Study of Future 3D Calorimetry Based on LYSO or $LaBr_3(Ce)$ Crystals for High Energy Precision Physics

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Overview

1. A Brief Introduction
2. A Word on the Simulation
3. Simulation Results
4. Conclusions Towards a Prototype

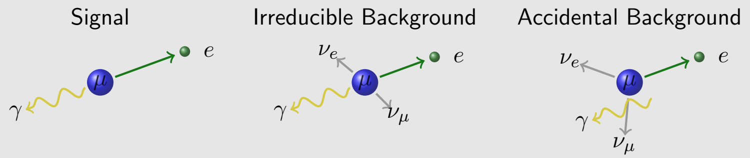
The Need for High Precision Calorimetry

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

Charged Lepton Flavour Violation [1, 2]

- 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: $\mu \to e\gamma$ [3, 4]



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

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

Affected by calorimeter performance

LYSO vs. Lanthanum Bromide

Short Radiation Length vs. High Light Yield and Fast Decay

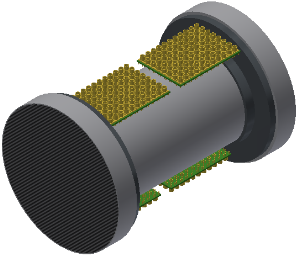
Selection of Scintillating Materials

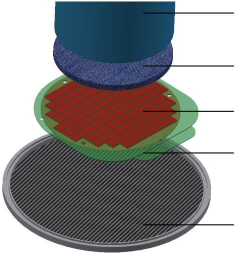
	Density ρ (g/cm^3)	Light Yield LY (ph/keV)	Decay Time τ (ns)	Radiation Lenth X_0 (cm)
$LaBr_3$(Ce)	5.08	**63**	**16**	2.1
LYSO	**7.1**	27	41	**1.21**
NaI(TI)	3.67	38	245	2.59
BGO	7.13	9	300	1.12

Crystal Sizes Investigated

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

Building a Prototype





- 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.

The MC Simulation

GEANT4 based using custom code for:

SiPM

- Include approximate geometry. Create active area physical volume, not single pixels.
- Determine pixel hit based on mathematical formula, includes fill factor check.
- Include quantum efficiency check.

Waveform Generation

- Use real SiPM plus DAQ response.
- Sum detected photons passing dead time check, add noise.
- Extract charge and time for each channel.
- Time extraction on each side on sum of waveforms.

Variable Estimation Algorithms

Charge: Sum integrated charge over all channels

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

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 times t_i, charges Q_i and their averaged position $\bar{x}_i$

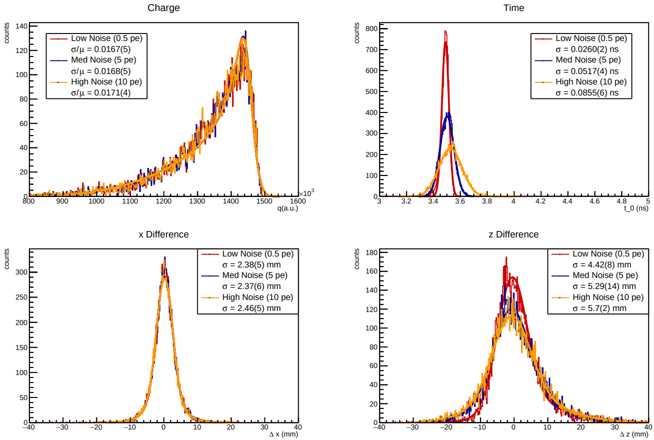
$$x = a_x \bar{x}_f + b_x \bar{x}_b + c_x$$
$$z = a_z \ln(Q_f) + b_z \ln(Q_b) + c_z t_f + d_z t_b + e_z$$

Parameters trained on the first 10 % of each configuration.

Noise Effects

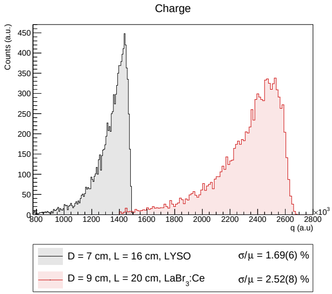
minor effect | significant effect

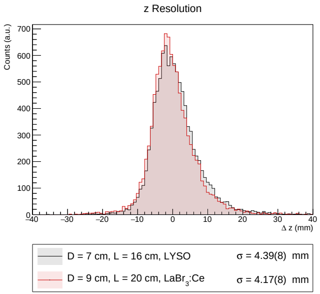
minor effect | observable effect



LYSO crystal $(R = 3.5\,\text{cm},\ L = 16\,\text{cm})$

Simulations of Available Sizes



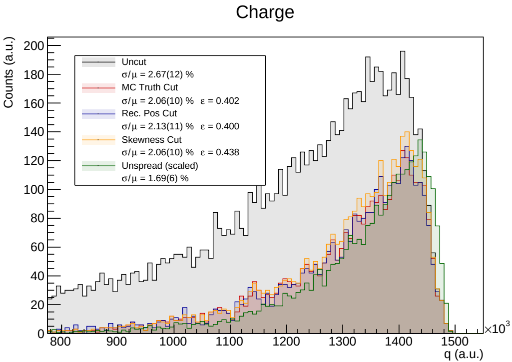


- Better charge resolution for LYSO due to larger energy leakage through lateral side in $LaBr_3$(Ce).
- Time resolution around 30 ps for both.
- Position resolution around 3 mm perpendicular to the crystal axis for both.

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

Spread Out Photons

Consider photons spread out over the whole front face:

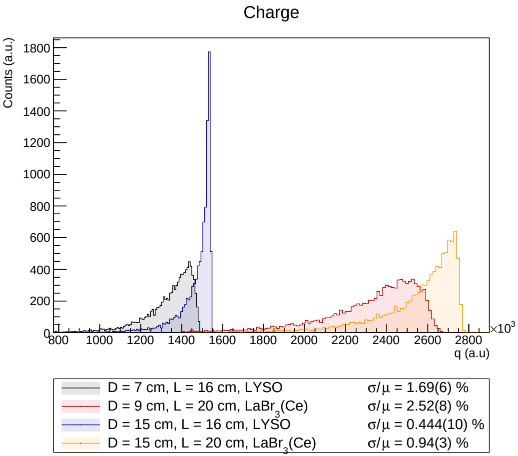


Reduced charge/energy resolution due to lateral events.
Recover to some extend by applying appropriate cuts.

Geometrical Cuts

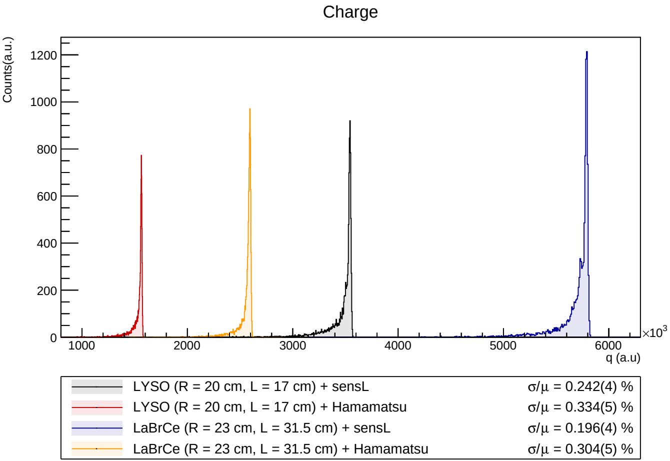
- **MC Truth Cut**
  Use true position of first interaction as recorded by MC simulation. Select events with some distance from the border. Used as a reference.
- **Reconstructed Cut**
  Use the reconstructed (x, y)-Position to reject events close to the border.
- **Skewness Cut**
  Analyse the radial distribution of the collected charge. Reject events below a certain skewness - most charge collected on the outer region with distinct tail towards the smaller radii.

Increasing the Size



Better energy resolution for larger diameters.

Ultimate Crystals



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

Summary

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.
- Spread out irradiation worsens resolution, geometrical cuts allow some recovery.

Next Steps

Simulation

- Mostly done.
- Further runs using the detailed information about the prototype.
- Refine analysis algorithms in the final configuration.

The Prototype

Selection based on simulations:

- LYSO crystal with 10 cm length and 7.5 cm diameter.
- Hamamatsu MPPC S13360-6025PE

Confirming final orders with industry. Assembly to follow soon.

Acknowledgements

Co-Author

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Future LYSO/LaBrCe Calorimetry

P. Schwendimann

Introduction

Simulation

Results

Prospects

References and Further Reading

References

[1] A. M. Baldini et al. arXiv:1812.06540v1 [hep-ex]

[2] G. Cavoto et al. Eur. Phys. J. C **78** (2018), 37

[3] A. M. Baldini et al. (MEG II Collaboration) arXiv:1301.7225v2 [physics.ins-det]

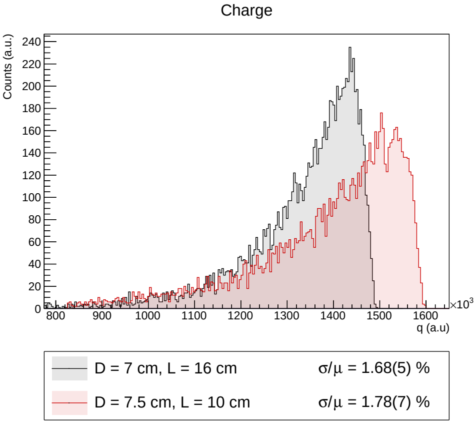
[4] A. M. Baldini et al. (MEG II Collaboration) Eur. Phys. J. C **78** (2018), 380

Further Reading

A. Papa, P. Schwendimann, NIM A **936** (2018), 130

Industry Issues

"Available" LYSO crystal has defects ...



Closest size: 7.5 cm diam., 10 cm length.

No significant decrease in performance.

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