HIKE SAC:
Risultati test beam e progetti R&D
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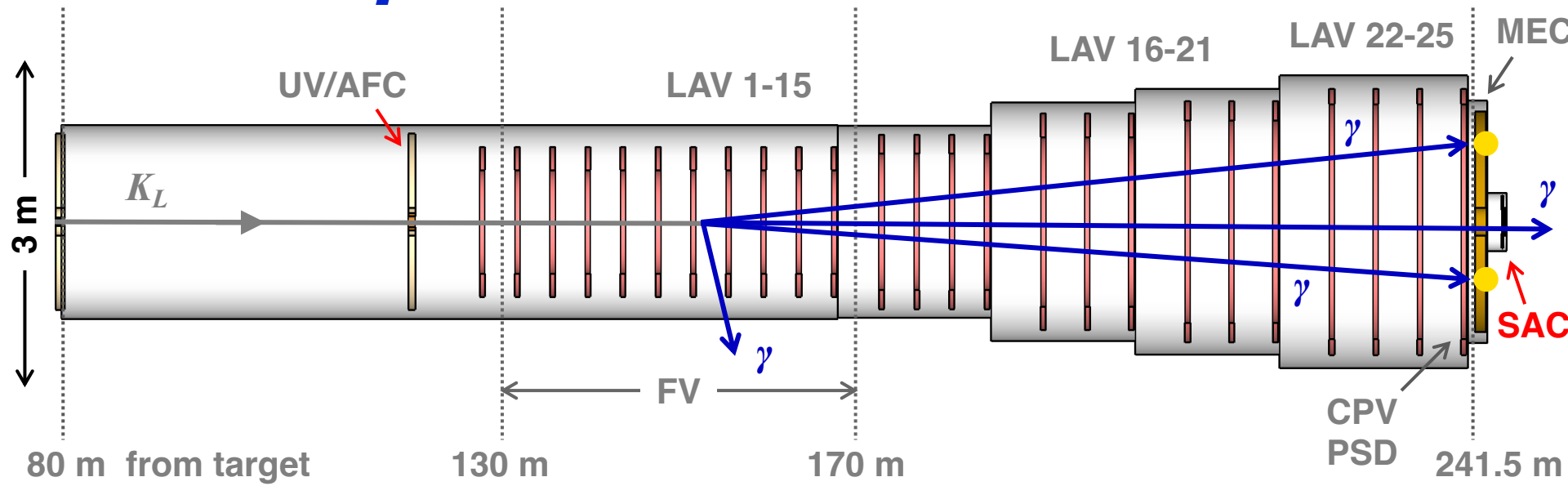
Referee CSN1 – NA62

19 luglio 2024

Small-angle photon veto

HIKE Phase 3: KLEVER BR($K_L \to \pi^0 \nu\nu$) to 20%



Small-angle photon calorimeter system (SAC)

- Rejects high-energy γs from $K_L \to \pi^0\pi^0$ escaping through beam hole
- Must be insensitive as possible to 430 MHz of beam neutrons

Beam comp.	Rate (MHz)	Req. $1-\varepsilon$
γ, $E > 5$ GeV	**50**	**10^{-2}**
γ, $E > 30$ GeV	**2.5**	**10^{-4}**
n	**430**	**–**

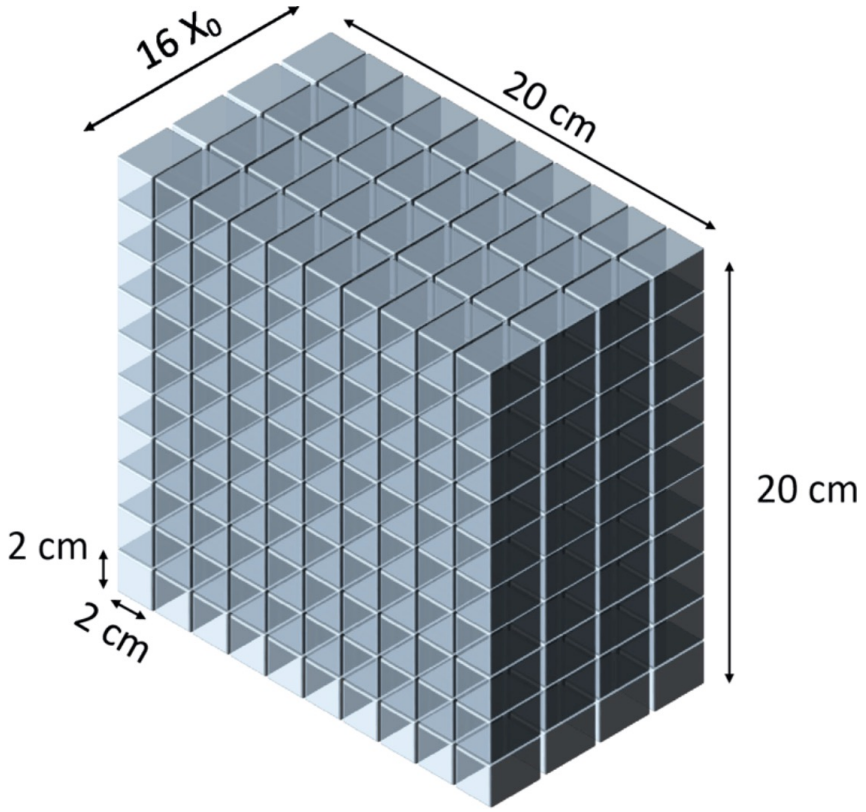
Baseline solution:

- **Ultra-fast heavy Cerenkov calorimeter (e.g. PADME, g-2)**

A Cerenkov SAC for HIKE

Proposed solution:
Ultra-fast, heavy Cerenkov calorimeter

- σ_t < 100 ps, 2-pulse separation ~ 1 ns
- Optimize choice of crystal
- Optimize choice of photodetectors
- Study response to neutral hadrons
- Verify radiation hardness to 10^{13}-10^{14} n/cm^2 and 10^5-10^6 Gy
- Possibilities for γ/n discrimination: multilayer structure/longitudinal segmentation
- Explore idea of exploiting coherent interactions in crystals to reduce thickness



Overview of R&D directions

CRILIN

Highly granular, longitudinally segmented PbF_2 calorimeter independently proposed at LNF for Muon Collider

Collaboration with CRILIN to study:

- Materials: PbF_2 vs PWO-UF
- Radiation resistance of crystals
- Photosensors: SiPMs, front-end
- Light collection in small crystals
- Longitudinal segmentation
- Mechanics, cooling, integration

OREO

CSN5 project to develop proof of concept for calorimeter with aligned crystals, inspired in large part by needs of HIKE SAC

Collaboration with OREO to study

- Enhanced interactions in single crystals with alignment
- Techniques for crystal characterization
- Techniques for crystal alignmnent
- Performance of aligned planes

Design for HIKE SAC

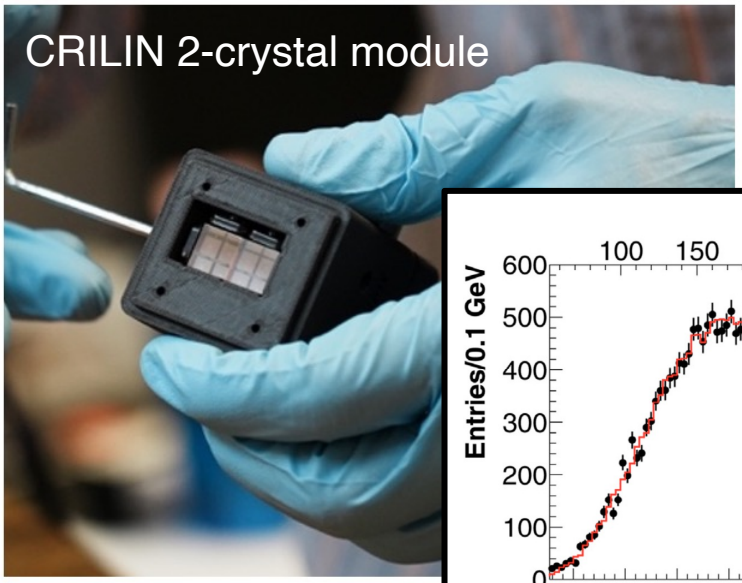
HIKE members share resources with and participate in CRILIN and OREO
CRILIN and OREO members have signed the HIKE proposal

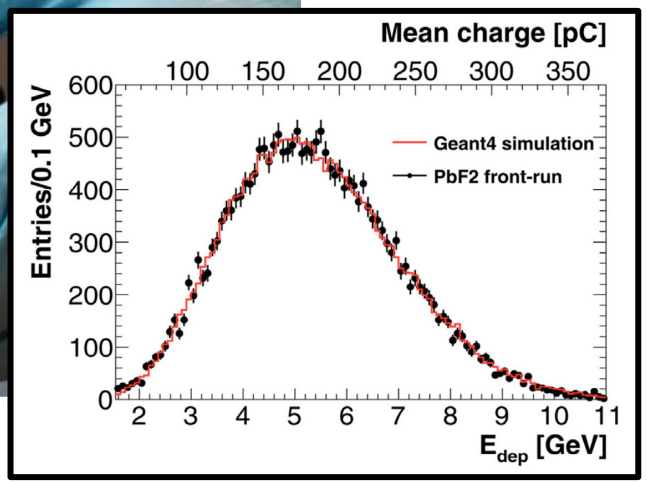
CRILIN people are non-signing members of the NA62 Collaboration
OREO people are full members of the NA62 Collaboration

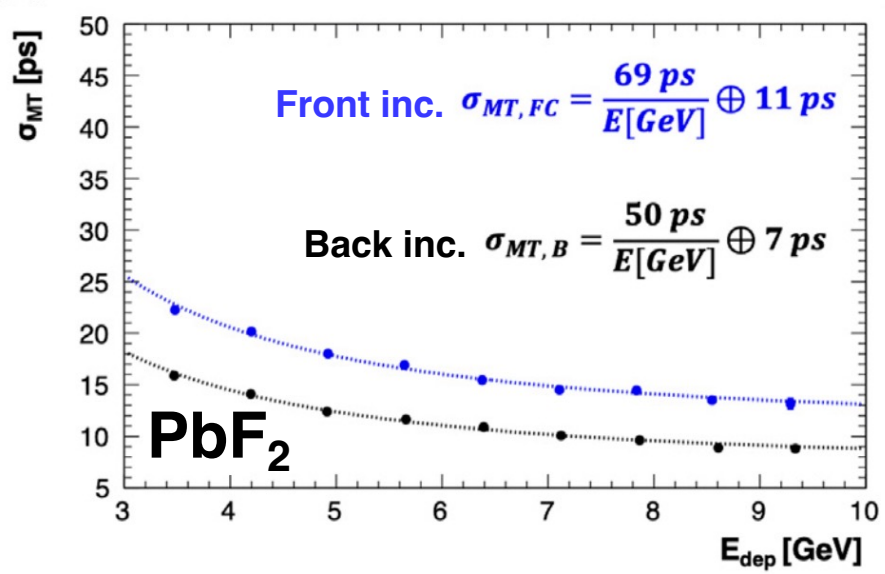
Tests with single crystals, fall 2022

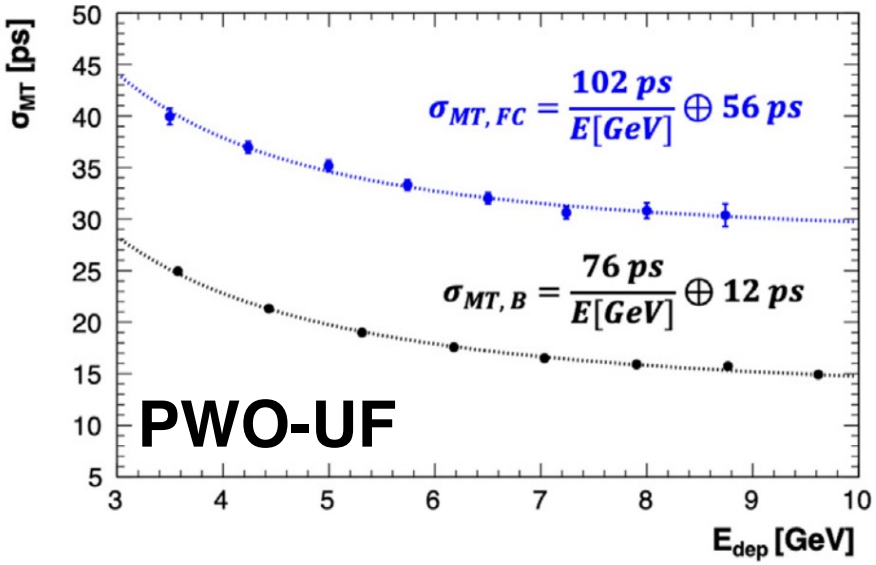
Front. Phys. 11 (2023) 1223183

- SPS H2 beamline: 20-120 GeV e^- and MIPs (150 GeV π)
- Validate CRILIN readout electronics
- Measure light yield and time resolution
- Study systematics of light transport in small crystals with high n

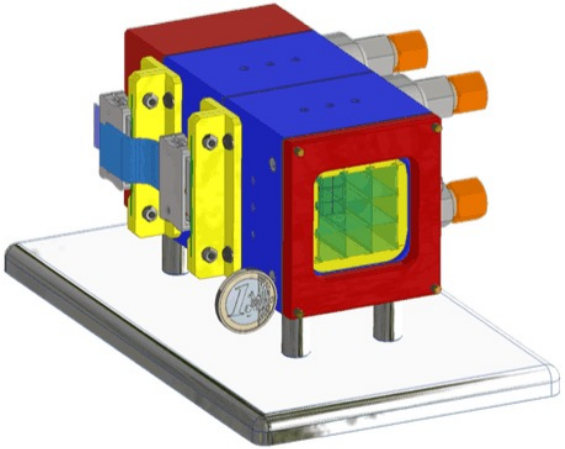


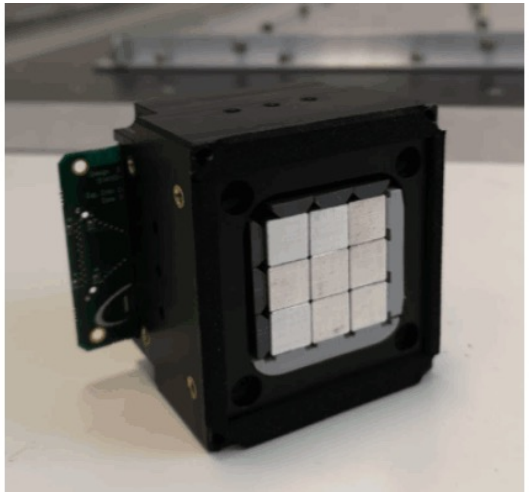


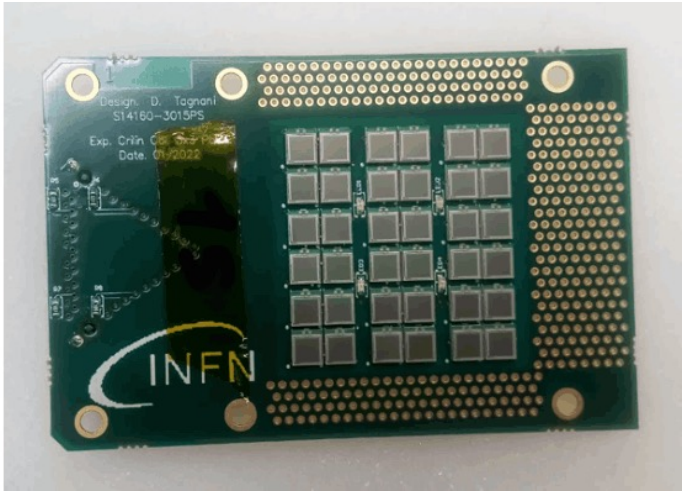




Tests of CRILIN 3x3x2 prototype: 2023-24



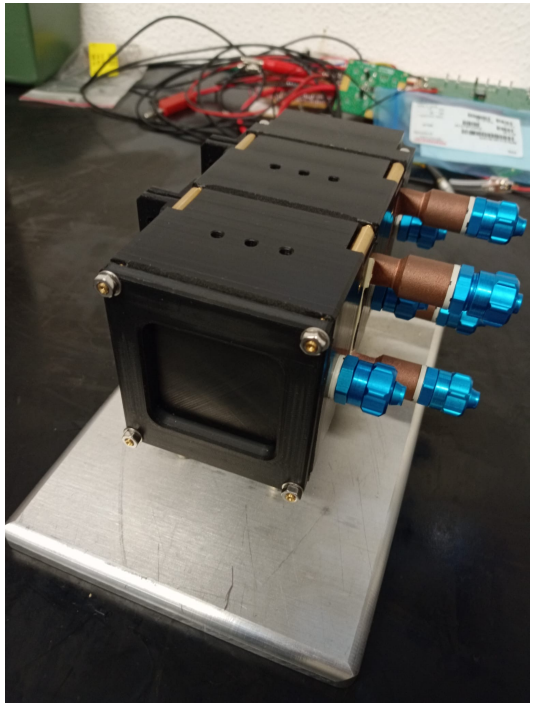




Two 3x3 CRILIN test layers, with PbF_2 and PWO-UF

Test objectives for 2023 and 2024:

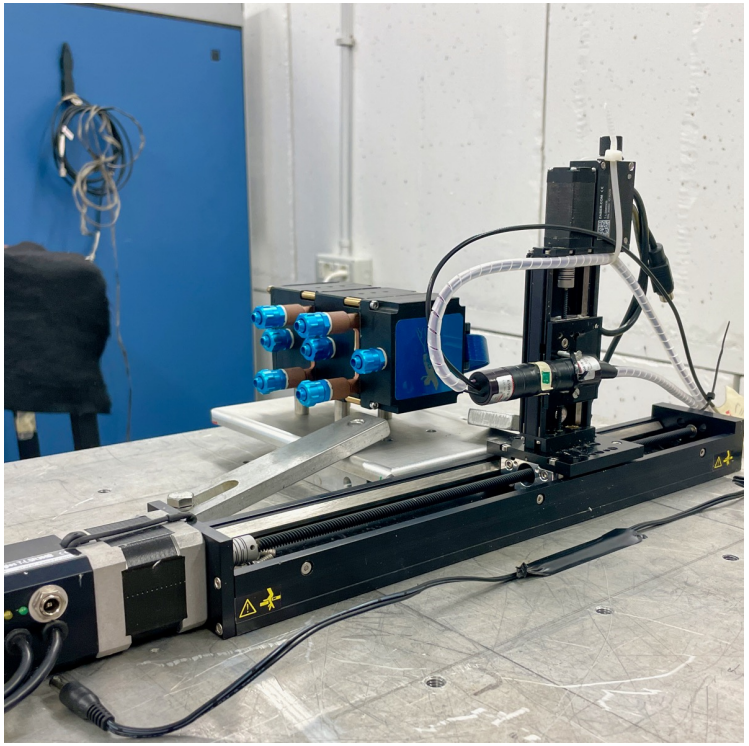
1. Perform complete operational test, including readout electronics (series vs parallel connection)
2. Test different crystal materials and surface treatments, to damp internal reflections
3. Conceptual test of longitudinal segmentation
4. Test cluster reconstruction capability and measure time resolution
5. Expose prototype to radiation and study effects



CRILIN test beam program 2023-2024

Jun 2023 **PS T9**	Parasitic to NanoCal First functional test of 3x3x2 prototype
Jul 2023 **BTF**	First complete test of 3x3x2 prototype Studies of crystal wrapping/surface finish
Aug 2023 **SPS H2**	Shared beam time with OREO Test of 3x3x2 prototype at high energy Time resolution measurements
Oct 2023 **PS T9**	Shared beam time with OREO Study effect of crystal alignment on time resolution and Molière radius: ***data corrupted by bad digitizer***
Apr 2024 **BTF**	Measure performance pre- and post-radiation at ENEA Calliope facility
Sep 2024 **PS T9 *scheduled***	Study effect of crystal alignment on time resolution and Molière radius
Nov 2024 **PS T10 *requested***	First test of next generation CRILIN 3x3 prototype Possible test of HIKE design with PMT readout

CRILIN test at BTF, Jul 2023



03-10 July

- 3x3x2 CRILIN module
- 450 MeV single e^-
- 50 ps trigger

Configurations tested (front + back)

PbF_2	• polished + black + mylar • matte + mylar • matte + teflon
PWO-UF	• polished + ESR

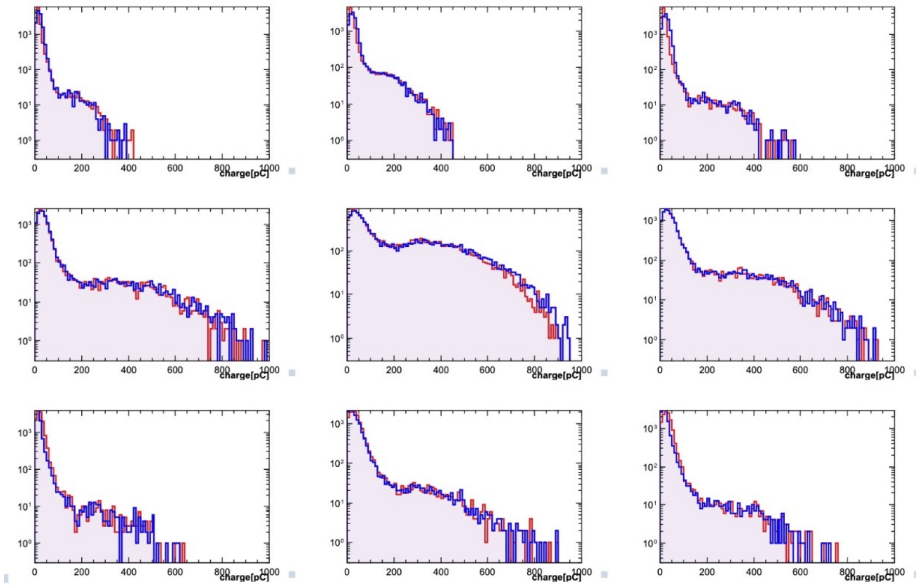
CRILIN equalization

Equalization verified "out of the box" in Jul/Aug 2023

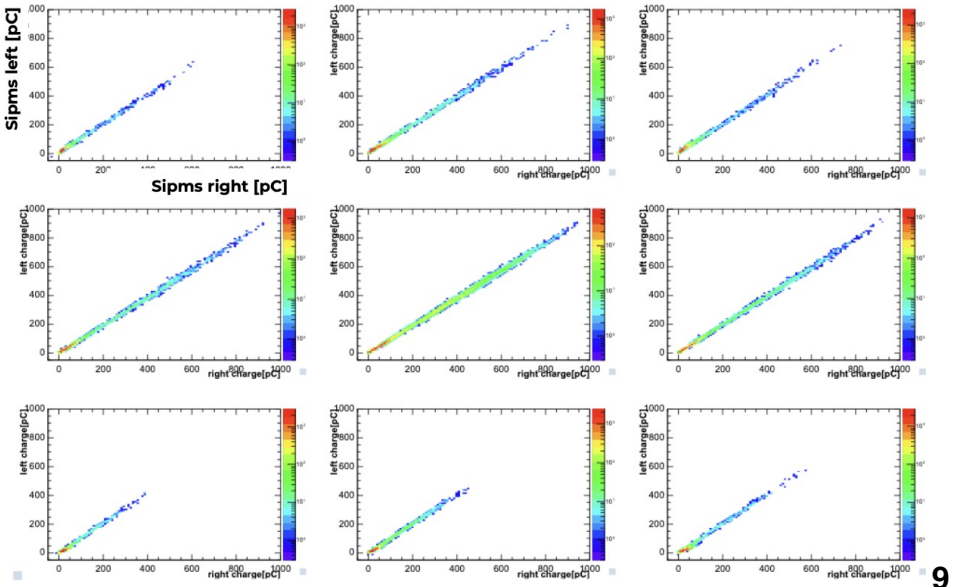
SiPMs from the same lot were requested when ordered from Hamamatsu and delivered with V_{br} measured uniform to within < 0.1V

No dedicated equalization procedure was needed

Charge spectra for SiPMs L & R



L/R charge correlations



CRILIN test at BTF

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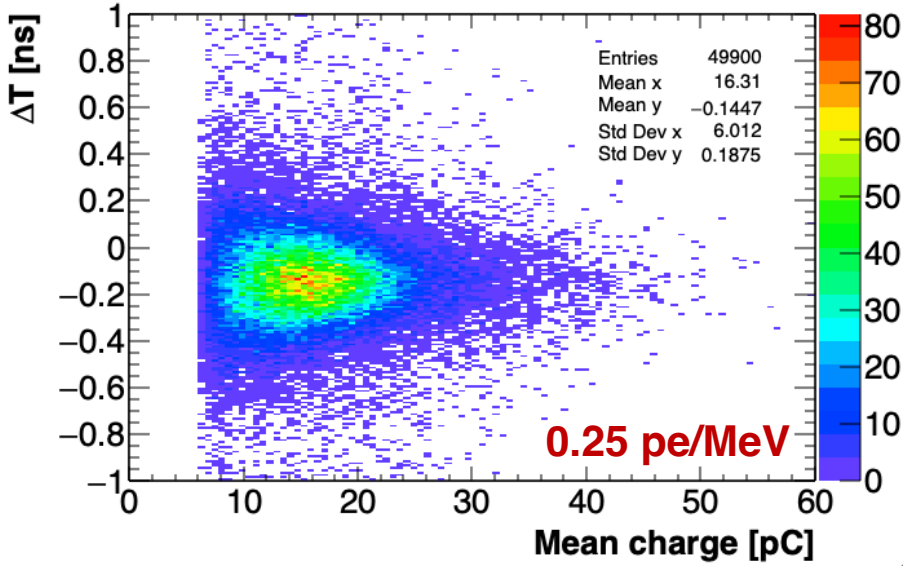
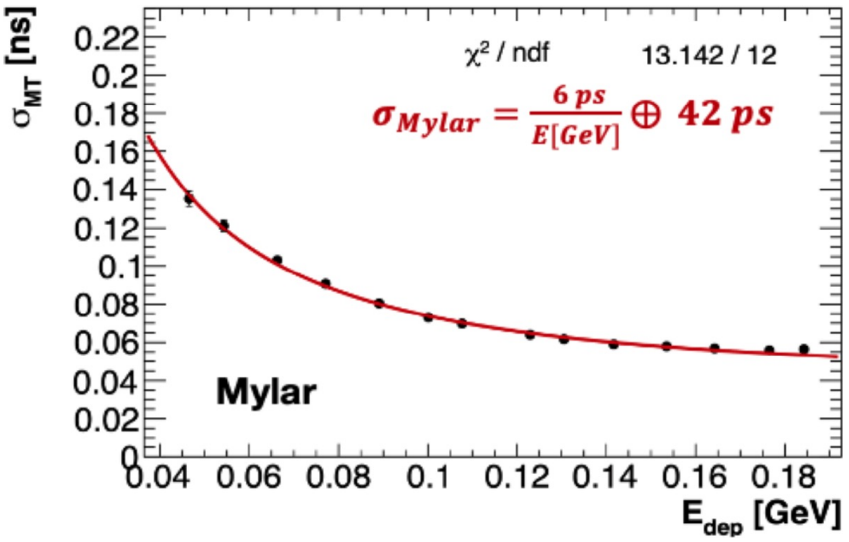
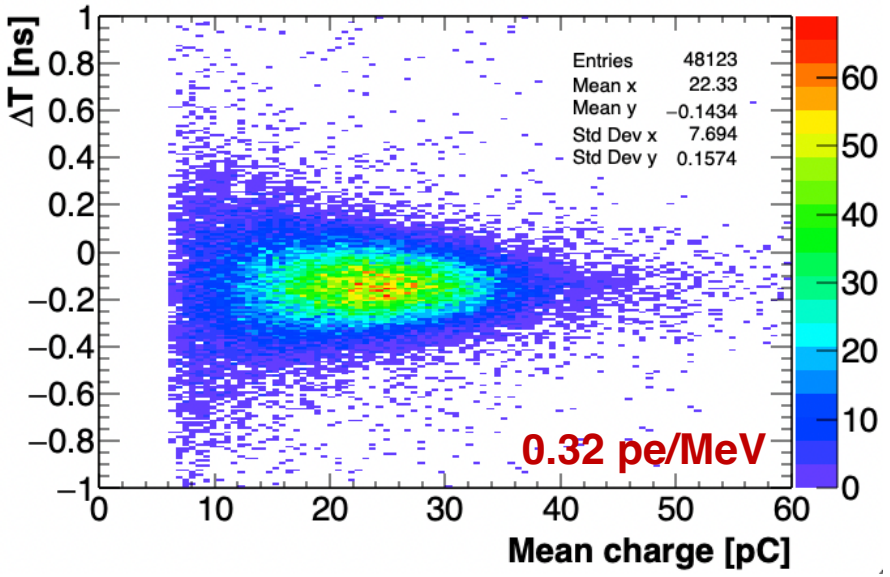
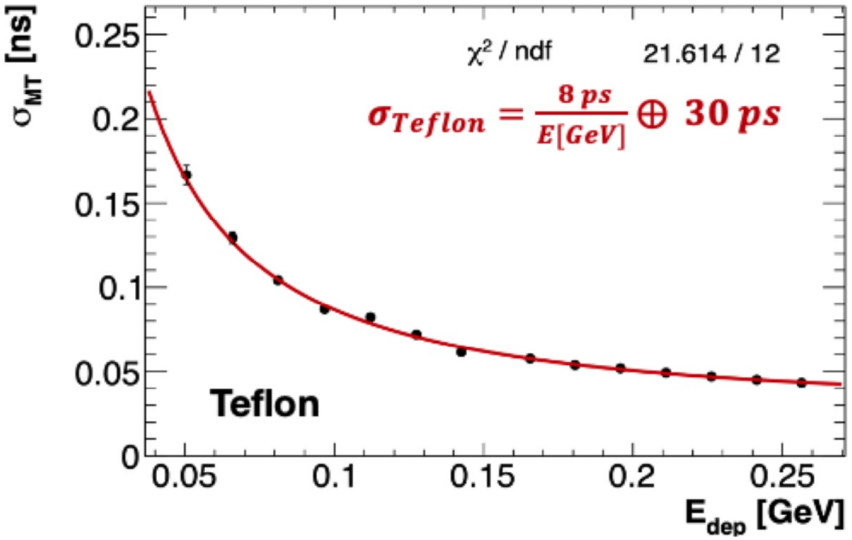
Mylar wrapping





Teflon wrapping

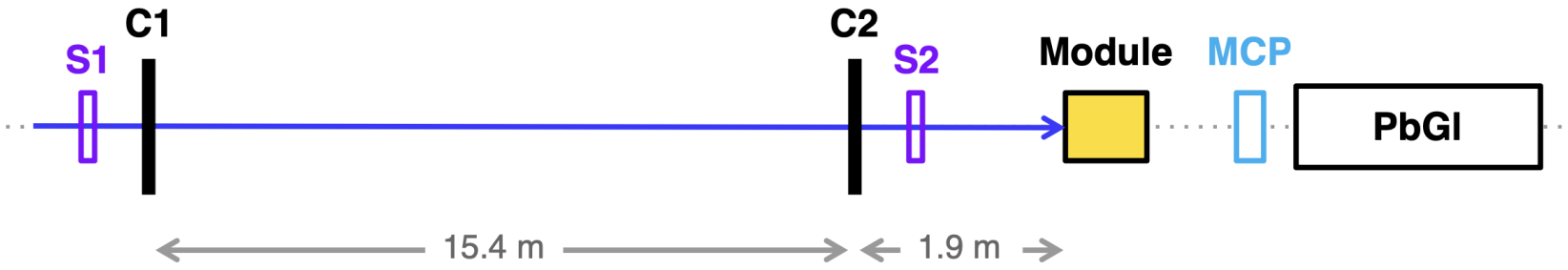




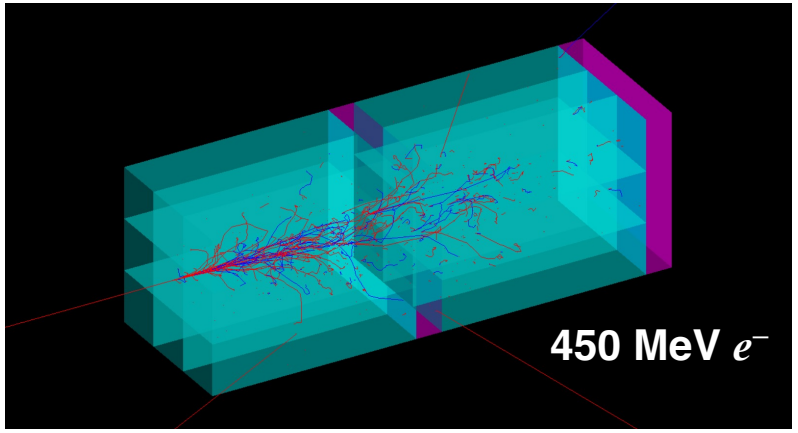
CRILIN test at H2: Aug 2023

1 week (16-23 Aug) split with OREO to allow alignment studies at H2

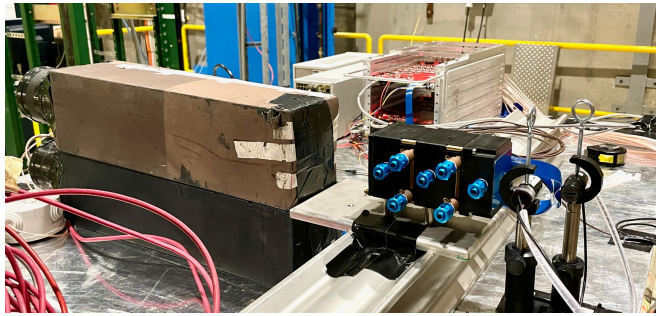
For CRILIN, use similar setup to 2022 run to test same configurations as in BTF (PbF_2, PWO-UF) with **20-120 GeV e^-** and **150 GeV mips**

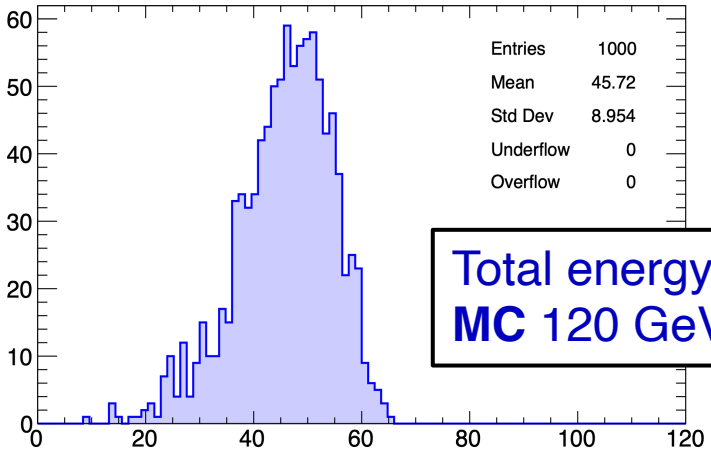


Meanwhile, complete MC developed for comparison to data taken at BTF and in H2

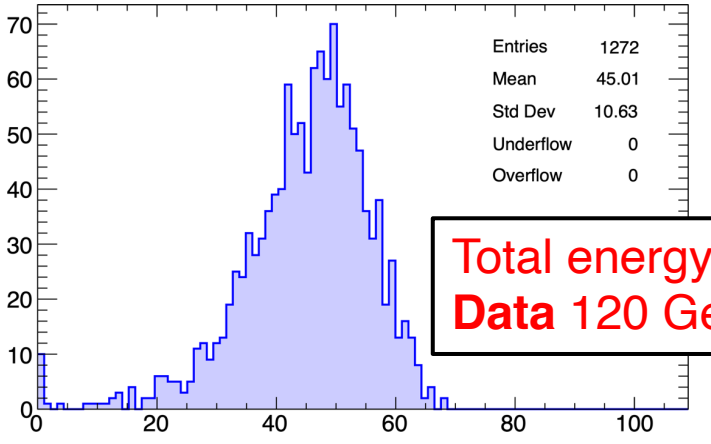


CRILIN validation



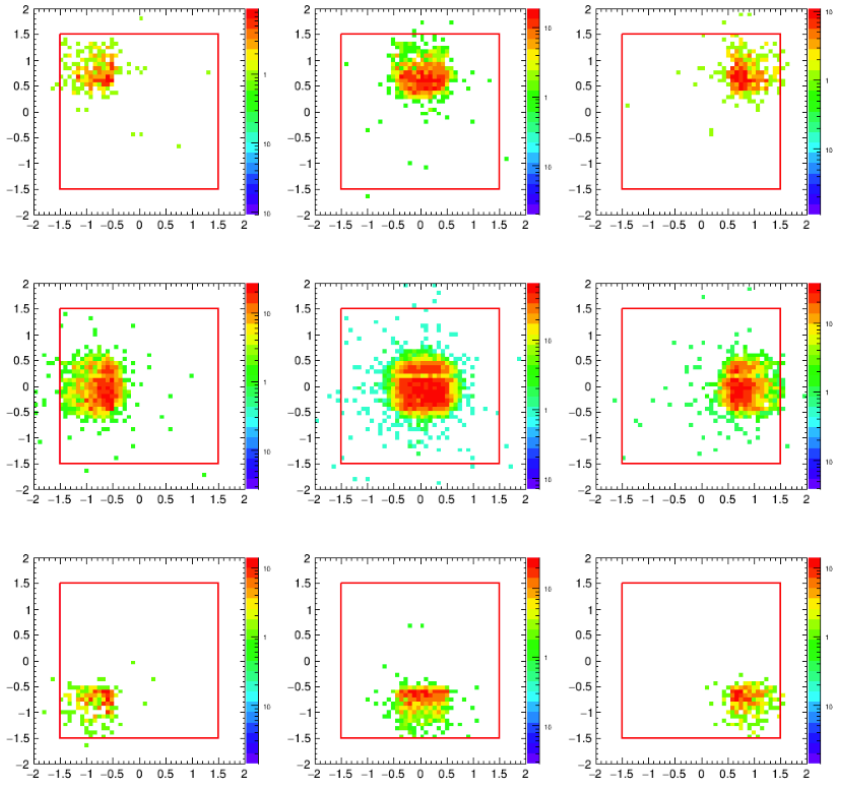


Total energy
MC 120 GeV e^-

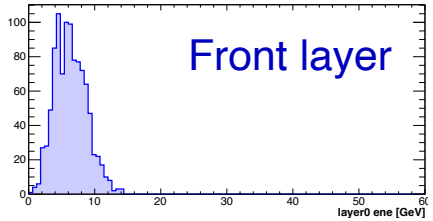


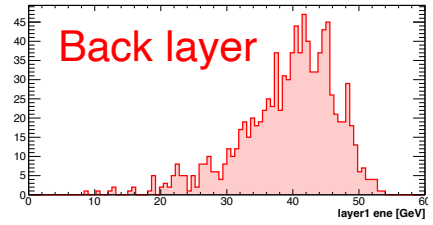
Total energy
Data 120 GeV e^-

Tracking data with cuts on each crystal

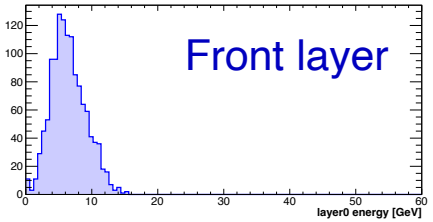


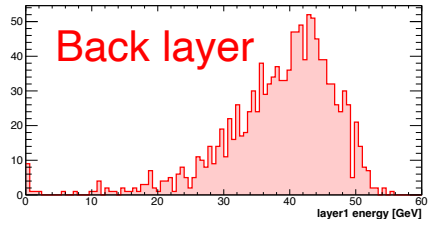
MC 120 GeV e^-



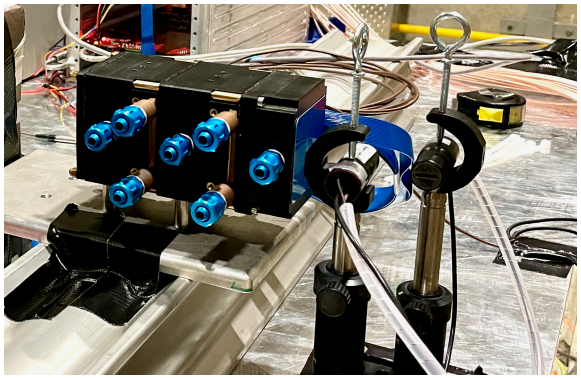


Data 120 GeV e^-

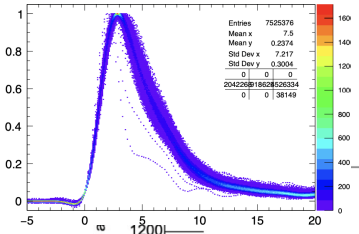


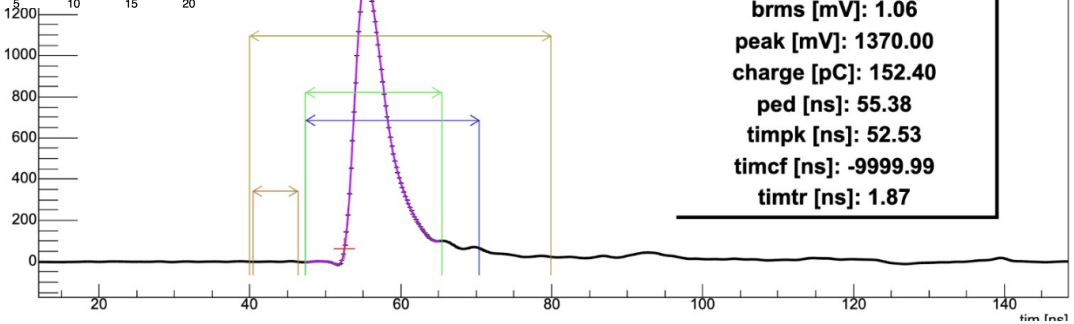


Reference t_0 and synchronization

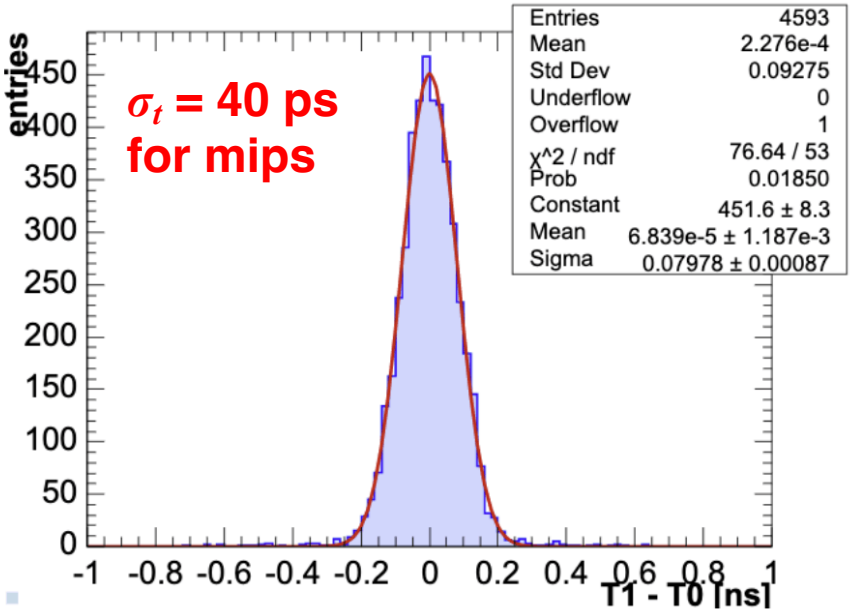


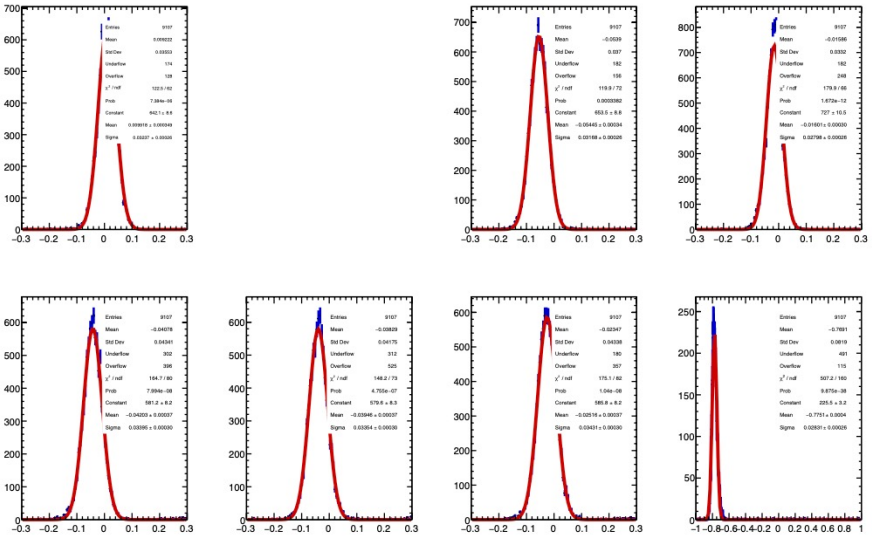
t_0 counter ("Cindy"):
Coincidence of 2 R9880 PMTs with 1 cm^3 fast scintillator





Waveform analysis and fitting same as for analysis of CRILIN signals

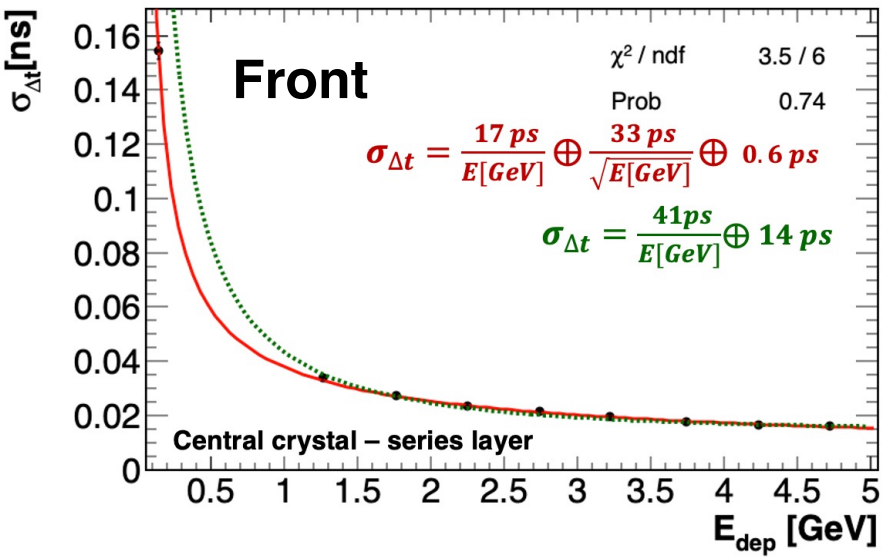




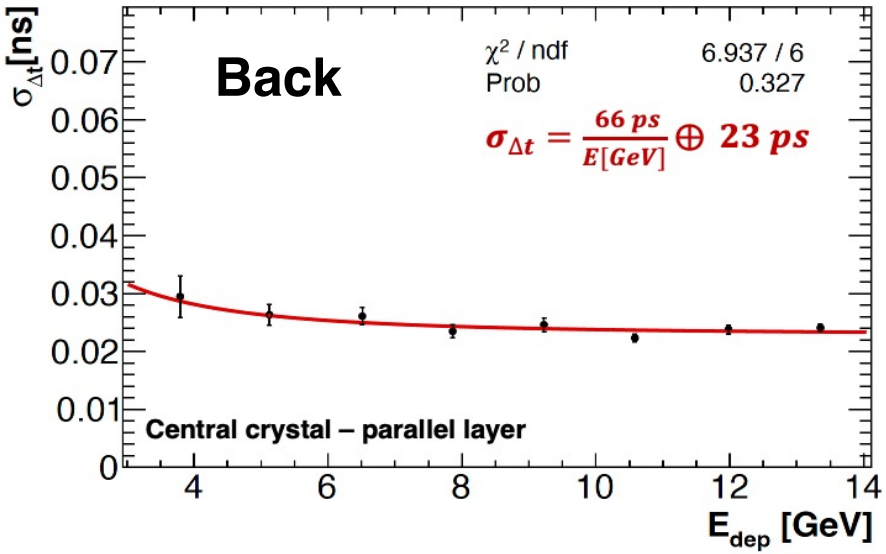
Synchronization between ADCs on V1742 by digitizing fast-trigger input

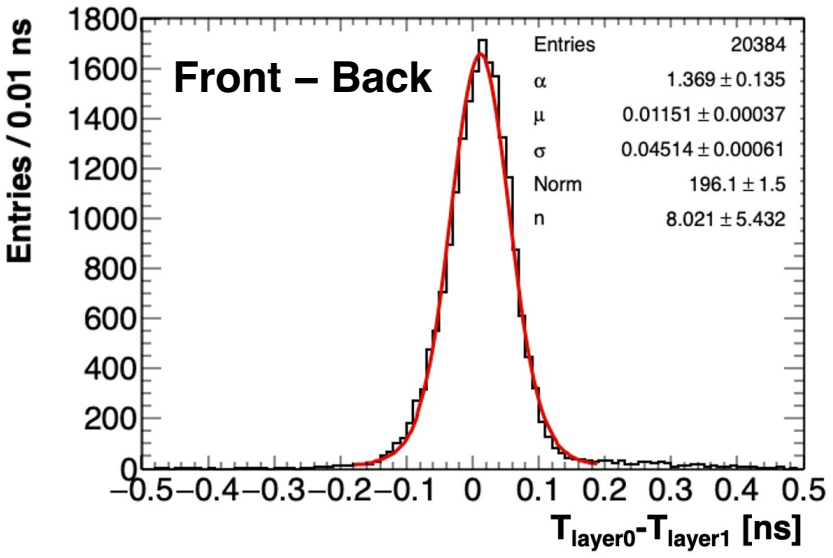
CRILIN time resolution

E. Di Meco, Pisa Meeting (in press)

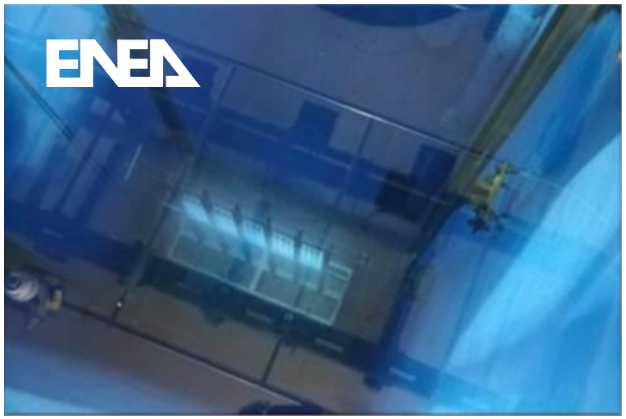


- Time resolution of **O(20 ps)** both in series (front) and parallel (back) layers using 2-channel time difference for central crystals
- Excellent results using most energetic crystal of different layers
- Time resolution dominated by the 2-board synchronisation jitter O(32ps)





Radiation hardness of PbF_2 and PWO-UF

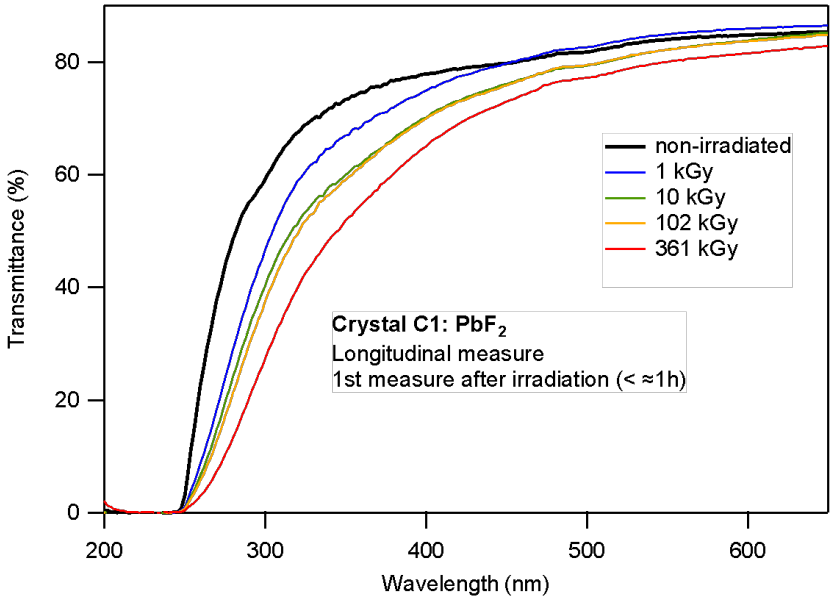


^{60}Co γ-irradiation tests at Calliope, ENEA Casaccia

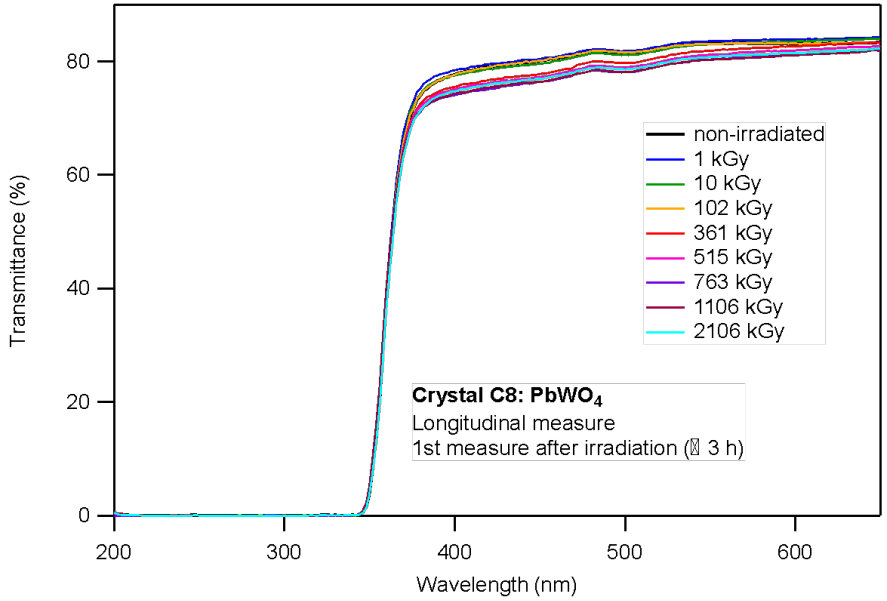
- Easy to accumulate MGy doses, full dosimetry support
- Support with transmission, light yield, fluorescence spectrometry measurements

Tests conducted April-May 2023 in collaboration between CRILIN and Calliope staff

PbF_2 irradiated to 361 kGy



PWO-UF irradiated to 2106 kGy!



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Radiation hardness of PbF_2 and PWO-UF

Expected SAC ionizing radiation dose: **10^5-10^6 Gy**

Expected SAC neutron fluence: **10^{13}-10^{14} *n*/cm^2 1 MeV eq**

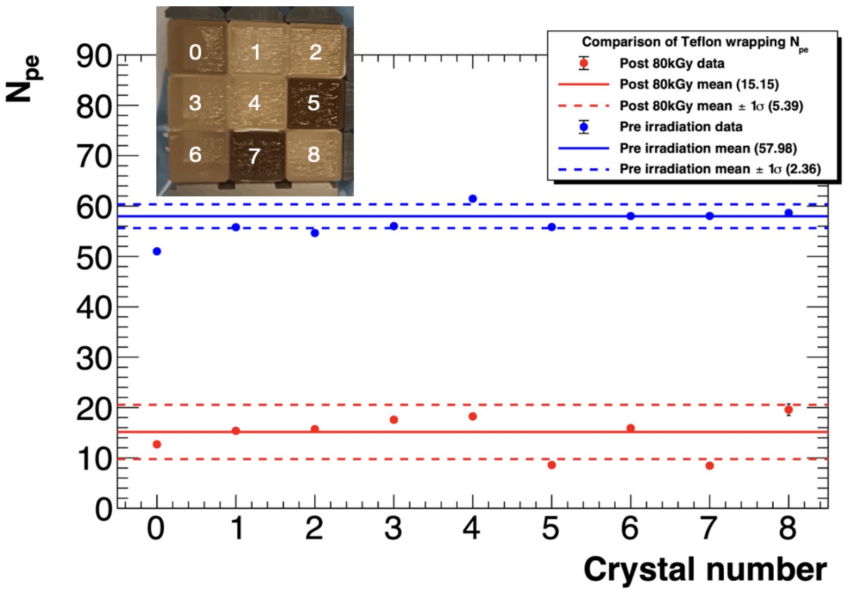
Preliminary conclusions:

- PbF_2 shows increased transmission threshold at low wavelength already at 10^4-10^5 Gy
- Blue-green transparency for PbF_2 can be recovered by exposure to blue light (e.g. natural light for several days)
- PWO-UF shows no shift in low-wavelength threshold and only ~2% loss of blue-green transparency even at 2 MGy!
- PWO-UF ionizing radiation robustness more than sufficient for SAC: next need validation with neutrons (protons)
- Czochralski-grown PWO (Crytur) is of high quality. Literature suggests that Bridgeman-grown PWO (SICCAS) may have inferior radiation hardness, requiring separate validation.

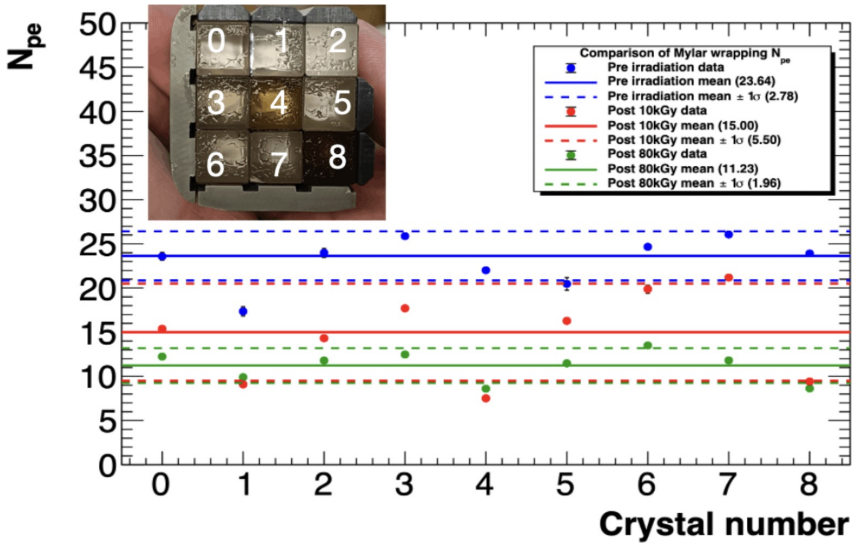
Irradiation beam test at BTF, Apr 2024

- Irradiation tests with two different wrappings
- Entire prototype exposed to γ rays up to 80 kGy at ENEA Calliope in each case
- Crystal by crystal characterization with 450 MeV e^- from BTF before and after irradiation

Teflon



Mylar

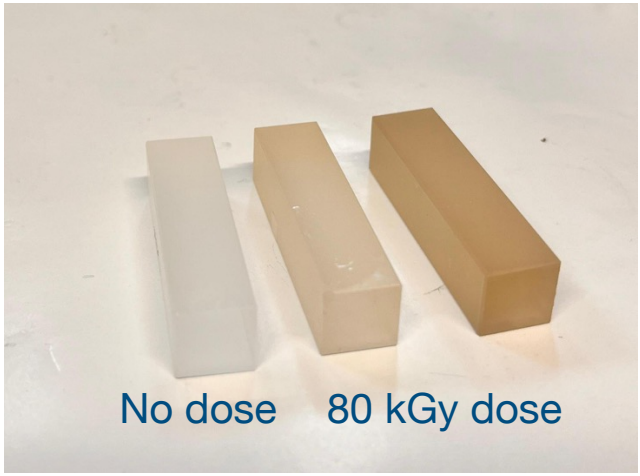


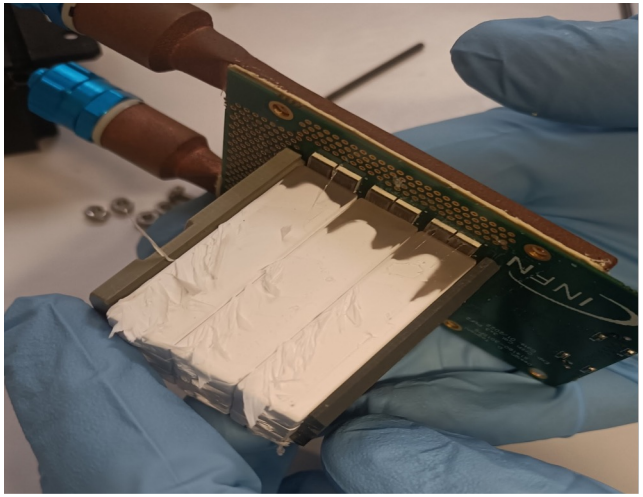
E. Di Meco, Pisa Meeting (in press)

Irradiation beam test at BTF, Apr 2024

In this batch, **major transparency loss was observed at doses as low as 10 kGy**

- Evident loss of transparency
- Transparency loss uniform over length of crystals
- **Considerable variability in response of individual crystals to radiation,** despite SICCAS claiming use of high-purity (>99.9%) PbF_2 powder for crystal growth
- Teflon was damaged and brittle
- SiPM dark counts increased significantly with absorbed dose
- New tests planned to evaluate loss of PDE for SiPMs and degradation of other components (e.g., optical grease)
- **Confirmation of choices of PWO-UF and PMT readout for HIKE SAC**

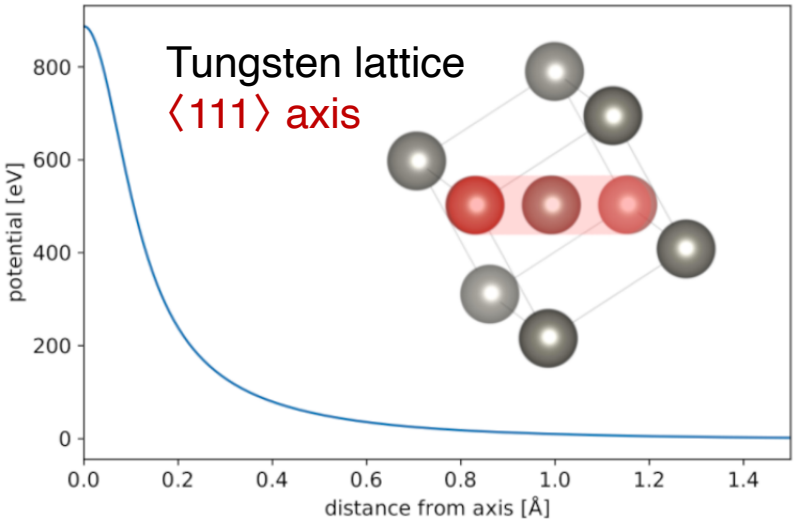




Coherent effects in crystals

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

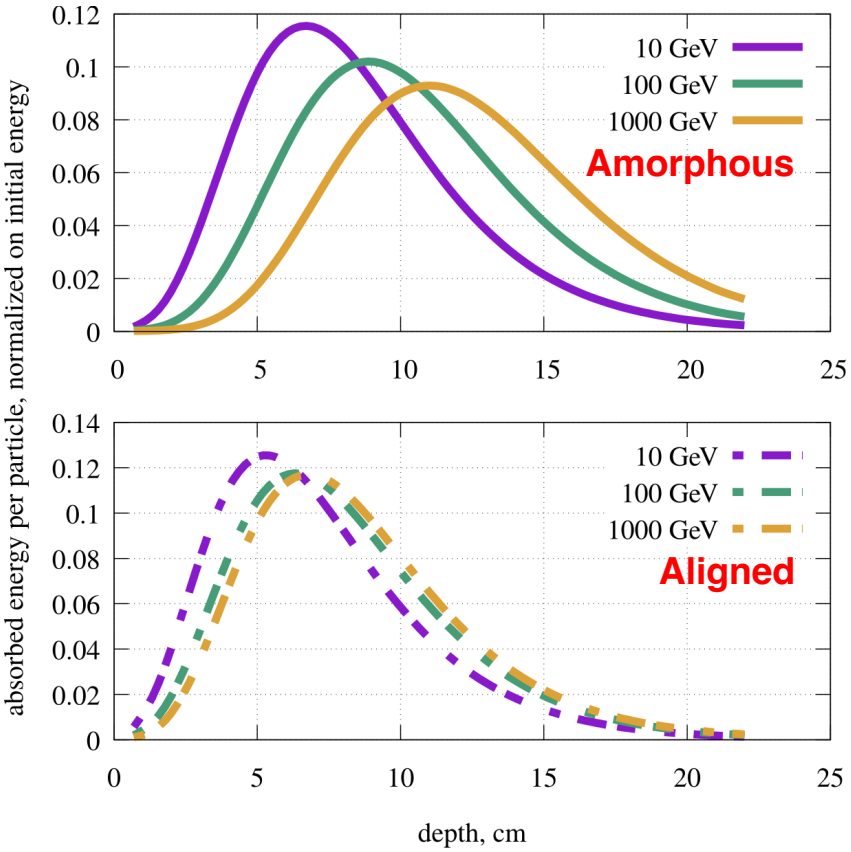
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

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

Bandiera et al., NIMA 936 (2019)

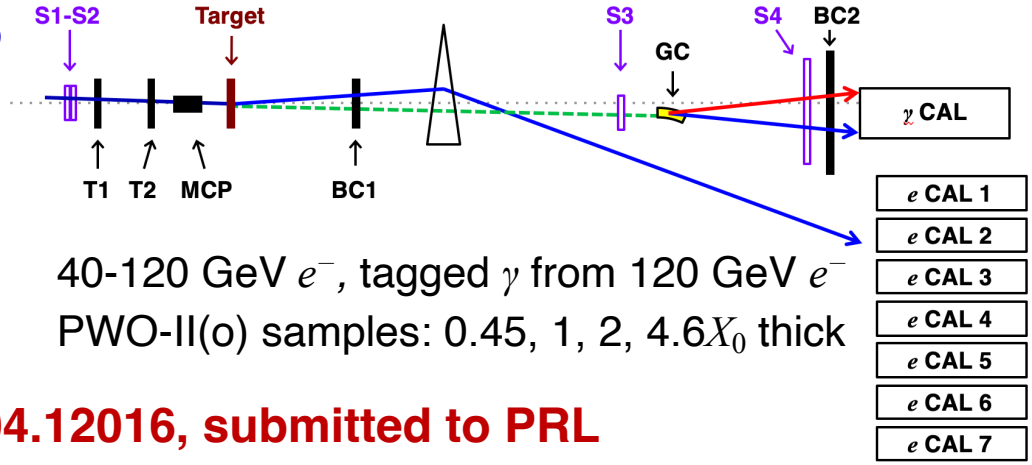


- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

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

Previous tests with aligned crystals

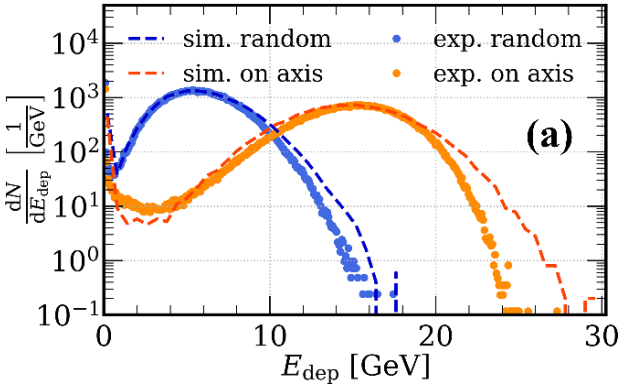
Many studies done by precursors to OREO (AXIAL, STORM) with NA62 participation (KLEVER), 2018-2022

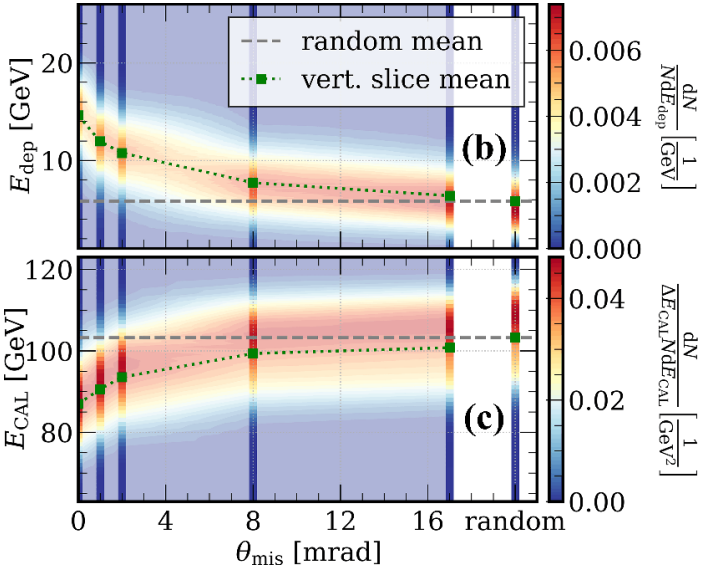


40-120 GeV e^-, tagged γ from 120 GeV e^-

PWO-II(o) samples: 0.45, 1, 2, 4.6X_0 thick

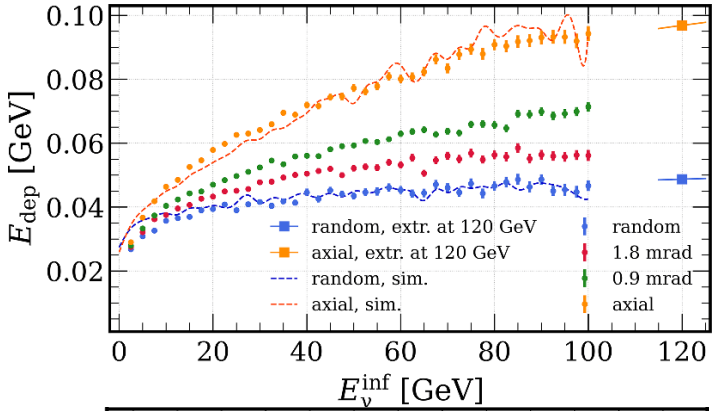
E_{dep} vs angle, 120 GeV e^- on 4.6X_0



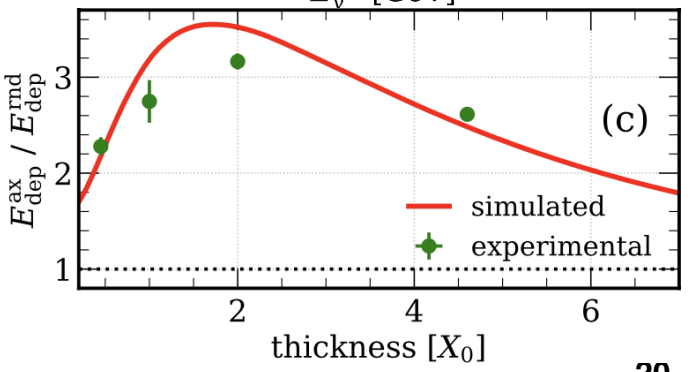


2404.12016, submitted to PRL

E_{dep} vs E_γ
Tagged γ from 120 GeV e^- on 1X_0



E_{dep} vs thickness
120 GeV e^-

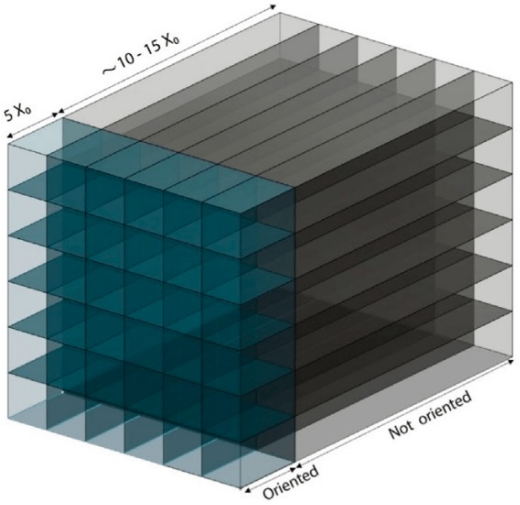


OREO: An oriented-crystal calorimeter

Exploit coherent interactions in crystals to develop a highly compact calorimeter

E.g. Small-angle calorimeter for HIKE:

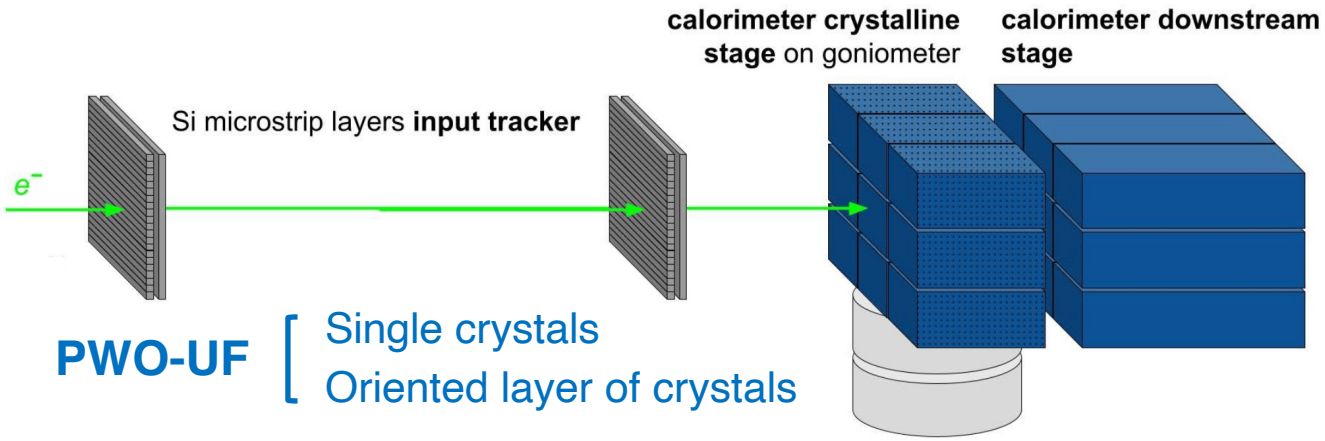
Require good response to photons, high transparency to neutrons

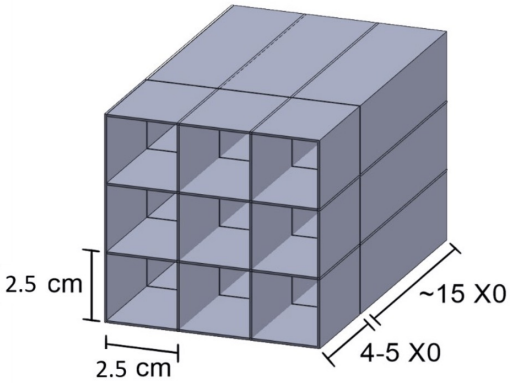


Areas of R&D:

- Development of techniques for crystal characterization, shaping, alignment and assembly
- Development of mechanics, SiPM readout, interface, and front-end

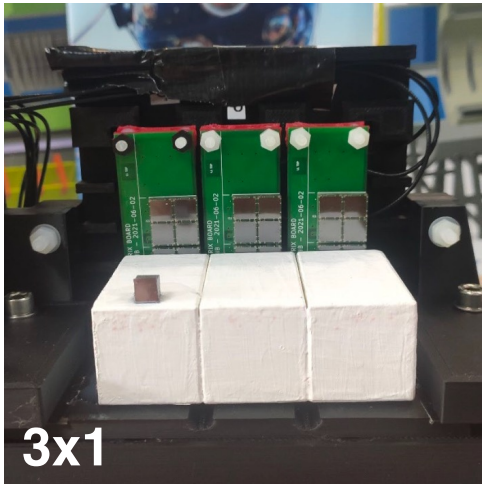
OREO prototype and test beam setup:

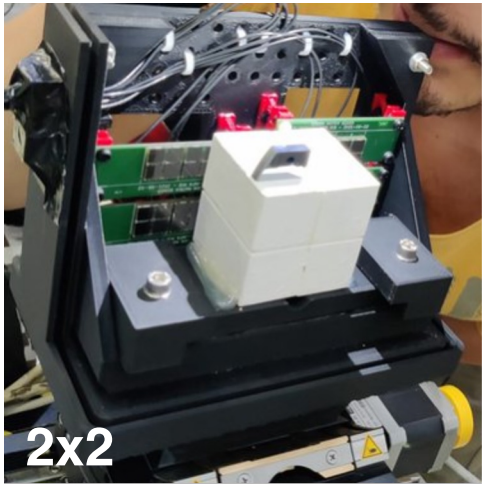


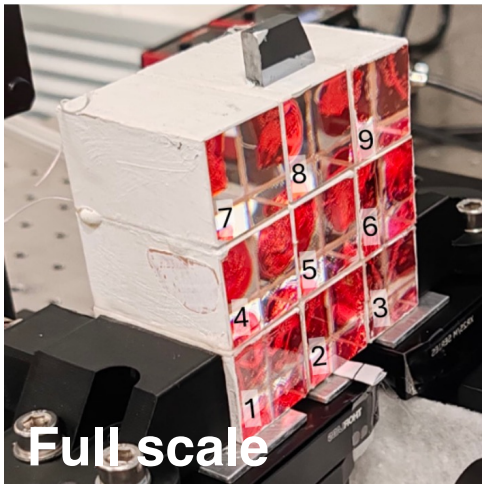


OREO test beam program 2023-2024

Aug 2023 **PS T9** **SPS H4**	Beam test of 3x1 crystal array 2 weeks at T9 (low energy, shared with others) 1 week at H4 (high energy, shared with CRILIN)
Oct 2023 **PS T9**	Beam test of 2x2 crystal array at low energy 1 week, shared with CRILIN
Jun 2024 **PS T9**	First test of full-scale OREO prototype at low energy 1 week validation at BTF in May 2024
Jul 2024 scheduled **SPS H4**	First test of full-scale OREO prototype at high energy Slot recently freed in SPS schedule 1 week, dedicated
Sep 2024 scheduled **SPS H4**	Test of full-scale OREO prototype at high energy 1 week, dedicated







Techniques for crystal characterization

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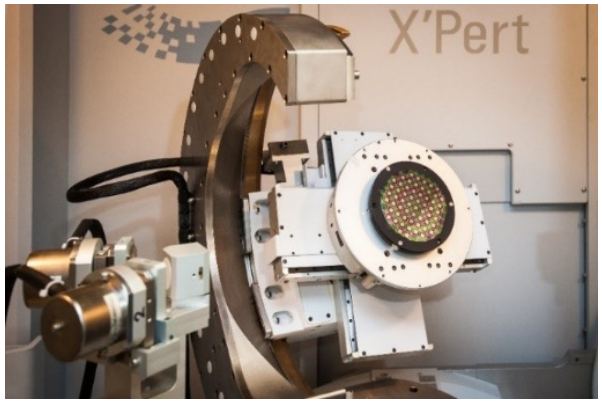
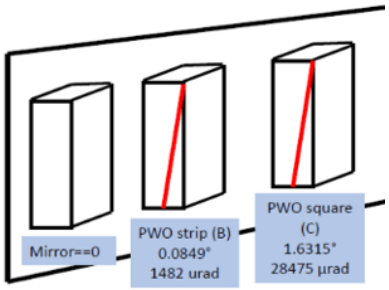
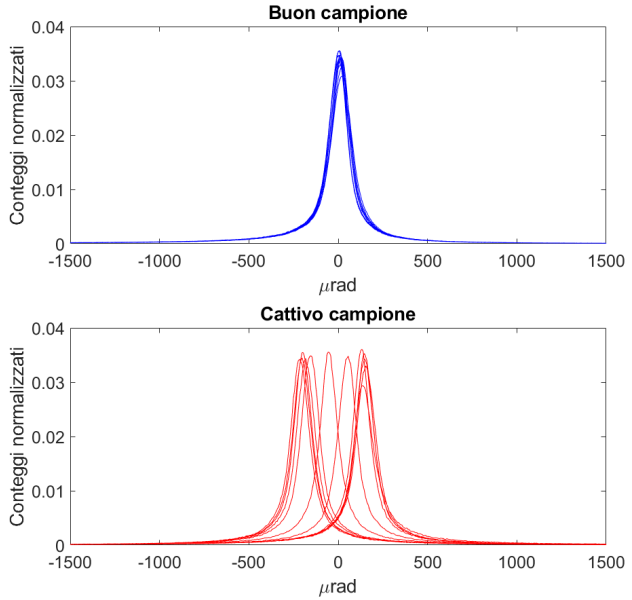
X-ray diffraction (Ferrara)
HR-XRD 8 keV



Measurement of axis inclination relative to face



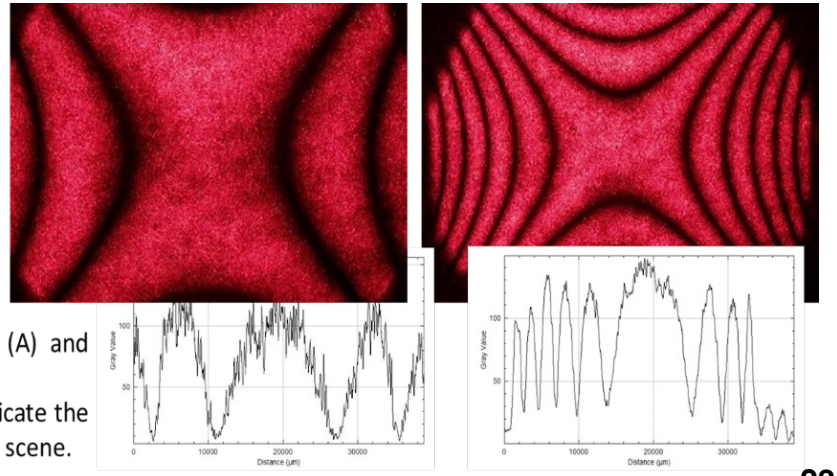
Surface scan of orientation



Photoelasticity measurements
Laser conoscopy (Ancona)

Internal stresses in crystal change polarization

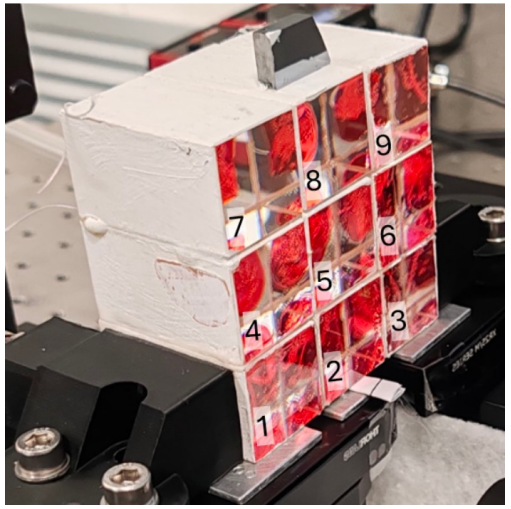
Fringe order and symmetry contain information on crystallographic orientation and quality

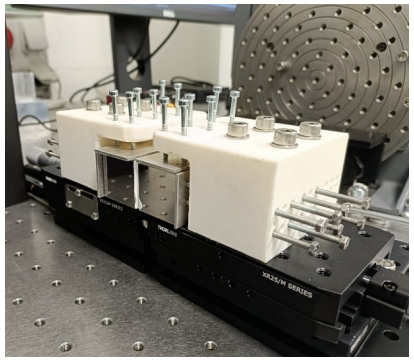


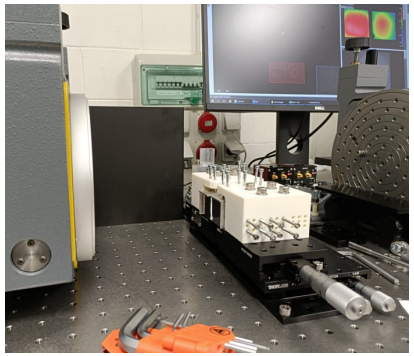
Typical image from face 4 (A) and face 1 (B).
The minima in the plots indicate the position of the fringes in the scene.

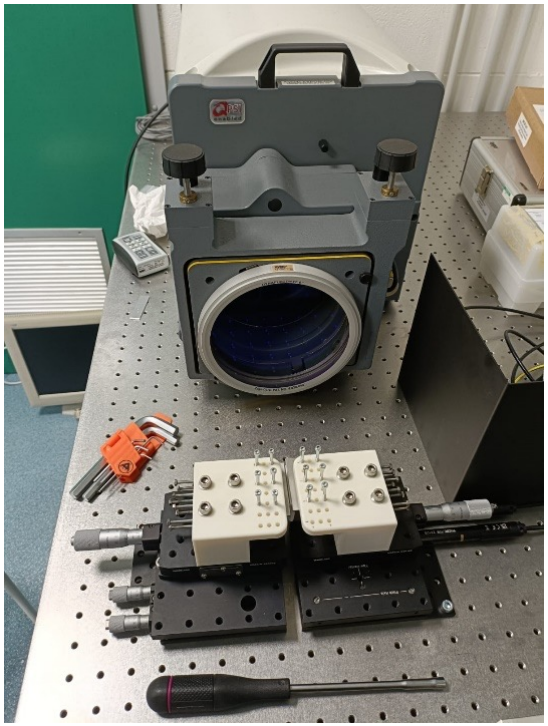
Technique for multi-crystal assembly

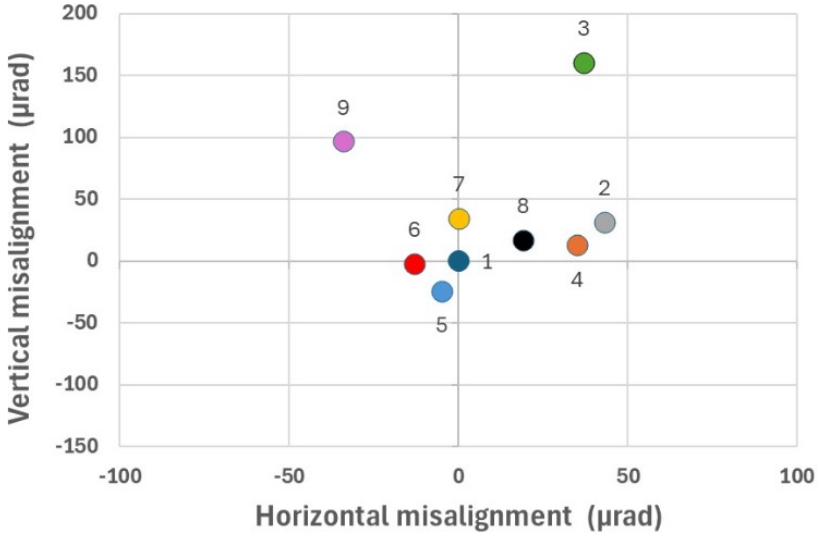
1. Crystals characterized and miscut measured
2. Surfaces painted with EJ-510
3. Mounted on vacuum fixture with 2 stages linear and 2 stages rotational motion
4. Inclination of front faces monitored during gluing with wide FOV laser interferometer
5. Epoxy applied at gel point and fine adjustments made during gluing











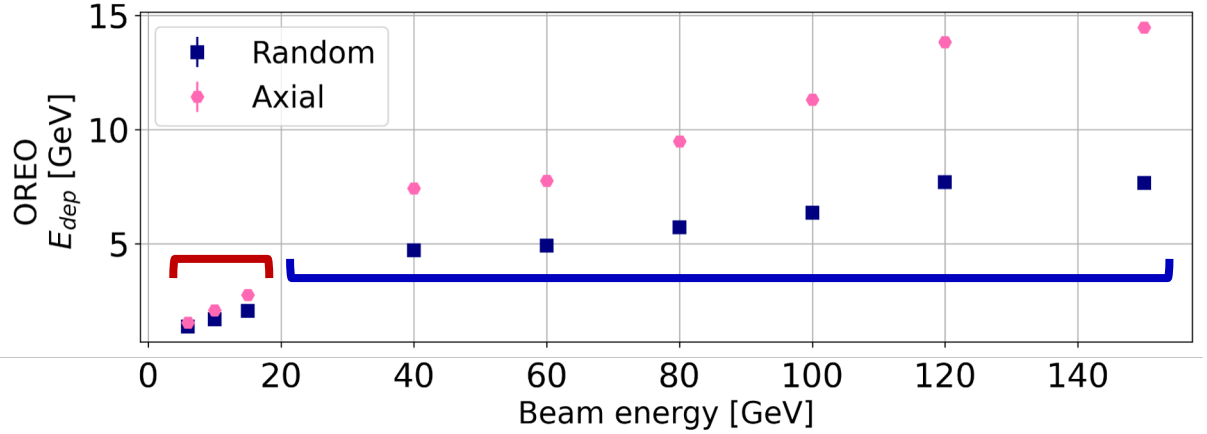
Front. Phys. 11 (2023) 1254020

A. Selmi, Pisa Meeting (in press)

OREO preliminary beam test results

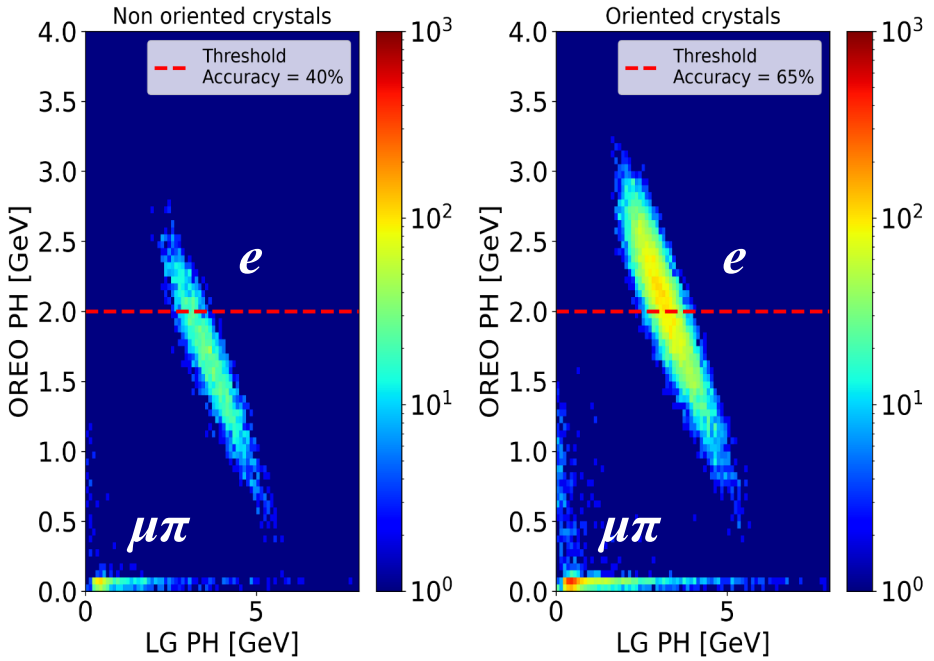
Results obtained with 3x1 (Aug 23) and 2x2 (Oct 23) assemblies

- Matrix on goniometer
- OPAL PbGl block used as second layer



PS T9
Sub-SF regime

SPS H4
Full strong-field (SF) regime

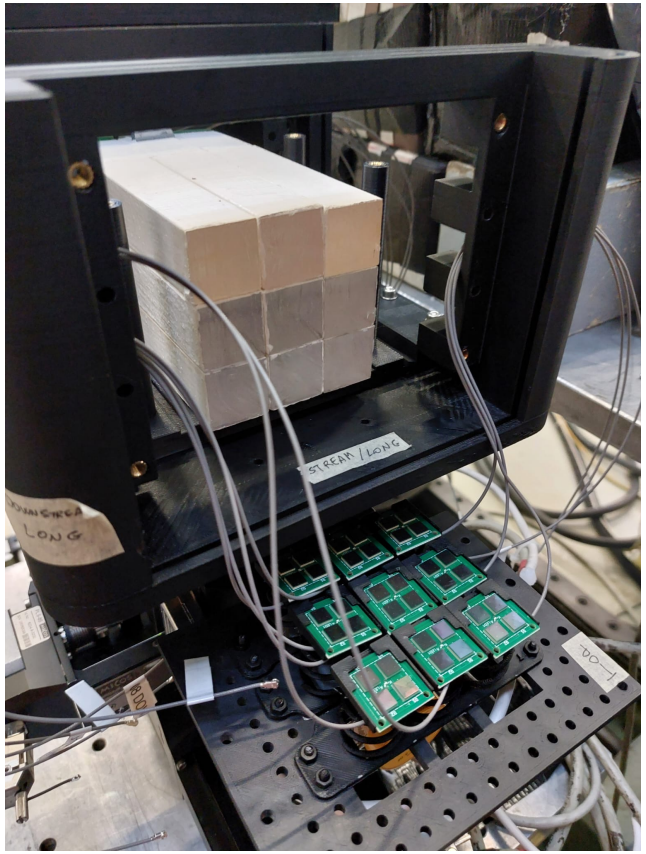


Deposited vs transmitted energy in 2x2 layer – PS T9 (Oct 23)

$$E_{\text{beam}} = E_{\text{dep}} + E_{\text{trans}}$$

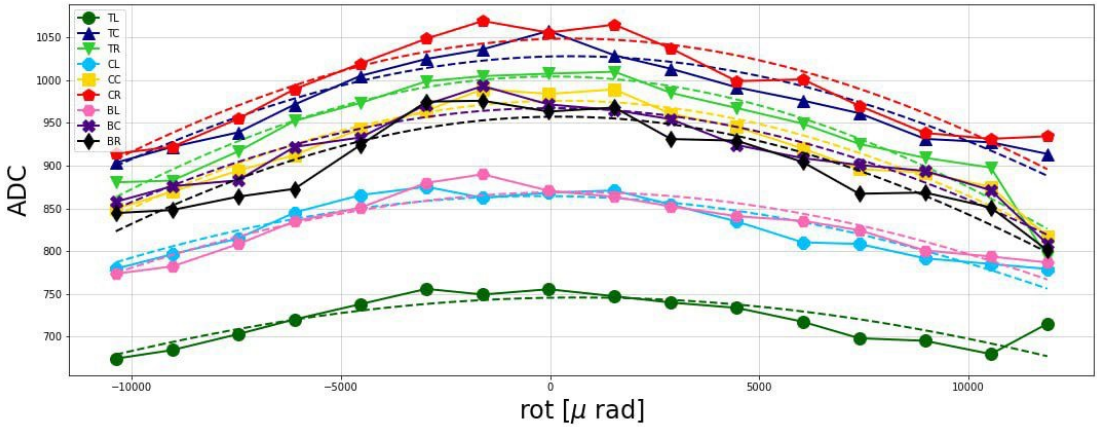
Results with full-scale prototype from Jun 2024 currently under analysis!

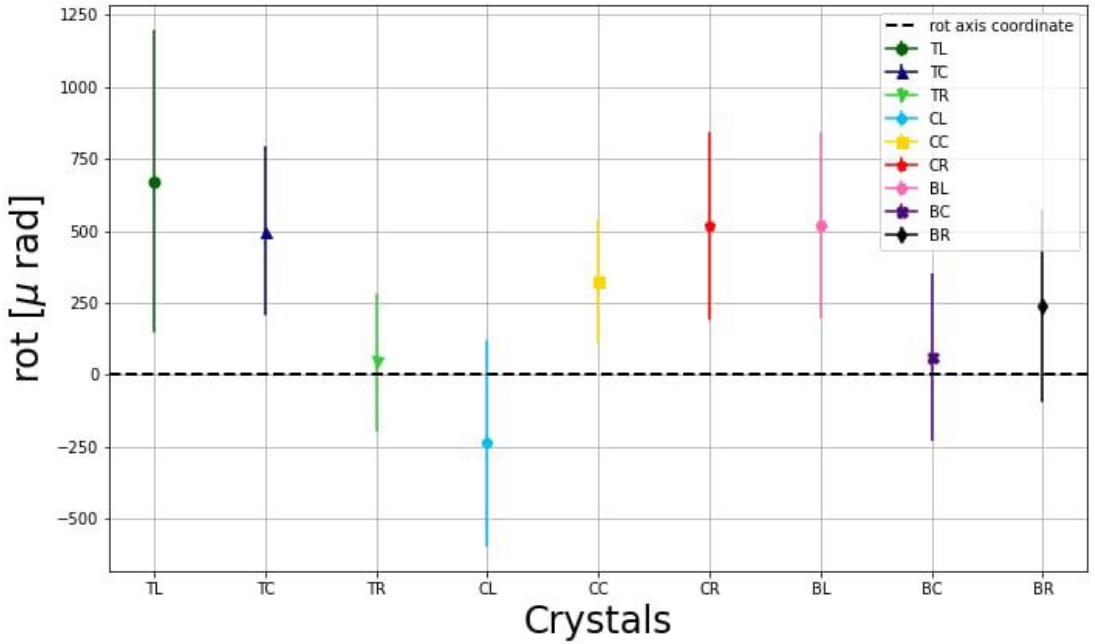
Jun 2024: Not even preliminary!



Full scale OREO prototype on T9 beamline, Jun 2024

Alignment quality from angular scan



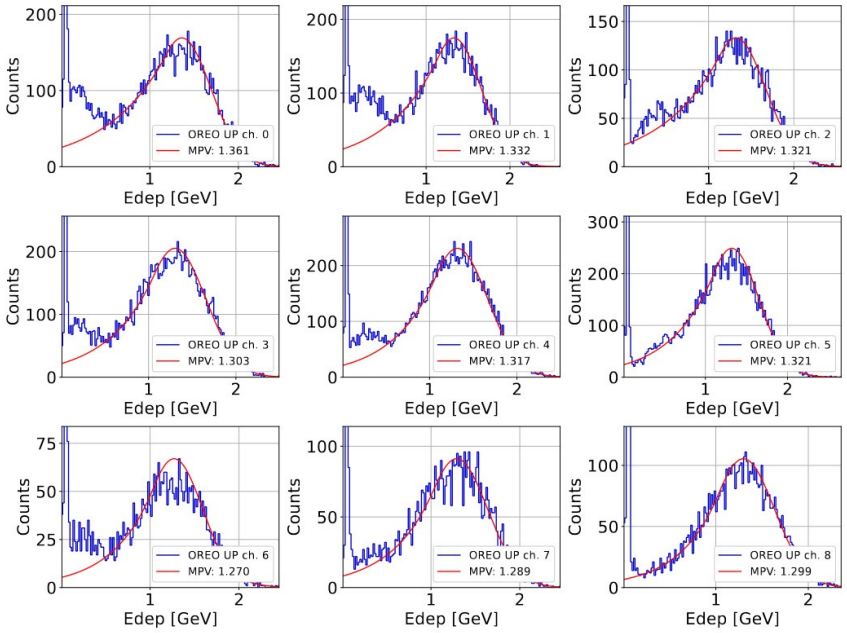


Jun 2024: Not even preliminary!

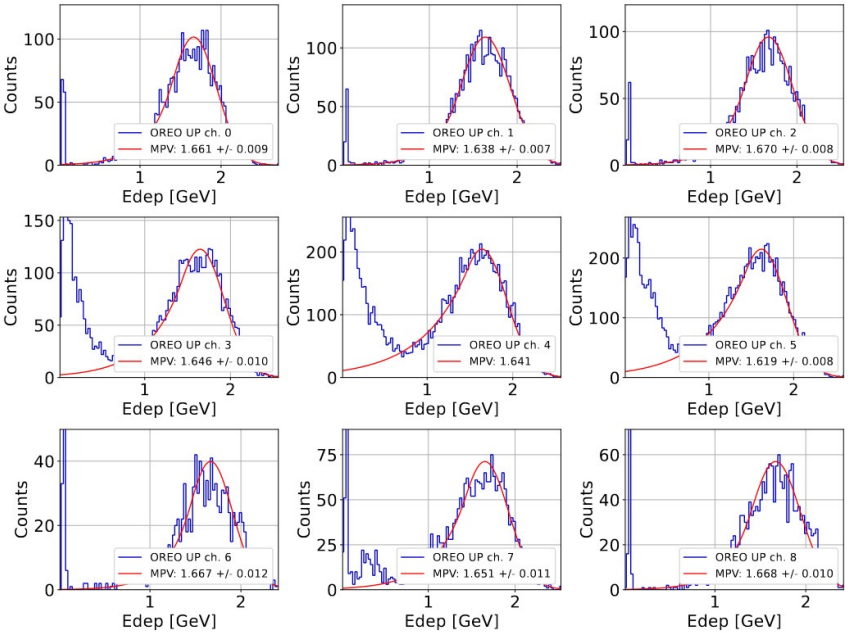
First layer, OREO full-scale prototype

PS T9: 6 GeV parallel beam

Random orientation



Axial orientation



All crystals in first layer well equalized

Enhanced signal with alignment observed on all channels

Planned SAC R&D program

Performance goals achieved:

- Time resolution: < 20 ps for single crystals, $E > 5$ GeV
- High granularity & longitudinal separation:
  Light transport understood in small crystals with high n
- Radiation resistance for crystal: PWO-UF robust to > 2 MGy
- Single-crystal alignment: 30% reduction in effective X_0 for first interaction plane

Performance goals remaining:

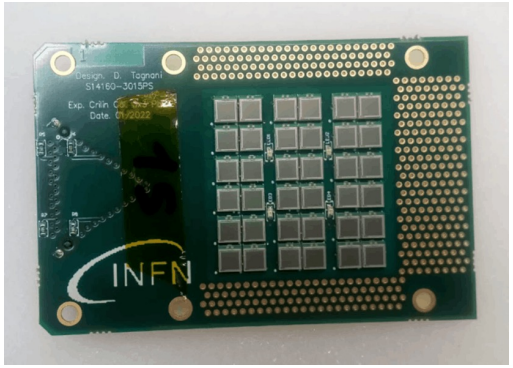
- Final granularity: Find optimal segmentation (ease of alignment, $R_M = 2$ cm)
- Double-pulse resolution: Current signal shaping at 70 ns → 2 ns!
- Radiation resistance for photosensor: When will rad-hard SiPMs be ready?
- Multi-crystal alignment: Develop final design to align stackable layers

Goal for 2024 was to test 1-layer prototype to meet above specifications

HIKE SAC Layer 0 demonstrator

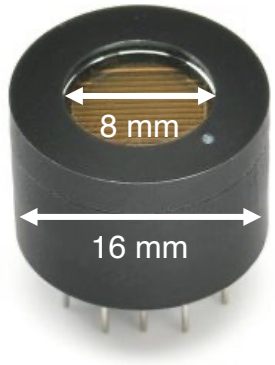
Stackable planes, like CRILIN, with PCB photosensor plane

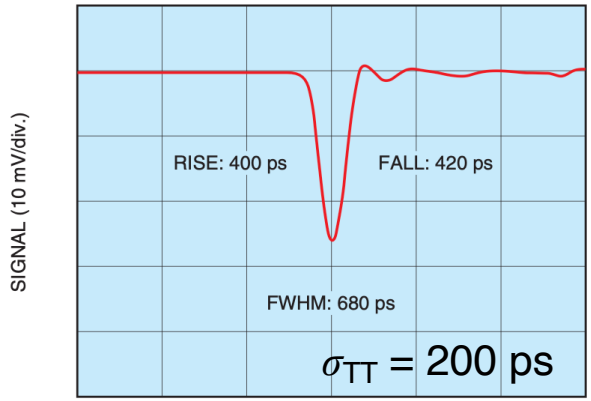
- Layer mechanics to allow alignment of crystal plane
- Crystals pre-aligned à la OREO

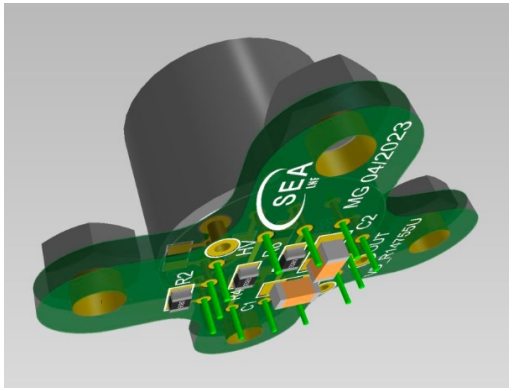


Hamamatsu R14755 PMTs instead of SIPMs

- 2 PMTs acquired for evaluation
- Designed custom divider for implementation on sensor board
- Validated PMTs + divider via design of t_0 counter for beam tests
- 10 unpackaged PMTs already acquired with other funds







In 2024 (or early 2025) test 1-layer prototype, 3x3 crystals 16x16x40 mm^3, with alignable mechanics and single-board PMT readout

Goal: Publication with test results for an ultra-fast, highly compact, radiation robust, alignable calorimeter for intensity frontier experiments

SAC R&D closeout: Plans for 2024-25

1. **Beam test in PS T9, Sep 2024 (scheduled)**
   - Redo unsuccessful measurement from Oct 2023 (digitizer problem): Study effect of crystal alignment on time resolution and Molière radius
   - Align beam to central crystal
   - **Standalone publication**
2. **Complete construction of 1-layer prototype**
   - 3x3 alignable crystals 16x16x40 mm^3, with single-board PMT readout
3. **Beam test in PS T10, Nov 2024 (requested)**
   - Possible test of new prototype, sharing beam time with first test of next generation CRILIN 3x3 prototype
4. **Request 1 week in SPS H2/H4 in 2025** for final validation of new prototype at high energy
   - Particular emphasis on light yield and time resolution
5. **Publication with test results** for an ultra-fast, highly compact, radiation robust, alignable calorimeter for intensity frontier experiments
6. **Going forward, work with OREO in context of DRD6** to test new prototype with crystals fully aligned

HIKE SAC: Richieste R&D 2024

Consumi (LNF): 27 kE → 20 kE

Per costruzione prototipo SAC, 9 ch., 1 layer:

- **10 cristalli PWO-UF (Crytur), 16x16x40 mm3, orientati** **15**
- 10 fotomultiplicatori Hamamatsu R14755U-100 **7**
- **Realizzazione stampato per PMT con partitori HT** **2**
- **Meccanica, componenti stampate 3d** **3**

Missioni: 6 kE → 3.5 kE (per MEC e SAC insieme)

Per test beam a SPS NA, s.j. beam time allocato

- Personale test beam: 4 settimane persona (LNF) **4**
- Esperti allineamento Legnaro: 2 settimane persona (FE) **2**

Manutenzione (FE): 3 kE

- Contributo contratto manutenzione diffrattometro raggi X **3**

Totale: 39 kE → 20 kE (23.5 con missioni in comune con MEC)