Development and beam-test characterization of crystal dual readout EM calorimeter prototypes for the IDEA detector concept

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on behalf of the DRDCalo-MAXICC group
The international conference for colliding beam physics 2026, Hefei, China



The Future Circular Collider

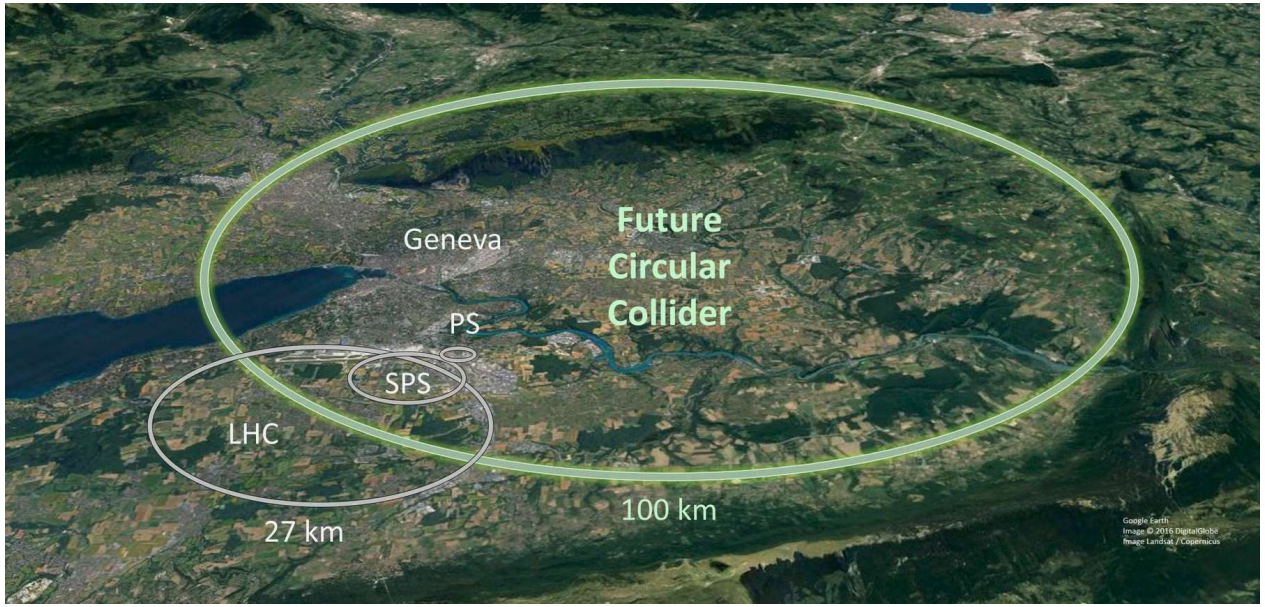
With the latest **European Strategy** for particle physics, CERN recommends the **FCC-ee** as the next **flagship collider**:

Technical specifics:

- 91 km tunnel
- $\sqrt{s}$: 90 - 360 GeV
- Luminosity: up to ~10^{36} $cm^{-2}s^{-1}$

FCC-ee would provide an outstanding **physics programme:**

- Electroweak sector
- Higgs physics
- Top quark physics
- Flavor physics



Project	Scope	TRL	R&D	Test facilities	Performance	Site preparation	Schedule	Cost	Risk
CLIC 380 GeV, 1.5 TeV		4 - 6 / 5.2							
FCC-ee 91-365 GeV		4 - 7 / 6.0							
FCC-hh 85 TeV		4 - 7 (Nb_3Sn) / 4.3 2 - 7 (HTS) / 3.2							
FCC-hh - SA 85 TeV		4 - 7 (Nb_3Sn) / 5					Nb_3Sn		
LCF 250 - 550 GeV		5 - 7 / 5.5							
LEP3 91 - 230 GeV		3 - 6 / 4.0							
LHeC: HL-LHC + 50 GeV ERL		3 - 6 / 4.5							
MC 3.2 TeV, 7.6 TeV		3.2 TeV: 3 - 5 7.6 TeV: 2 - 5							

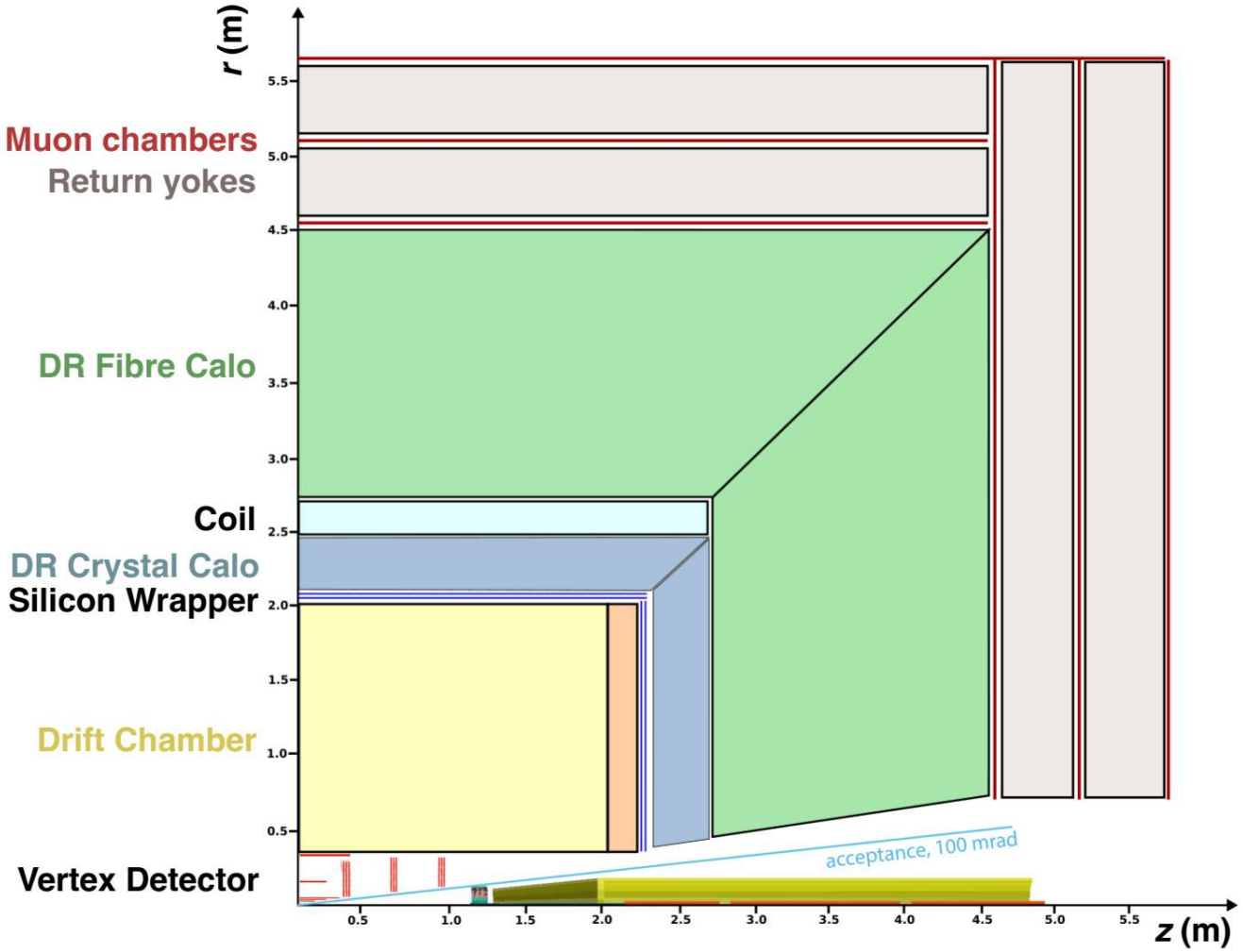
Arduini et al. Assessment of large-scale accelerator projects at CERN Report of ESG WG2a

The IDEA detector

Innovative Detector for E+e- Accelerators (IDEA) is a general purpose detector concept tailored for FCC-ee.

From the innermost to the outermost:

- **Vertex Detector**: CMOS sensors
- **Drift Chamber**: ultra light with PID capabilities
- **Electromagnetic Calorimeter**: dual readout crystal calorimeter
- **HTS Solenoid**: magnetic field up to 2 T
- **Hadronic Calorimeter**: dual readout fiber calorimeter
- **Muon System**: based on μRWELL detectors



IDEA study group., The IDEA detector concept for FCC-ee

Benchmark for calorimetry

Stringent requirements on calorimetry performance.

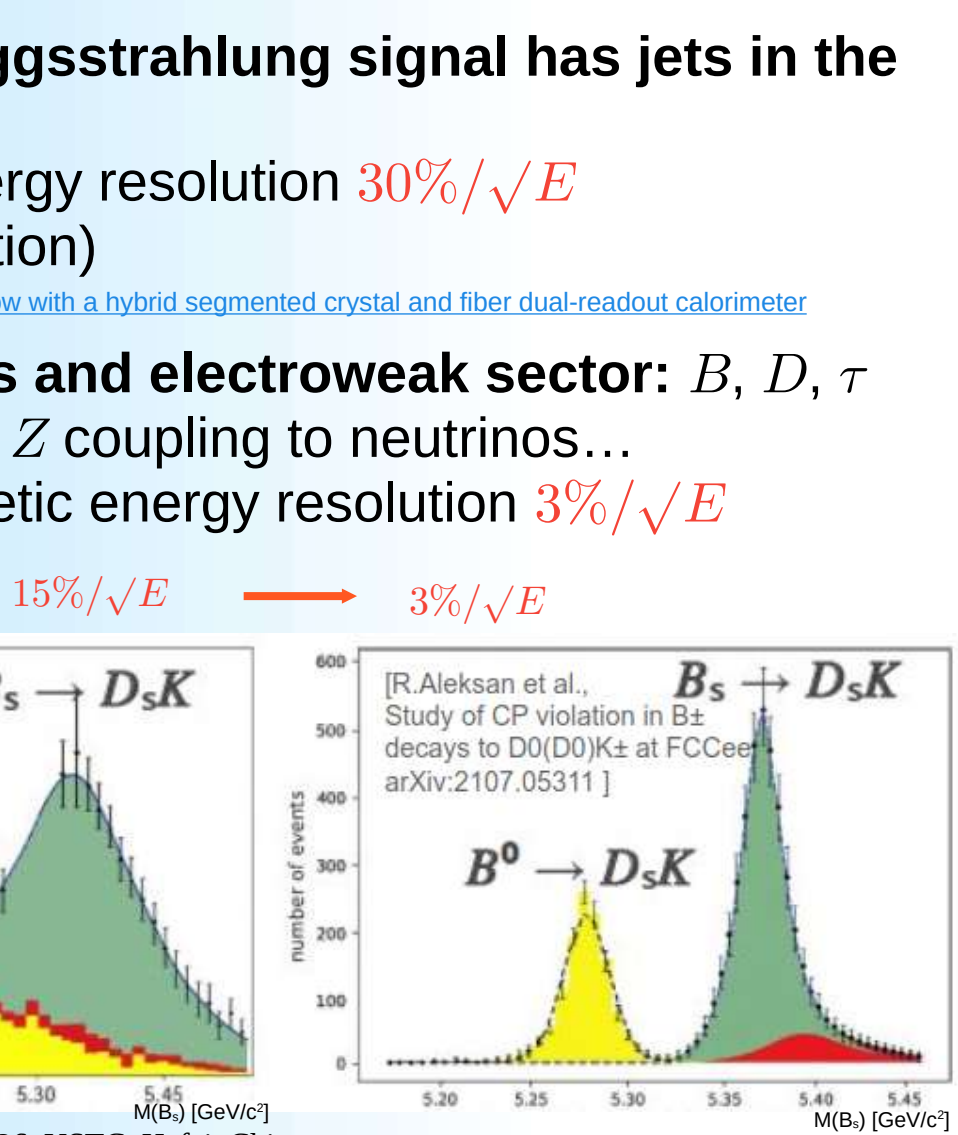
97% of the Higgsstrahlung signal has jets in the final state:

➔ Hadronic energy resolution $30\%/\sqrt{E}$ (W/Z separation)

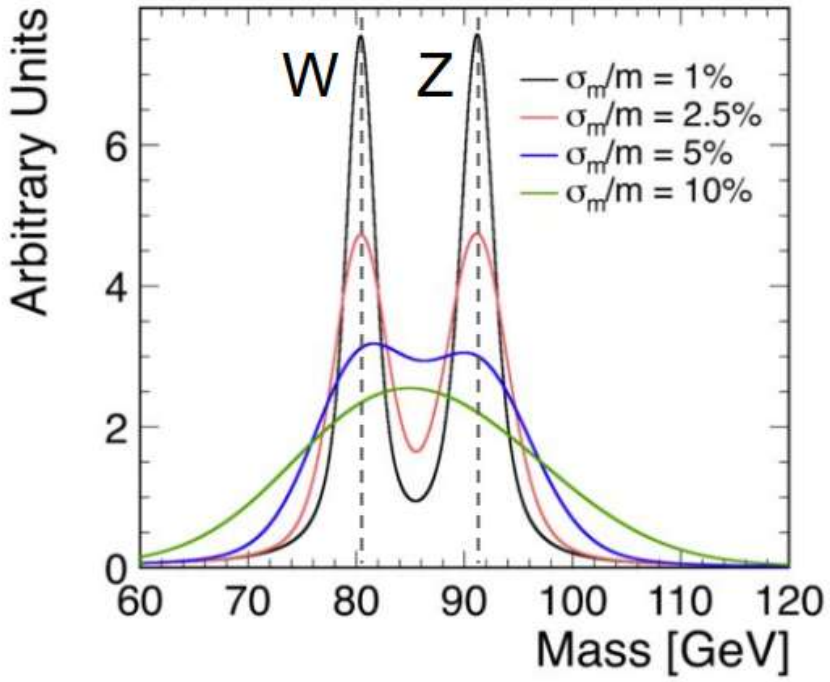
M. T. Lucchini et al., Particle flow with a hybrid segmented crystal and fiber dual-readout calorimeter

Flavor physics and electroweak sector: B, D, τ decay, $H \to \gamma\gamma$, Z coupling to neutrinos…

➔ Electromagnetic energy resolution $3\%/\sqrt{E}$



$15\%/\sqrt{E}$ ⟶ $3\%/\sqrt{E}$



Dual readout principle

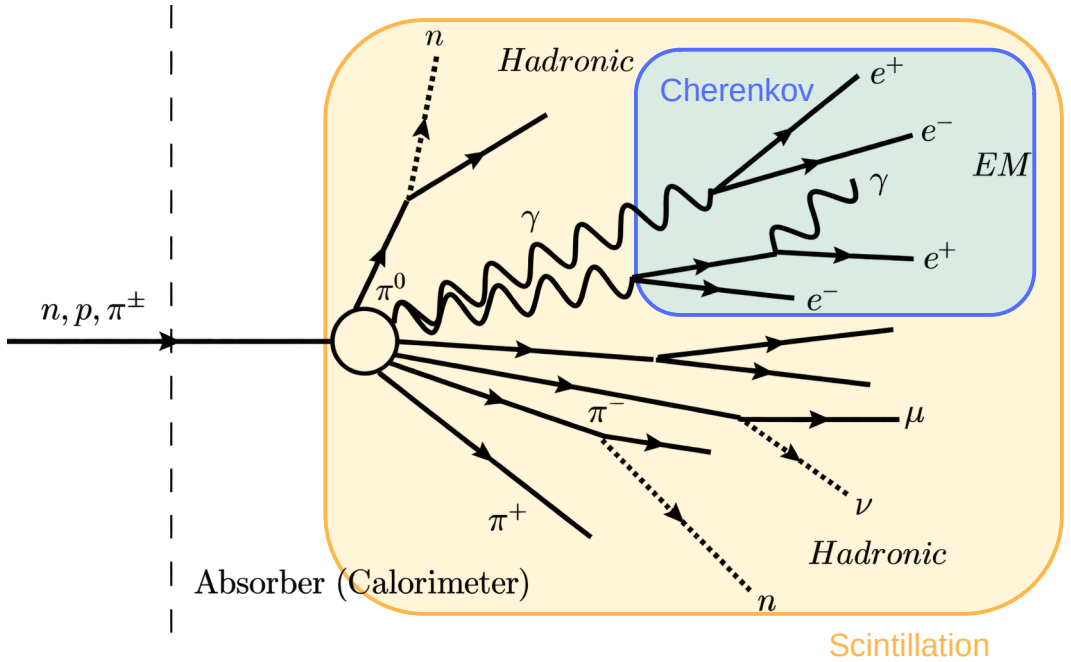
The **dual readout technique** is based on the simultaneous detection of scintillation (S) and Cherenkov light (C).

Event-by-event compensation

$$\frac{C}{S} = \frac{f_{em} + (\frac{h}{e})_C(1 - f_{em})}{f_{em} + (\frac{h}{e})_S(1 - f_{em})}$$

Approaches to dual readout:

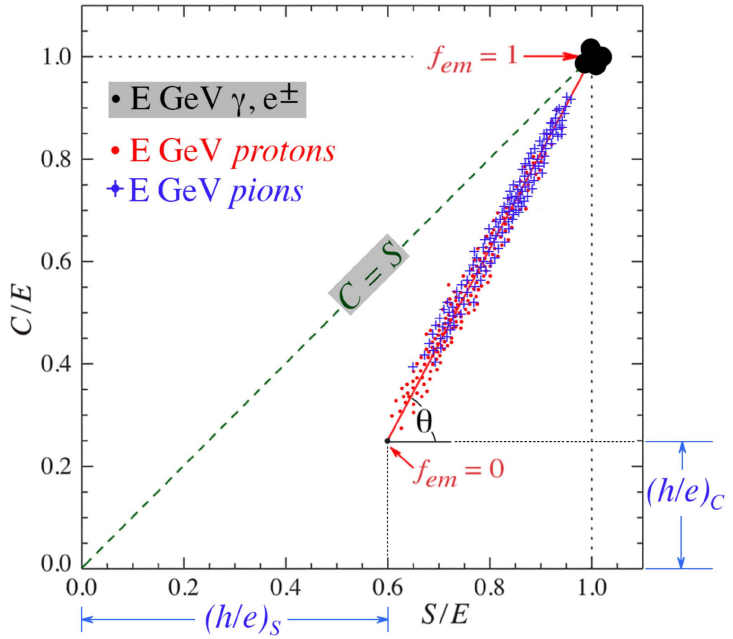
- Sampling calorimeter: scintillating fibers and Cherenkov fibers
- **Homogeneous calorimeter: exploit different light properties (spectrum, time of arrival)**



$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

$$E = \frac{S - \chi C}{1 - \chi}$$

R. Wigmans, 25 years of Dual-Readout calorimetry



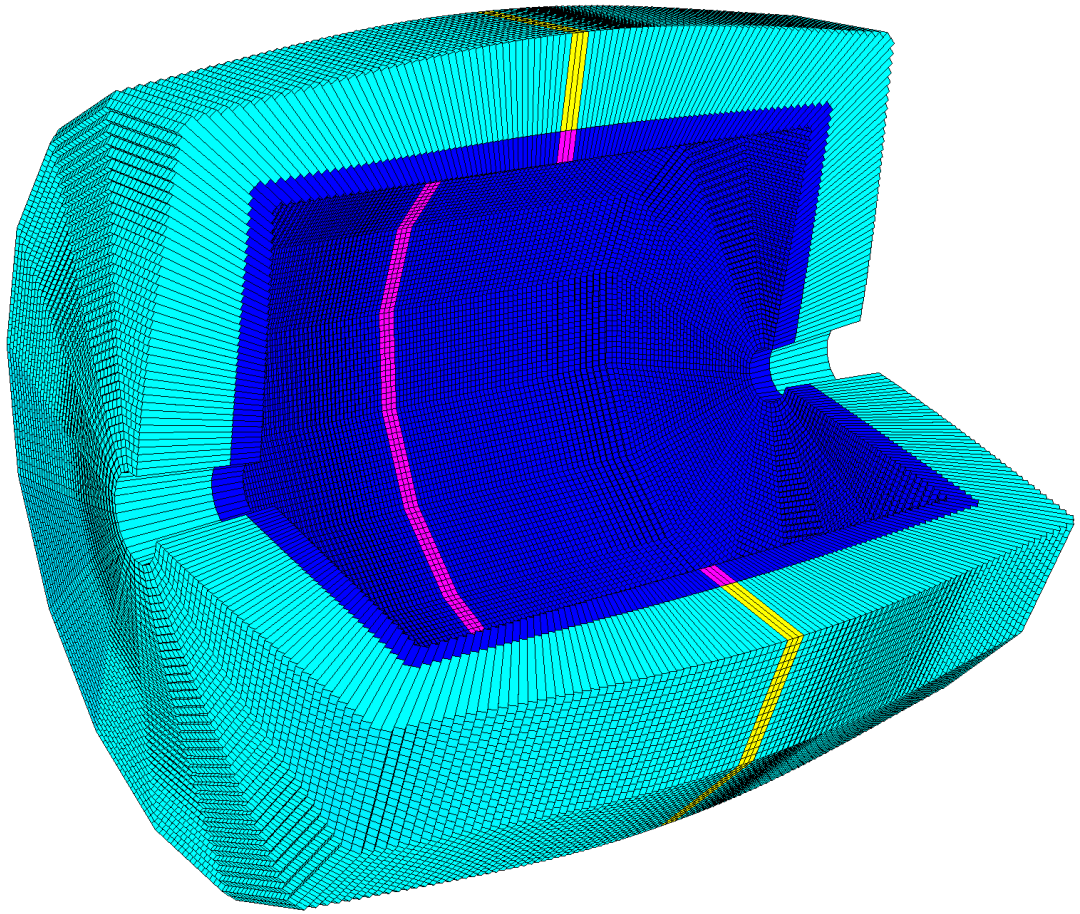
IDEA Ecal: MAXICC

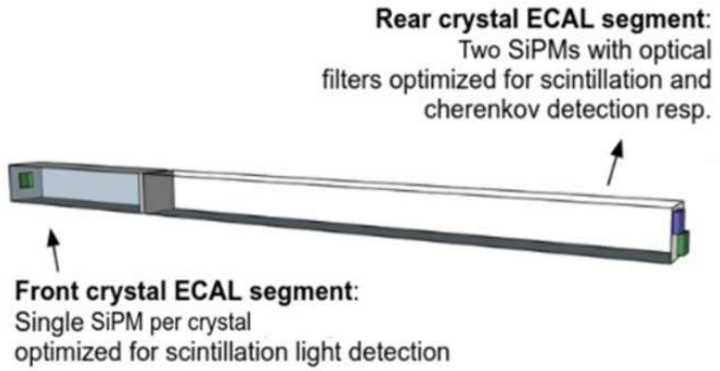
MAXimum Information Crystal Calorimeter
(6D: x, y, z, t, E, C/S)

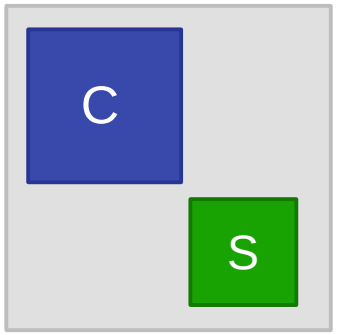
Baseline geometry:
- Longitudinal segmentation: 2 layers, 6 X_0 + 16 X_0
- Granularity: 1x1 cm^2 front, 1.5 x 1.5 cm^2 rear
- SiPM and electronics at front and rear sides
- Rear segment implements dual readout
- 2 millions channels

Constraints on photostatistics for target resolution:
- S > 1600 pe/$GeV \rightarrow 3\%/\sqrt{E}$
- C > 50 pe/$GeV \rightarrow 30\%/\sqrt{E}$

M. T. Lucchini et al., New perspectives on segmented crystal calorimeters for future colliders







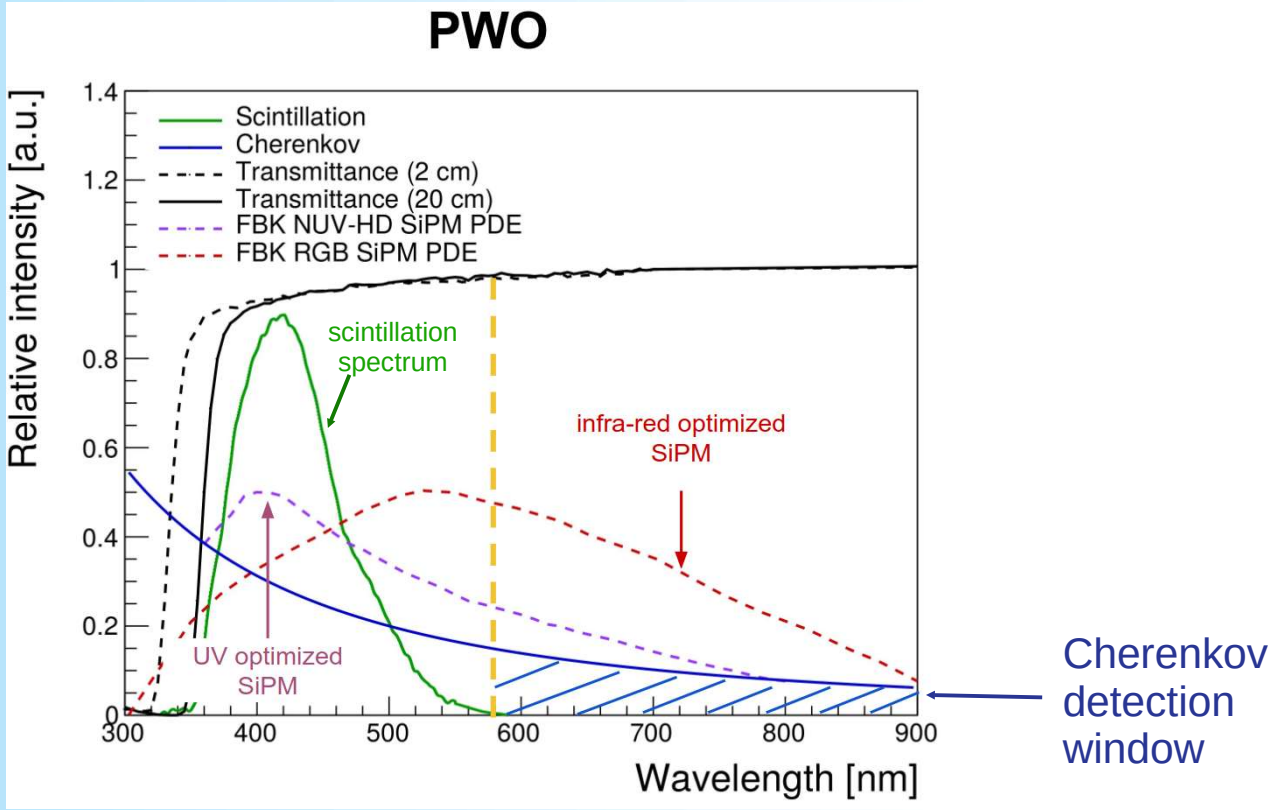
Crystal candidates

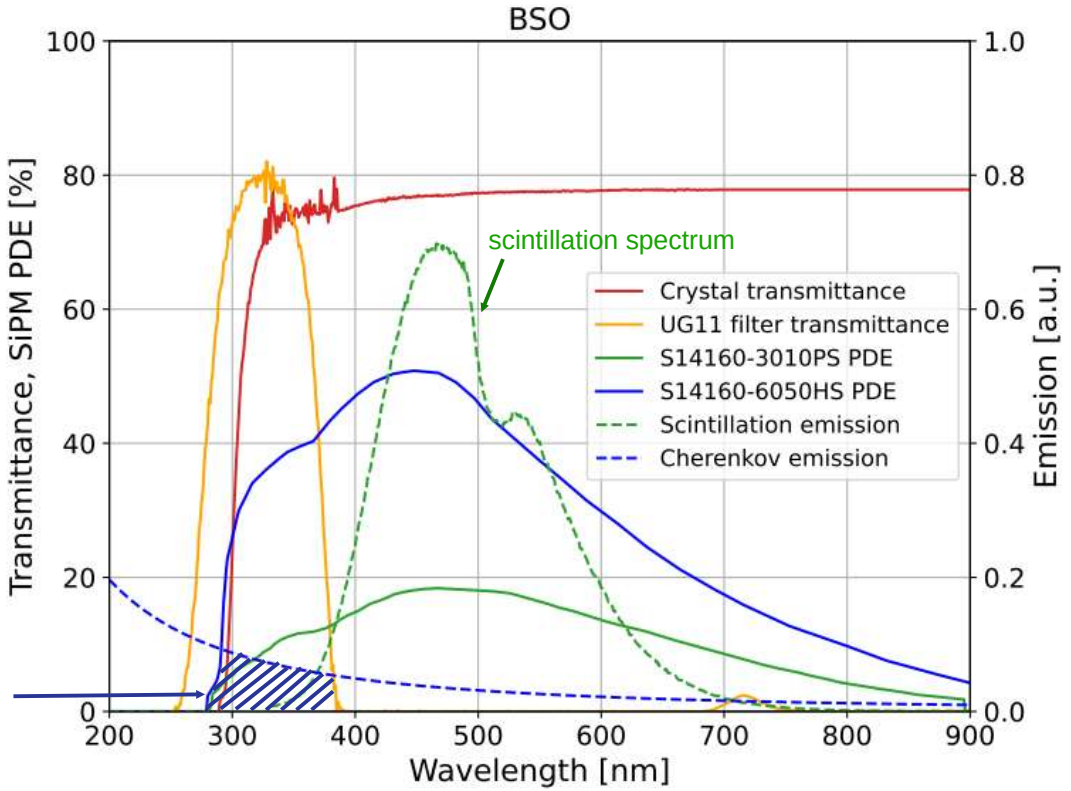
3 crystals under investigation: $PbWO_4$, $Bi_4Ge_3O_{12}$, $Bi_4Si_3O_{12}$.

Crystal	**Density** g/cm³	**X_0** cm	**R_M** cm	**Rel. light yield** photon/MeV	**Decay time** ns	**Emission peak** nm	**Refractive index** at emission peak
PWO	8.3	**0.89**	**2.00**	**1**	**10**	420	2.2
BGO	7.1	1.12	2.23	**35**	**300**	480	2.15
BSO	6.8	1.15	2.33	**9.5**	**100**	470	2.06

- **PWO**: Baseline material: fastest, most compact, well established in HEP
- **BGO**: compact, highest light yield, also well established in HEP
- **BSO**: compromise between BGO and PWO, not massively produced → a lot of space for R&D

Dual readout strategy for PWO and BGO/BSO





- Emission peak: 420 nm
- Filter out scintillation light with a short wavelength filter
- Detect Cherenkov photons above 580 nm with specialized SiPM.

- Emission peak: 470 nm
- Filter out scintillation with long wavelength filter
- Detect Cherenkov photons in the 320-380 nm range
- Slower decay time allows for temporal separation

Overview of beam tests…



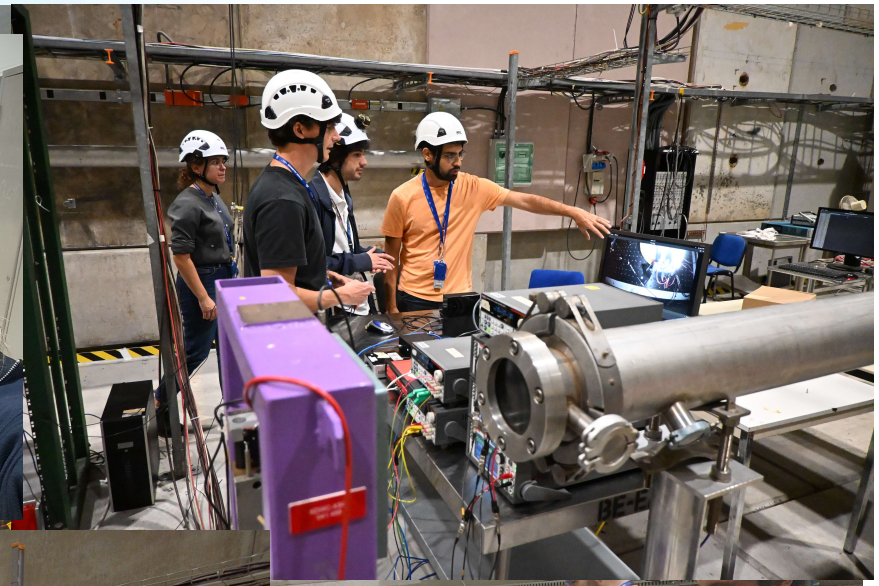


2024 CERN SPS

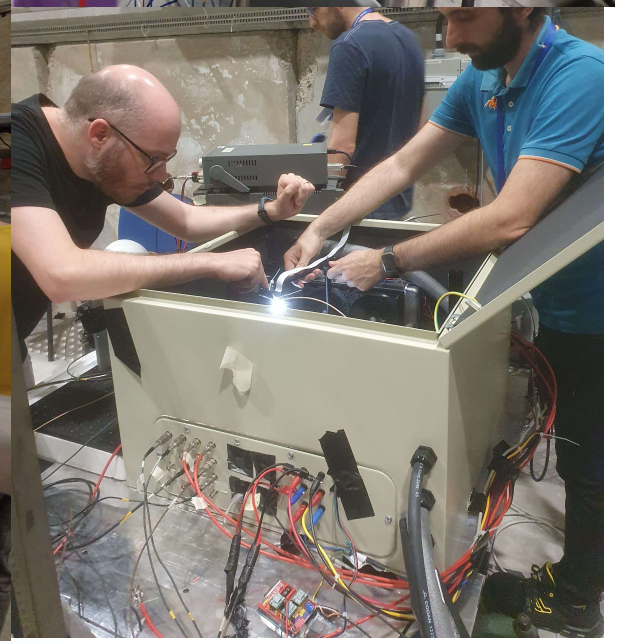
- Single crystal

Overview of beam tests…





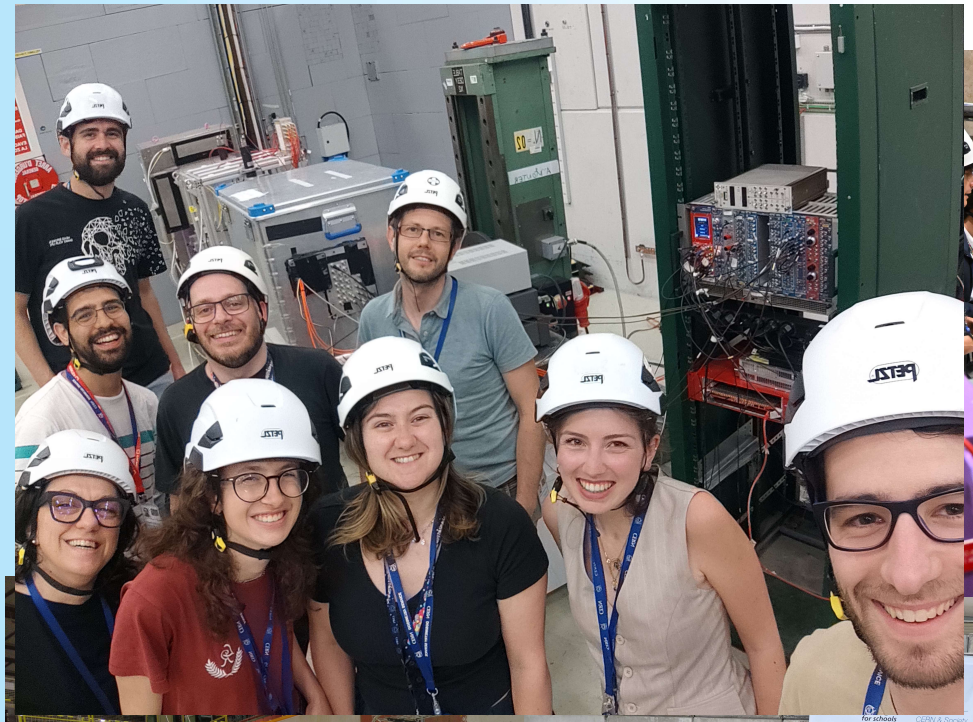


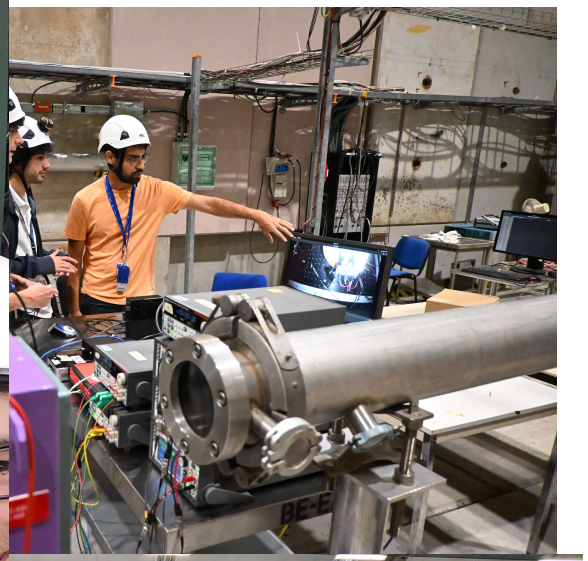


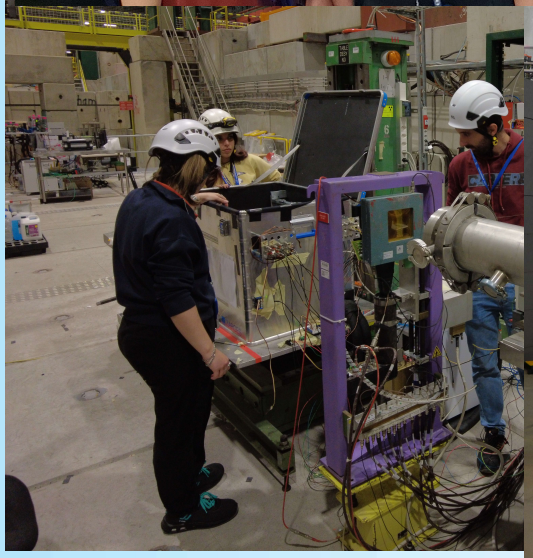
2024 CERN SPS
- Single crystal

2025 CERN SPS
- Single crystal with final light output

Overview of beam tests…









2024 CERN SPS
- Single crystal

2025 CERN SPS
- Single crystal with final light output

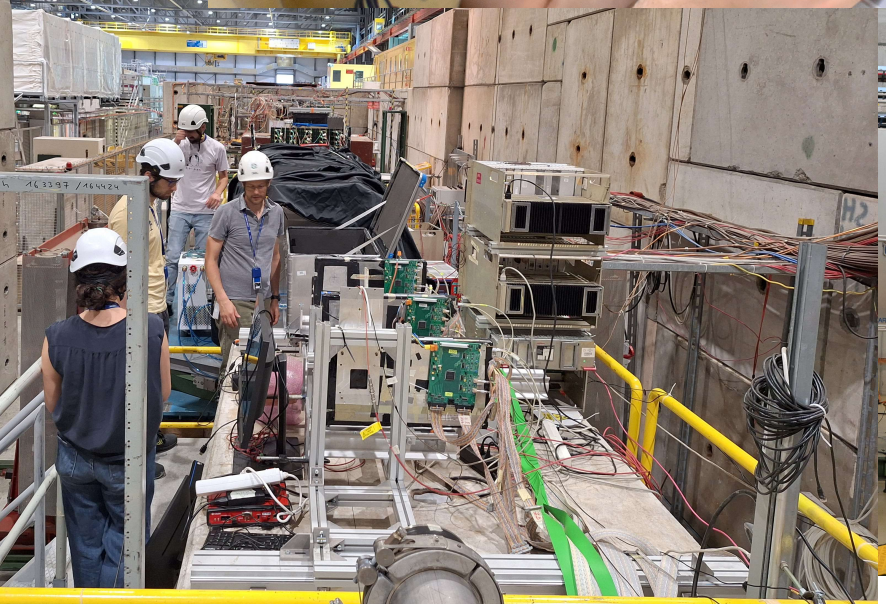
2026 CERN PS
- 3x3 matrix at low energy

Overvie











2024 CERN SPS
- Single crystal

2025 CERN SPS
- Single crystal with final light output

2026 CERN PS
- 3x3 matrix at low energy

2026 CERN SPS
- Full matrix with HIDRA

2024 test beam @ CERN SPS

Beam: 120 $GeV\,\mu^+$, 10 $GeV\,e^+$
Crystals on rotating stage

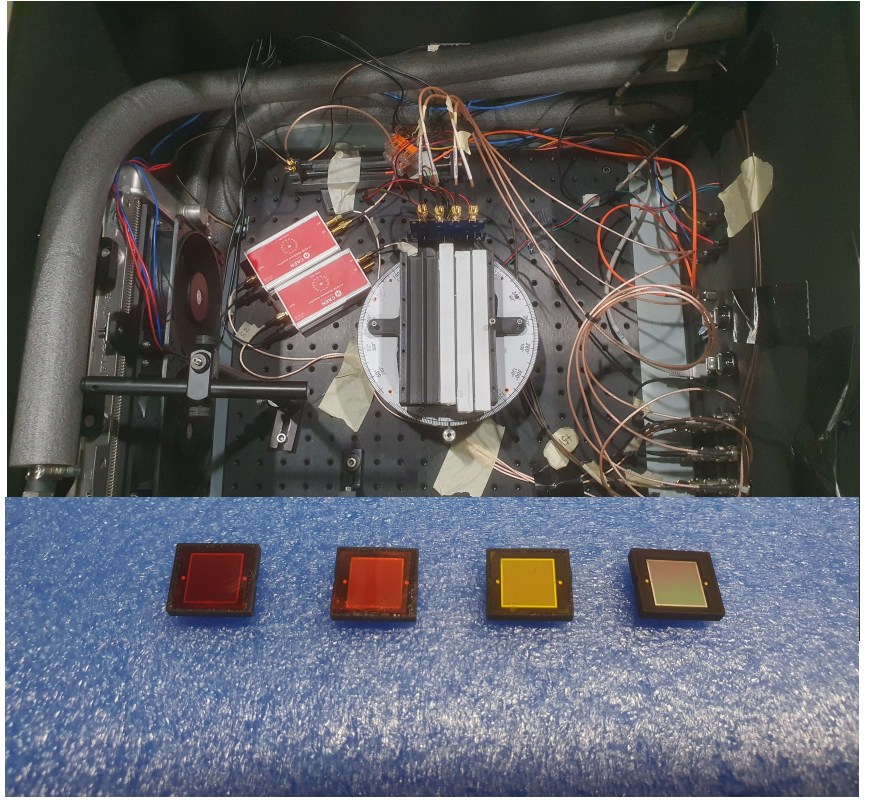
PWO SICCAS crystals, 13 x 13 x 150/50 mm^3

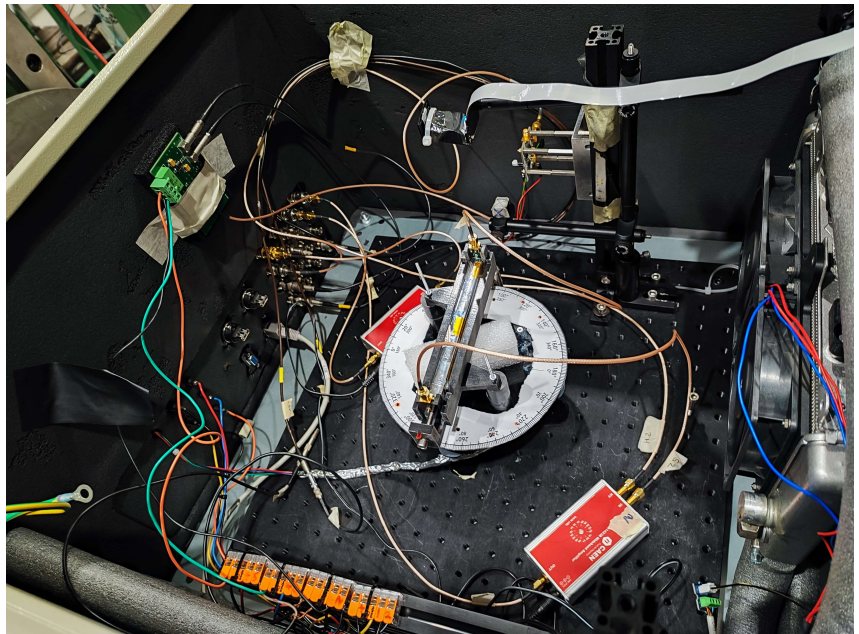
- Kodak thin filters
- S channel: Hamamatsu 3x3 mm^2 SiPM, 10 μm pitch
- C channel: Hamamatsu 6x6 mm^2 SiPM, 50 μm pitch
- Transimpedance amplifiers + CAEN digitizer

BGO/BSO SICCAS crystals, 12 x 12 x 150 mm^3

- SCHOTT UG11 thick filter
- S channel: Hamamatsu 3x3 mm^2 SiPM, 10 μm pitch
- C channel: Hamamatsu 6x6 mm^2 SiPM, 50 μm pitch
- Fast voltage preamp + waveform digitization with oscilloscope

Objective: demonstrate Cherenkov and scintillation separation



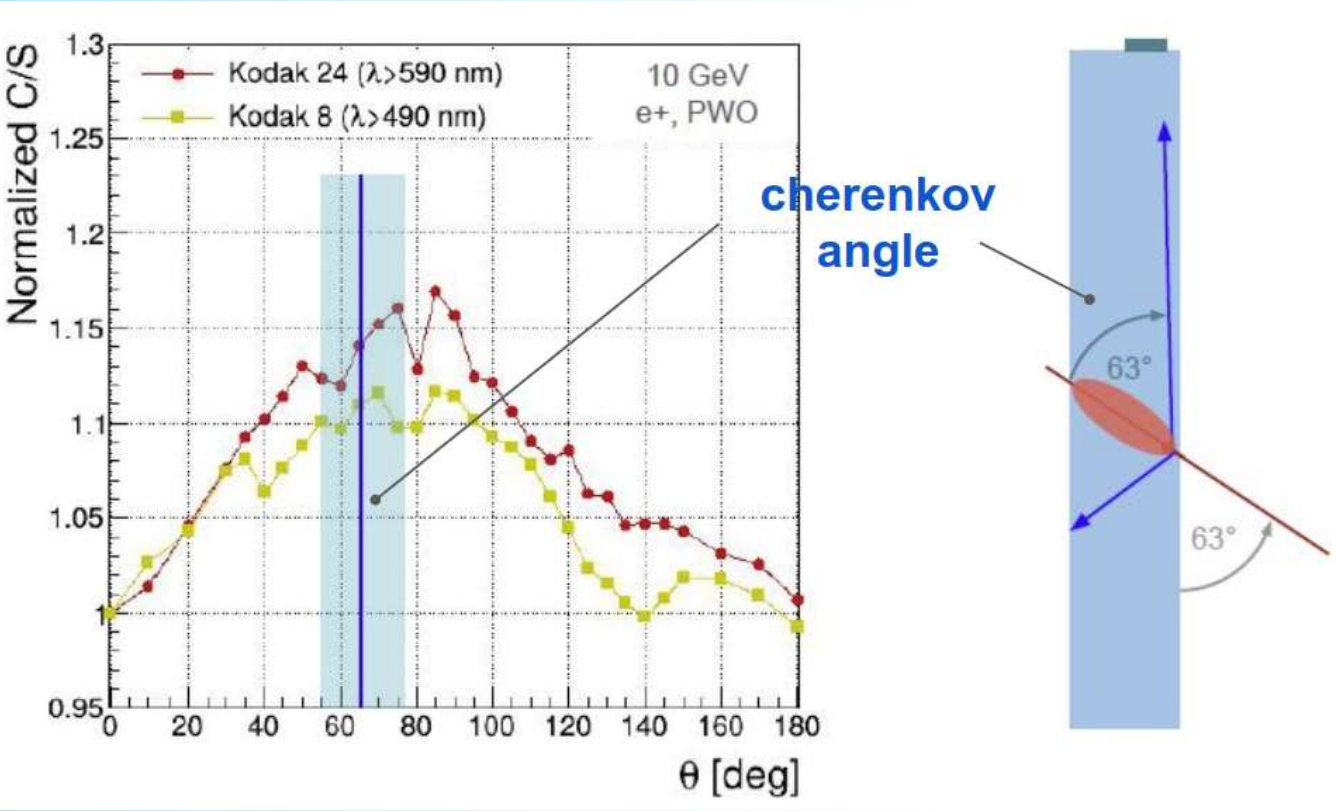


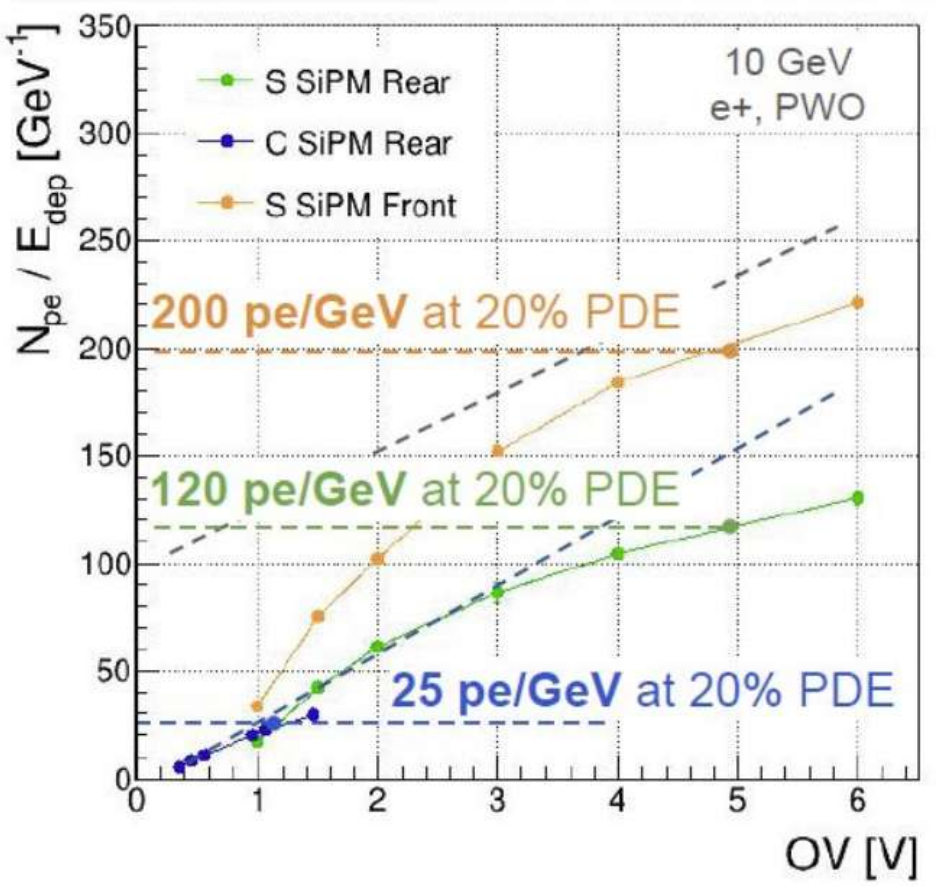
2024 test beam: PWO setup

Cherenkov effect directionality → C/S signal depends on angle between beam and crystal → **Smoking gun of Cherenkov separation!**

Number of photoelectrons measured:
Scintillation: **320 pe/GeV**
Cherenkov: **25 pe/GeV**

Required yield obtainable with further optimization.
6x6 mm^2 S SiPM, high OV
Starting point for the new prototype

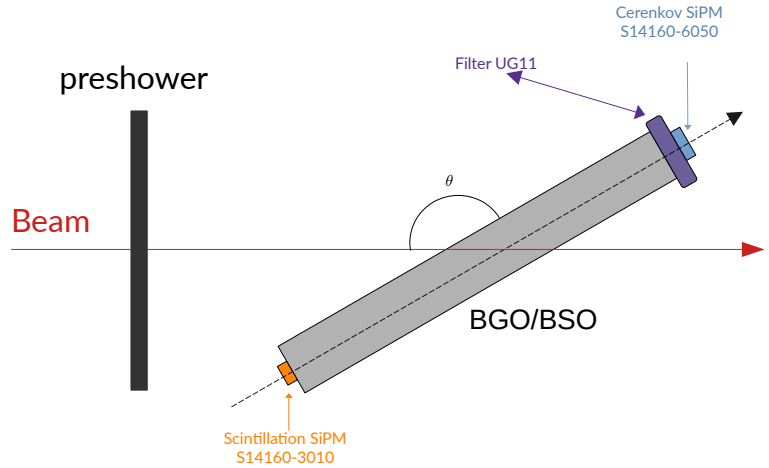




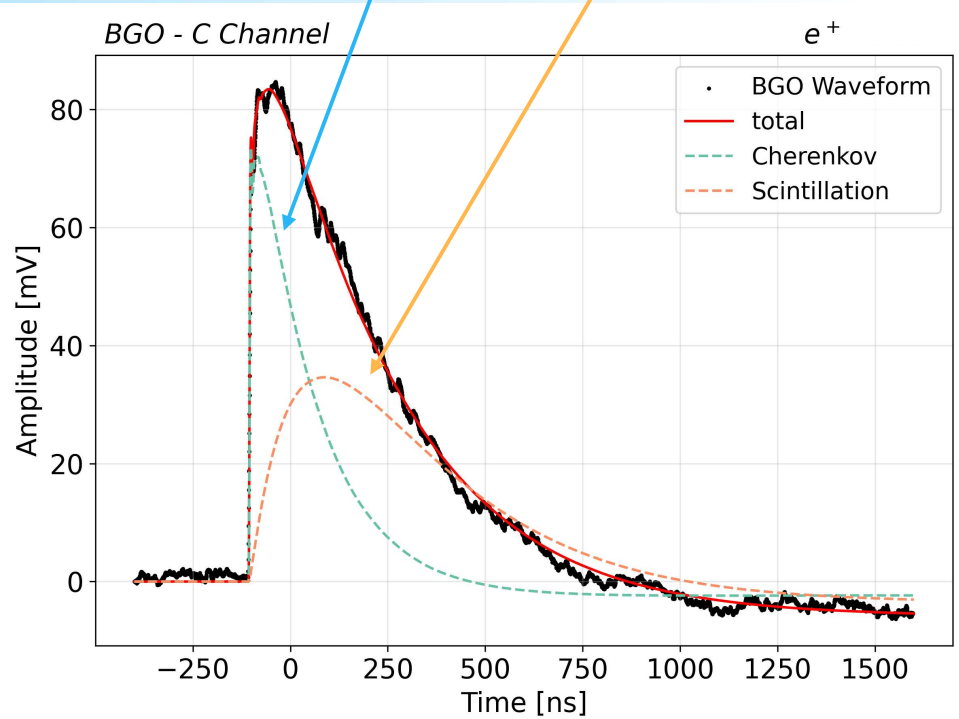
2024 test beam: BGO/BSO

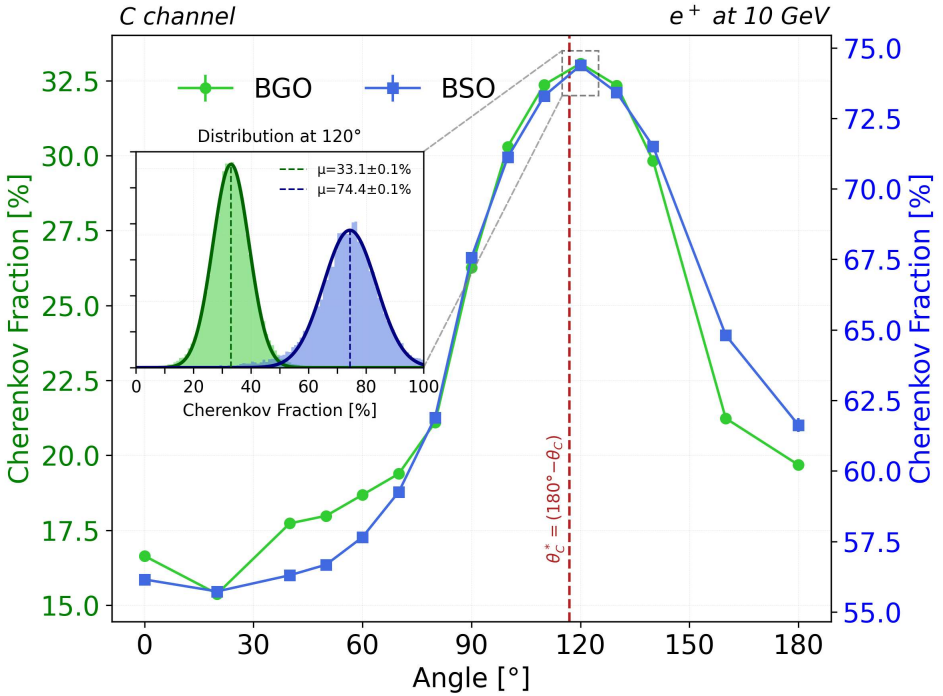
BGO/BSO have high light yields → considerable number of scintillation photons in the C channel.

The slower decay time allows time-based separation → Template fitting



Cherenkov ⊗ ***Scintillation***





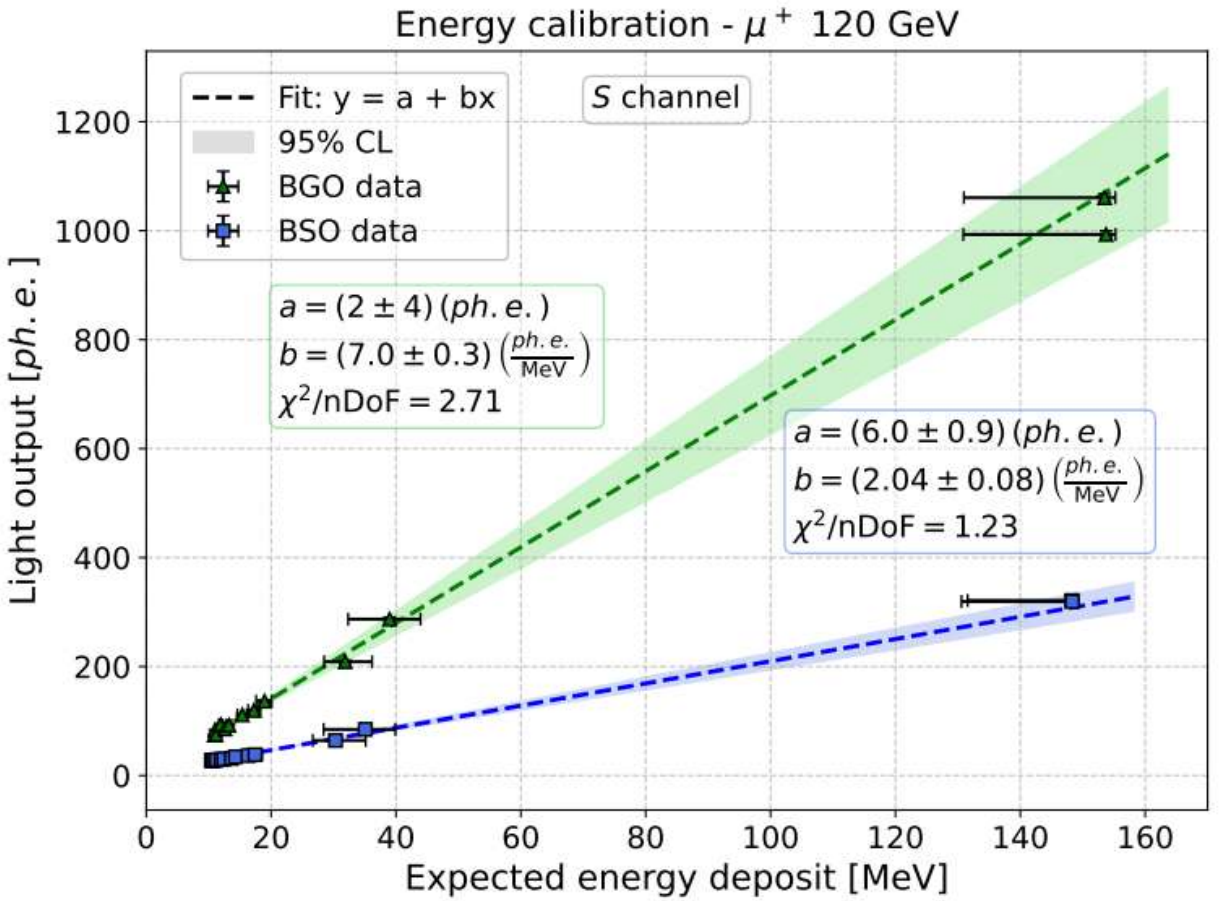
Alviggi et al., Cherenkov and scintillation light separation in BGO and BSO crystals coupled to SiPMs for dual-readout electromagnetic calorimetry at future colliders

2024 test beam: BGO/BSO

BGO/BSO scintillation yield obtained from muon runs, energy deposit estimated with Geant4 simulation.

Photoelectrons yield:

- Cherenkov yield is between **50-100 pe/GeV** in BGO and BSO
- Scintillion yield of BGO is **7000 pe/GeV** on 3x3 mm^2 SiPM
- Scintillation yield of BSO is **2000 pe/GeV** on 3x3 mm^2 SiPM



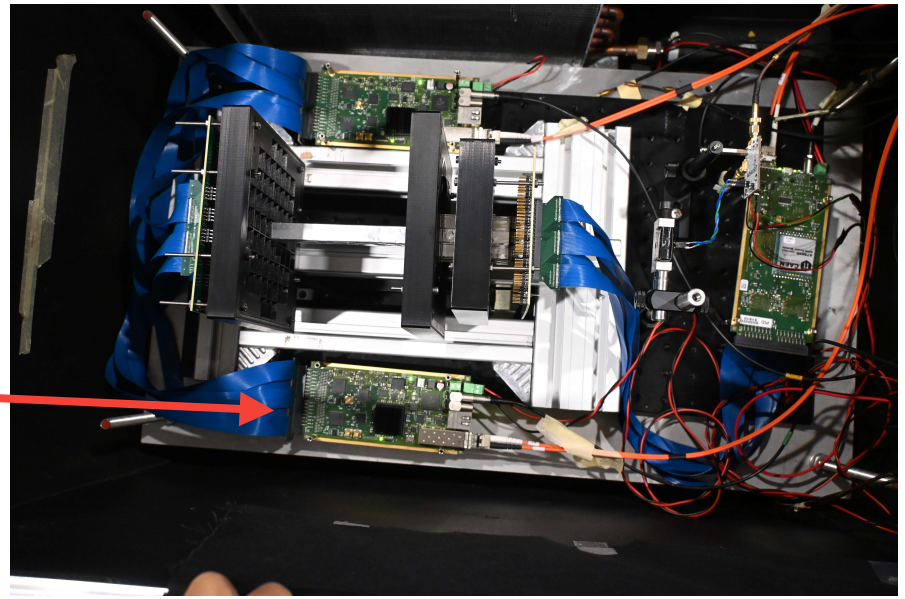
Alviggi et al., Cherenkov and scintillation light separation in BGO and BSO crystals coupled to SiPMs for dual-readout electromagnetic calorimetry at future colliders

2025 test beam @ CERN SPS

Objective: test of new electronics, new SiPMS, compare SICCAS and ISMA BSO crystals.

PWO setup:

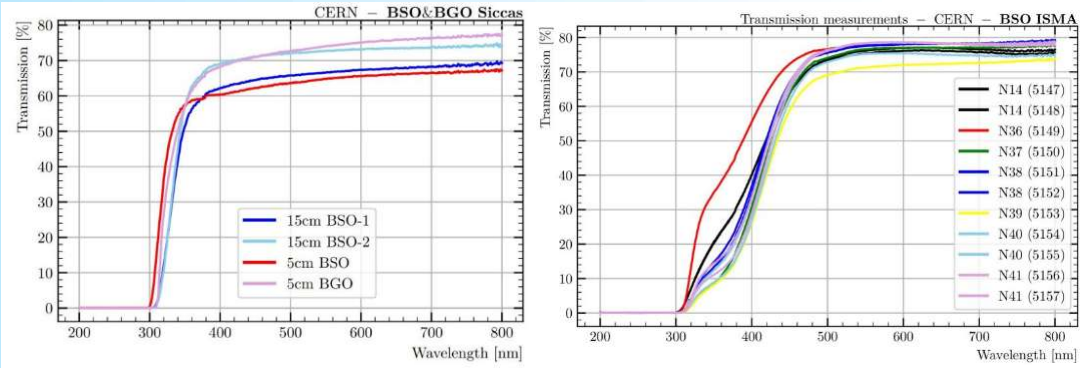
- CAEN FERS → fast signal integration across multiple channels.
- 6x6 mm^2 , 15 μm pitch SiPM on S channel.

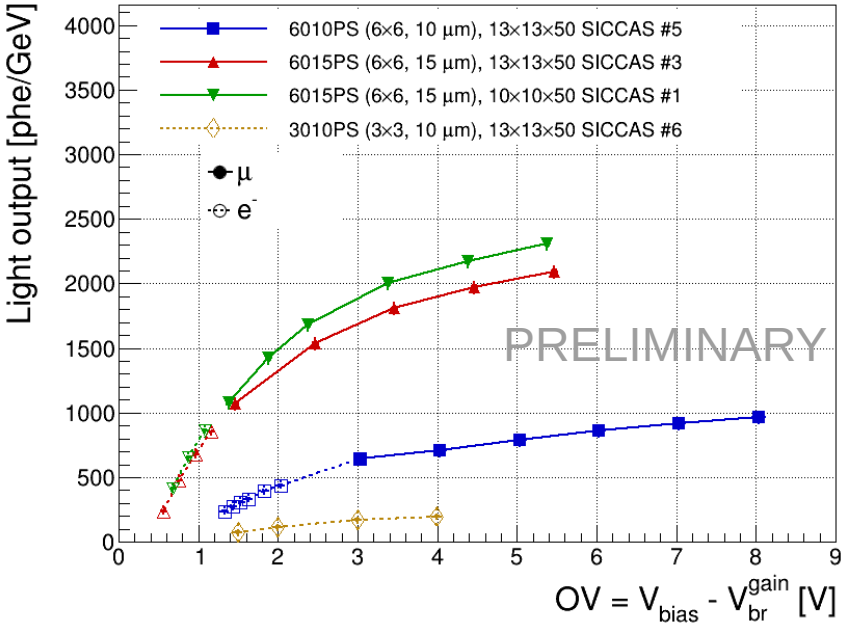


S SiPM, front crystal

BSO setup:

- test of digitizer for BSO
- comparison of crystals from SICCAS and ISMA (supported by European project TWISMA (GA101078960))

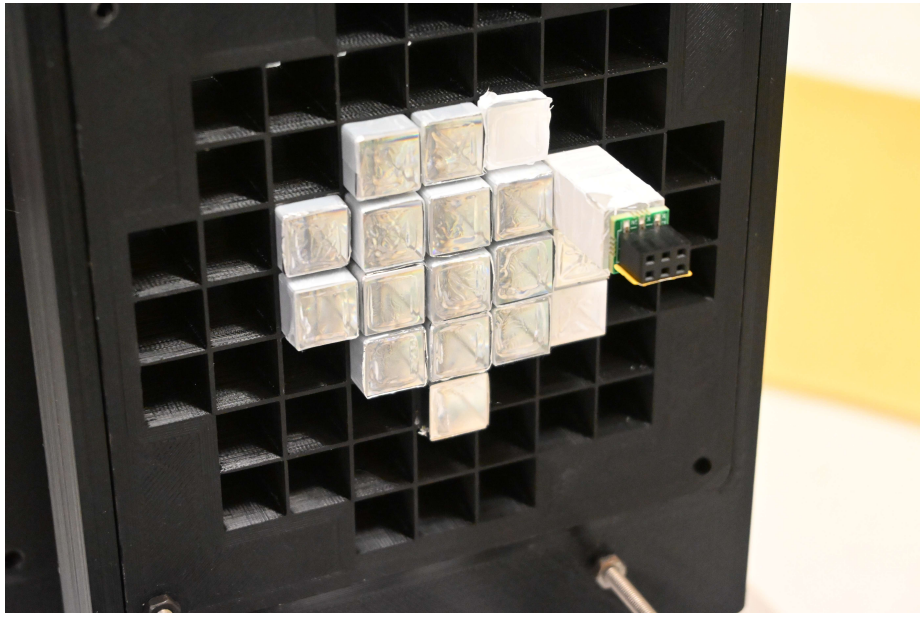




2026 test beam @ CERN PS

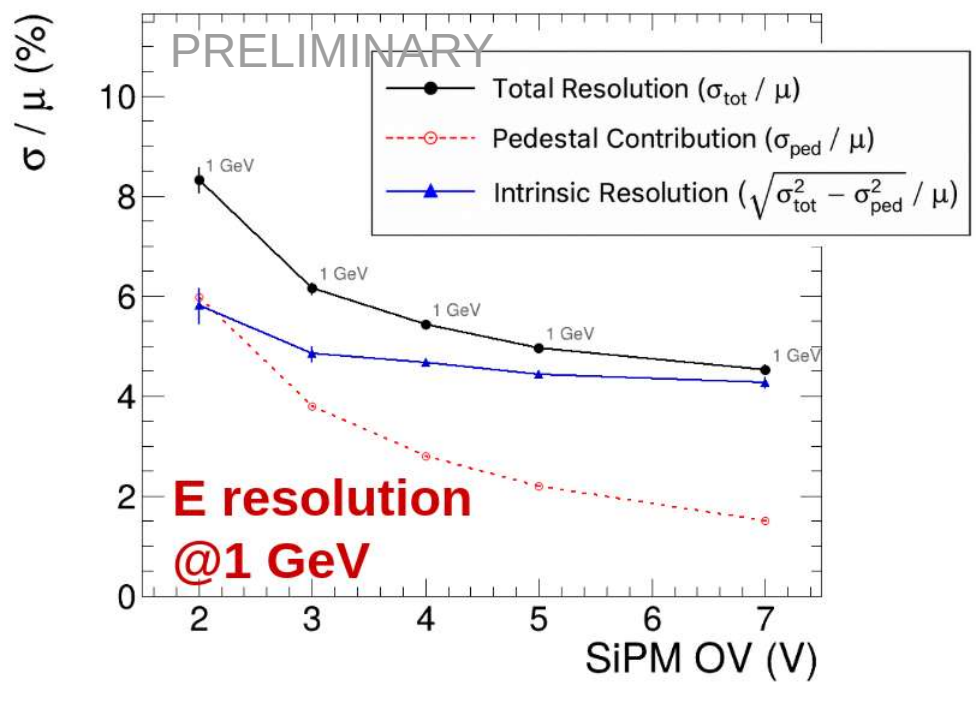
PWO: test of the first matrix prototype.

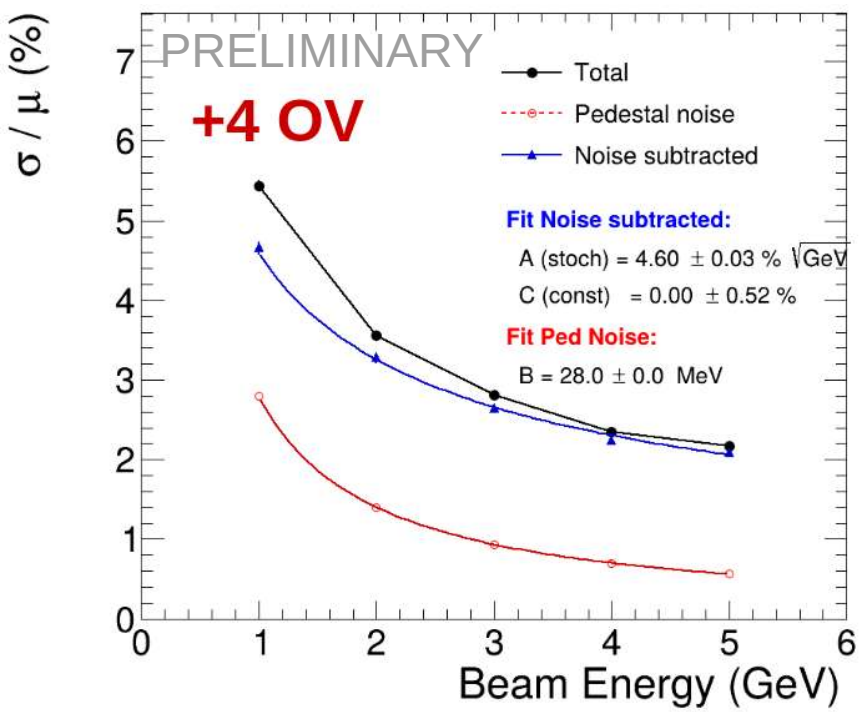
- Crystals from SICCAS and CRYTUR.
- “Almost full containment” → energy resolution and linearity
- **Overvoltage** scan at fixed energy
- **Energy** scan at fixed overvoltage



Very preliminary results
Data analysis is still ongoing

4.6% stochastic term





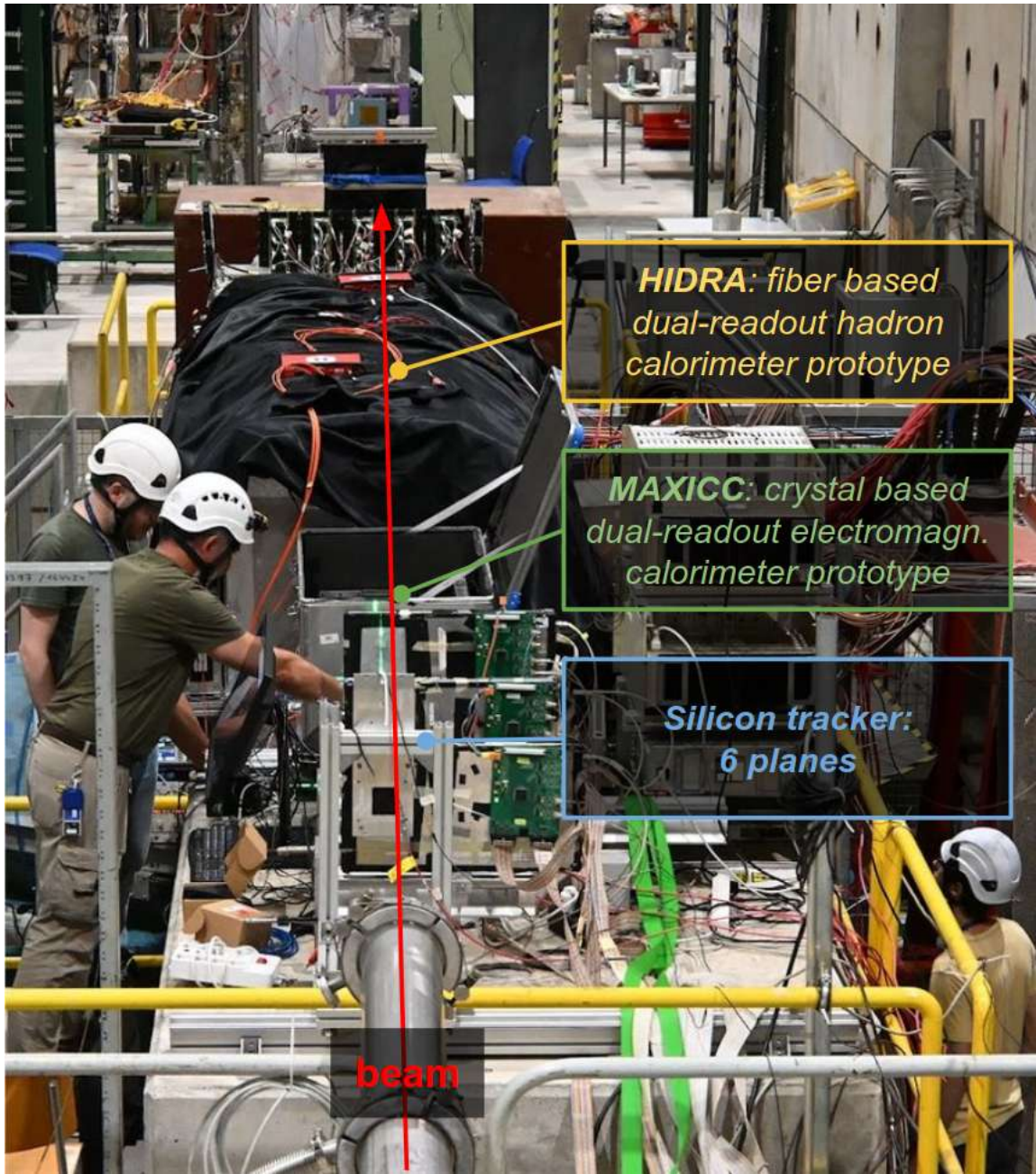
2026 test beam @ CERN SPS

Full containment PWO matrix. Joint test with HIDRA prototype (dual-readout fiber calorimeter)

- Energy resolution and linearity
- Angular and position resolution
- Response uniformity
- Joint reconstruction with HIDRA for hadronic resolution

Data analysis is still ongoing





Summary and outlook

- The IDEA crystal electromagnetic calorimeter combines excellent electromagnetic performance with dual-readout capabilities.
- The 2024 CERN SPS test beam demonstrated the separation of Cherenkov and scintillation light in PWO, BGO and BSO crystals with SiPM readout.
- The measured light yields confirm the strong potential of BGO and BSO for dual-readout applications; required light yield demonstrated also in PWO with using large SiPMs.
- The full containment PWO matrix has been tested and collected data will be used to assess energy resolution, linearity and dual-readout performance at prototype level.
- The test with HIDRA prototype provides useful data for validation of simulation and reconstruction algorithms.

Not covered in this talk

- Calvision group tested a full containment BGO matrix at DESY and data analysis is ongoing.
- Great effort is going on in the simulation of test beam setups and simulation of the full detector.