Suppressing α background in HPGe detectors for next-generation 0νββ searches

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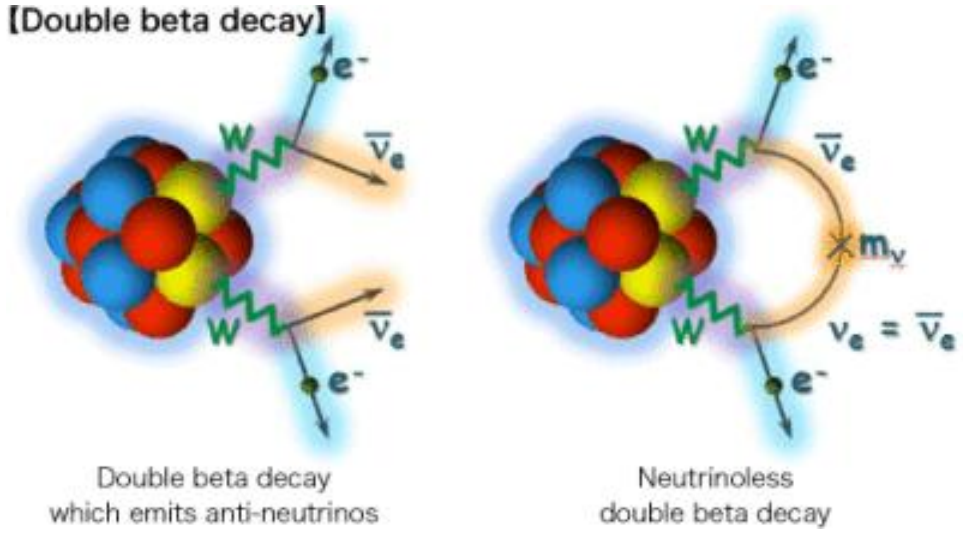
LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

NEUTRINOLESS DOUBLE BETA DECAY (0νββ)

- NOT OBSERVED YET!
- Forbidden in the Standard Model
- Search in the isotopes that are capable of 2νββ decay
- $(A,Z) \rightarrow (A,Z+2) + 2e^-$
- Estimated half-lives > 10^{26} yr
- Could help measure absolute neutrino mass down to meV
- Lepton number violation $\Delta L = 2$
- Could help understand matter-antimatter asymmetry and neutrino mass hierarchy



THE LEGEND EXPERIMENT

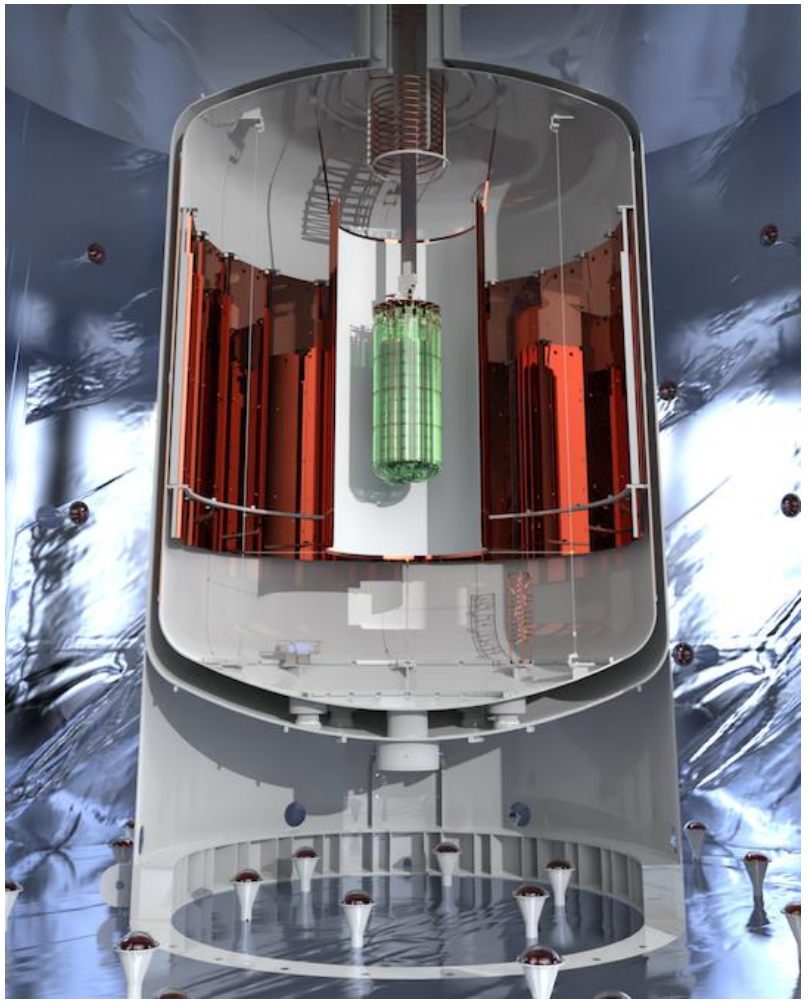
- Searches for $0\nu\beta\beta$ in ^{76}Ge using enriched HPGe detectors

- Located in Laboratori Nazionali del Gran Sasso, Italy

- LEGEND-200 (up to 200 kg of ^{76}Ge, $T_{1/2} \sim 10^{27}$ yr)
- LEGEND-1000 (up to 1000 kg of ^{76}Ge, $T_{1/2} > 10^{28}$ yr)

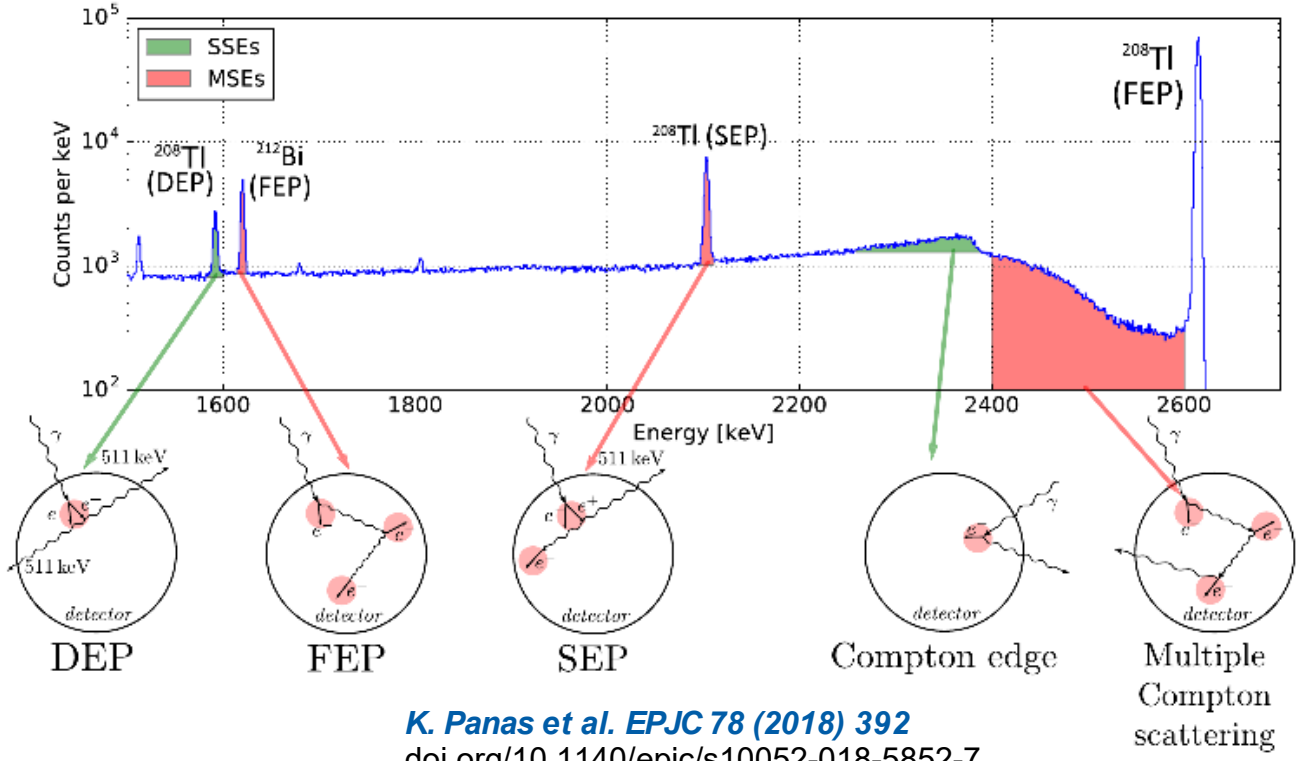
- **Quasi-background free**
- Blinded analysis
- Ultra-pure construction materials
- Background reduction: LAr veto, **Pulse Shape Discrimination (PSD),** muon veto

- From previous experience (GERDA, MAJORANA DEMONSTRATOR) alpha particles coming from p+ contact of germanium detectors are a considerable background source



PULSE SHAPE DISCRIMINATION

- Events classification based on pre-amplifier waveform
- Classifiers are trained on calibration with ^{228}Th
- Cut applied to physics run
- Traditionally used to distinguish between single-site events (signal-like) and multi-site events (background-like)
- Utilised to reject alpha background, but with unknown efficiency due to low statistics



K. Panas et al. EPJC 78 (2018) 392
doi.org/10.1140/epjc/s10052-018-5852-7

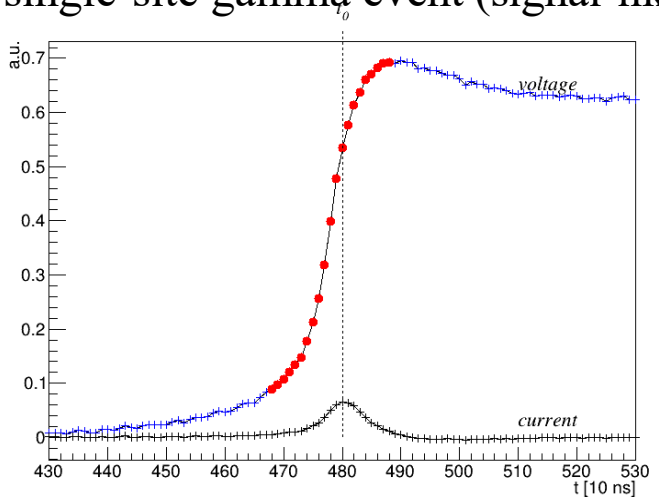
PSD FOR ALPHA BACKGROUND

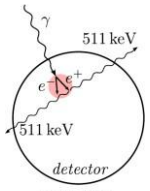
Not possible to train with alpha source!

↓

Permanent detector contamination

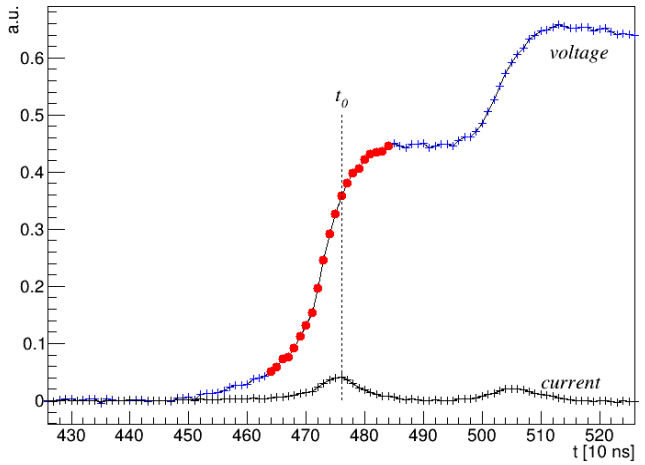
single-site gamma event (signal-like)

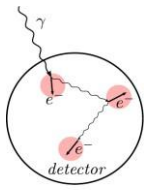




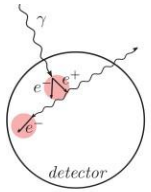
DEP

Idea: *Could we reject alpha background with a single PSD cut trained on gammas?*



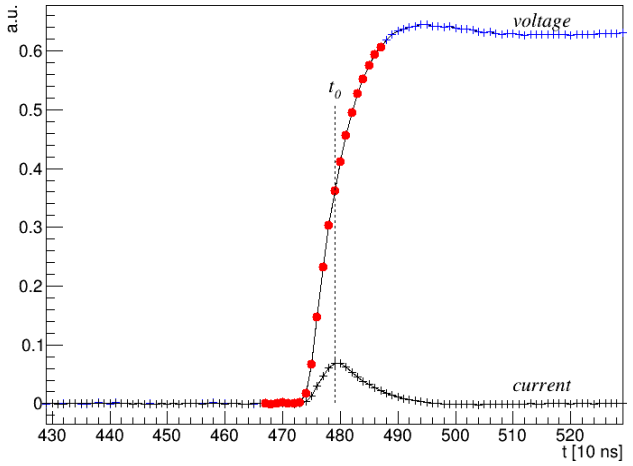


FEP



SEP

multi-site gamma event (background-like)



alpha event

ALPHA SOURCE

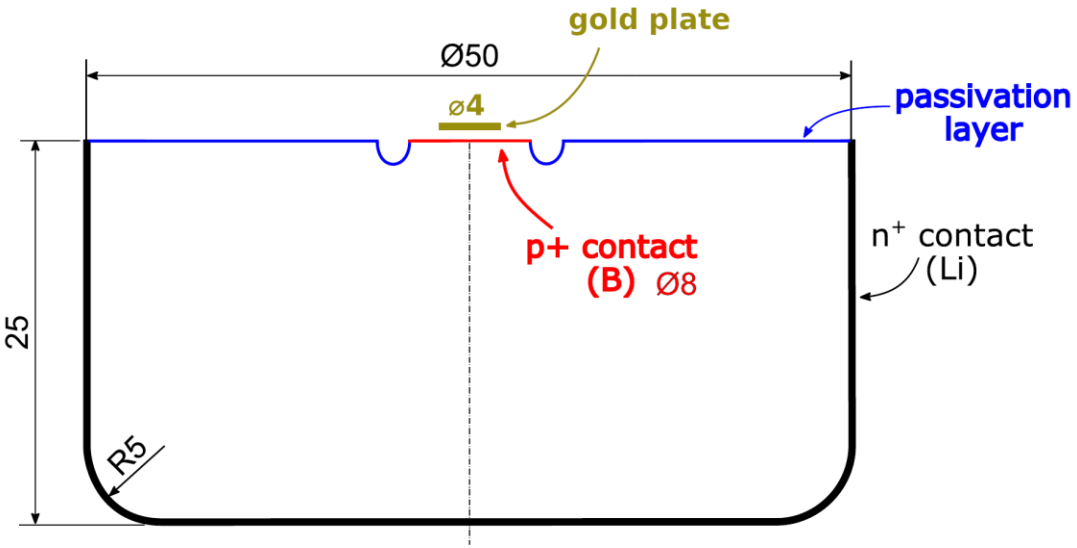
PTFE electroplating cell used for Po deposition

example of electroplated Po source

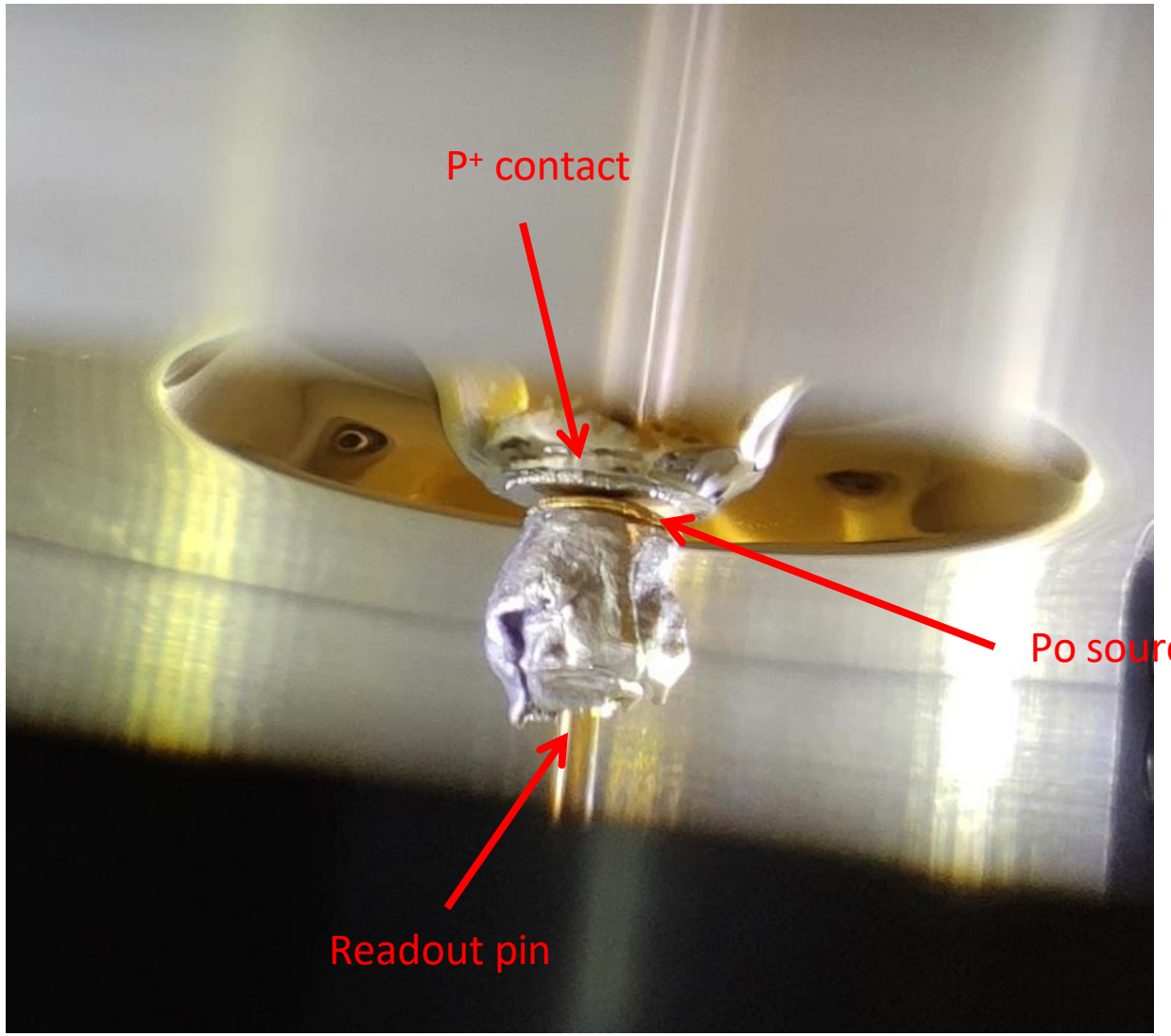
^{209}Po deposited on gold foil (~ 0.1 Bq activity)

^{210}Po separated from high activity lead (^{210}Pb) and deposited on gold foil (~ 1 Bq activity)

ALPHA SOURCE INSTALLATION



Point contact semi planar HPGe detector (BeGe-like)



A.Jany et al. EPJC 81 (2021) 38
doi.org/10.1140/epjc/s10052-020-08781-3

EXPERIMENTAL SETUP

Surface-level Lab in Jagiellonian University

BEGe-like Detector in Vacuum Cryostst

ACQ: Struck SIS3302 100Mhz FADC

Lead Shield

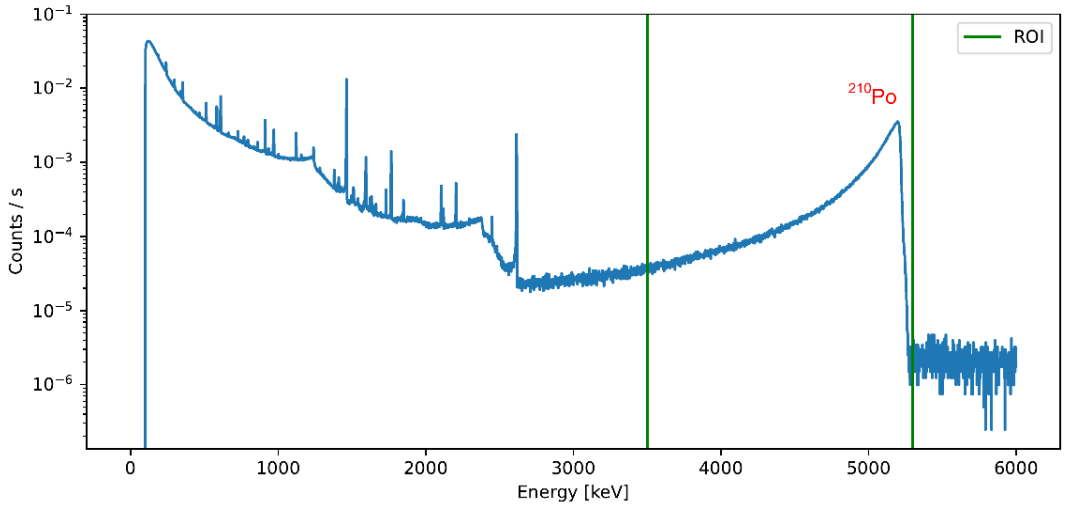
Muon Veto (plastic scintillator on top)

AVAILABLE DATA

- Calibration Runs with ^{228}Th
- Physics Runs with α sources
- Background Runs without any source

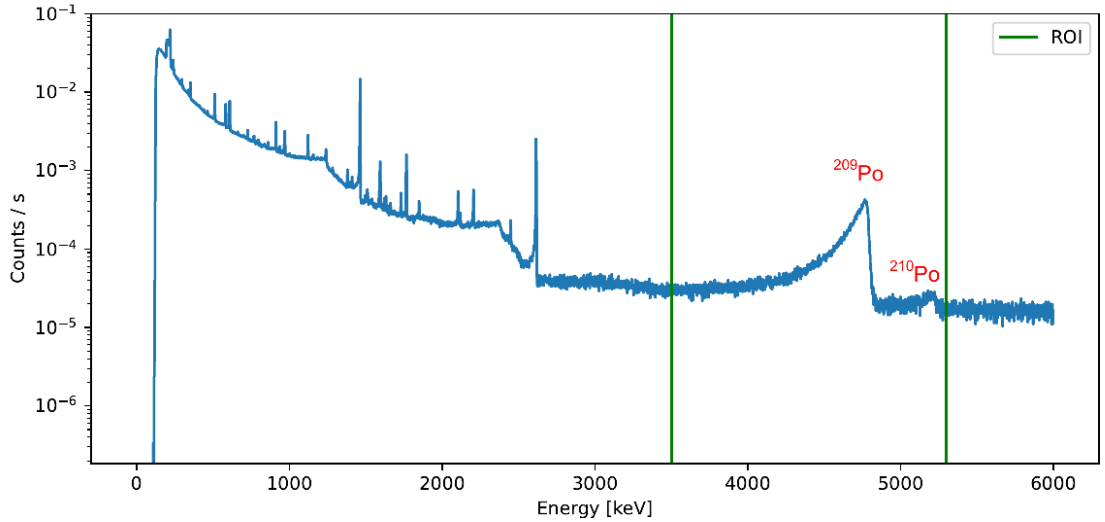
PHYSICS RUNS

High Statistics



$1.87 \cdot 10^6$ αs in ROI [3500, 5300] keV

Low Statistics



$1.36 \cdot 10^5$ αs in ROI [3500, 5300] keV

TESTED CLASSIFIERS

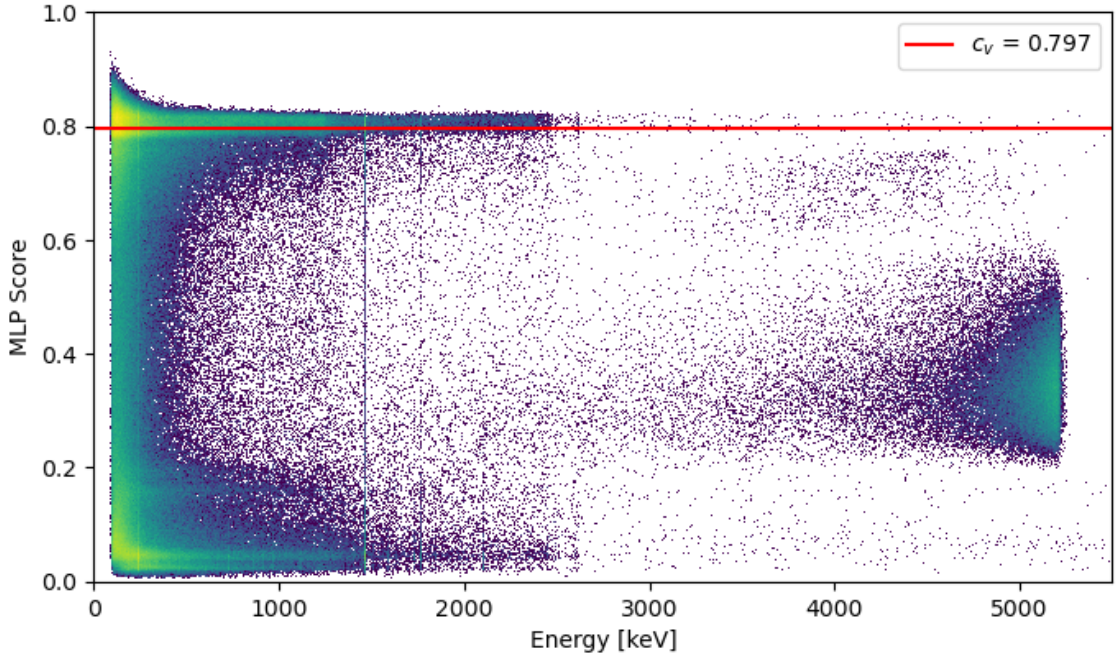
- **ANN Multi Layer Perceptron (MLP)**
- **Projective Likelihood (PLK)**
- **A/E Classifier**

TRAINING CONFIGURATIONS

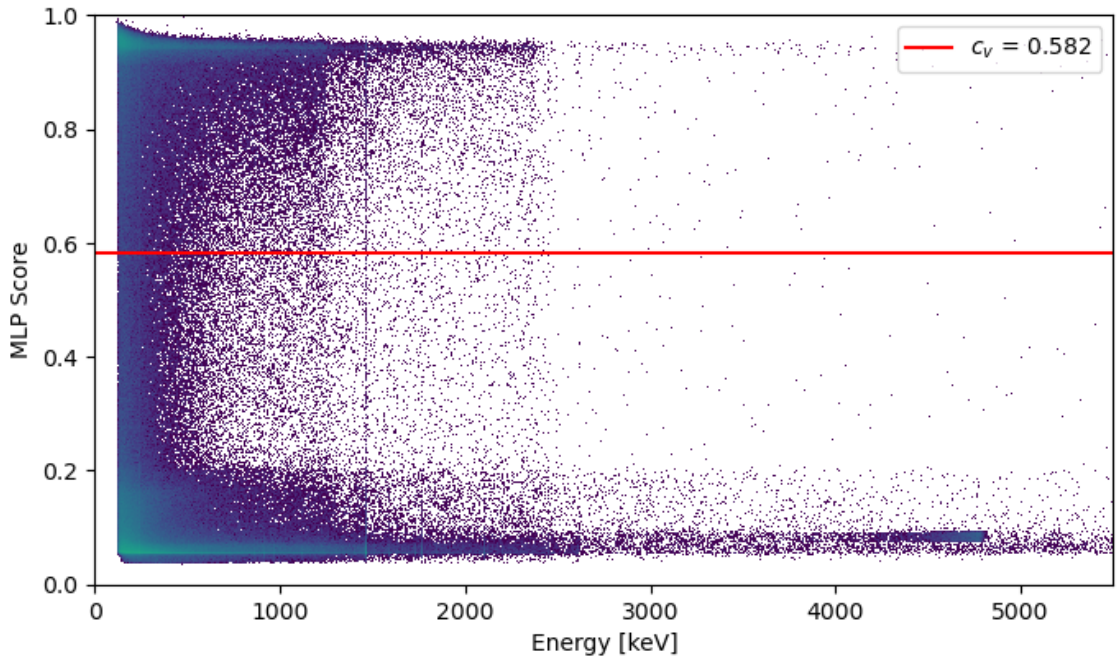
Configuration	SSE	MSE
TC1	^{208}Tl DEP	^{208}Tl SEP
TC2	^{208}Tl DEP	^{212}Bi FEP
TC3	^{208}Tl DEP	^{208}Tl MCS
TC4	^{208}Tl CE	^{208}Tl SEP
TC5	^{208}Tl CE	^{212}Bi FEP
TC6	^{208}Tl CE	^{208}Tl MCS

CUTS APPLIED TO PHYSICS RUN FOR MLP

High Statistics



Low Statistics

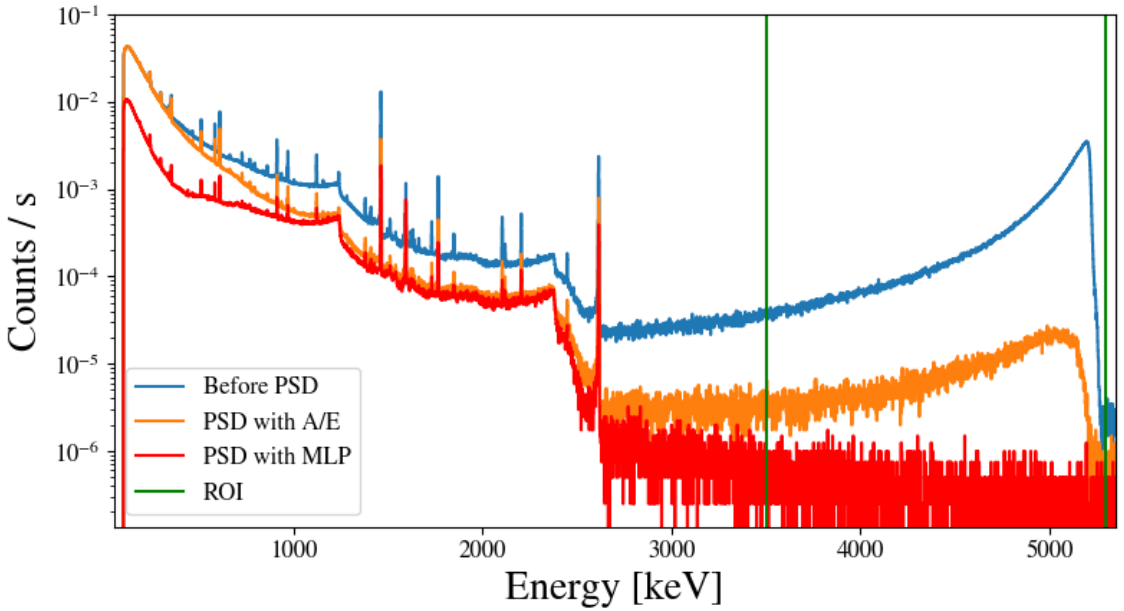


$$\mathrm{FoM}'(x) = \frac{S(x)}{\sqrt{S(x)+B(x)}}$$

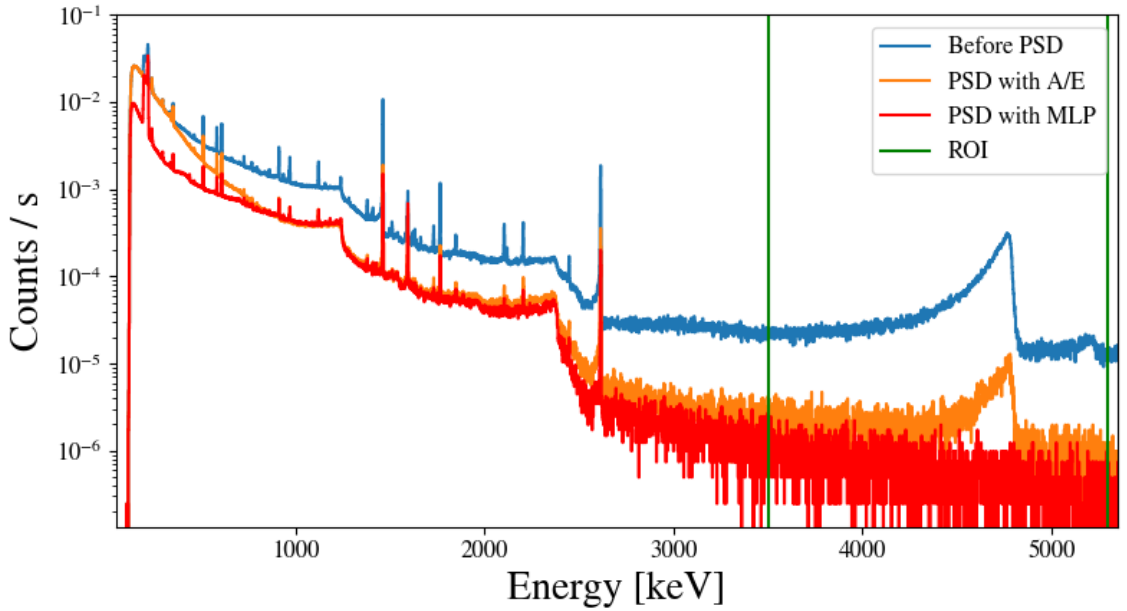
$$\mathrm{FoM}(x) = \frac{\varepsilon_{DEP}(x)}{\sqrt{\varepsilon_{DEP}(x) + \frac{B_{0SEP}}{S_{0DEP}}\varepsilon_{SEP}(x) + \frac{B_{0FEP}}{S_{0DEP}}\varepsilon_{FEP}(x)}}$$

SPECTRA AFTER PSD FOR MLP AND A/E

High Statistics



Low Statistics



STATISTICAL ANALYSIS

	Physics Run	Background Run
Time [s]	4 042 561	7 225 813
Counts before PSD	$1.89\times10^{6}\pm 1376$	$3.9\times10^{4}\pm 197$
Counts before PSD normalized	$1.89\times10^{6}\pm 1376$	$2.18\times10^{4}\pm 110$
Counts after PSD	1846 ± 43	3370 ± 58
Counts after PSD normalized	1846 ± 43	1885 ± 32
Background-subtracted quantities:		
Counts before PSD	$1.87\times10^{6}\pm 1381$	
Counts after PSD	-39 ± 54	
Counts after PSD 90% C.L.	< 69	
Alpha Rejection Factor (90% C.L.)	$> 2.71\times10^{4}$	

BEST RESULTS

Energy [keV]	Isotope	Survival Fraction [%]						
		TC1	TC2	TC3	TC4	TC5	TC6	A/E
727.3	^{212}Bi	19.9 ± 0.2	20.0 ± 0.2	21.3 ± 0.2	40.0 ± 0.5	30.2 ± 0.3	46.3 ± 0.5	40.5 ± 0.4
763.0	^{208}Tl	20.2 ± 0.7	20.4 ± 0.7	21.5 ± 0.7	37.1 ± 0.8	28.8 ± 0.7	48.3 ± 0.9	40.2 ± 0.8
785.0	^{212}Bi	19.5 ± 0.4	19.8 ± 0.4	21.1 ± 0.4	37.2 ± 0.5	28.4 ± 0.4	47.1 ± 0.6	38.8 ± 0.5
860.6	^{208}Tl	18.2 ± 0.2	19.1 ± 0.2	19.9 ± 0.2	36.9 ± 0.3	31.0 ± 0.3	46.0 ± 0.4	37.1 ± 0.3
1078	^{212}Bi	18 ± 1	18 ± 1	18 ± 1	34 ± 1	31 ± 1	44 ± 1	34 ± 1
1093	^{208}Tl	14 ± 3	15 ± 3	15 ± 3	39 ± 4	26 ± 3	39 ± 4	27 ± 3
1512	^{212}Bi	17 ± 2	16 ± 2	18 ± 2	29 ± 3	30 ± 2	41 ± 3	32 ± 2
1592	**^{208}Tl (DEP)**	**83.3 ± 0.8**	**84.0 ± 0.8**	**79.8 ± 0.8**	**84.0 ± 0.8**	**84.1 ± 0.8**	**87 ± 1**	**73.6 ± 0.7**
1620.5	^{212}Bi	17.3 ± 0.8	17.2 ± 0.6	18.5 ± 0.6	28.1 ± 0.9	30.6 ± 0.9	45 ± 1	33.0 ± 0.8
2103	^{208}Tl (SEP)	10.1 ± 0.3	11.8 ± 0.3	13.2 ± 0.3	14.7 ± 0.4	29.0 ± 0.6	44.8 ± 0.8	24.8 ± 0.5
2614.5	^{208}Tl	16.2 ± 0.2	17.4 ± 0.2	19.1 ± 0.3	28.5 ± 0.4	37.6 ± 0.5	48.6 ± 0.7	35.0 ± 0.4
Cut value		**0.818**	**0.797**	**0.859**	**0.522**	**0.459**	**0.674**	**6.31**
α rejection factor		**$> 2.62 \times 10^4$**	**$> 2.71 \times 10^4$**	**$> 2.74 \times 10^4$**	**84**	**96**	**2.89×10^2**	**54**

OUTLOOKS

- Cosmic rays are the main source of background in the analysis region
- Results limited by statistics
- New measure campaign underground in Książ Underground Laboratory or in Laboratori Nazionali del Gran Sasso
- Stronger alpha source in production
- Inverted Coaxial detector in production
- New PSD methods under developing
- Application of PSD procedures to LEGEND data

CONCLUSIONS

- Rejection of alpha events by PSD has been studied
- High-activity alpha source placed on the p+ contact of BEGe-like detector
- Best general result obtained with MLP TC2 : Alpha rejection factor > 2.71×10^4
- Survival Fraction of DEP > 80 %
- Survival Fractions of MSE peaks < 20 %
- **Possible to reject gamma and alpha background with a single PSD cut!**

Pulse shape discrimination for α event rejection in BEGe-type high-purity germanium detectors

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Received: date / Accepted: date

Abstract High-purity germanium detectors are widely used in rare-event searches due to their excellent energy resolution and extremely high intrinsic (radio)purity. In experiments searching for neutrinoless double beta decay in ^{76}Ge such as LEGEND, pulse shape discrimination is required to suppress multi-site γ events. In this work, we investigate whether pulse shape discrimination classifiers trained exclusively on γ ray data can be used to identify and reject

1 Introduction

High-purity germanium (HPGe) detectors have been successfully applied in γ-spectrometry due to their excellent energy resolution and high detection efficiency. In addition, they are also deployed in searches for rare events, such as dark matter particles interactions or neutrinoless double beta ($0\nu\beta\beta$) decay. The latter can theoretically occur in several

ArXiv: 2605.13498

NARODOWE CENTRUM NAUKI

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Ministerstwo Nauki i Szkolnictwa Wyższego

THANK YOU FOR YOUR ATTENTION!

BACKUP

RESULTS HS PLK

Energy [keV]	Isotope	Survival Fraction [%]						
		TC1	TC2	TC3	TC4	TC5	TC6	A/E
727.3	^{212}Bi	22.7 ± 0.2	36.7 ± 0.4	40.6 ± 0.4	25.5 ± 0.3	47.0 ± 0.5	60.5 ± 0.7	40.5 ± 0.4
763.0	^{208}Tl	24.7 ± 0.6	38.1 ± 0.8	41.1 ± 0.8	27.0 ± 0.7	48.3 ± 0.8	60.9 ± 1.0	40.2 ± 0.8
785.0	^{212}Bi	24.9 ± 0.4	37.7 ± 0.6	40.1 ± 0.6	26.2 ± 0.4	48.7 ± 0.6	60.7 ± 0.8	38.8 ± 0.5
860.6	^{208}Tl	24.2 ± 0.2	39.1 ± 0.3	40.0 ± 0.4	27.3 ± 0.2	51.4 ± 0.4	60.6 ± 0.5	37.1 ± 0.3
1078	^{212}Bi	25.7 ± 1.1	39.9 ± 1.4	39.7 ± 1.3	30.2 ± 1.3	53.9 ± 1.6	59.7 ± 1.6	33.6 ± 1.4
1093	^{208}Tl	24.6 ± 3.1	35.0 ± 3.5	34.2 ± 3.6	29.4 ± 3.4	46.7 ± 4.1	54.0 ± 4.4	27.3 ± 3.3
1512	^{212}Bi	26.9 ± 2.7	40.4 ± 2.8	39.5 ± 2.7	33.4 ± 3.1	54.7 ± 2.9	57.3 ± 3.2	31.9 ± 2.4
1592	**^{208}Tl (DEP)**	$\mathbf{81.6 \pm 0.8}$	$\mathbf{80.1 \pm 0.8}$	$\mathbf{78.2 \pm 0.8}$	$\mathbf{79.5 \pm 0.8}$	$\mathbf{88.5 \pm 0.9}$	$\mathbf{88.3 \pm 0.9}$	$\mathbf{73.6 \pm 0.7}$
1620.5	^{212}Bi	26.9 ± 0.8	41.3 ± 0.9	40.0 ± 1.0	34.6 ± 0.8	56.6 ± 1.1	59.2 ± 1.1	33.0 ± 0.8
2103	^{208}Tl (SEP)	18.2 ± 0.4	37.3 ± 0.6	34.7 ± 0.6	30.2 ± 0.5	54.7 ± 0.9	55.8 ± 0.9	24.8 ± 0.5
2614.5	^{208}Tl	25.4 ± 0.3	43.2 ± 0.6	41.2 ± 0.5	40.6 ± 0.5	59.6 ± 0.7	61.4 ± 0.8	35.0 ± 0.4
Cut value		**0.821**	**0.931**	**0.875**	**0.778**	**0.370**	**0.690**	**6.31**
α rejection factor		$\mathbf{> 1.88 \times 10^4}$	$\mathbf{> 1.51 \times 10^4}$	$\mathbf{> 1.65 \times 10^4}$	$\mathbf{2.4 \times 10^2}$	**67**	$\mathbf{> 1.32 \times 10^4}$	**54**

RESULTS LS MLP

Energy [keV]	Isotope	Survival Fraction [%]						
		TC1	TC2	TC3	TC4	TC5	TC6	A/E
727.3	^{212}Bi	21.6 ± 0.4	21.7 ± 0.4	21.6 ± 0.4	53.6 ± 0.9	40.8 ± 0.7	26.7 ± 0.4	33.2 ± 0.6
763.0	^{208}Tl	20.4 ± 1.6	21.3 ± 1.4	21.4 ± 1.4	49.7 ± 2.4	39.6 ± 1.9	28.2 ± 1.5	31.6 ± 1.7
785.0	^{212}Bi	20.1 ± 1.1	21.0 ± 1.0	20.6 ± 1.0	49.6 ± 1.5	41.2 ± 1.4	28.2 ± 1.1	28.8 ± 1.1
860.6	^{208}Tl	19.9 ± 0.4	20.3 ± 0.4	19.9 ± 0.4	50.0 ± 1.0	41.3 ± 0.8	27.1 ± 0.5	26.0 ± 0.5
1078	^{212}Bi	18.4 ± 2.7	18.5 ± 2.5	17.6 ± 2.4	43.4 ± 3.6	39.4 ± 3.1	24.1 ± 2.5	21.6 ± 2.5
1093	^{208}Tl	< 5	10.8 ± 6.6	8.8 ± 5.3	55.9 ± 7.3	33.2 ± 5.9	14.0 ± 5.0	7.0 ± 5.5
1512	^{212}Bi	16.0 ± 4.5	17.1 ± 4.5	16.7 ± 4.5	39.3 ± 6.4	42.4 ± 7.0	26.0 ± 5.5	25.0 ± 4.6
1592	**^{208}Tl (DEP)**	$\mathbf{92.3 \pm 1.3}$	$\mathbf{92.8 \pm 1.3}$	$\mathbf{92.1 \pm 1.3}$	$\mathbf{94.0 \pm 1.3}$	$\mathbf{86.2 \pm 1.3}$	$\mathbf{94.2 \pm 1.3}$	$\mathbf{85.2 \pm 1.2}$
1620.5	^{212}Bi	15.7 ± 1.2	15.4 ± 1.2	15.2 ± 1.2	33.4 ± 1.9	40.0 ± 2.0	22.8 ± 1.4	22.0 ± 1.5
2103	^{208}Tl (SEP)	9.1 ± 0.7	9.9 ± 0.7	9.3 ± 0.7	17.4 ± 1.0	36.7 ± 1.3	16.3 ± 0.8	15.5 ± 0.7
2614.5	^{208}Tl	13.6 ± 0.3	14.0 ± 0.3	13.1 ± 0.3	34.3 ± 0.8	58.3 ± 1.4	23.2 ± 0.5	24.3 ± 0.5
Cut value		**0.664**	**0.572**	**0.582**	**0.602**	**0.346**	**0.541**	**2.45**
α rejection factor		$> \mathbf{7.5 \times 10^2}$	$> \mathbf{1.0 \times 10^3}$	$> \mathbf{1.1 \times 10^3}$	**11**	**3**	$> \mathbf{7.5 \times 10^2}$	**30**

RESULTS LS PLK

Energy [keV]	Isotope	Survival Fraction [%]						
		TC1	TC2	TC3	TC4	TC5	TC6	A/E
727.3	^{212}Bi	18.7 ± 0.3	10.4 ± 0.2	10.6 ± 0.2	15.4 ± 0.3	9.1 ± 0.2	18.2 ± 0.3	33.2 ± 0.6
763.0	^{208}Tl	17 ± 2	12 ± 1	12 ± 1	16 ± 1	10.2 ± 0.9	20 ± 1	31.6 ± 1.7
785.0	^{212}Bi	17 ± 1	11.3 ± 0.6	11.7 ± 0.7	15.1 ± 0.9	11.2 ± 0.6	20.1 ± 0.9	28.8 ± 1.1
860.6	^{208}Tl	17.1 ± 0.3	14.1 ± 0.3	13.0 ± 0.3	17.1 ± 0.4	14.1 ± 0.3	21.1 ± 0.4	26.0 ± 0.5
1078	^{212}Bi	20 ± 3	20 ± 2	19 ± 2	22 ± 3	22 ± 2	25 ± 3	21.6 ± 2.5
1093	^{208}Tl	5 ± 5	4 ± 4	< 5	8 ± 5	10 ± 3	14 ± 5	7.0 ± 5.5
1512	^{212}Bi	23 ± 5	28 ± 5	26 ± 5	30 ± 5	33 ± 5	33 ± 6	25.0 ± 4.6
1592	**^{208}Tl (DEP)**	$\mathbf{90.9 \pm 1.3}$	$\mathbf{91.9 \pm 1.3}$	$\mathbf{90.5 \pm 1.3}$	$\mathbf{86.3 \pm 1.2}$	$\mathbf{86.7 \pm 1.2}$	$\mathbf{91.9 \pm 1.3}$	$\mathbf{85.2 \pm 1.2}$
1620.5	^{212}Bi	23.3 ± 1.4	27.5 ± 1.5	23.3 ± 1.4	28.7 ± 1.7	35 ± 2	33 ± 2	22.0 ± 1.5
2103	^{208}Tl (SEP)	15.9 ± 0.7	20.3 ± 0.9	16.5 ± 0.8	21.2 ± 0.9	29 ± 1	25.7 ± 1.0	15.5 ± 0.7
2614.5	^{208}Tl	24.4 ± 0.5	29.9 ± 0.6	24.9 ± 0.5	32.6 ± 0.7	41.8 ± 0.9	37.0 ± 0.8	24.3 ± 0.5
Cut value		**0.853**	**0.638**	**0.885**	**0.681**	**0.595**	**0.735**	**2.45**
α rejection factor		$\mathbf{> 5.5 \times 10^2}$	$\mathbf{> 7.1 \times 10^2}$	$\mathbf{> 6.4 \times 10^2}$	**8.1**	$\mathbf{> 2.5 \times 10^2}$	$\mathbf{> 6.4 \times 10^2}$	**30**