Journal Club
LYSO ZDC

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Experimental Requirement (1)

Measurements of a LYSO Crystal Array for a Rare Pion Decay Experiment (PIONEER)

PIONEER

David Hertzog; University of Washington

Physics Goals

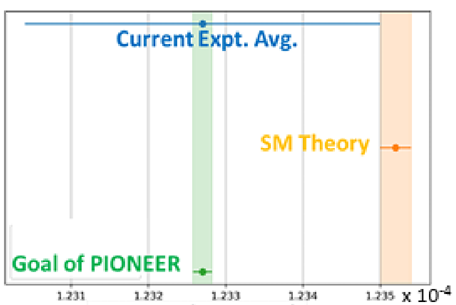
10 x Improvements in precision

- Lepton Flavor Universality (e vs μ to <10^{-4} in BR)
- Cabibbo Angle Anomaly (V_{ud}) pion beta decay) $\pi^+ \rightarrow \pi^0 e^+ \nu(\gamma)$
- Sterile neutrinos and exotic decays: $\pi \rightarrow e\nu_H, \pi \rightarrow \mu\nu_H, \pi \rightarrow e\nu X$

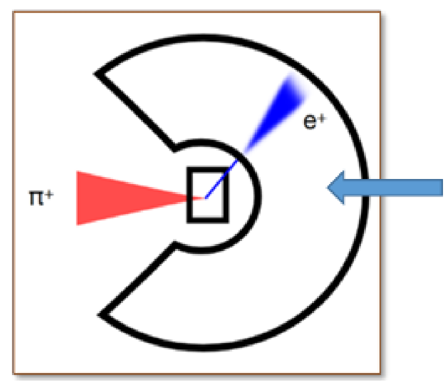
$$R_{e/\mu}^{theory} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$$

illustrate challenge with this channel

All of these involve high-resolution calorimetry in the (unusual) "below 100 MeV" range



$$R_{e/\mu}^{theory} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$$



2D cartoon of experiment

What is this?
- LXe?
- LYSO?

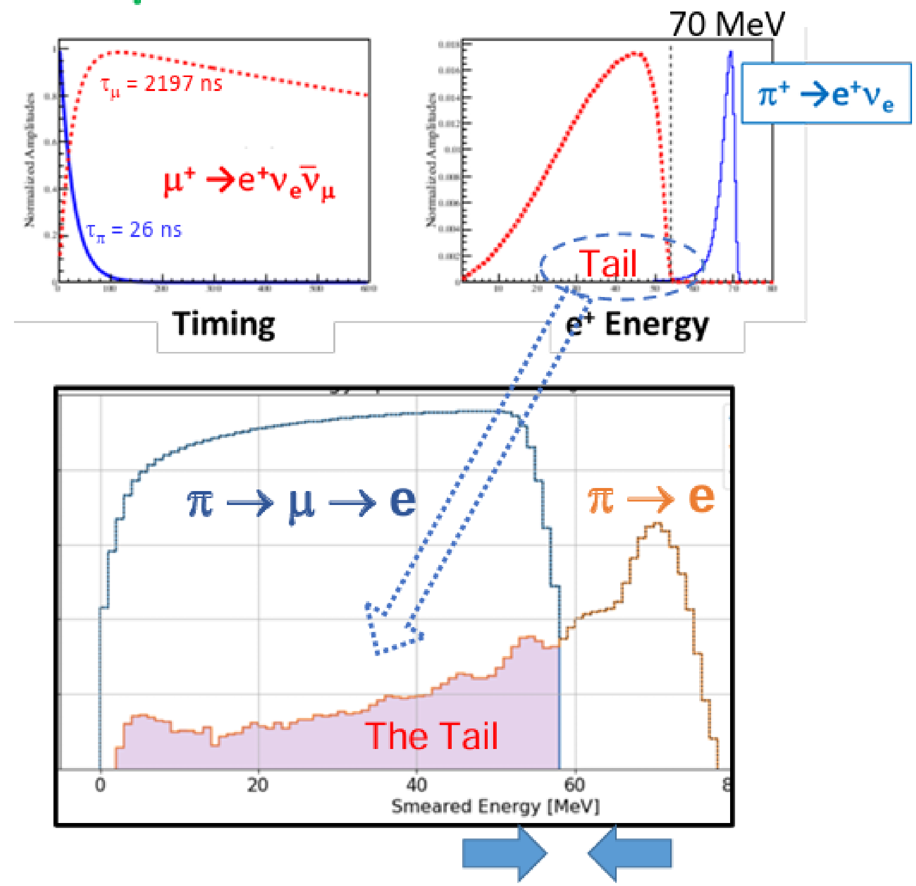
Experimental Requirement (1)

How the Calorimeter is used in a pi-e-nu measurement

The key is to minimize the fraction of $\pi \to e$ events that hide below the Michel spectrum: "The Tail", and determine that fraction well

Must measure (and model) the full line shape

Resolution makes Hi / Lo boundaries more distinct



20 X_0 deep calorimeter: *Tail fraction <0.5%*

Use a highly segmented, 5D tracking pion stopping detector to reject Michel and other low-energy events (subject of a separate talk)

Tail fraction uncertainty <0.01%

Resolution and Depth are important

See Y. Zhang; Pioneer presentation Room 121 at 3 PM today

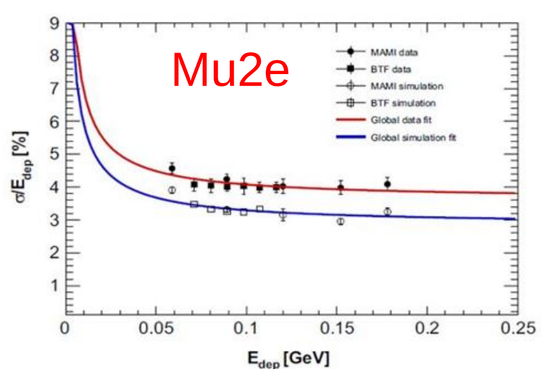
2

Good energy resolution at 70MeV

Considering two crystals : LYSO VS LXe

Feature	LXe	LYSO
State	Liquid (cryogenic)	Solid (room temperature)
Density	~3.0 g/cm³	~7.1 g/cm³
Radiation Length	Longer; suitable for large volumes	Shorter; allows compact detector designs
Light Yield	~40–45 photons/keV	~32–38 photons/keV
Emission Wavelength	VUV (~175 nm)	Blue (~420–430 nm)
Decay Time	Fast (few ns fast component)	~40 ns
Operational Complexity	Requires cryogenics and purity control	Easier handling at room temperature
Applications	Large homogeneous calorimeters, dark matter searches	High-resolution calorimetry, PET imaging

- LYSO usually used in PET (Positron-Electron-Tomography)
- LYSO in particle physics:
- COMET (J-PARC) : 4.5% @ 105MeV
- Mu2e (Femilab)   : ~4% @ 100MeV



Spec of LYSO

LYSO(Ce) - Lutetium Yttrium Orthosilicate (Lu_2SiO_5:Ce) is a relatively new scintillator crystal with a high density, high light output, short decay time and good radiation hardness characteristics.

LYSO(Ce) scintillator crystals advantages:

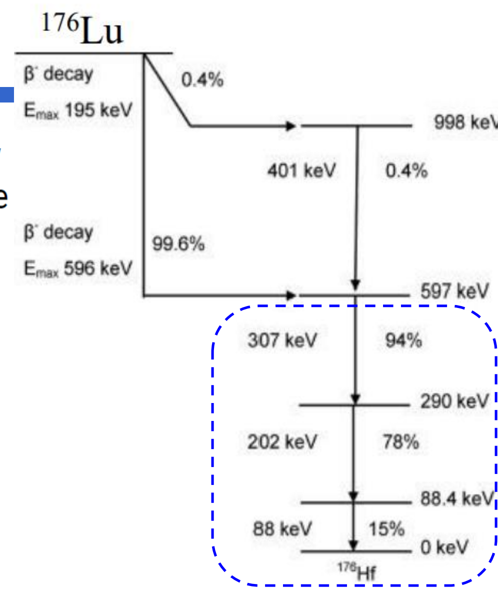
- Good light output - 70% of NaI(Tl), 25 photons/keV
- High density - 7.15 g/cm³
- Fast decay times - c.45ns
- Energy resolution - <12%
- Not hygroscopic
- Are relatively inexpensive

Issues to be aware of:

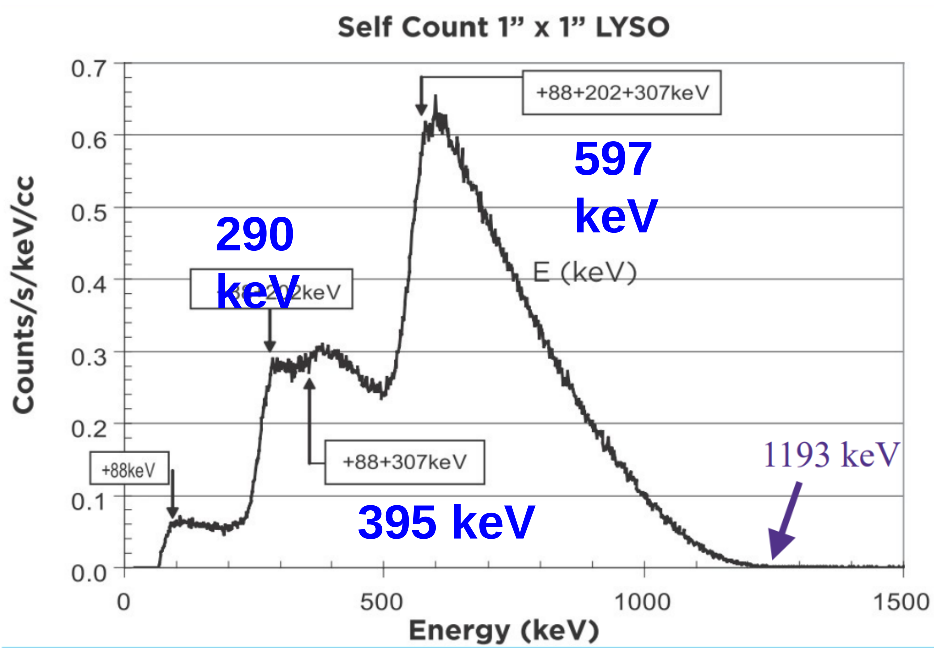
- Mechanically brittle

LYSO(Ce) - is a useful scintillator for applications such as:

- Time-of-Flight measurements
- Industrial/Medical CT/XCT
- Positron Emission Tomography (PET)
- Those looking to discriminate between gamma rays and neut
- Specialist applications in nuclear and high energy physics



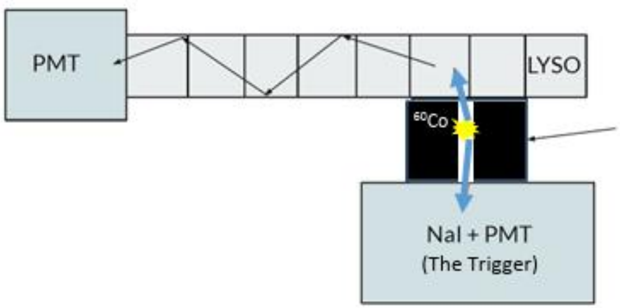
Intrinsic radiation due to "Lu" :Higher probability to have 290keV (88+202), 395keV (88+307), 597keV (88+202+307) energy peaks



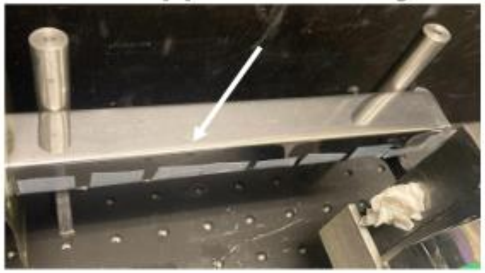
Lab Test (1)： Longitudinal Uniformity

Single crystal tests of recent SICCAS* formulation

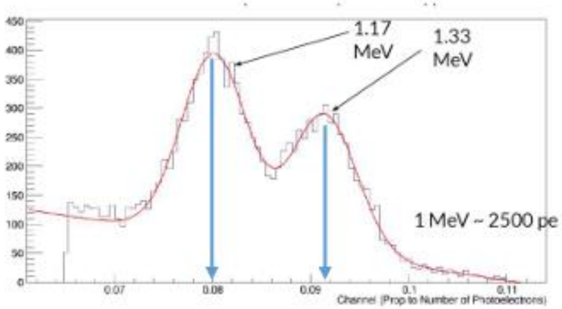
- 2.5 × 2.5 × 18 cm^3 (15.7 X0)
- Co-60 tomography to measure longitudinal uniformity / attenuation

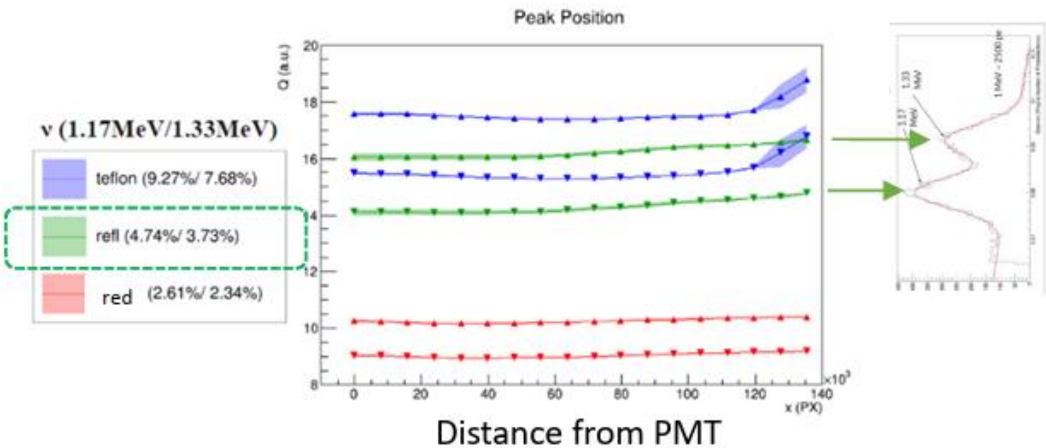


ESR-wrapped LYSO crystal



Measure Peak Positions vs Impact along crystal





Lab Test (1) : Longitudinal Uniformity

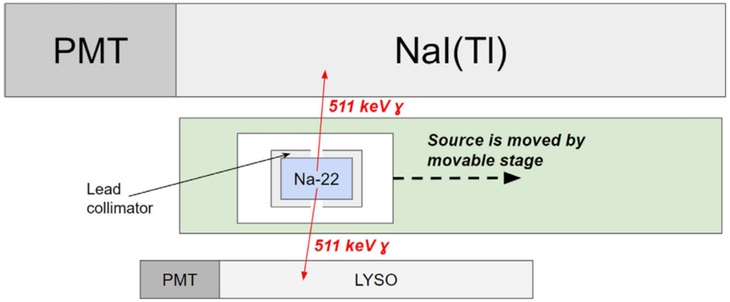


Fig. 6. Schematic of the setup using **511 keV γ-rays from Na-22** to test longitudinal uniformity of a LYSO crystal. **Back-to-back γ-rays from Na-22 are collimated so that a hit in a large NaI(Tl) detector corresponds to a time-coincident hit in the LYSO crystal.** The Na-22 source is moved using an automated movable stage along the long axis of the LYSO crystal and the LYSO crystal response uniformity is recorded along this axis. **Measurements were made at 15 positions.**

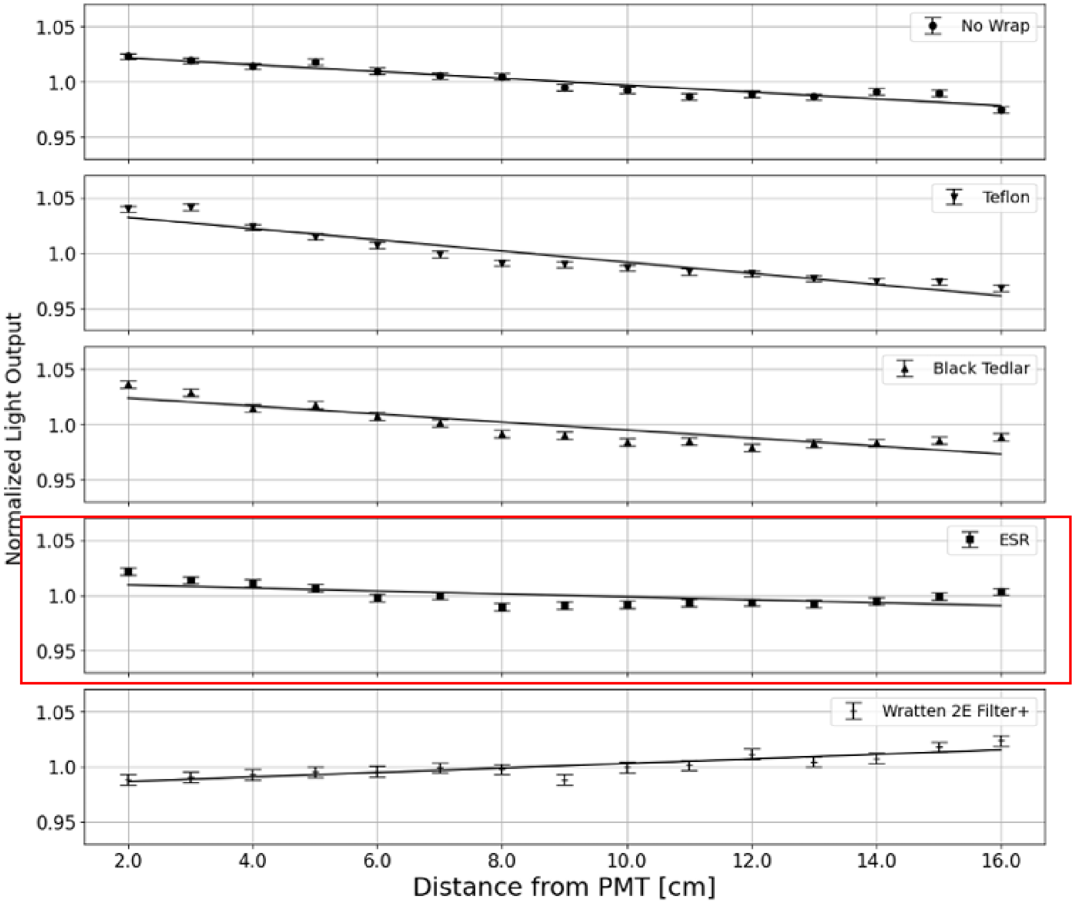
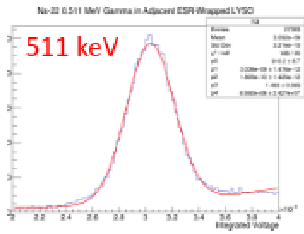


Fig. 7. **Variation in normalized light output for different choices of LYSO crystal wrapping and wavelength filter.** Light output was determined using the peak position from a Gaussian fit of energy deposits of a 511 keV gamma from a Na-22 source positioned along the long axis of the crystal. **The light outputs were normalized to the average light output along the length of the crystal. The high-pass filter was used to eliminate optical photons from scintillation with wavelengths less than 405 nm;** in this wavelength regime, the absorption length of light within LYSO is shortest and can therefore introduce unwanted position dependence to the light output of the crystal. **ESR was found to be the preferred wrapping for LYSO crystals**

Lab Test (2) : Energy Resolution w/ Source

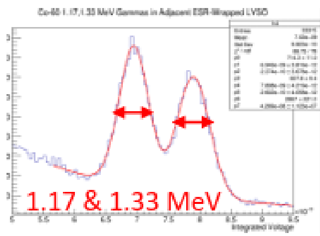
Energy resolution with “bench” sources

- Na22

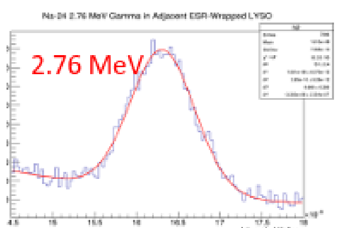


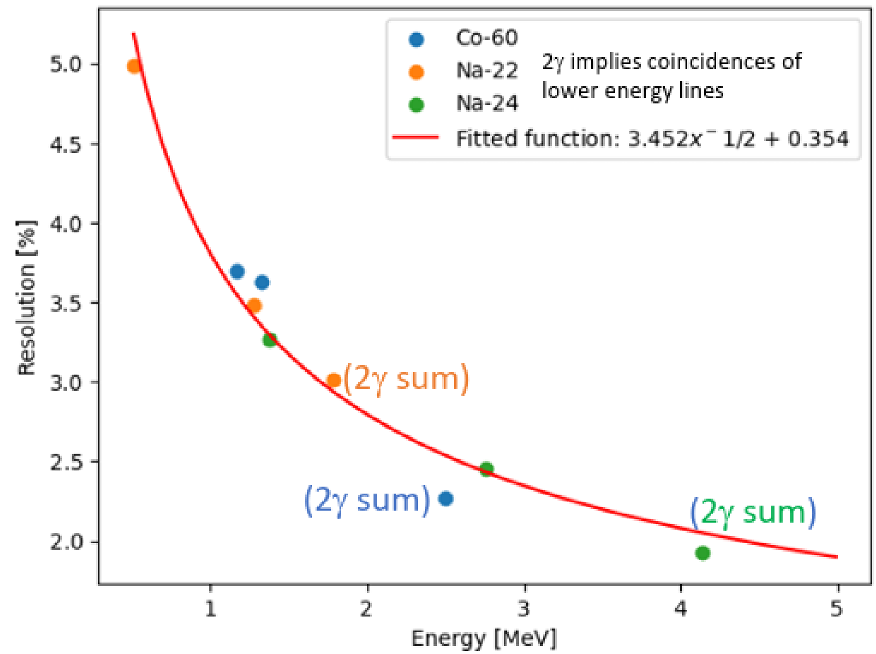
(this is why they are used in most PET scanners now)

- Co-60



- Na-24*
  - 1.38, 2.76 MeV





*Short lived (15 hr half life); emits a series of γ
Source made by bombarding 18 MeV deuterons, produces neutrons that strike an Al button (done at CENPA Van de Graaff)

(Resolution is sigma of a Gaussian)

Lab Test (2) : Energy Resolution w/ Source

Energy resolution measurements were performed using all three radioactive sources, which provided nine different energies in total. The resulting energy resolution of a LYSO crystal as a function of γ-ray energy is shown in Fig. 5. An electromagnetic calorimeter energy resolution is typically represented with the following functional dependence:

$$\frac{\sigma_{E_\mu}}{E_\mu}(\%) = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2)$$

where a, b, c are constants and E_μ is the incident particle energy in MeV. Here, $a/\sqrt{E}$ is a statistical term used to express the contribution from Poisson processes, such as photostatistics, to energy resolution. The b/E term parameterizes noise contributions to energy resolution from electronics and PMTs, and the constant c parameterizes contributions from shower leakage, crystal non-uniformity, and intra-crystal miscalibrations to energy resolution. In single crystal testing, the photosensor used to read out the crystal is operated at a high voltage where noise is minimized, thereby resulting in $b \to 0$ in the fit to Eq. (2). The constant term c is also assumed to be dominated by crystal non-uniformity for single crystal tests. We find $a = (3.84 \pm 0.19)\ \sqrt{\mathrm{MeV}}$ and $c = (0.64 \pm 0.57)$. Because the PIONEER experiment operates at a higher energy range than radioactive sources ($\mathcal{O}(10) - \mathcal{O}(100)$ MeV), the stochastic term will be greatly suppressed in the PIONEER energy regime.

Table 1
Gamma sources and corresponding energies used in single LYSO crystal tests of energy resolution.

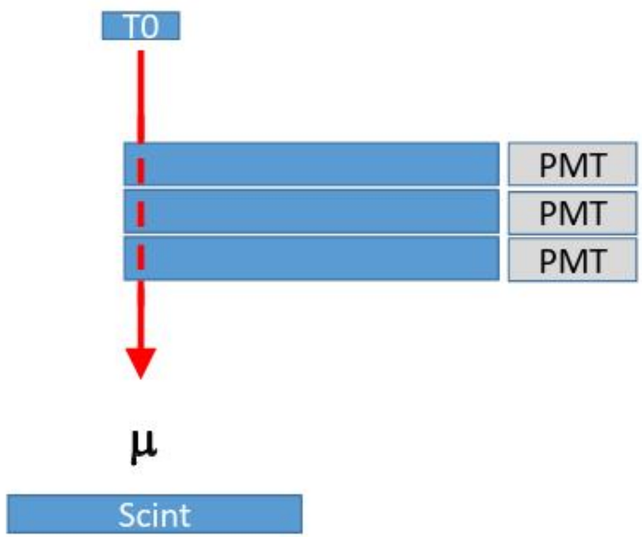
Source isotope	Gamma energies [MeV]	Coincident energy [MeV]
Na-22	0.511, 1.274	1.785
Co-60	1.172, 1.332	2.504
Na-24	1.369, 2.754	4.123

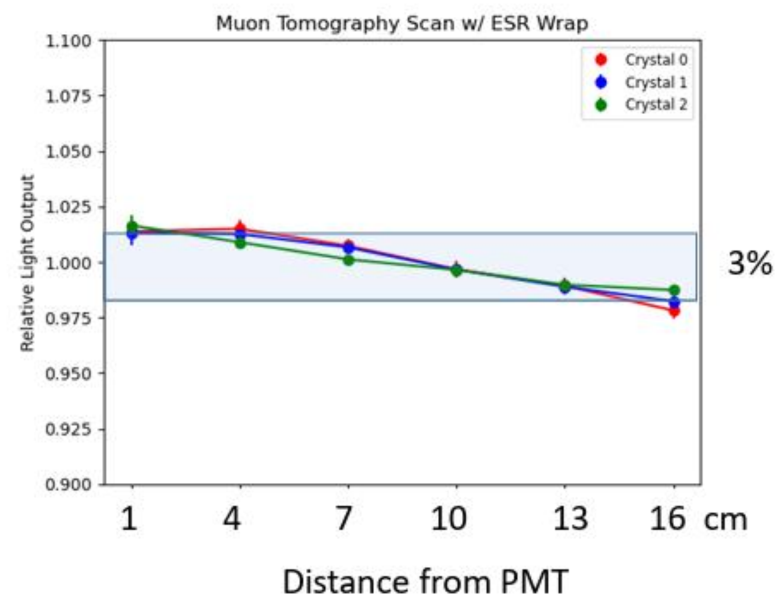
Test Beam @ PSI, Swiss (pi/mu/e beam)

Next, π/μ/e beam at PSI

- PiM1 is ideal up to a few hundred MeV/c
  - **ΔP/P** measured to be **<0.6%** for range of measurements
  - Positrons energy scan: **30 – 100** MeV
  - Muons @ 210 MeV/c used for transverse tomography

Its **590 MeV proton beam** is bunched with a frequency of 50.6 MHz. The ***π*M1** beam line is incident on a 2 mm thick rotating **carbon target** where pions are dominantly produced. **Electrons (or positrons) are emitted from the target region from neutral pion production** followed by pair production in the target.





Test Beam @ PSI : System

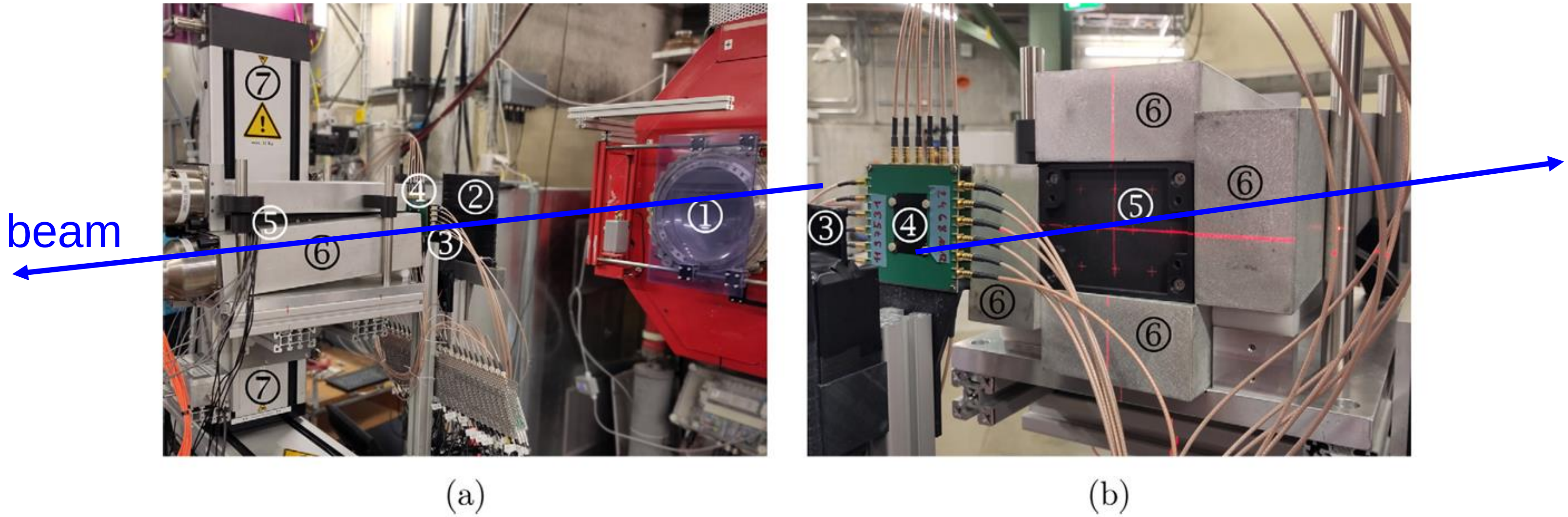


Fig. 9. A picture of the full detector setup during the PSI test beam (a) and a close-up of the front-face of the calorimeter during laser alignment (b). Positrons coming from the last quadrupole magnet ① pass the VETO counter ②, T0 ③ and beam hodoscope ④, before depositing their energy in the LYSO array ⑤. The LYSO crystals, together with the surrounding NaI detectors ⑥ are mounted on a movable XY table ⑦.

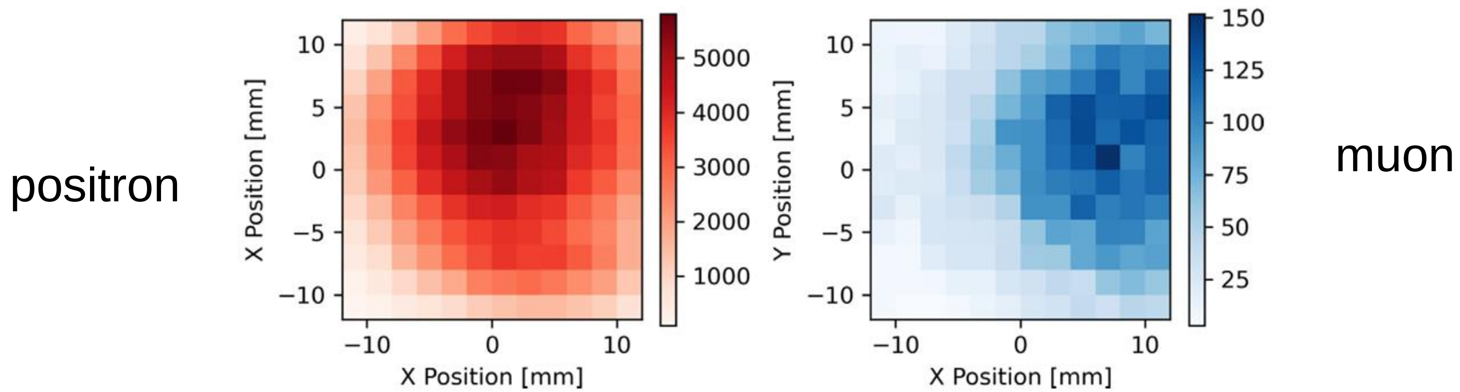
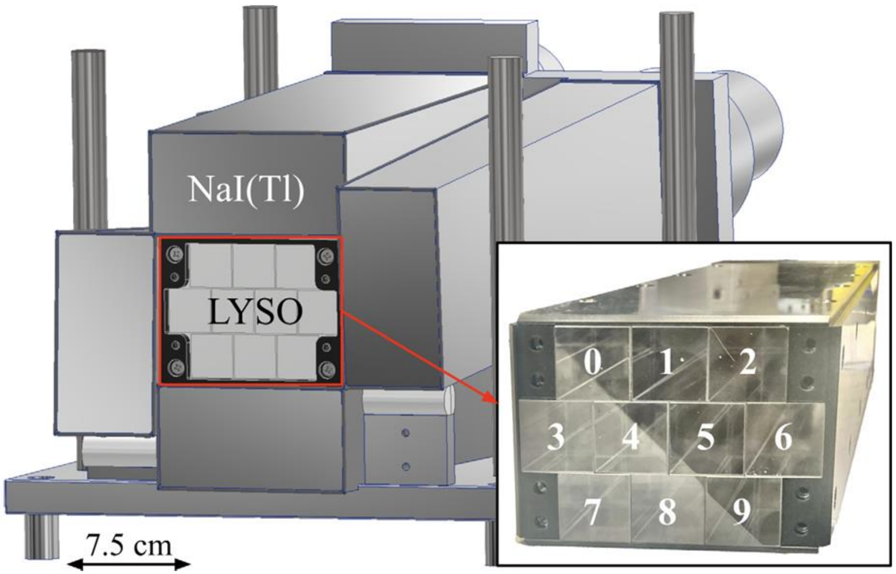


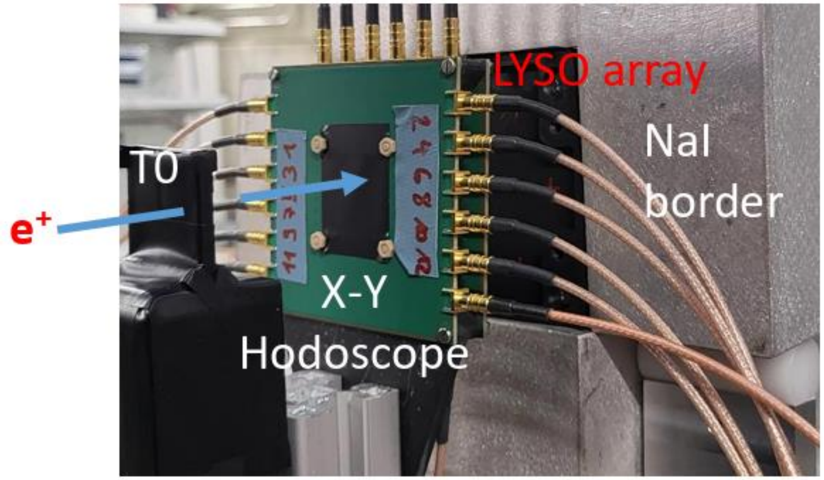
Fig. 10. Beam profile measured by the hodoscope for positrons in red and muons in blue, separated using an RF cut. It can be seen that the two particle distribution centers are approximately 7.5 mm apart.

Test Beam @ PSI : LYSO



- 10 LYSO crystals. Thin pieces of ESR fitted. EJ-550 optical grease
- NaI(Tl) detectors veto events leaked.
- Hammamatsu R1450 PMT (36% active coverage of LYSO). PMTs @ [−750 V, −950 V] to minimize PMT non-linearity effects.
- LED calibration system to **monitor the PMT voltage stability** at the back of crystal. At the back of each crystal, an **optical fiber was positioned at the corner to shine UVA light of 365 nm** into the crystal to excite it, causing it to fluoresce. Two monitor detectors, made from a piece of **plastic scintillator coupled to a PMT**, **received optical fibers from the same bundle as the LYSO crystals and served as external monitors of LED stability.**
- XY movable table. Auto adjust crystal center to beam position.

Test Beam @ PSI : LYSO



- XY Hodoscopy : scintillator + PMT, 1mm resolution. Beam monitor and T0.
- Veto : scintillator + SiPM. 22mm hole in the center.
- **Trigger = T0 && ~~VETO~~, ask for the positron pass through the hole, limit the size of beam to 22mm radius.**

Test Beam @ PSI : DAQ

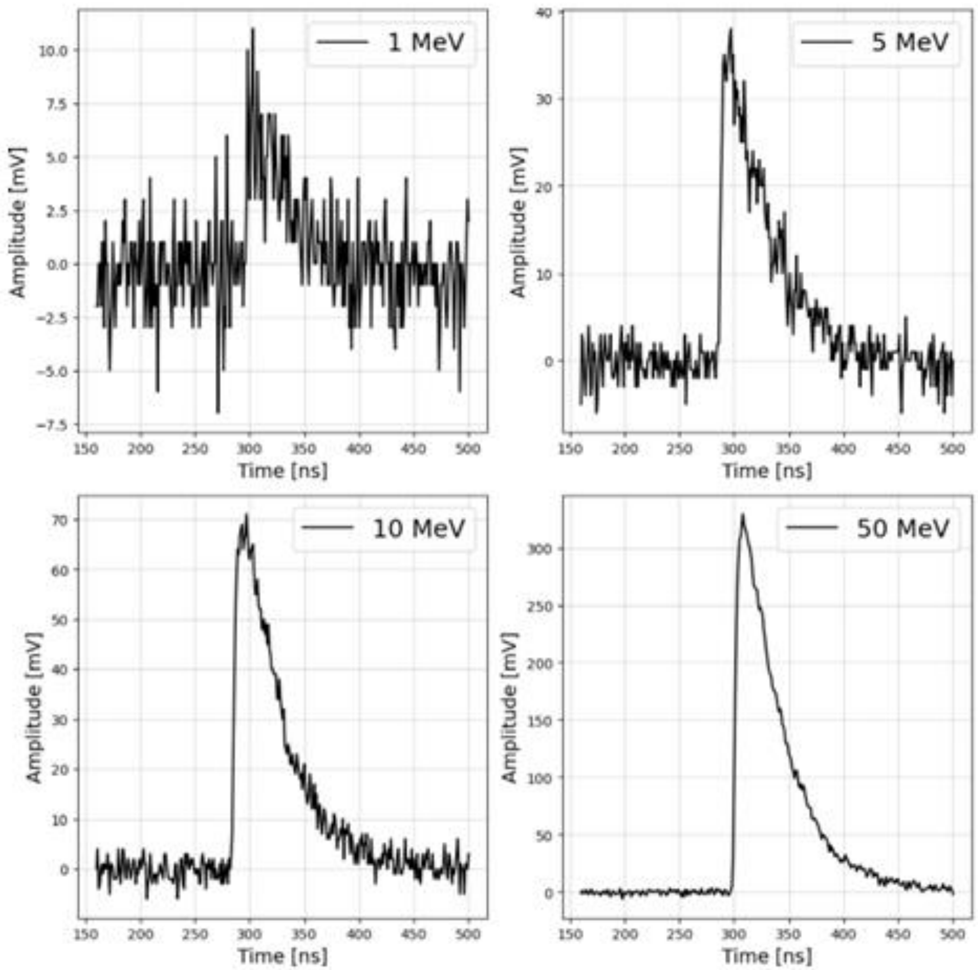


Fig. 11. A representative selection of waveforms in LYSO 4 corresponding to energy deposits ranging from 1–50 MeV.

- Waveform recorded.
- Time : peak time
- Charge : integral
- Window : 100ns

Data Analysis

- Calibration : Initial calibration w/ LYSO intrinsic radiation and Co60 to align the ADCmax of each crystals. Move to 30MeV-100MeV positron beam. Same procedure is done.

- Event Selection :

1. **RF-Phase Cut:**
   - Uses differences in **time-of-flight to select positrons.**
   - Removes events contaminated by muons and pions (especially above 70 MeV).
2. **T0 Upstream Detector Cut:**
   - Ensures each event has only **a single hit in the T0 detector.**
   - Eliminates events with multiple peaks in the T0 waveform.
3. **NaI(Tl) Veto Cut:**
   - **Rejects events with any energy deposits in the NaI(Tl) detectors.**
   - Aims to remove events with electromagnetic shower leakage (including low-energy 511 keV γ-rays) from the LYSO array.
4. **Timing Cut for LYSO Crystals:**
   - Sets the shower time ($t_{(c)}$) using the crystal with the largest energy deposit.
   - **Requires other crystals with deposits above 0.5 MeV to have times within [$t_{(c)}$ – 10, $t_{(c)}$ + 30] ns.**
5. **Waveform Quality and Filtering:**
   - For signals below 0.5 MeV, a Gaussian filter is applied to minimize high-frequency noise.
   - A Savitzky–Golay filter further smooths the waveform, including **only pulses with peak times within [$t_{(c)}$ – 20, $t_{(c)}$ + 40] ns.**
6. **Energy Threshold Cut:**
   - **Excludes calibrated energy deposits less than 0.1 MeV,** which are indistinguishable from PMT noise.

Data Analysis : Time Resolution

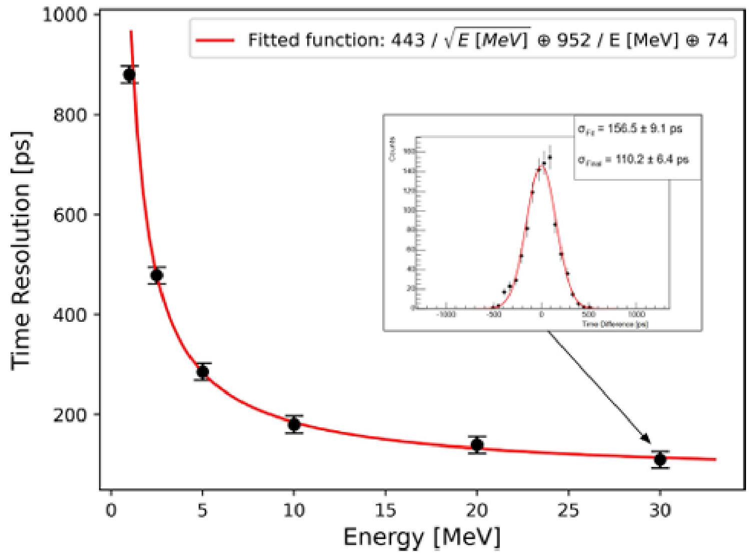


Fig. 13. Dependence of time resolution of a LYSO crystal in the array on the energy deposition in the LYSO crystal for energy deposition between 1–30 MeV. A 110 ps time resolution is measured for 30 MeV energy deposits after the resolution of the reference time is removed via quadrature from σ_{Fit}.

quadrature. The time resolutions were fit as a function of energy to the expression:

$$\Delta t = \frac{a_t}{\sqrt{E}} \oplus \frac{b_t}{E} \oplus c_t. \quad (4)$$

From this fit, we found the fit parameters $a_t = (443 \pm 51)\ \sqrt{\text{MeV}} \cdot \text{ps}$, $b_t = (952 \pm 63)\ \text{MeV} \cdot \text{ps}$, and $c_t = (74 \pm 16)$ ps. The dependence of time resolution on energy is shown in Fig. 13. A time resolution of 880 ps was found at 1 MeV and a resolution of 110 ps was found at 30 MeV.

- Positron beam : beam 70 MeV/c
- 880 ps at 1 MeV and 110 ps at 30 MeV.
- A separate analysis using an LED monitoring system compared each crystal's time to LYSO 0, resulting in crystal-to-crystal time resolutions ranging from 60–80 ps.

Data Analysis : Position resolution and ateral uniformity

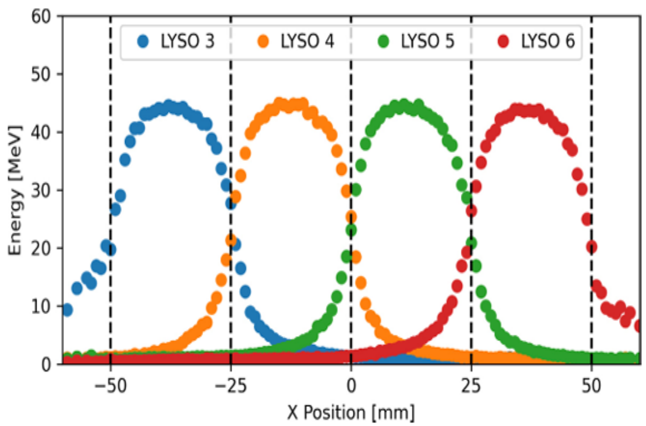
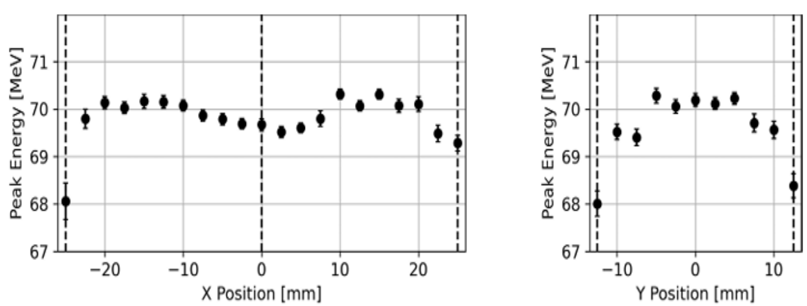


Fig. 14. Plot of the average energy in each crystal of the center row for particles hitting each x-position along the front face of the array. The dashed lines indicate crystal boundaries, corresponding to the points where two neighboring crystals produce the same average integral.



(a) (b)

Fig. 15. Fine scan along the horizontal (a) and vertical (b) axis of the crystal. Data was reorganized into 2.5 mm bins to increase statistics such that the reconstructed peak energy could be obtained from a fit to the dataset. The relative change in peak energy within the center crystals is less than 0.4 % in the horizontal scan and 0.5 % in the vertical scan. The dashed lines indicate the boundaries between crystals. Peak energy decreases for points in the fine scan near the outer parts of the array due to lateral leakage.

- **70 MeV/c positron**
- **Observations** :

1) Energy deposition decreases near crystal boundaries due to particles traveling in the gaps between crystals.
2) relative change in peak energy within the two center crystals was found to be less than 0.5%.

- **Position Res.**

energy-weighted **:** pos res = 6.4mm

in five to six crystals. The position of an event can be estimated through calculation of its energy-weighted center-of-mass, according to the formula found in [13]:

$$(x, y) = \left(\frac{\sum_i w_i \cdot x_i}{\sum_i w_i}, \frac{\sum_j w_j \cdot y_j}{\sum_j w_j} \right), \quad (5)$$

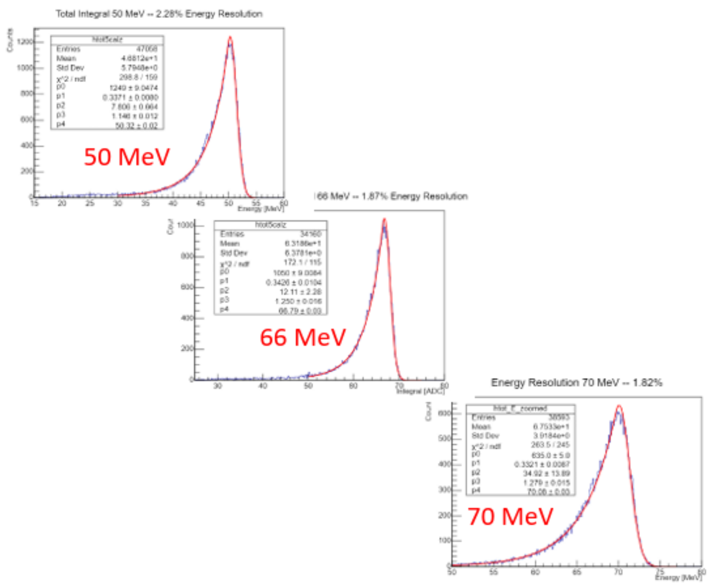
where

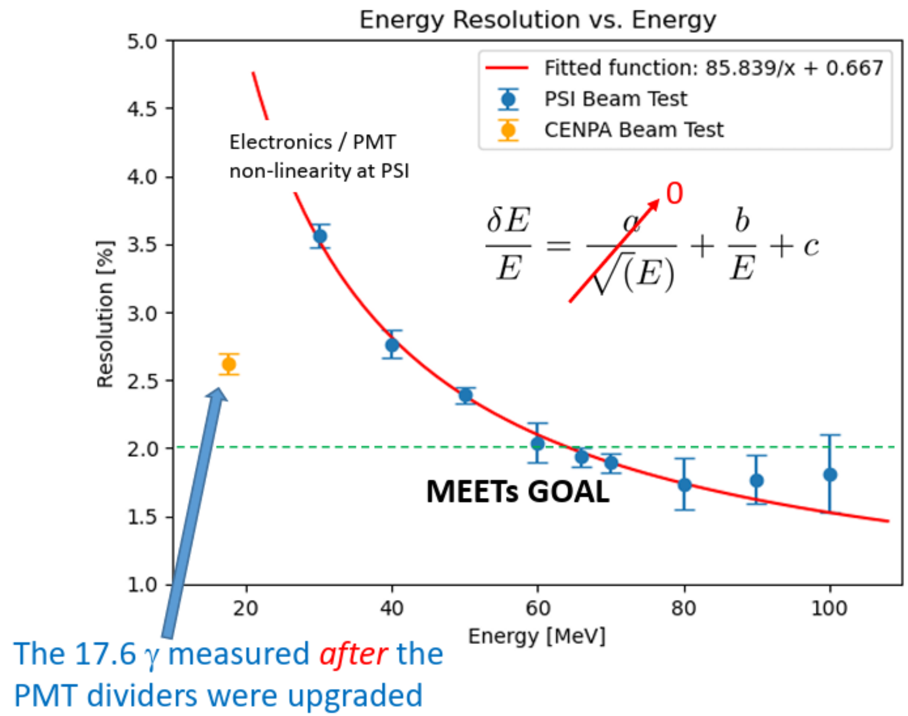
$$w_i = \max \left\{ 0, \left(w_0 + \log \frac{E_i}{\sum_i E_i} \right) \right\} \quad (6)$$

is a logarithmic weight that takes into account the exponential falloff of the energy deposition in the lateral direction. The free parameter w_0 was optimized for the specific calorimeter geometry using simulation in GEANT4. As an alternative, a fully connected feed forward convolu-

Data Analysis : Energy Resolution

- Fits using Crystal Ball function
- Resolution is sigma of high-side Gaussian





- a Crystal Ball function, featuring a Gaussian core (mean μ, standard deviation σ) and a power-law tail (exponent n, transition energy α) to model high energy loss processes.

- Energy deposit distributions from the weighted sums of crystal energies (after event selection) were used to extract energy resolutions.
- The resolution is 1.52% using the Crystal Ball fit
- The resolution remains unchanged when selecting events near the boundary between crystals.

Conclusion

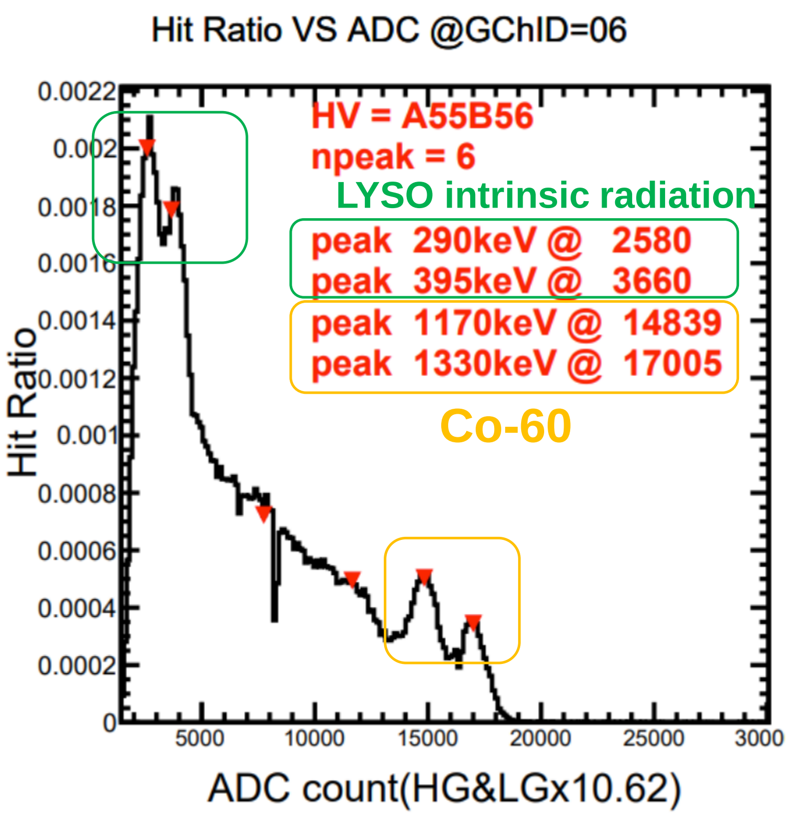
- **Uniformity :** Longitudinal response uniformity better than **4%** was achieved, independent of the photosensor viewing end.
- **Timing Resolution** : Better than 200 ps for energies above ~10 MeV, reaching 110 ps at 30 MeV.
- **Spatial Resolution** : Approximately 6 mm resolution was obtained at 70 MeV from energy sharing.
- **Energy Dependence** : For 70 MeV positrons, a 1.5% energy resolution was achieved, with further improvements expected using tapered voltage dividers at lower energies.
- **Energy Resolution** : With optimized PMT voltage dividers, a 2.6% resolution was measured for 17.6 MeV gammas from a p-Li reaction.
- **Future Work** : Full-size, 19 X_0 deep crystals in various shapes have been ordered for upcoming studies.
- **Overall Conclusion** : High-density, radiation-hard LYSO crystals—with high light yield and a 40 ns decay time—are excellent choices for electromagnetic calorimeters in nuclear and particle physics experiments.

Reference

- https://www.sciencedirect.com/science/article/pii/S0168900225001214?via%3Dihub
- https://indico.global/event/805/contributions/23435/attachments/11065/16340/LYSO%20for%20Pioneer.pdf
- https://indico.ihep.ac.cn/event/20052/attachments/69891/84565/Pioneer_ihep.pdf

Back up

Test w/ Radiation Source Co-60



We use Co-60 and LYSO intrinsic radiation to calibrate the detector.

- **@HV = 27.00V**

➔ 1.330 MeV @ 17005 digit
➔ 1.330 MeV / 17005 digit ~ 7.8e-5 MeV / digit
Saturated digit = 11, 0000 digit
➔ 11,0000 digit * 0.1268MeV = 8.6MeV
➔ **Saturated at 8.6MeV**
This HV/gain is too high for our beam test condition.

- HV setting range = 24.7V to 28.2V

We continue to lower HV setting to find a HV we can at least to see 200MeV beam without saturation.