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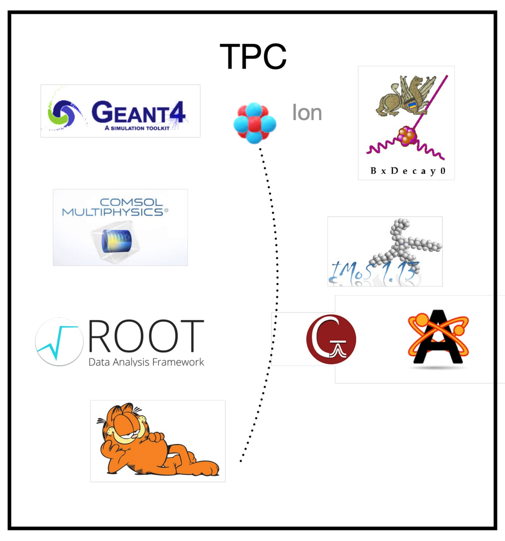

Studies of simulation framework for NvDEx experiment

arXiv

Indico link

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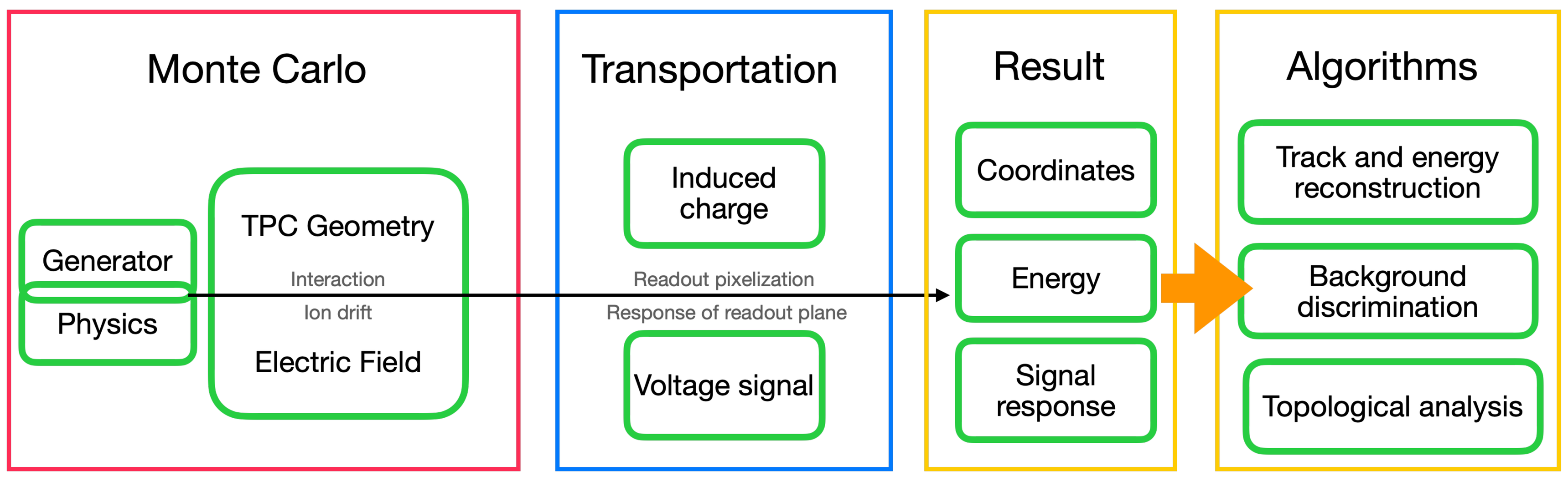
Introduction

The NvDEx experiment aims to search for the neutrinoless double beta decay of ^{82}Se using a high-pressure $^{82}SeF_6$ gas time projection chamber (TPC). Under the assumption of two kind of charge carriers would be formed, the difference in drift velocities between these ion species enables trigger-less event reconstruction and offers the potential for excellent energy resolution through direct charge collection. In this work, we present a simulation framework and preliminary study of the signal and background discrimination for the NvDEx experiment.



The diagram of simulation framework.

Simulation framework

Ion mobility calculation:

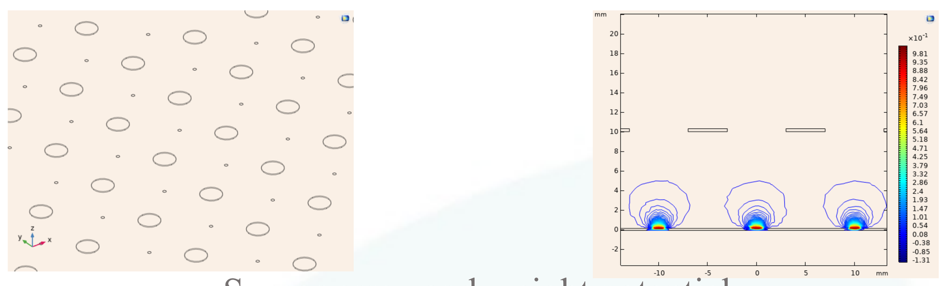
The ion mobilities of both SeF_6^- and SeF_5^- are calculated under density functional theory (DFT) and Mason-Schamp expression:

$$K = \frac{3}{16}\frac{q}{n}\left(\frac{2\pi}{\mu k_b T_{eff}}\right)^{\frac{1}{2}}\frac{1}{\Omega}$$

where q is the charge of an ion, n is the number density of a gas, k_b is the Boltzmann constant, $\mu = \frac{mM}{m+M}$ is the reduced mass, where M is the mass of the ion and m is the mass of the gas. $T_{eff} = T + \frac{mv^2}{3k_b}$ is the effective temperature, which accounts for the influence of a strong electric field. If the electric field is low, $T_{eff} = T$. Ω is the collision cross section.

Geometry and electric field:

TPC geometry with 10,000 sensors readout array. Both the weighting and electric fields of the TPC are constructed in COMSOL Multiphysics.



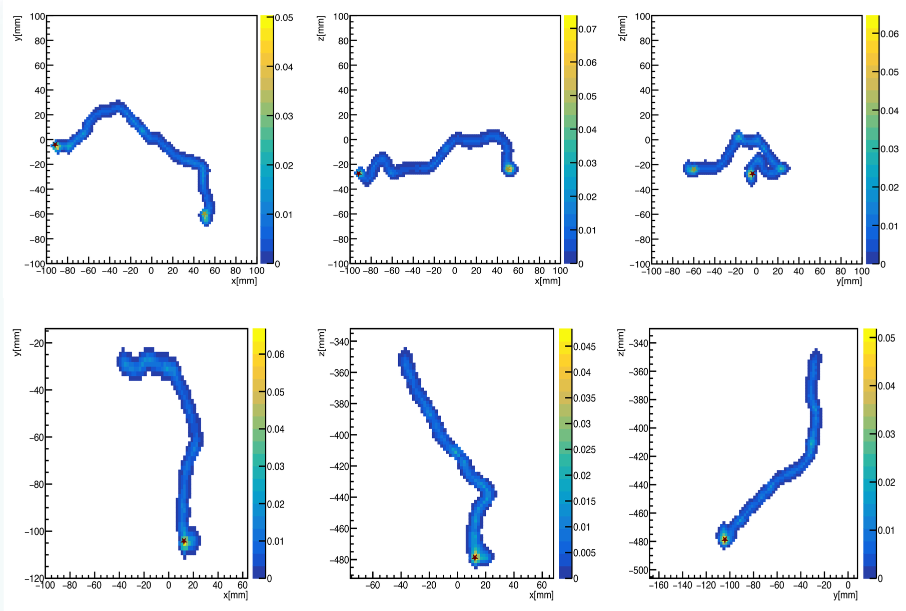
Sensor array and weight potential

Event generator and detector response:

The 0νββ events and backgrounds are generated using Geant4 and bxdecay0 package. The Garfield++ is used for the charge transportation in the gas and to calculate the induced current.

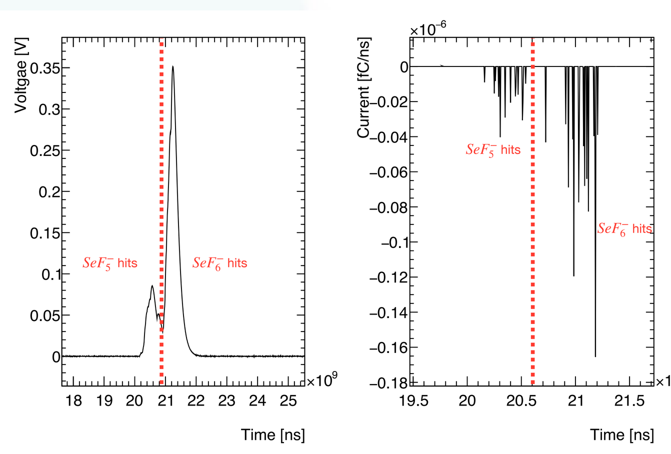
0νββ

^{208}Tl γ



Example of 0νββ signal and ^{208}Tl γ background at 2.88 MeV generated with Geant4 in 10 atm SeF_6. From the topological structure, the 0νββ signal exhibits two distinct high-energy deposition regions (“blobs”) at the track ends, characteristic of two emitted electrons. In contrast, the single-electron background from ^{208}Tl typically produces only one blob at one end of the track.

The CSA response was calculated by convolving the induced current using transfer function.



Waveform of an pixel. Right: CSA response. Left: induced current.

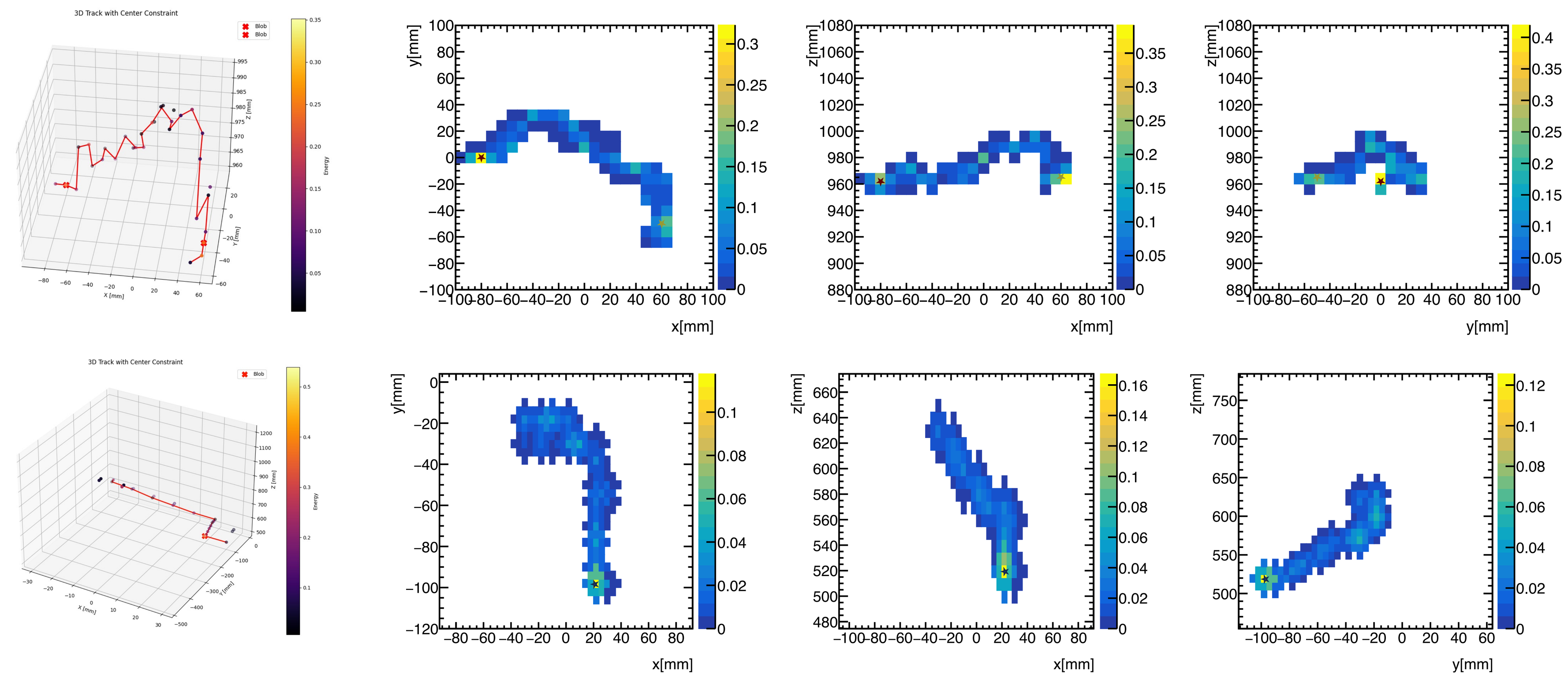
3-d track reconstruction:

Under the differences of drift velocities of both charge carriers, the z coordinate could be calculated.

$$z = \frac{v_{SeF_5^-} \cdot v_{SeF_6^-}}{v_{SeF_5^-} - v_{SeF_6^-}} \cdot \Delta t$$

Breadth-First Search (BFS) is a graph-traversal algorithm that explores vertices in order of their distance from the start node. Beginning at the source, it visits all neighboring nodes first, then proceeds to the next layer of neighbors, and so on. Implemented using a first-in–first-out (FIFO) queue, BFS guarantees finding the shortest path (in terms of edge count) in unweighted graphs, making it useful for shortest-path problems, connectivity analysis, and network exploration.

Using Breadth-First Search (BFS) algorithm, the 3-d track could be reconstructed.



Reconstructed 3D track under BFS and their projection. Top: signal. Bottom: ^{208}Tl **γ** background with 2.88 MeV

Background discrimination

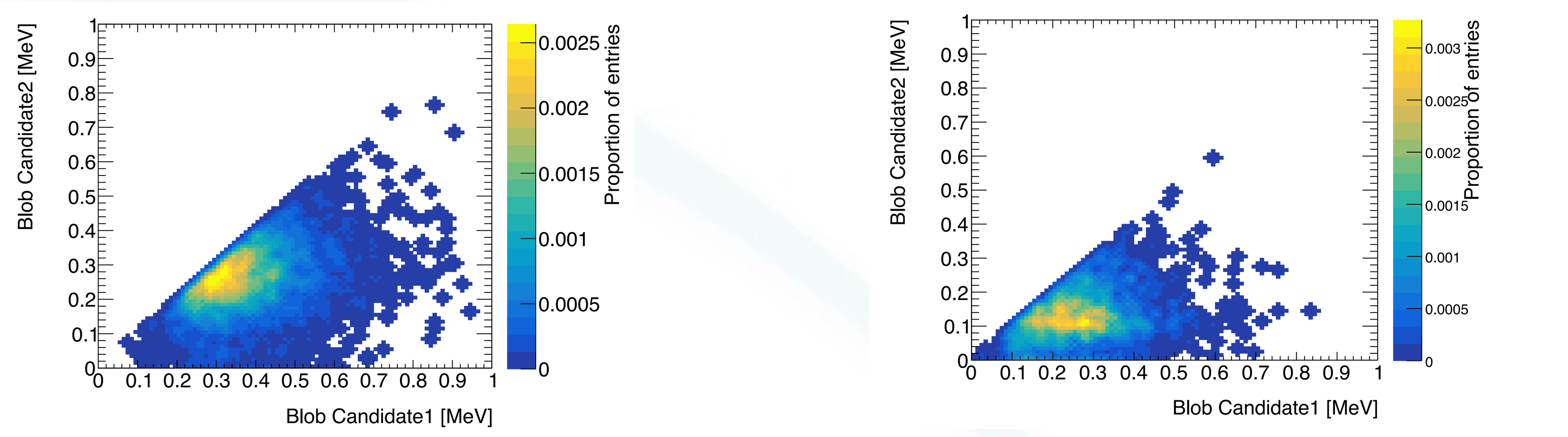
Background

Background events are predominantly caused by single electrons originating from energy emissions within the region of interest (ROI). These can be distinguished from signal events through topological reconstruction, provided that the tracking resolution is sufficiently high. In addition, 2νββ decays produce topologies similar to 0νββ events, but can be effectively rejected based on total energy deposition, which is generally well below the $Q_{\beta\beta}$ value for most events.

In this study, only background from γ for ^{208}Tl and ^{214}Bi, double beta decay are considered.

Blob distribution:

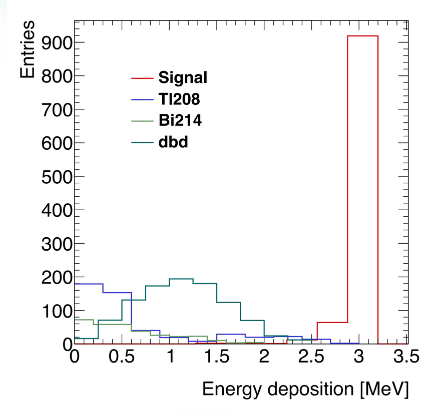
The energy blobs play important roles in background discrimination, which is crucial on the number of electrons.

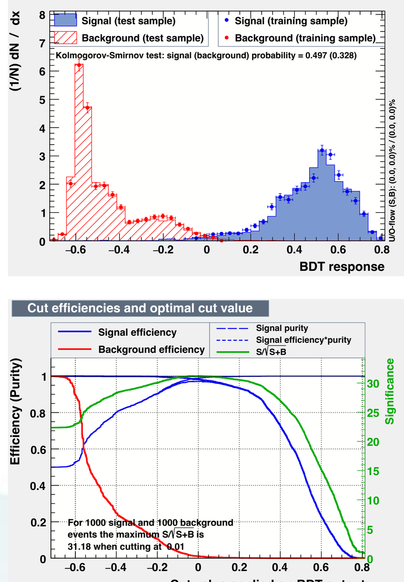


The distribution of the energy deposited in the blob candidates of the tracks for signal and ^{208}Tl background events simulated by the framework. Signal events tend to exhibit two blobs with closely matched energy depositions, whereas background events show a broader and more asymmetric distribution.

Preselection

The total reconstructed energy is used as an initial event filter to suppress obvious background contributions. Since the 0νββ signal in ^{82}Se has a Q-value of 2.996 MeV, only events with energy larger than 2.5 MeV are retained for further topological analysis. As shown in right fig, most γ backgrounds from ^{208}Tl and ^{214}Bi, as well as 2νββ events, populate lower-energy regions and are efficiently rejected at this stage.





BDT Classification Performance

Using TMVA Boosted Decision Trees (BDT), we achieve excellent signal–background separation. At the optimal cut (BDT = 0.0113), the signal efficiency reaches 98.1% while only 0.9% of background remain. This demonstrates that the BDT preserves almost all signal events while strongly suppressing background, providing a powerful tool for physics analysis.

classifier	Optimal-cut	S/sqrt(S+B)	NSig	NBkg	EffSig	EffBkg
BDT	0.0113	31.1782	981.2115	9.224091	0.9812	0.009244
DNN	0.6437	31.1691	986.7403	15.46392	0.9867	0.01546

Summary & outlook

- A full simulation framework for the NvDEx experiment, which contains ion mobility calculations, event generation, charge transport, and detector response modeling has been developed.
- Preliminary topological cuts demonstrate excellent background suppression while maintaining high signal efficiency.
- Next: Perform high-pressure SeF_6 ion-yield measurements to validate dual-ion assumptions. Explore machine-learning–based topology discrimination to further enhance background rejection.