T-Calorimetry

Goals and tools

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IAS workshop, January 2022

Disclaimer

Timing in calorimetry is still in its childhood. For the time being there is no large calorimeter with precise time measurement and thus there is no proof that all the ideas presented in this talk will be materialized in the near future.

The talk is a personal review using several works and presentations from other authors. My interpretation may differ from their so I apologize in advance if I misinterpret their thoughts.

Outline

- Timing in Calorimetry
- Goals
  - PID
  - Pileup mitigation
  - Cleaning&PFA
  - Energy construction
- Tools
  - Detectors
  - Electronics
- Conclusion

Goals

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

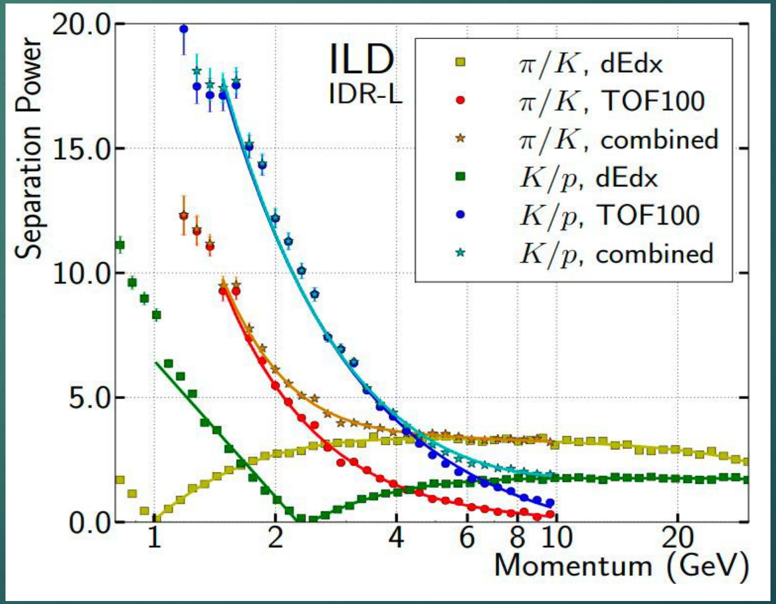
$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

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



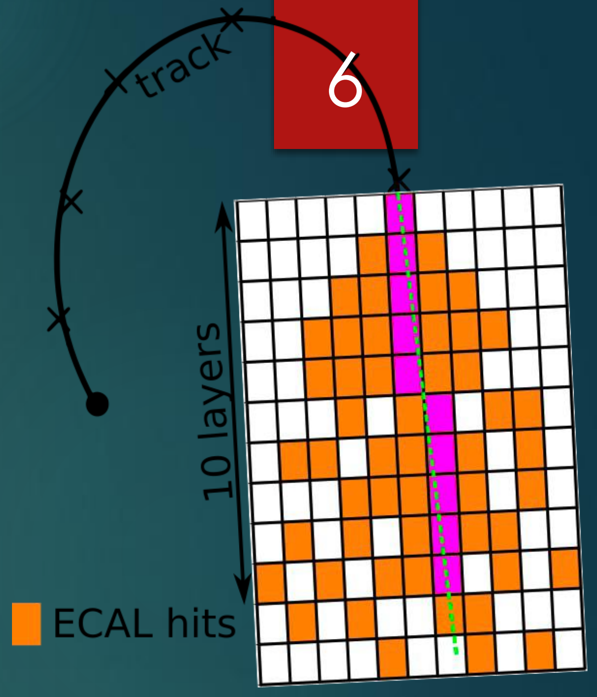
Particle Identification

In case of charged particles :

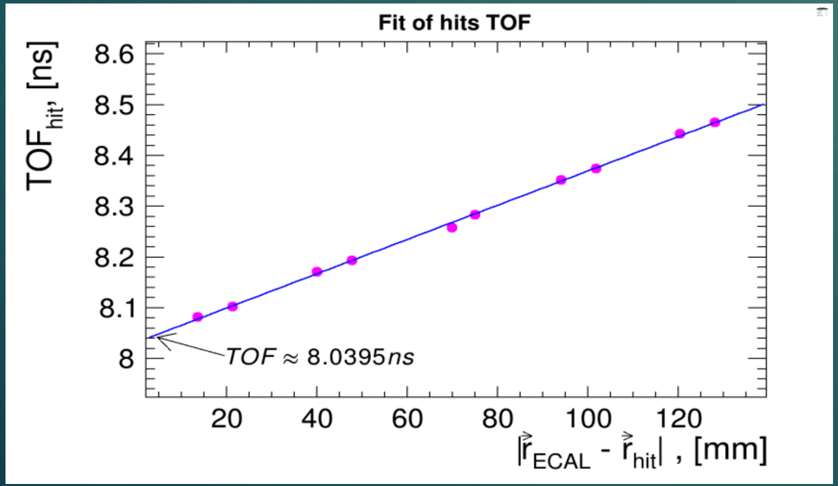
$$m = \frac{p}{\beta}\sqrt{1-\beta^2}$$

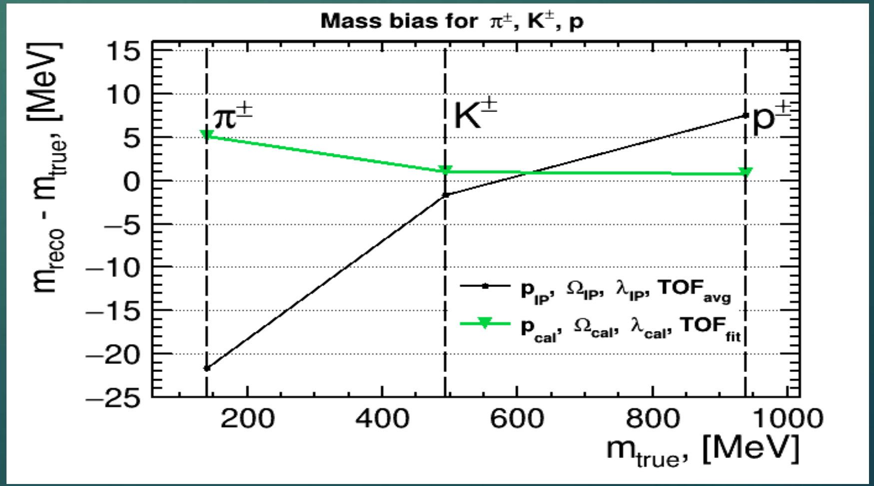
P is taken from the tracker at the ECAL entrance and β from ToF
To estimate the ToF in a granular calorimeter like the ILD ECAL in the case of charged particles several methods can be used:

- 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})



B. Dudard et al





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.

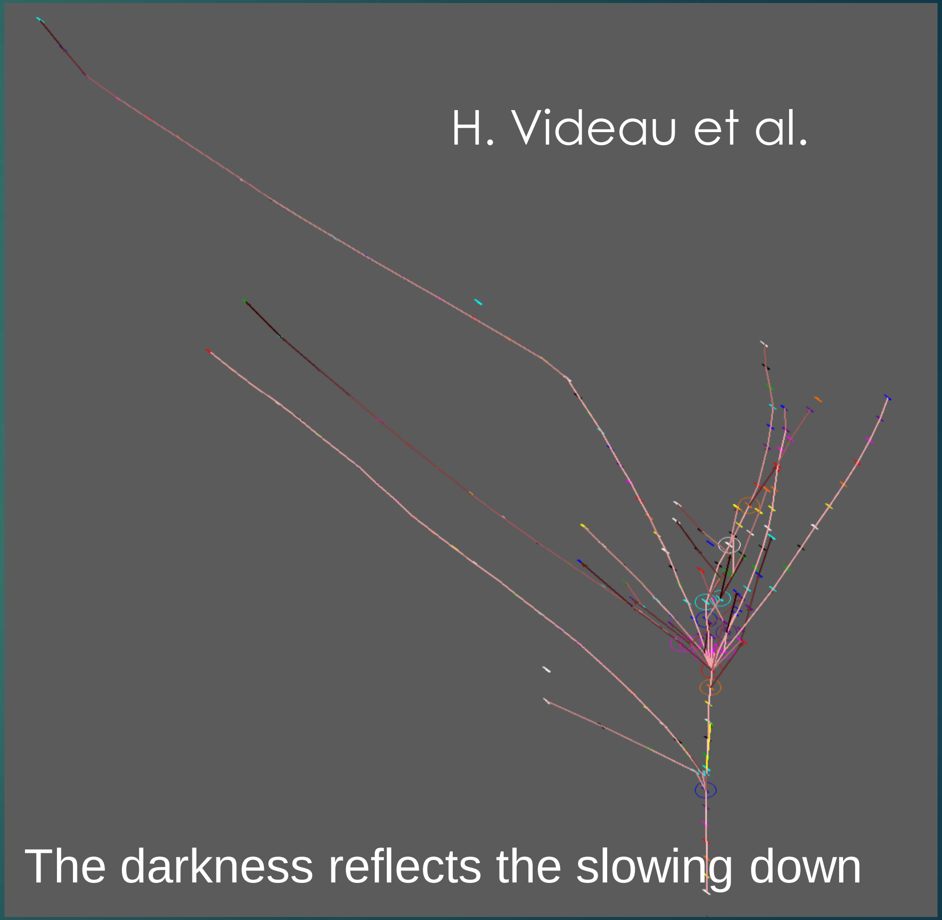
β could be known up to 10% according to a simulation study on hadronic showers in ILD SiW ECAL

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

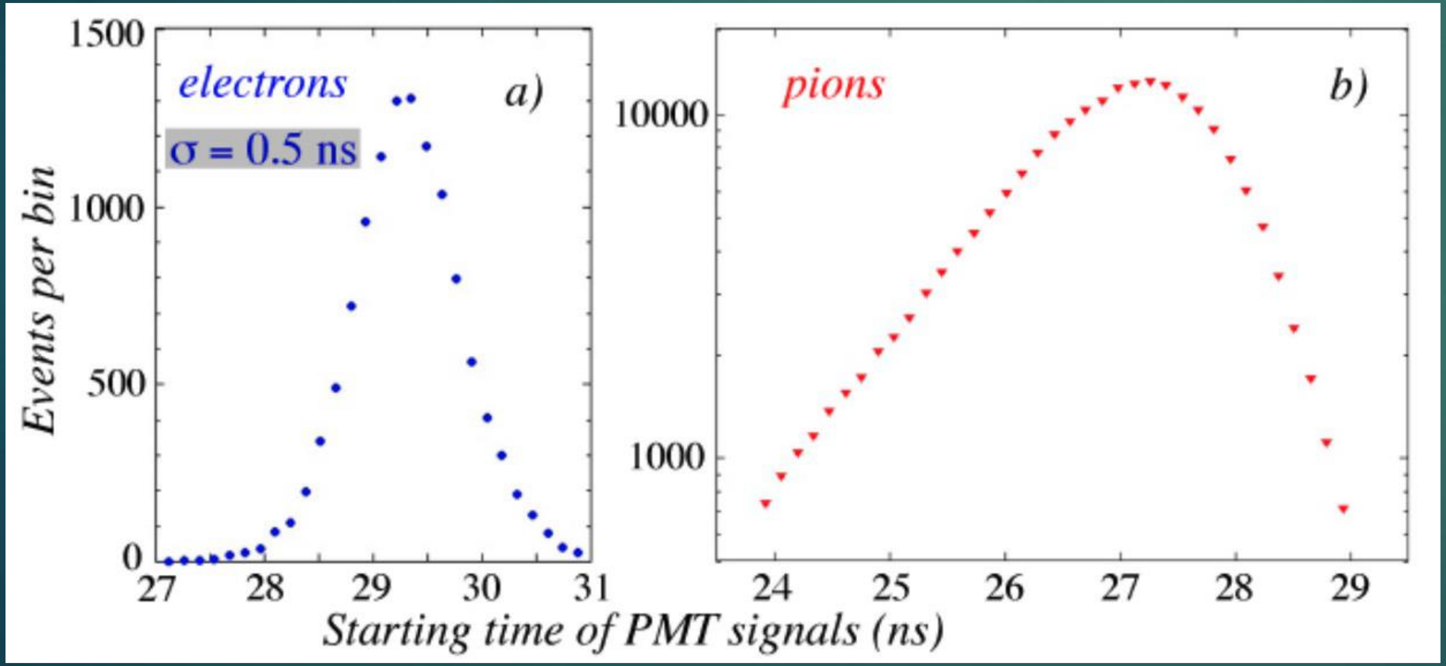
Time information is also very useful in other technologies than the one based on high granularity.

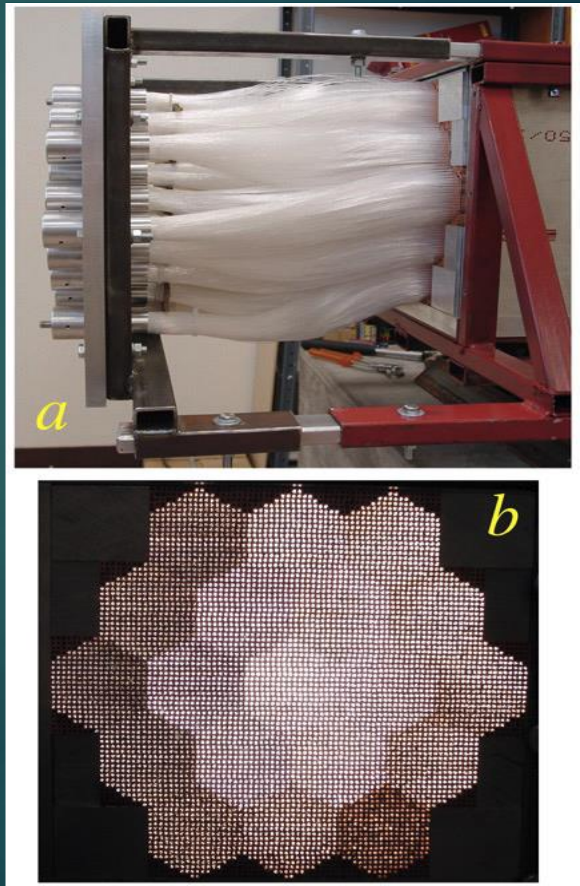
In Dual Readout technologies one can use precise time information to discriminate electrons against pions since the showers associated to those particles start on average in different depths of the calorimeter. This with the shape information are efficient tools for PiD.

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

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

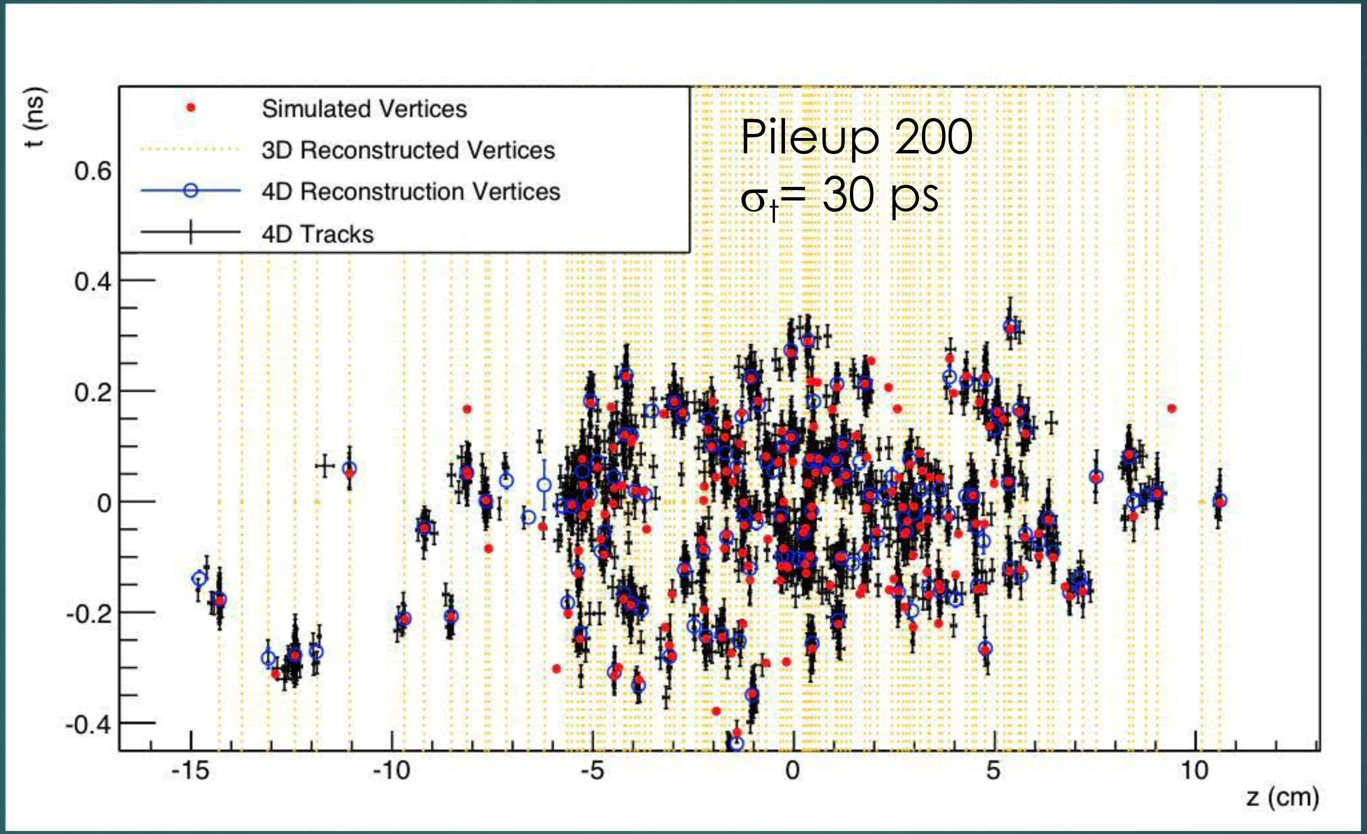
$$E = \frac{S - \chi C}{1 - \chi}$$





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

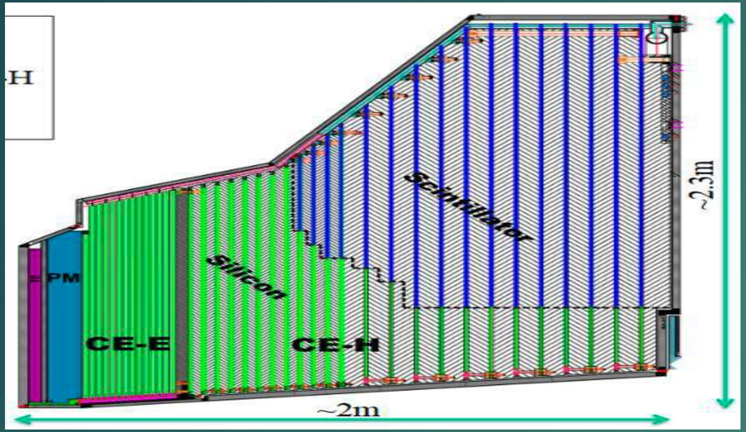
Pile Up Mitigation

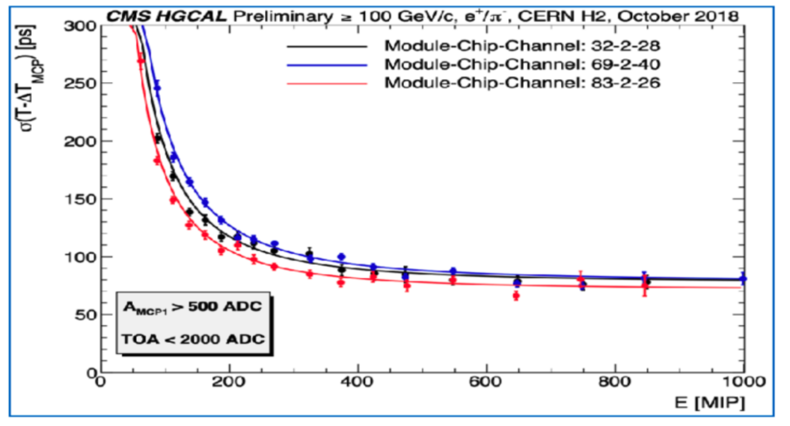


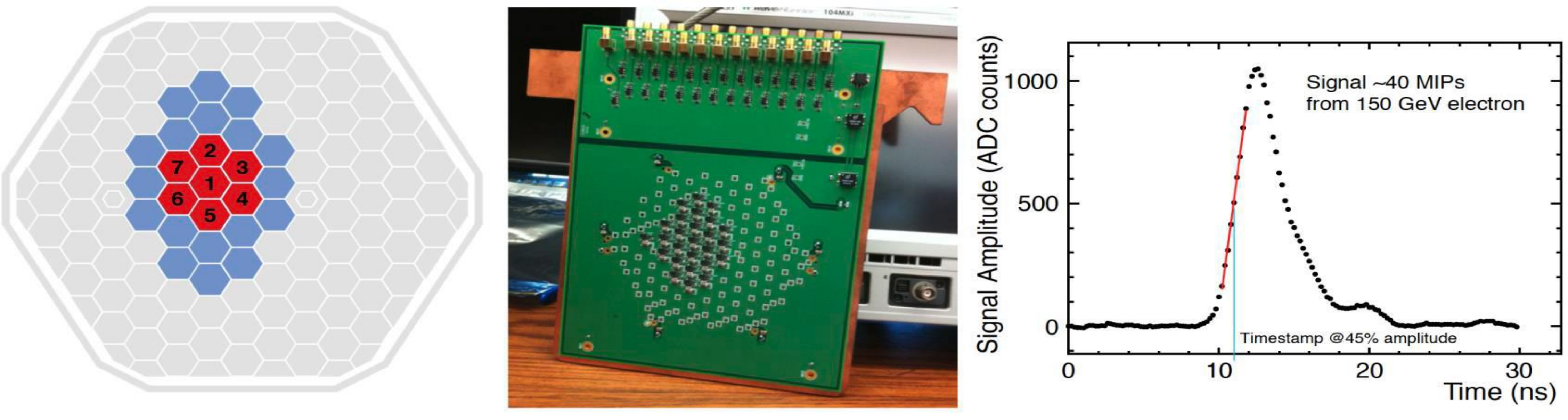
A precise time measurement is a key tool in mitigating pileup

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

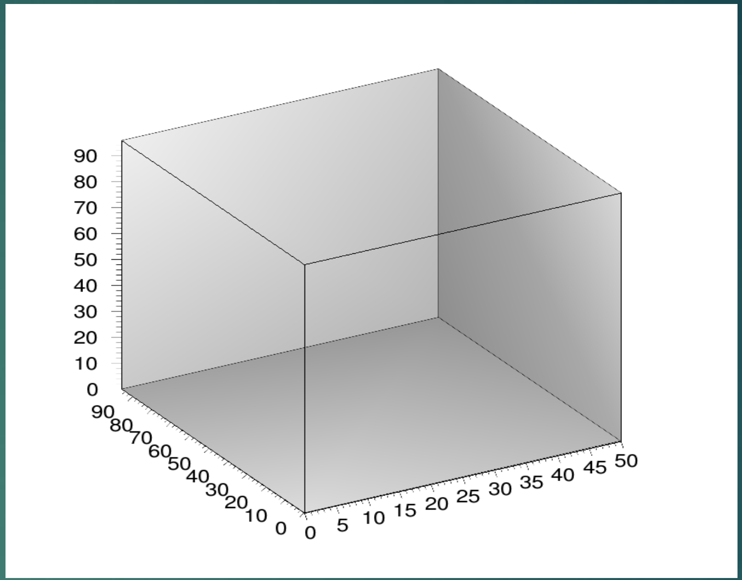
Cleaning and shower separation

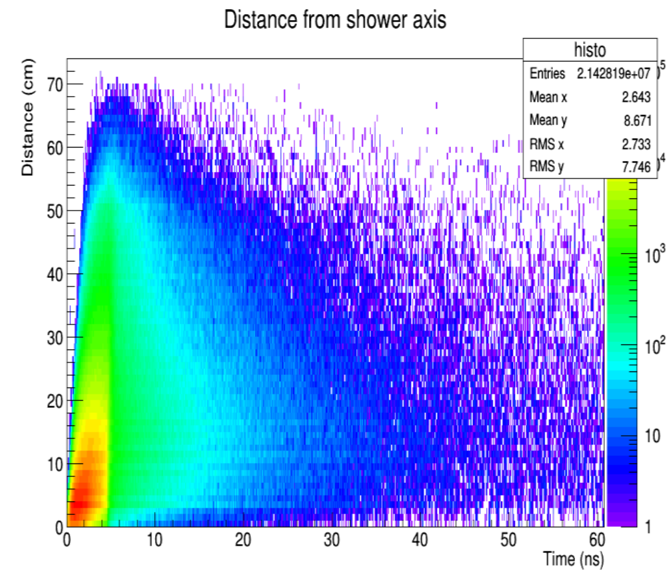
Hadronic showers feature many neutrons and many of them are delayed ones and can :

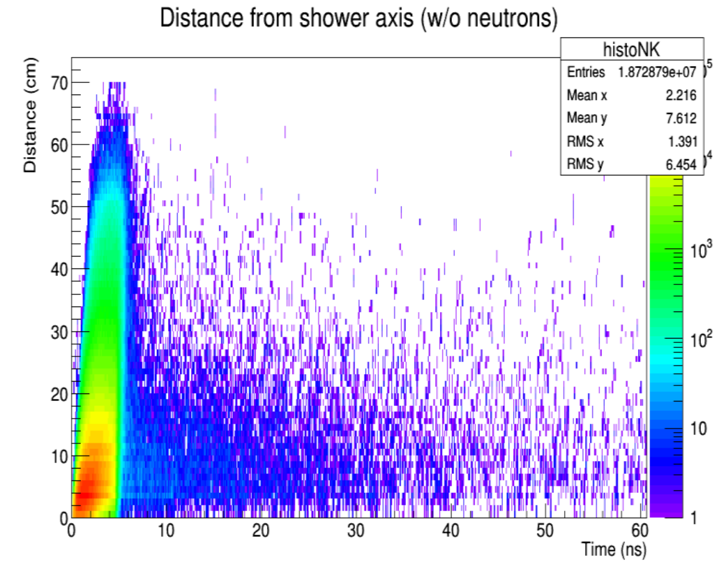
1- fake the energy measurement (fluctuations)

2- complicate nearby showers separation when PFA is used

Timing can then tag the hits produced by the neutrons.



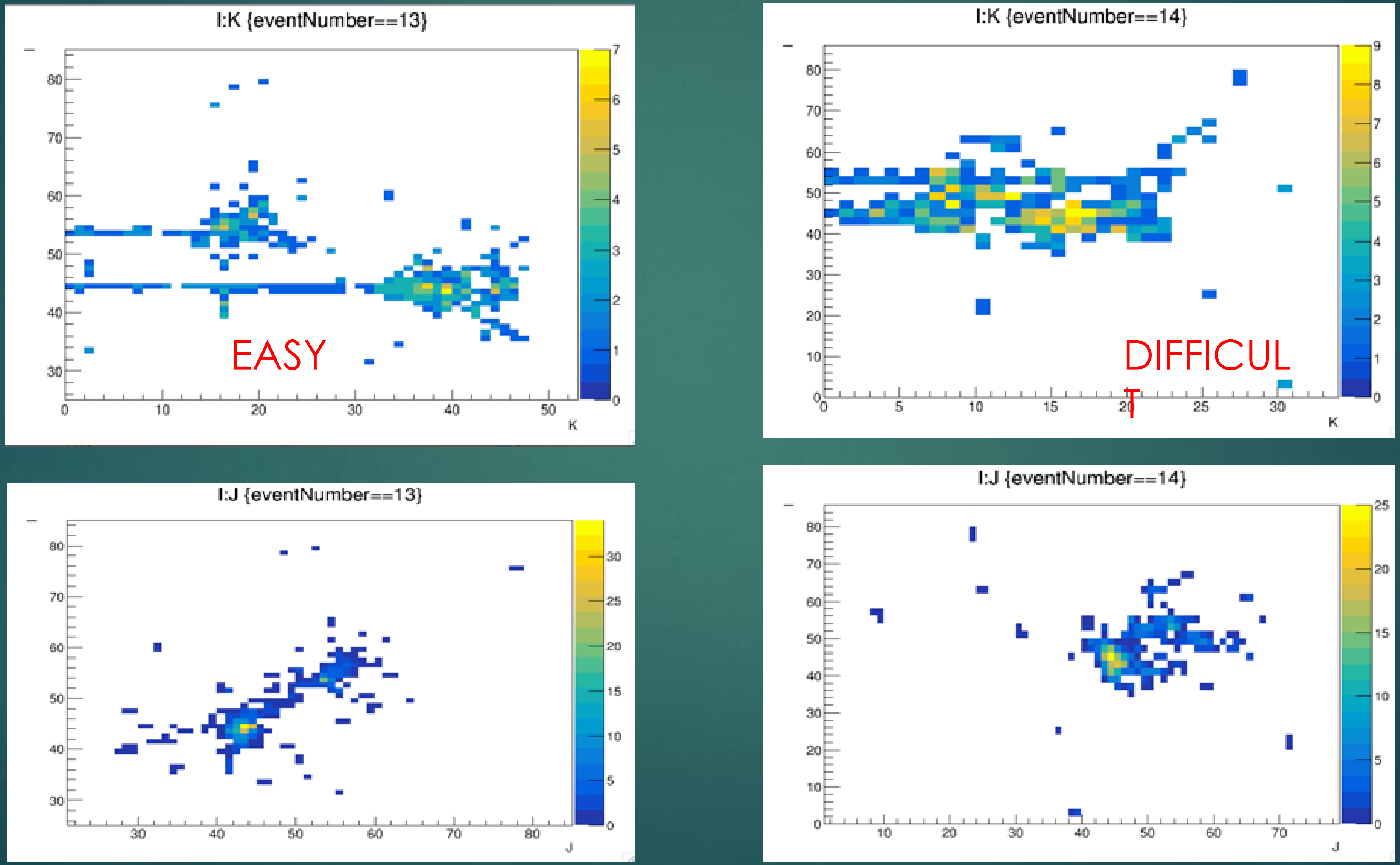




SDHCAL simulation

Cleaning and shower separation

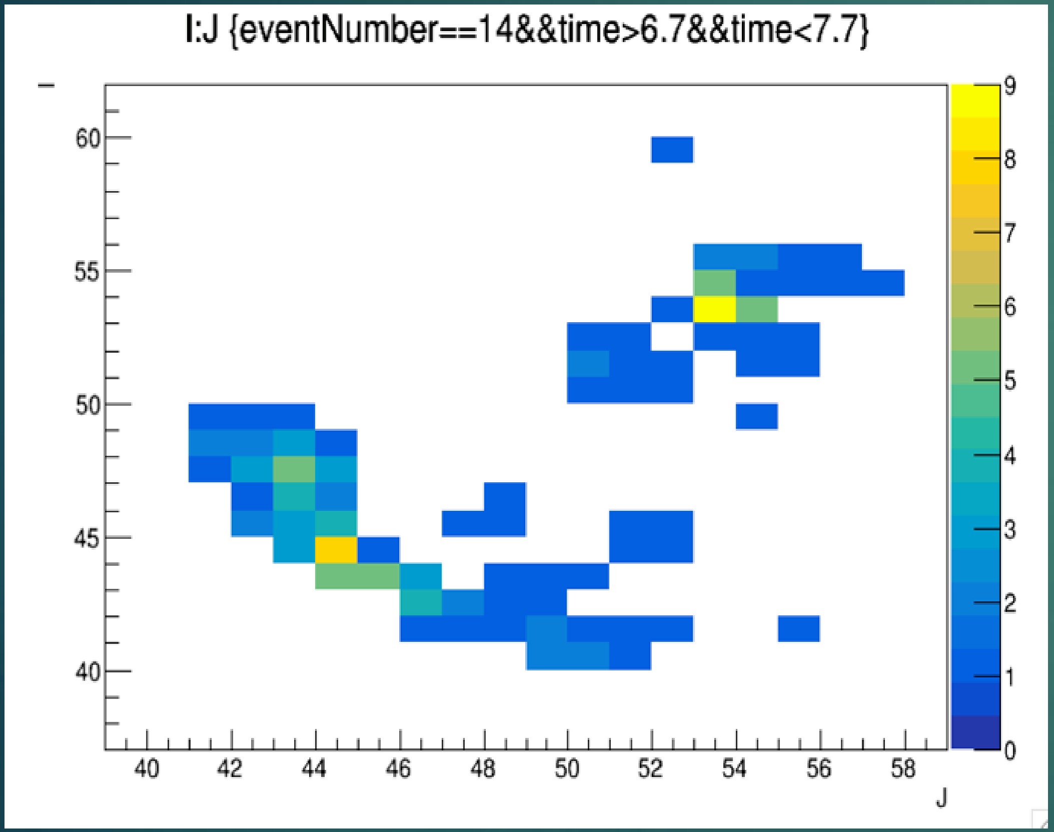
Time information can also help to separate close by showers and reduce the confusion for a better **PFA** application. Example: pi-(20 GeV), K-(10 GeV) separated by appox. 15 cm.

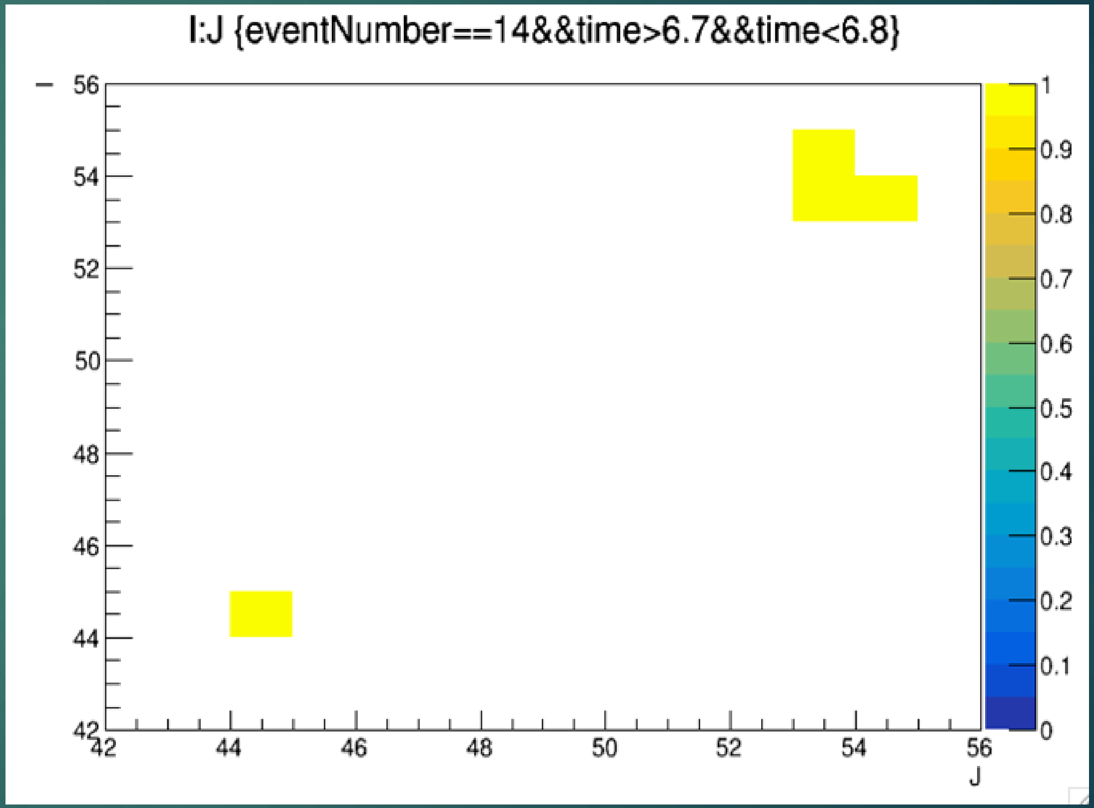


SDHCAL simulation

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”



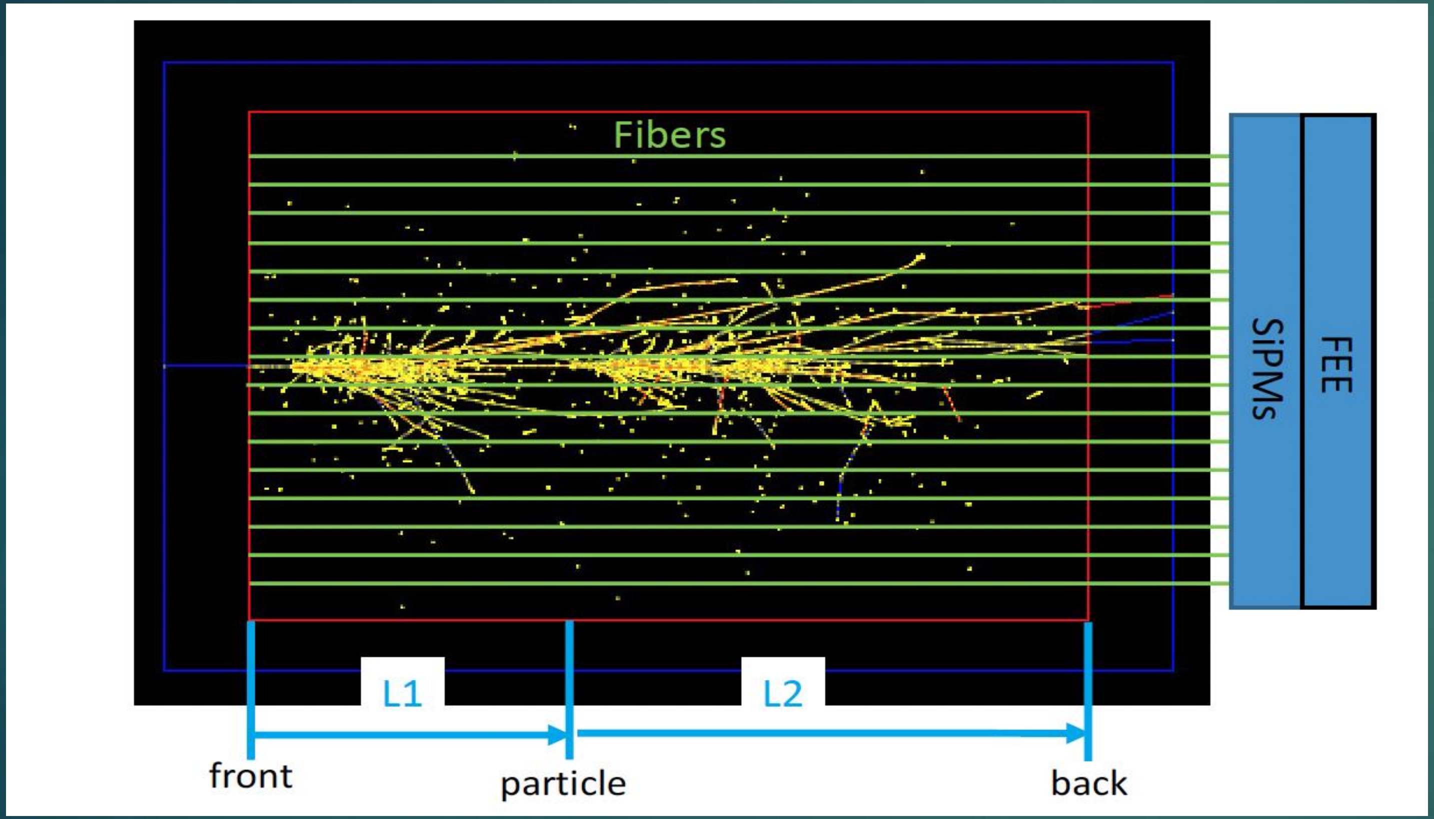


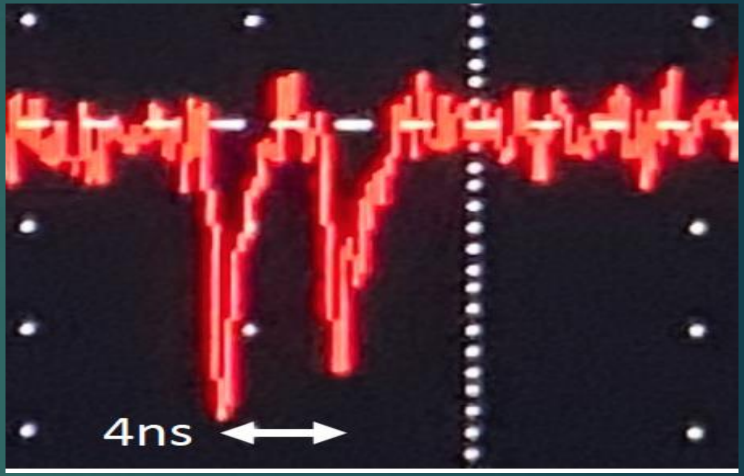
Shower projection on transversal plan

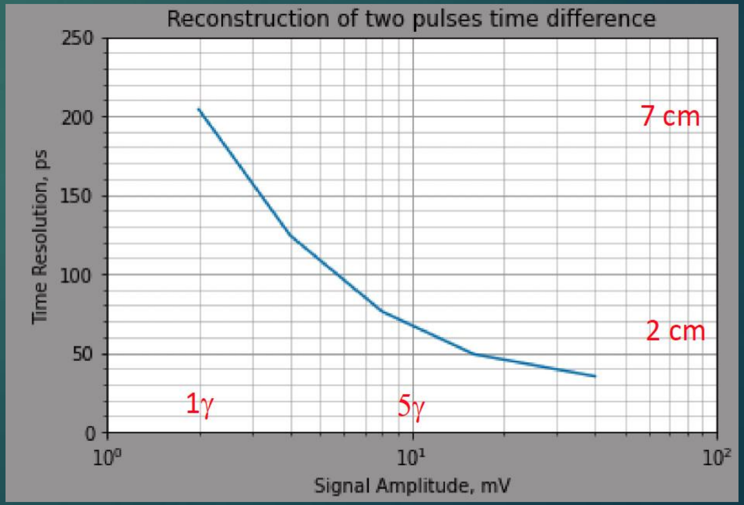
SDHCAL simulation

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





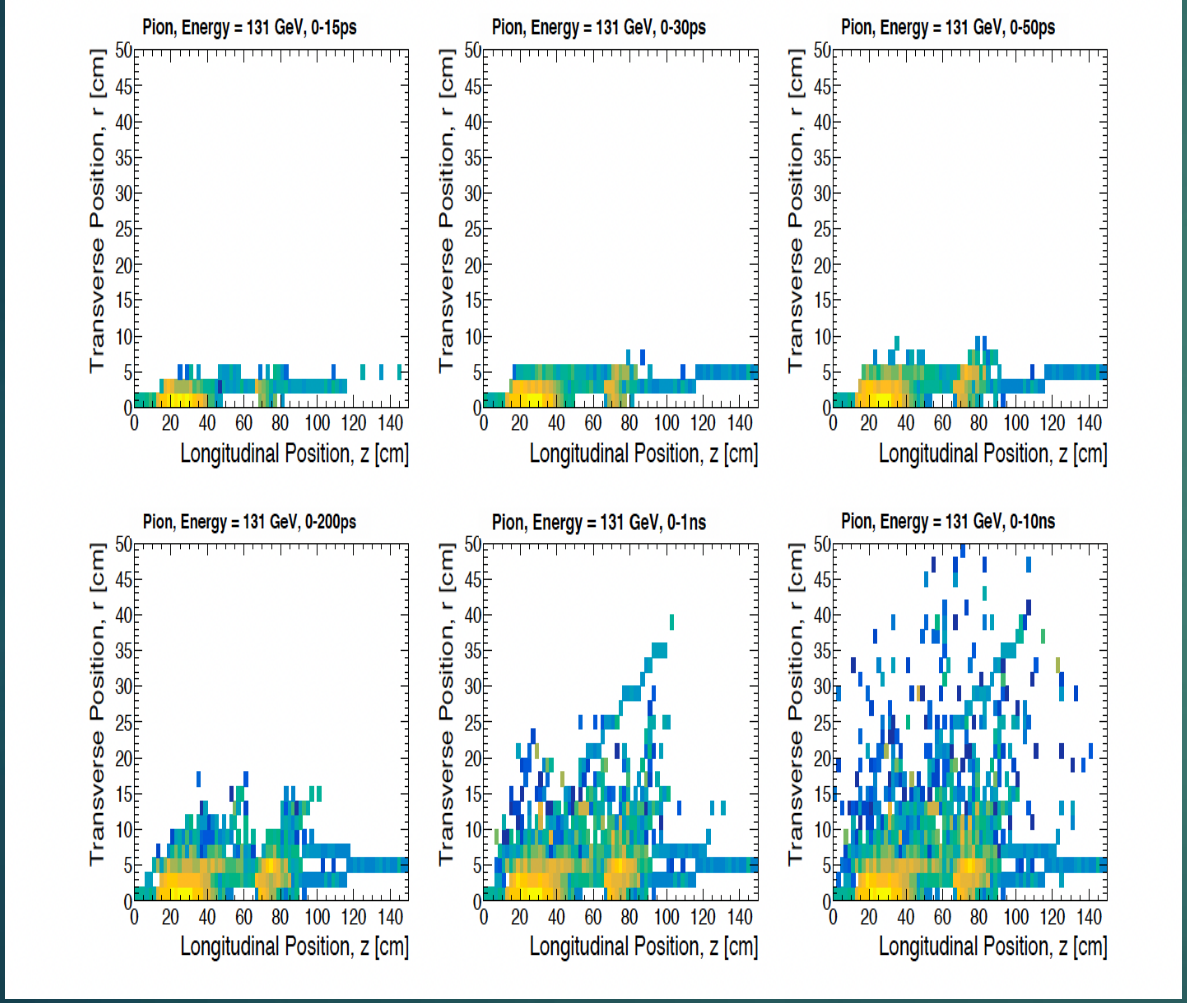


Signal Time = L1/c + L2/kc,
c = velocity of particle
kc = velocity of light in fiber (k~0.6)

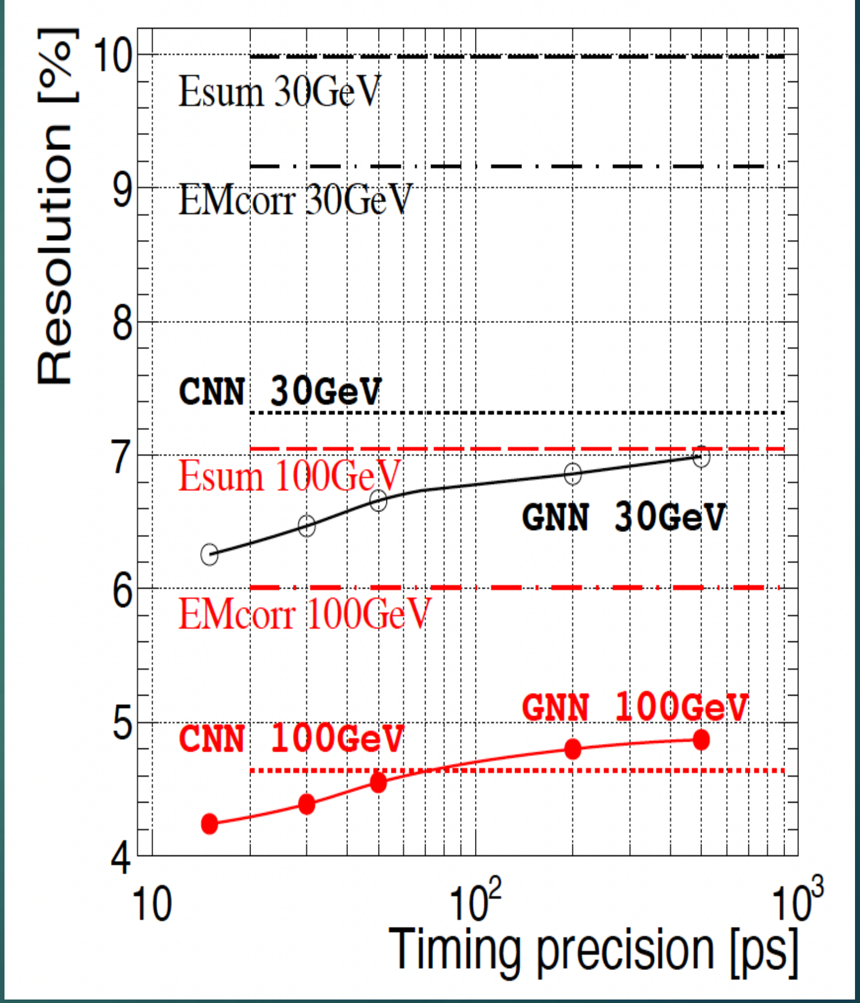
Courtesy S. Kunori

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

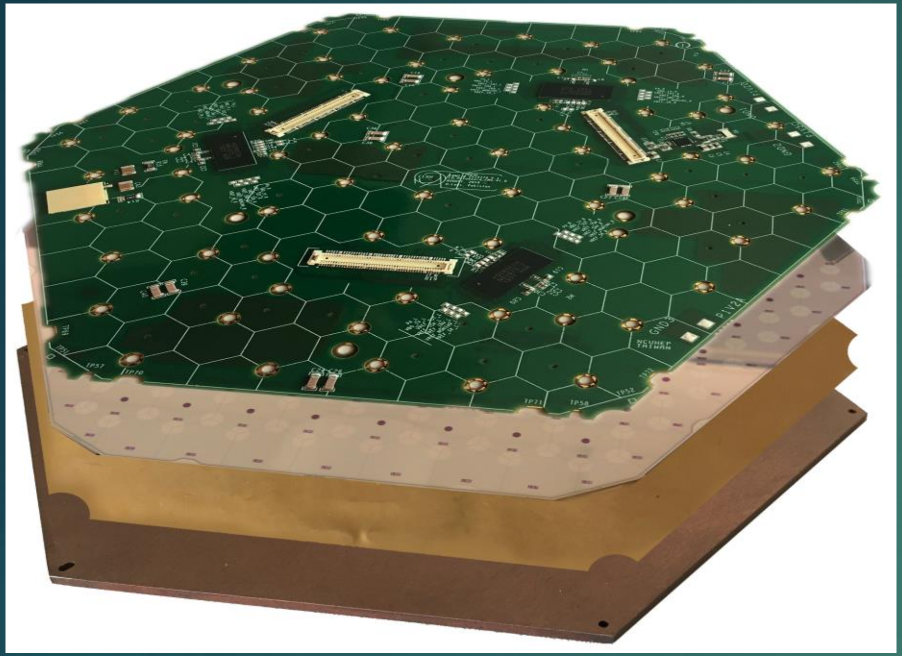
CNN uses the shape in addition

GNN uses shape and **timing**

arXiv:2107.10207v3

Detectors &Electronics

Silicon-based



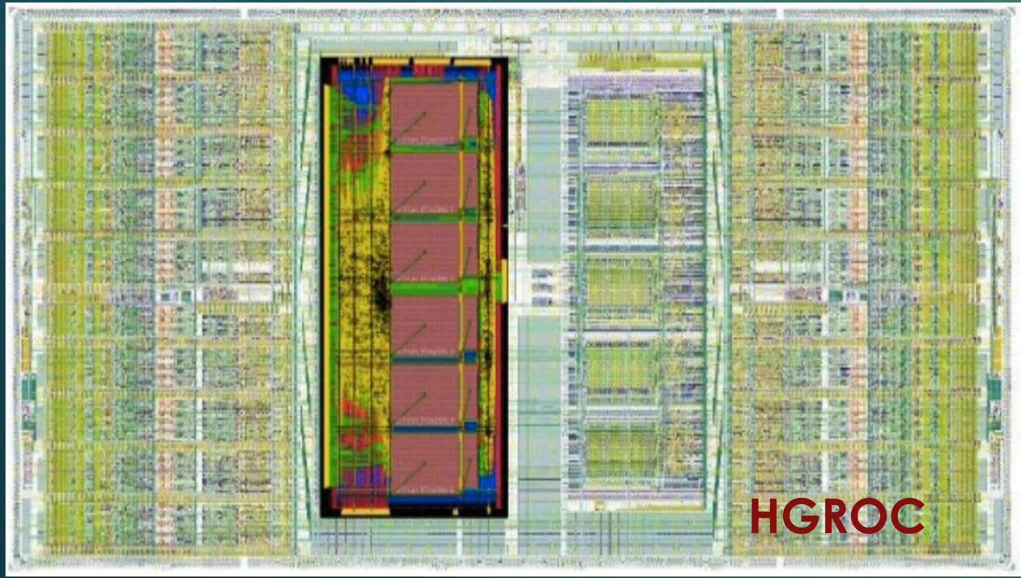
CMS HGCAL will be the first calorimeter using this technology at large scale. CALICE physical prototype was a proof of concept.

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).

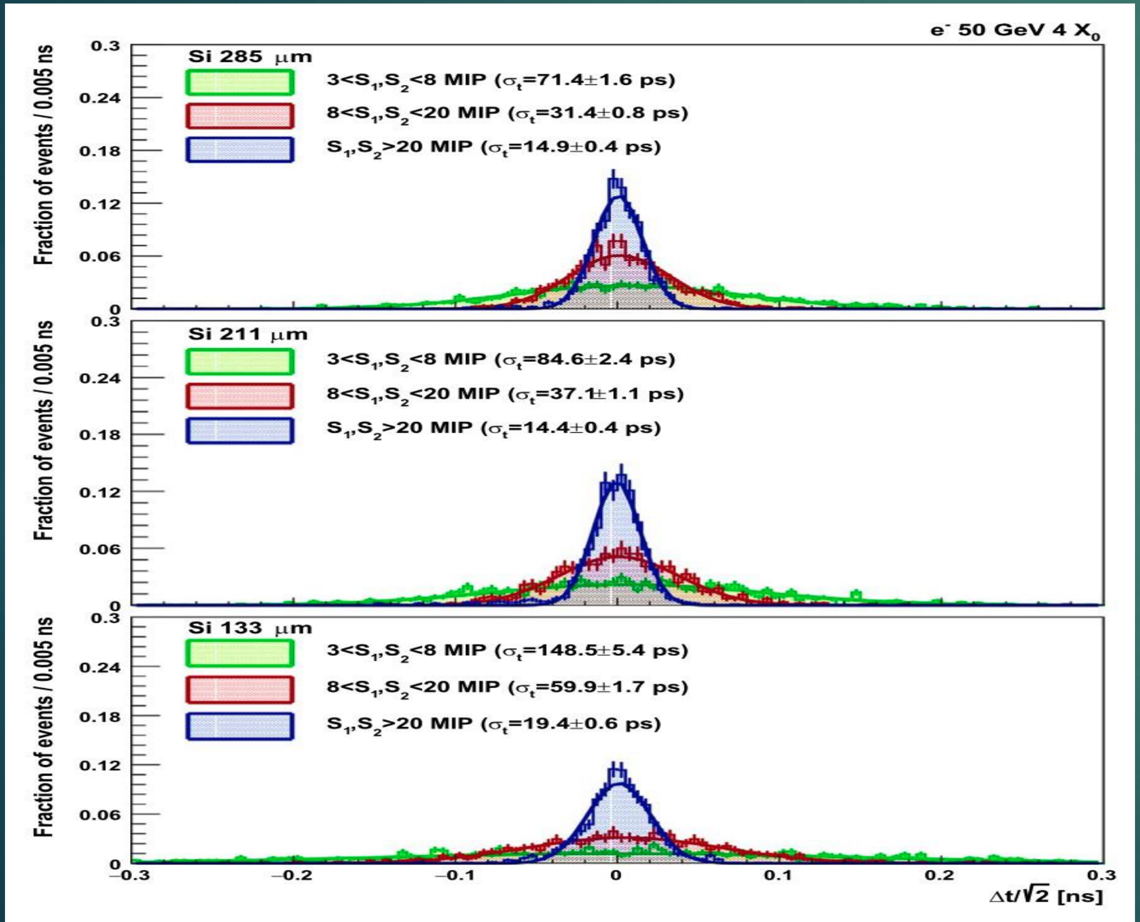
Silicon thickness (120, 200, 300 μm) depending on the rate

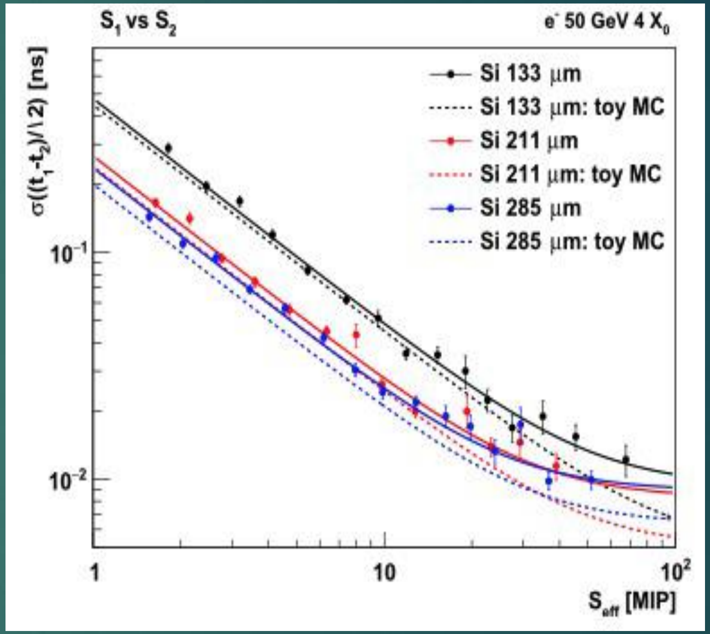


- ***Low noise*** (<2500e)
- ***High dynamic range*** (0.2fC -10pC).
- **Timing** information ***tens of picoseconds***
  Radiation tolerant.
- Consumption ***<20mW*** per channel (cooling limitation).
- ***Zero-suppression*** of data to transmit to DAQ.

Silicon-based

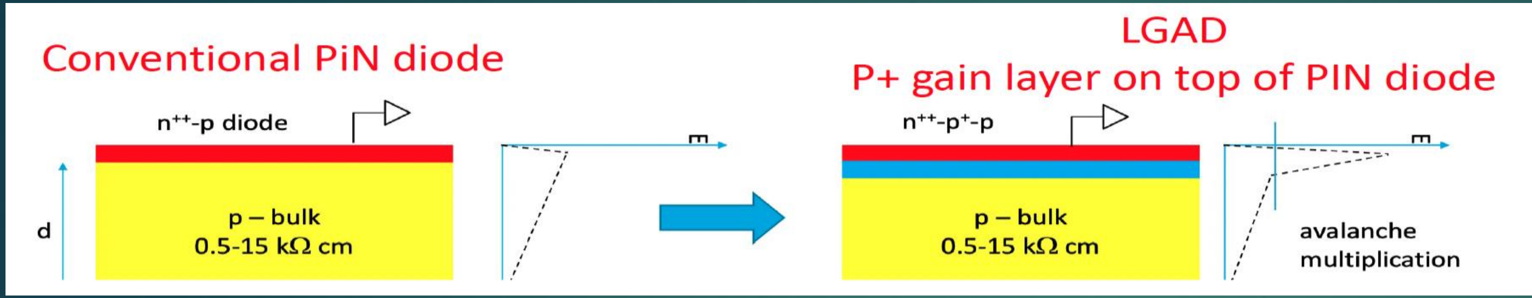
Silicon-based calorimeter could be optimized to improve on timing performance
wafer thickness is an important aspect:
The thicker the wafer the better the time resolution





N. Akchurin, V. Ciriolo, E. Currás, J. Damgov, M. Fernández, C. Gallrapp, L. Gray, A. Junkes, M. Mannelli, K. H. Martin Kwok, P. Meridiani, M. Moll, S. Nourbakhsh, S. Pigazzini, C. Scharf, P. Silva, G. Steinbrueck, T. T. de Fatis, and I. Vila, On the Timing Performance of Thin Planar Silicon Sensors, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 859, 31 (2017).

LGAD-based



Multiplication takes place in a limited space reducing the time spread

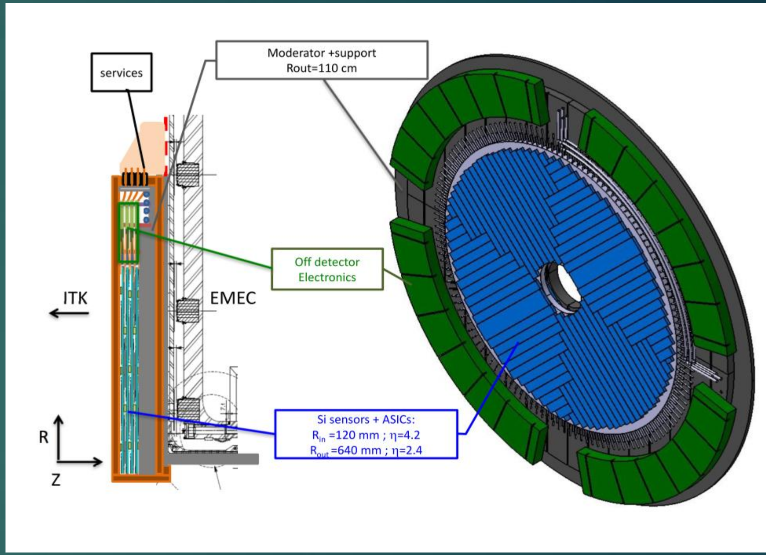
ATLAS HGTD

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

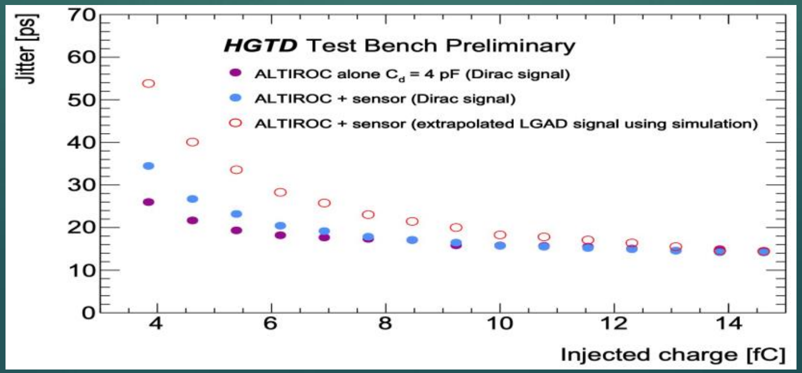


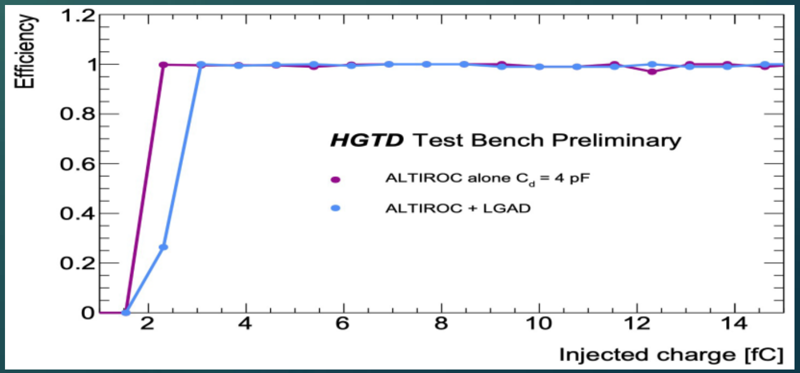
MTD (EndCaps of CMS) will also use the same technology

HGTD

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

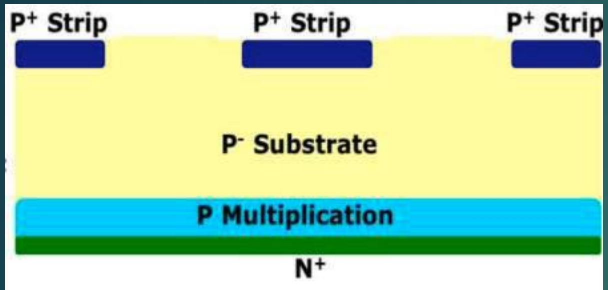
Courtesy Z. Liang

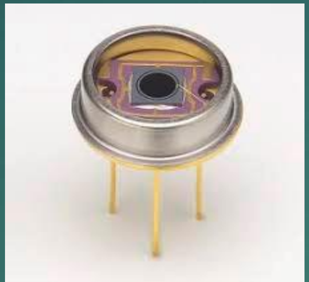


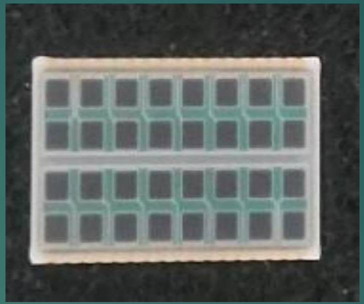


LGAD-based

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



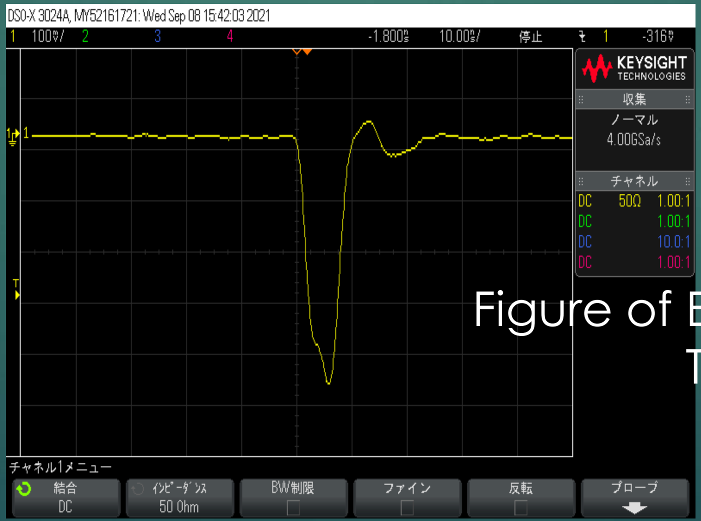

Single cell


Multi cell

Courtesy T. Suehara

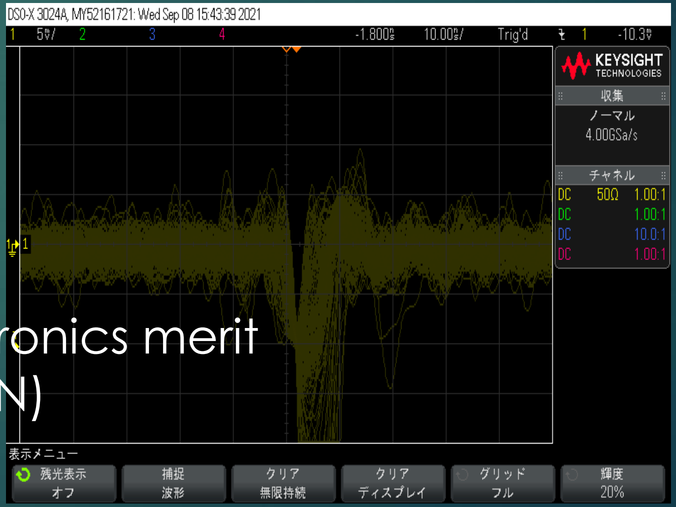
CALICE collaboration has started a new development to investigate the possibility to replace the silicon-based ECAL by a LGAD-based one

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



Pulse height ~500 mV, rise time ~ 2 ns

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



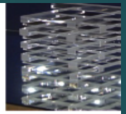
Noise ~ 2 mV (sigma)

Scintillator/Crystal-based

Using scintillation materials with fast response that are read out by fast photo-detectors adds to the excellent energy resolution, a timing information that can help not only to mitigate pileup but also to improve on the energy resolution.

Inorganic materials seem to perform better than others but big efforts are made to find new materials or revisit old ones

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 1[st] 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

Scintillator/Crystal-based

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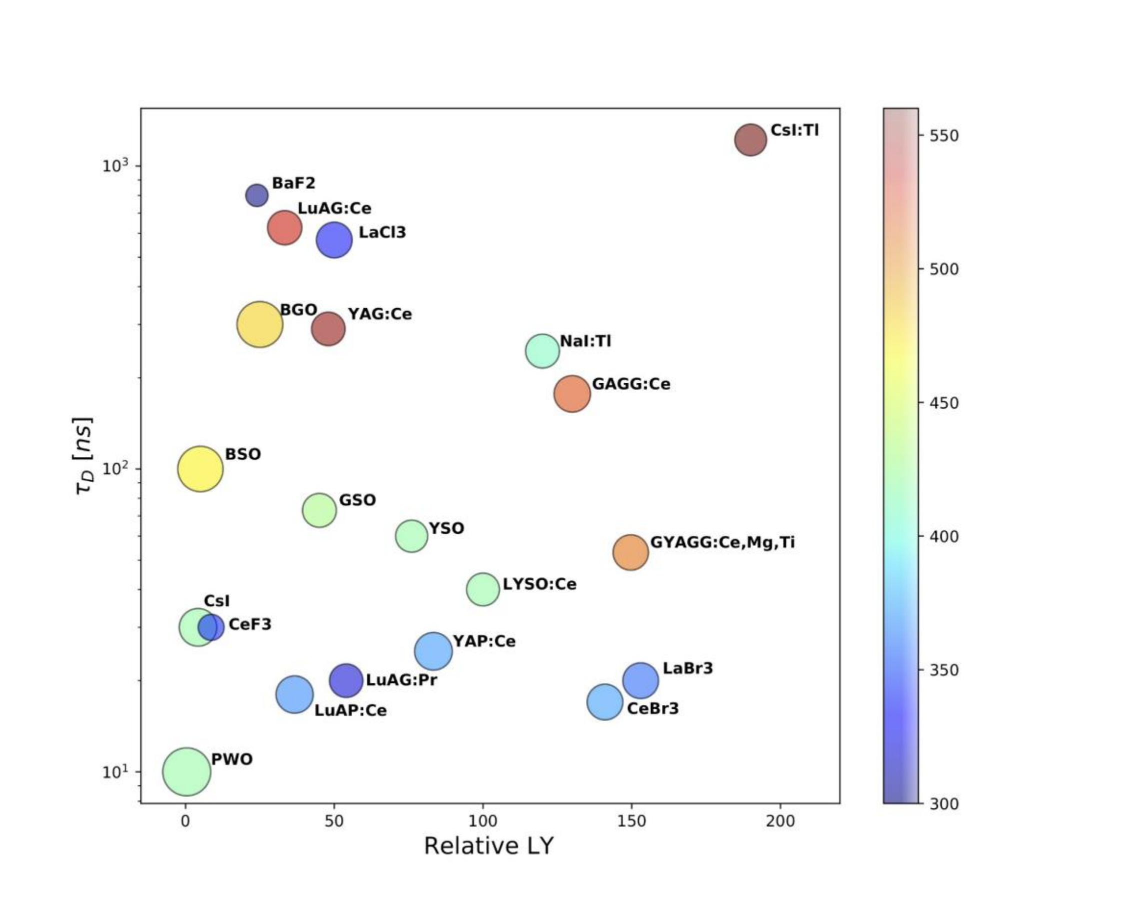
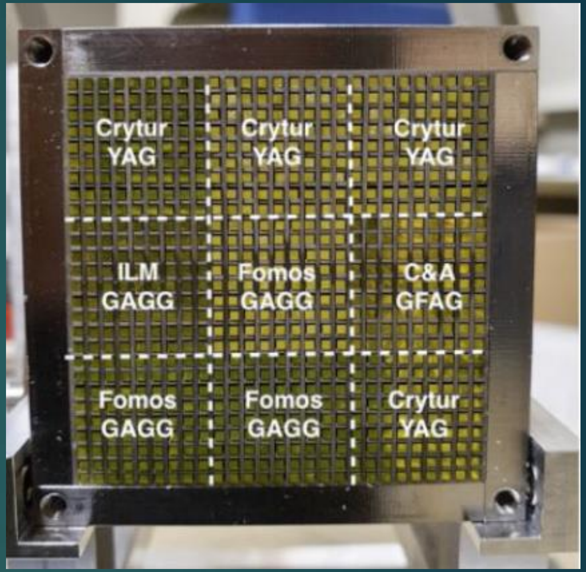


Scintillator/Crystal-based

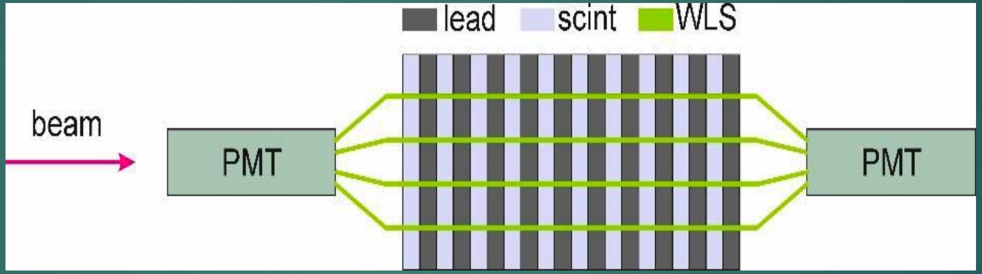
LHCB ECAL upgrade

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



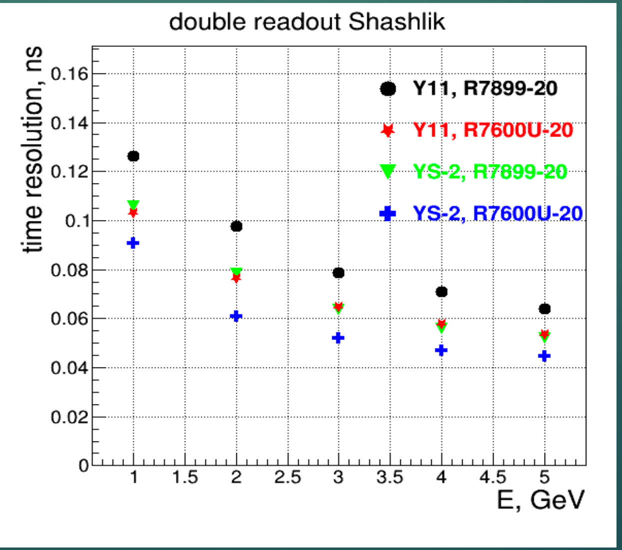
Courtesy of A.Schopper

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



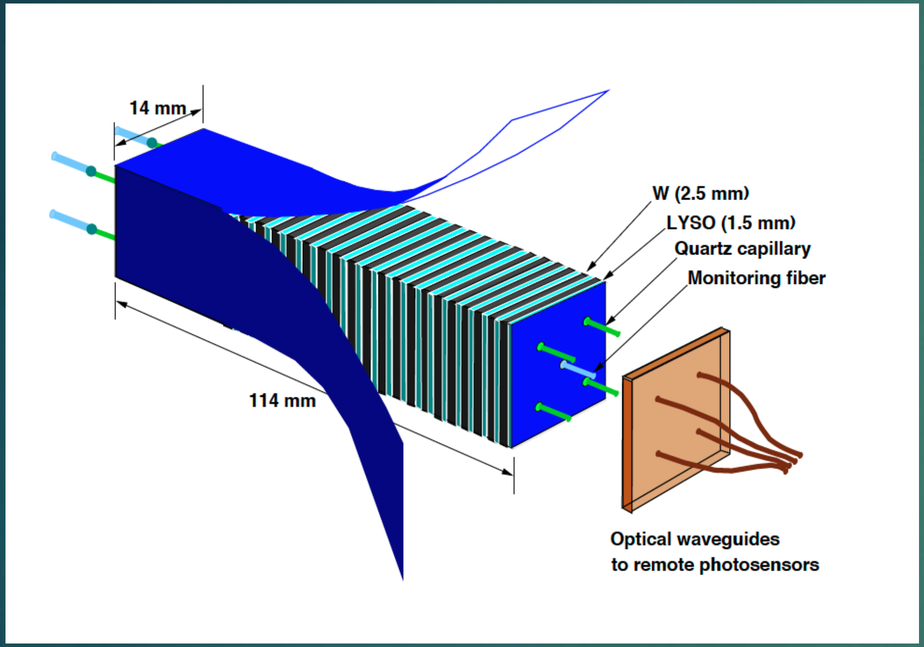
Photodetector
Use better PMT (small transit time spread and transit time uniformity over the photocathode)
- R7899-20 (TTS ≈ 1-2 ns)
- R7600U-20 (TTS ≈ 0.35 ns)

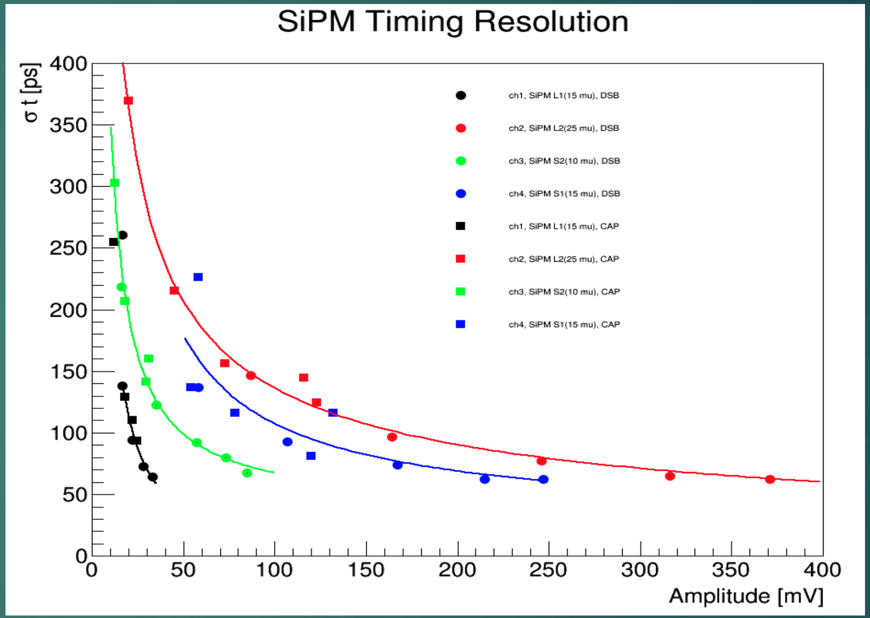
WLS fibers
- Use WLS fibers with shorter decay time
- Y11 decay time ≈ 7 ns
- Research work is ongoing in KURARAY aiming to develop faster WLS fibers with good light yield
- New KURARAY WLS: YS-2 (≈ 2.7 ns)



Scintillator/Crystal-based

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

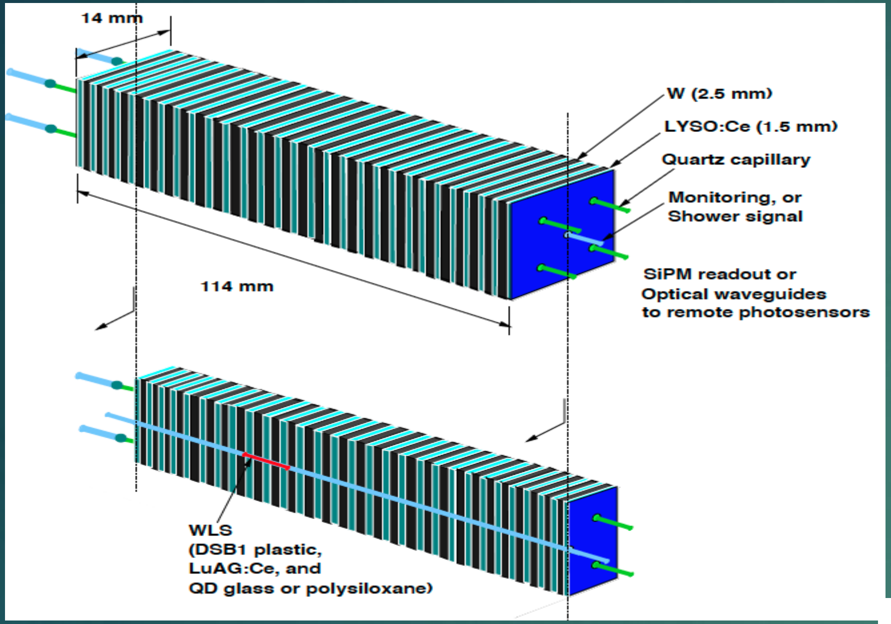




Courtesy R. Rushti

LYSO/W module, single channel time resolution with SiPM readout. Waveshifter readout was either DSB1 WLS dye in a multiclad optical fiber (dots) or DSB1 WLS in a liquid-filled capillary (squares). Fermilab Test Beam, A. Bornheim et al.

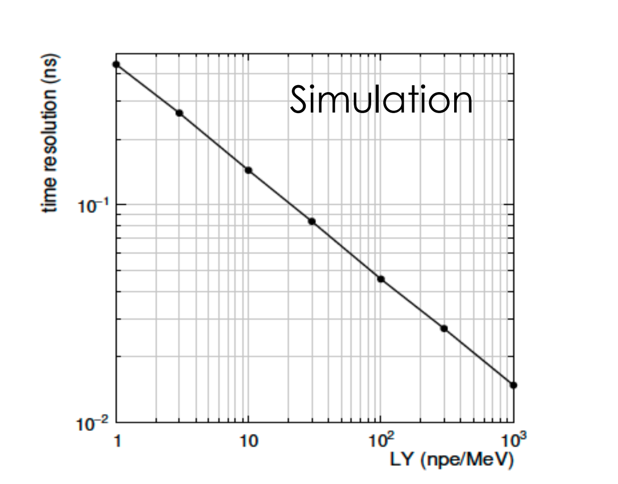
Scintillator/Crystal-based

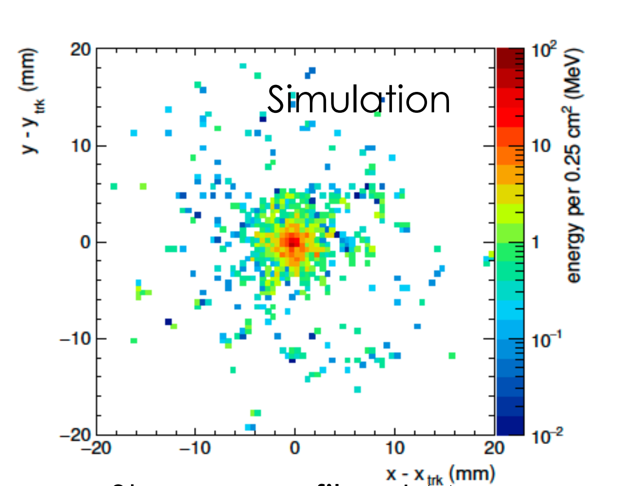


Time information is one of the main features

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

2. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing with quartz rods and the WLS capillary structures which are predominantly quartz material.



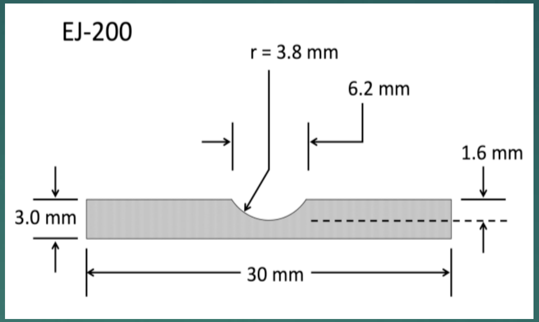


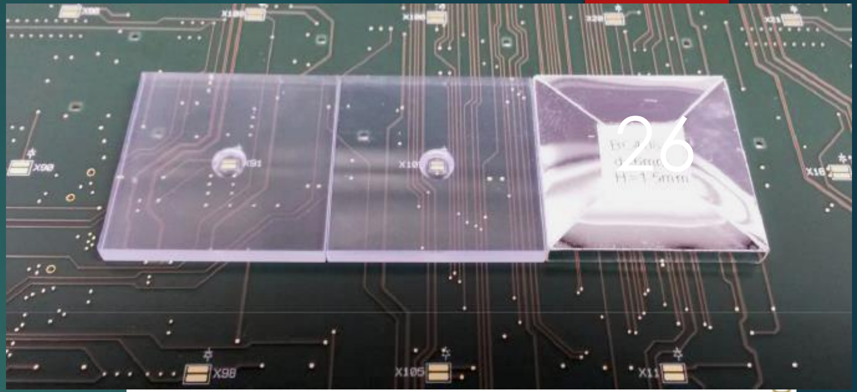
Shower profile at Max.

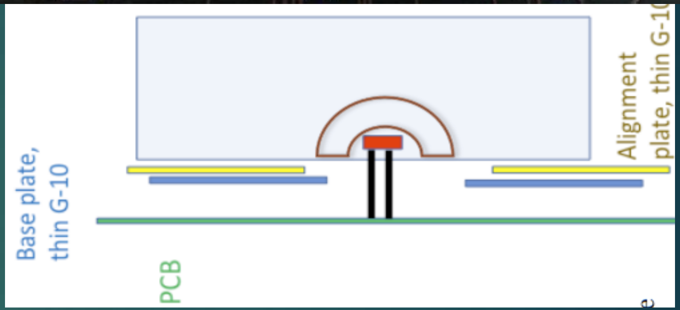
GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV

Courtesy R. Rushti

Scintillator/Crystal-based





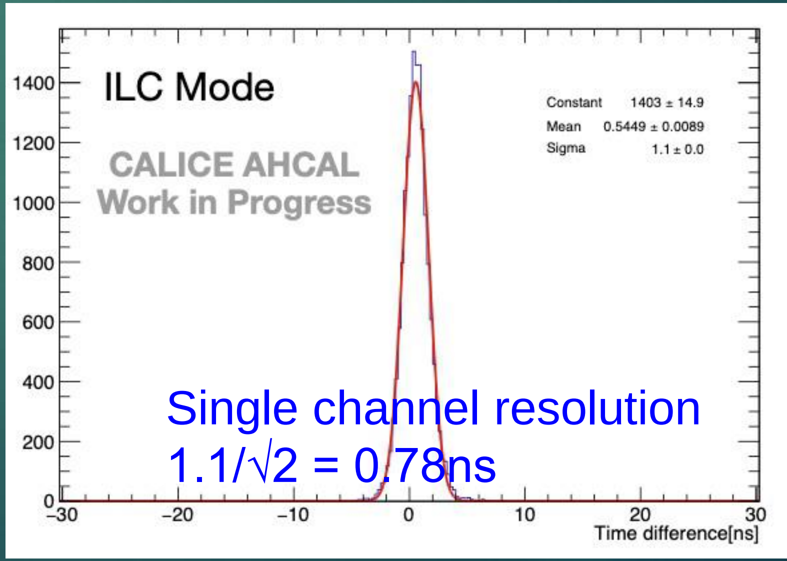


CALICE AHCAL uses 3cm X 3cm tiles read out by SiPM

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)



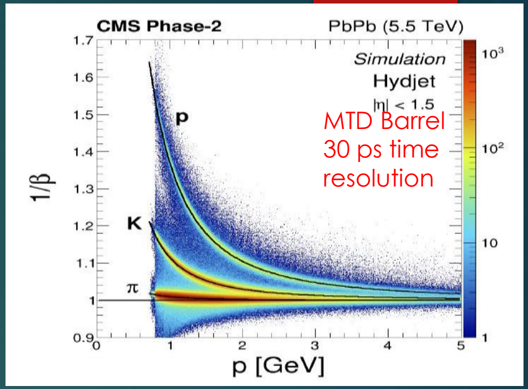
Courtesy M. Kroen

Scintillator/Crystal-based

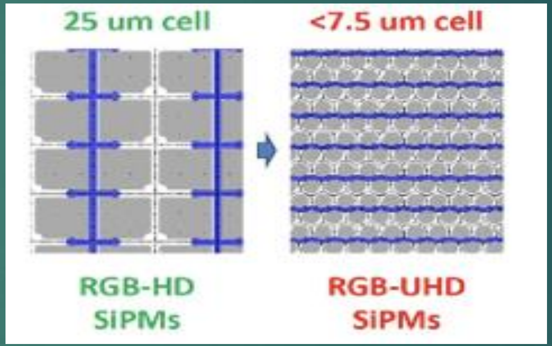
SiPM is becoming an important piece of the scintillator/crystal detectors/calorimeters
Associated to fast Scintillator/crystals
it can provide excellent time resolution

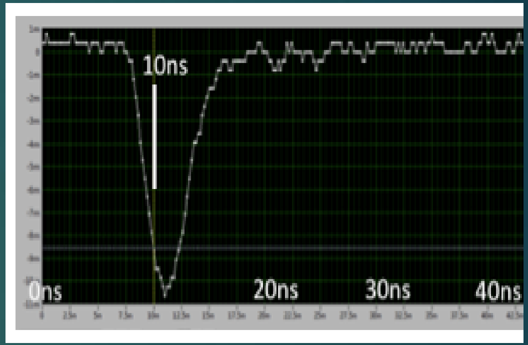
Time resolution of ~30 ps for single MIPs with single LYSO layer is expected from MTD (CMS, Barrel)

Array of LYSO crystals (CMS MTD)

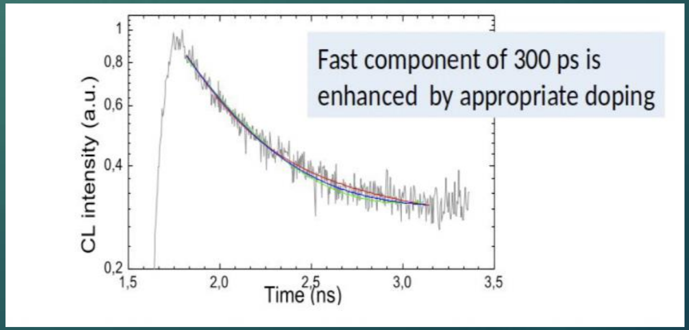


Efforts to go for small pixels < (10 µm) are to be carefully followed since the smaller the pixel the better the faster the time response.





Developments of the so-called Nano crystals (such as Perovskite sensitizer, CsPbBr3) that feature sub-nanosecond scintillation with good LY as well as colloidal quantum dot technology are ongoing and could lead to a breakthrough

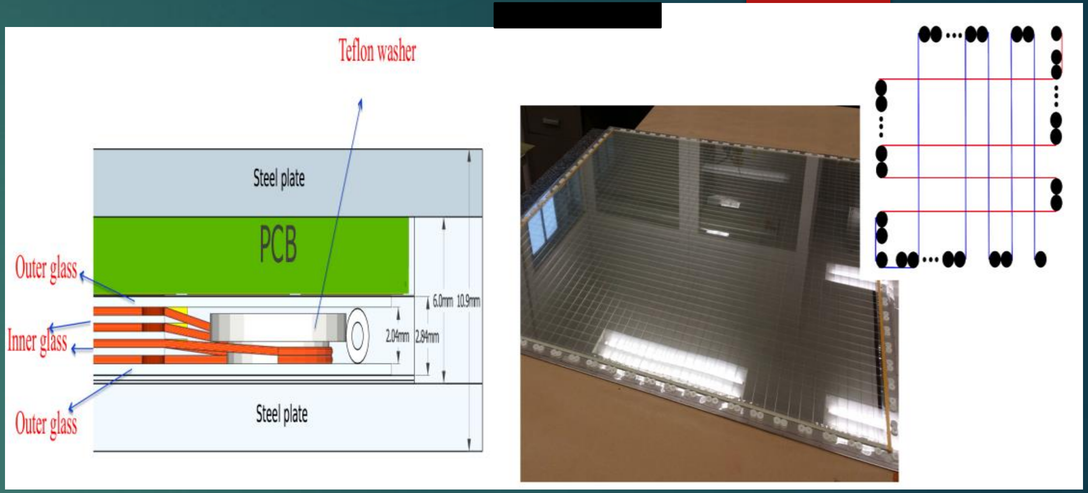


Courtesy of M.Korjik and G.Tamulaitis

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

Gaseous Calorimeters

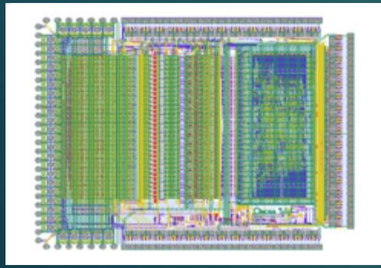
SDHCAL concept is being transformed into T-SDHCAL

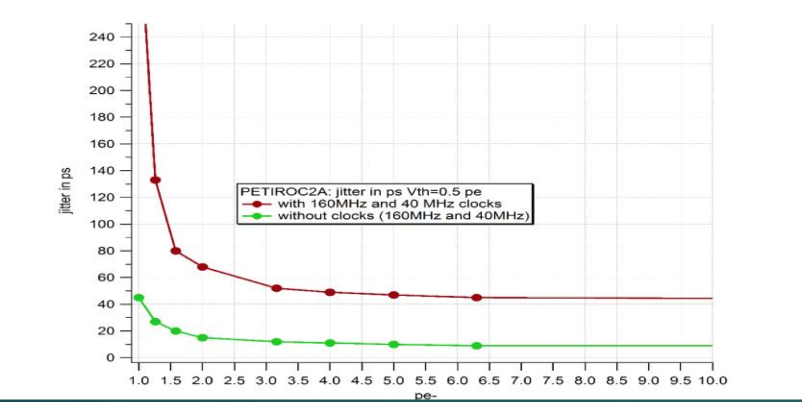


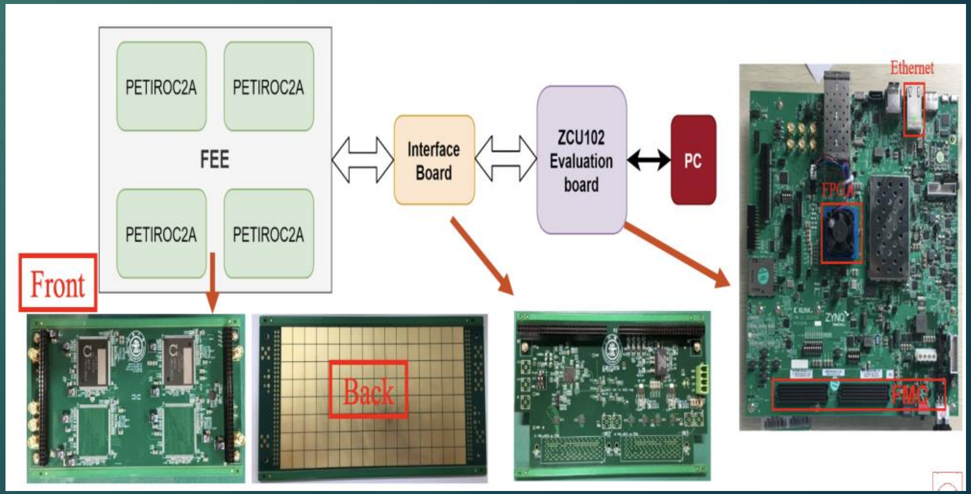
- ❑ RPC are replaced by MRPC (much faster)
- ❑ Semi-digital electronics (HARDROC) is replaced by low-time jitter PETIROC (> 20 ps @Q> 300 fC)

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

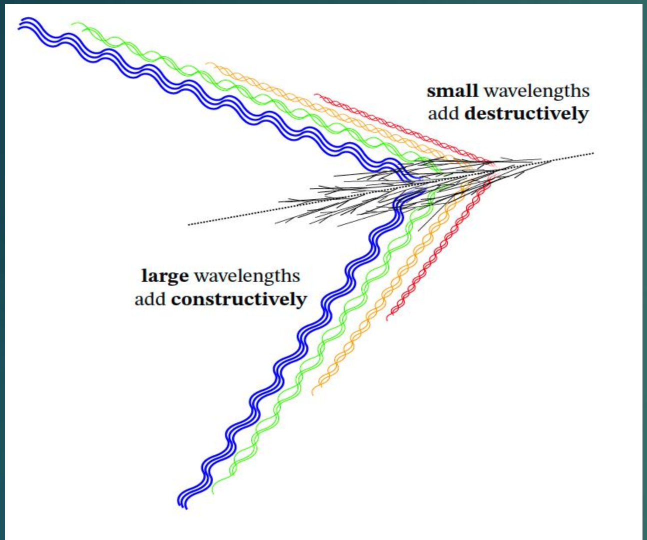


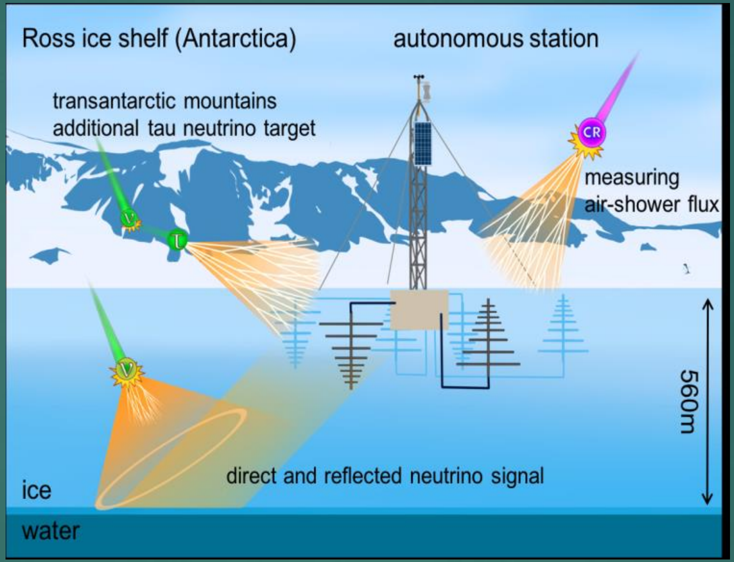


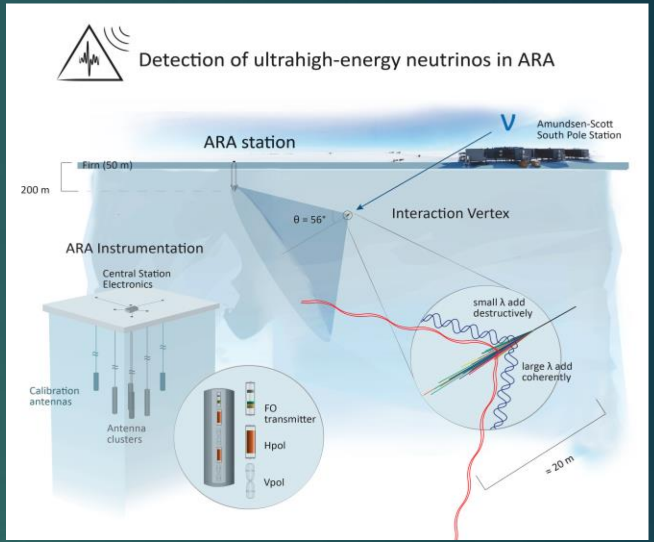


Askaryan Calorimeter

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







Courtesy R. Preschelt

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

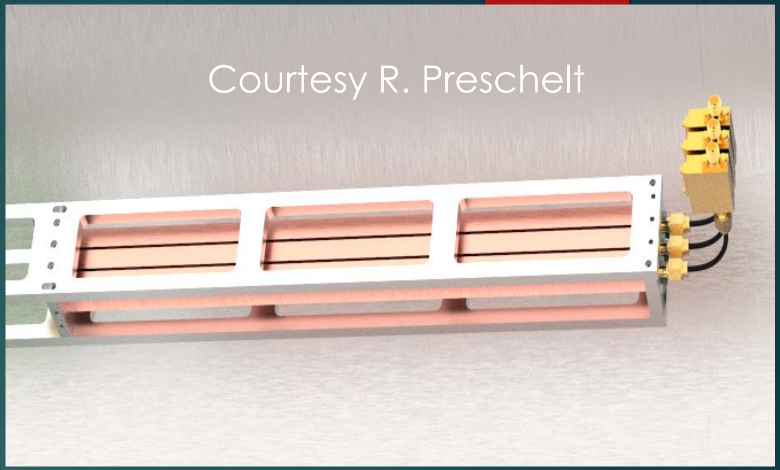
A small prototype was built:

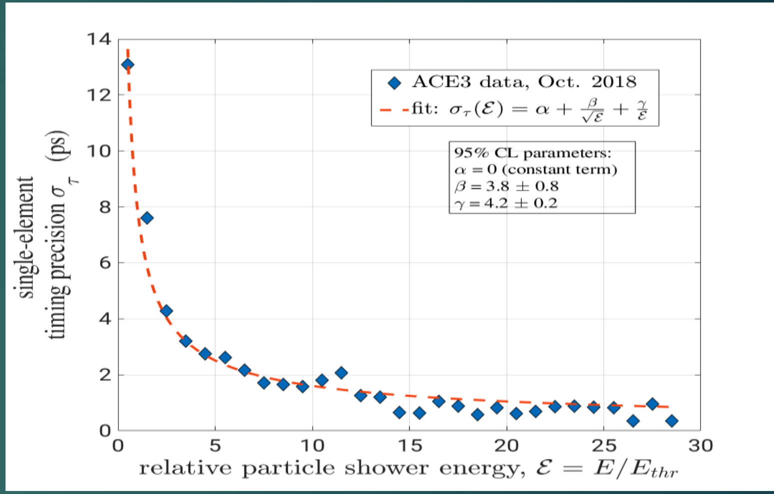
- Standard WR51 (12.6mm x 6.3mm) copper waveguides loaded with alumina bars (Al_2O_3) are used.

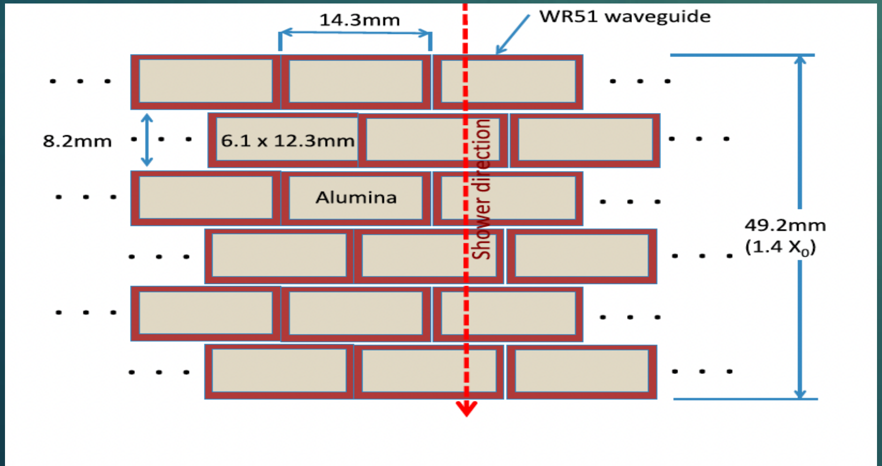
- Askaryan (microwave Cherenkov) from a shower moving through the waveguide is coupled into the TE10 mode (5-8 GHz) and propagates to each end.

- The ns-scale pulse is amplified with low-noise amplifiers (LNAs) and sample 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!







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

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

$$E_{\rm thr} \sim 20\text{ GeV}$$

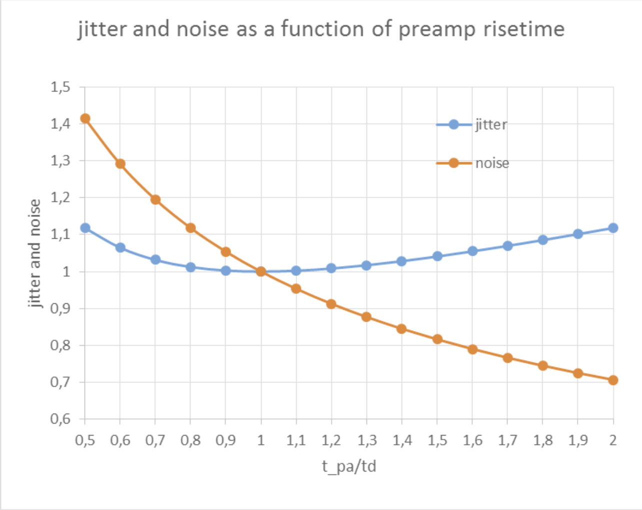
Electronics For time measurement

Role of electronics of time precision:

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

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

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



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

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.