Development of a new large calorimeter prototypes based on $LaBr_3$(Ce) and LYSO crystals coupled to silicon-photomultipliers

Monte Carlo simulations: A direct comparison

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Content

- Introduction
- Crystal main properties
- Photosensors: MPPC/SiPM
- Detector layout
- Monte Carlo simulation predictions: from point-like to extended impinging radiation. Part I and Part II

Motivations

- The aim of this study is to explore the possibility of a new calorimetry based on new crystals coupled to MPPC/SiPM able to work at relative high energy O(50-100) MeV and to sustain high rate (regime: Intensity Frontiers) for simultaneously:
  - Excellent energy resolution ($\sigma_E/E \leq 1\%$ @ E ~ 50 MeV)
  - Ultra-precise timing resolution ($\sigma_{t.} \leq 50$ ps)
  - 3D event reconstruction ($\sigma_{tx,y,z} \leq 10$ mm)

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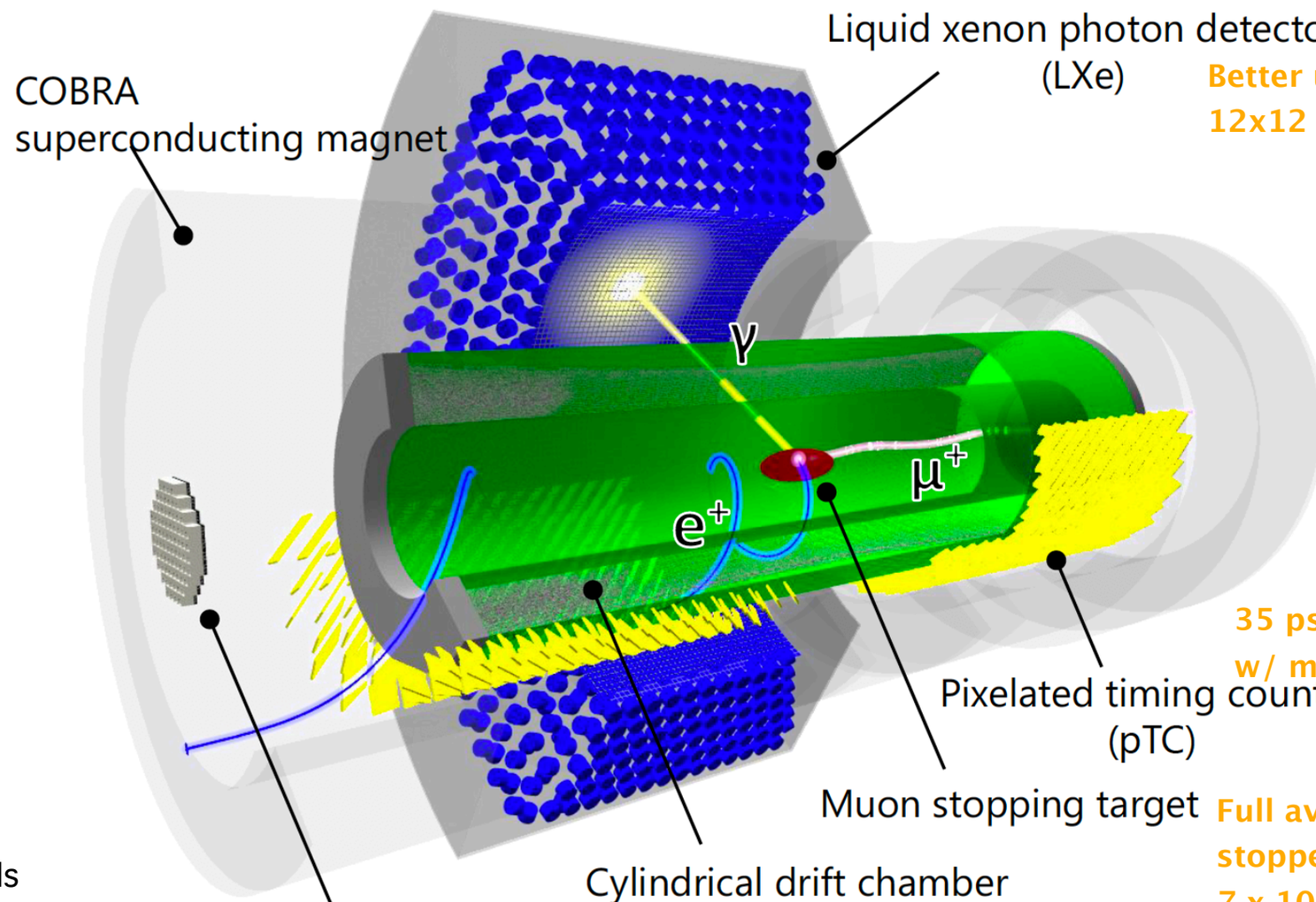
A new calorimetry for future cLFV researches

- The MEGII experiment aims to search for $\mu^+ \rightarrow e^+ \gamma$ with a sensitivity of ~6 10^{-14} (previous upper limit $BR(\mu^+ \rightarrow e^+ \gamma) \leq 4.2 \times 10^{-13}$ @90 C.L. by MEG experiment)
- Five observables (E_g, E_e, t_{eg}, ϑ_{eg}, ϕ_{eg}) to characterize $\mu \rightarrow e\gamma$ events



Liquid xenon photon detector (LXe)

Better uniformity w/ 12x12 VUV SiPM

COBRA superconducting magnet

New electronics: Wavedream

~9000 channels at 5GSPS

x2 Beam Intensity

x2 Resolution everywhere

35 ps resolution w/ multiple hits

Pixelated timing counter (pTC)

Miki Nishimura
Mon, 18.02., 17:30
ID:607

Muon stopping target

Full available stopped beam intensity 7×10^7

Updated and new Calibration methods

Quasi mono-chromatic positron beam

Radiative decay counter (RDC)

Background rejection

Cylindrical drift chamber (CDCH)

Single volume $He{:}iC_4H_{10}$

Malte Hildebrandt
Wed, 20.02., 11:30
ID:455

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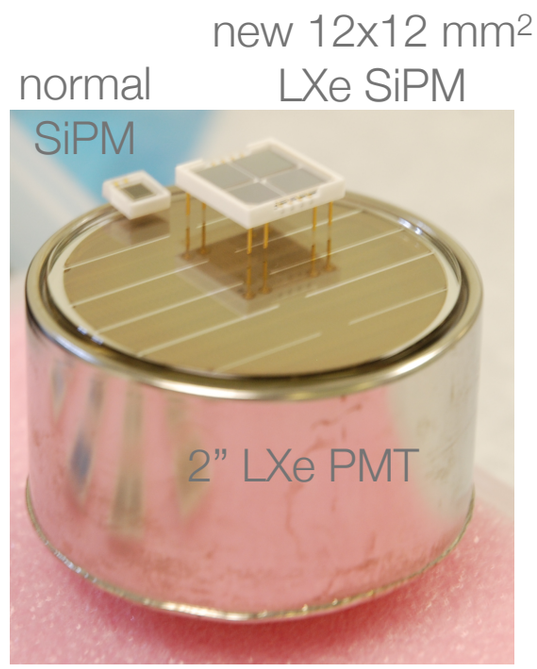
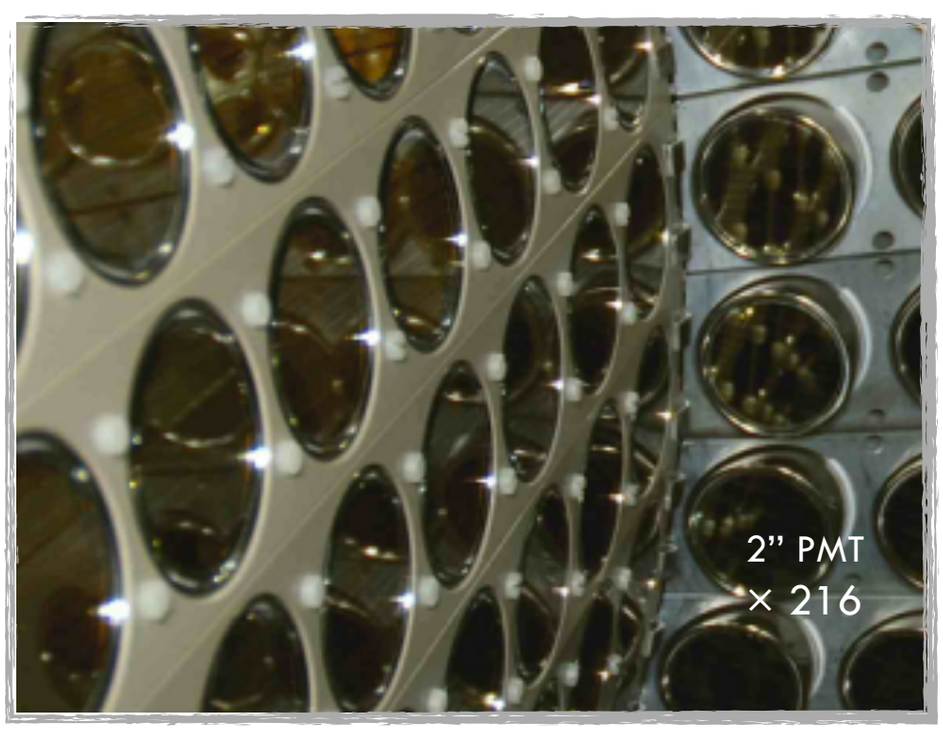
MEGII: The upgraded LXe calorimeter

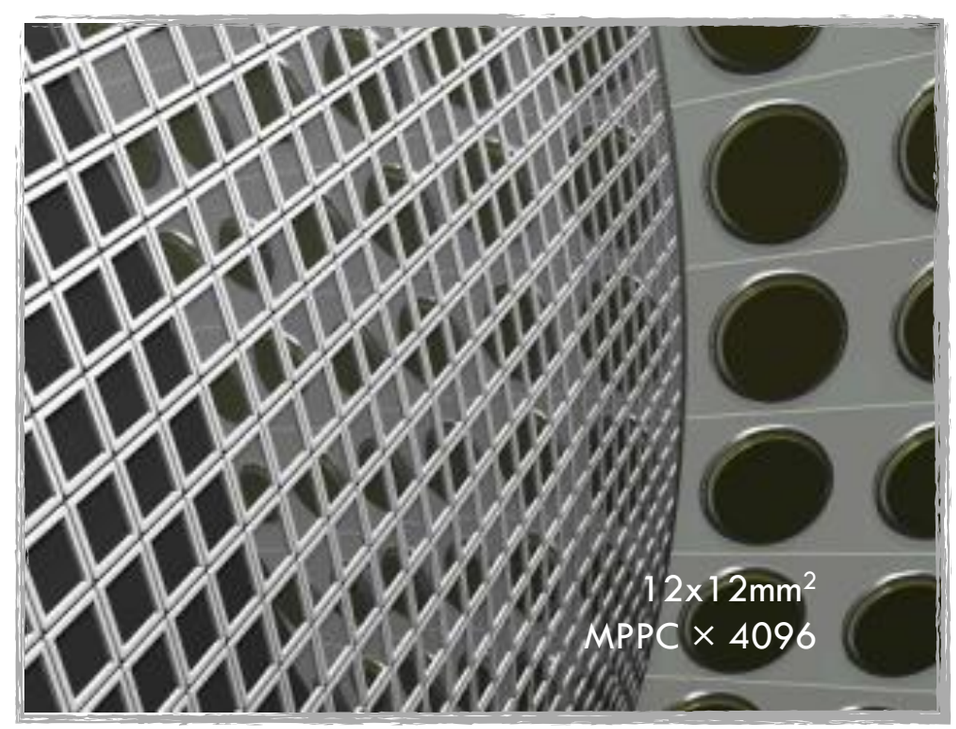
- Increased uniformity/resolutions
- Increased pile-up rejection capability
- Increased acceptance and detection efficiency
- Assembly: Completed
- Detector filled with LXe
- Purification: Ongoing
- Monitoring and calibrations with sources: Ongoing



	MEG	MEGII
u [mm]	5	2.4
v [mm]	5	2.2
w [mm]	6	3.1
E [w<2cm]	2.4%	1.1%
E [w>2cm]	1.7%	1.0%
t [ps]	67	60



900 L of Xe



A.M. Baldini et al. (MEGII collab.)
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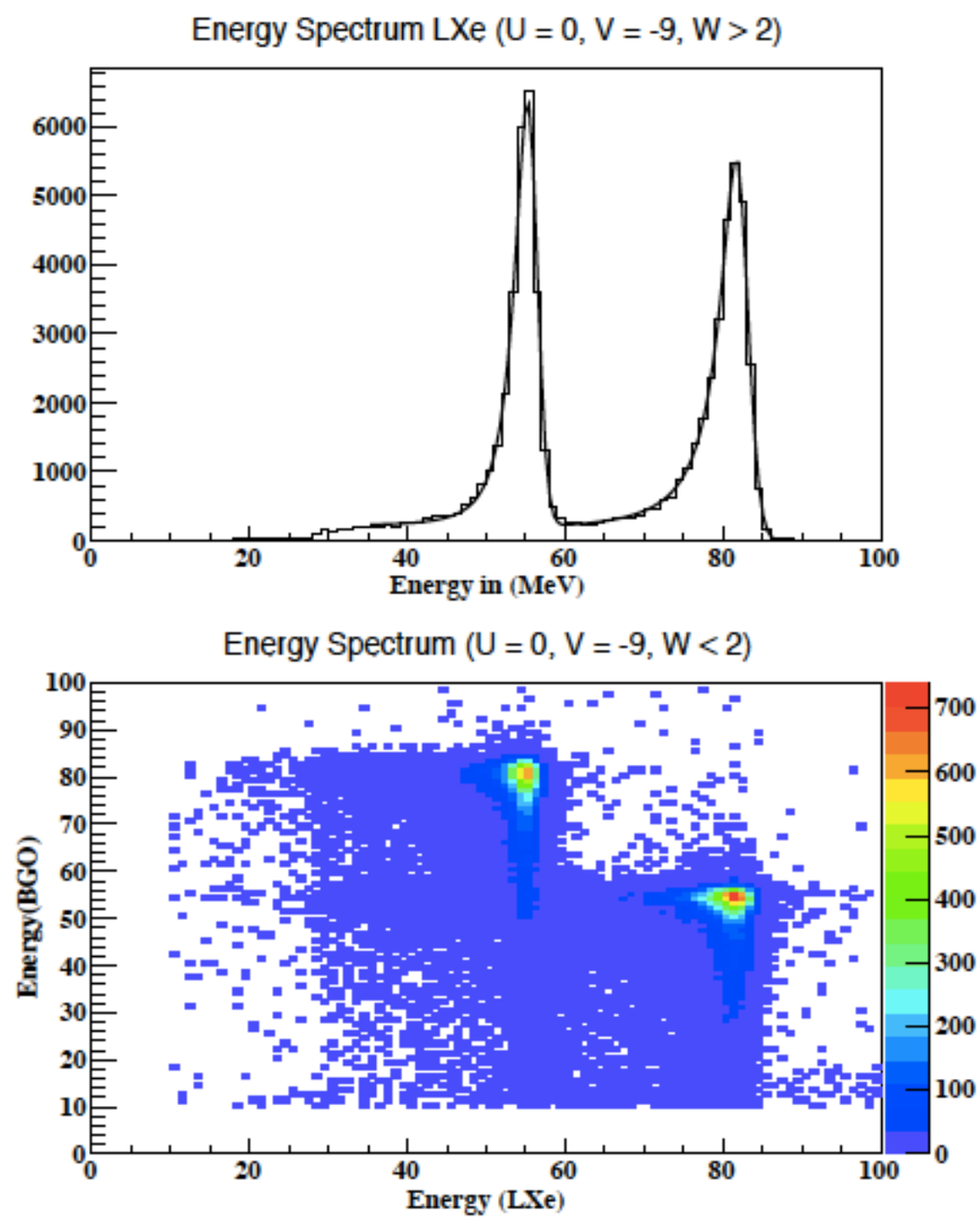
MEGII: A new auxiliary detector for the LXe calibration

- Two folded aims:
  - Auxiliary detector for selecting back-to-back gammas at 55 and 83 MeV for the full characterisation of the MEGII LXe calorimeter at the MEGII signal
  - Prototype for larger based crystal calorimeter for future cLFV and muon physics searches



The LaBr3(:Ce) and LYSO main properties

- LaBr3(:Ce): Ideal medium due to ultra high light yield LY (1.65 x LY(NaI)), ultra-fast response, high density (relative compact size)

- LYSO: Very attractive medium (excellent alternative to LaBr3(:Ce)). The very-high density and the fast response compensate for the reduced LY (0.70 x LY(NaI))

- Comparison with other scintillators via the figure of merite F.o.M. = $\sqrt{(\frac{\rho \cdot LY}{\tau})}$

Scintillator	Density ρ [g/cm^3]	Light Yield LY [ph/keV]	Decay time τ [ns]	F.o.M. $\sqrt{(\rho \times LY / \tau)}$
LaBr3(:Ce)	5.08	63	16	4.55
LYSO	7.1	27	41	2.17
YAP	5.35	22	26	2.13
LXe	2.89	40	45	1.61
NaI(Tl)	3.67	38	250	0.75
BGO	7.13	9	300	0.46

The LaBr3(:Ce) for high energy gamma calorimetry

Status:

- Well established low energy gamma calorimetry with detector sizes of (Diameter x Length): 1”x1”, 2”x2” and 3”x3”
- In rapid development for PET applications

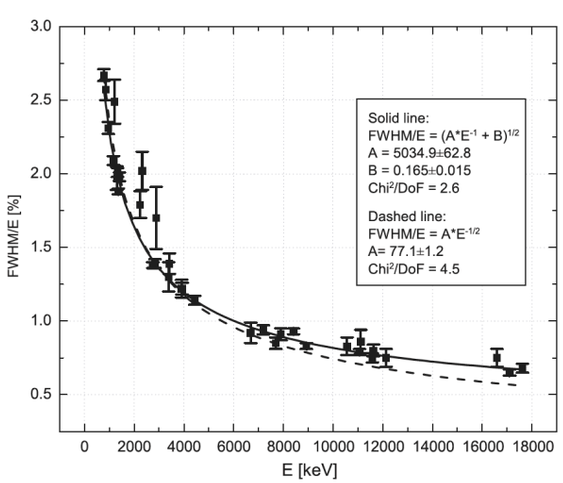
Prospects for high energy gamma calorimetry **O(50 MeV)** at high rate (intensity frontiers):

- Challenge: **Large size crystals**
  Desired: 5” x 8-10”, recently commercially available: 3.5” x 8” (Saint Gobain), under test: 3.5” x 9”
- Photosensors: multi-pixel photon counter/silicon photomultiplier (**MPPC/SiPM**)
- **For the first time** a large crystal coupled to MPPC to fully exploit the detector performances at high gamma energy

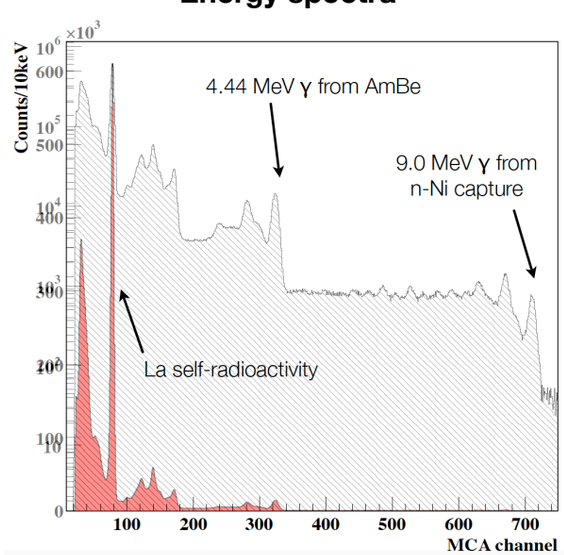
i.e. 2” x 2”
M. Ciema!a et al.
NIMA 608 (2009) 76–79

i.e. 3” x 3”
L. Galli et al. NIMA 718 (2013) 48-51
A. Papa et al. Nucl. Phys. B 248-250 (2014) 115-117

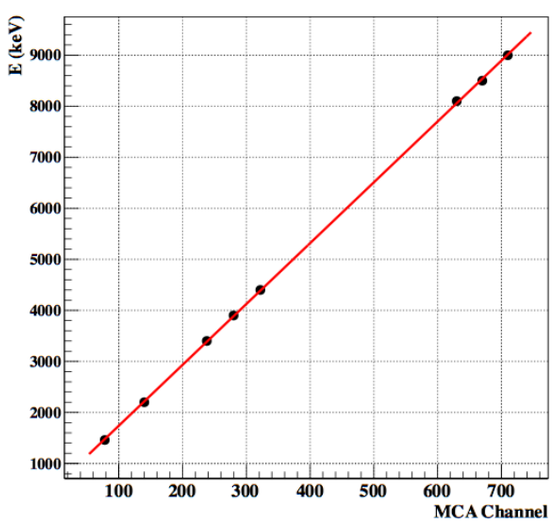
Detector:
3” x 3” $LaBr_3$(:Ce) coupled to a Photomultiplier PM XP53A2B



Energy spectra



Energy response Linearity



The Photosensors

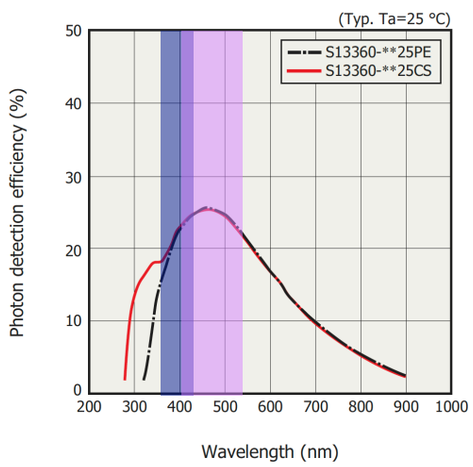
- The high LY and the short radiation length X_0 point towards relative small pixel size (< 50 um)
- Trade-off between DAQ channels and granularity: sensor size
- Two candidates: Hamamatsu S13360-6025 and SensL MicroFJ-60035TSV; active area 6 x 6 mm^2, pixel size respectively 25 um and 35 um

	Package [mm2]	Active area [mm2]	No. Of pixels	Fill factor [%]	PDE [%]	PCB cov. [%]	F.o.M*
Hamamatsu	7.35 x 6.85	6.0 x 6.0	57600	47	20-25	69	8.9
sensL	6.13 x 6.13	6.07 x 6.07	22292	75	40-50	91	9.1

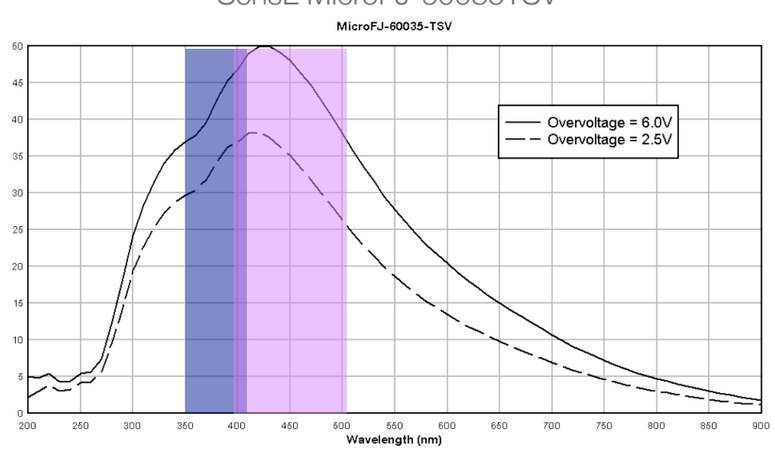
LaBr3(Ce) emission spectrum LYSO emission spectrum

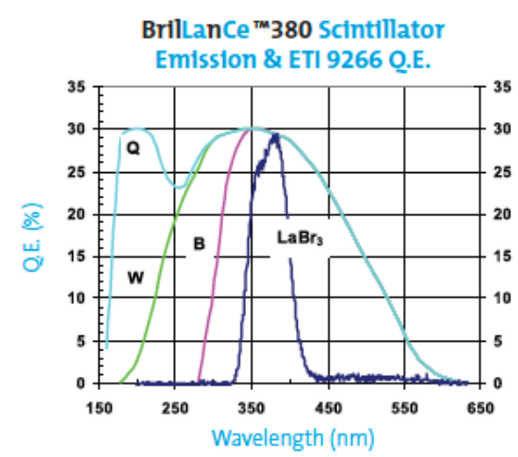
(*) F.o.M. =
No pixel x PDE x PCB cov. / 1000

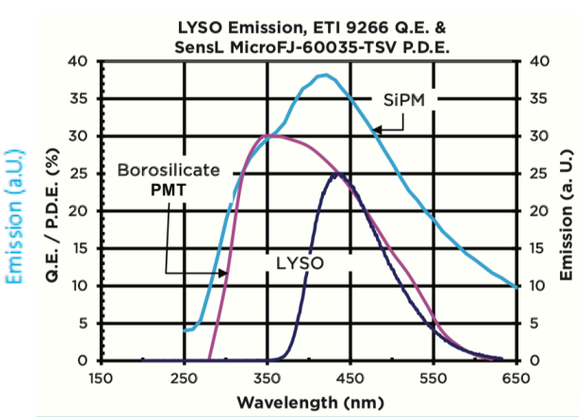
Hamamatsu S13360-6025PE



SensL MicroFJ-60035TSV



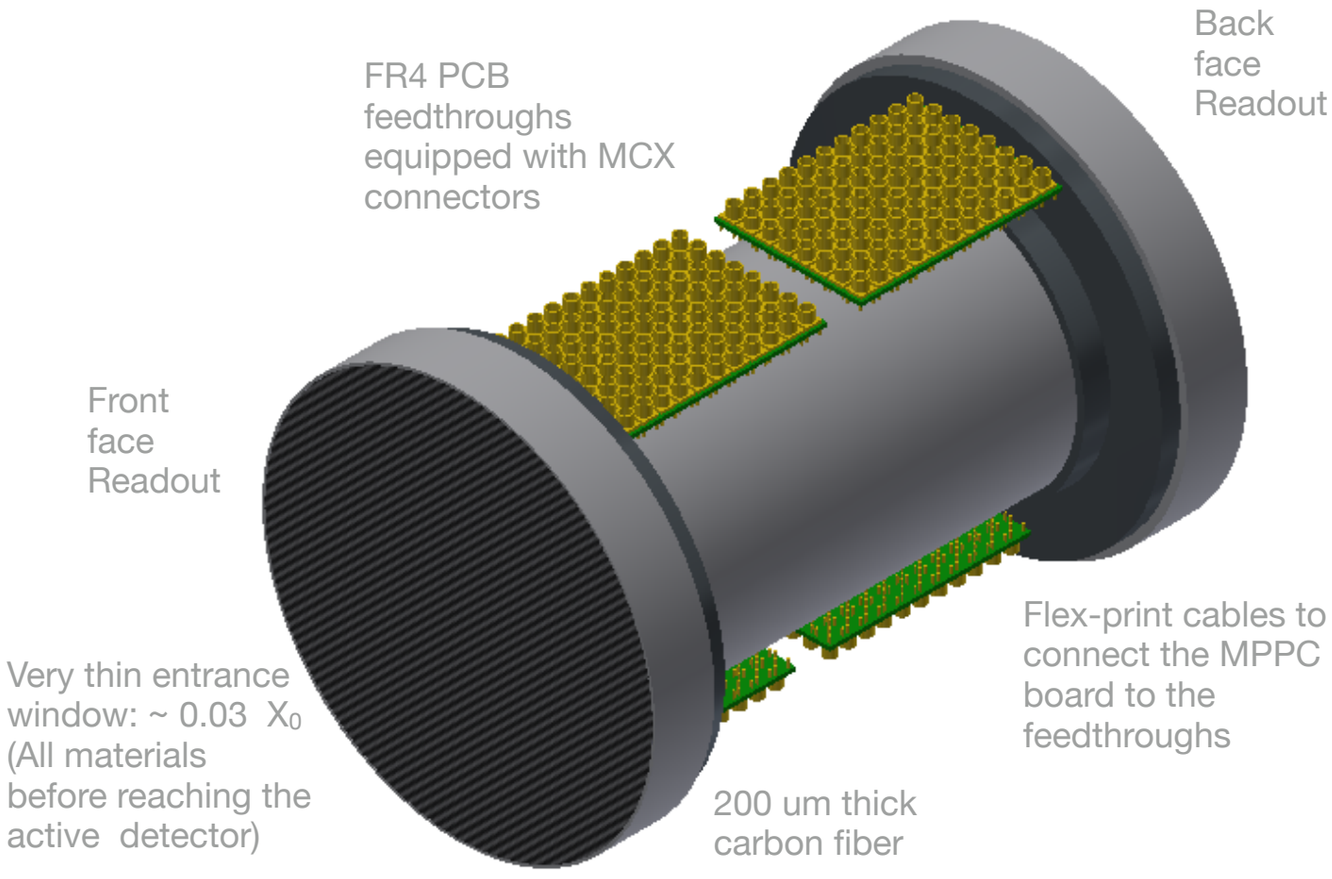


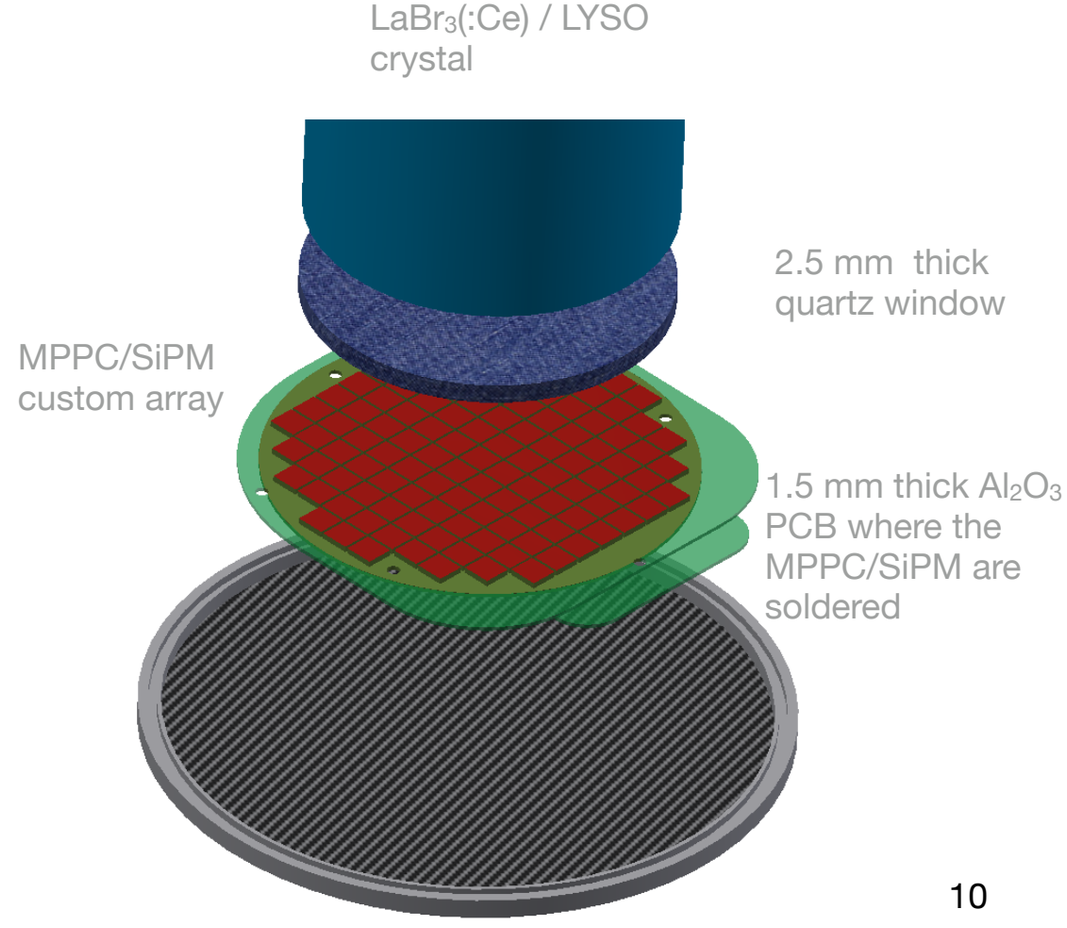


Detector layout

The first large crystal assembly for high energy gamma detection O(50) MeV with a **MPPC/SiPM** (&) **double** readout scheme for:

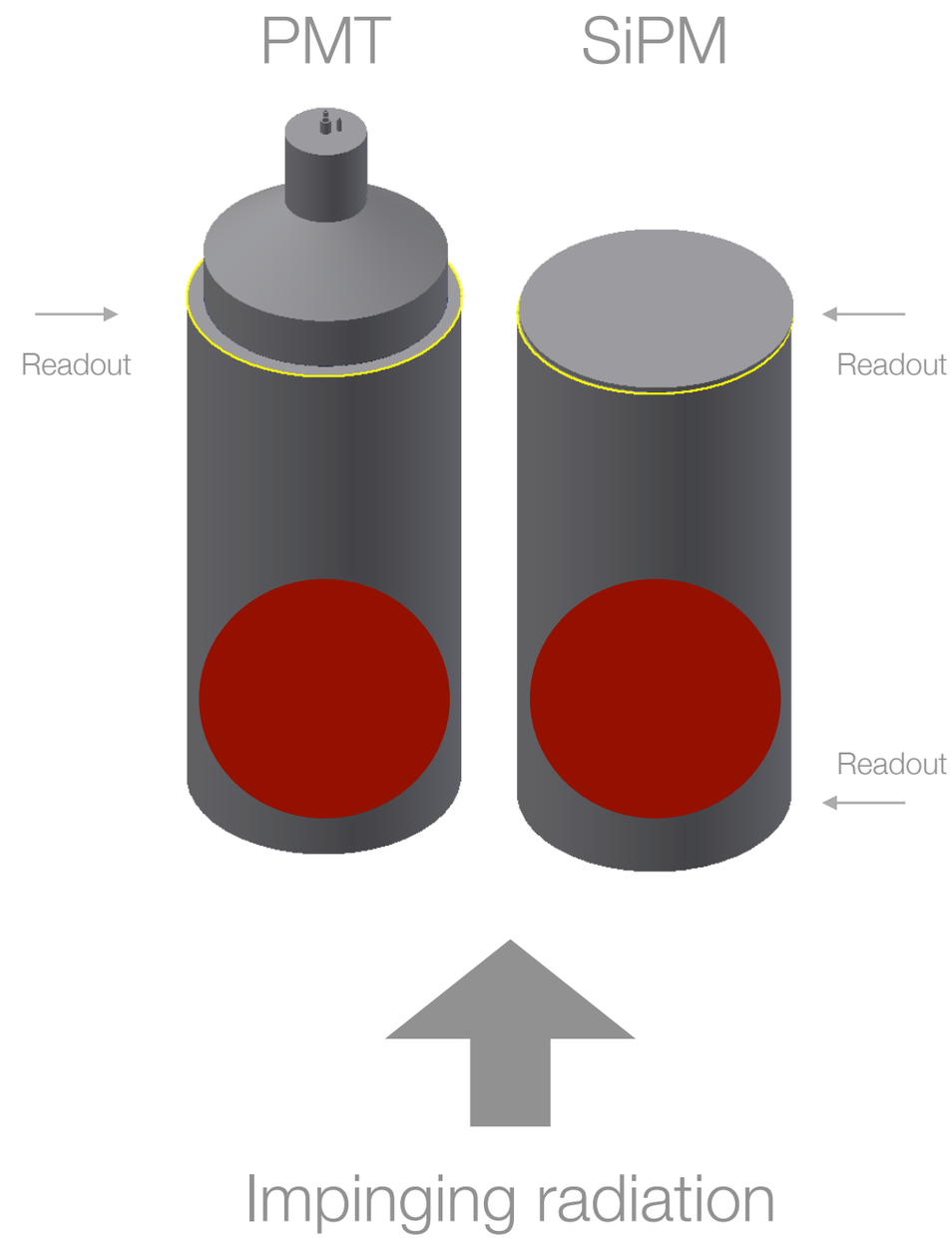
- Maximal photosensor coverage area
- Optimal geometrical acceptance
- Very high photosensor granularity
- High rate sustainability
- Optimum energy, timing and position resolutions: **5D** kinematical variable reconstruction
- Insensitive to magnetic field
- $LaBr_3$(:Ce) 4.45 (R) x 20.32 (L) cm or LYSO 3.5 (R) x 16 (L) cm
- Photosensors: Hamamatsu 240/152; sensL 336/214

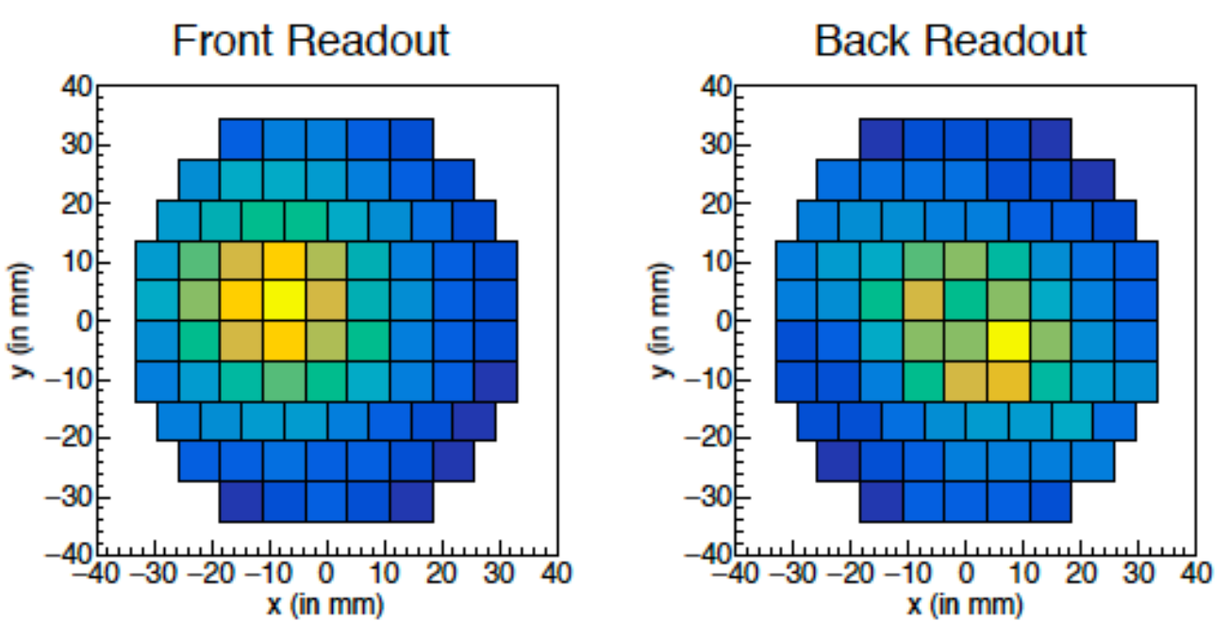




The Double readout out scheme with MPPC/SiPM

- The advent of the MPPC open the door to a more performing detector with a double readout
  - Larger photocathode coverage wrt single readout (i.e. old scheme with PMT)
    - Further benefit: Energy deposit near the front/entrance face
- For hygroscopic crystals (LaBr3(Ce)): double quartz window sealed inside a thin Al case





(a) Hit in Central Region: $(x, y) = (-10\,\mathrm{mm}, 3\,\mathrm{mm})$

Part I: Intrinsic kinematical variable resolutions

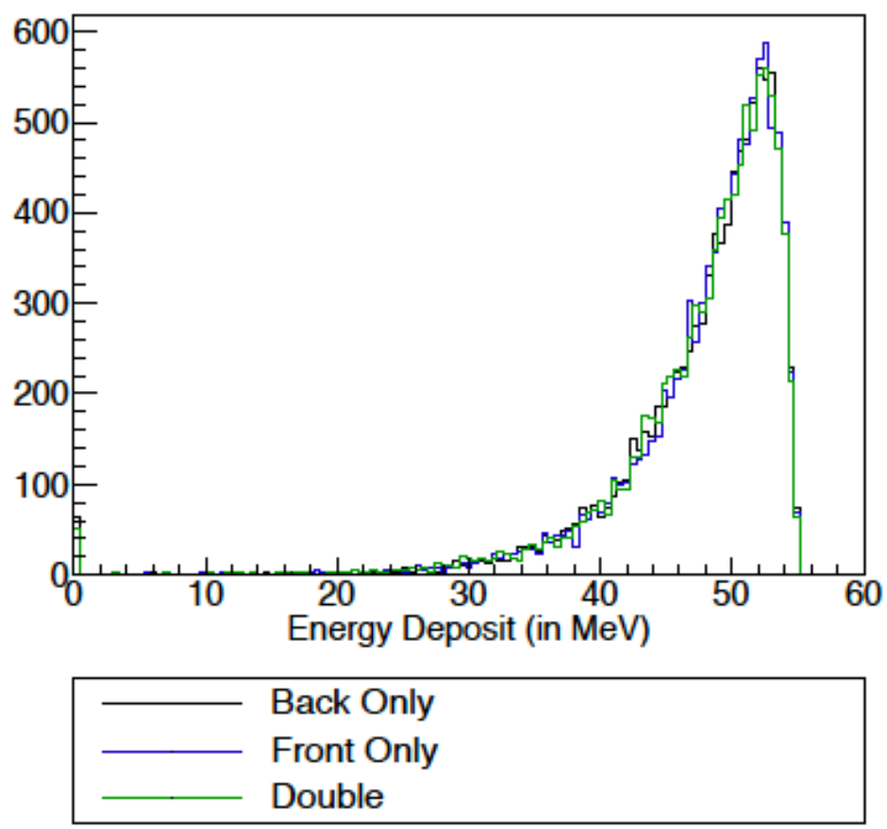
- Basic Monte Carlo simulation input
- Point-like impinging source: 55 MeV gammas
- Crystal sizes:
  - Available on the market (custom production)
    - LaBr3(Ce) (R,L) = (4.45, 20.32) cm [R = Radius, L = Length]
    - LYSO (R,L) = (3.5, 16) cm
  - Ideal
    - LaBr3(Ce) (R,L) = (7.62, 22.86) cm
    - LYSO (R,L) = (6.5, 20) cm
- Photosensors:
  - Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV

The Double readout: The photon collection

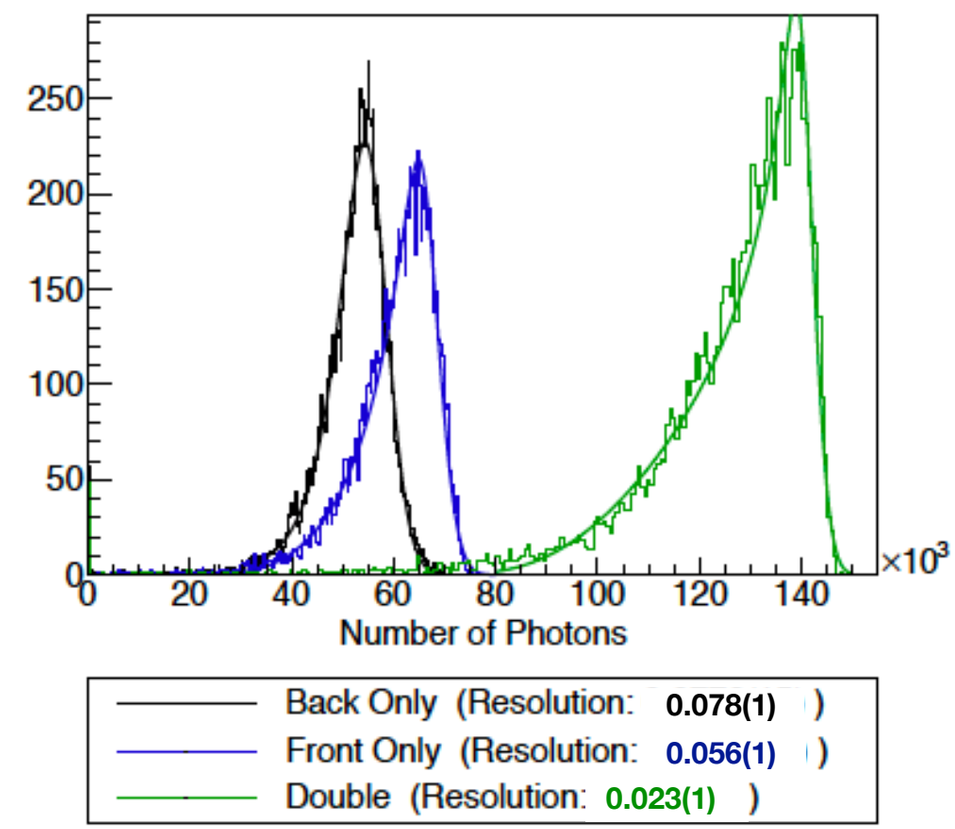
- Crystal: LaBr3(Ce), radius (R) 4.45 cm x length (L) 20.32 cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas

$$f(x|N,\mu,\sigma_1,\sigma_2,\sigma_3) = \begin{cases} N\exp\left(-\frac{(x-\mu)^2}{2(\sigma_1)^2}\right) & \text{if } x > \mu \\ N\exp\left(-\frac{(x-\mu)^2}{2(\sigma_1+\sigma_2(x-\mu)+\sigma_3(x-\mu)^2)^2}\right) & \text{if } x < \mu \end{cases}$$

Energy deposit: unaffected



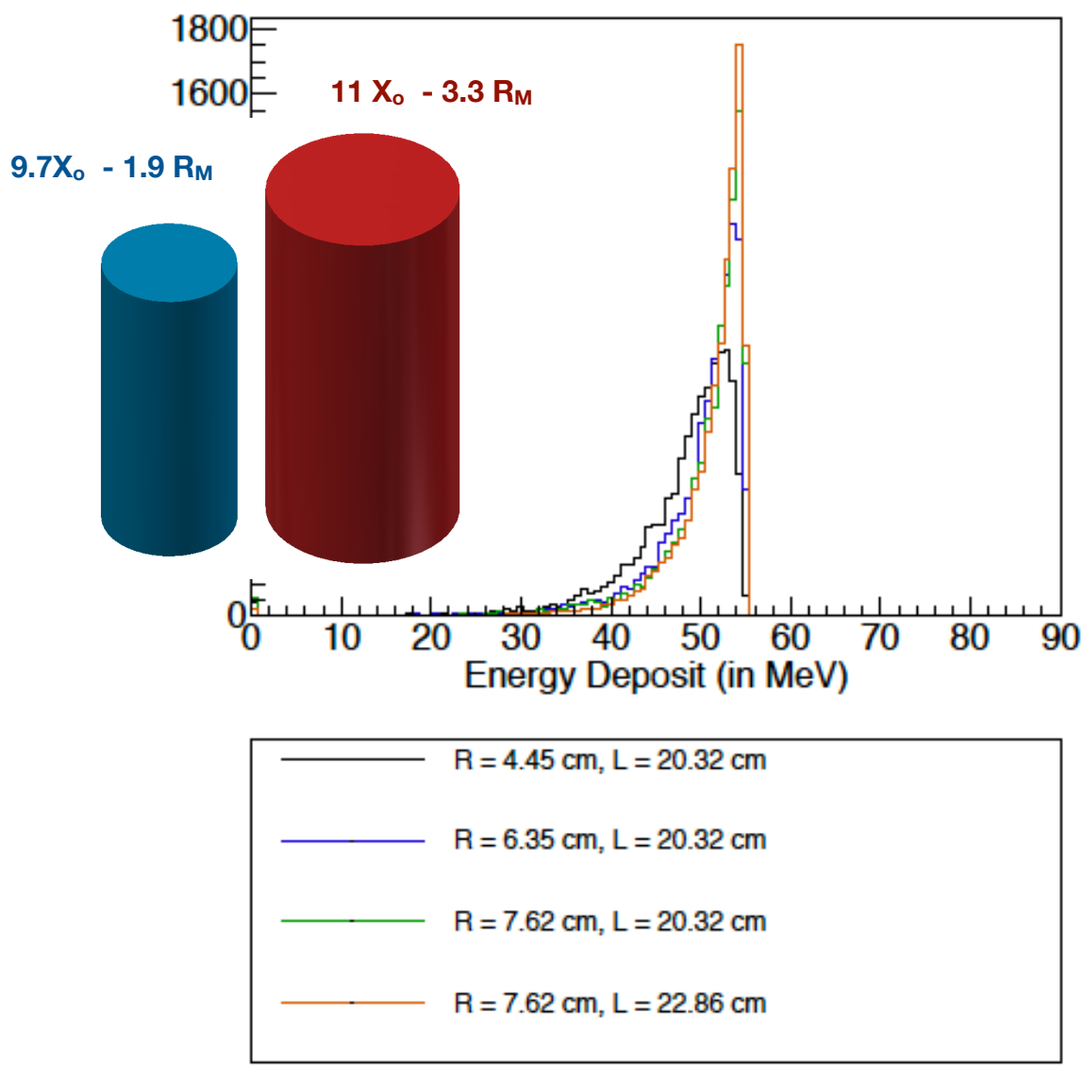
Number of photons and energy resolution: affected



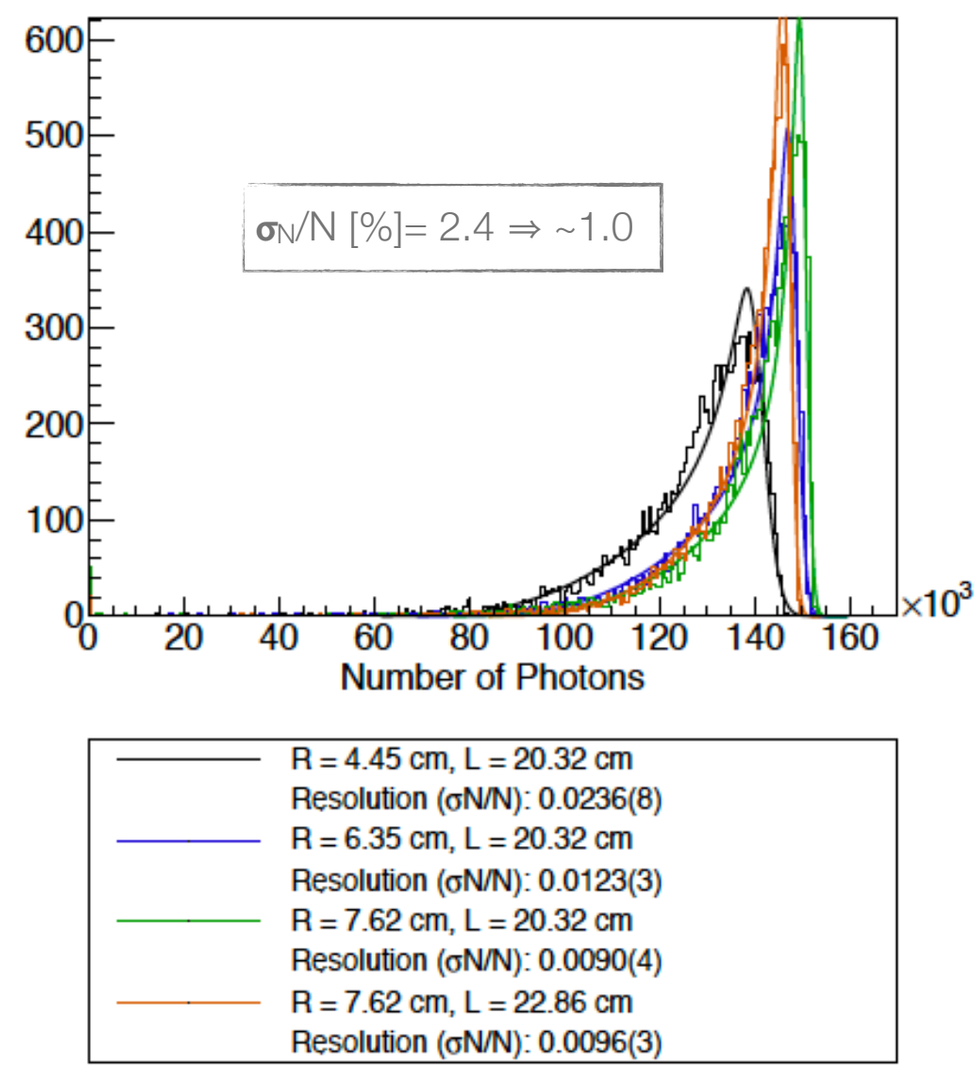
The Size of the crystal: The shower containment

- Crystal: LaBr3(Ce), variable sizes - see legend
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas

Energy deposit

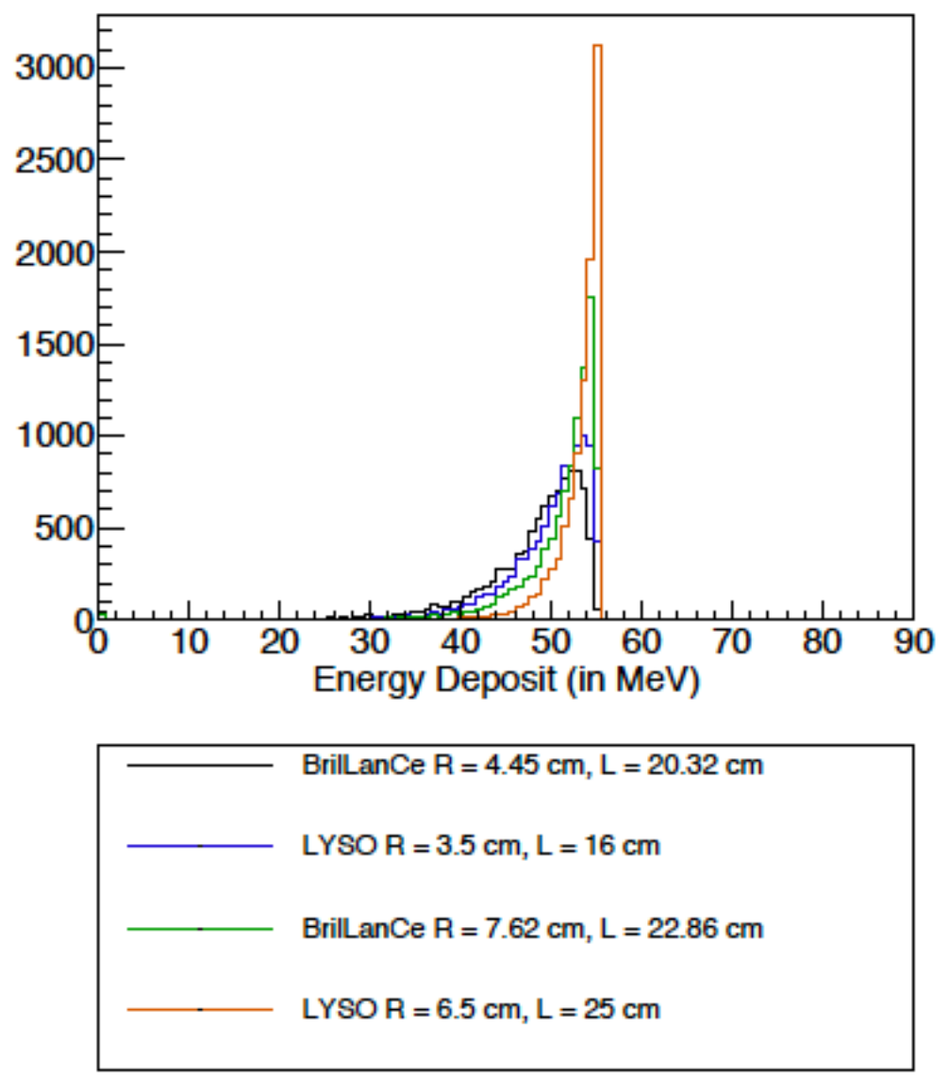


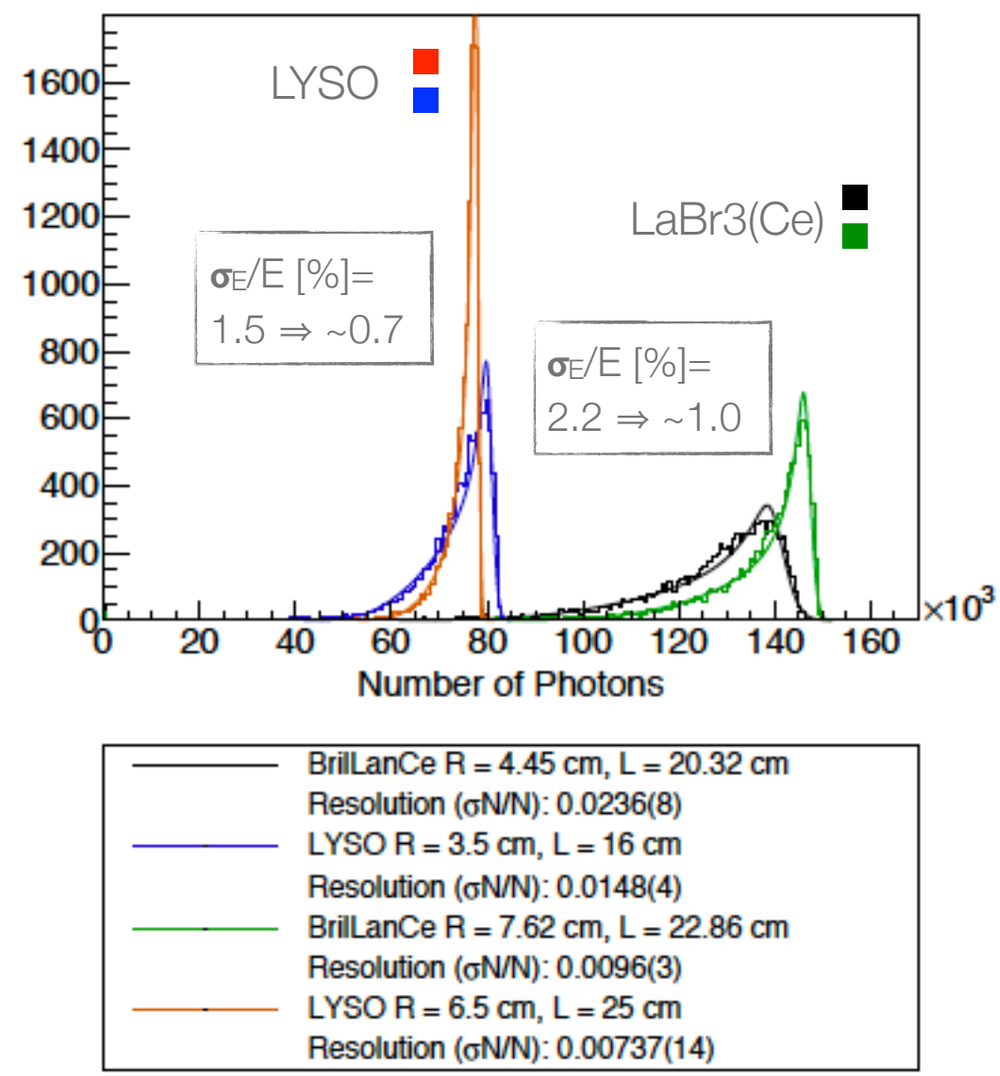
Number of photons and energy resolution



The Crystal type: The energy resolution

- Crystal: LaBr3(Ce) and LYSO, variable sizes: What available in the market and desirable - see legend
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: point-like 55 MeV gammas
- Although LaBr3(Ce) (■ and ■) has x2 LY of LYSO (■ and ■) and provides better photon statistics the resolution of LaBr3(Ce) is limited by the energy leakage. Available LYSO crystals perform better than available LaBr3(Ce) crystals

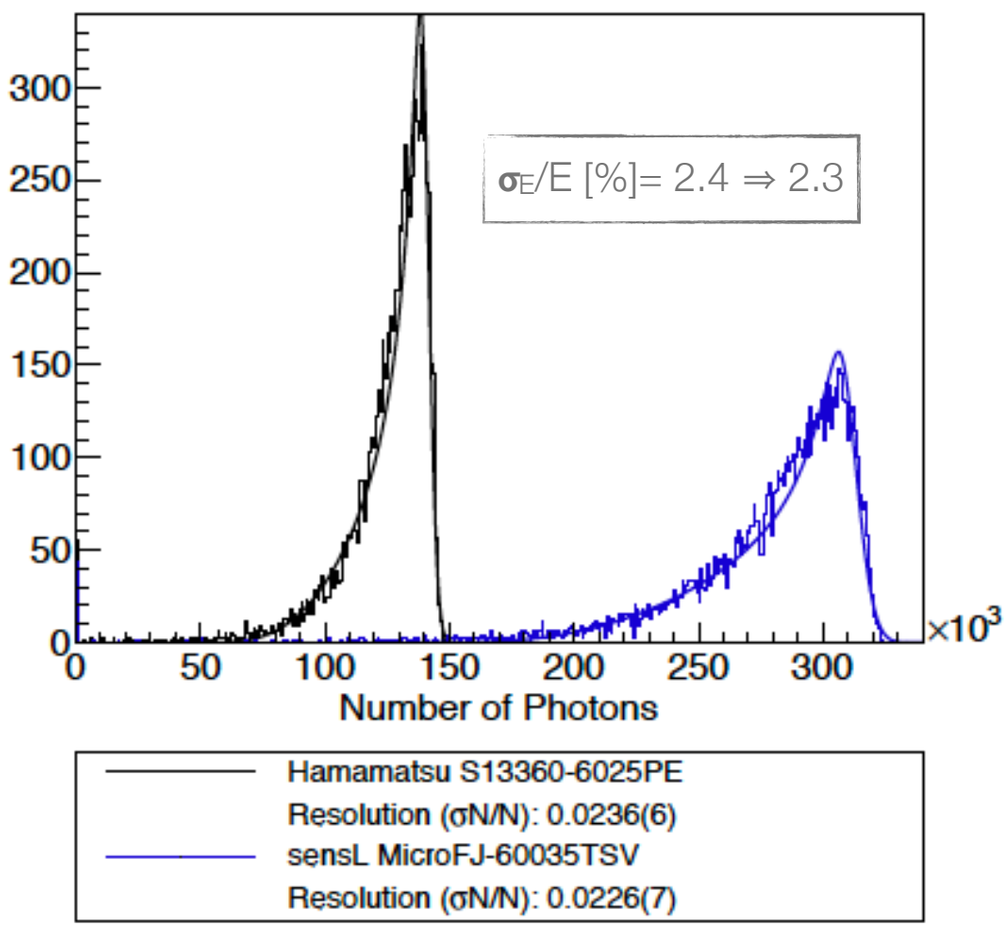




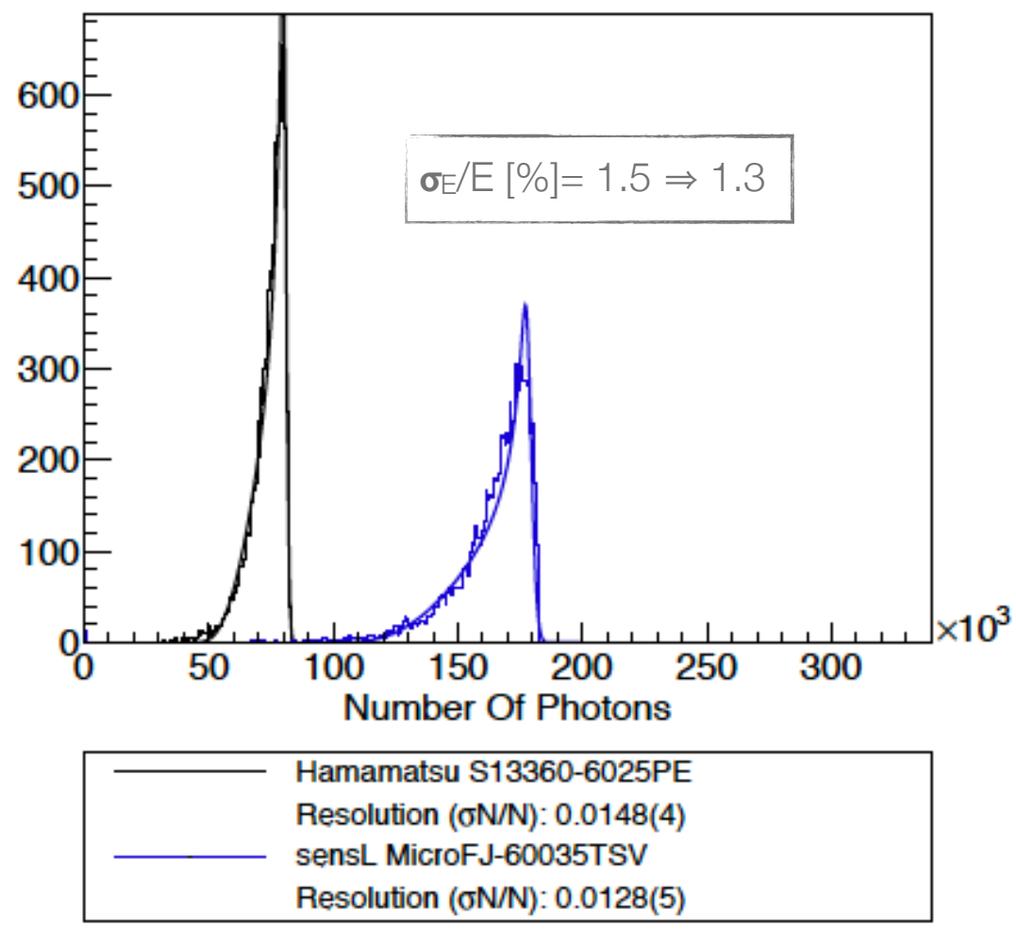
The Photosensor type: The energy resolution

- Crystal: LaBr3(Ce) with size (R,L) = (4.45, 20.32) and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- **Hamamastu** vs **sensL**: The first offers x2 pixels than the second (i.e. smaller size) yet the second has a significantly increased (x2) PDE and a smaller support structure. This suggests that sensL MPPC/SiPM will collect more photons yet more susceptible to saturation effect due to the larger pixel size.

LaBr3(Ce)

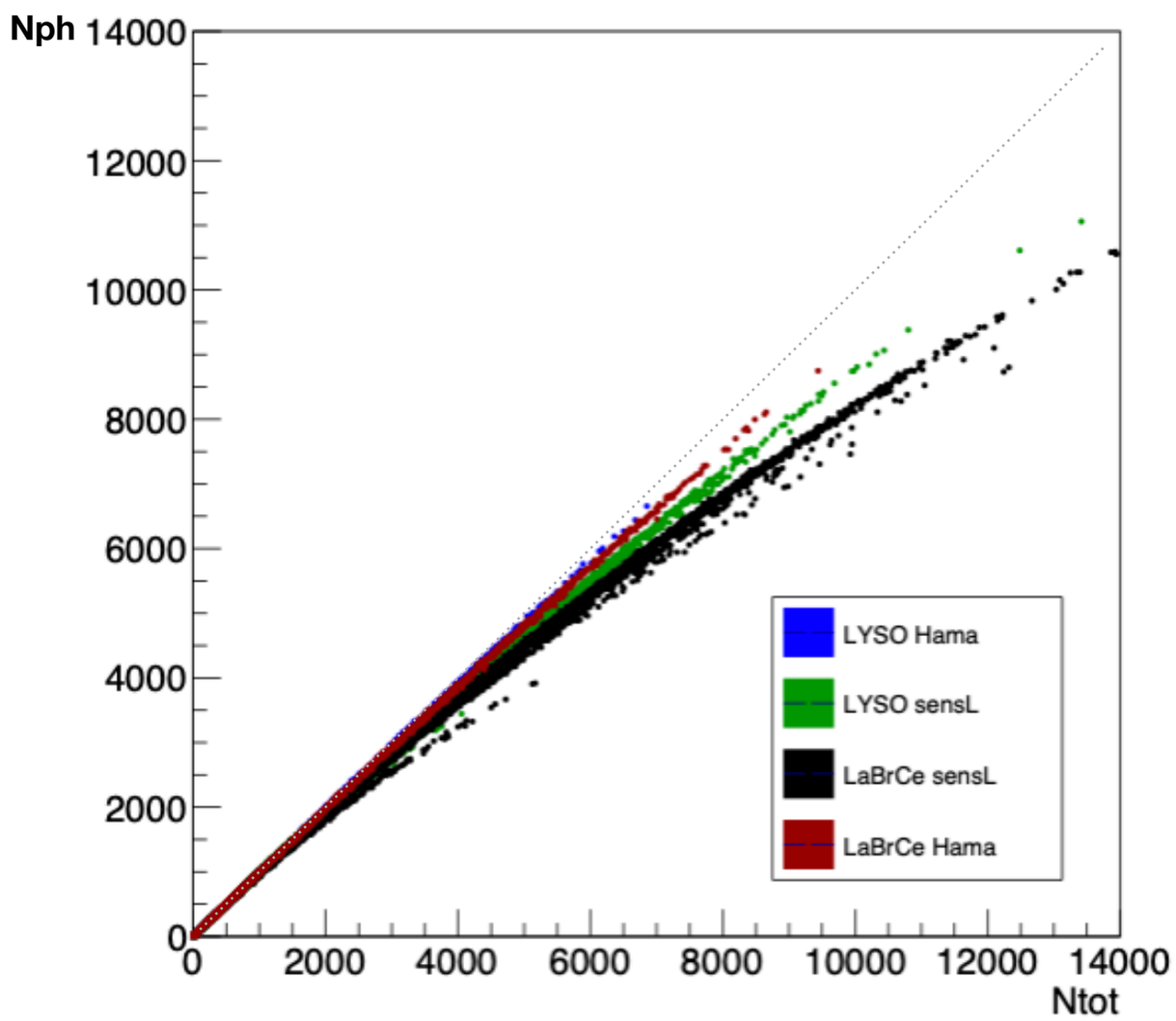


LYSO



The Photosensor type: The pixel saturation

- Crystal: LaBr3(Ce) with size (R,L) = (4.45, 20.32) cm and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- Saturation effect: LYSO ■ vs ■ , LaBr3(Ce) ■ vs ■

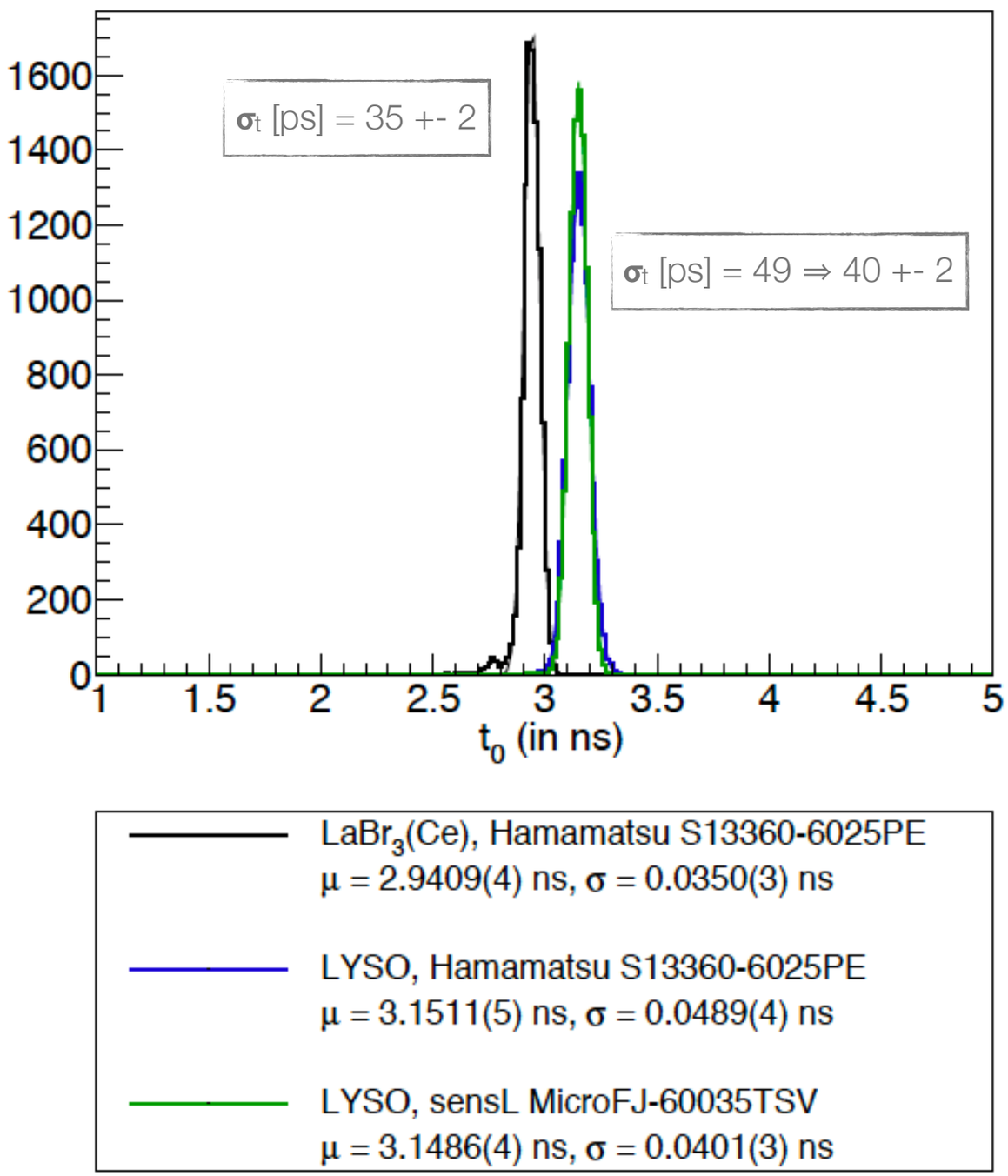


The timing resolution

- Crystal: LaBr3(Ce) with size (R,L) = (4.45, 20.32) and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas
- Input: Waveform analysis
- Variable: Time at which the gamma enters inside the detector t_0
- Algorithm: The average among the timing calculated with the constant fraction (threshold = 15%) of the most intense amplitude and its neighbours: Cons. Frac. Ave. To distinguish it from the timing of the most intense amplitude only

$$t_0 = \frac{(n-1)t_f + (n+1)t_b - \frac{L}{c}(n^2+n)}{2n}$$

- Where:
  - t_f and t_b are the reconstructed time on the front and back face
  - n and L the refractive index and length of the crystal respectively
  - c the speed of light



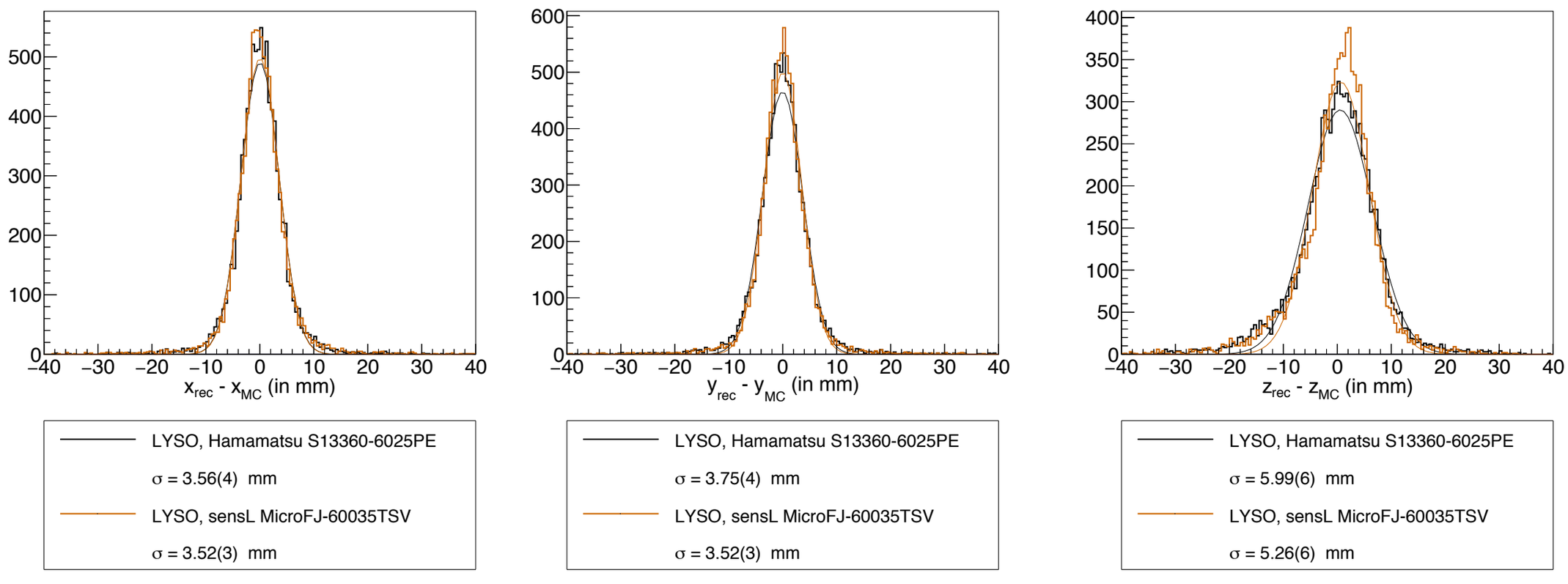
The position resolutions

- Crystal: LaBr3(Ce) with size (R,L) = (4.45, 20.32) and LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV
- Radiation: point-like 55 MeV gammas

$$x_{\mathrm{rec}} = a\bar{x}_{\mathrm{f}} + b\bar{x}_{\mathrm{b}} + c$$

$$z_{\mathrm{rec}} = a(t_{\mathrm{f}} - t_{\mathrm{b}}) + b$$

$$z_{\mathrm{rec}} = a \ln\left(\frac{N_{\mathrm{f}}}{N_{\mathrm{b}}}\right) + b$$

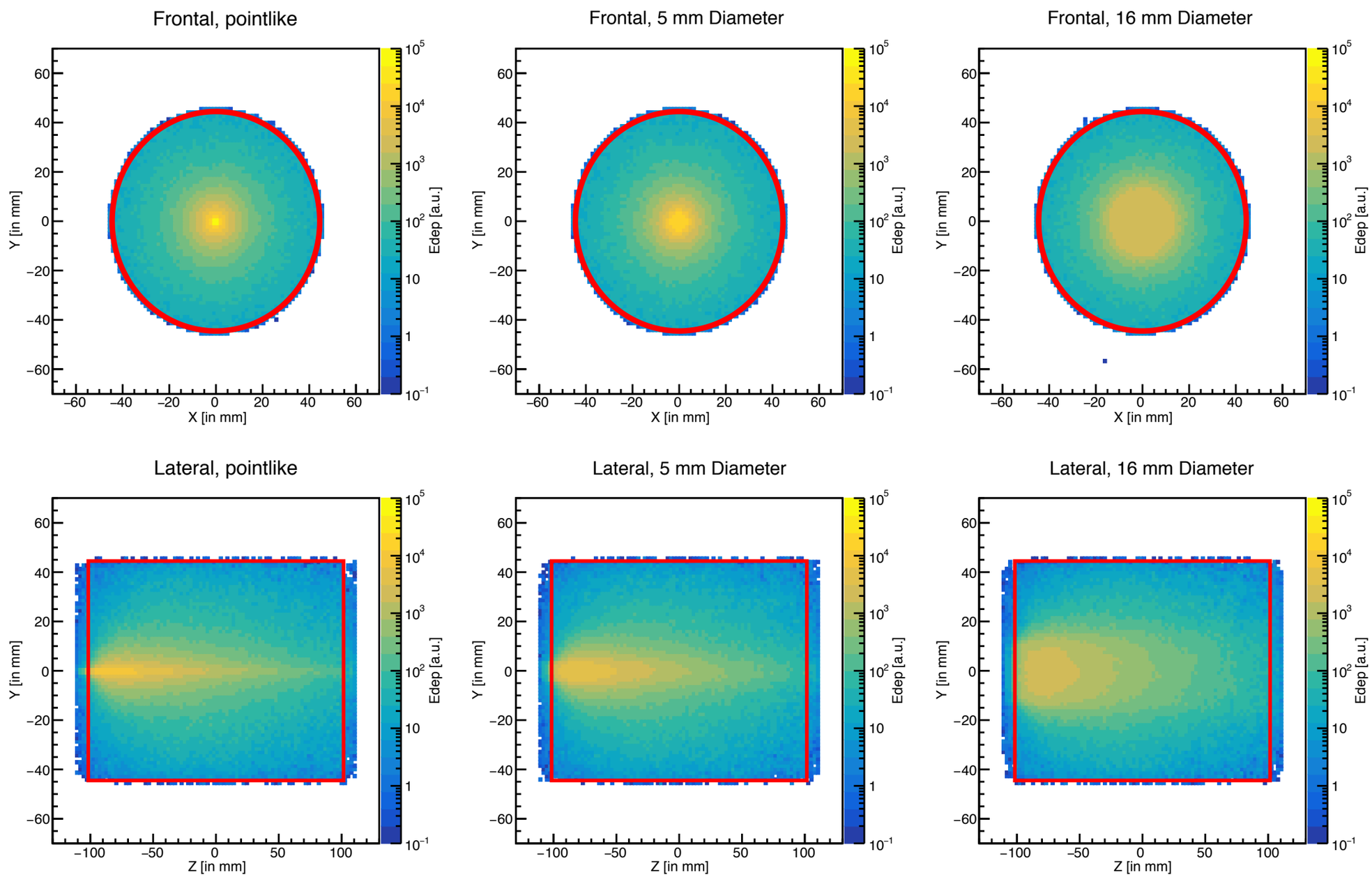


Part II: Effective kinematical variable resolutions

- Basic Monte Carlo simulation input
- Extended impinging source: 55 MeV gammas
- Geometrical cut
- Crystal sizes:
  - Available on the market (custom production)
    - LaBr3(Ce) (R,L) = (4.45, 20.32) cm [R = Radius, L = Length]
    - LYSO (R,L) = (3.5, 16) cm
  - Ideal
    - LaBr3(Ce) (R,L) = (7.62, 22.86) cm
    - LYSO (R,L) = (6.5, 20) cm
- Photosensors:
  - Hamamatsu S13360-6025PE and SensL MicroFJ-60035TSV

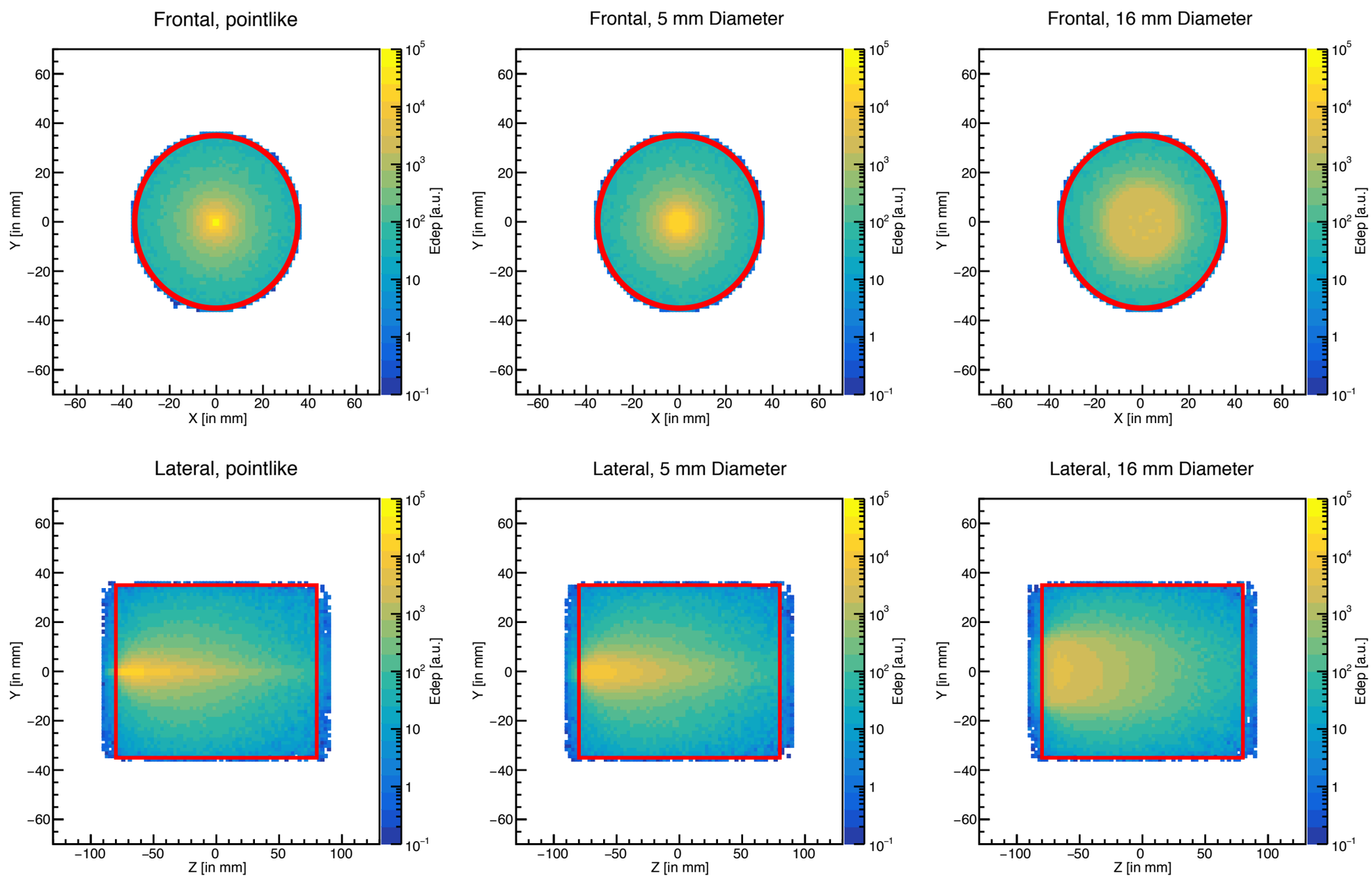
Shower inside the crystal

- LaBr3(Ce); crystal size (R,L) = (4.45, 20.32) cm; 55 MeV gamma with different impinging conditions



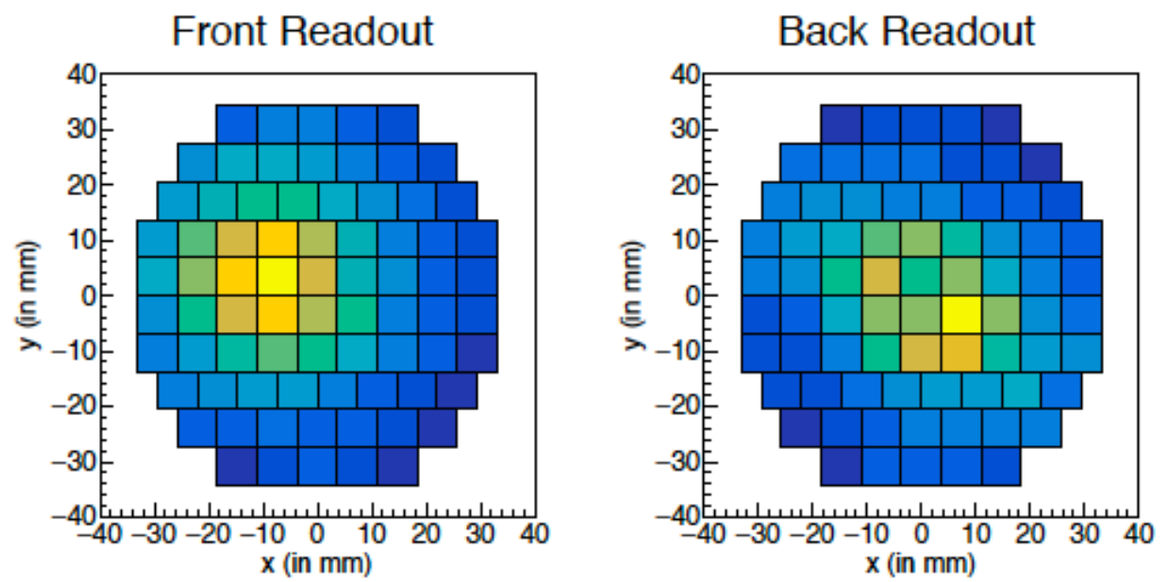
Shower inside the crystal

- LYSO; crystal size (R,L) = (3.5, 16) cm; 55 MeV gamma with different impinging conditions

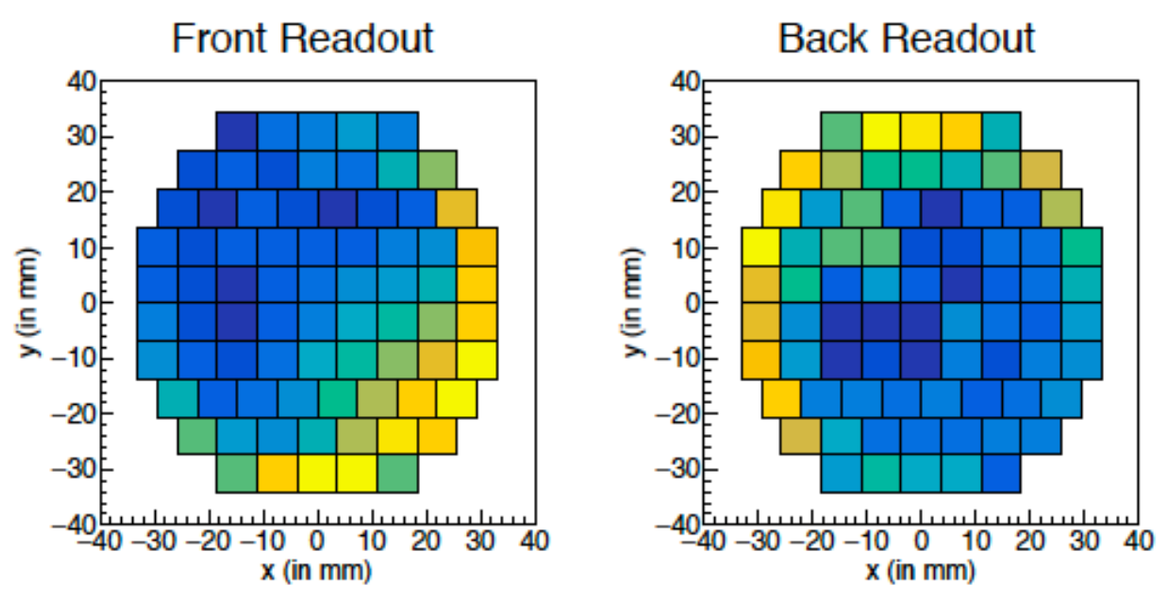


Extended source: Geometrical cut

- Two type of events: inner and border line events - simplified view
- Detector performances spoiled by border line events
- High segmented photosensor coverage: A powerful tool for geometrical cut
  - Optimal trade-off between kinematical variable resolutions and event selection efficiency
  - Valid in view of a segmented/multi-element scalable big calorimeter for increasing the detector uniformity - i.e. parallelepiped elements



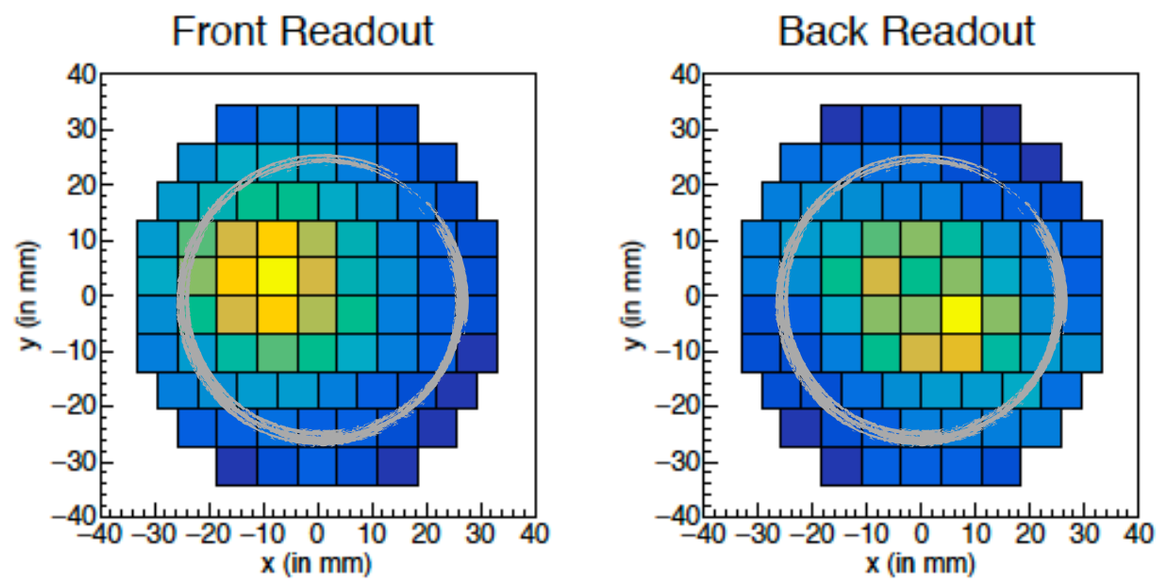
(a) Hit in Central Region: $(x, y) = (-10\,\mathrm{mm}, 3\,\mathrm{mm})$



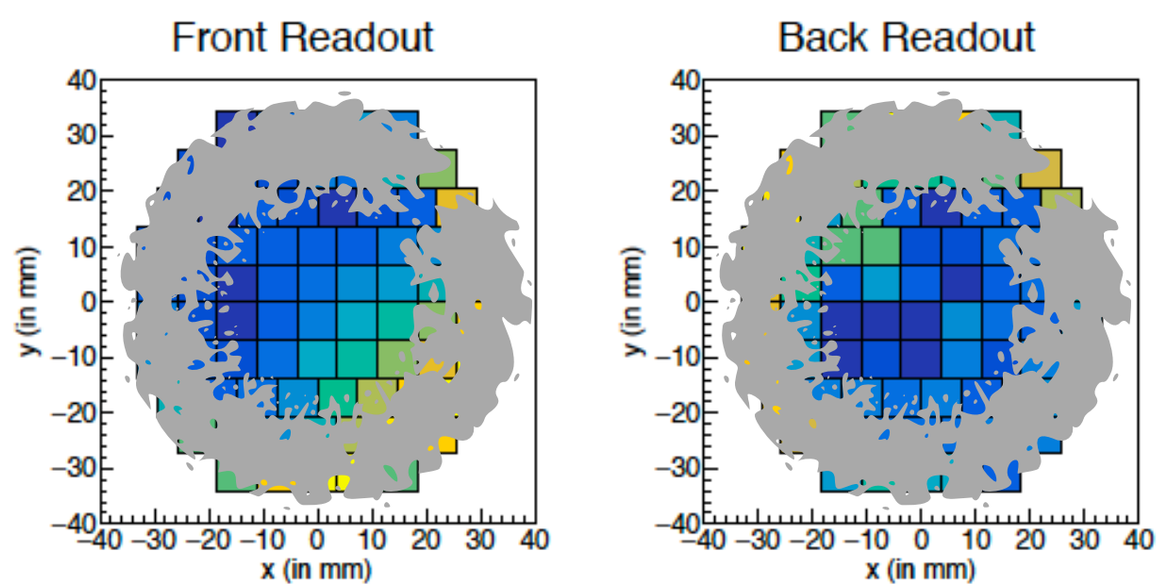
(b) Hit in Outer Region: $(x, y) = (23\,\mathrm{mm}, -21\,\mathrm{mm})$

Extended source: Geometrical cut

- Two type of events: inner and border line events - simplified view
- Detector performances spoiled by border line events
- High segmented photosensor coverage: A powerful tool for geometrical cut
  - Optimal trade-off between kinematical variable resolutions and event selection efficiency
  - Valid in view of a segmented/multi-element scalable big calorimeter for increasing the detector uniformity - i.e. parallelepiped elements
- Two methods:
  - Reconstructed radius cut
  - Skewness cut
  - Both compared to the simulated radius cut
- Effective kinematical variable resolutions



(a) Hit in Central Region: $(x, y) = (-10\,\mathrm{mm}, 3\,\mathrm{mm})$



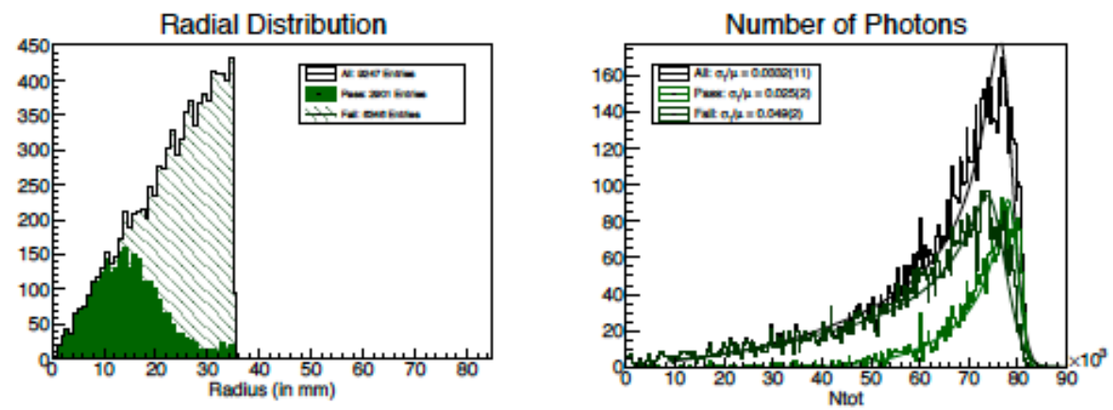
(b) Hit in Outer Region: $(x, y) = (23\,\mathrm{mm}, -21\,\mathrm{mm})$

Extended source: Geometrical cut

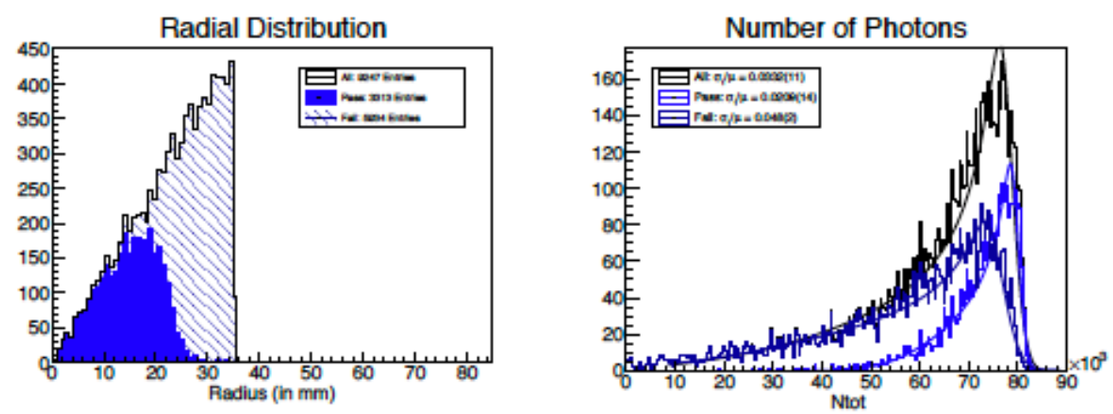
- Small crystal case
- Crystal: LYSO with size (R,L) = (3.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas

- $\sqrt{(x^2 + y^2)} < 20$ mm
- Radial Skewness (F,B) > -0.6

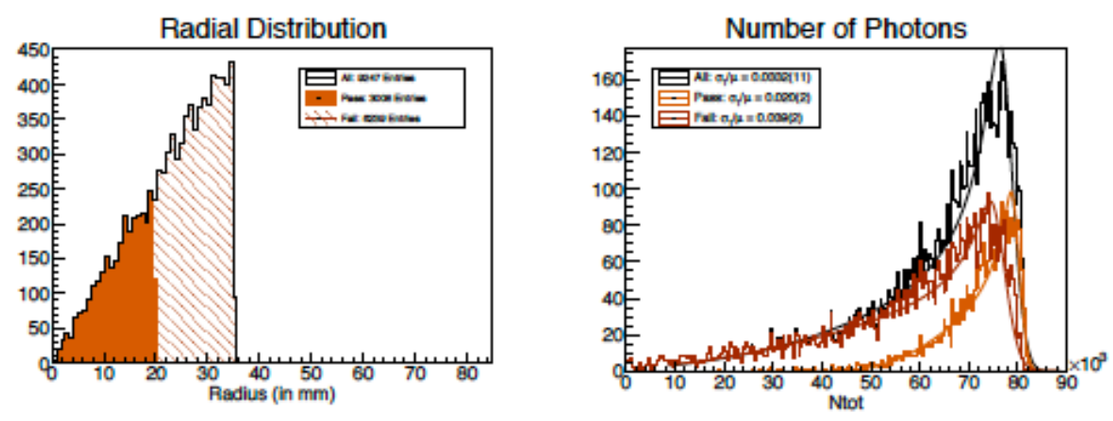
- σ_N/N [%] = 3.3 ⇒ 2.5, (reconstructed radius cut)
- σ_N/N [%] = 3.3 ⇒ 2.1, (skewness cut)
- σ_N/N [%] = 3.3 ⇒ 2.0 (simulated radius cut)
- For all cases: ε_{sel} ~30%



(a) Cut based on the reconstructed radius



(b) Cut based on the skewness



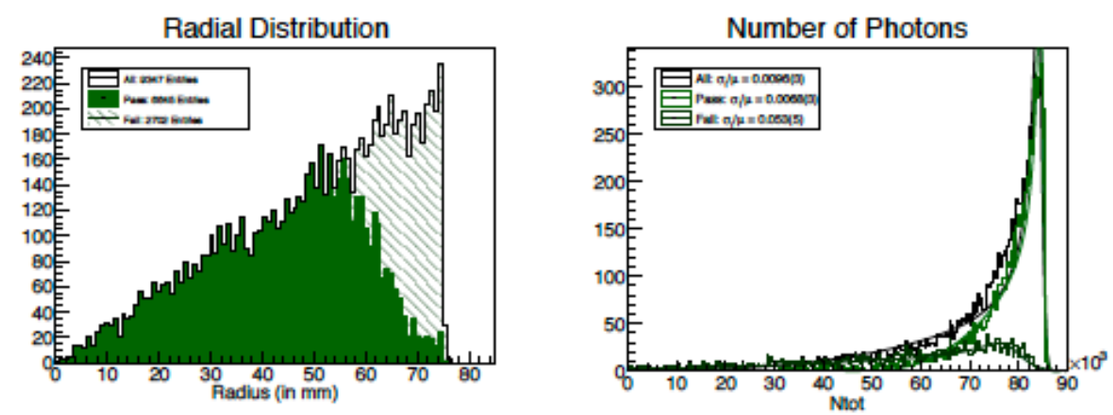
(c) Cut based on the MC truth radius

Extended source: Geometrical cut

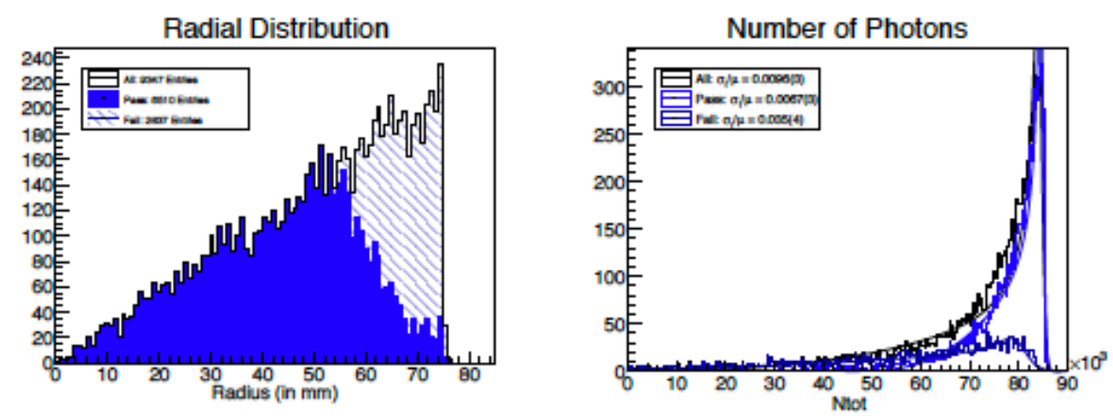
- Large crystal case
- Crystal: LYSO with size (R,L) = (7.5, 16) cm
- Photosensor: Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas

- $\sqrt{(x^2 + y^2)} < 65$ mm
- Radial Skewness (F,B) > -0.6

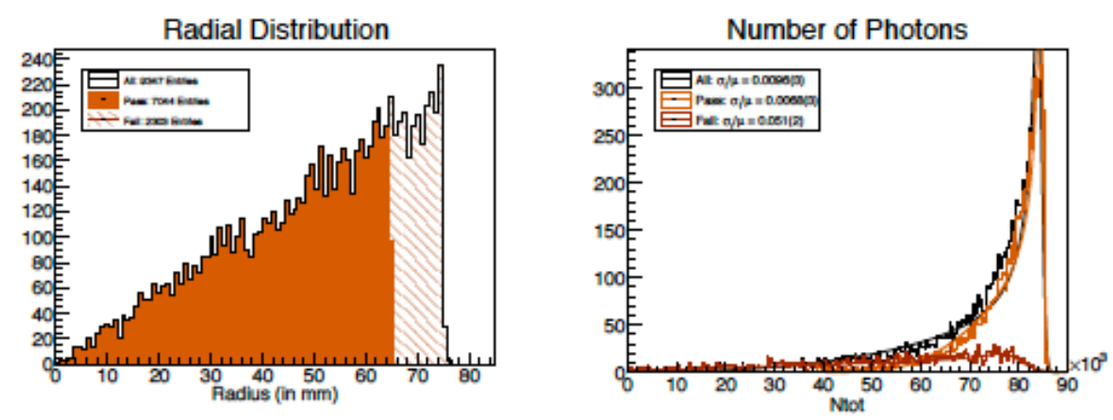
- σ_N/N [%] = 0.9 ⇒ 0.7, (reconstructed radius cut)
- σ_N/N [%] = 0.9 ⇒ 0.7, (skewness cut)
- σ_N/N [%] = 0.9 ⇒ 0.7 (simulated radius cut)
- For all cases: ε_{sel} > 75%



(a) Cut based on the reconstructed Radius



(b) Cut based on the skewness

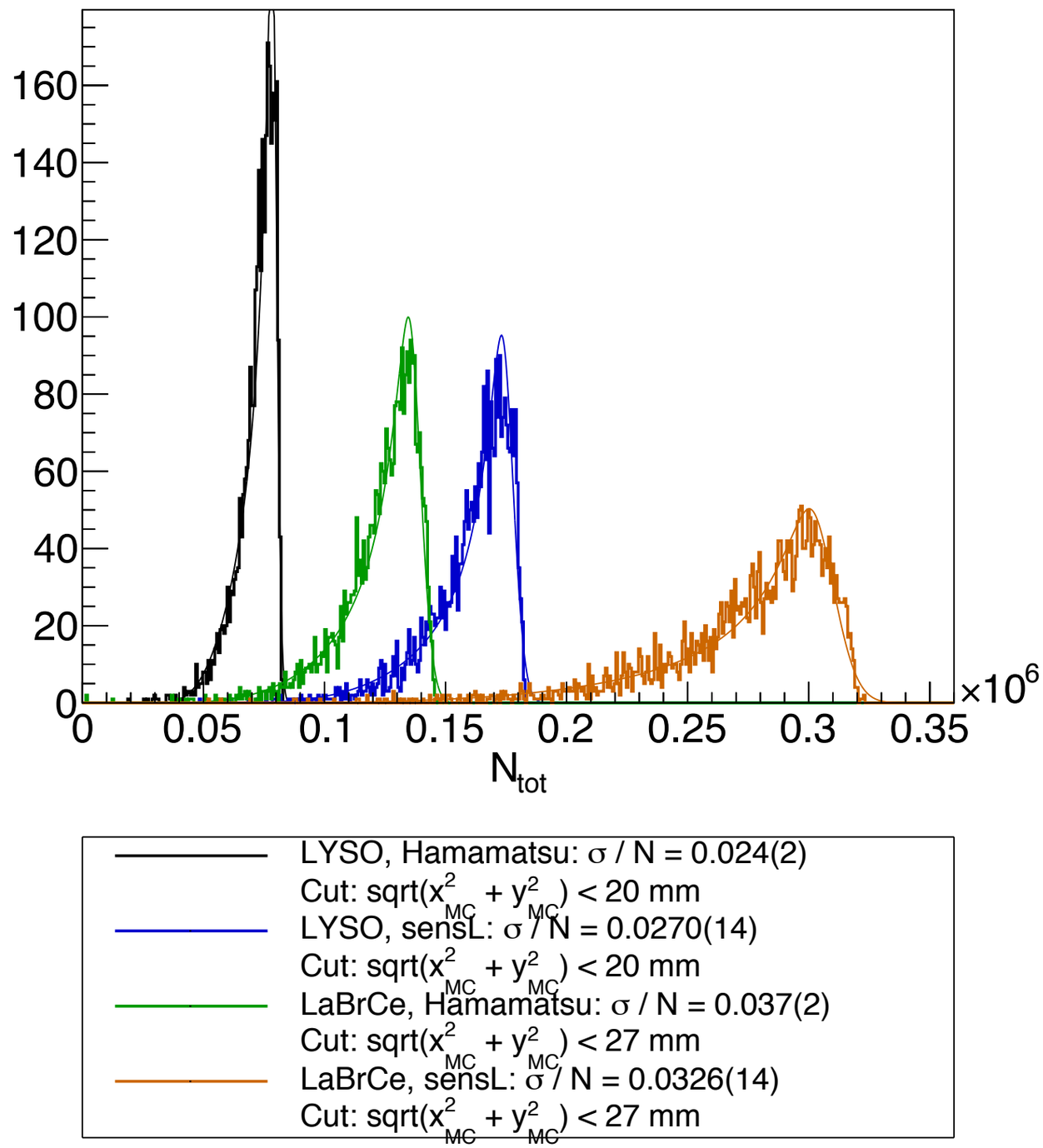


(c) Cut based on the MC truth Radius

Extended source: Energy resolution

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{(x^2 + y^2)} < 20$ mm

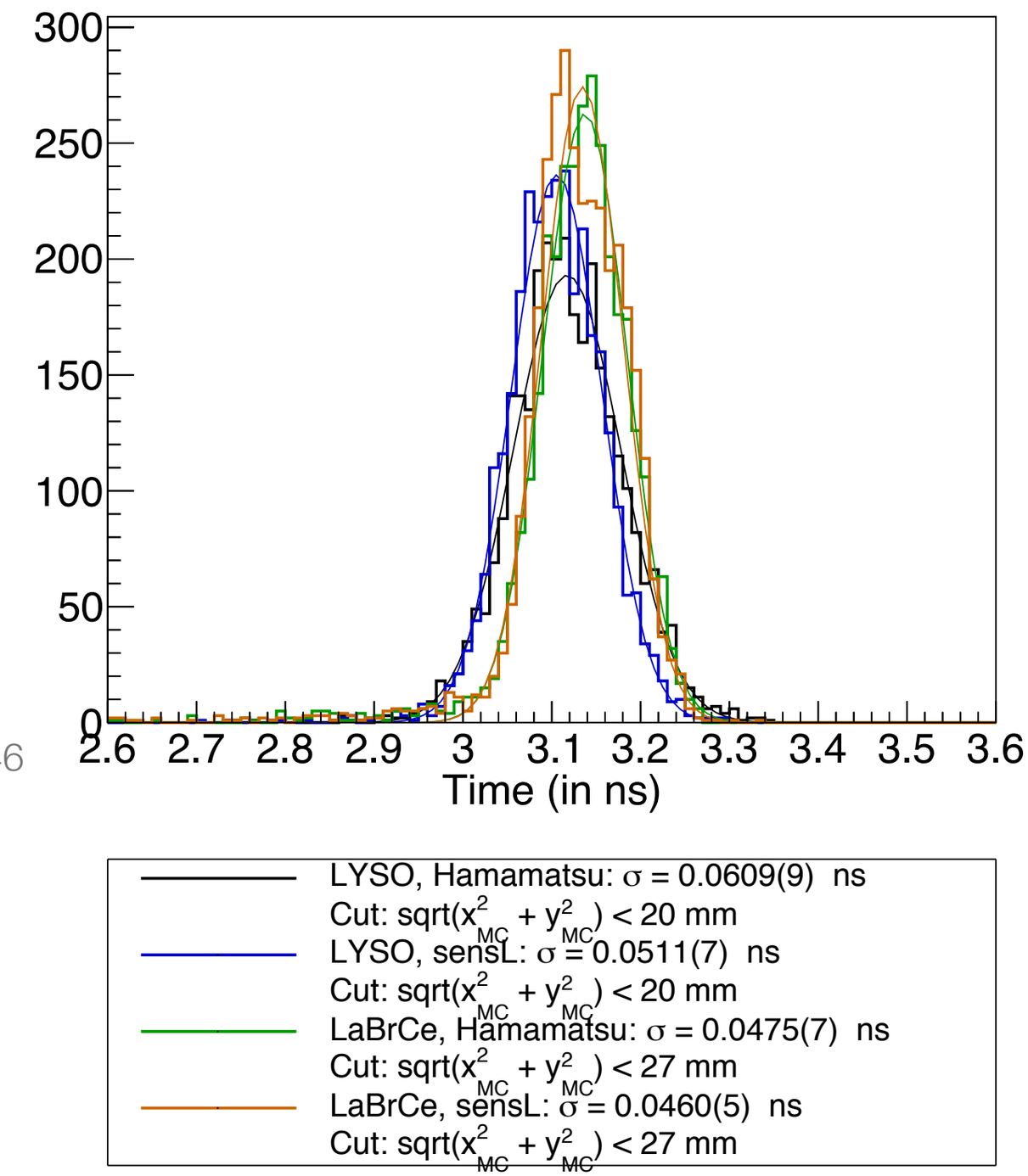
- LYSO + Hamamatsu: best σ_N/N [%] = 2.4
- LaBr3(Ce) + sensL: best σ_N/N [%] = 3.3



Extended source

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{(x^2 + y^2)} < 20$ mm

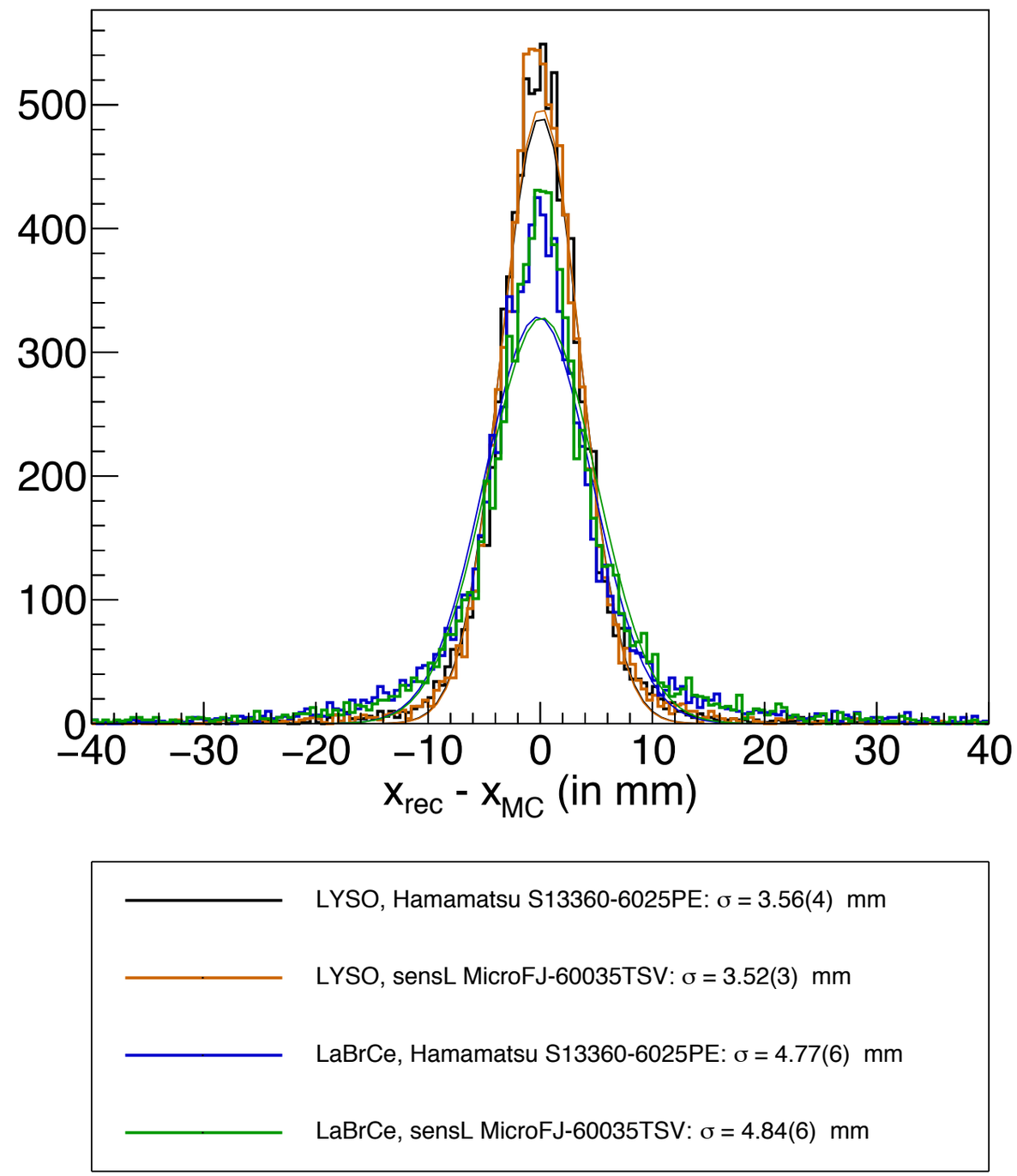
- LYSO + sensL: best σ_t [ps] = 51 +- few ps
- LaBr3(Ce) + sensL/Hamamatsu: best σ_t [ps] = 46 +- few ps



Extended source

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{(x^2 + y^2)} < 20$ mm

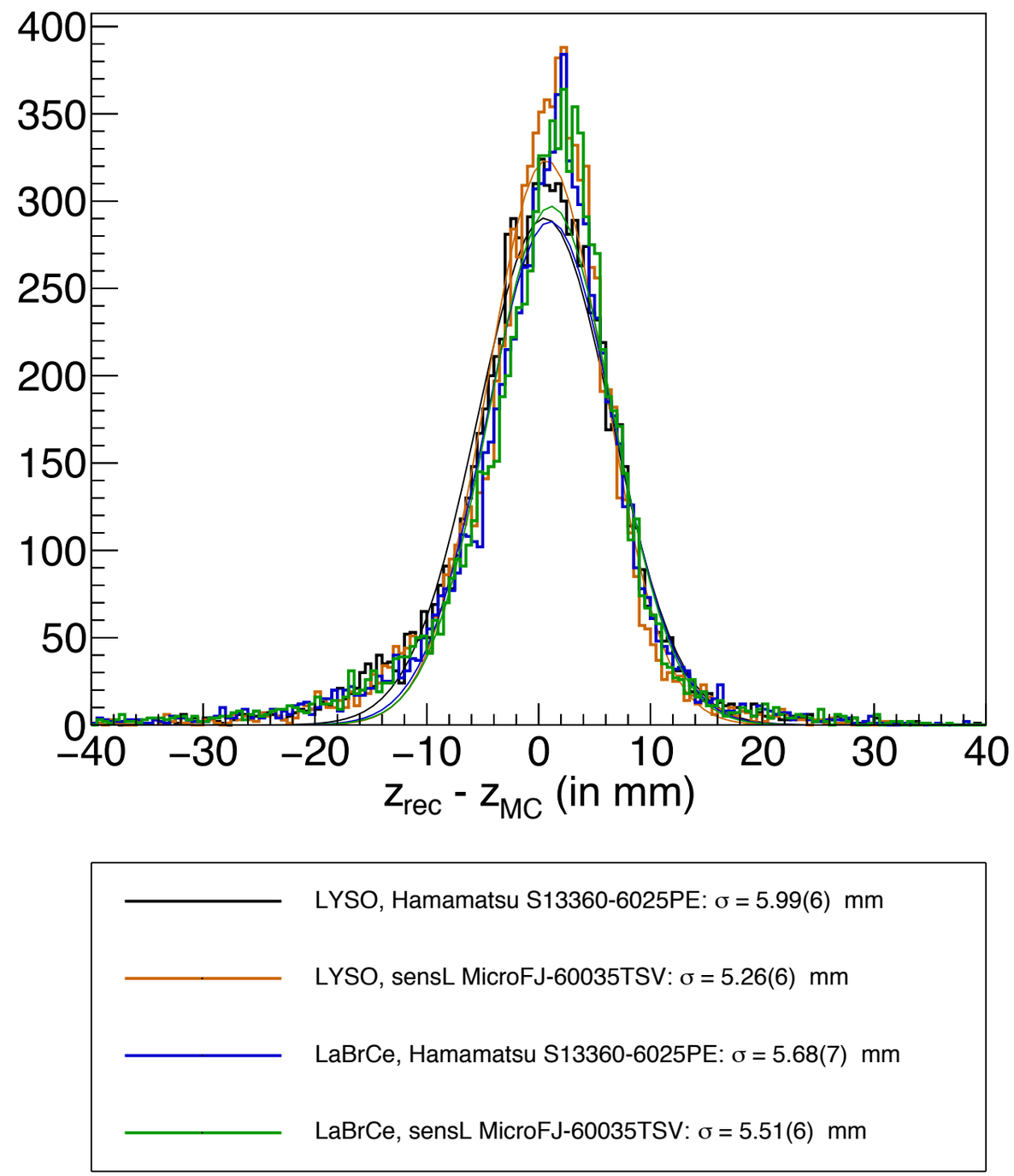
- LYSO + Hamamatsu/sensL: $\sigma_{X,Y}$ [mm] = 3.5 +- 0.5
- LaBr3(Ce) + Hamamatsu/sensL: $\sigma_{X,Y}$ [mm] = 4.8 +- 0.5



Extended source

- Crystals:
  - LaBr3(Ce) with size (R,L) = (4.45, 20.3) cm
  - LYSO with size (R,L) = (3.5, 16) cm
- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE
- Radiation: 55 MeV gammas
- Geometrical cut: $\sqrt{(x^2 + y^2)} < 20$ mm

- LYSO + sensL: best σ_Z [mm] = 5.3 +- 0.5
- LaBr3(Ce) + Hamamatsu/sensL: best σ_Z [mm] = 5.5 +- 0.5



Summary and Outlook

- $LaBr_3$(:Ce) and LYSO are a very attractive media for gamma calorimetry not only for low energy physics but also for high energy physics and in particular for the energy range of interest in charged Lepton Flavour Violation searches - O(50-100) MeV at the intensity frontier

- The well established MPPC/SiPM technology open the road to geometrical configurations never considered before (i.e.multiple readout scheme, with sensors along the path of the incident radiation, high granularity, geometrical cut for the best detector acceptance etc.) allowing to fully exploit the scintillation crystal characteristics [i.e. for $LaBr_3$(:Ce) 4.45 (R) x 20.32 (L) cm the energy resolution for single readout (back), single readout (front) and double readout are respectively: 7.8(2)%, 5.6(1)% and 2.25(7)%]

- Detailed Monte Carlo simulations including nowadays - available and custom size - and future cases of a single big crystal showed very promising results:
  - $LaBr_3$(:Ce) 4.45 (R) x 20.32 (L) cm
    - **σ_N/N [%]** ~ **2.2** [3.2 ext.] [3.8 ext. + waveform] ⇒ **1.0** [7.6(R) x 22.7 (L) cm crystal], **σ_t [ps] ~ 35** [46 ext.], **$\sigma_{X,Y}$[mm] ~ 3.5, σ_z[mm] ~ 6 mm**
  - LYSO 3.5 (R) x 16 (L) cm
    - **σ_N/N [%]** ~ **1.3** [2.4 ext.] [3.5 ext. + waveform] ⇒ **0.7** [7.5(R) x 16(L) cm crystal], **σ_t [ps] ~ 40** [51 ext.], **$\sigma_{X,Y}$[mm] ~ 3.5, σ_z[mm] ~ 6 mm**

- Calorimeters with such a performances are at the detector technology frontiers

- A first large $LaBr_3$(:Ce)/LYSO detector prototype coupled to MPPC /SiPM for high energy gamma calorimetry is under construction

Acknowledgements

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Backup

MPPC/SiPM characterisation

- Photosensors:
  - SensL MicroFJ-60035TSV
  - Hamamatsu S13360-6025PE