HIKE SAC R&D:
Stato e prospettivi

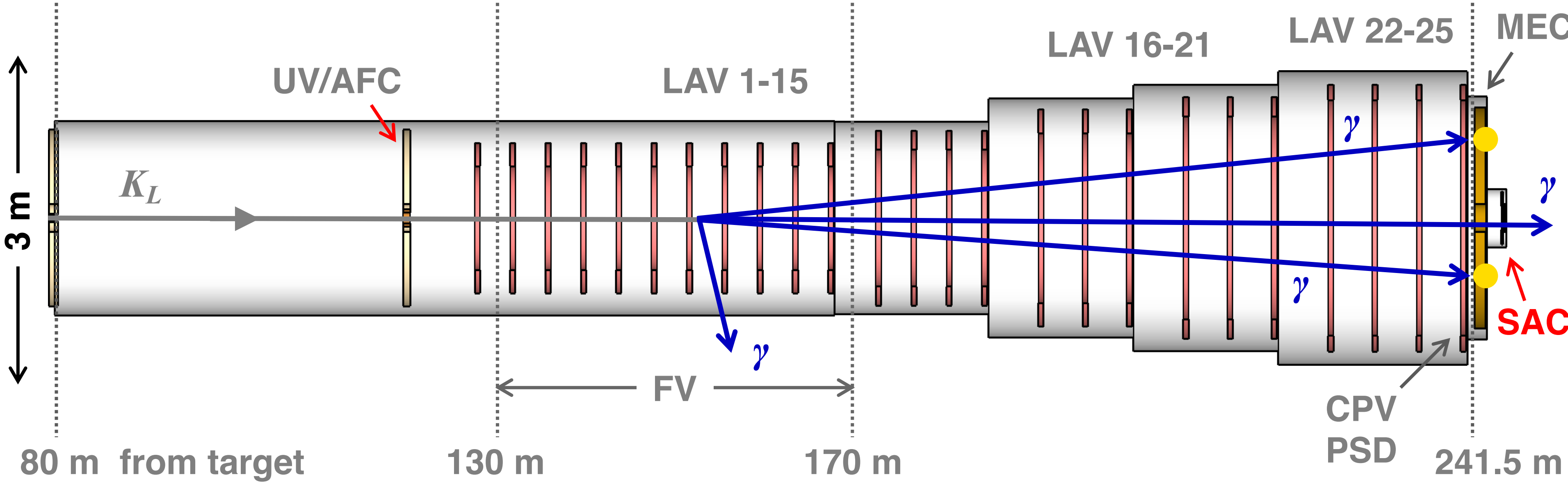
Matthew Moulson

Referee CSN1 – NA62
18 luglio 2025

High Intensity Kaon Experiments

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 high-density crystal calorimeter (e.g. PADME, g-2)**

NB: Continued post-HIKE interest in this solution, e.g, for KOTO II

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

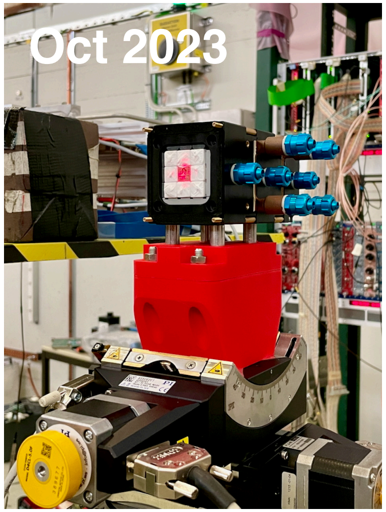
CSN5 project to develop proof of concept for calorimeter with aligned crystals, inspired in large part by needs of HIKE SAC

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 ←

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

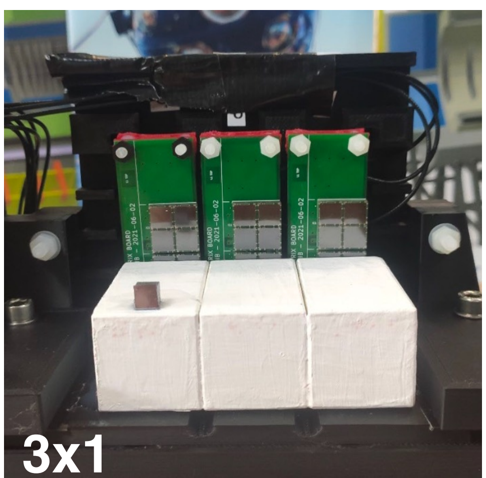
Study effect of crystal alignment on time resolution
and Molière radius ***See talk by Silvia***

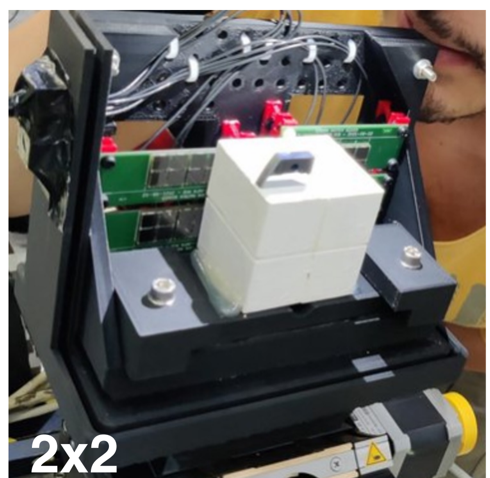
~~**Nov 2024**~~
~~**PS T10**~~ ***Not scheduled***

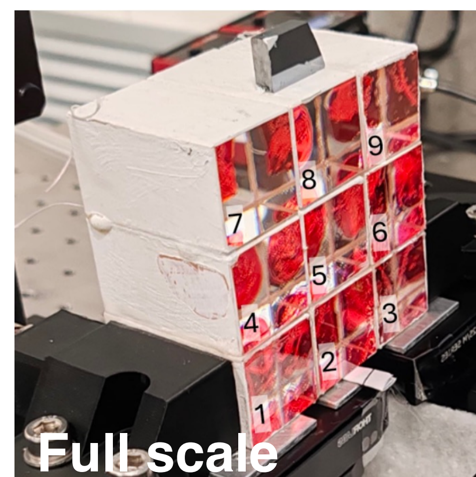
~~First test of next generation CRILIN 3x3 prototype~~
~~Possible test of HIKE design with PMT readout~~

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 **SPS H4**	First test of full-scale OREO prototype at high energy 1 week, dedicated
Sep 2024 **SPS H4**	Test of full-scale OREO prototype at high energy 1 week, dedicated


3x1


2x2



Full scale

HIKE SAC R&D program

Performance goals achieved:

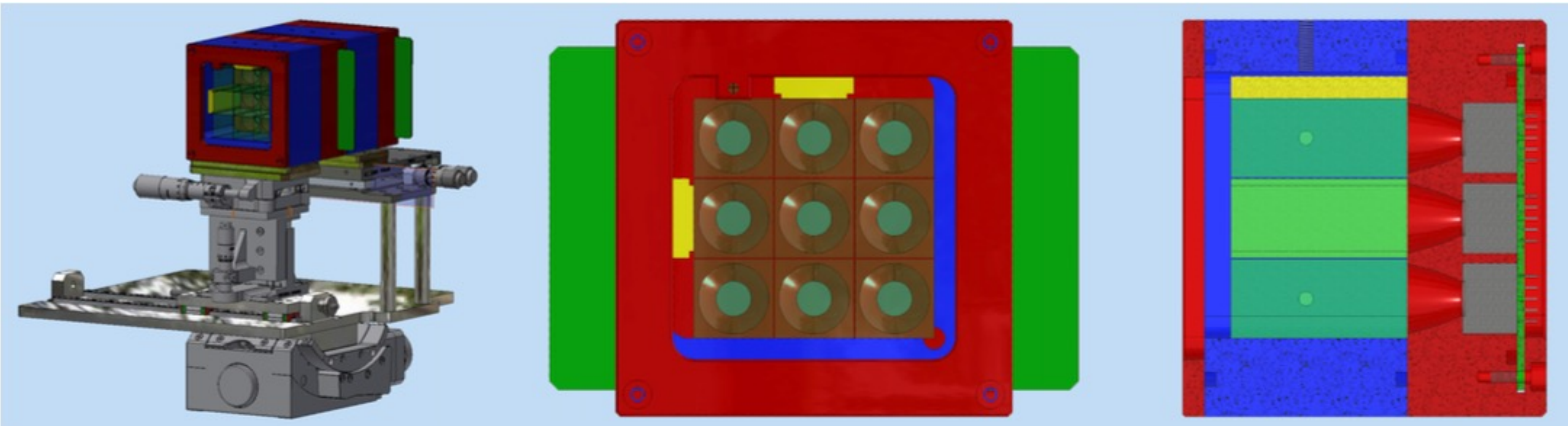
- Time resolution: < 20 ps for single crystals, $E > 5$ GeV
- High granularity & longitudinal separation:
  Light transport understood in small crystals with high n
- Radiation resistance for crystal: PWO-UF robust to > 2 MGy
- Single-crystal alignment: 30% reduction in effective X_0 for first interaction 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: Closeout HIKE R&D program with development of prototype meeting above specifications

SAC prototype: Overall design



Mechanical design A. Saputi

2 stackable layers, like CRILIN

- 3x3 crystals per layer, 18x18x40 mm^3:
  Highest granularity compatible with PMT geometry
- Crystals can be pre-aligned à la OREO
- Initial alignment of each plane performed separately
- Relative layer alignment adjusted manually once angles known for each layer
- Readout with compact, metal package PMTs:
  Single PCB sensor plane for each layer, like CRILIN
- Winston cone light concentrators to increase numerical aperture: 15% → 79%

SAC prototype: Crystals

PWO-UF (Crytur)

20 pieces, 18x18x40 mm^3

Small faces polished:

- CRILIN studes demonstrate that matte surfaces are better
- Coupling surface and front face polished
- Front face helps with angular alignment

Cut to preserve orientation:

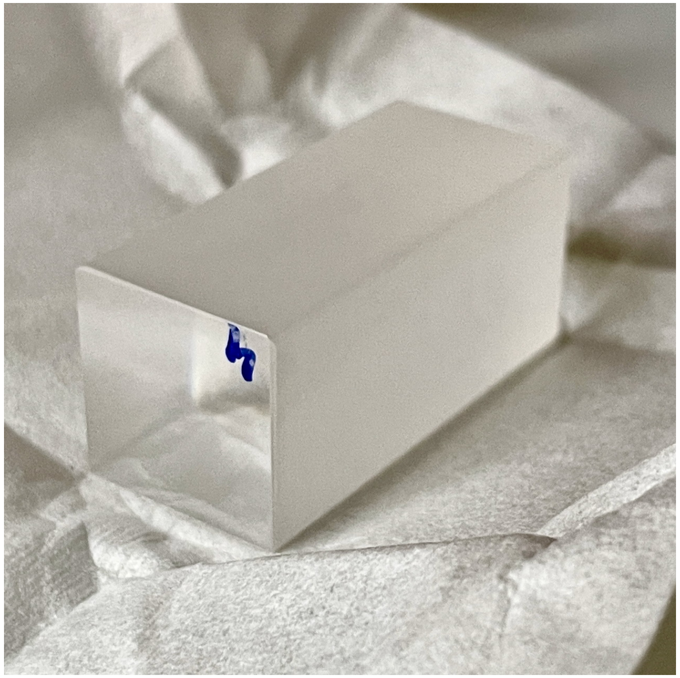
- ⟨100⟩ axis perpendicular to front face within 6 mrad
- ⟨001⟩ and ⟨010⟩ axes perpendicular to side faces within 35 mrad

All 20 crystals delivered by Crytur

Currently at Ferrara for angular measurement

- Not high priority yet: Only need 2 crystals to be measured for September test beam

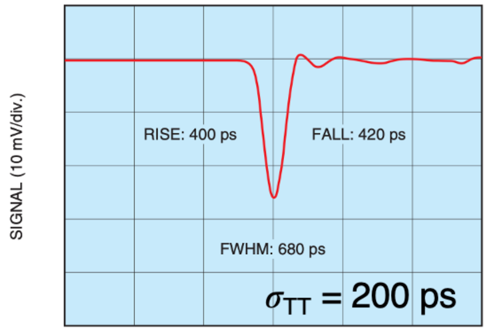
PWO-UF
ρ = 8.3 g/cm^3
X_0 = 0.89 cm, λ_{int}/X_0 = 22.8
LY = 7 pe/MeV, τ_{decay} = 640 ps
Radiation hard to 2 MGy



SAC prototype: Sensor planes

PMTs: Hamamatsu R9880 or R14755

- Higher gain vs better time resolution
- Same socket, nearly identical form factors



	R9880	R14755
Dynodes	**10**	**6**
Gain at V_{max}	**4×10^6**	**6×10^5**
Rise time [ps]	**570**	**400**
FWHM [ps]	**1250**	**680**

Design by R. Lenci and M. Gatta

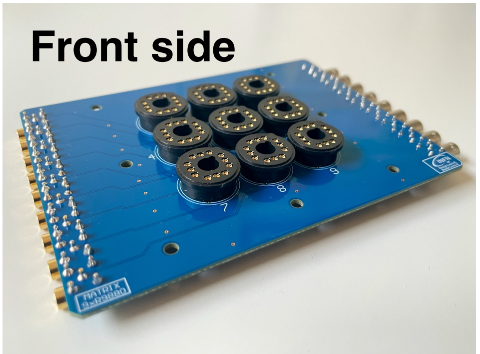
Sensor plane:

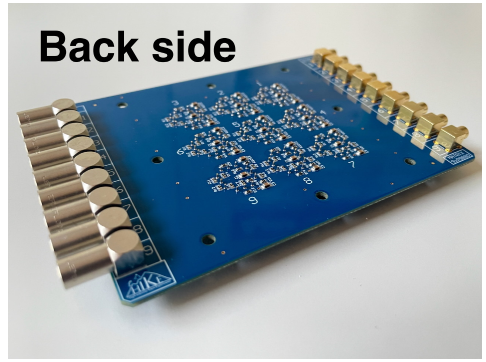
- Hosts 9 PMTs on sockets
- Independent HV inputs and divider circuits for each PMT
- Output to digitizer via MCX cables
- 2 variants of sensor board:

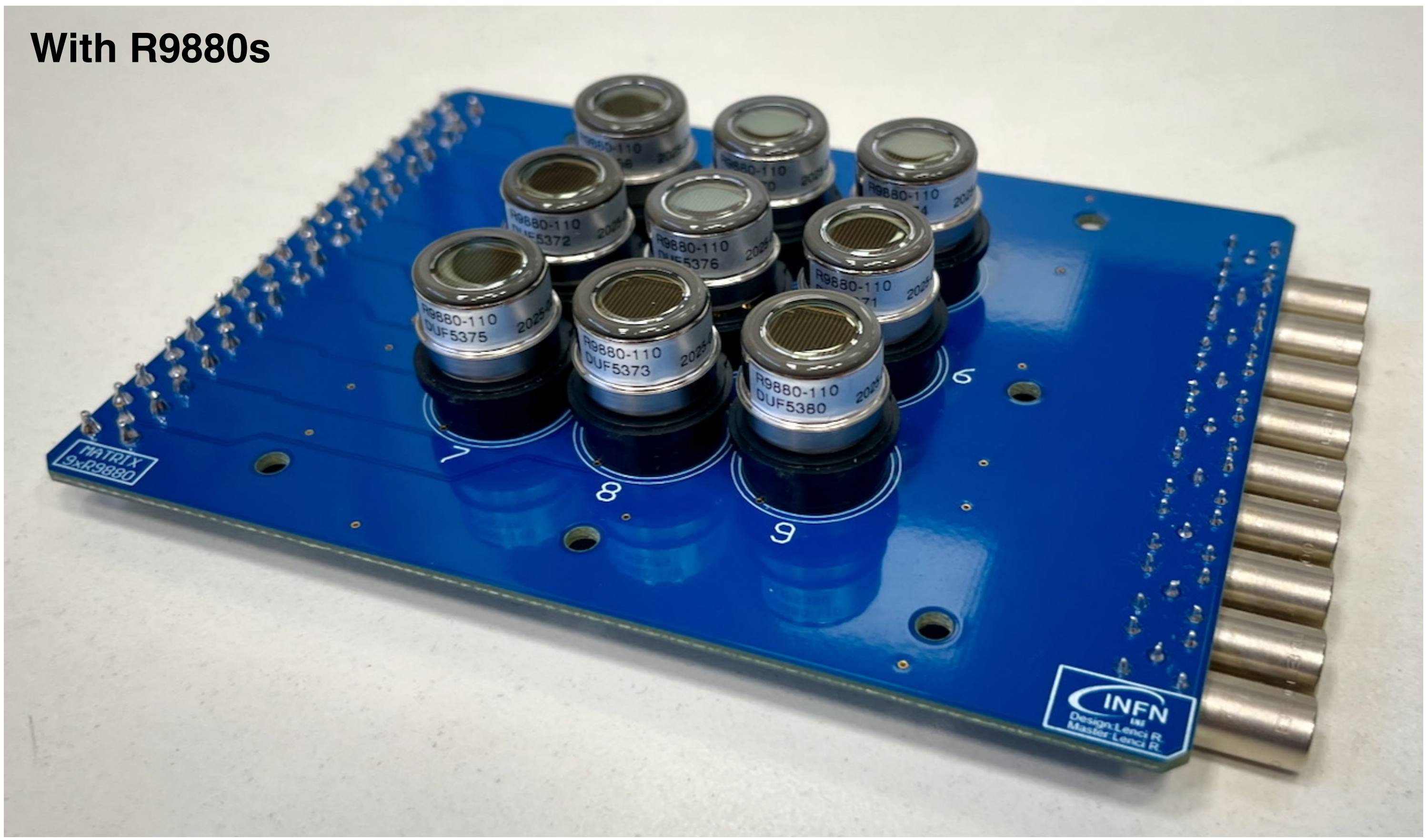
  R9880 (2 ready): Implementation of Hamamatsu divider with extra, removable 51 ohm resistors on last 2 dynodes to damp parassitic resistance if needed

  R14755 (1 ready): Custom divider with ballast capacitors and removable damping resistors on last dynodes

SAC prototype: Sensor planes


Front side


Back side

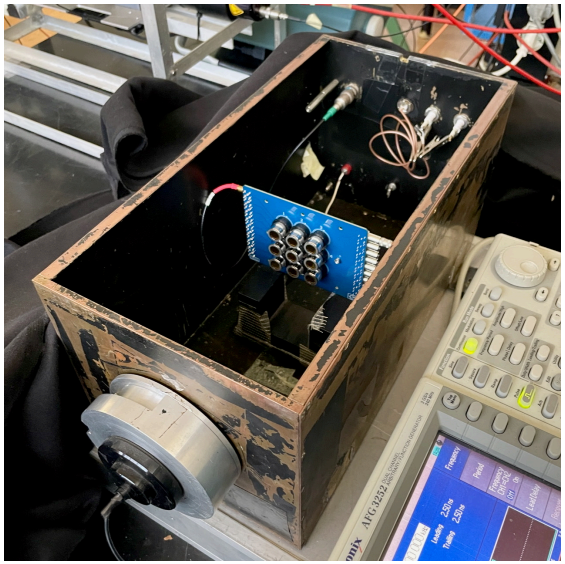


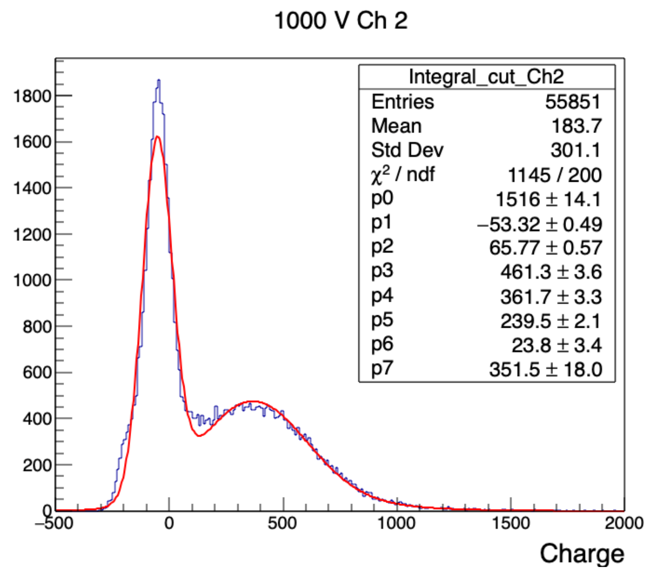
With R9880s

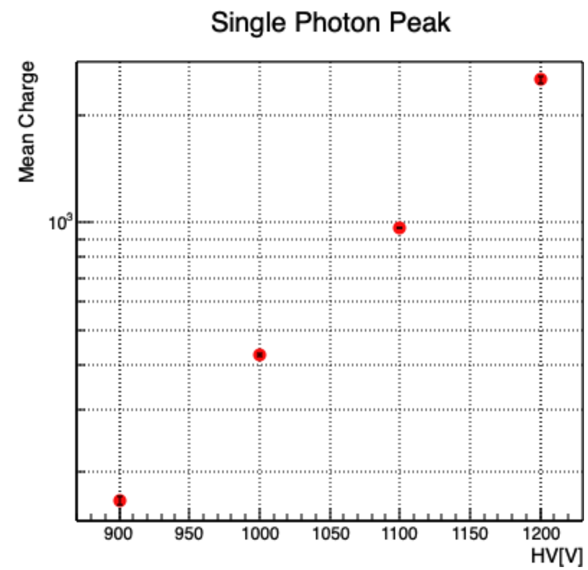
SAC prototype: PMT characterization

Measure single p.e. response and gain curve with dark box and LED pulser

Arrive at test beam with HV settings for full gain equalization







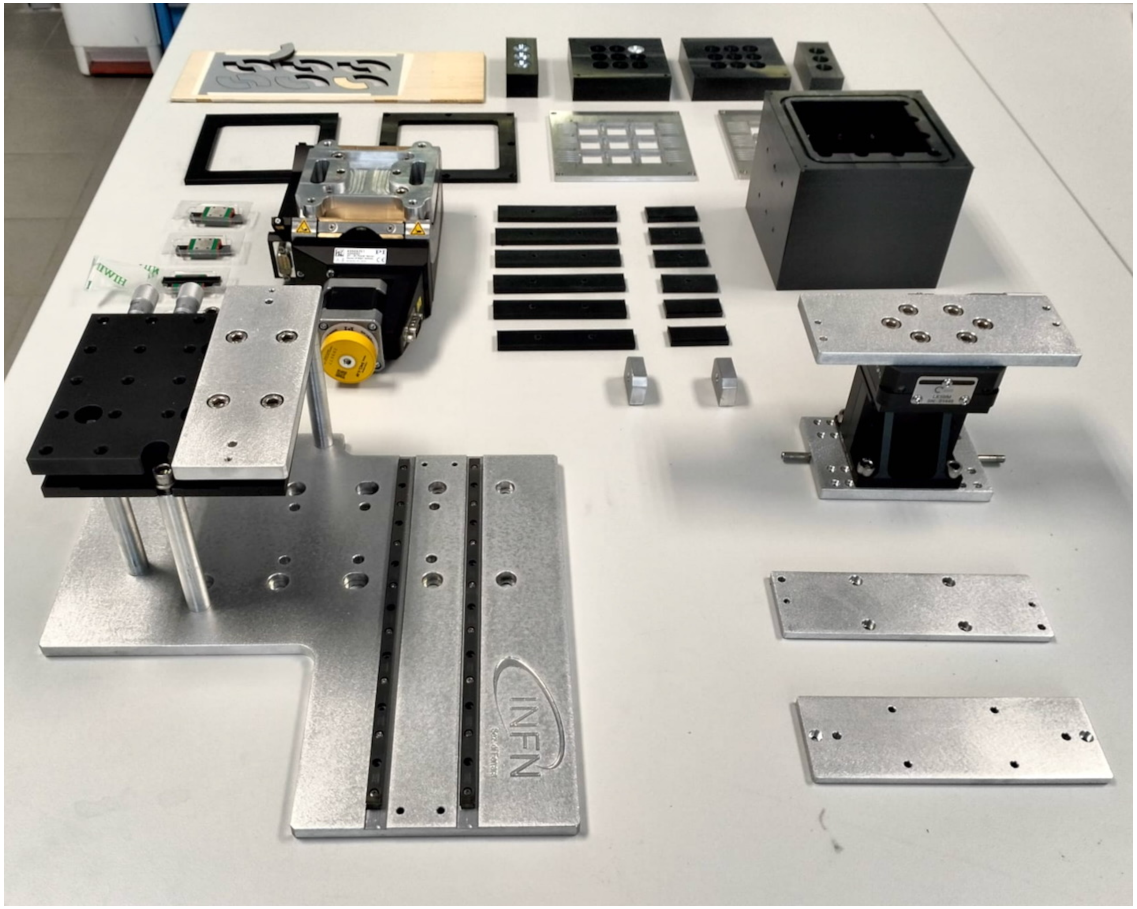
$Q_{1\text{pe}}$ = 0.82 pC
$G = 5.1 \times 10^6$

$Q \propto V^\alpha$
$\alpha = 10.2$

Procedure still being refined:

- Use polaroid filters to obtain mean photon multiplicity << 1 in 100 ns
- Fit spectrum for N_{pe} = 0, 1, 2 with 1 parameter for peak separation, 3 values of σ
- Repeat for different HV settings – can measure all channels at once

SAC prototype: Construction



Mechanical components:

- Manufactured at Ferrara, coordinated by A. Saputi (designer)
- Nearly all components in contact with crystals made of HDPE ($X_0 \sim 50$ cm)
- Almost all parts finished
- Ready for test of final assembly as soon as sensor boards characterized

Light concentrators:

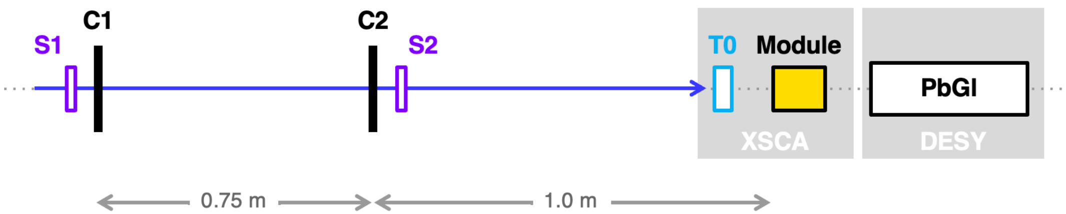
- Original idea: use parabolic cones, aluminze via spattering
- Potential problems with adhesion of aluminum to plastic
- Baseline solution: conical concentrators with ESR
- Study in future spatter-coated and polished aluminum concentrator blocks with parabolic cones

SAC prototype: Test beam plans

Before test beam:

- Finish measurement of PMT gain curves, get equalized HV settings
- Mechanical assembly test in Ferrara
- Operation in cosmic-ray stand at Frascati for shakedown

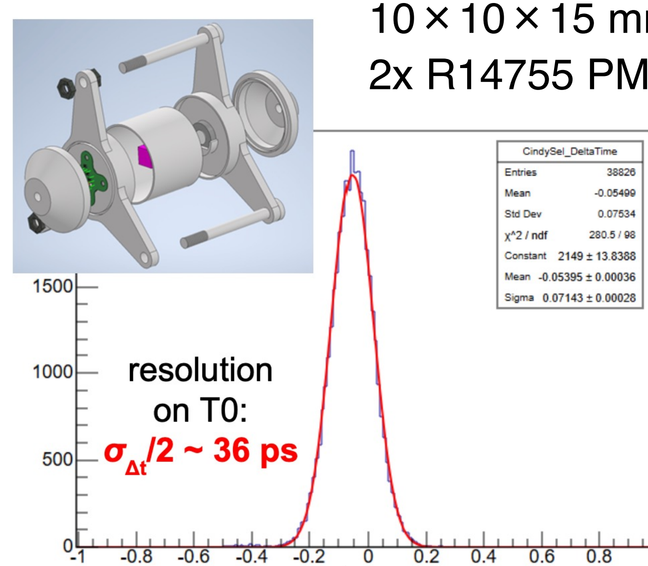
T9 beamline setup: 27 Aug – 03 Sep



S1, S2	Trigger scintillators
C1, C2	Silicon-strip tracking chambers, 10×10 cm^2
T0	Fast timing detector
Module	SAC prototype on goniometer
PbGl	Lead-glass calorimeter

t_0 reference

EJ232Q 0.5%
$10 \times 10 \times 15$ mm^3
2x R14755 PMTs



Test beam measurements:

- Quick validation of equalization with MIP beam
- 1, 2, 4, 6 GeV e^-, with and without alignment of central crystal:
  - Time resolution, pulse-shape analysis, light collection uniformity
  - Energy distribution profiles, longitudinal and transverse: compare to MC

SAC R&D closeout: Evolution of plans

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**

   Analysis in progress:
   Presentation by Silvia

2. **Complete construction of 1-layer prototype**
   - 3x3 alignable crystals 16x16x40 mm^3, with single-board PMT readout

   1 layer → 2 layers
   16x16 mm^2 → 18x18 mm^2
   Winston cone light concentrators

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

   No beam time in Nov 2024:
   Request made late in year
   Improved prototype for 2025 instead

4. **Request 1 week in SPS H2/H4 in 2025** for final validation of new prototype at high energy
   - Emphasis on light yield and time resolution

   Scheduled **27 Aug - 03 Sep**
   Construction on schedule

5. **Publication with test results** for an ultra-fast, highly compact, radiation robust, alignable calorimeter for intensity frontier experiments

   Poster with preliminary test beam results at KAON 25 (8-12 Sep)

6. **Going forward, work with OREO in context of DRD6** to test new prototype with crystals fully aligned

   Will seek resources for 2026 test from DRD6

HIKE SAC R&D: Informazioni aggiuntive

Matthew Moulson

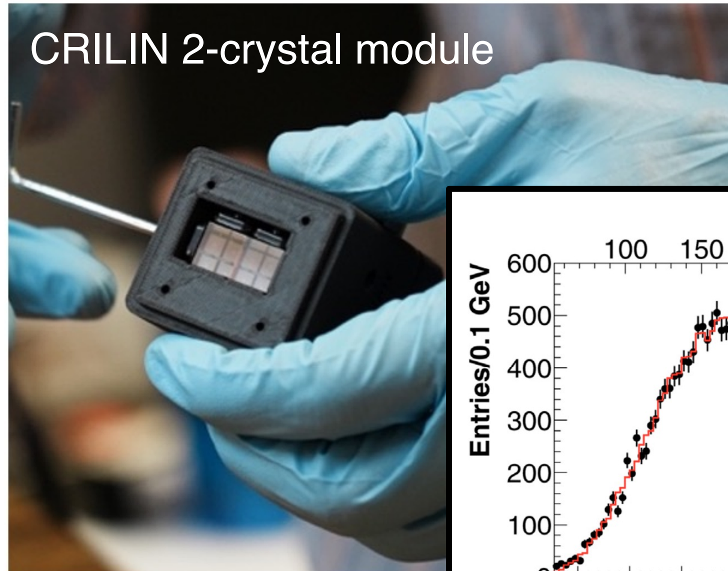
Referee CSN1 – NA62
18 luglio 2025

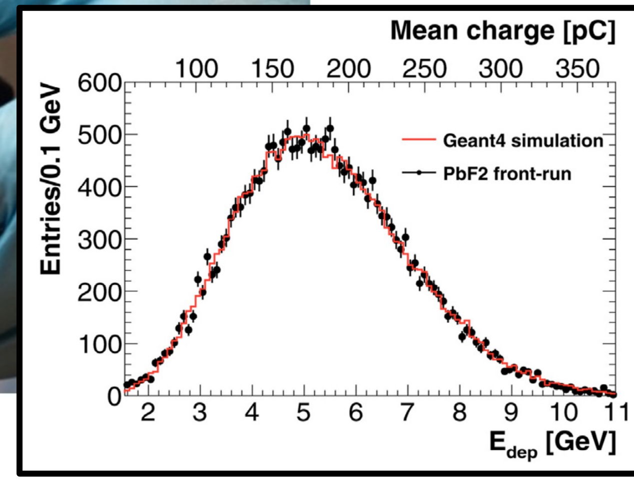
High Intensity Kaon Experiments

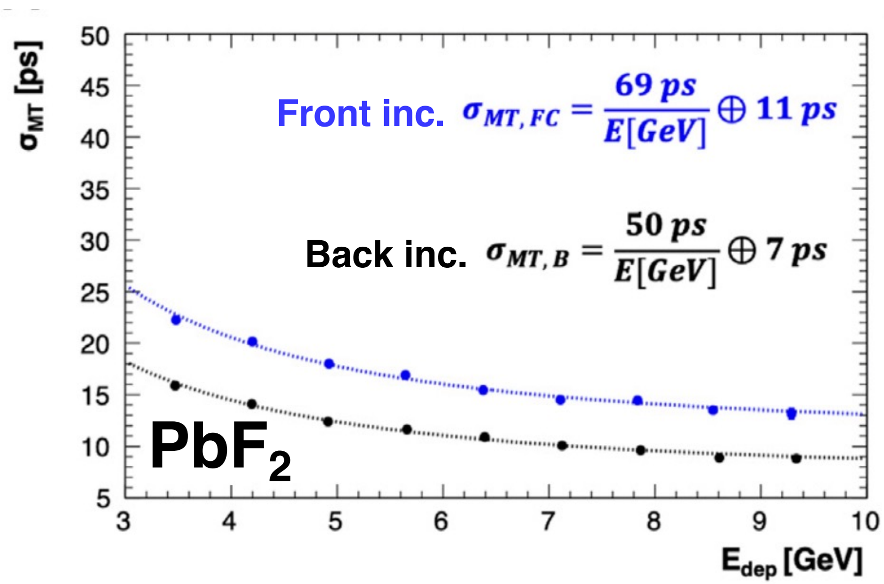
Tests with single crystals, fall 2022

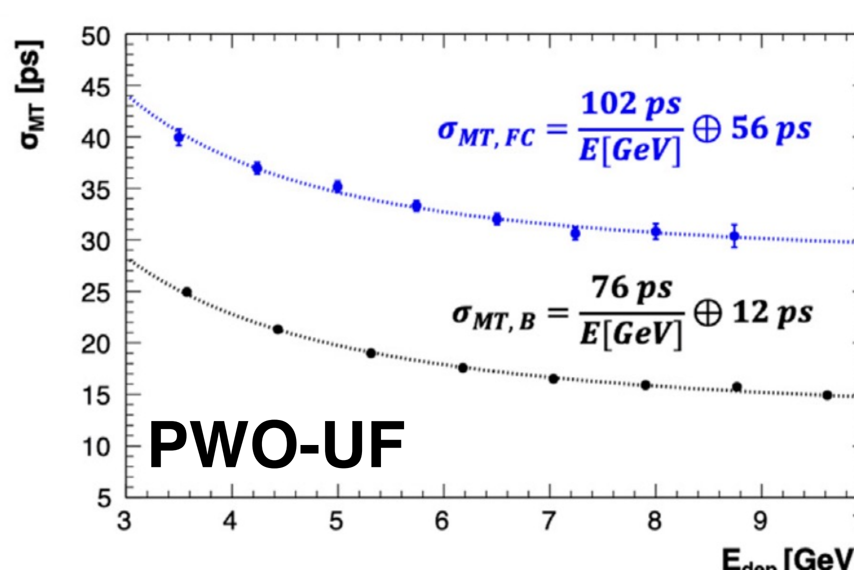
Front. Phys. 11 (2023) 1223183

- 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

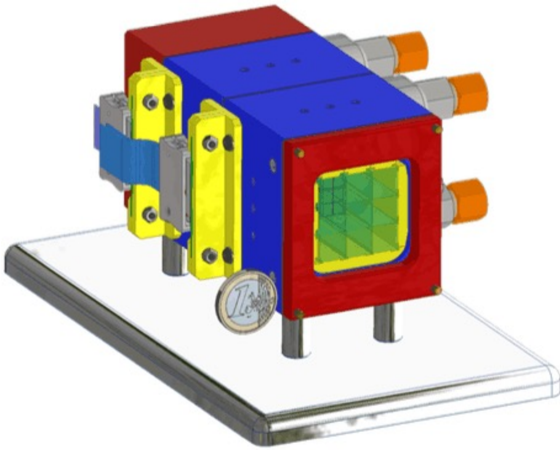


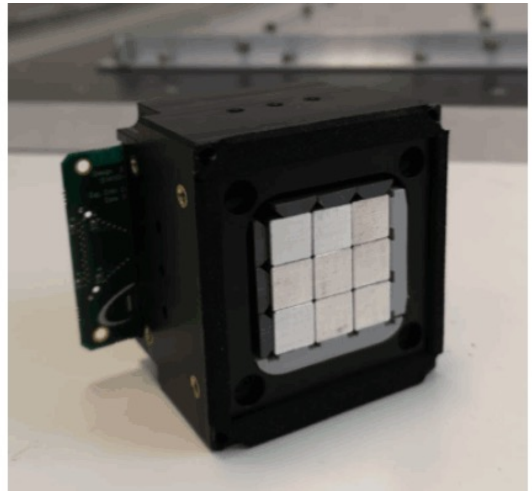






Tests of CRILIN 3x3x2 prototype: 2023-24

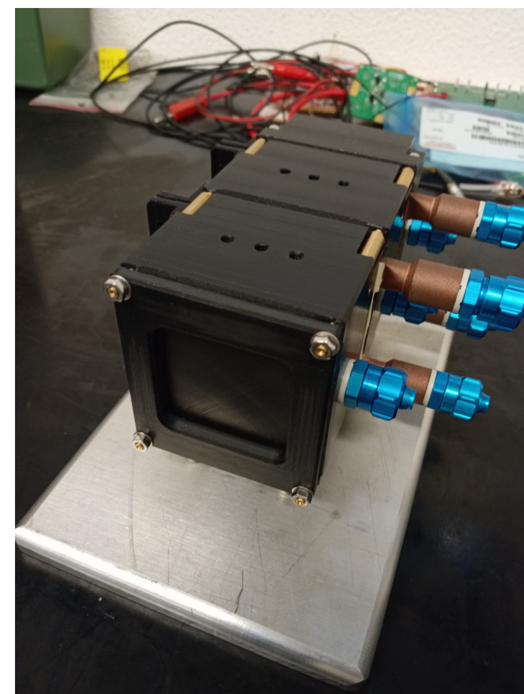




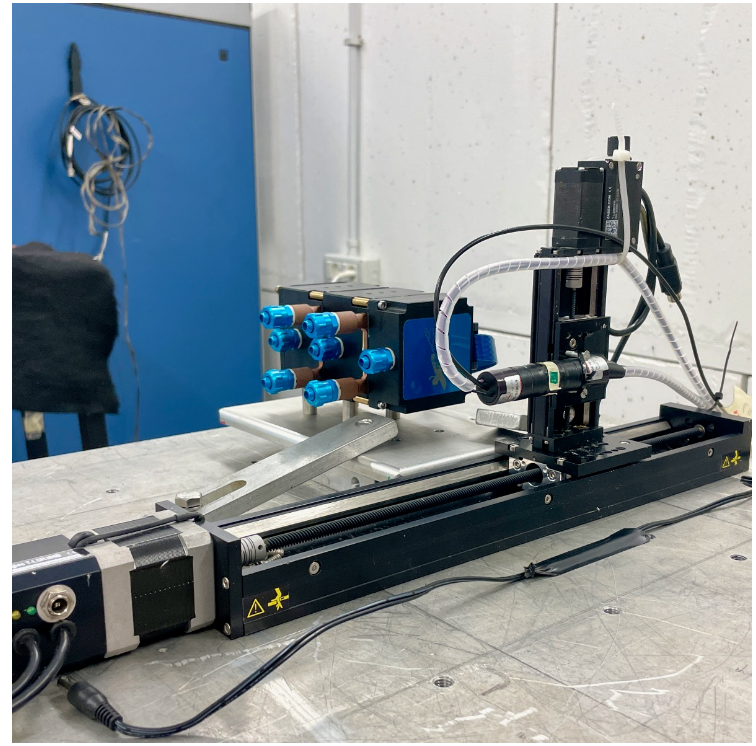
Two 3x3 CRILIN test layers, with PbF_2 and PWO-UF

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 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

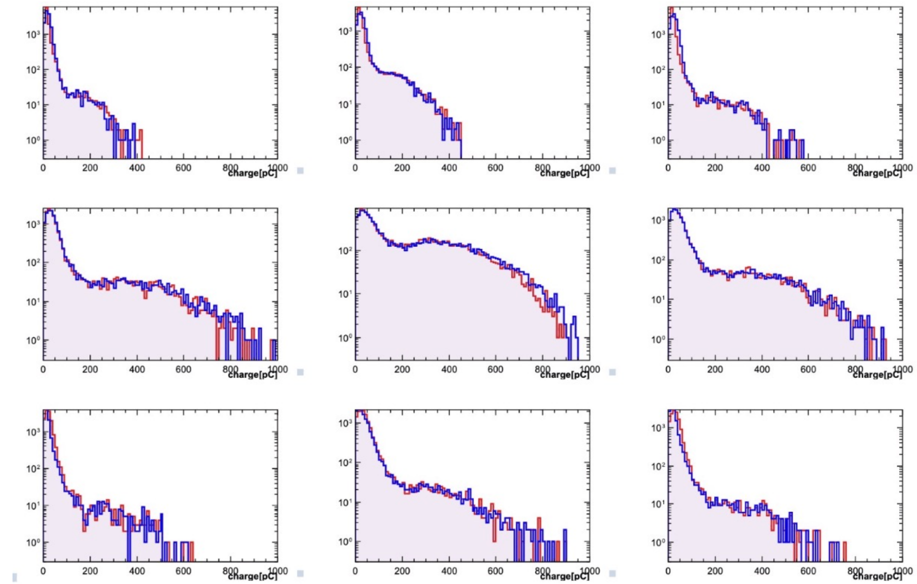
CRILIN equalization

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

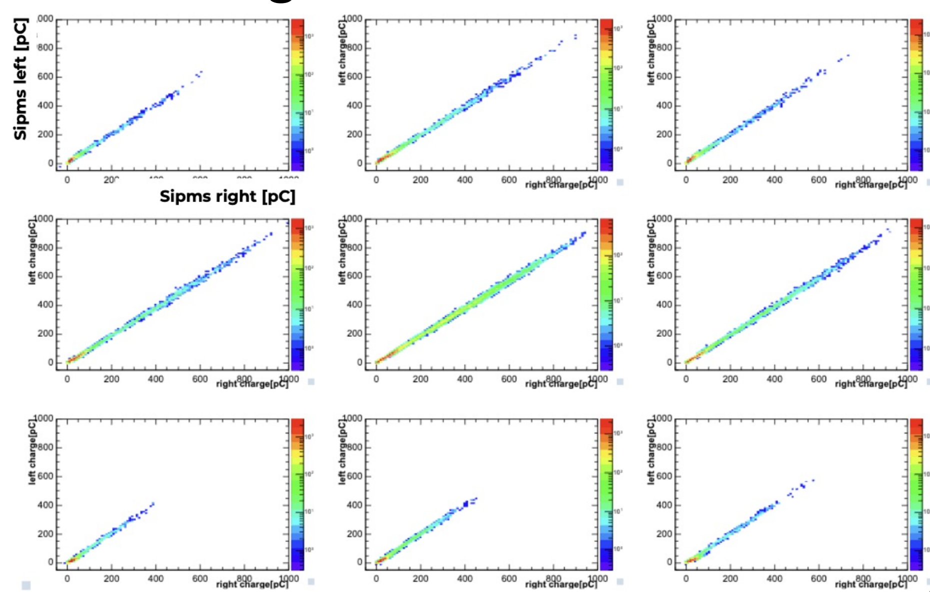
SiPMs from the same lot were requested when ordered from Hamamatsu and delivered with V_{br} measured uniform to within < 0.1V

No dedicated equalization procedure was needed

Charge spectra for SiPMs L & R



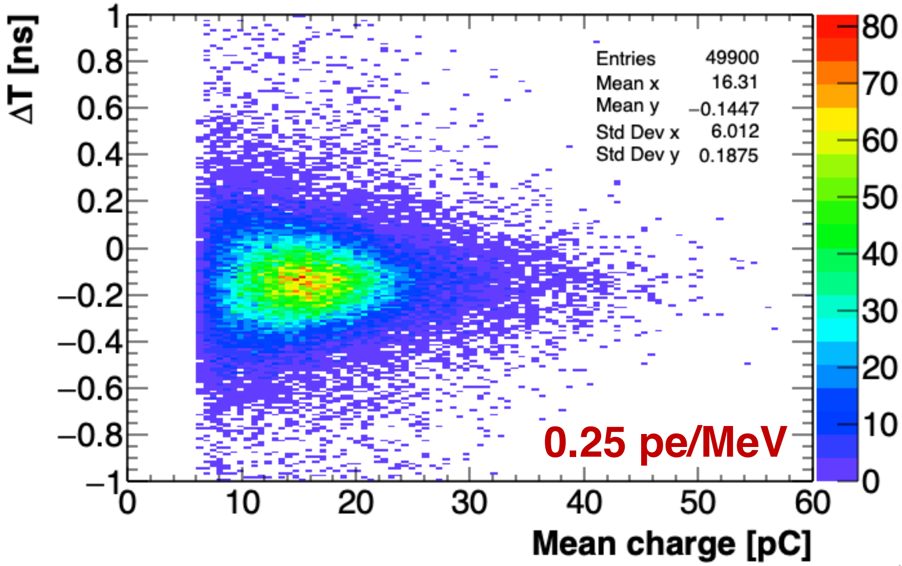
L/R charge correlations

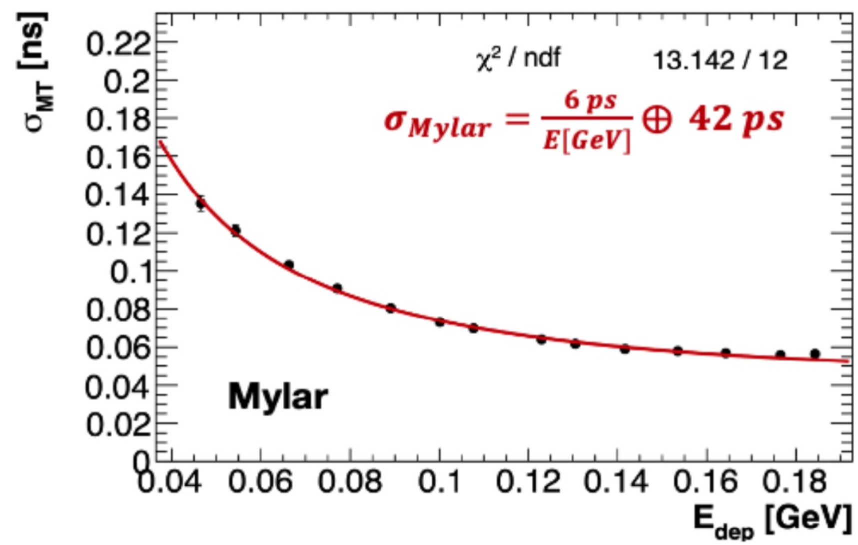


CRILIN test at BTF

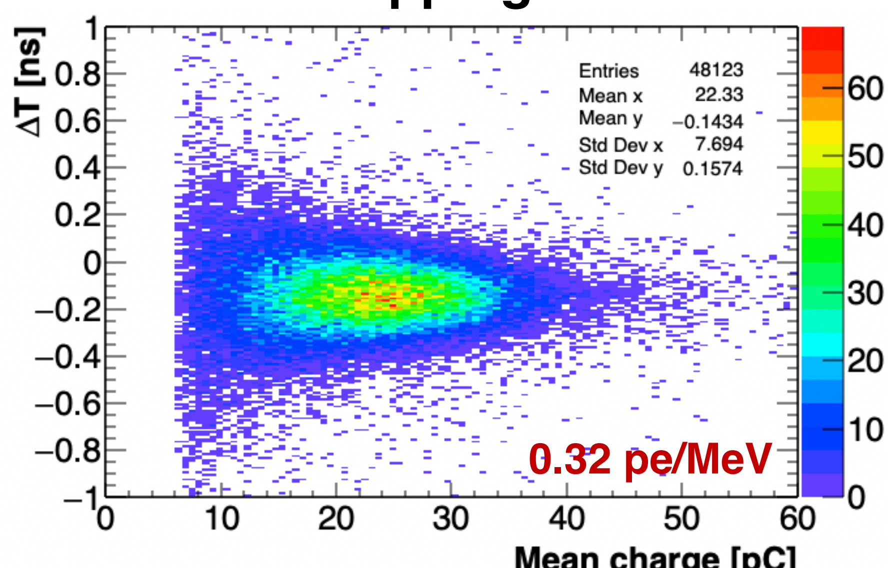
IEEE Trans. Nucl. Sci. 71 (2024) 1116

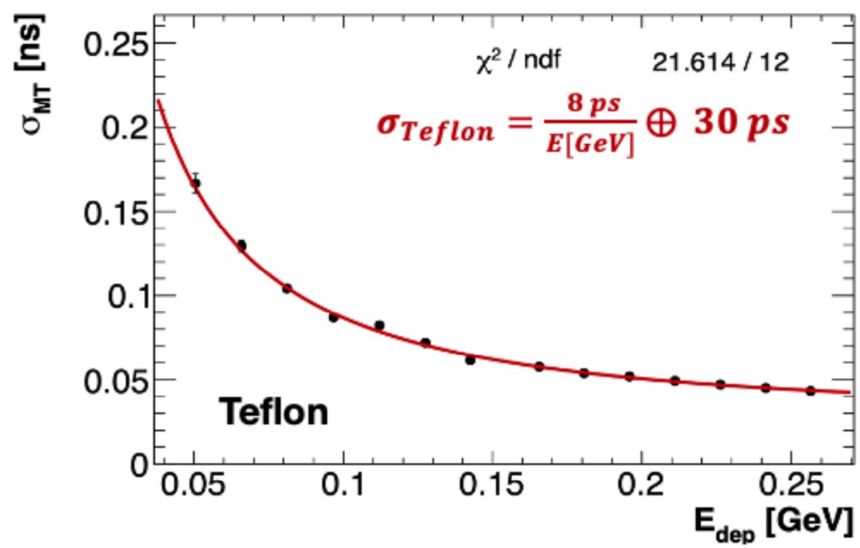
Mylar wrapping





Teflon wrapping

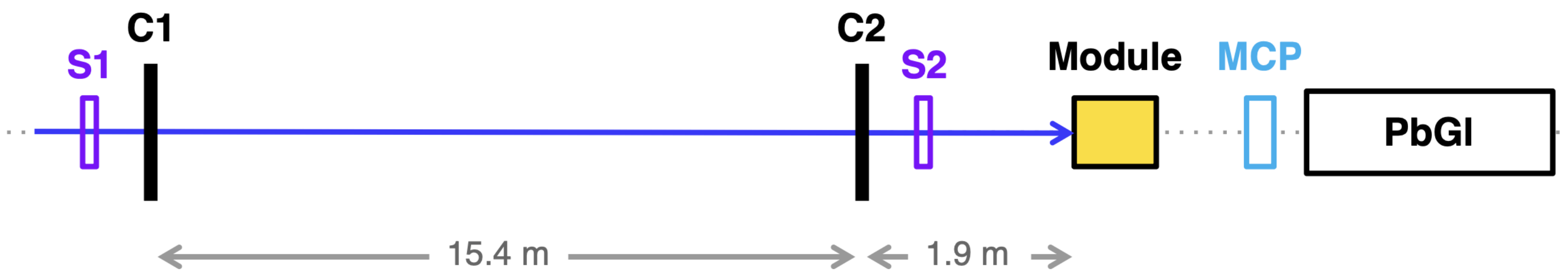




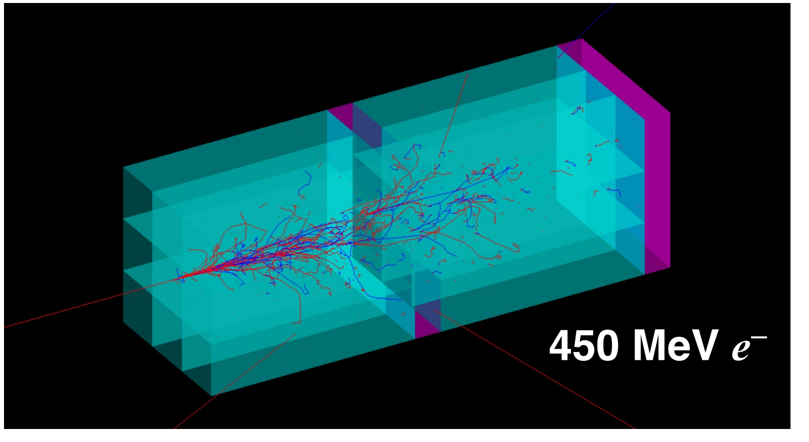
CRILIN test at H2: Aug 2023

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

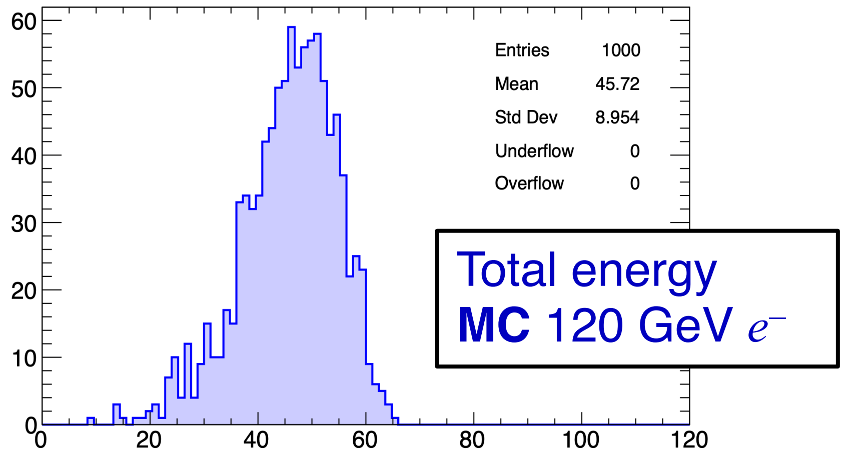
For CRILIN, use similar setup to 2022 run to test same configurations as in BTF (PbF_2, PWO-UF) with **20-120 GeV e^-** and **150 GeV mips**

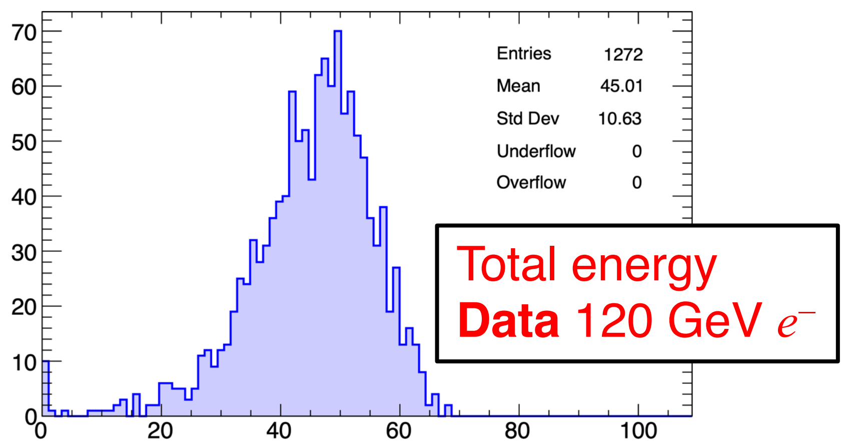


Meanwhile, complete MC developed for comparison to data taken at BTF and in H2

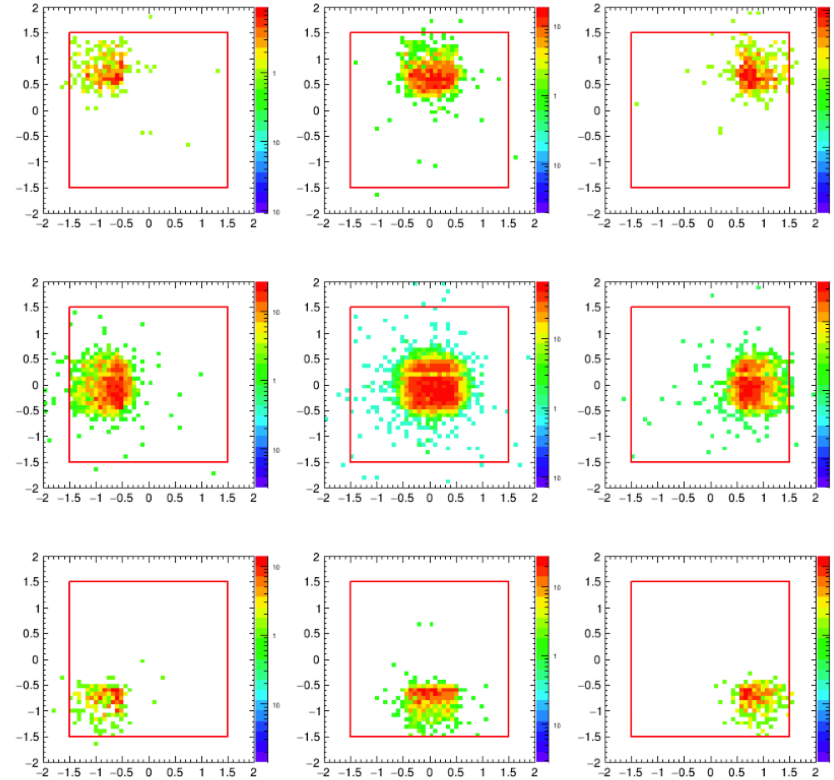


CRILIN validation

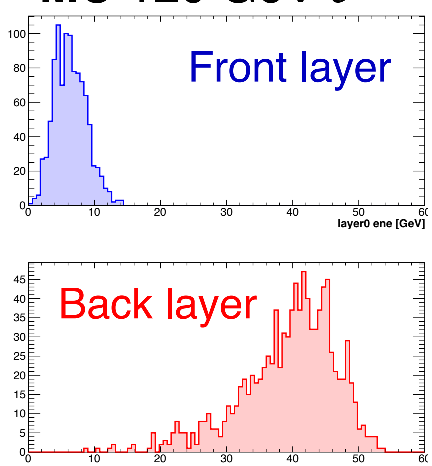




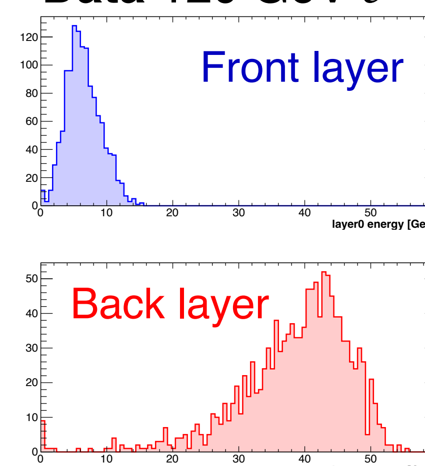
Tracking data with cuts on each crystal



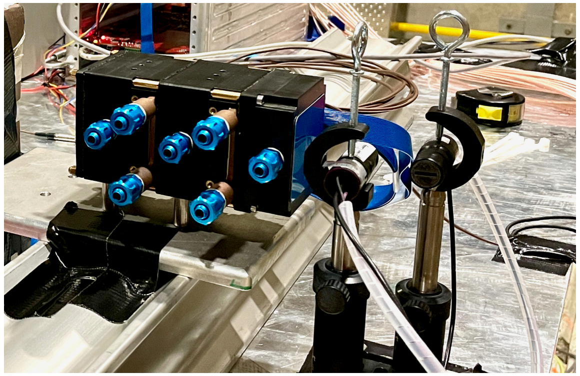
MC 120 GeV e^-



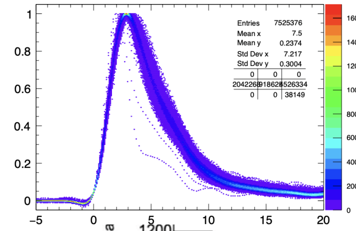
Data 120 GeV e^-



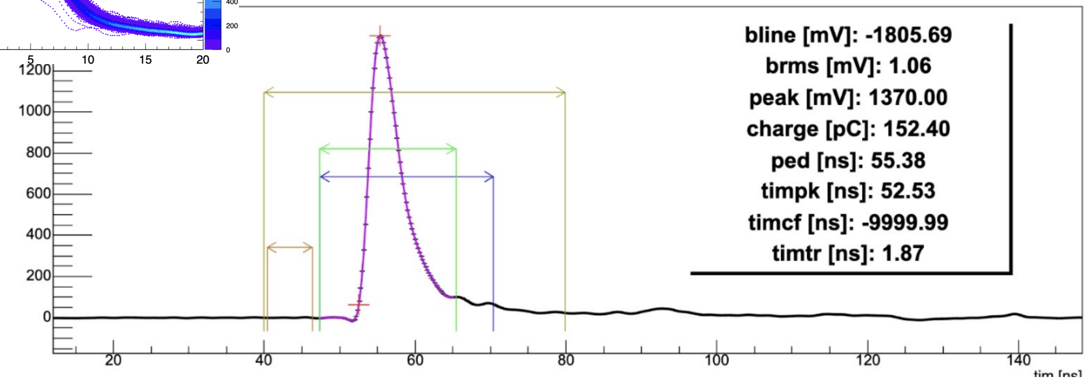
Reference t_0 and synchronization

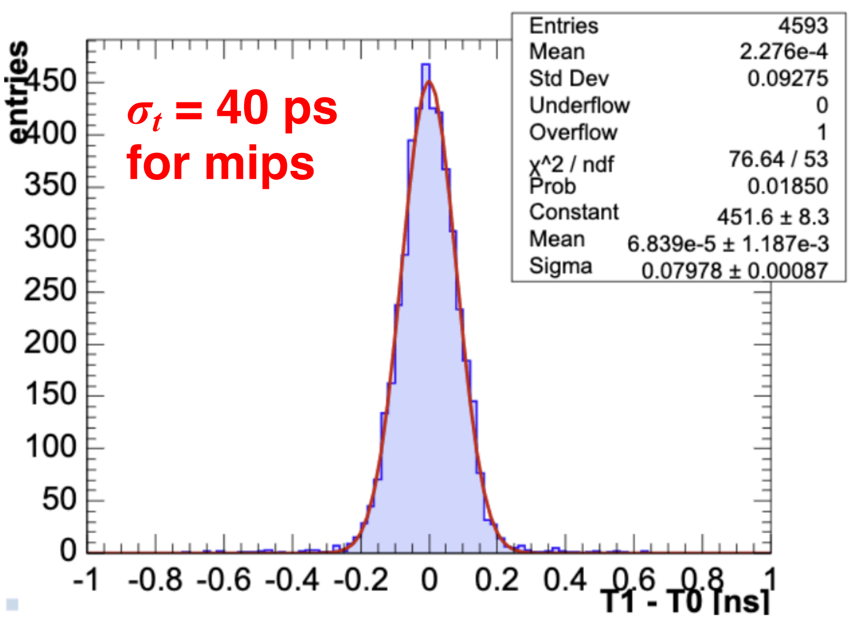


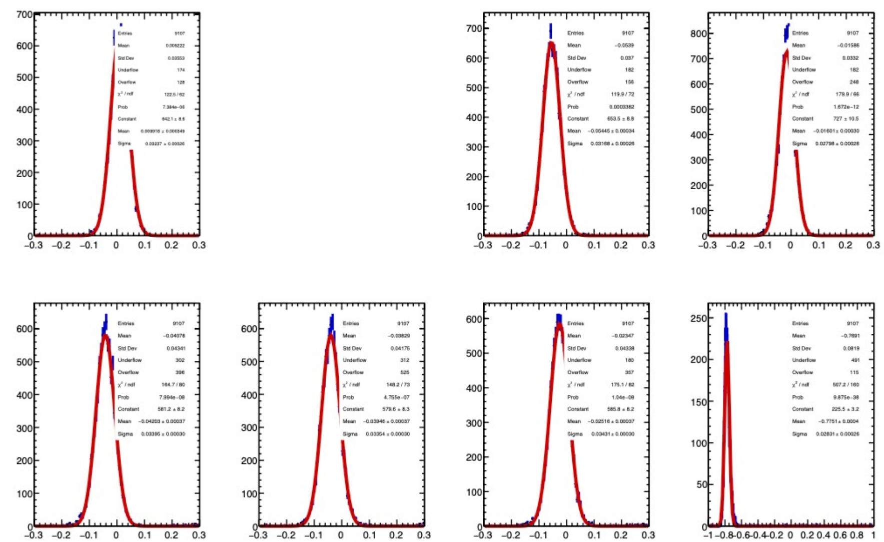
t_0 counter ("Cindy"):
Coincidence of 2 R9880 PMTs with 1 cm^3 fast scintillator



Waveform analysis and fitting same as for analysis of CRILIN signals



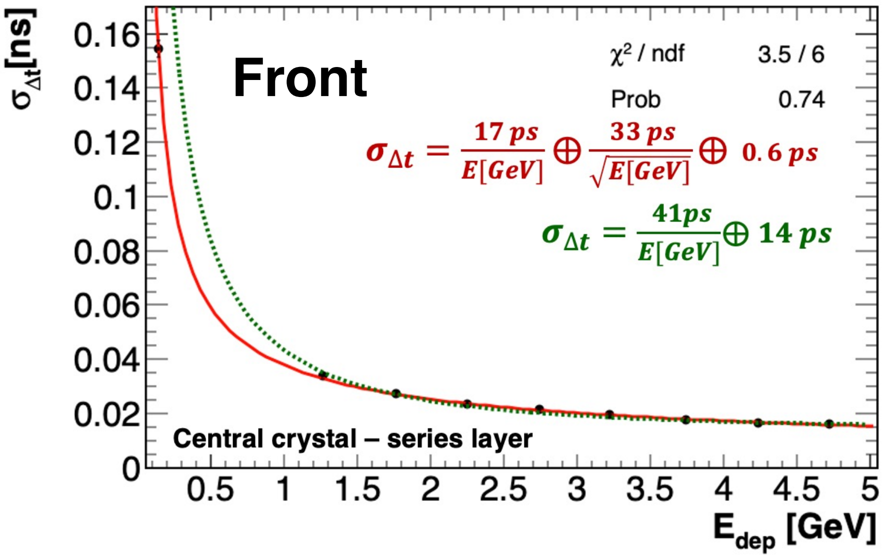




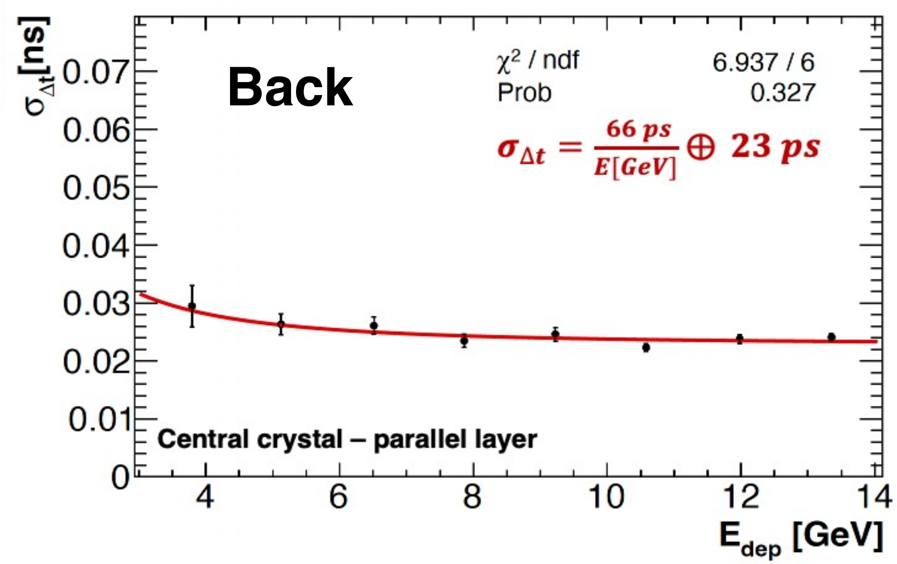
Synchronization between ADCs on V1742 by digitizing fast-trigger input

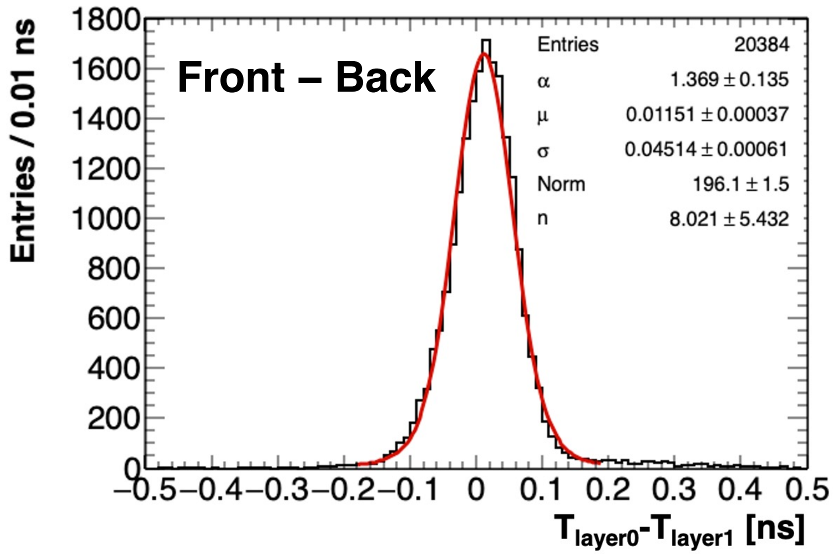
CRILIN time resolution

E. Di Meco, Pisa Meeting (in press)

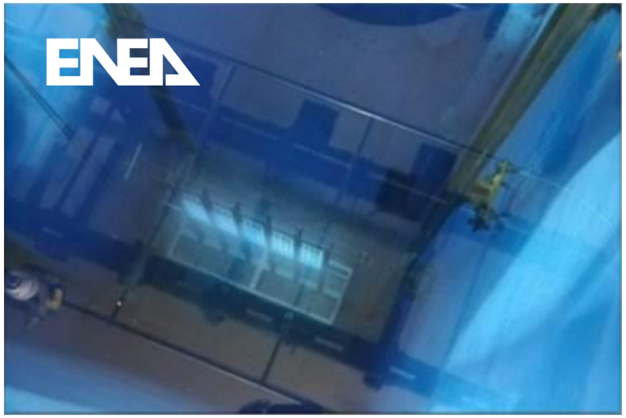


- Time resolution of **O(20 ps)** both in series (front) and parallel (back) layers using 2-channel time difference for central crystals
- Excellent results using most energetic crystal of different layers
- Time resolution dominated by the 2-board synchronisation jitter O(32ps)





Radiation hardness of PbF_2 and PWO-UF

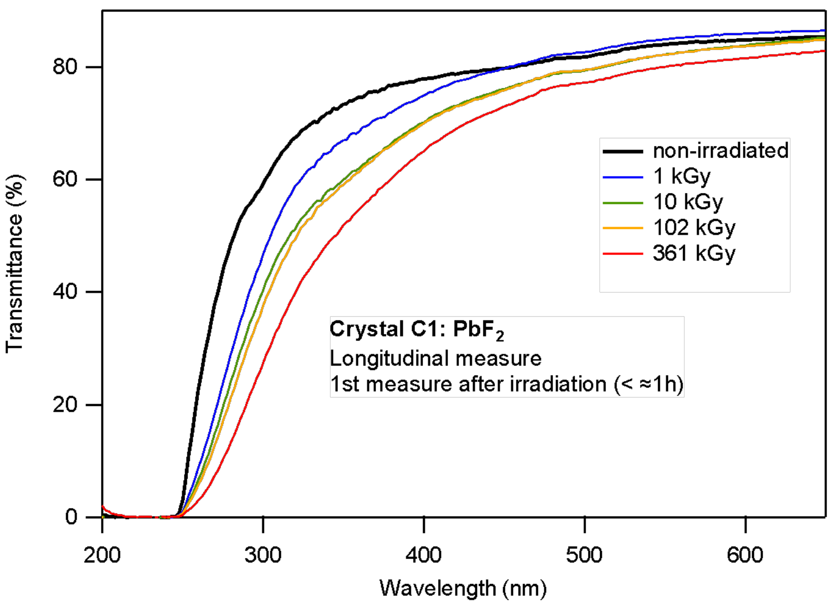


^{60}Co γ-irradiation tests at Calliope, ENEA Casaccia

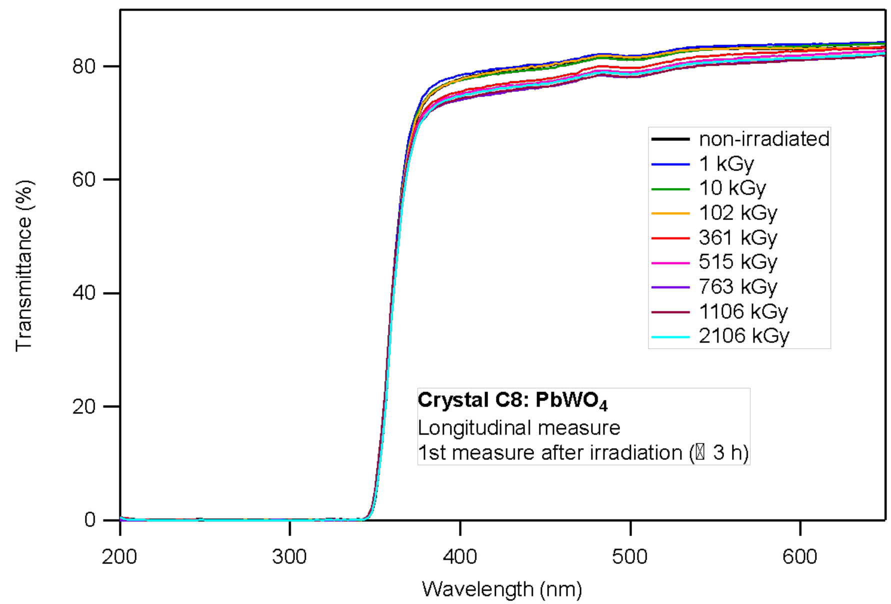
- Easy to accumulate MGy doses, full dosimetry support
- Support with transmission, light yield, fluorescence spectrometry measurements

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

PbF_2 irradiated to 361 kGy



PWO-UF irradiated to 2106 kGy!



IEEE Trans. Nucl. Sci. 71 (2024) 1116

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**

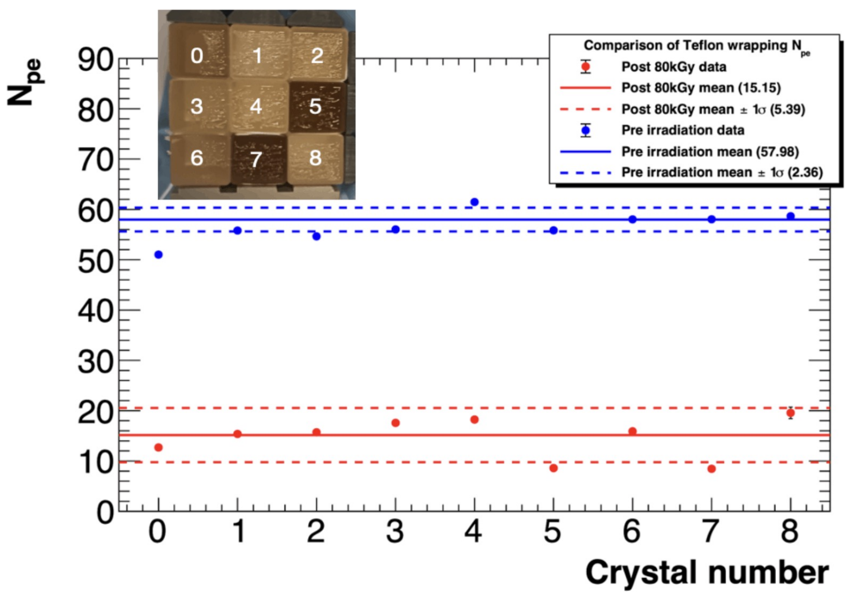
Preliminary conclusions:

- 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.

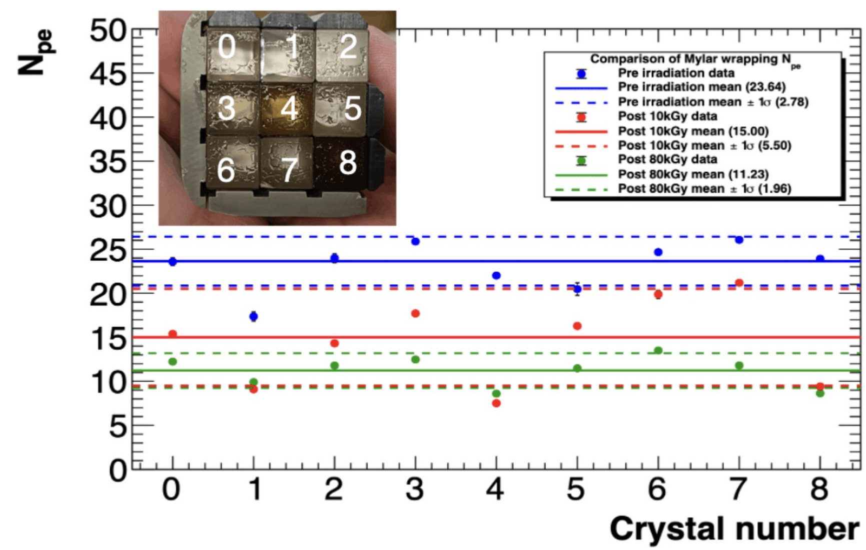
Irradiation beam test at BTF, Apr 2024

- 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

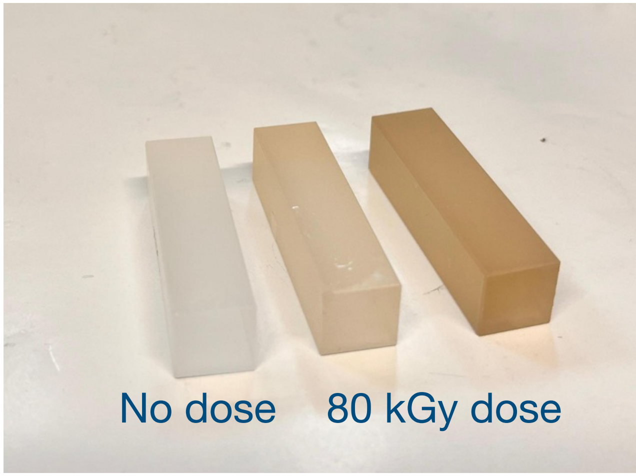


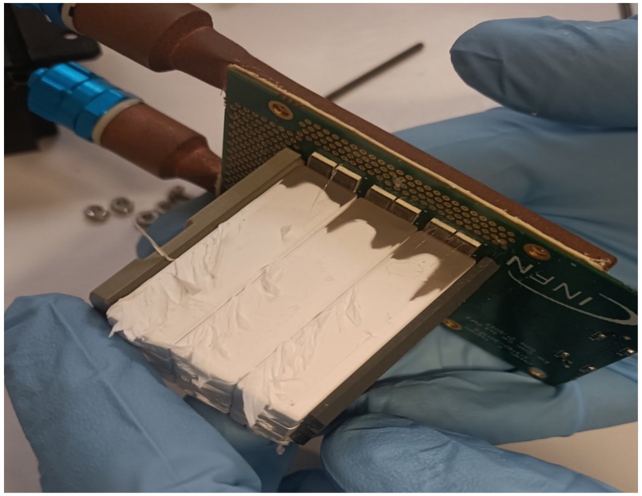
E. Di Meco, Pisa Meeting (in press)

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**

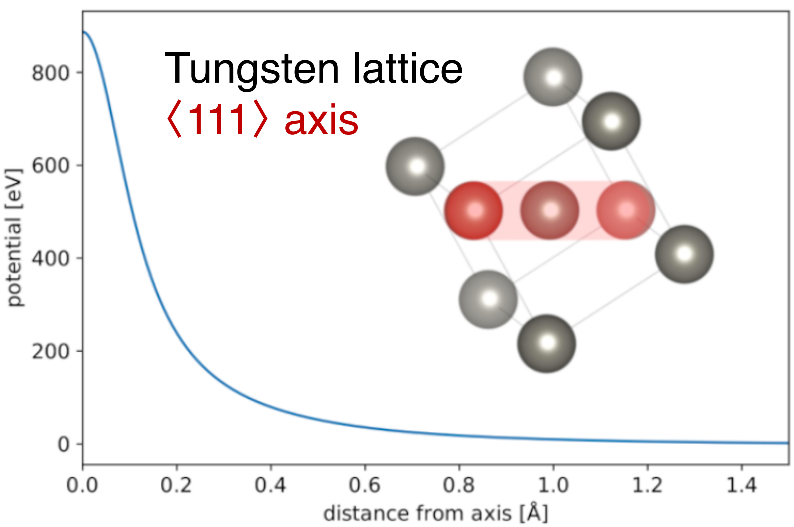




Coherent effects in crystals

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

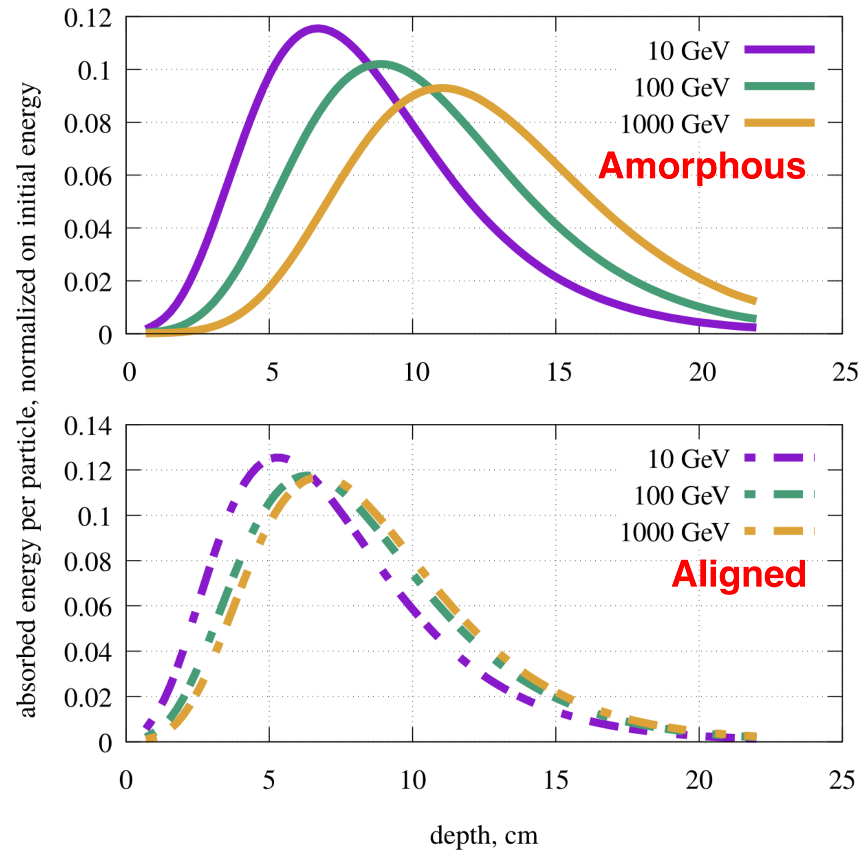
Electric field ε approx. const. ~ 10^{10}-10^{12} V/cm

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)

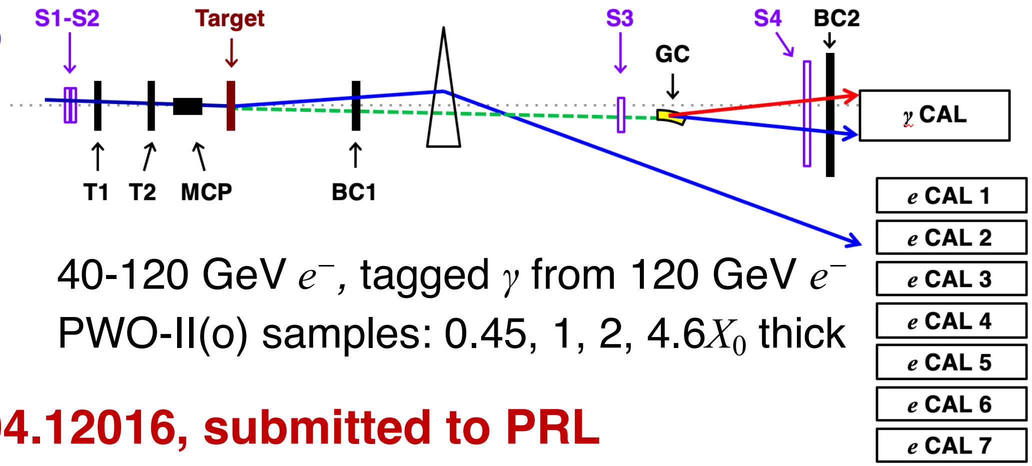


- Early initiation of EM showers
- Minimize fluctuations of deposited energy vs depth

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

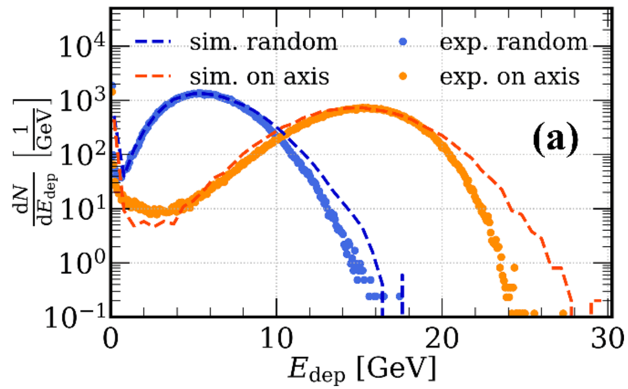


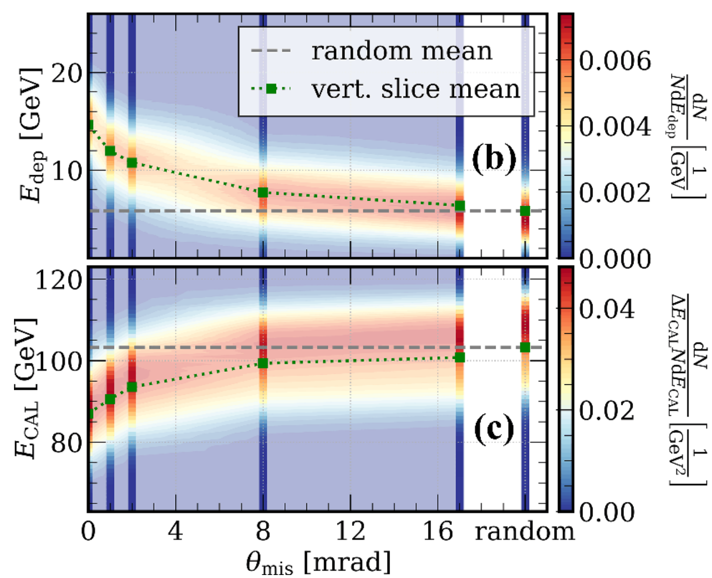
40-120 GeV e^-, tagged γ from 120 GeV e^-

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

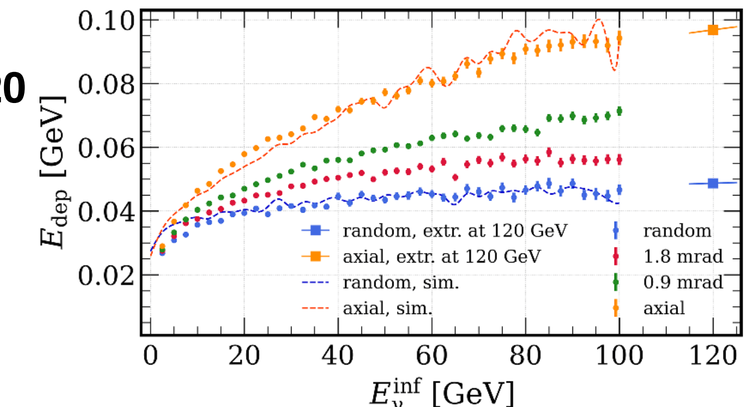
2404.12016, submitted to PRL

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

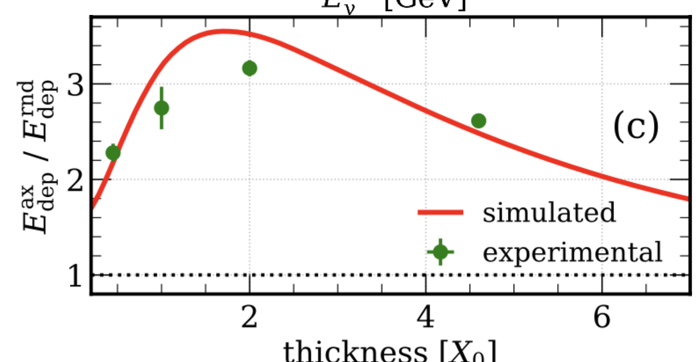




E_{dep} vs E_γ
Tagged γ from 120 GeV e^- on 1X_0



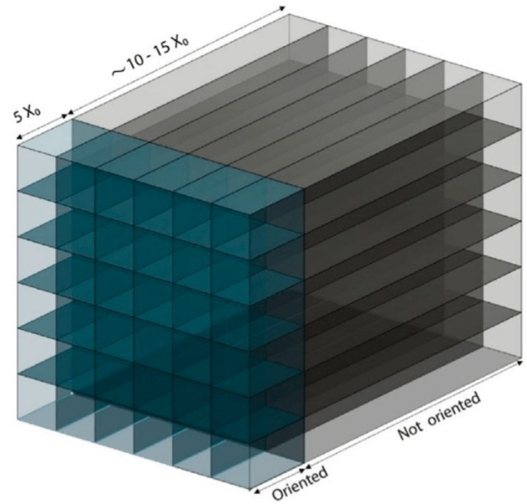
E_{dep} vs thickness
120 GeV e^-



OREO: An oriented-crystal calorimeter

Exploit coherent interactions in crystals to develop a highly compact calorimeter

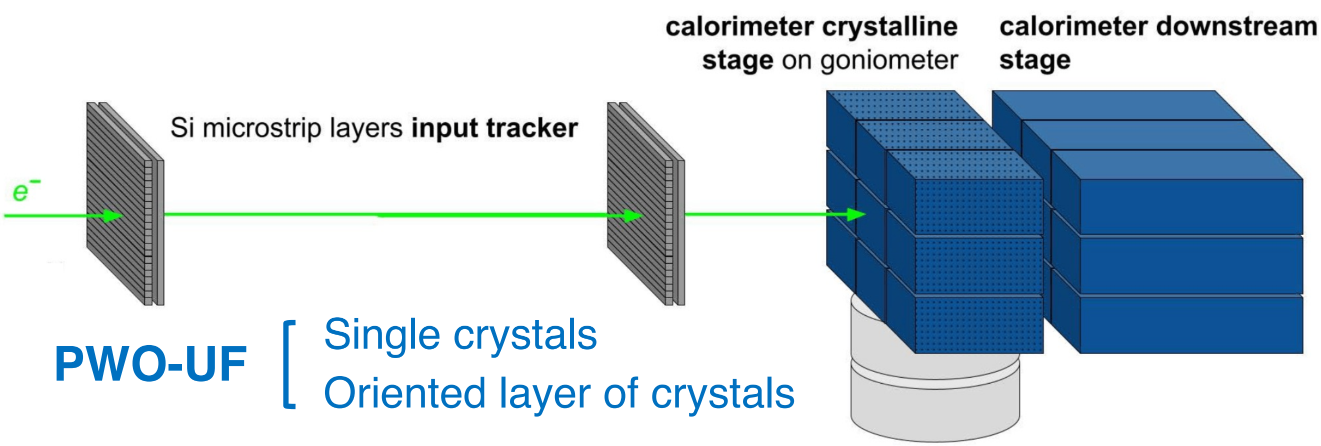
E.g. Small-angle calorimeter for HIKE:
Require good response to photons, high transparency to neutrons



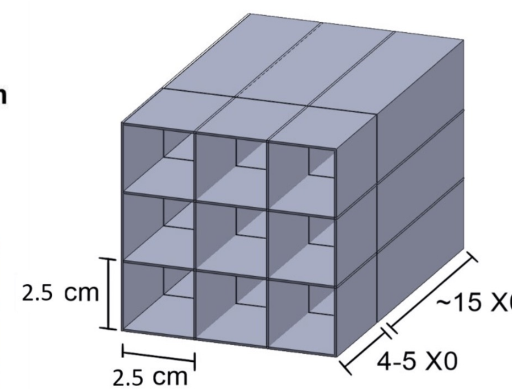
Areas of R&D:

- 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:



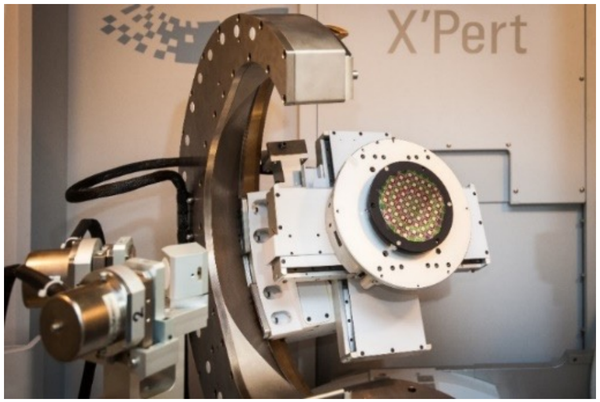
PWO-UF [Single crystals
Oriented layer of crystals



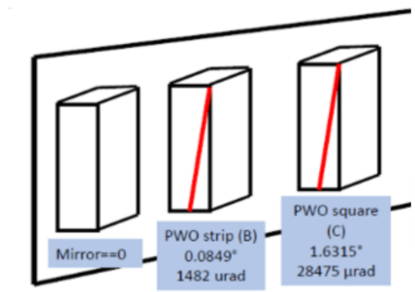
Techniques for crystal characterization

Front. Phys. 11 (2023) 1254020

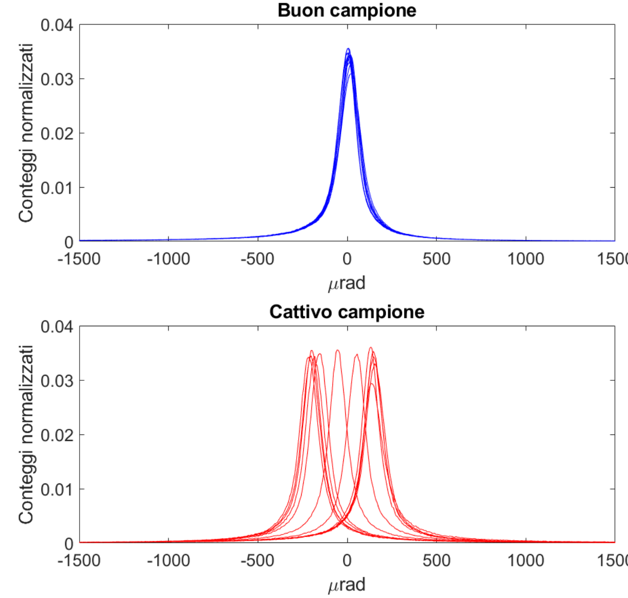
X-ray diffraction (Ferrara)
HR-XRD 8 keV



Measurement of axis inclination relative to face



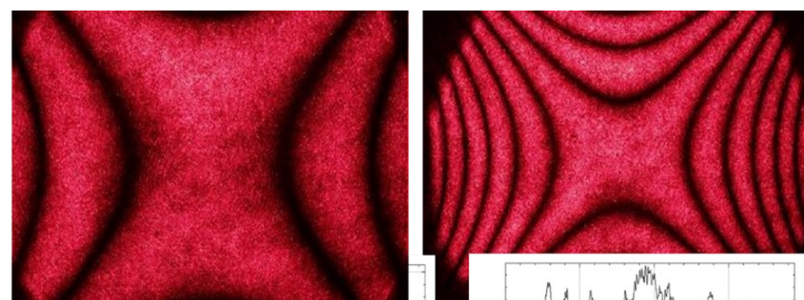
Surface scan of orientation

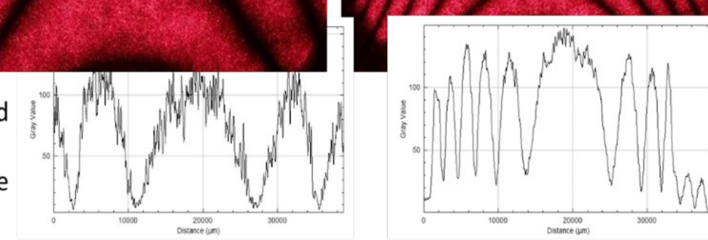


Photoelasticity measurements
Laser conoscopy (Ancona)

Internal stresses in crystal change polarization

Fringe order and symmetry contain information on crystallographic orientation and quality

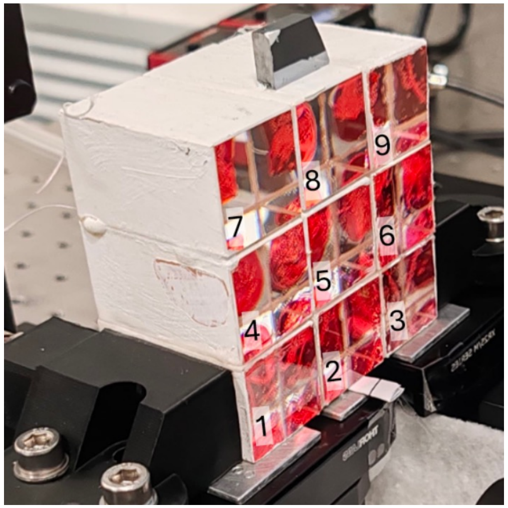


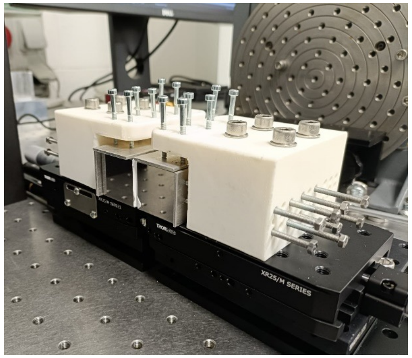


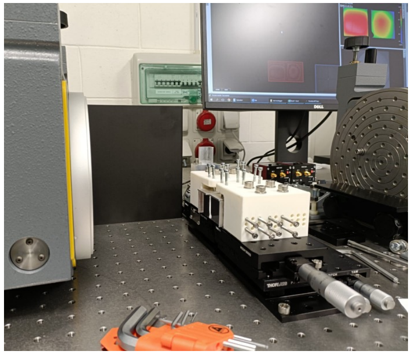
Typical image from face 4 (A) and face 1 (B).
The minima in the plots indicate the position of the fringes in the scene.

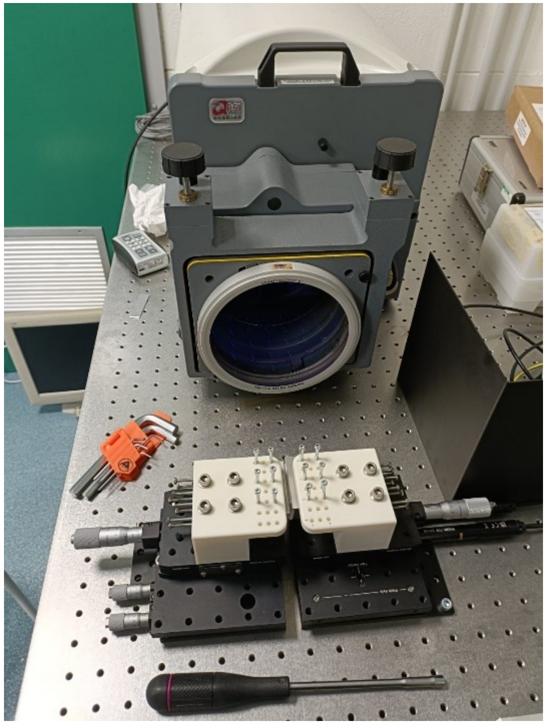
Technique for multi-crystal assembly

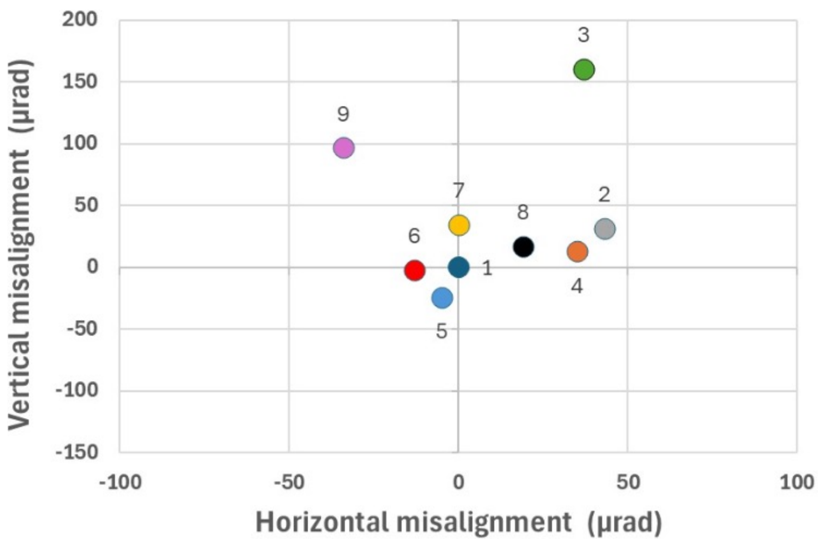
1. Crystals characterized and miscut measured
2. Surfaces painted with EJ-510
3. Mounted on vacuum fixture with 2 stages linear and 2 stages rotational motion
4. Inclination of front faces monitored during gluing with wide FOV laser interferometer
5. Epoxy applied at gel point and fine adjustments made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











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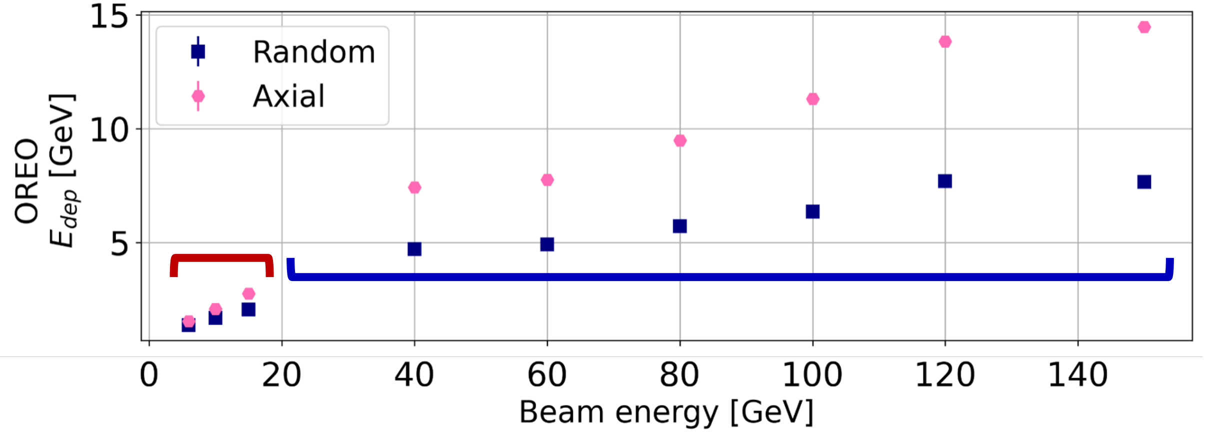
A. Selmi, Pisa Meeting (in press)

OREO preliminary beam test results

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

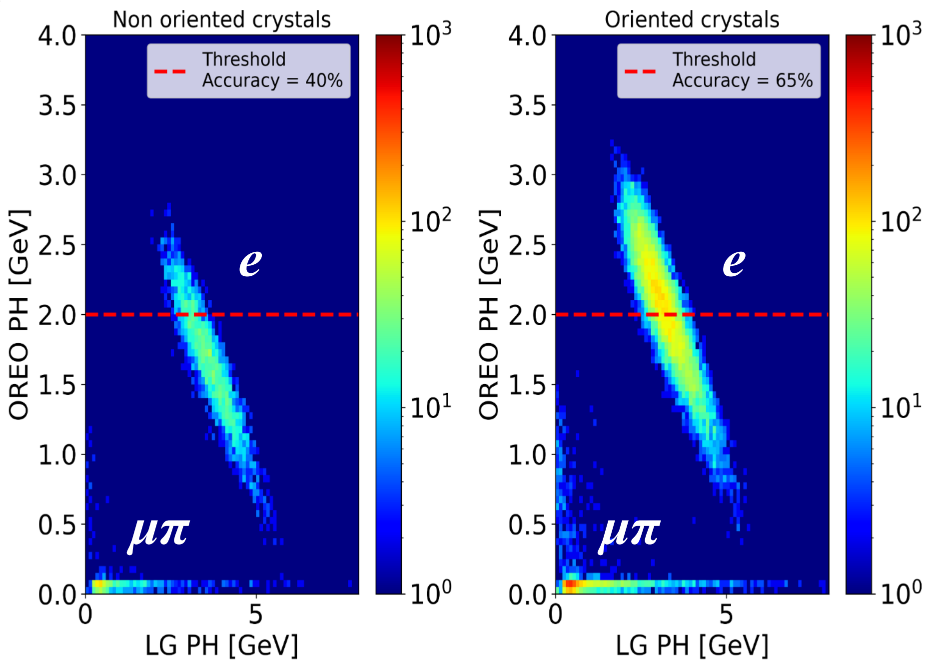
- Matrix on goniometer
- OPAL PbGl block used as second layer

Energy deposition in 3x1 layer (Aug 23)



PS T9
Sub-SF regime

SPS H4
Full strong-field (SF) regime

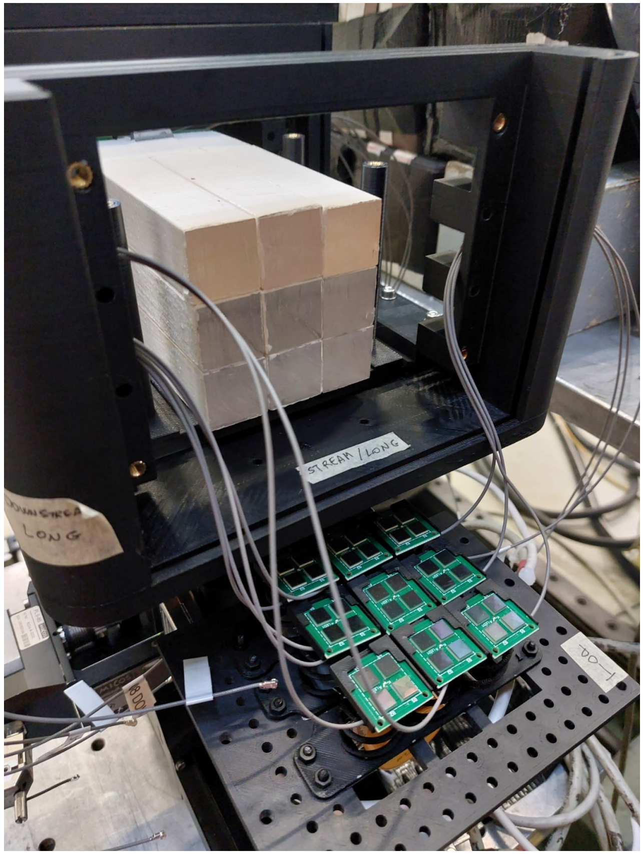


Deposited vs transmitted energy in 2x2 layer – PS T9 (Oct 23)

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

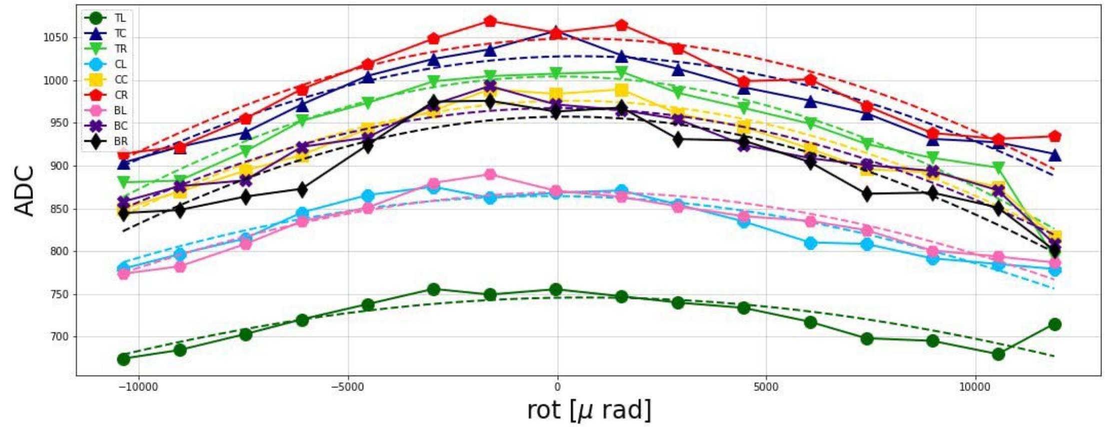
Results with full-scale prototype from Jun 2024 currently under analysis!

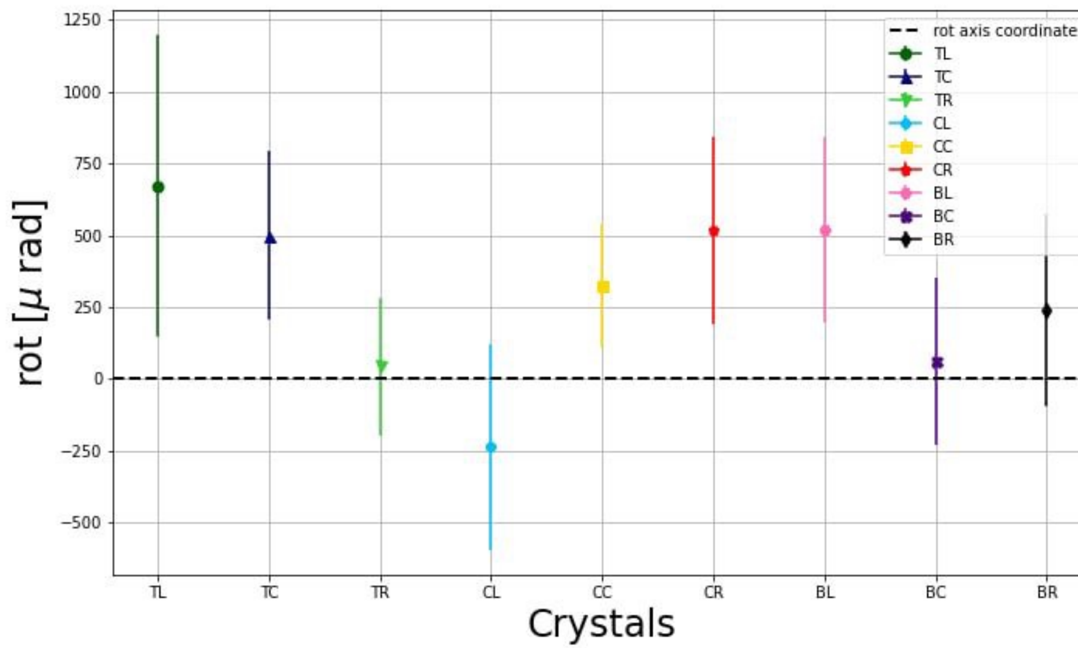
Jun 2024: Not even preliminary!



Full scale OREO prototype on T9 beamline, Jun 2024

Alignment quality from angular scan



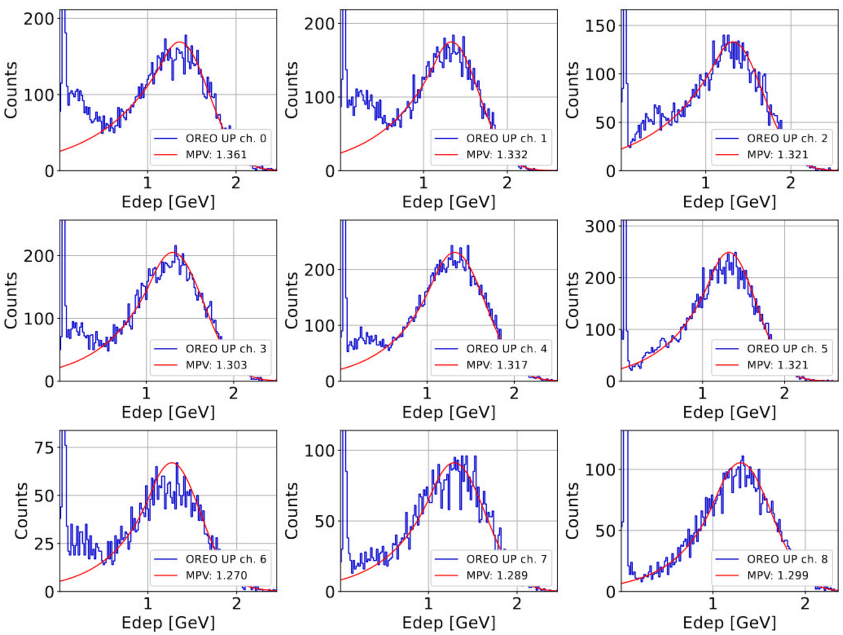


Jun 2024: Not even preliminary!

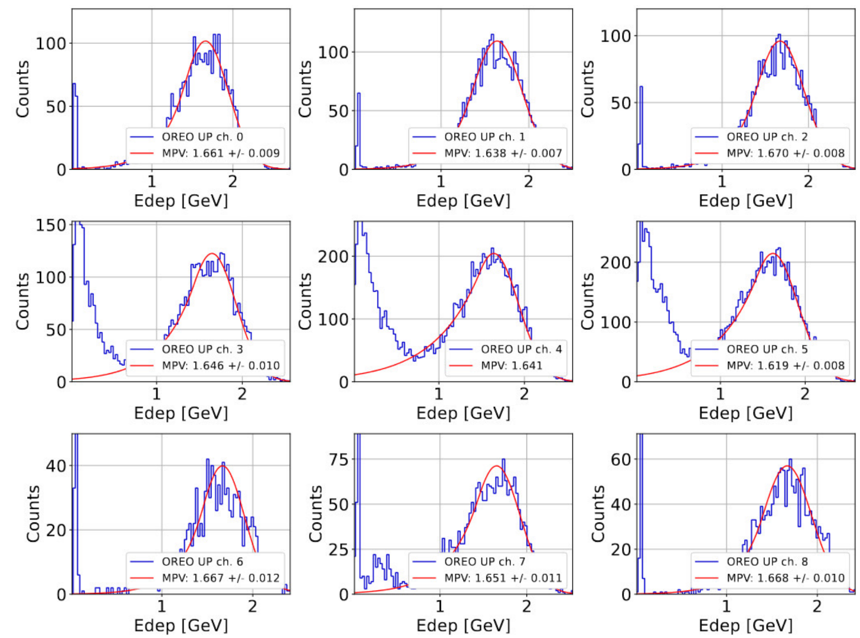
First layer, OREO full-scale prototype

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