Towards a Large Calorimeter based on LYSO Crystals for Future High Energy Physics

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Overview

The Need for High Precision Calorimetry

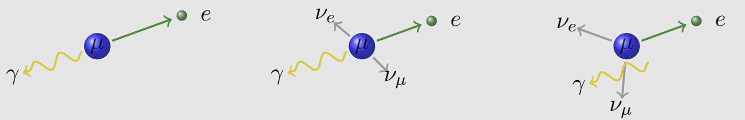
... to find evidence for BSM physics in testing SM predictions to an unprecedented accuracy.

Charged Lepton Flavour Violation

- Looking for decays like $\mu \to e\gamma$, $\mu \to eee$ etc.
- Prohibited by the SM, predicted by some BSM theories.

The Legendary Needle in the Haystack: $\mu \to e\gamma$ [1, 2]

Signal — Prompt Background — Accidental Background



Is the branching ratio $BR(\mu \to e\gamma) > 6 \times 10^{-14}$ **?**

$R_{\text{acc}} \propto R_\mu^2 \cdot \Delta E_\gamma^2 \cdot \Delta P_e \cdot \Delta \Theta_{e\gamma}^2 \cdot \Delta t_{e\gamma}$

Affected by calorimeter performance

LYSO vs. Lanthanum Bromide

Short Radiation Length vs. High Light Yield and Fast Decay

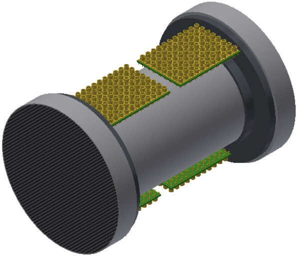
Selection of Scintillating Materials

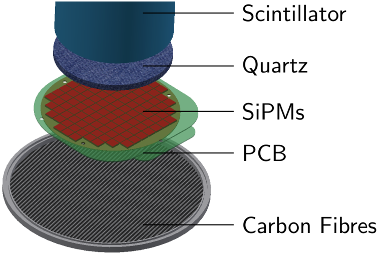
	Density ρ (g/cm^3)	Light Yield LY (ph/keV)	Decay Time τ (ns)	Radiation Lenth X_0 (cm)
$LaBr_3$(Ce)	5.08	**63**	**16**	2.1
LYSO	**7.1**	27	41	**1.21**
NaI(TI)	3.67	38	245	2.59
BGO	7.13	9	300	1.12

Crystal Sizes Previously Investigated [3, 4, 5]

Material	LYSO		$LaBr_3$(Ce)	
	Diameter	Length	Diameter	Length
"Available"	7 cm	16 cm	9 cm	20 cm
"Large"	15 cm	16 cm	15 cm	20 cm
"Ultimate"	40 cm	17 cm	46 cm	31.5 cm

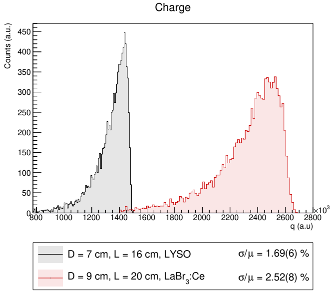
Prototype Configuration

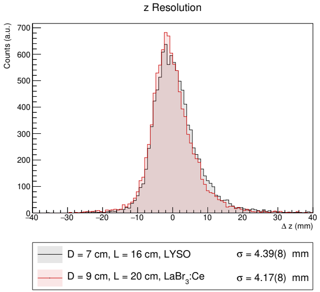




- Goal: Detect Photons of $\mathcal{O}(50\,\mathrm{MeV})$
- Attach SiPMs to LYSO or $LaBr_3(Ce)$ to build calorimeter.
- Thin SiPMs allow readout on front and back.
- Use granularity for geometrical reconstruction.

Simulations of Available Sizes



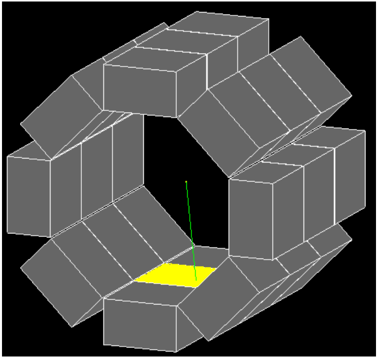


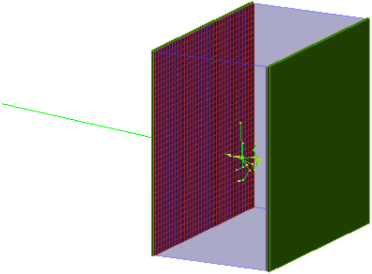
- Better charge resolution for LYSO due to larger energy leakage through lateral side in $LaBr_3$(Ce).
- Time resolution around $30\,\mathrm{ps}$ for both.
- Position resolution around $3\,\mathrm{mm}$ perpendicular to the crystal axis for both.

$\Rightarrow$ Prefer LYSO over $LaBr_3$(Ce)

Potential Use of Larger Crystals

Towards future High Precision Calorimeters



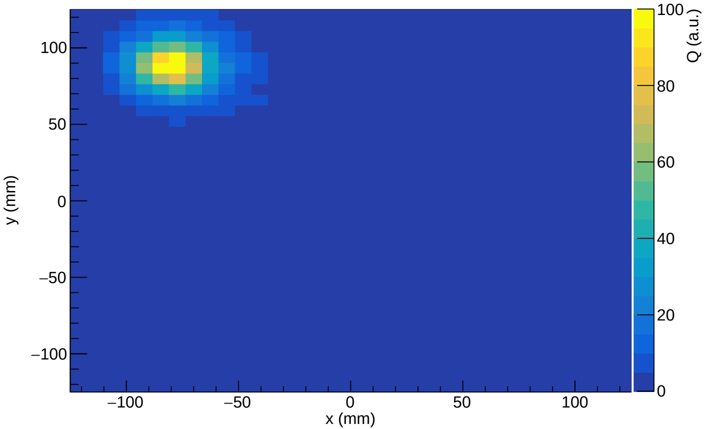


Combine multiple large crystals (e.g. $25\,\mathrm{cm} \times 25\,\mathrm{cm} \times 15\,\mathrm{cm}$)

Tracking Optical Photons

Photons detected per SiPM on the inner surface of a crystal

x = -81.1, y = 87.9



Variable Estimation Algorithms

Time: Estimate from front and back times t_f, t_b

$$t = \frac{(n-1)t_f + (n+1)t_b - L/c(n^2+n)}{2n}$$

Position: Estimate from granular charge collection and time

$$x, y : \text{Gaussian Fit}$$

$$z = \frac{1}{2}\left(\frac{c}{n} * (t_f - t_b) + L\right)$$

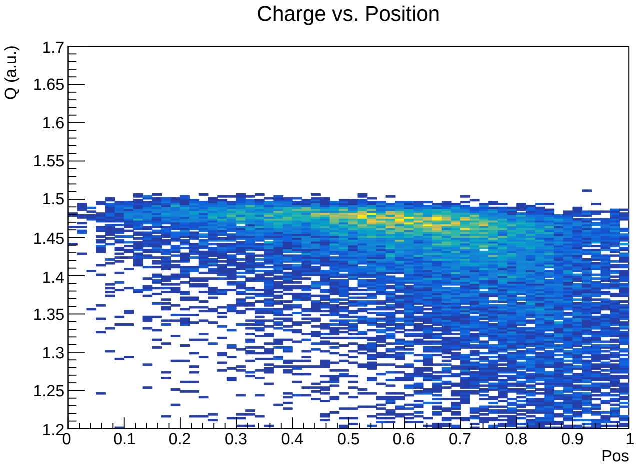
Charge: Sum integrated charge over all channels

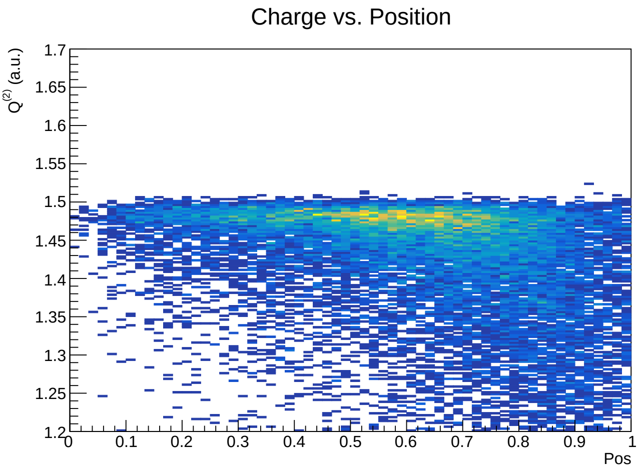
$$Q_{\text{tot}} = \sum q_i$$

$$Q_{\text{tot}}^{(2)} = \frac{Q_{\text{tot}}}{1 - a(x^2 + y^2)}$$

Charge Reconstruction

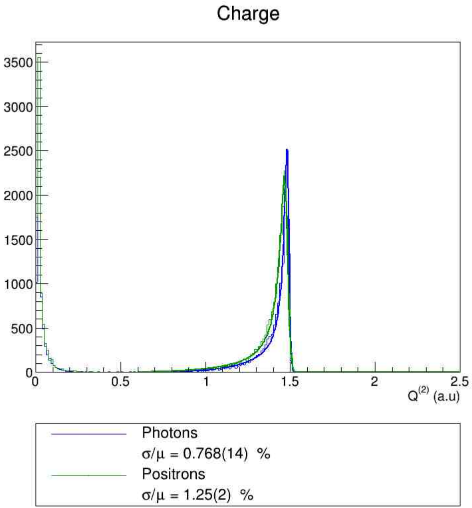
Before Correction



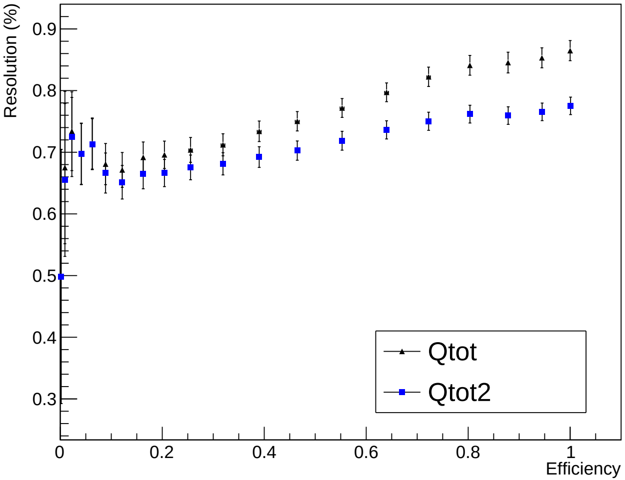


Charge vs. Position
$Q^{(2)}$ (a.u.)
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Pos

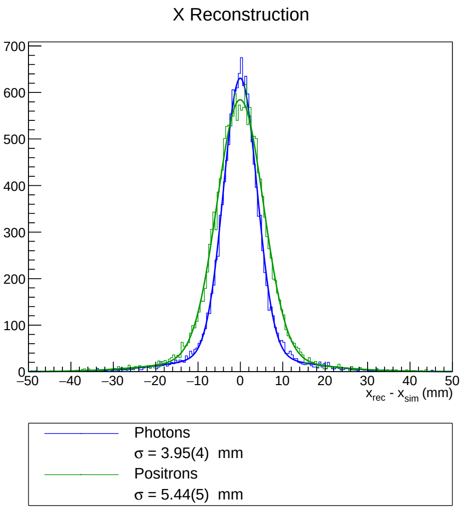
Charge Resolution



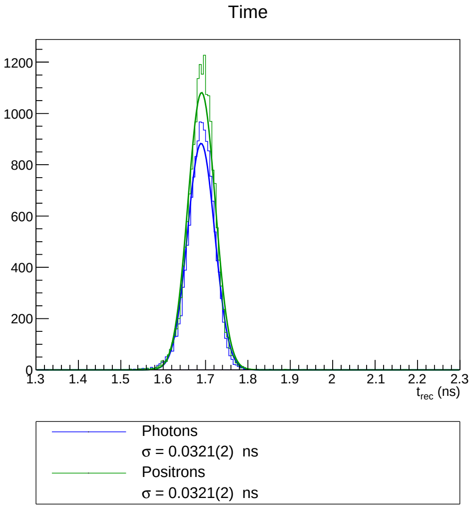
Geometrical Cuts



Position Resolution



Time Resolution



Conclusion

Promising Results

- Energy resolution below $1\,\%$ for $55\,\mathrm{MeV}$ photons.
- Position resolution below $5\,\mathrm{mm}$
- Time resolution below $40\,\mathrm{ps}$

Far Future Plans

There is still a long way to go until such crystals can be grown.

Not so Far Future Plans

Instead of large single crystals, build a calorimeter from smaller, tapered crystals. [6]

Acknowledgements

Co-Authors

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Grants

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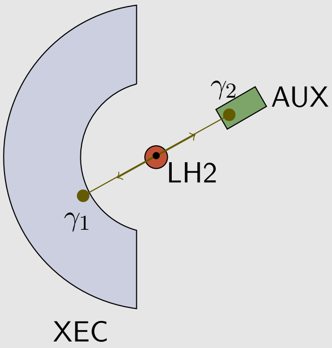
Swiss National Foundation n. 200020_172706

Xenon Calorimeter Calibration by Charge Exchange

Configuration



Charge Exchange Reaction

π^--beam on LH2 target

$$\pi^- p \to \pi^0 n$$

π^0 decays in flights

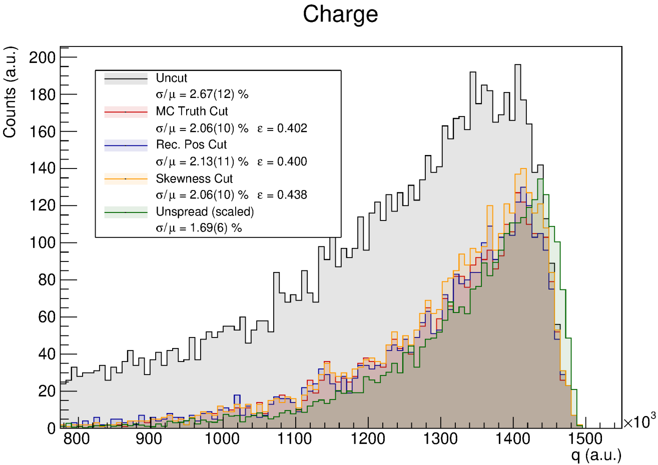
$$\pi^0 \to \gamma\gamma$$

$54.9\,\mathrm{MeV} \leq E_\gamma \leq 82.9\,\mathrm{MeV}$

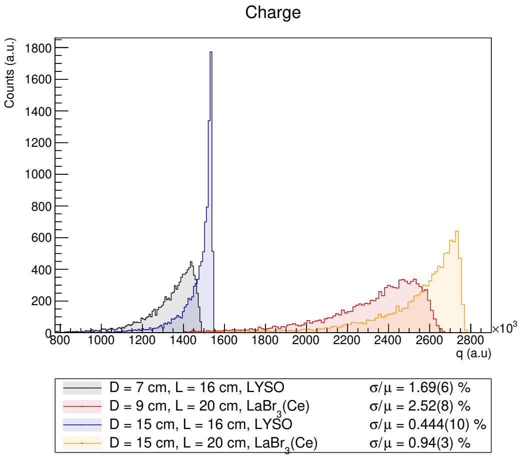
Extremal for $\Theta_{\gamma\gamma} = 180^\circ$

Require AUX detector to assert $\Theta_{\gamma\gamma} = 180^\circ$ and thus $55\,\mathrm{MeV}$ $(83\,\mathrm{MeV})$ γ in calorimeter. Opportunity to test prototypes.

Applying Geometrical Cuts

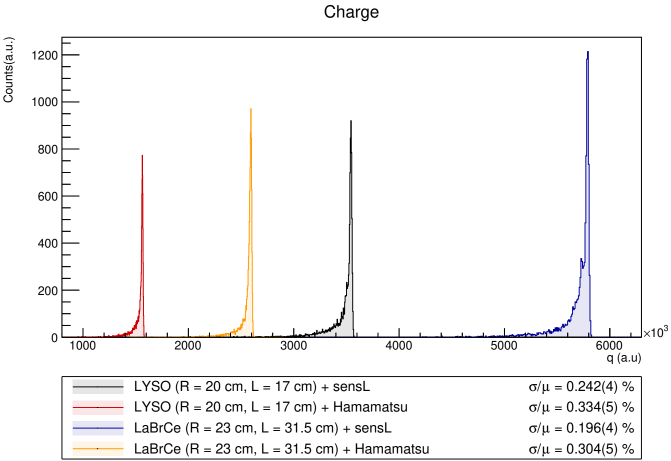


Increasing the Size



Better energy resolution for larger diameters.

Ultimate Crystals



Time resolution $\mathcal{O}(30\,\mathrm{ps})$, Position resolution $\mathcal{O}(5\,\mathrm{mm})$.

Summary of LYSO Prototype Studies

Resolutions

	$LaBr_3$(Ce)	LYSO
Energy (%)	2.5 / 0.9 / 0.3	1.7 / 0.4 / 0.3
Time (ps)	28 / 30 / 39	26 / 28 / 36
x Position (mm)	3 / 3.7 / 5.7	2.4 / 3.0 / 3.6
z Position (mm)	4 / 4.8 / 5.4	4.4 / 5 / 6

Values refer to available/ large/ ultimate crystals.

Conclusion

- Light yield is not the limiting factor for the resolutions.
- LYSO performs better due to higher density.

Prototype using a LYSO crystal with $10\,\mathrm{cm}$ length and $7\,\mathrm{cm}$ diameter is under construction.

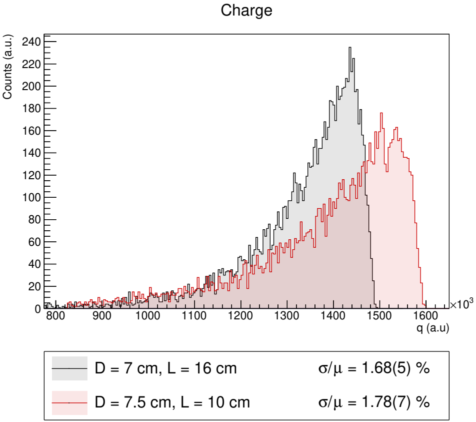
SiPMs

SiPMs

	Hamamatsu	sensL
Type	S13360-6025PE	MicroFJ-60035TSV
Size (mm^2)	7.35×6.85	6.13×6.13
Active Area (mm^2)	6.0×6.0	6.07×6.07
Number of Pixels	57 600	22 292
Fill Factor (%)	47	75
PDE (%)	25	38 to 50

Industry Issues

"Available" LYSO crystal has defects ...



Closest size: $7.5\,\mathrm{cm}$ diam., $10\,\mathrm{cm}$ length.

No significant decrease in performance.

Further Reading I

[1] A. M. Baldini et al. (MEG II Collaboration).
MEG Upgrade Proposal.
arXiv:1301.7225v2 [physics.ins-det], 2013.

[2] A. M. Baldini et al. (MEG II Collaboration).
The design of the MEG II experiment.
Eur. Phys. J. C, 78:380, 2018.

[3] A. Papa, P. Schwendimann.
A First Large Calorimeter Prototype Based on Lanthanum Bromide Coupled to Silicon Photomultipliers: Status and Prospects.
Nucl. Instr. Meth. A, 936:130, 2019.

Further Reading II

[4] A. Papa, P. Schwendimann.
Development of new large calorimeter prototypes based on $LaBr_3$(Ce) and LYSO crystals coupled to silicon photomultipliers: A direct comparison.
Nucl. Instr. Meth. A, 958:162999, 2020.

[5] P. Schwendimann, A. Papa.
Study of 3D calorimetry based on LYSO or $LaBr_3$:Ce crystals for future high energy precision physics.
J. Instr., 15:C06018, 2020.

[6] W. Altmannshofer et al. (PIONEER Collaboration).
PSI Ring Cyclotron Proposal R-22-01.1.
arXiv:2203.01981 [hep-ex], 2022.