DRD6 plans for crystal based homogeneous calorimeters

ECFA WG3 Topical workshop on calorimetry, PID and photodetectors

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Marco Lucchini

University of Milano-Bicocca
INFN Sez. Milano-Bicocca

General comments on the DRD6 process

- Many proposals received from a broad community:
  - A variety of target experiments with **different physics goals**
  - A variety of design flavors with many **common R&D interests and possible synergies**
  - Almost **each proposal has some uniqueness**
- Not only targeting e^+e^- EW/Higgs/Top/Flavour factories but also
  - FCC-hh
  - Muon collider
  - Neutrino physics (at low energy)
  - BSM and DM physics with η factory (REDTOP)

Link to 2nd DRD6 Community Meeting

DRD6 Track 3 proposals

Scintillator based sampling calorimeters	Homogeneous EM crystal calorimeters	Homogeneous (EM+HAD) calorimeters	Large mass cryogenic calorimeters
Dual Readout Fiber Calorimeter for Higgs Factories	Maximum Information Crystal Calorimeter for Higgs Factories	Triple-readout sandwich calorimeter for DM and BSM low energy physics (*ADRIANO3*)	Large mass cryogenic calorimeters for neutrinoless double beta decay
R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh	High Granularity Crystal Calorimeter for Higgs Factories	Dual-readout Sandwich Calorimeter for future colliders	
Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*) for FCC-hh	Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)		
High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee			
Scintillating Tile HCAL for FCC-hh, FCC-ee			

ScintCal: **Scintillator** material for future calorimeters

Common Readout **ASICs** for DRD6 calorimeter prototypes

DRD6 Track 3 proposals

Focus on homogeneous calorimeters explicitly designed for e^+e^- Higgs factories

Scintillator based sampling calorimeters

Dual Readout Fiber Calorimeter for Higgs Factories

R&D on Spaghetti (EM) Calorimeter technologies for LHCb Upgrade II, Higgs factories, FCC-hh

Fast-timing, ultracompact, radiation hard, EM calorimetry (*RADiCAL*) for FCC-hh

High sampling fraction EM calorimeter with crystal grains (*GRAiNITA*) for FCC-ee

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Homogeneous EM crystal calorimeters

Maximum Information Crystal Calorimeter for Higgs Factories

High Granularity Crystal Calorimeter for Higgs Factories

Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)

Homogeneous (EM+HAD) calorimeters

Triple-readout sandwich calorimeter for DM and BSM low energy physics (*ADRIANO3*)

Dual-readout Sandwich Calorimeter for future colliders

Large mass cryogenic calorimeters

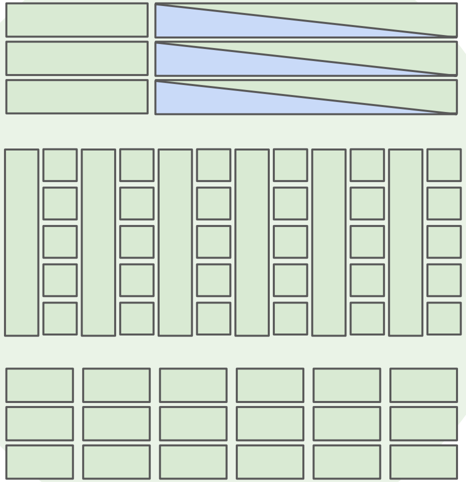
Large mass cryogenic calorimeters for neutrinoless double beta decay

[illegible] Scintillator materials for future calorimeters

Common Readout **ASIC** for DRD6 calorimeter prototypes

Homogeneous EM crystal calorimeters

EM calorimeter layouts



Strategy and target application

Maximum Information Crystal Calorimeter for Higgs Factories (SCEPCal)

High Granularity Crystal Calorimeter for Higgs Factories (HGCCal)

Fast, segmented Crystal calorimeter for Muon Collider (*CRILIN*)

Main scintillators proposed

PWO

BGO

BSO

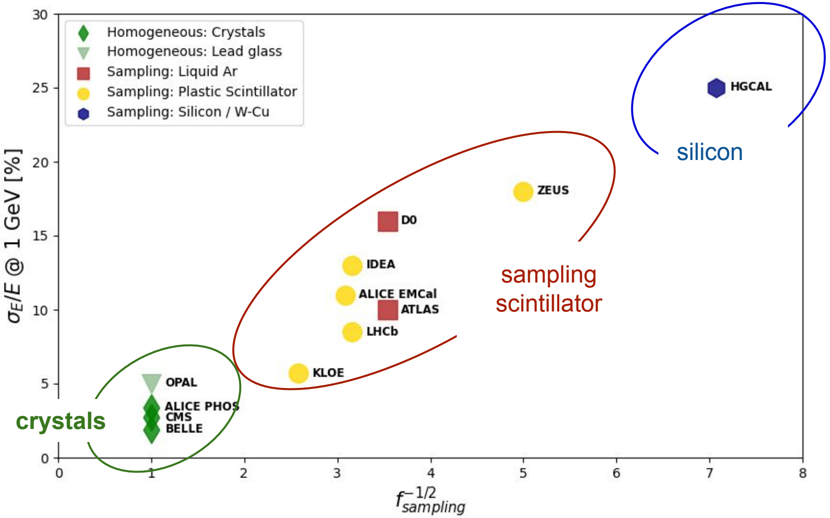
PbF_2

Silicon photomultipliers are proposed as candidate photodetector in all cases

Precision physics at e^+e^- Higgs Factories?

- Future e^+e^- Higgs Factories set **no stringent requirements on radiation tolerance** and pileup
- An opportunity to aim for the best possible precision of event reconstruction
- Homogeneous calorimetry remains the **only way to get a 1-3%/√(E) energy resolution for photons (and thus π^0's)** (but also a good option for shower imaging and time resolution)

A sample of existing and future calorimeters

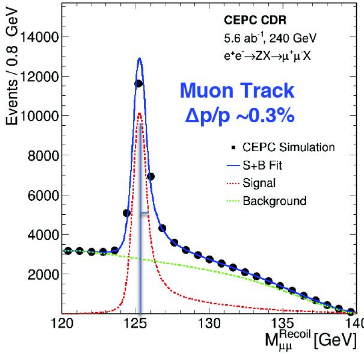


Motivations for homogeneous calorimetry at FCCee

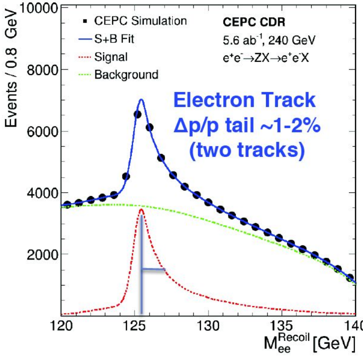
- Potential to improve event reconstruction and **expand the landscape of physics studies:**
  - Flavor physics: clean identification and good reconstruction of π^0, separation of D and D_s
  - Recovery of the Z→ee recoil mass resolution by measuring bremsstrahlung photons
  - Reconstruction of π^0 inside jets to enhance performance of jet reconstruction algorithms

Improving **resolution of the recoil mass signal from Z→ee decays** to about 80% of that from Z→ μμ decays with Brem photon recovery at EM resolution of 3%/√E [See **CEPC CDR**, 2020 *JINST* **15** P11005]

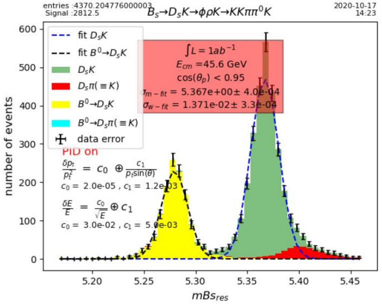
▸ $Z \rightarrow \mu^+\mu^-$ Recoil



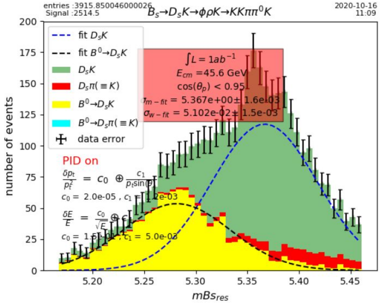
▸ $Z \rightarrow e^+e^-$ Recoil



3%/√E

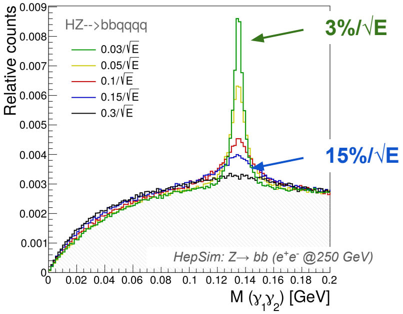


15%/√E



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

[R.Aleksan et al., *Study of CP violation in B± 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]

Not just aiming for excellent EM resolution

Proposed EM homogeneous calorimeter layouts **targeting also a good jet performance** as part of a bigger calorimeter/detector concept, **two approaches**:

- **SCEPCal**: moderately longitudinally segmented crystals to enable a PFA-like approach to jet reconstruction but mainly relying on dual-readout capabilities for integration with dual-readout HCAL
- **HGCCal**: aiming at a very high longitudinal granularity for optimal integration with particle flow algorithms (integration of dual-readout not excluded a priori)

SCEPCal proposal submitted to DRD6

Detector concept: Maximum information homogeneous calorimetry for lepton colliders using moderately-segmented crystals with dual-readout

Target application: Future Higgs factories (mainly e^+e^- colliders)

Unique challenges: Simultaneous readout of scintillation and cherenkov light signals from the same active element (heavy inorganic scintillator)

Technology: High density scintillating crystals with good cherenkov yield instrumented with dedicated optical filters and SiPMs

Next 3+ year goals: Identification of optimal crystal, optical filters and SiPM candidates and development of EM scale prototype for beam test

Existing international collaboration framework: see Calvision project

*University of Maryland (**USA**), University of Michigan (**USA**), University of Virginia (**USA**), Princeton University (**USA**), Caltech (**USA**), FNAL (**USA**), Argonne National Lab (**USA**), MIT (**USA**), Purdue University (**USA**), Texas Tech University (**USA**)*

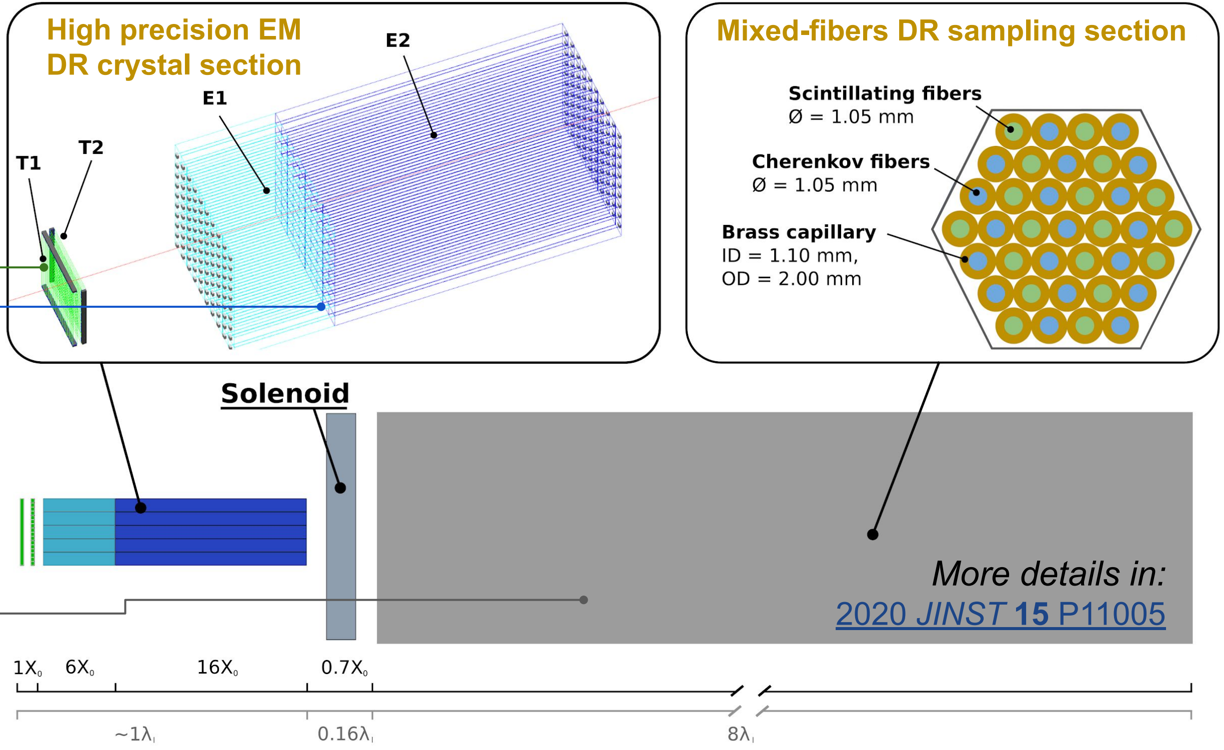
*CERN (**Switzerland**)*

*INFN and University of Milano-Bicocca (**Italy**), University of Napoli (**Italy**)*

Conceptual layout

- **Transverse and longitudinal segmentation** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals (~$1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment (~$6X_0$)
  - Rear segment (~$16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)
- **Ultra-thin IDEA solenoid**
  - ~$0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and “clear” PMMA fibers (for Cherenkov signal) inserted inside brass capillaries

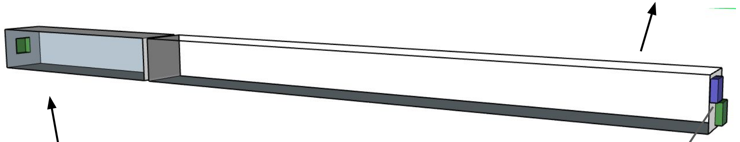


More details in:
2020 *JINST* **15** P11005

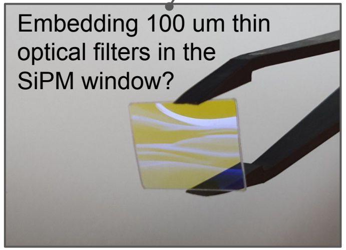
Implementation of dual-readout in the crystal section

- Simultaneous readout of scintillation and Cherenkov light from the rear segment with dedicated SiPMs+wavelength filters

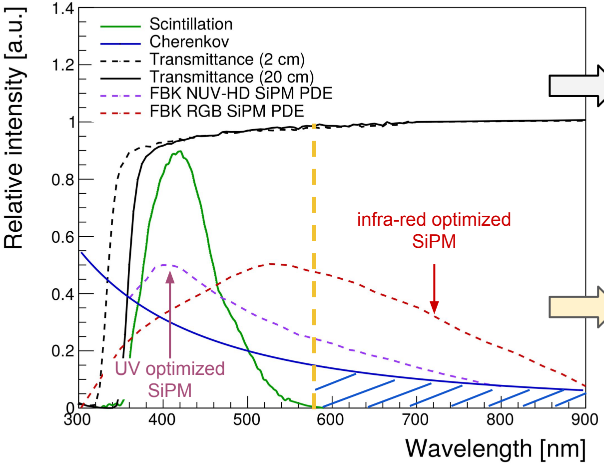
Rear crystal ECAL segment: Two 4x4 mm² SiPMs with optical filters optimized for scintillation and cherenkov detection resp.



Front crystal ECAL segment: Single 5x5 mm² SiPM per crystal optimized for scintillation light detection



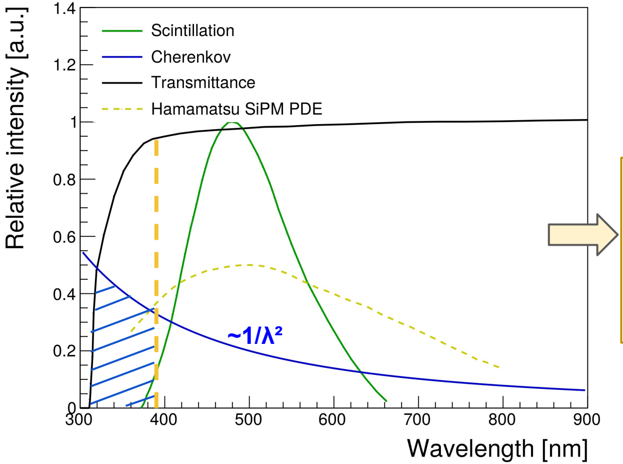
PWO



Estimated:
- >2000 phe/GeV for scintillation photons
- >100 phe/GeV for Cherenkov photons

Cherenkov photons above scintillation peak are much less affected by self-absorption

BGO / BSO



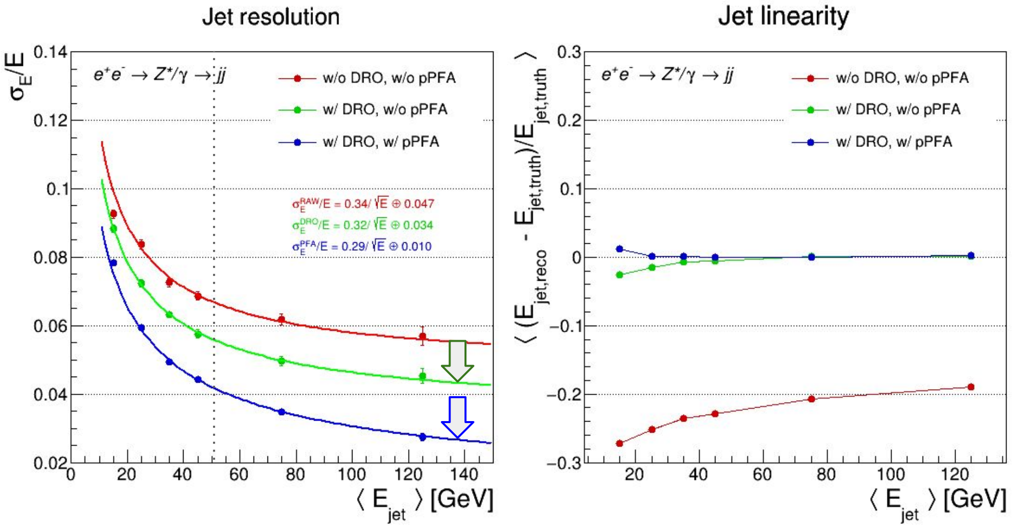
BGO/BSO have larger stokes shift, i.e. a wider range of transparency for 'UV Cherenkov'

Jet resolution: with and without DR-pPFA

More details in:
[2022 *JINST* **17** P06008]

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \rightarrow Z^* \rightarrow jj$ events (at different center-of-mass energies):

- crystals + IDEA w/o DRO
- crystals + IDEA w/ DRO
- crystals + IDEA w/ DRO + pPFA



Sensible improvement in jet resolution using dual-readout information combined with a particle flow approach → 3-4% for jet energies above 50 GeV

HGCCal proposal submitted to DRD6

Detector concept: Highly granular EM crystal based calorimeter to exploit maximum potential of PFA algorithms

Target application: Future Higgs factories (mainly e^+e^- colliders)

Unique challenges: Integration (readout, minimize gaps, material budget), reconstruction driven by grid layout

Technology: High density scintillating crystals with double-ended SiPM readout

Next 3+ year goals: Comprehensive feasibility study: single particle and jet performance with PFA, **mechanical** designs and integration, crystal-SiPM readout and front-end electronics optimization, EM prototype and beam tests

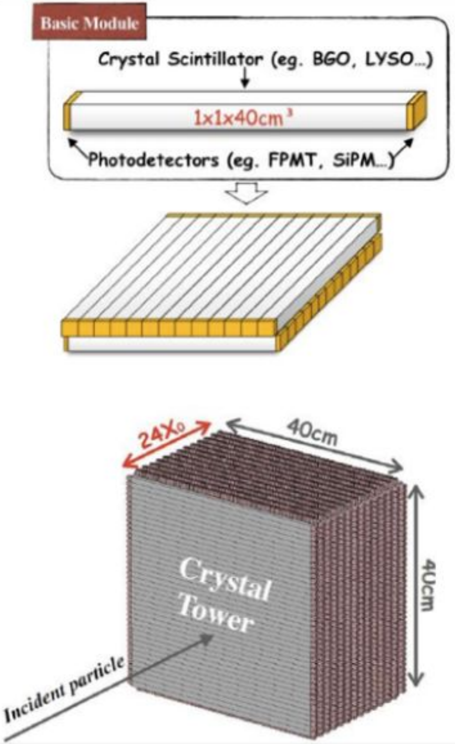
*Institute of High Energy Physics (IHEP) (**China**)*

*Shanghai Jiao Tong University (SJTU) and Tsung-Dao Lee Institute (TDLI) (**China**)*

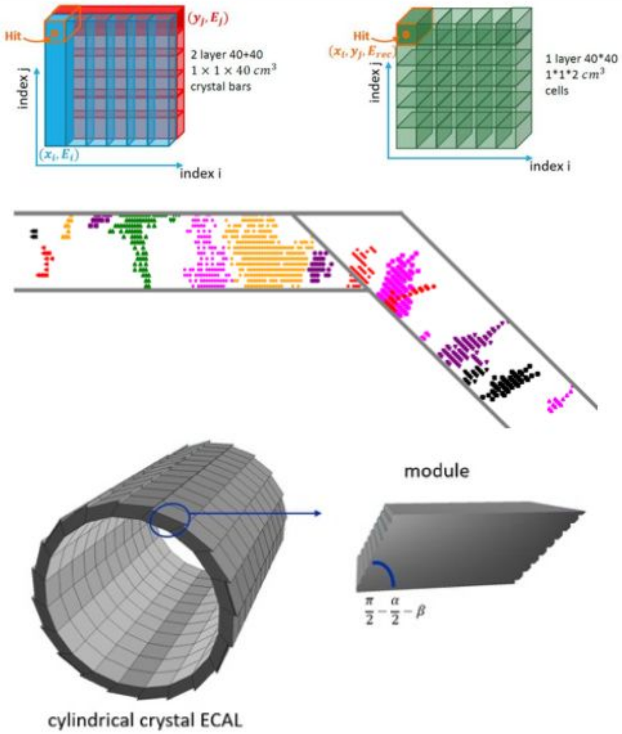
*The Shanghai Institute of Ceramics of the Chinese Academy of Sciences (SICCAS) (**China**)*

Highly Granular Crystal Calorimeter

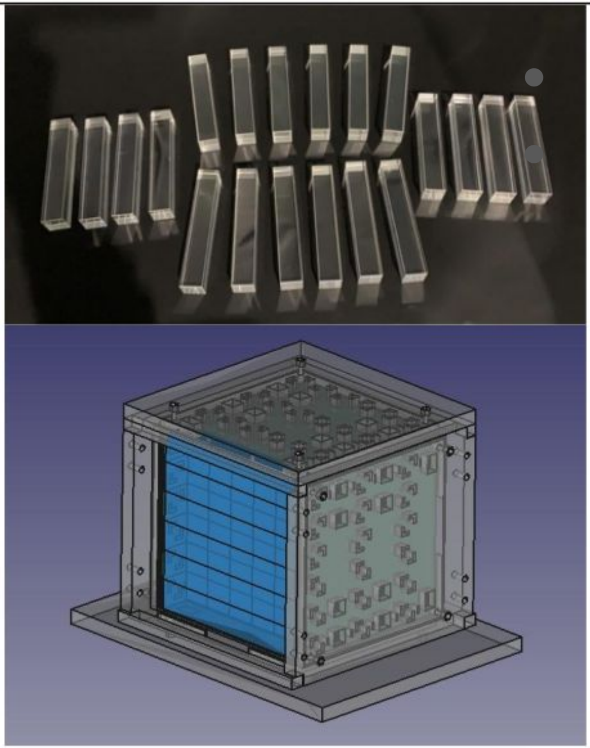
More in yesterday's talk by I.Vivarelli



EM calorimeter module: a grid of ~1x1x40cm³ crystal bars



Advanced simulation and reconstruction studies with PFA



Hardware developments on crystals, SiPMs, prototypes

CRILIN proposal submitted to DRD6

Detector concept: Cost effective and radiation tolerant design of a longitudinally segmented crystal EM calorimeter for mitigation of beam induced background at muon colliders.

Target application: Muon collider

Unique challenges: Very harsh radiation environment for SiPMs, high rate of operation, large beam induced background (BIB)

Technology: Lead fluoride (PbF_2) crystals, each readout with 2 channels consisting of a pairs of SiPMs connected in series

Not explicitly for e^+e^- but with small adaptation could be used at FCCee and certainly many synergies with the other calorimeter concepts

*INFN - Sezione di Trieste (**Italy**)*

*Helmholtz-Zentrum Dresden-Rossendorf (**Germany**)*

*INFN - Sezione di Torino (**Italy**)*

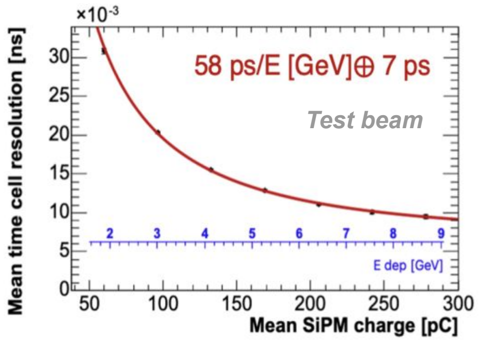
*INFN - Laboratori Nazionali di Frascati (**Italy**)*

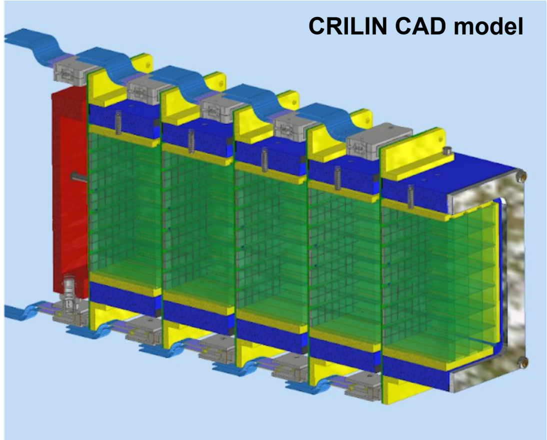
*INFN - Sezione di Padova (**Italy**)*

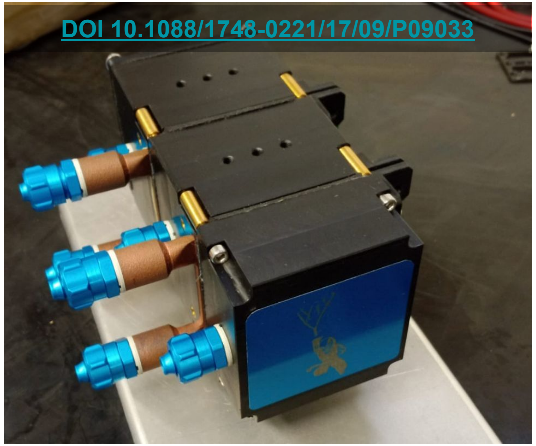
*Donostia International Physics Center (**Spain**)*

CRILIN: Development and test of an innovative semi-homogeneous calorimeter for Muon Collider

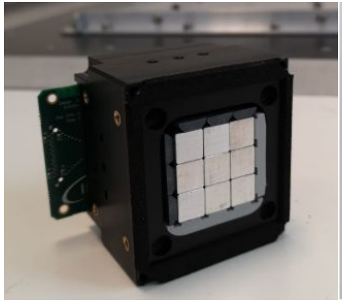
- **Timing and longitudinal segmentation** to tackle the beam induced background (BIB)
- **Advanced** R&D and **prototyping**
  - 5 layers: 1x1x4 cm³ **PbF_2** crystals with 3x3 mm² UV extended 10µm SiPMs
- Synergies with other collaborations (AIDAinnova, HIKE, …)

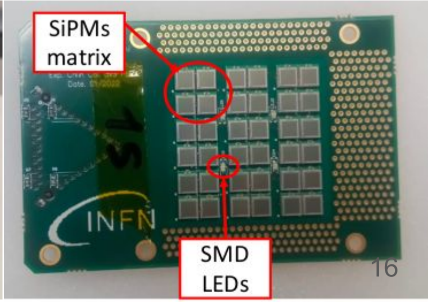






Modular architecture based on stackable modules





Possible **synergies within DRD6**

- **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
    - Sharing expensive R&D (and build a critical mass)
      - Development of custom **dense** scintillators with manufacturers
      - Common photodetector developments (e.g. **smaller cell size SiPMs, digital SiPMs, low power, radiation hard, …**)

Possible **synergies within DRD6**

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**

Summary

- Many enthusiastic **innovative concepts** of homogeneous calorimeters emerging in the **international community to offer a ~3%/√E EM resolution while meeting jet resolution requirements of future e^+e^- Higgs factories**

- **Many technological aspects, challenges and R&D strategies are in common** across various DRD6 proposal (e.g. enhance granularity with SiPM readout)

- The goal of **DRD6** is become a framework **to exploit synergies** and optimize resources (e.g. common infrastructure)

Additional material

*Scintillator material for future calorimeter (**ScintCal**)*

Detector concept: R&D on various scintillators and wavelength shifters

Target application: Homogenous and sampling calorimeters for HL-LHC, FCC-hh, Higgs factories

Unique challenges: Optimisation of materials (e.g. for radiation hardness, decay time, collection of Cherenkov light, mass production)

Technology: Inorganic and organic scintillators, glasses, ceramics, quantum materials

Next 3+ year goals: Clear overview of the state-of-the-art materials and propose scintillators with mass scale production capability for future collider experiments

*CERN (**Switzerland**) Vilnius University (**Lithuania**) Centre for Particle Physics of Marseille (imXgam) (**France**) University of Maryland (**USA**) Institute of Physics of the Czech Academy of Sciences (**Czech Republic**), ILM- CNRS & University Claude Bernard Lyon1 (**France**), Institute for Scintillation Materials NAS of Ukraine (**Ukraine**), Università Politecnica delle Marche, Ancona (**Italy**), Institute of Physics, University of Tartu (IPUT), (**Estonia**), FH Aachen (Germany), Giessen University (**Germany**), ORNL (**USA**), University of Notre Dame (**USA**), University of Iowa (**USA**), University of Virginia (**USA**), Caltech (**USA**), Istanbul University (**Turkey**), CEA Saclay / IRFU (**France**) University of Milano-Bicocca (**Italy**)*

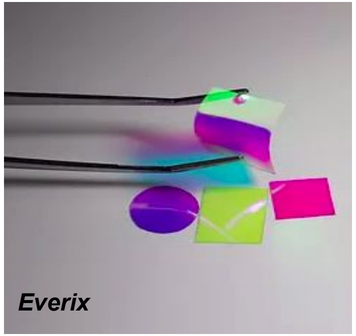
Ongoing R&D: dual-readout challenge

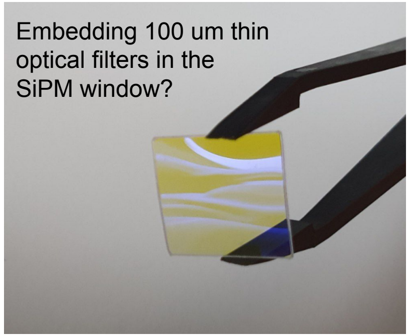
Multi-signal readout challenges:

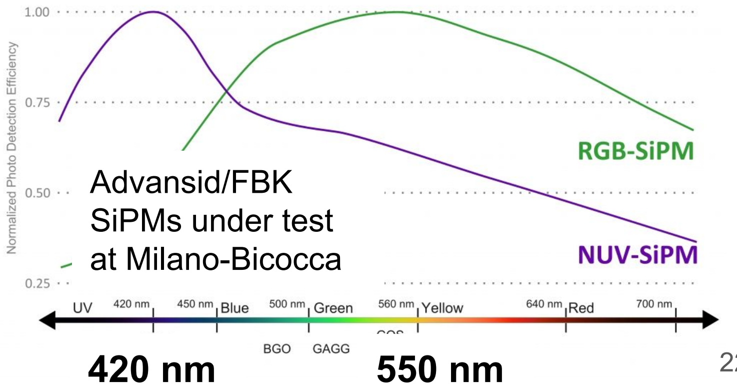
- Challenging dynamic range and photon sensitivity with SiPMs
- Reasonable **scintillation** and **cherenkov** light yields (>2000 phe/GeV and >100 phe/GeV resp.)
- **Good separation of scintillation and cherenkov signals** (e.g. based on thin wavelength filters)

Exploring crystal candidates with high Cherenkov yield and density (PWO, BGO, BSO)

Exploring SiPMs with different spectral sensitivities, to better match the S and C spectra (e.g. near infra-red sensitive SiPMs)





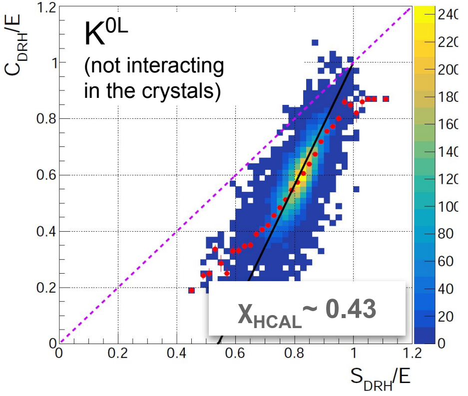


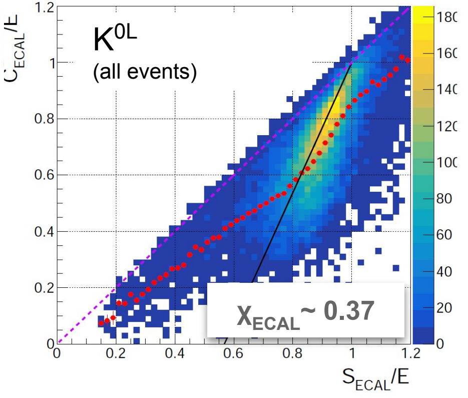
The **dual-readout method** in a hybrid calorimeter

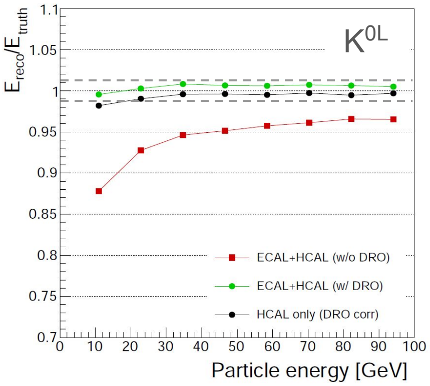
- Apply the DR correction on the energy deposits in the crystal and fiber segments first and then s um up the corrected energy from both segments

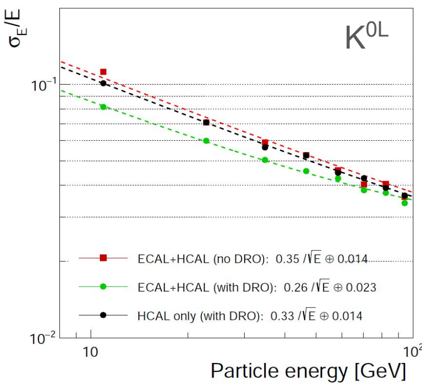
$$E_{HCAL} = \frac{S_{HCAL} - \chi_{HCAL} C_{HCAL}}{1 - \chi_{HCAL}}$$
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1 - \chi_{ECAL}}$$
$$E_{total} = E_{HCAL} + E_{ECAL}$$

- **Dual-readout method confirms its applicability in a hybrid calorimeter**
  - Response linearity to hadrons restored within ±1%
  - Hadron energy resolution comparable to that of the fiber-only IDEA calorimeter



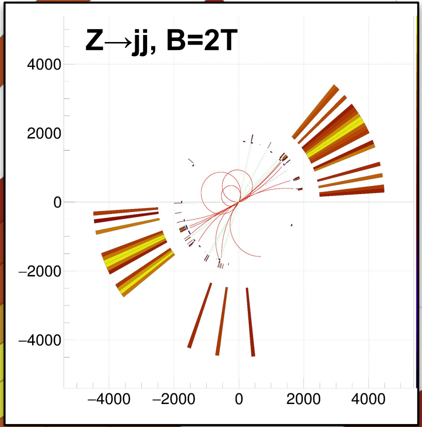


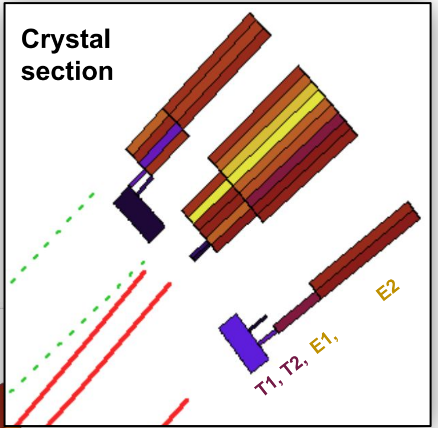


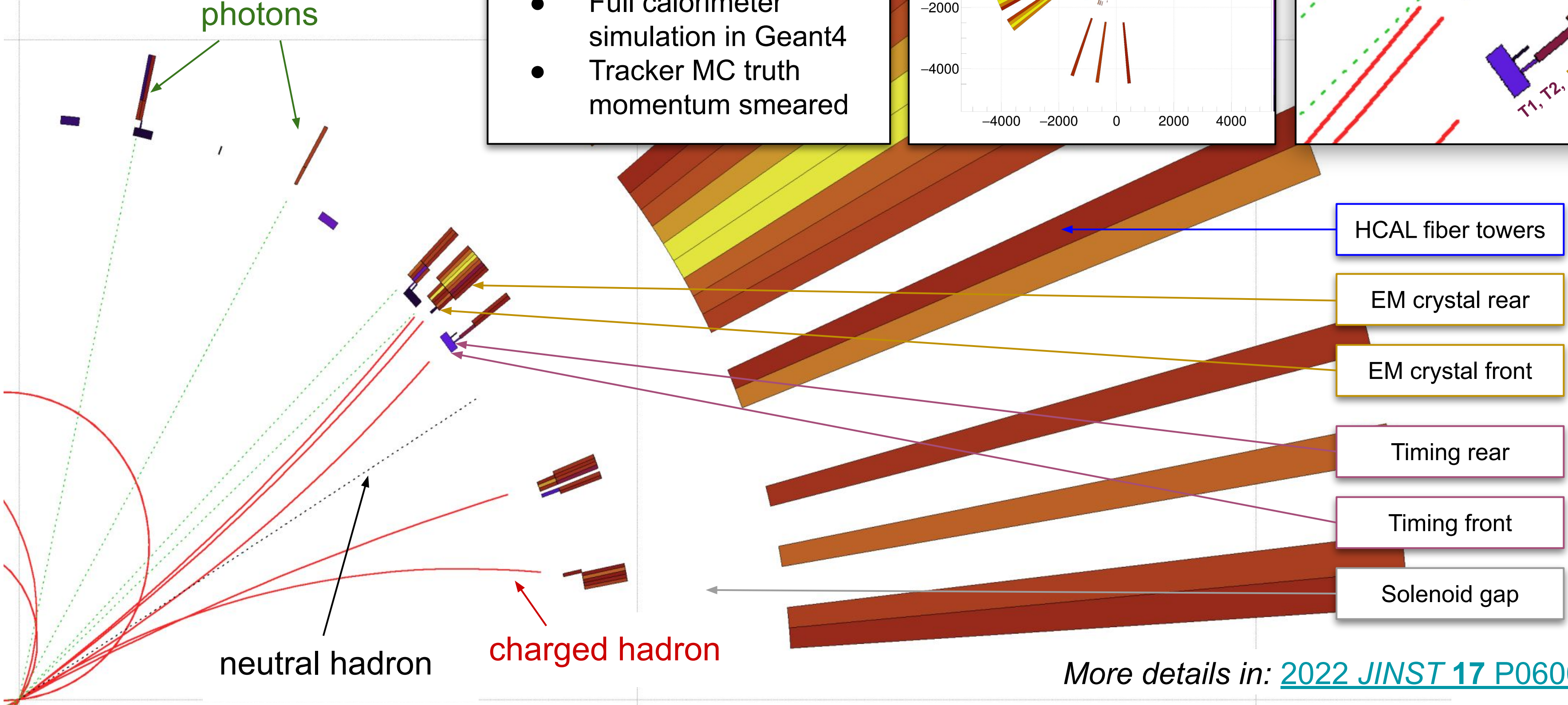


A Dual-Readout ‘prototype’ Particle Flow Algorithm (DR-pPFA)

- Full calorimeter simulation in Geant4
- Tracker MC truth momentum smeared







More details in: [2022 *JINST* **17** P06008]