

Calorimetry for future kaon experiments

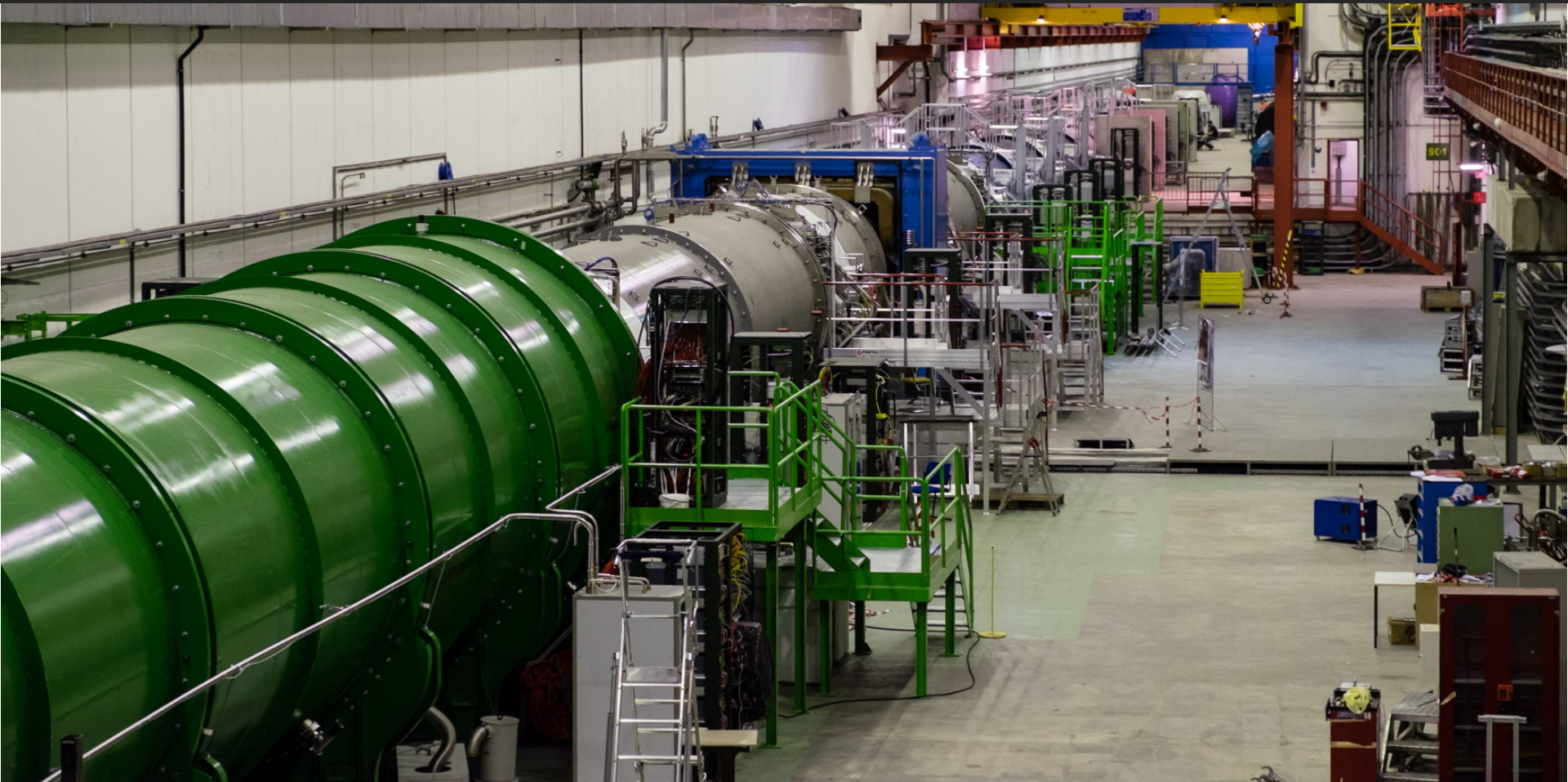
Matthew Moulson

INFN Frascati

Fourth Italian Workshop on Physics at High Intensity (WIFAI 2025)

Bari, 11 November 2025

The NA62 experiment at the CERN SPS

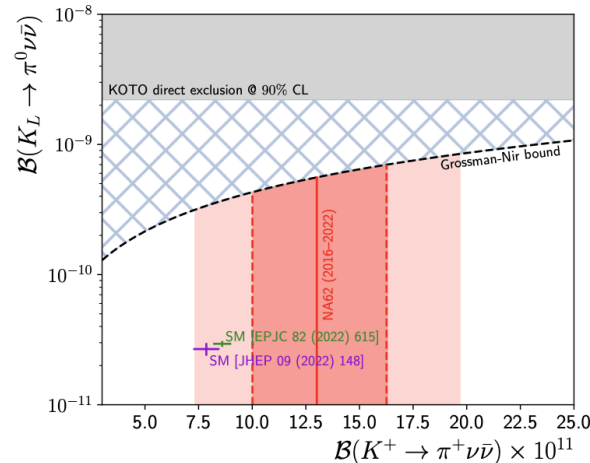
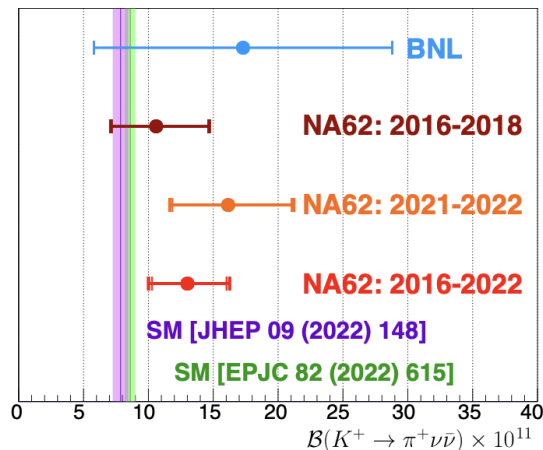
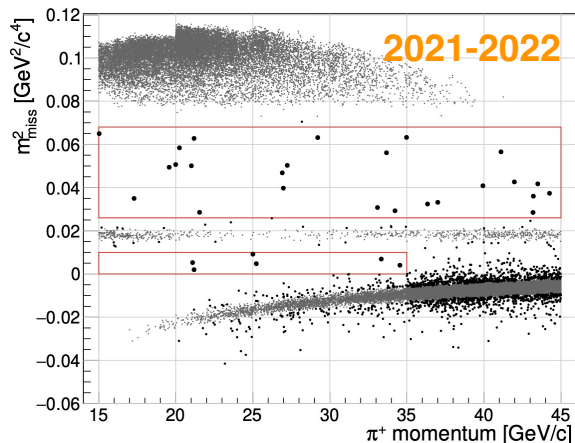


BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) from NA62



$$\text{BR}_{16-22}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (13.0^{+3.0}_{-2.7 \text{ stat}} \pm 1.3_{\text{syst}}) \times 10^{-11}$$

JHEP 02 (2025) 191



New $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ result from 2021-2022 data!

- Expected signal (SM): 10 events
- Expected background: 11 events
- Total observed: 31 events

Combined with result from 2016-2018 data:

- Total observed: 51 events, 18 expected background
- First conclusive ($> 5\sigma$) observation of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

- 22 SM signal events expected in 2023-2024 data
- Similar amount expected from 2025-2026 data

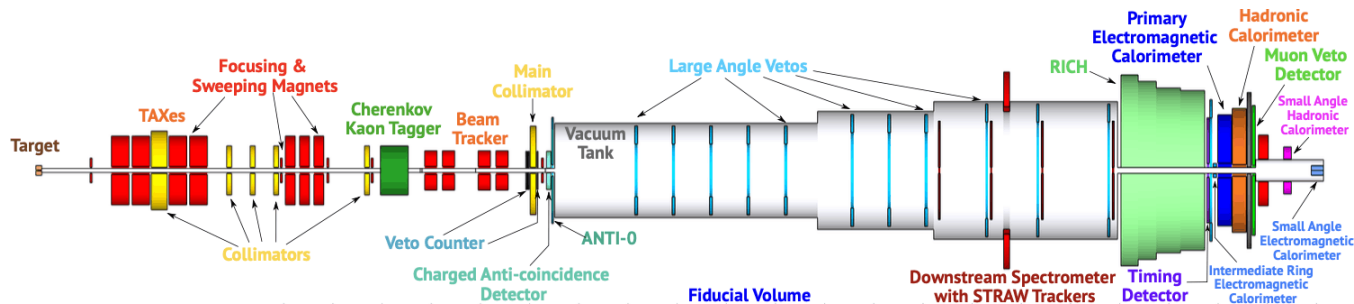
**NA62 expects to measure
BR($K^+ \rightarrow \pi^+ \nu \bar{\nu}$) to 15-20%
by LS3 (Aug 2026)**

From NA62 to HIKE

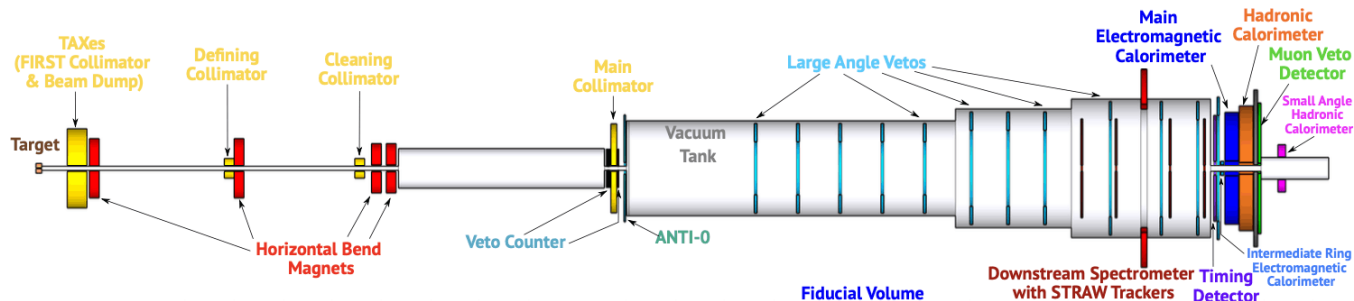
HIKE was a multi-phase, general purpose kaon experiment proposed to extend the NA62 physics program into the HL-LHC era and beyond



Phase 1: $K^+ \rightarrow \pi^+ \nu \nu$ to 5%, LFV/LNV & other rare decays, precision mmts



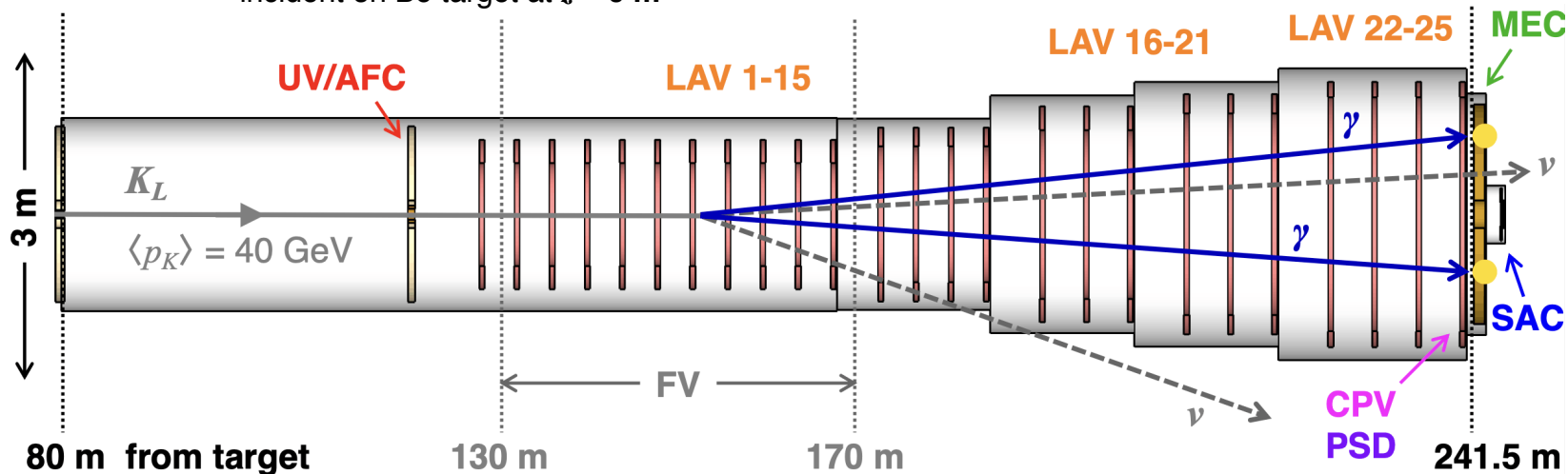
Phase 2: $K_L \rightarrow \pi^0 \ell \ell$ to 12-18%, LFV/LNV & rare decays, precision mmts



Plus FIP searches with kaon beams and in periodic dump-mode runs

K_LEVER

400-GeV SPS proton beam (2×10^{13} pot/16.8 s)
incident on Be target at $z = 0$ m


$$\delta\text{BR}/\text{BR}(\pi^0\nu\nu) \sim 20\%$$

Pre-shower detector

The end of kaon physics at CERN

Original plan:

HIKE to succeed NA62 in ECN3 hall at CERN SPS after LS3

15-year program with start of data taking around 2030

Phase 1: K^+ beam, 4x NA62 primary intensity

$K^+ \rightarrow \pi^+ \nu \nu$ to 5%, LFV/LNV & other rare decays, precision measurements

Phase 2: K_L beam, 6x NA62 primary intensity

$K_L \rightarrow \pi^0 \ell \ell$ to 12-18%, LFV/LNV & rare decays, precision measurements

HIKE proposal SPSC-P-368 (2311.02831) made public Oct 2023

Decision of CERN Directorate at Research Board, 06 Mar 2024:

SHiP experiment approved to run in ECN3 after LS3

HIKE physics case judged excellent, but decision made on “strategic” grounds

NA62 experiment will begin to decommission at start of LS3 (Aug 2026)

- No dedicated kaon experiment at CERN for the first time in many decades
- No experiment to carrying out the HIKE suite of measurements at any facility in the world

$K_L \rightarrow \pi^0 \nu \bar{\nu}$ at J-PARC



Primary beam: 30 GeV p

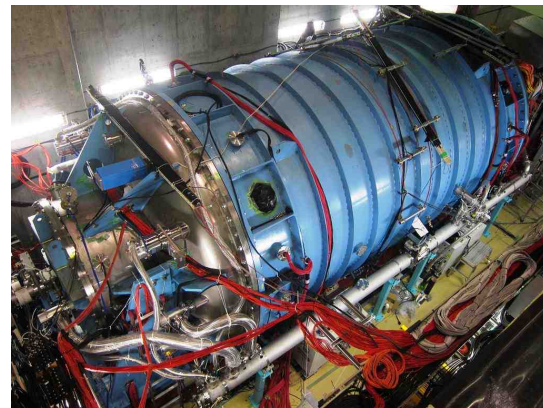
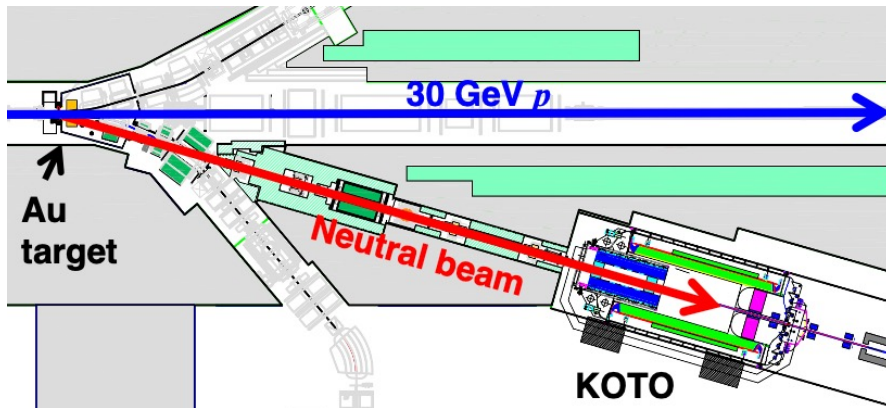
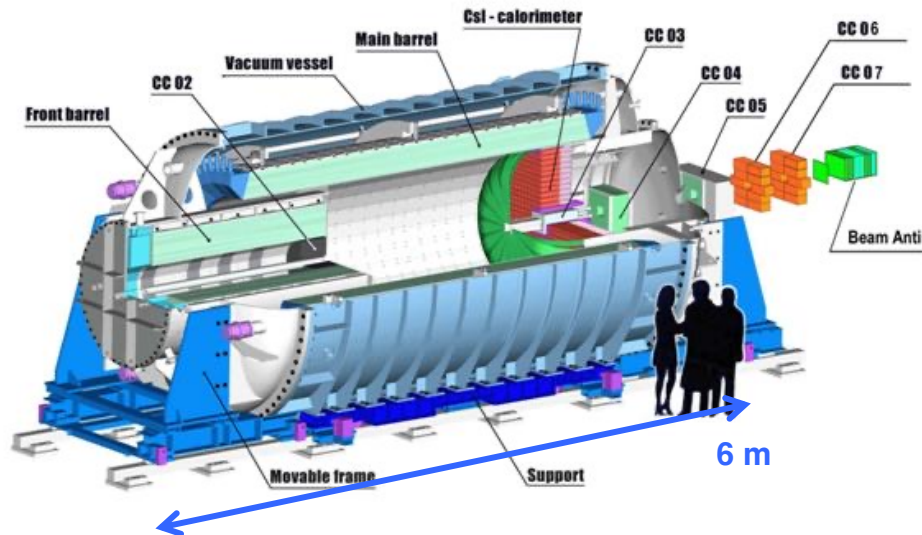
92 kW = 8×10^{13} p/4.2 s

Neutral beam at 16°

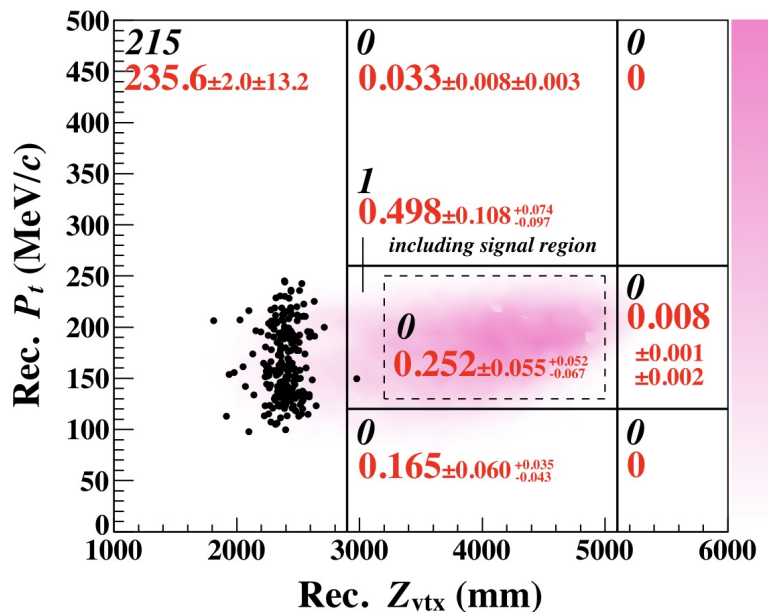
$\langle p(K_L) \rangle = 2.1$ GeV

50% of K_L have 0.7-2.4 GeV

8 μ sr “pencil” beam



Recent result for $\text{BR}(K_L \rightarrow \pi^0 \nu \nu)$



Main expected backgrounds

Source	Expected
π^0 from upstream int.	0.060 ± 0.047
$K_L \rightarrow \pi^0 \pi^0$	0.059 ± 0.059
$K_L \rightarrow \gamma \gamma$ halo	0.045 ± 0.012
$K_{e3}^\pm + K_{\mu 3}^\pm + K_{\pi 2}^\pm$	0.042 ± 0.032
n interaction in Csl	0.024 ± 0.007
η production in CV	0.023 ± 0.013
Total	0.252 ± 0.087

PRL 134 (2025) 081802

$\text{BR}(K_L \rightarrow \pi^0 \nu \nu) < 2.2 \times 10^{-9}$ (90%CL)

2021 data: Total K_L flux $\sim 7 \times 10^{12}$

SES = 9.33×10^{-10} c.f 7.2×10^{-10} in 2016-2018

0.032 SM signal + 0.255 background events expected

No events in signal box

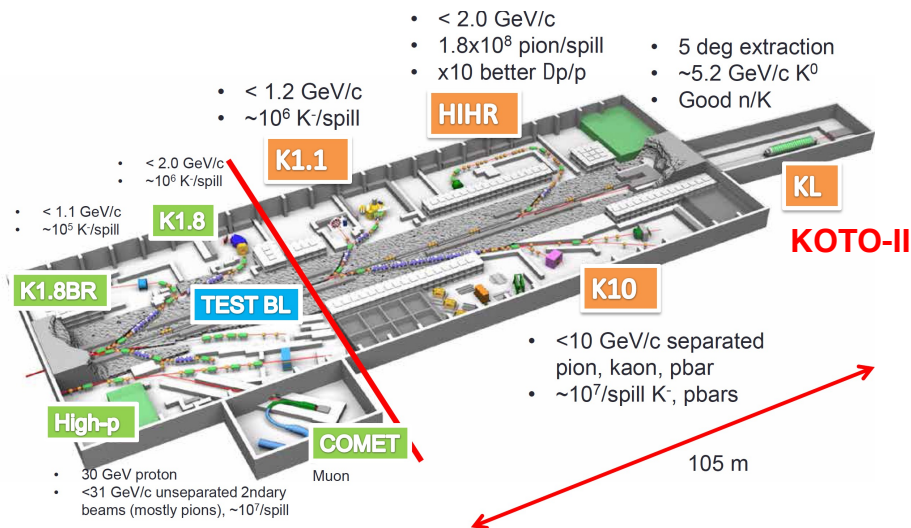
**Expect to reach SES $< 10^{-10}$
by end of KOTO running
(2030?)**

KOTO long-term plans



- Long-term plan outlined in 2006 proposal to upgrade to O(100) SM event sensitivity
- Stage-1 proposal submitted Jan 2025 – obtained scientific approval by J-PARC PAC

- Increase beam power to > 100 kW
- New neutral beamline at 5°
 $\langle p(K_L) \rangle = 5.2$ GeV
- Increase FV from 2 m to 12 m
Complete rebuild of detector
- **Requires Hadron Hall extension**

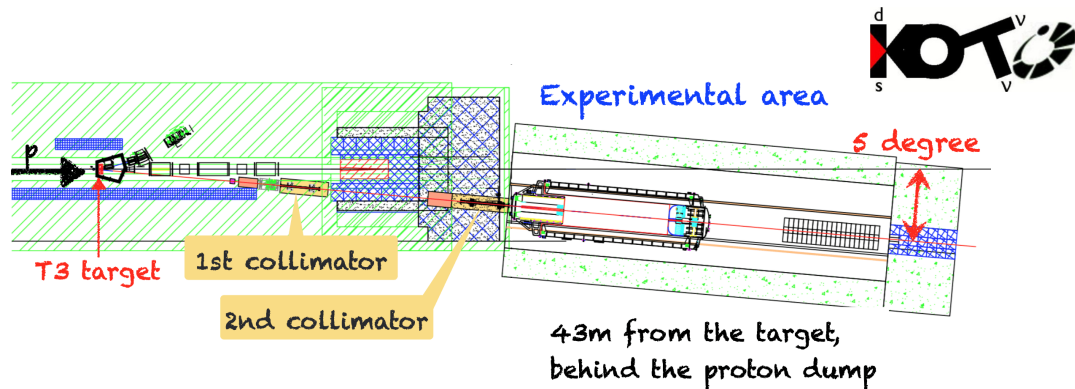


- Hadron Hall extension is a joint project with nuclear physics community
- Extension is supported by KEK Project Implementation Plan since 2022
Top priority for new budget requests

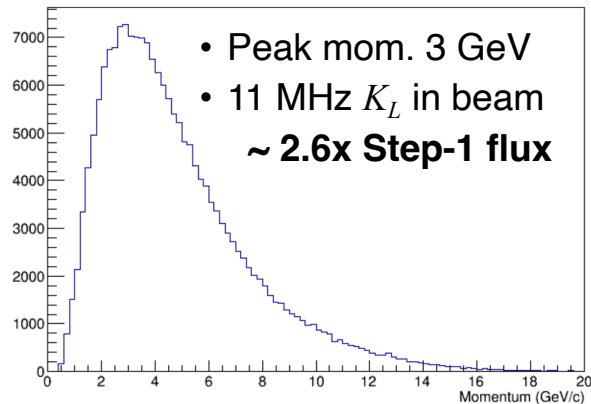
KOTO-II detector

Step-2 beamline setup in Hadron Hall extension

- Smaller angle ($16^\circ \rightarrow 5^\circ$)
- Longer beamline (20 $\rightarrow$ 43 m)
- 2 collimators

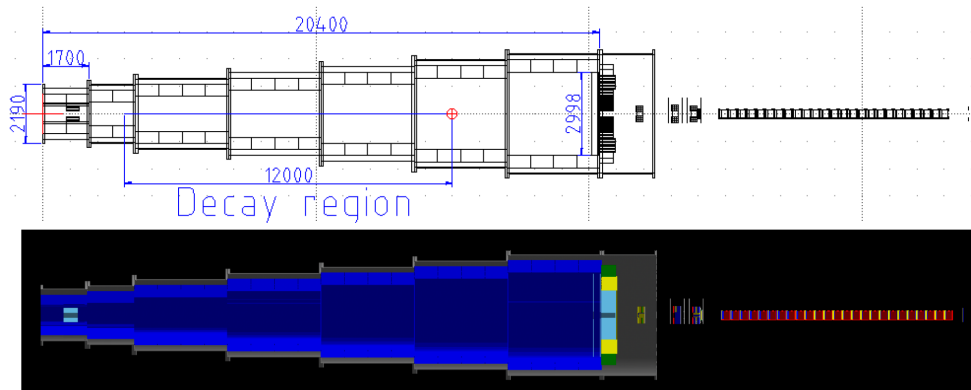


K_L spectrum at beam exit



~ 35 SM evts with $S/B \sim 0.9$

4-5x increase in fiducial volume for K_L decays to maintain geometric acceptance while improving selection efficiency



BR($K_L \rightarrow \pi^0 \nu \nu$) to 25%: New physics at 90% CL for 40% deviation from SM

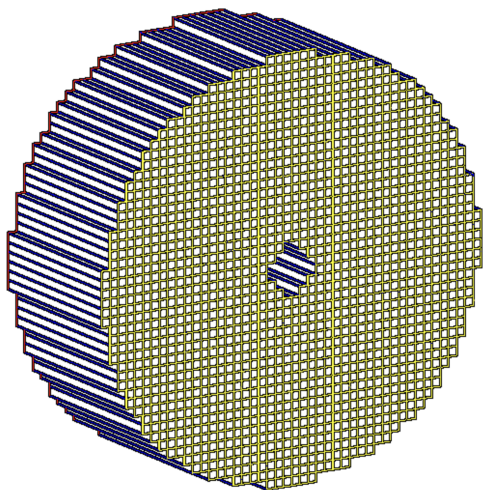
The HIKE Main Electromagnetic Calorimeter

NA62 currently uses NA48 liquid-krypton calorimeter (LKr)

- Quasi-homogeneous ionization calorimeter: $27X_0$ of LKr
- Photon efficiency likely adequate even for K_L program
- Time resolution inadequate for HIKE
 - $\sigma_t \sim 500$ ps for π^0 with $E_{\gamma\gamma} > 20$ GeV
 - Need 4x improvement in K^+ phase to maintain accidental veto
 - Critical for K_L phase: Accidental rate ~ 140 MHz!
- For K_L phase, LKr inner bore limits beam solid angle

$$\frac{\sigma_E}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\%$$

$$\sigma_t = \frac{2.5 \text{ ns}}{\sqrt{E}}$$



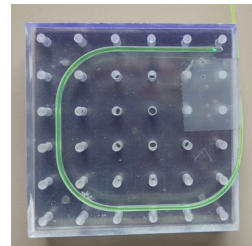
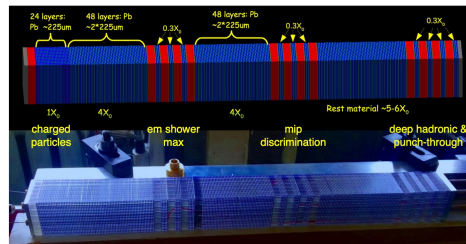
Baseline MEC concept:

Fine-sampling shashlyk like PANDA forward EM calorimeter produced at Protvino

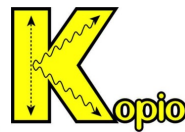
Possible to obtain longitudinal shower information from spy tiles

- PID information: identification of μ , π , n interactions
- Shower depth information: improved time resolution for EM showers

1st prototype assembled in Protvino and tested at OKA in April 2018 and DESY in Nov 2019



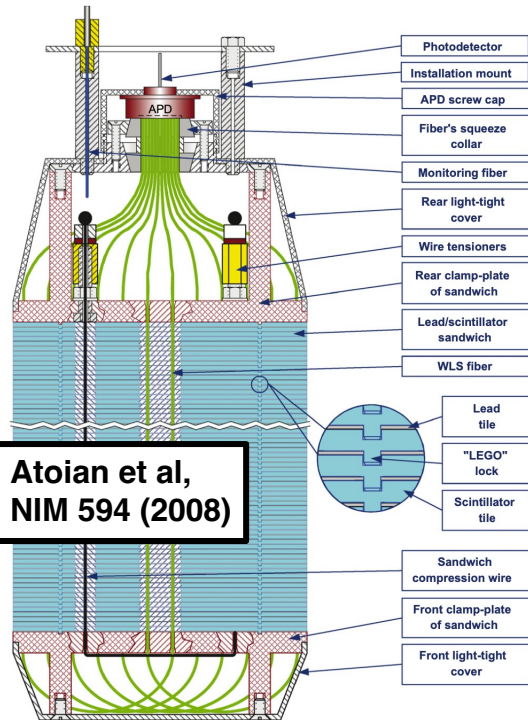
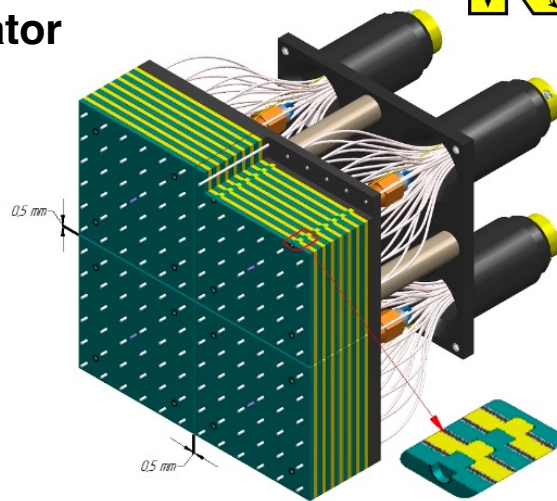
The KOPIO/PANDA fine-sampling shashlyk



0.275 mm Pb + 1.5 mm scintillator

Parameters of the improved Shashlyk module

Transverse size	110 × 110 mm ²
Scintillator thickness	1.5 mm
Spacing between scintillator tiles	0.350 mm
Lead absorber thickness	0.275 mm
Number of the layers	300
WLS fibers per module	72 × 1.5 m = 108 m
Fiber spacing	9.3 mm
Hole diameter (lead/scintillator)	1.3 mm
Diameter of WLS fiber (Y11-200MS)	1.0 mm
Fiber bunch diameter	14.0 mm
External wrapping (TYVEK paper)	150 μm
Effective radiation length, X_0	34.9 mm
Effective Moliere radius, R_M	59.8 mm
Effective density	2.75 g/cm ³
Active depth	555 mm (15.9 X_0)
Total depth (without photo-detector)	650 mm
Total weight	21 kg

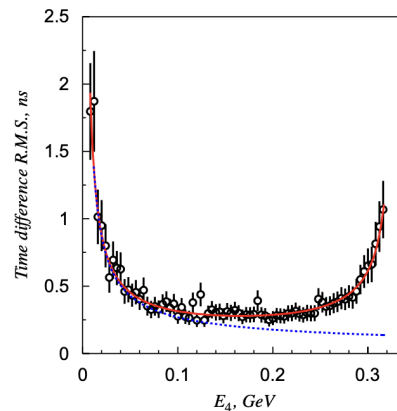
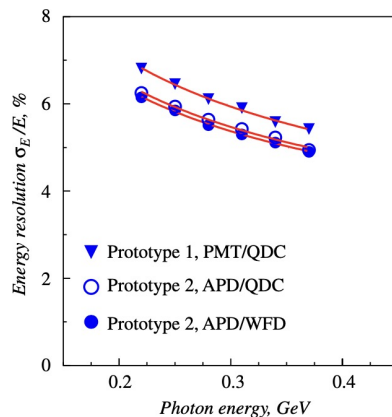


Atoian et al,
NIM 594 (2008)

KOPIO prototype:

300 layers, APD readout

- $\sigma_E/\sqrt{E} \sim 3\% \sqrt{E}$ (GeV)
- $\sigma_t \sim 72 \text{ ps} \sqrt{E}$ (GeV)
- $\sigma_x \sim 13 \text{ mm} \sqrt{E}$ (GeV)



PANDA prototypes:

380 layers

PMT readout (R7899)

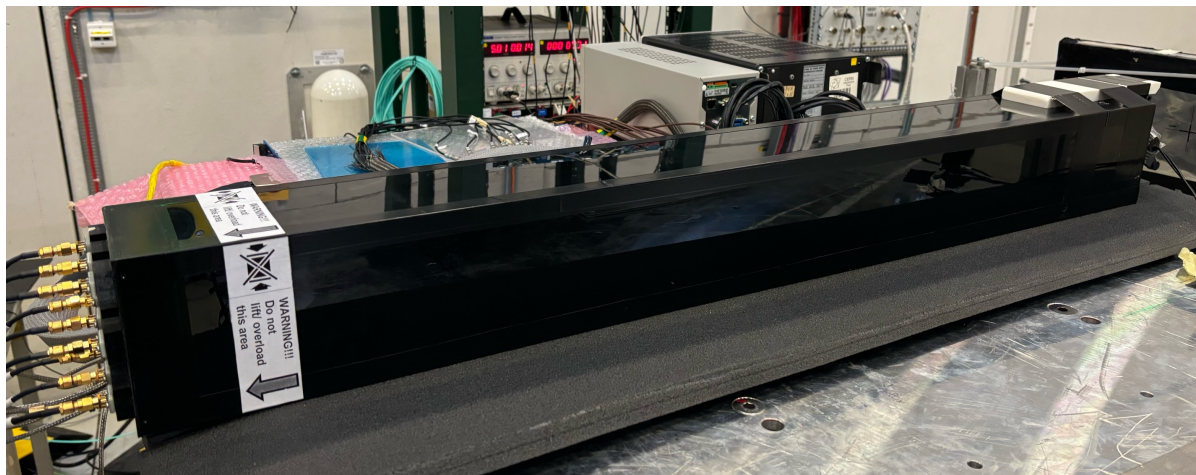
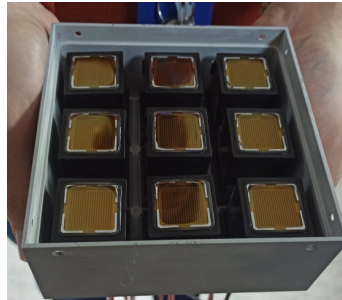
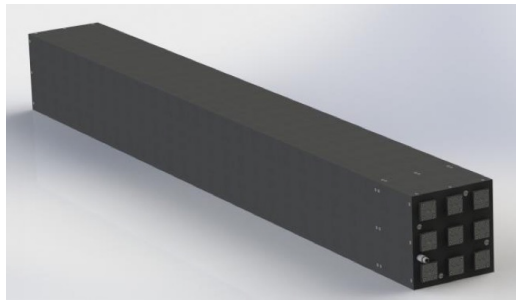
- $\sigma_E/\sqrt{E} \sim 3.5\% \sqrt{E}$ (GeV)
- $\sigma_t \sim 100 \text{ ps} \sqrt{E}$ (GeV)
- $\sigma_x \sim 15 \text{ mm} \sqrt{E}$ (GeV)

PANDA FS TDR
1704.02713

Shashlyk prototype for HIKE

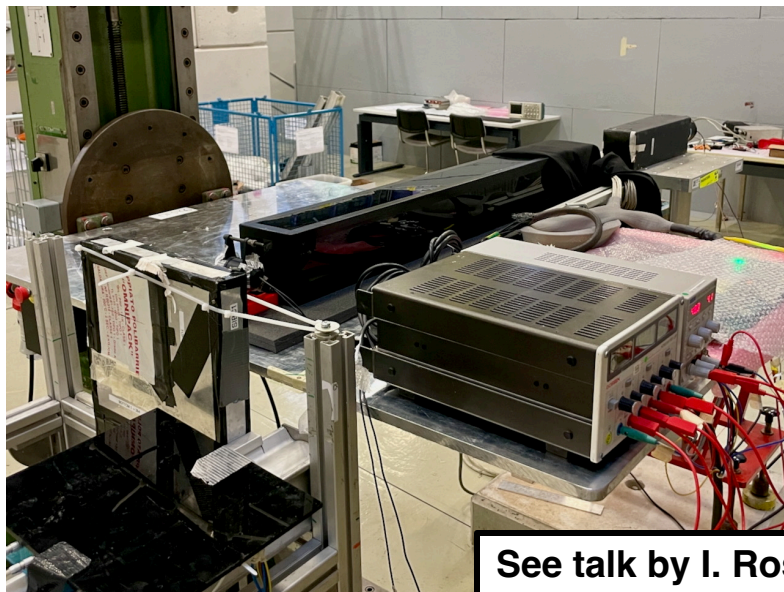
Design similar to PANDA forward EM calorimeter:

- Very fine sampling
 - 0.3 mm Pb/1.6 mm scintillator
- ISMA UPS-923A scintillator
 - 2% PTP + 0.03% POPOP
- BCF-92XL WLS, 1.2 mm dia.
- 500-layer depth = $27X_0$
 - Can be reconfigured
- Fine granularity
 - 3x3 cells, 4x4 cm² each
- Alternatives for light readout
 - SiPM: Hamamatsu S13360-6025
 - PMT: R7600-300 (green ext.)
- Parts & main assembly at ISMA



Test beam studies of shashlyk prototype

Tests with 1-6 GeV e^- T9 beamline, Oct 2024

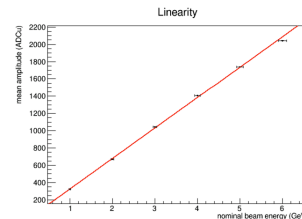
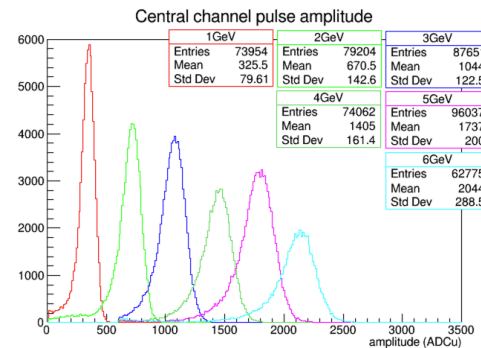


See talk by I. Rosa

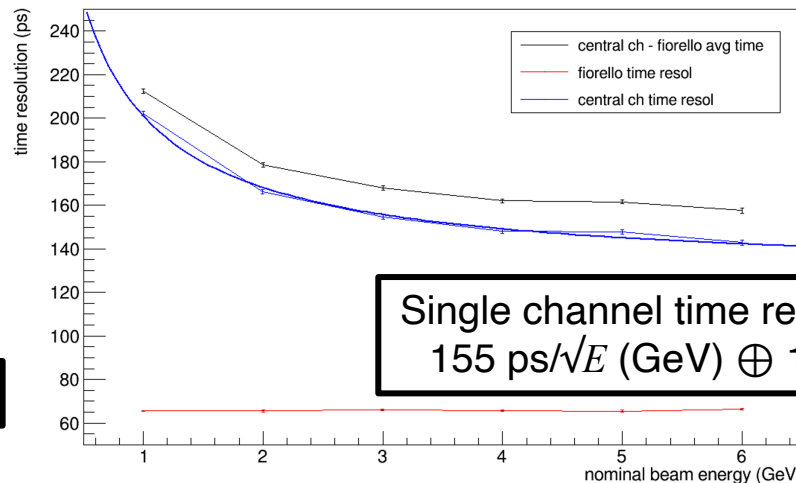
Second beam test 03-10 Sep 2025!

Dual side readout with R9880-20 PMTs

- Good amplitude linearity for single channels
- Analysis in progress



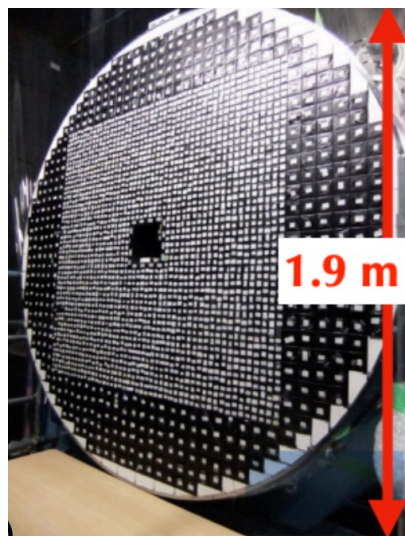
Central PMT time resolution



Single channel time resolution
 $155 \text{ ps}/\sqrt{E} \text{ (GeV)} \oplus 127 \text{ ps}$

Further studies planned with faster fibers (YS-4, etc.)

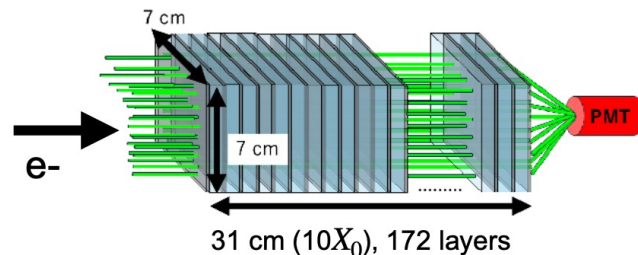
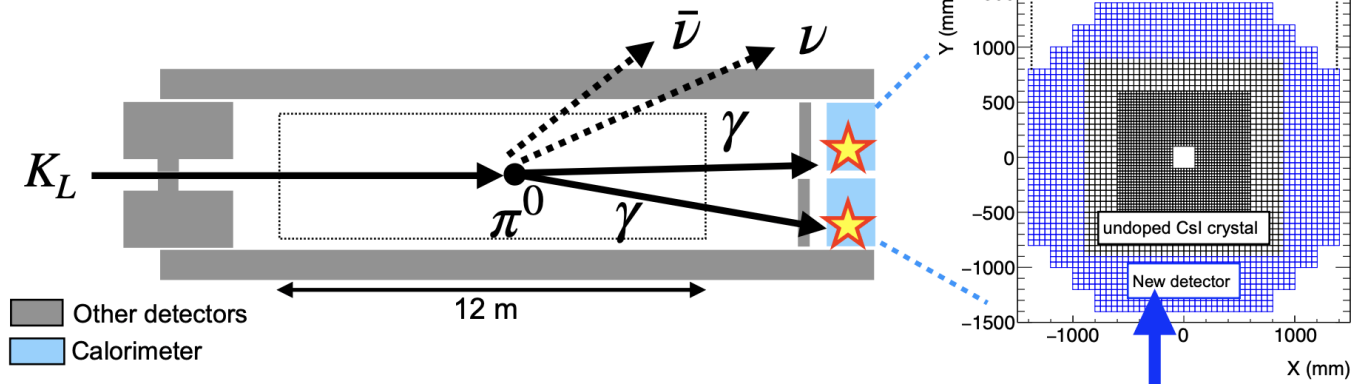
Shashlyk prototype for KOTO II



Current KOTO calorimeter: Pure CsI

- $2.5 \times 2.5 \text{ cm}^2$ or $5 \times 5 \text{ cm}^2$ crystals
- 50 cm in depth = $27X_0$
- Upstream SiPMs added 2018

Calorimeter diameter
 $2 \rightarrow 3 \text{ m}$ for KOTO II



$10X_0$ shashlyk prototype under construction

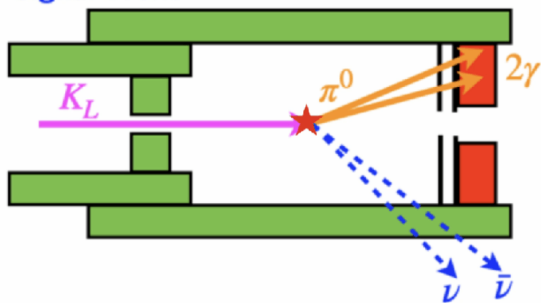
- 0.3 mm Pb + 1.5 mm EJ 212 scintillator
- Single $7 \times 7 \text{ cm}^2$ tower with 64 Y11 WLS fibers
- To be tested with e^- beam Dec 2025

Preshower for photon angle measurement

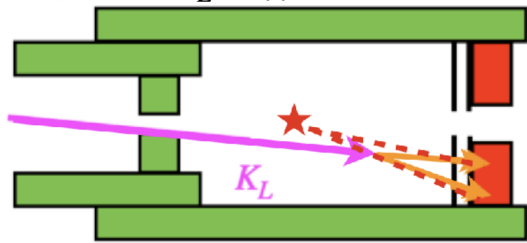
Measurement of incident photon angles extremely useful for $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Extra constraints for π^0 reconstruction: eliminate backgrounds from $K_L \rightarrow \pi^0 \pi^0$, $K_L \rightarrow \gamma \gamma$, etc

Signal event



Halo Kaon ($K_L \rightarrow \gamma \gamma$)

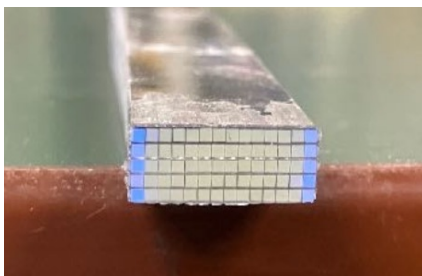


PASCAL

Calorimeter with projective tracking

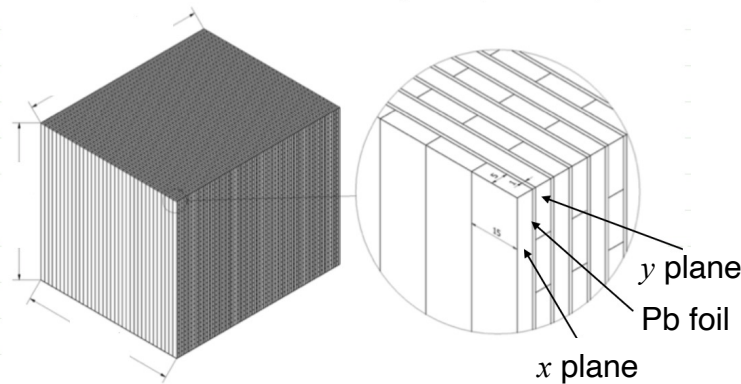
15 mm strips in x, y

1 mm sq fibers + 0.15 mm W foils

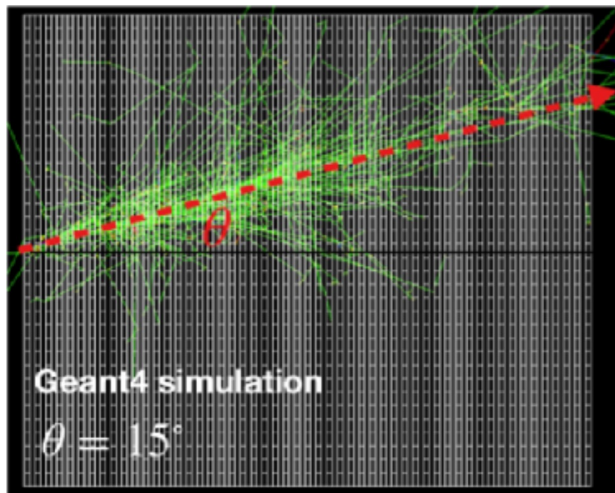


Prototype:

- 24 layers
- $5.35X_0$
- $25 \times 25 \text{ cm}^2$



Preshower for photon angle measurement



Angular reconstruction with XGBoost

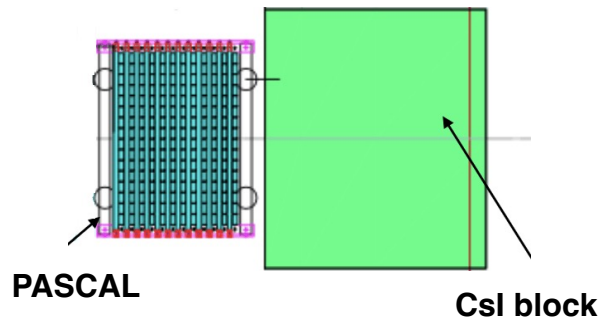
Gradient boosting of decision trees

Beam test of PASCAL prototype

- 200-800 MeV e^+
- Incident angles 0-30 deg

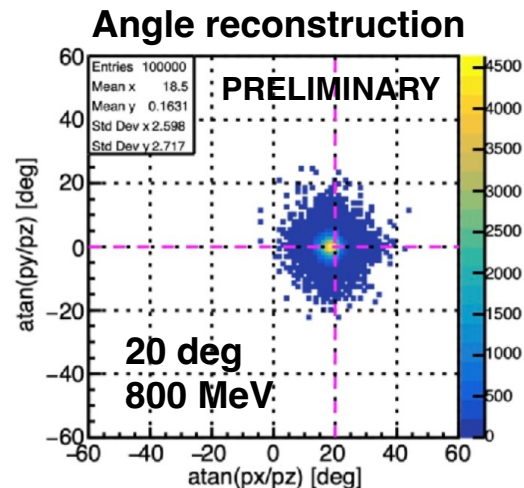
Study:

- Angular resolution
- Energy resolution in combination with CsI block



Preliminary observations:

- Angular resolution 2.4 deg for 800 MeV e^+ at 20 deg
- MC angular and energy resolution better than measured, especially at lower energies
- Delicate intercalibration issues



Nanocomposite scintillators

Next-generation detectors for experiments at the intensity frontier demand scintillators with

- faster response ($\tau < 1$ ns)
- higher radiation resistance (> 50 kGy)
- better light output ($> 10k$ ph/MeV)

than currently available

Nanocrystals and composite can be **engineered** to meet performance requirements

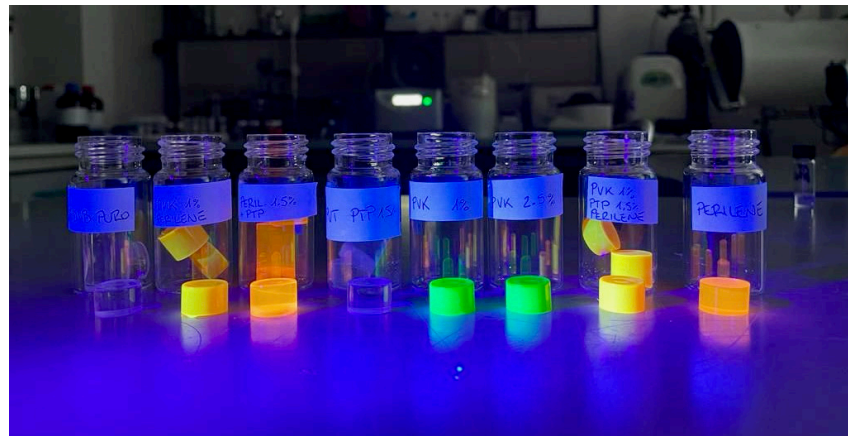
- **Nanocrystal:** emission wavelength, decay time, etc.
- **Composite:** concentration of nanocrystals and/or additional fluors,

e.g. very high concentration of nanocrystals to obtain shorter radiation length

Nanocomposites can make **very fast WLS materials**

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

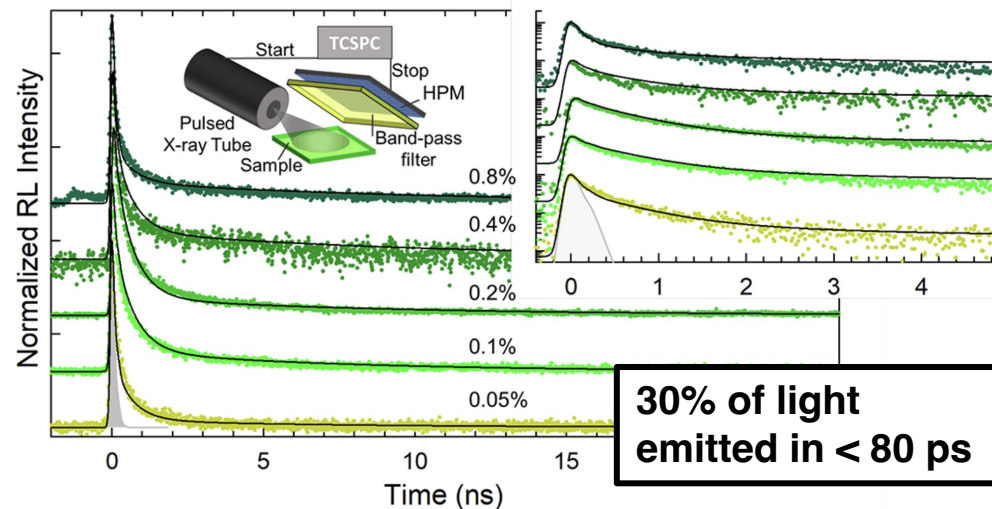
- Perovskite (ABX_3) or chalcogenide (oxide, sulfide) nanocrystals, typically 5-10 nm in size
- Cast with polymer or glass matrix
- Decay times down to $O(100$ ps)
- Radiation hard to $O(1$ MGy)



NCs have high potential for use in innovative, high-performance calorimeters

The promise of lead halide perovskite NCs

Ultrafast and Radiation-Hard Lead Halide Perovskite Nanocomposite Scintillators



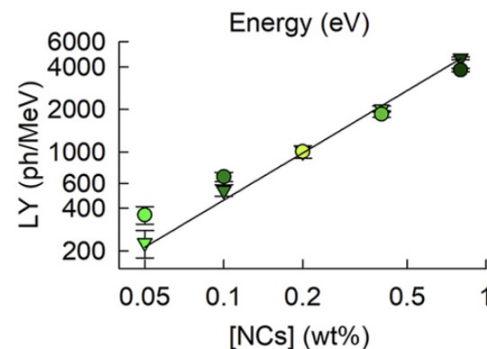
3-component fit to pulse shape for 0.2% sample:

- 34% prompt (Gaussian, 160 ps IRF)
- 22% with $\tau_{\text{decay}} \sim 600$ ps (R_1)
- 44% with $\tau_{\text{decay}} \sim 10$ ns (R_2)

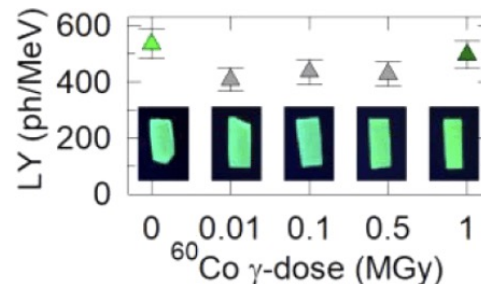
CsPbBr₃ nanocrystals (~10 nm)

0.05 to 0.8% w/w in UV-cured polyacrylate matrix,
measured with **radio-** and **photoluminescence**

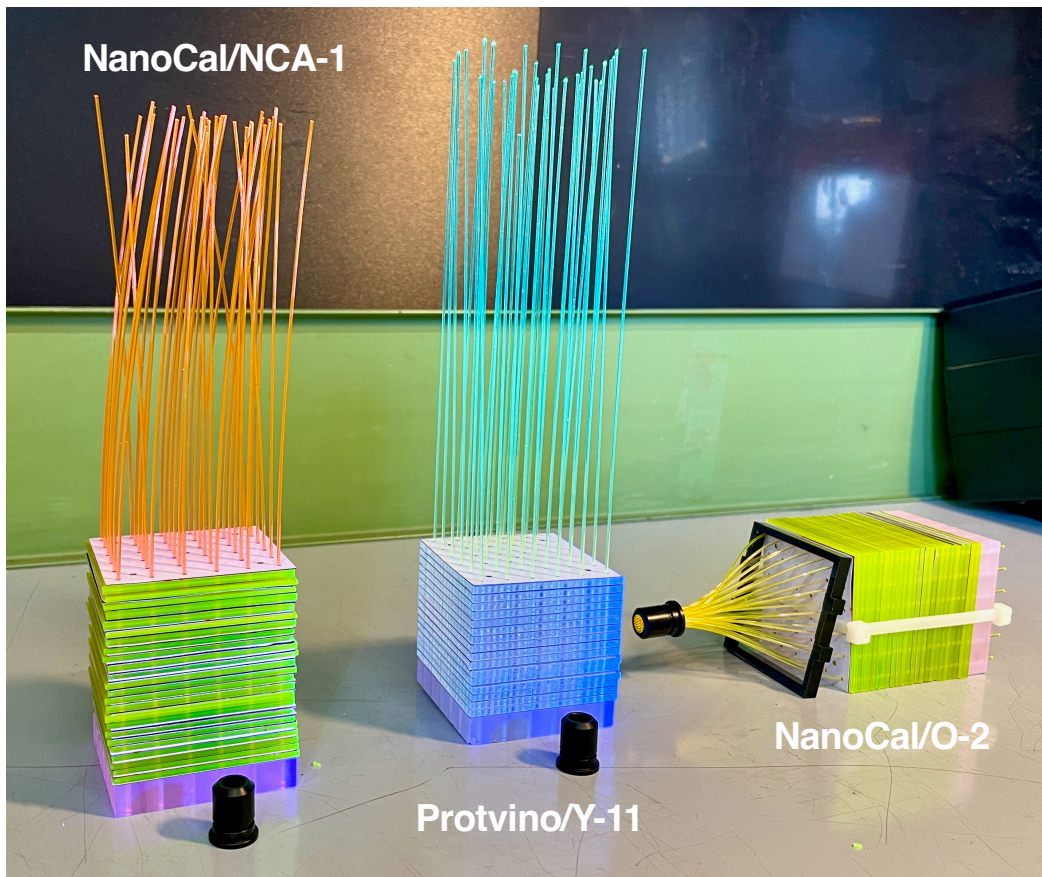
4800 ph/MeV at 0.8% w/w



No decrease in LY up to 1 MGy



Second-generation shashlyk test modules



Prototypes tested in PS T9

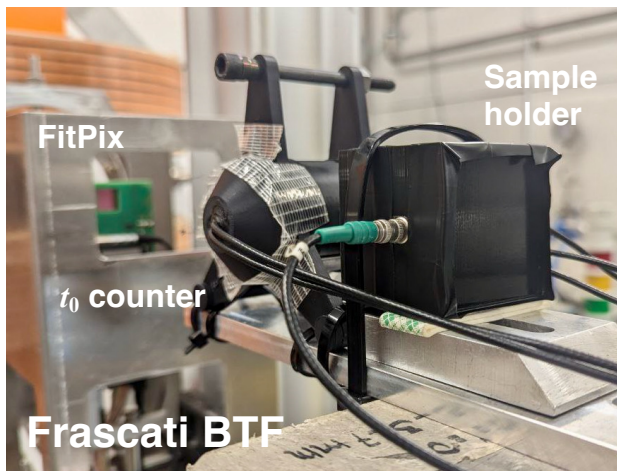
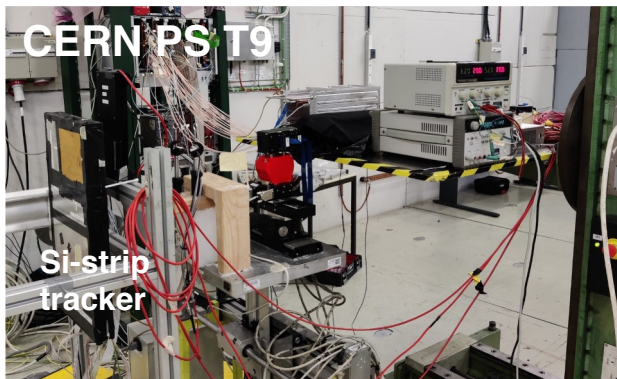
1-4 GeV e^- , 10 GeV mips

- Conventional scintillator (Protvino), Y-11 fibers
- Conventional scintillator (PVT + BTP 0.02%), Y-11 fibers
- PMMA + CsPbBr₃ 0.2%, O-2 fibers
- PMMA + CsPbBr₃ 0.2%, custom NCA-1 fibers*
- PMMA + CsPb(Br,Cl)₃ + coumarin-6, NCA-1 fibers

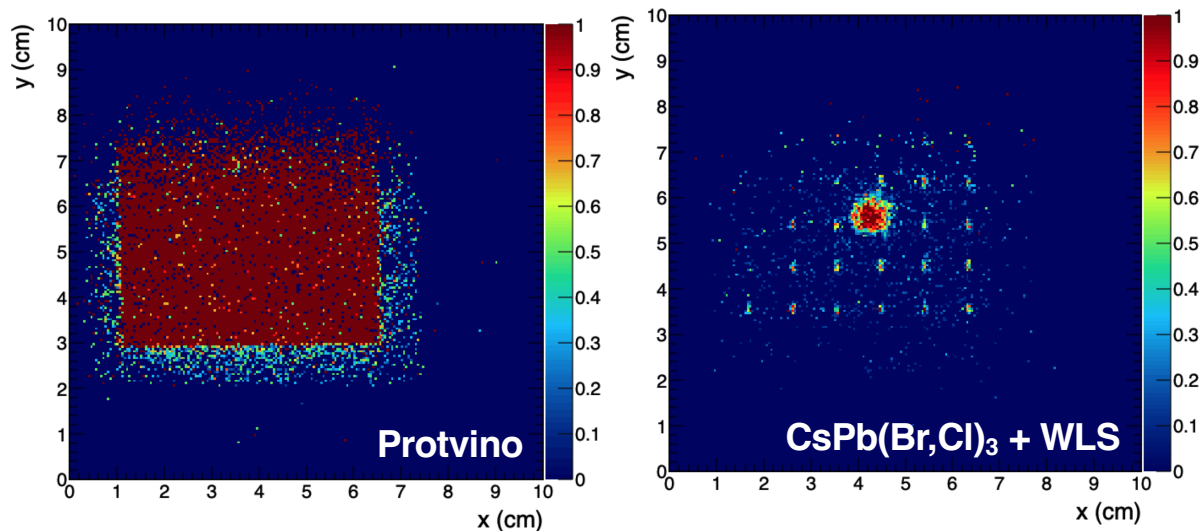
*NCA-1 fibers

Custom produced by Kuraray
Perylene dyad 200 ppm in PS

Beam tests with shashlyk modules



Efficiency maps at CERN PS (10 GeV μ , threshold = $5\sigma_{\text{noise}}$)



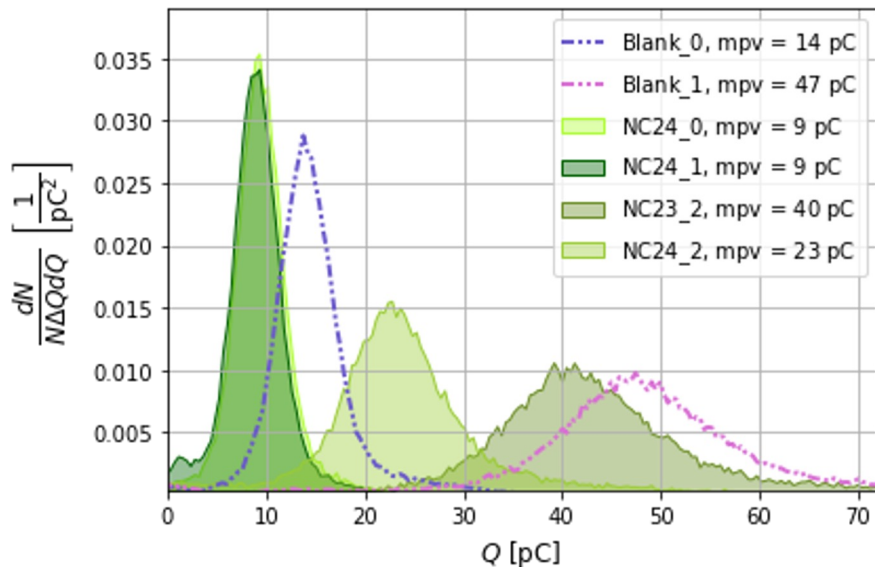
Reliable combination of Protvino scintillator and Y-11 fibers shows good performance

Signal from the NC-based modules entirely from the fibers:

- Reabsorption, in part because WL-shifted NC scintillator not working because of (resolvable) quality problems
- Inefficient nanocrystal excitation: low concentration, inert matrix

Light yield for PVT-based NC scintillator samples

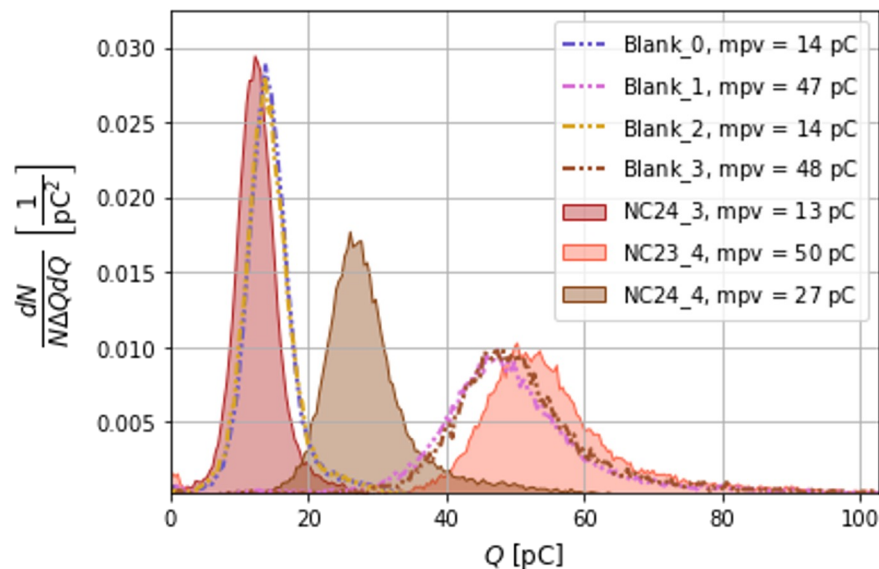
Unshifted NC samples: PVT(+PTP)+CsPbBr₃



Measurements with 450 MeV e^- , R7600 ERMA PMT

- **Unshifted samples:** With or without intermediate fluor (PTP), adding CsPbBr₃ slightly decreases LY
- **Shifted samples:** With or without PTP, adding CsPbBr₃ slightly increases LY

Shifted NC samples: PVT(+PTP)+CsPbBr₃+perylene



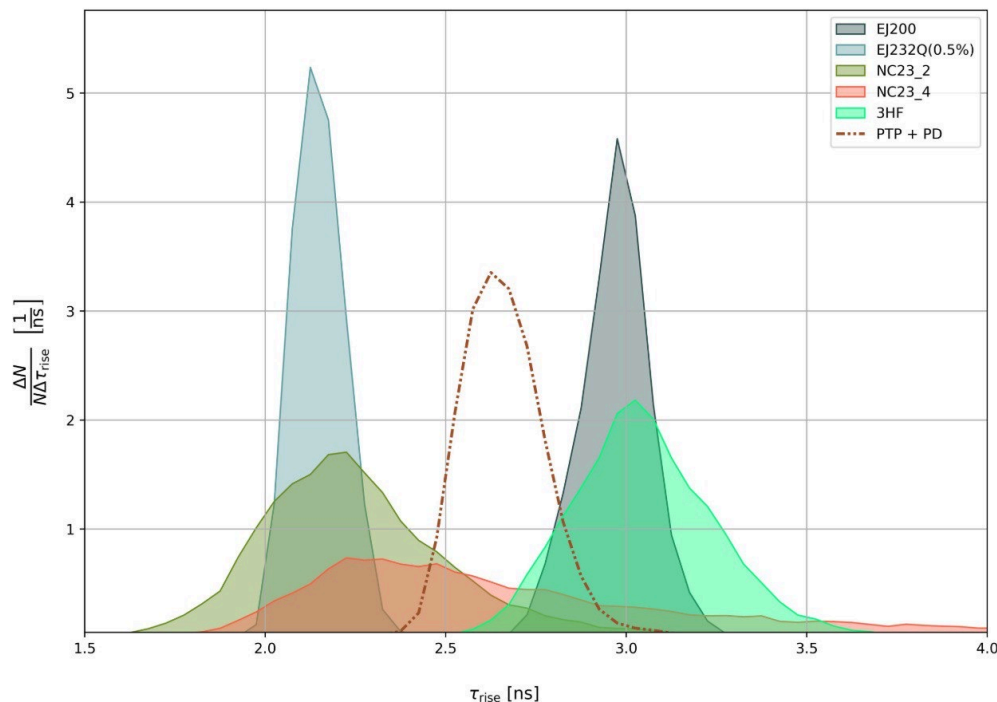
Some evidence that WLS mitigates self absorption

Relative to EJ200:

- Our molecular samples have 40-50% of LY
- Our best NC samples have 20-30% of LY

Timing characterization for PVT NC samples

Signal rise times



Measurements with 450 MeV e^- , R7600 ERMA PMT

Preliminary results indicate that fast kinetics for NCs seen in RL also are obtained with beams

Rise time differences visible by eye

- **NC23_2: 2.2 ns rise time**
 - Faster than **EJ200** (0.9/2.1 ns rise/fall)
 - Not quite as fast as **EJ232Q** (0.11/0.70 ns rise/fall)
- **NC23_4: 2.3 ns rise time**
 - Spread in RT distribution evidence of effects from different spectral components (possible inefficiencies in spectral coupling)
 - Need measurements with band selection (filters)

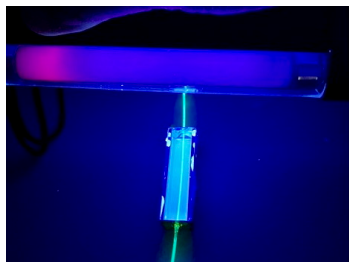
UV-cured polyacrylate scintillators

- UV-cured PMMA used for NC scintillators because thermal curing can destroy quantum dots
- Also allow casting of complex scintillator geometries with embedded WLS fibers
- Potential high-performance/low-cost/easy-to-fabricate scintillator for large-scale use

Osaka recipe for UV-cured scintillator:

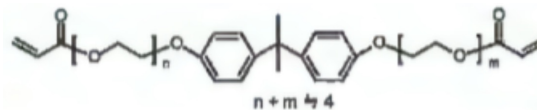
1. EBECRYL-150 – commercial BPA acrylate resin
2. DPO primary (20% wt.)
3. POPOP WLS secondary
4. Ominrad TPO-L photoinitiator

Very preliminary first result: 50% LY of BC404 (comparable commercial scintillator)



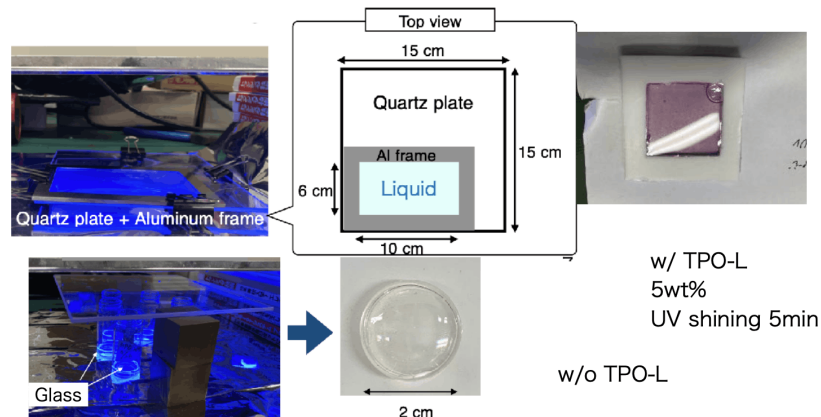
Successful casting and curing with embedded WLS fiber

EBYCRYL-150: Aromatic rings from BPA



Expect some UV scintillation from matrix

Casting and curing:



Fast organic scintillators with long-wavelength emission

Development of NC shashlyk prototypes has required work with long-wavelength organic scintillators, e.g., coumarins (green) and perylene dyes (orange), mainly as WLS agents

Long-wavelength scintillators generally more radiation resistant than blue scintillators

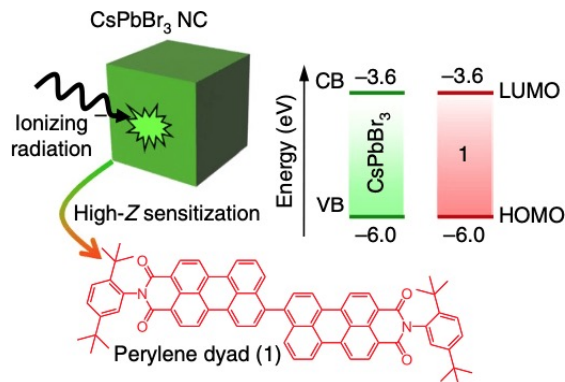
- Radiation-induced color centers absorb more strongly at short wavelengths
- Standard for green scintillators: **3HF** (~ 7 ns emission)
- Modern photocathodes and SiPMs $\rightarrow$ possible to consider orange scintillators as well

Synergy with LHCb PicoCal project to develop fast, radiation hard scintillating fibers

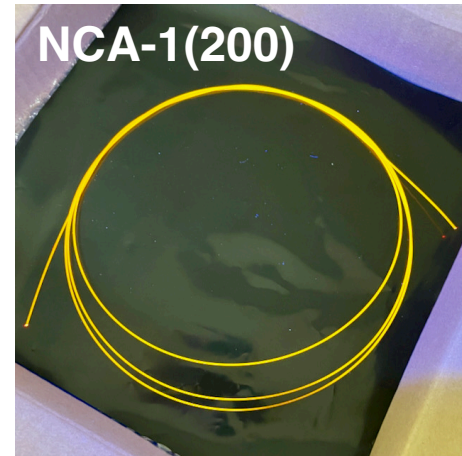
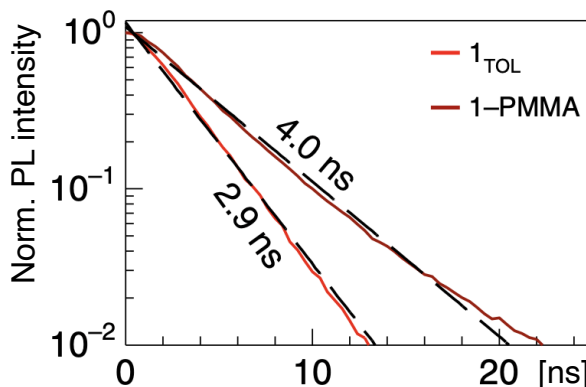
- LS3 enhancement of the LHCb ECAL will use 3HF, but a faster, radiation-hard alternative for PicoCal (LS4) is worth investigating
- In collaboration with CERN and Milano Bicocca Materials Science, manufacture, characterize, and test samples of perylene orange scintillator and scintillating fibers
- In collaboration with LHCb, construct and test orange scintillating fiber calorimeter prototype

Perylene-based WLS fibers for NanoCal

Efficient, fast and reabsorption-free perovskite nanocrystal-based sensitized plastic scintillators



Perylene dyad in toluene and PMMA



Commissioned production of custom WLS fiber from Kuraray (NCA-1)

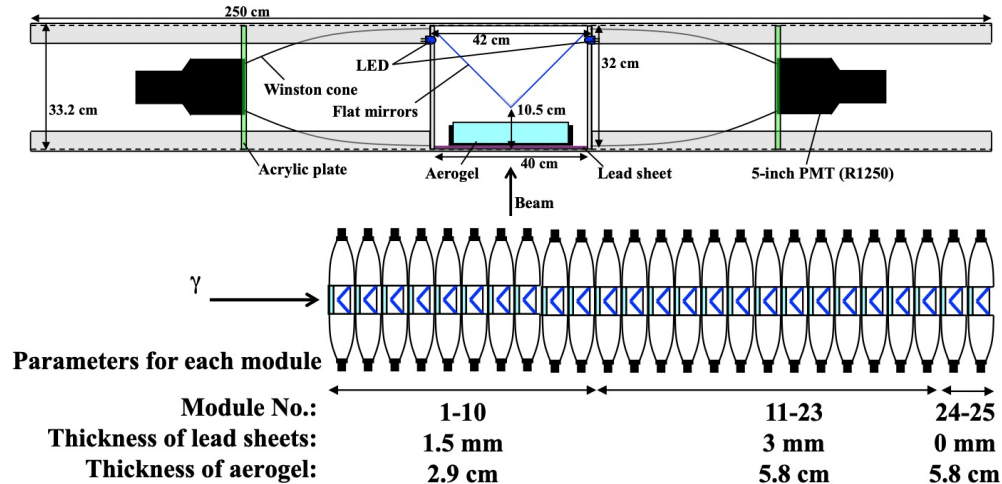
- Absorption peak well matched to CsPbBr₃ emission (520 nm)
- Emission peak at 580 nm (like O-2): **60 nm Stokes shift**
- Expected $\tau_{\text{decay}} \sim 4 \text{ ns}$

Compare to 5.3 ns for O-2, 7.5 ns for Y-11

- Determine saturation concentration: all light from PS converted by TPB
Saturation observed at 1.5% w/w



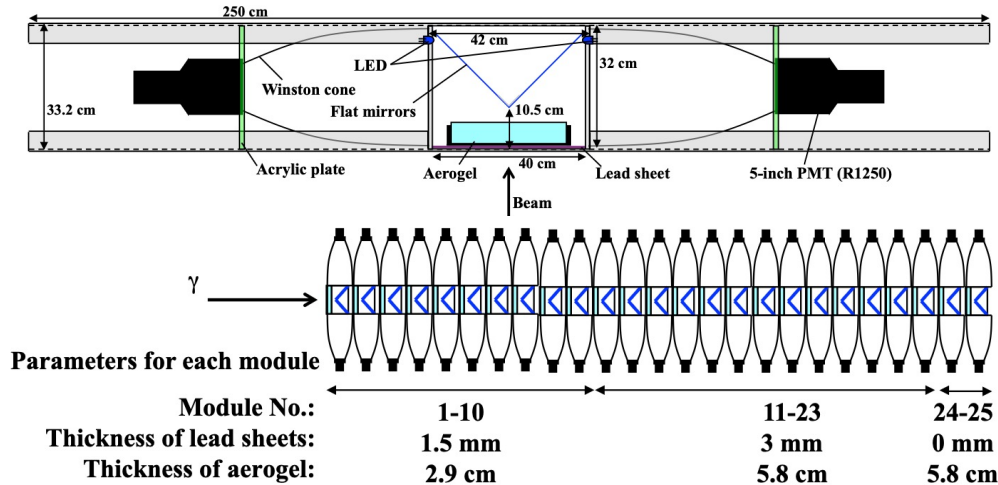
The KOTO Beam-Hole Photon Veto (BHPV)



Detects photon conversions from Cherenkov radiation in silica aerogel

- Required inefficiency: $< 10^{-3}$ for 2 GeV photons
- Total thickness of lead converter: $9.6 X_0$
- Insensitive to hadron beam interactions: Most shower particles below Cherenkov threshold
- Time resolution: ~ 600 ps $\rightarrow$ 20% random veto loss at 35 MHz rate of detected particles

The KOTO Beam-Hole Photon Veto (BHPV)



KOTO II BHPV

Particle	Energy range	Yield (per 2×10^{13} POT)	On-spill rate (MHz)
K_L		1.1×10^7	24
Photon	>10 MeV	5.3×10^7	110
	>100 MeV	1.2×10^7	24
Neutron	>0.1 GeV	3.1×10^8	660
	>1 GeV	2.1×10^8	450

HIKE SAC (Phase 3)

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

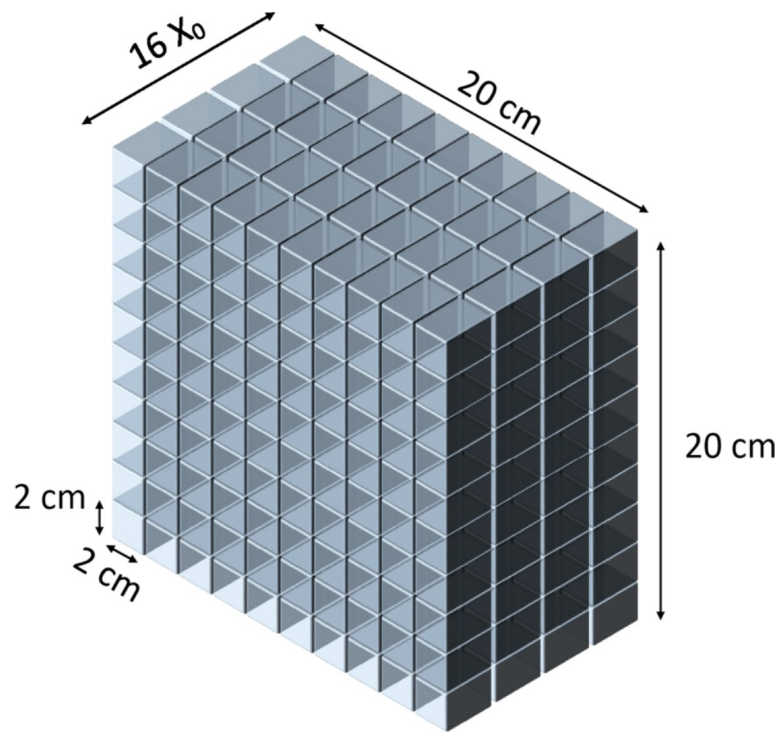
The HIKE Small-Angle Calorimeter as BHPV

HIKE had very similar neutral beam rates to KOTO and similar requirements for the small-angle photon veto

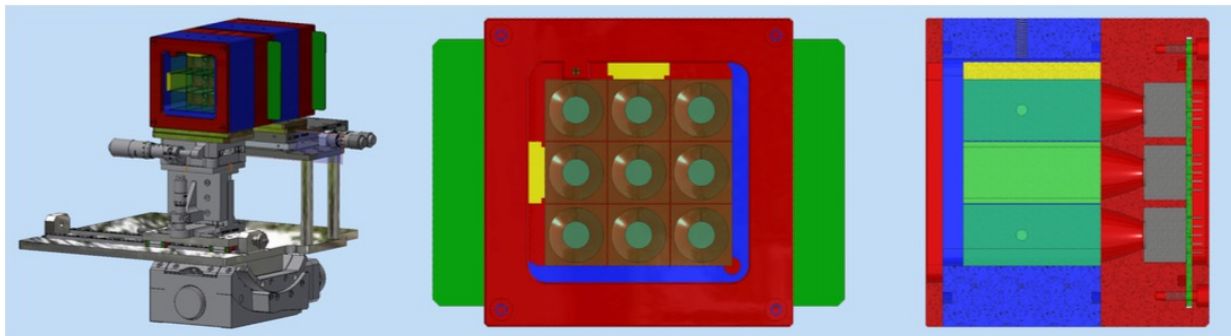
Proposed solution:

Ultra-fast, highly segmented crystal calorimeter

- Ultra-fast lead tungstate (PWO-UF) crystal
- Readout with metal-channel PMTs
- $\sigma_t < 100$ ps, 2-pulse separation ~ 1 ns
- Radiation hard to 10^{13} - 10^{14} n/cm^2 and 10^5 - 10^6 Gy
- Fine transverse and longitudinal segmentation to enhance γ/n discrimination
- Exploit coherent interactions in crystals to reduce thickness (only works at high energy)



A prototype SAC for KOTO II

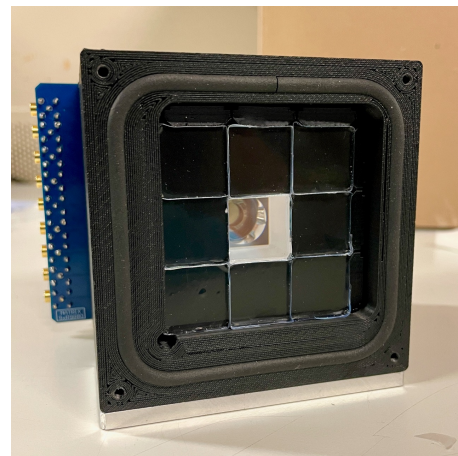


2 stackable layers

3x3 crystals per layer, 18x18x40 mm³

Highest granularity compatible with PMT geometry

- Crystals can be pre-aligned with XRD and laser
- Initial alignment of each plane performed separately
Relative layer alignment adjusted manually
- Readout with compact, metal package PMTs
- Winston cone light concentrators with ESR:
Numerical aperture: 15% → 79%



Crystals for KOTO II SAC



PWO-UF (Crytur)

Korzhik et al. NIMA 1034 (2022)

18 pieces, 18x18x40 mm³

Only small faces polished:

- Matte surfaces and ESR foil reflectors on sides for diffuse reflection
- Coupling surface and front face polished
- Front faces blacked out after angular alignment

Cut to preserve orientation:

- $\langle 100 \rangle$ axis perpendicular to front face within 6 mrad
- $\langle 001 \rangle$ and $\langle 010 \rangle$ axes perpendicular to side faces within 35 mrad

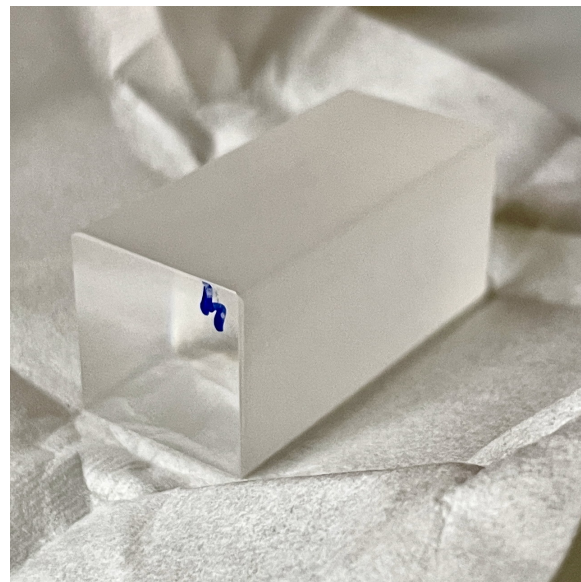
PWO-UF

$$\rho = 8.3 \text{ g/cm}^3$$

$$X_0 = 0.89 \text{ cm}, \lambda_{\text{int}}/X_0 = 22.8$$

$$\text{LY} = 7 \text{ p.e./MeV}, \tau_{\text{decay}} = 640 \text{ ps}$$

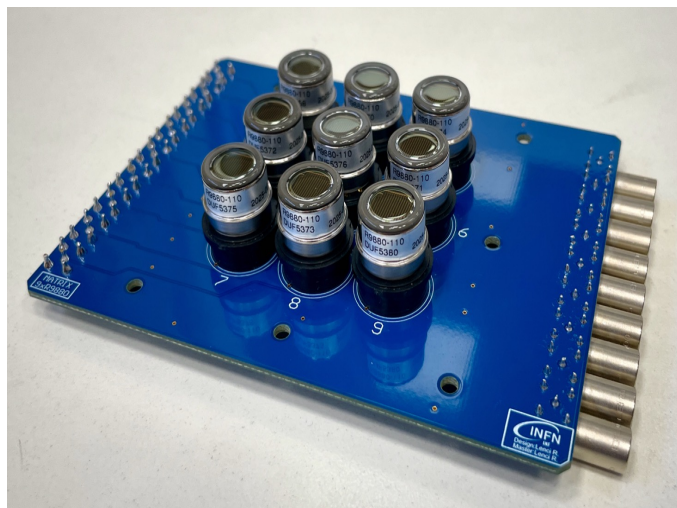
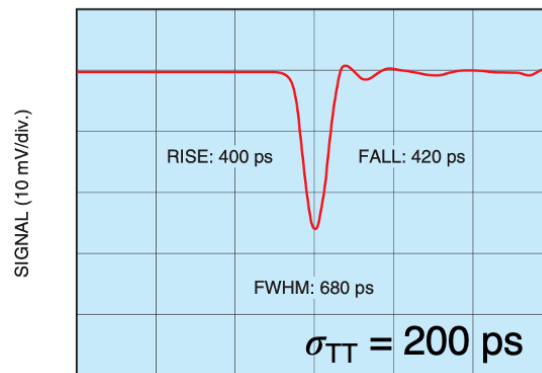
Radiation hard to 2 MGy



Photodetectors for KOTO II SAC

PMTs: Hamamatsu R9880 or R14755

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



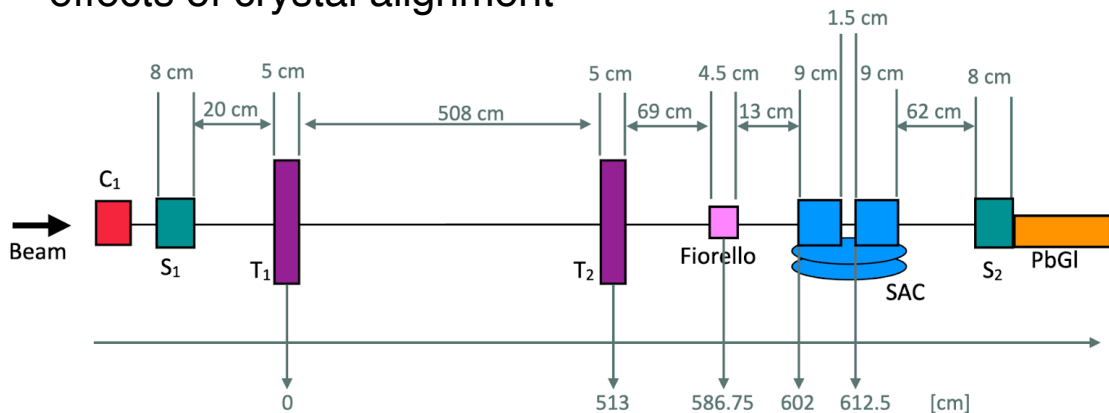
Sensor plane:

- Hosts 9 PMTs on sockets
- Independent HV and divider circuits for each PMT
- Output to digitizer via MCX cables
- 2 variants of sensor board:
 - R9880:** Implementation of Hamamatsu divider
 - R14755:** Custom divider design

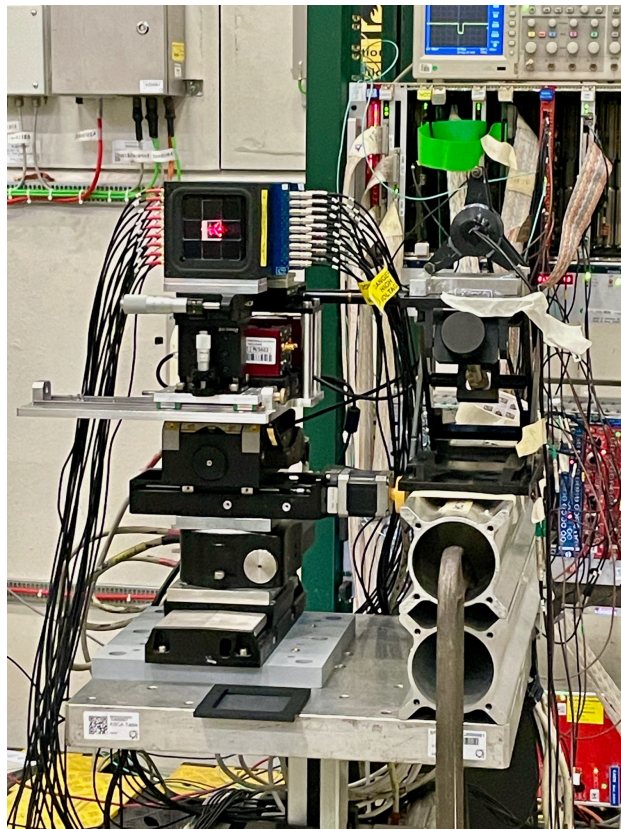
SAC prototype beam test

Prototype tested 27 Aug-03 Sep
in CERN PS T9 beamline

- 5 GeV parallel mips
- 5 GeV parallel e^+
- 2, 4, 6 GeV focused e^+ to study effects of crystal alignment

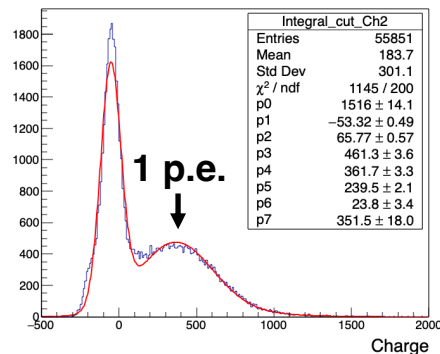
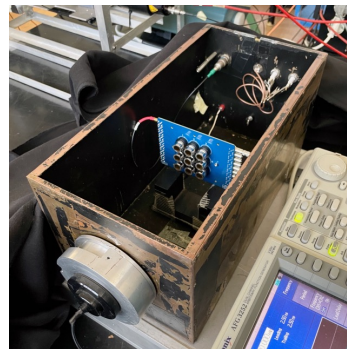
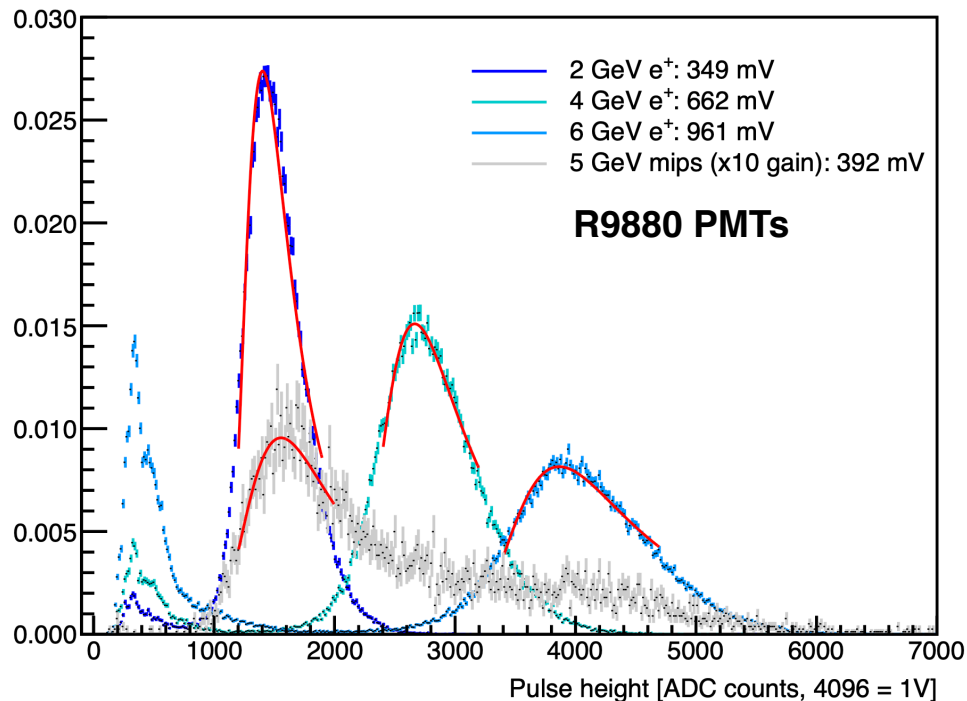


- Cherenkov (C₁) and lead-glass calorimeter (PbGl) for e/mip ID
- Beam tracking with silicon-microstrip chambers (T₁, T₂)
- Timing and trigger detector (Fiorello): 2 cm², $\sigma_t \sim 35\text{-}40$ ps



Preliminary results: Signals and light yield

Pulse height sum, incidence on central crystal

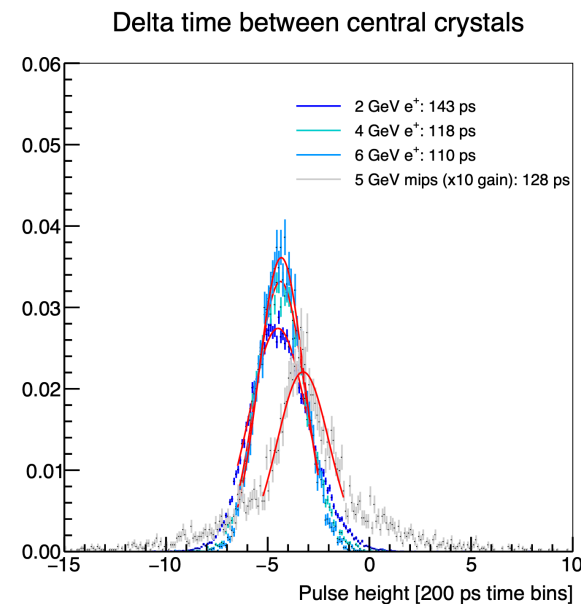
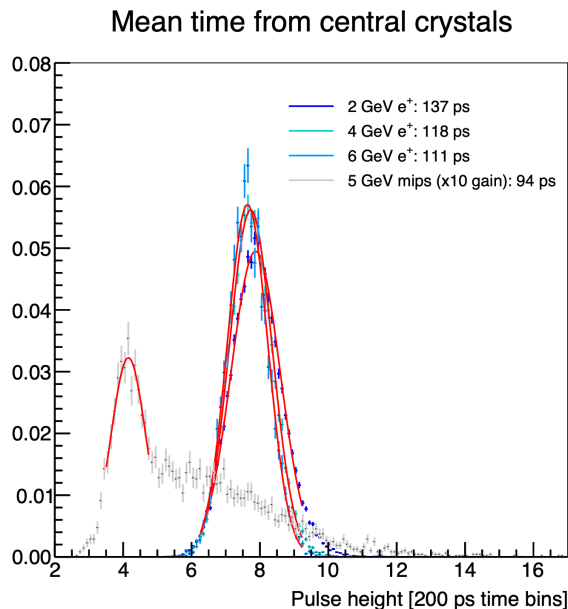


- Mip in 8 cm of PWO leaves 80 MeV
- 400 mV mip signal = 50 pC of charge
- From lab measurements of PMTs:
 $Q_{1\text{p.e.}} = 0.82 \text{ pC at } G = 5.1 \times 10^6$
- LY(Mips 50 pC) = 60 p.e.
0.75 p.e./MeV

Preliminary results: Time resolution

With beam incident on central crystals, measure time resolution in two ways:

1. From mean time of central crystals on front and back layers with respect to ref. time provided by t_0 detector ($\sigma_{t_0} \sim 36$ ps, subtracted)
2. From difference in time between central crystals on front and back layers:
 $\sigma_t = \sigma(\Delta t)/2$ if resolution same on both layers (e.g. for mips)



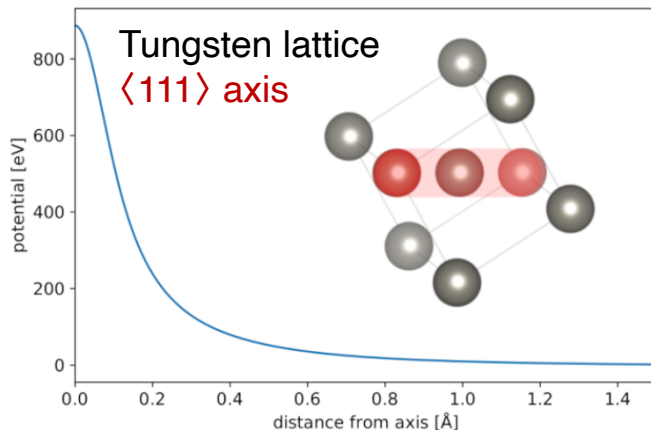
Good consistency between methods!

$$\sigma_t \sim 140 \text{ ps}/\sqrt{E \text{ (GeV)}} \oplus 95 \text{ ps}$$

Coherent interactions in crystals

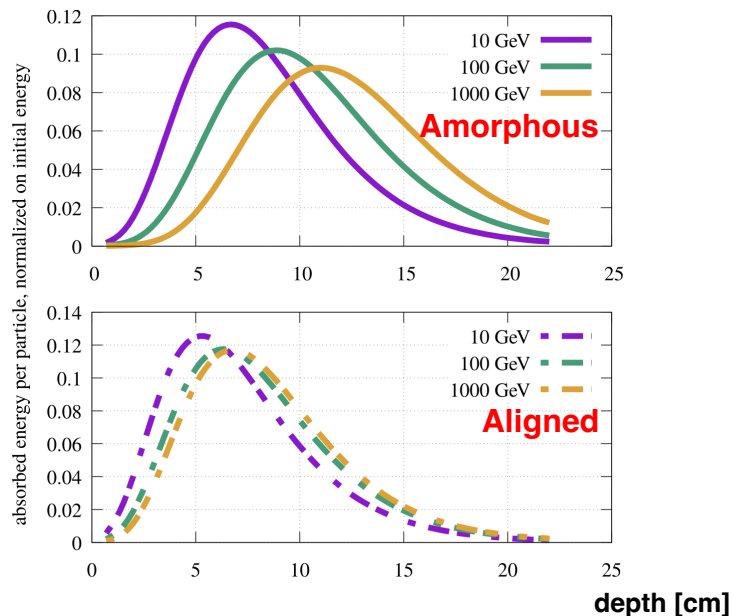
Coherent effects increase cross-section for electromagnetic shower processes (bremsstrahlung, pair production)

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



Coherent superposition of Coulomb fields
 Electric field ε approx. const. $\sim 10^{10}$ - 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 variation of E_{dep} vs depth

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

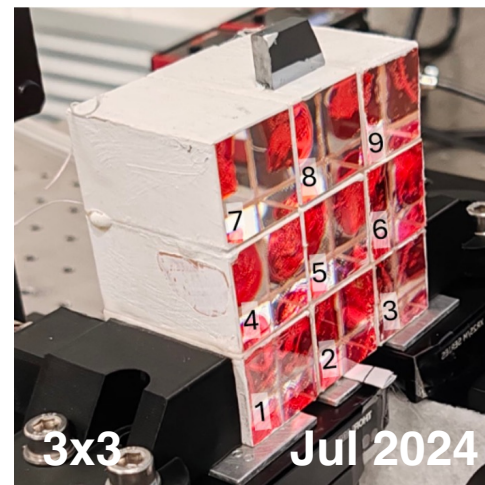
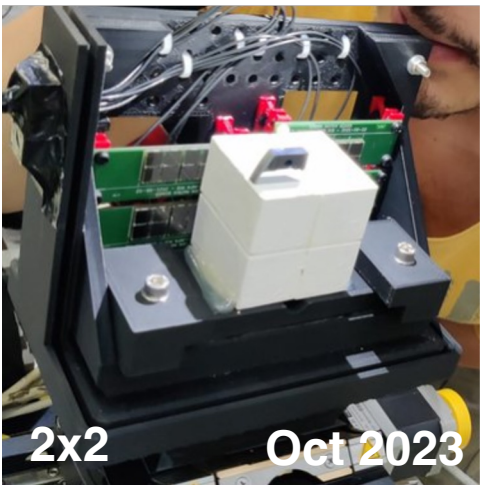
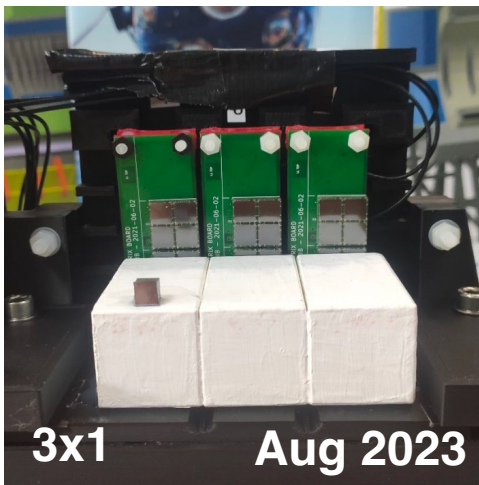
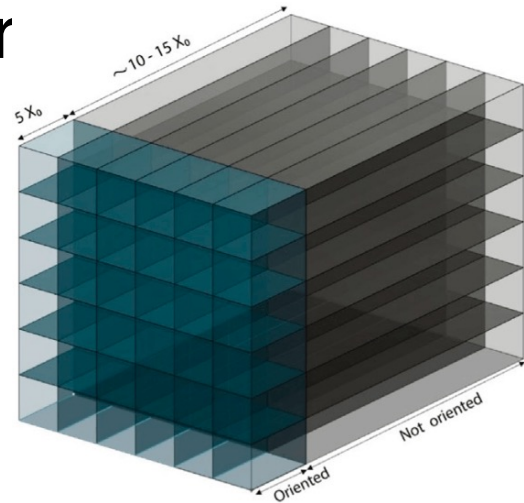
OREO: An oriented crystal calorimeter

Exploit coherent interactions in crystals to develop a highly compact calorimeter

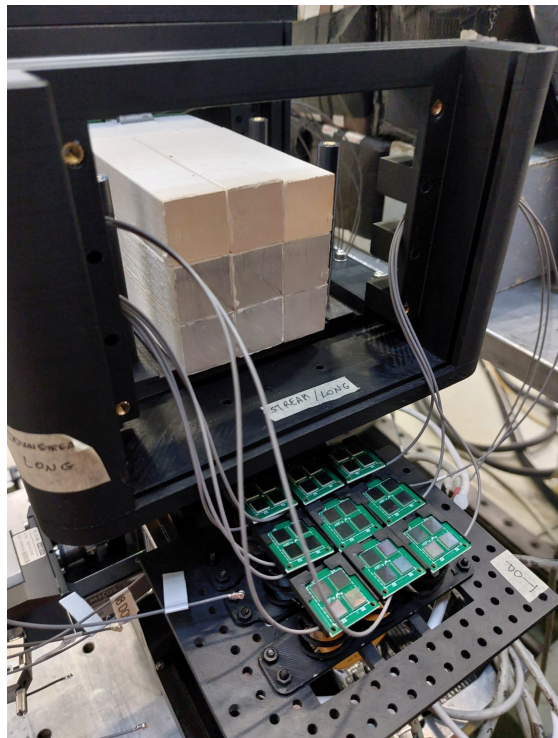
E.g. Small-angle calorimeter for HIKE:

Require good response to photons, high transparency to neutrons

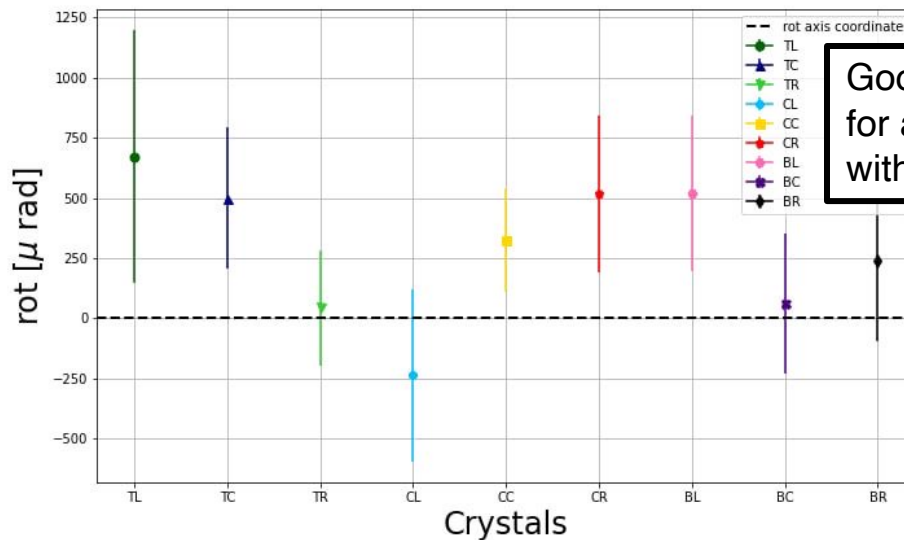
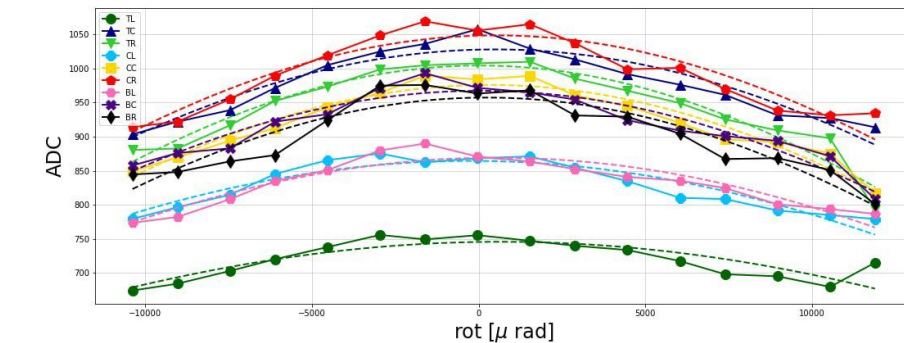
New techniques developed to align PWO crystals



OREO: Preliminary results - alignment

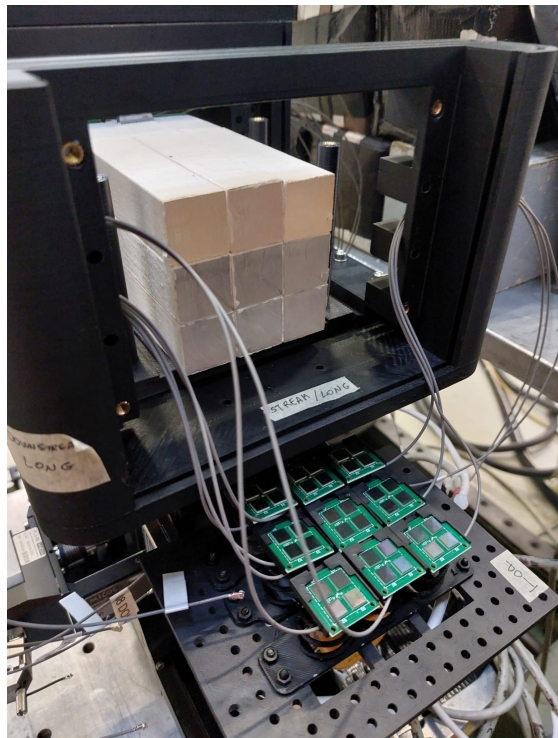


**Full scale OREO prototype
on T9 beamline, Jun 2024**

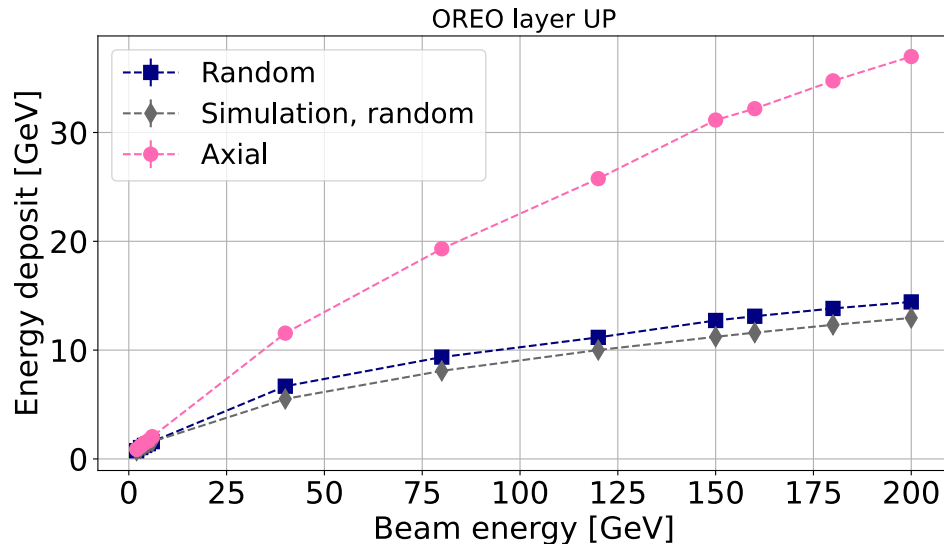


Good alignment
for all crystals to
within 0.5 mrad

OREO: Preliminary results - response



**Full scale OREO prototype
on T9 beamline, Jun 2024**



PS T9: 6 GeV e^- beam:

- All crystals in first layer well equalized
- Enhanced signal with alignment observed on all channels

SPS H4: 200 GeV e^- beam

- Confirmation of angular effect at high energy, good comparison with simulations

Summary and outlook

The needs of next-generation kaon experiments (HIKE and KOTO II) have inspired many interesting new ideas for advanced calorimetry

- 
- Excellent photon detection efficiency at low energy
 - Excellent energy resolution
 - Excellent time resolution for high rate operation
 - Good radiation resistance
 - Low cost – ease of large-scale manufacturing
- Fine-sampling shashlyk designs with novel readout configurations
 - Preshower detectors for photon vectoring
 - Fast nanocomposite scintillators
 - Castable scintillators
 - Radiation-resistant scintillators with long-wavelength
 - Fast calorimetry with oriented crystals

Most concepts still under investigation, with more ideas to come!