Calorimetry for future colliders

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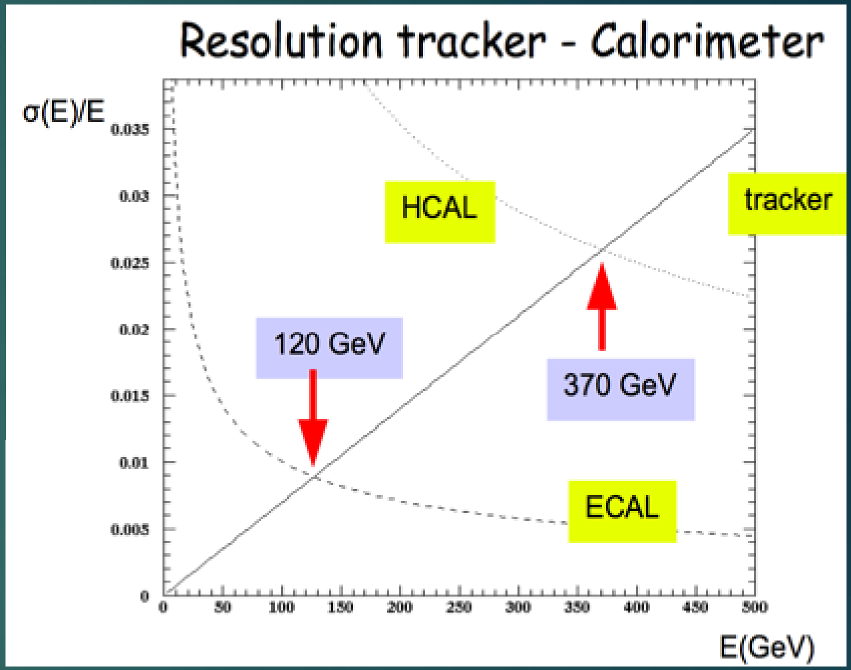
Outline

- Introduction

  Calorimeters in general
- Calorimeter for future colliders
  - PFA-based granular calorimeters
  - Dual-Readout calorimeters
  - Liquid Nobel Gas calorimeters
  - Optical-Scintillating calorimeters
  - Other technologies
- Timing in calorimeters of the future colliders
- Conclusion

Calorimeters what for?

Calorimeters are used to measure the energy of particles when trackers fail:
1- Neutral particles
2- High energy charged particles



ECAL vs HCL
There are usually two kinds of calorimeters
1- Electromagnetic calorimeters: gammas, electrons
2- Hadronic calorimeters: hadrons

Sampling vs homogenous
Calorimeters could be either sampling or homogeneous ones

Sampling detectors are made of
1- **absorbers :** in which particles interact
2- **active media :** where interaction products are detected

In **homogeneous** calorimeters the two are the same

What is a compensating Calo?

Electromagnetic showers produced by electron, gammas and $\pi^0 \rightarrow \gamma\,\gamma$ resulting in detectable energy (visible)

Hadronic showers produced by hadrons have two contributions:
Electromagnetic part (rather in the core) and hadronic part. The hadronic part involves nuclear interactions. Some of the energy is not visible (biding energy..) and this fluctuates from one event to another.

Response to hadronic and electromagnetic particles of similar energy is not the same in general (**$e/h \neq 1$**).

Calorimeters could be conceived (appropriate sampling schemes) to have same response **e=h** leading to simplifying calibration and operation of calorimeters → **Compensating Calo**

However this may lead to a weak sampling factor → Energy resolution degradation
→ Larger calorimeters

Important features

Moliere radius R_M : 95% of the electromagnetic shower is contained within 1 R_M

Important to characterize the electromagnetic shower **transversal** containment

Example: $\pi^0 \rightarrow \gamma\,\gamma$

Radiation length X_0 : $N^e = N^e_0 \exp(- l/X_0)$

Important to characterize the electromagnetic shower **longitudinal** containment

Interaction length λ_ι: $N^h = N^h_0 \exp(- l/\lambda_\iota)$

Important to characterize the hadronic shower **longitudinal** containment

ECAL: X_0, R_M (length scale &Moliere Radius)

- in W: X_0 ~ 3.5 mm, R_M ~ 9 mm
- in Fe: X_0 ~ 18 mm, R_M ~ 17 mm

W is better in the ECAL to separate close-by photons and also longitudinal EM/had contributions.

HCAL: length scale ~ λ_I

- in W: λ_I ~ 11 cm
- in Fe λ_I ~ 17 cm

However, robust mechanical structure and aspects related to neutrons production favors Iron.

Calorimeters for future colliders

ILC/CLIC

Proposed calorimeters are all high granular with embedded electronics to apply PFA.
No cooling problem since they use the power-pulsing scheme.
For ILC the cycle duty (5 Hz) is 1 ms every 200 ms. Two major experiments are proposed for ILC: ILD & SiD and one for CLIC: CLD

CEPC/FCCee

Different kinds of calorimeters are proposed
Duty cycle of 40 MHz (every 25 ns) and high rate (in particular for Z pole run) implies high rate capability for electronics/detectors with cooling and data transmission issues for high granularity calorimeters
Several experiments are proposed: CLD, IDEA, Nobel Gas Liquid, ILD and others

SPPC/FCChh

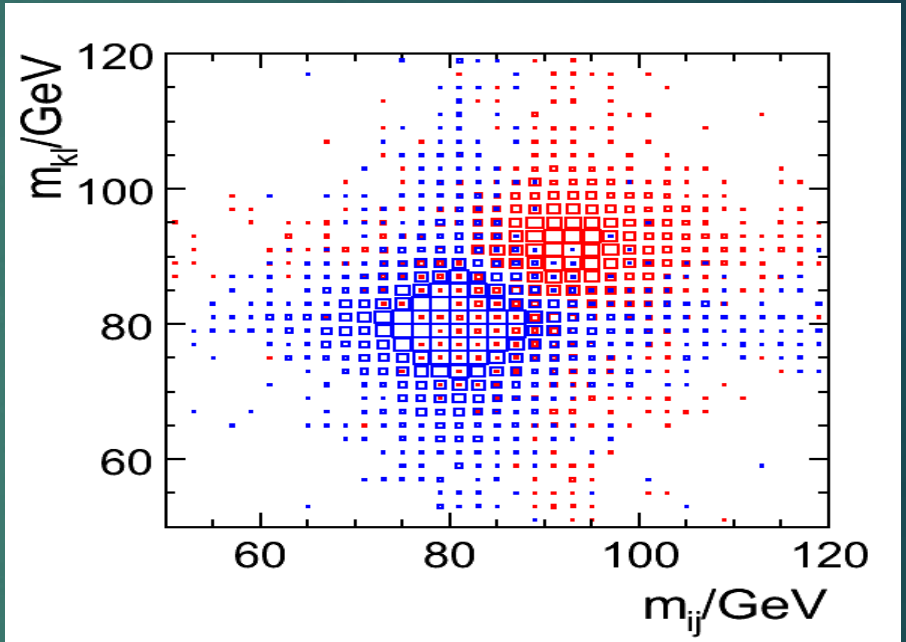
High rate and PileUp issues (up to 1000) requires very precise timing calorimeters with radiation hardness.

Muon collider

Beam background is important and thus good granularity is important

Why we need to have excellent calorimeters

Future calorimeters should achieve $\sigma_E/E = 30\%/\sqrt{E}$
to reach Jet Energy Resolution of 2-4%
since for Higgs factories >90% of events have >2 jets
So having excellent JER will help study particles and their interactions



PFA-based granular calorimeters

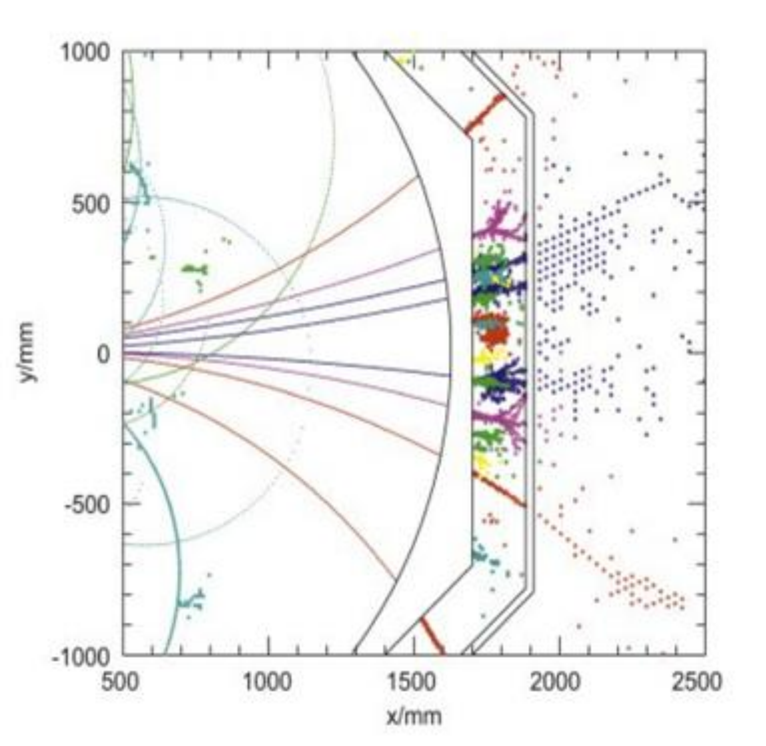
PFA: Construction of individual particles and estimation of their energy/momentum in the most appropriate sub-detector.

PFA requires the different sub-detectors including calorimeters to be highly granular.

PFA uses the granularity to separate **neutral** from **charged** contributions and exploits the **tracking system** to measure with precision the energy/momentum of charged particles

E_{jet} =	$E_{charged}$ +	E_{γ} +	E_{h0}
fraction	65%	26%	9%

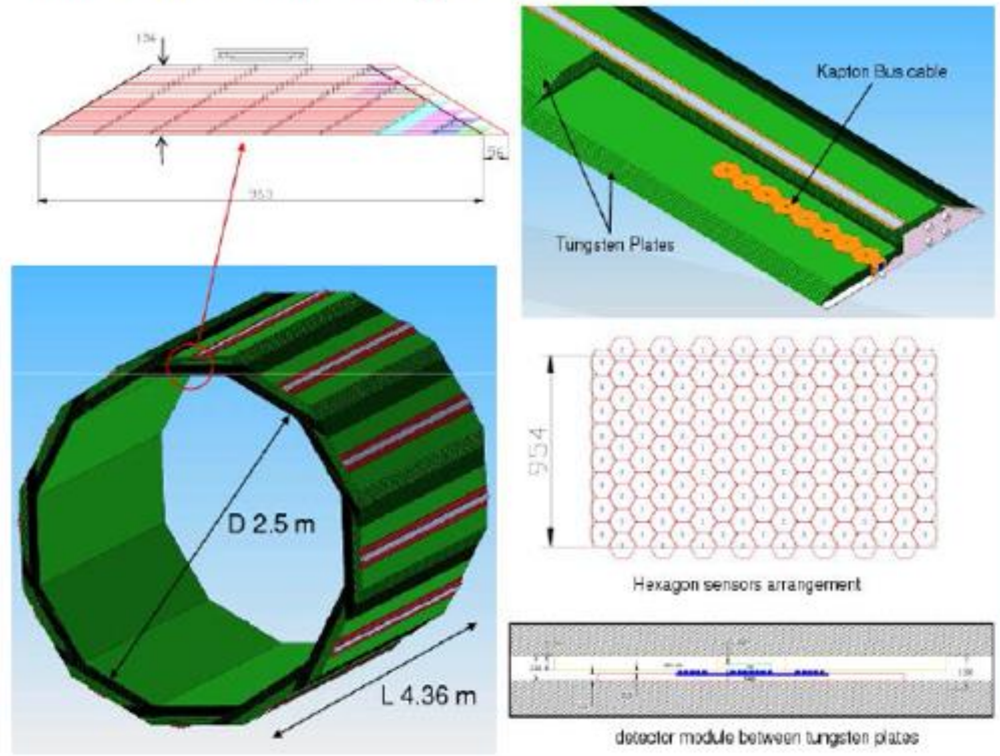
Charged tracks resolution	$\Delta p/p \sim$ few10^{-5}
Photon(s) energy resolution	$\Delta E/E \sim 12\% / \sqrt{E}$
Neutral hadrons energy resolution	$\Delta E/E \sim 45\% / \sqrt{E}$



Technologies proposed for ILC calorimeters

ECAL for SiD

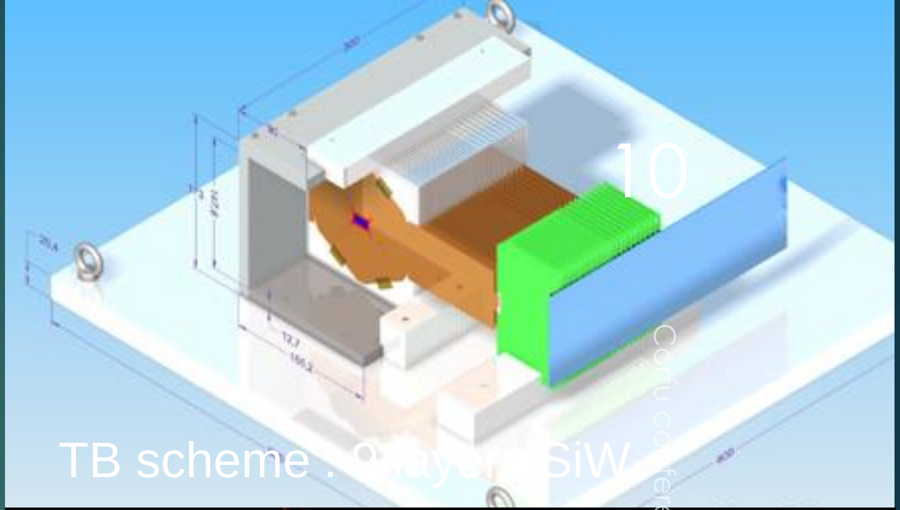
An imaging calorimeter: 30 layers tungsten interleaved with 30 layers pixellated silicon

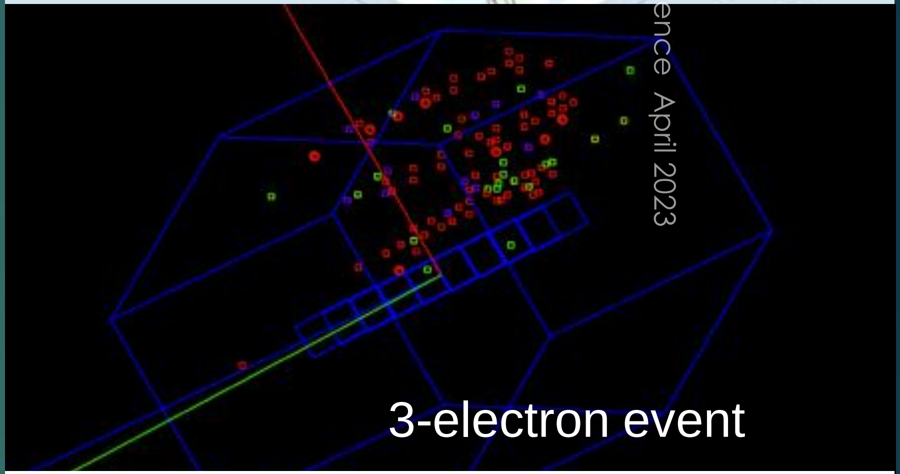


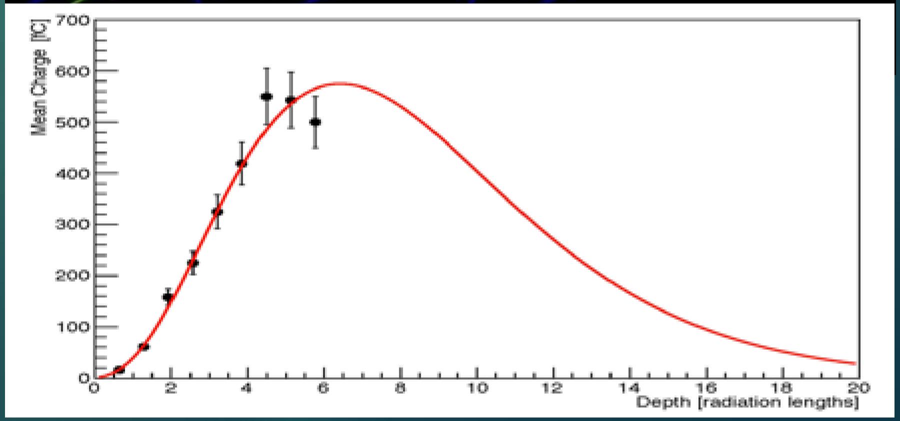
Baseline configuration:

- transverse: 12 mm² pixels
- longitudinal: (20 x 5/7 X_0) + (10 x 10/7 X_0) ⇒ 17%/sqrt(E)
- 1 mm readout gaps ⇒ 13 mm effective Moliere radius

1024 KPiX ASIC, power-pulsed → very low power consumption and thus no active cooling is needed







Technologies proposed for ILC calorimeters

ECAL for ILD

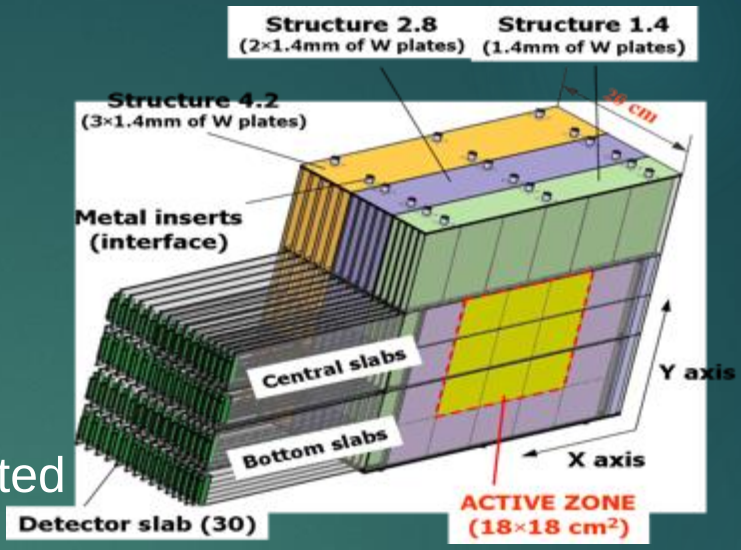
30 layers of tungsten ($24X_0$) interleaved with
-Pixelated Silicon of 5x5 mm^2,

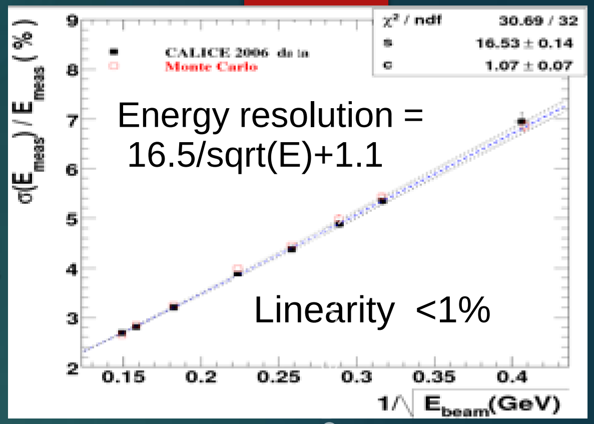
A physics prototype (1x1 mm^2 cell size) with a deported electronics was built and successfully tested.

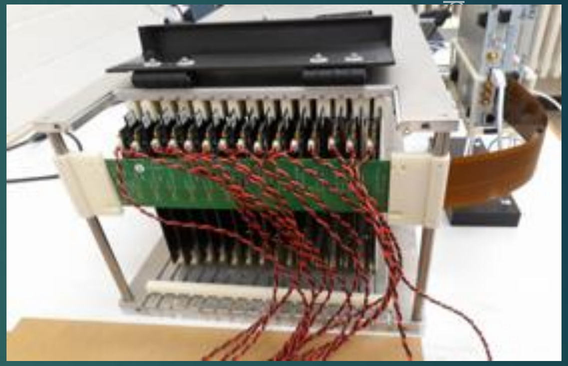
A technological prototype fulfilling the ILD requirements is being completed :

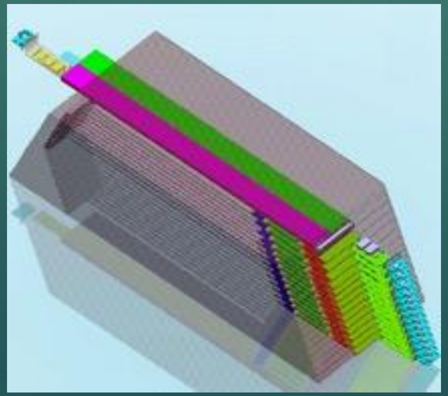
- Self-supporting structure (alveolar)
- Embedded power-pulsed electronics
- Large surface detector

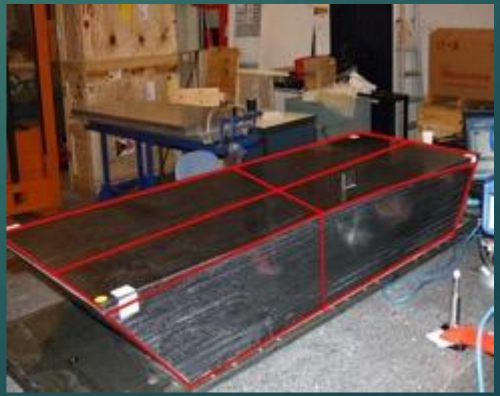
Several beam tests took place at DEASY and CERN to improve on the detector performance (efficiency, homogeneity, pedestals, MIPs response…)



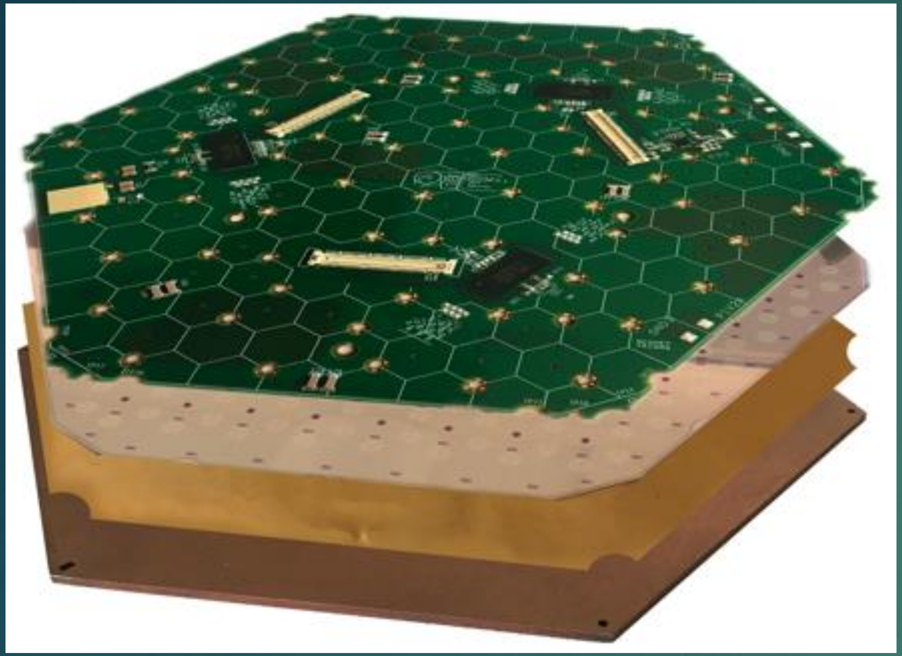








Silicon-based



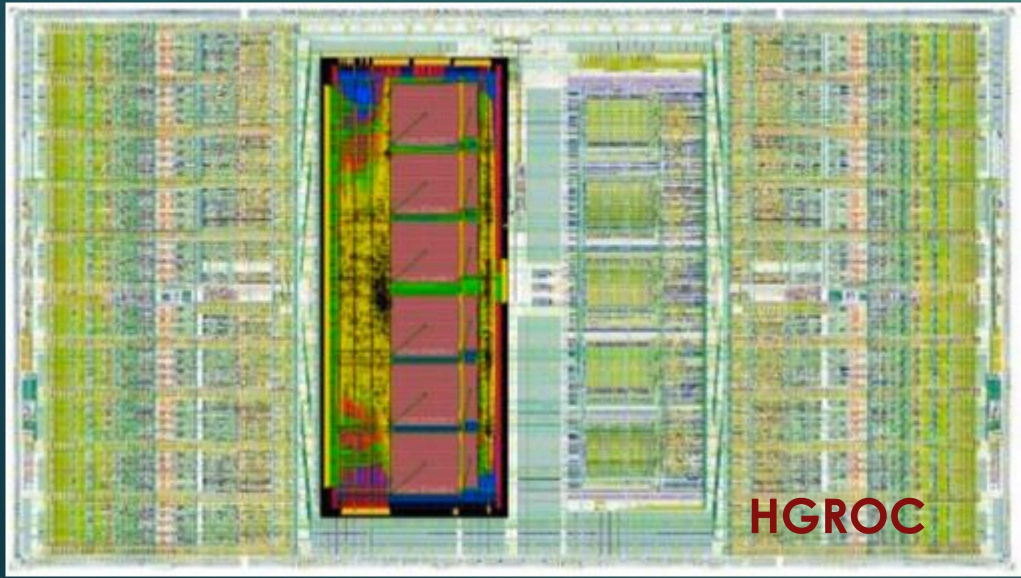
CMS HGCAL will be the first calorimeter using this technology at large scale. CALICE physical prototype was a proof of concept.

CMS Silicon modules

Sandwich of **PCB**, **sensor**, biasing/insulation layer and **baseplate** for rigidity/cooling.

- Wire-bonding from PCB onto the silicon.
- CE-E: Cu W baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

Silicon thickness (120, 200, 300 μm) depending on the rate

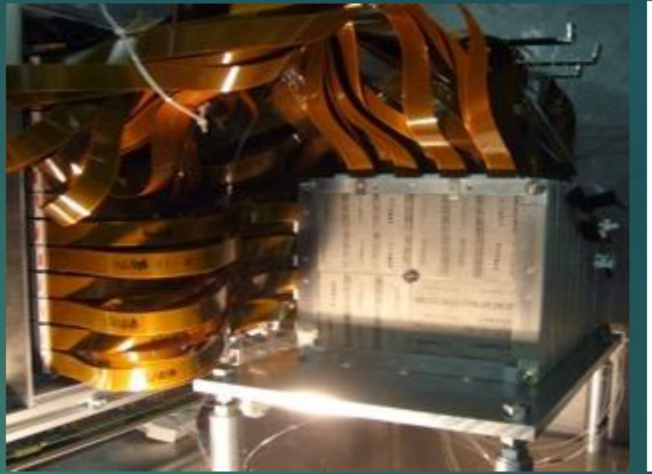


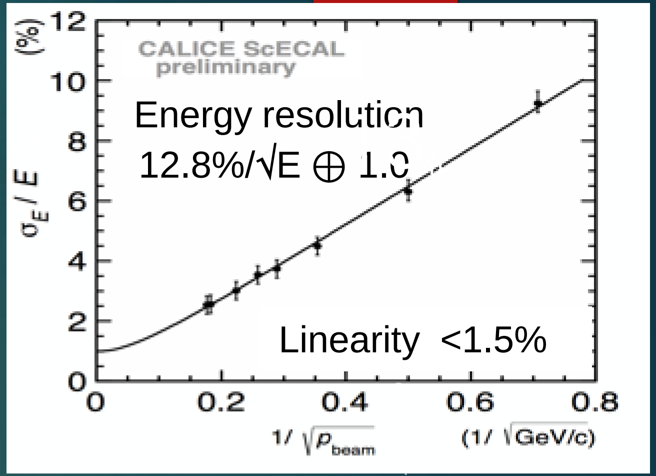
- ***Low noise*** (<2500e)
- ***High dynamic range*** (0.2fC -10pC).
- **Timing** information ***tens of picoseconds*** ***Radiation tolerant.***
- Consumption ***<20mW*** per channel (cooling limitation).
- ***Zero-suppression*** of data to transmit to DAQ.

Technologies proposed for ILC calorimeters

ECAL for ILD

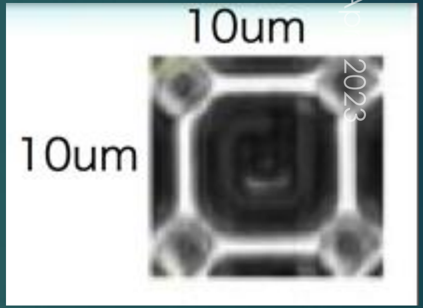
30 layers of tungsten ($24X_0$) interleaved with of 5x45 mm^2 scintillator strip with alternating direction layers (X&Y) → equivalent of 5x5 mm^2 (SSA)
Read out by SiPM
A physics prototype with a deported electronics was built and successfully tested

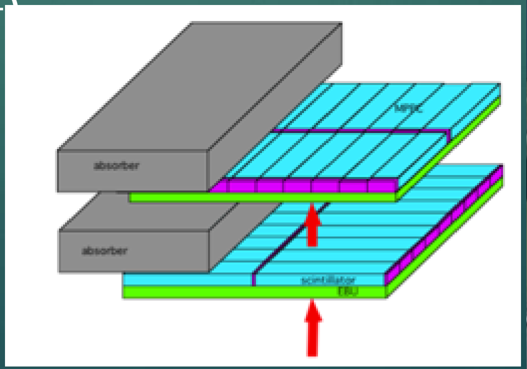


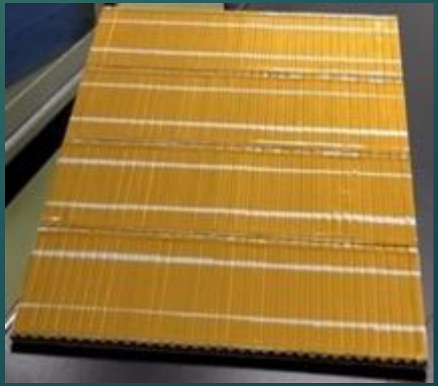


A technological prototype is being completed with

- Scintillator shape that optimizes light collection and reduces dead zones : rectangular, wedge, tapered..
- SiPM more compact with higher linearity range and less noise (MPPC 10000 ch in 1x1mm^2)
- Electronic board to host ASIC on one side and scintillator plane on the other.





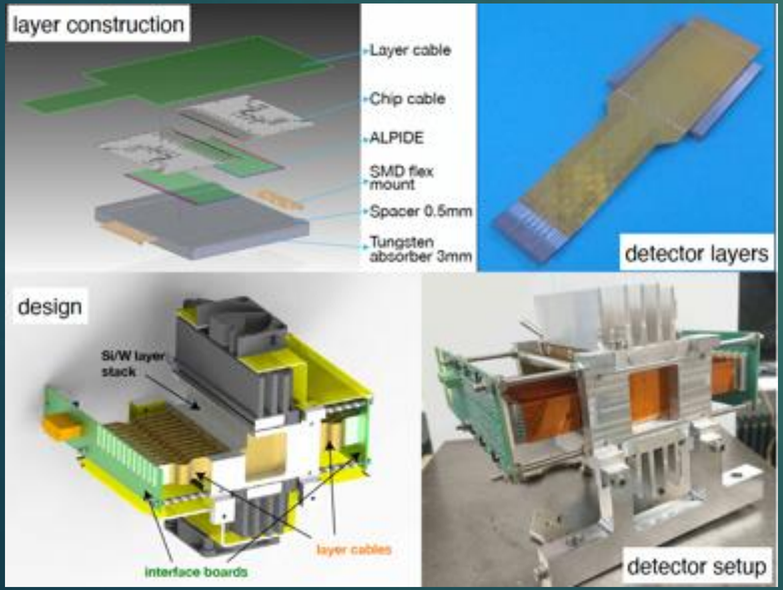


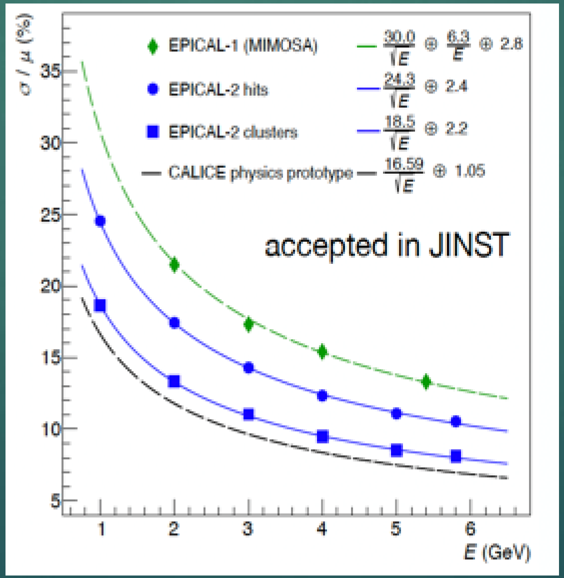
MAPS for ECAL

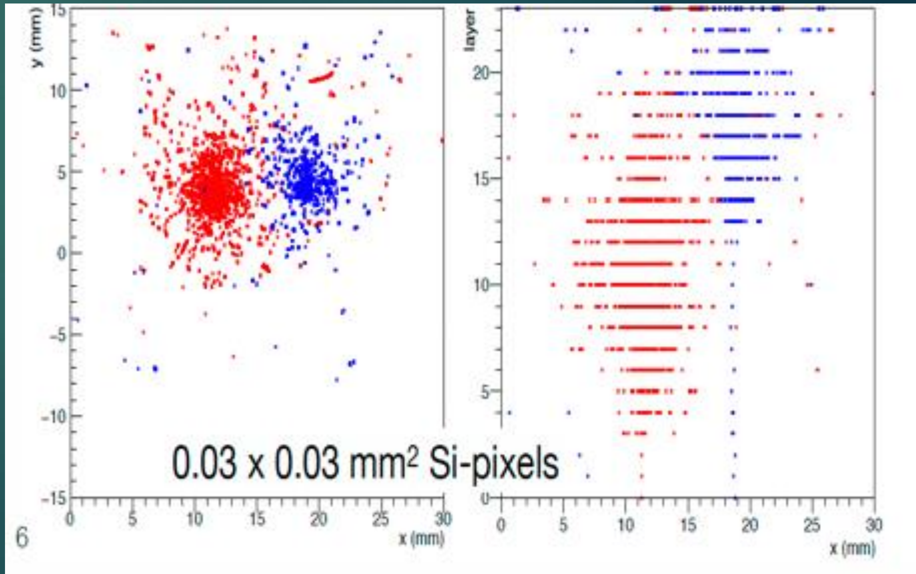
Monolithic Active Pixel Sensor proposed for trackers can also be used for ECAL providing ultra high granularity (20-50 μm pixels). Its readout could be either digital or semi-digital.

Initiated in CALICE DECAL and ALICE FoCal proposal

A prototype made of 24 layers each with
-3 mm W absorber, 2 ALPIDE CMOS sensors, ultra-thin flex cables
29.24 x 26.88 μm^2 pixel size, active cross section 3 x 3 cm2, R_M of 11 mm







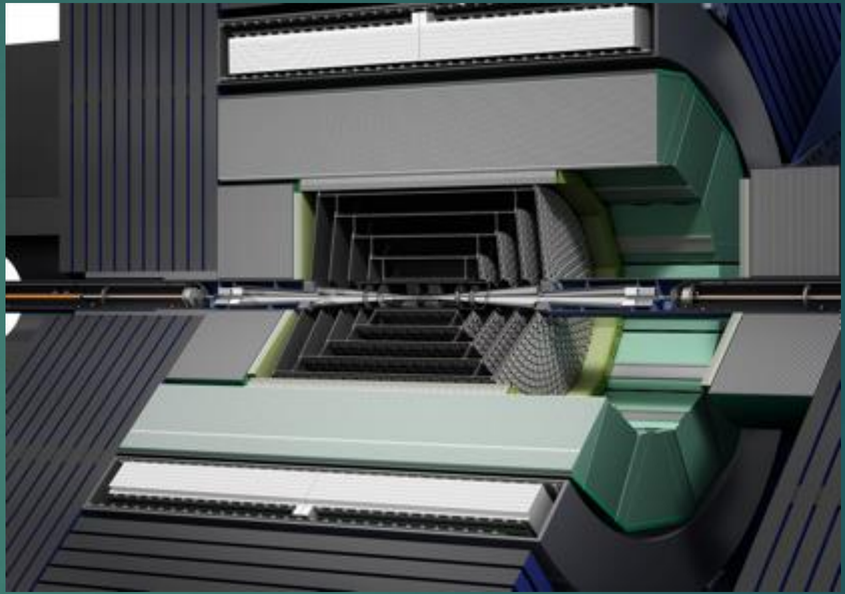
20 GeV electron& 40 GeV pion

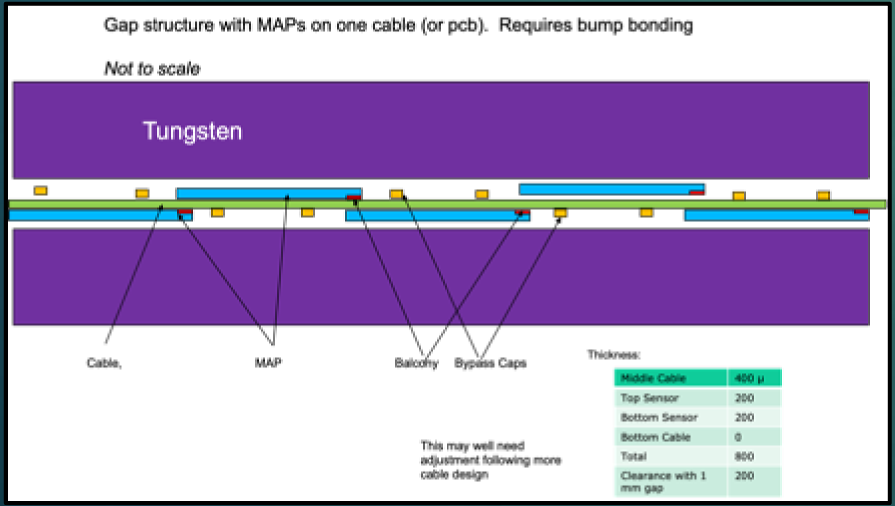
Technologies proposed for ILC/FCCee calorimeters

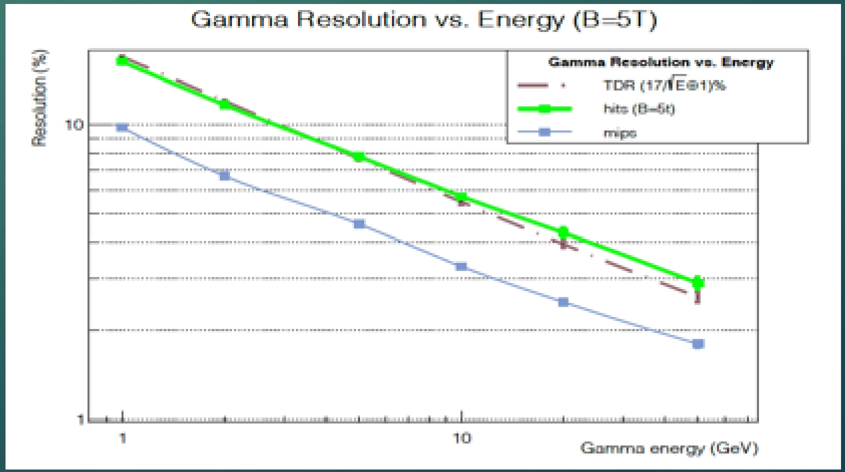
MAPS for ECAL

A similar activity is ongoing to propose MAPS in SiD

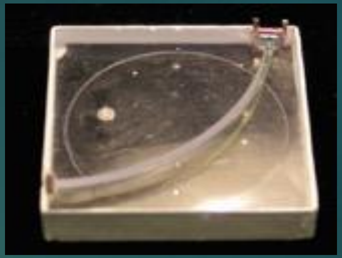
Parameter	Value
Min Threshold	140 e-
Spatial resolution	7 µm
Pixel size	25 x 100 µm2
Chip size	10 x 10 cm2
Chip thickness	300 µm
Timing resolution	~ ns







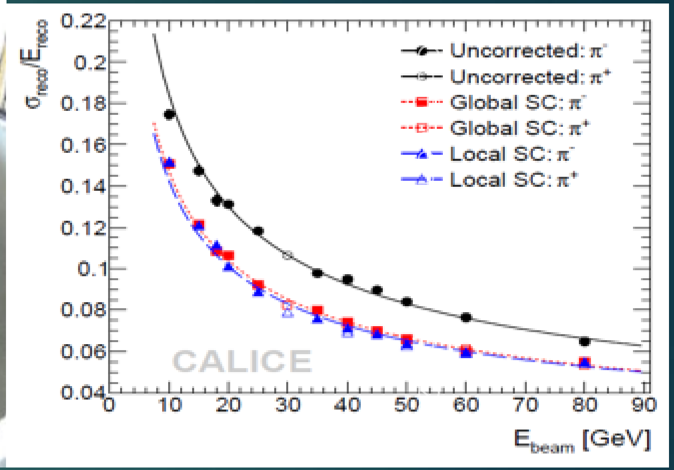
Technologies proposed for ILC/CEPC/FCCee calorimeters



AHCAL

48 layers of 2 cm stainless steel interleaved with planes made of **3x3** cm^2 tiles, read out directly by SiPM and embedded electronics.

A physical prototype of 38 layers of 1 m^2, totalizing (5.3 λ_I) accompanied by a tail catcher (6 λ_I) with deported electronics was built and successfully tested

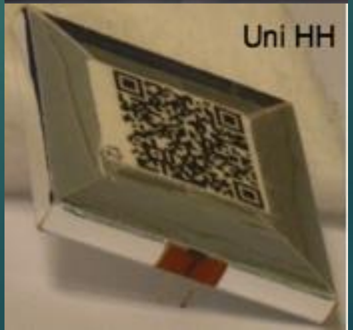


A technological prototype with **38** layers fulfilling the ILD requirements was also built in 2017:

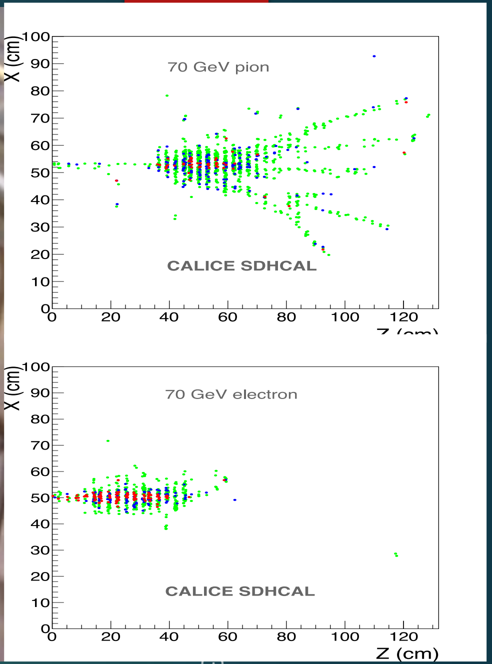
- ➢ Optimized tile shape for direct readout
- ➢ Embedded, power-pulsed readout electronics
- ➢ Large plane with tiles assembled in a way to reduce dead zones
- ➢ Self-supporting mechanical structure

AHCAL was adopted to complete HGCAL hadronic part

Another prototype for CEPC with **4 X4 cm²** and **43** layers was built in 2022 and exposed to beam test



Technologies proposed for ILC&CEPC calorimeters

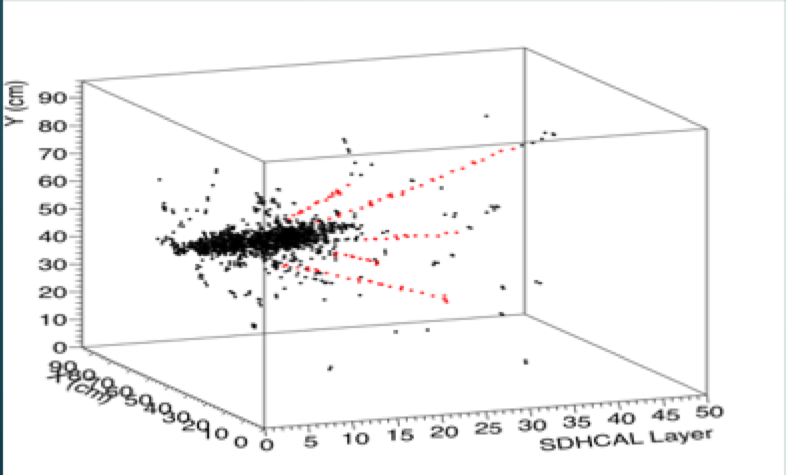


SDHCAL

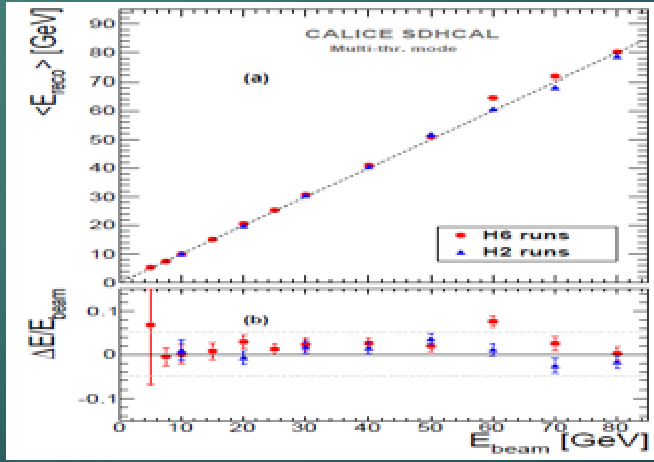
48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of 1 cm^2

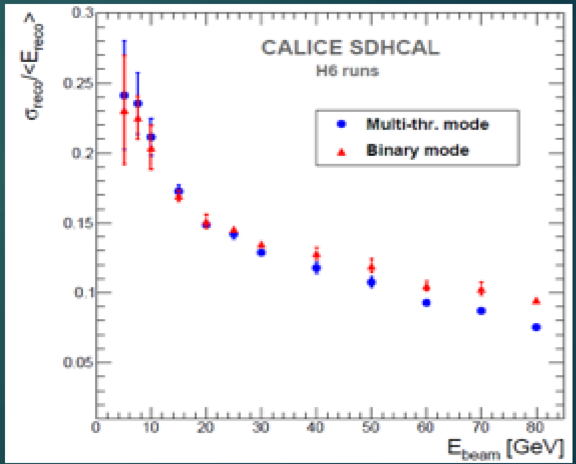
A technological prototype of 48 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 2-bit electronics allowing a lateral segmentation of 1 cm^2 fulfilling all the ILD requirements

- compactness
- self-supporting mechanical structure.
- Triggerless mode
- Power-pulsing mode



Hough transform tracks to control the





$$E_{rec} = \alpha (N_{tot}) N_1 + \beta (N_{tot}) N_2 + \gamma (N_{tot}) N_3$$

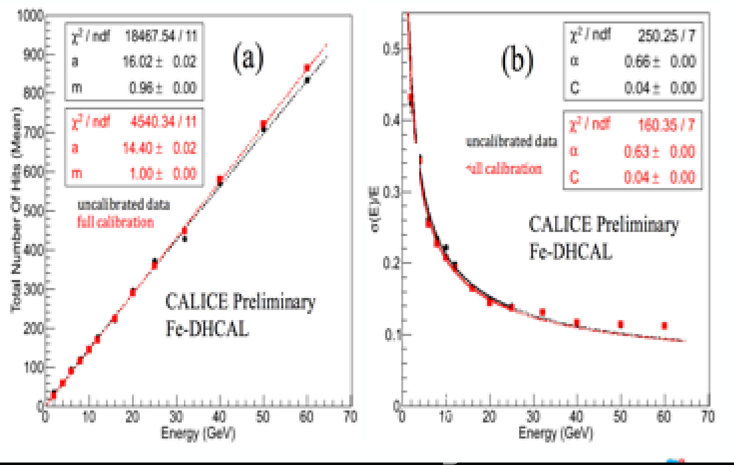
Technologies proposed for ILC calorimeters

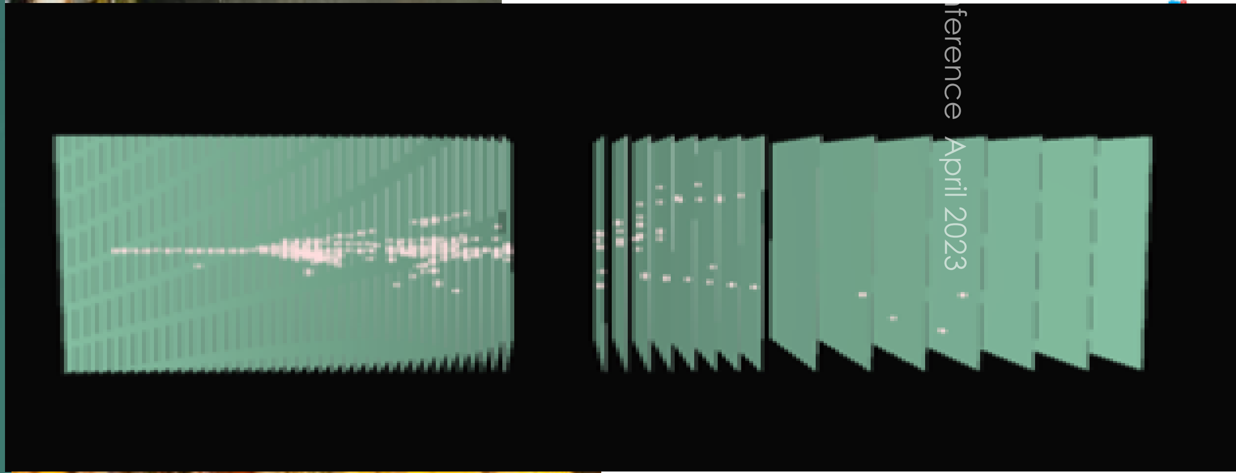
DHCAL for SiD

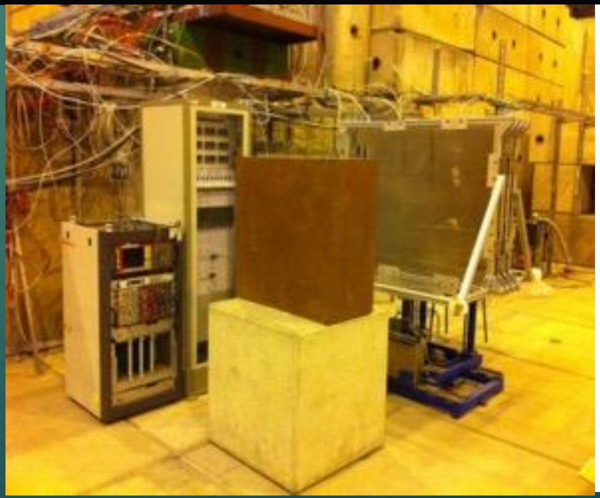
40 layers of 2 cm stainless steel interleaved with planes made of Glass RPC and their embedded readout 1-bit electronics allowing a lateral segmentation of 1 cm^2

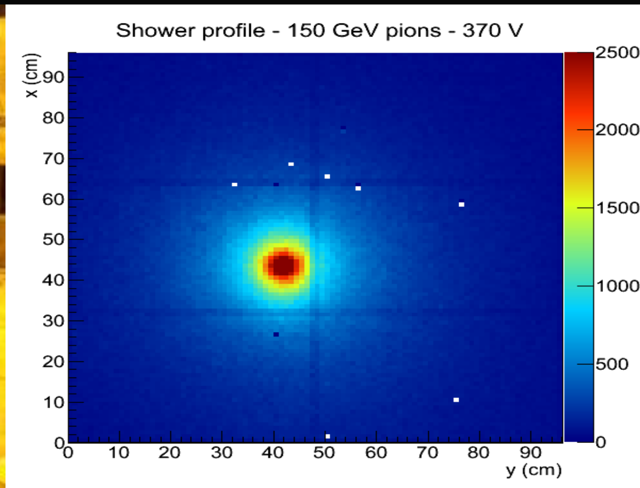
An advanced physical (embedded electronics) prototype of 54 was built and successfully run.

Other options with GEM and micromegas detectors are also proposed as active layers for the SiD HCAL Several layers of mm were built and tested using 2-bit readout electronics. Few GEM planes are also in preparation.

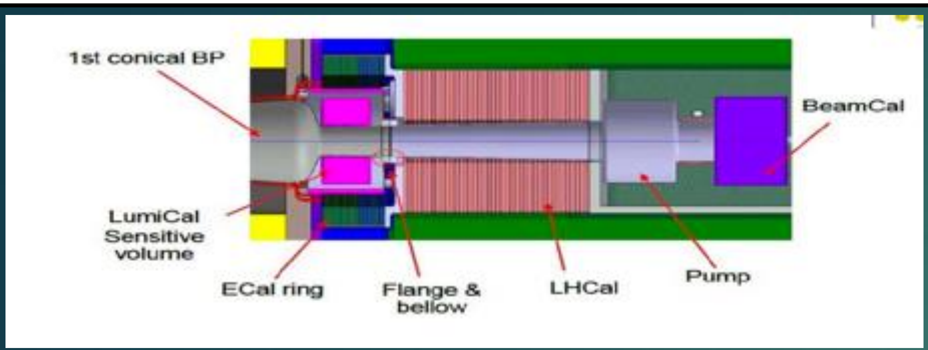




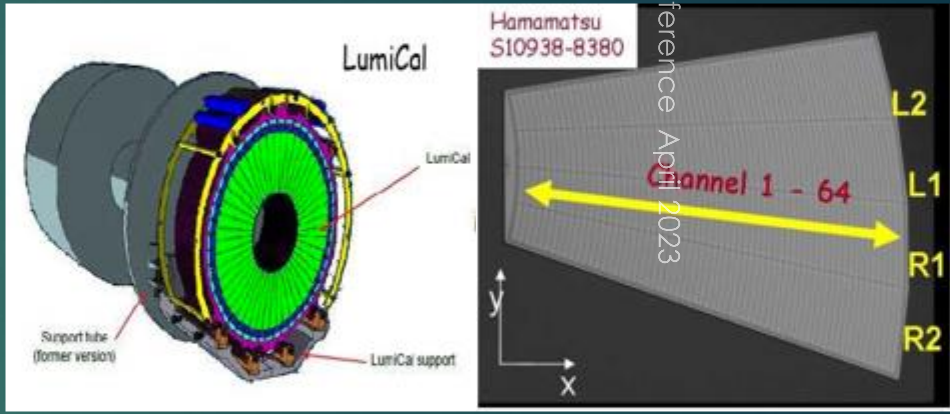




Technologies proposed for ILC forward calorimeters



LumiCal: Precise luminosity measurement (10^{-3}) at 500 GeV.
BeamCal : Instantaneous luminosity measurement, beam diagnostics but very high radiation load (up to 1MGy/ year)
LHCaL: Extends the calorimeter measurements to small polar angles



LumiCal (31 -77 mrad)

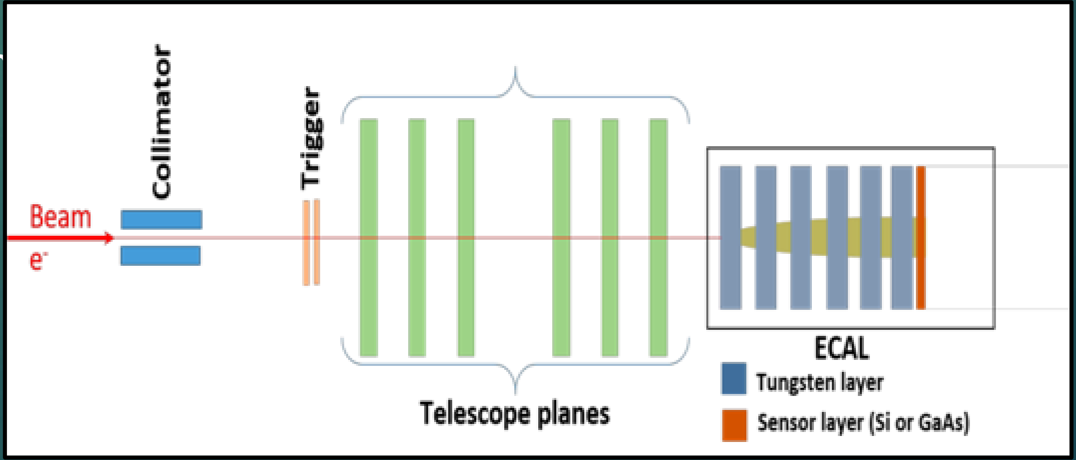
- Two Si-W sandwich EM calo at ~ 2.5 m from the IP (both sides).
- 30 tungsten disks of 3.5 mm thickness. Si sensor pitch of 1.8 mm
- Two tracking layers in front are envisaged to improve angle measurement and separate e/γ.

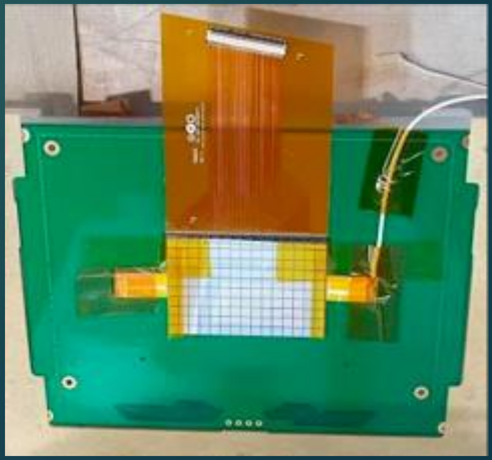
BeamCal (5 – 40 mrad)

- similar W-absorber as for the LumiCal but radiation hard sensors (GaAs, CV Diamond, Sapphire, Si).
- Several segmentation and orientation scenarios are envisaged

LHCal

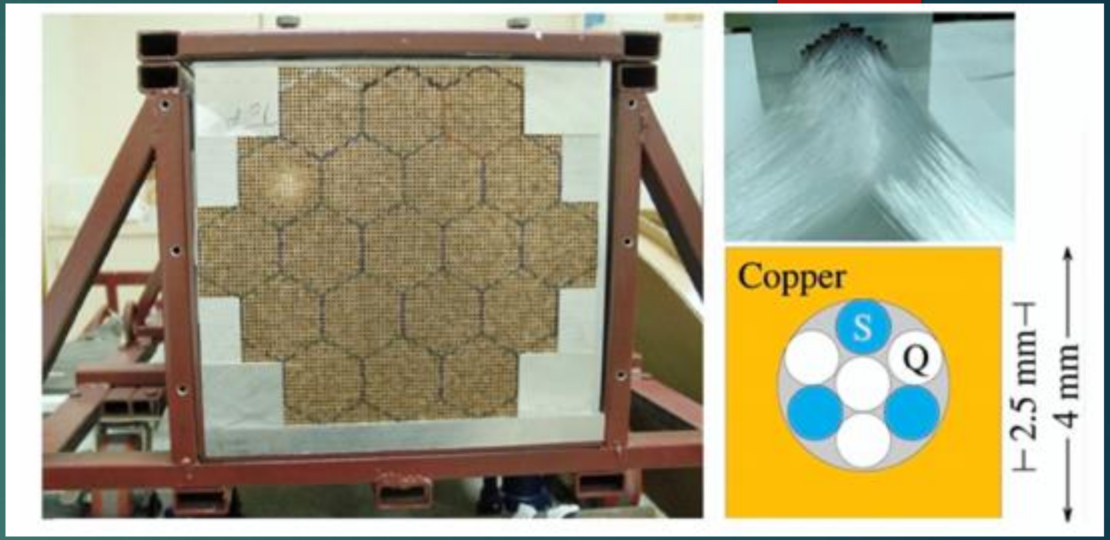
- 29 layers of 16 mm thickness each
- Silicon for active medium
- Absorbers either W or Fe





Dual Readout-based calorimeters

Energy is deposited in two different ways
1) Scintillation light
2) Cerenkov light → relativistic particles
   80% of the hadronic component is not relativistic



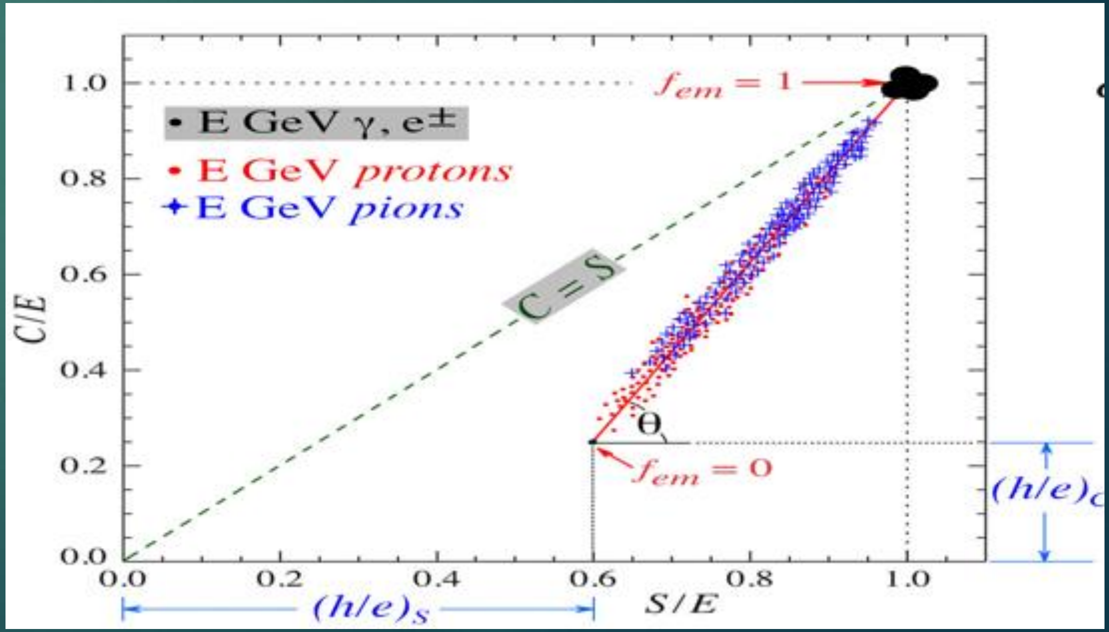
$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$
$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1 - f_{em})\right]$$

If one has $(e/h)_S$ and $(e/h)_C$ then

$$\chi = \frac{1-(h/e)_S}{1-(h/e)_C}$$

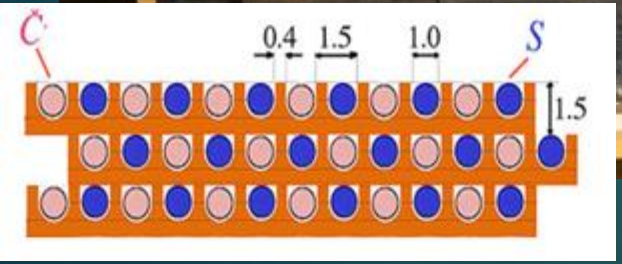
χ Is independent of E and particle nature

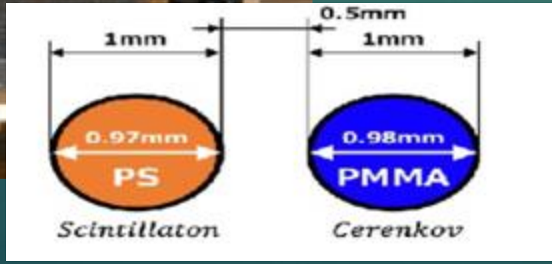
$$E = \frac{S - \chi C}{1 - \chi}$$



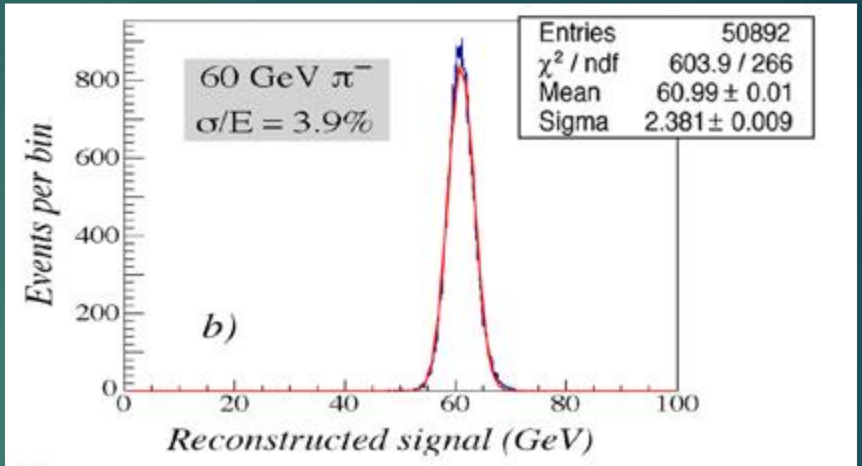
Double Readout technique can use either fibers or crystals

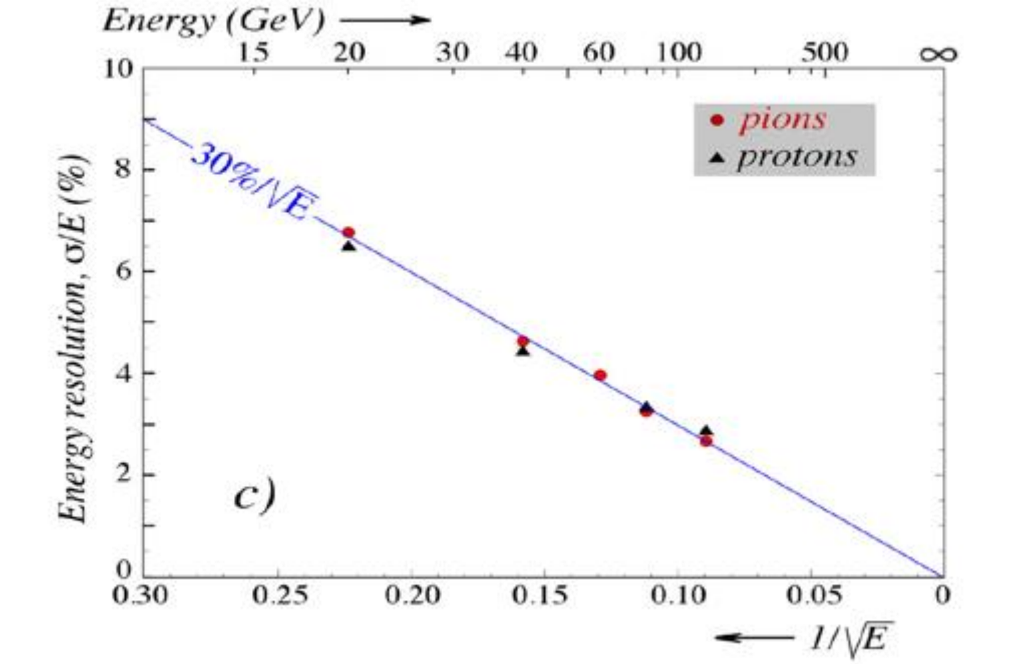
Dual Readout-based calorimeters



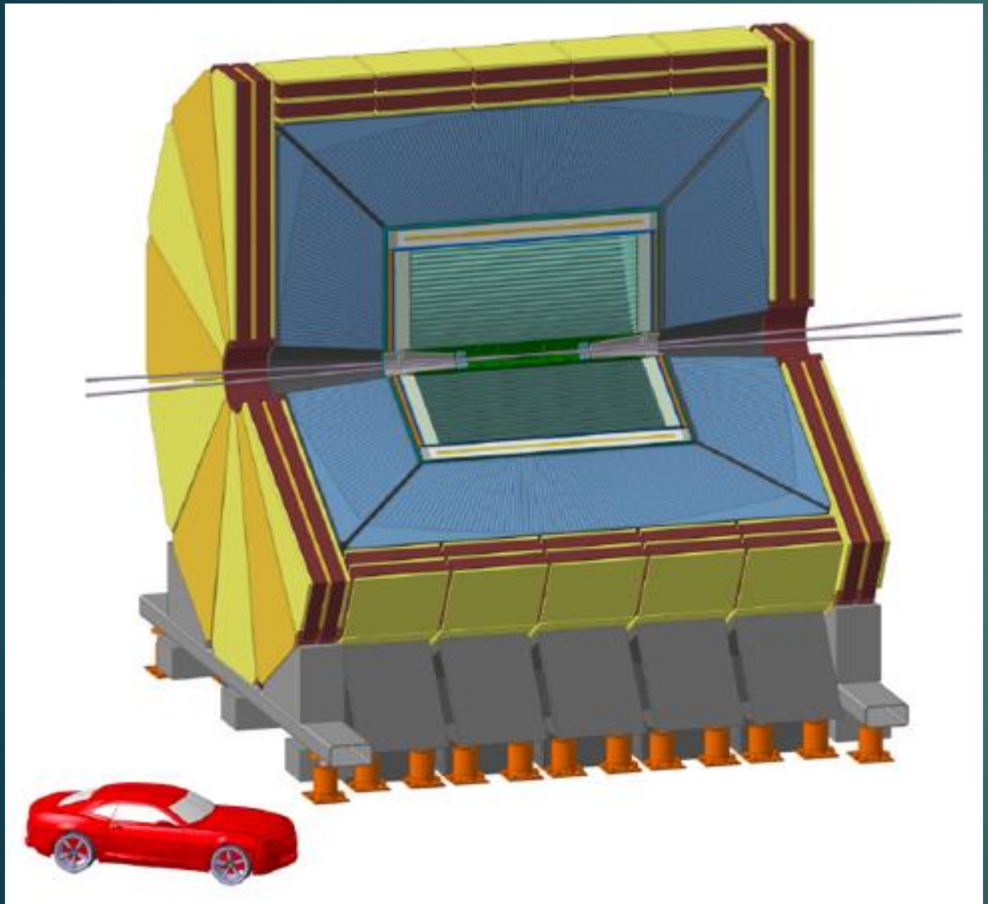


(Kuraray SCSF-78) (Mitsubishi SK-40)

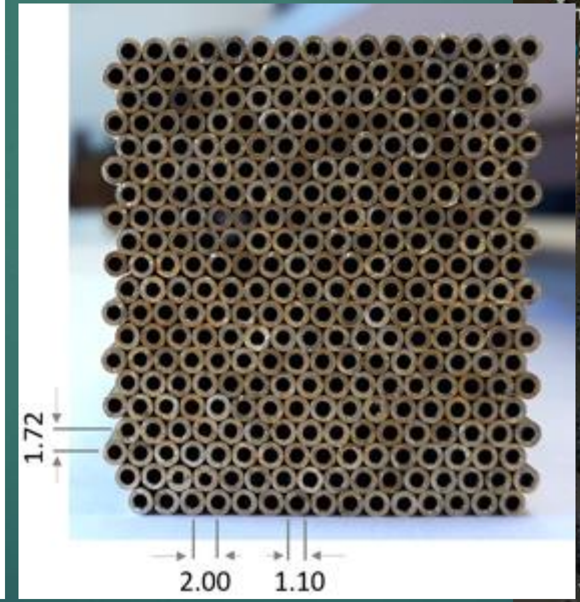


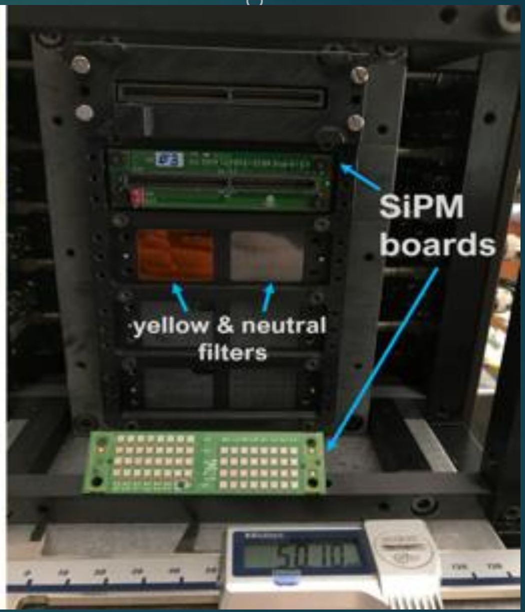


IDEA detector

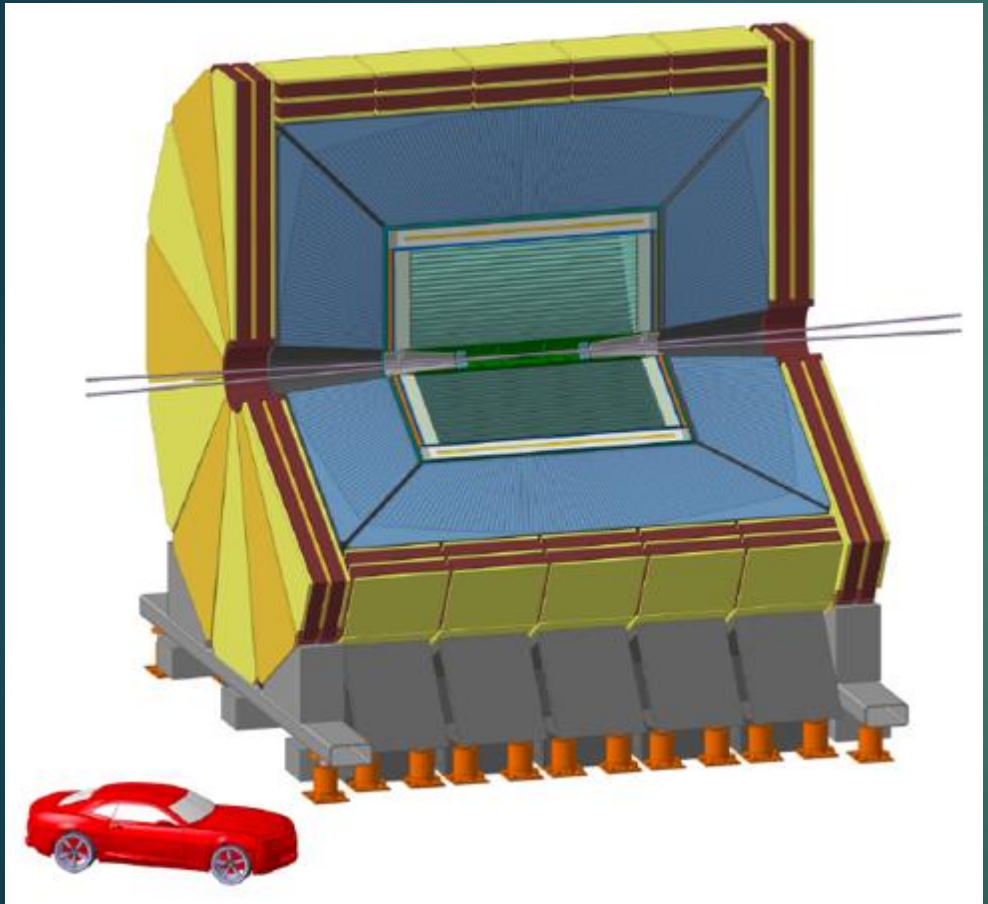


An EM-size prototype has been built
Modules of 10 cm x 10 cm X 100 cm
Made of 9 towers each.
Each tower is a made of 320 brass tube filled with S and C fiber alternatively
The central tower is read out using SiPM
The others with PMT

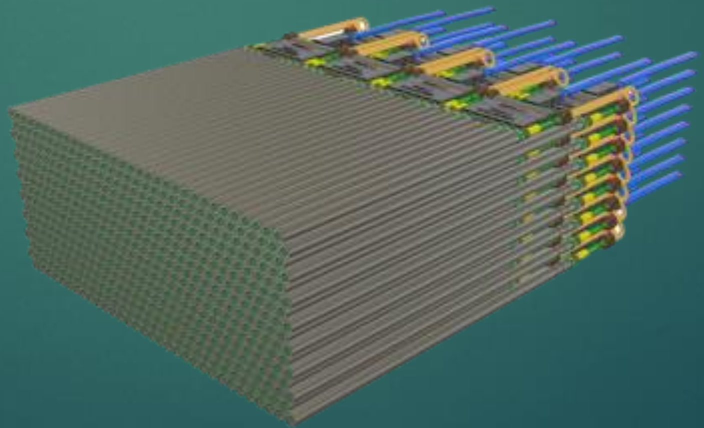


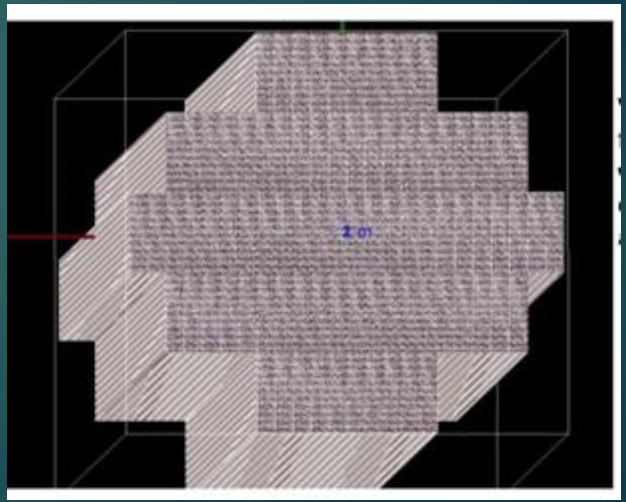


IDEA detector



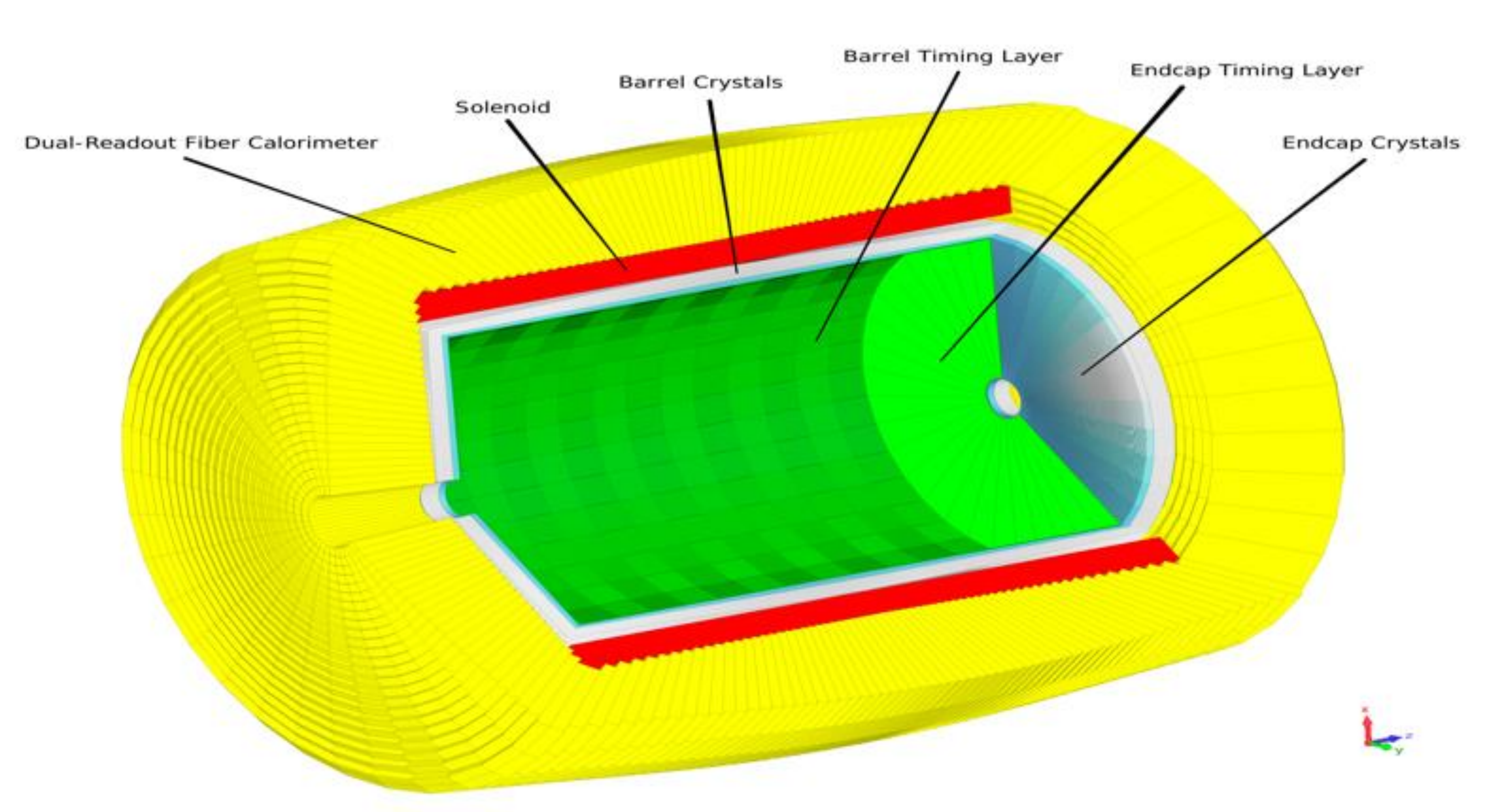
A hadronic-size prototype (HiDRA) is being built with 16 modules each made of 10 mini module With 250 depth each
The two central will be equipped with SiPM
This intends to validate the DR concept for future colliders





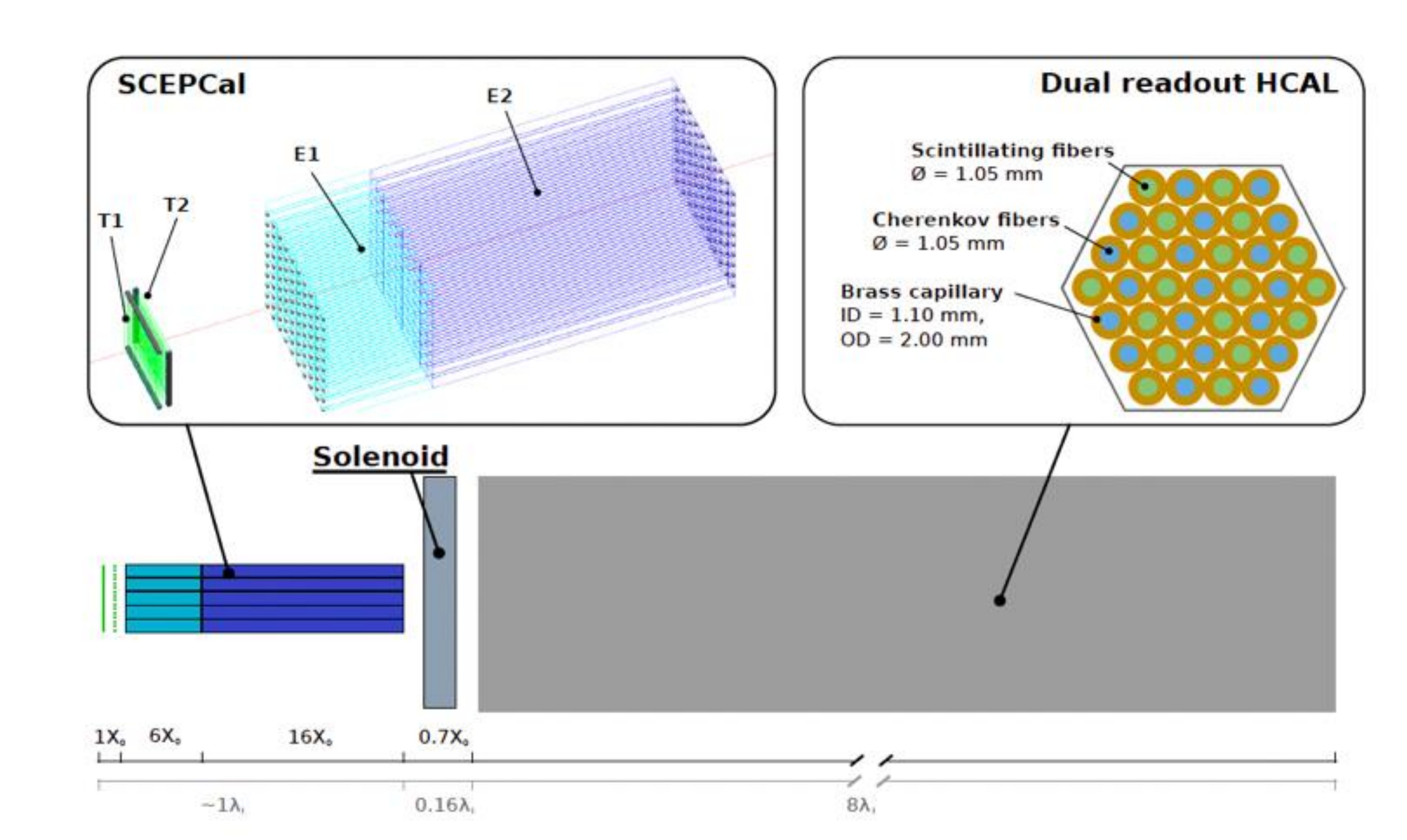
SCEPCAL detector

DR concept based on fibers could not reach very precise EM resolution (> 15%/√(E)) but one can make much better with DR based on crystals



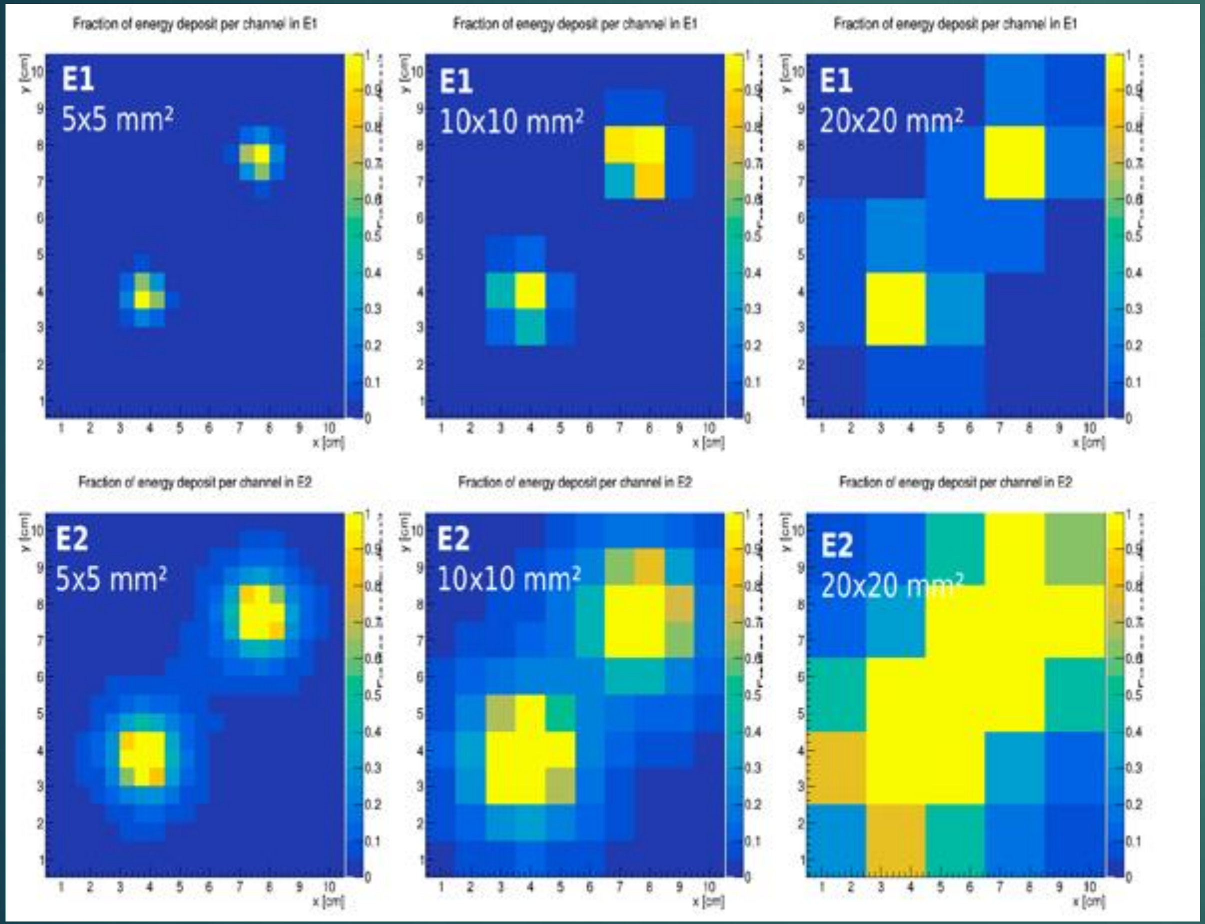
SCEPCAL detector

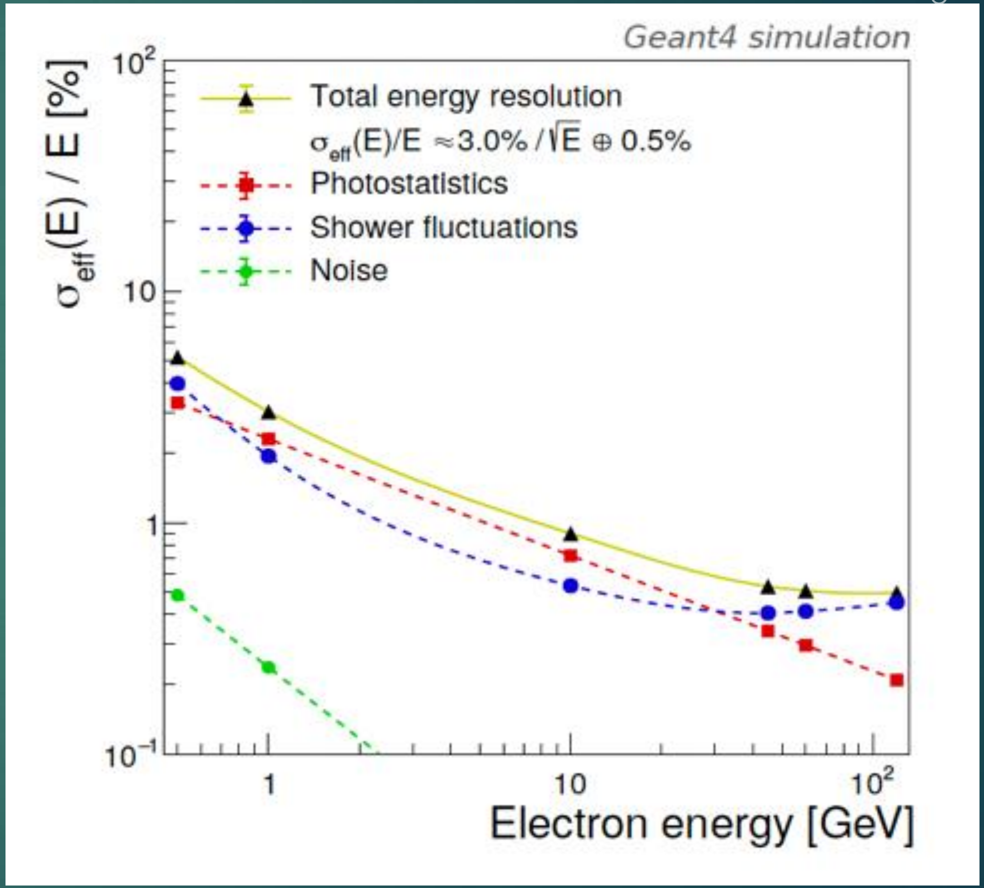
Two timing crystal-based detectors followed by two sections made of long crystal bars. Each bar could be read out by two kinds of SiPM (with different sensitivities).



SCEPCAL detector

- Transversal segmentation is important. Molière radius is 1 cm
- Longitudinal one is much less (4 layers)





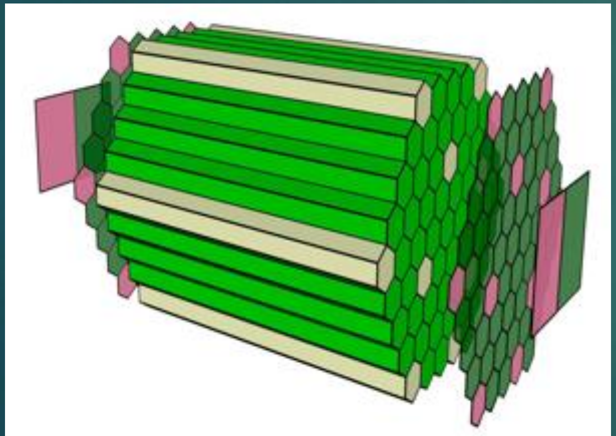
$$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}} \oplus \frac{0.2\%}{E} \oplus 0.5\%$$

Homogeneous hadron calorimeters

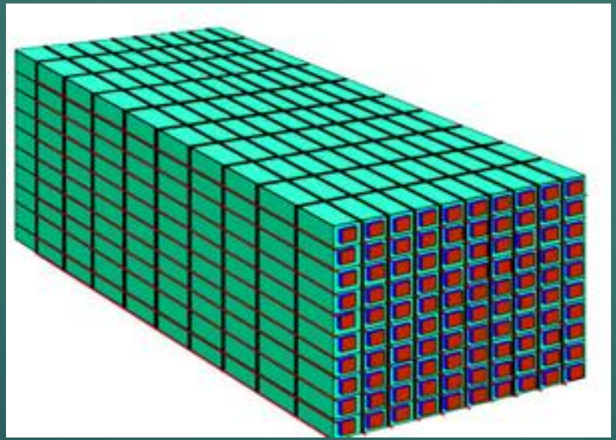
It is possible to combine homogenous calorimeter and dual readout technique to reach 15%/√(E) for hadronic energy measurement by using high density scintillators

Challenges on mass production and cost reduction:

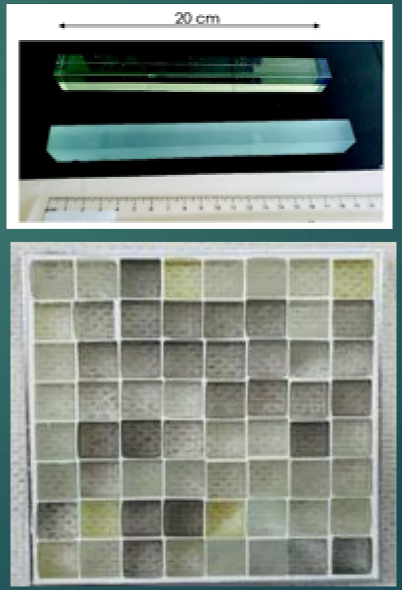
Several materials are investigated (DSB:Ce, AFO:Ce, Gd-rich heavy glasses, …)



Bundles of meta-crystal fibers



Bulk dense scintillators

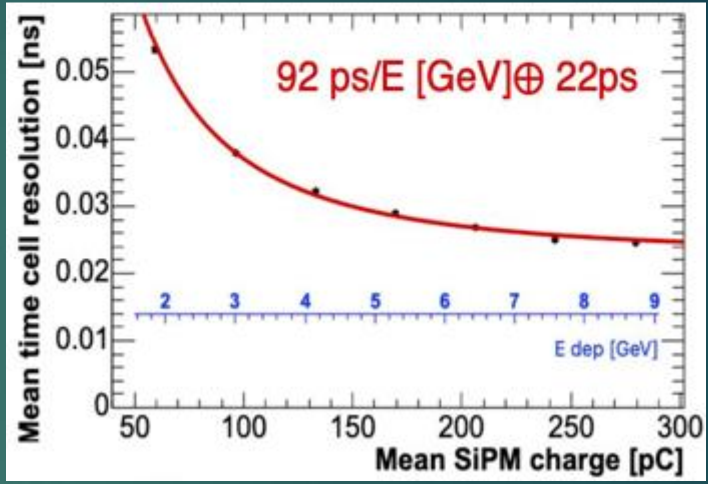


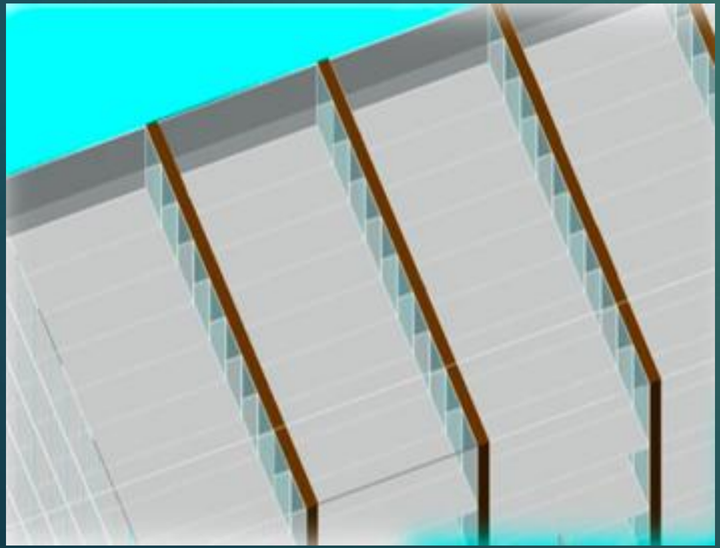
Heavy glass

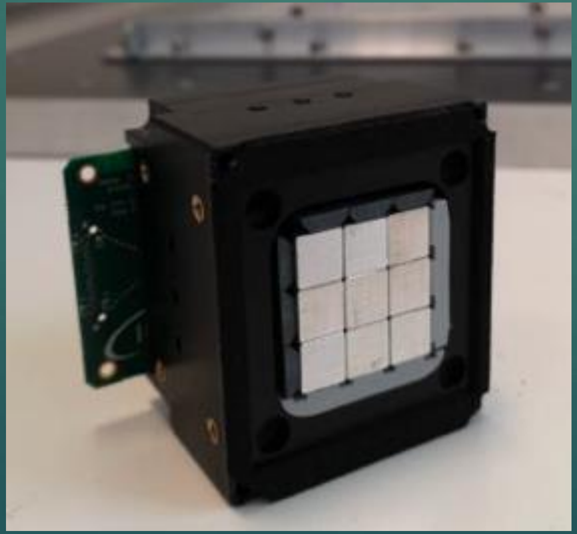
Homogeneous hadron calorimeters

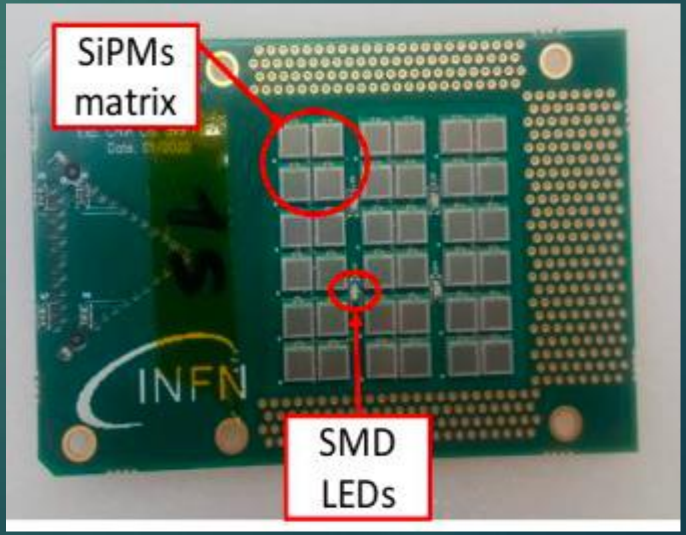
Timing and longitudinal segmentation are needed to tackle BIB
Radiation hardness is a major challenge 10x10x40 mm³

- 10 x 10 X 40 mm² PbF2/PWO-UF crystals are under study
- 3x3 mm² UV extended SiPM readout









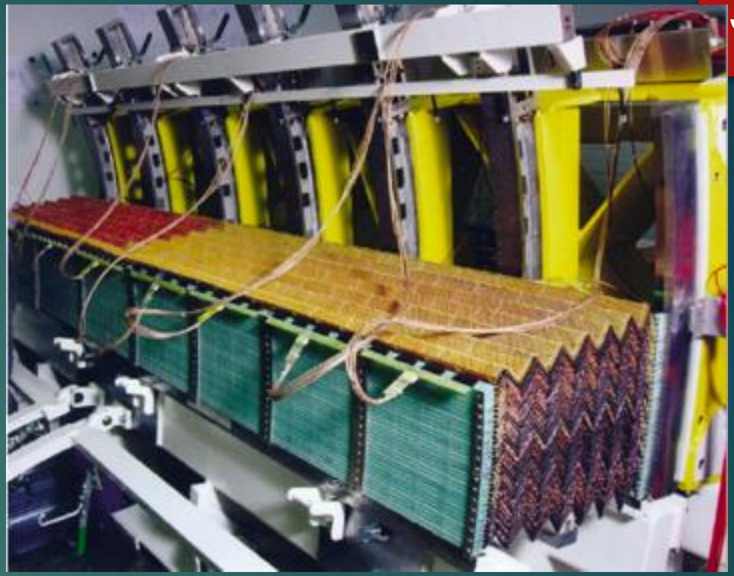
Old concepts revisited

Technologies proposed for FCC calorimeters

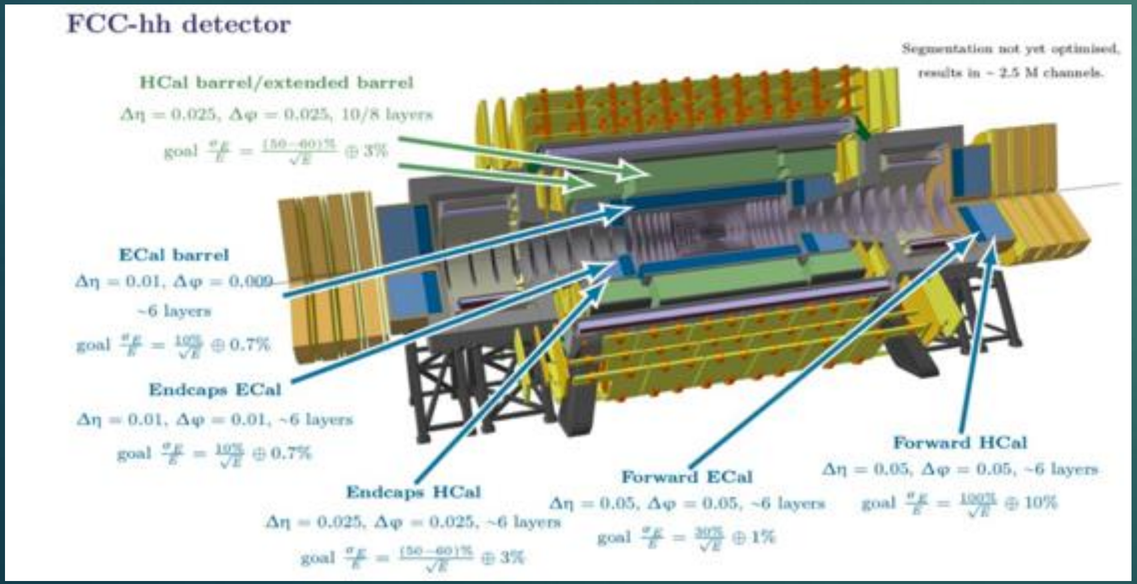
Nobel liquid gas calorimeter

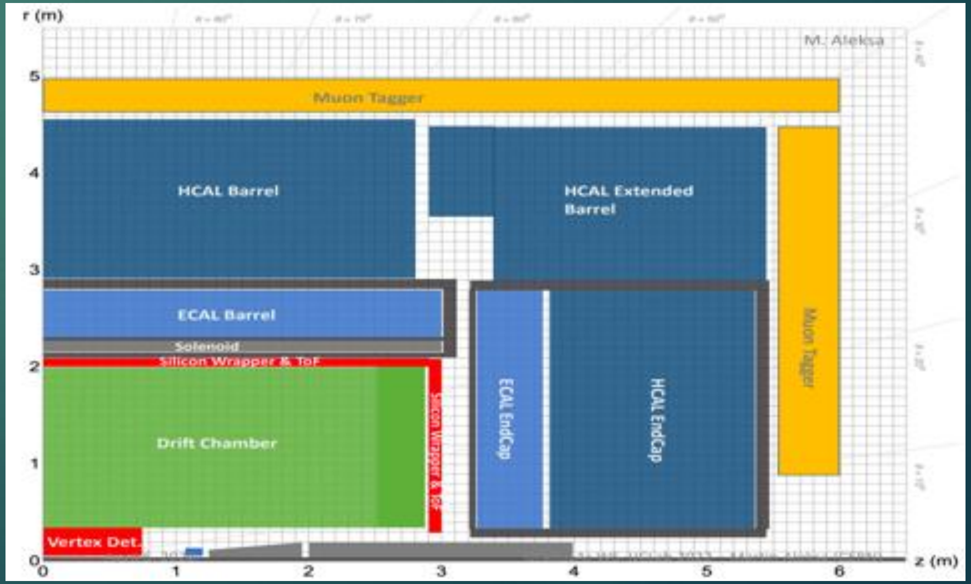
Long history (HERA, D0, NA31, NA48, ATLAS)
Excellent performances

$10\%/\sqrt{E} \oplus 0.2/E \oplus 0.7\%$ in ATLAS



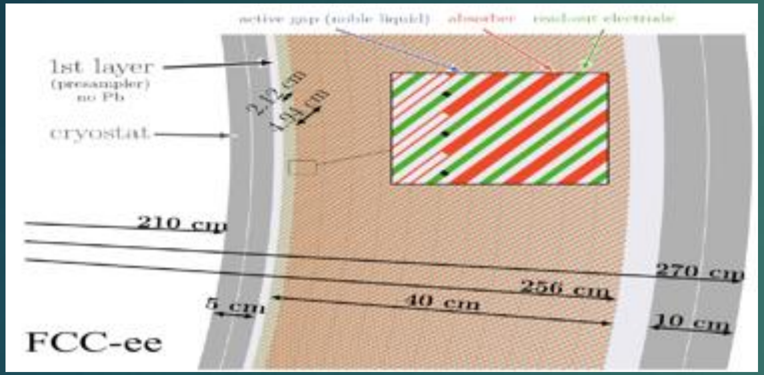
It was first proposed for FCChh for its radiation hardness and then adapted to FCCee with the aim to achieve also high granularity for PFA application
Absorber Pb or W, Liquid: LAr of LKr



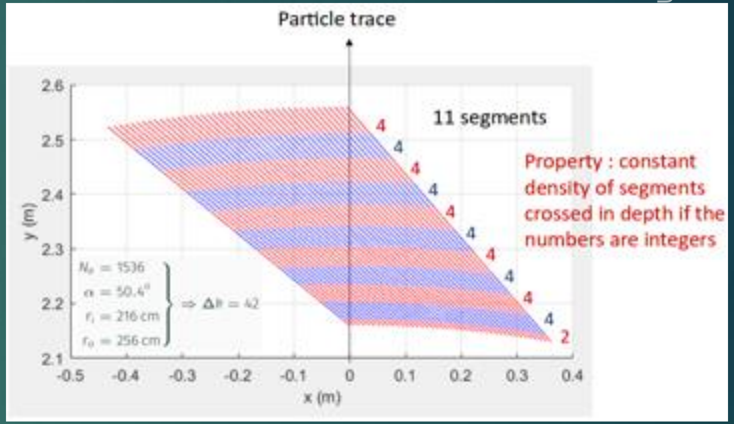


Nobel liquid gas calorimeter

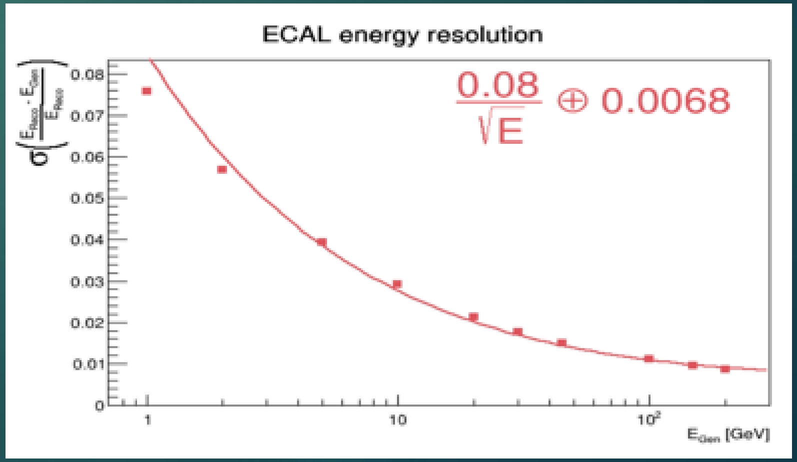
A priori the same concept used for ATLAS but more granular (10 times) → Kapton/copper electrodes with accordion shape need to be replaced by multilayer PCB for signal transfer and old "hot" electronics to be replaced by **COLD electronics** in the FCCee



Tilted planes geometry is being optimized in order to have even distributed granularity in θ, ϕ.



- 12 layers, 22 X0
- 2x1.2 mm LAr, 2mm Pb/Steel, 1.2mm PCB, inclined by 50^0
- Typical cell size: 2x2x3 cm^3

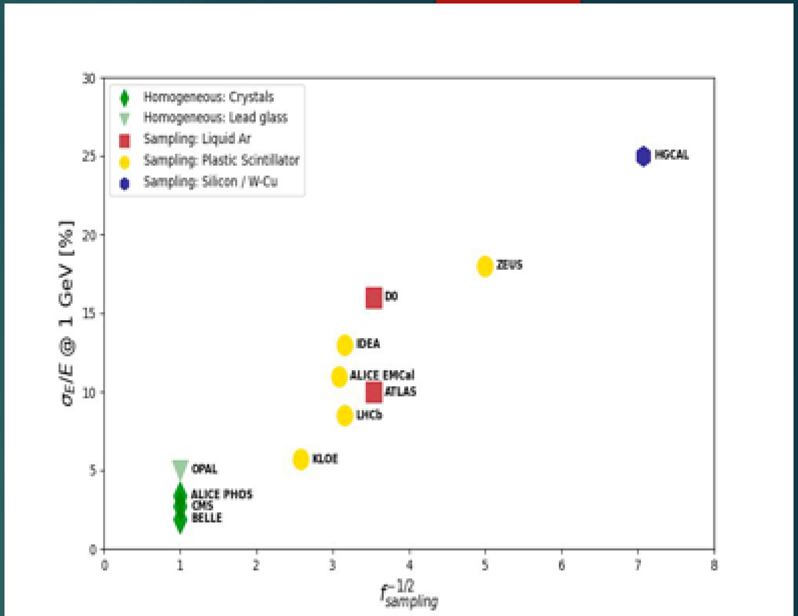


Timing is being studied.
Doping to increase signal yield is a possibility

Optical & Scintillation calorimeters

Optical calorimeters can be sampling or homogeneous calorimeters
The latter provide the best results for electromagnetic measurements
❖ 1-3%/√(E) for photons

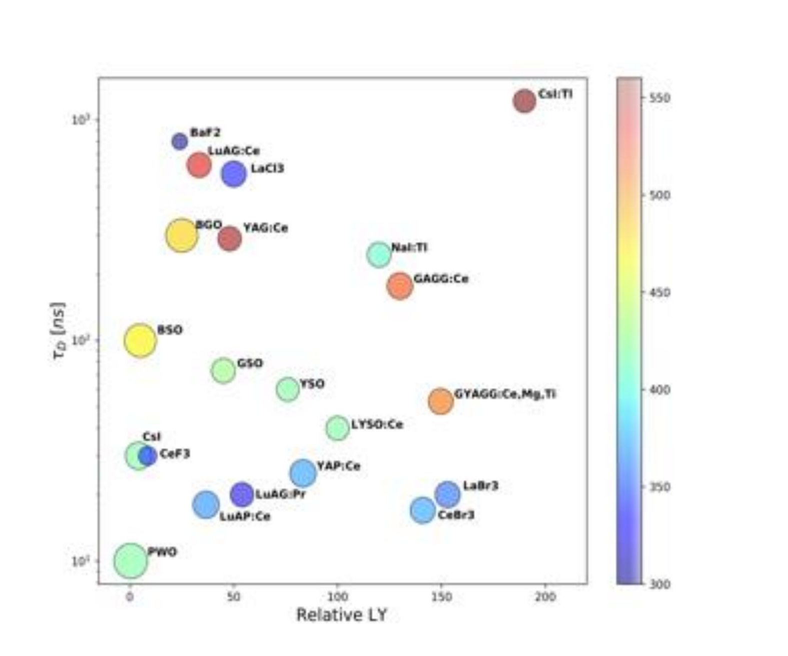
New features like time resolution and radiation hardness
with high light yield are actively looked for



Fast and Ultrafast Inorganic Scintillators

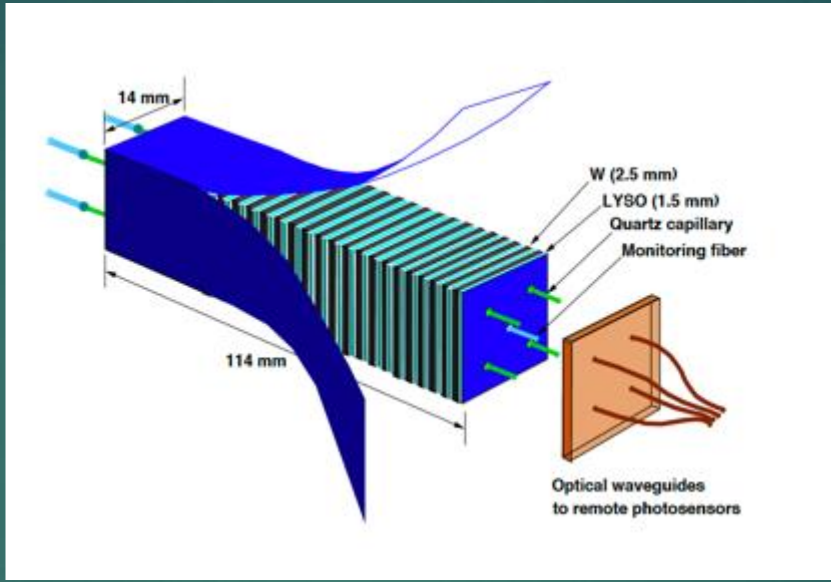
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 <0.6	600 <0.6	<1	1.5	4	148 6	40	820 50	191 25	800 80	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

December 8, 2019 Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI

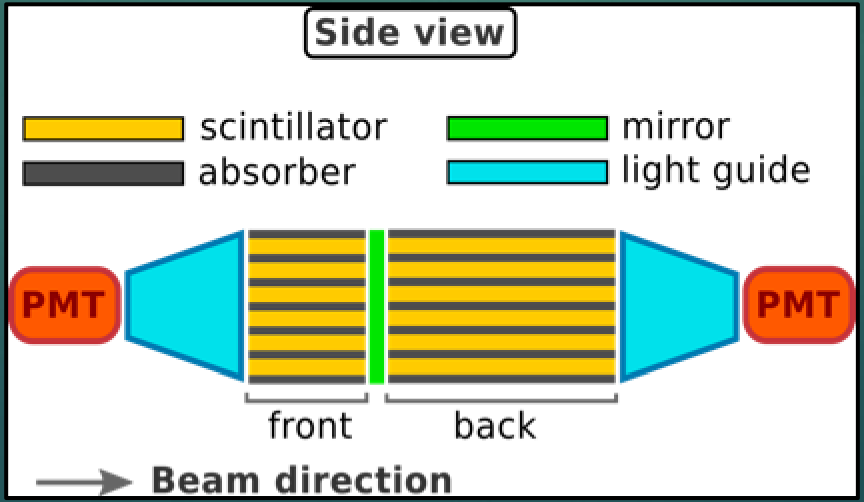


There are traditionally two kinds of structure adapted for sampling optical/scintillation calorimeters

1) Shashlik

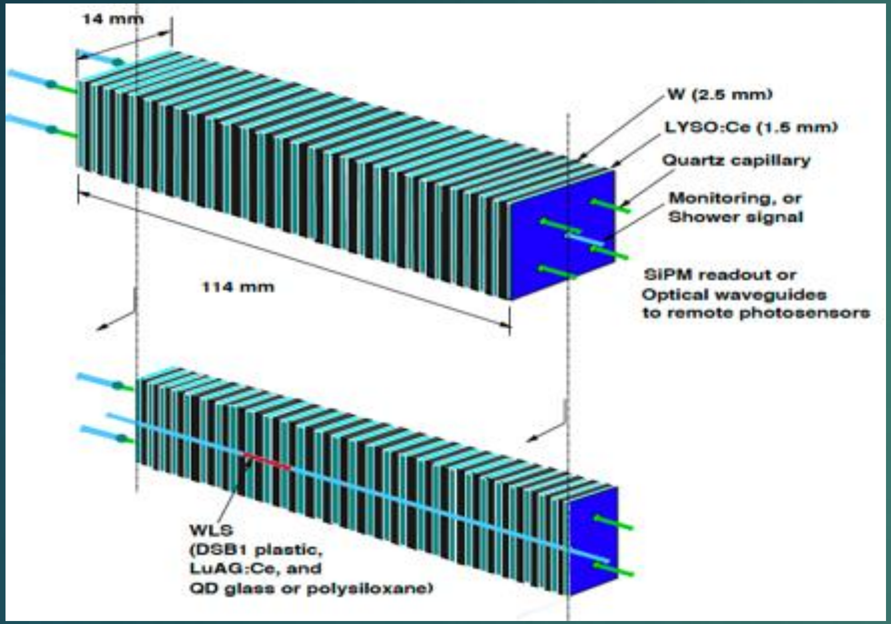


1) SPACAL



Technologies proposed for FCC calorimeters

RADiCAL concept is also a compact shashlik-like concept aiming at excellent energy resolution and excellent timing in harsh conditions (FCChh)

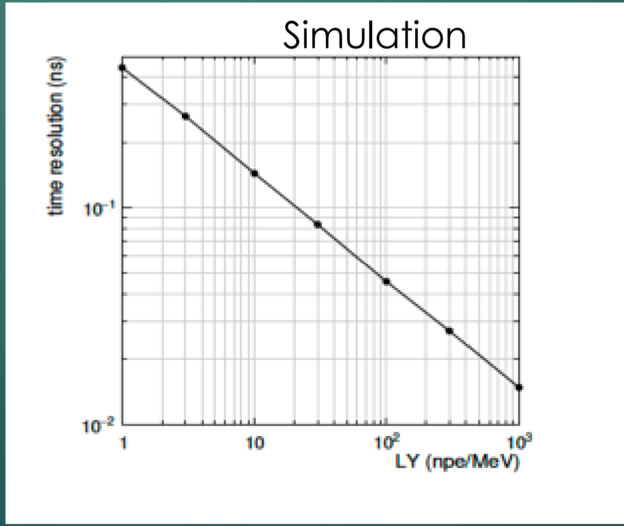


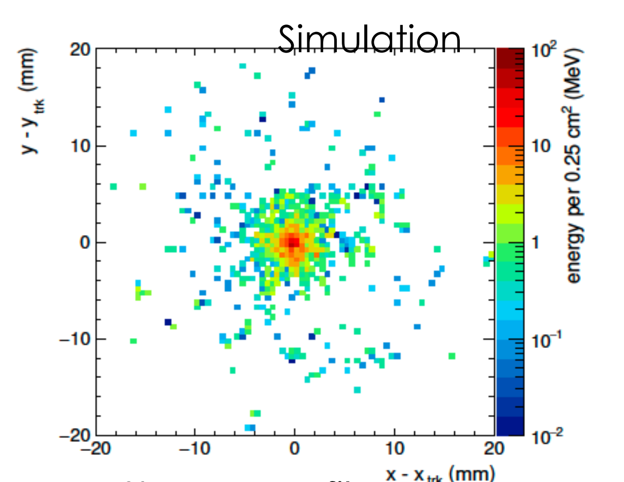
Time information is one of the main features

1. Positioning of WLS filaments at Shower Max for timing studies.

2. Incorporation of dual readout for both scintillation and Cerenkov measurement

GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV

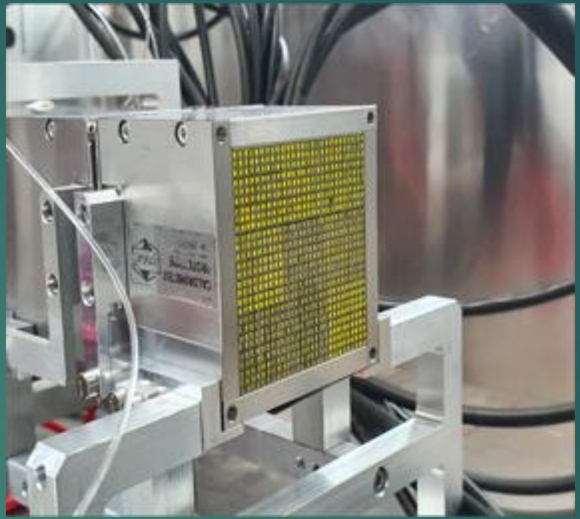


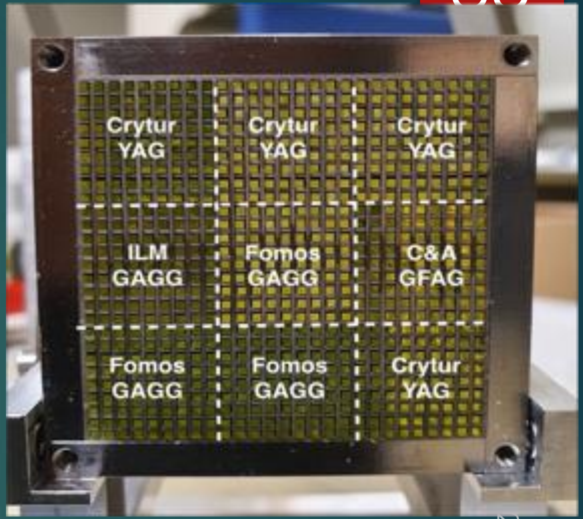


Shower profile at Max.

SPACAL-W proposed for LHCB upgrade but also for future colliders

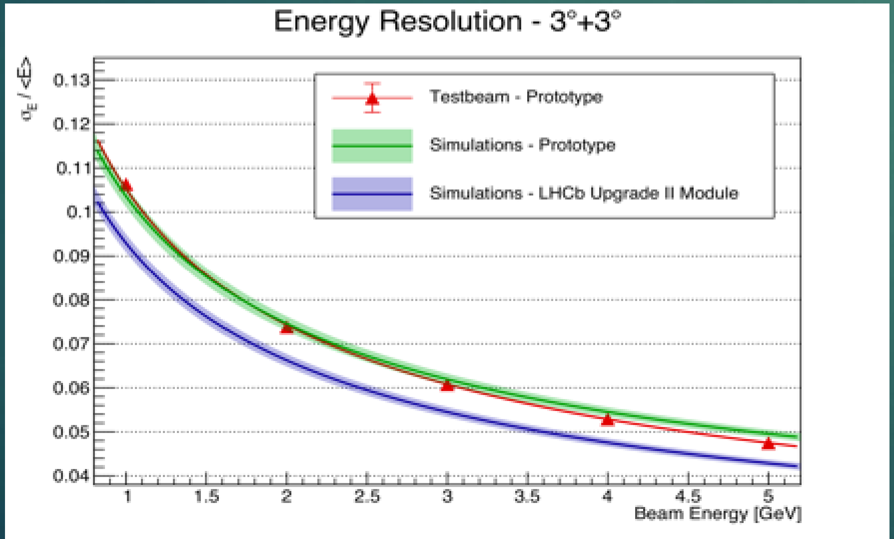
Garnet crystal fibers in a W structure

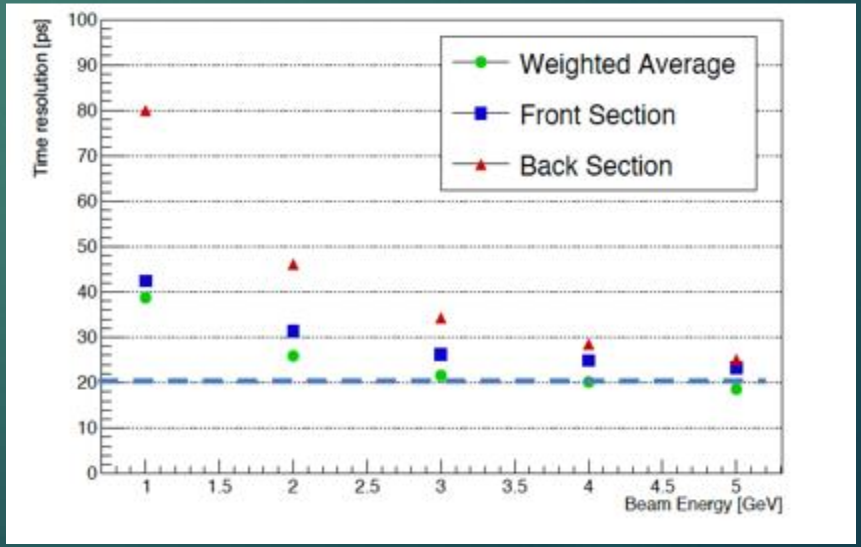




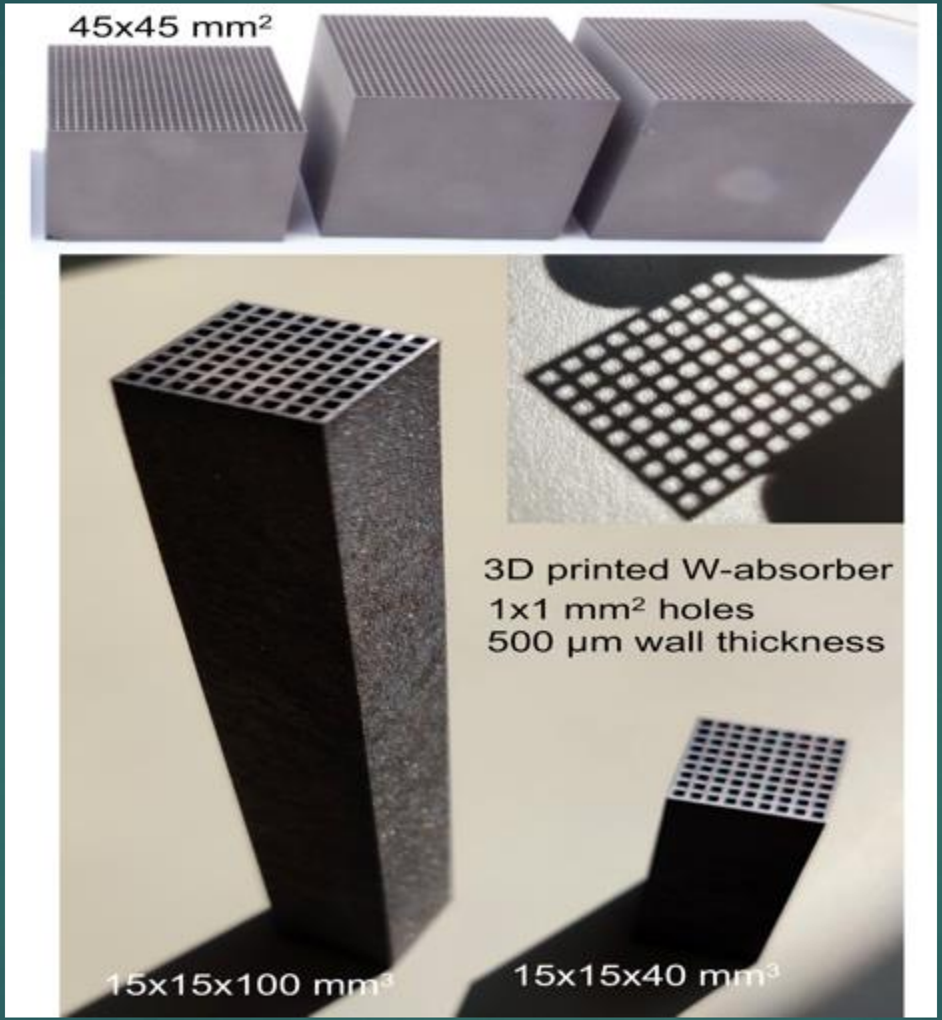
Different kinds of garnets are being studied
- YAG
- GAGG
- GFAG

Different kinds of photodetectors
- PMT (through light guide)→ Energy Resolution
- MCD (direct contact)→ Time measurement



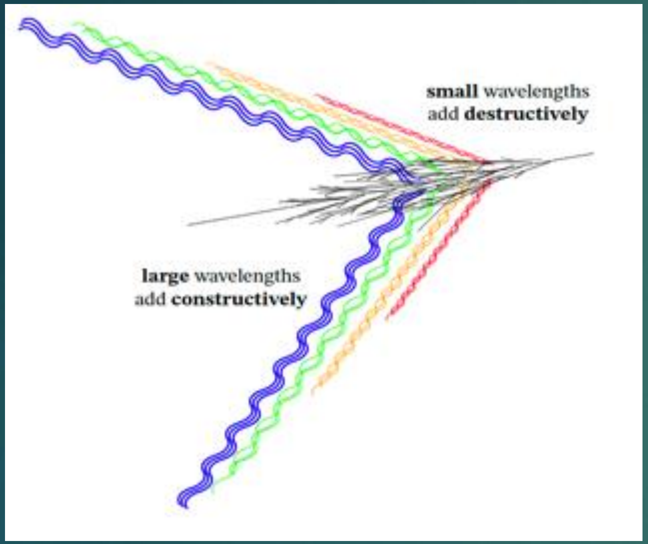


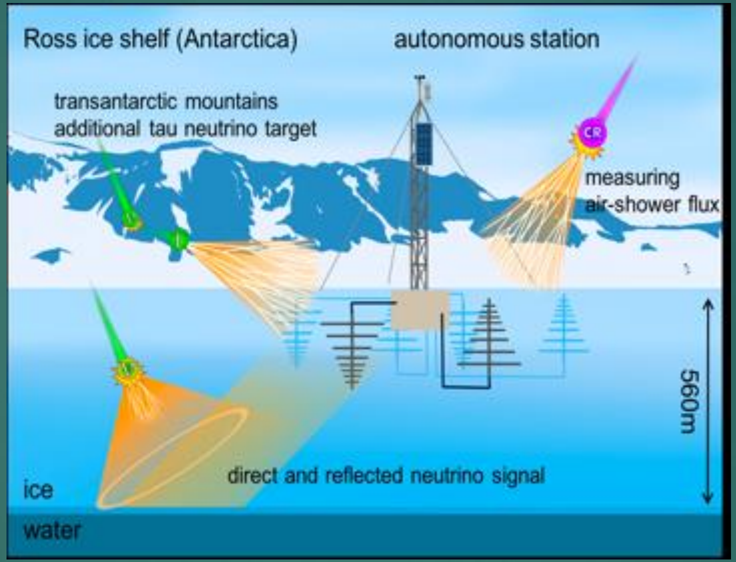
3D printing technique to be used to build the absorber

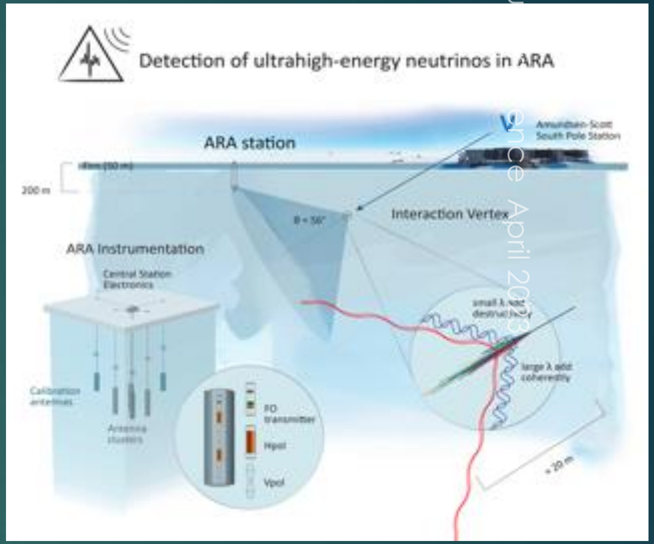


Askaryan Calorimeter

In dense media about 10-20% of the electromagnetic shower is formed of negative particles that are concentrated in the front of the shower. They produce a coherent microwave Cherenkov. This emission provides an excellent estimator of the energy and the time of the shower



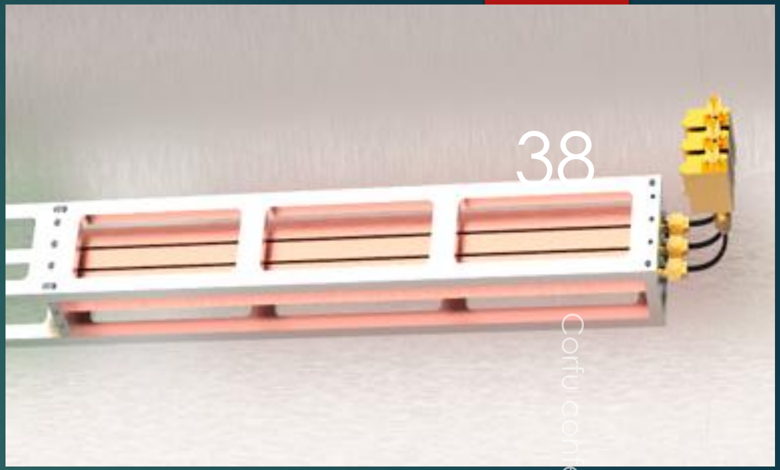


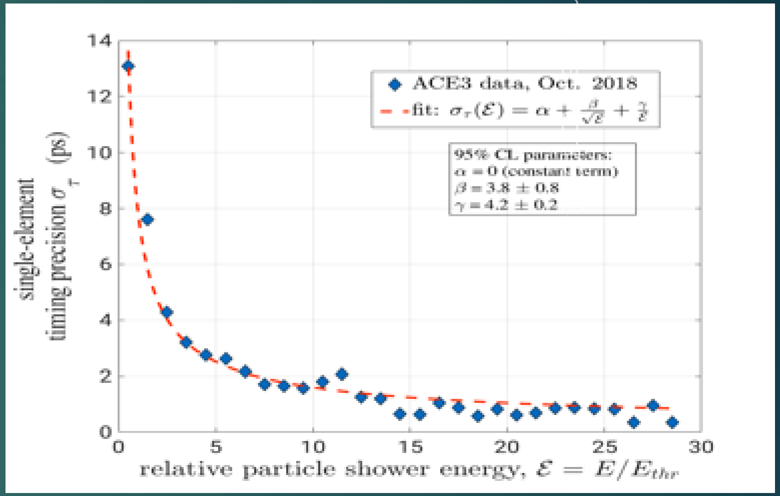


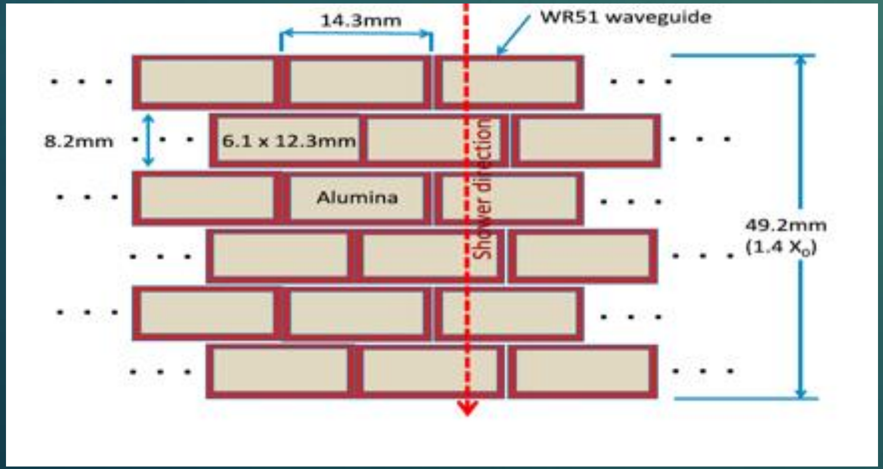
This phenomenon, already used in neutrino astrophysics detection, could be used in HEP calorimeters since the Cherenkov emission can provide a very precise time measurement

A small prototype was built:

- Standard WR51 (12.6mm x 6.3mm) copper waveguides loaded with alumina bars (Al_2O_3) are used.
- Askaryan (microwave Cherenkov) from a shower moving through the waveguide is coupled into the TE10 mode (5-8 GHz) and propagates to each end.
- The ns-scale pulse is amplified with low-noise amplifiers (LNAs) and sampled with high-bandwidth digitizers.
- The measured waveform is a direct measurement of the shower energy via the coupled Askaryan emission and provides a precise time of arrival!







$$\sigma_t \sim 1.8\ \mathrm{ps} \left(\frac{E_{\mathrm{thr}}}{E}\right)$$

$$\frac{\sigma_E}{E} \sim 10\% \left(\frac{E_{\mathrm{thr}}}{E}\right)$$

$$E_{\mathrm{thr}} \sim 20\ \mathrm{GeV}$$

Summary

- Calorimeters are an essential piece for the experiments of future collider experiments
- PFA-based calorimeters for linear colliders are mature. They need to be adapted for circular colliders namely for the high rate capabilities
- Dual Readout-based calorimeters are entering maturation period through large prototypes. They intend to significantly improve on the hadronic energy measurements
- Optical/scintillation-based calorimeters are adopting PFA and DR to provide excellent perfomances

Timing in future calorimeters

- PiD
- Pileup mitigation
- Shower separation
- Energy measurement improvement

Particle Identification

PiD is important for many topics

Heavy Flavor &Higgs (B and D reconstruction), CP measurement (Jet Charge)..

To identify particles, the usual tool is : dE/dX from detectors like TPC

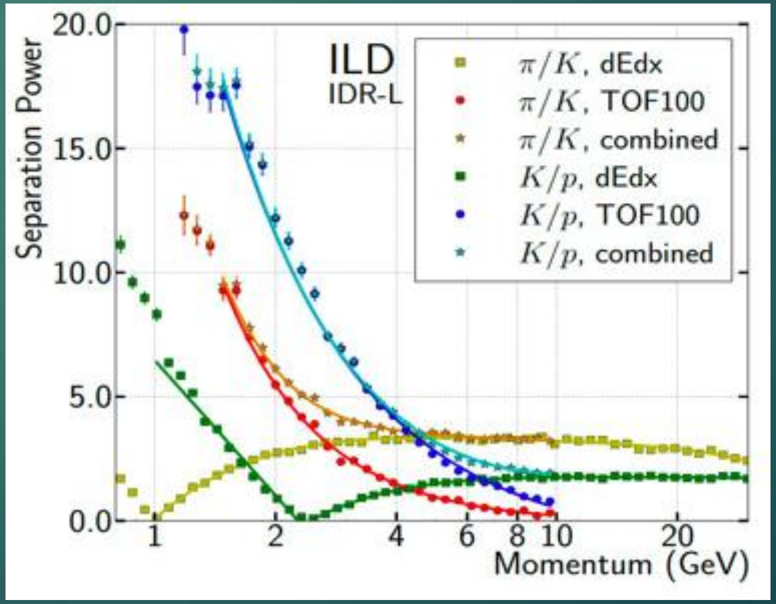
$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

ToF is another important tool.

Dedicated ToF detectors (MRPC/Alice, MTD/CMS, HGTD/ATLAS) bring precious information for charged particles but not for all neutral particles

Calorimeters equipped with high-precision time detectors could help for both. However:

- Limited momentum range < 10 GeV/c
- Limited number of detectors able to provide excellent time precision



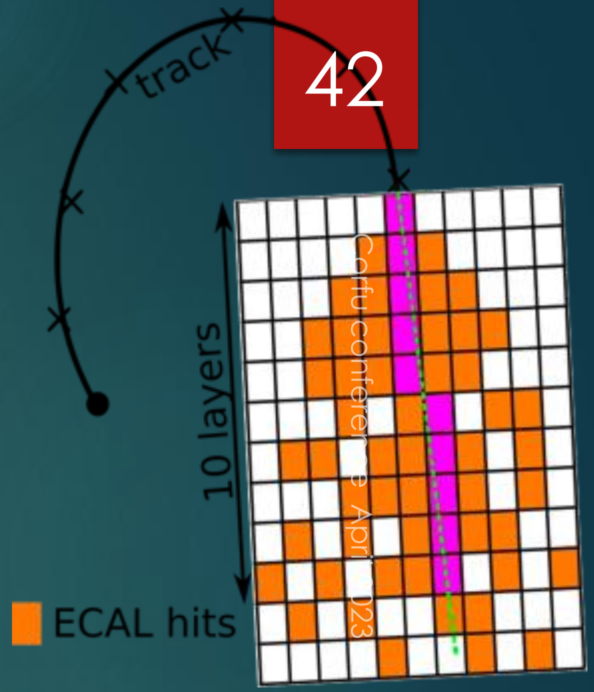
Particle Identification

In case of charged particles :

$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

P is taken from the tracker at the ECAL entrance and β from ToF
To estimate the ToF in a granular calorimeter like the ILD ECAL in the case of charged particles several methods can be used:

- Using time of the closest hit to the track
- Using time of the fastest hit
- Using the average time of hits along the track extrapolation in a few layers in case of longitudinally segmented ECAL (ToF_{Avg})
- Using the time information of the hits of the first layers to determine the time at entrance of the ECAL (ToF_{Fit})



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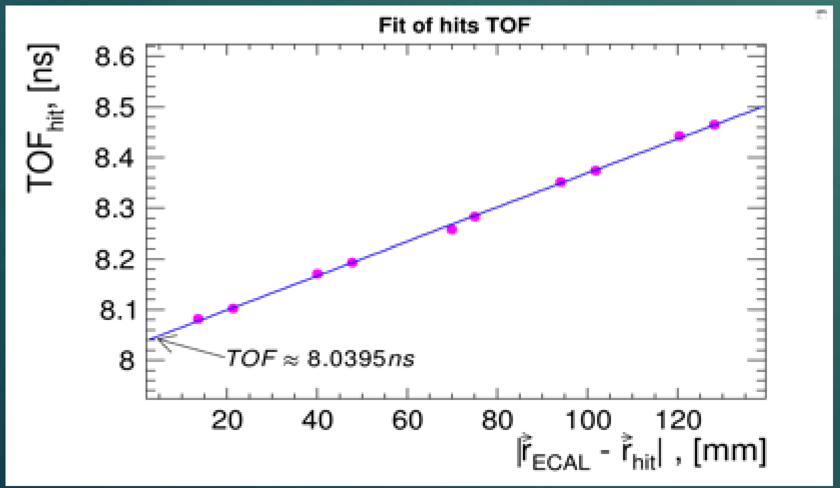
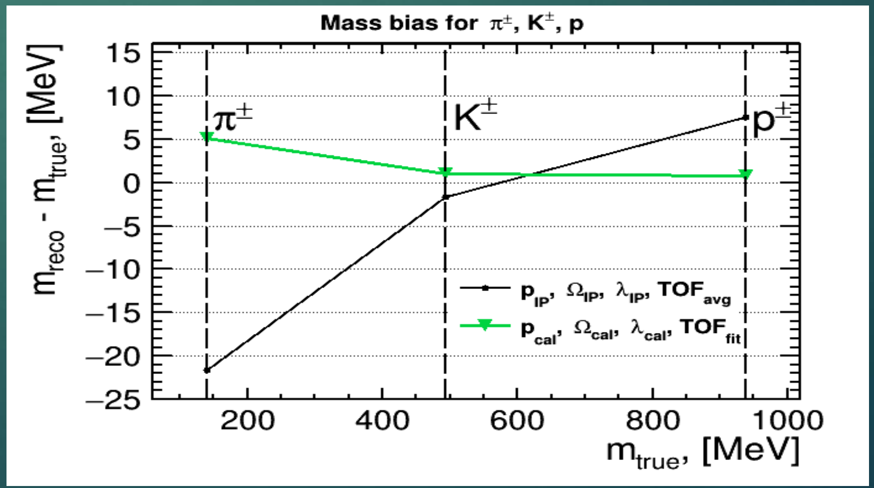




Particle Identification

Another approach that can be applied in very high granular calorimeters is to estimate β of track segments within a shower as well as the energy loss to identify the nature of the particle and then its momentum.

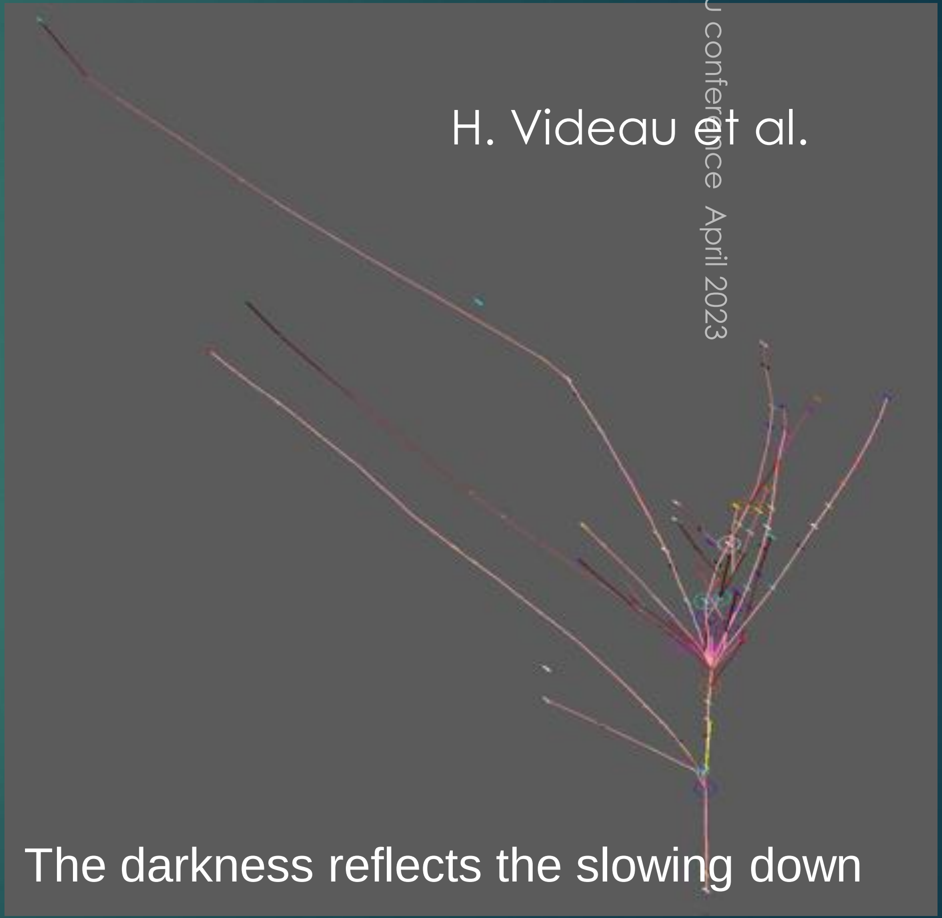
β could be known up to 10% according to a simulation study on hadronic showers in ILD SiW ECAL

To achieve this, a time resolution better than the Calorimeter longitudinal segmentation is needed.

In case of

ILD ECAL (6.5 mm → 20 ps) hard to achieve for the moment
ILD HCAL (30 mm → 100 ps) rather possible

The measurement of β and energy loss of the different particles within a shower as well as the shape could be exploited to determine the nature of the incoming particles



The darkness reflects the slowing down

Particle Identification

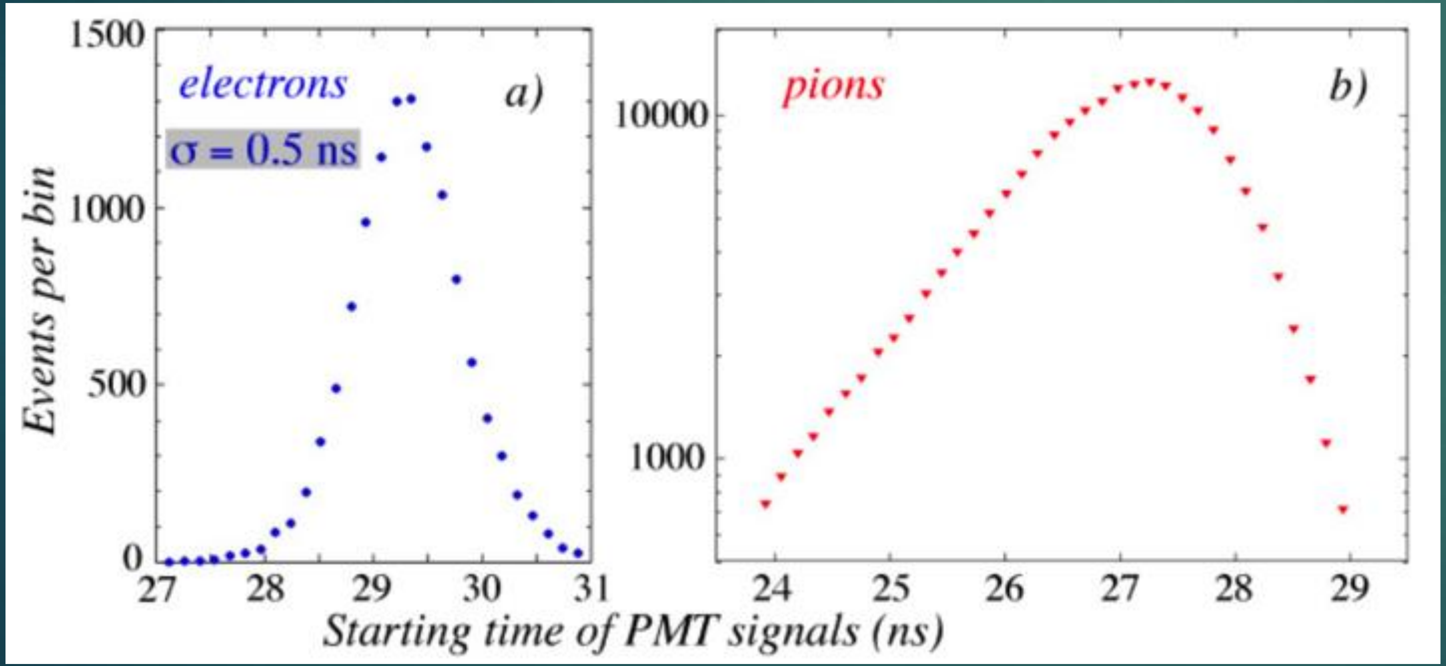
$$S = \left[f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em}) \right] E$$

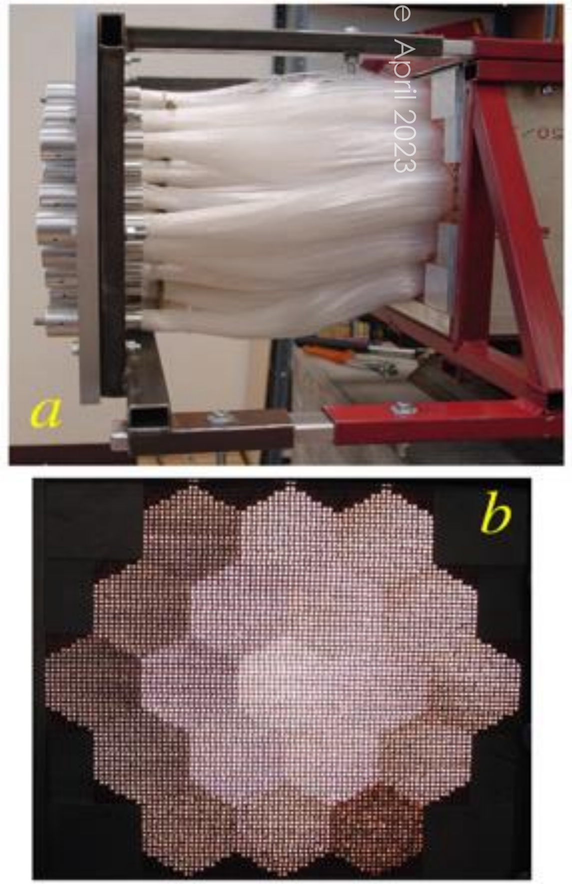
$$C = \left[f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em}) \right] E$$

$$E = \frac{S - \chi C}{1 - \chi}$$

Time information is also very useful in other technologies than the one based on high granularity.

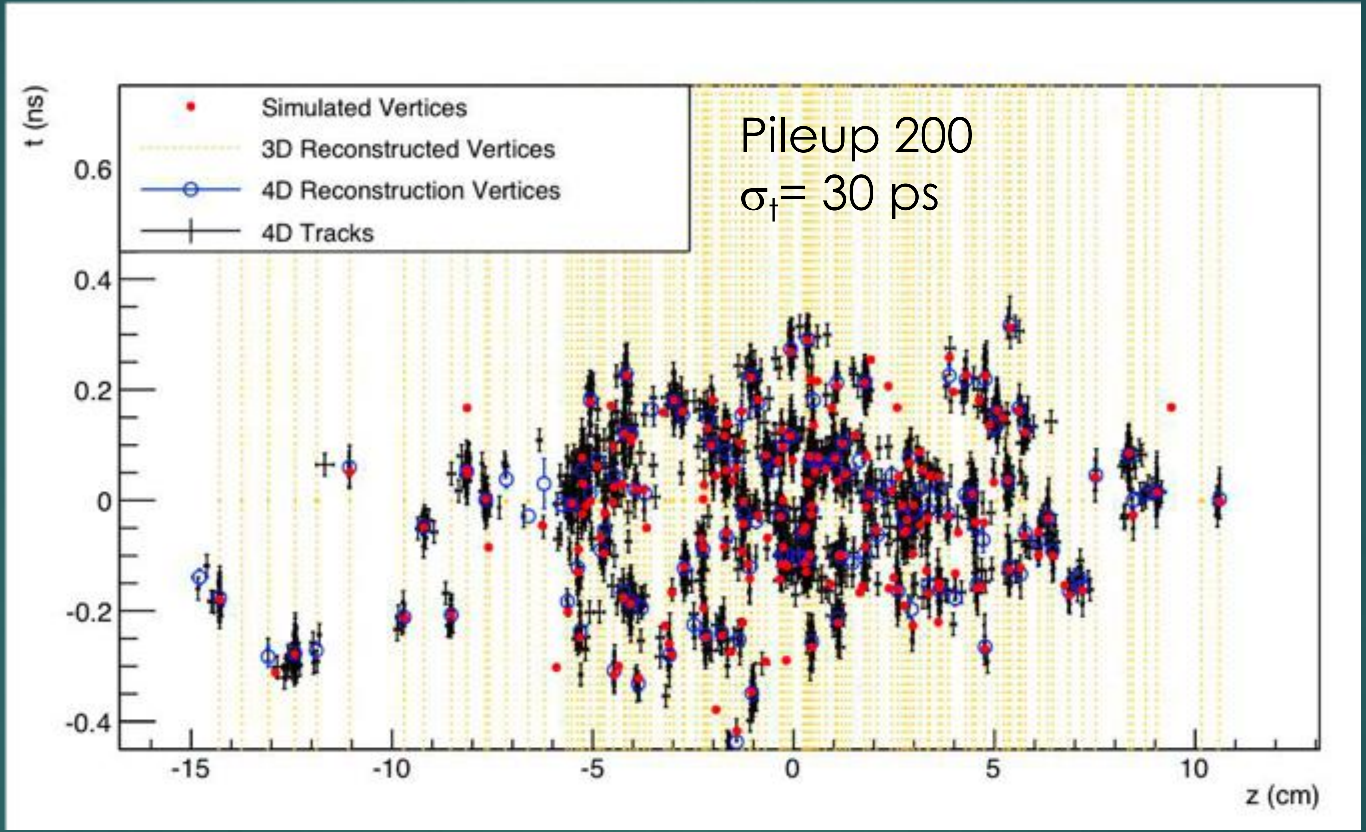
In Dual Readout technologies one can use precise time information to discriminate electrons against pions since the showers associated to those particles start on average in different depths of the calorimeter. This with the shape information are efficient tools for PiD.





S. Lee, M. Livan, R. Wigmans, , Rev. Mod. Phys. 90 (2018) 025002

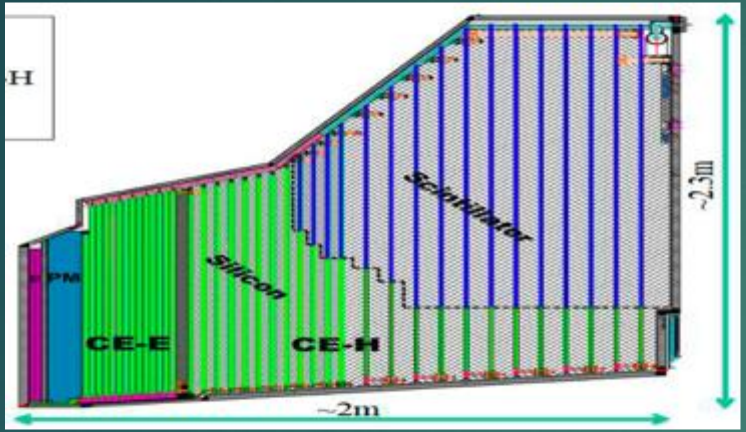
Pile Up Mitigation

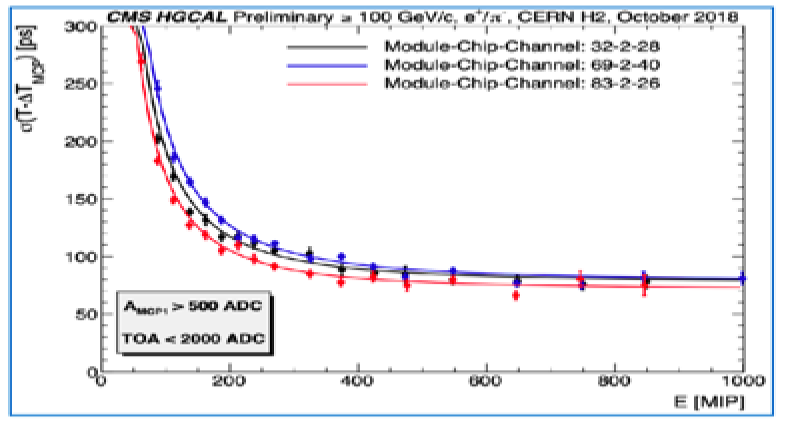


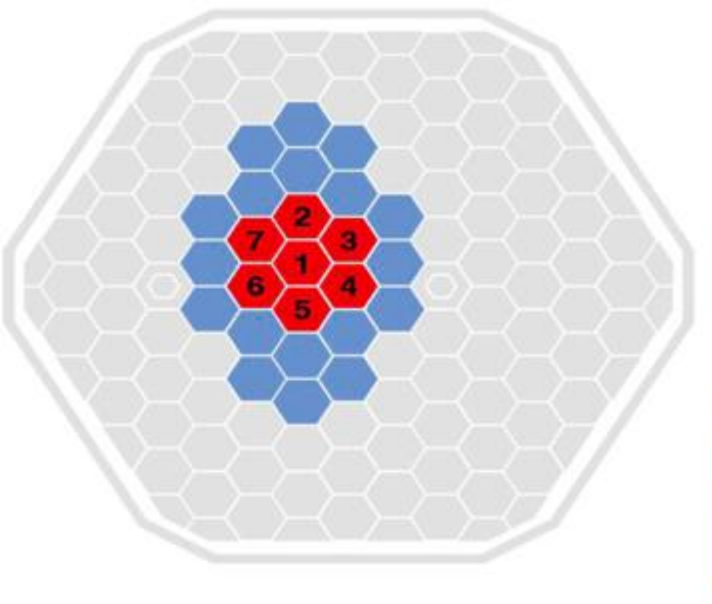
A precise time measurement is a key tool in mitigating pileup

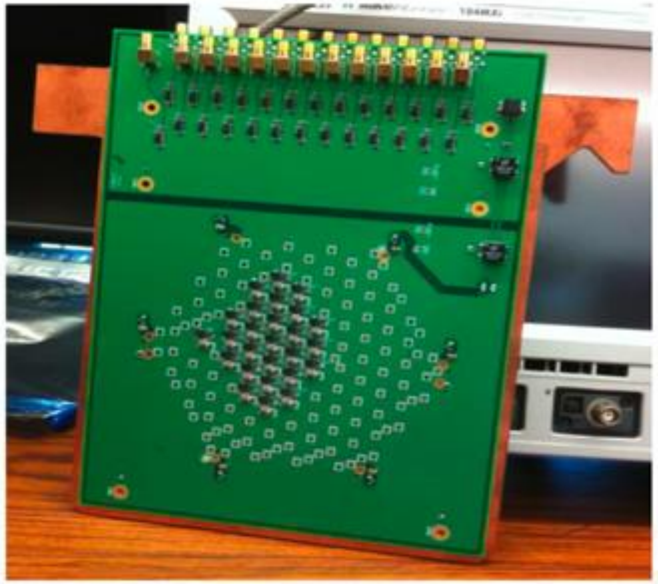
Pile Up Mitigation

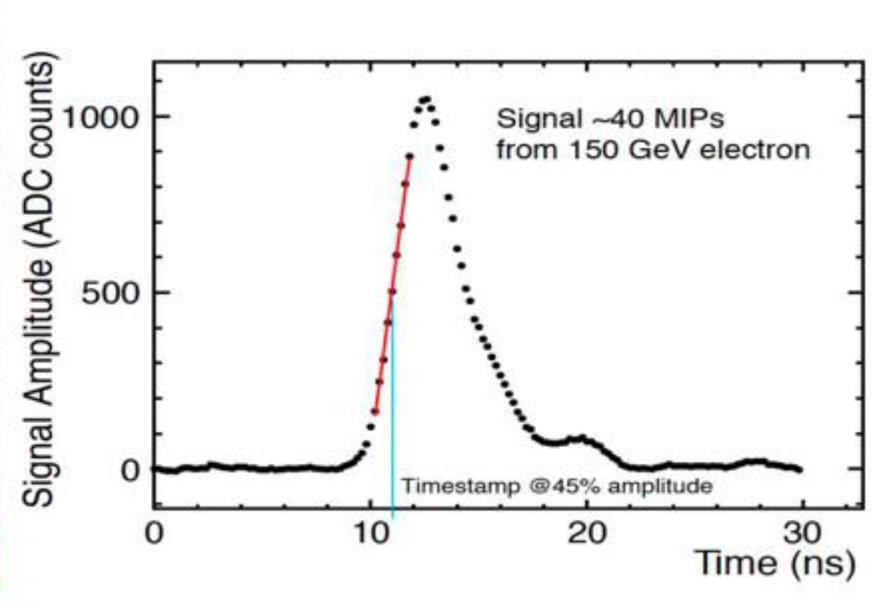
CMS HGCAL will be the first large calorimeter to provide precise time information useful for pileup mitigation. This is possible thanks to the use of Silicon sensors.











Courtesy: D. Barney and T. Quast

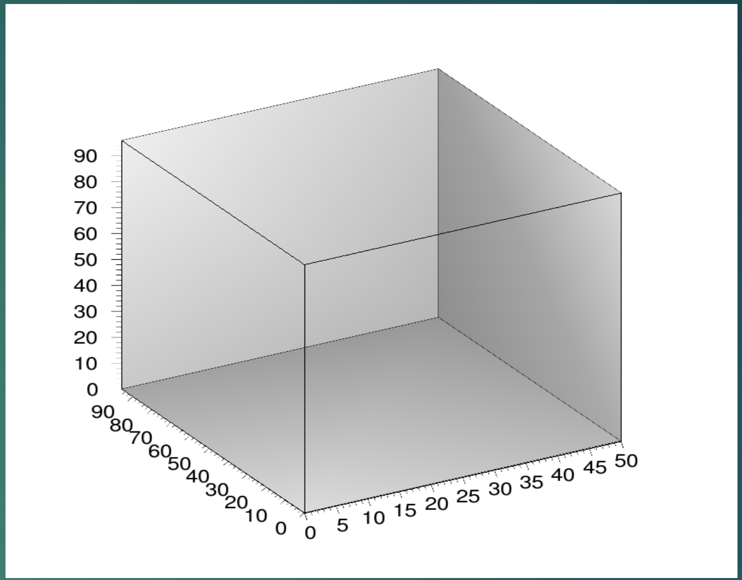
Cleaning and shower separation

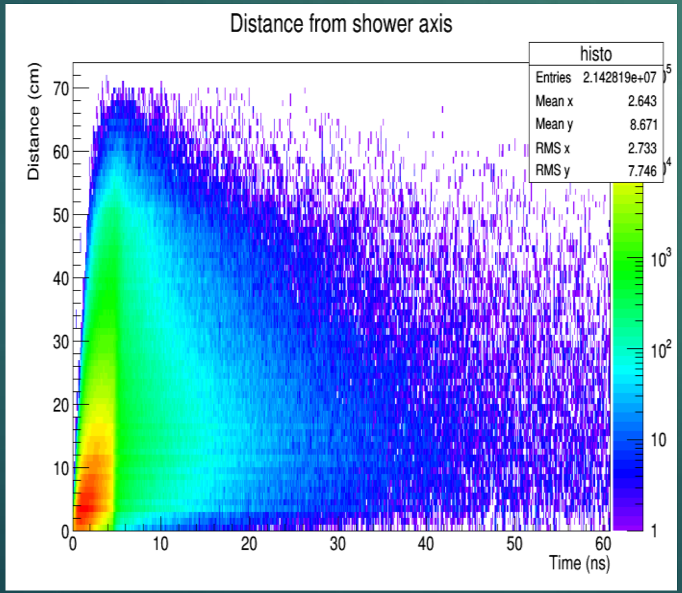
Hadronic showers feature many neutrons and many of them are delayed ones and can :

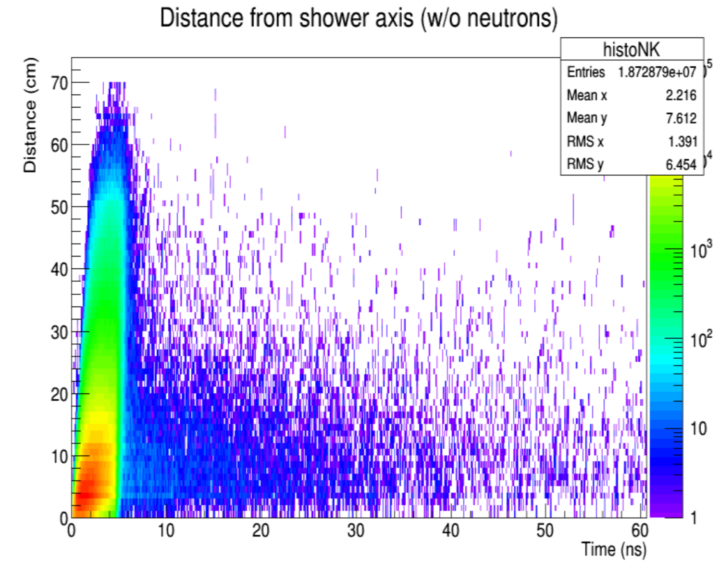
1- fake the energy measurement (fluctuations)

2- complicate nearby showers separation when PFA is used

Timing can then tag the hits produced by the neutrons.



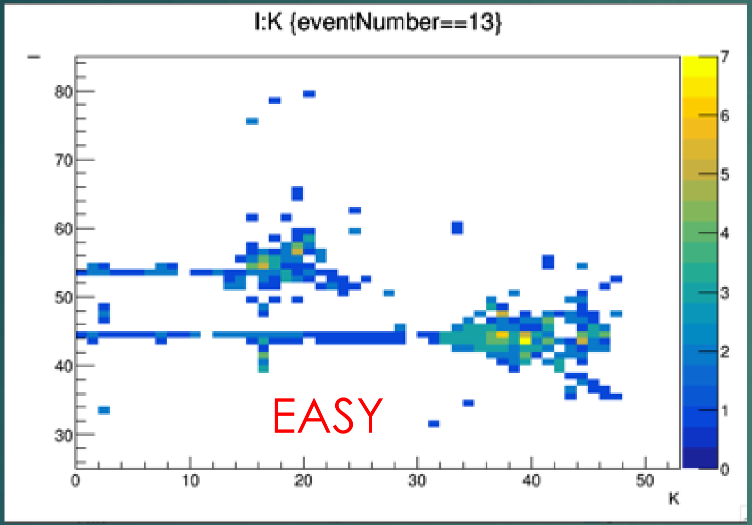


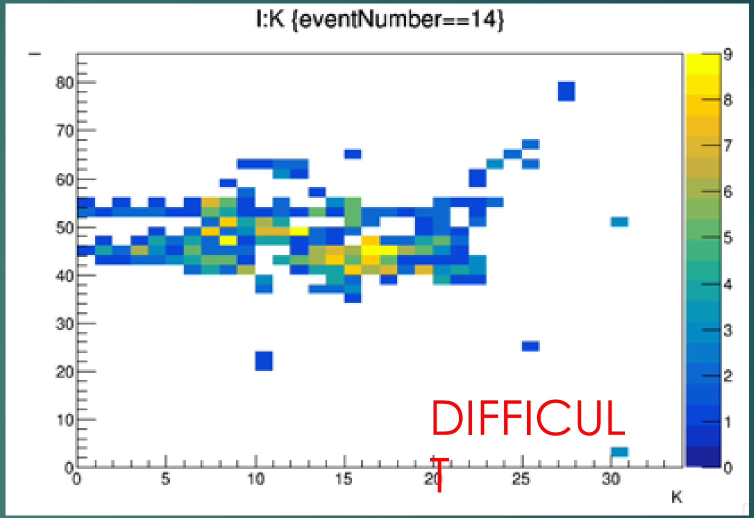


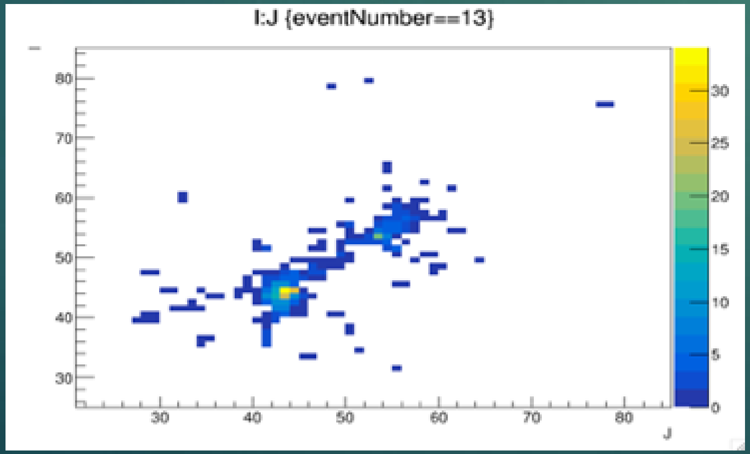
SDHCAL simulation

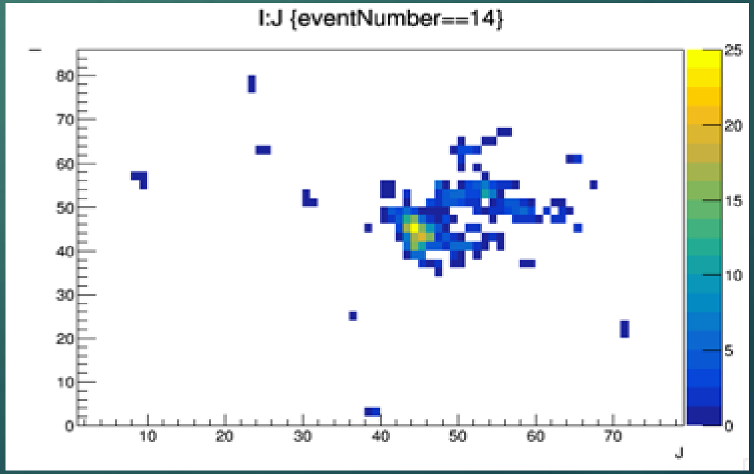
Cleaning and shower separation

Time information can also help to separate close by showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by appox. 15 cm.





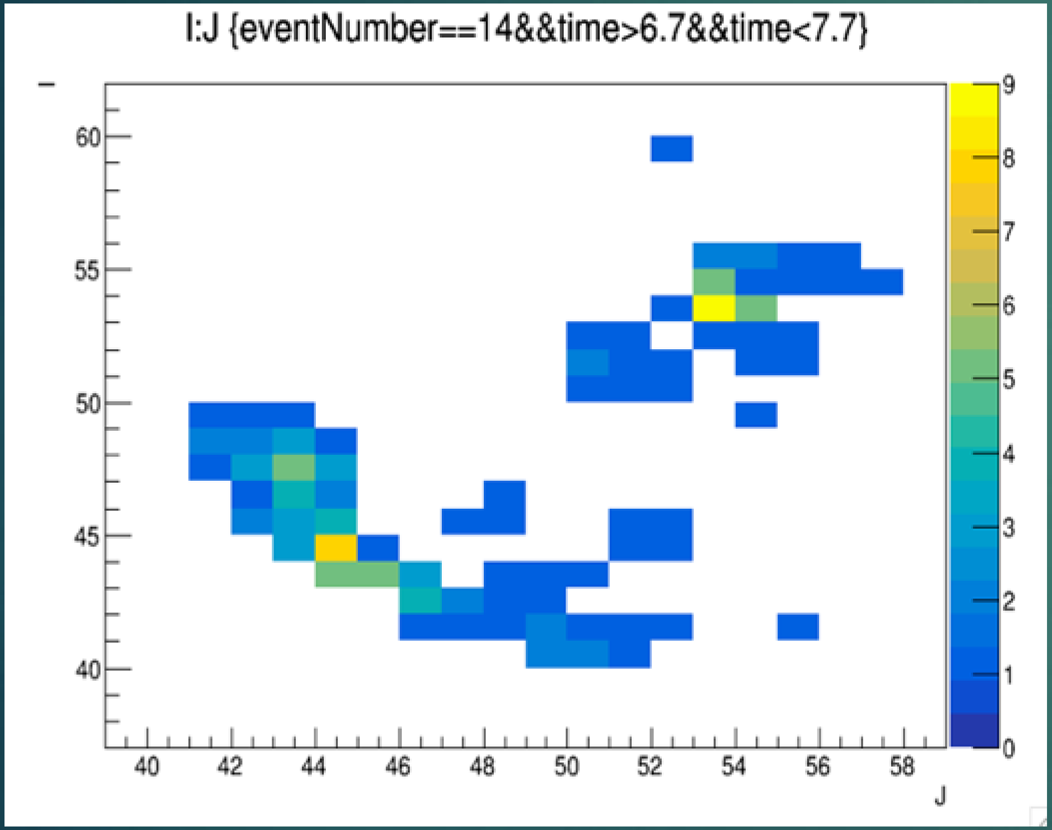


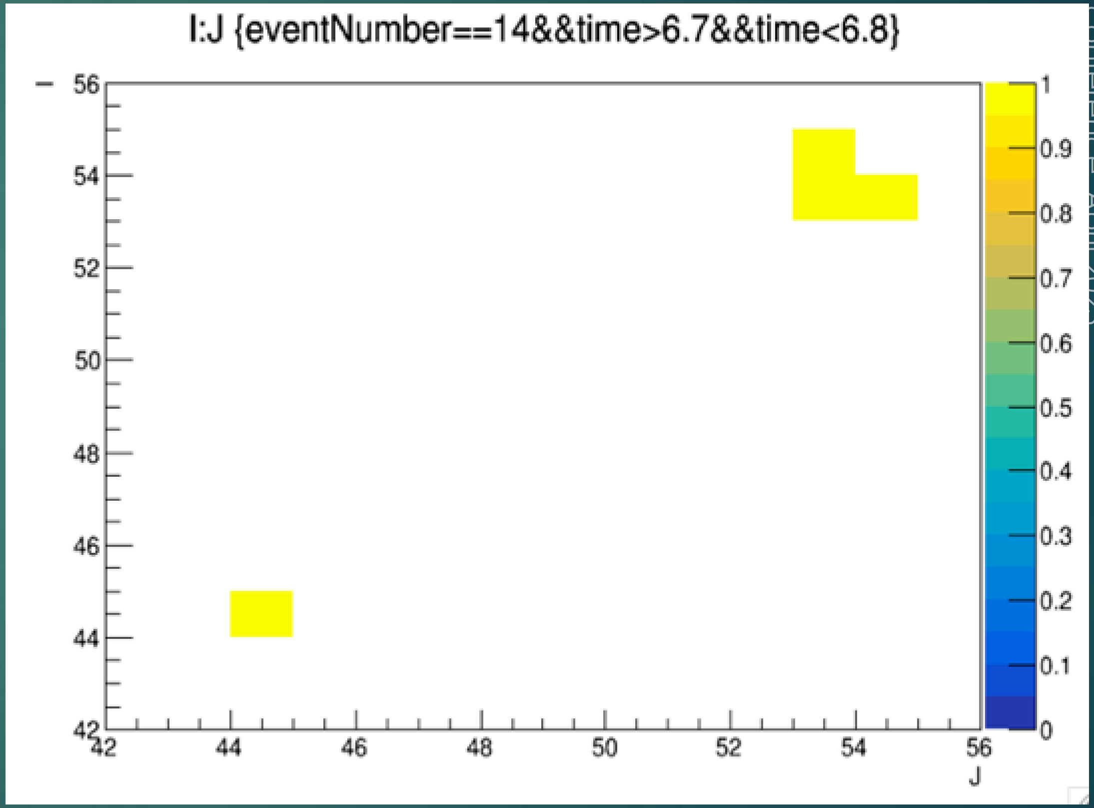


SDHCAL simulation

Cleaning and shower separation

Having precise time measurement allows to know how many showers and then the construction of shower by basing the algorithms of construction on the found "skeletons"



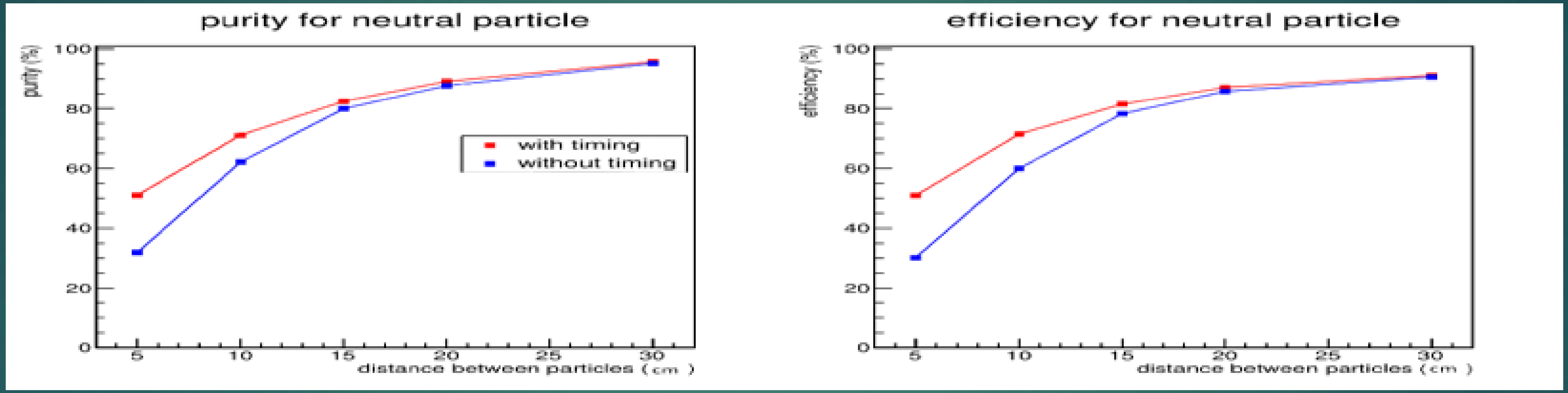


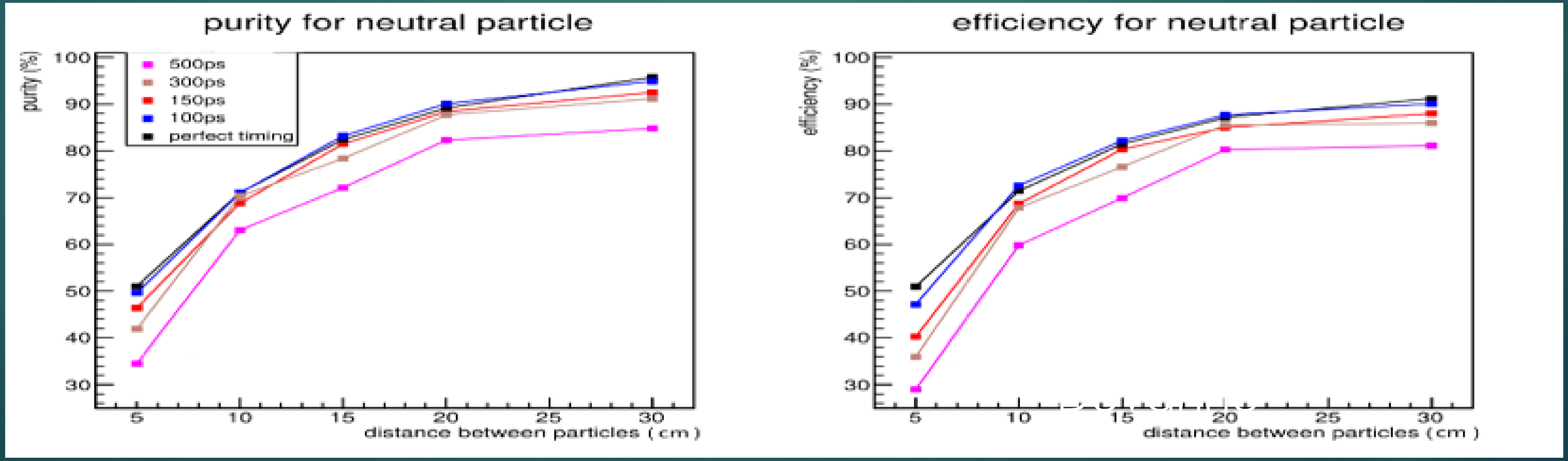
Shower projection on transversal plan

SDHCAL simulation

First step towards transforming SDHCAL into T-SDHCAL

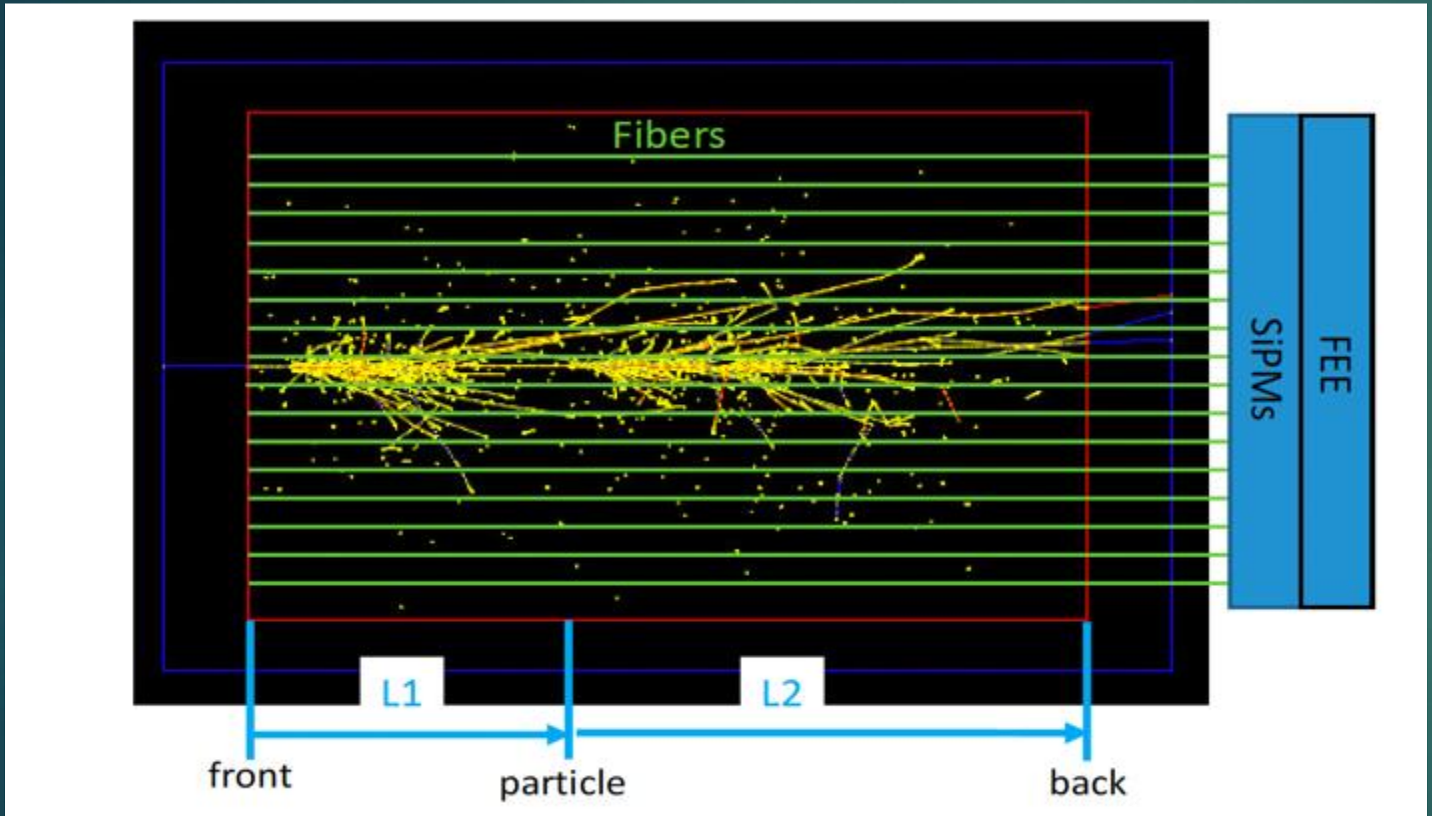
Including time information in the simulation to separate hadronic showers (10 GeV neutral particle from 30 GeV charged particle) using techniques similar to ARBOR's ones.

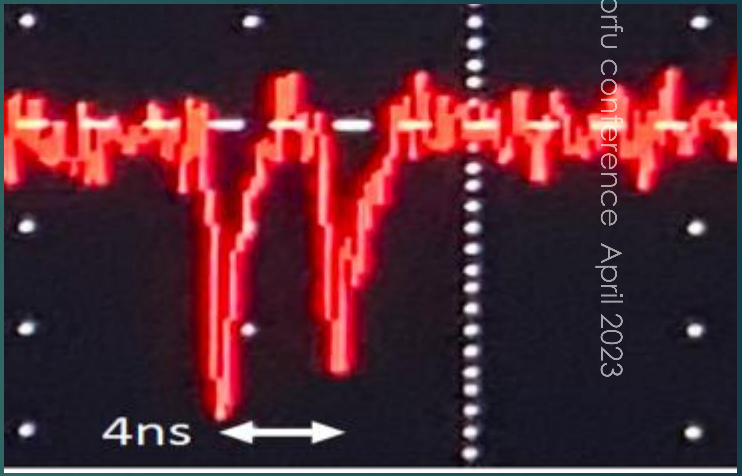


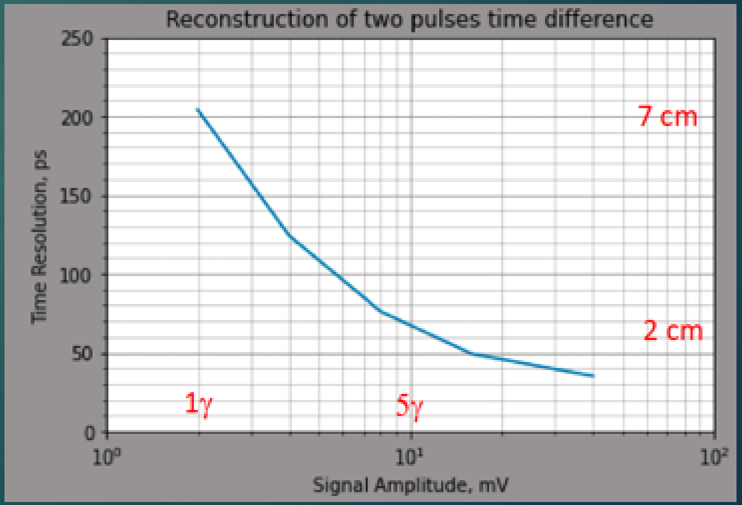


Longitudinal Granularity

With good time resolution, longitudinal segmentation could be replaced by the signal time arrival measurement and then Neural Network techniques can be used to extract position information based on the signal shape collected by fibers and read out by Photodetectors+Fast timing electronics





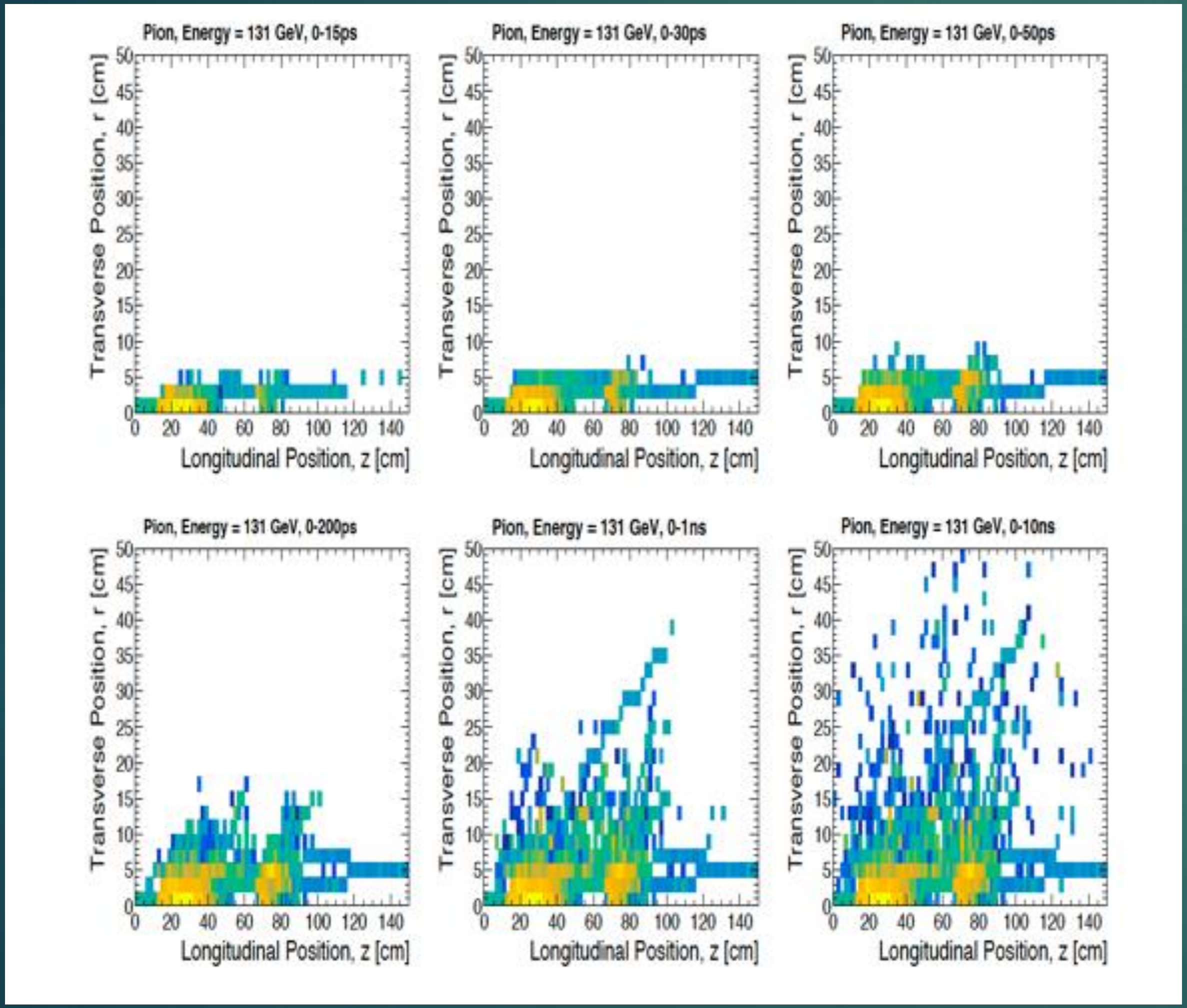


Signal Time = L1/c + L2/kc,
c = velocity of particle
kc = velocity of light in fiber (k~0.6)

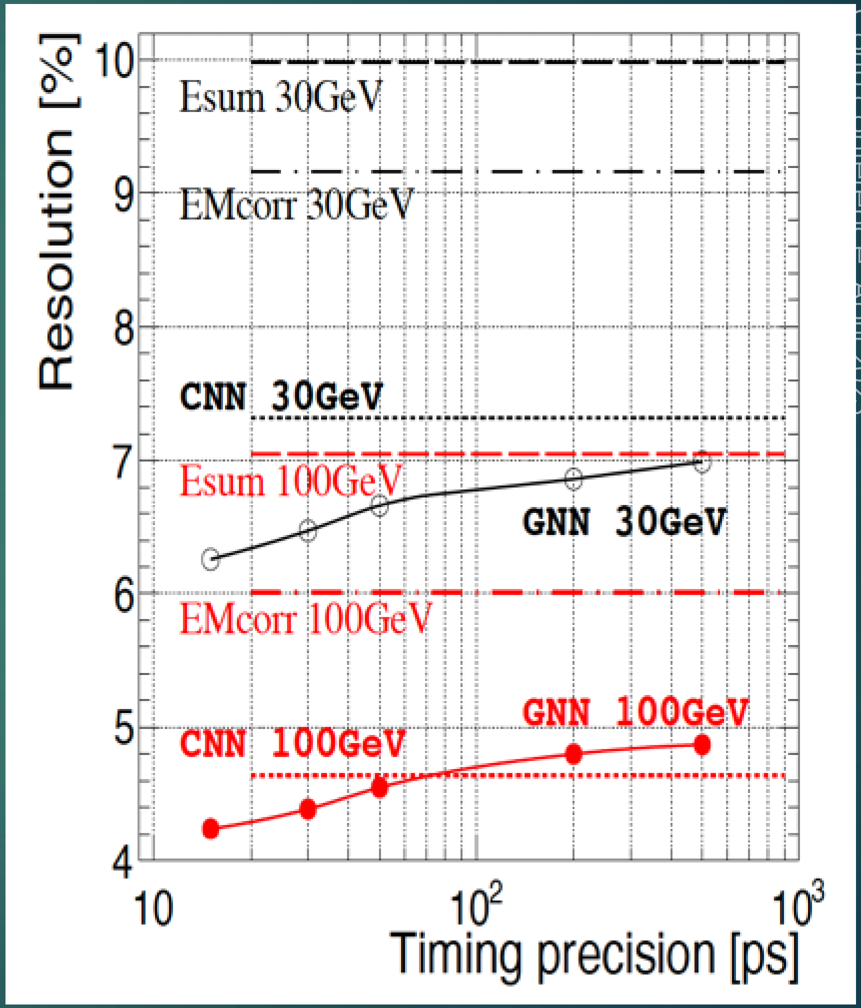
Courtesy S. Kunori

Energy Measurement

Simulation of electrons and hadrons in 3D calorimeter made of Uranium as absorber and 3 mm Silicon as active medium and



Using GNN with time information improves energy reconstruction



Esum: standardd

EMcorr

DR-based

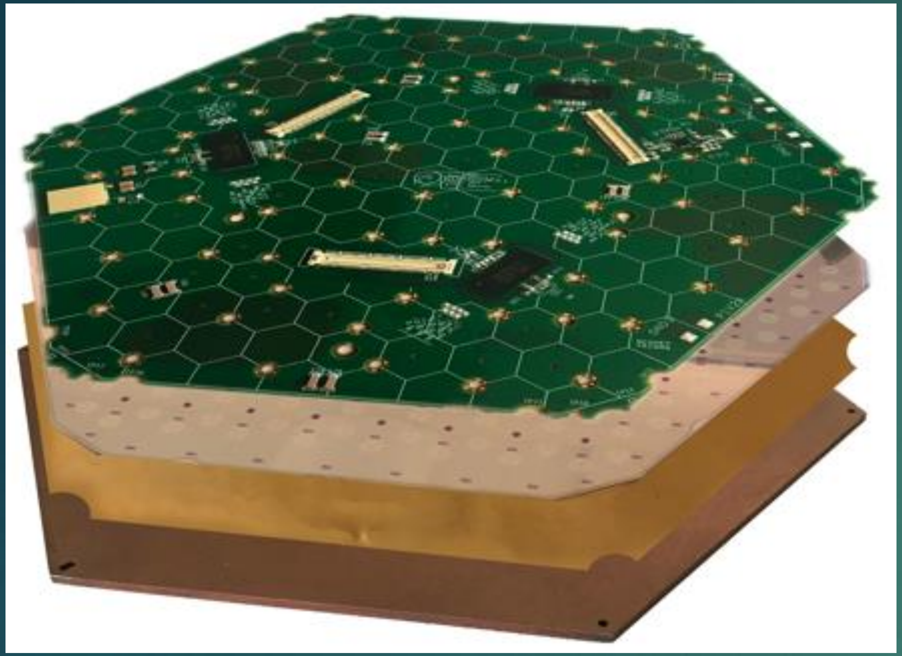
CNN uses the shape in addition

GNN uses shape and **timing**

arXiv:2107.10207v3

Detectors &Electronics

Silicon-based



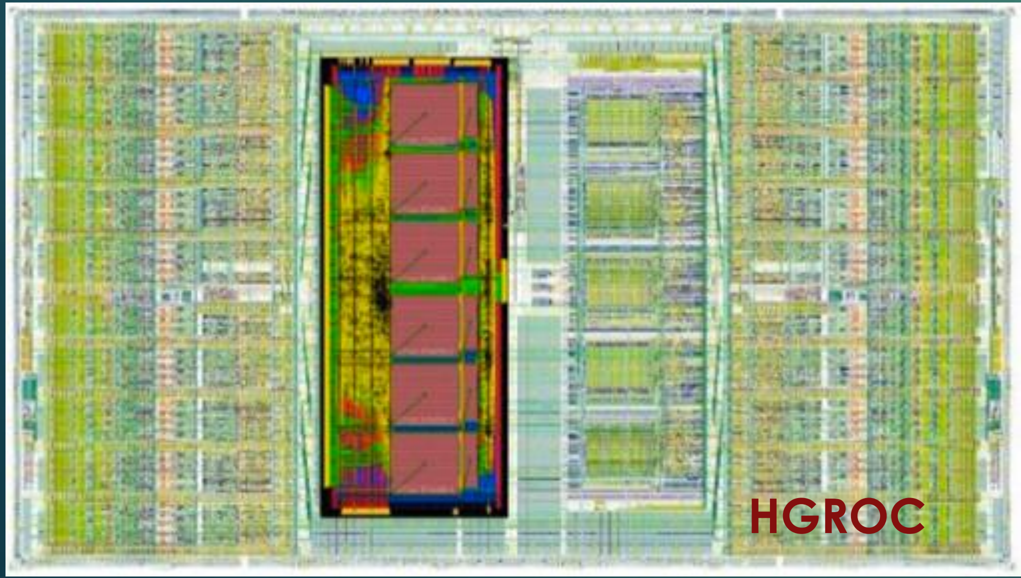
CMS HGCAL will be the first calorimeter using this technology at large scale. CALICE physical prototype was a proof of concept.

CMS Silicon modules

Sandwich of **PCB**, **sensor**, biasing/insulation layer and **baseplate** for rigidity/cooling.

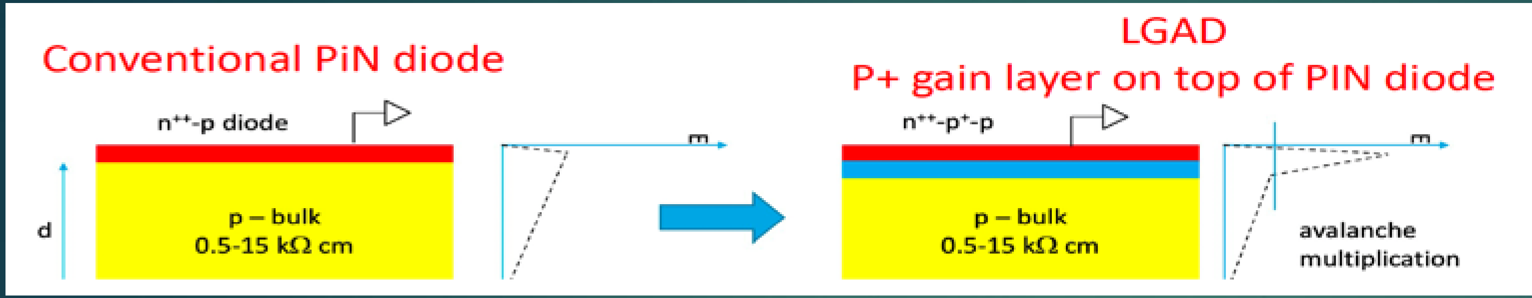
- Wire-bonding from PCB onto the silicon.
- CE-E: Cu W baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

Silicon thickness (120, 200, 300 μm) depending on the rate



- ***Low noise*** (<2500e)
- ***High dynamic range*** (0.2fC -10pC).
- **Timing** information ***tens of picoseconds*** ***Radiation tolerant.***
- Consumption ***<20mW*** per channel (cooling limitation).
- ***Zero-suppression*** of data to transmit to DAQ.

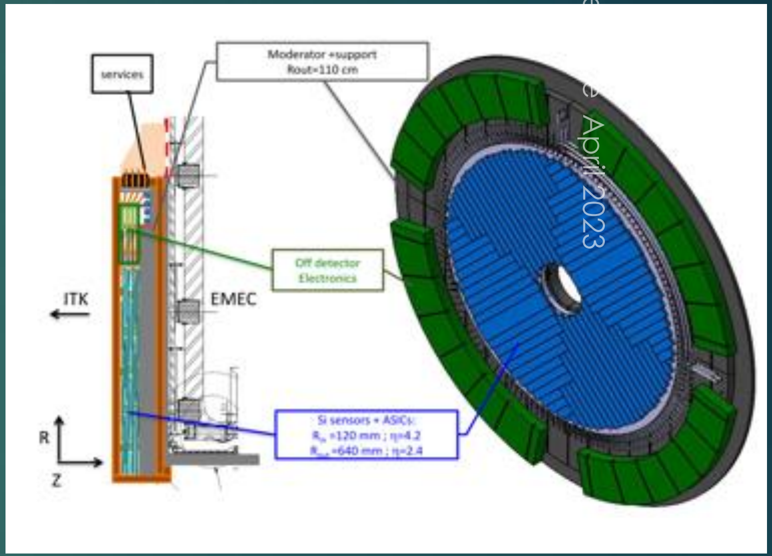
LGAD-based



Multiplication takes place in a limited space reducing the time spread

ATLAS HGTD

Is the first large detector to use this very promising technology
LGAD sensors will be read out thanks to **ALTIROC**:
TSMC 130 nm, 225 channels
Targeted time performance: 20 ps

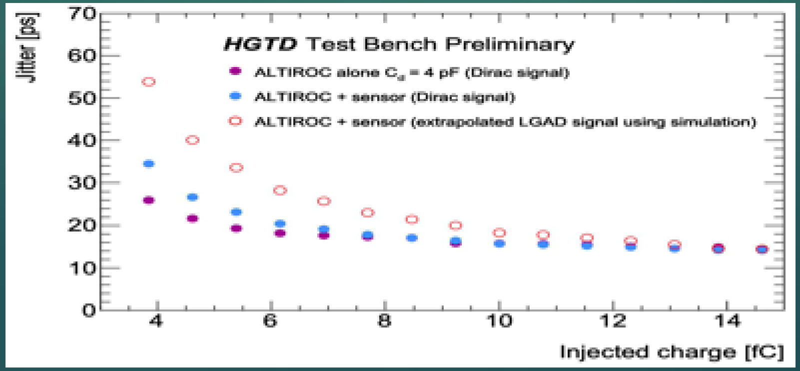


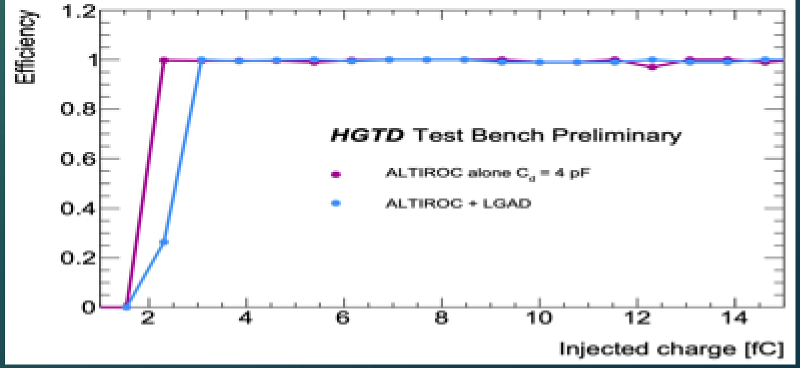
MTD (EndCaps of CMS) will also use the same technology

HGTD

~15ps jitter @ 15fC, better than 70ps jitter@ 4fC
and excellent efficiency

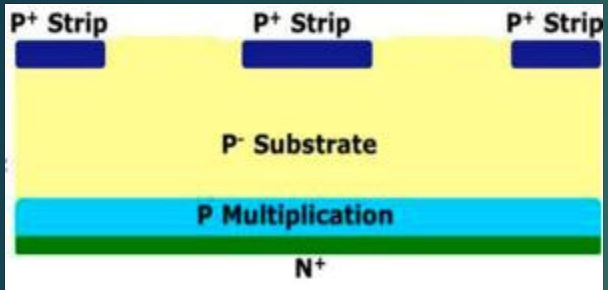
Courtesy Z. Liang

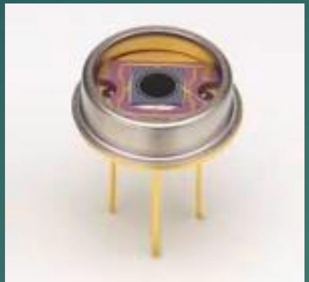




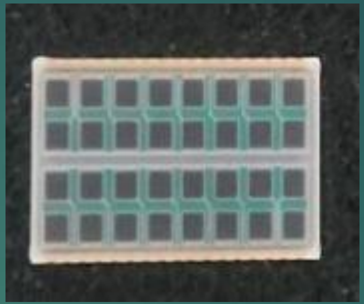
LGAD-based

Inverse type (Single Sided) presents → Better flatness & thinner active area`





Single cell

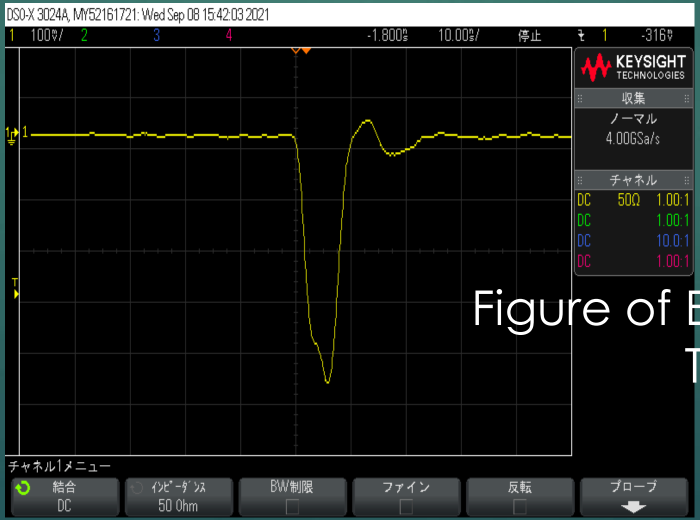


Multi cell

Courtesy T. Suehara

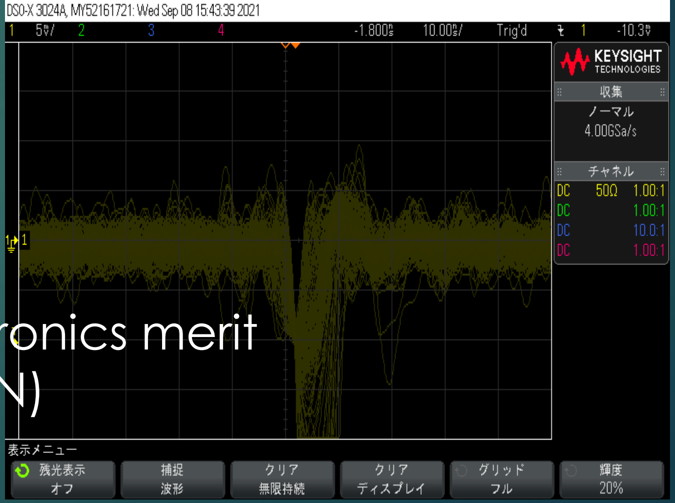
CALICE collaboration has started a new development to investigate the possibility to replace the silicon-based ECAL by a LGAD-based one

LGAD amplifier
Gain (100) & 3 GHz
Expected jitter 10 ps



Pulse height ~500 mV, rise time ~ 2 ns

Figure of Electronics merit
$T_r/(S/N)$

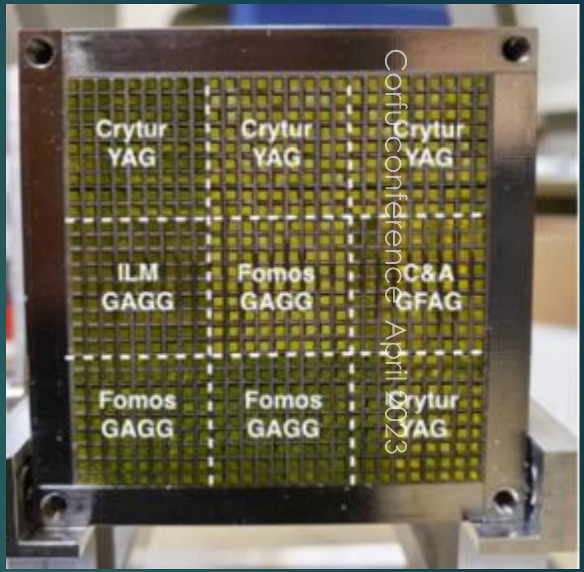


Noise ~ 2 mV (sigma)

Scintillator/Crystal-based

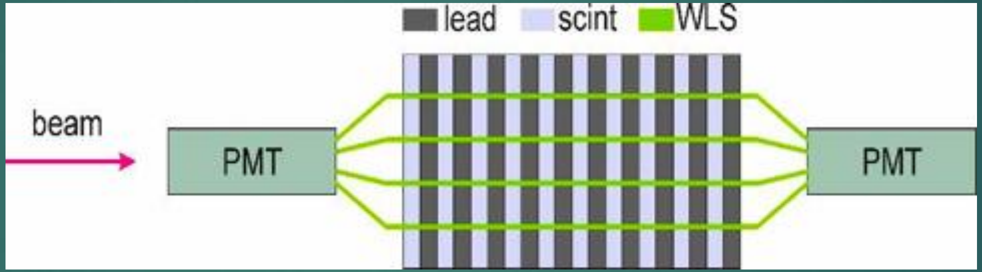
LHCB ECAL upgrade

Shashlik structure is proposed for the LHCB ECAL upgrade aiming at time resolution of few tens of ps



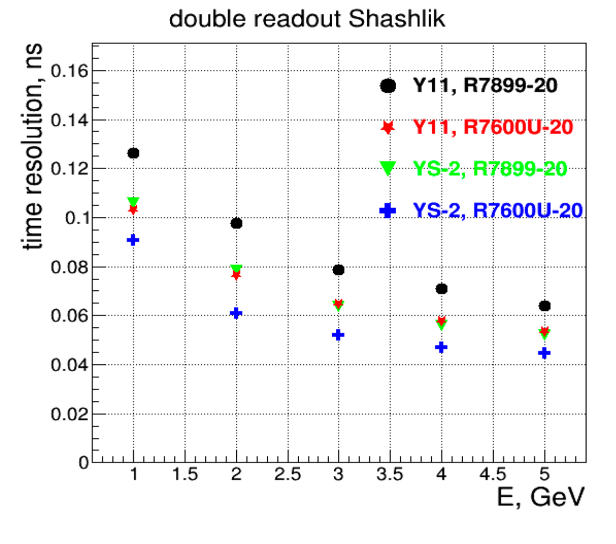
Courtesy of A.Schopper

Scint
Several Scintillators are
Being studied:
-YAG
-GAGG
-GFAG

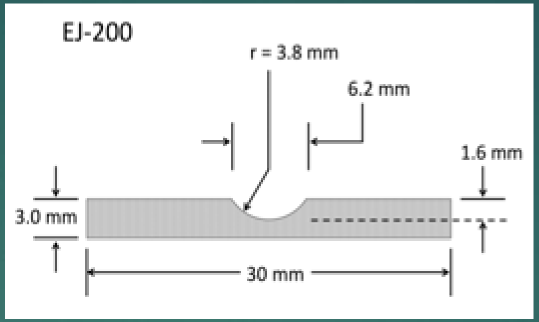


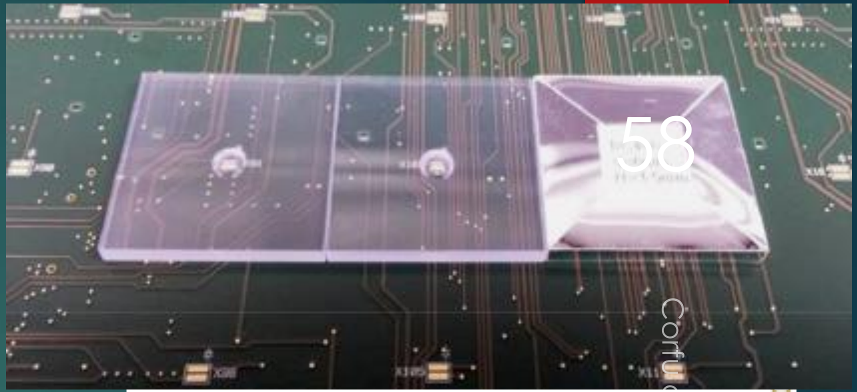
Photodetector
Use better PMT (small transit time spread and transit time uniformity over the photocathode)
- R7899-20 (TTS ≈ 1-2 ns)
- R7600U-20 (TTS ≈ 0.35 ns)

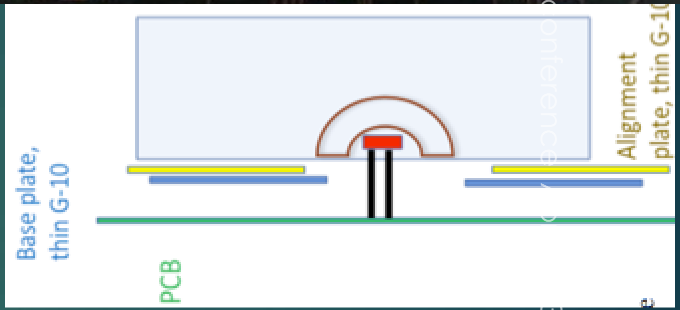
WLS fibers
- Use WLS fibers with shorter decay time
- Y11 decay time ≈ 7 ns
- Research work is ongoing in KURARAY aiming to develop faster WLS fibers with good light yield
- New KURARAY WLS: YS-2 (≈ 2.7 ns)



Scintillator/Crystal-based





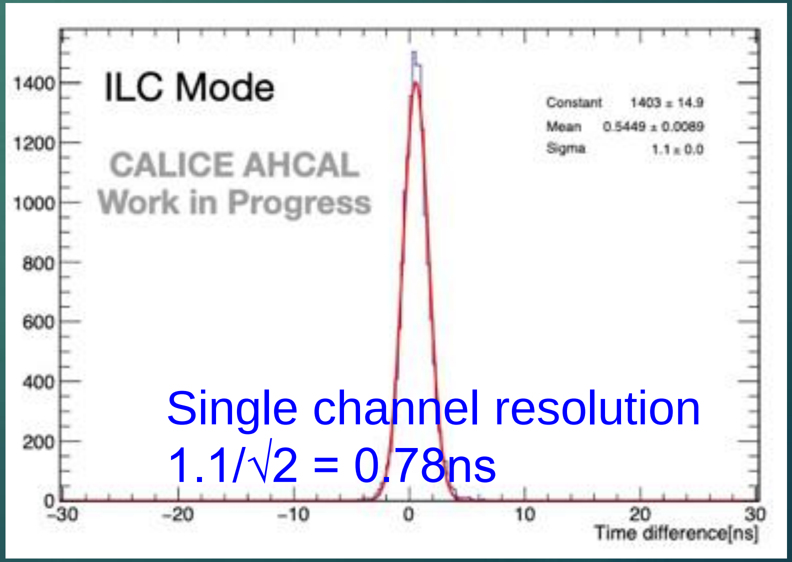


CALICE AHCAL uses 3cm X 3cm tiles read out by SiPM

SiPM used in AHCAL
S13360-1350
- Historical reference to compare with previous measurements
- Breakdown voltage = 51.76V
- **S14160-1315**
- Best representative of SiPMs in HGCAL: Hamamatsu S14160 series will be used
- Breakdown voltage = 38.31V

SiPM are fast timing but need appropriate scintillation media and adequate readout electronics.

For AHCAL proposed for ILC moderate time measurement is needed to eliminate delayed neutrons (> few ns)



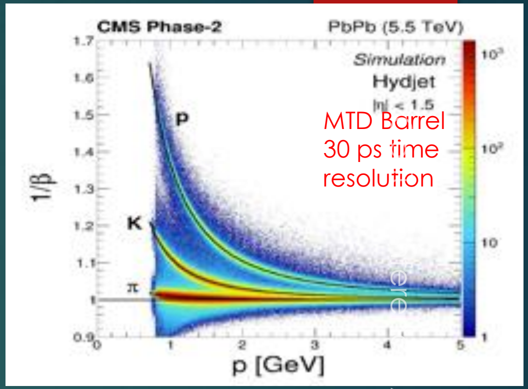
Courtesy M. Kroen

Scintillator/Crystal-based

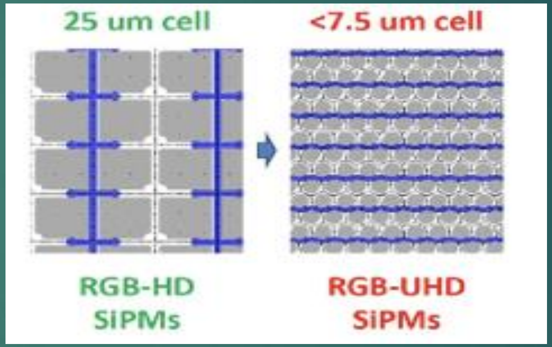
SiPM is becoming an important piece of the scintillator/crystal detectors/calorimeters
Associated to fast Scintillator/crystals
it can provide excellent time resolution

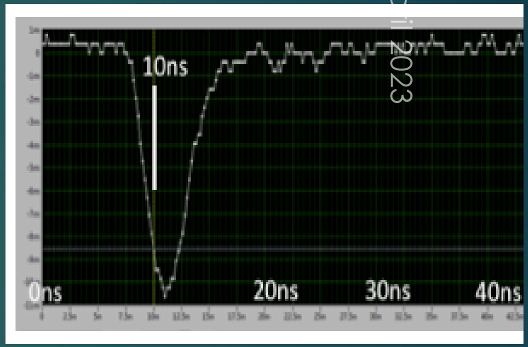
Time resolution of ~30 ps for single MIPs with single LYSO layer is expected from MTD (CMS, Barrel)

Array of LYSO crystals (CMS MTD)

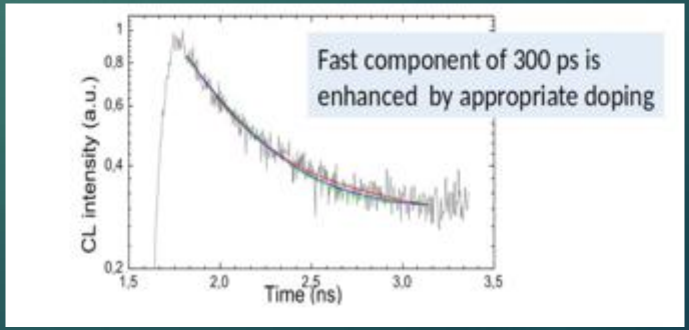


Efforts to go for small pixels < (10 μm) are to be carefully followed since the smaller the pixel the faster the time response.





Developments of the so-called Nano crystals (such as Perovskite sensitizer, $CsPbBr_3$) that feature sub-nanosecond scintillation with good LY as well as colloidal quantum dot technology are ongoing and could lead to a breakthrough



Courtesy of M.Korjik and G.Tamulaitis

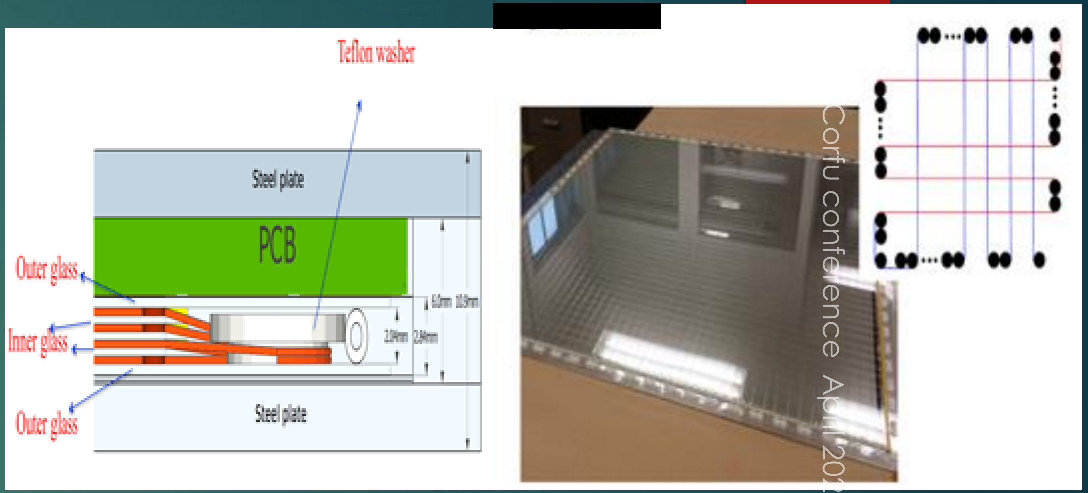
In addition, revisiting known material (doping) to better distribute scintillation in favor f fast component→ PWO-III

Gaseous Calorimeters

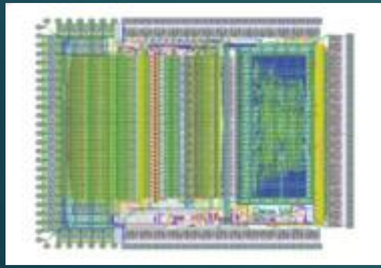
SDHCAL concept is being transformed into T-SDHCAL

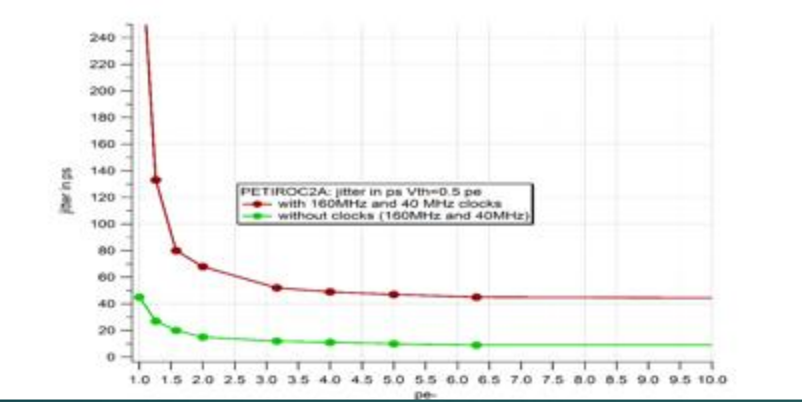
- ❑ RPC are replaced by MRPC (much faster)
- ❑ Semi-digital electronics (HARDROC) is replaced by low-time jitter PETIROC (> 20 ps @Q> 300 fC)

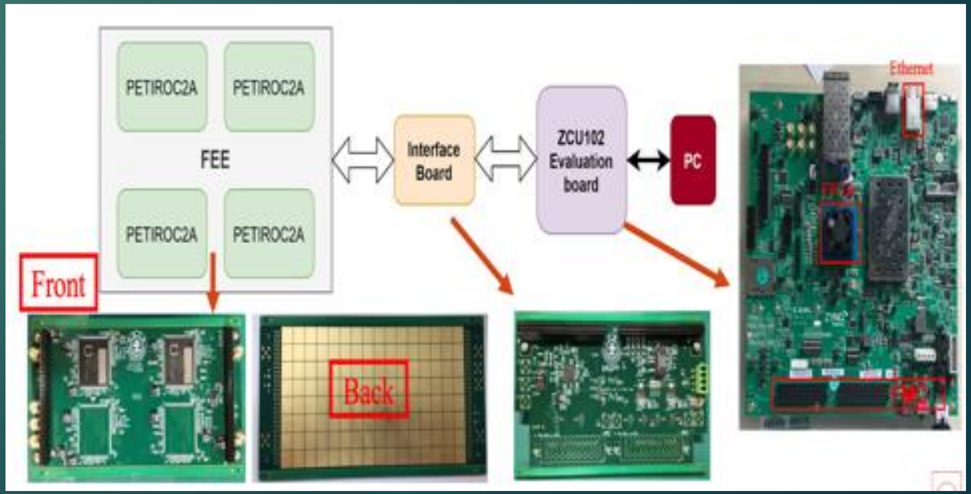
The hope is to reach time resolution better than 100 ps/mip over all the surface.



Advantage of the gaseous detector option is its low cost and limited dead zone







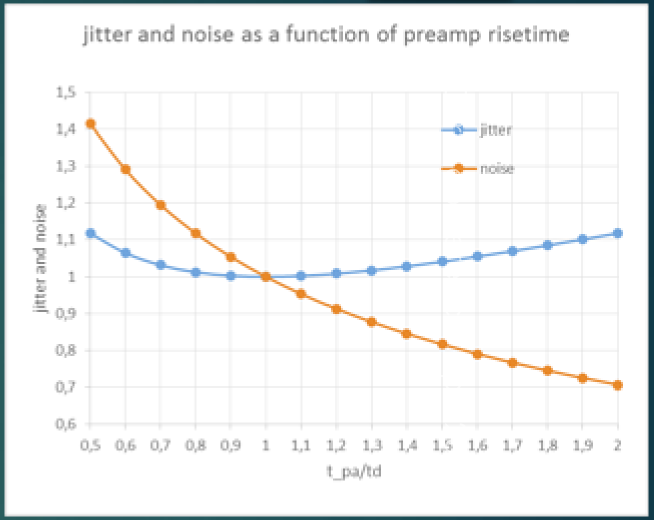
Electronics For time measurement

Role of electronics of time precision:

$$\sigma_t^J = \frac{N}{dV/dt} = \frac{e_n}{\sqrt{2t_{10-90\_PA}}} \frac{C_d\sqrt{t_{10-90\_PA}^2 + t_d^2}}{Q_{in}} = \frac{e_n C_d}{Q_{in}} \sqrt{\frac{t_{10-90\_PA}^2 + t_d^2}{2t_{10-90\_PA}}}$$

$$\sigma_t^J = \frac{e_n C_d}{Q_{in}} \sqrt{t_d}$$

$$e_n = \sqrt{\frac{2kT}{g_m}} \approx \frac{2kT}{\sqrt{qI_D}}$$



A few ASICS as examples

		sensor	polarity	BW	Zin	Cd	TDC	dyn range	FOM	min thresh	"@Cd="
PETIROC	VPA	SiPM/RPC	both	900 MHz	200	10-100 pF	25 ps			1 mV	
LIROC	VPA	SiPM/RPC	both	300 MHz	1k	10-100 pF	no	10fC-100 pC	2 ns/Q (fC)	40 fC	
ALTIROC	VPA/TZ	LGAD	neg	300-800 MHz	2k/200	1-10 pF	20 ps	0.1-50 fC	100 ps/Q(fC)	2 fC	5 pF
HGCROC	TZ	Si	neg	100 MHz	40	10-100 pF	25 ps	0.1 fC-10 pC	2 ns/Q (fC)	20 fC	50 pF
H2GCROC	CC	SiPM	pos	80 MHz	25	100p-1nF	25 ps	10 fC-200 pC			

Courtesy Ch. De la Taille

TDC

Several TDC (either on ASICS or FPGA) are now able to provide time resolution lower than 10 ps

ASICs present more stability and less power consumption

- SAMPIC (Waveform digitizer) -> 3.5 ps
- AARDVVARC V3 (waveform digitiser) -> 4-6 ps
- PicoTDC (PLL) → 1.5-3 ps

Of course, for large systems the synchronization of all the electronics is challenging but systems like White Rabbit + Local distribution system (lpGBT) can achieve excellent time precision.

Conclusion on timing in future calorimeters

Time measurement in future calorimeters can add precise information so to

- ❑ Mitigate pileup
- ❑ Identify particles
- ❑ Apply PFA more efficiently
- ❑ Improve on energy reconstruction

New algorithms including the time information is being developed. First estimations from the simulation are very encouraging

-Only fast time detectors will survive this evolution toward 5D calorimeters. several technologies exist and being adapted.

-Excellent and time precision electronic readout systems have been developed

-The challenge will soon become to ensure that all the components of the calorimeters are able to preserve the excellent time precision of the detectors and their electronics and this requires huge engineering efforts.