The LYSO:Ce crystals of SICCAS, Saint-Gobain and Zecotek comparison

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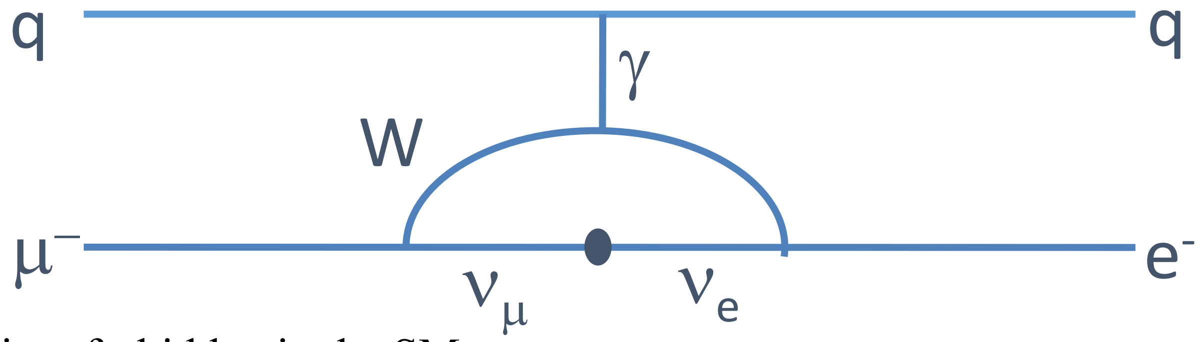
CLFV in the Standard Model

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (CLFV)



- Strictly speaking, forbidden in the SM
- Even in ν-SM, extremely suppressed (rate $\sim \Delta m_\nu^2 / M_W^2 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation CLFV experiments

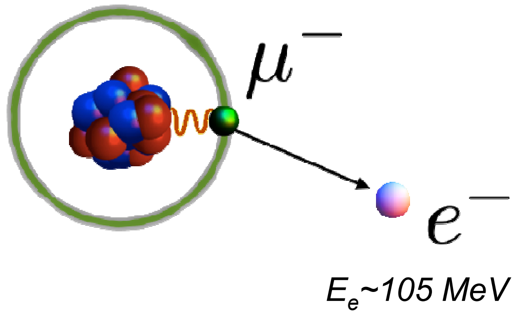
Muon to electron conversion in the field of a nucleus

Mu2e will measure Charged Lepton Flavor Violation (CLFV) with a single-event sensitivity of 2.5×10^{-17} (relative to ordinary muon capture)

$$\mu^{-}N \rightarrow e^{-}N$$

- Initial state: muonic atom
- Final state:
  - a single mono-energetic electron.
    - the energy depends on Z of target.
  - recoiling nucleus is not observed
    - the process is coherent: the nucleus stays intact.
  - neutrino-less
- Conventional Signal Normalization:
- Standard Model ($m_\nu \neq 0$) rate is $\sim 10^{-52}$
- There is an observable rate in many new physics scenarios.

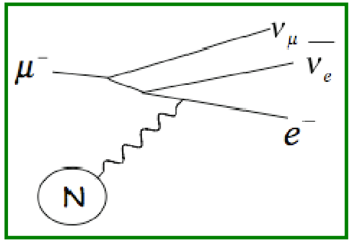
$$\mu N \rightarrow eN$$

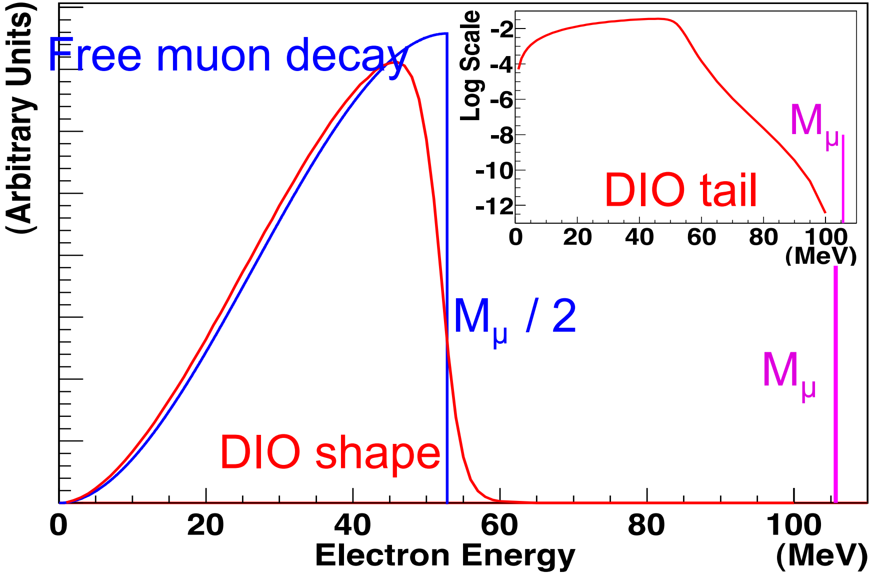


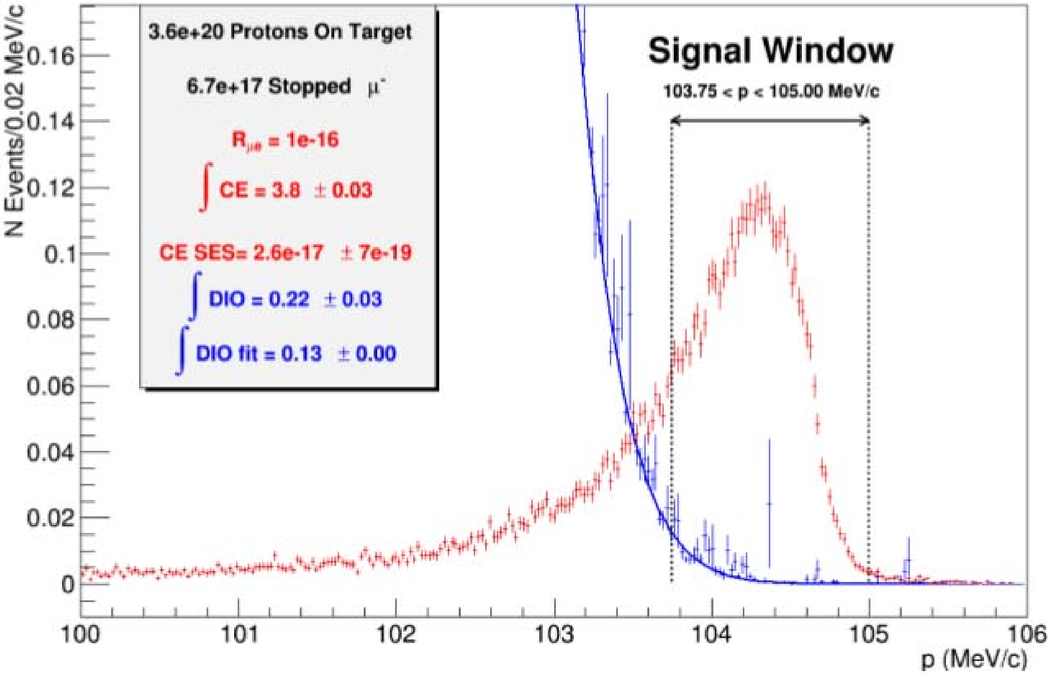
$$R_{\mu e} = \frac{\Gamma(\mu^{-} + N(A,Z) \rightarrow e^{-} + N(A,Z))}{\Gamma(\mu^{-} + N(A,Z) \rightarrow \text{all muon captures})}$$

Decay–in-Orbit: Dominant Background

DIO: Decay in orbit



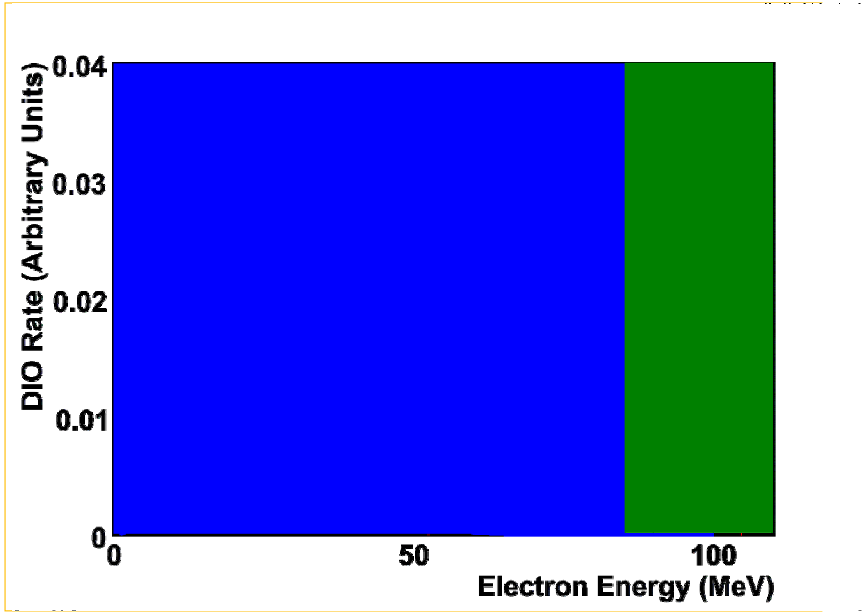




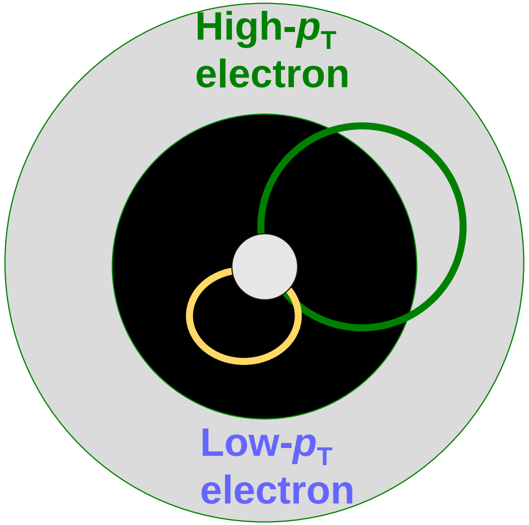
Reconstructed Momentum (MeV)

Designing the tracker and calorimeter

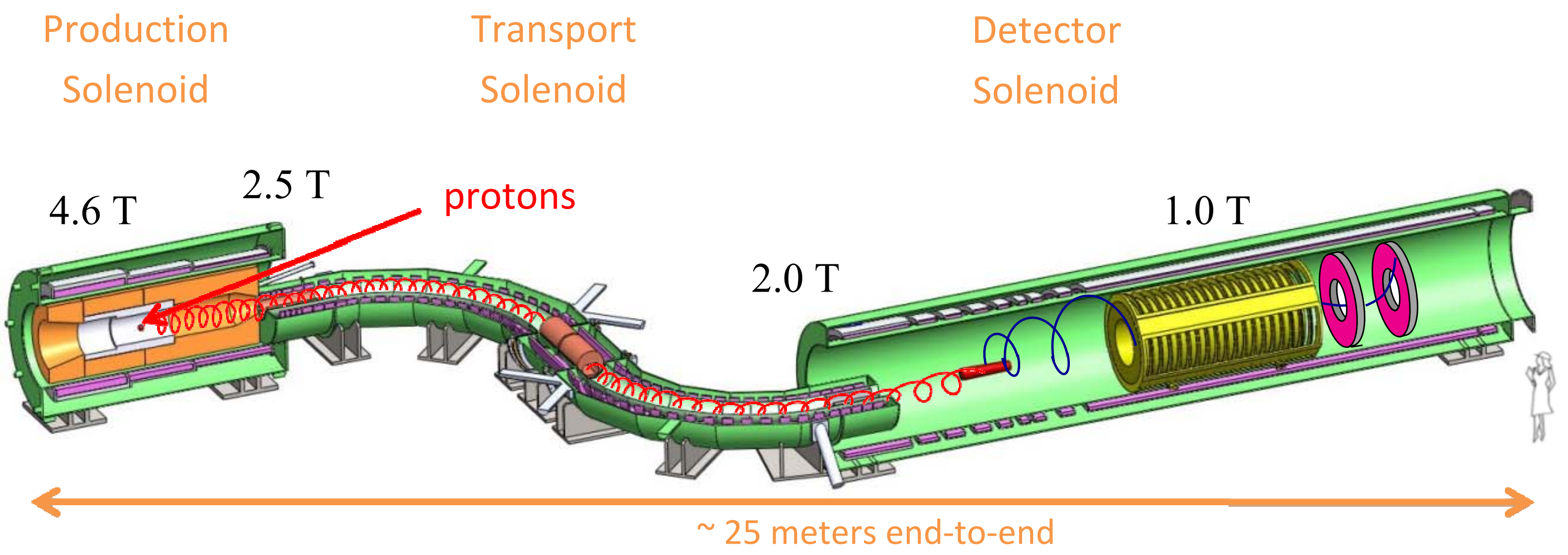
- Remember the DIOs.



- Since radius of track is proportional to p_T, design the detectors to only see tracks with large enough radii.
  - Annular design



Mu2e Experimental Apparatus



PS: 8 GeV protons interact with a tungsten target to produce μ^- (from π^- decay)

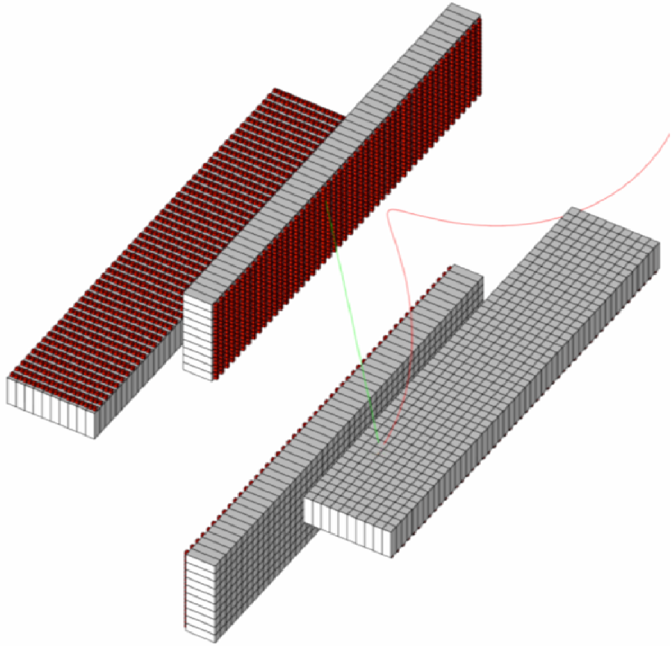
TS: Captures π^- and subsequent μ^-; momentum- and sign-selects beam

DS: Upstream – Al. stopping target, Downstream – tracker, calorimeter

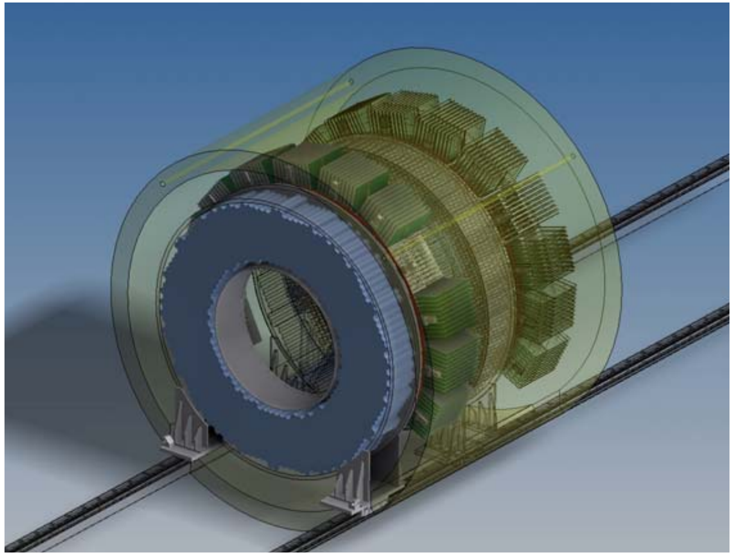
Graded fields are important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

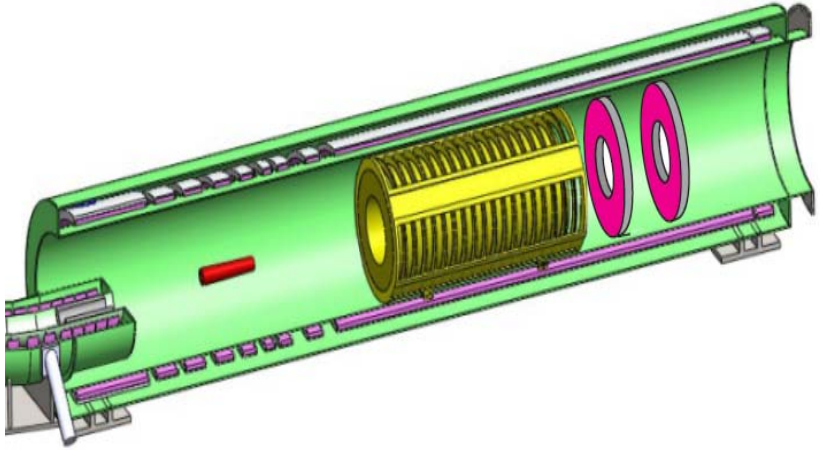
Calorimeter design history

Initial design:
1936 square cross-section crystals in 4 vanes



Present design:
1860 hexagonal cross-section crystals in two disks





Calorimeter crystal history

- Initial choice PbWO4: small X0, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small X0, high light yield, expensive (→very expensive)
- TDR choice: BaF2: larger X0, lower light yield (in the UV), very fast component at 220 nm, readout R&D required, cheaper

Crystal	BaF_2	LYSO	CsI	$PbWO_4$
Density (g/cm^3)	4.89	7.28	4.51	8.28
Radiation length (cm) X_0	2.03	1.14	1.86	0.9
Molière radius (cm) Rm	3.10	2.07	3.57	2.0
Interaction length (cm)	30.7	20.9	39.3	20.7
dE/dx (MeV/cm)	6.5	10.0	5.56	13.0
Refractive Index at λ_{max}	1.50	1.82	1.95	2.20
Peak luminescence (nm)	220, 300	402	310	420
Decay time τ (ns)	0.9, 650	40	26	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	3.6	0.3, 0.1
Light yield variation with temperature (% / °C)	0.1, -1.9	-0.2	-1.4	-2.5
Hygroscopicity	None	None	Slight	None

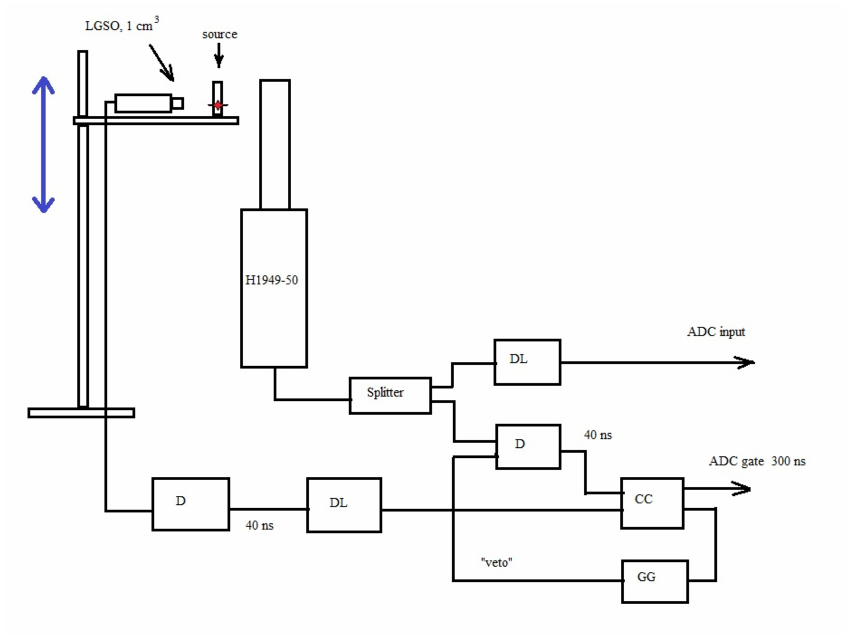
Crystals and apparatus

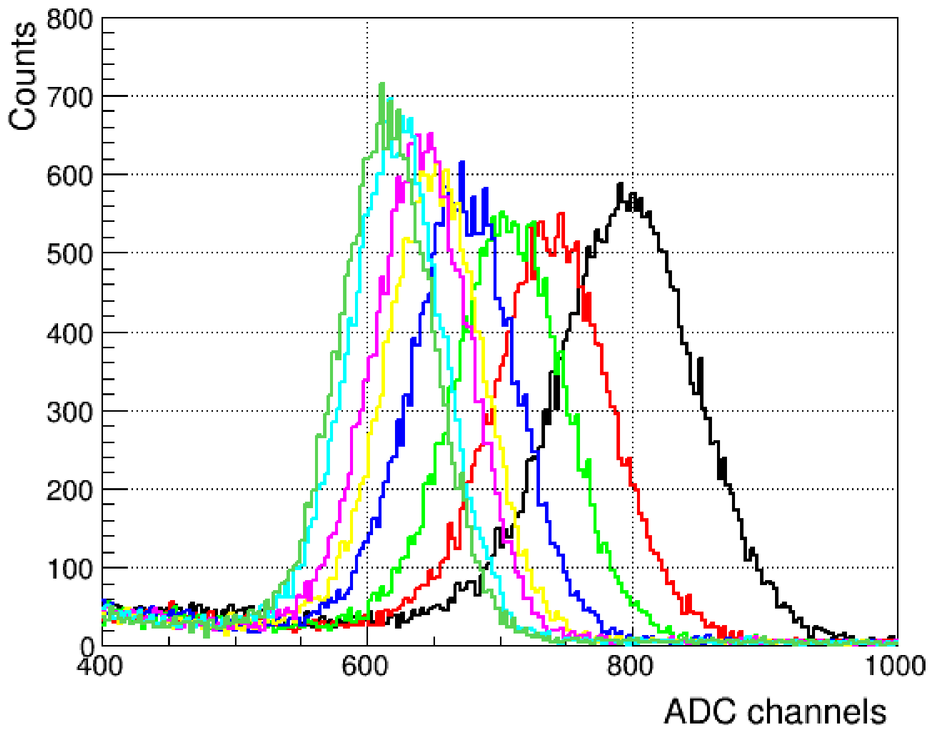
3 crystals have been tested:

- LYSO from SICCAS: 20x20x150 mm^2
- LFS (Lutetium Fine Silicate) from Zecotek: 20x20x130 mm^2
- PreLude 420 (LYSO) from Saint-Gobain: 30x30x130 mm^2

- All measurements were done with Hamamatsu PMT module H1949-50
- Crystals were attached to the PMT photocathode by means of optical grease
- Hamamatsu 5783 PMT with 1 cm^3 LGSO crystal was used for runs where coincidences with tested crystals required
- ^{22}Na, ^{137}Cs and ^{60}Co gamma sources were used for measurements of all crystals.
- LeCroy ADC 2249W was used for signal processing. Signals from the PMT fed the ADC input with no additional amplification

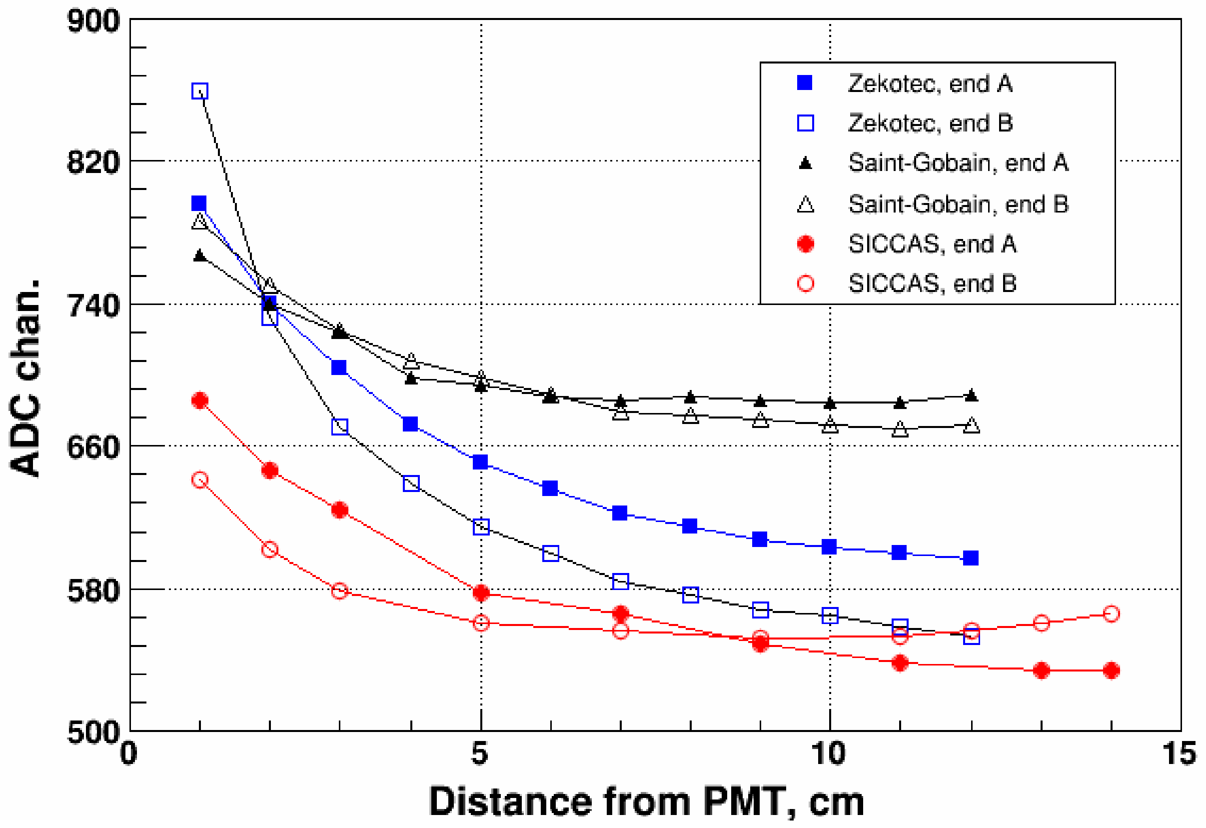
Longitudinal Light Response Uniformity (LRU) measurements





- ^{22}Na source was used for the measurements
- Source and trigger PMT moved along the crystals
- Data were taken with bare crystals, on both ends

Longitudinal LRU of three crystals



Graphs for the bare crystals measurements look reasonable:

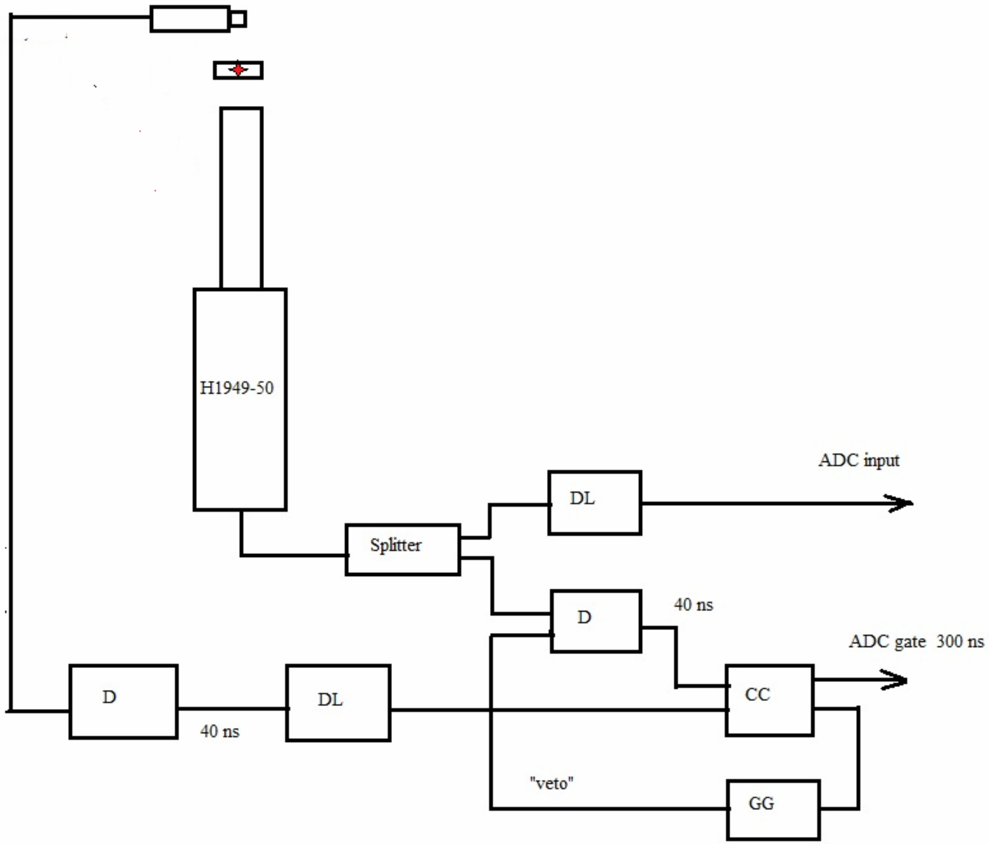
- Each crystal has bigger response on one end (A>B for SICCAS, B>A for Zekotec, B>A for Saint-Gobain). Curves with A and B ends cross in the middle
- Saint-Gobain has a smallest difference among three crystals

Ratio $\frac{H-L}{H}$ for bare crystals:

SICCAS:	6.5%
Zekotec:	7.3%
Saint-Gobain:	2.4%

(H – bigger signal, L – smaller one)

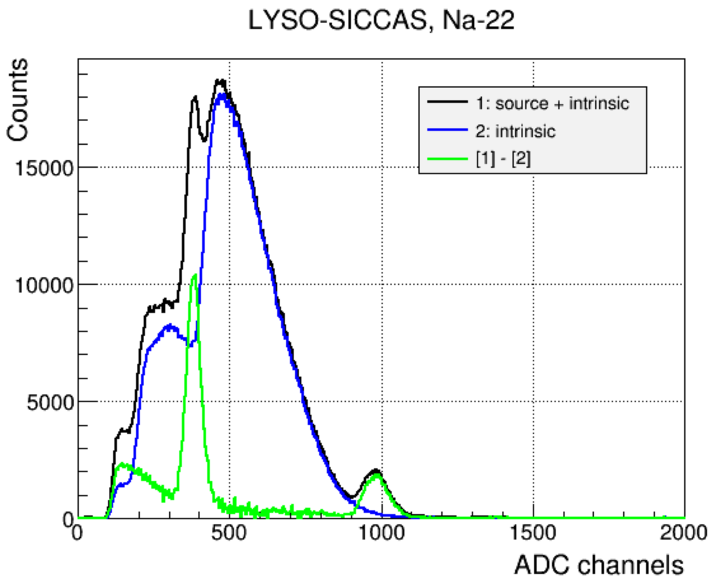
Energy resolution measurements

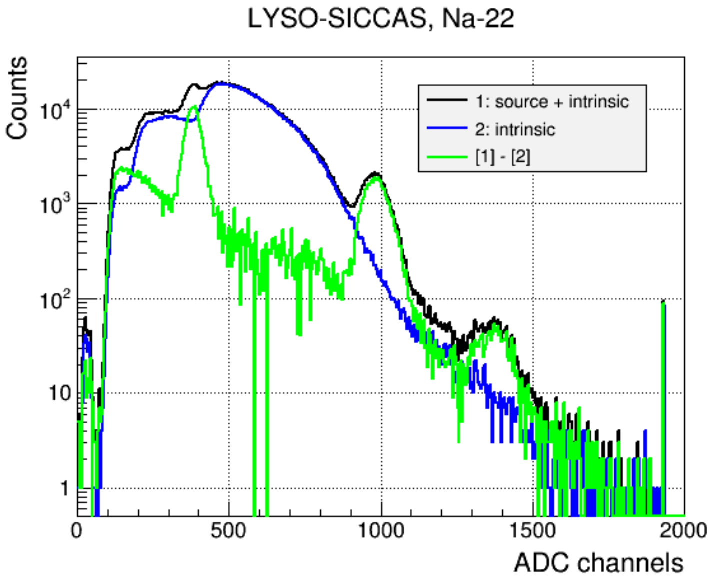


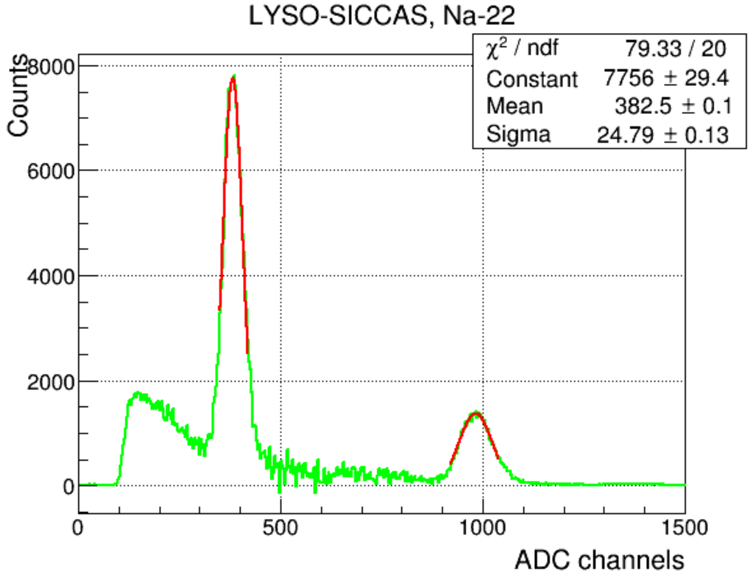
- Sources were placed over the crystals irradiating their far ends
- Data were taken in self triggering mode and in coincidence with 1 cm^3 LGSO crystal attached to Hamamatsu 5783 PMT (in the former case CC unit required a single input signal)
- ^{22}Na, ^{137}Cs and ^{60}Co gamma sources were used for all crystals irradiation

LYSO – SICCAS: ^{22}Na, self triggering

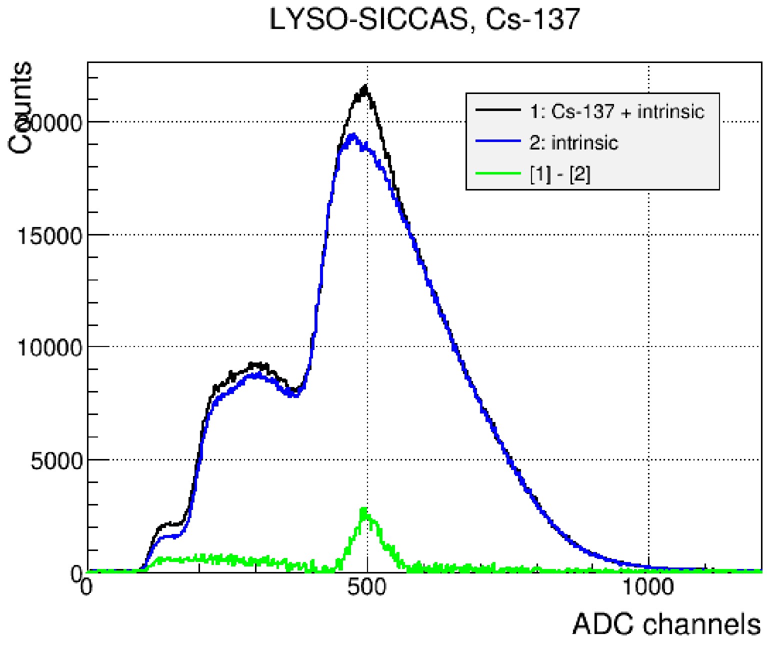
- Source+intrinsic and intrinsic spectra are normalized according to their rates
- Two left frames: normalized Na-22+intrinsic and intrinsic spectra and their difference in linear and log scales
- Bottom right frame: difference spectrum in linear scale with fitted 511 keV and 1275 keV peaks

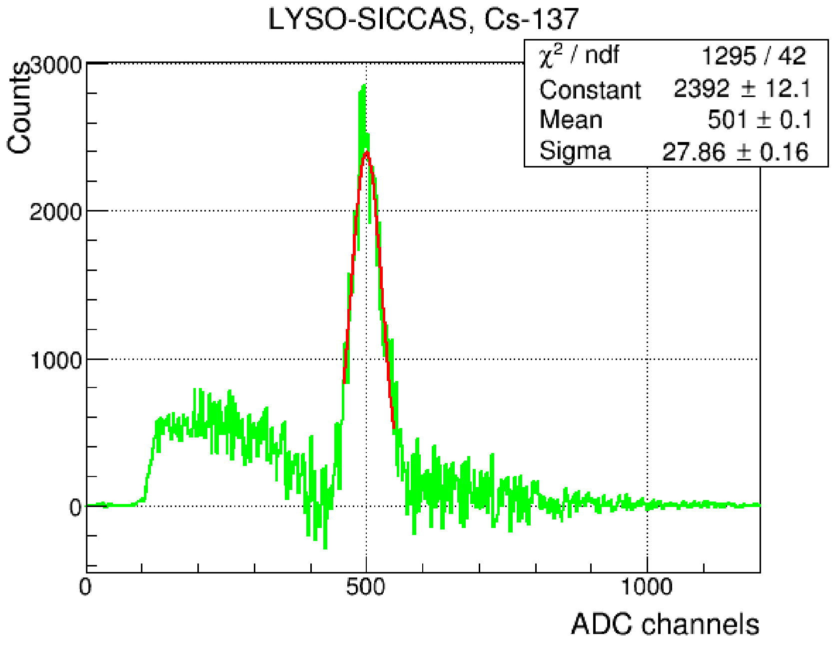






LYSO – SICCAS: ^{137}Cs, self triggering

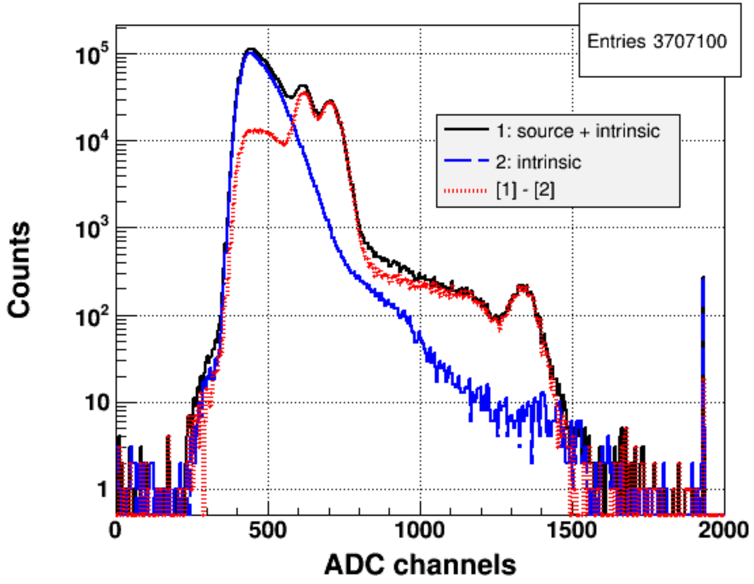


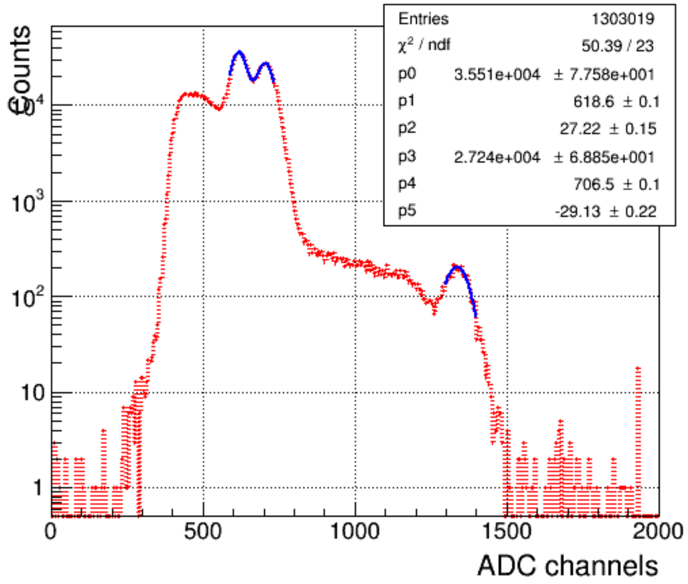


- Left frame: normalized Cs-137+intrinsic and intrinsic spectra and their difference
- Right frame: difference spectrum with fitted 662 keV peak

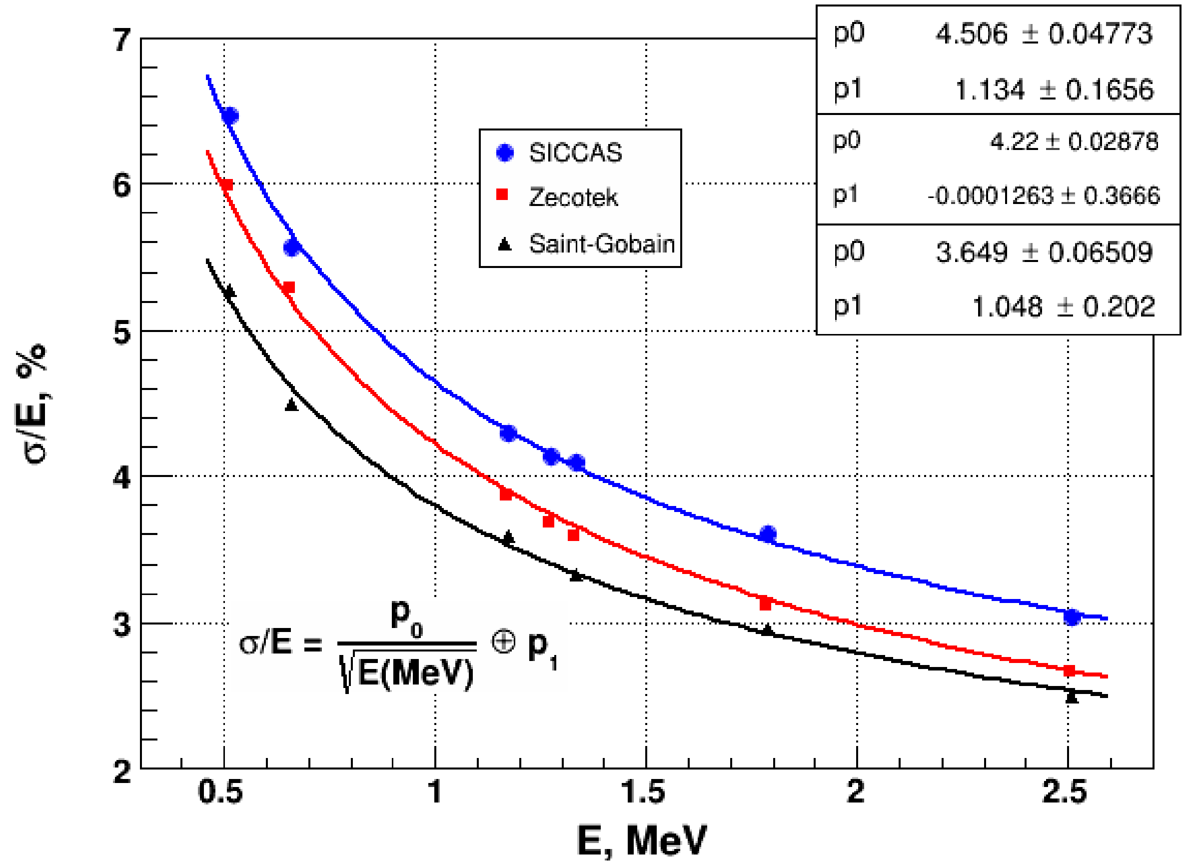
LYSO – SICCAS: ^{60}Co, self triggering

- The discriminator threshold was set to 150 mV in order to suppress low energy gammas (typical level was 30 mV)
- **3 dB attenuator** in the ADC input line (multiply the peak position by 1.4125)
- Left frame: normalized Co-60+intrinsic and intrinsic spectra and their difference log scales
- 1173+1333 keV peak clearly seen on the log scale
- Bottom right frame: difference spectrum in log scale with three fitted peaks.

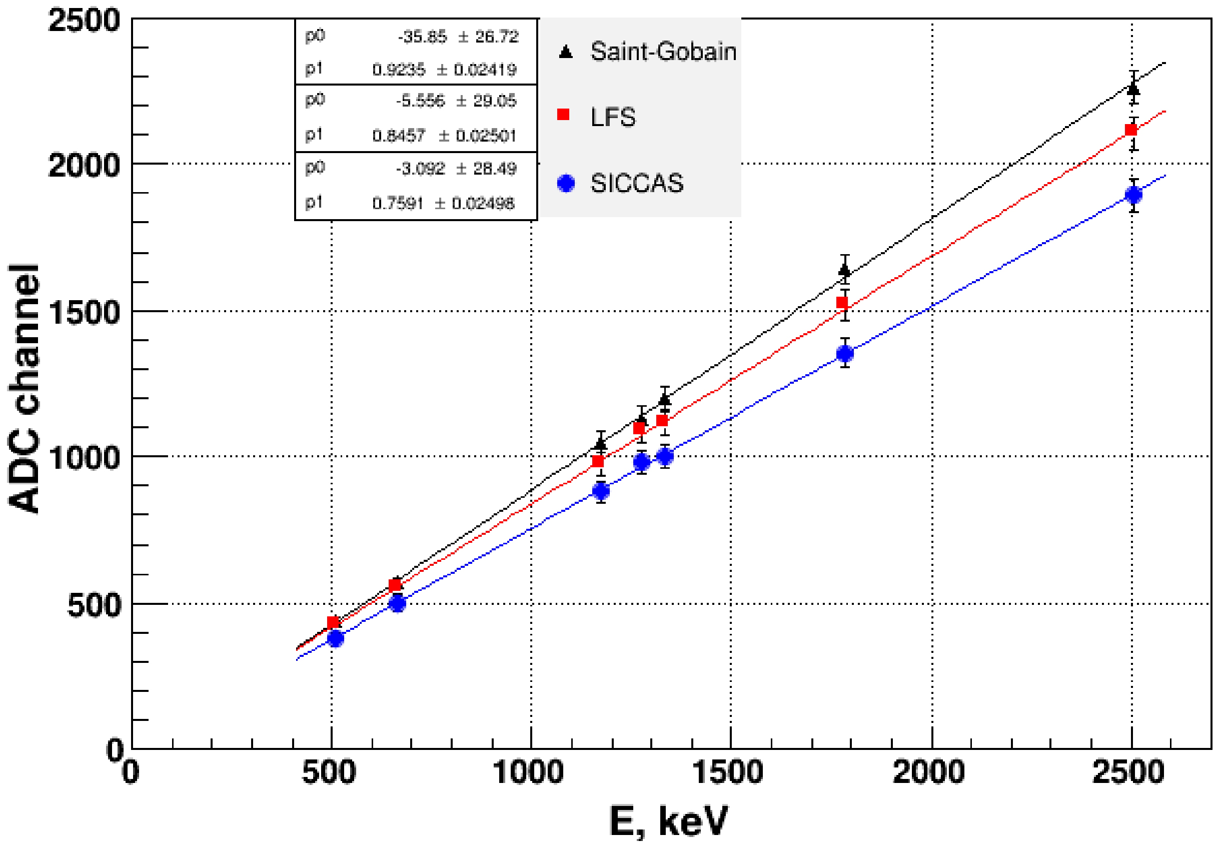




Energy resolution



Linearity of the energy response



- Peak position vs energy graphs are fitted with linear functions
- All three crystals demonstrate good energy response linearity
- Bigger slope reflects higher light output

Conclusion

- All three tested crystals demonstrate good energy resolution and linearity of energy response
- Crystals have different light outputs from two ends, with Saint-Gobain showing a minimal difference ≈ 2.4%.
- The Saint-Gobain crystal has best energy resolution in the whole 511-2500 keV energy range, it showed energy resolution $\sigma/E=2.5\%$ at E=2500keV
- Overall Prelude 420 from Saint-Gobain has best parameters among three tested crystals