors

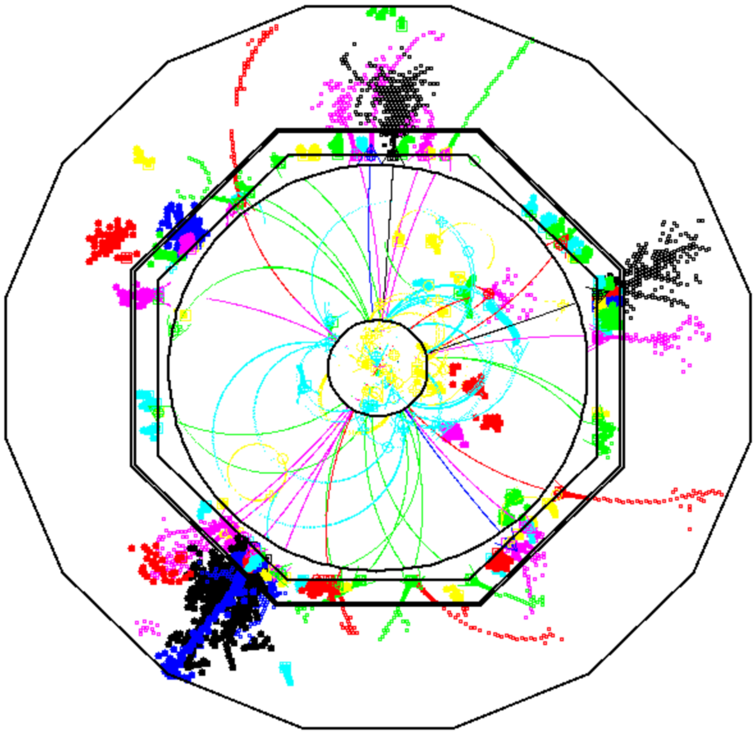


# How small should the cells be?

1*1 $cm^2$ HCAL cell size



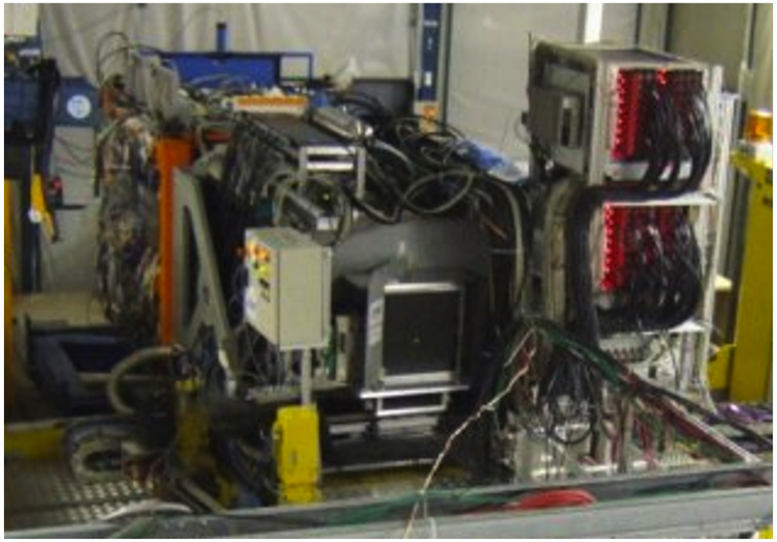
3*3 $cm^2$ HCAL cell size



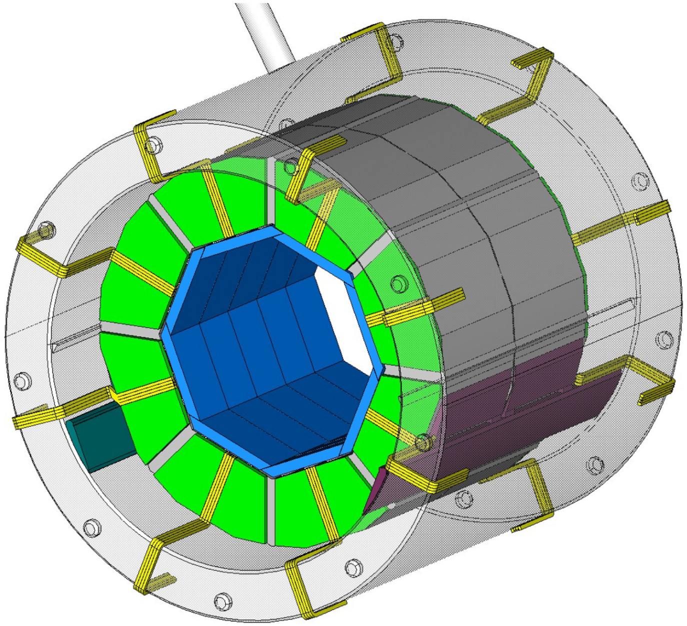
# From physics prototypes to engineering prototypes

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

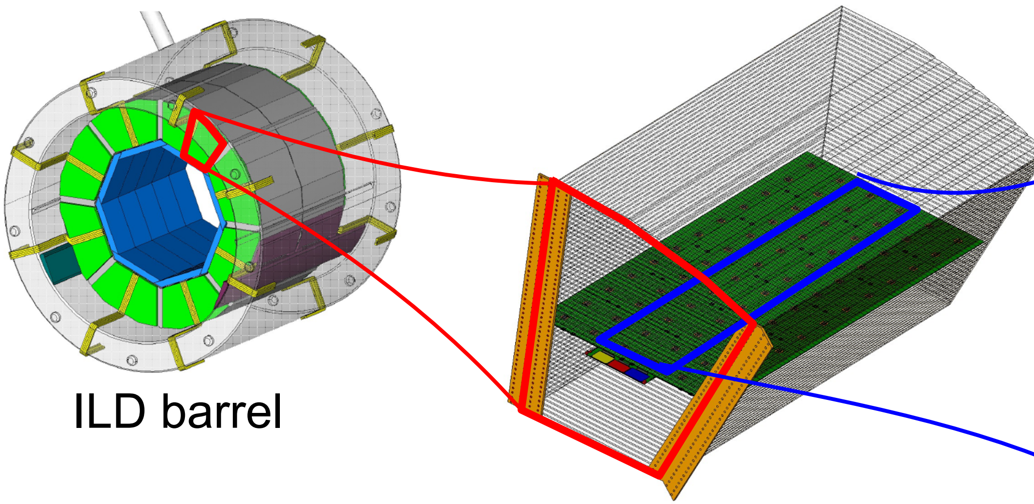
- but these were designed for beam tests, not really scalable to a collider detector



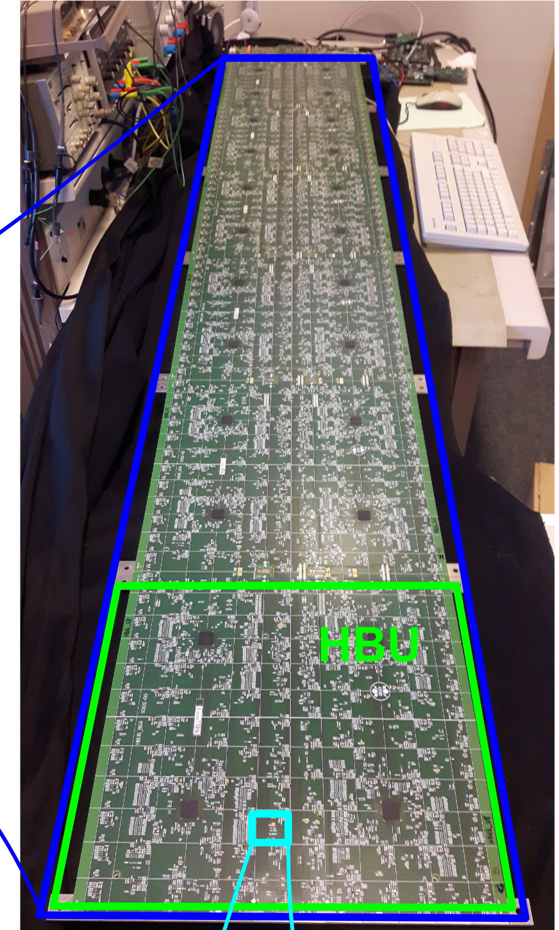
- goal for the "engineering prototype": develop, build and test a prototype scalable to the full collider detector layout
  - integration of electronics into layers
  - realistic infrastructure
  - easy mass assembly



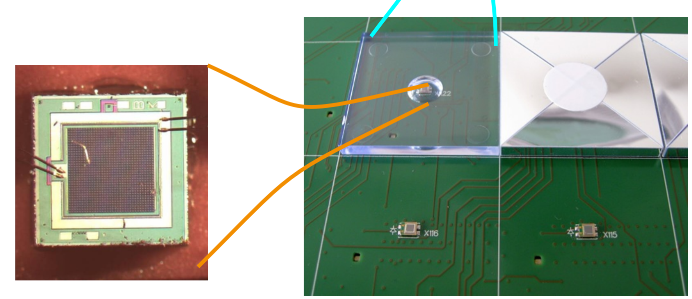
# Analog HCAL Engineering Design



ILD barrel



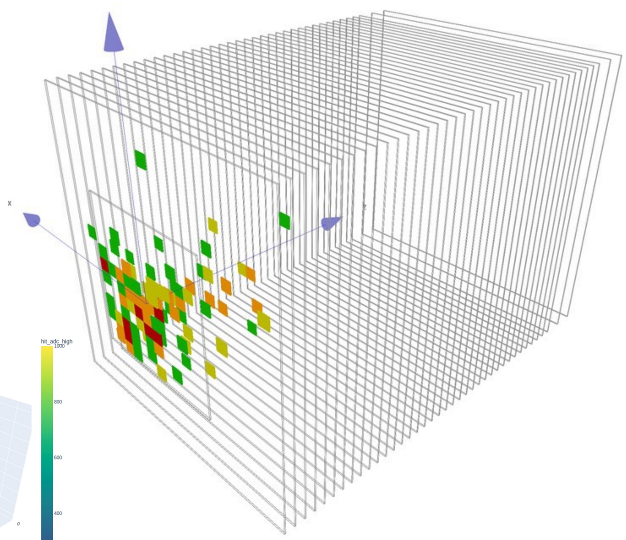

- highly granular scintillator SiPM-on-tile hadron calorimeter, 3*3 cm² scintillator tiles
- fully integrated design
  - front-end electronics, readout
  - voltage supply, LED system for calibration
  - no cooling within active layers
- scalable to full detector (~8 million channels)



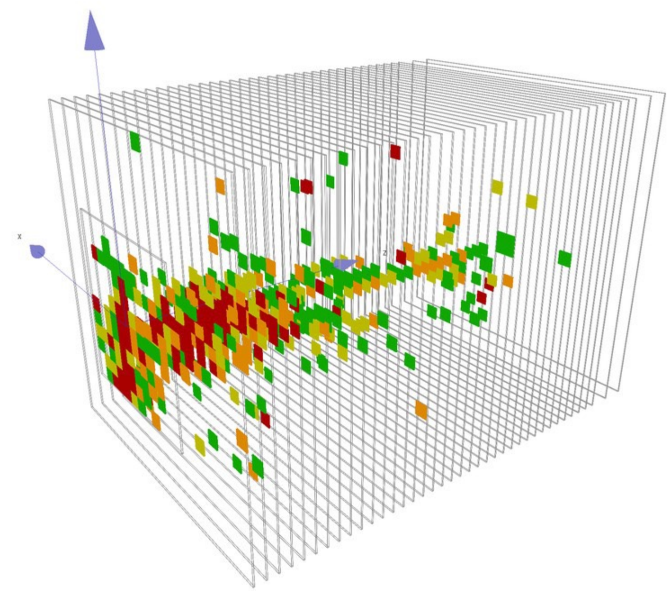
# Silicon ECAL + Analog HCAL in Testbeam

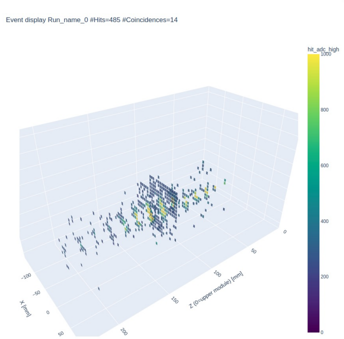
> Have just finished 2 weeks of testbeam at the CERN SPS with combined silicon ECAL + analog HCAL engineering prototypes

AHCAL: tail of an electron shower



AHCAL: pion shower, starting in ECAL



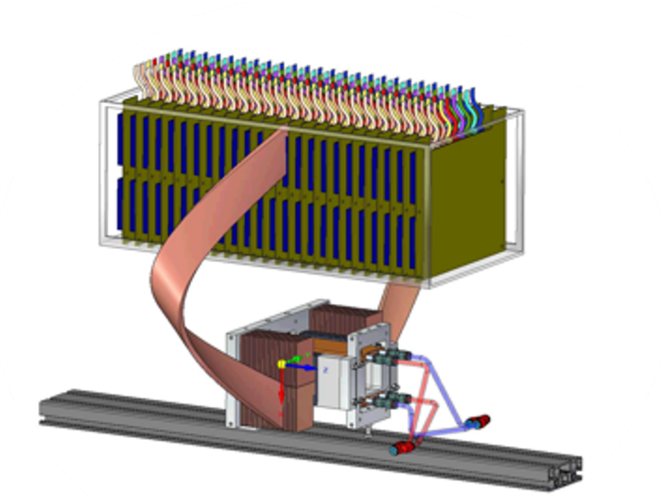


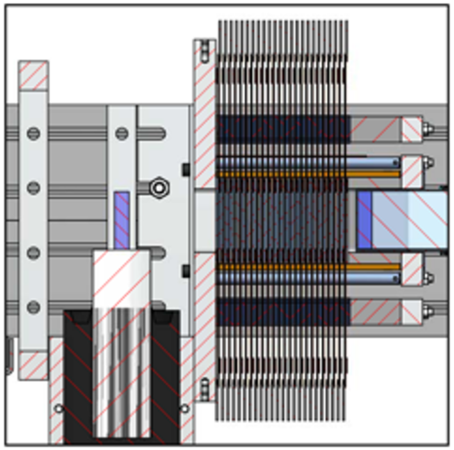

SiECAL: electron shower

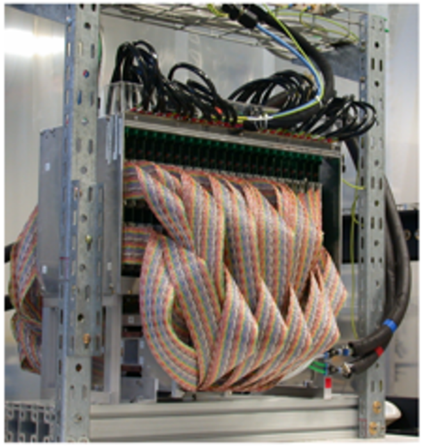
# High Granularity beyond electron-positron colliders

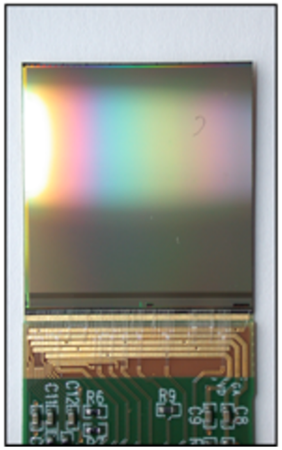
- recently also LHC detector collaborations adopted the idea of highly granular calorimeters
- granularity driven by pile-up mitigation, NOT particle flow

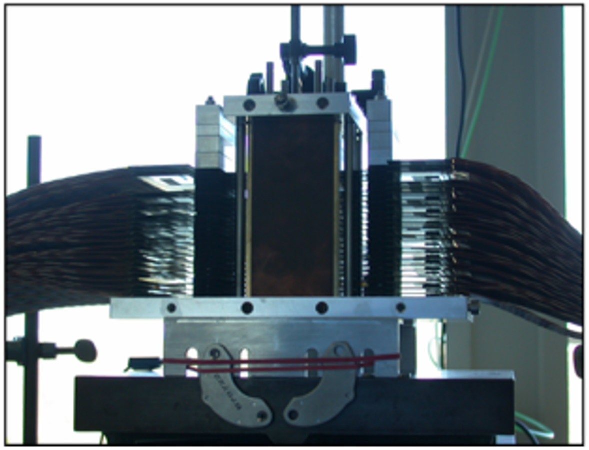
# Digital ECAL: Pixel Calorimeter Prototype







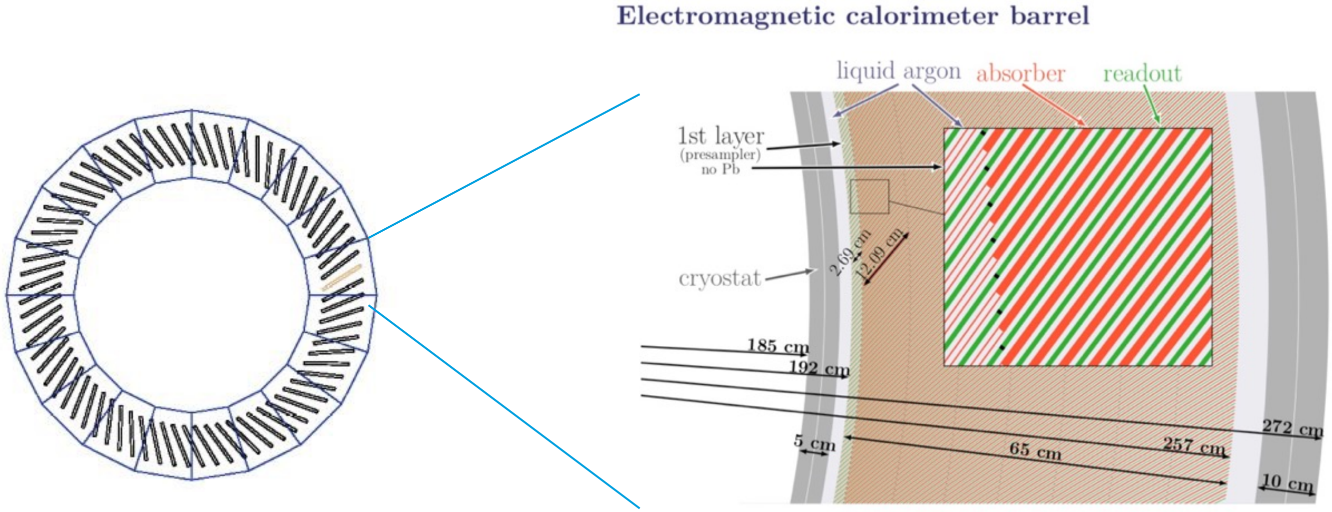




- R&D for ALICE FoCal upgrade
- full MAPS prototype, 24 layers
  - 3mm W
  - 1mm sensor layer
  - 120µm sensor (2x2 chips) + PCB, glue, air, …
- **39 M pixels in 4x4x10 cm³ !**

# FCC-hh: LAr with high(er) granularity

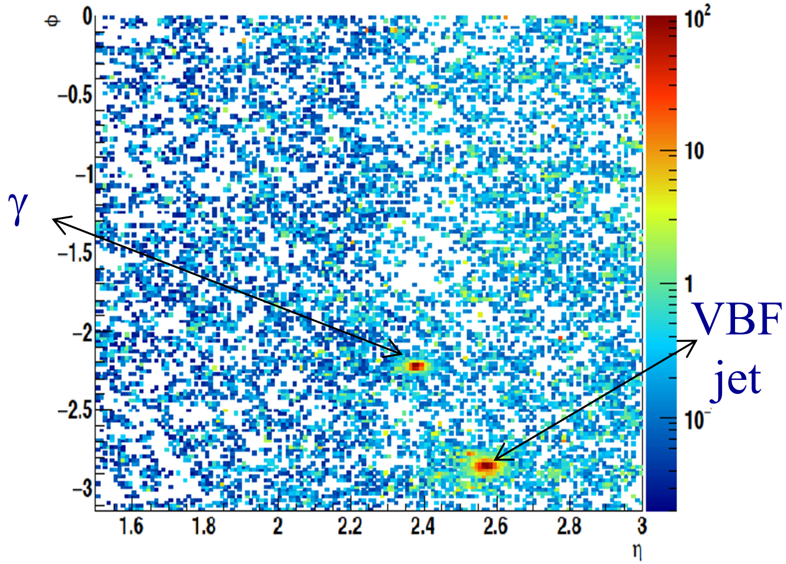
- Compared to ATLAS, FCC-hh Calo needs finer longitudinal and lateral granularity
  - Optimized for particle flow
  - 8 longitudinal compartments, fine lateral granularity
- Noble liquid (LAr) as active material
  - Radiation hardness, linearity, uniformity, stability
- EM Barrel: Absorbers 50° inclined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



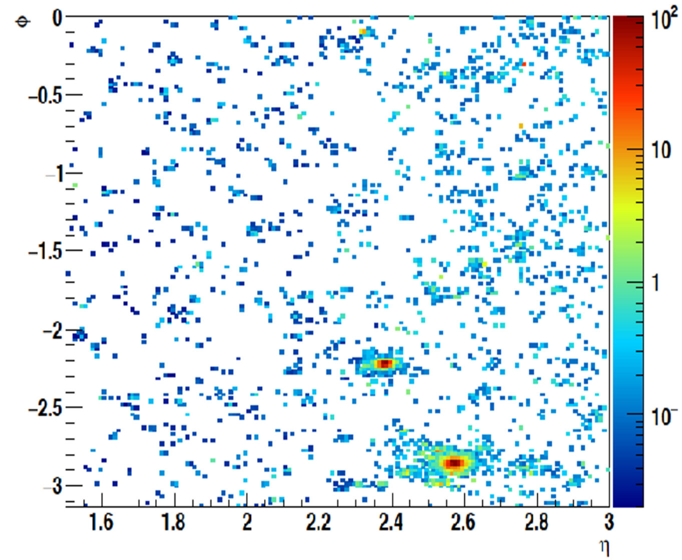
# Granularity and Timing for Background (Pileup) Rejection

- 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



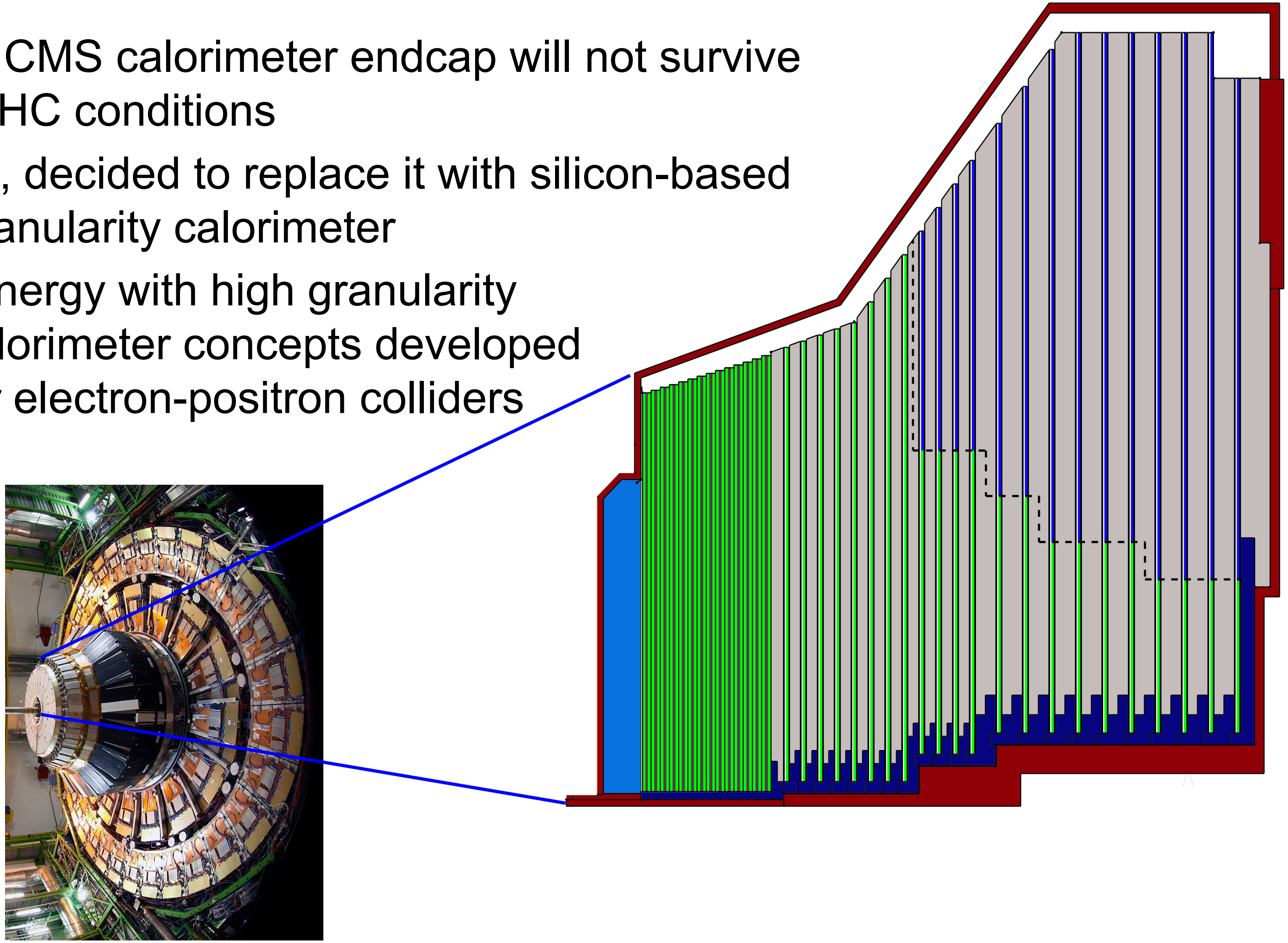

Cut $\Delta t < 90$ps (3σ at 30ps)




Plots show cells with Q > 12fC (~3.5 MIPs @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

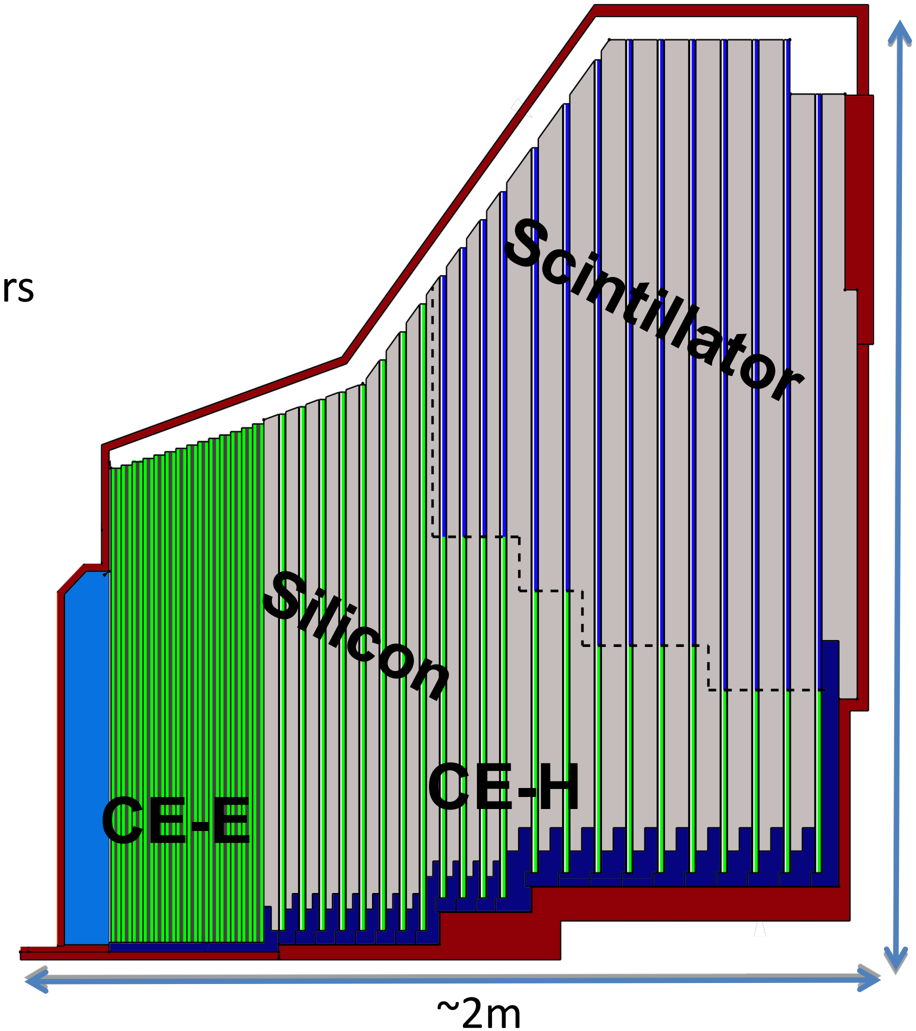
- current CMS calorimeter endcap will not survive in HL-LHC conditions
- in 2015, decided to replace it with silicon-based high-granularity calorimeter
  - synergy with high granularity calorimeter concepts developed for electron-positron colliders



# 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

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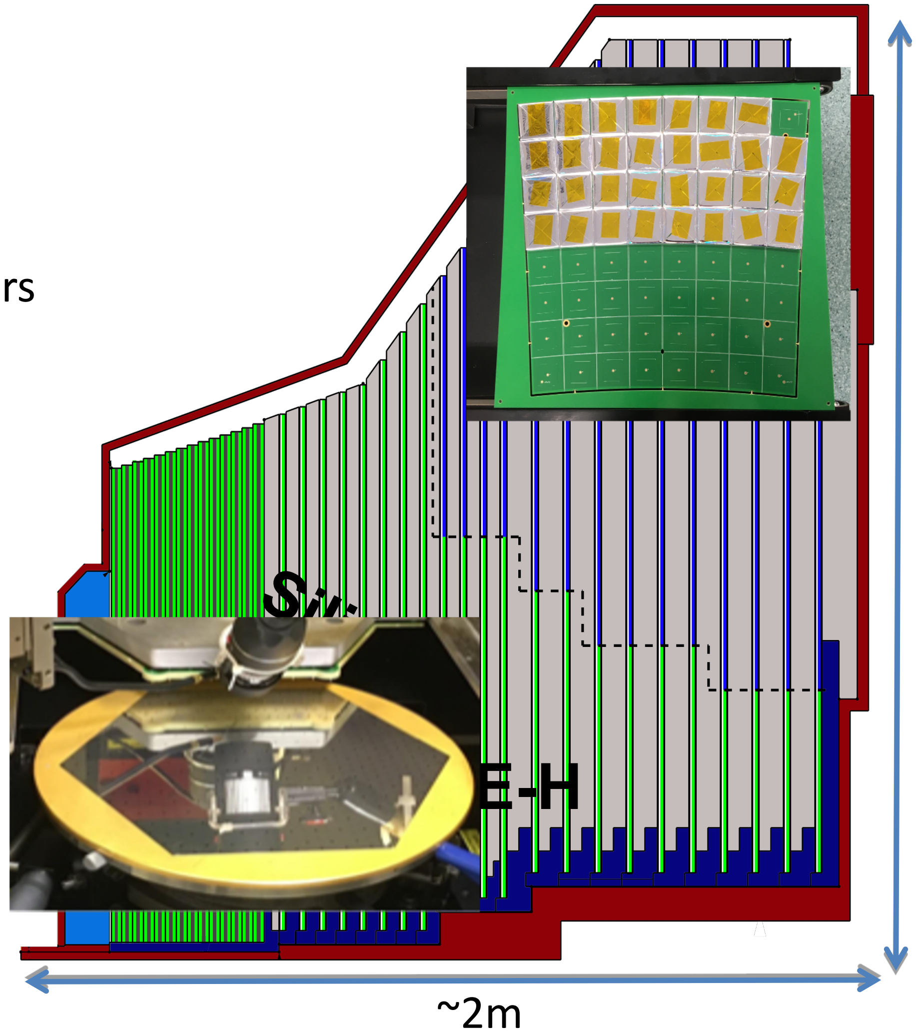


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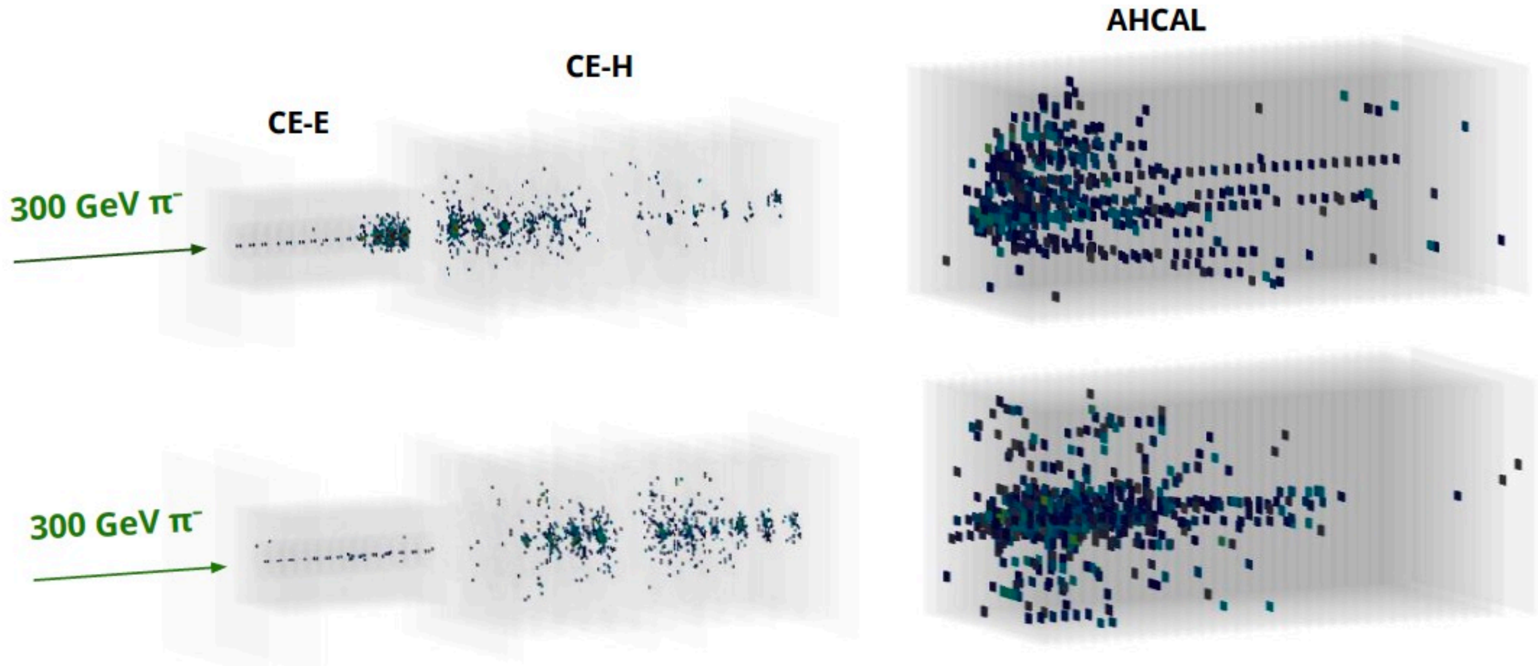
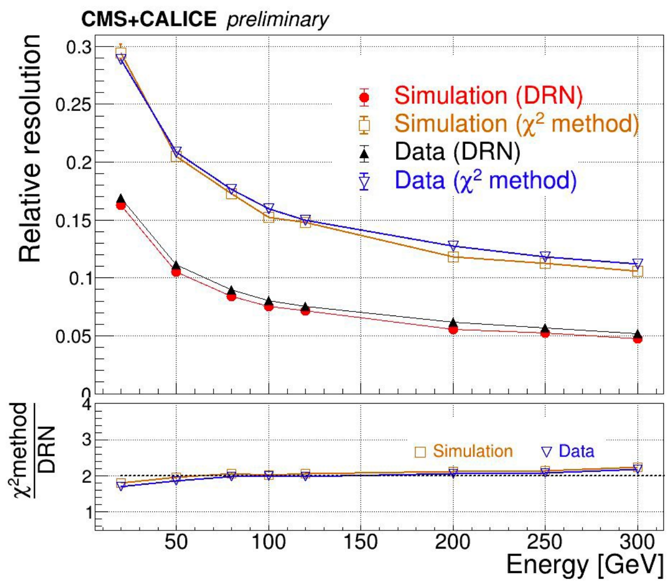
# Common Running of AHCAL & HGCAL silicon prototype

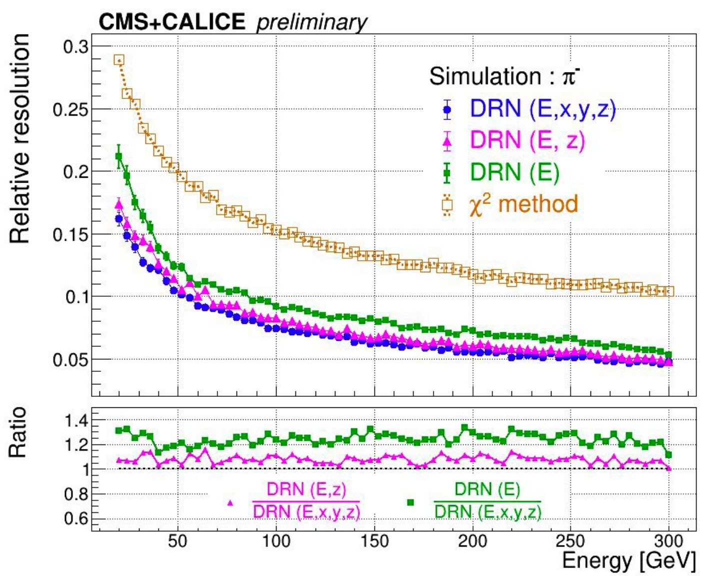



- In October 2018, collected hadron data with HGCAL silicon module prototypes and the AHCAL prototype
  - 28 layers HGCAL EE (silicon/lead), 12 layers HGCAL FH (silicon/steel), 39 layers AHCAL (scintillator/steel)

# HGCAL prototype: GNN reconstruction

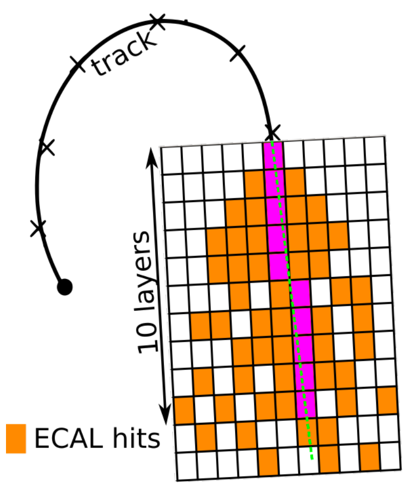
- High granularity allows sophisticated reconstruction algorithms
  - Physicist's knowledge: software compensation
  - Machine learning: train a Graph Neural Network
    - With hit energies alone (E) already better than "classical" energy sum
    - Adding position information (E,z) and (E,x,y,z) even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

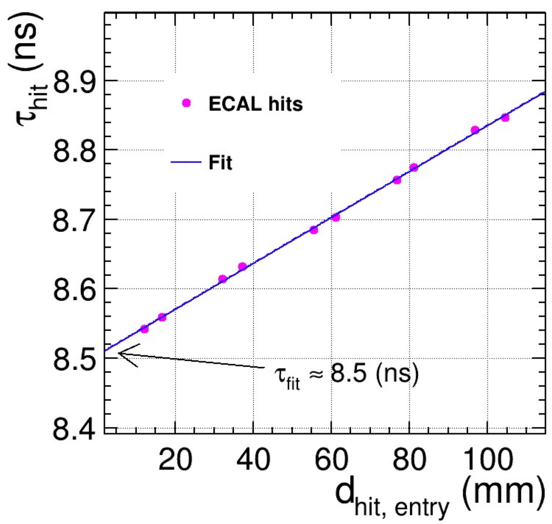


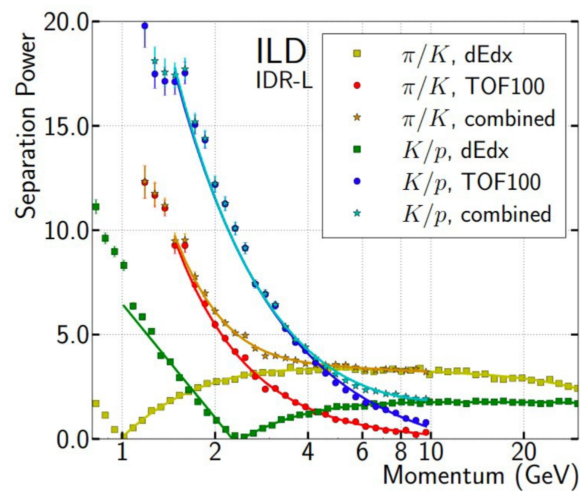



# Other uses of timing

- 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



# Calorimetry 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