Study of Future 3D Calorimetry Based on LYSO or LaBrCe Crystals for High Precision Physics

Patrick Schwendimann
patrick.schwendimann@psi.ch

Paul Scherrer Institut

Zurich PhD Seminar
9.10.2019

Overview

The Quest of High Precision Particle Physics

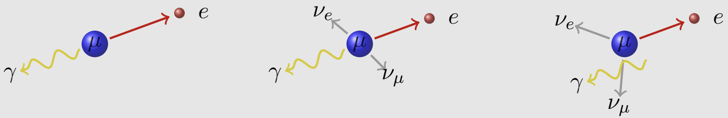
Find evidence for BSM physics in testing SM predictions to an unprecedented accuracy.

Charged Lepton Flavour Violation [1, 2]

- Looking for decays like $\mu \to e\gamma$, $\mu \to eee$ etc.
- Prohibited by the SM, highly suppressed by light neutrinos.
- Predicted by some BSM theories.

The Legendary Needle in the Haystack: $\mu \to e\gamma$ [3, 4]

Signal | Radiative Muon Decay | Accidental Background



$BR(\mu \to e\gamma) > 6 \cdot 10^{-14}$ **???**

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

Measuring Energy Deposits

Calorimetry

Measure the energy a particle deposits in the detector. If it is large enough, the total energy of the particle will be deposited.

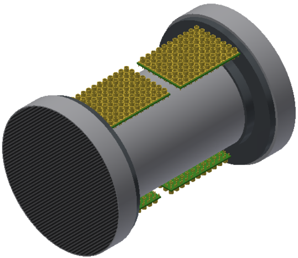
Scintillator

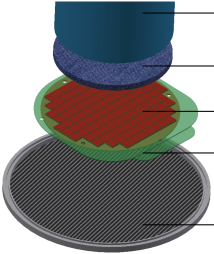
Scintillators emit visible light when hit by high energy radiation. The number of photons is roughly proportional to the energy deposit inside the scintillator.

Silicon Photo-Multipliers (SiPMs)

Semiconducting device to detect optical photons. They consist of thousands of pixels - each of them can be fired by a single photon.

The Idea in General





- Goal: Detect Photons of $\mathcal{O}(50\,\mathrm{MeV})$
- Build a calorimeter by attaching SiPMs to a scintillator.
- Thin SiPMs allow readout on front and back.
- Use granularity for geometrical reconstruction.

What kind of Scintillator to use?

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(Tl)	3.67	38	245	2.59
BGO	7.13	9	300	1.12

Properties

Light Yield: Amount of visible light emitted per energy deposit
Decay Time: Time scale on which the light gets emitted
Radiation Length: Depth scale on which the energy is deposited

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.
- Include quantum efficiency check.

Waveform Generation

- Use real SiPM and DAQ response to 1 photoelectron.
- 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.

Crystal Sizes Investigated

"Available"

These crystal sizes were promised by industry:

$LaBr_3$(Ce)	20 cm length, 9 cm diameter
LYSO	16 cm length, 7 cm diameter

"Large"

Crystals with increased diameter:

$LaBr_3$(Ce)	20 cm length, 15 cm diameter
LYSO	16 cm length, 15 cm diameter

"Ultimate"

Crystals with 10 *Molière radii and* 15 *radiation lengths:*

$LaBr_3$(Ce)	31.5 cm length, 46 cm diameter
LYSO	17 cm length, 40 cm diameter

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 (next slide)

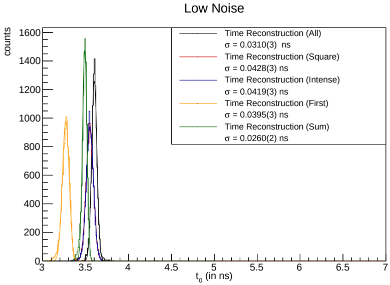
$$t = \frac{(n-1)t_f + (n+1)t_b - L/c(n^2+n)}{2n}$$

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.

Time Extraction Algorithms



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

All: average over all channels

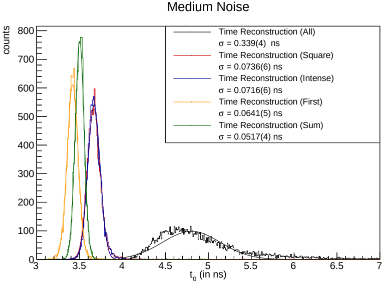
Square: average over the channels in a square around the one with the most charge

Intense: average over the 10 channels with the most charge.

First: average over the 10 first channels

Sum: Sum up all waveforms on each side, then take CF

Time Extraction Algorithms



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

All: average over all channels

Square: average over the channels in a square around the one with the most charge

Intense: average over the 10 channels with the most charge.

First: average over the 10 first channels

Sum: Sum up all waveforms on each side, then take CF

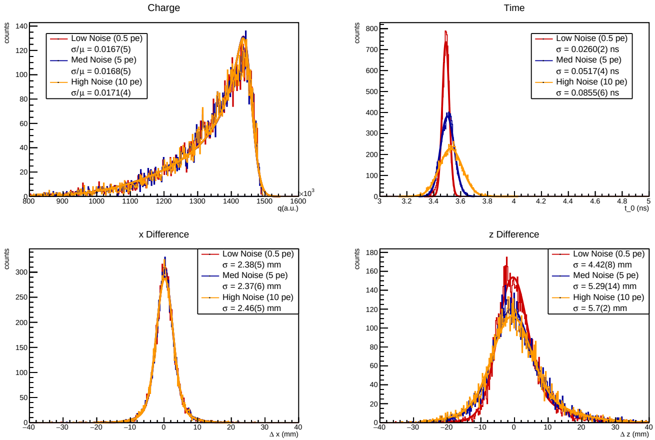
Noise Effects

minor effect

significant effect

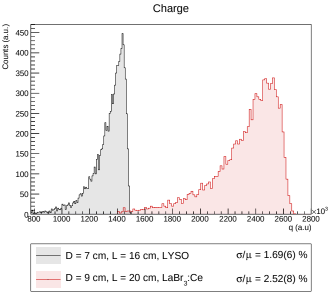
minor effect

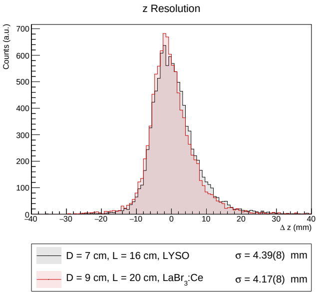
observable effect



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

Simulations of Available Sizes

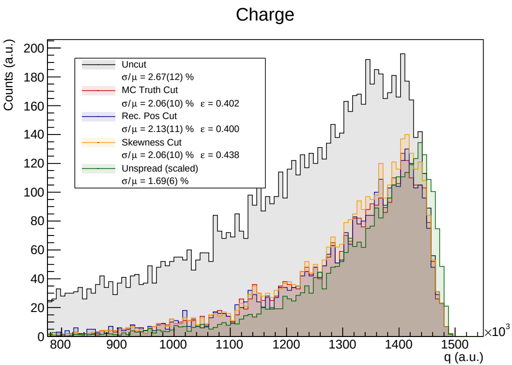




- Significant differences only for charge resolution. Explained by larger energy leakage through lateral side in $LaBr_3$(Ce).
- Time resolution around 30 ps
- Position resolution around 3 mm perpendicular to the crystal axis

Spread Out Photons

Consider photons spread out over the whole front face:

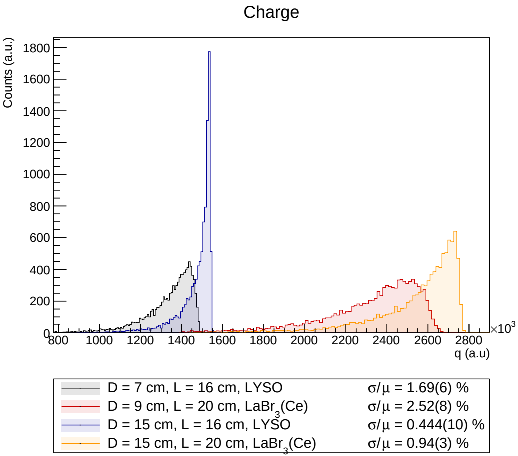


Reduced charge/energy resolution due to lateral events.
Recover to some extend by applying appropriate cuts.

Geometrical Cuts

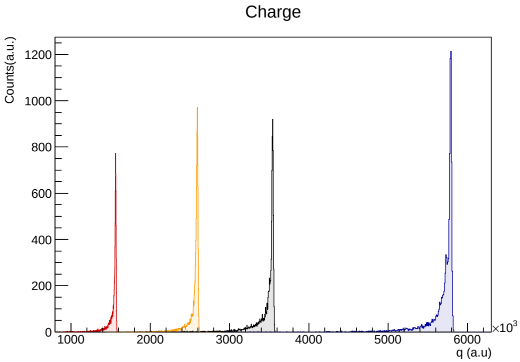
- **MC Truth Cut**
  Use true position of first interaction as recorded by MC simulation. Select events with some distance from the border.
- **Reconstructed Cut**
  Use the reconstructed (x, y)-Position to reject events close to the border.
- **Skewness Cut**
  Analyse the radial distribution of the 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

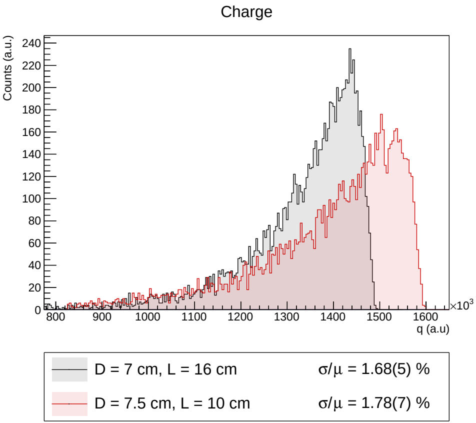


LYSO (R = 20 cm, L = 17 cm) + sensL	σ/μ = 0.242(4) %
LYSO (R = 20 cm, L = 17 cm) + Hamamatsu	σ/μ = 0.334(5) %
LaBrCe (R = 23 cm, L = 31.5 cm) + sensL	σ/μ = 0.196(4) %
LaBrCe (R = 23 cm, L = 31.5 cm) + Hamamatsu	σ/μ = 0.304(5) %

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

Industry Issues

"Available" LYSO crystal has defects ...



Closest size: 7.5 cm diam., 10 cm length.
No significant decrease in performance.

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.

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