Calorimetry:
Present trends and technology progress

P.Bloch
Imperial College

Disclaimer

- This presentation covers *mostly* HEP. Apologies to the Astro and NP community
- It is assumed that calorimetry at cryogenic temperature will be covered by the next speaker

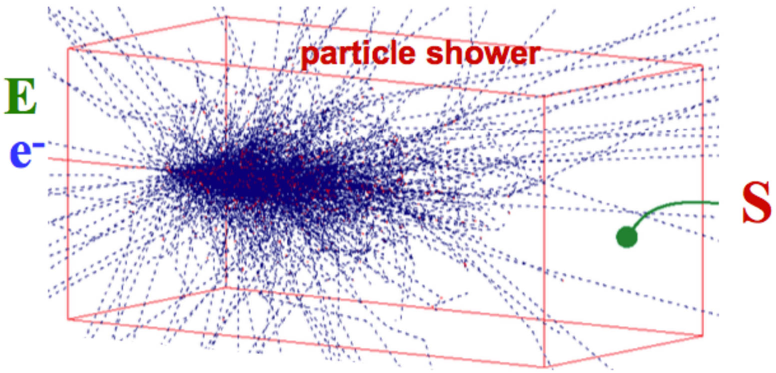
Outlook

- Introduction
- Electromagnetic calorimetry. Prospects for inorganic crystals.
- Calorimetry for hadrons and jets
  - The problem..
  - The solutions ?
    - Compensating calorimeters
    - Dual readout calorimeters
    - Particle flow and high granularity calorimeters (Silicon, scintillator tiles)
  - Fast timing and 5D calorimetry
  - One slide about electronics

Calorimetry

- Need to measure the energy of all particles in a reaction, in particular neutral ones (photons, K_L, neutrons) which can not be detected in a charged particles Tracker
- Need to use a detection method whose size does not increase dramatically with the energy of the particles
  - **calorimeters length $\propto$ ln (E) and resolution $\propto 1/\sqrt{E}$**

- The word "calorimetry" is misleading : usually we do not measure the temperature increase of the detection media but a quantity proportional to the incoming energy.
  - Measurement of heat deposition in cryogenic detectors (Dark Matter ..) will be covered in the next talk

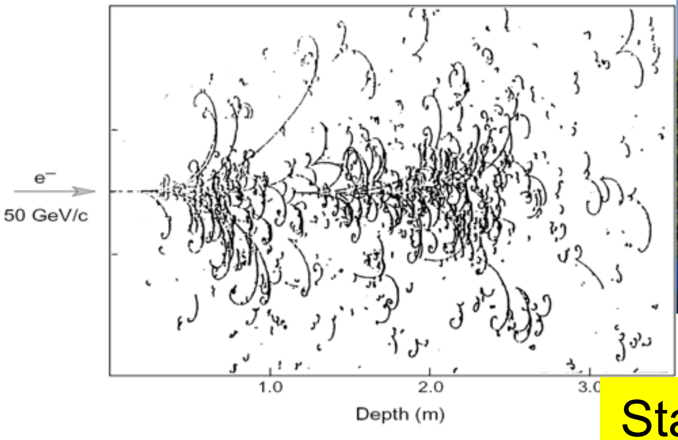


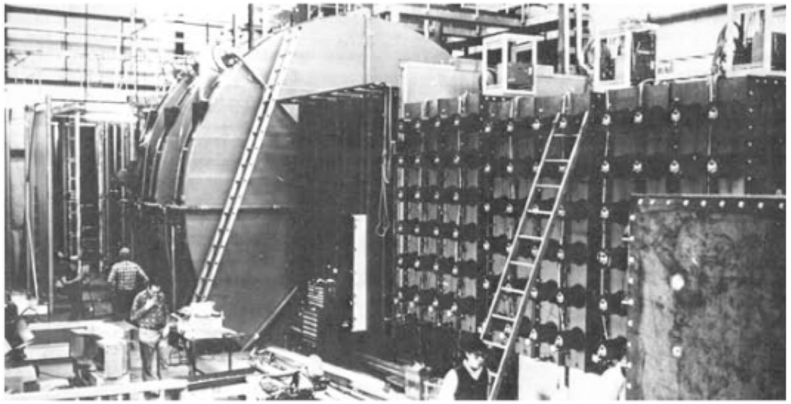
Depending on the technique , the signal S is detected
- -optically (light in crystal, scintillator,Cerenkov..)
- -electrically (signal in semiconductor, ionization in liquid)
- -thermally (bolometers at mK temperature)

Converts energy E of incident particles to detector response S:

$$S \propto E$$

Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron





A LIQUID-SCINTILLATOR TOTAL-ABSORPTION HADRON CALORIMETER FOR THE STUDY OF NEUTRINO INTERACTIONS*

A. BENVENUTI, D. CLINE, W. T. FORD, R. IMLAY, T. Y. LING, A. K. MANN, F. MESSING+, J. PILCHER†, D. D. REEDER, C. RUBBIA, R. STEFANSKI and L. SULAK

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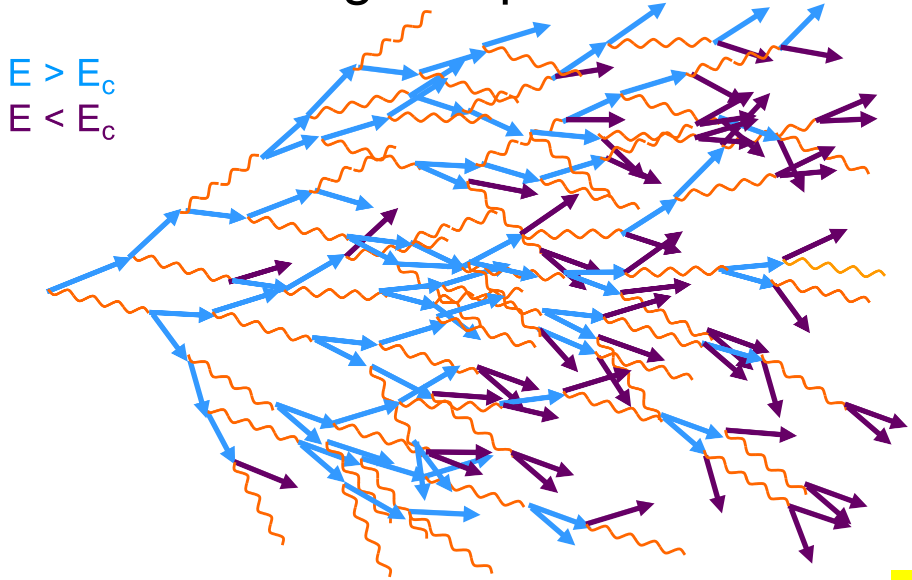
Received 5 February 1975

Started to be used in the 70's

NIM 125(1975) 447

Electromagnetic calorimetry

Electromagnetic showers result from electrons and photons undergoing bremsstrahlung and pair creation until they reach the critical energy Ec



Longitudinal development governed by radiation length X_0

$$X_0 \approx \frac{180\,A}{Z^2} g.cm^{-2}$$, 5.5 mm in Pb

Lateral development governed by Moliere Radius

$$\lambda_{pair} \approx \frac{9}{7} X_0$$

$$N_{tot} \propto \frac{E_0}{E_c}$$

$$R_M = \frac{21MeV \cdot X_0}{E_c} \approx \frac{7A}{Z} g \cdot cm^{-2}$$ 14mm in Pb

Electromagnetic showers are short and compact and linear,

The emphasis is usually on resolution.

The resolution is given by the statistical fluctuations of the detection method (stochastic term) + all kind of experimental factors like noise, calibration -> (noise & constant term)

Semiconductor based detectors for Nuclear Physics

High Purity Germanium Detectors
34000 e-h pairs @ 100 KeV

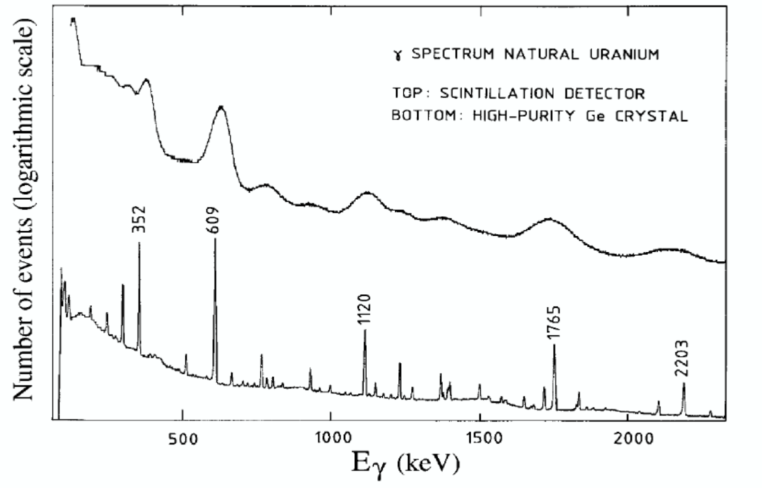
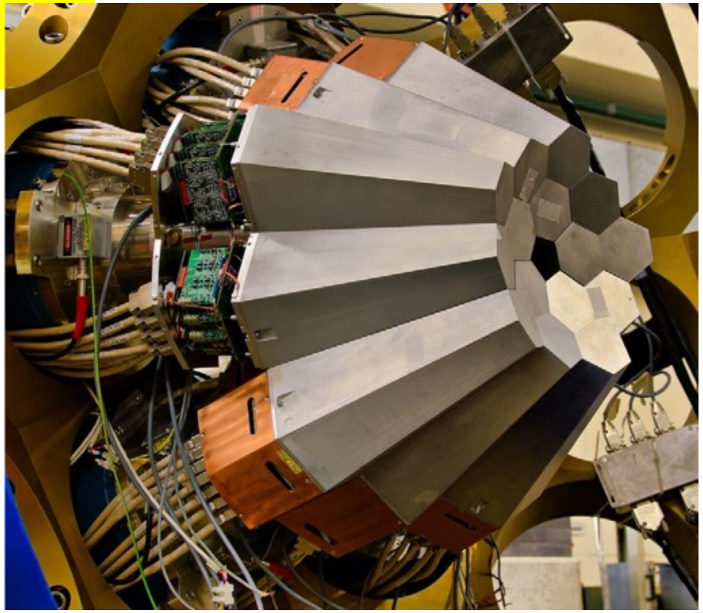


FIG. 1.1. Nuclear γ-ray spectrum of decaying uranium nuclei, measured with a bismuth germaniumoxide scintillation counter (*upper curve*) and with a high-purity germanium crystal (*lower curve*). Courtesy of G. Roubaud, CERN.



few ‰ at 100 KeV
Actually better than purely statistical (Fano factor)

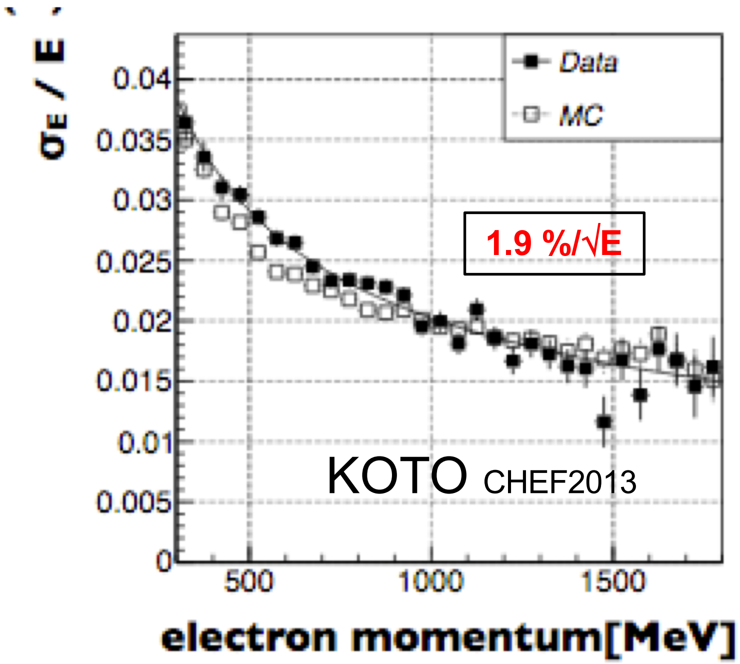
AGATA n-type HPGe
Legnaro, GANIL, GSI

NIMA 668 (2012) 26–58

Unfortunately very expensive !

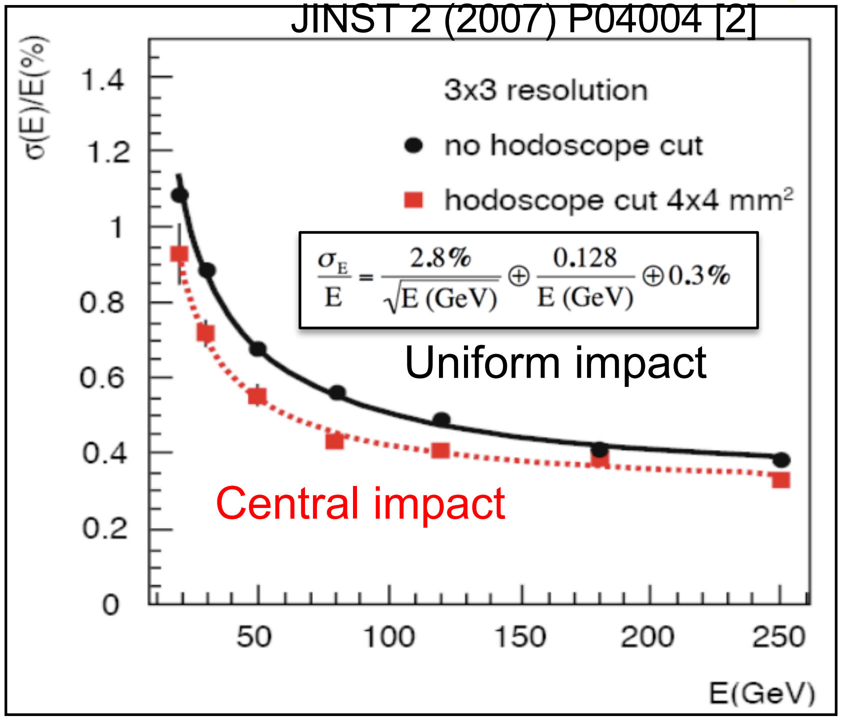
Homogeneous electromagnetic calorimeters HEP

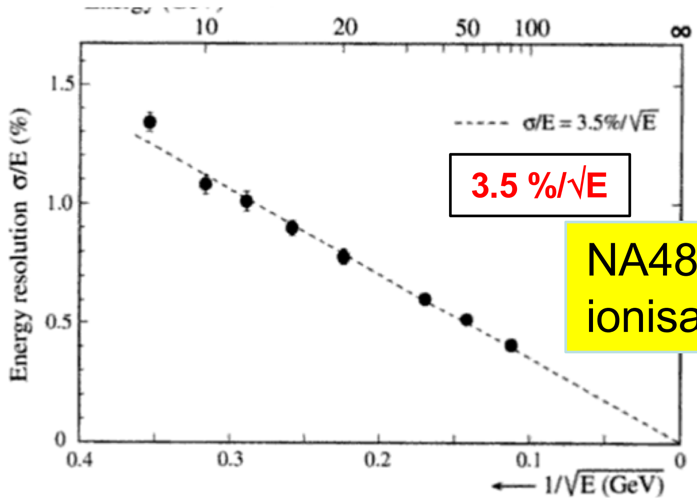
CsI(Tl)calorimeter (scintillation light, slow) Belle(2), Babar, …



CMS calorimeter $PbWO_4$ (scintillation light, fast)

JINST 2 (2007) P04004 [2]





NA48/62 Liquid Krypton ionisation

ArXiv hep-ex/0012011

Other examples
CALET TASC PbWO
Meg2 LXe

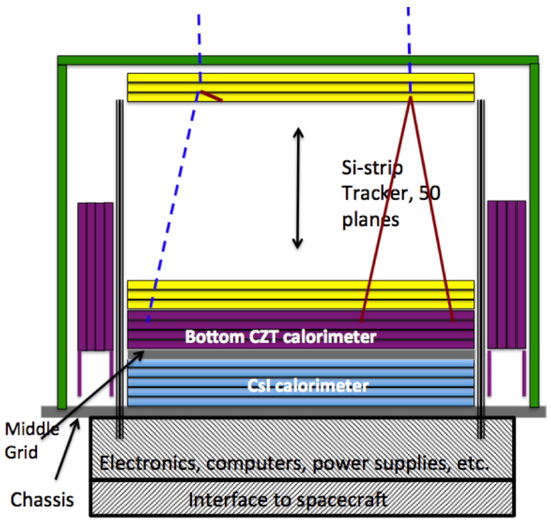
Inorganic crystals

Inorganic crystals are still planned for many future HEP experiments where high precision is a must

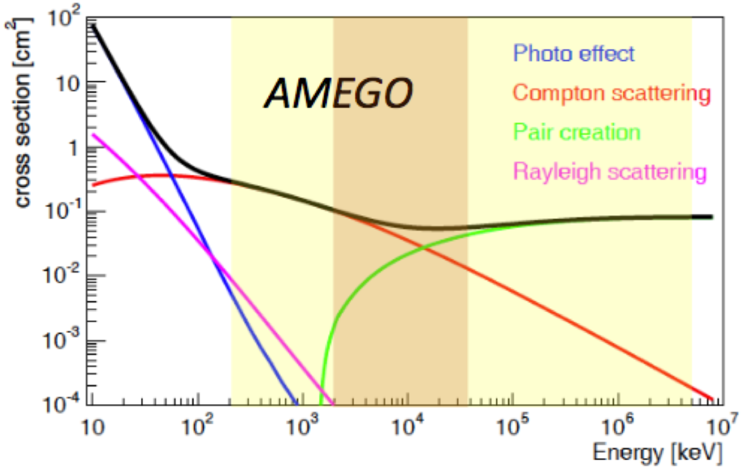
- CsI undoped for Mu2e@ FNAL -PWO for Panda @ FAIR
- LYSO for COMET @ JPARC -PbF2 for g-2 @ FNAL
- LHCb Phase 2@ HL-LHC YAG:Ce or GAGC:Ce fibers

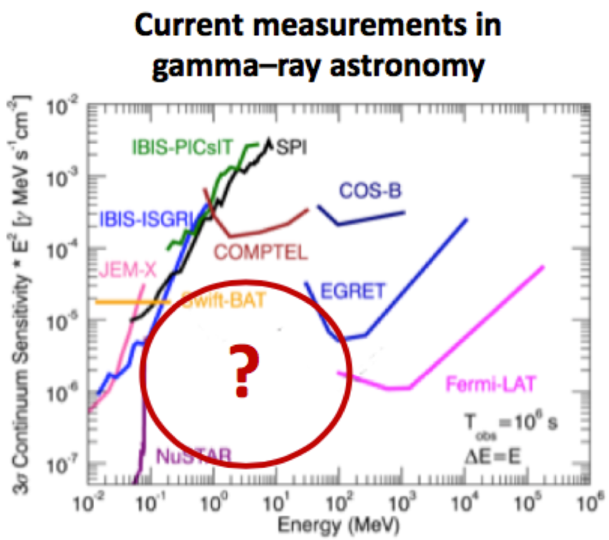
but are unlikely (in my opinion) to be used in future large collider experiments (as it was for CMS) due to their high cost

Space future examples: AMEGO (FERMI-LAT successor), HERD (China s.s., LYSO)



"impossible energy range" where Compton and pair production compete





Inorganic crystals (2)

The field is extremely active in two domains

– Medical applications (PET).

Novel routes towards ultra-fast timing performance(sub-ns) are explored.
A fast timing detector for CMS Upgrade is based on LYSO

– Homeland security (luggage control, search for explosive or radioactive material). High light output, high resolution <2% at 662keV

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 8, AUGUST 2018

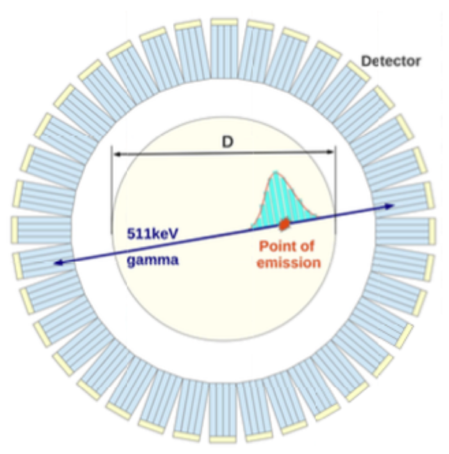


Fig. 3. TOF information in PET constraints the positron emission region along the LOR, leading to an improved SNR.

S/N can be improved by factor 5.2 (16.4) by timing at 100 (resp.10) ps

DUJARDIN et al.: NEEDS, TRENDS, AND ADVANCES IN INORGANIC SCINTILLATORS 1979

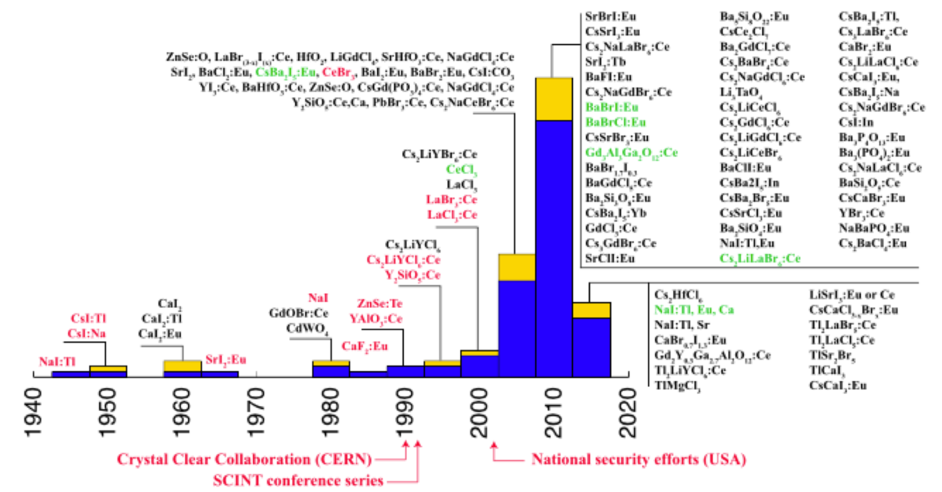
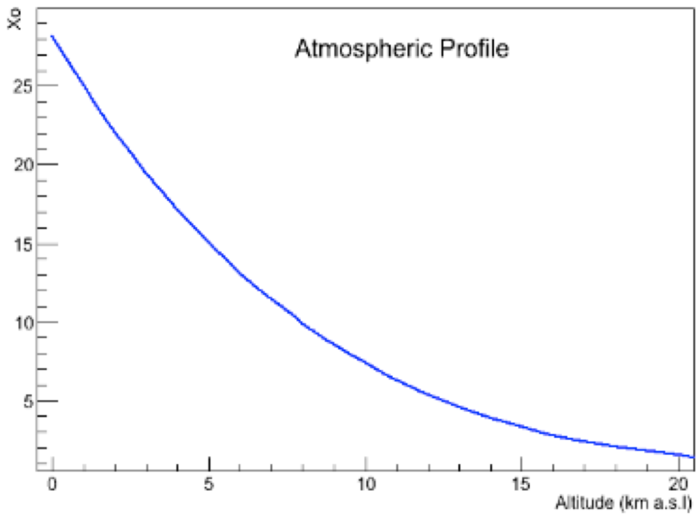


Fig. 1. History (1940–2017) of first publication of scintillators with light output of >20000 ph/MeV, representing scintillators published in peer-reviewed articles, excluding those containing Rb, Lu, and K due to a high natural radioactivity background not suited for the national security applications. Blue bars: new compounds. Yellow bars: known compounds with new activator or codoped. Red letters: commercial products. Green letters: under development.

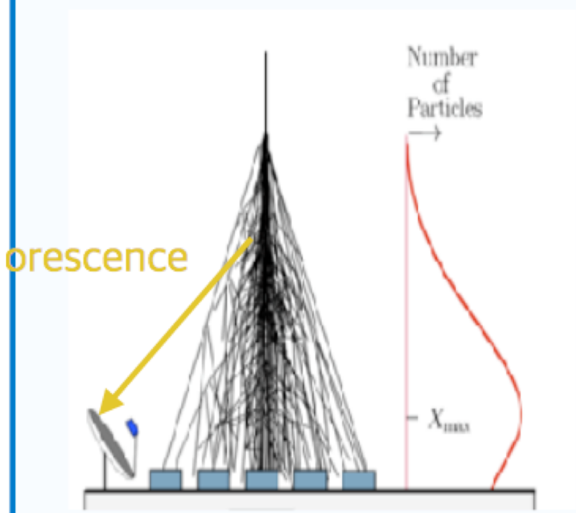
UHECR: Air showers



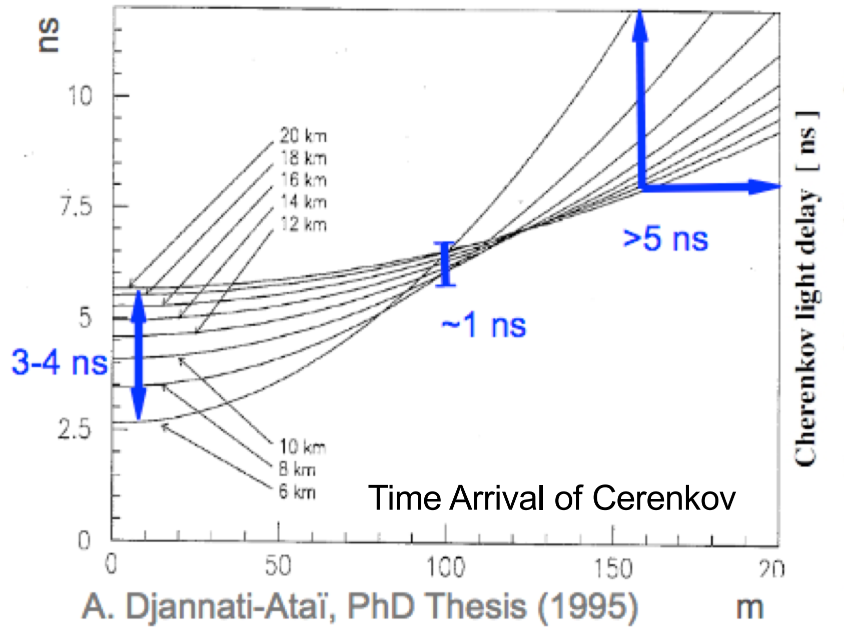
The atmosphere is an inhomogeneous calorimeter offering about 26 X_0.   Ec = 86 MeV

Detection methods
- Cerenkov radiation
- For E>> 10 x^{17} eV
  - Fluorescence of nitrogen
  - Coherent Radio emission

Air Shower:CR interaction with air



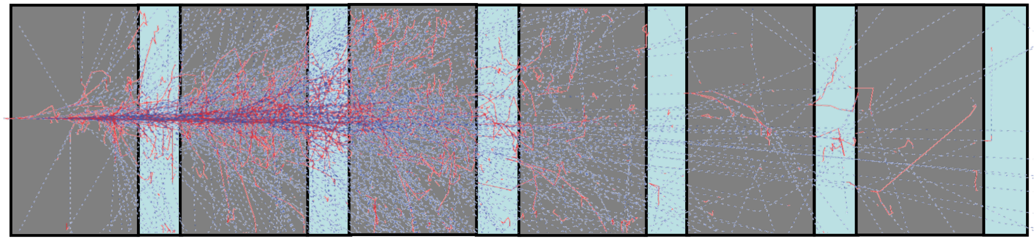
Courtesy BK Shin CHEF 2017



A. Djannati-Ataï, PhD Thesis (1995)

Good timing is important

Sampling electromagnetic calorimeters



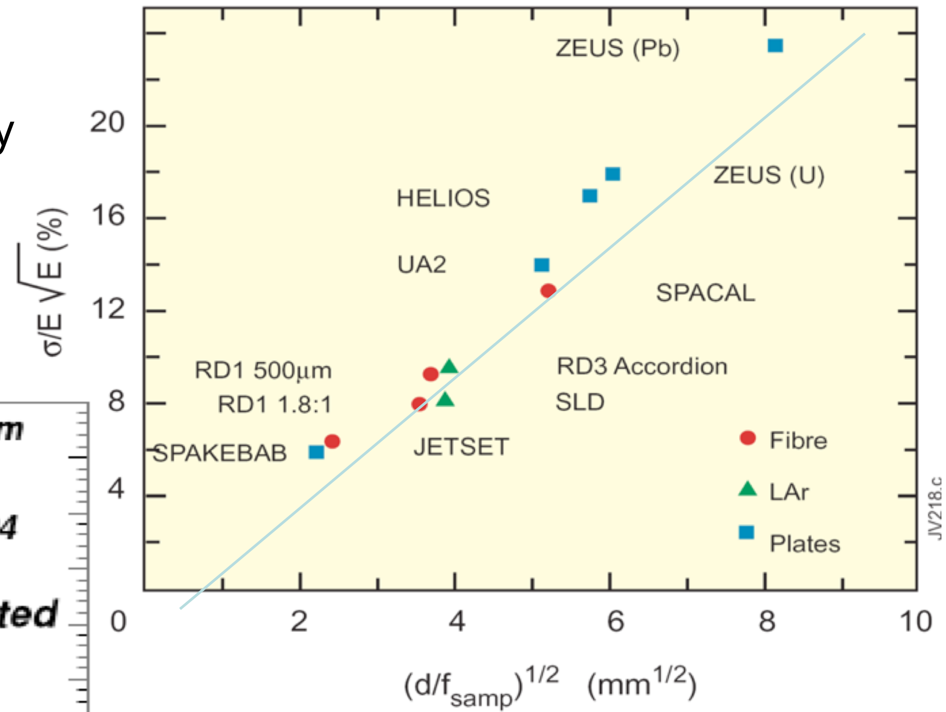
The resolution depends on:

1) the sampling fraction

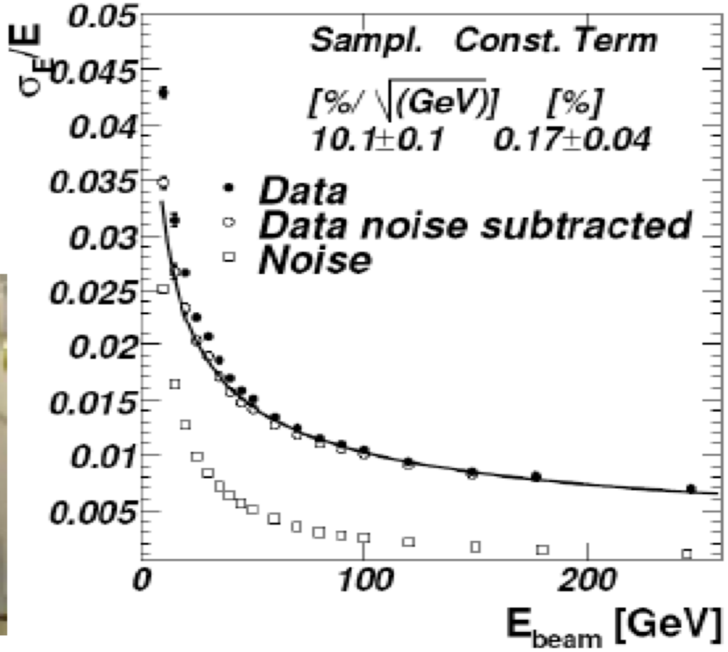
The more you sample, the better

2) the active layer thickness

- The thinner the active medium, the better. Mainly due to the ability to capture low energy electrons (even < Ec) from the absorber



ATLAS LAr



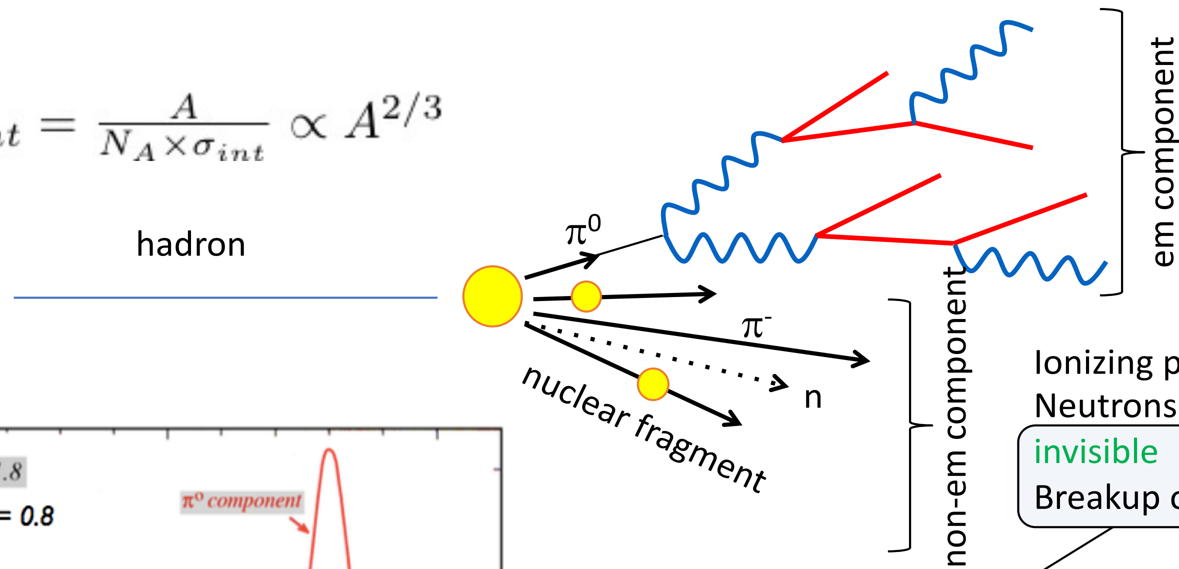
d is thickness of active layer
f_{samp} is sampling fraction

Measurement of hadrons and jets

Much more complex!

Electromagnetic and hadronic components have a different response ("e/h")

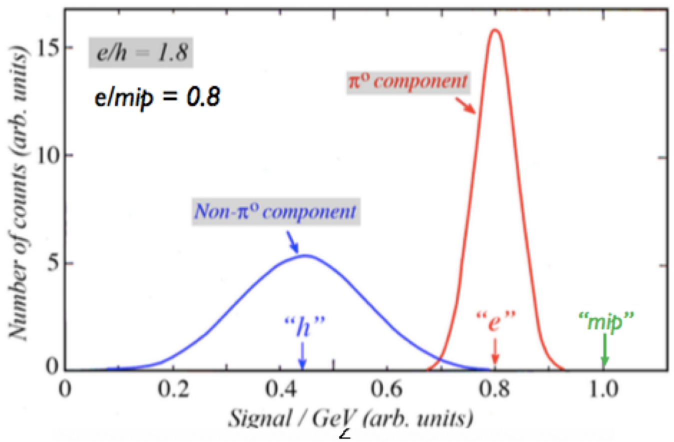
$$\lambda_{int} = \frac{A}{N_A \times \sigma_{int}} \propto A^{2/3}$$



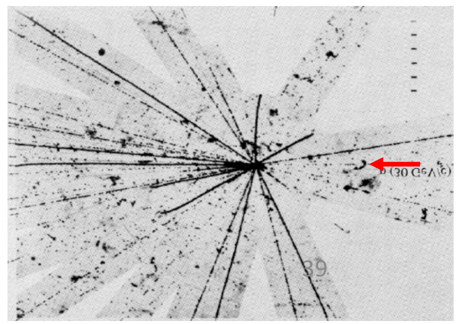
Electrons, photons
$\pi^0 \rightarrow 2\gamma$
➔ em sub-shower

Ionizing particles	[58-72%]
Neutrons	[9 - 5%]
invisible Breakup of nuclei	[33-23%]

Either not detected or too slow to be within detector time window ➔ invisible energy

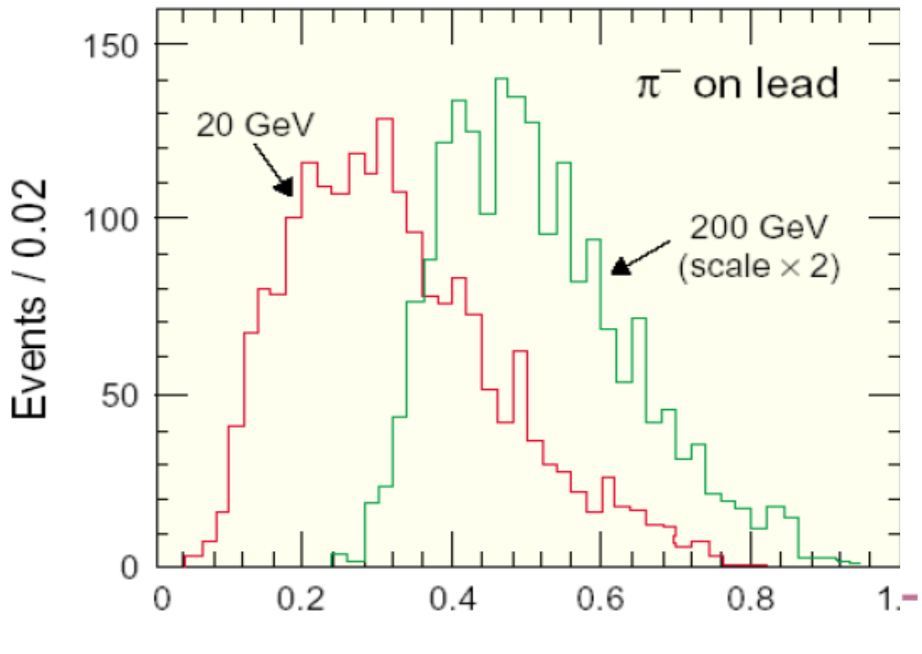


P.Bloch Imperial 2019

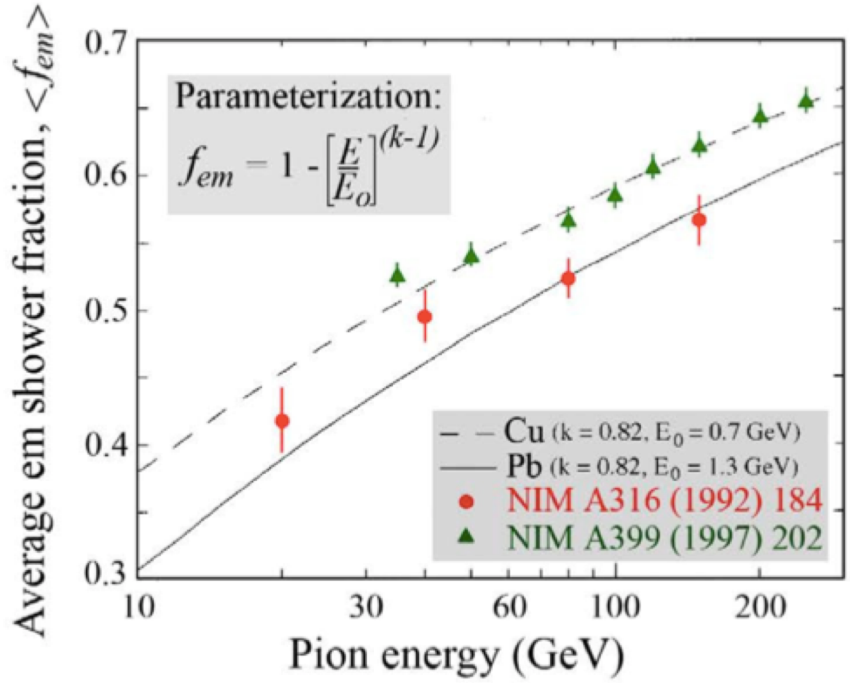


Electromagnetic fraction f_{em}

Varies with energy -> non linearity
Fluctuates event by event -> poor resolution



f_{em}



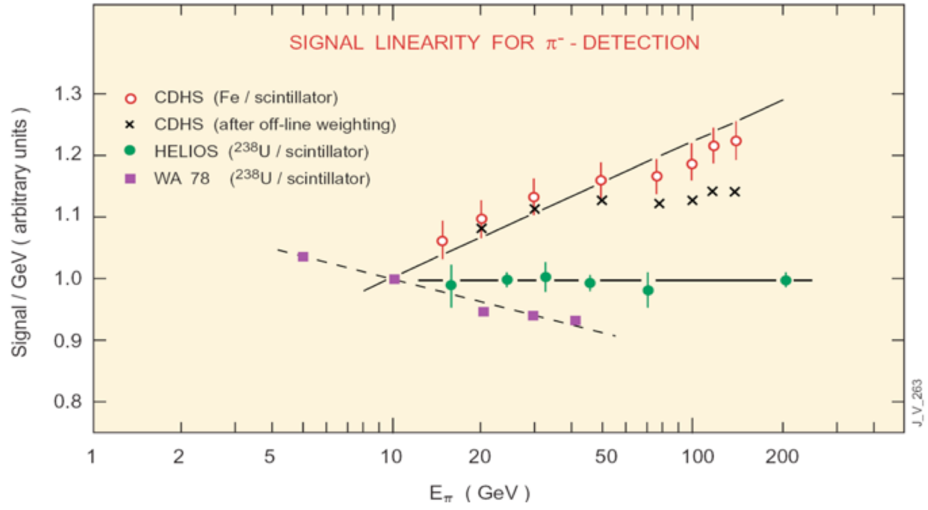
How to improve?
1- Compensating calorimeter e/h ~1

Boost non-e.m. response

- by using depleted uranium (^{238}U), extra energy contribution to the hadronic component from fissior of nuclei . Used by L3, D0, ZEUS.

  drawback: natural radioactivity, nuclear waste !

- and/or by boosting the response to low energy neutrons (high hydrogen content in active medium, longer measurement gate). n+H -> n+p



R.Wigmans [2] p.175

and/or suppress the e.m. response

- thin layers of plastic scintillator in a calorimeter with high *Z* absorber (for example W)

  $\sigma_{photo\ electrique} \propto Z^4$ -> γ< 1MeV captured in absorber

  poorer e.m. energy resolution

  expensive

  Example : CALiCE AHCAL with W absorber

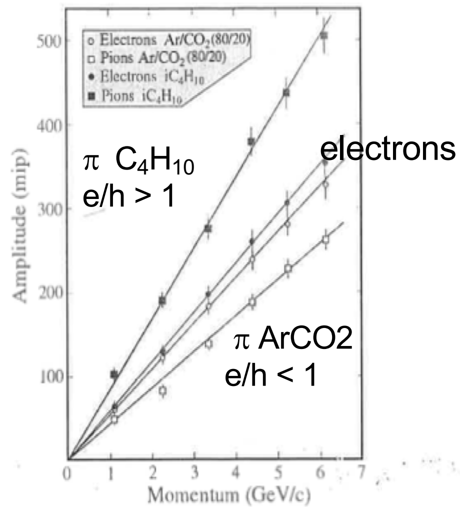


FIG. 3.39. The average signal amplitude for electrons and pions, measured with the uranium/gas calorimeter of the L3 Collaboration, for two different choices of the gas mixture that was used in the proportional wire chambers [Gal 86].

How to improve?
2-Dual Readout calorimeter(1)

DREAM: Dual REAdout Method – CERN RD52 project

measuring f_{em} on an event by event basis

Simultaneous measurement of scintillation light (dE/dx) and Cerenkov light produced in showers:

- ***Cerenkov*** light only produced by relativistic particles: em component
- ***Scintillation*** light produced by relativistic and non-relativistic: em + hadronic component

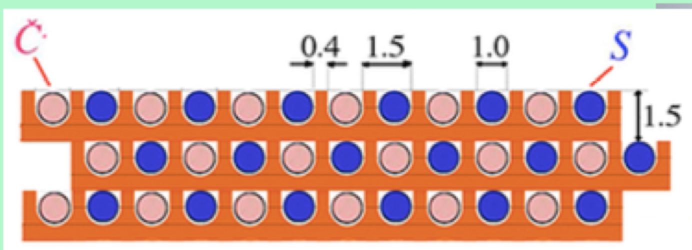
2012 RD52

Copper, 2 modules

Each module: 9.3 * 9.3 * 250 cm^3

Fibers: 1024 S + 1024 C, 8 PMT

Sampling fraction: 4.5%, 10 λ_{int}



2012 RD52

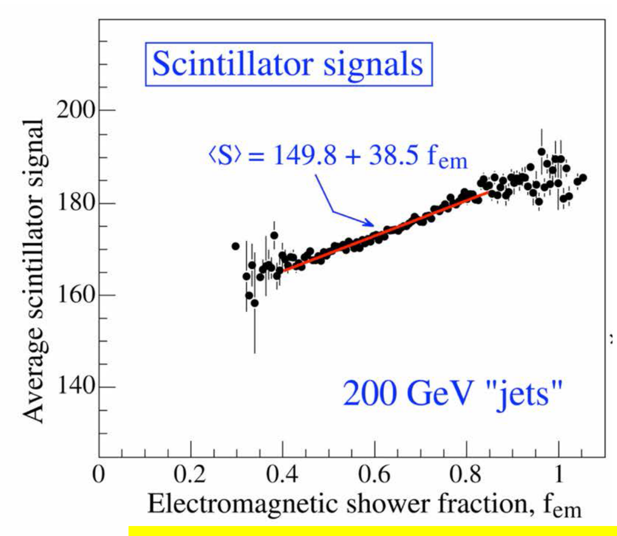
Lead, 9 modules

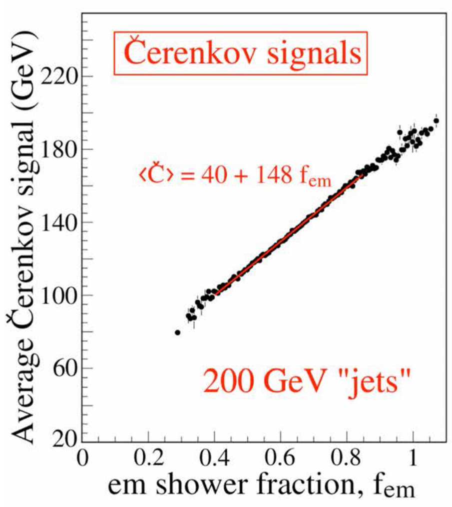
Each module: 9.3 * 9.3 * 250 cm^3

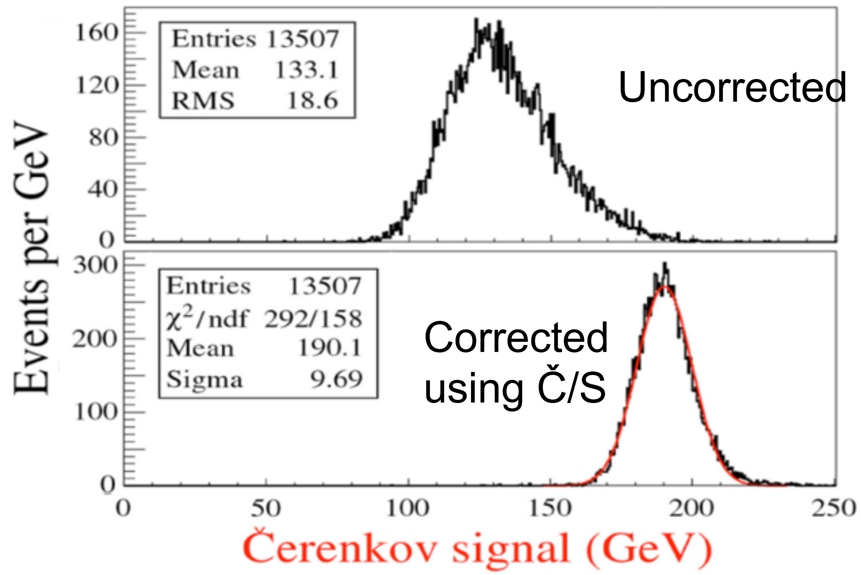
Fibers: 1024 S + 1024 C, 8 PMT

Sampling fraction: 5%, 10 λ_{int}

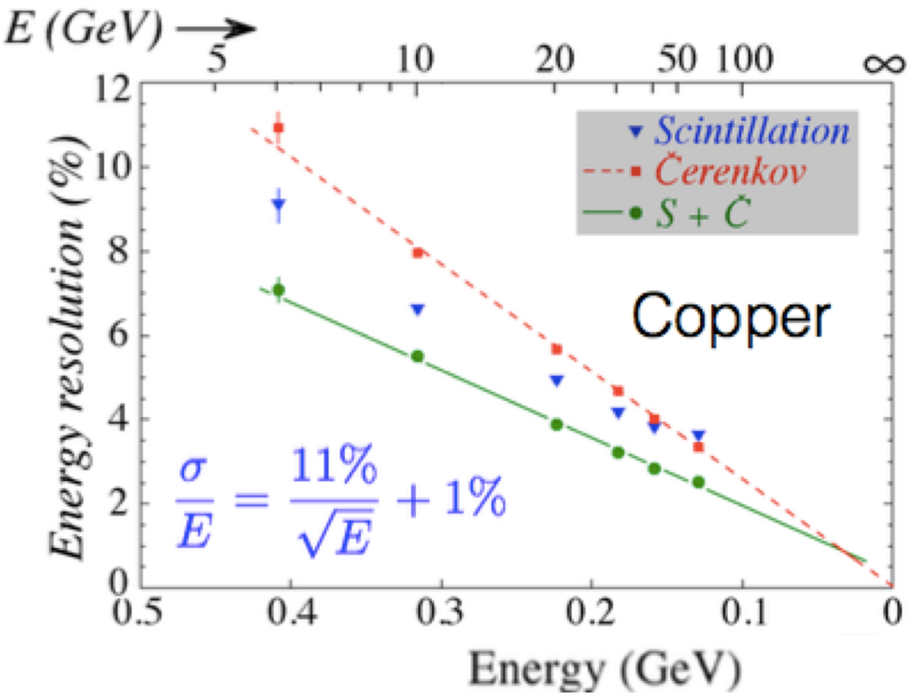
Dual Readout Calorimeter (2)

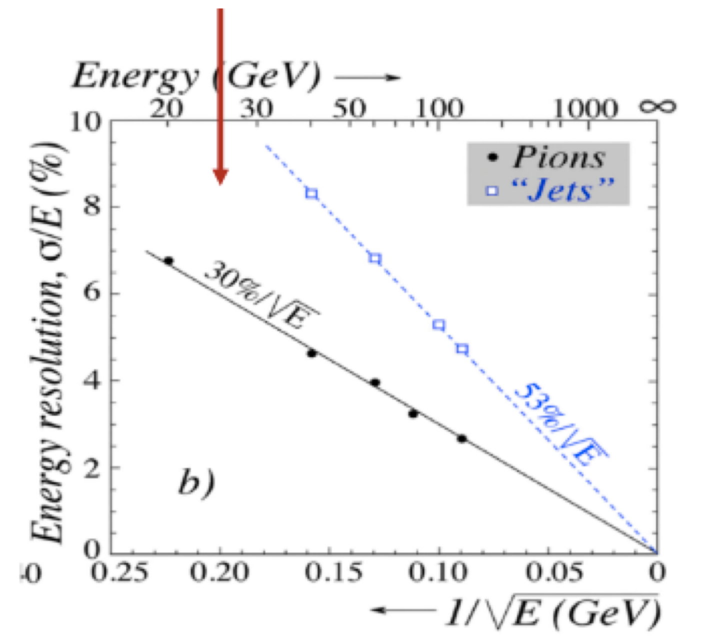






Cerenkov signal proportional to e.m. fraction





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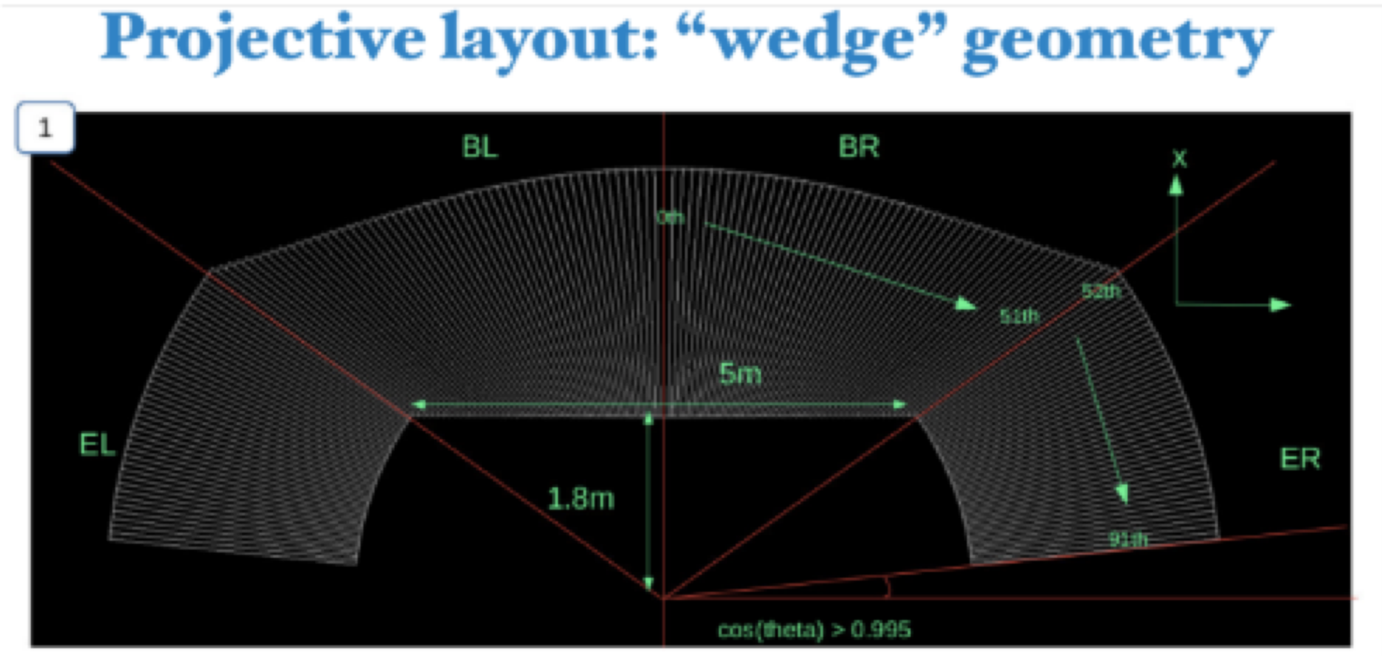
Dual Readout Calorimeter(3)

Growing interest for Dual Readout Calorimeter for FCC-ee or CepC detector

Still many developments needed

- projective geometry
- longitudinal segmentation (fibres starting at different depths, extended use of timing information, …)
- rad-hardness (quartz fibres YAG, but expensive)
- use of SiPMs to get rid of fibres forest
- industrial production of grooved absorber
- (Possibility to mix with homogeneous (crystal) calorimeter)



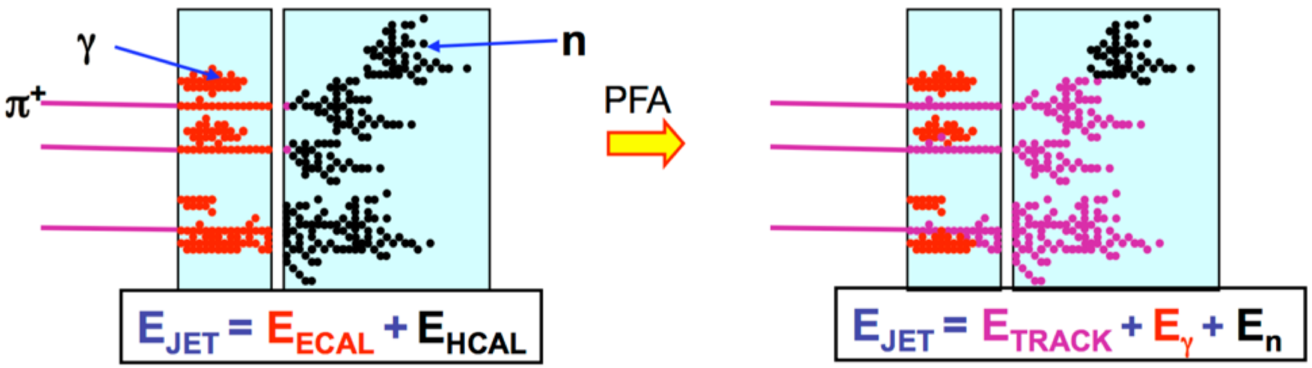
IDEA D.R. calorimeter
For FCC-ee

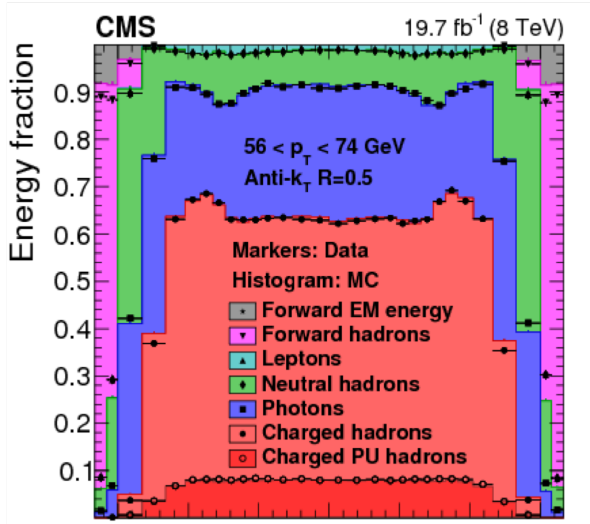
How to improve?

3- Particle Flow Approach for Jets measurement (PFA)

Principle: use the hadron calorimeter as little as possible !

- Charged tracks from tracker measurement
- e/g from e.m. calorimeter
- Only n and K_L are measured in the hadron calorimeter (10%)



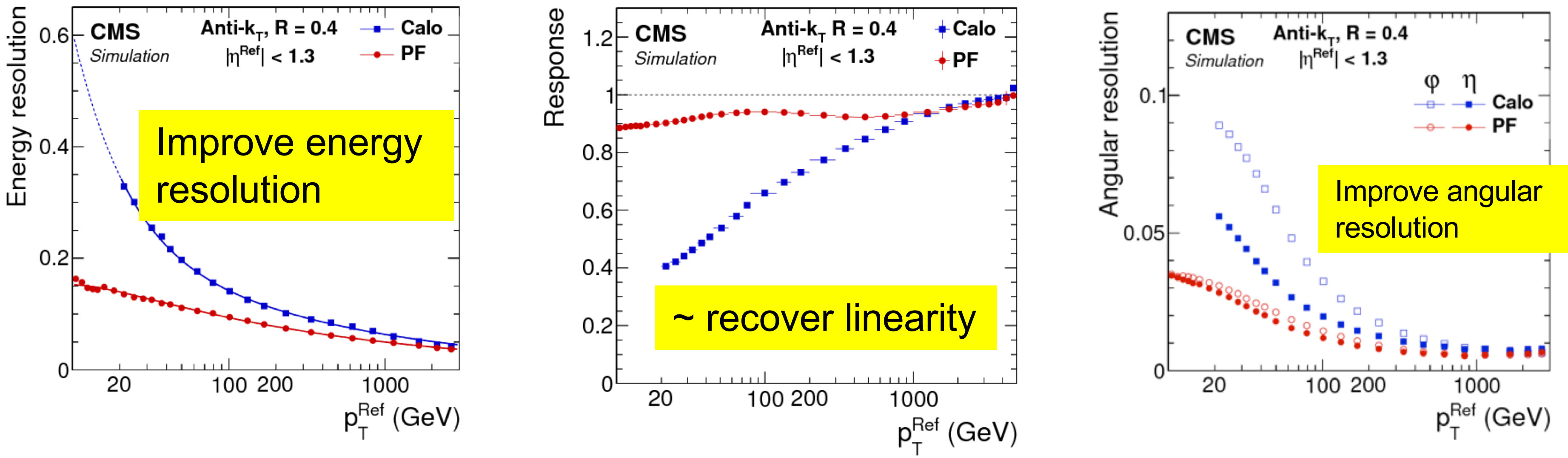


Particle flow was

- pioneered by ALEPH
- extensively developed and studied in the past 15 years for Linear Collider Detectors (e.g. CALICE) => shown that jet energy resolution goals (3%-4% for energies from 45 GeV to 500 GeV) can be met
- routinely used by CMS (whose hadron calorimeter has a rather poor energy resolution $90\%/\sqrt{E}$)

Particle Flow (2)

Example: performance in actual CMS



JINST **12** (2017) P10003

Particle Flow requires to separate spatially the showers from different particles

The limitation of the method is the confusion between nearby objects

For a Particle-Flow Calorimeter, granularity is more important than energy resolution!
-> High Granularity calorimeters

High granularity calorimeters

Inspired by PFA approach, several High Granularity calorimeters are under design for collider experiments most notably for ILC detectors (CALICE collaboration) and for CMS HL-LHC upgrade
Components:

- Silicon
- Scintillators tiles readout by SiPMs
- (option gaseous detector CALICE)

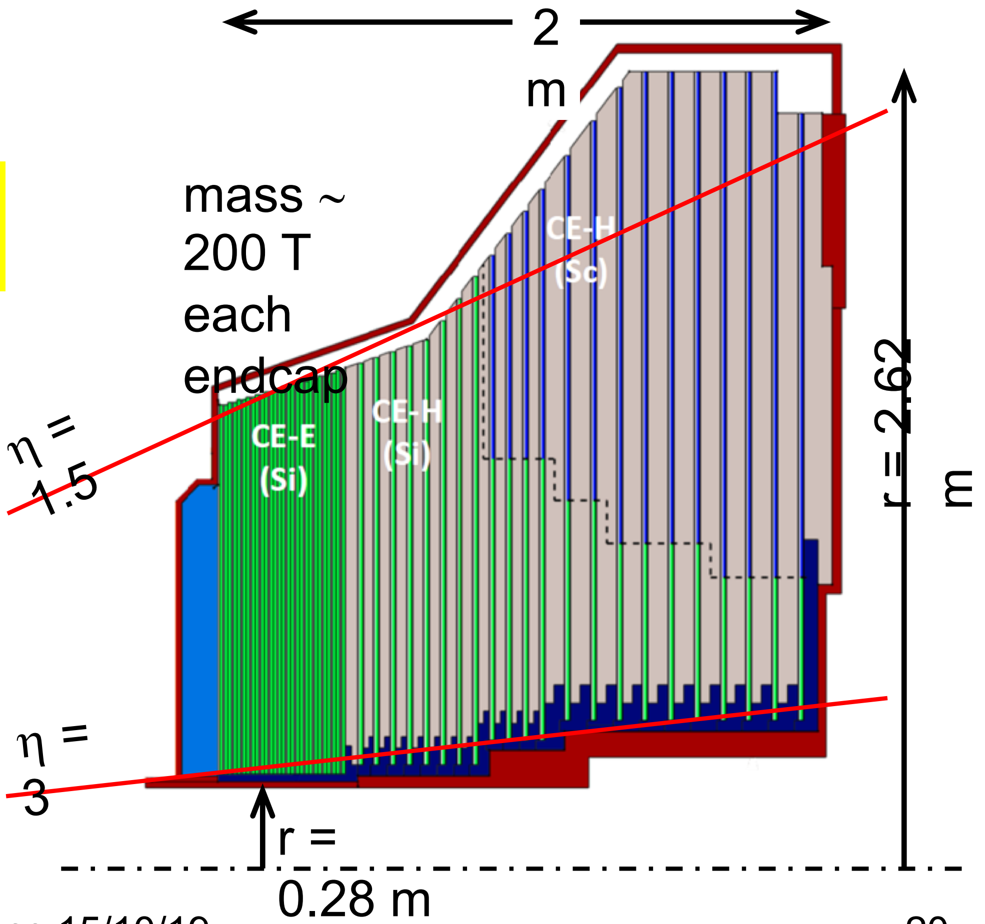
CMS HL-LHC upgrade of the Endcap Calorimeter (HGCAL)

Key Parameters

- HGCAL covers 1.5 < η < 3.0
- **Full system maintained at -30°C**
- **~640 m²** of silicon sensors
- **~370 m²** of scintillators
- 6.1M Si channels, 0.5 or 1.1 cm² cell size (*6M*)
  240k scint-tile channels (η–ϕ)
- ~31000 Si modules (incl. spares)

Active Elements:

- Si sensors (full and partial hexagons) in CE-E and high-radiation region of CE-H.
- SiPM-on-Scintillating tiles in low-radiation region of CE-H



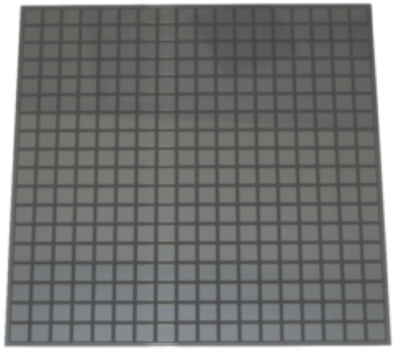
Silicon calorimetry

- Pioneered in the 80's (P.G. Rancoita), revisited for LHC (RD35), applied at small scale in 2005 for CMS Preshower ($20m^2$)
- Decisive momentum by ILC detectors R&D, following **strong reduction of Si wafers cost** and **progress in low feature-size/power VFE electronics**
- Adopted by CMS for its HL-LHC upgrade (Endcaps) and ALICE for forward rapidities (FoCal)

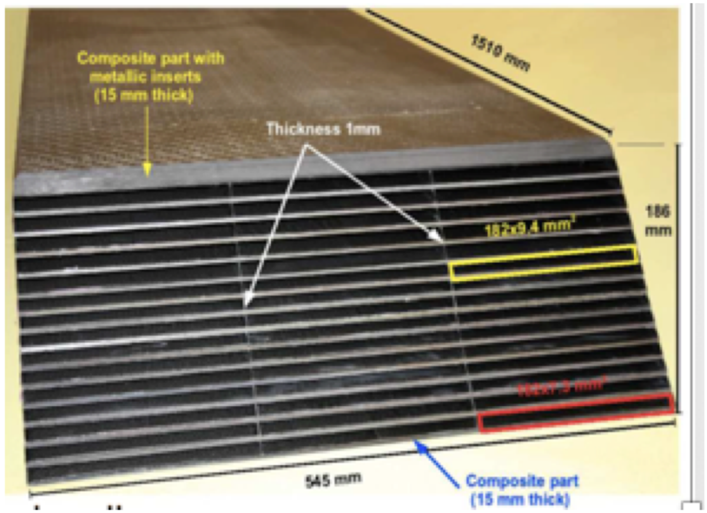
Silicon advantages:

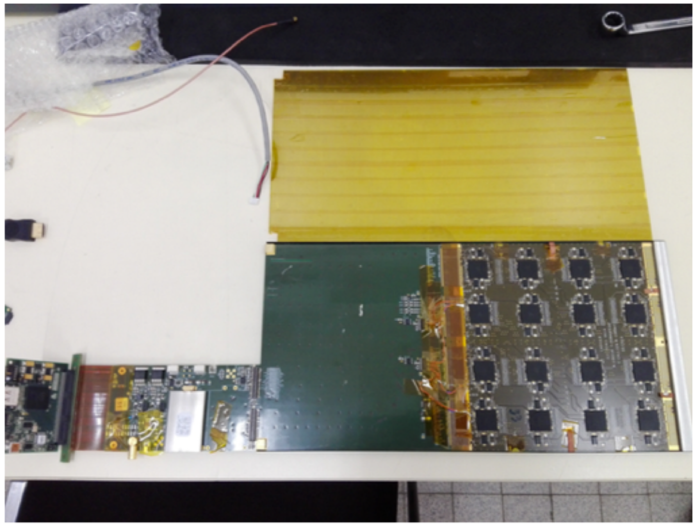
- Fast response ~ 5ns
- Small transverse granularity (cm^2 or less) easy
- Longitudinal granularity (independent layers, thin active medium)
- Good S/N at MIP
- Radiation tolerance > $10x^{16}$ n/cm2 (leakage current counteracted by low T). Can vary the silicon thickness to optimise this aspect
- Low power FE electronics (20 mW/channel CMS, ~100 times less @ILC with power pulsing). Good S/N.
- Large wafers (6", 8") available
- Automated module assembly

Silicon calorimetry CALICE



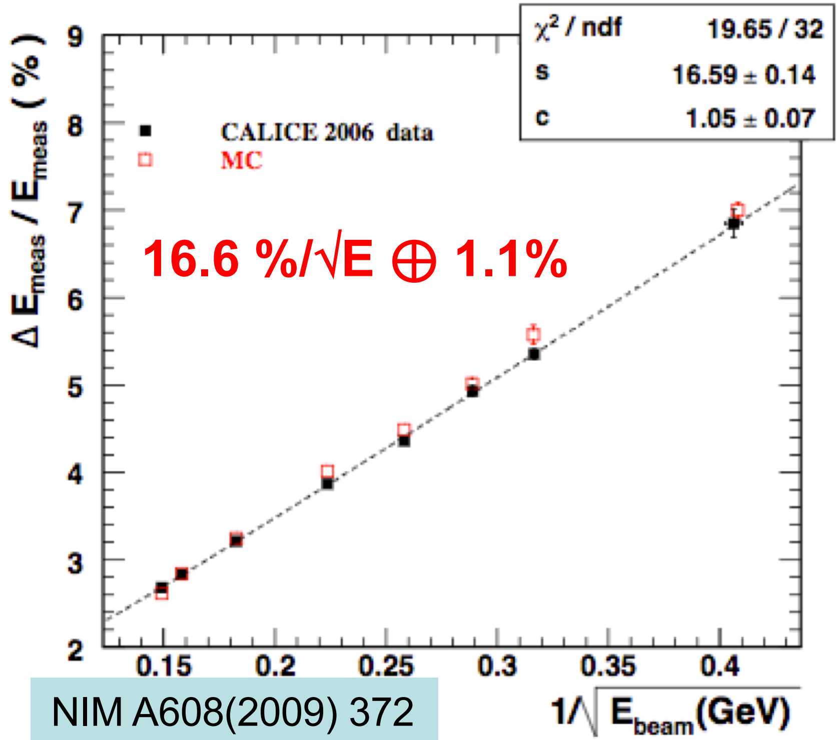
CALICE: 18x18 cm^2, 5x5mm^2 pixels (HPK)





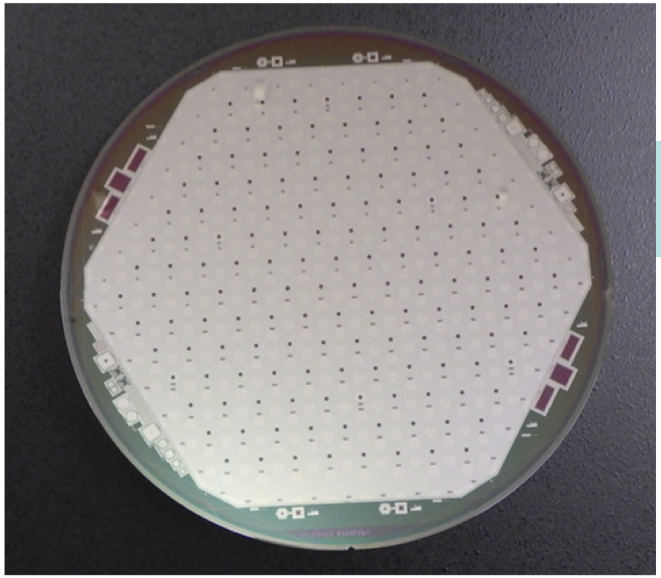
CALICE technological prototype
arXiv 1810.05133

JENAS confer

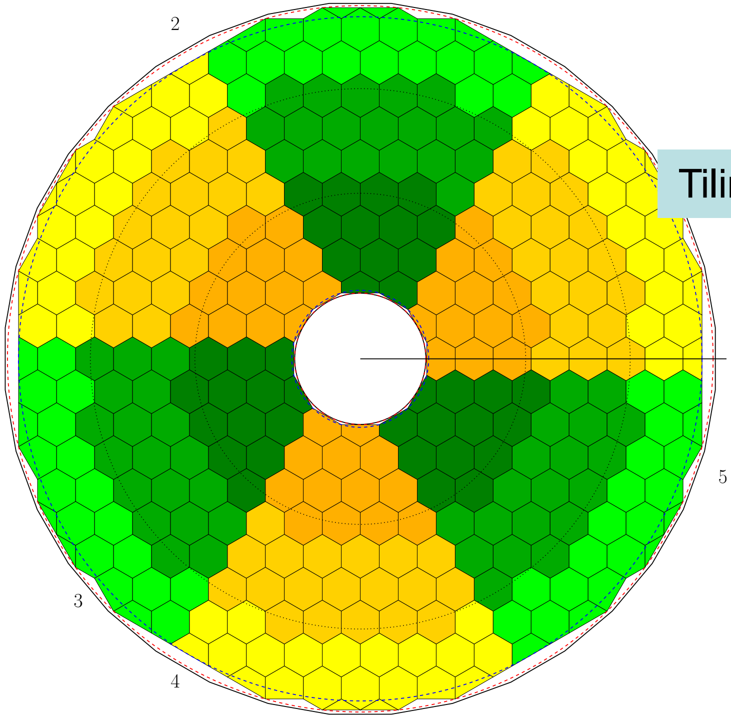


NIM A608(2009) 372

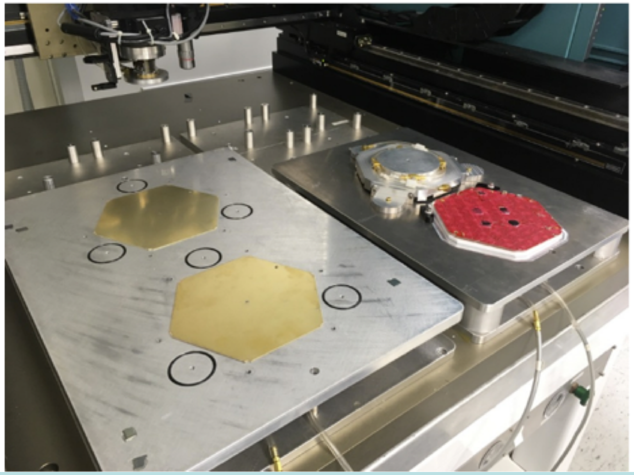
Silicon calorimetry CMS Endcap



CMS HGCAL: 8” silicon wafer with 1cm^2 cells (HPK)

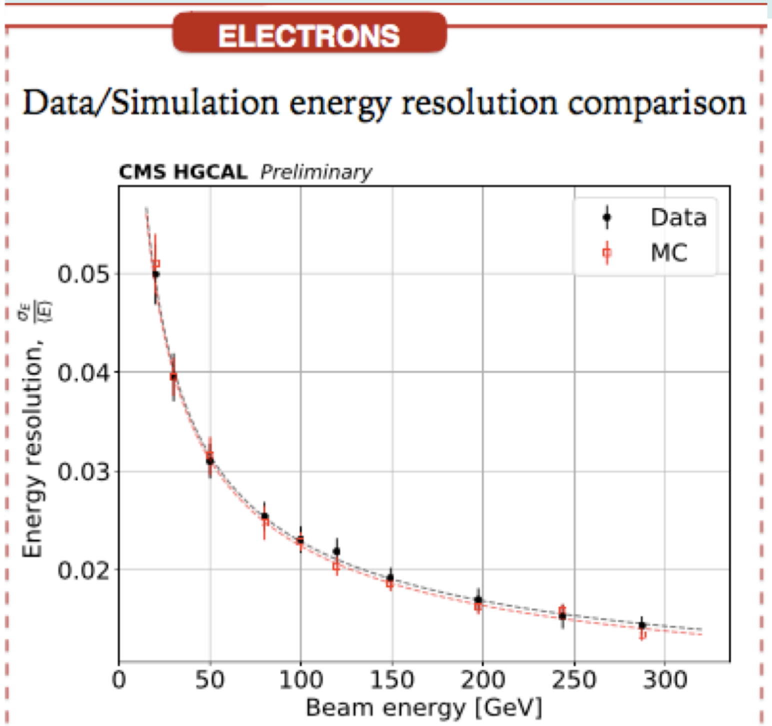


Tiling of an em layer

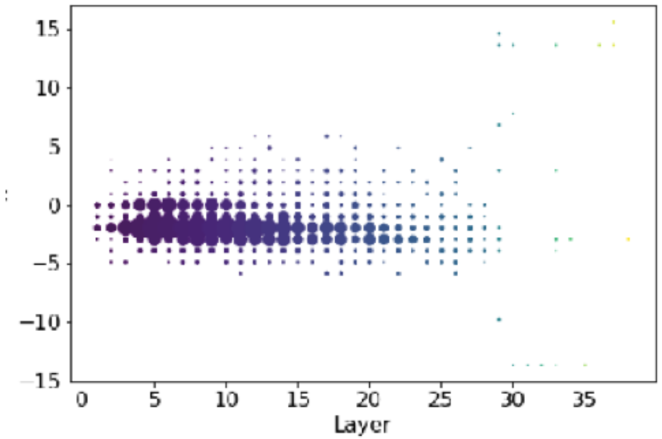


CMS HGCAL: gantry for 8” automated module assembly (base plate, Kapton,sensor and readout PCB gluing (UCSB)

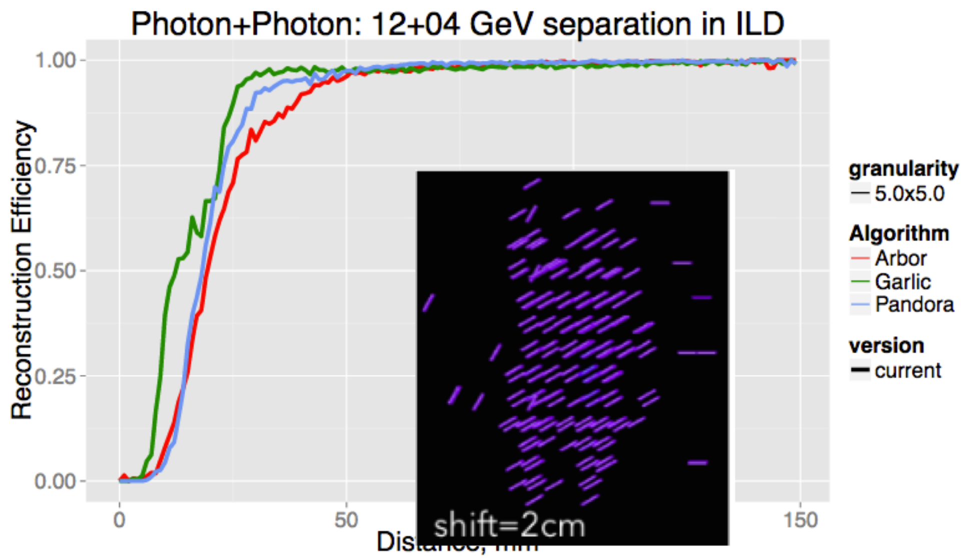
Silicon calorimetry

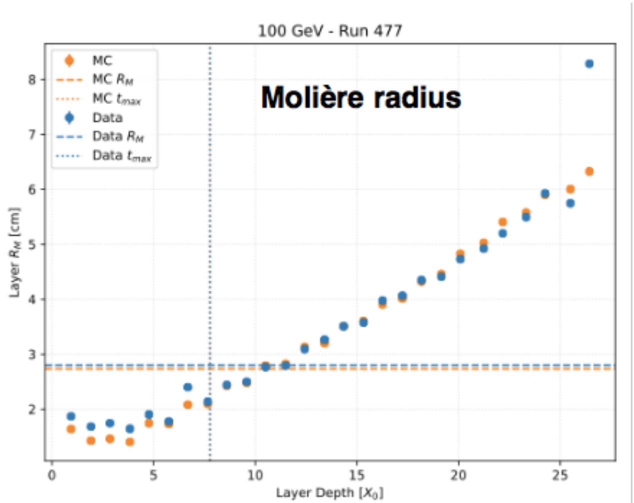


CMS test beam Nov 2018: 300 μm silicon
28 layers, 26X_0, W-Co/Pb absorber



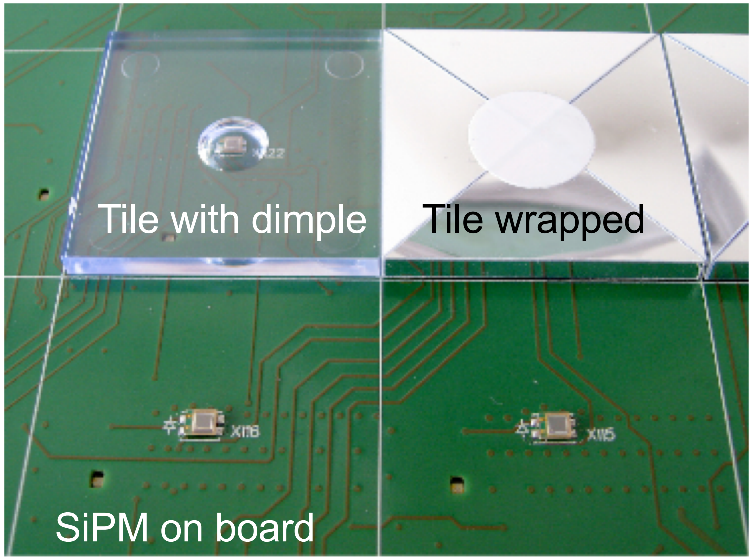
CMS test beam 2018 : event with a bremsstrahlung photon close to an electron (~2.5 cm)





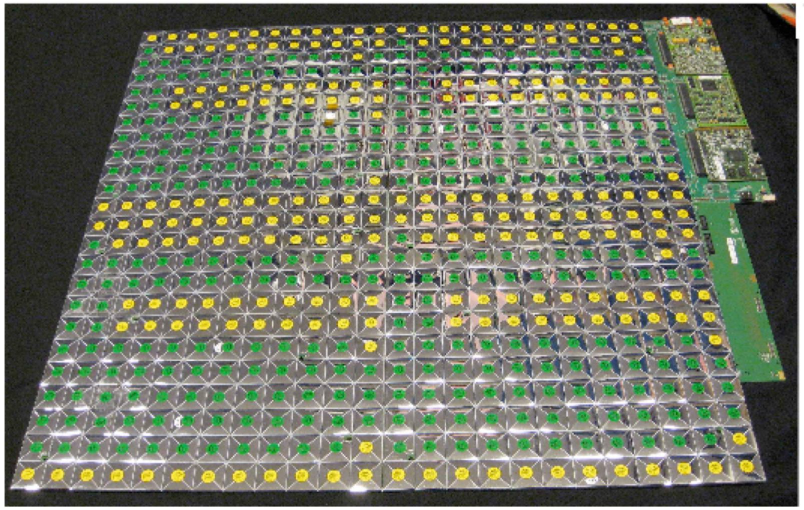
Expected two showers separation in ILD
With 5x5 mm^2 cells CALICE-CAN-2017-001

Tile Calorimeter with SiPM readout



The development of SiPMs has paved the way to high granularity hadron calorimeters with scintillator tiles
Pioneered by the CALICE AHCAL group

- Tiles 3x3 cm^2 with dimple to uniformize the light collection and wrapped in ESR foil
- Large 22K channels prototype constructed
- Assembled with pick and place machine



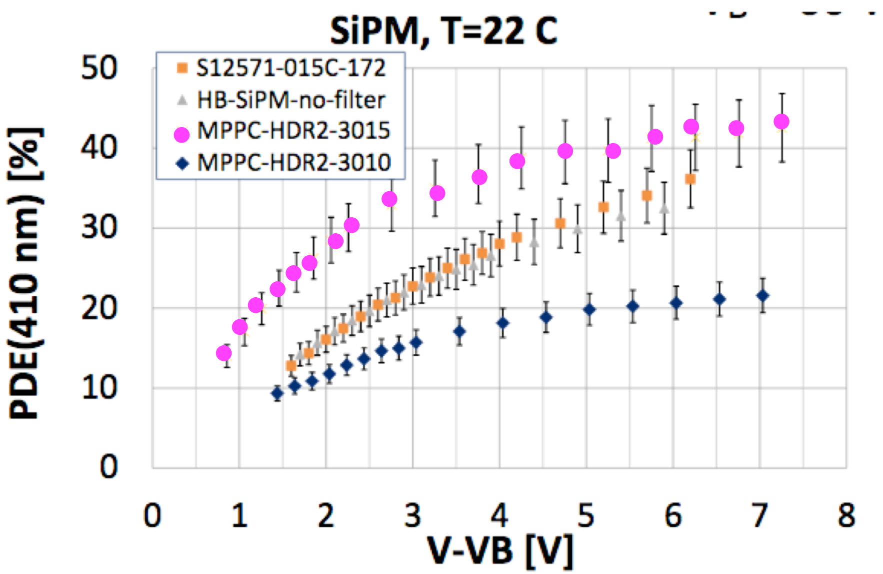
arXiv:1808.09281v2

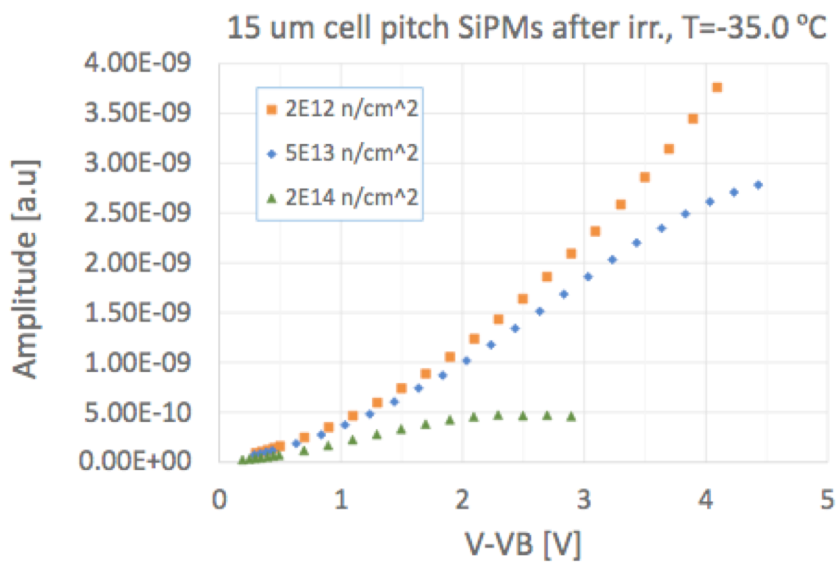
SiPMs

Large progress on SiPMs by various firms: FBK, HPK,…

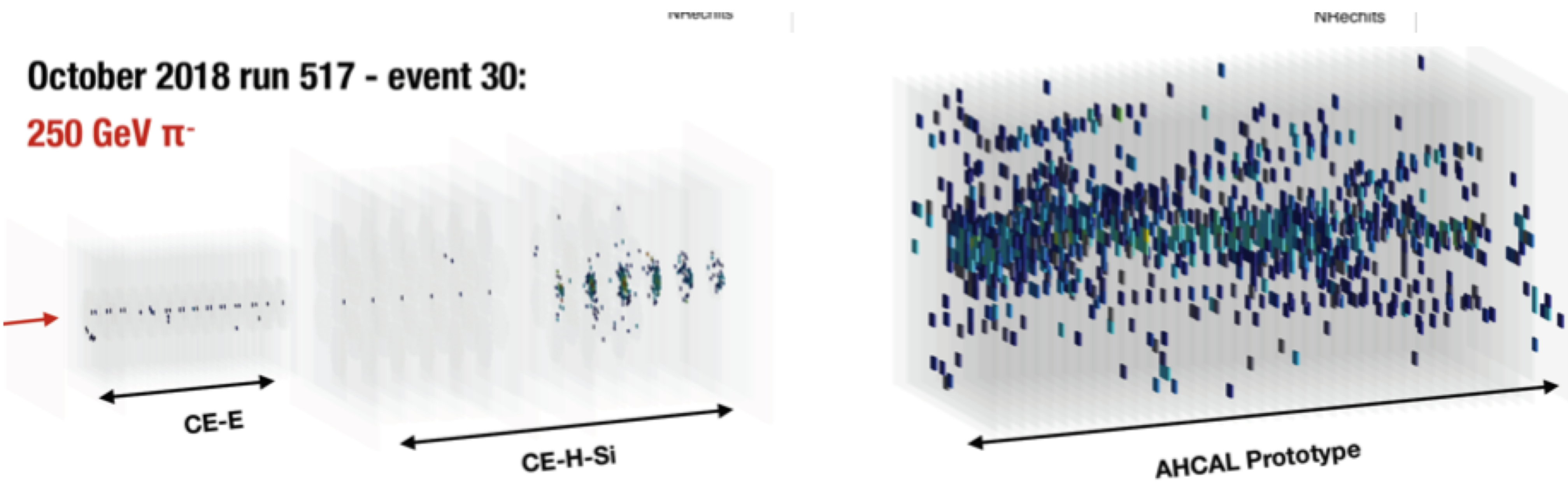
also pushed by possible automotive applications (like LIDAR)

- Very fine pitch (10um or 15um)
- Trenches to avoid cross talk, while keeping high Photon Detection Efficiency (PDE)
  - Excess noise factor ~1
- Lower quench resistor for faster response
- Tested up to 2 $10x^{14}$ n/cm^2. Requires operation at low T (-30^{o}C in CMS upgrade) to keep low dark count
- Need for good T/voltage stabilisation (breakdown voltage is T dependent)



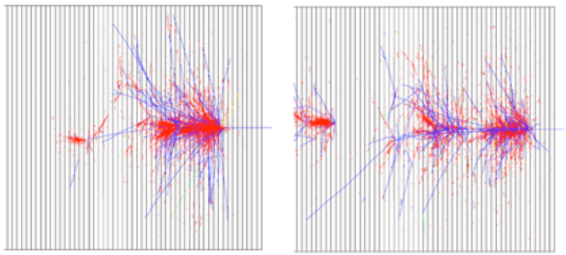


Combined CALICE-CMS test beam Nov 2018



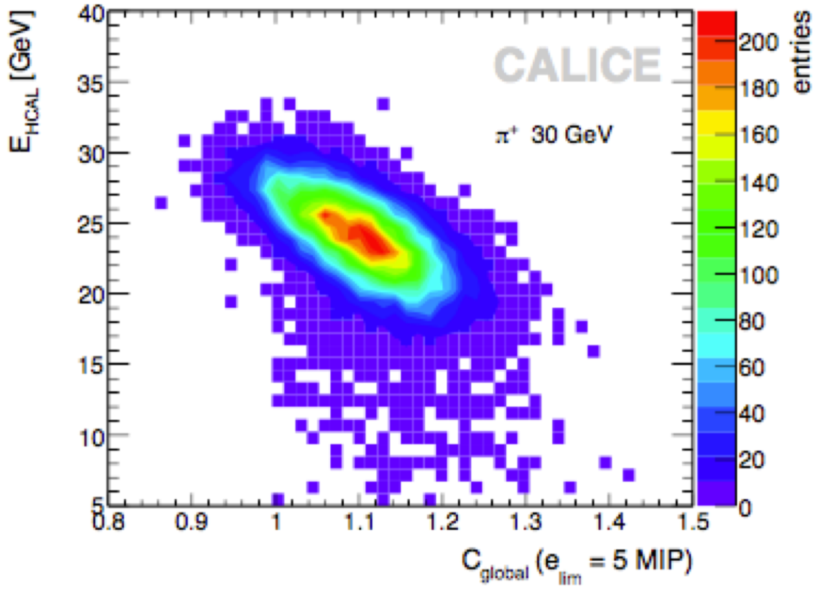
Data under analysis…

High granularity enables some (software) compensation

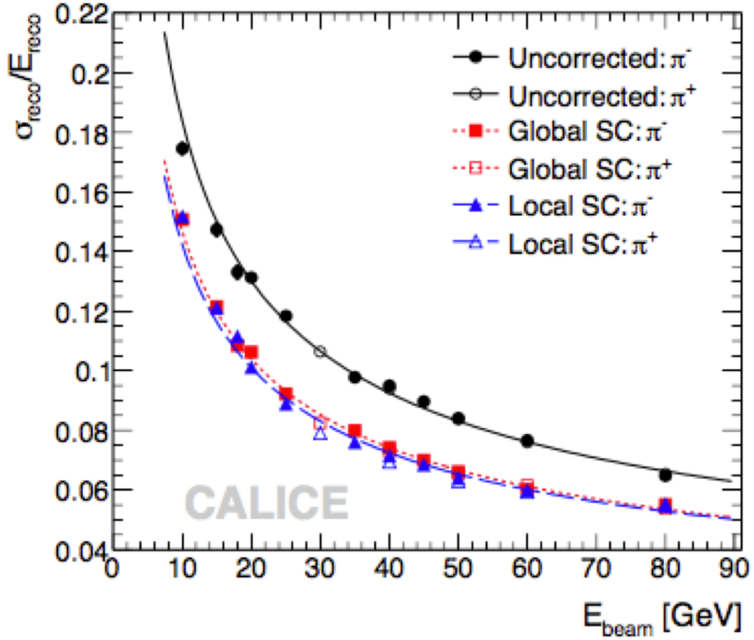


CALICE AHCAL: Fe absorber, 48 layers, scintillator tiles 3x3 cm^2

2012 JINST 7 P09017



Correlation between total reconstructed energy and a factor linked to the number of hits with deposit < limit (5 MIP)



Improvement of resolution using this correlation

$$\frac{\sigma}{E} = \frac{57\%}{\sqrt{E}} \oplus 1.6\% \qquad \frac{\sigma}{E} = \frac{45\%}{\sqrt{E}} \oplus 1.8\%$$

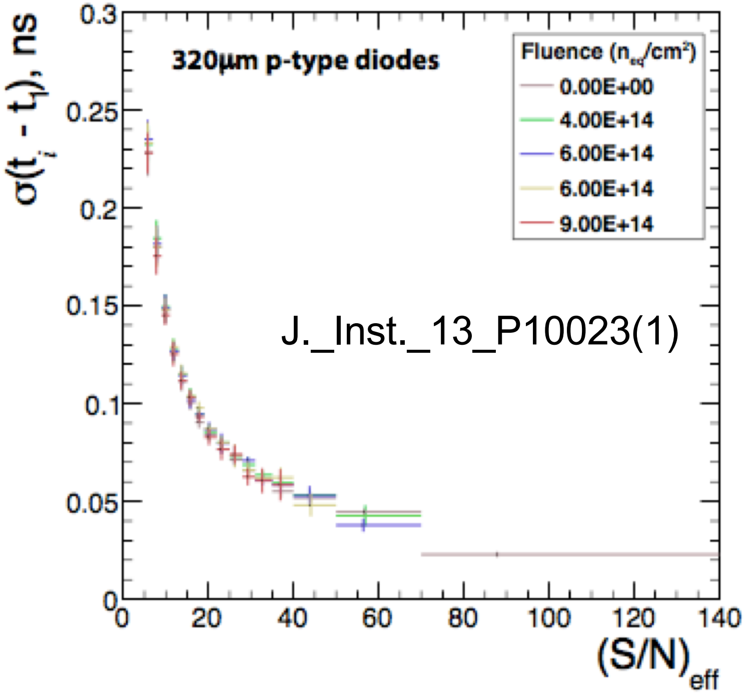
5D calorimetry

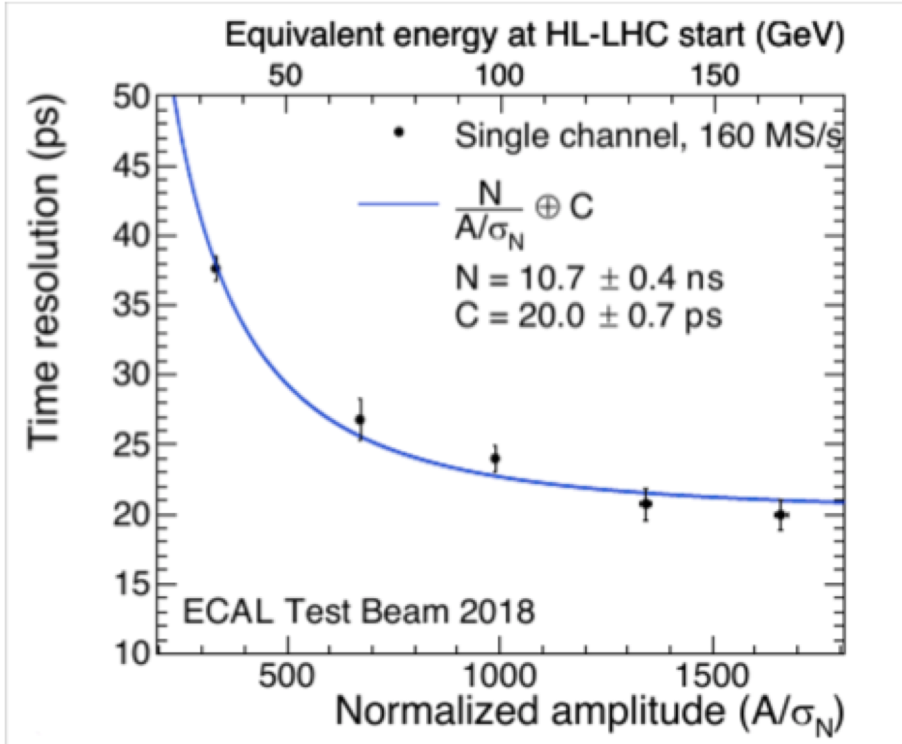
Strong recent effort to exploit fast timing in calorimeters
-PET (already mentioned)
-High energy : reduce pileup at high rate (HL-LHC, CLIC,..)

HL-LHC: bunch crossing collision Δt (rms) ~150 ps
A resolution O(30ps) could allow reducing the pileup by factor 5, bringing the HL-LHC pileup situation (up to 200 simultaneous events) similar as today (~50 simultaneous events @ $L=2\times10^{34}$ cm^{-2} s^{-1})

Can be obtained with calorimeters !

Fast timing in calorimeters





Silicon diodes

- 20 ps resolution
- Irradiation does not deteriorate performance
- ~ 40 such cells in a high-energy (100 GeV) electromagnetic shower
- Several such cells in a hadronic shower
- (CMS TB 2018 under analysis)

$PbWO_4$: 25 crystals matrix
CMS Test beam 2018 with new (Phase2) electronics @160 MHz

Q: could it be useful for Air Showers detectors?

A word on electronics

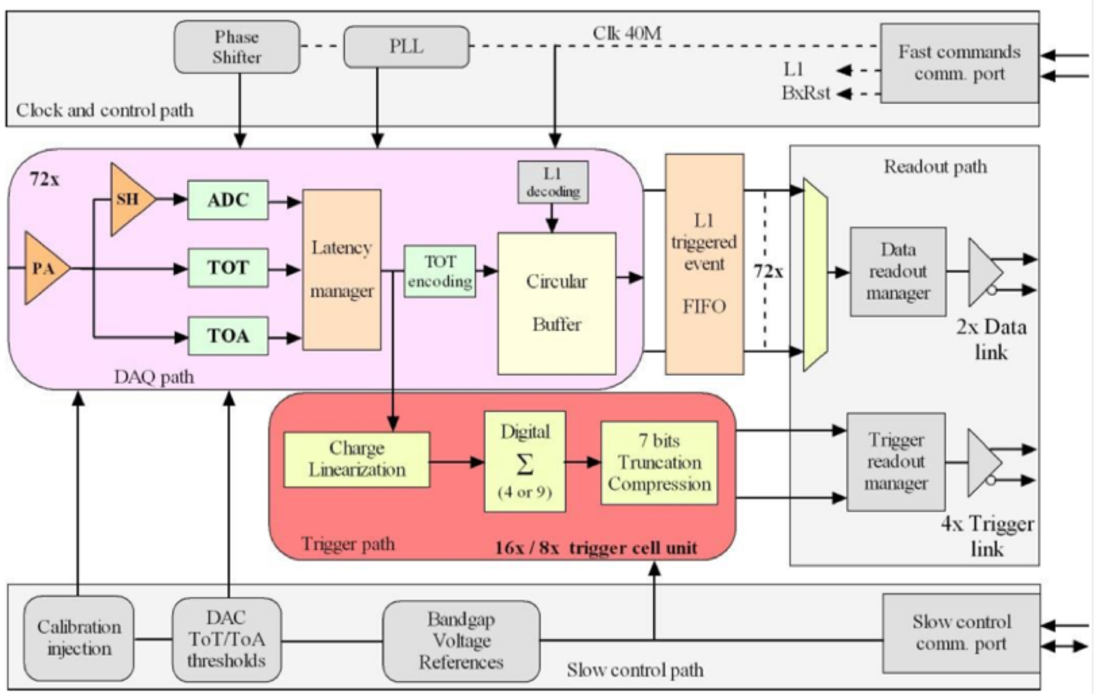
None of the steps I have mentioned could have been done without tremendous progress

- in Front-End electronics, using low feature-size (and radiation tolerant) CMOS technology and fast optical data transmission
- In Back-End electronics, using new generations of FPGAs

Since we are in Paris…

HGCROC for CMS HGCAL

130nm CMOS
20ns peaking time
40 MHz sampling
17 bits dynamic with ADC + ToT
20 ps resolution with ToA
78 channels
Low power (< 15 mW/channel)
Trigger primitive formations



Summary

Calorimeters are an essential component of our detectors

New lines of developments are going on, enabled by the progress in active media (new crystals, semi-conductors), in sensors (large silicon wafers, SiPMs), in electronics (low power allowing millions of channels).

Precise measurement of hadron showers remains difficult. Alternative approaches are being pursued, in particular in view of future collider experiments.

5D (energy-position-time) calorimetry is also emerging.

Backup

PoS(ICHEP2018)686

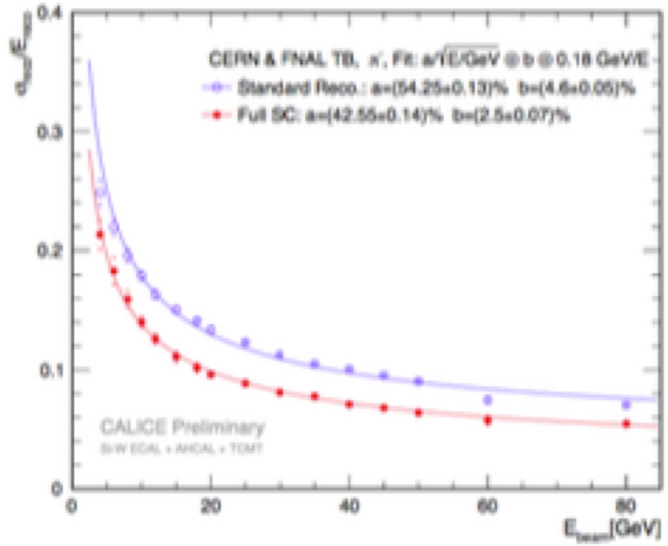


Figure 1: Relative energy resolution for the standard (blue circles) and SC (red circles) reconstruction in the combined setup [8]. The curves are plotted using the fit parameters from the legend. The overall uncertainties are shown.

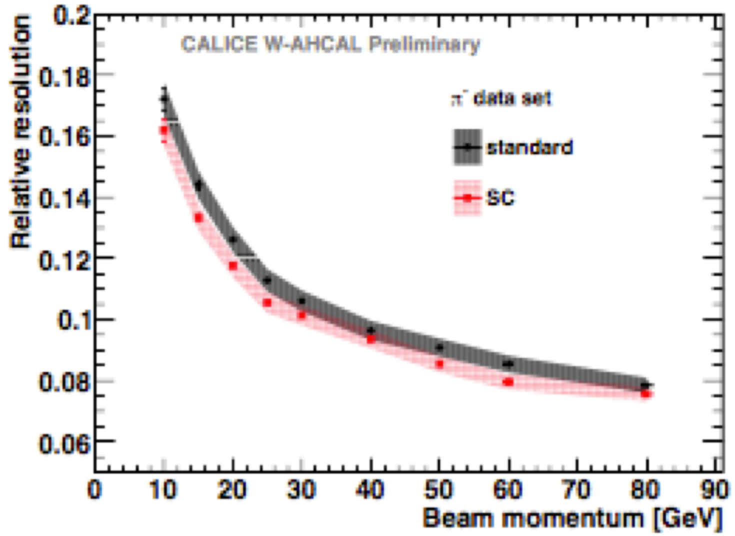


Figure 2: Relative energy resolution for the standard (black circles) and SC (red squares) reconstruction in the W-AHCAL [9]. The error bars (bands) show the statistical (systematic) uncertainties.

CALICE AHCAL: Fe absorber (left) e/h~1.2
W absorber (right) e/h~ 1