Innovative calorimeters with optical readout Crystal detectors (Sub-task 8.3.1):

Results from beam tests of fast crystals and nanocomposite scintillators

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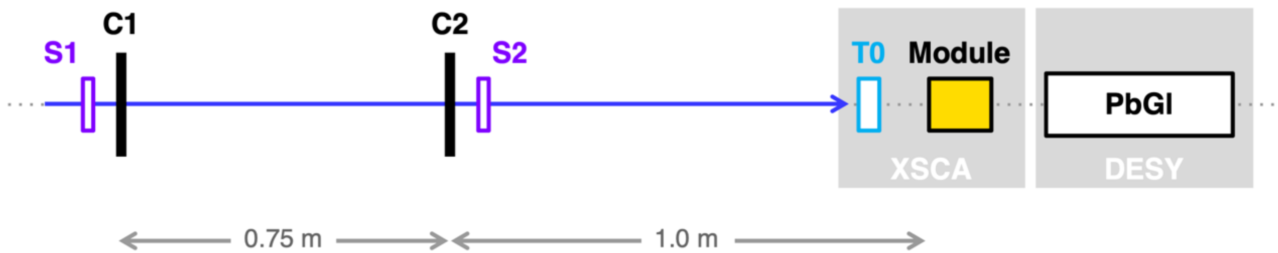
For the Frascati, Torino, Glass To Power groups
with contributions from Ferrara, Napoli, Insubria, and CERN

AIDAinnova WP8 Face-to-Face Meeting
18 January 2024

Beam tests and measurement program



Setup:

S1, S2	Trigger scintillators
C1, C2	Si-strip trackers, 10×10 cm^2, $\sigma = 50$ µm
T0	Timing reference, $\sigma_t = 25$-50 ps
Module	Device under test, with goniometer
PbGl	Lead-glass calorimeter

Facilities and beams:

SPS H2	e^-, mips, 20-150 GeV
PS T9	e^-, mips, 1-10 GeV
Frascati BTF	e^-, 450 MeV

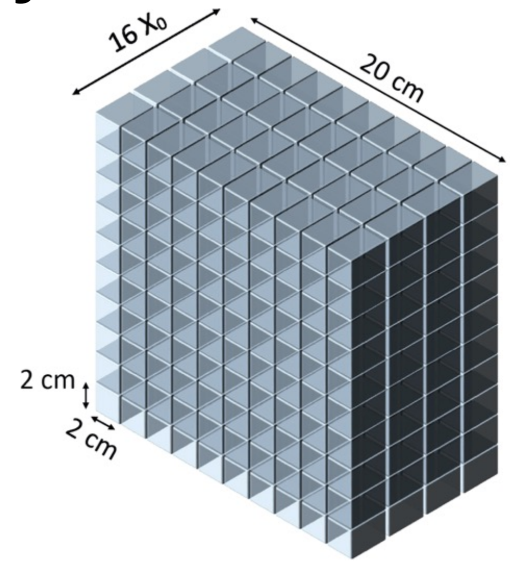
Topics to investigate:

- Crystals for fast, compact calorimeters (WP8.3.1)
- Nanocomposite scintillators for calorimetry (WP8.3.1 + 13.5)

Fast, compact crystal calorimetry

R&D for future experiments to develop new concepts for crystal calorimeters

- Cerenkov radiators like PbF_2 or ultra-fast scintillators such as PWO-UF
- Transverse and longitudinal segmentation for γ/n discrimination
- Exploit coherent interactions in crystals to reduce thickness?

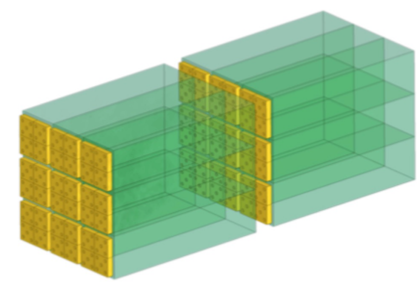


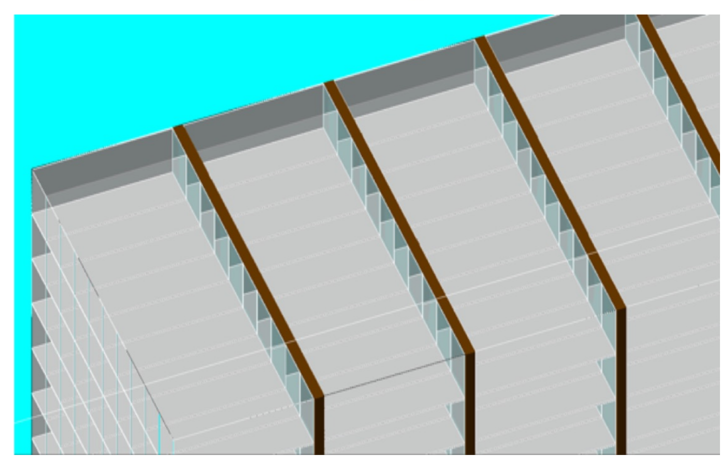
HIKE small-angle calorimeter

- 4 layers
- 40x20x20 mm^3

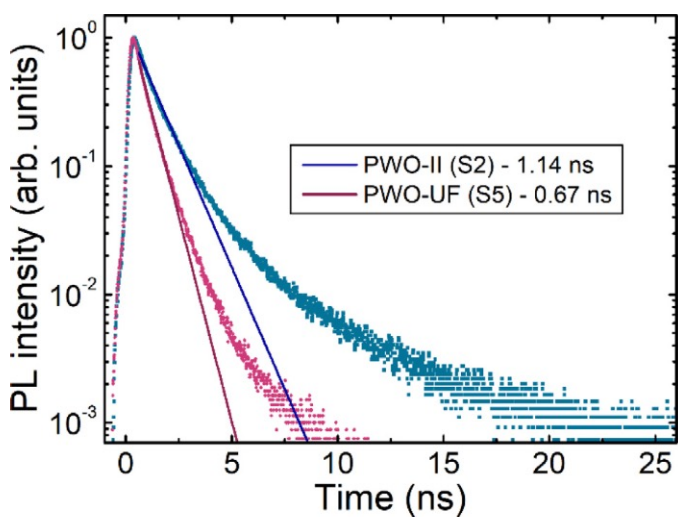
CRILIN calorimeter for muon collider
arXiv:2206.05838

- 5 layers
- 40x10x10 mm^3





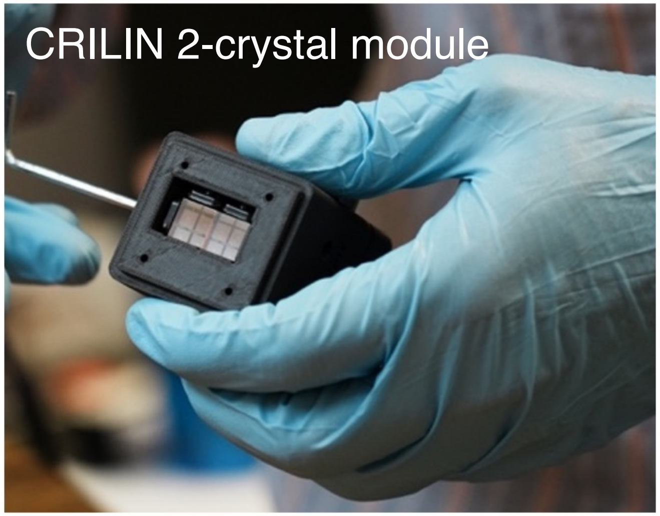
PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781

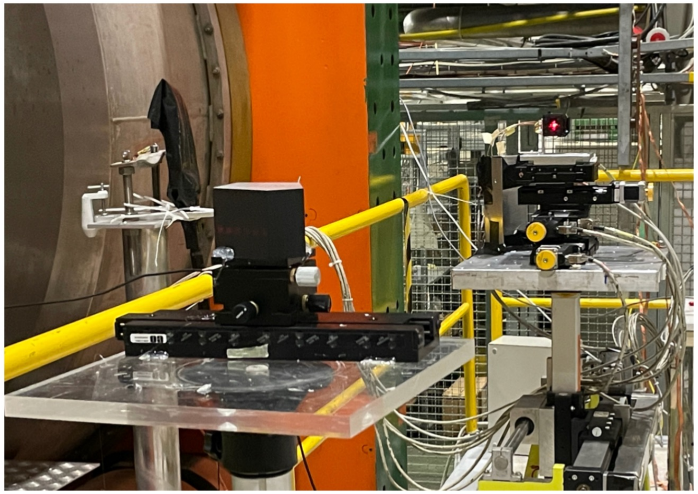


Tests with single crystals in 2022

Sept/Oct 2022 run at SPS H2 beamline:

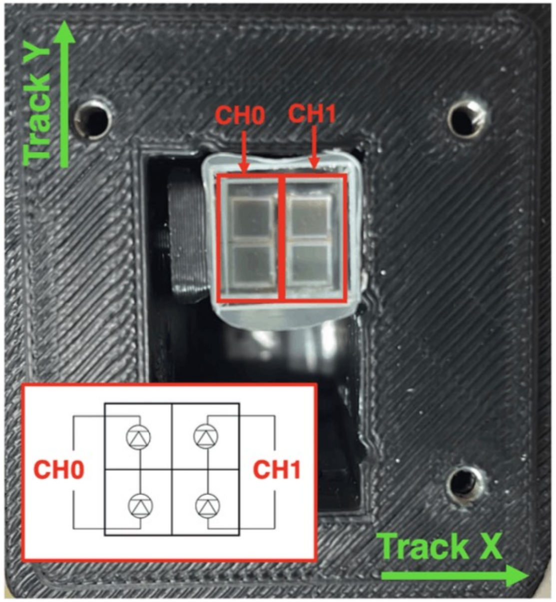
- 20-120 GeV e^- and MIPs (150 GeV π)
- Validate CRILIN readout electronics
- Study systematics of light transport in small crystals with high n
- Measure time resolution achievable for PbF_2 and PWO-UF

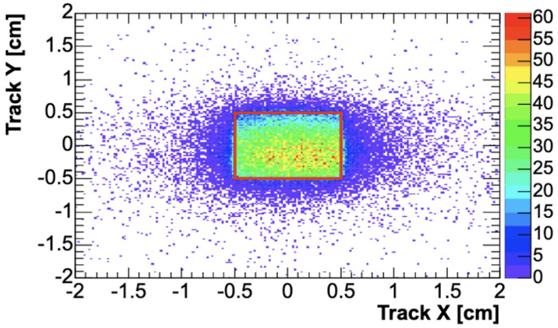




Positioning of module on beamline

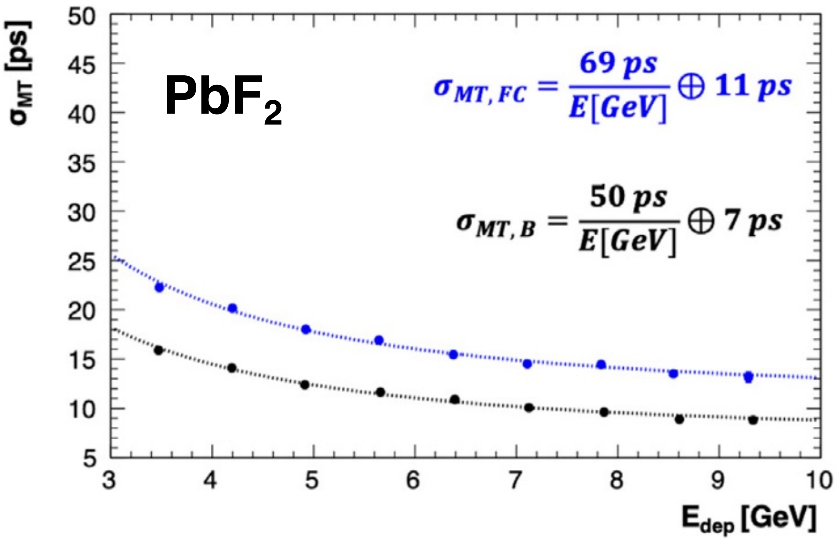
SiPM readout scheme

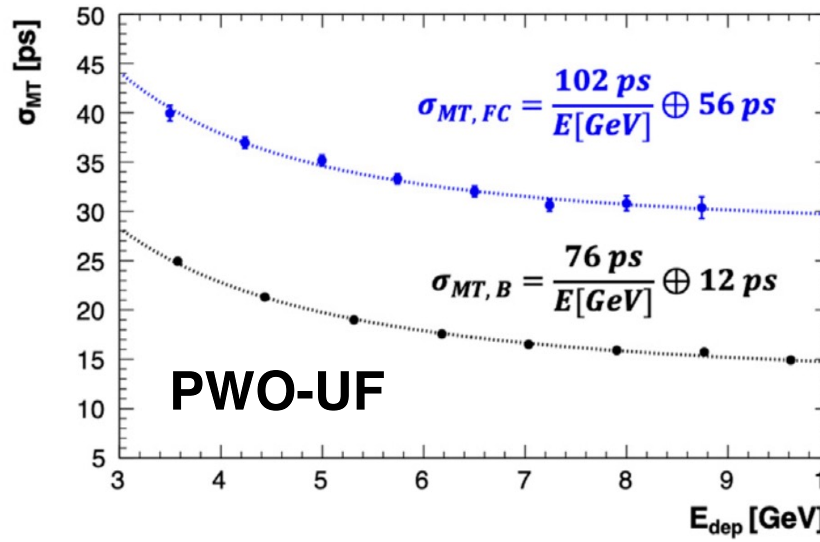




Beam image from Si-strip tracker with condition on signal from crystal

Time resolution for single crystals





Front. Phys 11 (2023) 1223183

$$\sigma_{MT} = \sigma(t_{ch0} - t_{ch1})/2$$

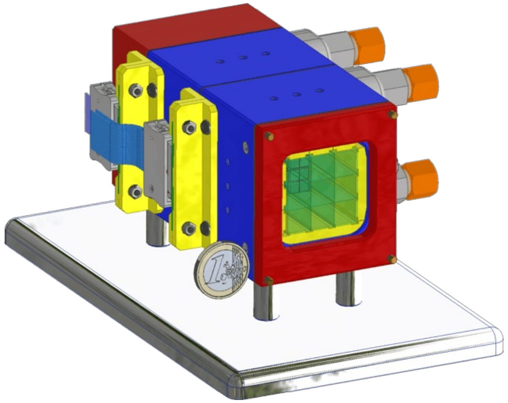
FC Beam incident from front

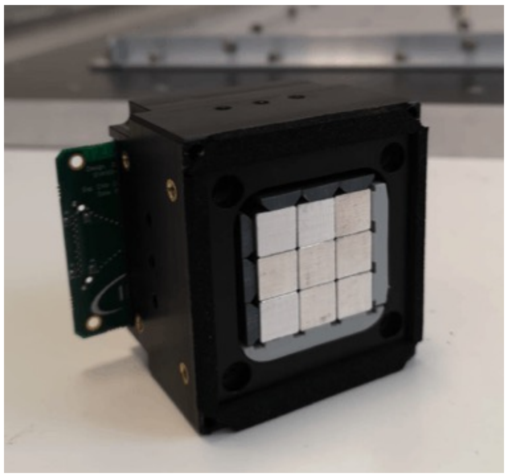
BC Beam incident from back (SiPM side)

Conclusions:

- Effects of light transport degrade timing resolution for frontal incidence, despite higher light yield
- PbF_2 provides better time resolution due to pure Cerenkov emission, even with 50% light yield of PWO-UF
- Both single crystals give σ_t **< 30 ps** for $E_{dep} > 3$ GeV!

Tests of CRILIN prototype in 2023





From single crystals to first calorimeter prototype:

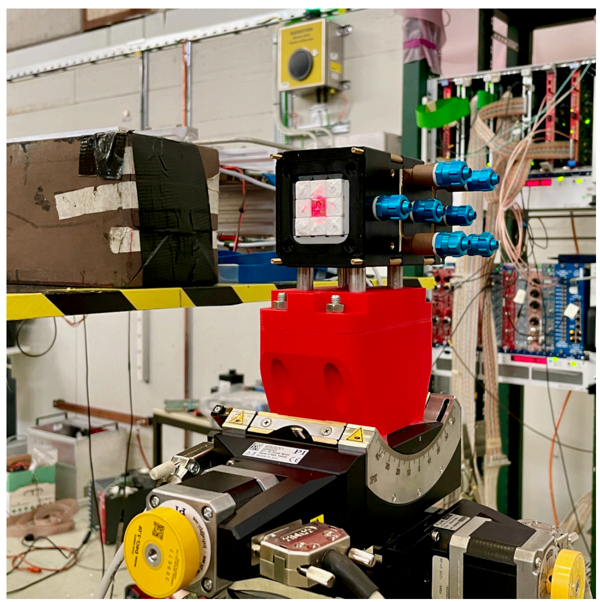
New prototype with two 3x3 CRILIN test layers

Load layers with different crystals: PbF_2, PWO-UF

Different surface treatments to damp internal reflections

Test objectives:

1. Perform complete operational test
2. Test cluster reconstruction capability
3. Conceptual test of longitudinal segmentation
4. Study angular effects: align beam with central crystal



Test beam runs in 2023:

June: Commissioning

- 1-4 GeV e^-, mips in T9
- 450 MeV e^- at BTF

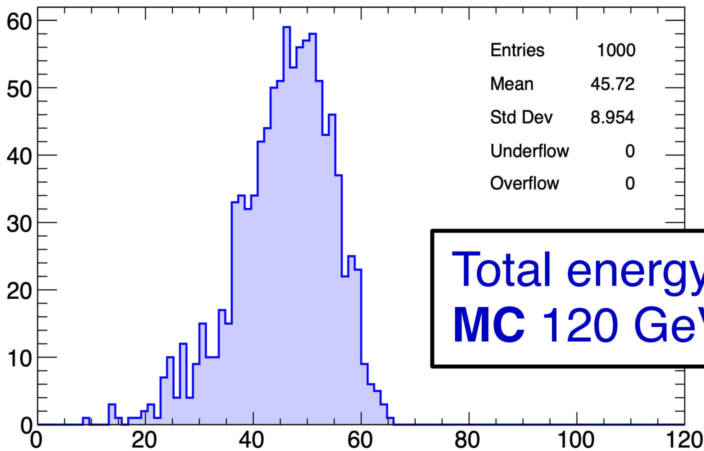
Aug: Data taking

- 20-120 GeV e^- in H2

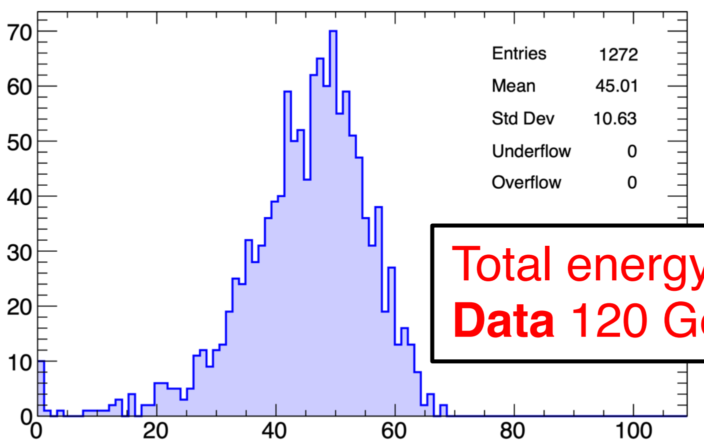
Oct: Alignment studies

- 4 GeV e^- in T9

CRILIN results

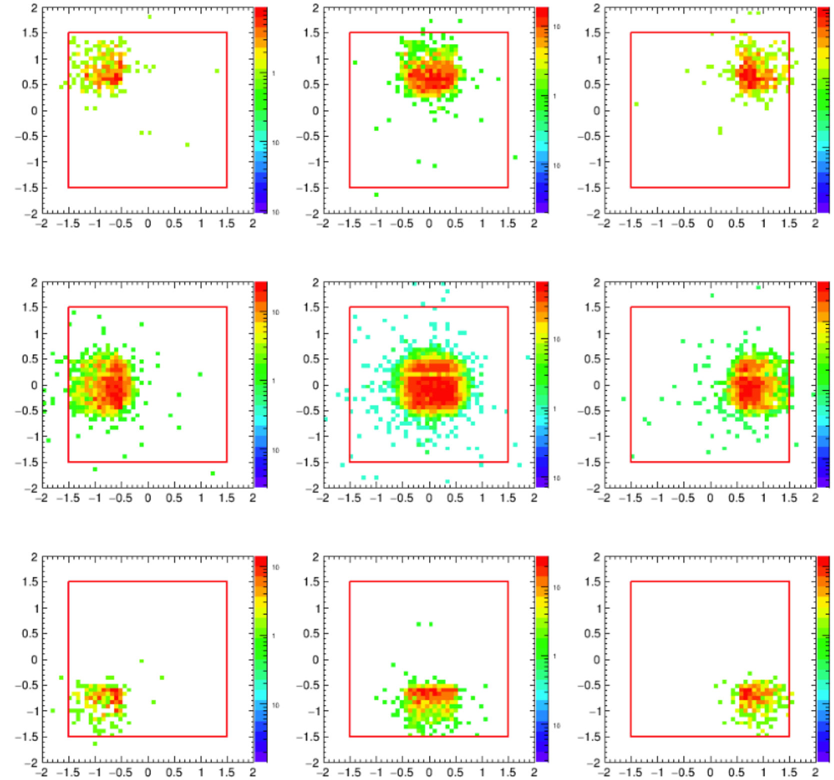


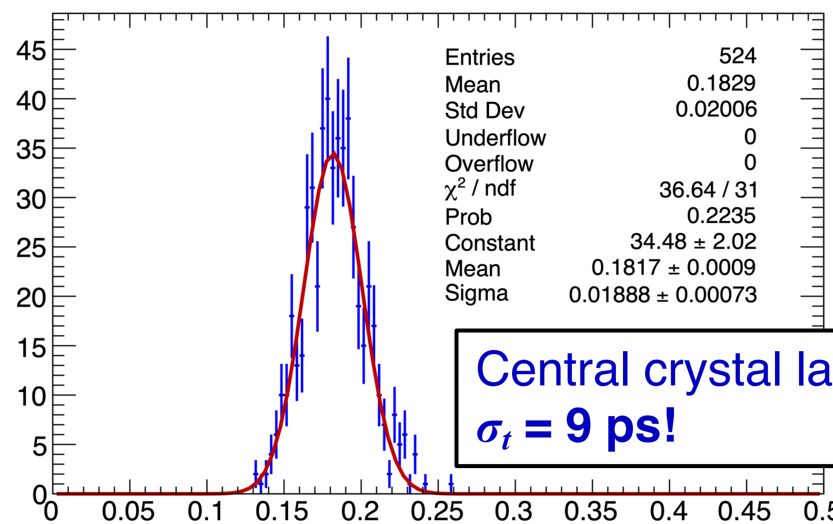
Total energy
MC 120 GeV e^-



Total energy
Data 120 GeV e^-

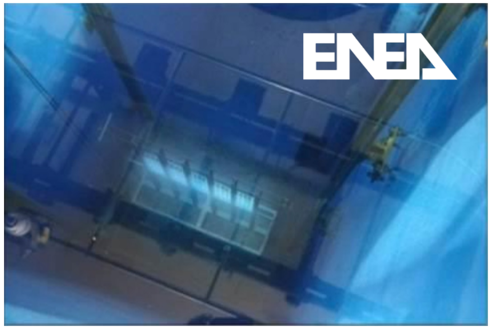
Tracking data with cuts on each crystal





Central crystal layer 1
σ_t **= 9 ps!**

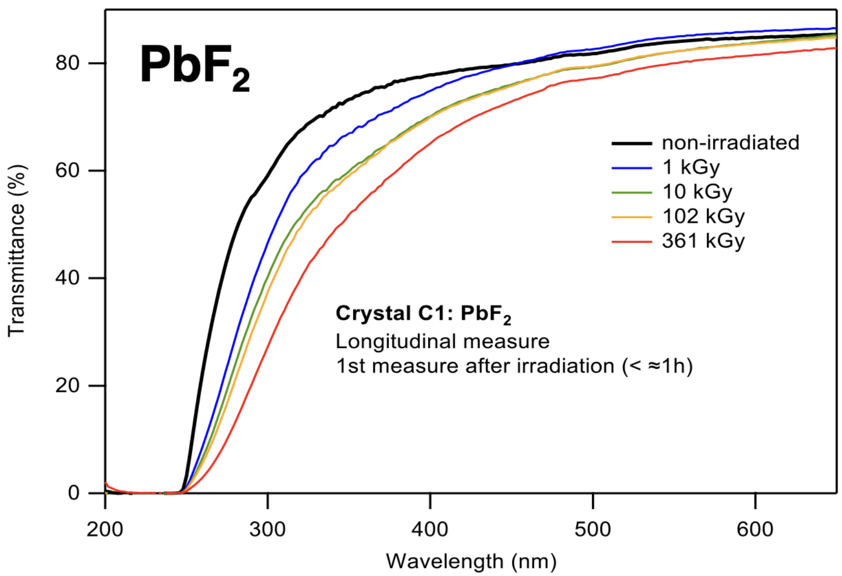
Radiation resistance of crystals

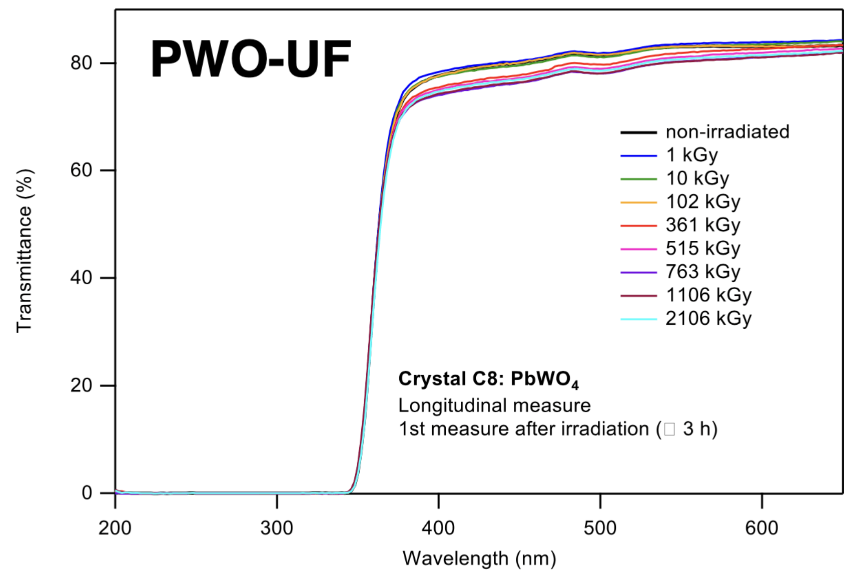


^{60}Co γ irradiation at Calliope, ENEA Casaccia, June 2023

- Easy to accumulate MGy doses, full dosimetry support
- Support with transmission, light yield, fluorescence spectrometry measurements

Preliminary results:





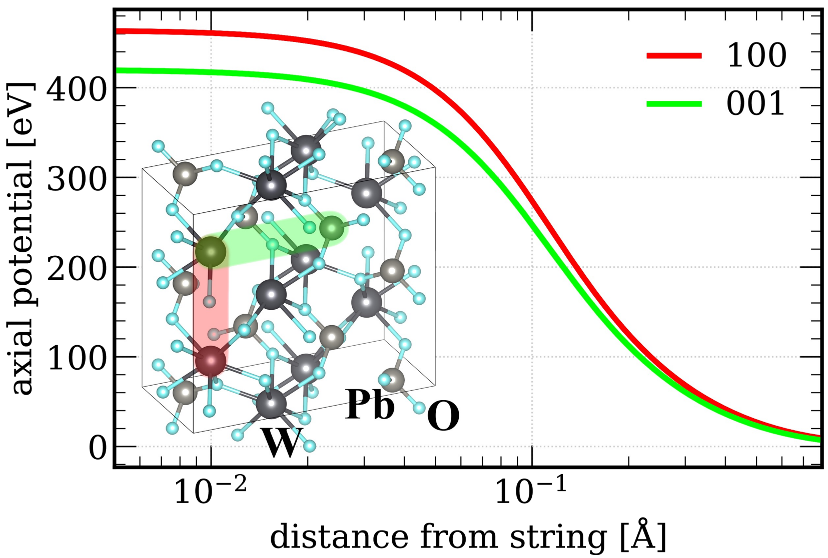
- At **360 kGy ~ 20% transmission loss** at λ = 400 nm
- Substantial recovery after annealing several days in ambient light

- At **2100 kGy ~ 5% transmission loss** at λ = 400 nm
- Only modest recovery after annealing several days in ambient light

Coherent effects in crystals

Coherent effects increase cross-section for electromagnetic shower processes (bremsstrahlung, pair production)

- **Decrease effective value of X_0**
- **Exploit coherent effects for calorimetry?**



Coherent superposition of Coulomb fields

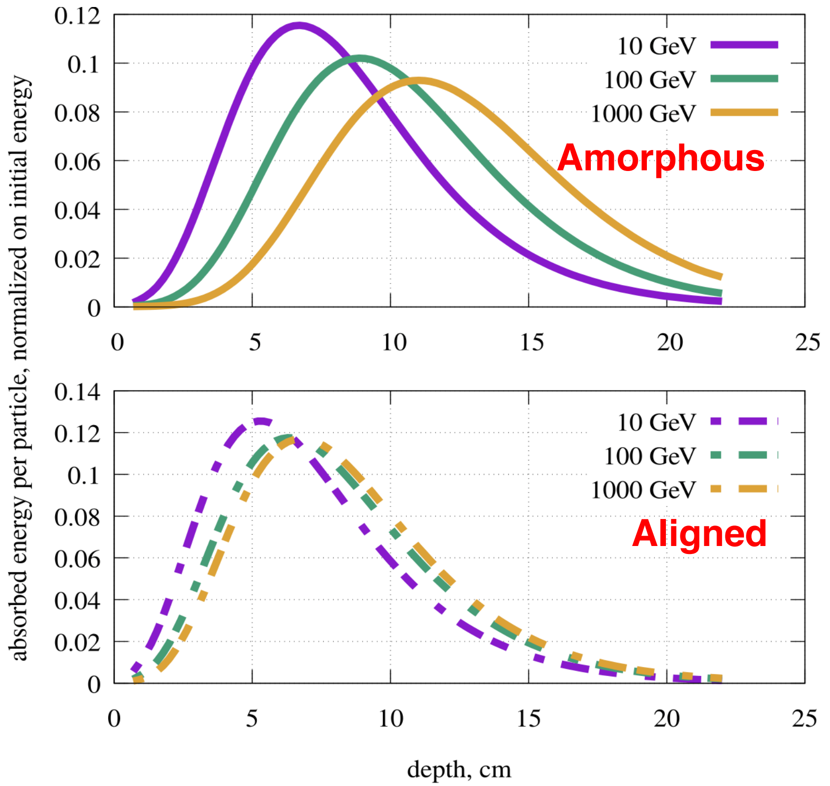
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

Effective field $\varepsilon' = \gamma_{\text{eff}}$ ($\gamma_{\text{eff}} = E/m_e c$)

For $\varepsilon' \sim \varepsilon_0 = 2\pi m^2 c^3/eh$ virtual pairs disassociate

Geant4 simulation: e^- on PWO

Bandiera et al., NIMA 936 (2019)

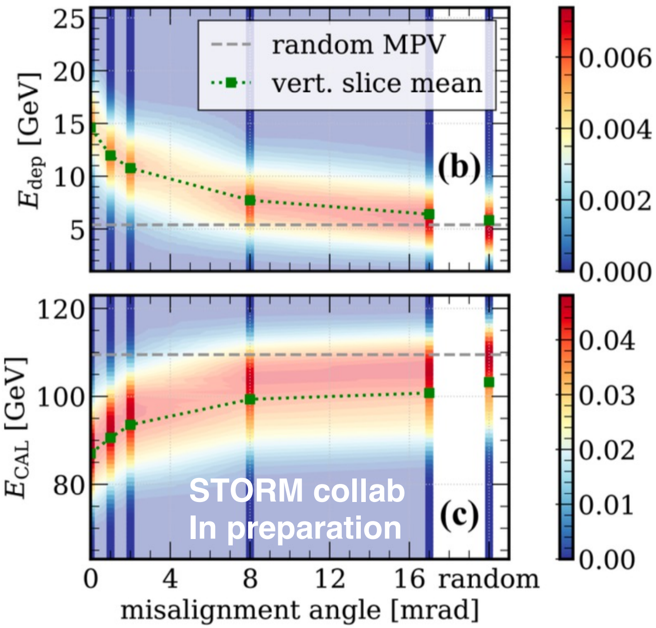


- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

Pair production enhanced by coherent effects at small θ_γ and high E_γ

Calorimetry with aligned crystals

E deposited vs absorbed
120 GeV e^- on $4.6X_0$ PWO



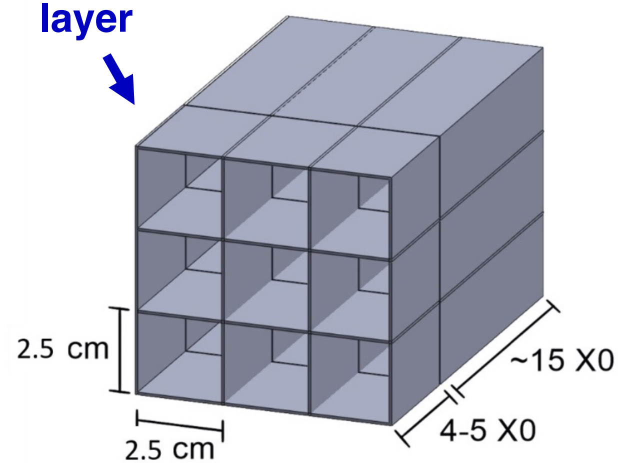
Exploit effects of coherent interactions in crystals to develop a highly compact calorimeter

- Excellent response to photons

  Enhanced probability for γ conversion

- High transparency to hadrons

  γ/n discrimination



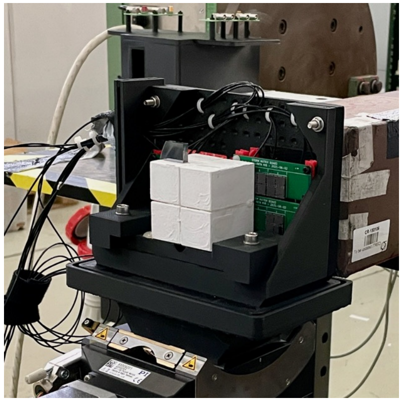
OREO prototype

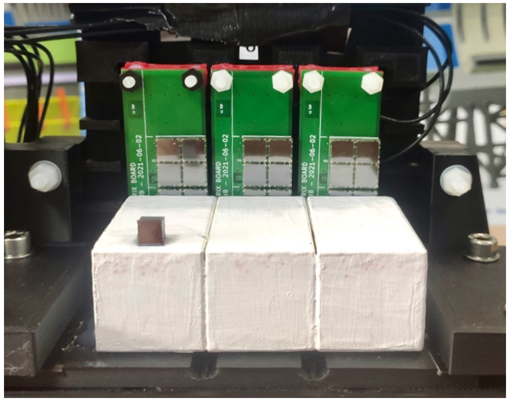
OREO project for aligned PWO-UF crystal calorimeter

- Developed techniques for crystal characterization, shaping, alignment and assembly

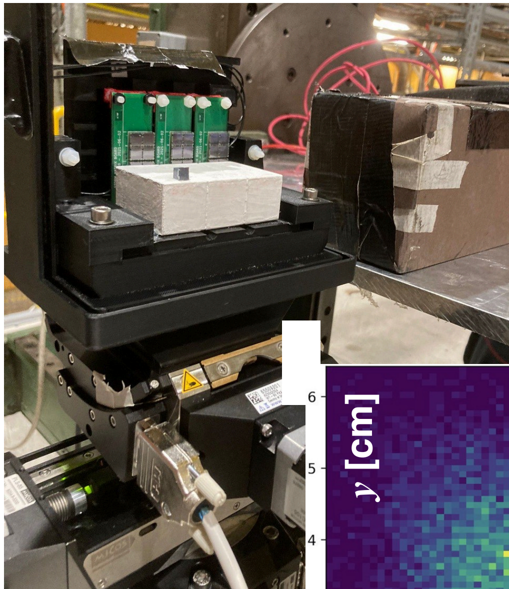
  Front. Phys, 11 (2023) 1254020

- Obtained alignment of 1-dim and 2-dim matrices to ~ 0.2 mrad

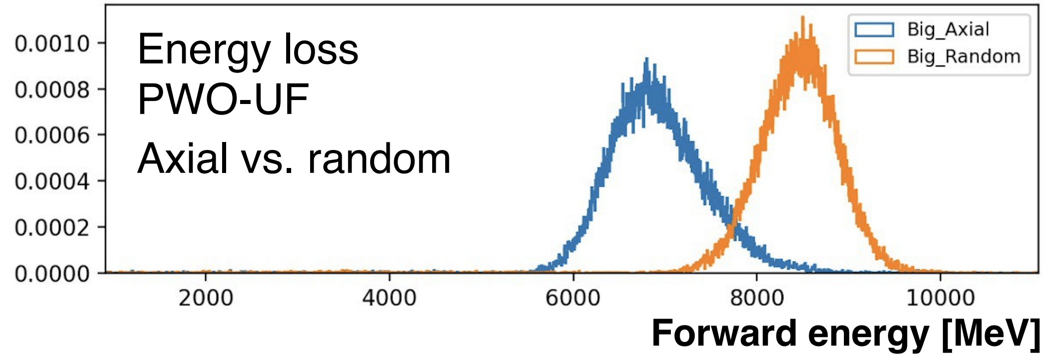


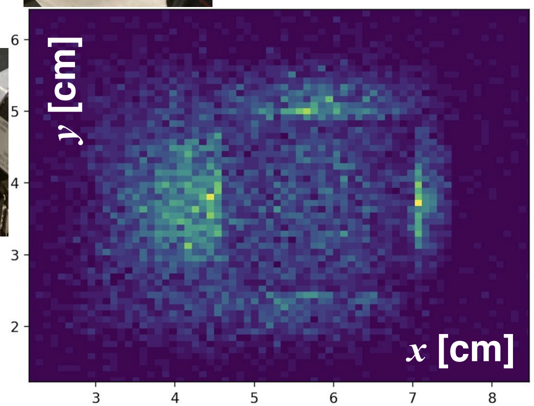


OREO results



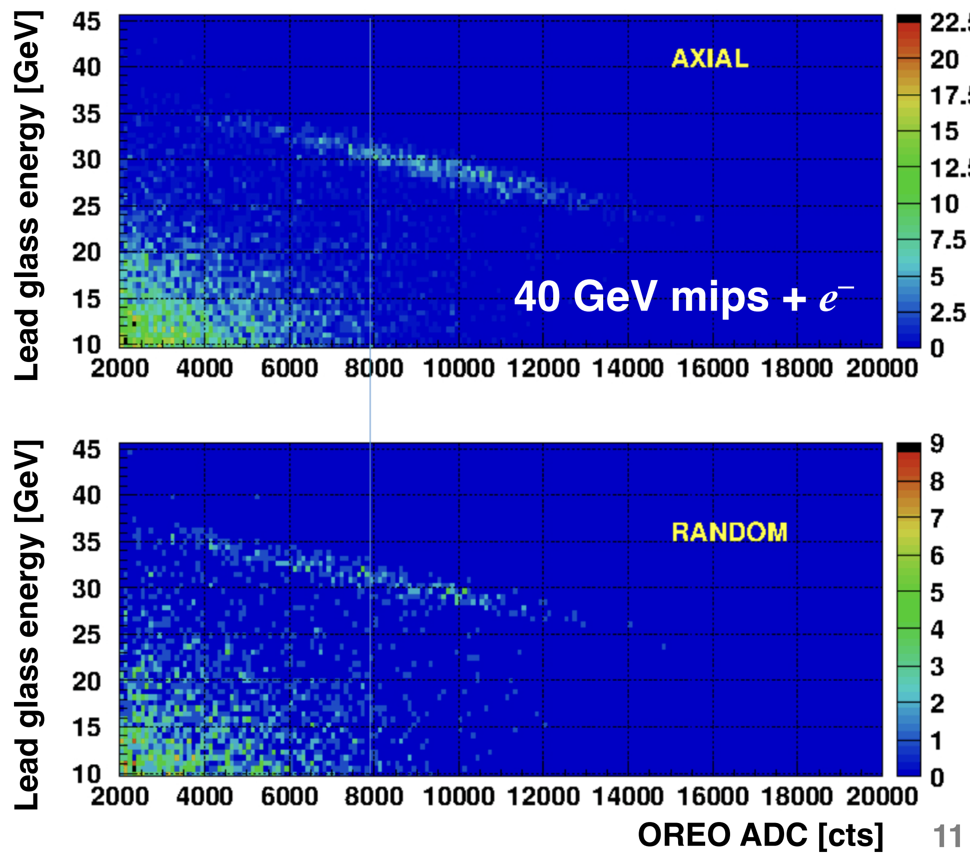
3x1 crystals with SiPM on goniometer



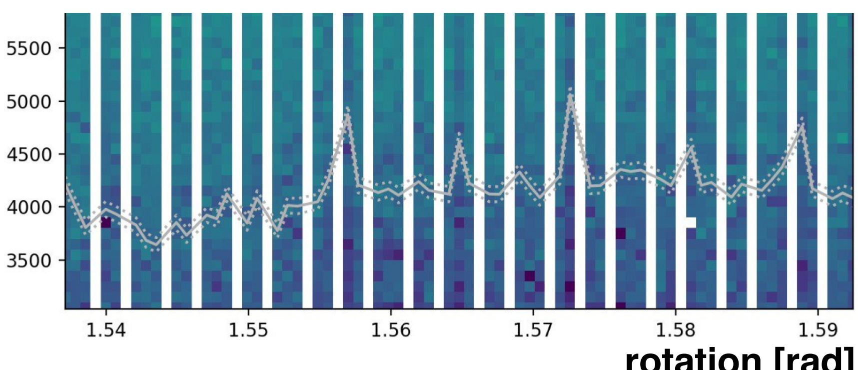


Crystal imaged with beam

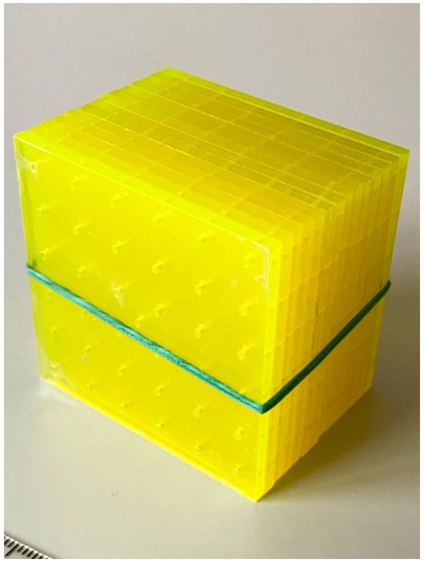
Mixed beam: Anticorrelation for e^- between forward energy and light from crystals

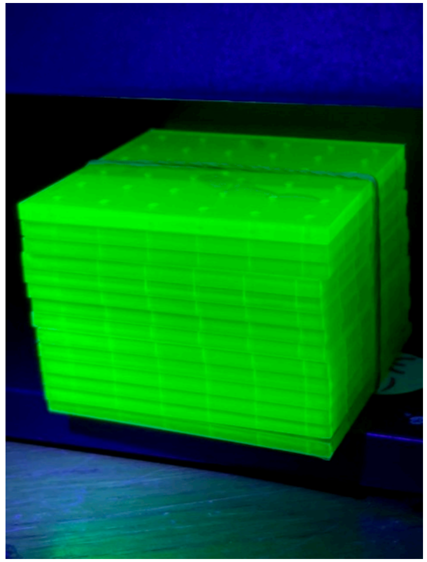


Crystal planes in PWO-UF revealed by scintillation light read out from crystals



Nanocomposite scintillators for calorimetry





Semiconductor nanostructures can be used as sensitizers/emitters for ultrafast, robust scintillators:

- Perovskite (typically $CsPbX_3$, X = Br, Cl…) nanocrystals cast into polymer matrix
- Cast with polymer matrix
- Emission components with τ << 1 ns
- Radiation hard to O(1 MGy)

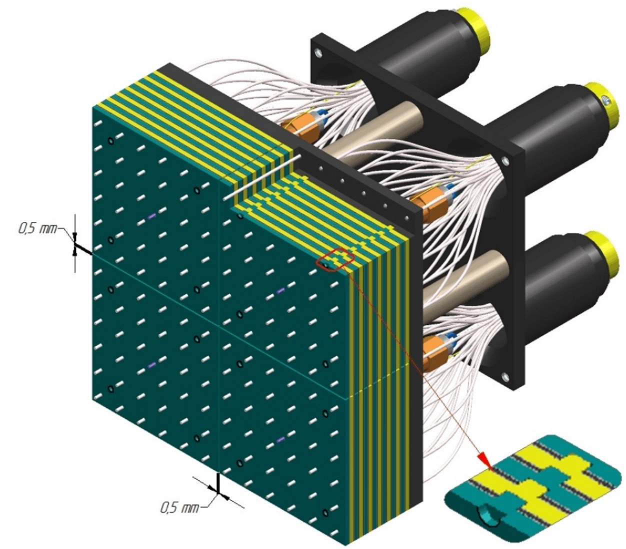
NanoCal project: Construct a calorimeter prototype with NC scintillator and test with high-energy beams

Shashlyk design naturally ideal as a test platform:

- Easy to construct with very fine sampling
- Primary scintillator and WLS materials required: both can be optimized using NC technology

Additionally exploring:

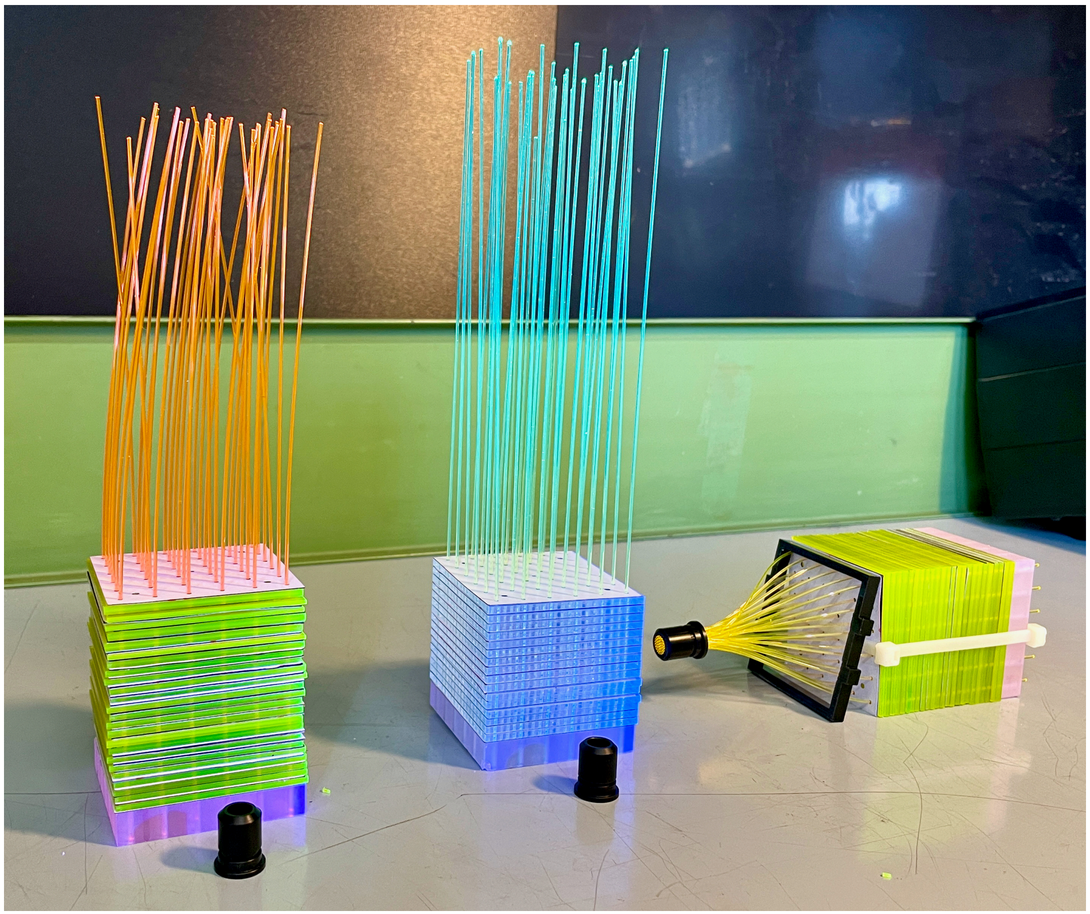
- **New dyes** for optimized conventional scintillators
- Fast, bright **green scintillators** for additional radiation hardness



KOPIO/PANDA design
Fine-sampling shashlyk

NanoCal project goals and status

- **Oct 2022: First shashlyk component test at CERN: fibers/tiles/SiPMs**
- **2023**: Further iterations to improve performance of NC scintillator prototype
- **2024:** Construction of full-scale shashlyk modules; performance comparison
- **Possible application for construction of HIKE (future NA62) calorimeter**



Prototypes tested in summer 2023:

- Conventional scintillator (Protvino), Y-11 fibers
- Conventional scintillator (PVT + DDB), Y-11 fibers
- PMMA + $CsPbBr_3$ 0.2%, O-2 fibers
- PMMA + $CsPbBr_3$ 0.2%, Custom NCA-1 fibers
- PMMA + $CsPb(Br,Cl)_3$ + coumarin-6, NCA-1 fibers

Example of nanocomposite optimization

Previously used $CsPbBr_3$ in PMMA (green emission) → **too much self absorption**

A promising solution:

1. Use $CsPb(Br,Cl)_3$: Substitution of some Br with Cl shifts emission to blue
2. Add coumarin-6 as a high-Stokes-shift WLS → shifts emission back to green

Synthesis of $CsPbBr_3$

Substitution of 50% of Br with Cl

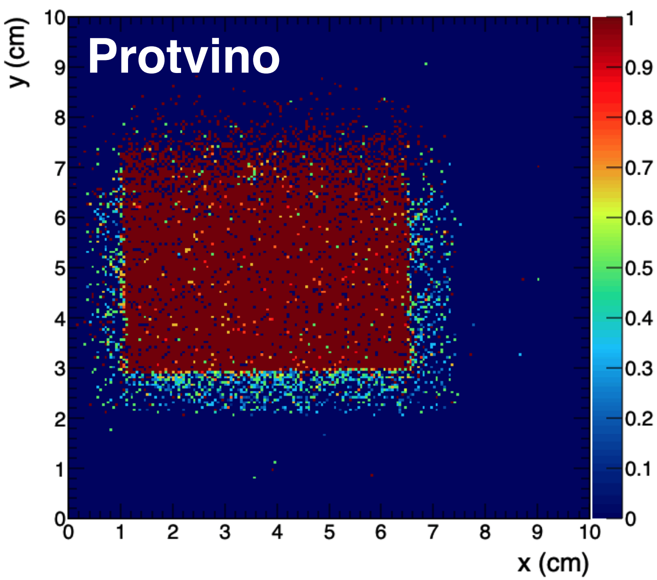
Addition of coumarin-6

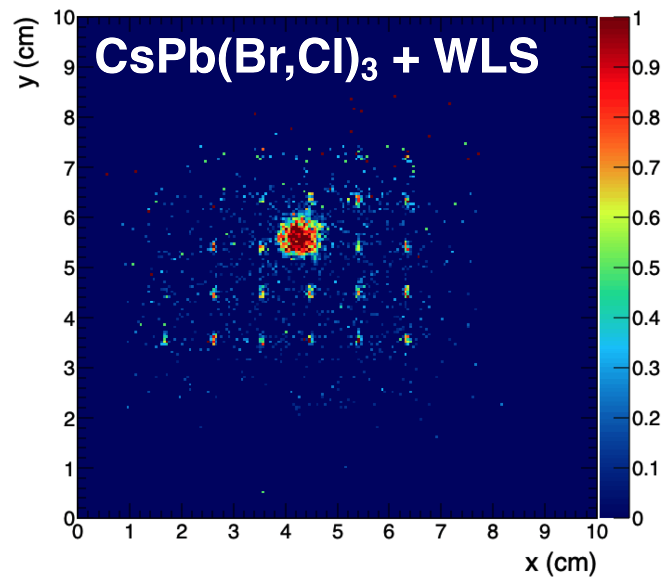
However, surface passivation of nanocrystals destroyed during substitution reaction, leading to aggregation (milky appearance, poor transparency)

First prototype tested anyway with custom (NCA-1) fibers at June test beam

Results from shashlyk prototypes

June test beam: Efficiency maps with 10 GeV μ, threshold = $5\sigma_{noise}$
Disappointing result from new nanocomposite: only light is from readout fibers



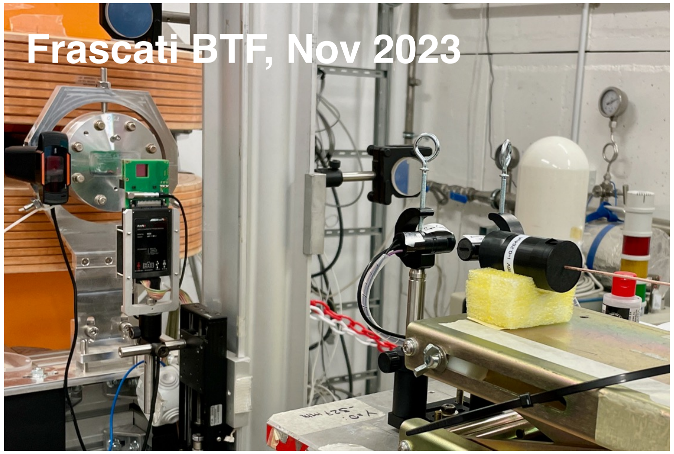


However: Lots of good ideas for next steps

- Direct synthesis of $CsPb(Br,Cl)_3$ to preserve surface passivation
- Use of an aromatic matrix material, e.g., PVT as in conventional scintillator
  - Current formulations use PMMA: gives no primary scintillation contribution
  - Now have new protocol to use perovskites with thermally polymerized matrix, with or without additional WLS

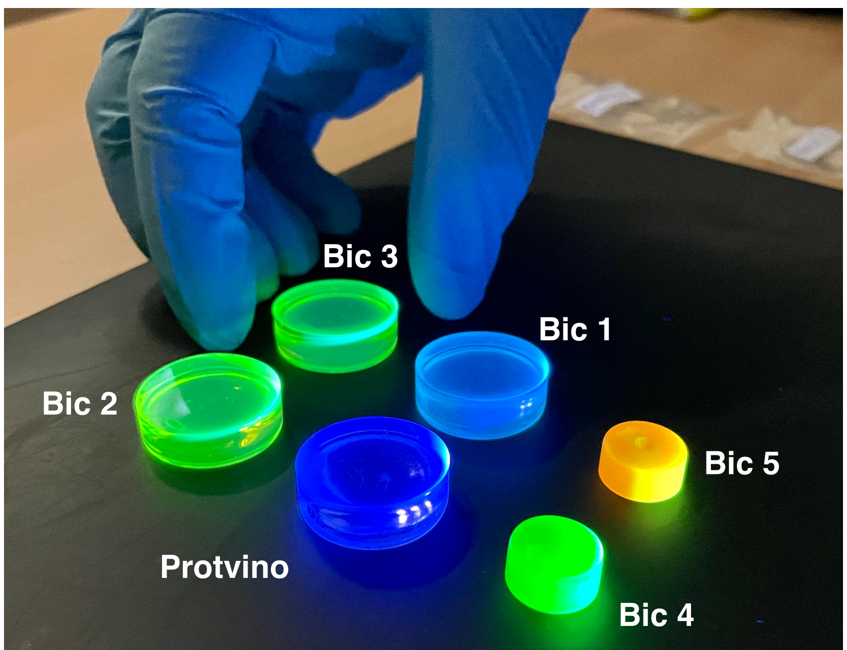
New samples synthesized and tested in fall 2023:
Develop scintillator to test in beam at BTF in spring 2024

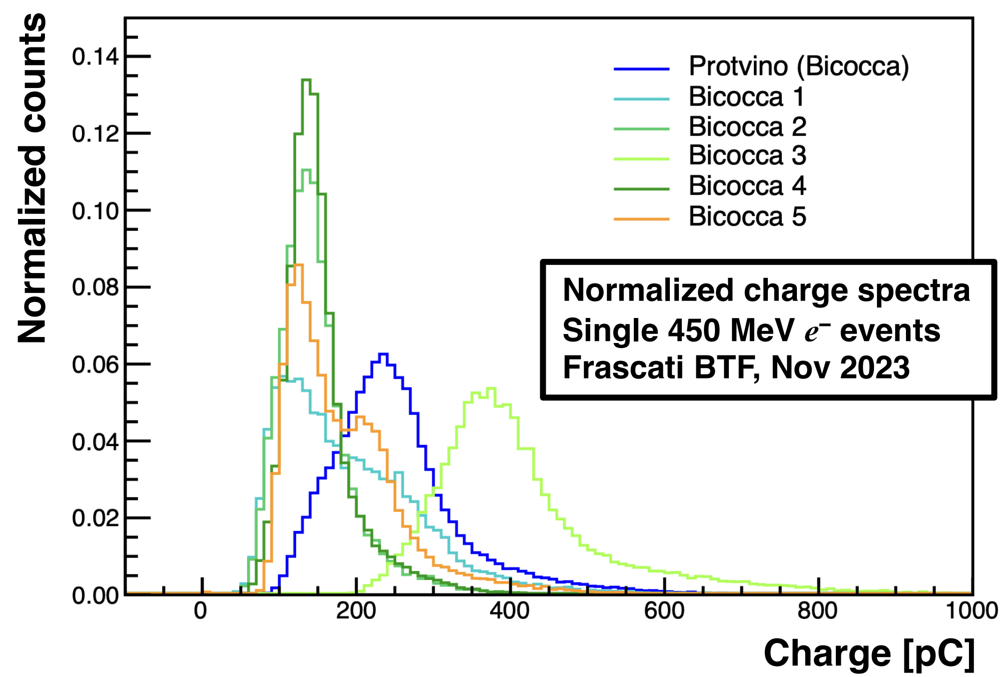
Light yield tests with new samples



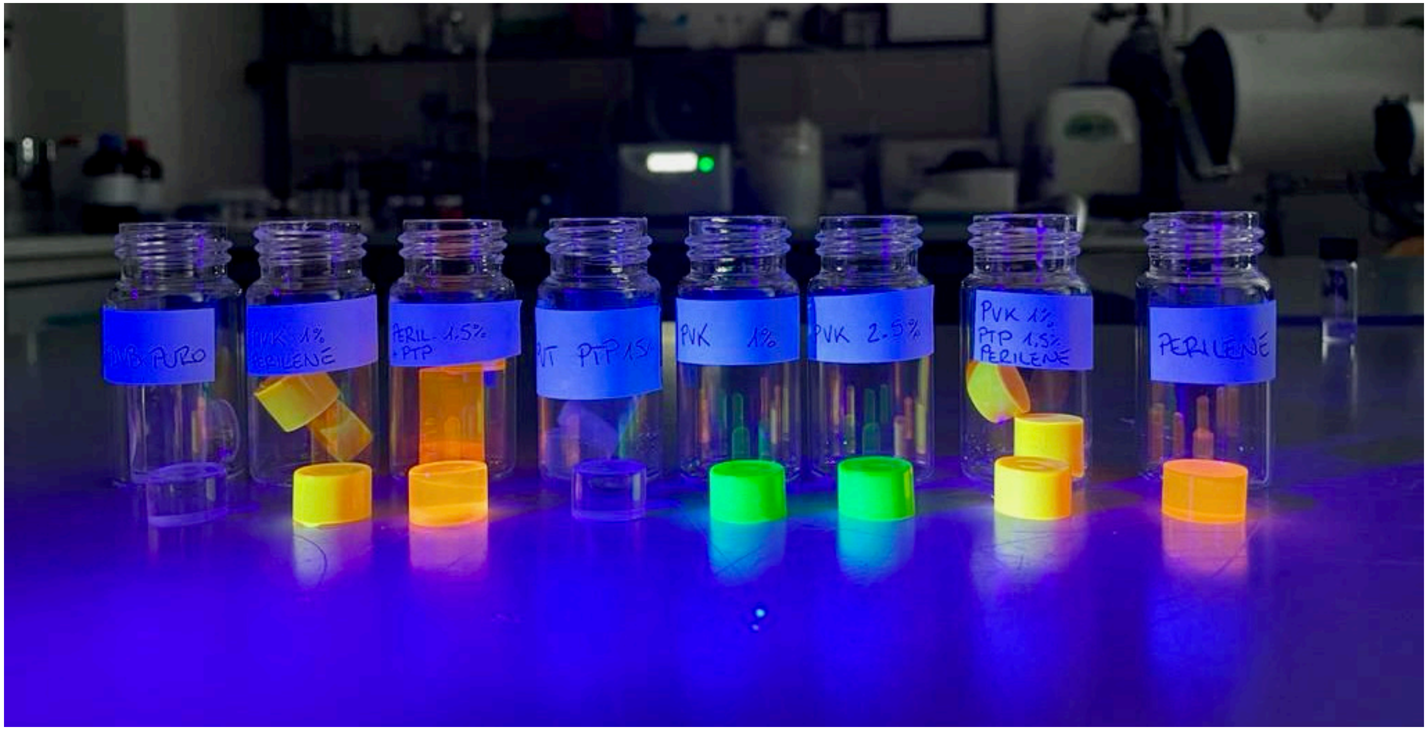
Tests with mip and e^- beams at PS and BTF:

- Reference sample:
  1.5% PTP + 0.04% POPOP in PVT ("Protvino")
- Bicocca 4, 5: $CsPbBr_3$:Yb perovskites in PVT
  ~50% light yield of ref. sample
  Our first nanocomposites with good mip response!
- Bicocca 3: Coumarin-6 in PVT with PTP + BTP
  ~160% light yield of ref. sample!





New scintillators and future directions



New samples with 1-2.5% $CsPbBr_3$:F in PVT with/without additional dyes to be tested at BTF in Feb 2024!

- Surface passivation with fluorine allows use of thermally polymerized matrix (PVT) and higher nanocrystal concentration
- Additional BTF beam time reserved for Apr 2024 if needed (new ideas?)
- Ready to build new prototypes as soon as optimized candidates are ready