Simulations and Background Estimation For NνDEx

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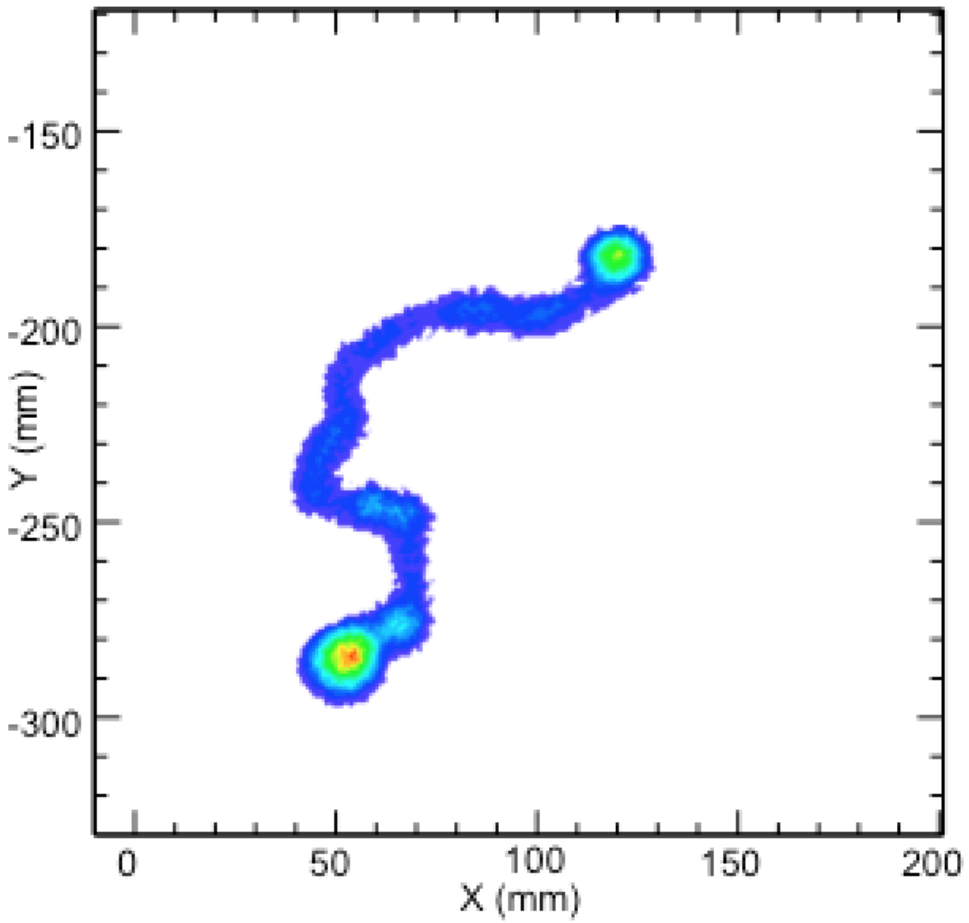
Overview

- Background Estimations
  EC (IMP), Surja Ghorui (IMP), Zeyu Huang (LanDa), Hao Qiu (IMP), Qiangmin Wang (LanDa)
  - γ background
  - Fast Neutron Background
  - Cosmogenic Activation
  - Radon Background
- REST Framework & Neural Network
  Tao Li (SYSU), Shaobo Wang (SJTU), Siyuan Huang (UCAS & IMP)
  - Detector Geometry
  - Ion Drifting
  - Electronics Response
  - Convolutional Neural Network (CNN)

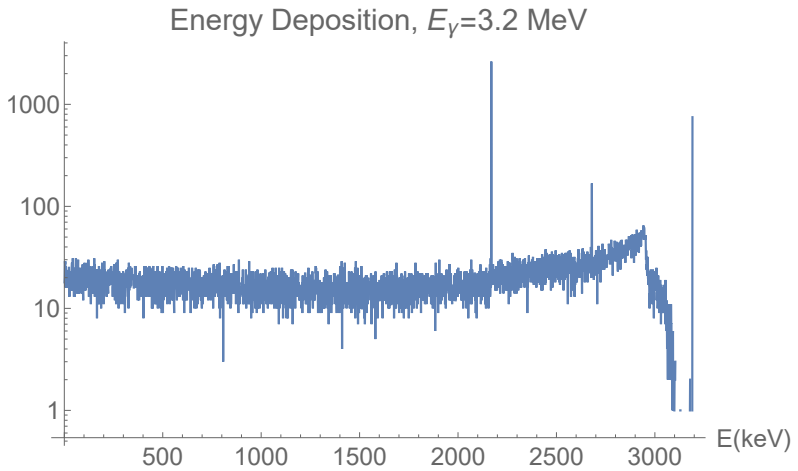
Signal

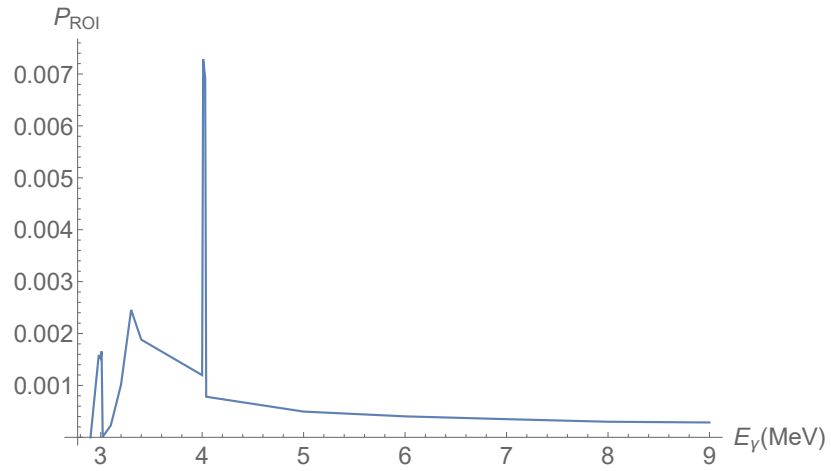
- **$0\nu2\beta$ events**: 2 β tracks, with 2 Bragg peaks at the end



Background

- α: track very different from β, no background
- β: Only 1 Bragg peaks, can be rejected using topology (suppression factor in NEXT ~ 0.1)
- γ: cannot deposit energy in the detector directly, but they can transfer energy to e^- via three processes
  - **Compton Scattering**: continuous spectrum
  - **Photoelectric effect**: $E_\beta = E_\gamma$
  - **Pair production**: e^--e^+ pair created, $E_{pair} = E_\gamma - 2m_e$.

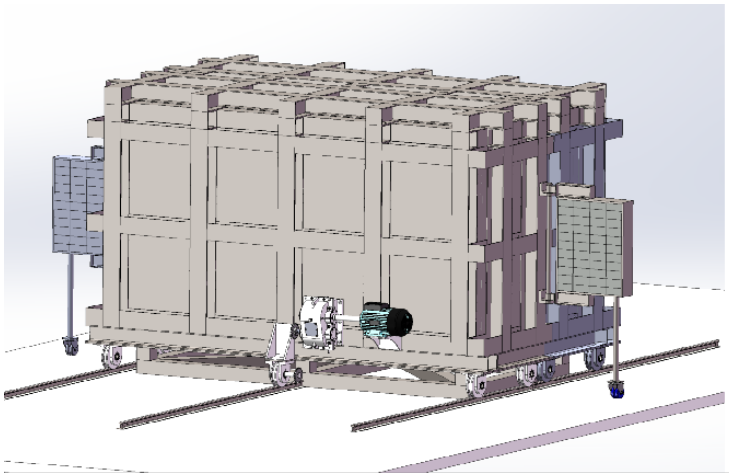


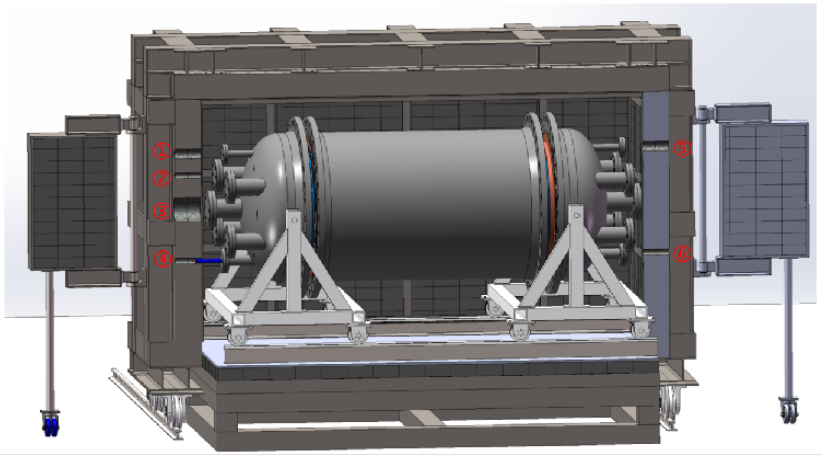


Sources Of Background

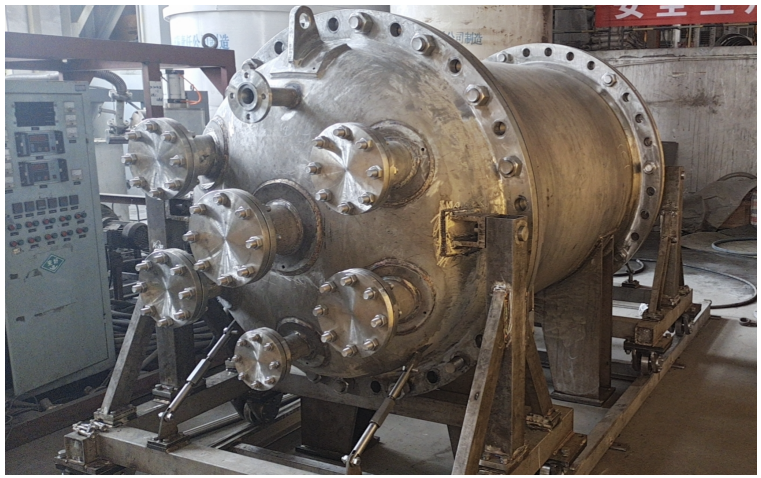
- Natural radioactivity $\Rightarrow$ in principle α's, β's and γ's, but the first two are easily shielded, only the latter is relevant
- Fast neutron background
- Cosmogenic activation of the material of the detector $\Rightarrow$ activation rate is negligible underground, but it is a problem on the surface
- Radon background
- Also: pile-up background, cosmogenic muons background (negligible at CJPL, due to the rock overburden), etc...

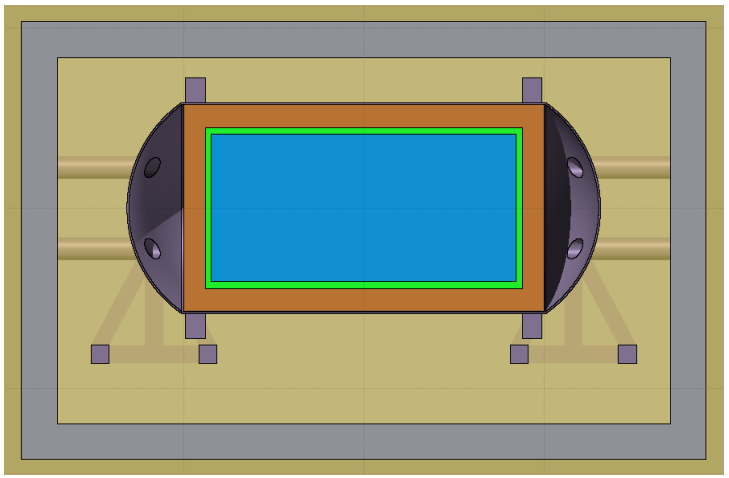
Detector





20 cm thick lead shielding to stop the γ rays

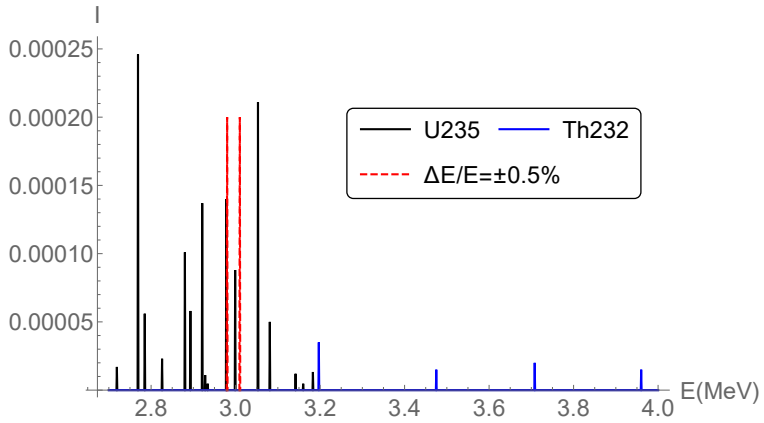


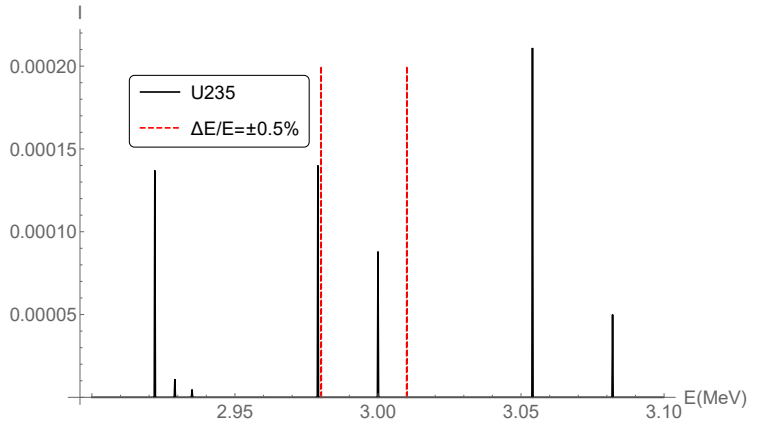


HDPE placed inside and outside the LS to stop neutrons

γ Bakground

- Only ^{214}Bi (from ^{238}U decay chain) and ^{208}Tl (^{232}Th) will create high energy γ's
- Dominant contribution from ^{214}Bi, ^{208}Tl is negligible
- Contamination of detector materials taken from NEXT-TDR





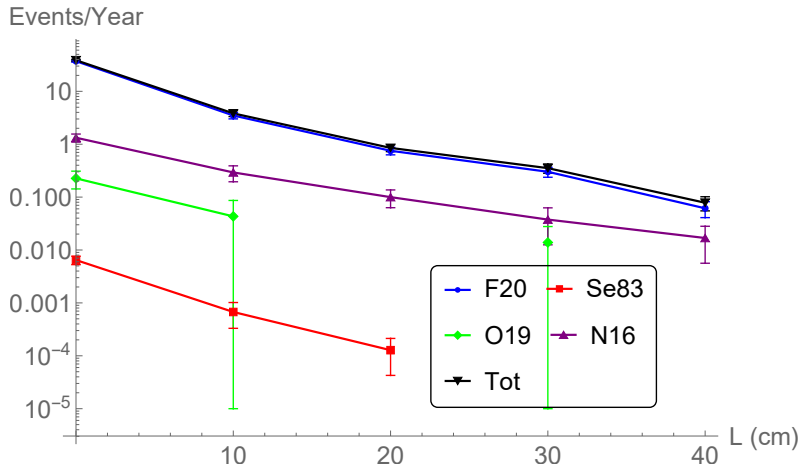
Source	Evts/yr	Source	Evts/yr	Source	Evts/yr
Walls	0.004	Lead	0.003	HDPE	0.005
SSV	0.026	ICS	0.050	POM	0.330

In total, **0.42 evts/yr (1.4$\times 10^{-4}$ evts/(keV·kg·yr)** without topological cuts, main contribution from Field Cage (not shielded) $\rightarrow$ cannot be reduced by additional shielding

Neutron Induced β's

If unstable isotopes are created **in the gas**, their decay can provide background. 4 dangerous isotopes

$$^{19}F + n \rightarrow ^{20}F$$
$$^{19}F + n \rightarrow ^{19}O + p$$
$$^{19}F + n \rightarrow ^{16}N + \alpha$$
$$^{82}Se + n \rightarrow ^{83}Se$$

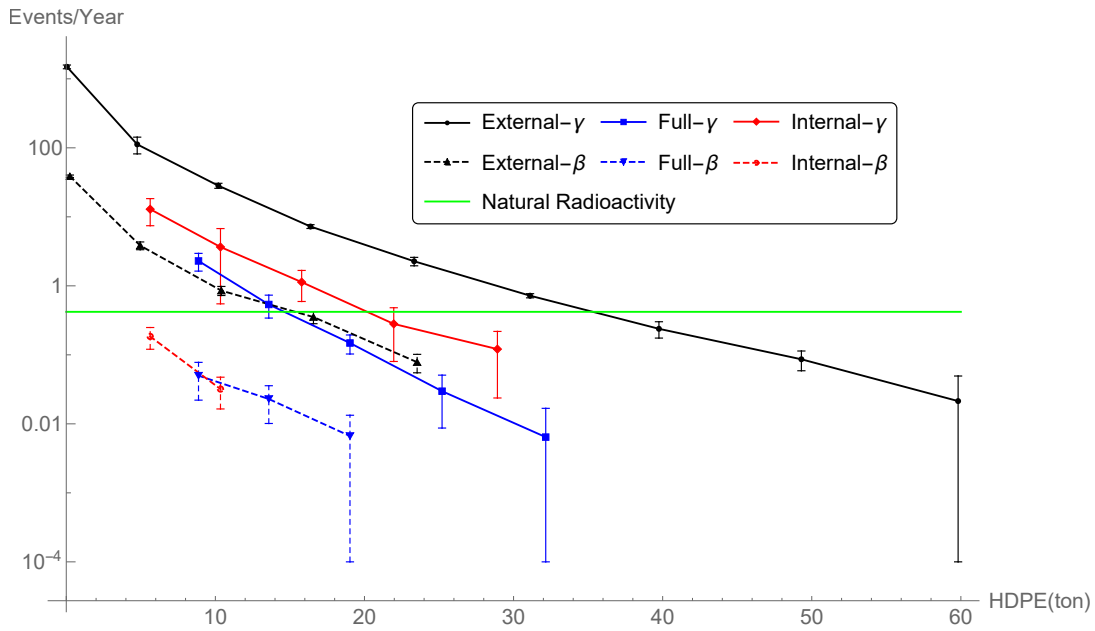


Isotopes	Q-Value	P_{ROI}	Isotopes	Q-Value	P_{ROI}
^{20}F	7.02	9.1×10^{-3}	^{16}N	10.04	6.3×10^{-3}
^{19}O	4.82	4.6×10^{-3}	^{83}Se	3.67	2.4×10^{-5}

P_{ROI}: probability for a β to have energy within ROI.
^{20}F$\rightarrow$ main contribution
^{19}O and ^{16}N $\rightarrow$ suppressed due to energy threshold, $E_n > 3.5, 0.5$
^{83}Se $\rightarrow$ P_{ROI} is very low, 2.4×10^{-5}

Neutron Induced γ's

If neutrons are absorbed (**anywhere in the detector**) γ's are created via (n,γ) or (n,n'γ) reactions (energy up to 10 MeV) $\rightarrow$ dominant contribution

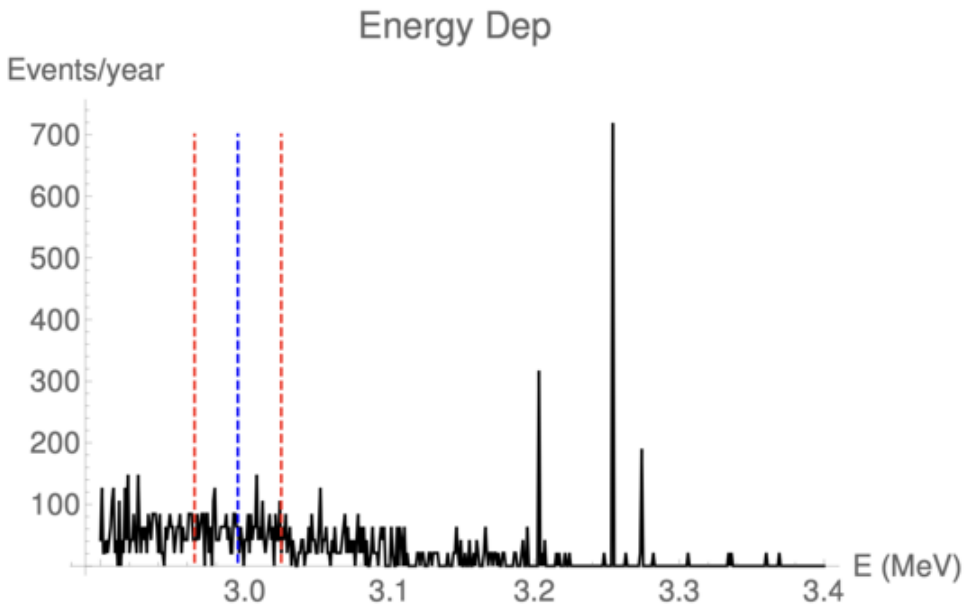


HDPE filler between SSV and Lead + 30 cm-thick external HDPE shield: neutron background down to 0.03 evs/yr.

Cosmogenic Activation

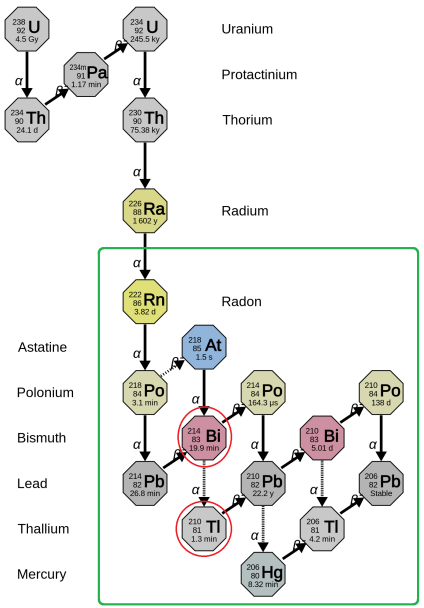
- Cosmic rays can activate nuclei in the material of the detector on surface
- ^{56}Co is the most dangerous isotope, after exposure in Lanzhou, estimated background $\sim$ 3400 events/year.
- 3 yrs cooldown $\rightarrow$ 0.18 evts/yr;
  2 yrs cooldown $\rightarrow$ 4.8 evts/yr;
  1 yrs cooldown $\rightarrow$ 127 evts/yr

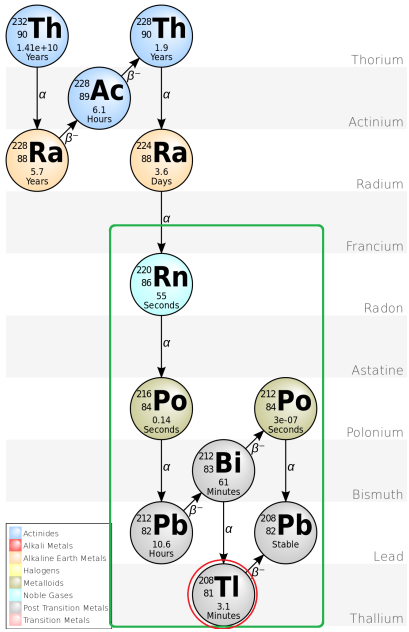
isotope	Q (MeV)	$T_{1/2}$
^{54}Mn	1.4	312d
^{56}Co	4.6	77d
^{57}Co	0.8	272d
^{58}Co	2.3	71d
^{60}Co	2.8	5.3yr



Radon Background

Radon is a gas part of the ^{238}U and ^{232}Th decay chains.
It can diffuse and reach directly the fiducial volume: possible issues from β and γ





Decay	Type	BR	E_β
^{208}Tl	γ	0.36	1.8
^{210}Tl	β	$\sim 10^{-4}$	4.4
^{214}Bi	β	$\sim$1	3.3
^{214}Po	α	1.0	7.8
^{214}Bi	γ	$\sim$1	3.3

- β from ^{214}Bi can be vetoed using α from ^{214}Po (space and time coincidence)
- Maybe γ from ^{214}Bi as well? (only time coincidence)
- **Problem**: ions produced in the decay chain will be charged: they could drift (not taken into account so far)

Radon Background

For 1 Bq activity

- ^{214}Bi (from ^{238}U), β: large bg rate, but automatically vetoed via α: $2720 \pm 30 \mathrm{evts/yr}$
- ^{214}Bi (from ^{238}U), γ: lower than β, but it can happen far away from α: $8.9 \pm 0.2 \mathrm{evts/yr}$
- ^{210}Tl (from ^{238}U): suppressed by BR, but not negligible $12.21 \pm 0.02 \mathrm{evts/yr}$
- ^{208}Tl (from ^{232}Th): some contribution from γ's from here, but subdominant: $1.0 \pm 0.03 \mathrm{evts/yr}$

Rn activity from PANDA-X: $\sim$18 mBq

If only ^{210}Tl relevant: 16.4 mBq Rn activity to have 0.2 evts/yr

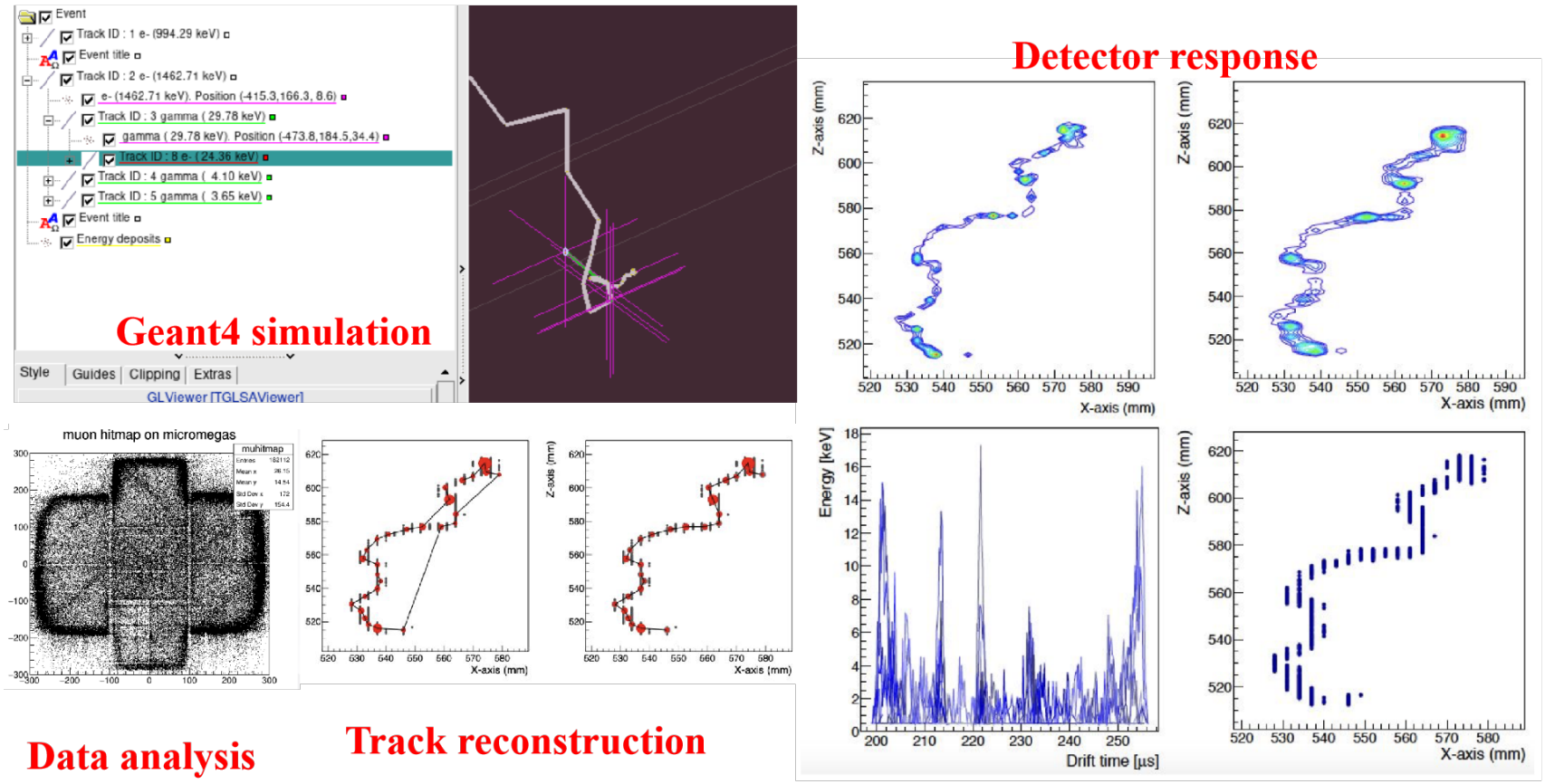
If only ^{214}Bi-γ relevant: 22.5 mBq Rn activity to have 0.2 evts/yr

If both are relevant: 9.5 mBq Rn activity to have 0.2 evts/yr

Material surface in the pressure chamber clean and smooth $\Rightarrow$ lower Rn activity

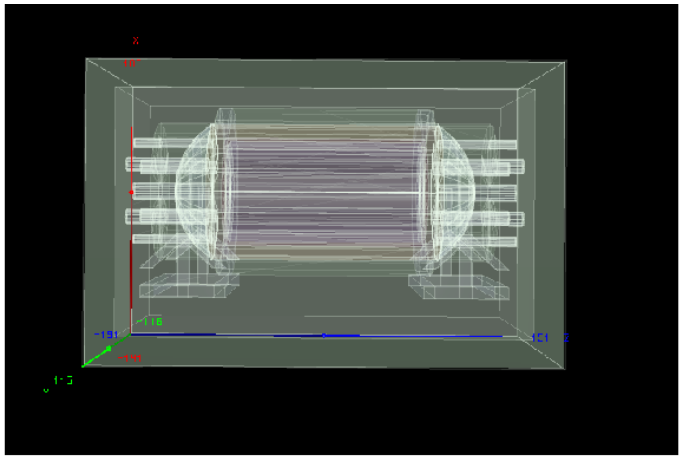
REST Framework

REST is an event-based analysis framework unifying analysis and simulation.

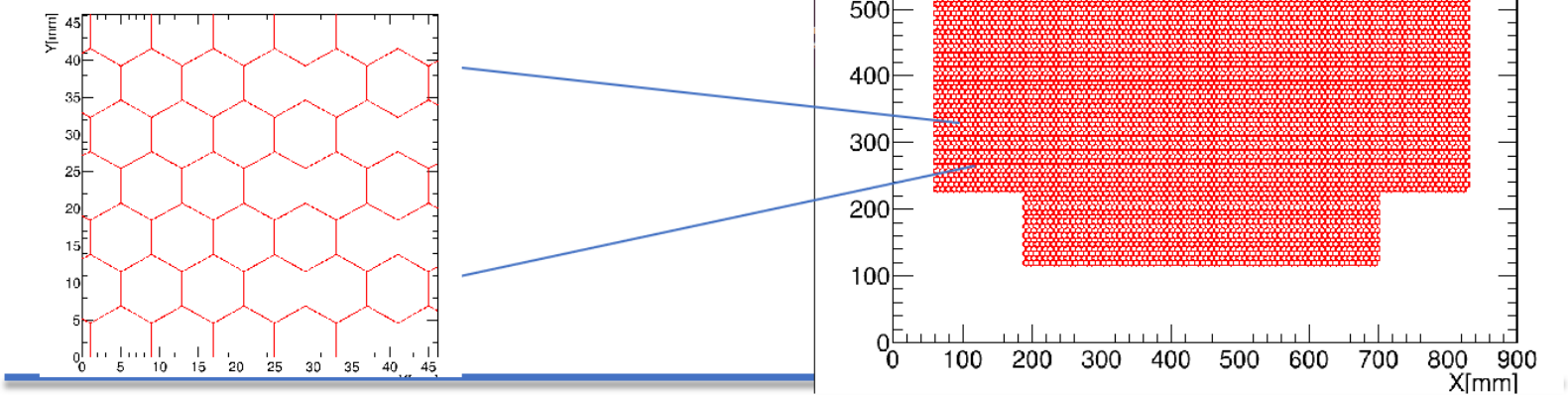


Detector Geometry

Detector Geometry: Preliminary construction of the geometric structure is complete. This includes gas, copper shielding, high-density polyethylene (HDPE) shielding, and lead shielding shielding.



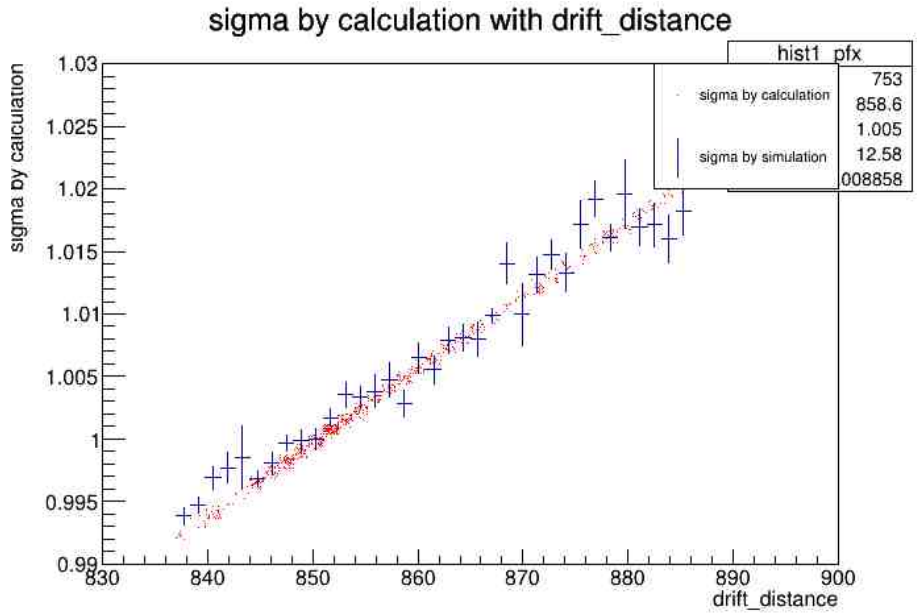
Read out Plane: Adjacent pixels have a spacing of 8mm, with a total of 8192 pixels. The readout is performed on a pixel-by-pixel basis.



Ion Diffusion

The simulation of the ion diffusion has been completed.
The diffusion is related to the drift length:

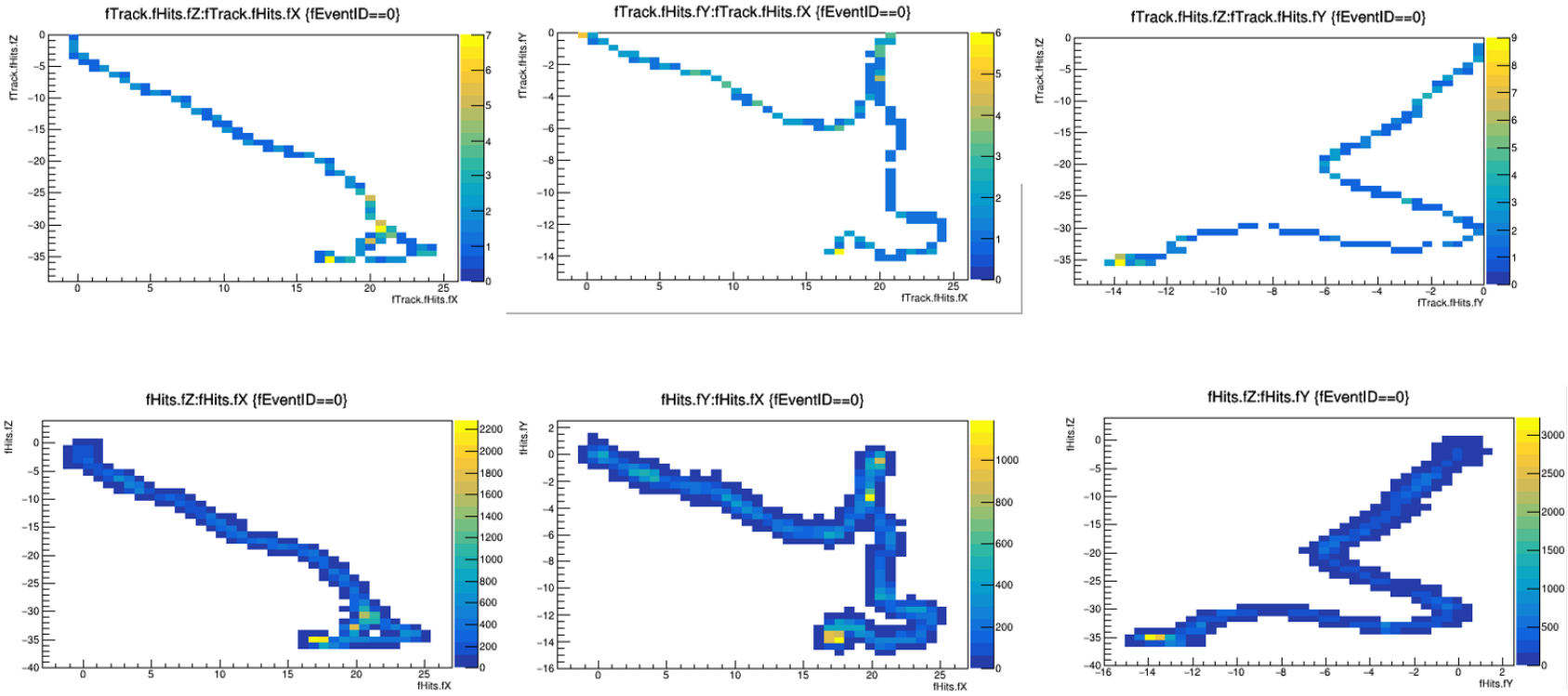
$$D_z(SeF_5^-) = \frac{\mu_0(SeF_5^-)kT}{e(P/1atm)} \qquad \sigma_z(SeF_5^-) = \sqrt{\frac{2D_z(SeF_5^-)L}{v_d}}$$



Red points: σ_z computed using the above formula; blue points with error bar: simulated data

Ion Diffusion

Upper panels: tracks without added ion diffusion, lower panels: tracks with added ion diffusion.

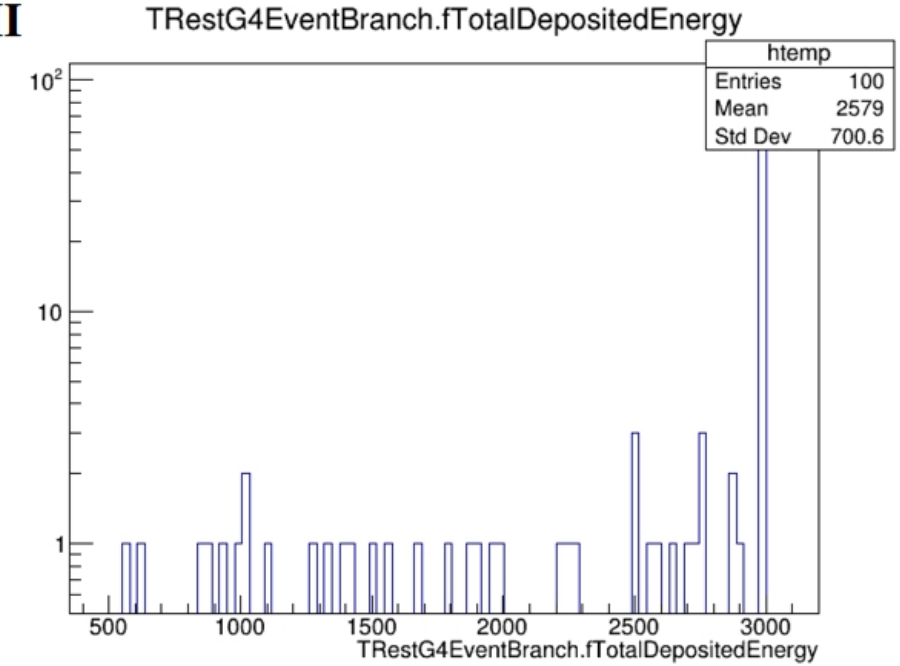


➢ Signal simulation with restG4

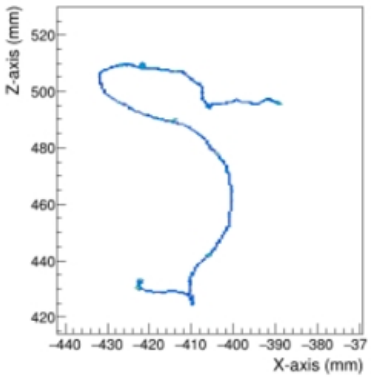
Geometry: modified from PandaX-III

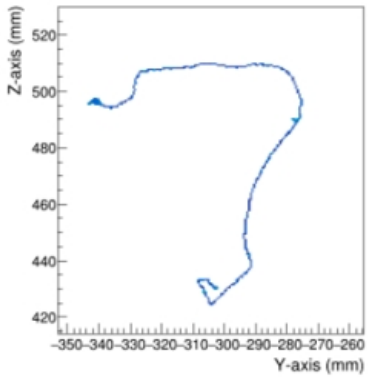
The geometry of NvDEx detector is under development

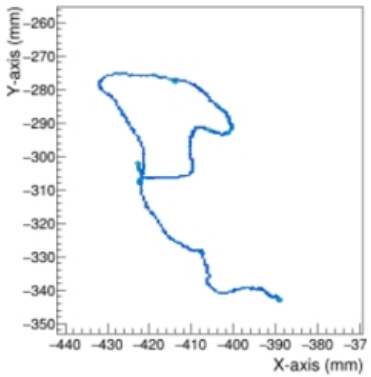
Note: in PandaX-III, 3mm sensors; in NvDEx, 8mm sensors




```
Gas name : SeF6
Gas temperature : 293.15
Gas density : 0.078 g/cm3
Generated from volume : Gas
Generator type : volume
```





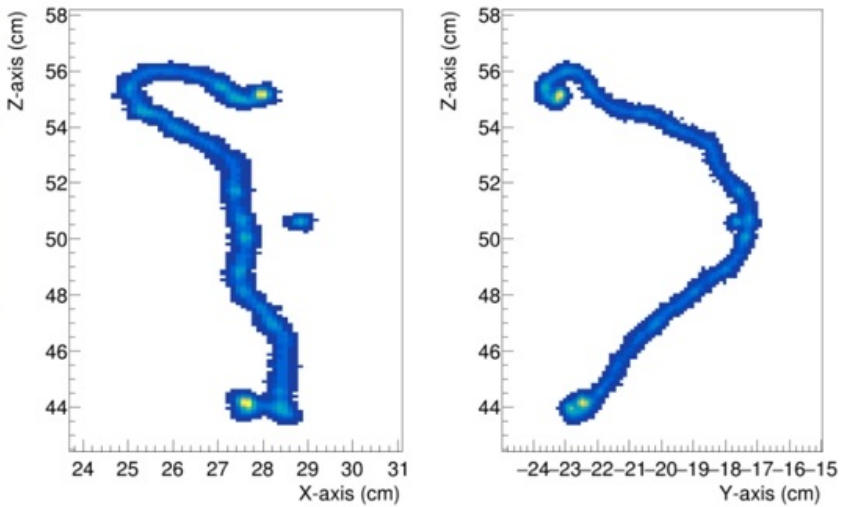


Detector Response

SeF_6 is not included in Garfield, gas parameters are directly set in REST

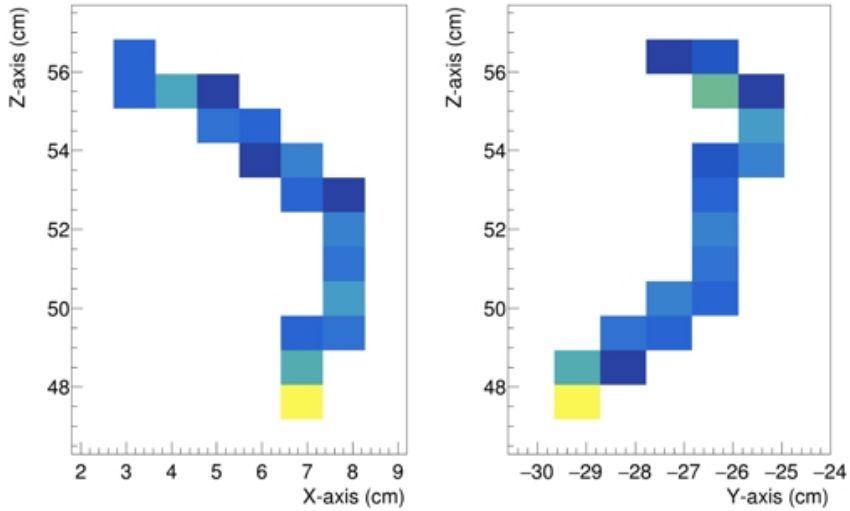
```
Process : TRestG4toHitsProcess
Name: G4ToHits  Title: defaultTitle  VerboseLevel: info

Process : TRestHitsShuffleProcess
Name: HitsShuffle  Title: defaultTitle  VerboseLevel: info

Iterations : 1000

Process : TRestElectronDiffusionProcess
Name: eDiff_1kVcm_1atm  Title: defaultTitle  VerboseLevel: info

eField : 437.5 V/cm
attachment coeficient : 0
gas pressure : 10 atm
setting transversal diffusion coefficient : 0 cm^1/2
longitudinal diffusion coefficient : 0.010375 cm^1/2
drift distance 780 mm, the longitudinal sigma : 0.916295 mm
transversal diffusion coefficient : 0.010375 cm^1/2

Process : TRestSmearingProcess
Name: smear_3FWHM  Title: defaultTitle  VerboseLevel: info

reference energy (Eref): 2996
resolution at Eref : 1
```

Parameter	Value
Pressure	10 atm
Temperature	293.15K
Electron Field	437.5 V/cm
Reduced mobility	0.466 cm2/(V·s)
Drift velocity	22.7247 cm/s
Diffusion coefficient	7.2006E-3 $cm^{0.5}$

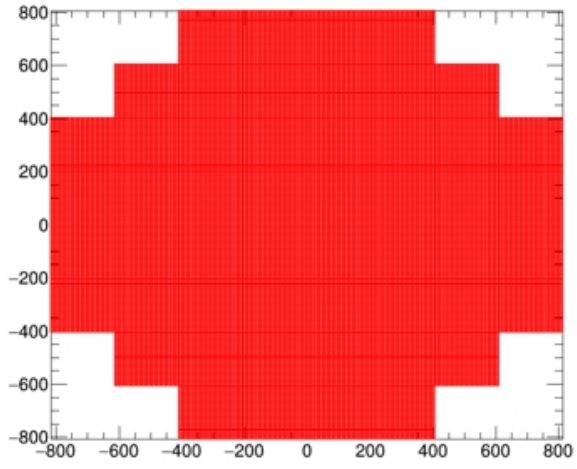


Readout scheme and Electronic Sampling

```
================================================================================
||                  Process : TRestHitsToSignalProcess                        ||
||      Name: hitsToSignal  Title: defaultTitle  VerboseLevel: info           ||
||            ---------------------------------------------                   ||
||                                                                            ||
||                          Sampling : 0.2 us                                 ||
||                     Electric field : 437.5 V/cm                            ||
||                        Gas pressure : 10 atm                               ||
||                    Drift velocity : 0.00227247 mm/us                       ||
||                                                                            ||
================================================================================
||                  Process : TRestSignalToHitsProcess                        ||
||      Name: signalToHits  Title: defaultTitle  VerboseLevel: info           ||
||            ---------------------------------------------                   ||
||                                                                            ||
||                     Electric field : 437.5 V/cm                            ||
||                        Gas pressure : 10 atm                               ||
||                    Drift velocity : 0.00227247 mm/us                       ||
||                      Signal to hits method : all                           ||
||                All Deposited Energy Range : ( 0, 1e+08 )                   ||
||                                                                            ||
================================================================================
```




```
||                          Number of readout planes : 1                      ||
||                           Decoding was defined : NO                        ||
--------------------------------------------------------------------------------
||                              -- Readout plane : 0                          ||
--------------------------------------------------------------------------------
||                  -- Position : X = 0 mm,  Y : 0 mm, Z : 600.5 mm           ||
||                     -- Vector : X = 0 mm,  Y : 0 mm, Z : -1 mm             ||
||            -- Cathode Position : X = 0 mm,  Y : 0 mm, Z : -601 mm          ||
||                    -- Total drift distance : 1201.5 mm                     ||
||                          -- Charge collection : 1                          ||
||                           -- Total modules : 52                            ||
||                         -- Total channels : 32500                          ||
--------------------------------------------------------------------------------
********************************************************************************
```

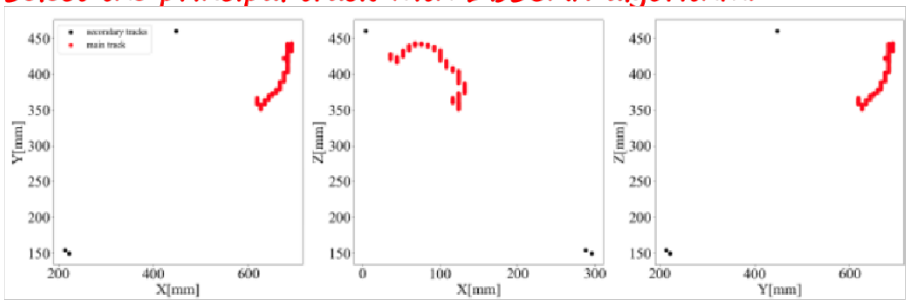


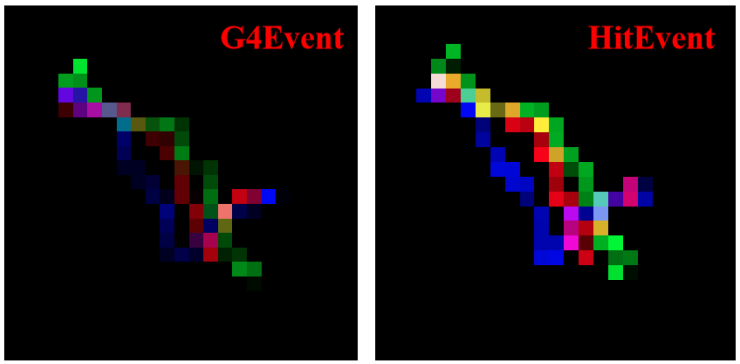
Signal And Background

- Signal: $0\nu2\beta$ decay of ^{82}Se
- Background (example): 3 MeV γ from AcrilicPart in PandaX-III geometry (need to add other backgrounds)
- Energy Cut: E>2.5 MeV

RGB image conversion

Select the principal track with DBSCAN algorithm.

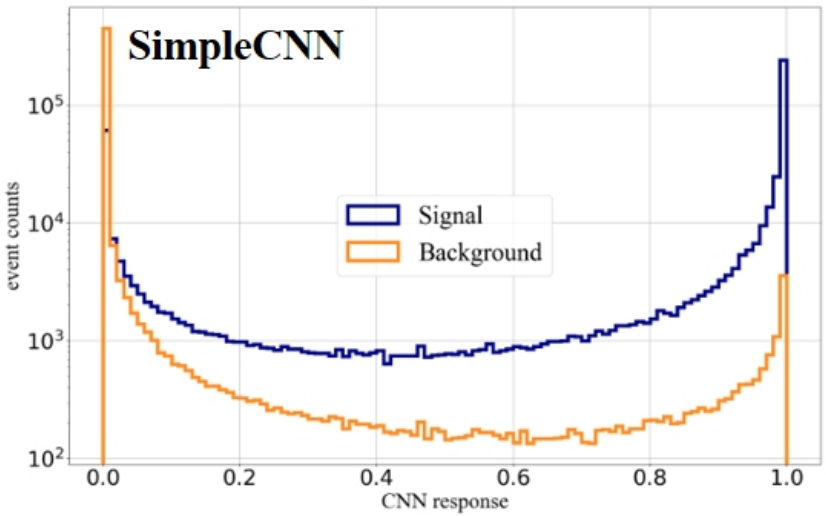


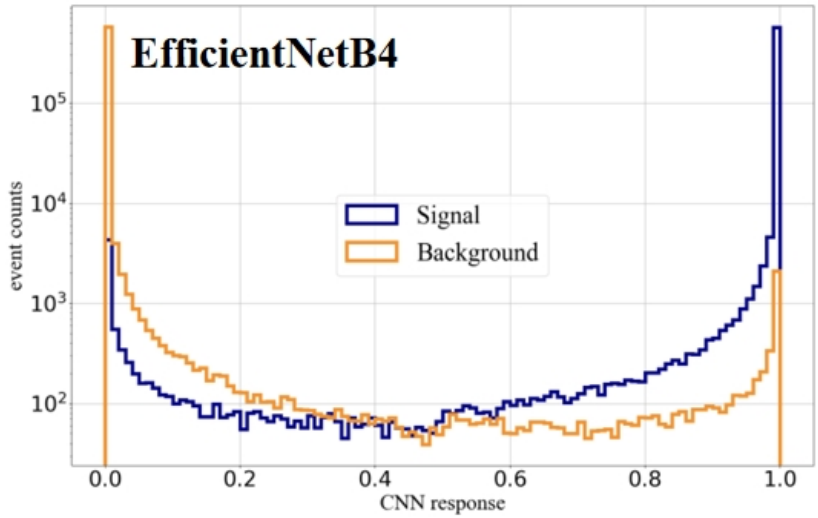


XZ/YZ/XY track in R/G/B channel;

Preliminary Results!

CNN Model	DataSet(train+test)	Cut	Signal	Bg Rej.
SimpleCNN	20k+10k	0.995	42.21%	5.4×10^{-3}
SimpleCNN	600k+100k	0.999	88.83%	4.8×10^{-3}
EfficientNetB0	20k+10k	0.995	52.16%	5.1×10^{-3}
EfficientNetB0	600k+100k	0.999	92.46%	6.9×10^{-3}
EfficientNetB4	**600k+100k**	**0.999**	91.83%	2.3×10^{-3}





Summary

- Using HDPE shield, fast neutron bg is subdominant with respect to γ
- In the short term, the main source of background will be ^{56}Co from cosmogenic activation $\rightarrow$ ICS should be stored underground as soon as possible
- Radon could be an issue, it will depend on the contamination level and other factors, including the drifting, recombination and possibility of vetoing some of the decays.
- Completed the detector geometry in REST framework, working on signal and background simulations
- Topological cuts using CNN should allow us to further reduce the background, with limited loss of signal efficiency

Backup Slides

γ Background: Radioactive Contamination

Values of radioactivity assumed in the simulations for different parts of the geometry (for the materials of the detector, NEXT values were used)

Material	Subsystem	^{238}U Activity (mBq/kg)
Concrete	Experimental hall	6.8×10^3[1]
Lead	External shielding	0.37 [2]
HDPE	External shielding	0.23 [2]
Steel	Pressure vessel	1.9 [2]
Copper	Inner copper shielding	0.012[2]
POM	Field cage	0.23[2]

[1] H. Ma *et al.*, "In-situ gamma-ray background measurements for next generation CDEX experiment in the China Jinping Underground Laboratory.", Astropart. Phys., 128:102560, 2021.
[2] V. Alvarez *et al.*,"NEXT-100 Technical Design Report (TDR): Executive Summary" NEXT-TDR, JINST,6237:T06001, 2012.

^{238}U Decay Chain : Main

Isotope	Type	BR	$T_{1/2}$	Q-Value (MeV)	E_β
^{222}Rn	α	1.0	3.8222 d	5.5904	-
^{218}Po	α	0.9998	3.098 min	6.11468	-
^{214}Pb	β	1.0	26.8 min	1.018	1.018
^{214}Bi	β	0.99979	19.9 min	3.269	3.269
^{214}Po	α	1.0	164.3 μs	7.83346	-
^{210}Pb	β	$\sim$1.0	22.20 yrs	0.0635	0.0635
^{210}Bi	β	$\sim$1.0	5.012 d	1.1622	1.1622
^{210}Po	α	1.0	138.376 d	5.03647	-
^{206}Pb	stable				

^{238}U Decay Chain: Secondary

] Isotope	Type	BR	$T_{1/2}$	Q-Value (MeV)	E_β
^{218}Po	β	2×10^{-4}	3.098 min	0.259913	?
^{218}At	α	2×10^{-4}	1.5 s	6.874	-
^{218}At	β	2×10^{-7}	1.5 s	2.881314	?
^{218}Rd	α	2×10^{-7}	35 ms	7.26254	-
^{214}Bi	α	2.1×10^{-4}	19.9 min	5.62119	-
^{210}Tl	β	2.1×10^{-4}	4.202 min	5.48213	4.386
^{210}Pb	α	1.9×10^{-6}	22.2 yrs	3.7923	-
^{206}Hg	β	1.9×10^{-6}	8.32 min	1.308	1.308
^{210}Bi	α	1.32×10^{-6}	5.012 d	5.03647	-

^{232}Th Decay Chain

Isotope	Type	BR	$T_{1/2}$	Q-Value (MeV)	E_β
^{220}Rn	α	1.0	55.6 s	6.404	-
^{216}Po	α	1.0	0.145 s	6.906	-
^{212}Pb	β	1.0	10.64 h	0.570	0.570
^{212}Bi	β	0.64	60.55 min	2.252	2.252
^{212}Po	α	0.64	299 ns	8.784	-
^{212}Bi	α	0.36	60.55 min	6.208	-
^{208}Tl	β	0.36	3.053 min	5.0	1.803
^{208}Pb	stable				

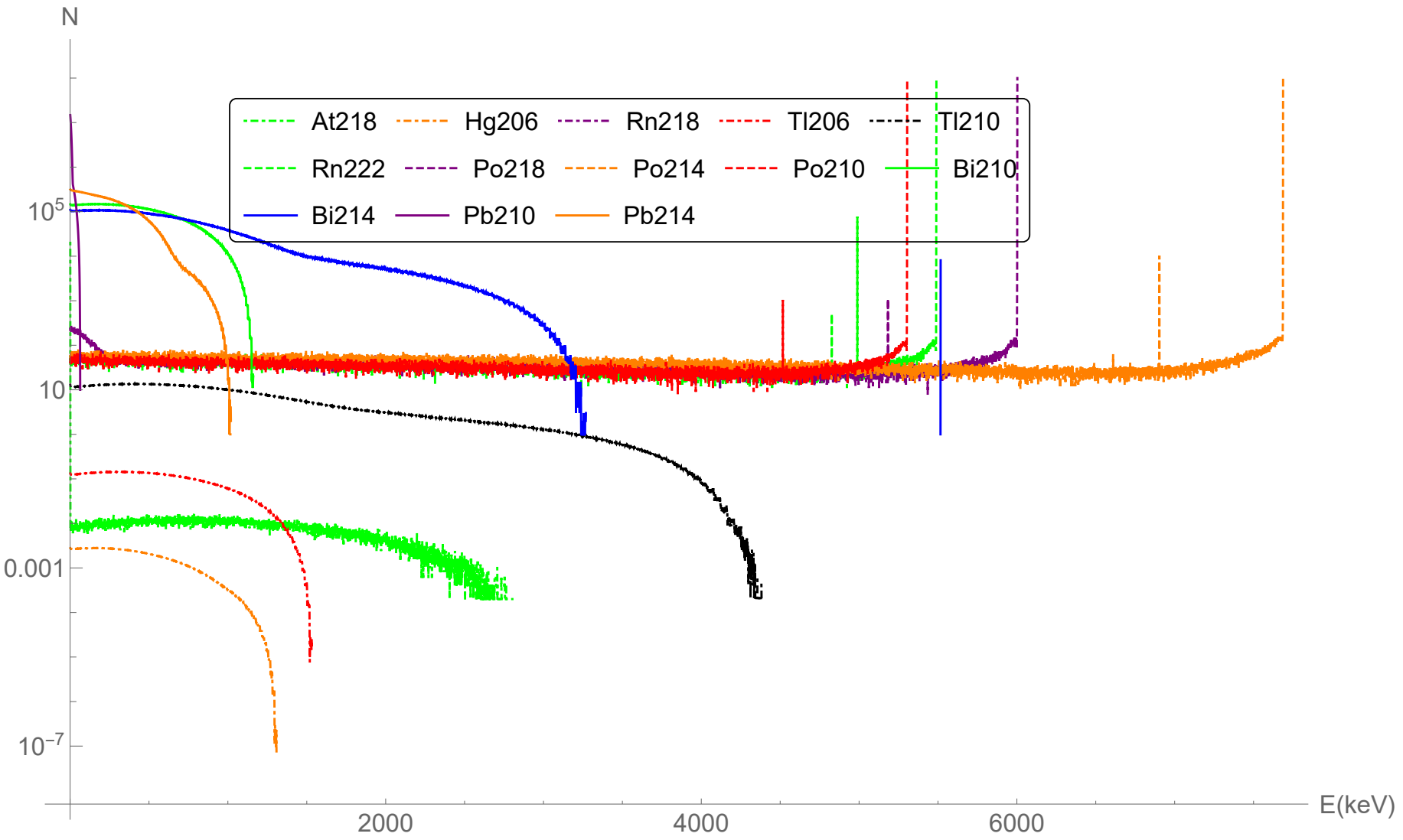
Dangerous Isotopes

For 1 Bq Rn activity

Isotope	Type	BR	$T_{1/2}$	E_β	evts/yr
$^{208}\mathrm{Tl}\rightarrow{}^{208}\mathrm{Pb}$	β	0.36	3.1 min	1.8	0
$^{208}\mathrm{Tl}\rightarrow{}^{208}\mathrm{Pb}$	γ	0.36	3.1 min	1.8	1.0
$^{210}\mathrm{Tl}\rightarrow{}^{210}\mathrm{Pb}$	β	2.1×10^{-4}	4.2 min	4.4	12.2
$^{214}\mathrm{Bi}\rightarrow{}^{214}\mathrm{Po}$	β	$\sim$1	19.9 min	3.3	2720
$^{214}\mathrm{Po}\rightarrow{}^{210}\mathrm{Pb}$	α	1.0	164.3 μs	7.8	-
$^{214}\mathrm{Bi}\rightarrow{}^{214}\mathrm{Po}$	γ	$\sim$1	19.9 min	3.3	8.9

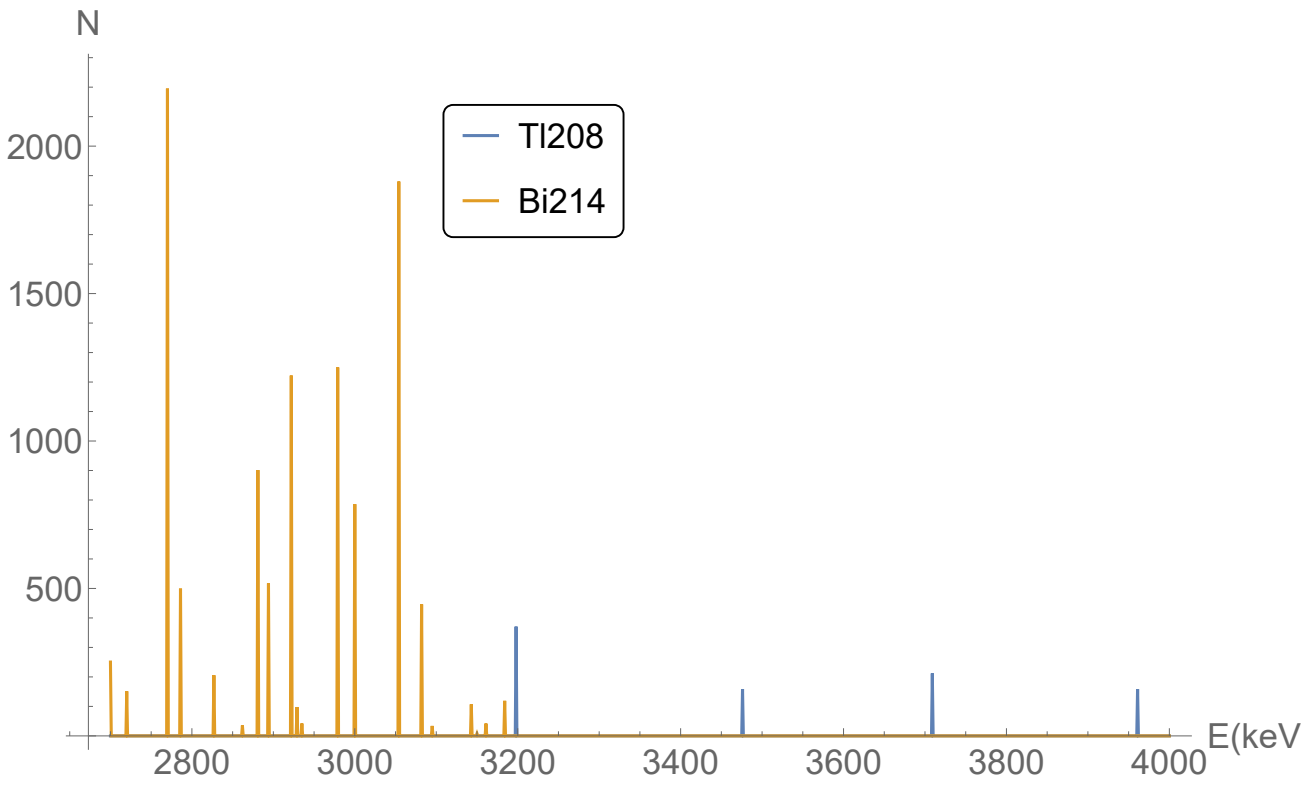
- β from $^{214}\mathrm{Bi}$ can be vetoed using α decay of $^{214}\mathrm{Po}$
- Maybe also γ from $^{214}\mathrm{Bi}$ can be vetoed as well?
- Main contribution from $^{208}\mathrm{Tl}$, this cannot be vetoed
- Without considering $^{214}\mathrm{Bi}$, Rn activity should be $<$8.3 mBq to have bg rate 0.1-0.2 evts.yr
- In PANDA-X, Rn activity $\sim$18 mBq

Energy Deposited - U chain



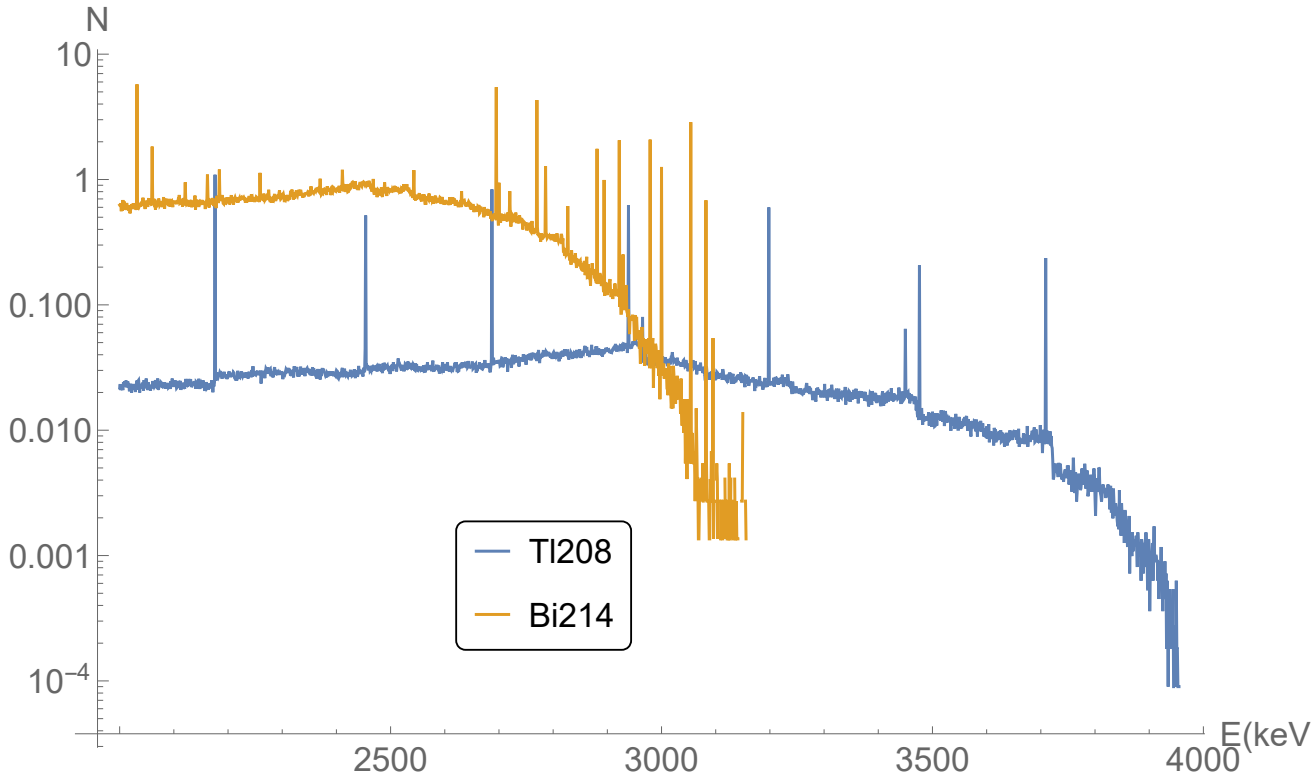
Energy Deposited - Gamma

Gamma Spectrum



Energy Deposited - Gamma

Energy Deposited



Energy Deposited - Gamma

Energy Deposited