7th International Workshop on Future Tau Charm Facilities

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Dual readout crystal calorimeter for the IDEA detector

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On behalf of DRDcalo-MAXICC group

INFN
Istituto Nazionale di Fisica Nucleare

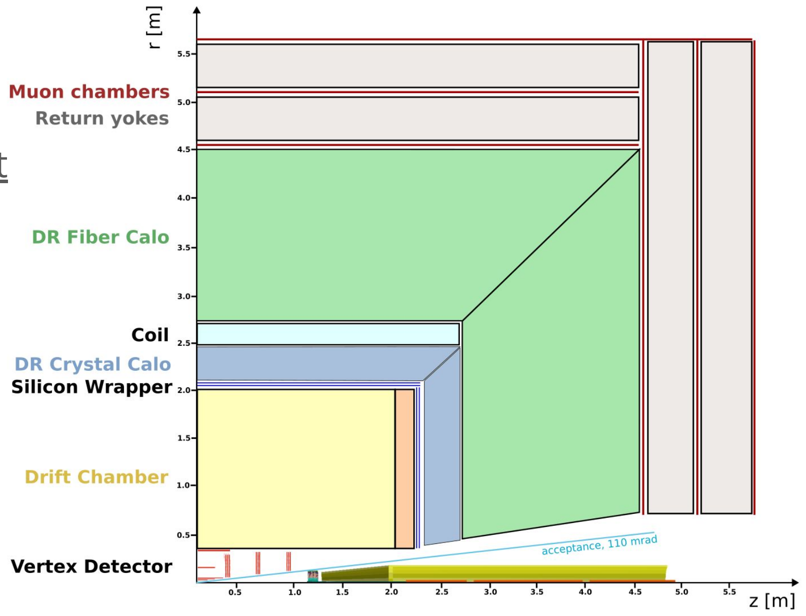
IDEA detector concept

arXiv:2502.21223

Future e^+e^- Tera-Z /Higgs / Top factory, $\sqrt{s} \approx$ 90–360 GeV

IDEA detector concept:

- **Vertex/tracking**: pixel detector (e.g. MAPS), large-volume drift chamber, silicon wrapper → excellent resolution, minimal material budget
- **Calorimeter**: electromagnetic crystal calorimeter, hadronic fiber calorimeter → high granularity, dual readout capabilities
- **Magnet and muon system**: thin HTS solenoid, muon chambers in the return yoke



Focus of this talk: the *dual readout homogeneous crystal electromagnetic calorimeter*

Benchmarks for IDEA calorimeter

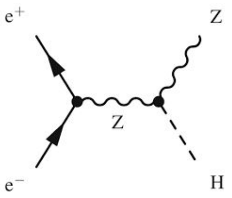
- **Jet** energy resolution **~3% @50 GeV** to separate W/Z (e.g. for tagging Higgstrahlung)

  → Rely on particle flow algorithms (**PFA**): need **high spatial resolution** to isolate neutral particles in jets, and some **longitudinal segmentation** to reduce confusion

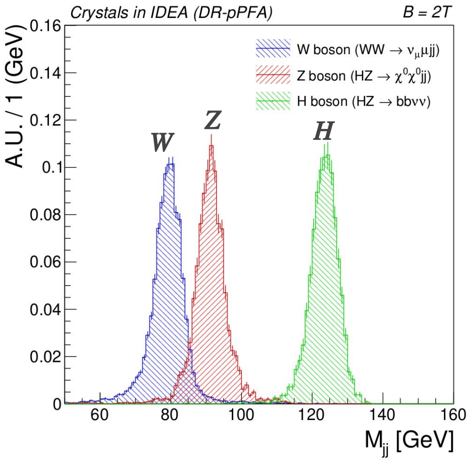
  → Need **neutral hadron energy resolution σ_E/E < 30%/$\sqrt{E}$**: **dual readout** (DR) compatibility

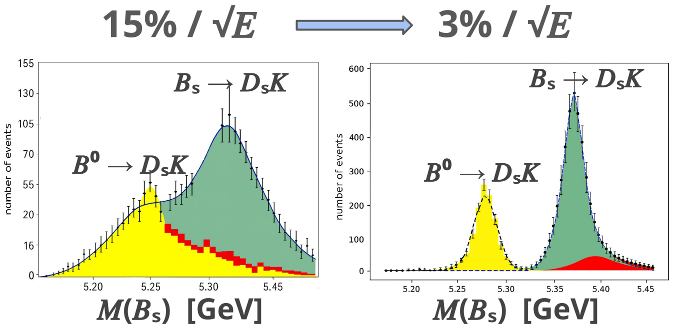
- Fully exploit **flavor physics** potential of the machine: B, D decays with π^0 (e.g. CPV in B_s), ALPs searches

  → need **e.m. energy resolution σ_E/E < 3%/$\sqrt{E}$**: feasible with homogeneous crystals



2022 JINST 17 P06008





arXiv:2107.05311

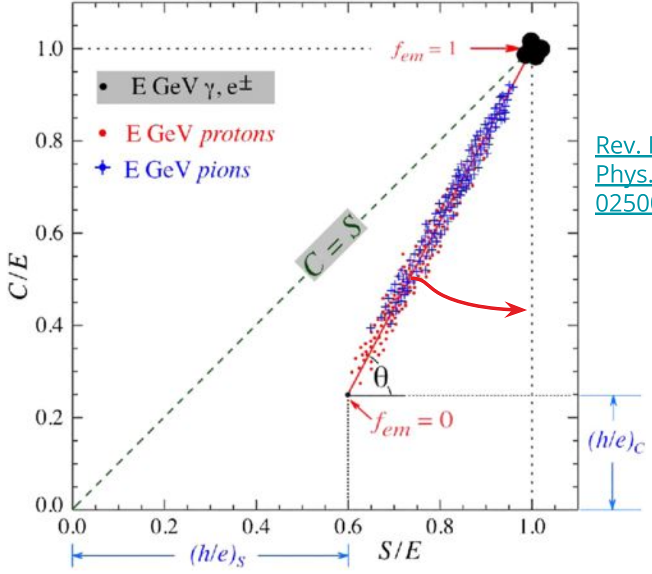
Dual readout principle

Hadronic showers have a **non-compensating** response (***h≠e***), and the electromagnetic fraction (***f*$_{em}$**) fluctuates event-by-event → degraded resolution

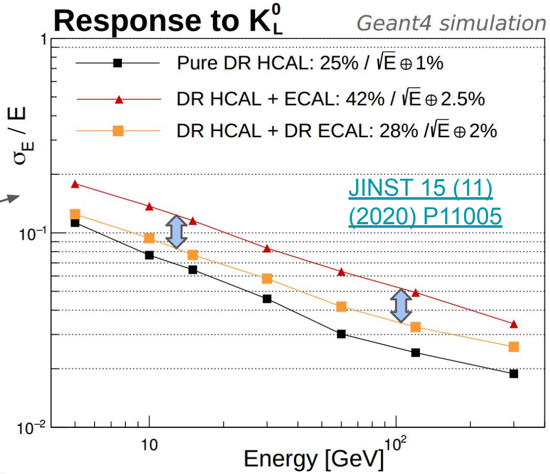
- Cherenkov signal (**C**) → sensible mainly to fast e.m. component
- Scintillation signal (**S**) → measures total deposited energy (including slow hadrons)

Shower-by-shower correction of the f_{em} fluctuations using **(C, S)** values → restore **linearity** and improve **hadronic energy resolution**

To keep same performance on the "hybrid" e.m. + had. calorimeter, **extend DR corrections to the e.m. section** (~1 λ of material)



Rev. Mod. Phys. 90, 025002 (2018)



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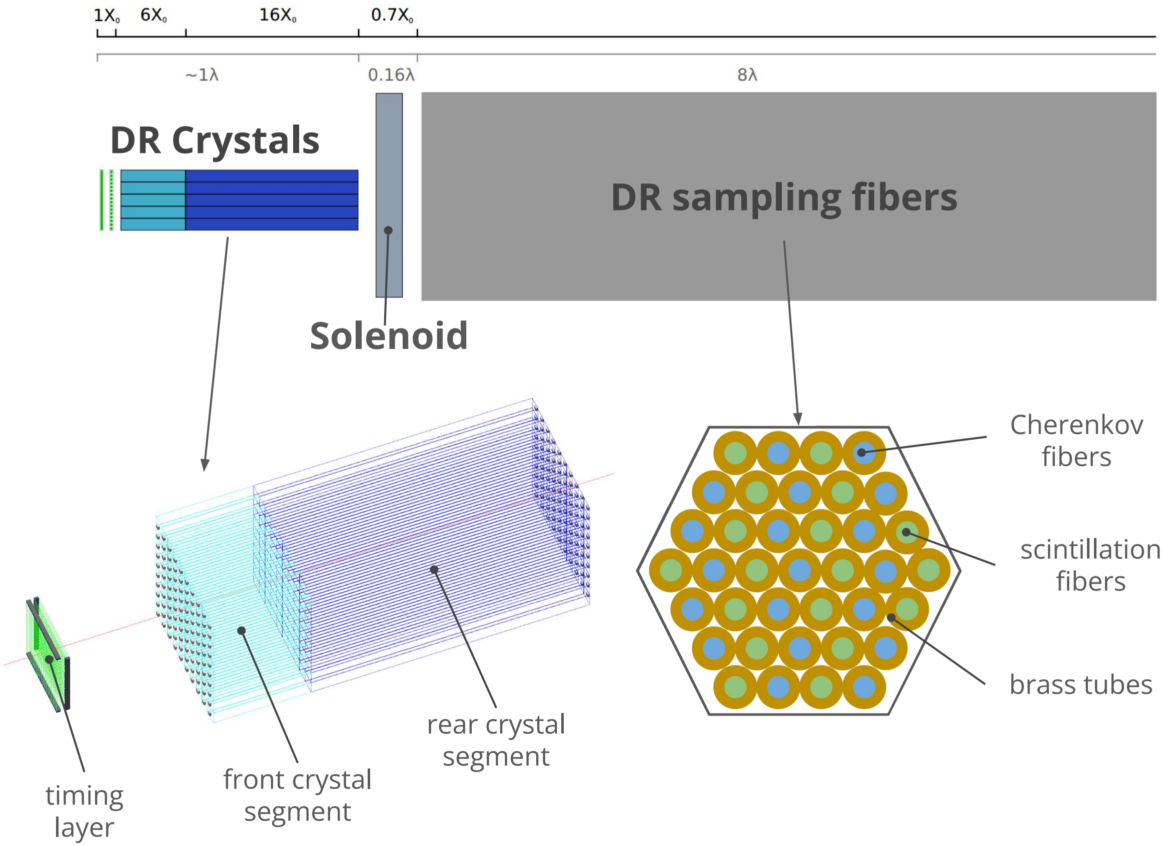
Conceptual layout

Electromagnetic and hadronic calorimeters, separated by solenoid magnet

- **Timing layer**: LYSO + SiPM, σ(t) ~ 20 ps
- **E.m. calorimeter**: two crystal layers with SiPM readout, DR on the rear layer (read S and C on the same crystal)
- **Hadronic calorimeter**: scintillating and PMMA fibers inside brass tubes, SiPM readout



Dual strategy for *dual readout* in crystals

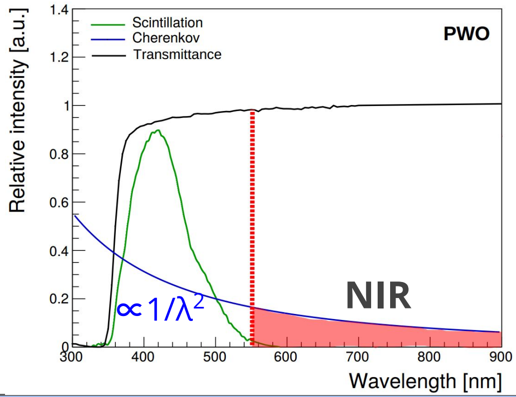
Cherenkov: prompt emission, spectrum ∝ $1/\lambda^2$ — **Scintillation**: narrow emission band
→ exploit spectral separation: wavelength filters to suppress scintillation peak

small X_0, R_M
short τ

PWO: λ

Cherenkov photons detected in **NIR** region

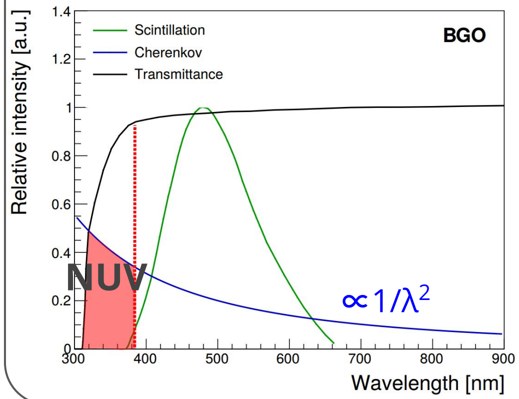
✔ **low LY** → reject most of scintillation light with thin filters
✘ **very fast decay time** (~10 ns) → scintillation emitted at the same time as Cherenkov

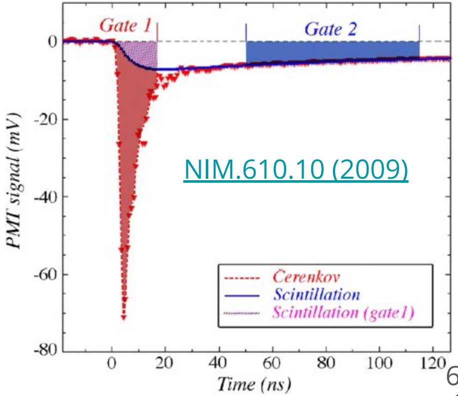


BGO / BSO: λ + t

Cherenkov photons detected in **NUV** region

✔ **moderate decay time** (~100–300 ns) → exploit time to separate Cherenkov and scintillation signals
✘ **high LY** → scintillation light contamination even with thick filters





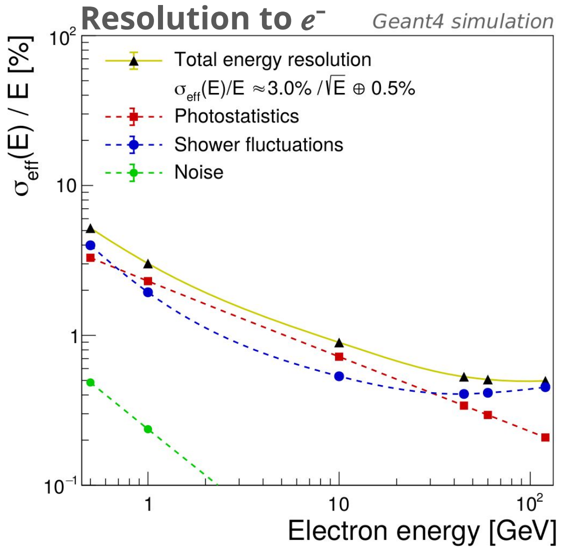
[NIM.610.10 (2009)]

Requirements for S and C yields

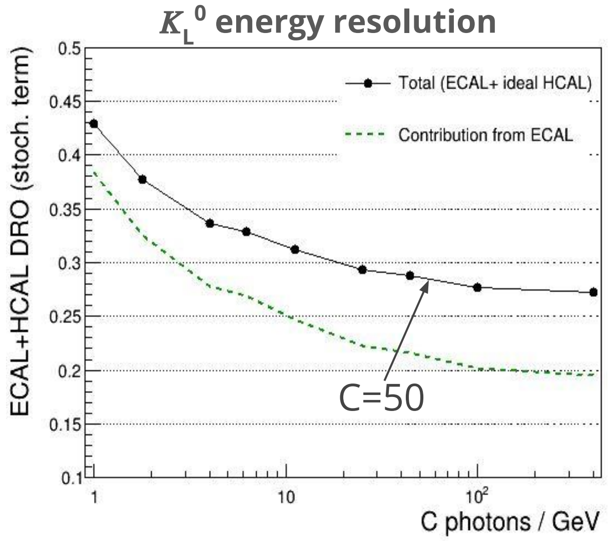
[JINST 15 (11) (2020) P11005]

Evaluate expected energy resolutions from Poisson photo-statistics

- Required **scintillation** yield for e.m. resolution <3%/$\sqrt{E}$
  - **S > 1600 pe/GeV**



- Required **Cherenkov** yield for hadronic resolution <30%/$\sqrt{E}$ with DR
  - **C > 50 pe/GeV**



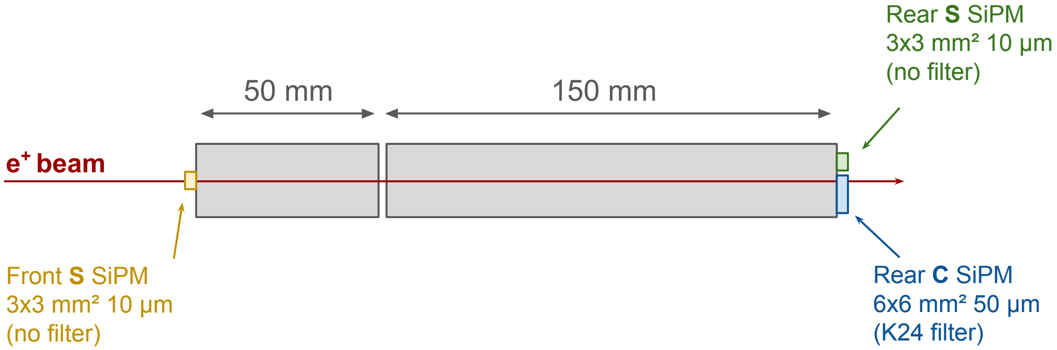
⇒ Need **experimental validation**

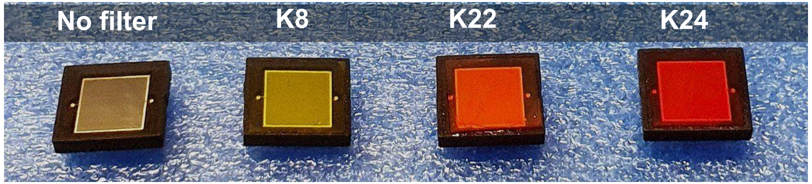
R&D campaign

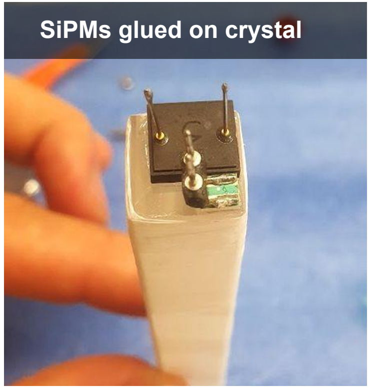
2024 test beam @SPS H6

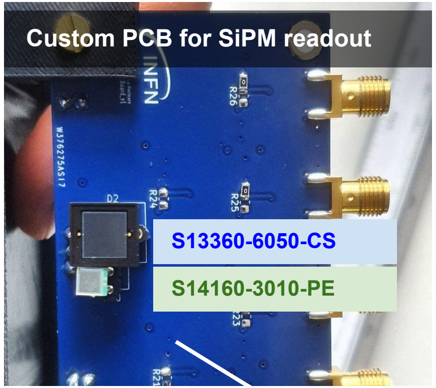
Single crystal test to assess Cherenkov and scintillation photo-electrons yields

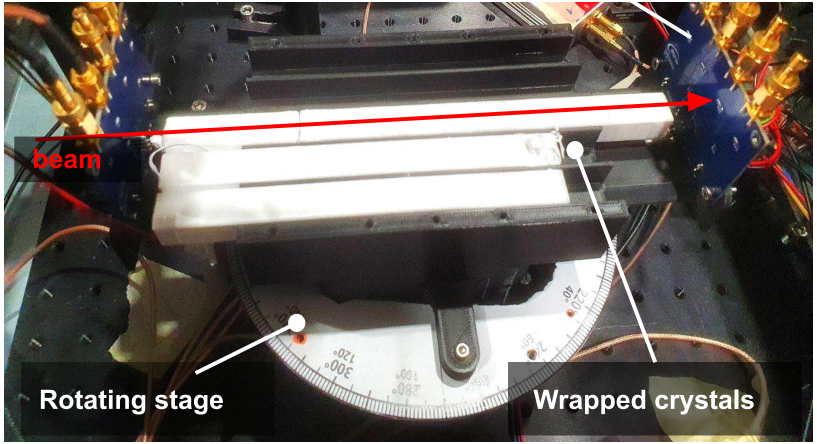
- Rotating stage to study **angular dependence** of Cherenkov signal
- SiPM readout using two alternatives readout:
  - **PWO**: transimpedance amplifiers on custom PCB + CAEN V1742 digitizer for PWO
  - **BGO/BSO**: voltage pre-amplifiers + Tektronix oscilloscope







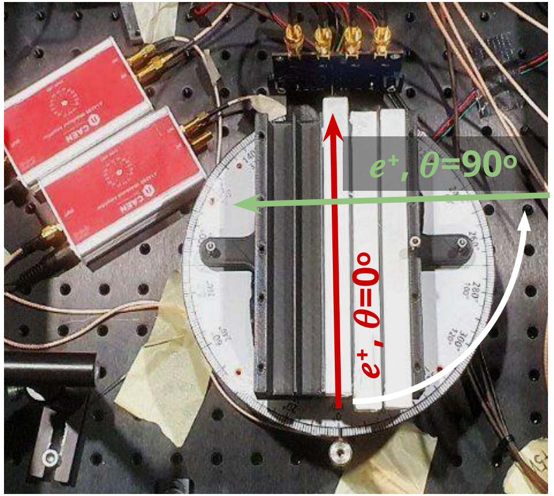


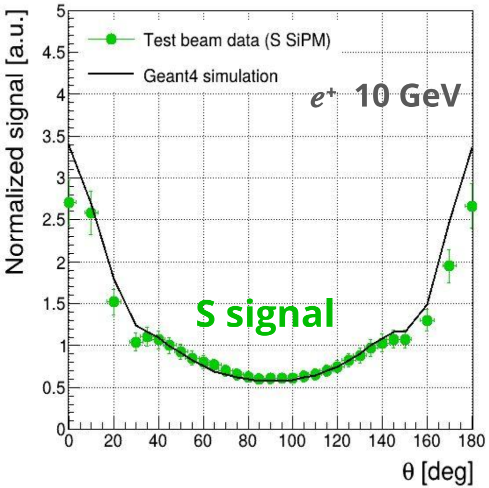


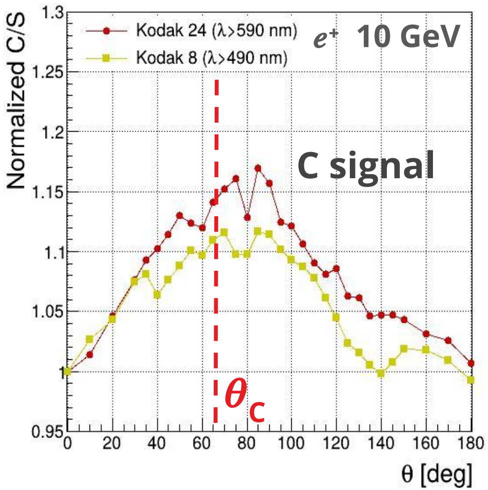
2024 test beam results
C angular dependence in PWO

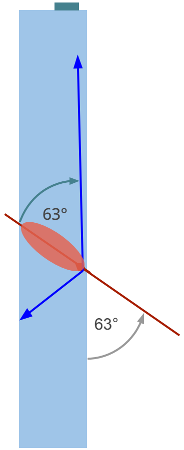
Scan incident angles between 0º and 180º and measure C and S signals

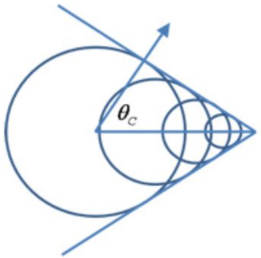
- Energy deposited in the crystal (**S** signal) reproduced in simulation → symmetric around 90º
- The ratio **C/S**, computed event-by-event, shows strong angular dependance peaking at the PWO **Cherenkov angle**
  - less pronounced with more S contamination (K8 vs K 24 filter)







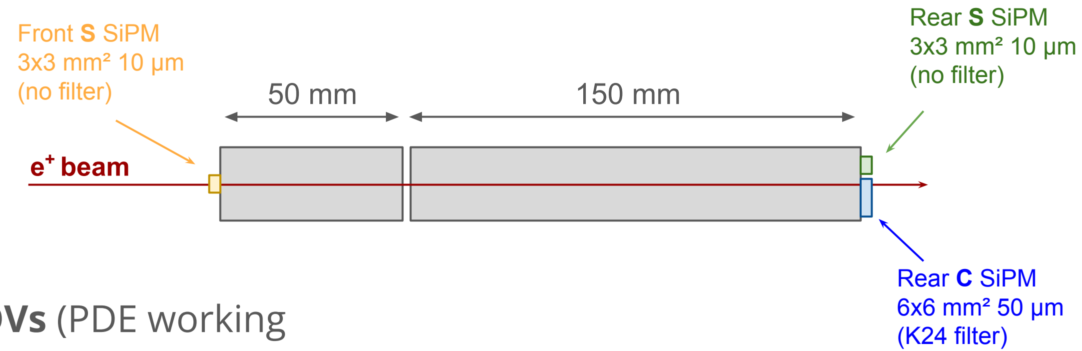




$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$

$n_{PWO} = 2.2$

2024 est beam results
light yields in PWO



Compute photo-statistics for different **SiPM OVs** (PDE working points)

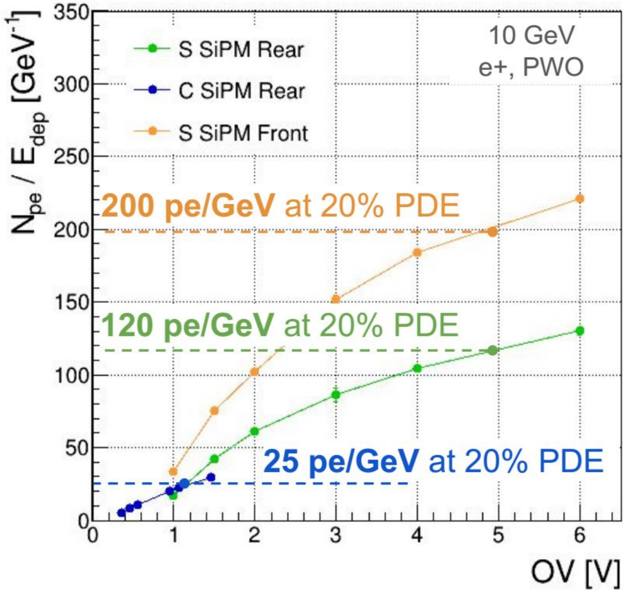
Scintillation channel

Measured **320 pe/GeV** @20% PDE (front + rear SiPMs)

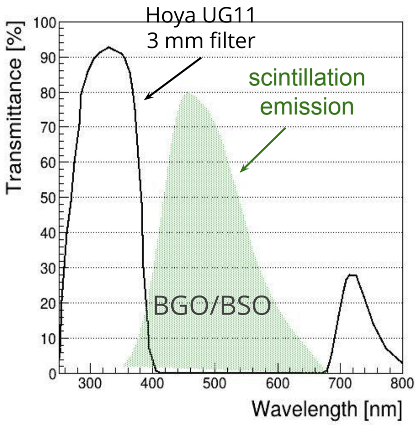
Target is >1600 pe/GeV → need 40% PDE and 6x6 mm^2 SiPMs

Cherenkov channel

- Measured **25 pe/GeV** @20% PDE (rear 6x6 mm^2 SiPM)
- Target is >50 pe/GeV → need >40% PDE
- **Contamination** from scintillation photons **<10%** → **OK**

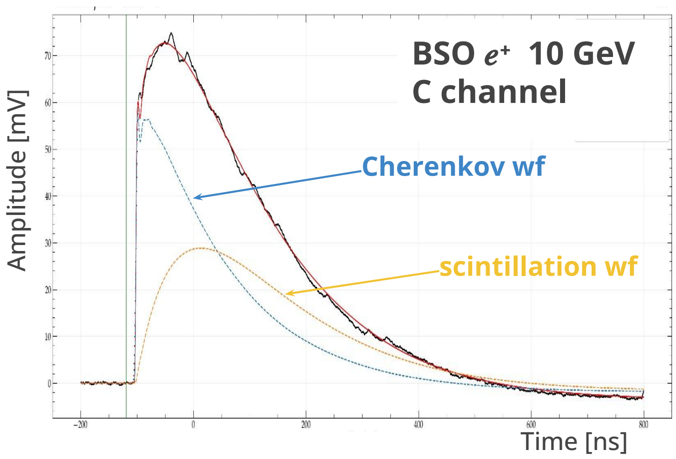


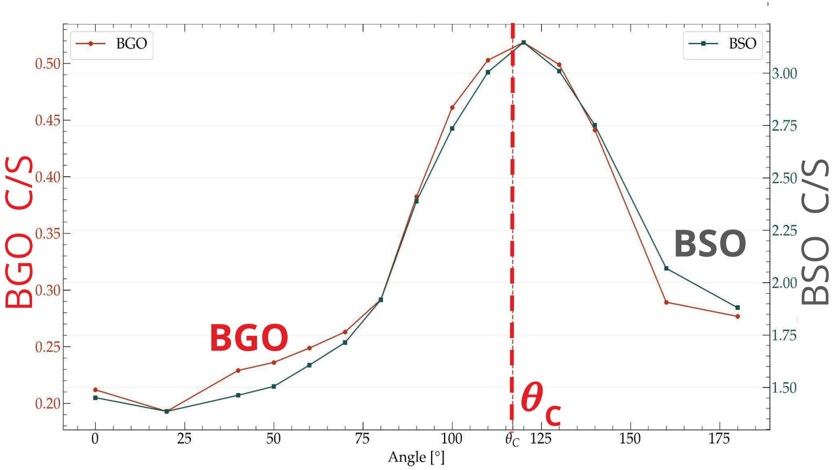
2024 test beam results
BGO and BSO crystals



Non-negligible **residual scintillation** in the C channel → extract **C** yield with **template fit**: exploit time differences between C and S signals

- Angular dependence of **C/S** peaks at the expected **Cherenkov angle**
- Estimated Cherenkov yield is **~80 pe/GeV** (**BGO**), **~110 pe/GeV** (**BSO**) → requirements are satisfied



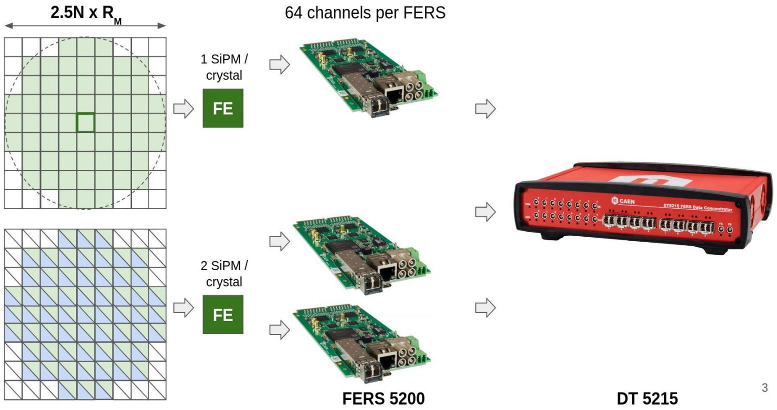


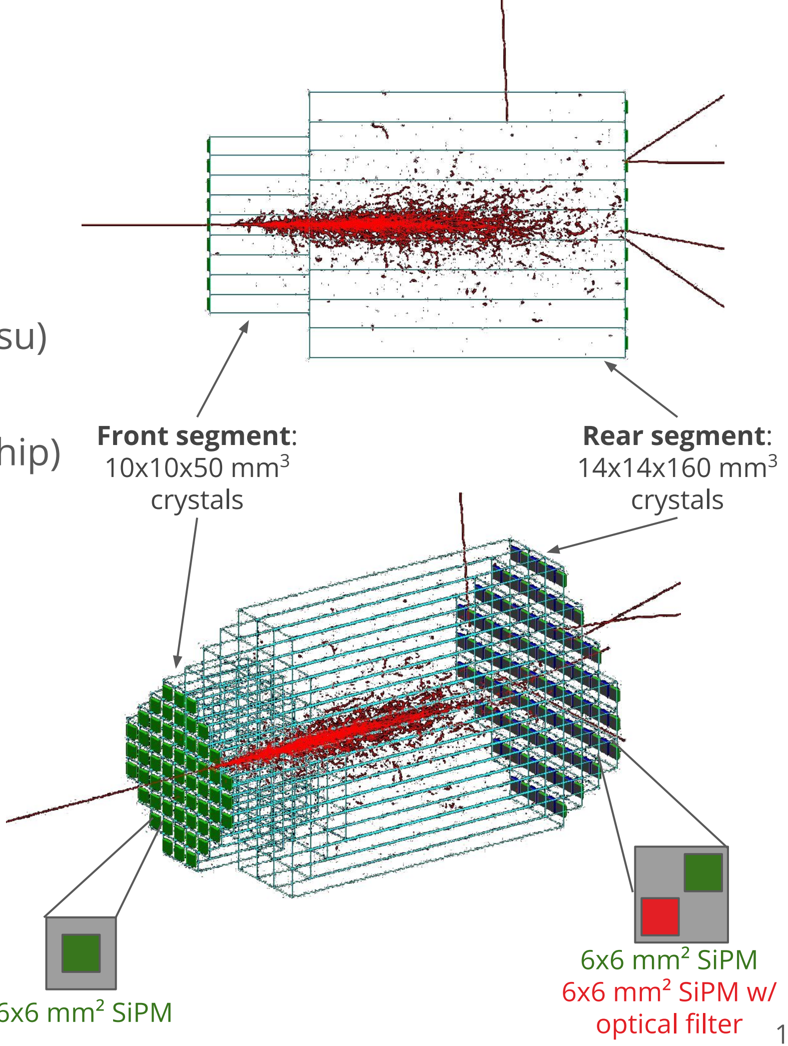
Prototype design

A **full containment 9x9 PWO matrix** under construction

→ Test **linearity** response. Measure **constant term** of e.m. energy resolution

- Procurement of **crystals** (SICCAS) and **SiPMs** (Hamamatsu) is ongoing
- **Readout electronics** with CAEN **FERS 5200** (Citiroc-1A chip) + DT5215 Concentrator
- Mechanics designed for exchange with a **3x3 BSO** core, readout with pre-amp + VX2730 digitizer

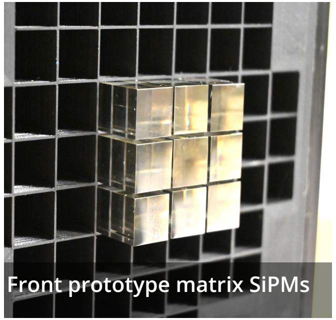


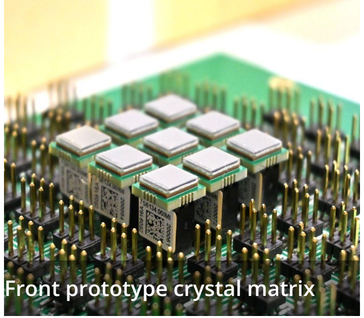


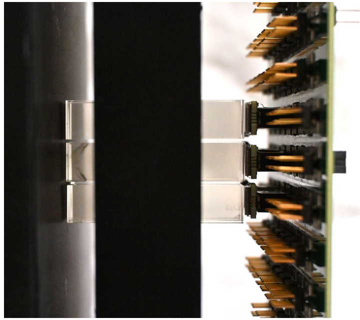
2025 test beam @SPS H6
first pictures with preliminary prototype

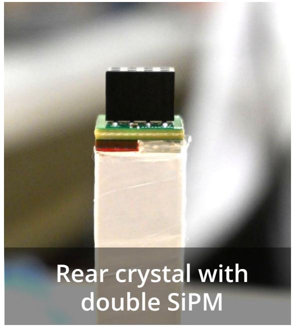
Sep.-Oct. 2025

Test with only few crystals but with full prototype-matrix **mechanics**, **electronics** and **readout** chain
→ data analysis is ongoing

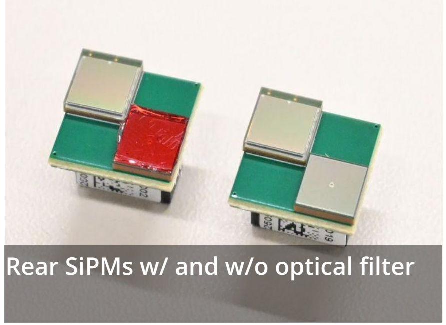

Front prototype matrix SiPMs

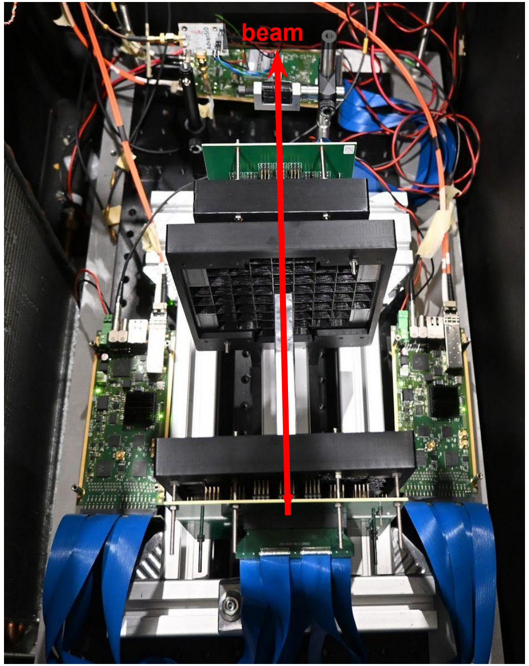

Front prototype crystal matrix




Rear crystal with double SiPM


Rear crystal with single SiPM


Rear SiPMs w/ and w/o optical filter



Summary and outlook

DR crystal calorimeter is a promising candidate detector for future e^+e^- colliders

- Homogeneous crystals can achieve **<3%/√E e.m. resolution**, enabling precision flavor physics and π^0 reconstruction
- Extending **DR corrections** to crystals enable to preserve **<30%/√E hadronic resolution**
- DR + **PFA** shown in simulation to significantly improve jet energy resolution

Broad **R&D program** is ongoing

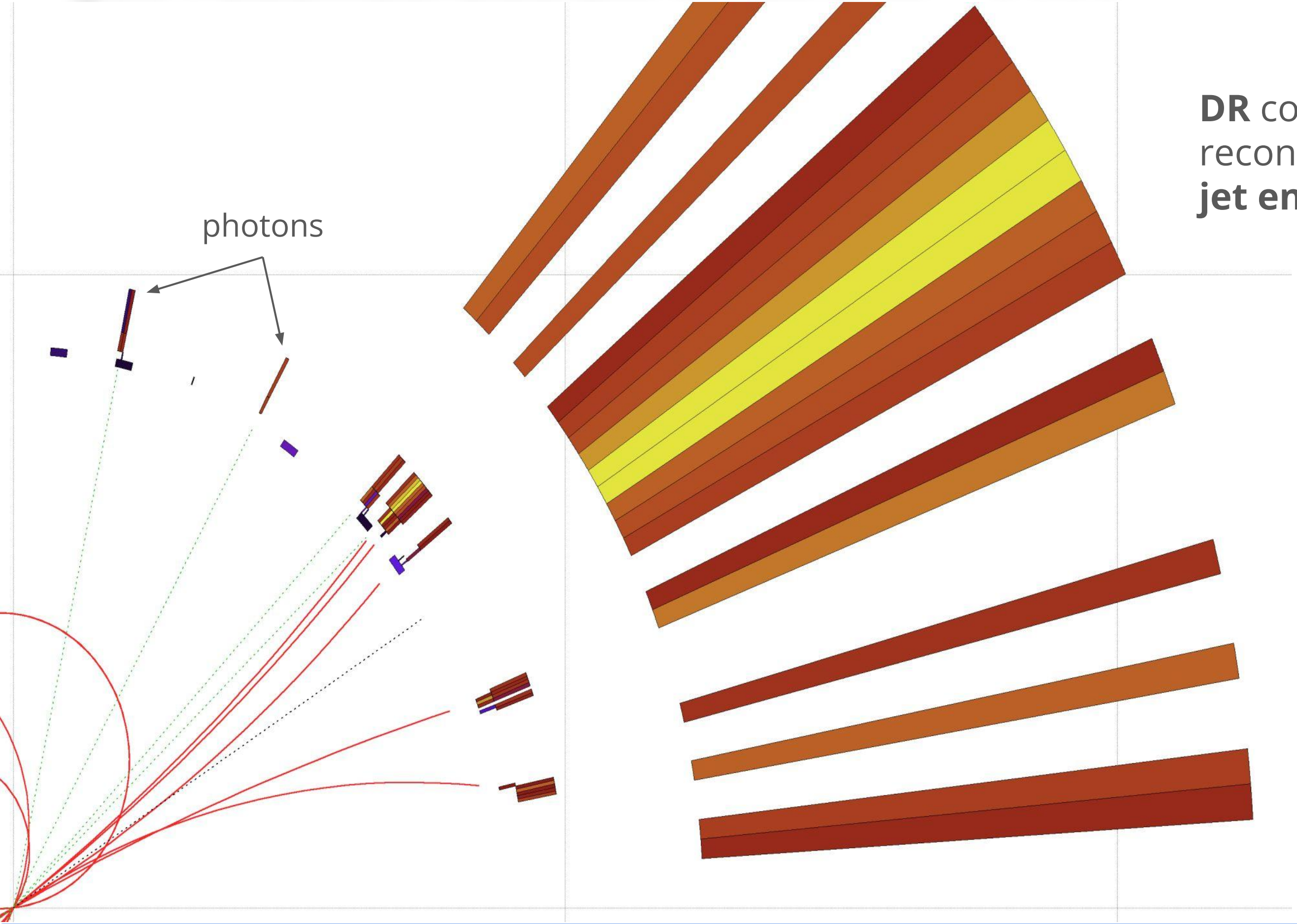
- 2024 TB results confirm that required **S** and **C** yields are achievable for all crystal candidates (PWO, BGO, BSO)
- Completion of **full containment prototypes** planned for **2026**
- Combined test beam with fiber dual-readout HCAL foreseen as well → test full **DR hybrid calorimeter** concept

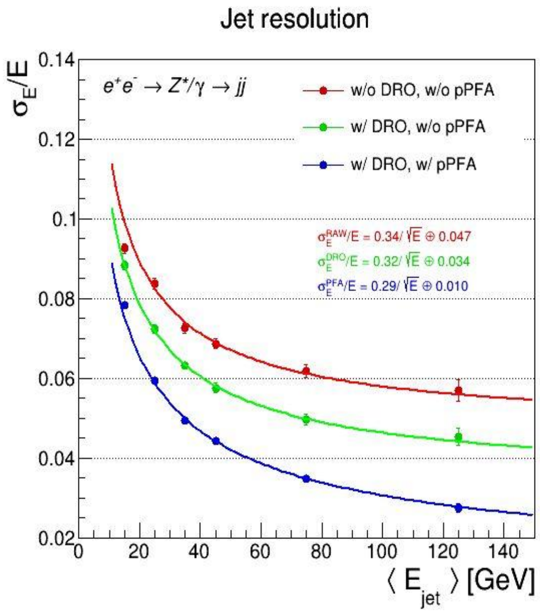
Backup

Jet reconstruction with DR + PFA

2022 JINST 17 P06008

DR corrections with **PFA** reconstruction allow to reach target **jet energy resolution**

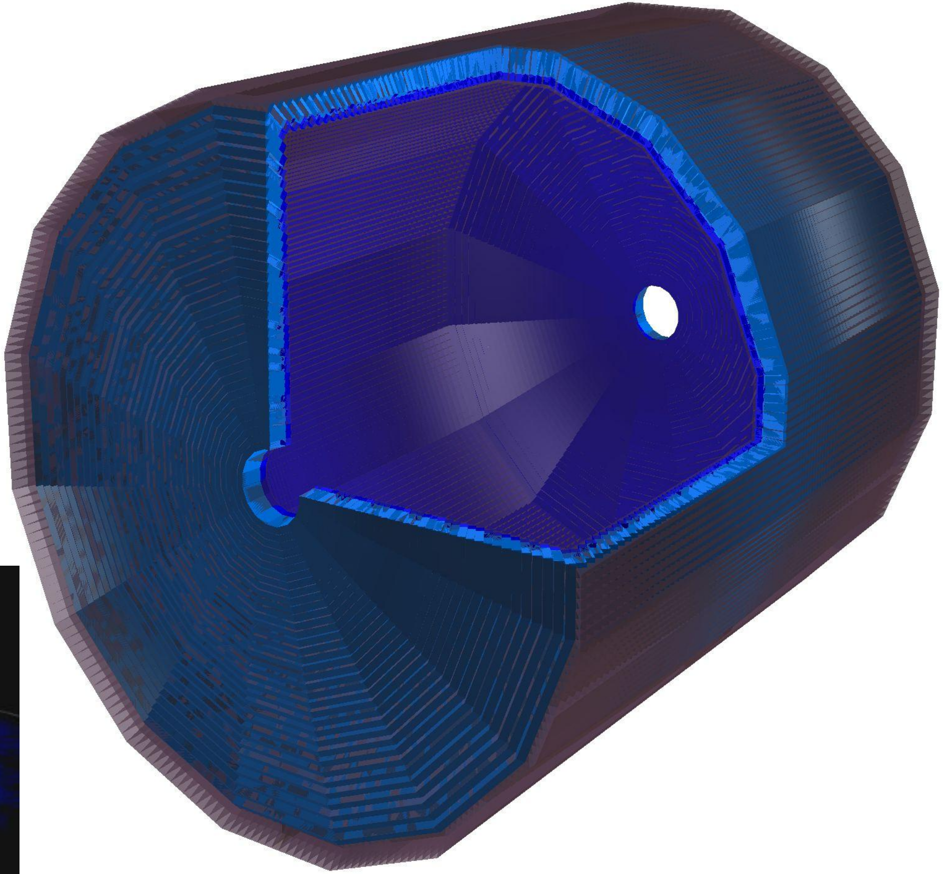




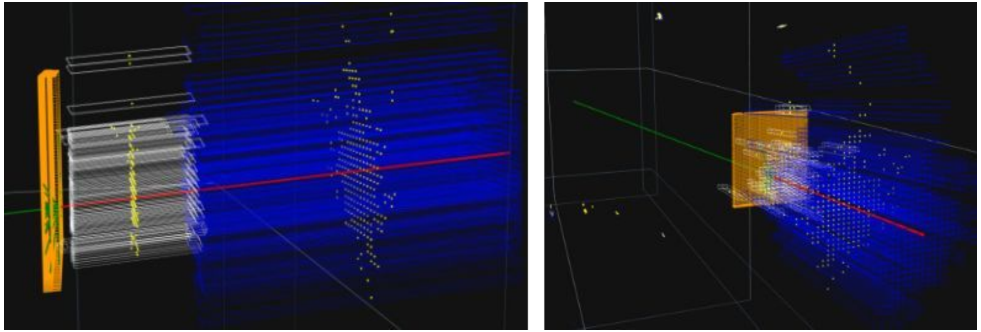
Detector simulation

arXiv:2408.11027

- Implementation in **key4hep** with fully differentiable geometry
- SiPM and digitized readout implemented. Still a lot of work to do
- Integration with full IDEA detector ongoing



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

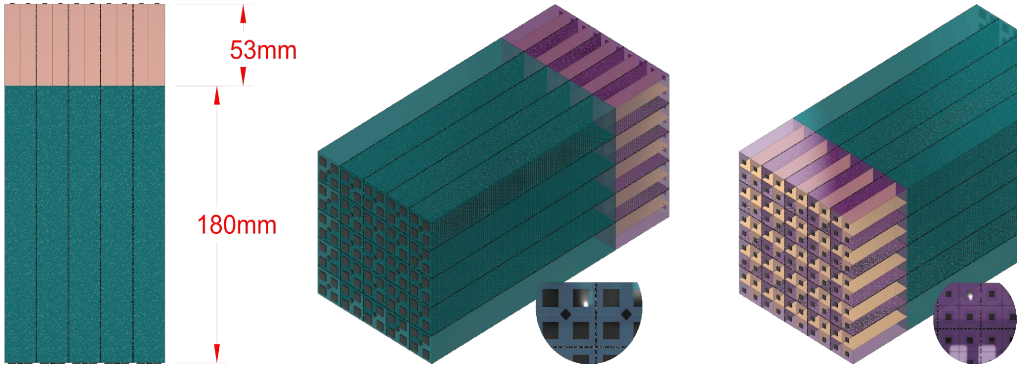


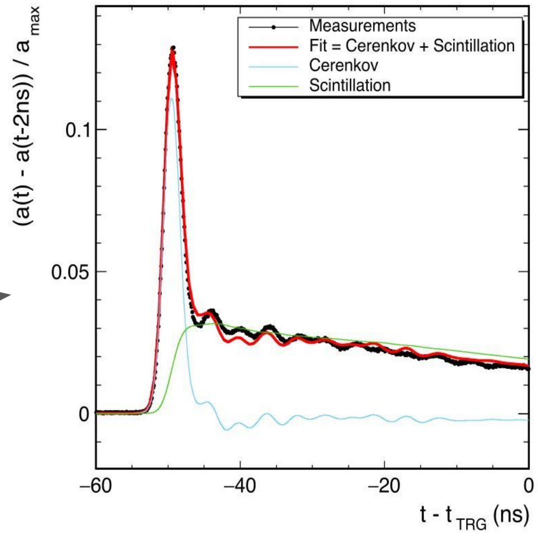
BGO prototype design

Development of a full containment BGO matrix by Calvision group

Similar layout wrt PWO prototype

- **front segment**: **10x10** array, 1 SiPM/crystal
  - readout with FERS (Citiroc-1A)
- **Rear segment**: **5x5** array, 4 SiPM/crystal with UG330 optical filters
  - readout with DRS (or equivalent ≥2GS/s digitizer)
  - S, C waveform fitting after SDL filtering





A broad collaboration

Interest and efforts growing since 2023

- **INFN**
  - INFN groups: Milano-Bicocca, Napoli, Perugia
  - Coordination within the RD_FCC italian collaboration and national grants (PRIN 2022 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
- **CERN** (Switzerland) with the support of European widening project TWISMA (GA 101078960)
- **IN2P3-IP2I** (France)