# A dual-readout segmented crystal calorimeter for the IDEA detector

R. Hirosky[1], M. Lucchini[2]
[1] University of Virginia, USA
[2] INFN & University of Milano-Bicocca, Italy

*on behalf of the Calvision / MAXICC groups*

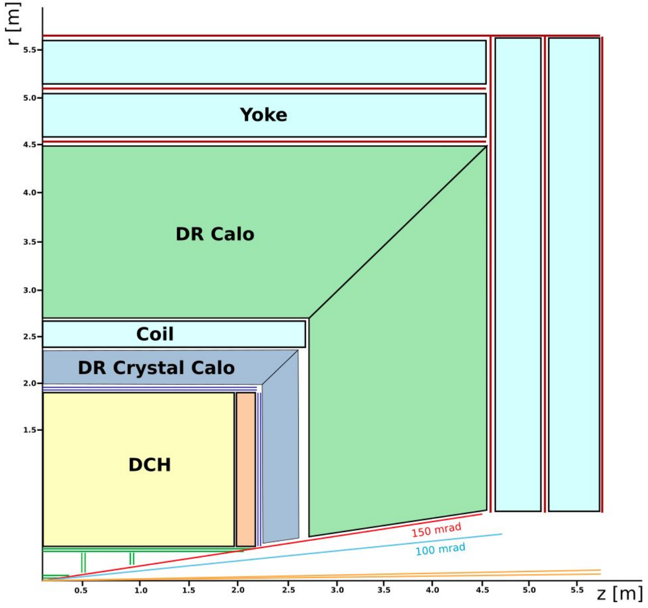
**First IDEA International Meeting**
15 October 2024

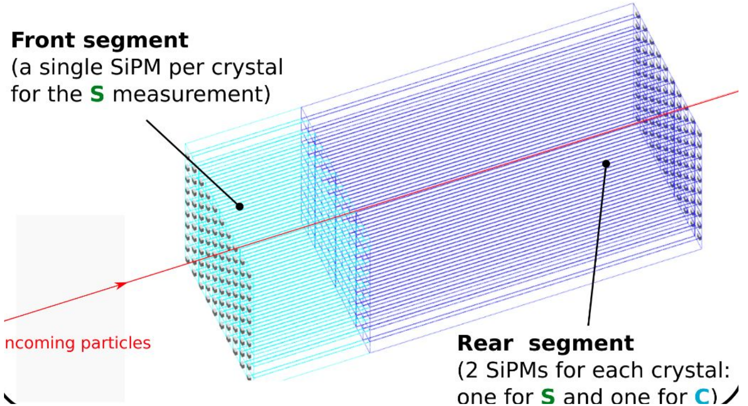
# Overview of the project

- Evaluate the potential and the feasibility of integrating a **cost-effective homogeneous dual-readout segmented** crystal **EM** calorimeter in the IDEA detector

- First studies and concept descriptions in:
  - [2020 *JINST* **15** P11005]
  - [2022 *JINST* **17** P06008]

- Activity at 360 degrees:
  - Simulation studies (from standalone to full sim)
  - R&D on technology and proof-of-principle
  - Prototyping of a calorimetric module



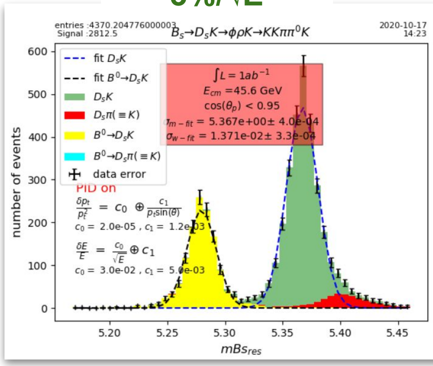



# High EM energy resolution potential at e+e- Higgs factories

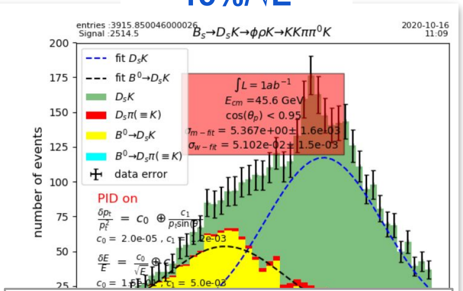
A calorimeter with **3%/√E EM** energy resolution has the potential to improve event reconstruction and **expand the landscape of possible physics studies** at $e^+e^-$ colliders

- **CP violation studies** with $B_s$ decay to final states with low energy photons
- **Clustering of $\pi^0$'s photons** to improve performance of jet clustering algorithms
- **Improve the resolution of the recoil mass signal from Z→ee decays** to ~80% of that from Z→ μμ decays (recovering Brem photons)

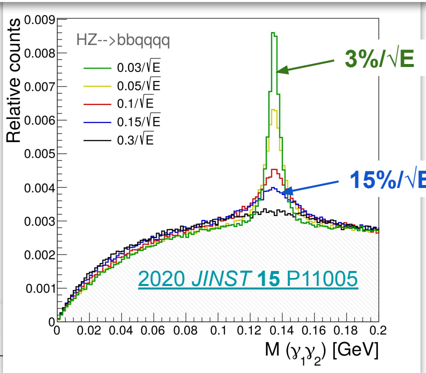
3%/√E

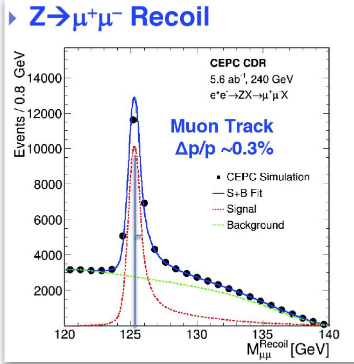


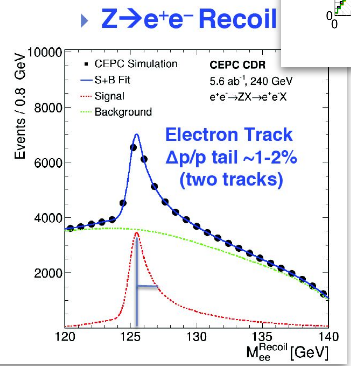

15%/√E




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




*Example from CEPC CDR*

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

Including a **dual-readout** in the crystal EM calorimeter section enables the use of DR method in a hybrid calorimeter configuration

1. Evaluate the χ-factor for the crystal and fiber section
2. Apply the DRO correction on the energy deposits in the crystal and fiber segment independently
3. Sum up the corrected energy from both segments

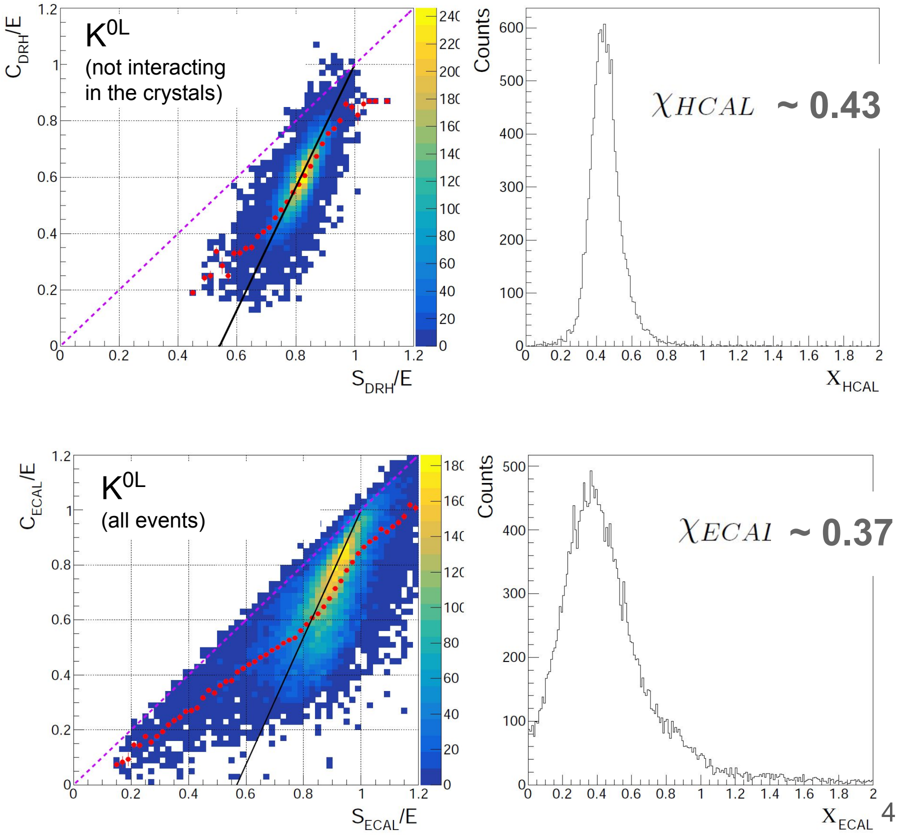
$$\chi_{HCAL} = \frac{1-(h/e)_s^{HCAL}}{1-(h/e)_c^{HCAL}}$$

$$\chi_{ECAL} = \frac{1-(h/e)_s^{ECAL}}{1-(h/e)_c^{ECAL}}$$

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

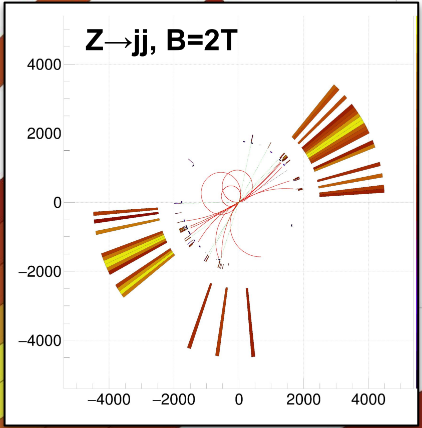
$$E_{ECAL} = \frac{S_{ECAL} - \chi_{ECAL} C_{ECAL}}{1-\chi_{ECAL}}$$

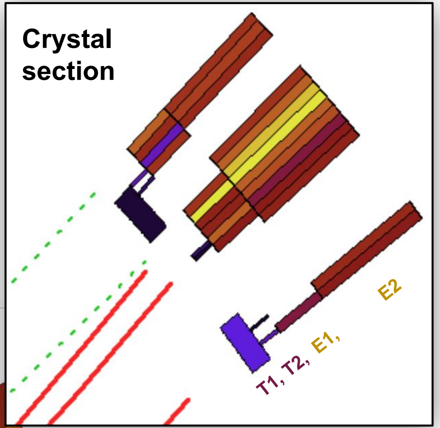
$$E_{total} = E_{HCAL} + E_{ECAL}$$

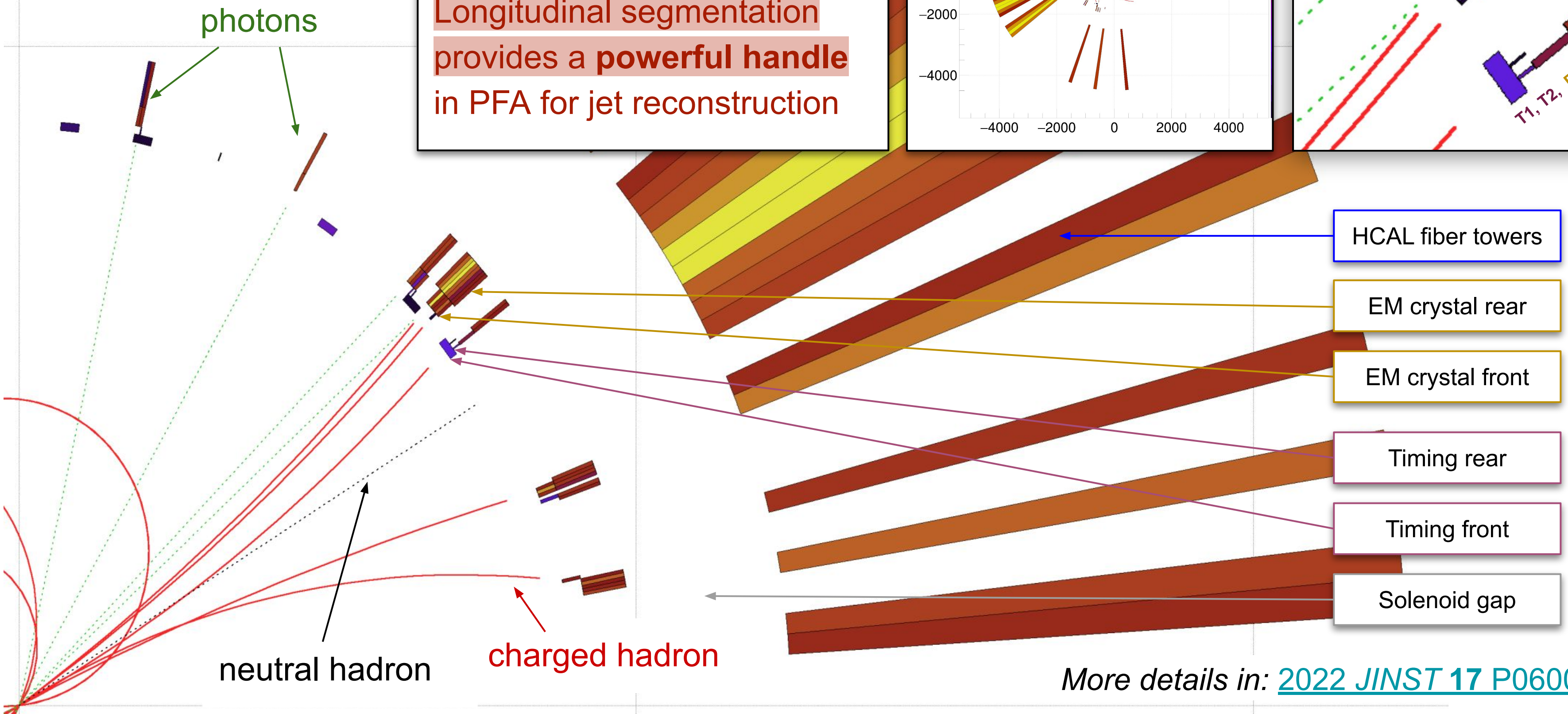


# A Dual-Readout ‘prototype’ Particle Flow Algorithm (DR-pPFA)

Longitudinal segmentation provides a **powerful handle** in PFA for jet reconstruction



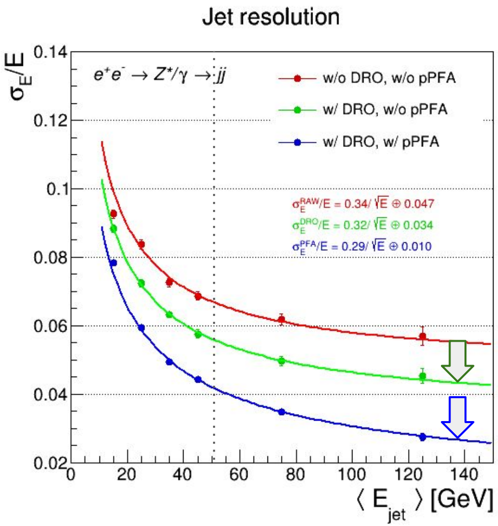

More details in: *2022 JINST* **17** *P06008*

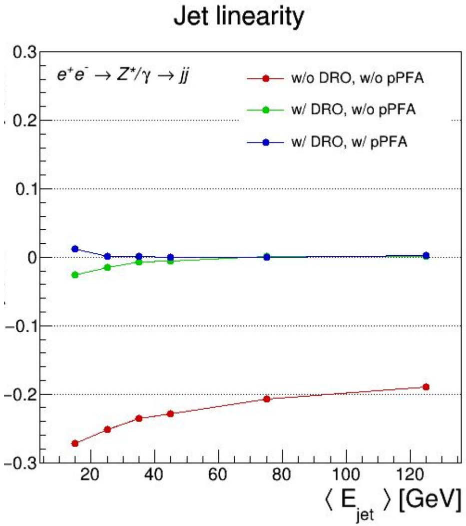
# **Jet resolution**: with and without DR-pPFA

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

Jet energy resolution and linearity as a function of jet energy in off-shell $e^+e^- \to Z^* \to jj$ 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**

# Existing collaborations and synergies

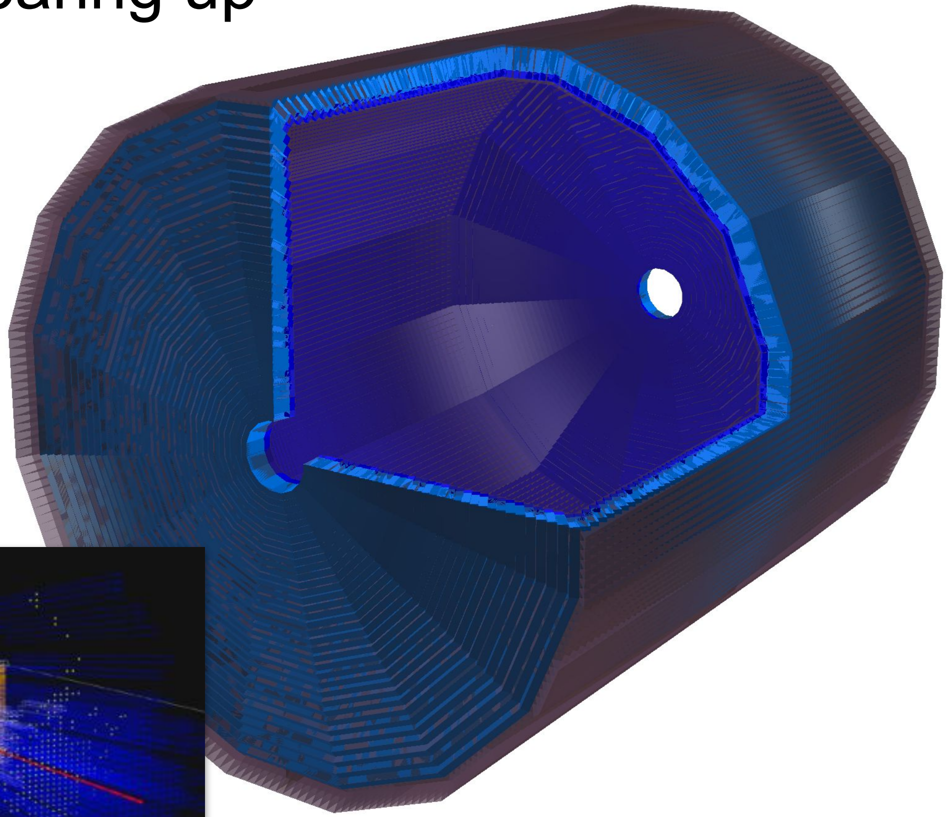
- An international effort ramping up since 2023:
  - **INFN**:
    - Napoli, Milano-Bicocca, Perugia
    - Efforts ramped up in synergy with PRIN **MAXICC**
  - **CALViSION**:
    - A DOE funded project bringing together several US institutions
    - Maryland, Princeton, UVa, Caltech, FNAL, ANL, SLAC*, Michigan, Catholic University of America*, Brandeis*, Stonybrook*, Rutgers*, TTU. MIT, Baylor*, Purdue, Caltech

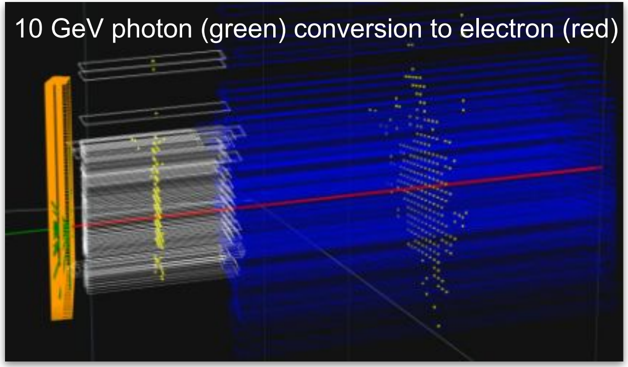
      *new
  - CERN and IN2P3-IP2I
- **The project goals are aligned with the strategic objectives identified in the ECFA R&D roadmap** and part of DRD6 collaboration (on calorimetry), WP3 task 3.1.2

# Highlights from 2024

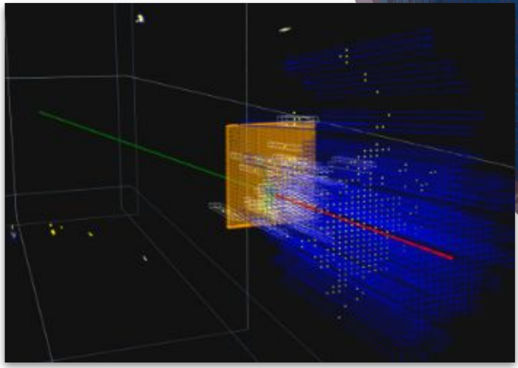
# Implementation in key4hep gearing up

- Fully differentiable detector geometry and simulation in key4hep (github)
  - SiPMs and digitized readout implemented
  - ML angular resolution and e/gamma regression studies underway
  - Integration with IDEA detector underway
  - See W.Chung at CALOR2024





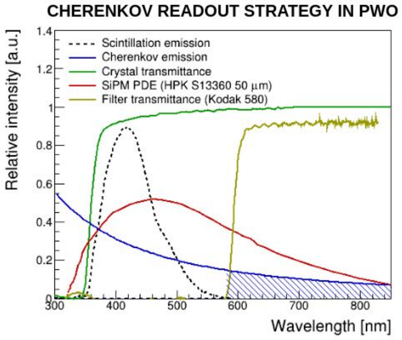
10 GeV photon (green) conversion to electron (red)

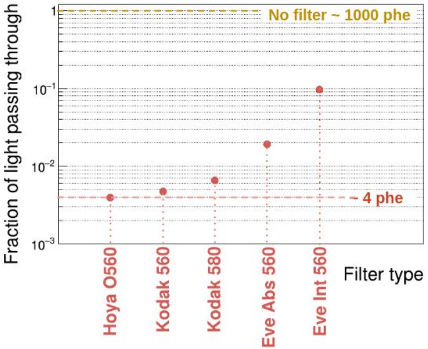


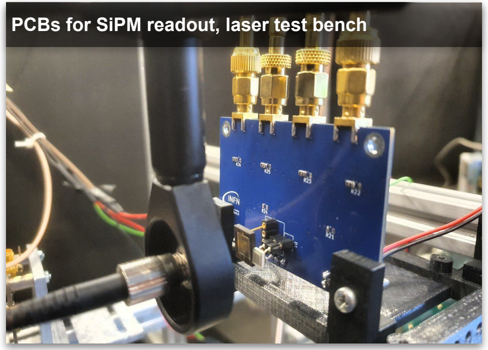
*W.Chung*
*(Princeton University)*

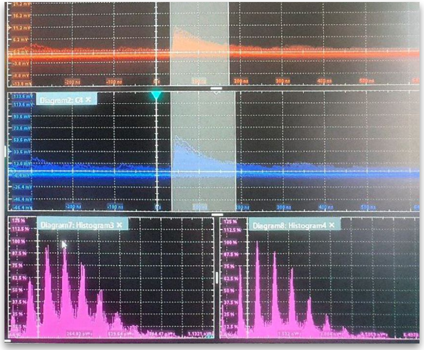
# Characterization of SiPMs, crystals and optical filters

- Laboratory benches exploiting radioactive sources, laser excited photoluminescence and cosmic rays for single calorimetric cell R&D
- Characterization of scintillating crystals (PWO, BGO, BSO, …), SiPMs (Broadcom, Hamamatsu) and ultrathin absorptive optical filters to isolate the Cherenkov light
  - **Interference filters excluded, optimal absorptive filters identified for use in test beam**

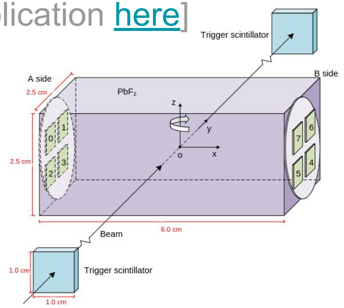



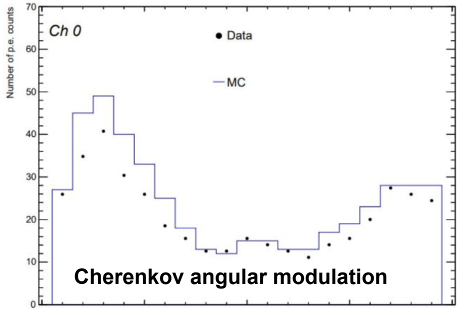



# Analysis and submission of 2023 test beam work

## Concentrated on tests of optical photon modeling

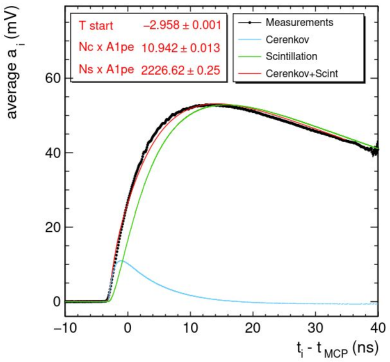
- Study modeling of light collection in of PbF2 (pure Cherenkov radiator) [recent publication here]

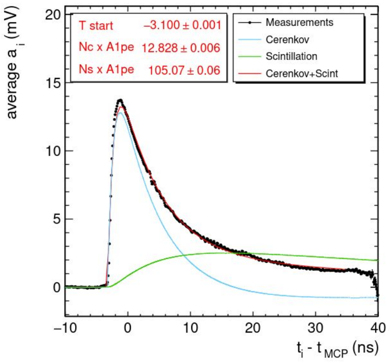


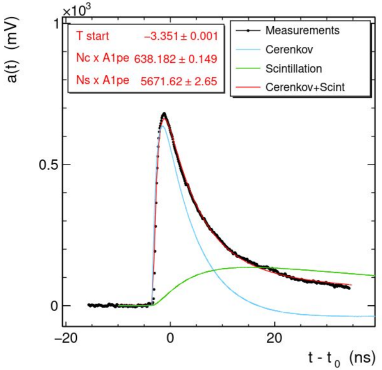



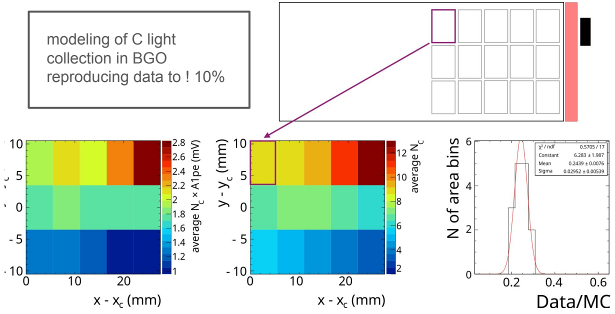


- Initial tests of S/C light light collection and modeling in BGO [recent publication here]



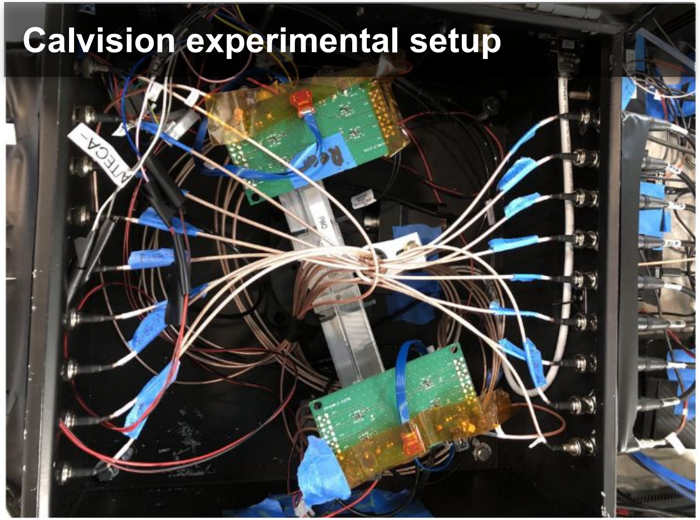



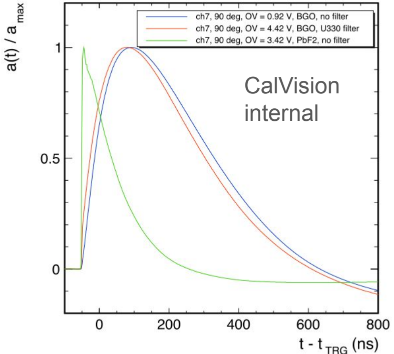



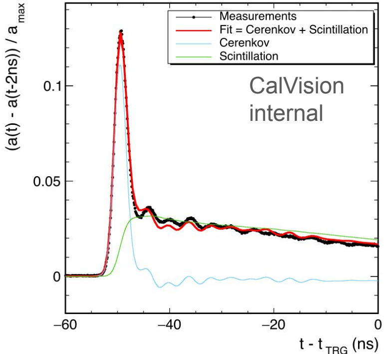
# Test beam at DESY (April 2024)

- Coordinated by Calvision US groups with participation from Milano-Bicocca
- Test of PbF2 as a pure Cherenkov radiator for reference, PWO, BGO and (new!) heavy glasses
- Test of different filters using silicon cookies as optical interface and Broadcom SiPMs
- Focus on large crystals with multiple SiPM readout



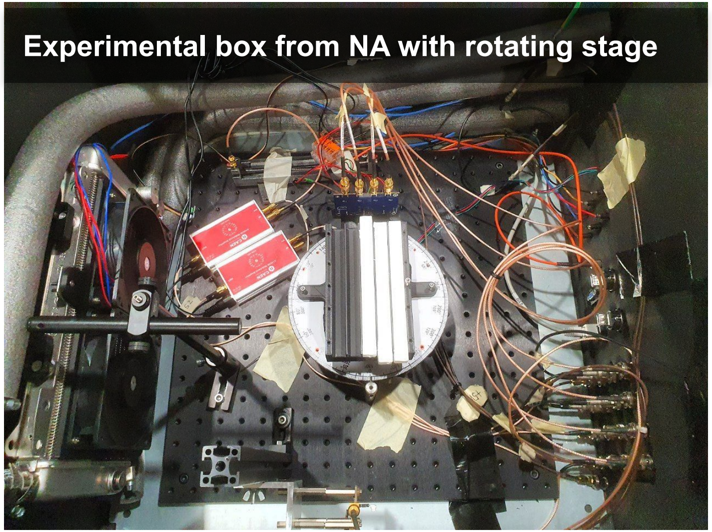


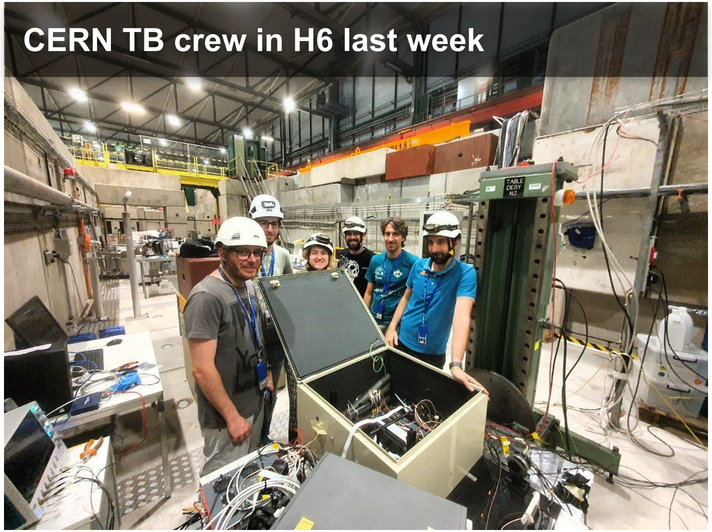


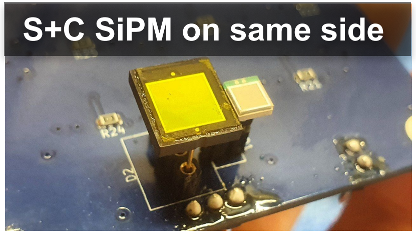




# Test beam at CERN (July 2024)

- Prepared and coordinated by Napoli and MIB with participation from Perugia, US and CERN
- Tests with electrons (10-100 GeV), muons, hadrons
- Tested a variety of filters and crystals to assess Cherenkov yield as a function of of beam angle
- **Plenty of useful data to steer the next R&D steps** and technological choices for the prototype construction




# Plans for 2025

# Mid-term plans

2023 | 2024 | 2025 | 2026+

Technology surveys and R&D (crystal, sipm, filters)

Set up and consolidation of laboratory benches

Single sensor beam test with various flavors of crystal, filters and SiPMs

Full containment EM calorimetric module prototype (10x10 matrix) built (and tested) using most promising technology

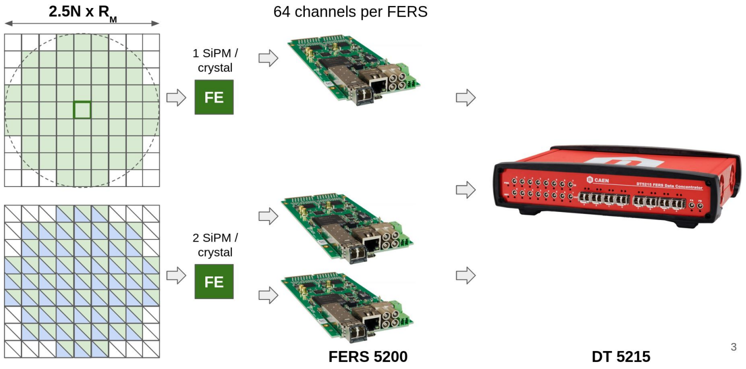
Central tower (3x3/5x5) EM calorimetric module prototype built (and tested) using alternative technology

Combined test beam with fibre calorimeter prototype

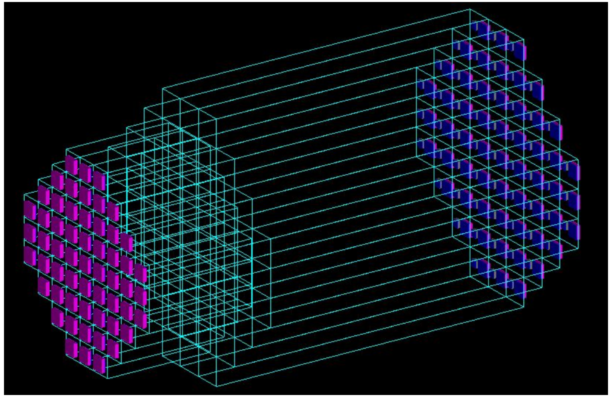
# Towards a multi-channel prototype

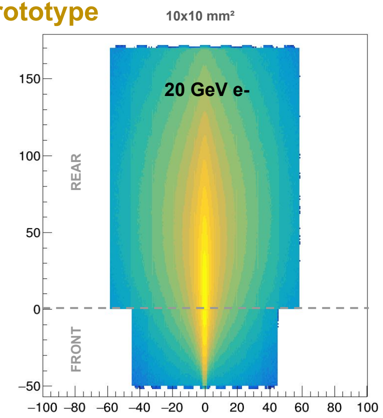
- 2024 lab and beam test results will inform the choice of a baseline technology to **build a full containment EM calorimeter prototype (~200 channels)**
- Procurement of electronics for readout started, procurement of crystals and SiPMs in early 2025 (informed by test beam results in 2024)
- **Test of the prototype on beam** at DESY or CERN in the second half of 2025 (possibly joint test with HIDRA fiber calorimeter prototype to anticipate beam shortage from 2026)

**Prototype readout schematics**



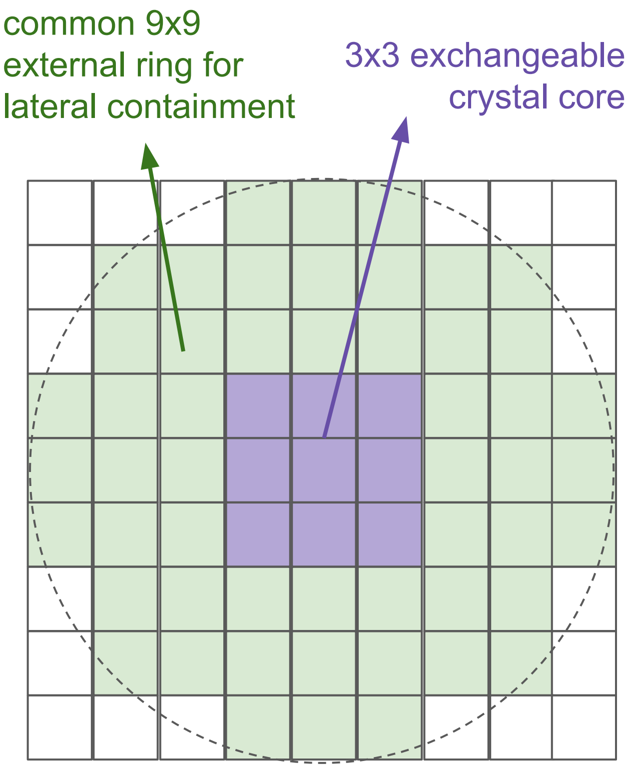

**Geant4 simulation of prototype**





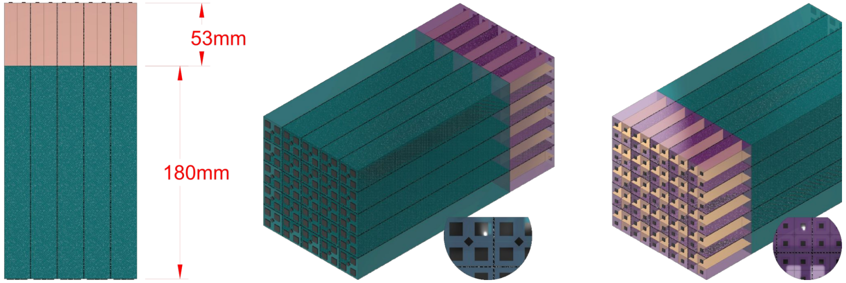
# **A modular design** to change the prototype core matrix

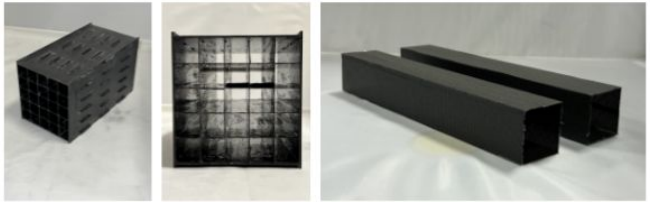
- **Strategy**: build a large **PWO** crystal array as a lateral containment unit and design the prototype mechanics in a modular way to enable exchange of the central 3x3 crystal matrix
- **Alternative technology critical to test**: baseline could be PWO (fast but low light yield and with scintillation in the UV range), alternative option with **slower but brighter crystal with scintillation at higher wavelengths** (e.g. BGO, BSO)
- Coordinated/supported/funded by MAXICC/INFN

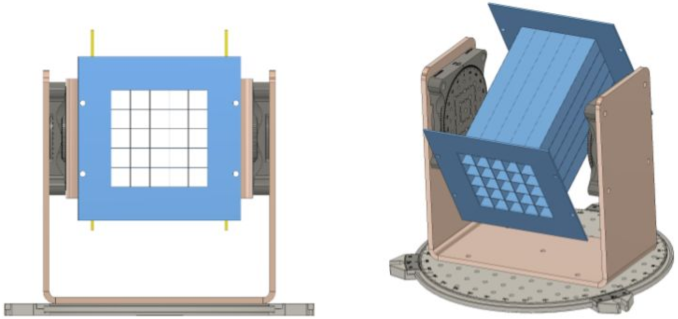


# Complementary matrix plan

- **BGO** matrix: $22X_0$ deep, $5X_0$ x $5X_0$ lateral with $1X_0$ and $¼X_0$ lateral granularity
  - Crystal purchase in progress - expected to arrive and complete testing in spring
- **Carbon fiber alveolar, mechanic support, and cooling options, R&D in progress**
- **Studies to improve electronics (e.g. linearity) over next 6-8 months**
  - Similar readout w/ FERs 5200 for front section, most likely DRS or NALU HDSoc for rear section
- Form factors and mechanics of electronics for EM containment scale will be challenging
- Coordinated/supported/funded by Calvision





# Summary

- The **potential of an enhanced EM energy resolution** of the IDEA detector by mean of a crystal calorimeter is a growing interest both at the national and international level

- **R&D and proof-of-principle** of this innovative calorimeter concept is ongoing, with efforts that have been ramping up in 2024 with a series of beam tests

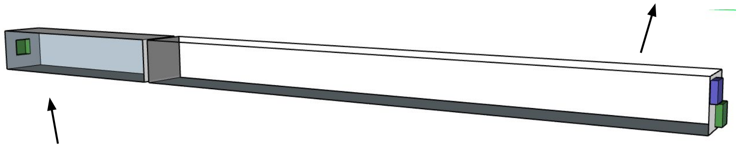
- **An R&D plan** to achieve the demonstration of this calorimetric technique using a full scale EM calorimeter prototype **by the next european strategy for particle physics update** is being pursued

# Additional material

# **Implementation** of dual-readout in the crystal section

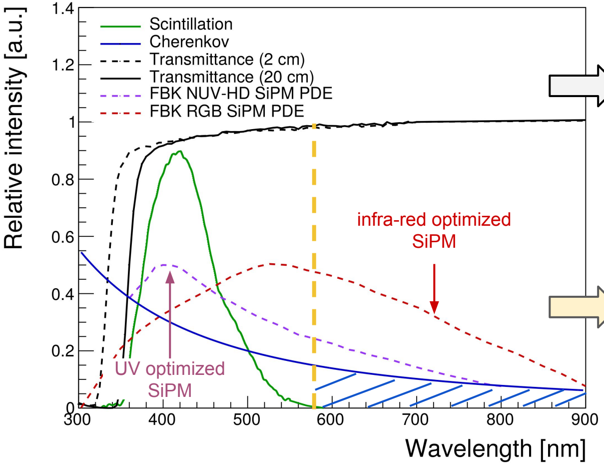
- Simultaneous readout of scintillation and Cherenkov light from the rear segment with dedicated SiPMs+wavelength filters

**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

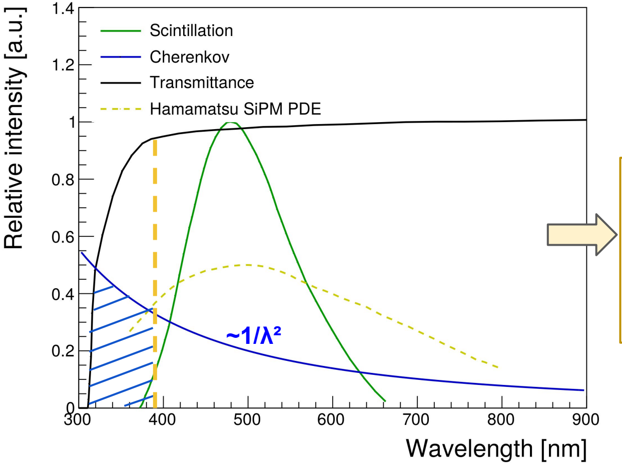
## PWO




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'

# **Photo-statistic** requirements for S and C

- A poor S (scintillation signal) impacts the hadron (and EM) resolution stochastic terms:
  - S > 400 phe/GeV
- A poor C (Cherenkov signal) impacts the C/S and thus the precision of the event-by-event DRO correction
  - C > 60 phe/GeV
- **Baseline layout choices** (granularity and SiPM size) to **provide sufficient light collection efficiency** in Geant4
  - Need experimental validation with lab and beam tests