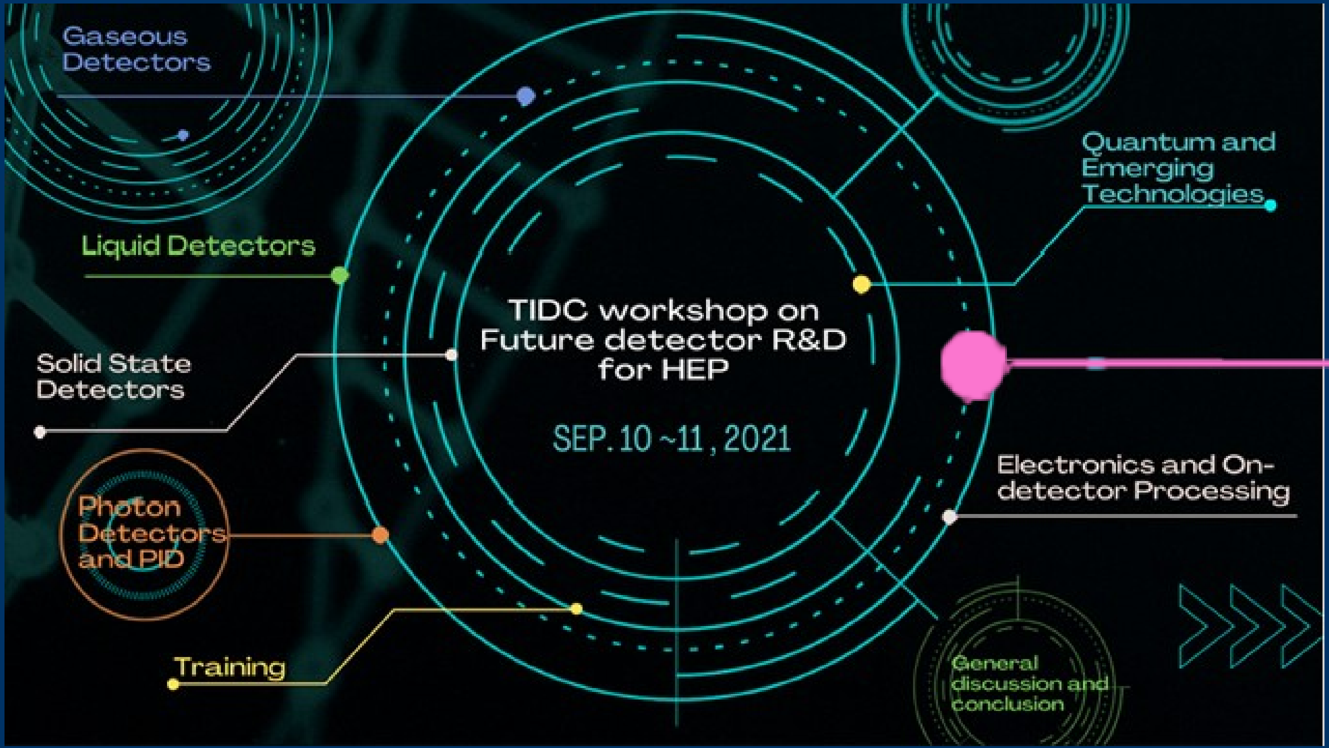
Summary of ECFA 2021 TF6

R&D roadmap for future CAL



Calorimetry

2021,0911 (0900 ~ 0930)
Jing-Ge Shiu/NTU

Symposium agenda

8:59 AM → 9:00 AM **Answers to TF6 Questionnaire**

Answers-DidierCon... | Answers-Gerald-Eig... | ECFA TF6 Question... | Questions of TF6 C...

9:00 AM → 9:25 AM **Introduction**

Speakers: Philip Patrick Allport (University of Birmingham (UK)) , TF6 Taskforce

talk070521-final.pdf

9:30 AM → 9:55 AM **Lessons learned: calorimeter upgrade R&D for HL-LHC & by Calice**

Speaker: David Barney (CERN)

ECFA_TF6_Lessons... | ECFA_TF6_Lessons...

10:10 AM → 10:30 AM **Precision timing and their applications in calorimetry**

Speaker: Nural Akchurin (Texas Tech University (US))

ECFA_PrecisionTim... | ECFA_PrecisionTim...

10:45 AM → 11:00 AM **Coffee break**

11:00 AM → 11:20 AM **Si based highly and ultra-highly granular calorimeters**

Speaker: Vincent Boudry (LLR – CNRS, École polytechnique, Institut Polytechnique de Paris)

ECFA_TF6_SiHGCal... | ECFA_TF6_SiHGCal... | ECFA_TF6_SiHGCal...

11:35 AM → 11:55 AM **Future Noble Liquid Systems**

Speaker: Brieuc Francois (CERN)

ECFA_TF6_NobleLi...

12:10 PM → 12:25 PM **Gaseous calorimeters**

Speaker: Maria Fouz Iglesias (Centro de Investigaciones Energéti cas Medioambientales y Tecno)

ECFATF6_Gaseous...

12:30 PM → 12:45 PM **Discussion and spillover**

12:45 PM → 1:55 PM **Lunch break**

1:55 PM → 2:15 PM **Tile and strip calorimeters**

Speaker: Katja Kruger (Deutsches Elektronen-Synchrotron (DE))

TF6_Tiles_strips_v2...

2:30 PM → 2:50 PM **Crystal calorimetry**

Speaker: Marco Toliman Lucchini (Princeton University (US))

2021_05_07_ECFA_...

3:05 PM → 3:25 PM **R&D for Dual-Readout fibre-sampling calorimetry**

Speakers: Gabriella Gaudio (INFN-Pavia) , Gabriella Gaudio (Dipartimento di Fisica Nucleare e Teorica)

20210407_DualRea...

3:40 PM → 3:55 PM **Coffee break**

3:55 PM → 4:15 PM **Compact and high performant readout systems**

Speaker: André David (CERN)

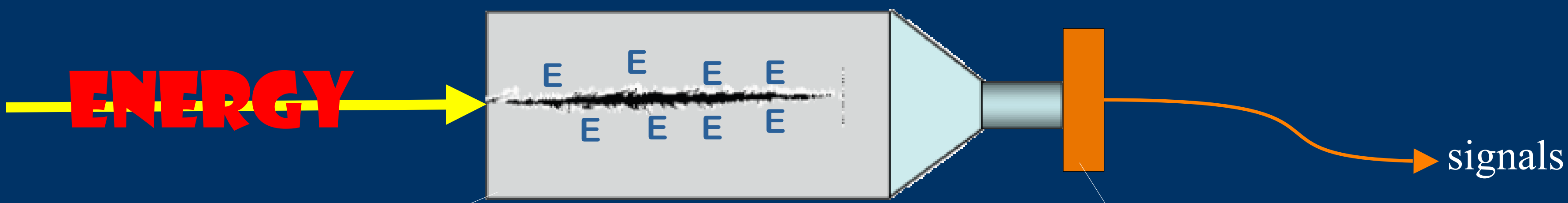
20210507 ECFA TF...

4:30 PM → 6:00 PM **Wrap up and discussion**

Speaker: TF6 Taskforce

tf6-symposium-dis... | tf6-symposium-dis...

Calorimeter: split a bulk of energy into pieces which your detector can see, and try to collect them as much as possible.（化整為零，各個擊破）



Sensor
(active medium, scintillator, raidator)

Sensor arrangement
(homogeneous, sampling, ...)

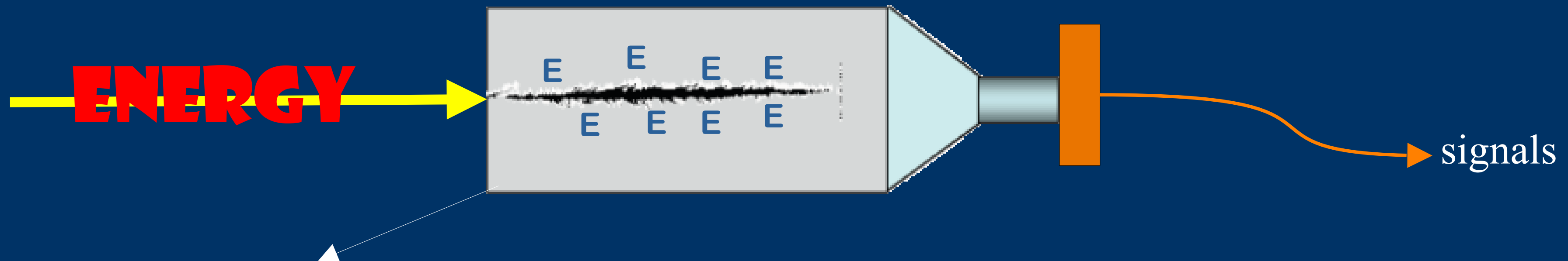
Detector (transducer)
and readout electronics

Data processing
and algorithm

Others
Precision timing measurement in CAL.
Lesson learned in R&D and construction

Discussion

Calorimeter: split a bulk of energy into pieces which your detector can see, and try to collect them as much as possible.（化整為零，各個擊破）



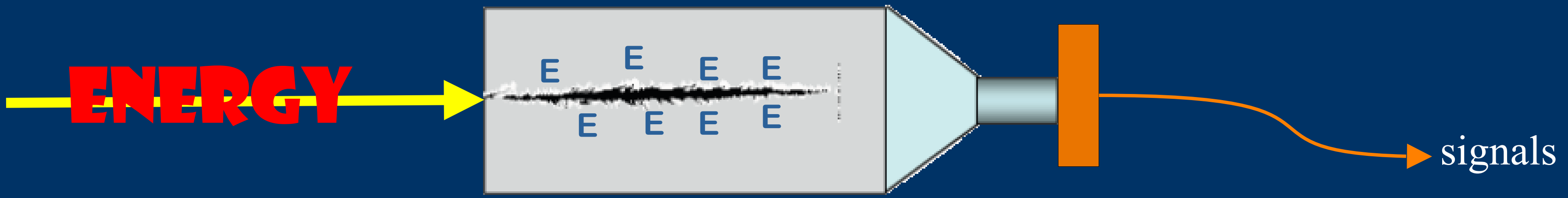
We more or less know what happened inside this material, but not yet make use of that as much as possible. In general, we just count the collected energy channel by channel to get a 2D+E dimensional shower information. Plus matching with tracker and some pattern recognition algorithm, we could roughly distinguish showers from different particles, but very hard to separate mixed showers in one cluster. Energy and 2D spatial resolutions are the major concern in the past.

However, (due to scientist's ambition, feasible in technology and budget(?)), the R&D of CAL. moves toward 3D+E+t (5D) measurement

→ high granularity, segmented CAL.

→ precise timing

Calorimeter: split a bulk of energy into pieces which your detector can see, and try to collect them as much as possible.（化整為零，各個擊破）



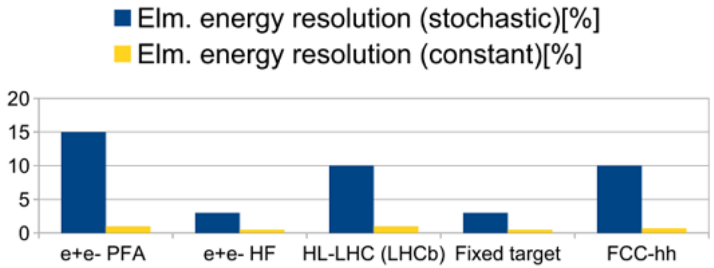
- General consideration for future projects
- Precision timing measurement in CAL.
- Sensor (active medium and arrangement)
- Readout system (TF7)
- Lesson learned in R&D and construction (TF8+9)
- Summary and discussion

General consideration for future projects

- Detector at future high energy e+e- colliders → manpower for CAL.
- Detectors at future hadron colliders
  - calorimeters can stand severe conditions w/o degradation (or upgrades are priced in from the beginning)
- Requirements on energy resolution
  - ultimate energy resolution may not be the key metric
- Requirements on timing precision is a wide field
  - a look to 2030 make resolutions 20~100ps?!

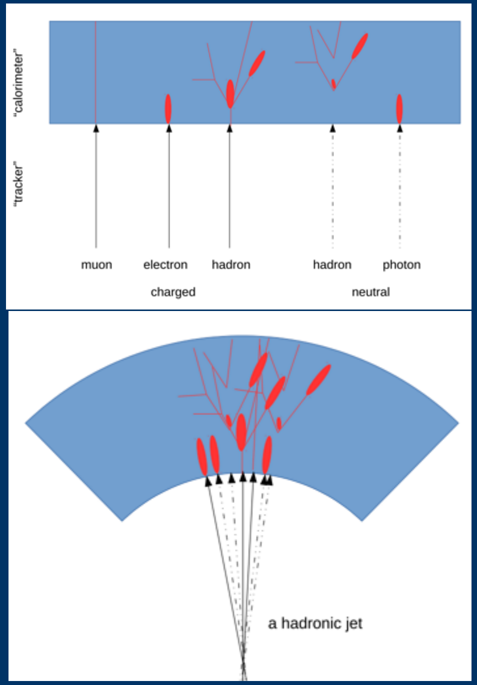
- For which purpose ?
  - Mitigation of pile-up (basically all high rate experiments)
  - Support of PFA – unchartered territory
  - Calorimeters with ToF functionality in first layers?
    - Might be needed if no other PiD detectors are available (rate, technology or space requirements)
    - In this case 20ps (at MIP level) would be maybe not enough
  - Longitudinally unsegmented fibre calorimeters

- Electromagnetic energy resolution (stochastic term):
  - HL-LHC (LHCb LS4): 10%
  - Linear e+e- Colliders: 10-15% (Particle Flow Based Approach)
    - May require another look
  - Circular e+e- Colliders: 3-15% (ranging from Heavy Flavour Programme to PFA requirements)
  - EiC: 2-10% depending on angular range
  - FCC-hh: 10% (Order of current ATLAS LAr-Calorimeter)
- Electromagnetic energy resolution (constant term):
  - Requirements formulated in input sessions range from ~0.5% to 3%
- Hadronic or rather jet energy resolution
  - Linear e+e- Colliders: 3-5% (Particle Flow Based Approach)
  - Circular e+e- Colliders: Same as Linear Colliders



Recent development direction shifts in CAL.

- Precision timing (motivated by need for pile-up suppression (t))
- High-granularity segmentation (energy, position measurements)
- Particle flow (combining CAL. and tracker information)
- Dual-readout (event-by-event compensation, e/h = 1)
- Ultimate energy resolution (by sensor+detector) may not be the key concern



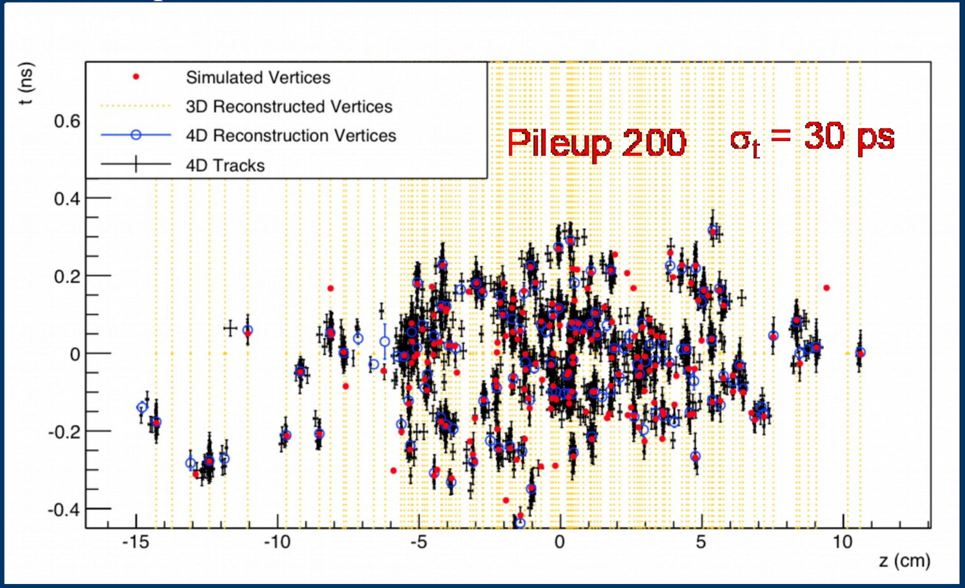
Traditionally, CAL. measured the energy collected in every channel in a "cluster" as a shower energy. Possible to use shower pattern recognition algorithm to distinguish the particles.

The particle flow approach is to use the best suited detector to measure the individual particles. (各司其職)
→ all charged particles reconstructed in tracker
→ neutral particles can be determined in the calorimeters.

This implies the possibility to separate charged and neutral particles in the calorimetric system. This challenge can be met by a calorimetric system with very high granularity that allows us to separate close-by particles, and well trained particle flow algorithms that are able to do effective clustering.
It is also aiming to improve the hadronic Jet energy measurement, which was mainly relied on HCAL.

Precision timing measurement in CAL.

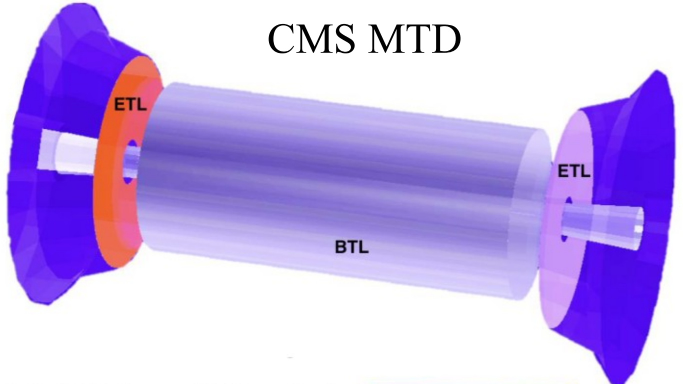
Power of precise time measurement → one motivation of this R&D



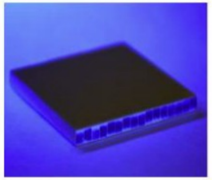
US DOE Basic Research Needs Study in HEP (2019)
In ~10 years, high precision 5D CAL. in e+e- machines
σ_t < 10 ps (e.g. long-live particles)
In ~20 years, high precision 5D CAL. in hh machines
σ_t < 5 ps (~ 1ps pile-up suppression and PID)
Ultrafast CAL.
σ_t < 1 ps

Key parts:
Active medium property
Photon detector (SiPM, LGAP, MCP-PMT)
Special designed ASIC for readout

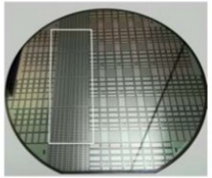
Applications:
- Separation of two signals close in time
- Effectively segment the CAL. in depth (longitudinal segmented CAL.)
- Apply to scintillation/Cherenkov light coexisting fiber.
- Enhancement in performance fast timing in NN (CNN, RNN, GNN).
- Study time spectrum of a shower
- Emerging digital sensors dSiPM

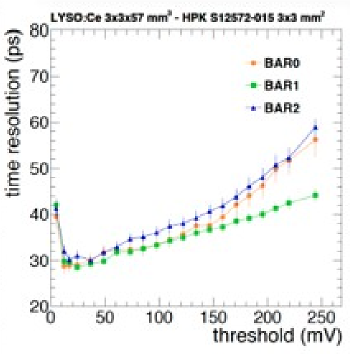


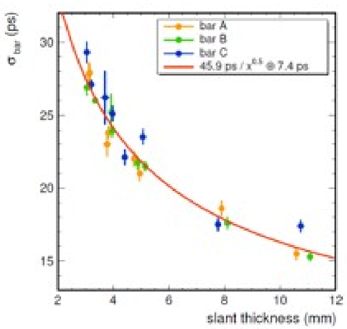
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2







σ_t^{min}= 28.4±0.4 ps

$$\sigma_t = \sigma^{phot} \oplus \sigma^{clock} \oplus \sigma^{elec} \oplus \sigma^{digi} \oplus \sigma^{noise} \oplus \ldots$$

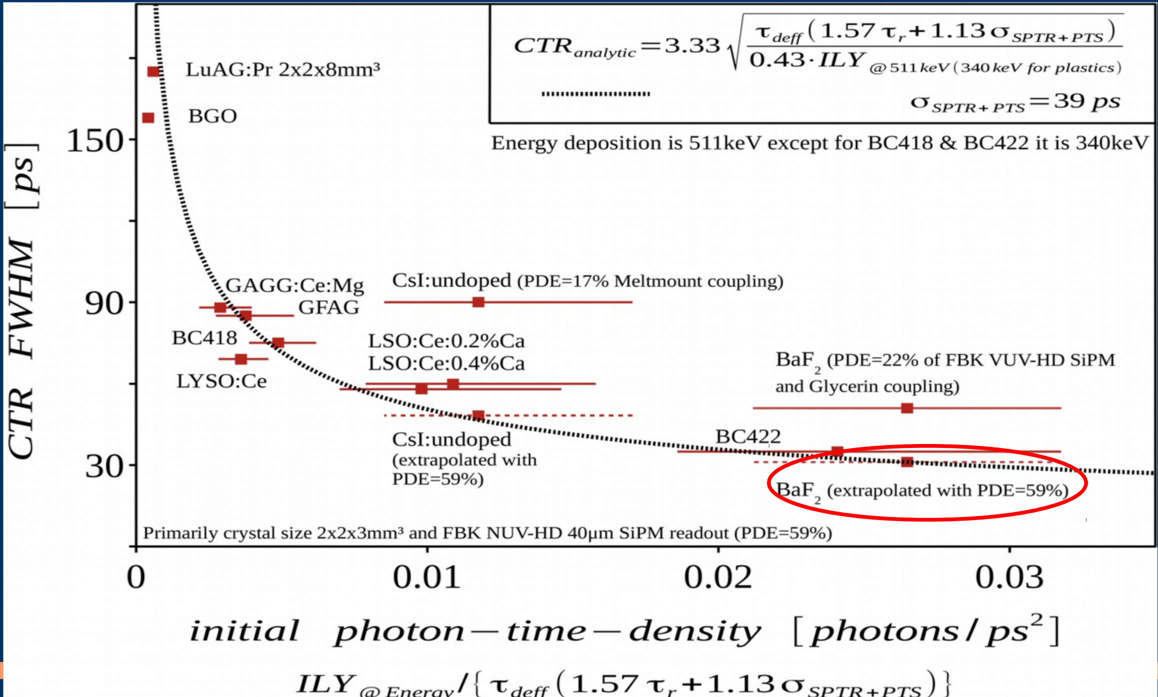
$$\sigma^{phot} \propto \sqrt{\frac{\tau_{rt}\tau_{ft}}{N_{pe}}} \approx \sqrt{\frac{\tau_{rt}\tau_{ft}}{E_{dep}(LY)\epsilon_{LC}(PDE)}}$$

readout

sensor

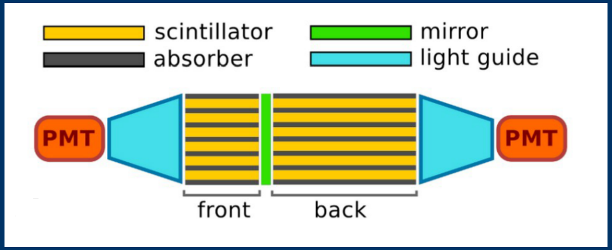
detector

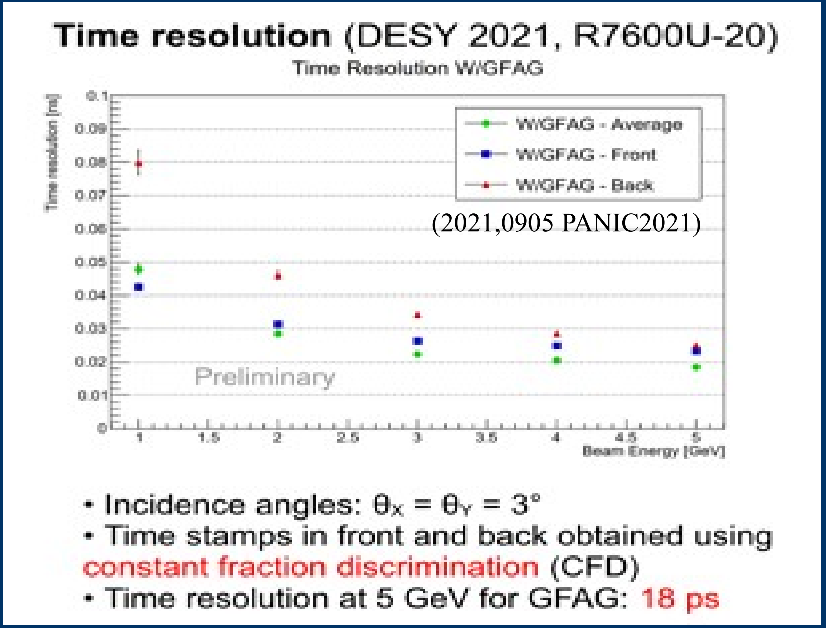
environment



[10]

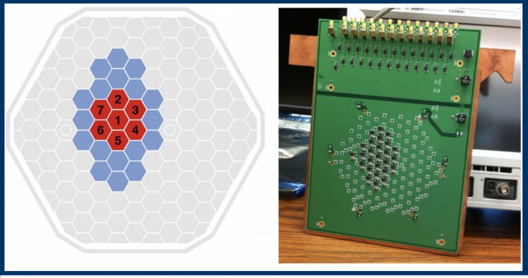
LHCb SPACAL-W

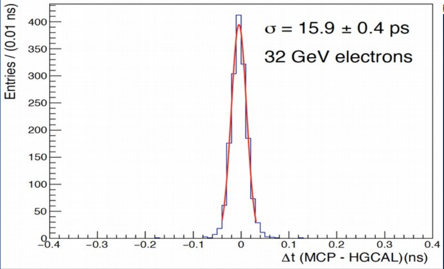


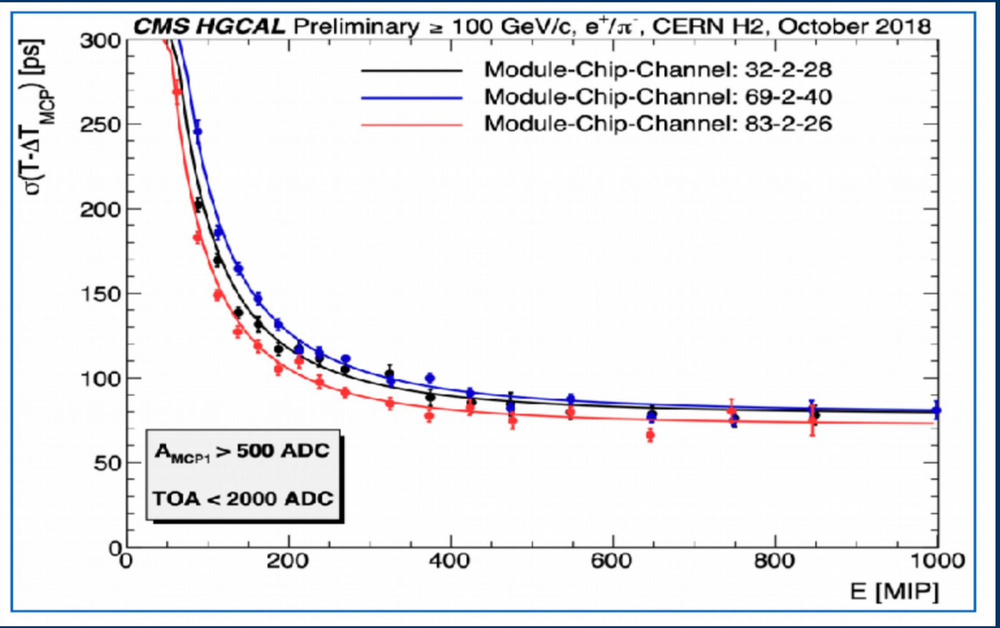


LHCb Shashlik: WLS+PMT, ~50ps@5GeV

CMS HGCAL



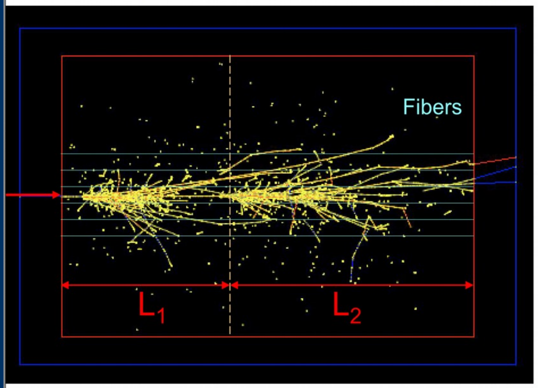




Silicon planar sensors for CAL. is a revolution.

Longitudinal segmented CAL. with precision timing

Fibers in spaghetti CAL. With appropriate timing strobes, it may be possible to segment the CAL. in depth.

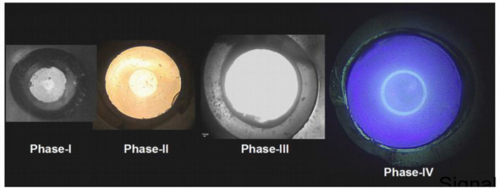


Signal time = $L_1/c + L_2/(c/n)$,
(c/n) = velocity of light in fiber (n~1.45)
~20 cm/ns or ~1 cm/50 ps

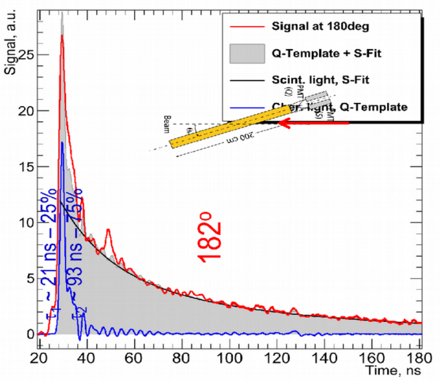
There is significant savings in channel count (and calibration) as one fiber represents many channels along the depth of calorimeter.

Scintillation/Cherenkov light in a single fiber

The Cherenkov light can be used for timing purpose.



The Cherenkov (SiO2) and scintillation (SiO2:Ce3+) light coexist in a single fiber and the balance between the two types of light can be “tuned.” Cherenkov light can be used for timing purposes



Sensor (active medium and arrangement)

Current options for (near) future CAL.

Project	~Earliest Start of data taking	Current Calorimeter options					
		Solid state TF3	Scintilling tiles/strips	Crystals	Fibre based r/o (including DR)	Gaseous TF1	Liquid Noble Gas TF2
HL-LHC (>LS4)	2030			✔	✔		
SuperKEKb (>2030)	2030			✔			
ILC	2035	✔	✔			✔	
CLIC	2040	✔	✔				
CEPC	2035	✔	✔	✔	✔	✔	✔
FCC-ee	2040	✔	✔	✔	✔	✔	✔
EiC	2030		✔	✔	✔		
FCC-hh (eh)	>2050	✔	✔				✔
Muon Collider	> 2050	✔	✔	✔	✔	✔	
Fixed target	“continous”		✔	✔	✔		✔
Neutrino Exp.	2030		✔				(✔)

In most of the cases final choices have still to be made.

Sensor (active medium and arrangement)

Solid state: natural selection for HG CAL., robust technology, rad. hard, fast and excellent S/N; intrinsic stability
fragile handling, expensive

Scintillating tile/strip: working horse for hadron CAL., relative cheap
rad. hard, complexity in integration, coarse information on shower shapes, pile-up rejection difficult

Crystal: large sampling fraction, excellent energy resolution, ok rad. hard., time resolution,cost effective, recyclable

Fiber-based readout: dual readout CAL.

Gaseous: small sampling fraction less than liquid and semiconductor, rad. hard, robust and less expensive
good candidate (RPC, MPGD) for HG
energy resolution is usually not a big consideration in design
good time resolution for this generation, can reach 100ps or lower with semiconductor glass.
gas mixture uniformity while covering large area, create dead zones if using smaller modules
size is also limited by available PCB size (~60cm)

Liquid noble gas: linear, radiation hard, stability over time
biggest challenge is to keep a good S/N and a low cross-talk for future project to get high granularity(!)
R&D on warm liquid tried.

Sensor (active medium and arrangement)

Solid state: natural selection for HG CAL., robust technology, rad. hard, fast and excellent S/N; intrinsic stability
fragile handling, expensive

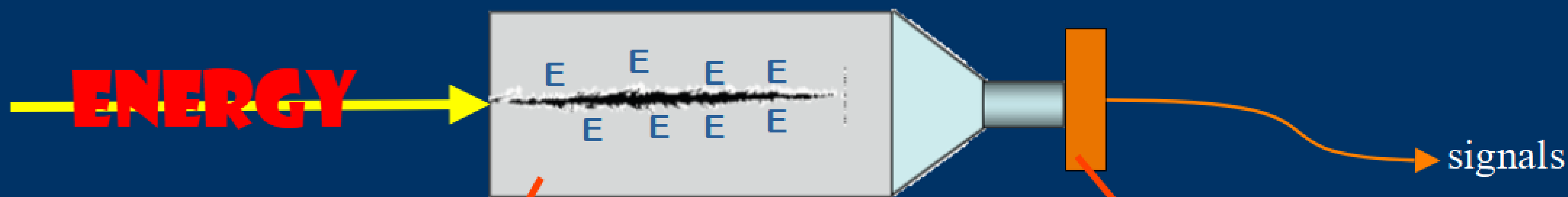
Scint

Cryst ble

Fiber

Gase

Liqui)



- gas
- liquid
- solid
  - solid-state (semiconductor)
  - crystal scintillator
    - crystal
    - plastic
    - …

- light yield
- response time

- radiation hardness
- stability
- uniformity
- ….

- PMT – industry monopolized?!
- Solid-state photo detector
  - PD
  - APD
  - LGAD
  - SiPM
  - …

- gain
- response time jitter

How small one channel can be and how precise the signal can be produced? → HG and precision timing

Tile and Strip CAL.

Thin scintillator tile or strip as sensor. The photodetectors and readout electronics could be outside (classical) or integrated in (integrated) the active volume

Comparison of the two concepts

Pros and Cons

Classical

+ Radiation hardness only determined by scintillator
+ Photodetectors and electronics can be replaced

- Limited number of channels
  + Relatively cheap
  + Customizable tile shape(s)
  – Coarse information on shower shapes
  – Very sensitive to single cell calibration
  – Pile-up rejection difficult
  – Not optimal for Particle Flow

Integrated

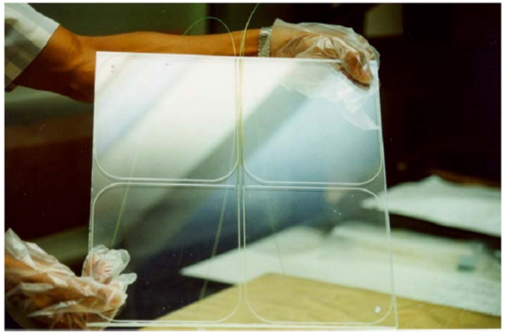
– Also photodetector and electronics in radiation area
– Only complete detector units can be replaced

- Large number of channels possible
  – More expensive (but still moderate cost)
  – Scalable production techniques needed
  + Detailed information on shower shapes
  + Only sensitive to global calibration shifts
  + Pile-up separation possible
  + Optimisation for Particle Flow Algorithms

Tile and Strip CAL.

"Classical" scintillator tile calorimeters

Working horse for hadron calorimeters



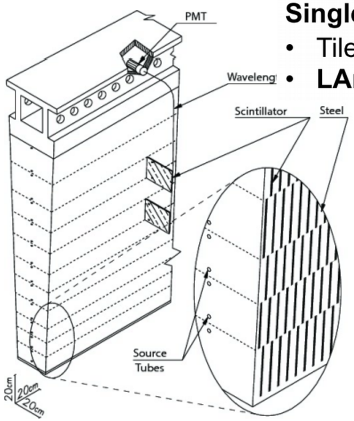
CMS HO tile

Characteristics:

- Relatively large scintillator tiles (typically ~20*20 cm^2)
- Photodetector and readout electronics outside of active volume
  - Light transport via WLS fibre
  - Grouping of tiles into readout channels

Examples:

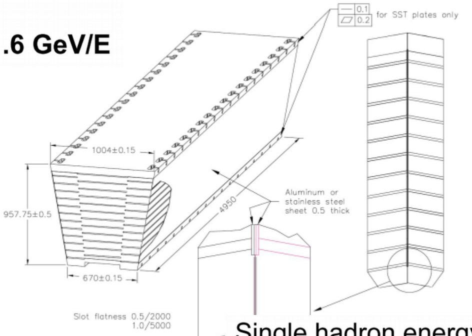
- **ATLAS TileCal:** 500,000 plastic scintillator tiles, ~10,000 readout channels in Barrel + Extended Barrel
- **CMS HCAL:** 70,000 tiles (barrel) + 20,000 tiles (endcaps), 2592 readout channels each

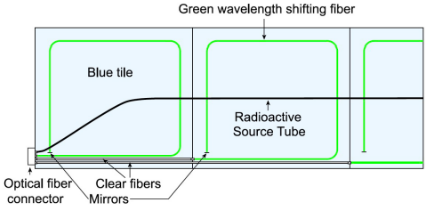


Single hadron energy resolution (testbeam)

- TileCal stand-alone: ~56% $\sqrt{E} \oplus 5.5\%$
- **LAr-ECAL+ TileCal: ~52% $\sqrt{E} \oplus 3\% \oplus 1.6$ GeV/E**

ATLAS TileCal





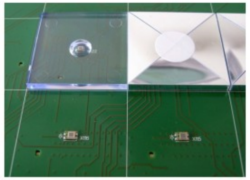
CMS HCAL

Single hadron energy resolution (testbeam)

- ~110%/ $\sqrt{E} \oplus 7\%$ (without weighting) (ECAL π/e=0.55 … 0.7)

Tile and Strip CAL.

"Integrated" scintillator tile and strip calorimeters



Scintillator calorimeters going high granularity

Characteristics

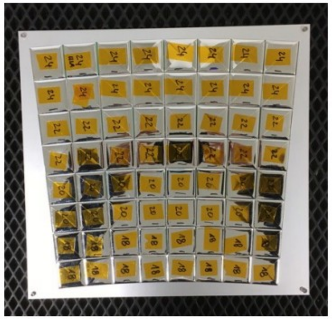
- Photodetector (SiPM) and frontend electronics integrated in active volume
- Small tiles and strips possible
- Individual readout of each tile (strip)

Examples

- Scintillator part of **CMS HGCAL** (endcap): 2.5*2.5 to 5.5*5.5 cm² tiles, ~240,000 tiles (= readout channels)
- **CALICE AHCAL**: 3*3 cm² tiles, ~24,000 tiles (prototype), ~8,000,000 tiles (ILC detector)
- **CALICE ScECAL**: 0.5*4.5 cm² strips, ~6,000 strips (prototype), ~10,000,000 strips (ILC detector)

first application in a collider detector

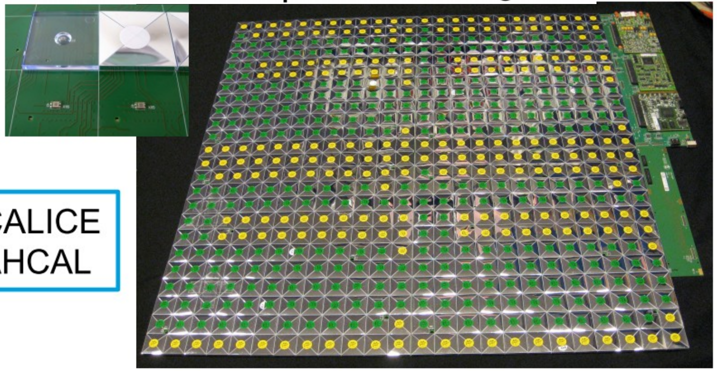
CMS HGCAL



Single hadron energy resolution 58% √E ⊕ 1.6%

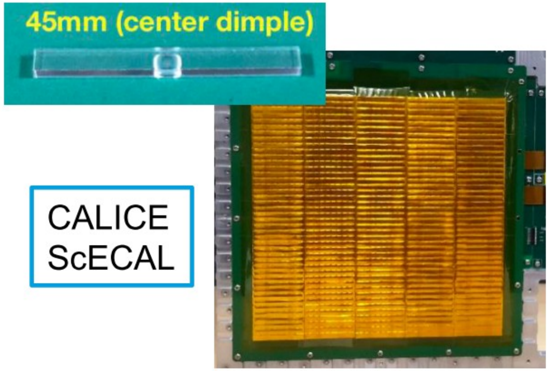
- **With software compensation 44% √E ⊕ 1.8%**

CALICE AHCAL



Electron energy resolution 12.5% √E ⊕ 1.2%

CALICE ScECAL

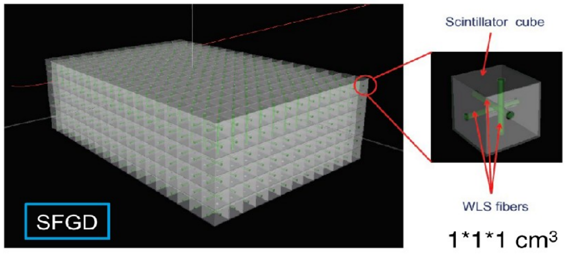


Tile and Strip CAL.

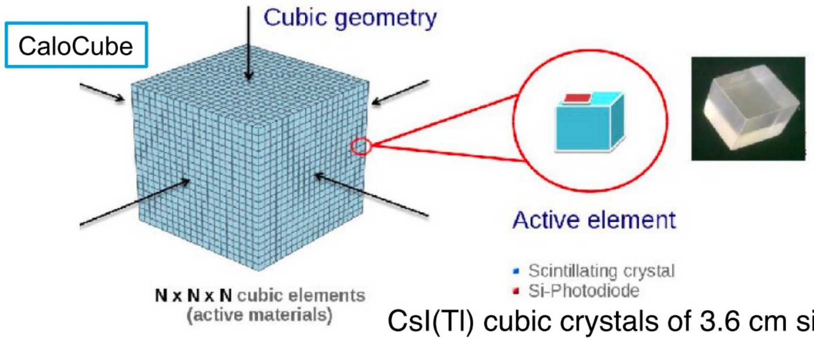
Potential of tile and trip scintillation CAL. by far not exhausted

- Concepts for future experiments: Higgs Factories, DUNE ND-Gar, FCChh
- Ideas for future developments: timing, spectral sensitivity, novel materials, ...
  towards 5D CAL.: dual readout for energy reconstruction
  HG with PFA for shower time spectrum
- Explore to ultimate granularity:

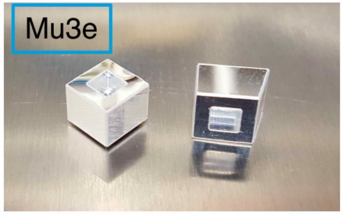
  - CaloCube: EM calorimeter for satellite experiment with large angular acceptance
  - HyperK ND280 Super-Fine-Grained Detector: active target (and tracker) for neutrino interactions
  - Mu3e tile detector: time measurement with ~50 ps resolution for MIPs



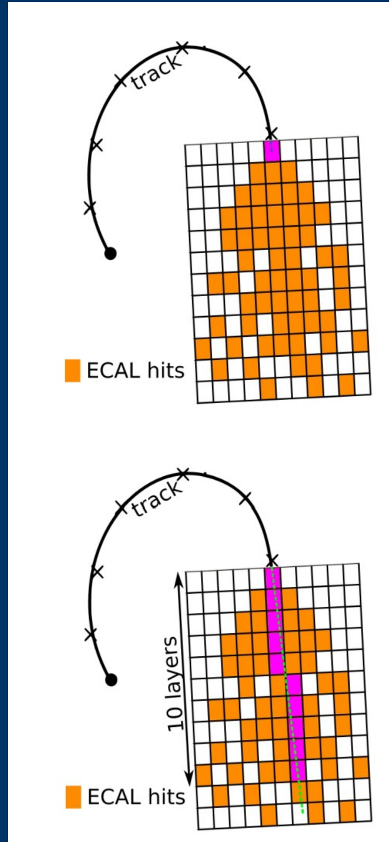
$1*1*1\ cm^3$



CsI(Tl) cubic crystals of 3.6 cm size

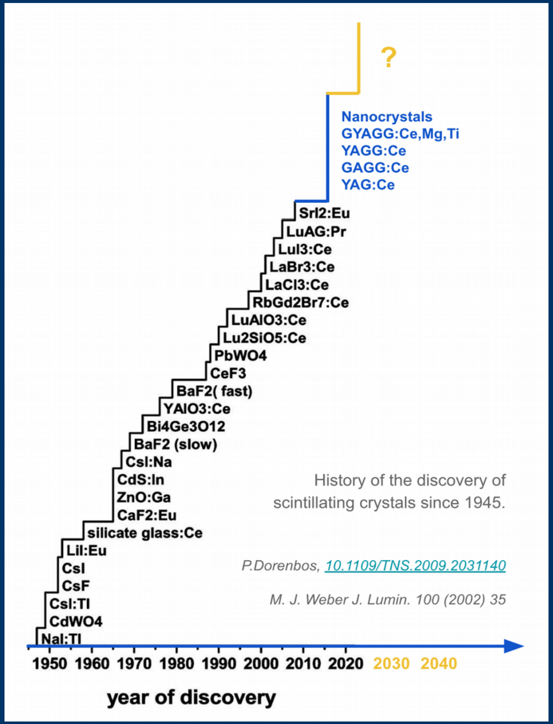


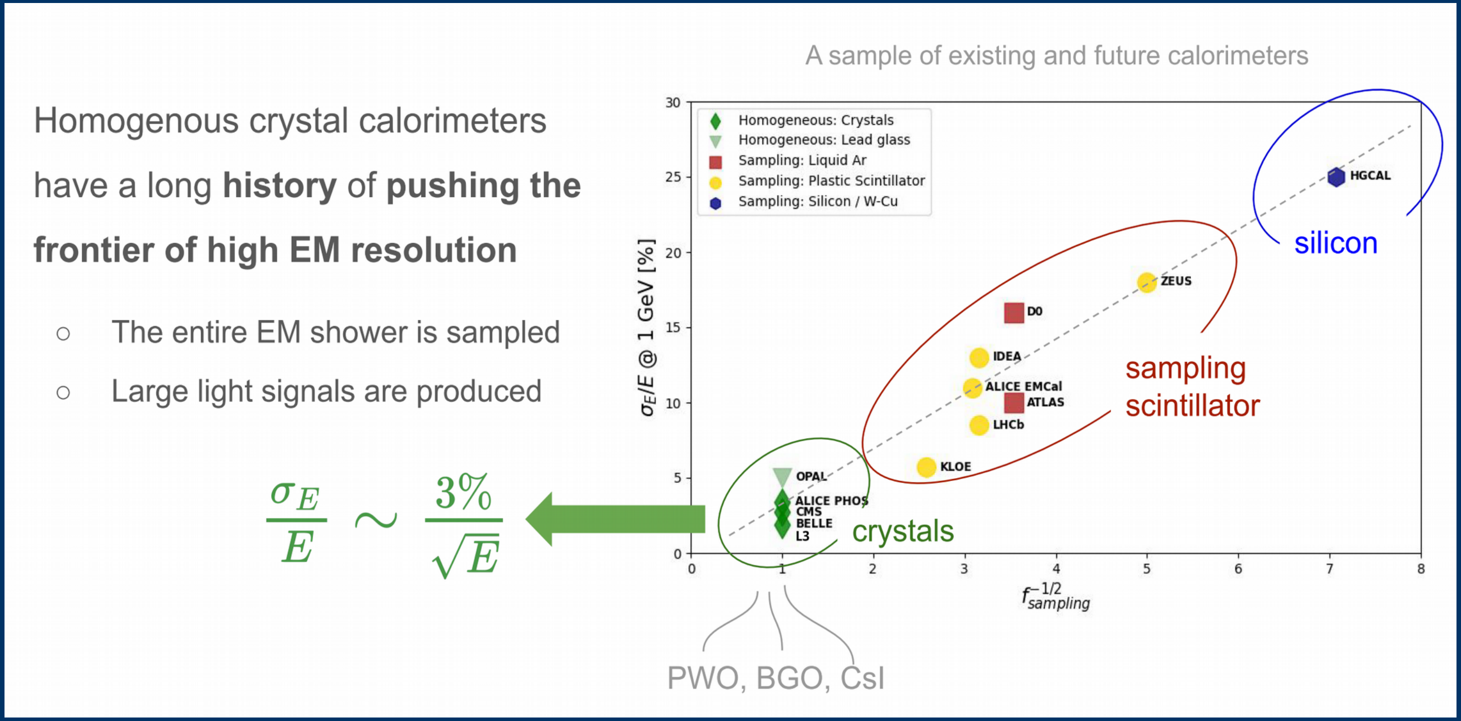
$6.3 * 6.2 * 5.0\ mm^3$



Crystal CAL.

- Scintillating crystal has a long history in development and it is still continuing in it.
- A crystal with same physics properties can be tuned by different processes (doping, co-doping, reshuffling matrix composition, …) to have quite different scintillation performance.





Crystal CAL.

New *and renewed* materials

Cost effective

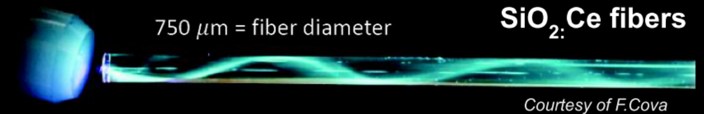
- Silica doped fibers (SiO_2:Ce, SiO_2:Pr)
  - [F.Cova et al.]
- Heavy scintillating glasses (DSB:Ce, AFO:Ce)
  - [E.Auffray et al.]
- Scintillating ceramics (LuAG:Ce, YAG:Ce, GYAG:Ce)
  - [T.Yanagida et al.]
- Polysiloxane polymers
  - [F.Acerbi et al.]

A new look

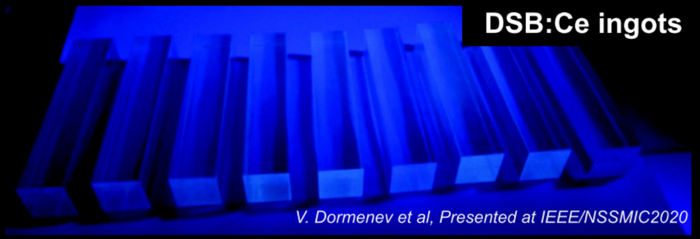
- PWO → PWO II → PWO III (improving LY by a factor 3, decreasing decay time at the ~2 ns level)
  - [A.Borisevich et al., M.Follin et al.]
- Crossluminescence in BaF_2 and Cherenkov 'rediscovery'
  - [R.Zhu, R.Pots et al., N.Kratocwhil et al., S.Gundacker]

A possible future

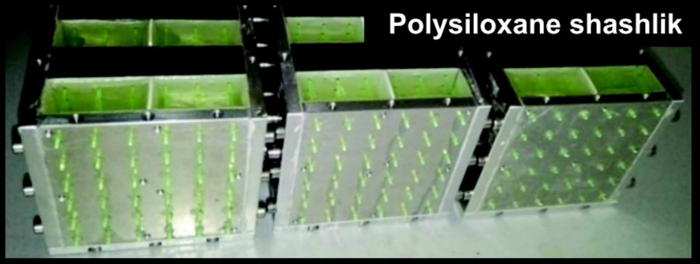
- Nano scintillating crystals (ZnO:Ga, InGaN/GaN QW, perovskites), many developments in Crystal Clear
  - [see E.Auffray @ ECFA Task Force 5]

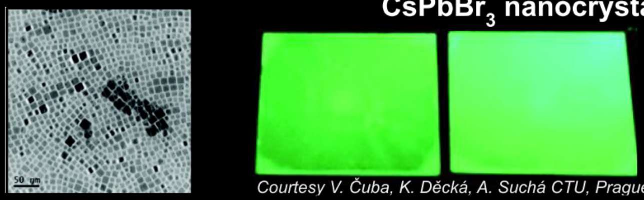


Courtesy of F.Cova

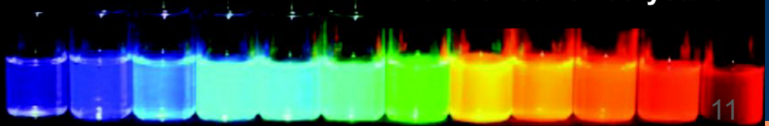


V. Dormenev et al, Presented at IEEE/NSSMIC2020





Courtesy V. Čuba, K. Děcká, A. Suchá CTU, Prague



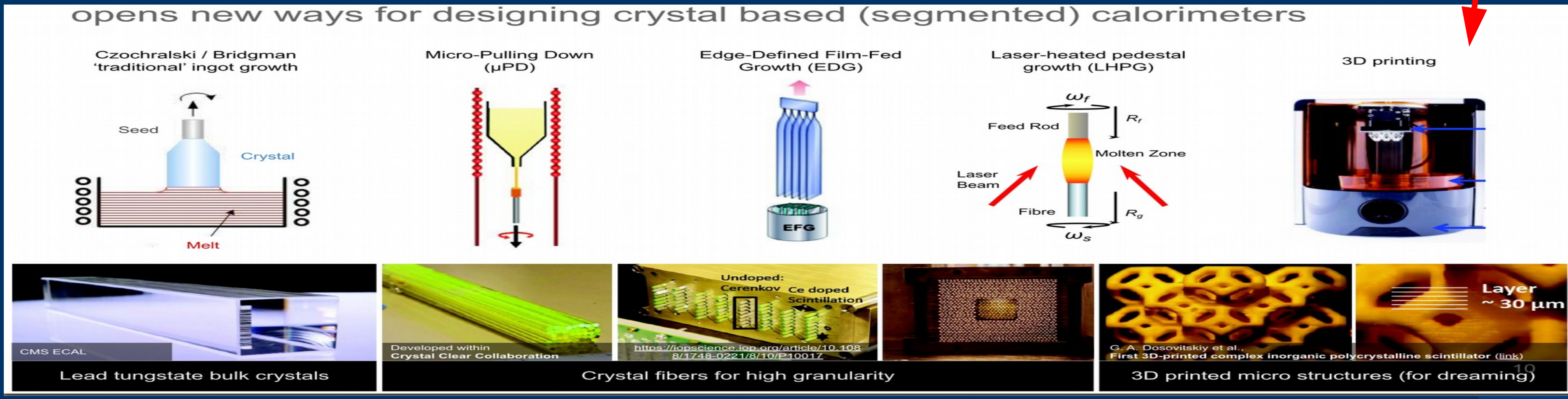
L. Protesescu et al. Nano Lett. 2015, 15, 3692−3696

Crystal CAL.

New perspectives for crystal CAL.

- Fine granularity
- Precision & maximum information
  - E
    - → hybrid dual-readout CAL.
    - → segmented crystal CAL. with PFA
  - t
    - → time resolution of ~30ps for single MIPs (CMS MTD, LYSO+SiPM)
    - → time resolution of ~30ps for EM shower (CMS ECL, PWO+APD)
    - → require rad. hard fast photodetectors (TF4)
    - → nano crystals for sub-nanosecond scintillation
  - positioning
- Process to recycle crystal material

200μm achieved



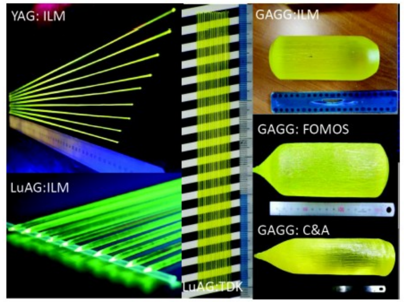
Crystal CAL.

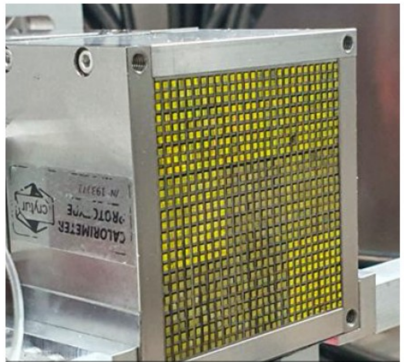
Three (future?) crystal CAL examples

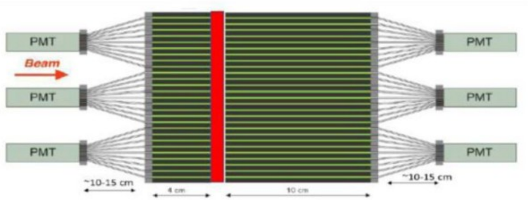
Radiation tolerant sampling crystal calorimeters

Spaghetti calorimeter (candidate for the LHCb phase II upgrade)

- Crystal fibers inside an absorber 'groove' (more details here)
- Co-doped garnet crystals (GAGG, YAG, GYAGG)
- **Possibility to mix different type of fibers** (e.g. Cerenkov, neutron sensitive)
- Targets: $\sigma_E/E \sim 10\%/\sqrt{E}$, $\sigma_t \sim O(10)$ps

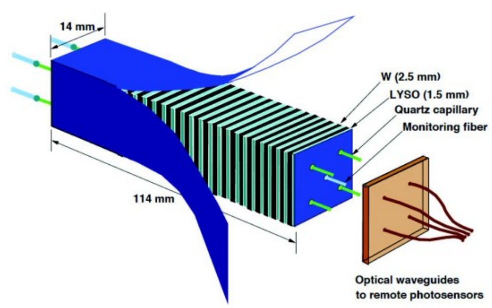



2020 SPACAL-W prototype



Shashlik calorimeter (was candidate for CMS phase II upgrade)

- Crystal slabs interleaved with tungsten slabs and read out with wavelength shifting fibers
- UV-emitting crystals (LYSO, CeF_3)
- SiO2:Ce or LuAG:Ce fibers as WLS
- Targets: $10\%/\sqrt{E}$, $\sigma_t \sim O(10)$ps
- Ongoing R&D targeting FCC-hh applications with the ***RADiCAL*** detector concept (CPAD 2021)



Combining tungsten with radiation tolerant crystals for compact calorimeters at hadron colliders

Crystal CAL.

Three (future?) crystal CAL examples

Fast segmented crystals for BIB mitigation

- **Timing and longitudinal shower distribution** provide a handle to mitigate Beam Induced Background in ECAL
  - Readout energy reduced by 3x with loose timing cuts
  - High granularity + precise timing of each channel would allow to use sophisticated BIB subtraction at the Particle Flow reconstruction level
  - A Cherenkov calorimeter with PbF_2 crystals read out by SiPMs could offer a cost-effective solution
- **Ongoing R&D on rad-hard fast crystals** (e.g. PbF_2, BaF_2, PWO)
- Synergies with KLEVER and LHCb

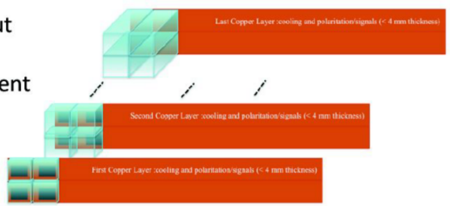
Detector R&D requirements for muon colliders

- Calorimeter Layout: **the calorimeter can be segmented longitudinally** as a function of the energy of the particles and the background level.

Cherenkov light, semi-homogeneous calorimeter: PbF2 + copper + SiPM read-out

Design specific for Muon Collider experiment (Electromagnetic Calorimeter)

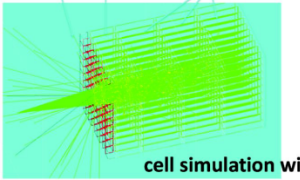
CRYLIN: CRYstal calorimeter with Longitudinal Information (idea by Ivano Sarra)



- A reduced first layer used as active pre-shower for timing → PbF2 or LYSO (5÷10 mm).

- A first layer of LYSO could be used for time measurement, then PbF_2 layer to absorb the BIB
- PbF_2 has good light yield (3 pe/MeV), fast signal (300 ps for muons 50 ps for pions), radiation hard, relatively cheap

1 cm of LYSO (for timing) + 3 cm of PbF2 (to stop the BIB) + 3x 5 cm of PbF2 + 5x3 mm copper bias layers

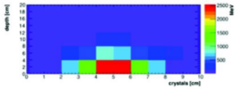


cell simulation with Geant

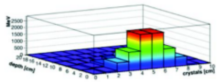
Most of BIB photons are absorbed in the first layer

BIB parametrized as 1.7 MeV photons – 300 particles/cm² per event

Single Event



Average of 1000 events



Exploiting crystal timing and longitudinal segmentation for BIB rejection at muon collider

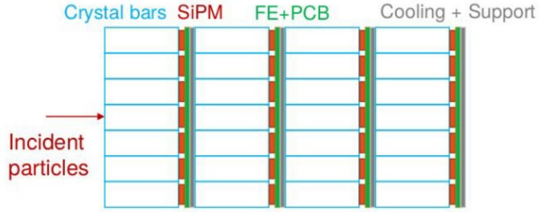
Crystal CAL.

Three (future?) crystal CAL examples

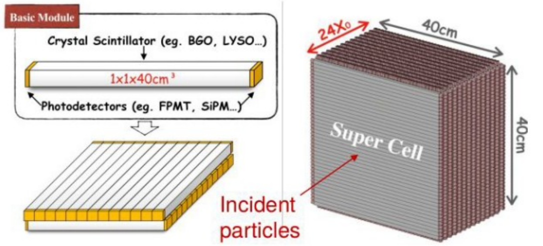
High granularity crystal calorimeter for CEPC

Y.Liu, Detector concept with crystal calorimeter @IAS Conference 2021

Design 1

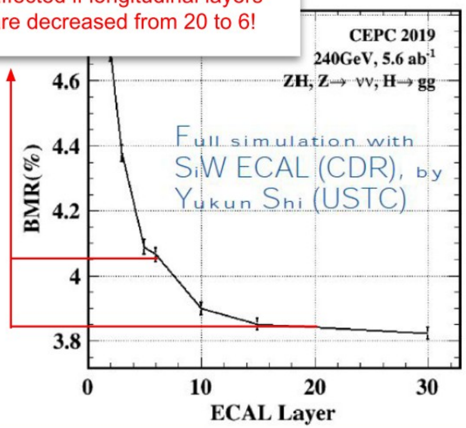


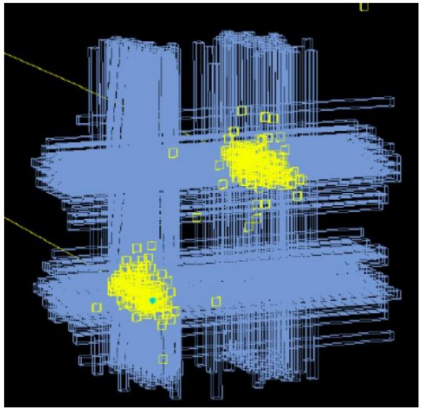
Design 2

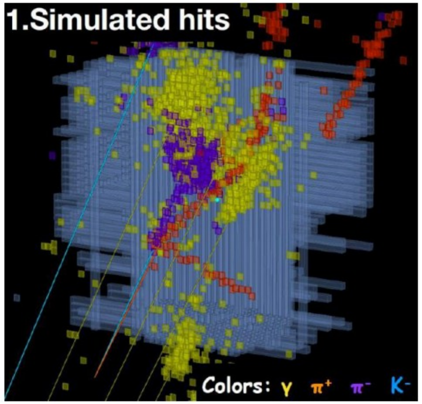


Evaluating optimal crystal configuration for granular 3D imaging

PFA performance not too affected if longitudinal layers are decreased from 20 to 6!





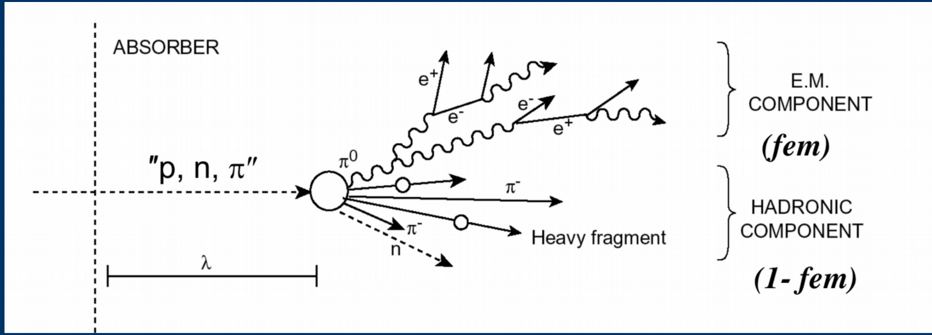


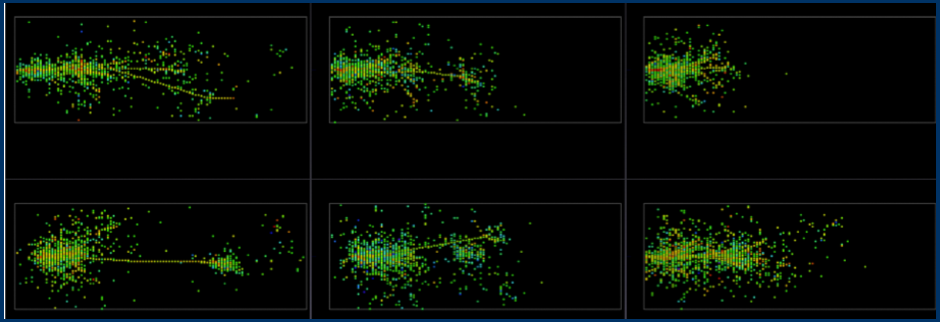
Developing precision particle flow optimized for crystal calorimetry

Merging high granularity and high energy resolution for precision physics at e^+e^- colliders

Dual-readout Fibre-Sampling CAL.

Hadronic shower includes EM component produced by π^0, η^0, the detector response to EM and HAD components is different. The fraction of energy in EM and HAD components fluctuates a lot event by event.



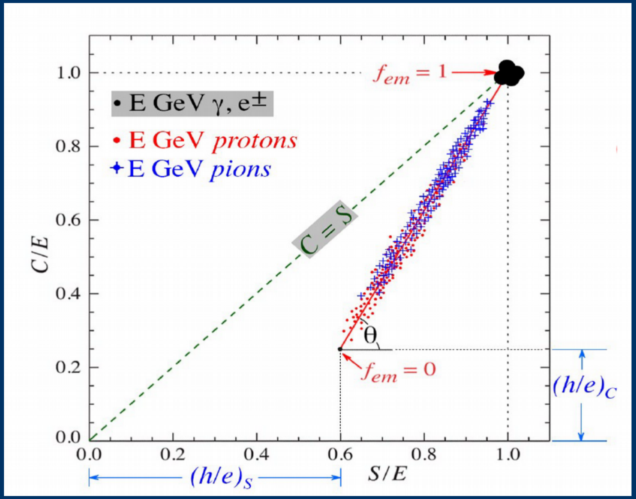


Dual-readout is to measurement on event-by-event basis of em fraction of hadron showers simultaneously.

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

$$s = \left(\frac{h}{e}\right)_S ; \quad c = \left(\frac{h}{e}\right)_C$$

$$\begin{cases} f_{em} = \dfrac{c - s(C/S)}{(C/S)(1-s) - (1-c)} \\ E = \dfrac{S - \chi C}{1-\chi} \end{cases}$$

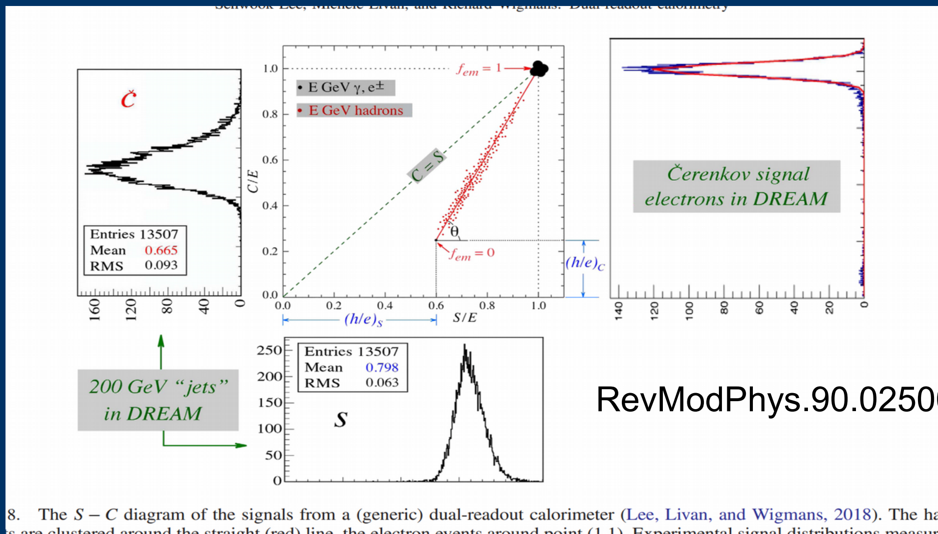


f_{em} : fraction of EM shower

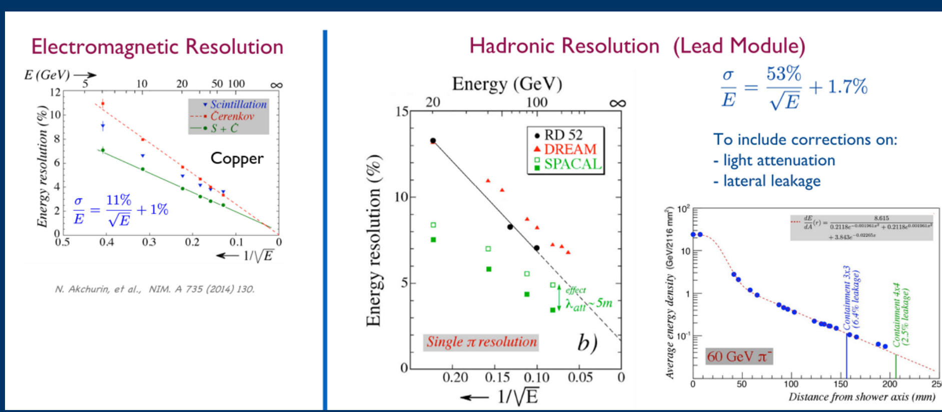
E : total shower energy to measure

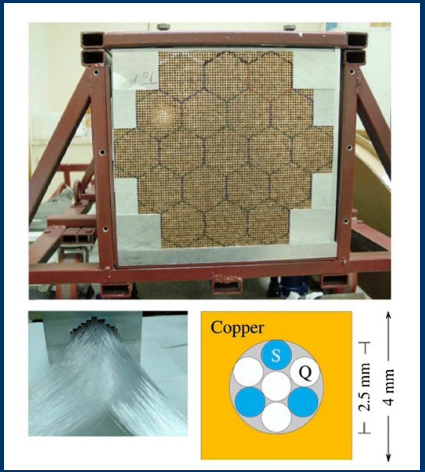
Dual-readout Fibre-Sampling CAL.

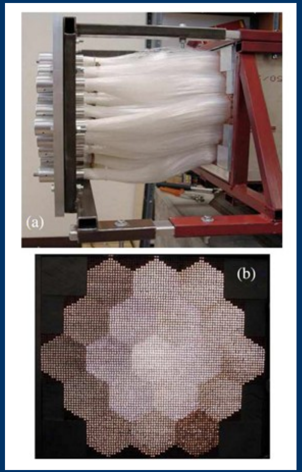
State of the art – DREAM & RD52

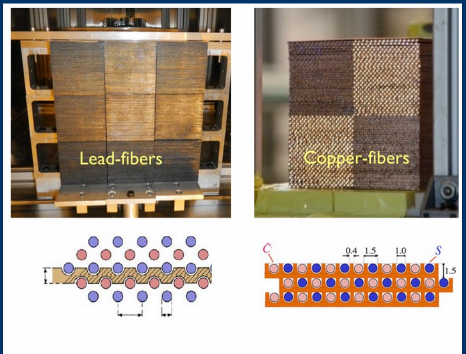


RevModPhys.90.025002

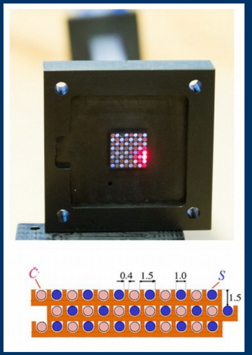








PMT readout

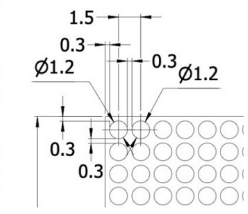


SiPM readout

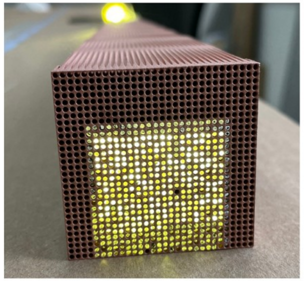
Dual-readout Fibre-Sampling CAL.

Short-term program: scaling up (next 3-4 years)

- Assess feasibility in scalable mechanical structure
- Handling of O(10K) SiPMs
  - A scalable sensor-readout-DAQ chain
  - Timing and shower shape info for PID
- …



Copper 3D-printed projective geometry
20x20 holes front
30x30 holes rear
5 pieces 100 mm long



(Some) key elements for future DR

- Full understanding of dual readout (χ parameter)
- Invisible energy and triple readout
- MIP-like particles in the calorimeter

deepening the understanding of DR mechanism and of calorimetric response

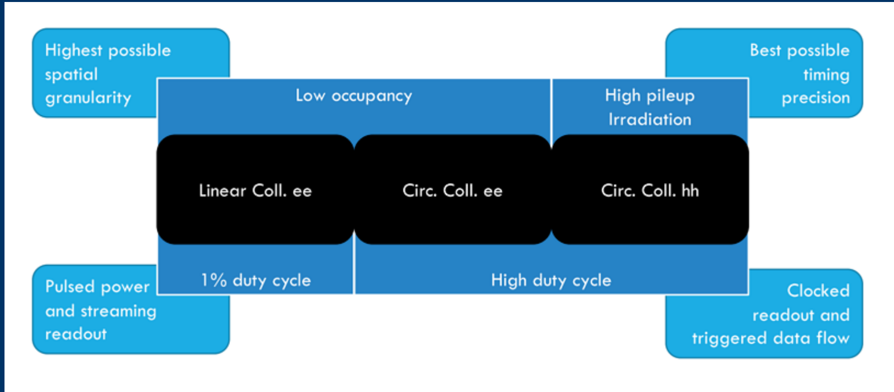
- The Cherenkov component
- How to shape the absorber
- Effect of non-uniformity on the calibration and performance
- Longitudinal segmentation... or not?
- Crystal fibers
- SiPM and dSiPM

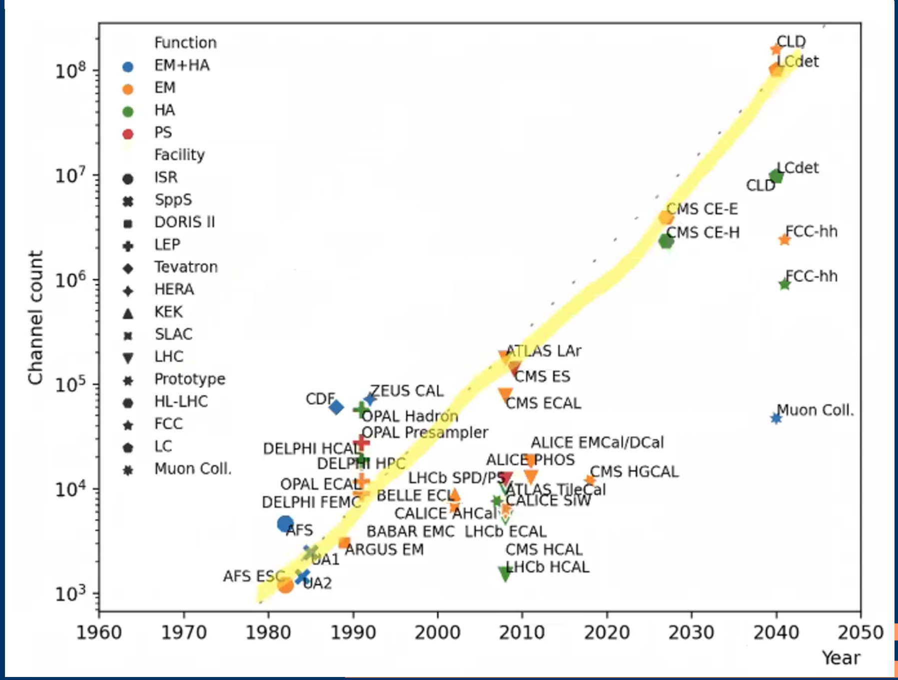
detector related development

It is meant to be a high resolution ECAL + HCAL in one detector.

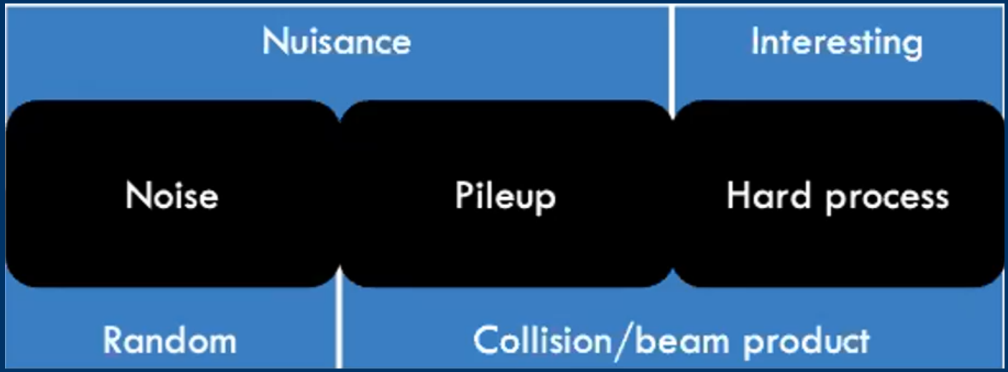
Readout system

Main drives and consequences





Readout is not just to produce data, but to produce insight.

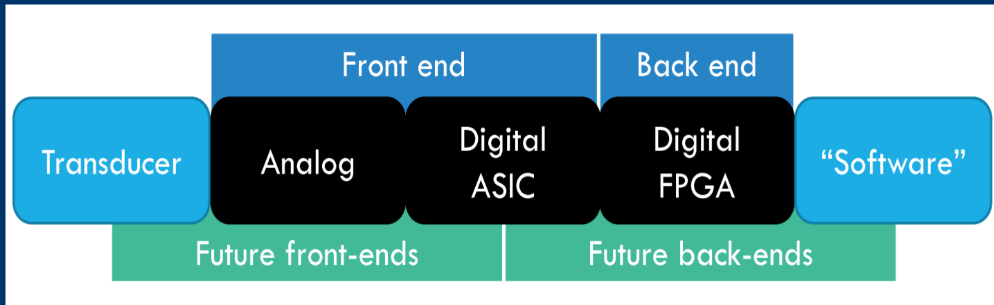


5D reconstruction and calibration
→ novel algorithms needed

Pile-up is not noise, just physics we are not interested in
→ opportunities for more processing on-detector, beyond noise rejection.

Trigger-less data taking. (for new physics?)

Readout system



The boundary between the FE and BE will move.

In the past: CPU-FPGA-ASIC

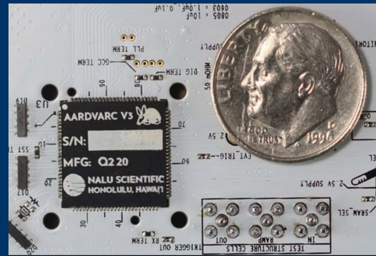
Now also: GPU, TPU, DPU

Firmware is the next software. (hls4ml)

Special ASIC design
enabling digitizer AARDVARC V3

Compact, high performance waveform sampling and digitizing

- ✔ 10-14 GSa/s
- ✔ 12 bits ADC
- ✔ 4-8 ps timing resolution
- ✔ 32K sampling buffer
- ✔ 2 GHz bandwidth
- ✔ System-on-chip



Higher channel density per chip planned
Good for precision timing CAL.

Lesson learned in R&D and construction

Speaker: David Barney
Calorimeter upgrade R&D (T&E) for HL-LHC & by Calice

Beyond the lesson learned in sensor, electronics, connectivity, power distribution, mechanical engineering, and software for simulation/reconstruction/analysis, some other concerns are raised and indeed in discussion for quite a fraction of time.

- project system management
- adequate flexible engineering support (electronics, mechanical, software)
- long term sustainability of expertise
- building good relationships with industry
  academic: feasibility oriented, from 0 to 1, how to make it possible
  industry: profit oriented, from 1 to infinite, how to cost-down
  e.g space shuttle (NASA) vs. Starship (SpaceX)
- for simulation and analysis tools, software group needs to go hand in hand with detector group.
  for large scale project like HGCAL, any small re-optimizing can affect the whole picture and hard to understand it in advance. Software simulation is needed, but lack of experience to feed into the simulation.
- recognition issue
  within 4K collaborators in CMS, only handful people are doing the real blue-sky research.

Summary and discussion

- CAL. R&D has been moving into totally new (revolutionary) directions recently
  - high granularity, longitudinally segmented
  - precision timing
  - new algorithm (PFA)
  - dual-readout
- It is moving from 2D+E camera to 3D+E+t video.
  - shower evolution in time
  - split EM and HAD components in hadronic shower
- Using semiconductor as active medium is another revolution
  - conventional active materials do not lose their importance
- The readout system (ASIC, FE) could be next to revolt (high bandwidth, real-time processing, …)
- Large-scale project management and long term resource/supports become more and more serious issues. (It takes decades to develop one new generation detector. Apple wishes you to change a phone every year.)
  - To forge a close bond with industry is important, not only for production, but also for their expertise.

- What may be suitable for us in Taiwan.