Homogeneous Calorimetry

ECFA Detector R&D Roadmap Task Force 6:
Calorimetry Community Meeting

12/01/2023

Marco Lucchini

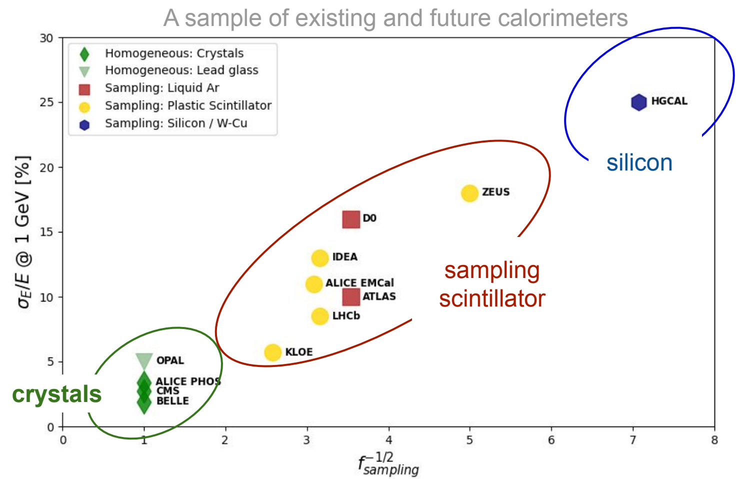
Outline

- Motivations for homogeneous calorimetry
- Requirements and directions within the ECFA roadmap context
- Panorama (most likely incomplete) of existing R&D's
- A possible path for the next 5+ years
- Synergies within the DRD
- Wishlist for the DRD

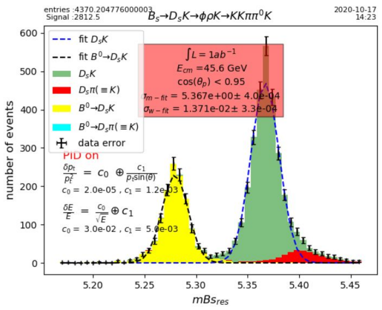
Charge of the talk: *The presentation should focus on the plans for the coming* ***five to six years*** *but a look beyond that period is allowed. It should outline the goals of the R&D in that period and intermittent steps.The research plans are to be* ***oriented at the goals formulated in the ECFA Detector Roadmap****). Outline also what kind of collaborative tools you would expect from a DRD Calorimetry. Note that at this community meeting no commitment in terms of milestones and deliverables is required. The meeting should issue a panorama of the envisaged actions and should attract groups to join the DRD.*

Motivations for homogeneous calorimetry

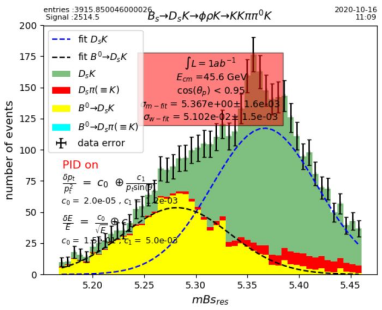
- Homogeneous calorimetry remains the **only way to get a 1-3%/√(E)** energy resolution for photons (but also a good option for shower imaging and time resolution)
- Potential to improve event reconstruction and **expand the landscape of physics studies**



3%/√E

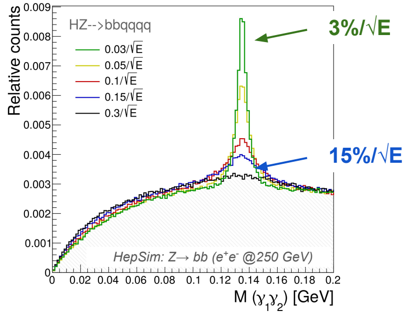


15%/√E



CP violation studies with B_s decay to final states with low energy photons

[R.Aleksan et al., *Study of CP violation in $B^{\pm}$ decays to D0(D0)K± at FCCee*, arXiv:2107.05311]



Clustering of π^0's photons to improve performance of jet clustering algorithms

[M.Lucchini et al., New perspectives on segmented crystal calorimeters for future colliders, 2020 *JINST* **15** P11005]

Qualitative representation of **requirements** for calorimetry **at future colliders**

e^+e^- colliders

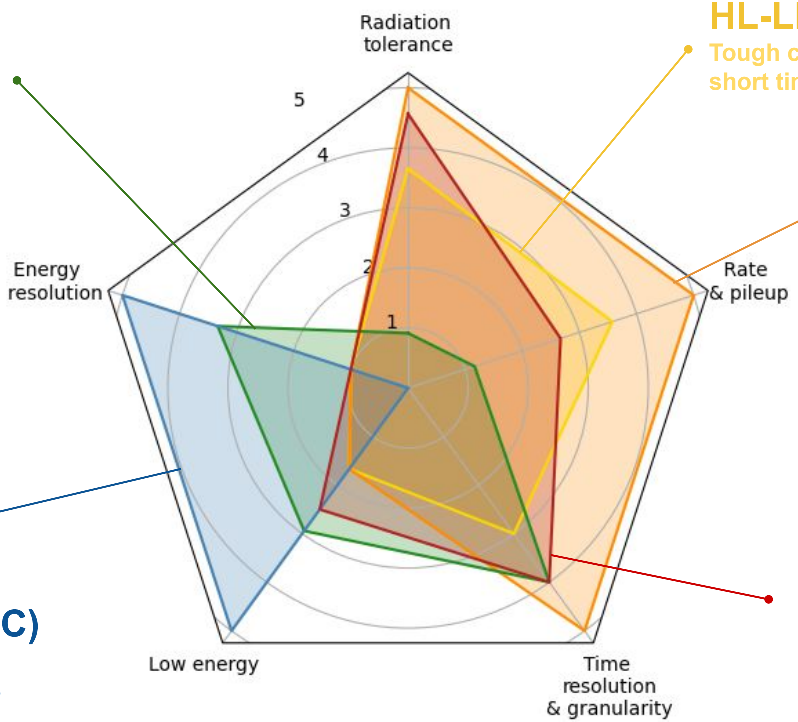
Precision physics benefits from exploiting the best possible energy and time resolution

HL-LHC

Tough challenges on a short timescale

FCC-hh

Setting the toughest challenge on radiation tolerance and pileup conditions



Very high energy (longitudinal containment)

Strong interaction experiments (e.g. EIC)

Requiring the highest energy resolution for low energy photons

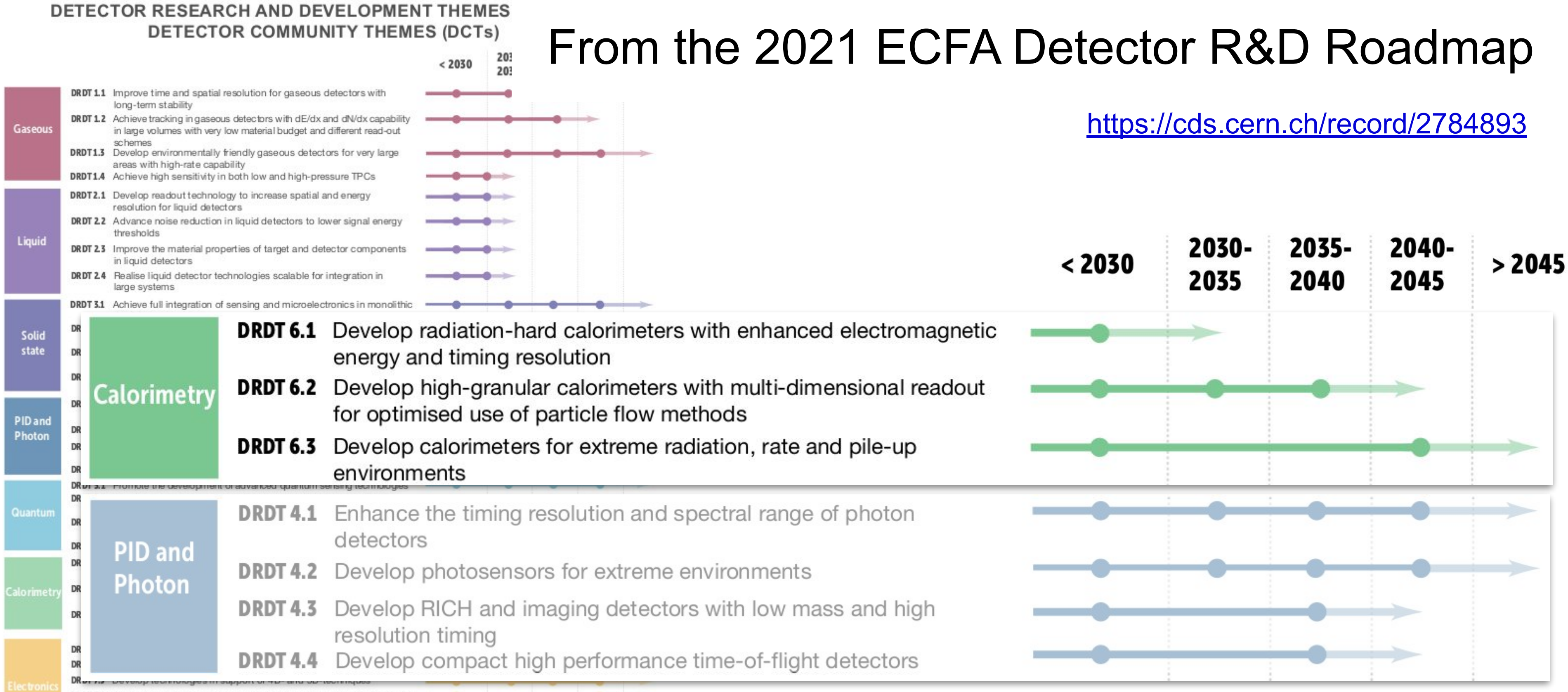
$\mu^+\mu^-$ colliders

High beam induced background and radiation levels, need for ambitious time resolution

Inspired from https://indico.cern.ch/event/994685/

From the 2021 ECFA Detector R&D Roadmap

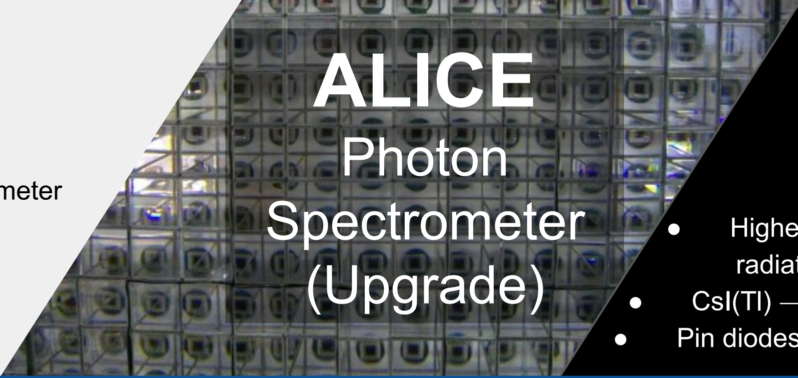
https://cds.cern.ch/record/2784893



- **Cost-effectiveness** (exploiting SiPM readout and new cheaper scintillators)
- **Low power** / environmental impact awareness

CMS
ECAL
(Upgrade)

- Electron Endcap EM Calorimeter for Electron Ion collider [ref]
- **PWO** / heavy glasses
- **SiPMs** (TBC)
- Target: 1-2% / √E



ALICE
Photon Spectrometer
(Upgrade)

- Higher rate and radiation levels
- CsI(TI) →**Pure CsI**
- Pin diodes → **APDs**

Bulk crystal technology: a consolidated solution in the short-mid term

- upgrades mainly targeting enhanced time resolution with new electronics
- new calorimeters for measurements of low energy photons/electrons

- **PWO** + **APDs** + upgraded FEE

EIC
EEMCal

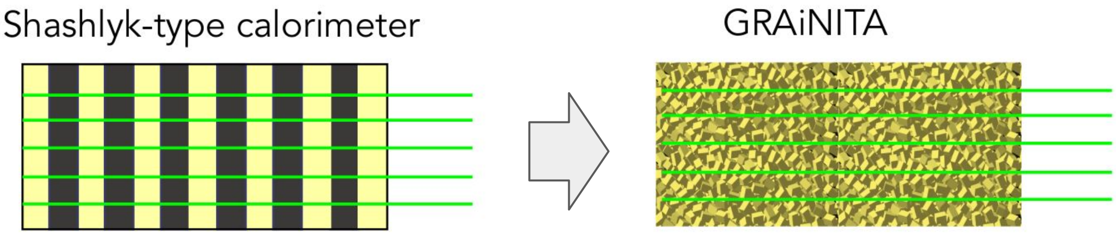
- Same **PWO** crystals
- Upgrade of FE and photodetectors (APDs→**SiPMs**) [ref]
- Measure photons with p_T<1GeV

Belle II
ECAL
(Upgrade)

GRAiNITA calorimeter

- **Ultra fine sampling opaque EM calorimeter** readout with WLS fibers
- Geant4 simulation of $ZnWO_4$ + CH_2I_2 cubes → $\sigma_E/E \sim 2\%/\sqrt{E}$
- Ongoing proof-of-concept with lab measurements and prototypes
- See presentation at FCC Italy-France Workshop [Ref]
  by M-H Schune (Université Paris-Saclay, CNRS-IN2P3)

Target application: **e^+e^- colliders**



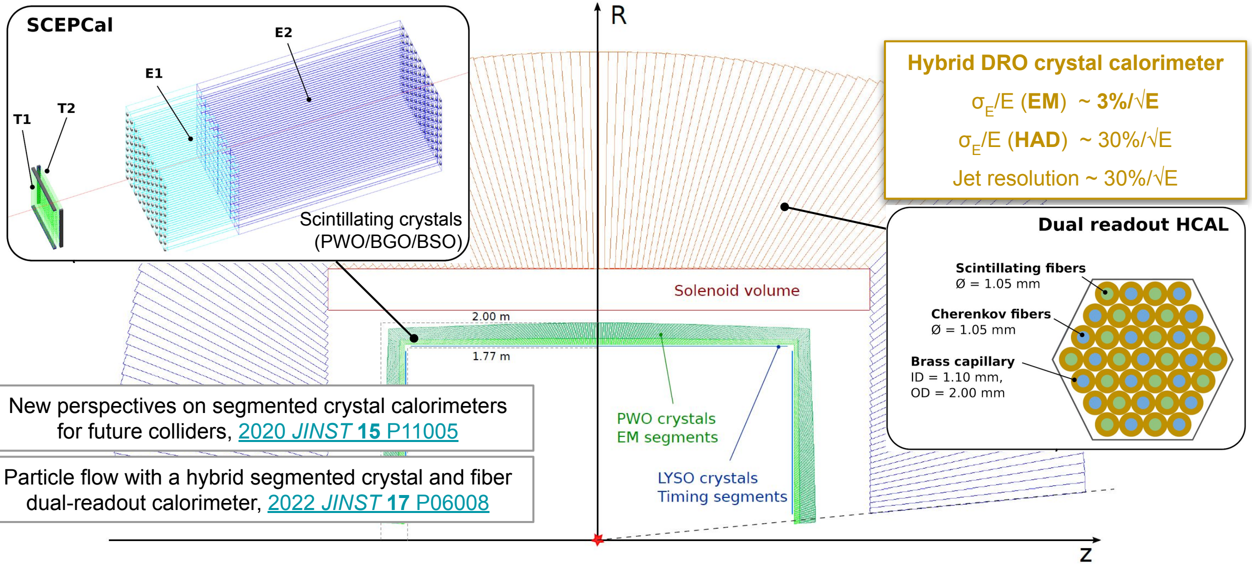
$ZnWO_4$ grains

$ZnWO_4$ + propanol
+ Y11 WLS fibers

Segmented Crystal EM Precision Calorimeter

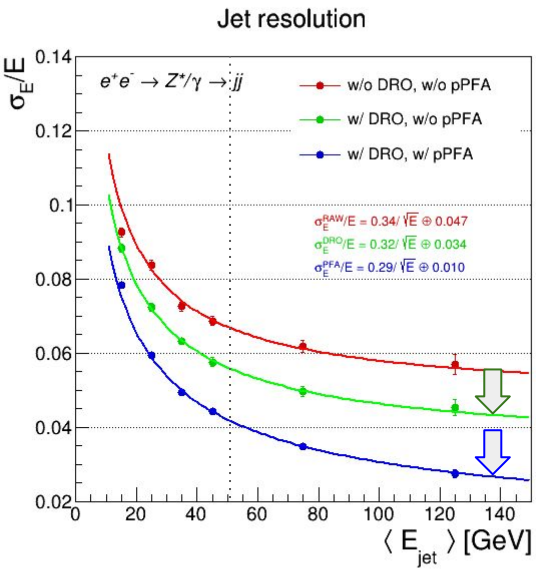
- **Includes timing and dual-readout** capabilities for optimal integration with a dual-readout fiber calorimeter à la IDEA and PFA algorithms (see presentation by R.Santoro)
- **Ongoing efforts** within the **US Calvision, IDEA** and CERN **Crystal Clear** collaborations
  - Proof-of-concept with lab measurements and prototypes (PWO, BGO, BSO, … with SiPMs)
  - Ongoing simulation effort in DD4HEP and FCC software + DR-PFA developments

Target application: **e^+e^- colliders**



New perspectives on segmented crystal calorimeters for future colliders, [2020 *JINST* **15** P11005]

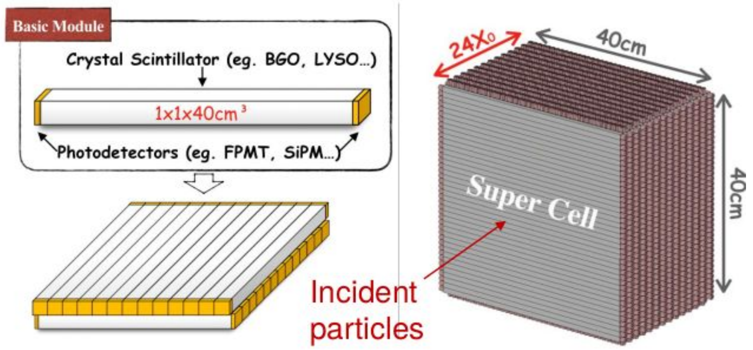
Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter, [2022 *JINST* **17** P06008]

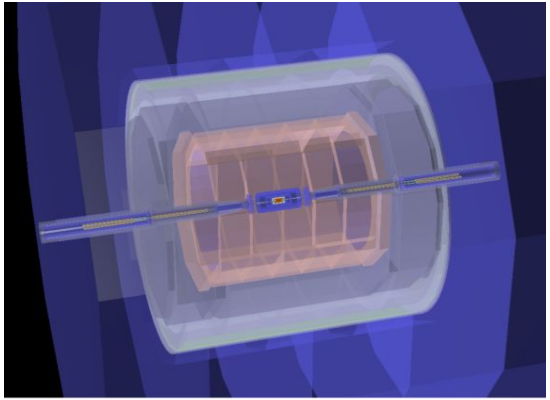


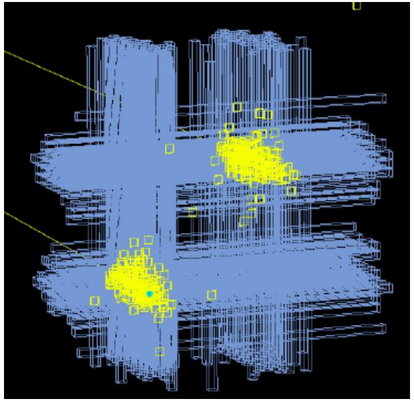
High Granularity Crystal Calorimetry

Target application: e^+e^- colliders

- **High granularity** crystal EM calorimeter made of a grid of ~1x1x40cm³ bars
- Baseline concept under development **for CEPC** (Y.Liu, M.Ruan, et al.)
- **Advanced simulation** and reconstruction effort including PFA algorithms
- **Ongoing R&D** and prototyping [Ref]: BGO/PWO with SiPM readout





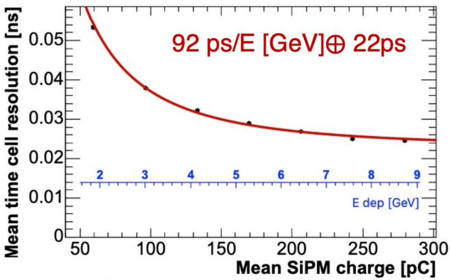


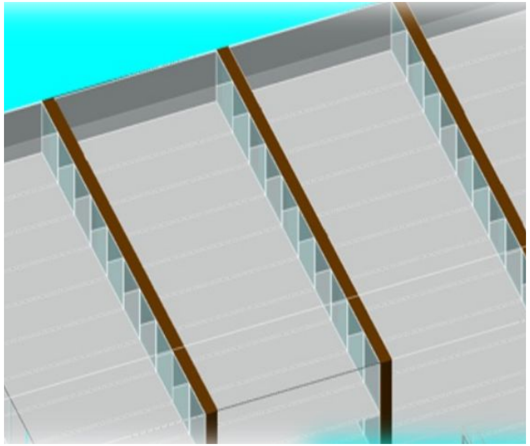
CRystal calor**I**meter with **L**ongitudinal **I**nformatio**N**

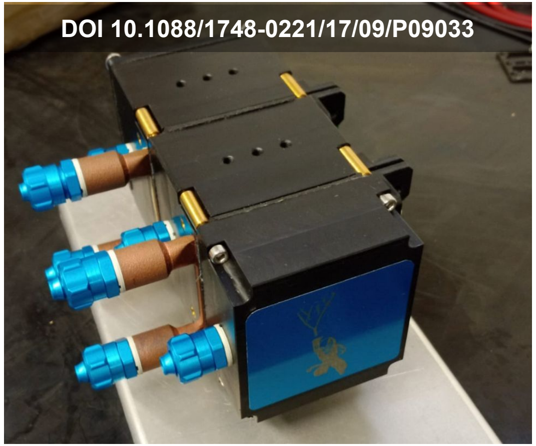
- **Timing and longitudinal segmentation** to tackle the beam induced background (BIB) challenge of muon colliders
- Radiation hardness is a major challenge (segmentation helps)
- **Ongoing** R&D and **prototyping** (I.Sarra, L.Sestini et al. [ref]):
  - 10x10x40 mm³ **PbF_2/PWO-UF** crystals
  - 3x3 mm² UV extended SiPM readout

Target application:
$\mu^+\mu^-$ colliders

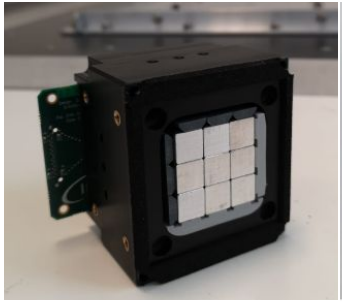
Test beam

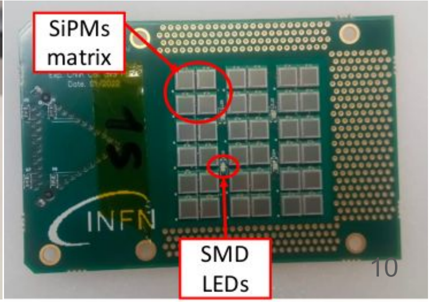






Modular architecture based on stackable modules

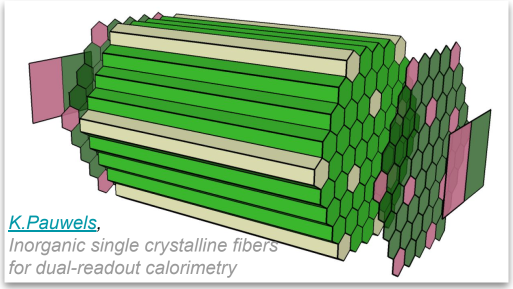




Homogeneous **H**adron **Cal**orimeters

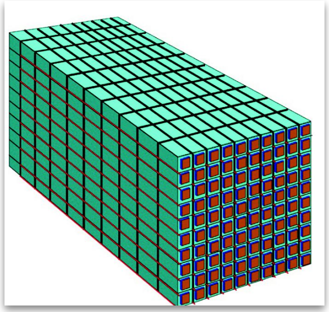
- Full absorption dual-readout hadron calorimetry concepts aiming at further boosting the energy resolution for hadronic showers→~15%/√E
- **Major challenges**: **requires breakthrough in mass production** (quality/uniformity) and cost reduction for high density scintillators (crystals/heavy glasses)
    - Various options under investigation by the international community (DSB:Ce, AFO:Ce, …)
    - Recent R&D collaboration and progress on Gd-rich heavy glasses for a HHCAL for CEPC

Exploiting bundles of meta-crystal **fibers** *[P.Lecoq, J PHYS 160 (2009) p12016* & *G.Mavromanolakis et al.]*

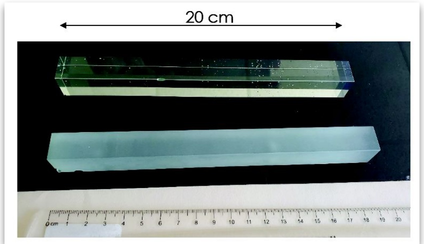


K.Pauwels, *Inorganic single crystalline fibers for dual-readout calorimetry*

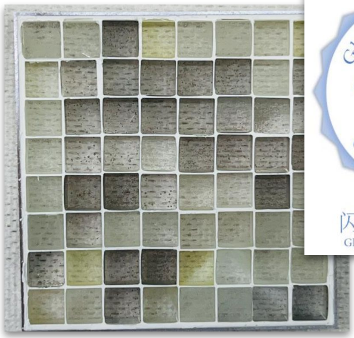
Exploiting **bulk** cost-effective dense scintillators *[CPAD2021, M.Demarteau et al.]*



Bulk scintillating glass production as part of EIC R&D



Sen.QIAN, R&D for high density, high light yield glass scintillator for CEPC



Glass Scintillator Collaboration
闪烁玻璃合作组
Glass Scintillator Collaboration

State-of-the-art and outlook

- Where do we stand?
  - **Scintillator technology** for homogeneous calorimetry has made several progress in the last decade (continuous discovery of new crystals and new high density scintillating glasses)
    - A wide range of options is now available and customizable for a specific application (see talk by E.Auffray) although ‘traditional’ crystals remain often a baseline choice (PWO, BGO, BSO, CsI)
    - Market driven by non-HEP applications (many vendors but often relying on cheaper Chinese producers)
  - **Silicon Photomultiplier** technology is becoming the preferred choice for most high granularity, cost-effective and compact calorimeter concepts
    - Market driven by LIDAR/PET applications: new manufacturers joining the business but not many offer small cell size and radiation tolerant products (typically relying on a few vendors)
  - **Achieving the target energy and time resolutions for EM showers** (1-3%/√E and 10-30 ps resp.) **is within reach** for many detector concepts
- What would require substantial technological progress (‘breakthrough’)?
  - Scintillators with enhanced radiation tolerance at levels of 10^{15-16} neq/cm² and O(10) MGy
  - Compact photodetectors with radiation tolerance up to 10^{15-16} neq/cm²
    ⇨ For extreme radiation environments
  - Dense scintillators with <1$/cm³ ⇨ For HHCAL concepts
  - Time resolution below 5 ps ⇨ Is there a compelling case?

A possible path for the next 5+ years

- **Proof-of-principle**
- Optimization of conceptual designs
- Development of prototypes
- **Beam test with prototypes**

Can fit within 5 years for most ECAL concepts

In parallel but also beyond the 5+ years

- **Technology development**
  - New materials
  - New photodetectors
  - Characterization and radiation testing
  - Strengthen collaboration with manufacturers

Possible **synergies**

- **Innovative homogeneous calorimeter concepts are pushing the R&D in similar directions → there are many potential synergies**
  - **Infrastructure**
    - Test beam infrastructure
      - DAQ, tracking systems, movable tables, reference timing detectors, cold boxes?
      - Common lateral “containment” calorimeters to allow testing single cell performance
    - Irradiation facilities
      - Common facilities and instrumentation for irradiation of components
  - **Sharing of knowledge and technological developments:**
    - New materials, new photodetectors, electronics, mechanics, cooling
    - Software development and simulation (migration to key4hep software package?)
    - Sharing expensive R&D (and build a critical mass)
      - Development of custom **dense*** scintillators with manufacturers
      - Consider common photodetector developments (e.g. common SiPM wafers at vendors) (**smaller cell size SiPMs*, digital SiPMs, low power, radiation hard, …**)

Possible **synergies**

Most **synergies** in common with other calorimeter concepts (and DRDs), some are **particularly important for homogeneous calorimetry:**

- **High density** (small X_0, R_M, λ_I) **scintillators**
- **Large dynamic range** (and low noise) photodetectors and electronics readout
- **Low-material-budget mechanical supports, cooling and readout**

Wishlist for the DRD?

- **Become a place to exploit the above synergies at best**
- Support for common beam time requests (e.g. on behalf of the calorimetry DRD) ?
- Offer technical/engineering taskforce and support to develop common DAQ, mechanics, etc. for prototyping?
- Common DRD fundings to support specific activities?
- More… ?

Summary

- Many enthusiastic R&D's on **innovative concepts** of homogeneous calorimeters are ongoing in the **international community** to address the requirements of possible future colliders experiments

- **Many technological aspects, challenges and strategies are in common** (enhance granularity with SiPM readout, embed timing capabilities, enhance radiation tolerance)

- The **DRD** could become a framework **to exploit synergies** and optimize resources

Additional material

US Dual Calorimetry effort

The US Department of Energy has awarded a 3 -year grant (April 2022 start) totaling 1.5M$ to a consortium of US Universities and laboratories to work on "maximal information calorimetry", using dual-readout/timing/advanced simulation techniques. The current participants are FNAL (Freeman, Hirschauer, Merkel, Wenzel), Argonne (Chekanov), Caltech (Newman, Zhu), Maryland (Belloni, Eno), MIchigan (Qian, Zhou, Zhu), Milano-Bicocca (Lucchini), MIT (Harris),Oak Ridge (Demarteau), Princeton (Tully), Purdue (Jung), Texas Tech (Akchurin, Kunori), U. Virginia (Hirosky, Ledovskoy). More information can be found at: https://detectors.fnal.gov/projects/calvision/

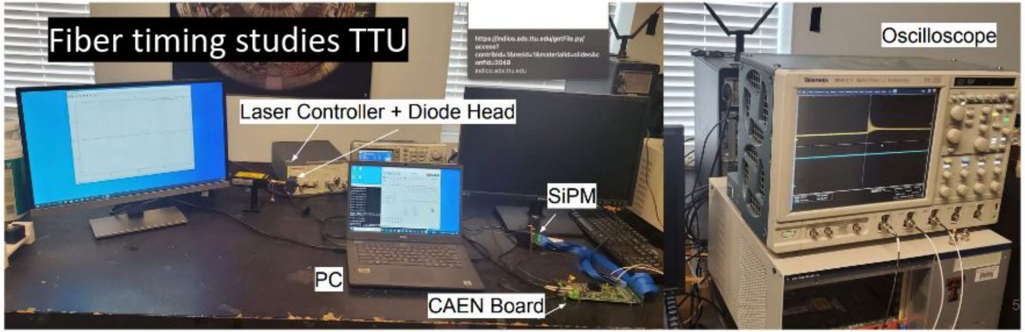
During our first year, we have started work in the following areas:

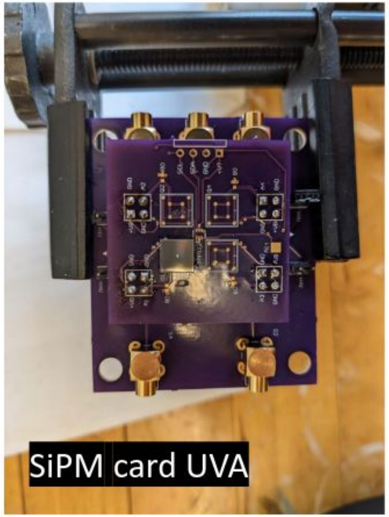
- Using cosmic rays and test beam to measure scintillation/Cherenkov light separation in scintillating crystals with extended wavelength SiPMs
- Using test beam to investigate the use of timing in a dual-readout scintillating fiber/ quartz fiber spaghetti calorimeter
- Simulation of a collider detector with a homogeneous crystal dual-readout ECAL and a dual-readout fiber spaghetti calorimeter
- Working with scintillating glass experts and our needs to understand what could be engineered towards cheaper dual-readout materials
- Advanced reconstruction algorithms

One of our main goals for the full period is to build a large crystal array to be used in conjunction with the IDEA calorimeter for test beam studies.

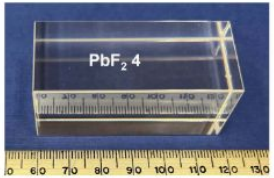
We are in collaboration with the CERN homogeneous materials group and the IDEA collaboration.

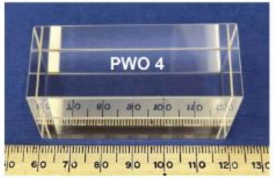
Our work: hardware





Crystal characterization CalTech

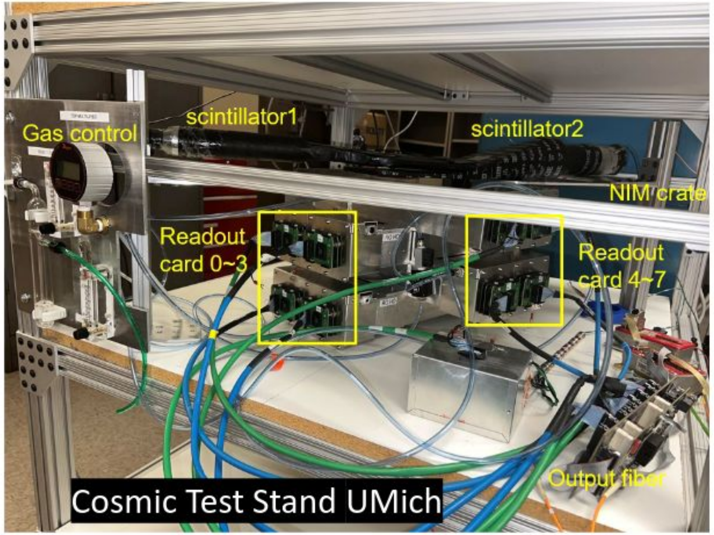


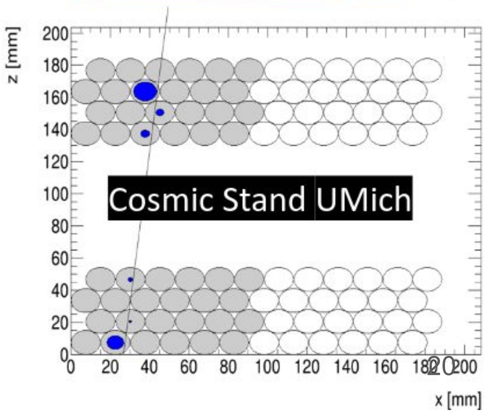


ID	Dimension (mm³)	Qty.	Polishing
PbF_2-4	25×25×60	1	All faces
PWO-4	25×25×60	1	All faces
Two samples from U. Maryland received on Oct. 28, 2022			

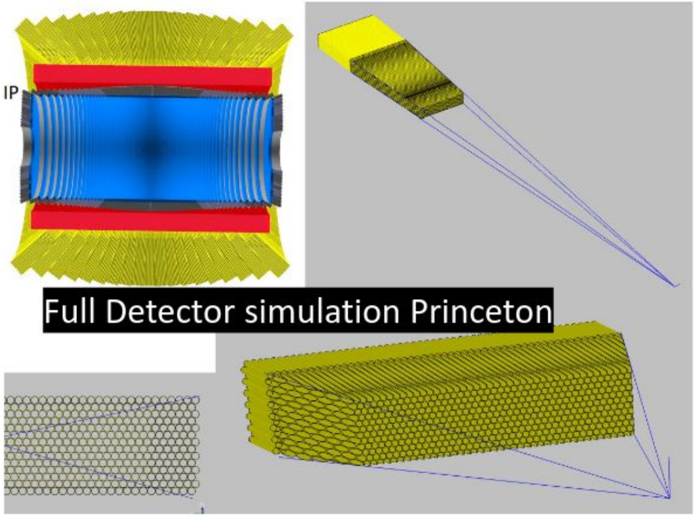
Experiments

Measured at room temperature: X-ray excited luminescence (XEL), Longitudinal/Transverse transmittance (LT/TT), Emission Weighted Longitudinal transmittance (EWLT), Pulse Height Spectra (PHS), Light Output (LO) & Decay Time (τ), Light Response Uniformity (LRU). Light Yield (LY) with Emission Weighted Quantum Efficiency (EWQE) taken out.





Our work: simulation



https://atlaswww.hep.anl.gov/calvision/

SIM files for 1 GeV muons for ECAL with PbWO4 (5cm x 1 cm, 4 crystals in depth)

SIM+REC+DST files for HZ→ gg+nunu. Standard CLIC with Si/W ECAL. 2 jets mass should be 125 GeV

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README	706 B	12/08/2022 8:21 PM	

Full Size: 706 B File: 1 Folder: 3

Full Simulation: Argonne

SIM+REC+DST files for HZ→ gg+nunu using CLIC but with ECAL based PbWO4 (5cm x 1 cm, 4 crystals in depth)

Jets are mis-calibrated i.e. 2 jet mass ≠ 125 GeV!