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

David Hertzog; University of Washington

Physics Goals

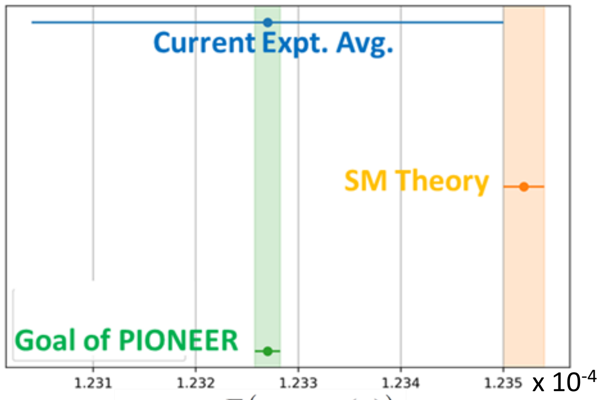
10 x Improvements in precision

- **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:** $\pi \rightarrow e\nu_H, \pi \rightarrow \mu\nu_H, \pi \rightarrow e\nu X$

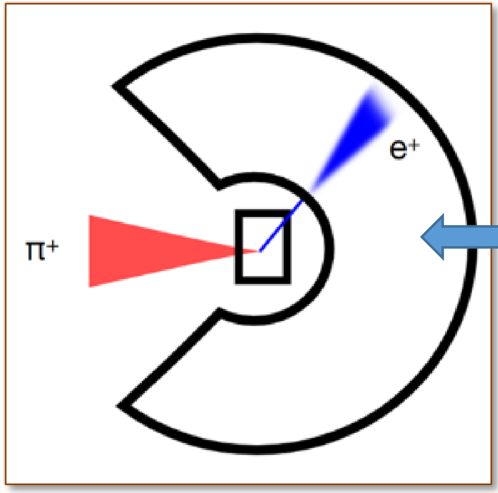
$$R^{theory}_{e/\mu} = \frac{\Gamma(\pi \rightarrow e\nu(\gamma))}{\Gamma(\pi \rightarrow \mu\nu(\gamma))}$$

illustrate challenge with this channel

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



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



2D cartoon of experiment

What is this?

- LXe?
- LYSO?

Interested in growing PIONEER Collaboration? Contact me: hertzog@uw.edu

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

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

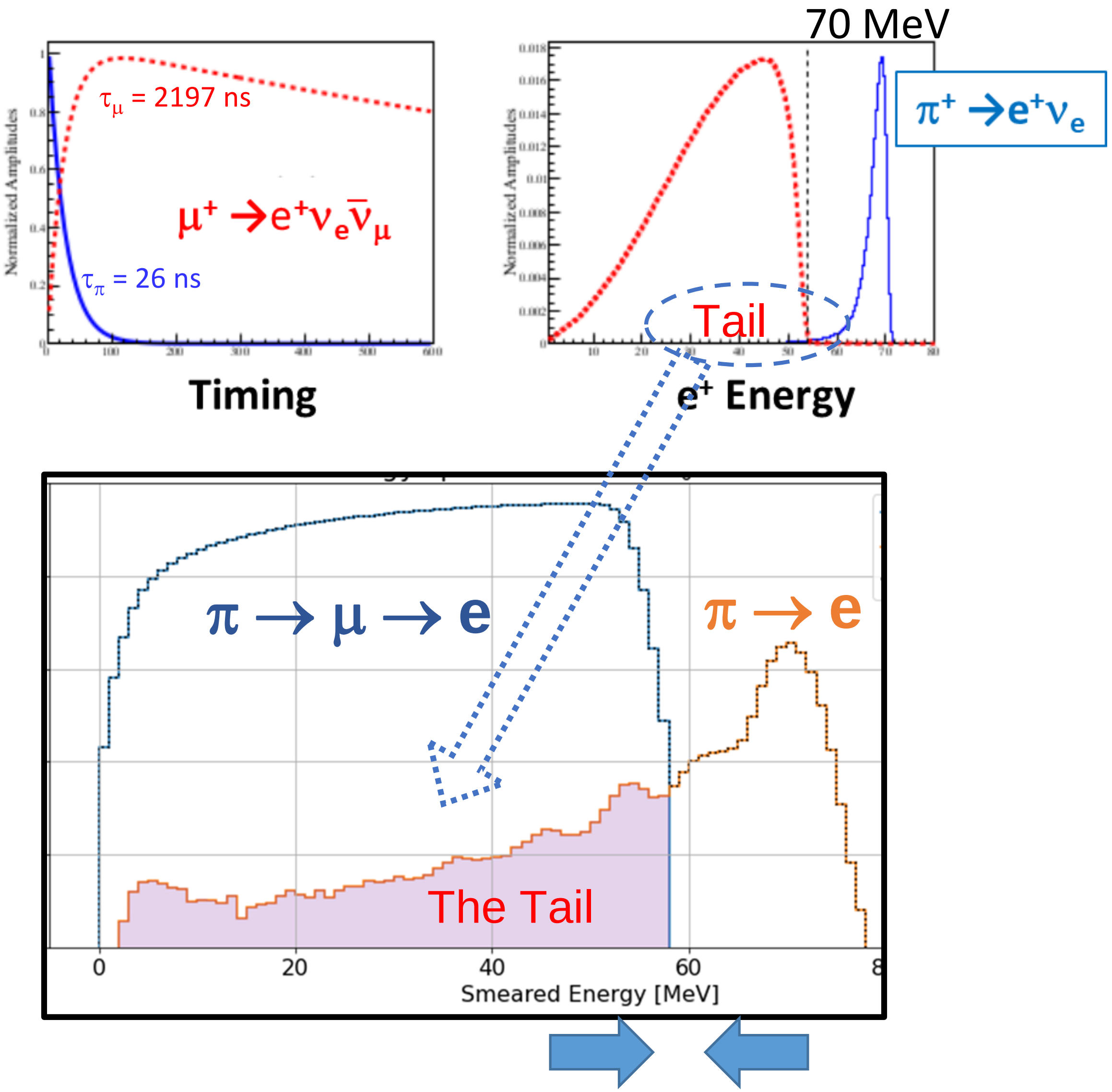
Must measure (and model) the full line shape

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

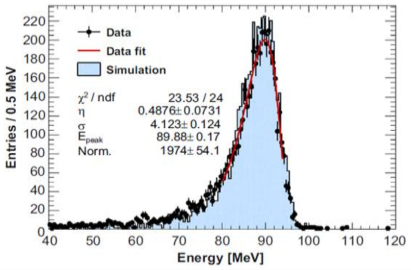
See Y. Zhang; Pioneer presentation Room 121 at 3 PM today

What material might work?

- LXe (used in MEG II) has excellent properties, but cannot be segmented
- LYSO crystals look promising, but no one has yet achieved needed resolution
- **Goal of this R&D**: Test newer LYSO formulation with attention to details to achieve the resolution promised by the intrinsic properties.
- History: Some arrays tested, obtained 4.5% @70 MeV, which met their goals
  - Can we do better?

Lutetium–yttrium oxyorthosilicate (LYSO):

- By weight: 72% Lutetium, 17% Oxygen, 6% Silicon, **3% Cerium (dopant)**, 2% Yttrium
- **X_0 = 1.14 cm** , R_M = 2.07 cm
- Decay time = **40 ns**
- Light yield **30,000 γ/MeV**
- λ_{peak} 420 nm -> conventional PMTs
- Radioactive (< 1 MeV constant rumble)
- Non hygroscopic
- No Temp dependence
- n = 1.82
- Not so cheap … ☹



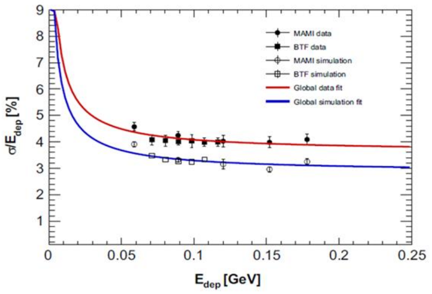
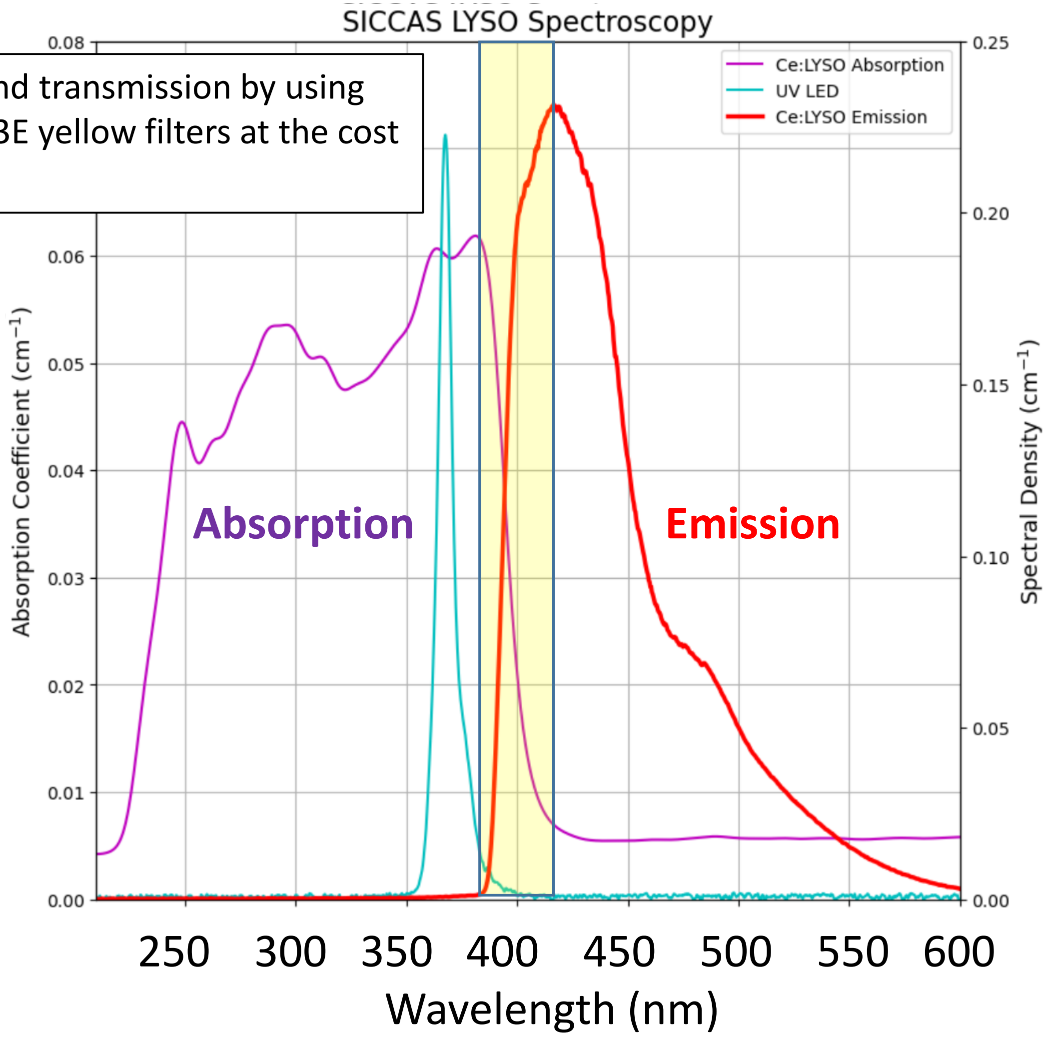


Fig. 2. Energy resolution as a function of the deposited energy for γ's (dots) and e⁻ (full squares). Corresponding MC expectations are reported in circles and open squares, respectively. Simulation points are obtained without the 2.6% Gaussian smearing needed to describe real data.

A test by Mu2e

LYSO Intrinsic Light Properties

Can extend transmission by using Wrattan 3E yellow filters at the cost of light

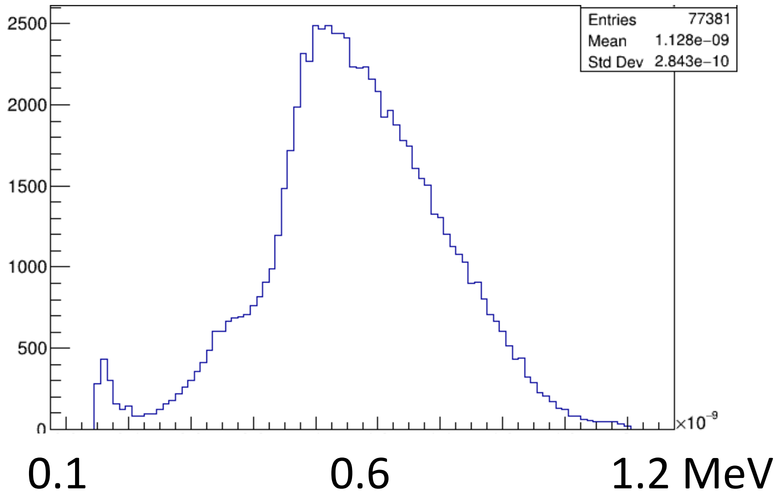


An interesting fact, LYSO intrinsic radioactivity.

→ From the beta decay of Lu-176

☺ Built in calibration!

☺ Slight concern when seeking best resolution at low energies from an array

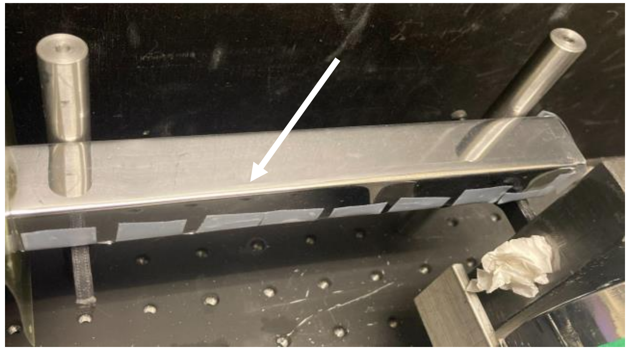


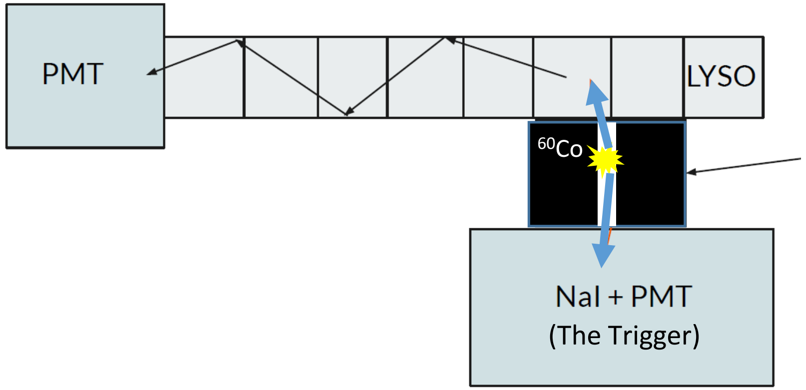
Alva-Sánchez et al. Understanding the intrinsic radioactivity energy spectrum from 176Lu in LYSO/LSO scintillation crystals. Sci Rep 8, 17310 (2018).

Single crystal tests of recent SICCAS* formulation

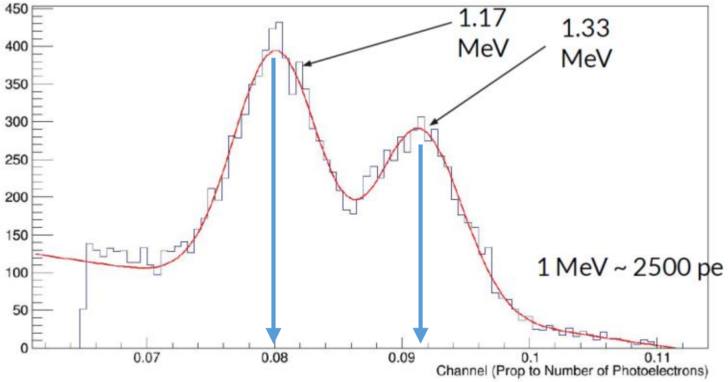
- 2.5 × 2.5 × 18 cm^3 (15.7 X0)
- Co-60 tomography to measure longitudinal uniformity / attenuation

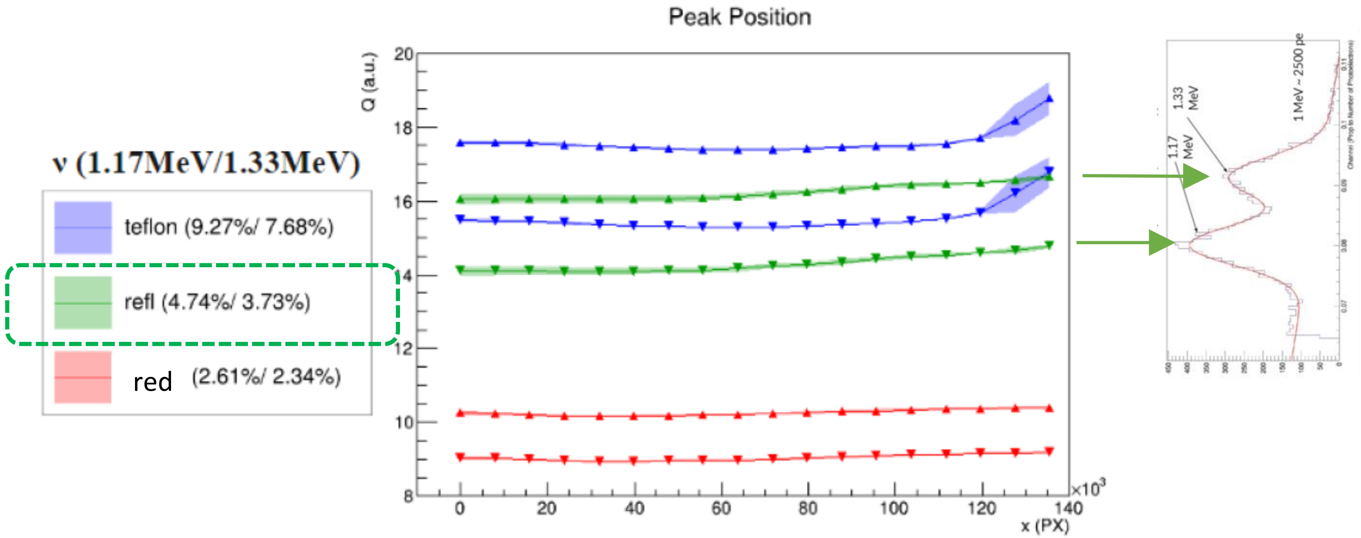
ESR-wrapped LYSO crystal





Measure Peak Positions vs Impact along crystal

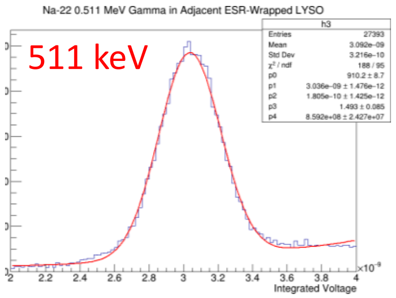




*Shanghai Institute of Ceramics (made our PbF_2 crystals for g-2)

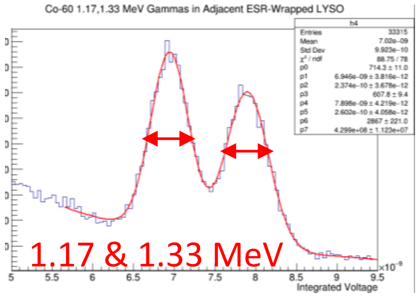
Energy resolution with “bench” sources

- Na22

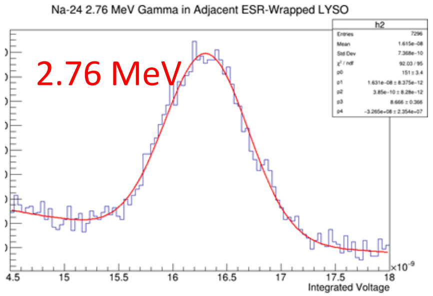


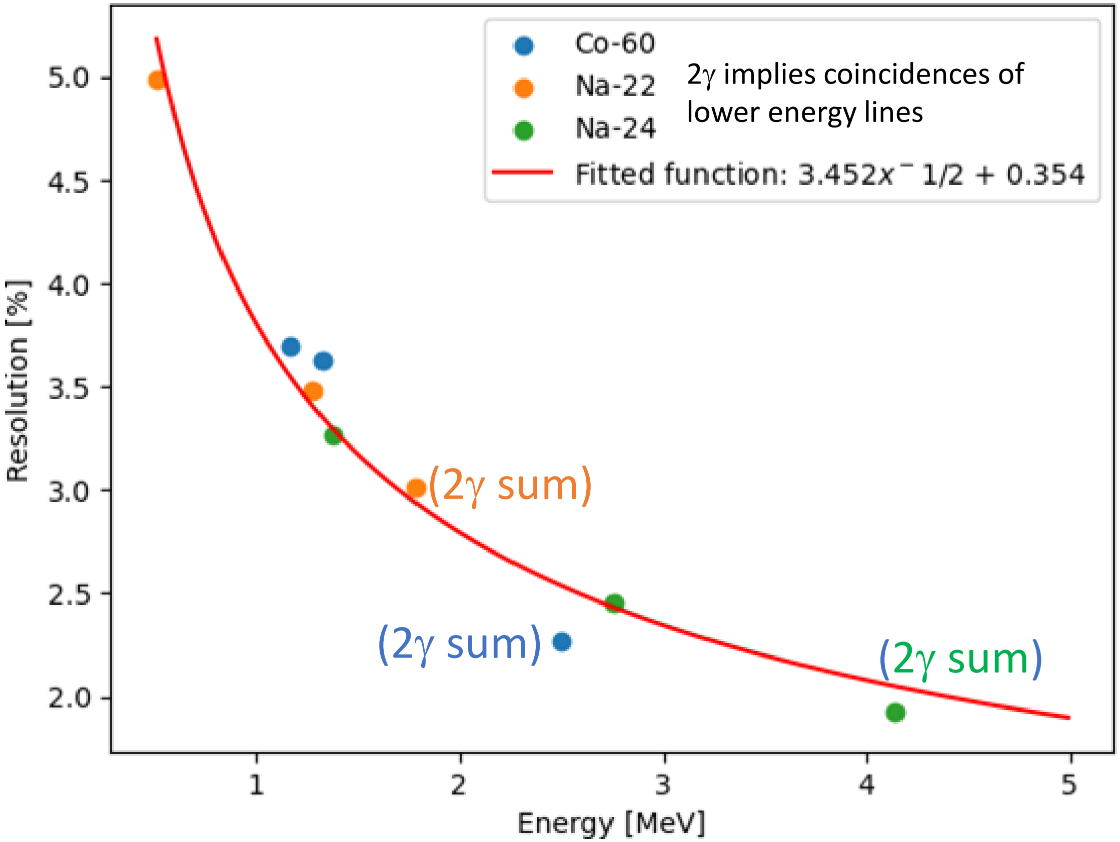
(this is why they are used in most PET scanners now)

- Co-60



- Na-24*
  - 1.38, 2.76 MeV

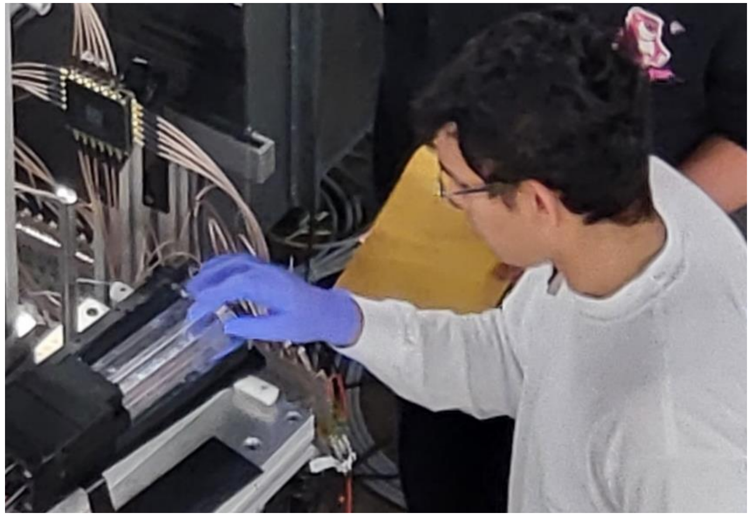


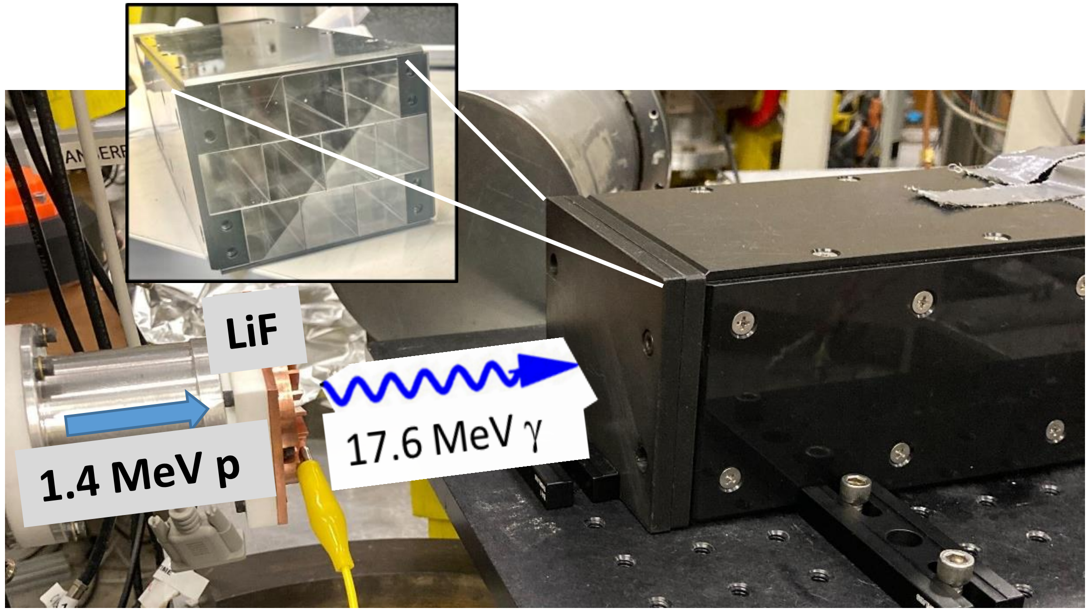


*Short lived (15 hr half life); emits a series of γ
Source made by bombarding 18 MeV deuterons, produces neutrons that strike an Al button (done at CENPA Van de Graaff)

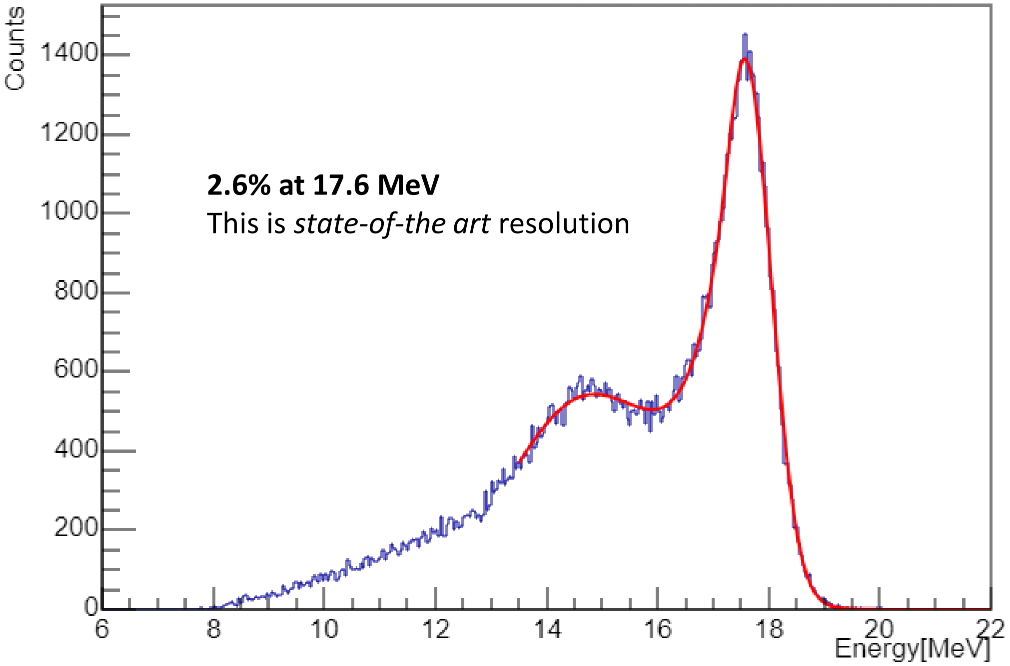
(Resolution is sigma of a Gaussian)

Measurements with 10 crystals



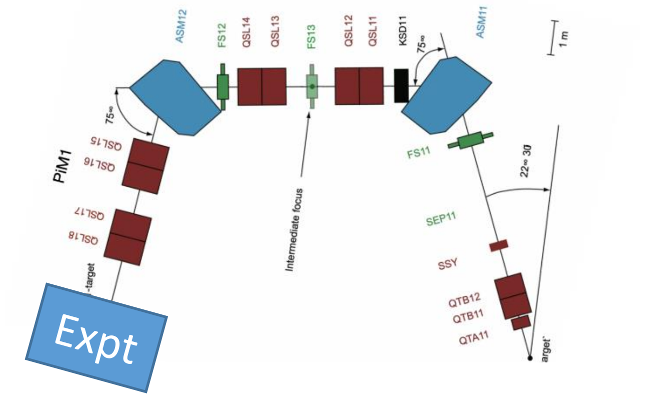


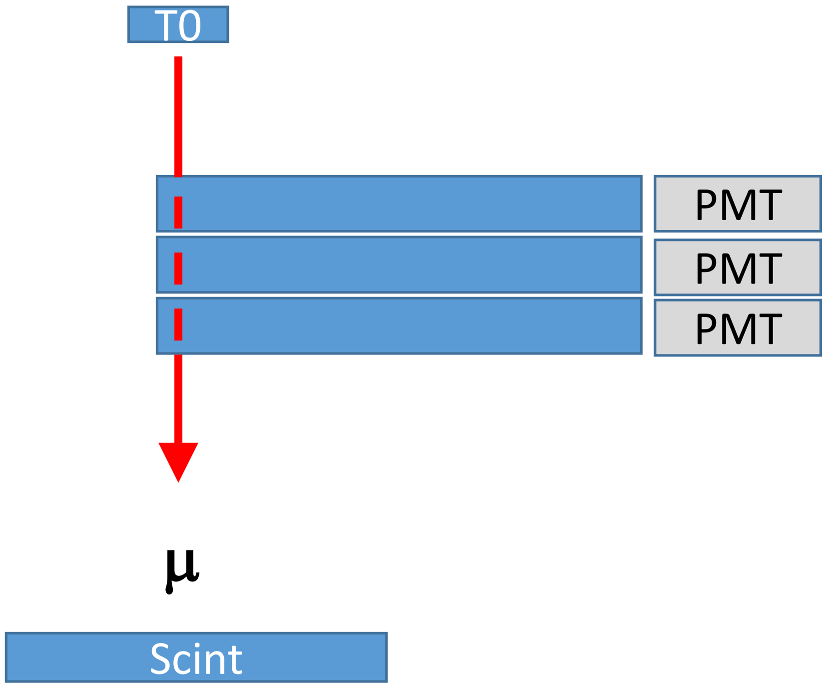
- Read out with R1450 Hamamatsu 19-mm PMTs using a customized, tapered voltage divider
- **p-Li** calibration following L3 @ LEP and MEG-II.
- We use a 1.4 MeV proton beam degraded and impinging on a LiF foil. **@440 keV** it excites a resonance, which decays with a 17.6 MeV gamma (and other lower energy lines)

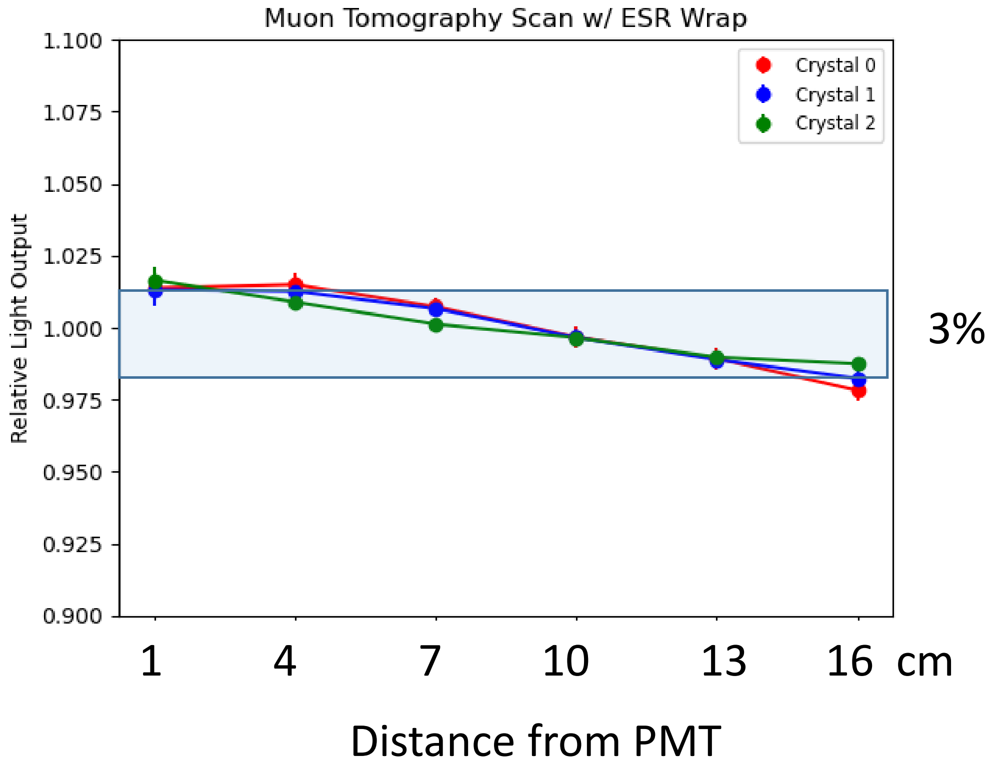


Next, π/μ/e beam at PSI

- 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

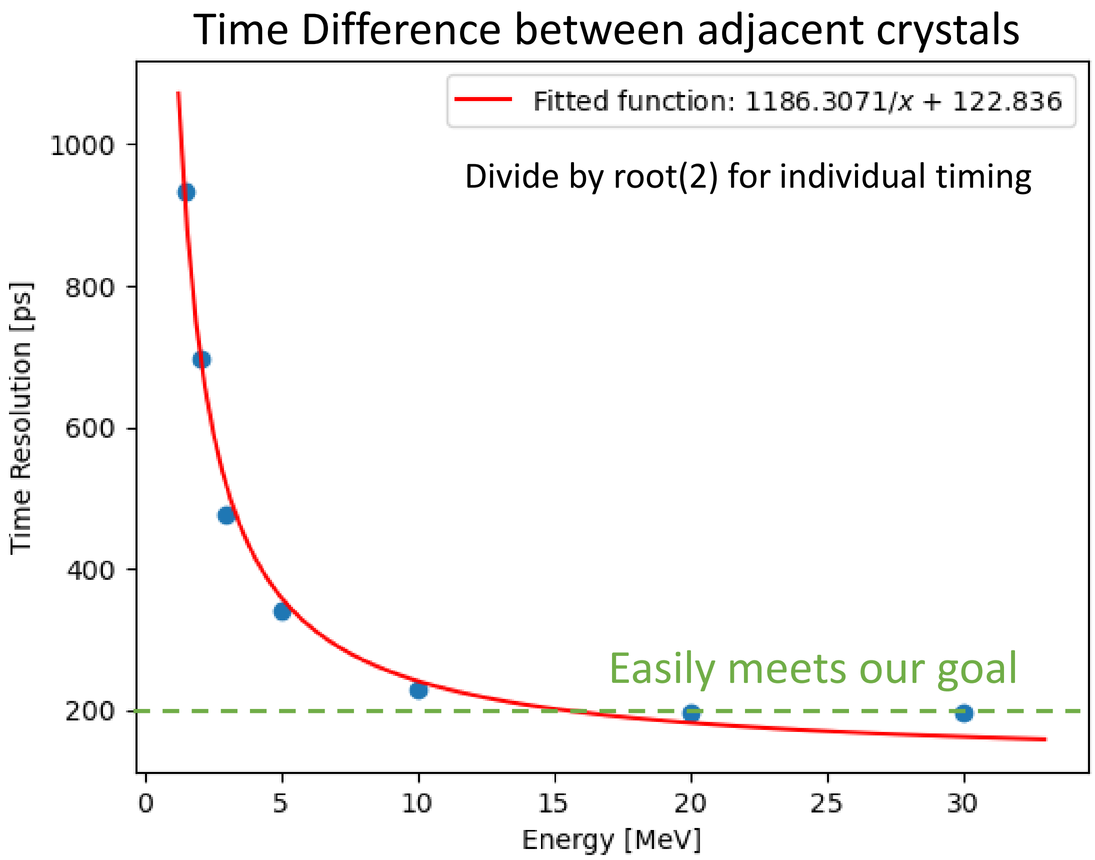


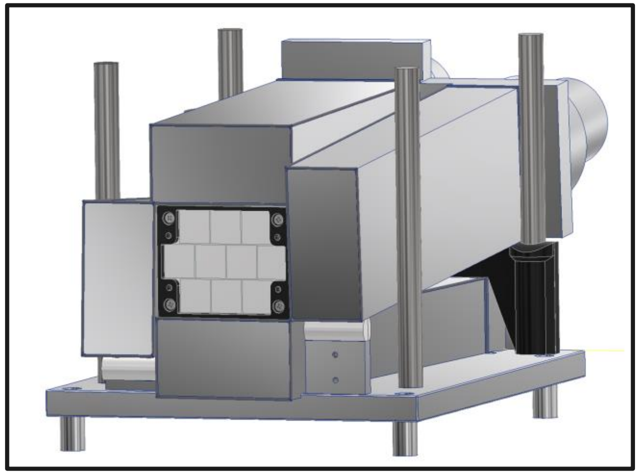


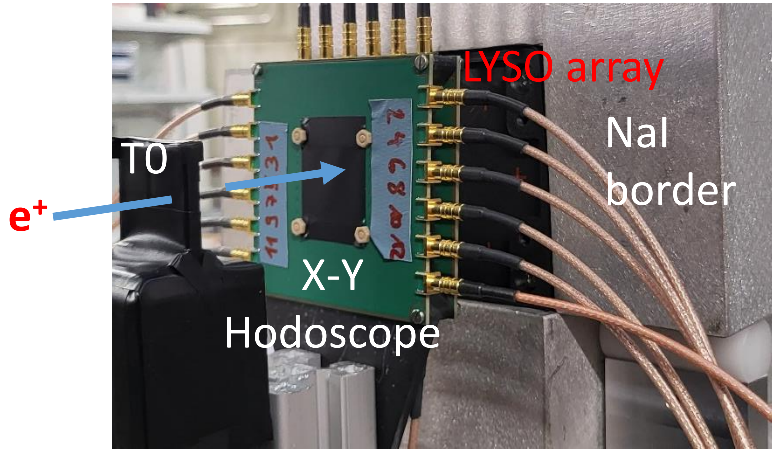


Timing Resolution vs Positron Energy

- Use T0 vs fitted Crystal waveform time
  - Plot is Xtal to Xtal time diff

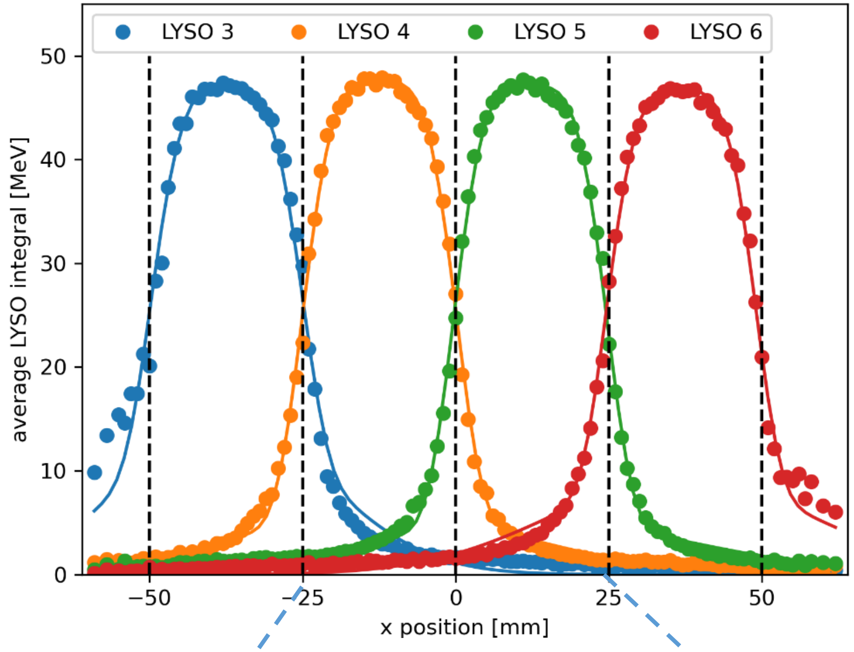




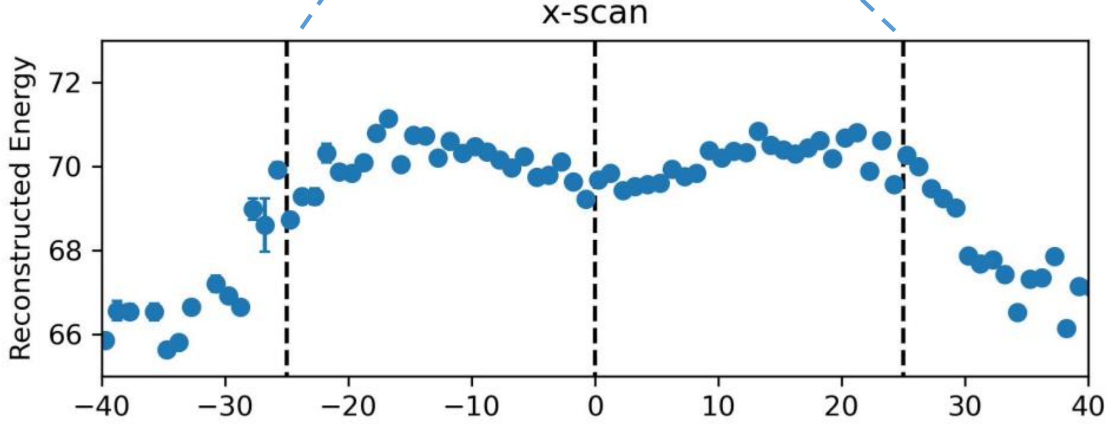


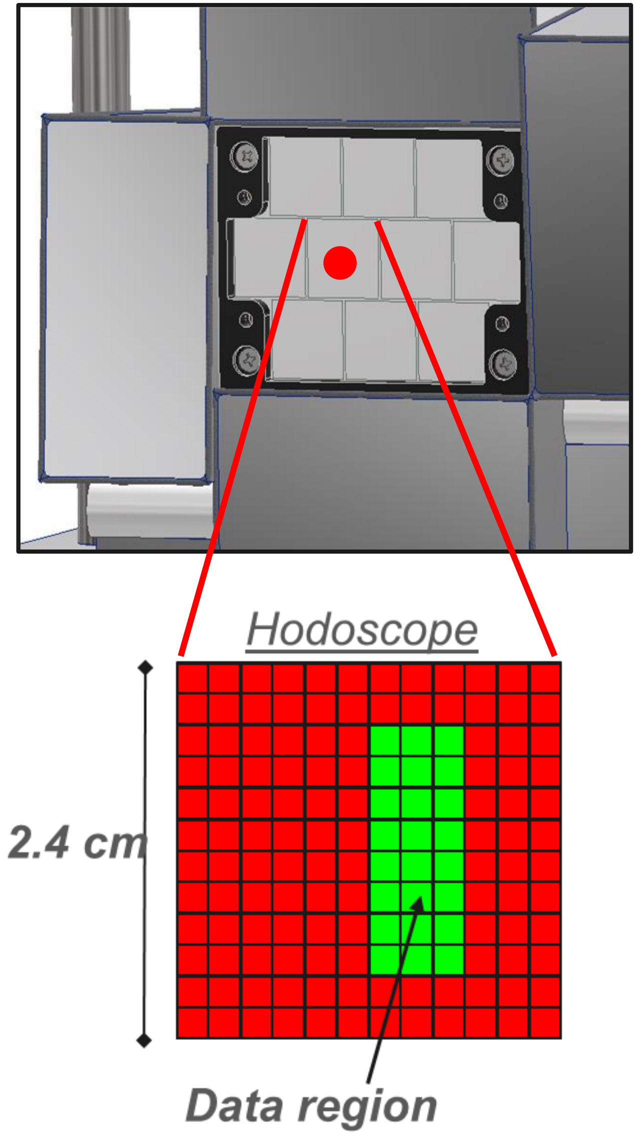
Uniformity across Crystal Boundary at 70 MeV

- Used X-Y hodoscope and moving table to scan front of array



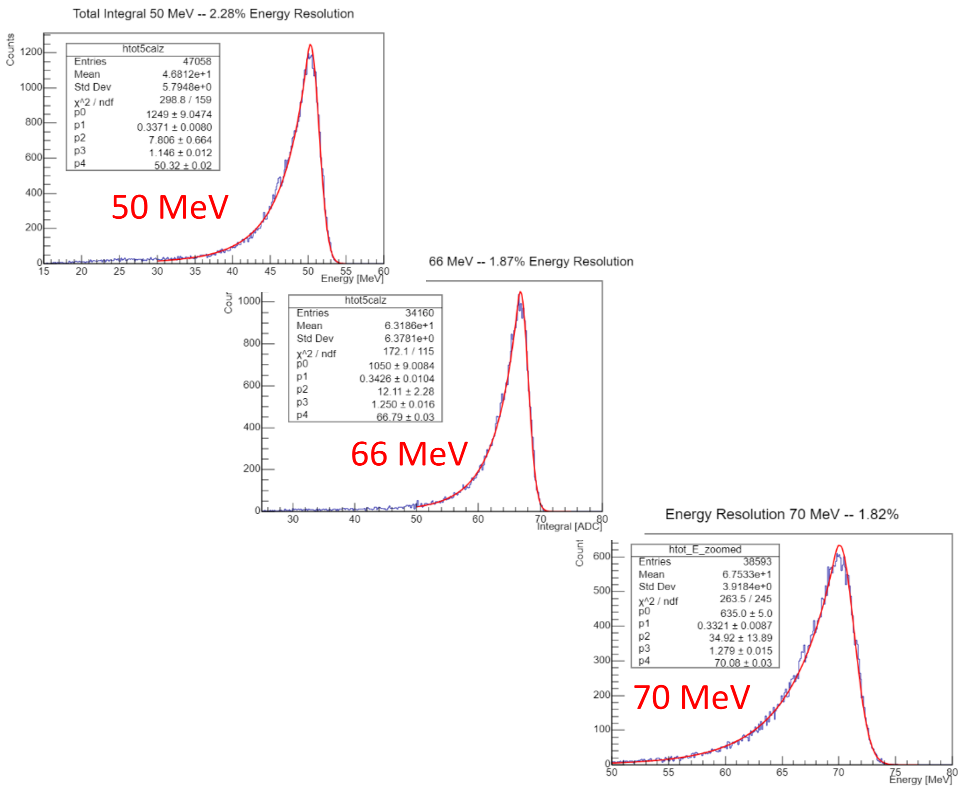
Result: Uniformity: 99.5 % middle / 97.7% array

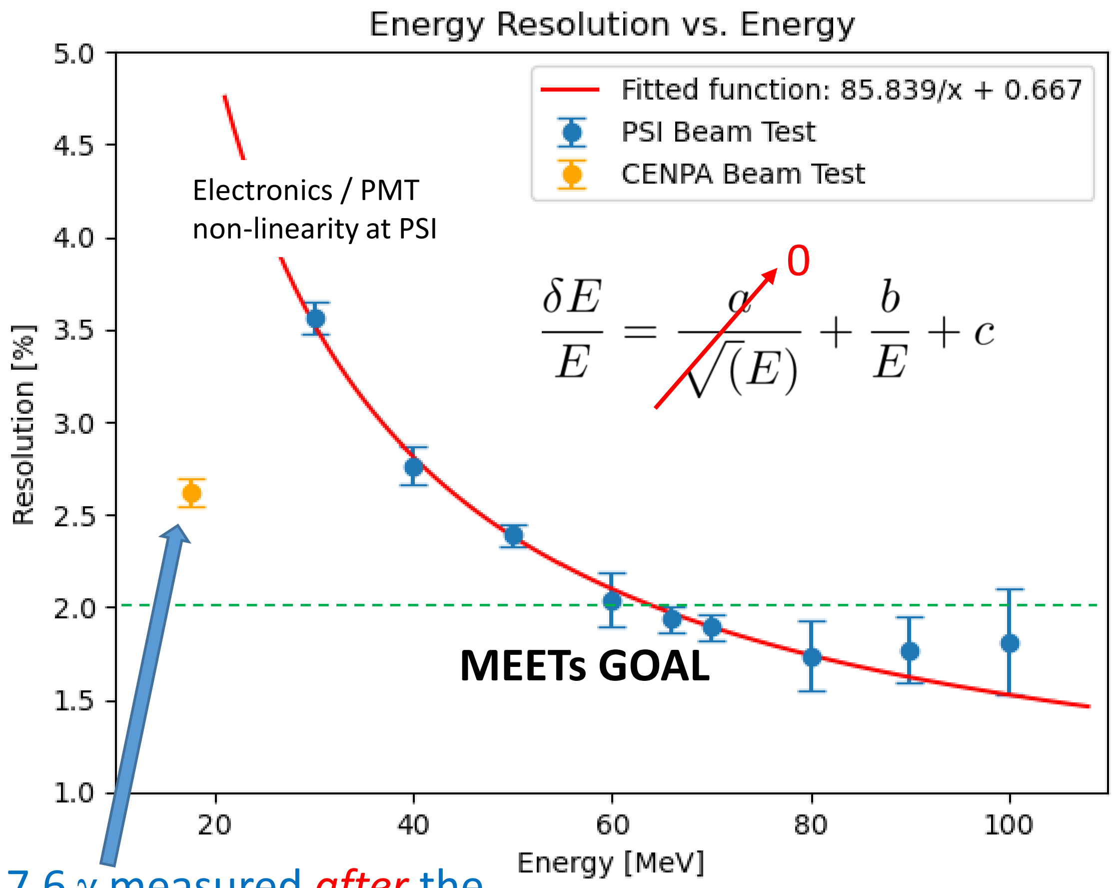




Energy Resolution vs Positron Energy

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

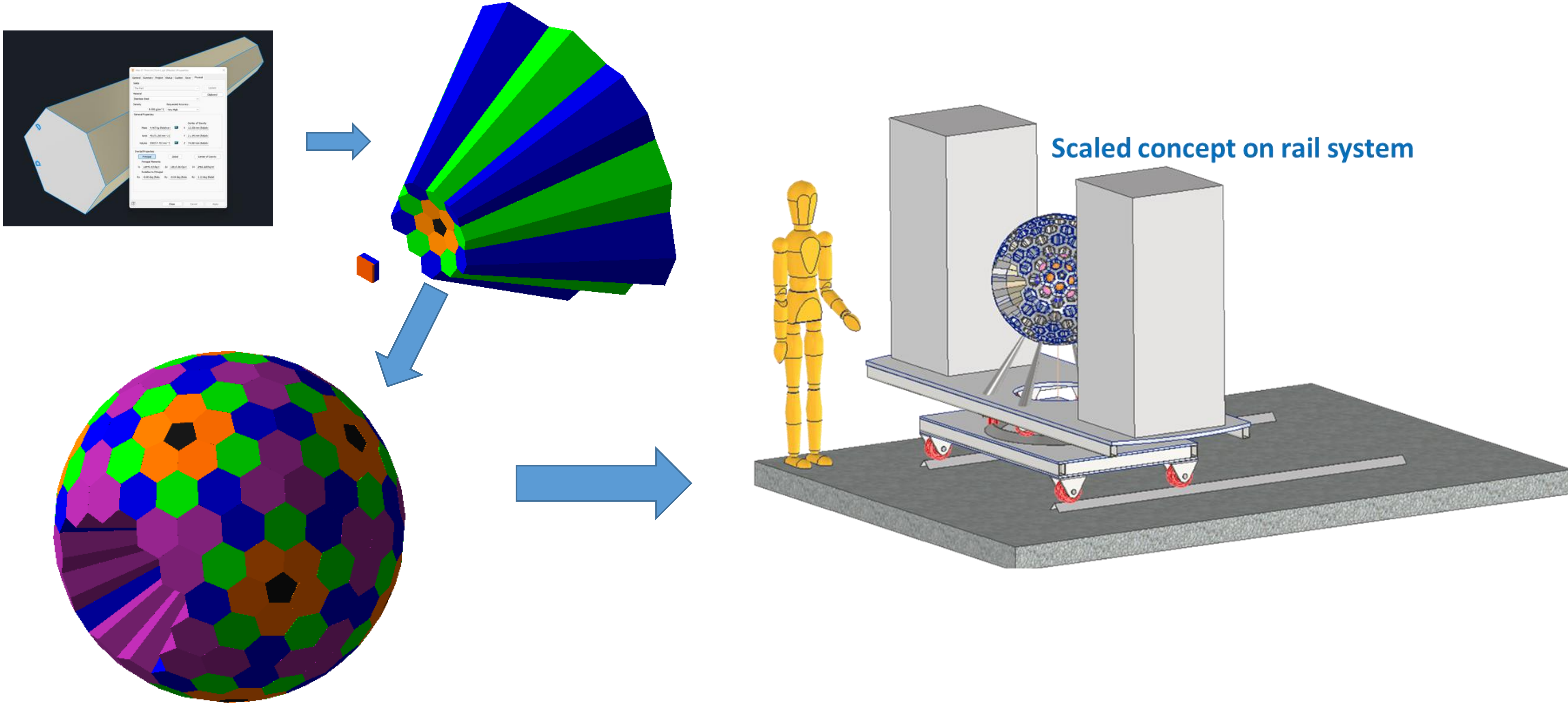




The 17.6 γ measured *after* the PMT dividers were upgraded

Notes: Many configurations were tested. Yellow filters (out/in); PMT dividers (built-in vs tapered);
Only 7 tapered dviders were available at PSI; later made 10 made for follow-up run with p-Li source @CENPA

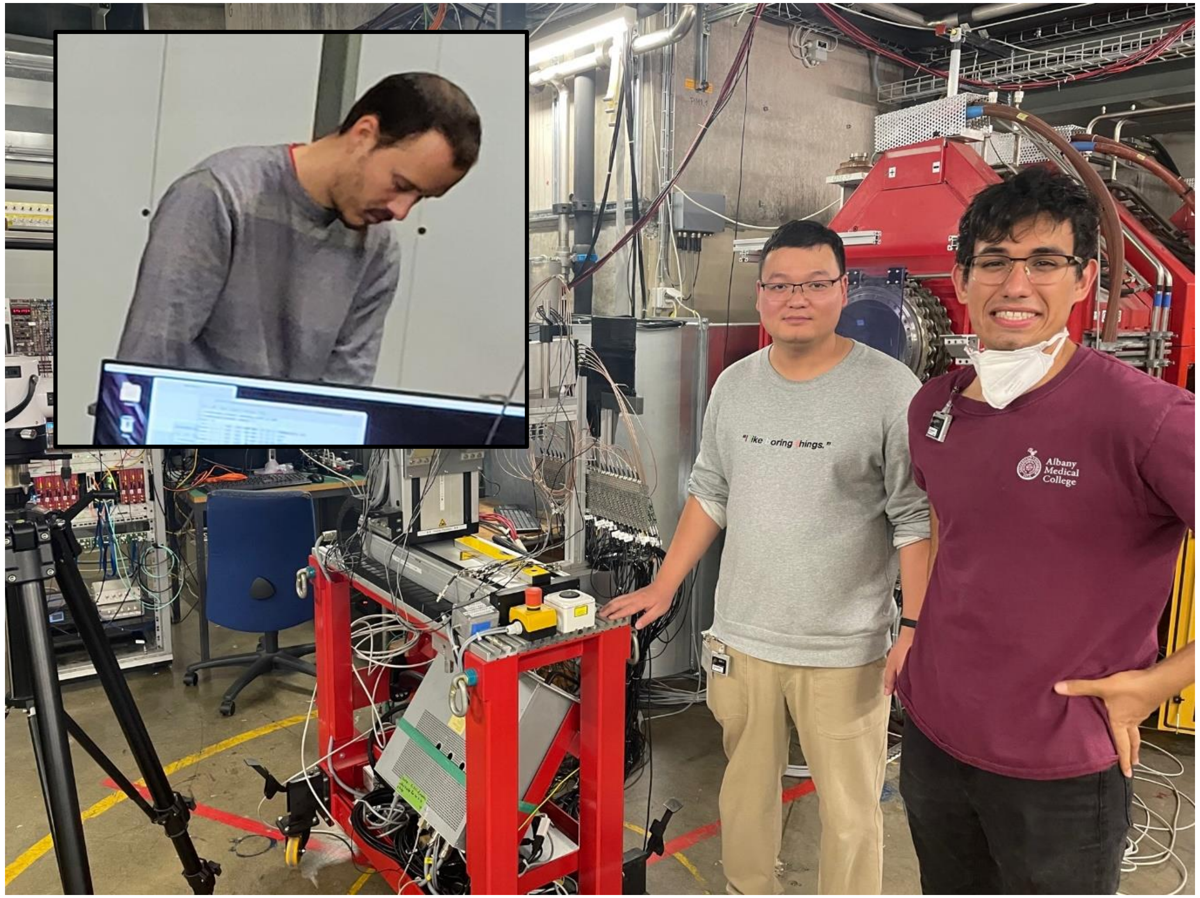
Next: Test 3 tapered crystals in a realistic final geometry for the experiment (concepts shown)



Summary

- LYSO tests of single crystals and array of 10 confirm performance expectations
  - Fast, Dense, Uniform, Bright
- Timing resolution **<200 ps**
- Energy resolution **<2% at 70 MeV**
  - Meets our target for $\pi \rightarrow e$ decay
- A paper is being written

- Next Steps: Explore tapered crystals



The Team

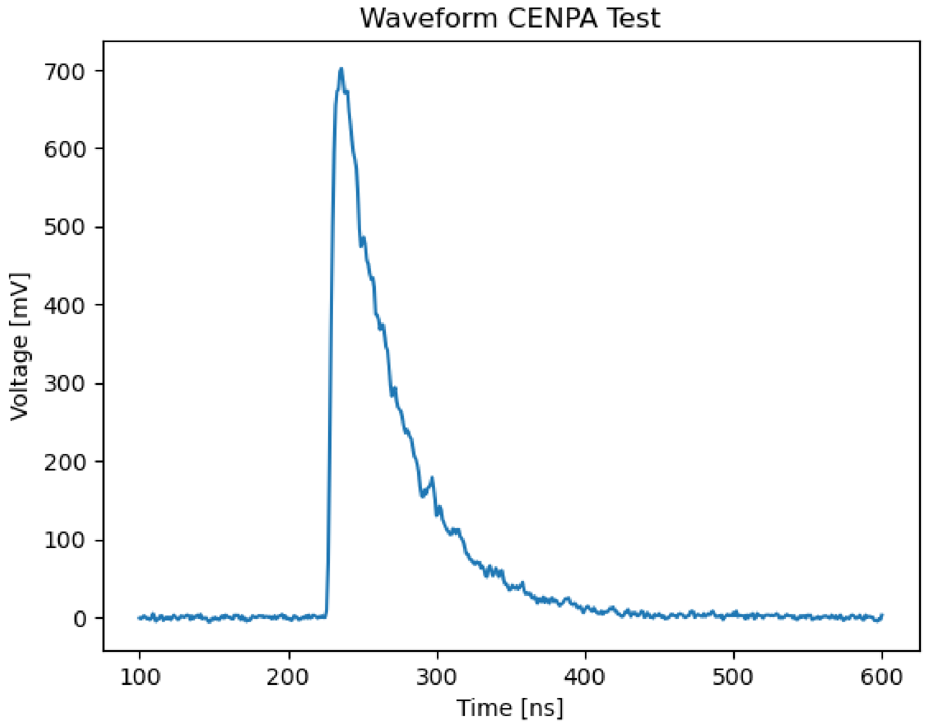
O. Beesley[a], J. Carlton[b], B. Davis-Purcell[c], S. Foster[b], K. Frahm[d], L. Gibbons[e], T. Gorringe[b], D.W. Hertzog[a], S. Hochrein[d], J. Hui[f], P. Kammel[a], J. LaBounty[a], J. Liu[f], R. Roehnelt[a], P. Schwendimann[a], A. Soter[d], B. Taylor[a], E. Swanson[a]

[a] *Center for Nuclear Physics and Astrophysics (CENPA) University of Washington Seattle WA 98195 USA*
[b] *University of Kentucky USA*
[c] *TRIUMF Canada*
[d] *ETH Zurich Switzerland*
[e] *Cornell University USA*
[f] *Shanghai Jiao Tong University Shanghai 200240 China*

Grad students

Undergrad

Pulse shape


Waveform CENPA Test
Voltage [mV]
Time [ns]
700
600
500
400
300
200
100
0
100
200
300
400
500
600

MEG resolution with p-Li

3.6% Energy Resolution

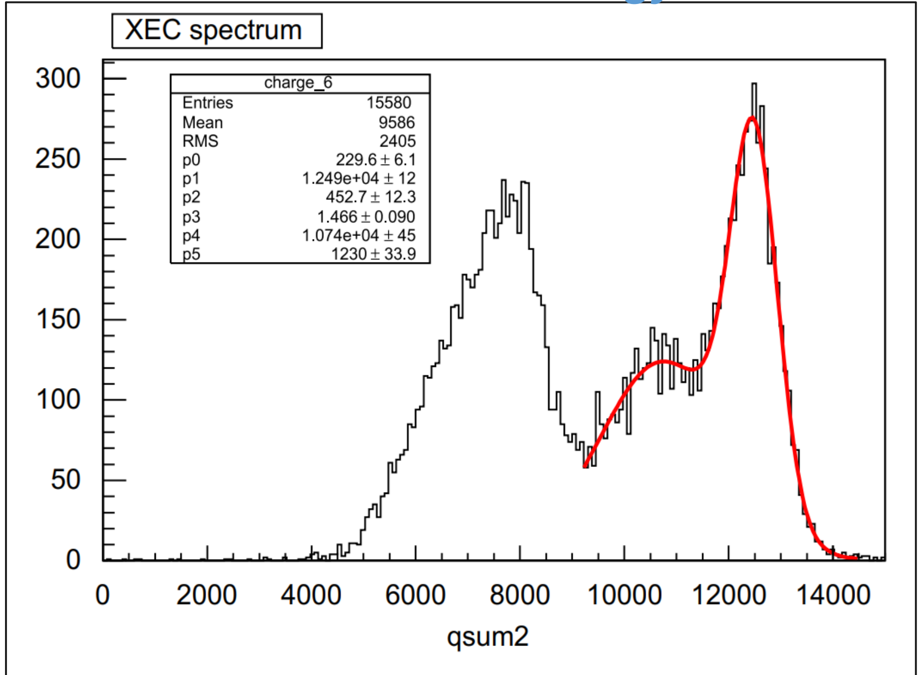
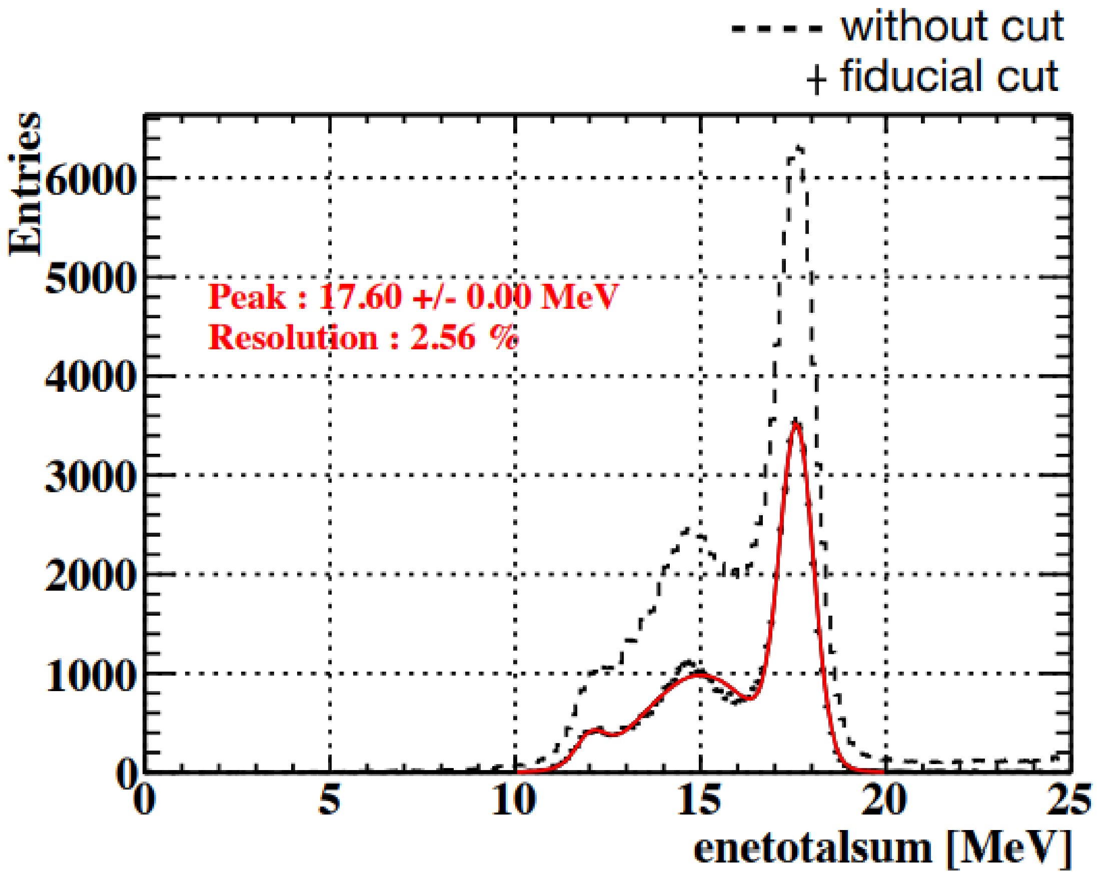


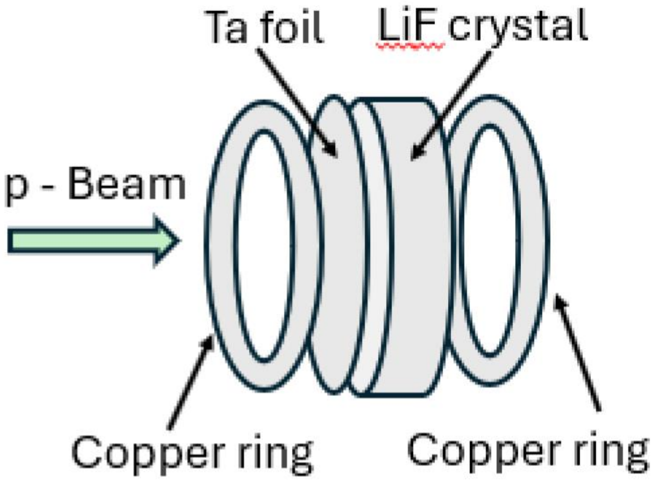
Fig. 24. LXe calorimeter resolution at the 17.6 MeV γ-line. The events in the 5000–9000 region are due to the α-particles from the calibration wire sources.

MEG 1



MEG 2

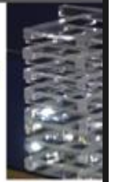
Details of the p-Li method



A 440 keV proton excites the 17.6 MeV level which decays to both the ground state and to a 3 MeV level with a 14.6 MeV gamma.

We use a 1.4 MeV proton beam, which is appropriate degraded through theta foil and the LiF crystal itself to the resonance energy

Crystals with Mass Production Capability



Crystal	NaI:Tl	CsI:Tl	CsI	BaF_2	CeF_3	PbF_2	BGO	BSO	$PbWO_4$	LYSO:Ce	AFO Glasses	Sapphire:Ti
Density (g/cm^3)	3.67	4.51	4.51	4.89	6.16	7.77	7.13	6.8	8.3	7.40	4.6	3.98
Melting points (°C)	651	621	621	1280	1460	824	1050	1030	1123	2050	\	2040
X_0 (cm)	2.59	1.86	1.86	2.03	1.65	0.94	1.12	1.15	0.89	1.14	2.96	7.02
R_M (cm)	4.13	3.57	3.57	3.10	2.39	2.18	2.23	2.33	2.00	2.07	2.89	2.88
λ_I (cm)	42.9	39.3	39.3	30.7	23.2	22.4	22.7	23.4	20.7	20.9	26.4	24.2
Z_{eff}	50.1	54.0	54.0	51.6	51.7	77.4	72.9	75.3	74.5	64.8	42.8	11.2
dE/dX (MeV/cm)	4.79	5.56	5.56	6.52	8.40	9.42	8.99	8.59	10.1	9.55	6.84	6.75
λ_{peak}[a] (nm)	410	560	420 310	300 220	340 300	\	480	470	425 420	420	365	750
Refractive Index[b]	1.85	1.79	1.95	1.50	1.62	1.82	2.15	2.68	2.20	1.82	\	1.76
Normalized Light Yield[a,c]	120	190	4.2 1.3	42 4.8	8.6	\	25	5	0.4 0.1	100	1.5	\
Total Light yield (ph/MeV)	35,000	58,000	1700	13,000	2,600	\	7,400	1,500	130	30,000	450	\
Decay time[a] (ns)	245	1220	30 6	600 0.5	30	\	300	100	30 10	40	40	3200
Hygroscopic	Yes	Slight	Slight	No	No	No	No	No	No	No	No	No

Ren-yuan Zhu, Caltec

LYSO Intrinsic radioacivity

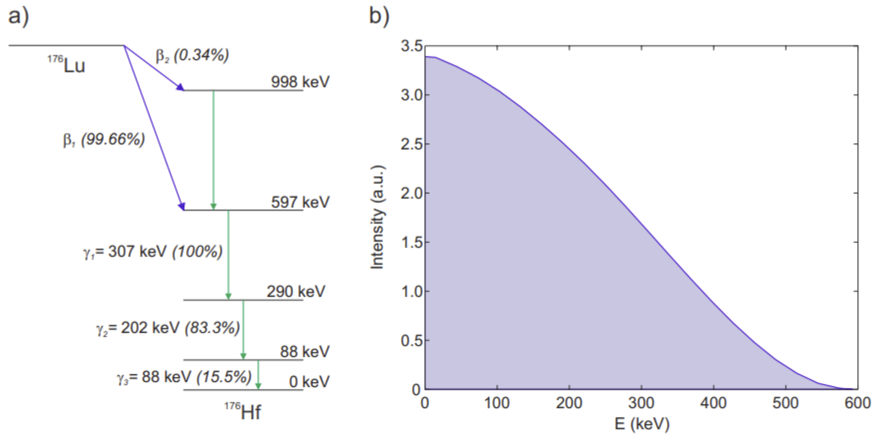


Figure 1. (**a**) Simplified ^{176}Lu decay scheme and (**b**) β-particle energy spectrum corresponding to the β_1 transition.

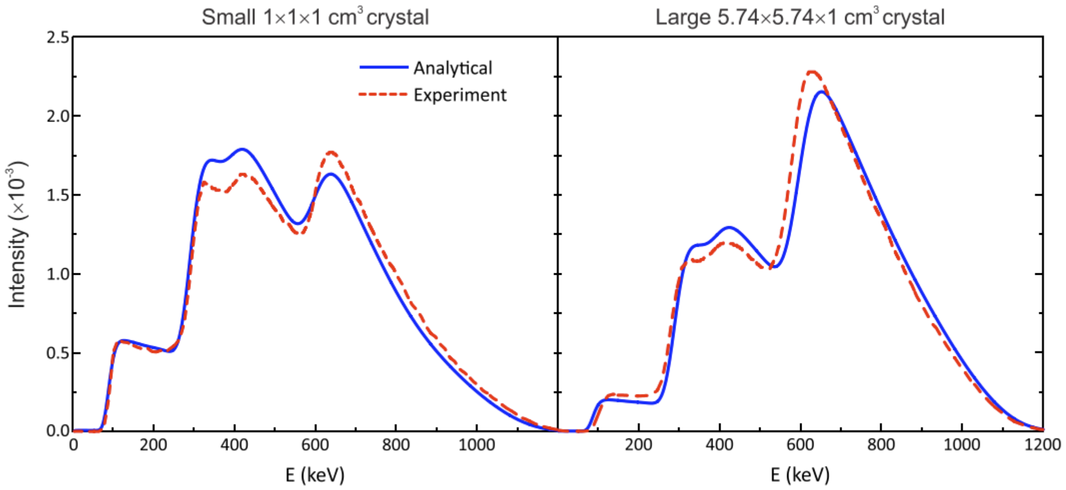


Figure 3. Analytical (solid line), convolved with a varying Gaussian kernel, and experimental (dashed line) LYSO normalized energy spectra.

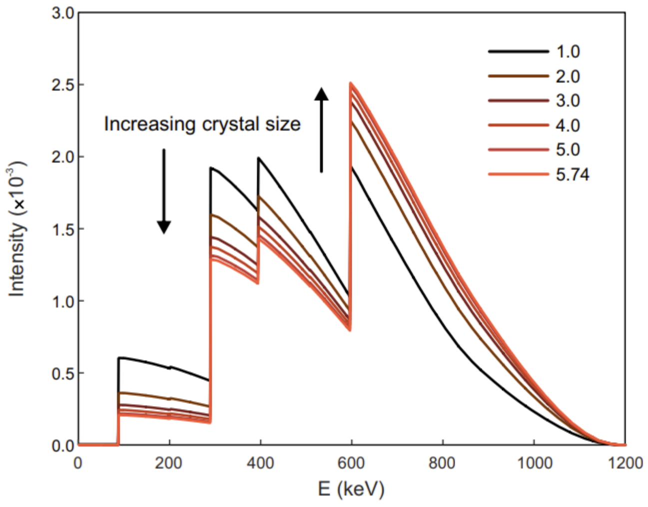


Figure 5. Calculated LYSO energy spectra for 1.0 cm thick square base prisms of different sizes.