Low-energy neutrinos with DUNE, data reconstruction and analysis with DUNE Prototypes and sensitivity to solar neutrinos

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18th September 2026

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Introduction

Neutrino :

- Elementary particle ⇒ Lepton
- There are 3 Flavor-Eigenstates (e, μ, τ) which are mixings of 3 Mass-Eigenstates (1, 2, 3)
- The oscillations imply that the ν has mass

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}|\nu_i\rangle \quad U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

PMNS Matrix

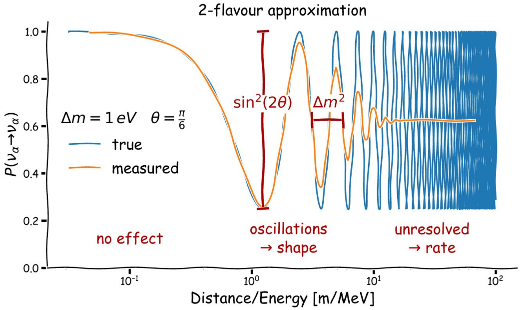
Oscillation parameters :

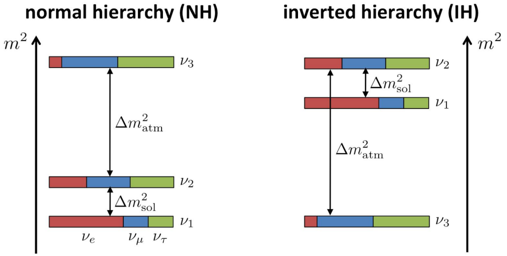
- Mixing angle θ_{ij} ⇒ Oscillation amplitude
- Mass differences Δm² ($m_i^2 - m_j^2$) ⇒ Oscillation frequency
- Oscillations are expressed as a function of a probability ⇒ Depends on the energy and the distance

→ Improve the precision of oscillation parameter values, determine the mass ordering and measure the CP-violating phase (δ_{CP})

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta) = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$





The DUNE experiment

- Next-generation long baseline neutrino experiment
- Located in the United States (Fermilab and SURF)

DUNE features :

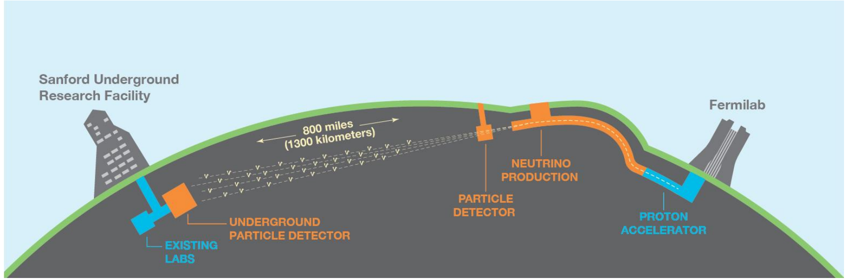
- A (anti-)neutrino beam → Most powerful beam ever used
- A near detector → Monitoring the unoscillated flux
- A far detector → 1300 km downstream to measure the oscillated flux with large matter effect

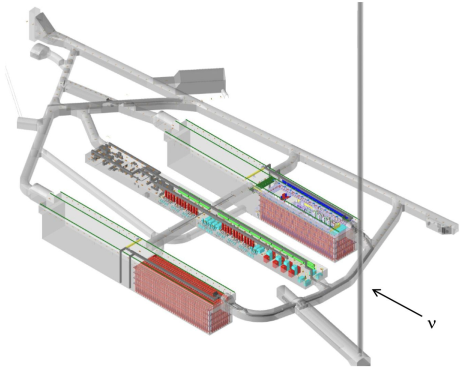
DUNE far detector :

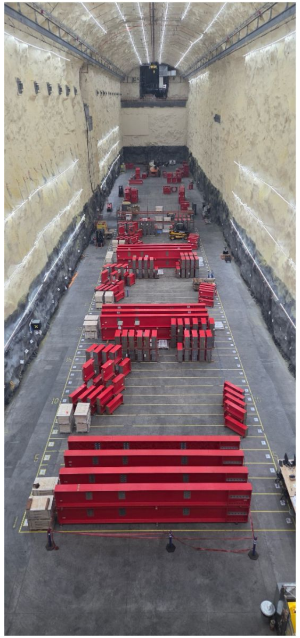
- 4 modules of 14 kilotons of active mass
- Liquid Argon Time Projection Chamber (LArTPC) detector for the first 2 modules →*Vertical Drift* and *Horizontal Drift*

DUNE physics goals :

- Matter–antimatter asymmetry ⇒ δ_{CP}
- Neutrino mass ordering ⇒ Δm^2
- Solar neutrinos and Supernovae neutrinos







DUNE cavern

DUNE at CERN

Construction of two full-scale prototypes at the CERN neutrino platform : *ProtoDUNE-HD* and *ProtoDUNE-VD*

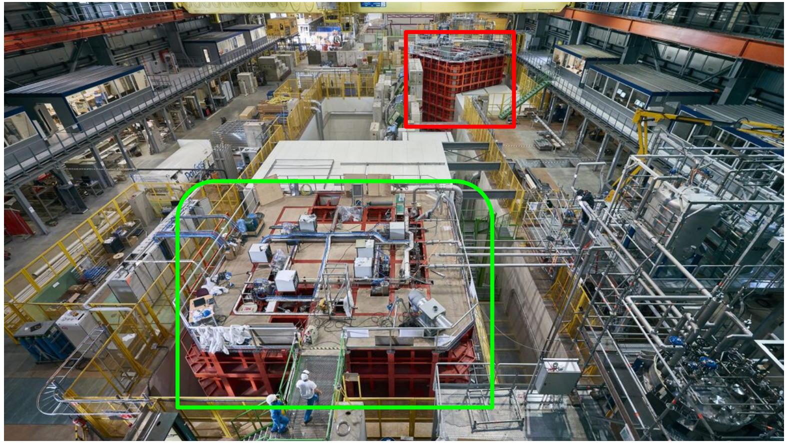
Purpose → Test the different technologies of the LArTPC far detectors

ProtoDUNE-HD :

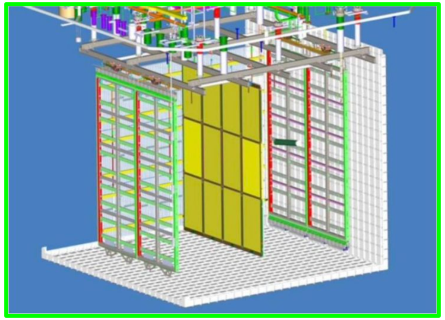
- Data taking from may 2024 to november 2024
- 10 weeks of SPS beam (e-, π, K…)
- **^{207}Bi sources for low energy calibration**

ProtoDUNE-VD :

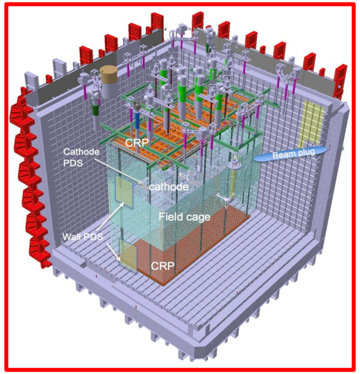
- Data taking from september 2025 and still ongoing
- few days of SPS beam (e-, π, K…)
- **Pulsed Neutron Source (PNS) for low energy interaction analysis**



Neutrino platform



ProtoDUNE-HD



ProtoDUNE-VD

Solar neutrinos

DUNE aims to explore the MeV range → Supernova and **solar neutrinos**

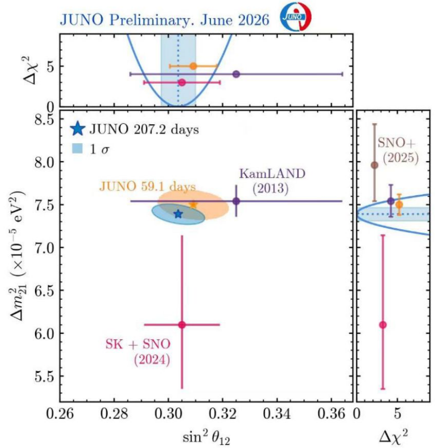
Possibility to measure oscillation parameters (θ_{12}, θ_{13} and Δm^2_{21}) and the matter effect with day/night asymmetry

Discrepancy of ~ 2σ between solar and reactor measurements

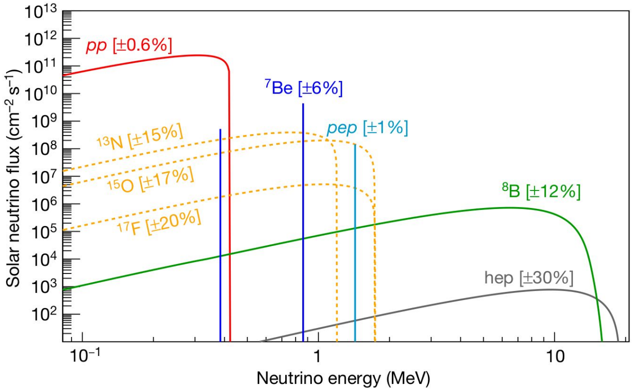
Low energy observation in DUNE :

- Measurement of two different solar flux : ^{8}B and *Hep*
- Very good reconstruction capability thanks to the LArTPC
  ⇒ Separation of the different types of events (γ or e^-)
- Two channels of interaction for detecting neutrinos :

$$\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*$$
$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$



Δm^2_{21}	7.388±0.078 (1.60% → 1.06%)
$\sin^2\theta_{12}$	0.3036±0.0064 (2.8% → 2.1%)



1st year work

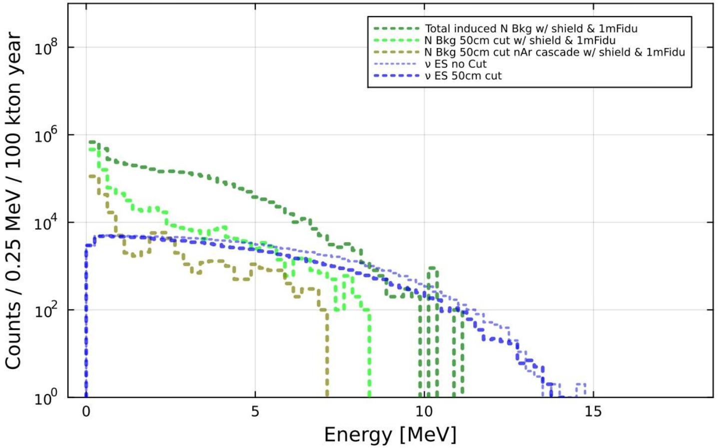
Neutron background reduction for solar ES neutrino observation :
→ Shielding
→ Fiducialization cut
→ Energy threshold reduced to 100 keV
→ Discrimination method

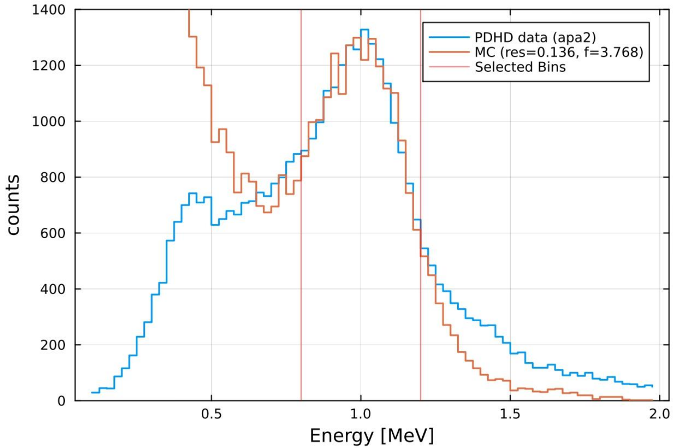
Global reduction of a factor 10² & discrimination helps to **reduces by more than a factor 10 the N bkg**

Study of the Low-Energy features of the ProtoDune-HD by analysing Bismuth sources and radiological data

Measurements of the energy resolution, fCtoMeV factor and recombination factor

→ Preliminary result of **15% for the energy resolution**
→ **Good recombination factor agreement** between PDHD data and former experiments



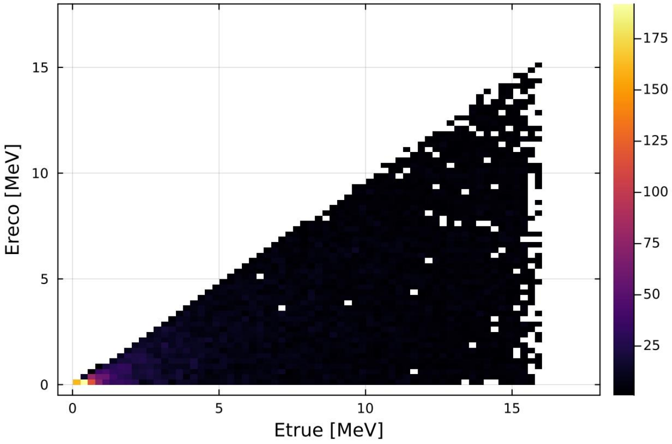


Energy reconstruction of the ES electron

For significant ES neutrino contribution in solar oscillation parameters → Good energy reconstruction

Problem : The primary energy reconstruction for ES events is very poor because of its dependency on the scattering angle θ

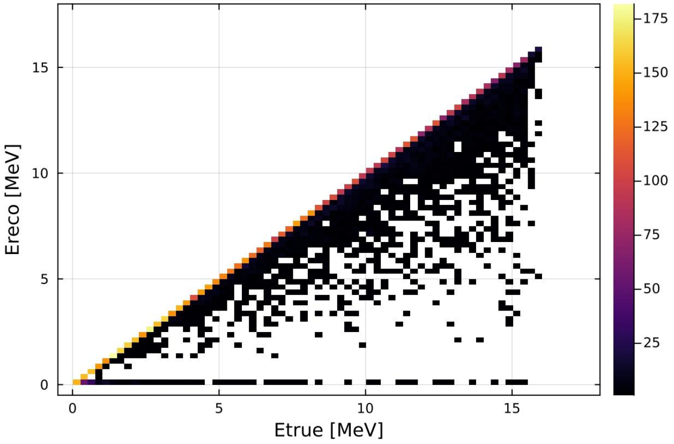
Goal : Enhance the reconstruction by using this angle



Scattering angle θ formula used for the energy reconstruction (Supernova Pointing Capabilities of DUNE, arXiv:2407.10339v1) :

$$\cos\theta_e = \frac{E_\nu + m_e}{E_\nu}\sqrt{\frac{T}{T+2m_e}},$$

In an ideal case (True electron momentum to compute θ), we should obtain :



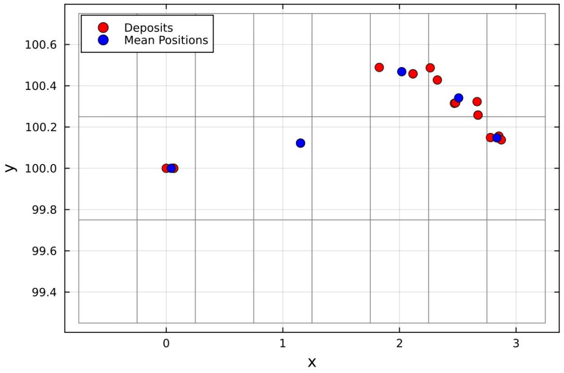
Fitting direction method

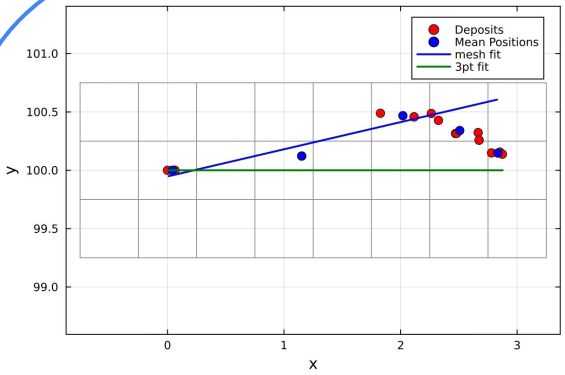
Chosen method to compute the scattering angle :

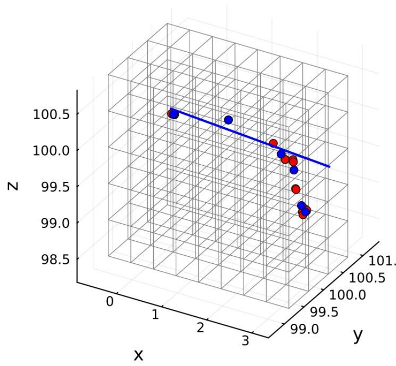
- Use **a 5 mm meshgrid** to reproduce the expected spatial resolution of the detector
- **Compute the mean position** of the deposits in a pitch
- **Fit a straight line** with **the first three mean positions**

→ Simulation of electrons at different energies to test the fitting method

Application of the fitting method on ES events



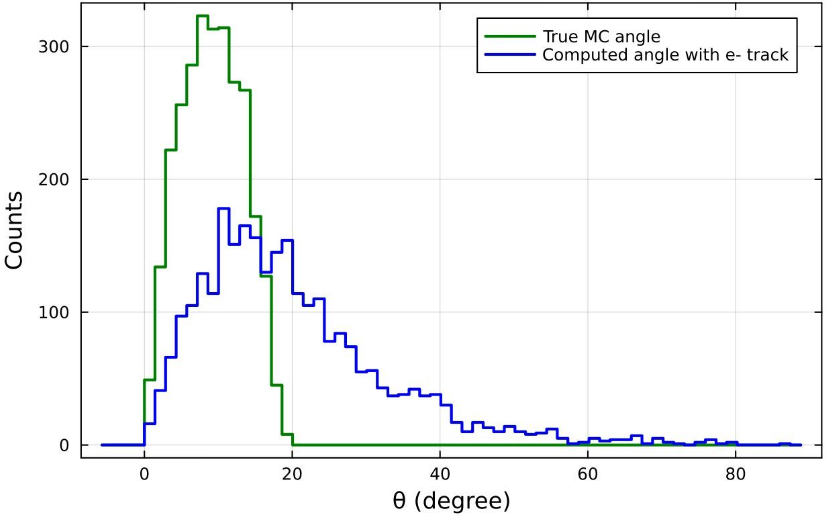




Angle distribution for ES events

The simulation using electrons showed us that at low energy, the deposits are too scattered to accurately fit a straight line

→ Only outgoing ES electrons with an energy > 4 MeV will be taken into account



→ Despite an efficient fitting method, the distribution of the computed scattering angle is diffuse

→ Event by event, the difference can be important

Example with a 7.2° difference :
$\theta_M = 9.6°$, $\theta_{e-} = 16.8°$

From $E_{e-} = 8.36$ MeV, we obtain
With θ_M : $E_{reco} = 11.5$ MeV
With θ_{e-} : $E_{reco} = 35.3$ MeV

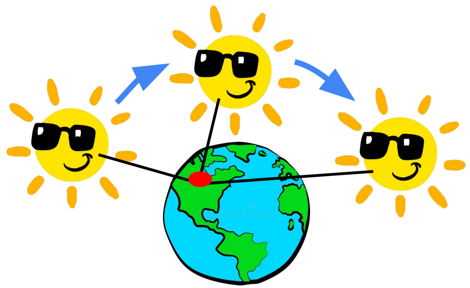
Sun position in Marley

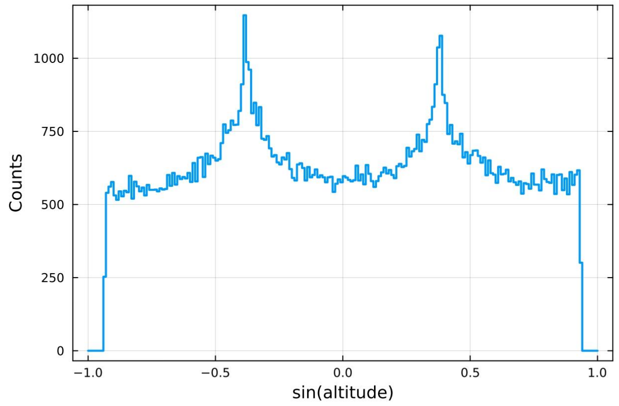
MARLEY (Model of Argon Reaction Low Energy Yields) is a Monte Carlo event generator for neutrino interactions at energies of tens-of-MeV and below

The software offers only two modes to launch neutrinos : a fixed direction or an isotropic distribution

Necessary modifications for solar neutrinos

- Implementation of the sun position to compute the realistic neutrino direction→Marley modifications needed
- Computation of 120 000 sun position at random dates over a period of one year

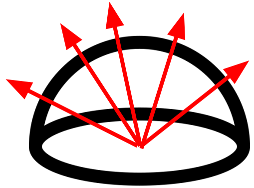


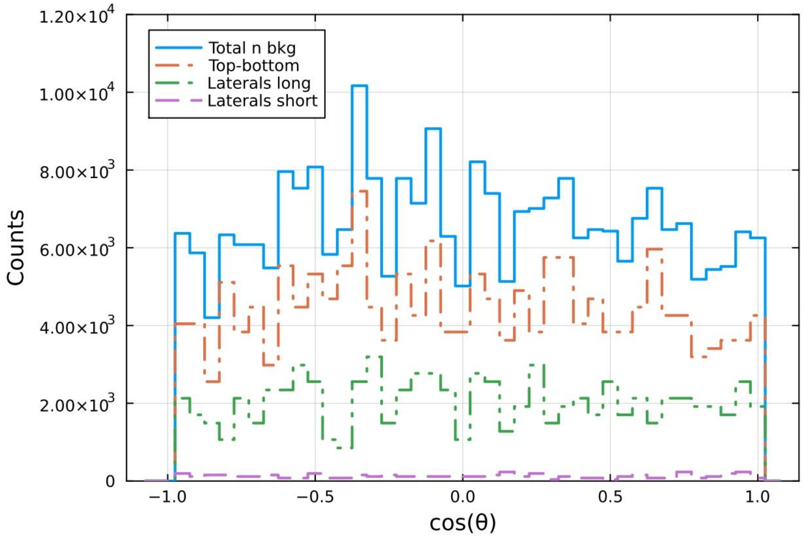


Angular distribution for the N bkg

Neutrons are launched from outside with a half sphere random direction towards detector walls

The angle is computed with a random position of the Sun



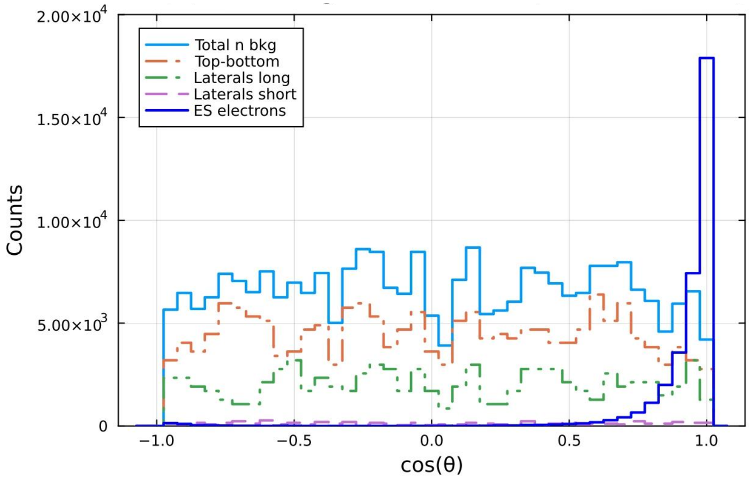


Unlike the case with ES events, The neutron angular distribution is mostly flat

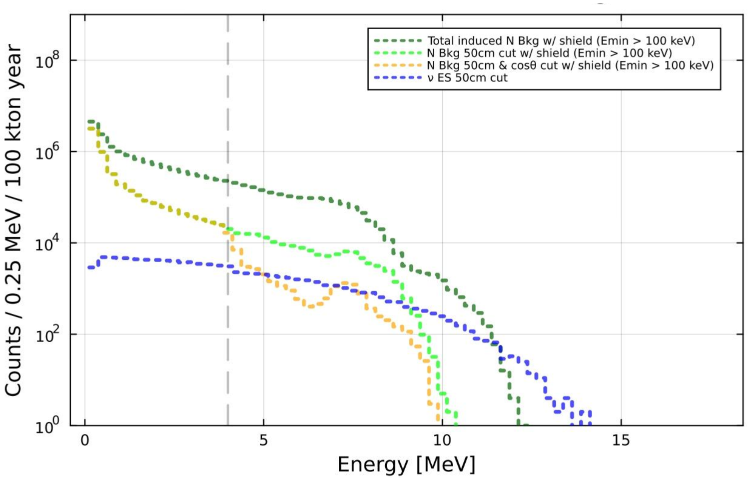
→ Possibility to distinguish neutrons and ES electrons with the angle !

Angular distribution and energy spectrum

With shielding + Discrimination :



With shielding + Discrimination :



ES signal higher than neutron background around cos(θ) ≈ 1 → **Possibility to remove the background by selecting events near this region**

There is a clear improvement by applying the angle cut → **The neutron background becomes inferior to the ES signal above 4 MeV**

It might be possible to observe ES neutrinos thanks to the applications of all these methods

Space Charge Effect analysis

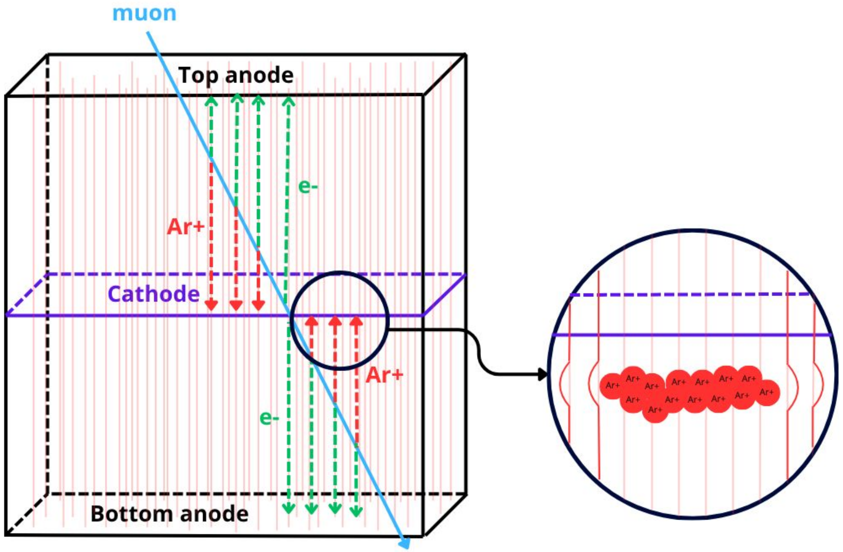
Space Charge Effect is the build-up of slow moving positive ions in a detector → Distortion of the electric field

Modification of ionisation electron trajectories → **Error on the position measurements !!**

Characterize this phenomenon in ProtoDUNE-VD by using cosmic muon tracks

Parameters :

- LARDON as the data reconstruction software
- Cosmics run as our data



Type of tracks

- **Anode-Cathode-Anode tracks :**

An accurate entry point and accurate exit point are known

- **Anode-Cathode tracks**

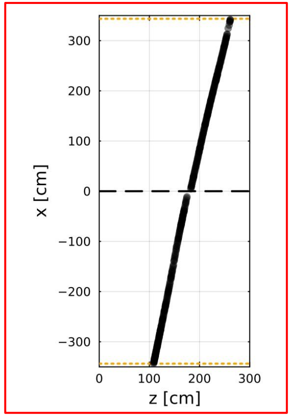
An accurate entry point or accurate exit point is known

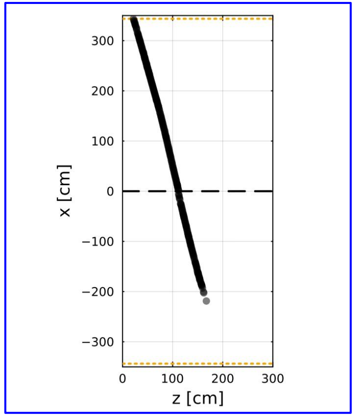
- **Anode crosser tracks**

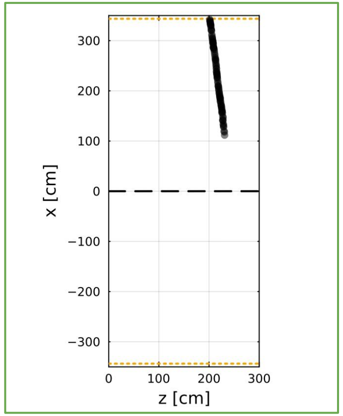
An accurate entry point or accurate exit point is known

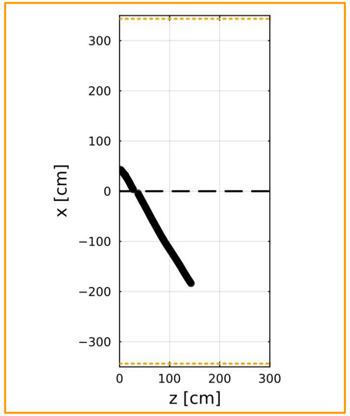
- **Cathode crosser tracks**

Neither an accurate entry point or accurate exit point is known









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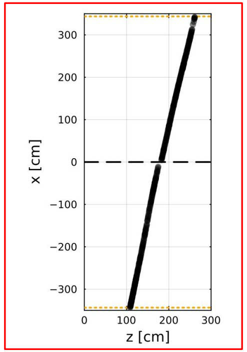
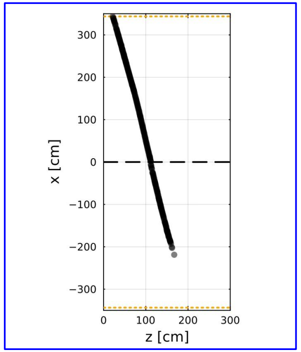
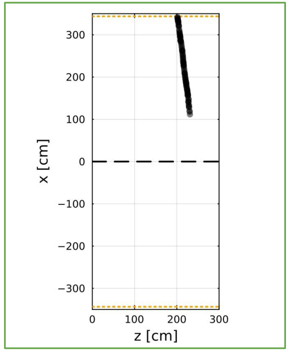
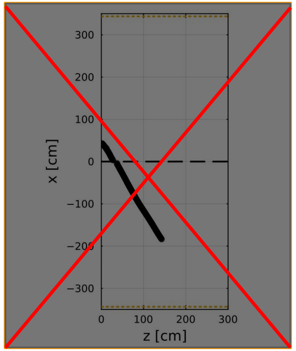








The first three cases cross anode planes where the space charge effect don't bias the position reconstruction

→ An accurate point (entry or exit) can be used to estimate the deviations due to this phenomenon

Space Charge computation

Deviation due to the Space Charge is computed by comparing the expected positions with the reconstructed positions

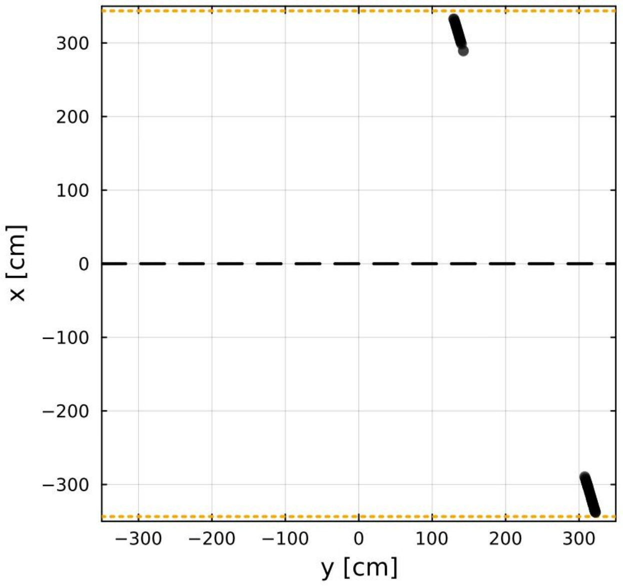
How the expected positions are calculated :

→**Hits of the track in the first 50cm near the anode planes are selected**

→A direction is computed with a reference point

→The reconstructed positions are projected on the fitted straight line

→The difference between the reconstructed position and the expected position is calculated for each axis at each position



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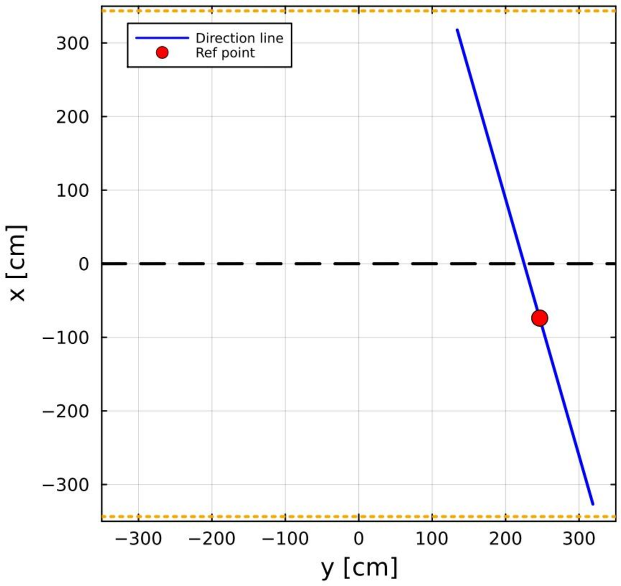

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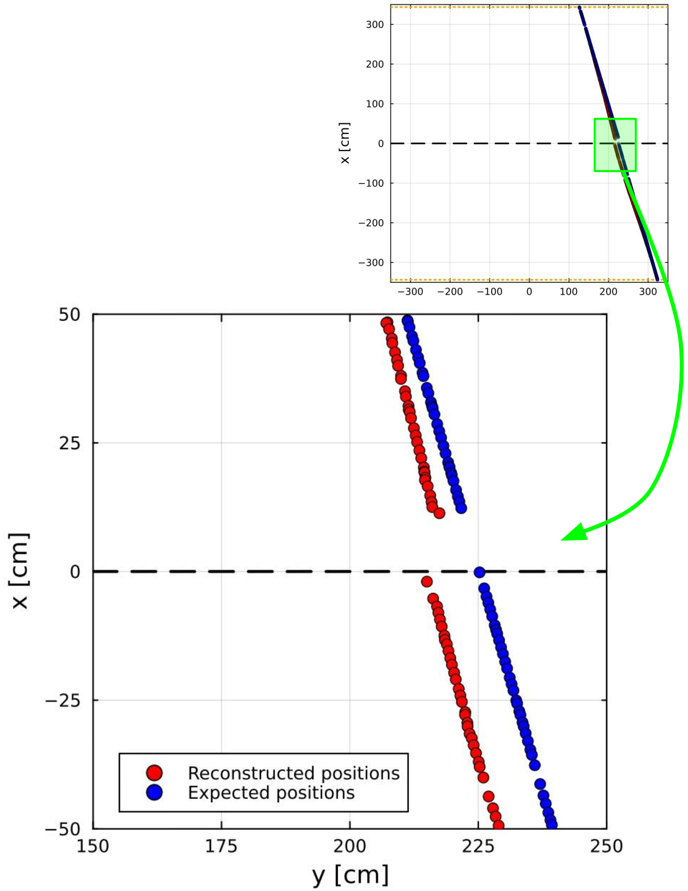

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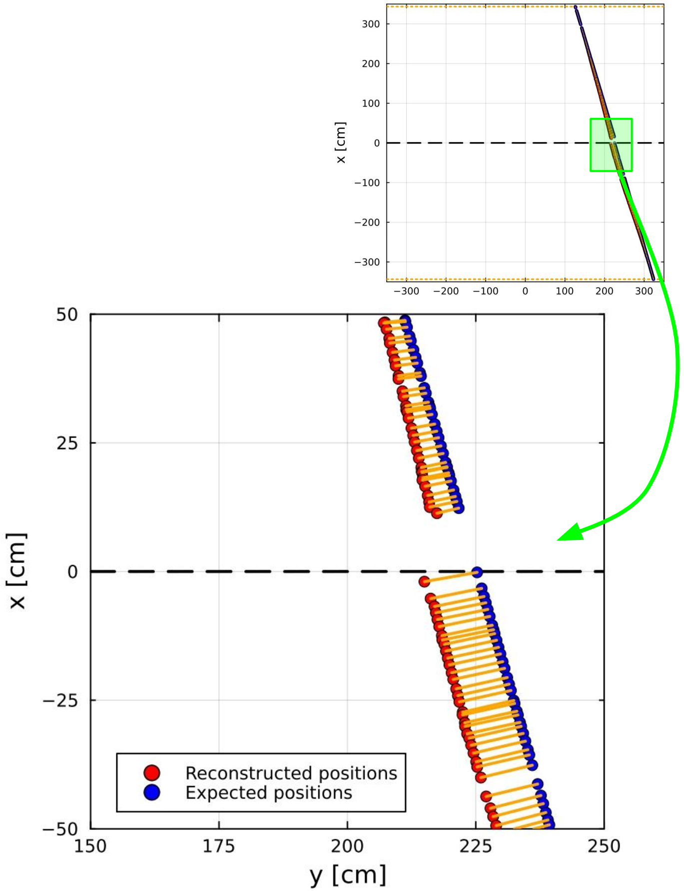
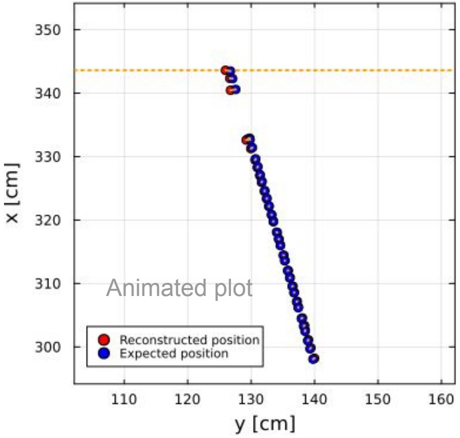
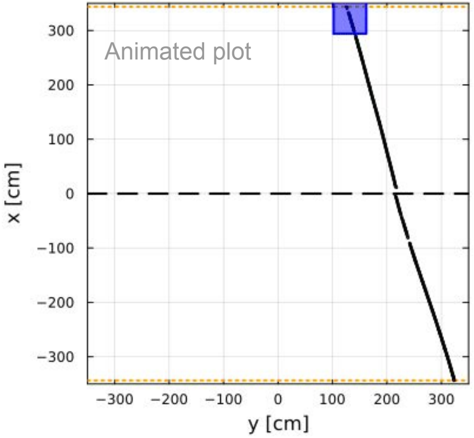


Space Charge computation

Example for one track :

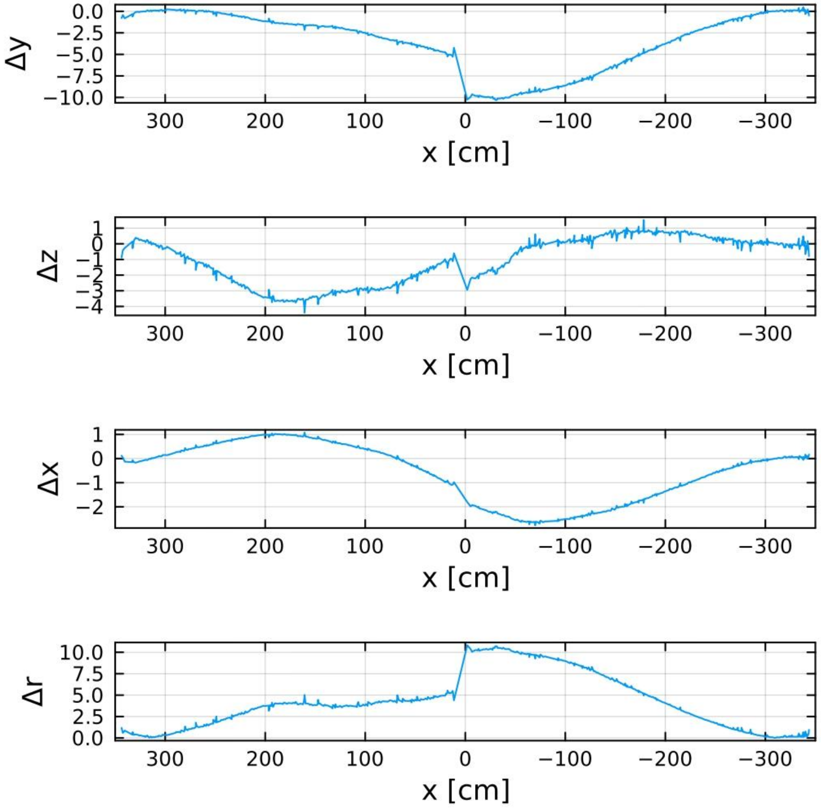




→ Along the track, the differences become more and more important when moving toward the cathode

Top Anodes

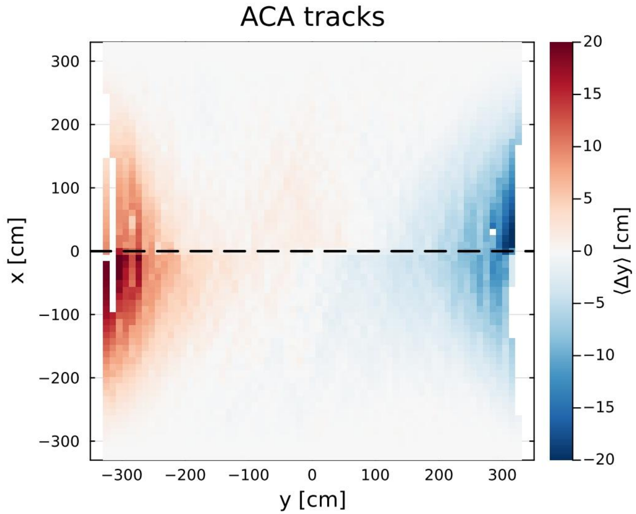
Bottom Anodes



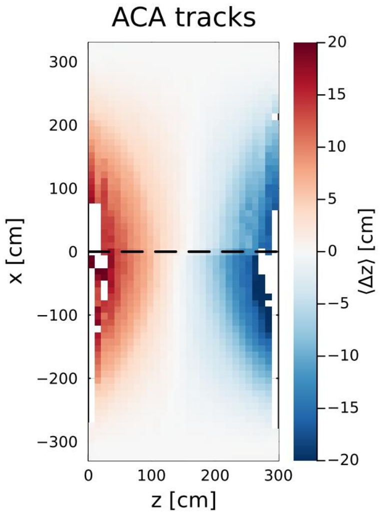
Result for one track

Results for Anode-Cathode-Anode tracks

Average lateral differences of all the Anode-Cathode-Anode tracks : Δy and Δz



Color description :
Red : right shift
Blue : left shift

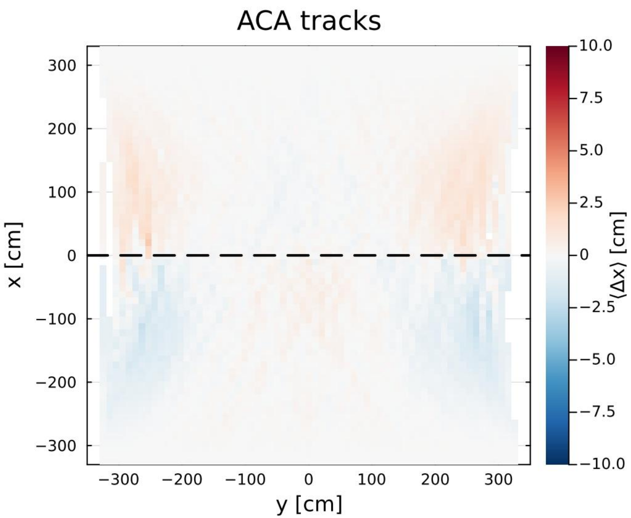


→ The differences along the lateral axis show that the Space Charge shifts the positions towards the center of the volume

→ The modification of the electric field lines by the Space Charge effect is more significant at the edge of the detector, near the field cage and the cathode

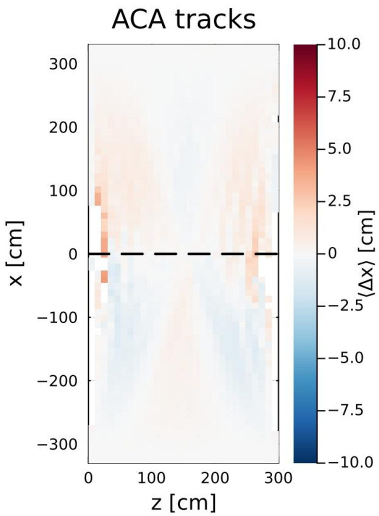
Results for Anode-Cathode-Anode tracks

Average vertical differences of all the Anode-Cathode-Anode tracks : Δx



Color description :
Red : up shift
Blue : down shift

Color scale is reduced to (-10,10)



→ The differences along the vertical axis are less important and show that the Space Charge shifts the positions differently according to the location in the detector

→ The flow of argon is not uniform at the center of the detector due to different components (ex : ARAPUCAs) and the electric field lines are modified according to the number of accumulated ions

Topography of the selected tracks

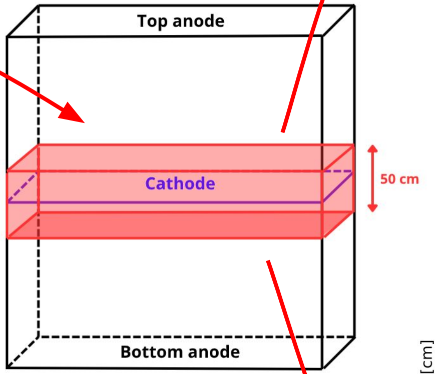
The analysis has been extended to **Anode crosser tracks**
→ **Different results** obtained for **vertical deviations**

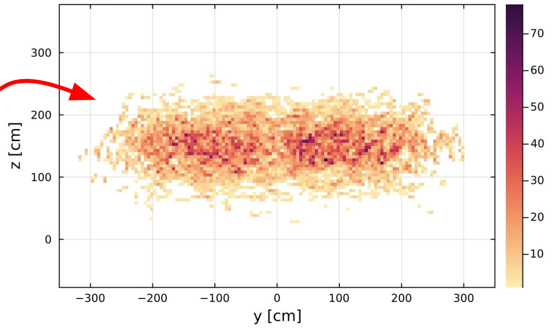
By looking at the hits of the tracks around the cathode plane, different results were obtained :

→The selected Anode-Cathode-Anode tracks are mostly in the center of the detector

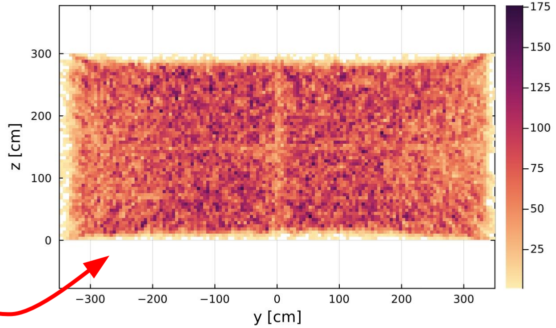
→The selected Anode crosser tracks are all over the ZY plane

Different components are involved in the Space Charge effect such as Field cage at the edge of the active volume





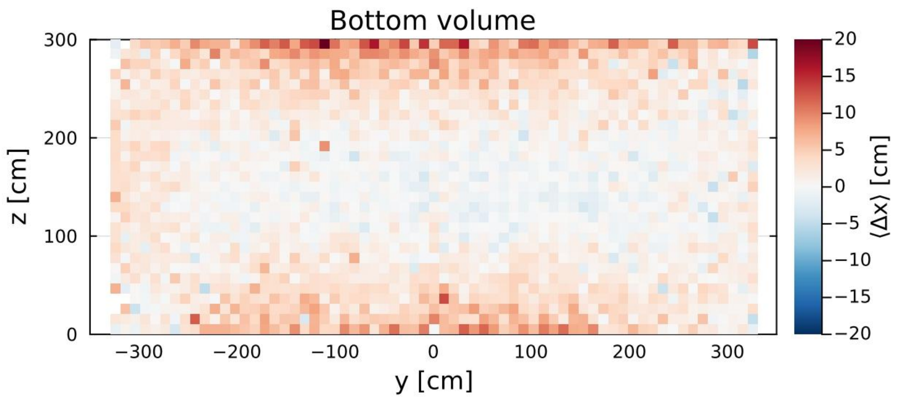
Anode-Cathode-Anode tracks



Anode crosser tracks

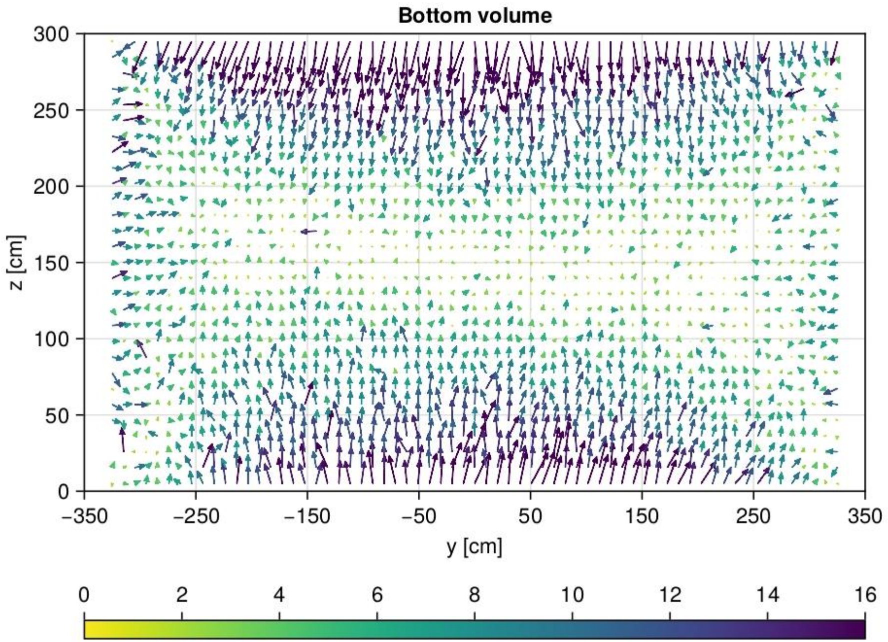
Space Charge on the cathode plane

Here, Δx, Δy, Δz only computed for the last point of the track before the cathode plane



Positive Δx at the edges →up shift corresponding to the Anode crosser tracks results

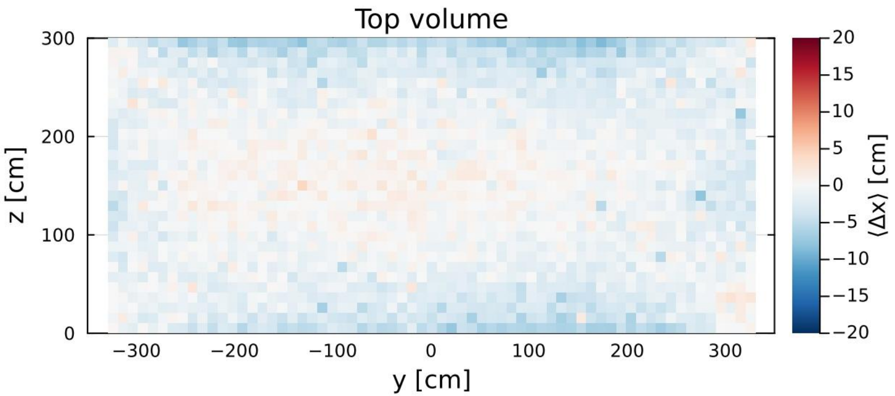
Negative Δx at the center → down shift corresponding to the Anode-Cathode-Anode tracks results

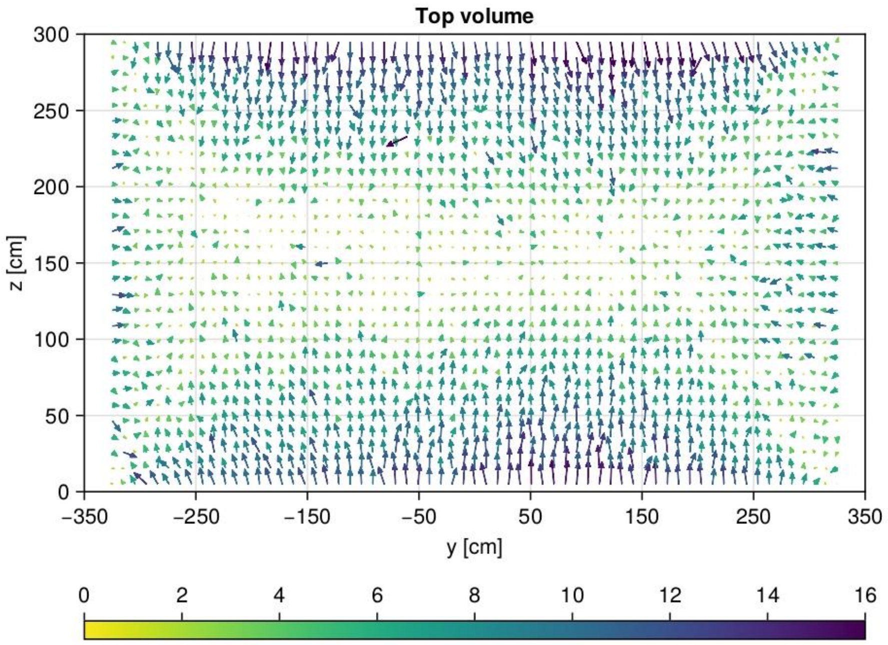


Combination of Δy and Δz → show shift toward the center of the volume

Space Charge on the cathode plane

Here, Δx, Δy, Δz only computed for the last point of the track before the cathode plane





Negative Δx at the edges →down shift corresponding to the Anode crosser tracks results

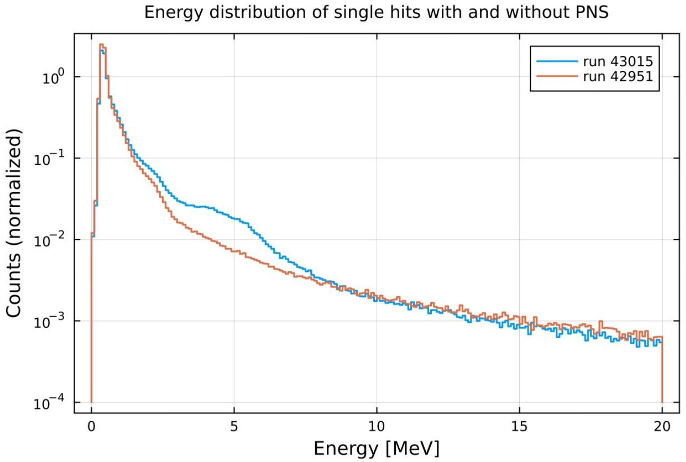
Positive Δx at the center → up shift corresponding to the Anode-Cathode-Anode tracks results

Combination of Δy and Δz →show shift toward the center of the volume

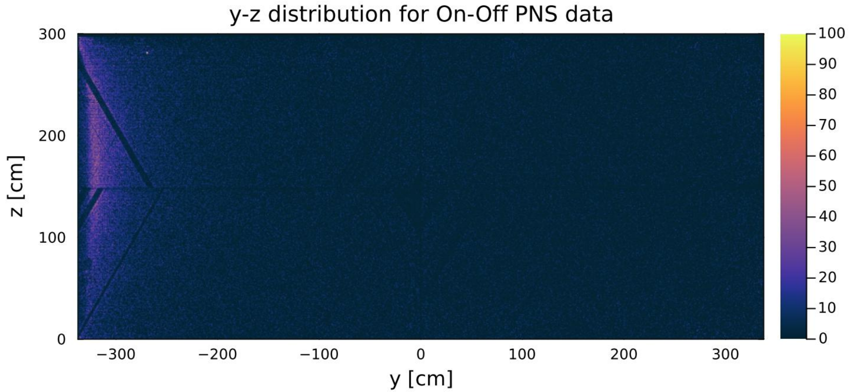
Pulsed neutron source at PDVD

Installation of a neutron source for study low energy interaction in ProtoDUNE-VD

LARDON reconstructed single hits show PNS activities :
→Bump at 5 MeV in the energy spectrum
→Higher density at the edge of the detector



PNS location at ProtoDUNE-VD :
(x = -30, y = -580, z = 190),
outside the cryostat



PNS energy reconstruction

Goal : Reconstruct the full de-excitation γ cascade after neutron capture → collect the 6.1 MeV energy

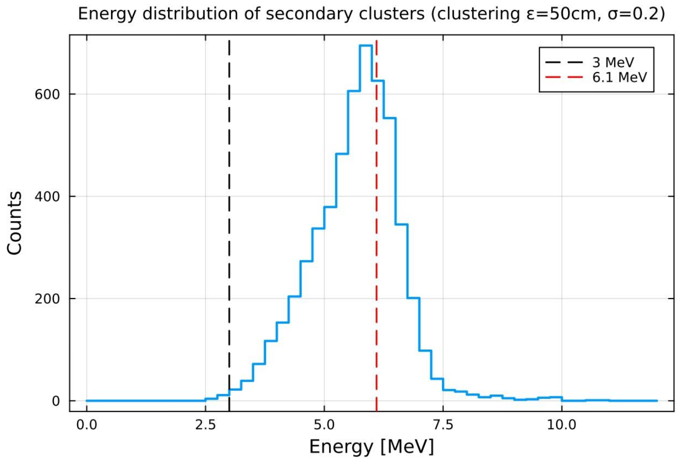
Comparison between ProtoDUNE-VD data and Geant4 simulation

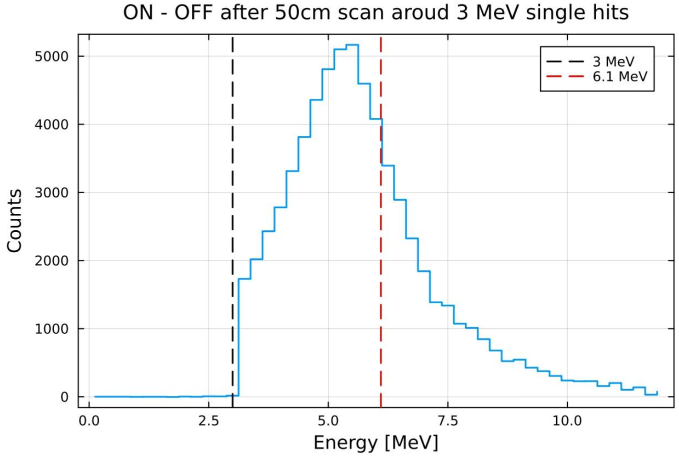
Method :

- First DBScan clustering on simulation to "reproduce" LARDON single hits
- Selection of a 3 MeV seed single hits and sum the energy of the surrounding ones in a radius of 50 cm (for both simulation and data)

Good energy reconstruction for simulation → 6.1 MeV peak

Missing energy for data reconstruction → peak shifted at lower energy





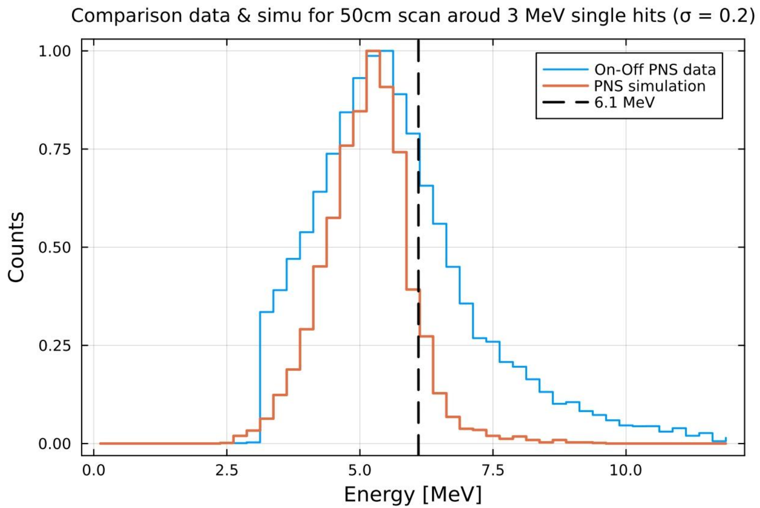
PNS energy reconstruction

Application of a threshold in the simulation → Better agreement between data and simulation

Data and simulation still show differences in their energy spectra and further applications are needed to reduce them

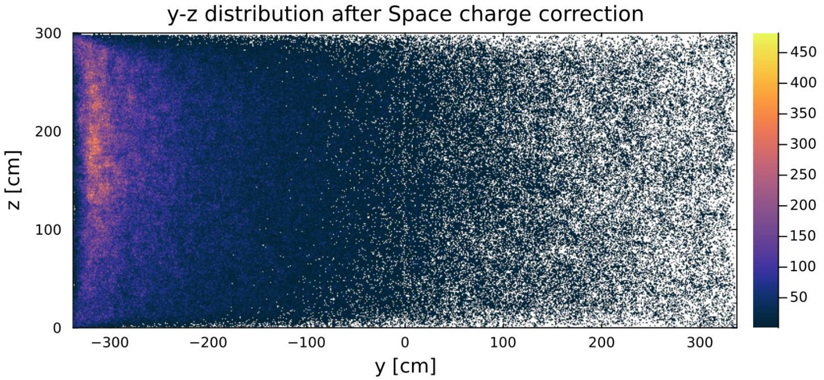
Several methods have been considered such as :

- Taking into account the neutron capture time
- Analysing the waveforms of the single hits and modify the data reconstruction to lower the energy threshold

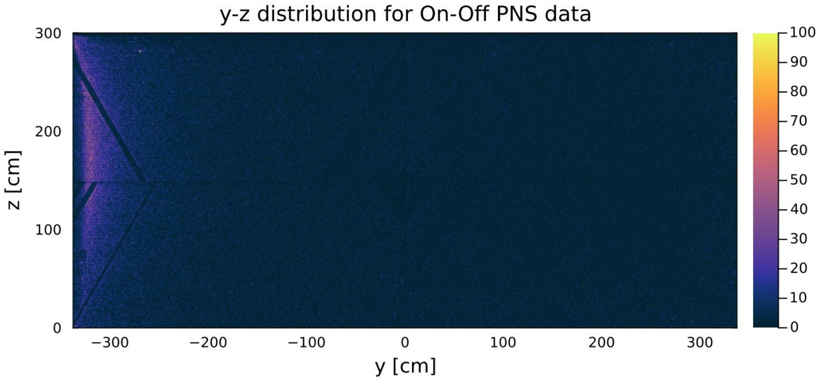


Application of Space Charge Effect on PNS

Simulation



On-Off PNS data (run 43015 and 42951)



→The application of Space Charge Effect on the simulation moves the single hits away from the edges of the detector

→The same effect is observed in the PNS data

Conclusion & perspectives

For low energy signals :
→ New cut taking into account the angle of the outgoing particle
→ New mode available in Marley to use the Sun position as the initial direction
→ The combination of all the reductions decreases considerably the N bkg and permits ES neutrino observation
Next step : Develop a second discrimination method for CC interaction

Space Charge Effect :
→ Characterisation of this phenomenon
→ Computation of the deviations due to the Space Charge Effect
Next step : Develop a simulation to compare with data and estimate the bias of our method

Neutron source :
→Development of a charge reconstruction method
→Application of the Space Charge Effect on the neutron data
Next step : Refine the charge reconstruction by looking at more parameters (single hits waveforms)

Scientific production during the second year :
→ Three talks given during collaboration meetings and one talk given during DUNE France meeting
→ Attended the JRJC conference (talk + proceeding)
→ Participation in the International Neutrino Summer School in Santa Barbara, California in July

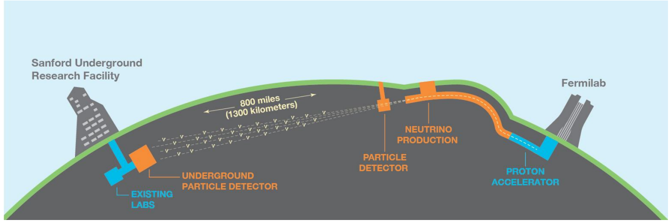
Doctoral training almost complete (137 / 120 hours but “Éthique de la recherche” not done :/)

Backup

DUNE detectors

The facilities :
- An accelerator at Fermilab for a neutrino beam production
- A near detector (ND)
- A far detector (FD)

DUNE's TDR



DUNE facilities

Far detector→4 modules :

- 62.0 m * 15.1 m * 14.0 m ⇒ ~ 14 kilotons of active mass
- Liquid Argon detector

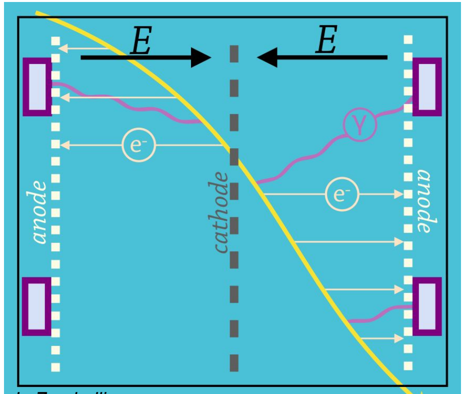
First phase ⇒ 2 modules built for 2030

Use of LArTPC for the first two modules :

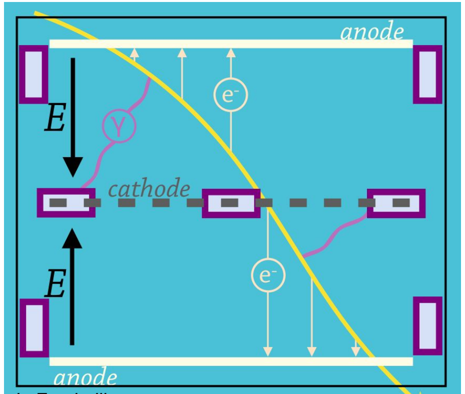
- Ionization e- produced after particle-Argon interaction
- Drift of ionization e- towards the detection systems thanks to an electric field of 0.5 kV/cm
- Recombination of electrons produces the emission of a light signal detected by an ARAPUCA

Two different technologies→*Horizontal Drift* and *Vertical Drift*

Two full-scale prototypes have been built at CERN, *ProtoDUNE-HD* and *ProtoDUNE-VD,* to test these technologies



L. Zambelli



L. Zambelli

Solar neutrino spectrum

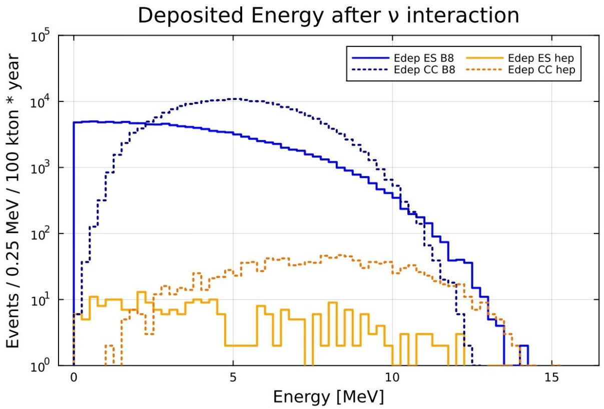
$N_{CC/ES} = \Sigma\, \phi_\nu * \sigma_{CC/ES} * n_{Ar/e-}$

ϕ_ν ⇒ Flux ^8B predicted : $5.25*10^6$ cm^{-2}.s^{-1}
⇒ Flux ^8B measured : $2.315*10^6$ cm^{-2}.s^{-1} (2312.12907)

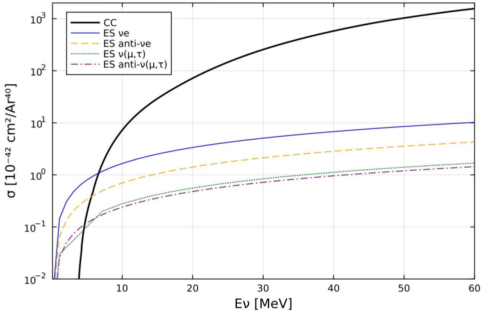
σ_{CC} ⇒ Charge-Current cross section computed by Marley (2101.11867)
σ_{ES} ⇒ Elastic-Scattering cross section élastique (Fundamentals of Neutrino Physics and Astrophysics)

$$\sigma(E_\nu, T_e^{\mathrm{th}}) = \frac{\sigma_0}{m_e}\left[\left(g_1^2+g_2^2\right)\left(T_e^{\max}-T_e^{\mathrm{th}}\right) - \left(g_2^2+g_1 g_2 \frac{m_e}{2\,E_\nu}\right)\left(\frac{T_e^{\max 2}-T_e^{\mathrm{th}^2}}{E_\nu}\right)+\frac{1}{3}\,g_2^2\left(\frac{T_e^{\max 3}-T_e^{\mathrm{th}^3}}{E_\nu^2}\right)\right]$$

n_{Ar} ⇒ Number of argon in the active volume : ≈ $1.45*10^{32}$
n_{e-} ⇒ Number of electrons in the active volume : ≈ $2.7*10^{33}$



	^8B	*Hep*
CC	≈ 220 000	≈ 1 200
ES	≈ 120 000	≈ 250



Low-energy background in DUNE

Neutrons ⇒ highest contribution of background :

- Neutron capture on argon or outside the detector

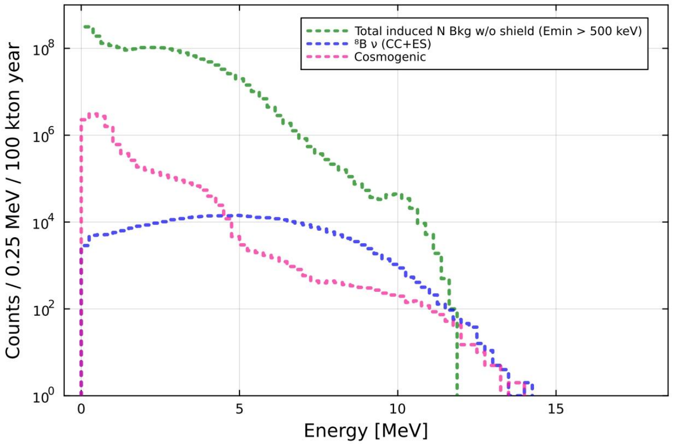
^{36}Ar ⇒ 8.8 MeV

^{40}Ar ⇒ 6.1 MeV

γ cascade greater than 10 MeV

Cosmogenics ⇒ Unstable Isotopes produced by atmospheric muons :

- Decay by emitting particles with an energy above 12 MeV



Expected energy spectrum for the different signals

Background reduction :

Neutrons :

- Shielding application around the detector
  → Thermalisation and capture
- Fiducialization cut ⇒ Exclude deposits in a certain perimeter
  → Removal of events produced at the edge of the detector

Cosmogenics :

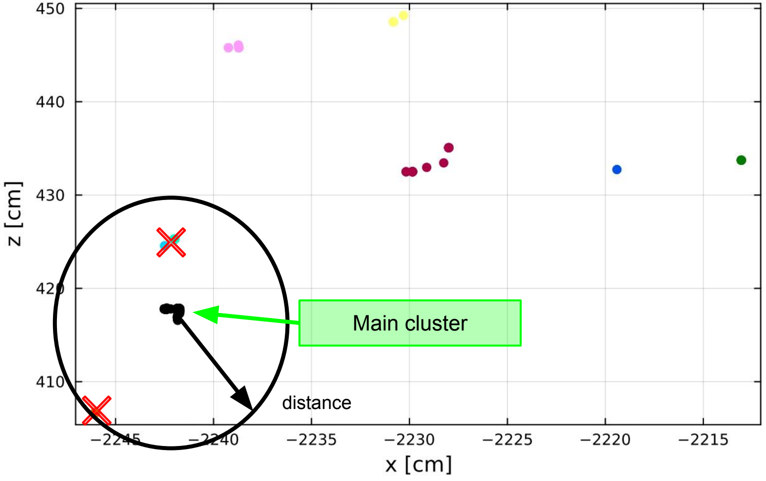
- Time cut
  → Decrease of the upper part of the energy spectrum
- Combine with a spatial cut around the muon track

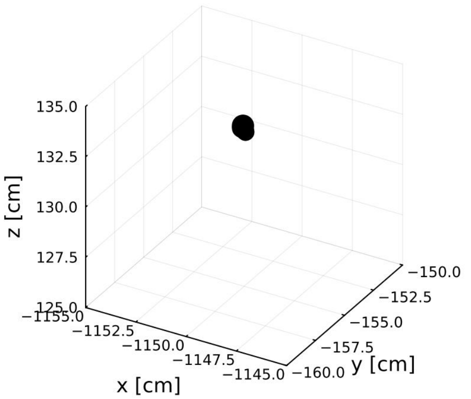
⇒ Significant reduction allowing solar neutrino observation

Cluster discrimination for ES events

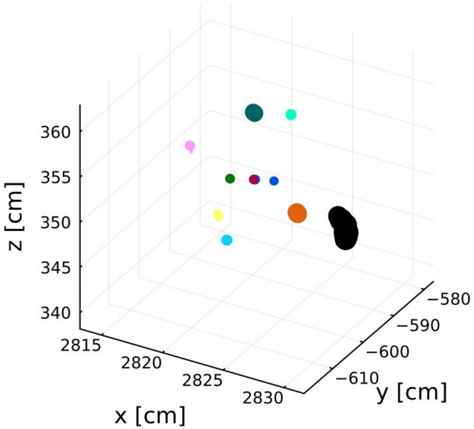
Application of a new method to further reduce neutrons → Using neutron capture signatures to reject neutrons

⇒ Removal of events with secondary clusters around the main cluster within a certain perimeter





Event kept



Event that can be rejected

Space Charge computation

Deviation due to the Space Charge is computed by comparing the expected positions with the reconstructed positions

How the expected positions are calculated :

→Hits of the track in the first 50cm near the anode planes are selected

→A direction is computed with a reference point

→**The reconstructed positions are projected on the fitted straight line**

→The difference between the reconstructed position and the expected position is calculated for each axis at each position

Calculus of the projection

Parameters :

(x,y,z) = reconstructed positions
(p1,p2,p3) = reference point
v = direction vector

Distance from the reference point :

dx = x - p1 ; dy = y - p2 ; dz = z - p3;

Projection parameter :

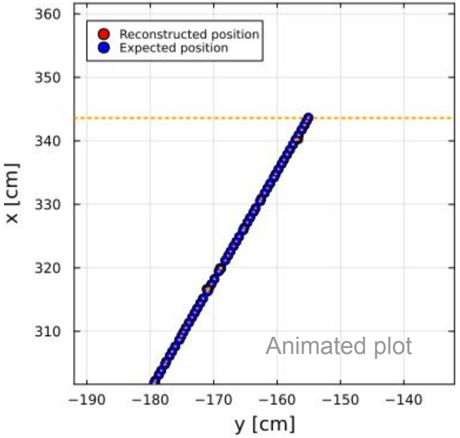
$t = (dx * v_x + dy * v_y + dz * v_z) / ||v||^2$

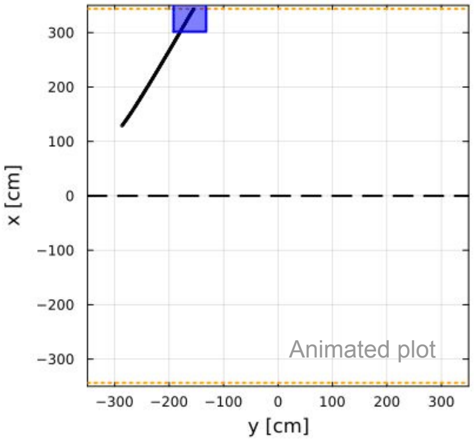
Expected positions :

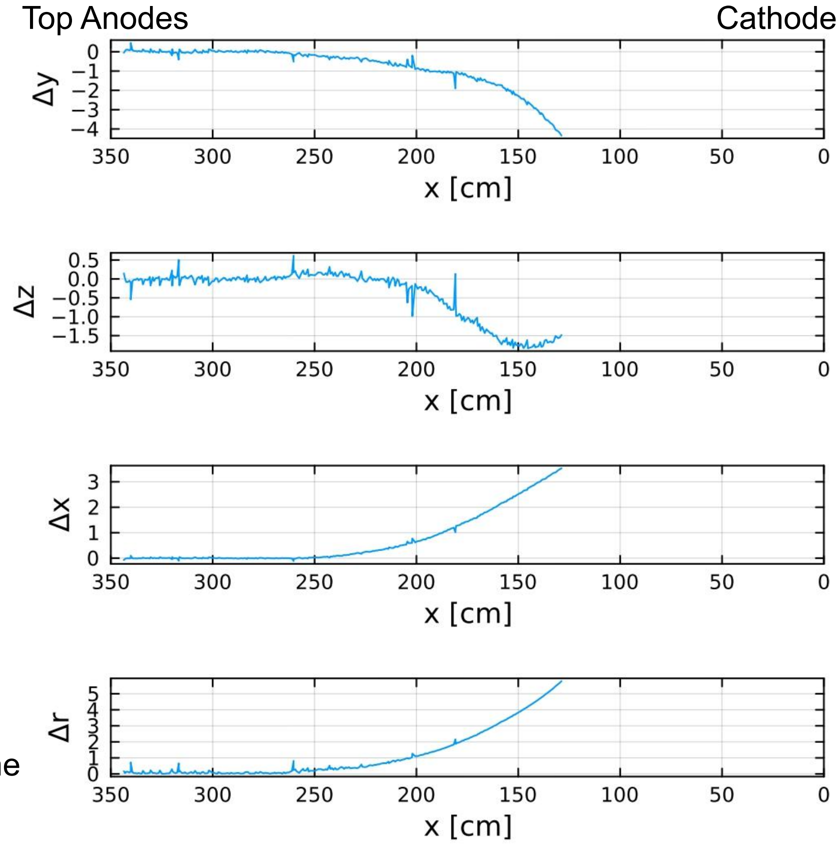
$x_e = p1 + t * v_x$
$y_e = p2 + t * v_y$
$z_e = p3 + t * v_z$

Space Charge computation for anode crosser

The same method is applied here :
first 50cm hits selection →Direction fit→Projection→Differences





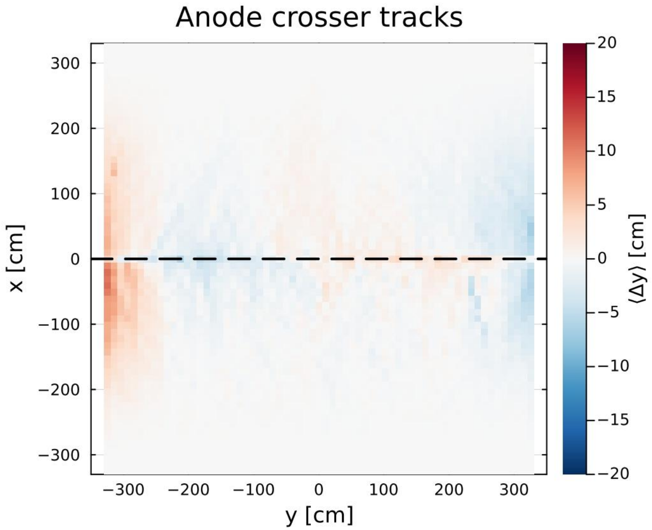


→ The differences becomes increasingly significant as one moves away from the anode plane

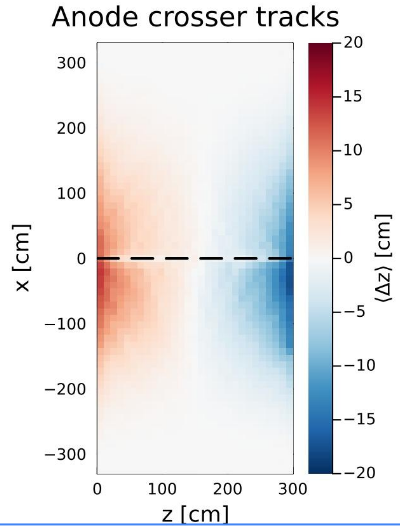
Result for one track

Results for Anode crosser tracks

Average lateral differences of all the Anode crosser tracks : Δy and Δz



Color description :
Red : right shift
Blue : left shift

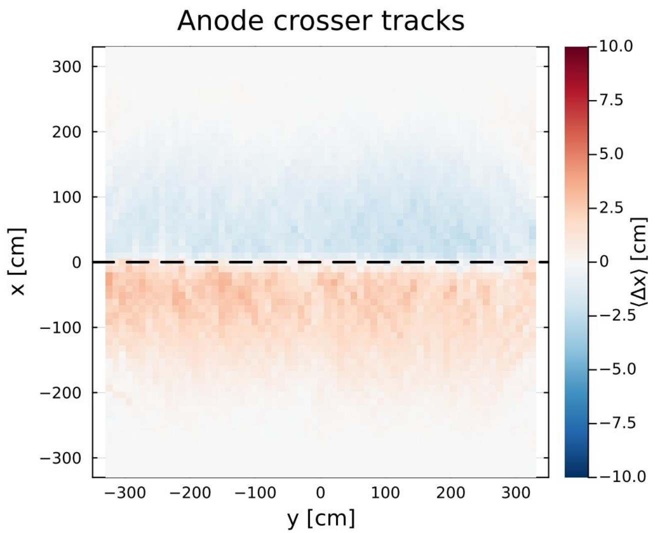


→ The differences along the lateral axis show that the Space Charge shifts the positions towards the center of the volume

→ As for the Anode-Cathode-Anode tracks, the modification of the electric field lines is more important near the field cage

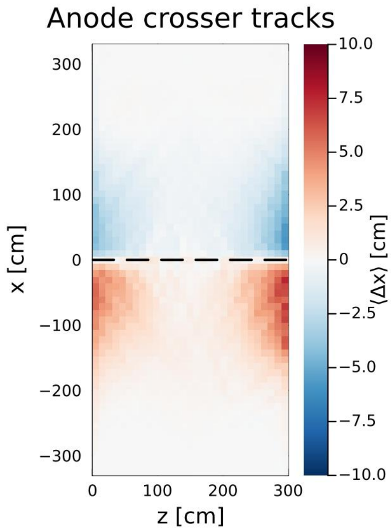
Results for Anode crosser tracks

Average vertical differences of all the Anode crosser tracks : Δx



Color description :
Red : up shift
Blue : down shift

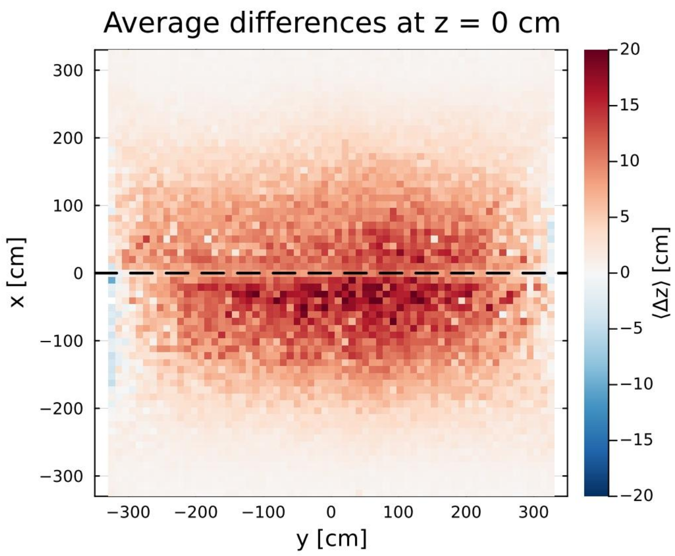
Color scale is reduced to (-10,10)

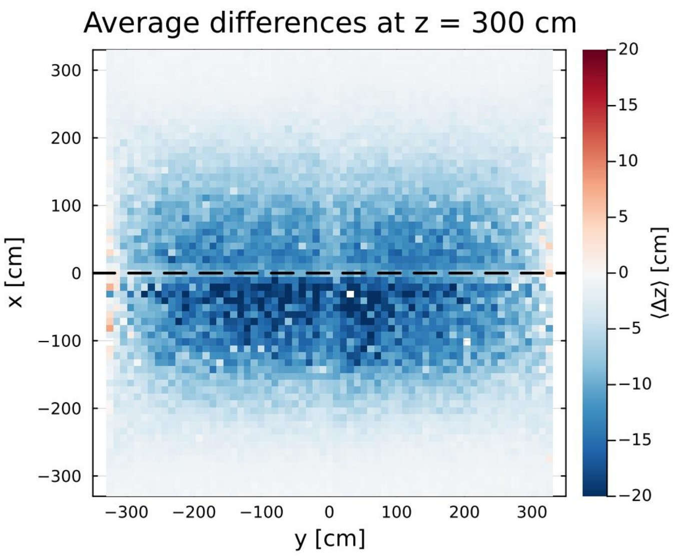


→ The differences along the vertical axis are less important and show that the Space Charge shifts the positions towards the cathode plane

→ Unlike the Anode-Cathode-Anode tracks, the Space Charge effect is uniform and reversed

Space Charge on the detector's surfaces





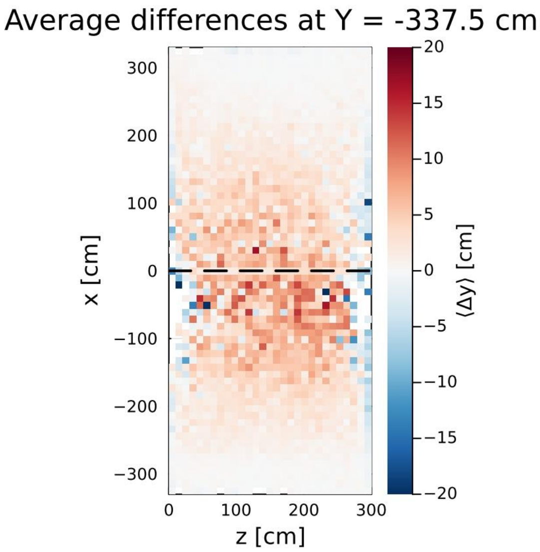
Here, Δz only computed for the last point of the track

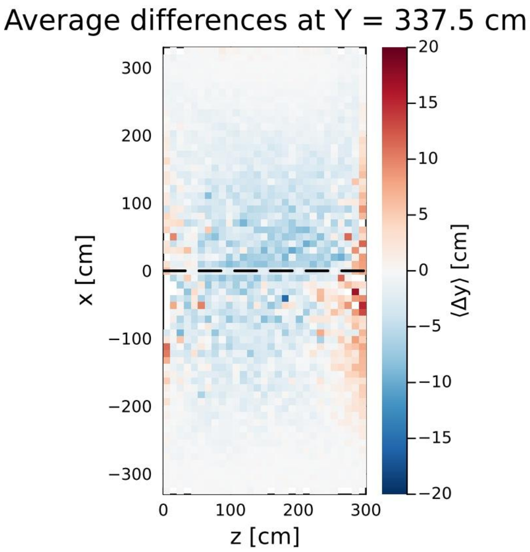
For each surface, Δz shows a shift toward the center

Higher values near the cathode plane

Asymmetry between Top and Bottom volumes

Space Charge on the detector's surfaces





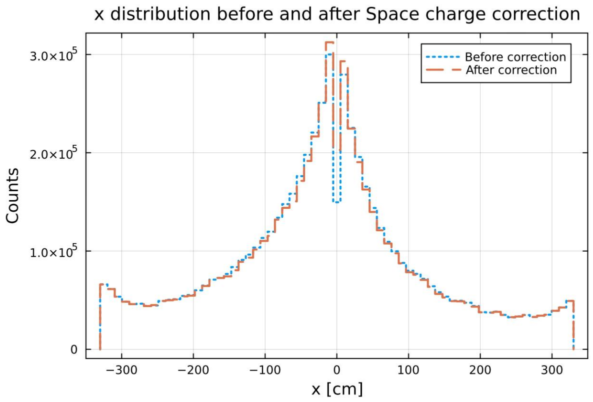
Here, Δy only computed for the last point of the track

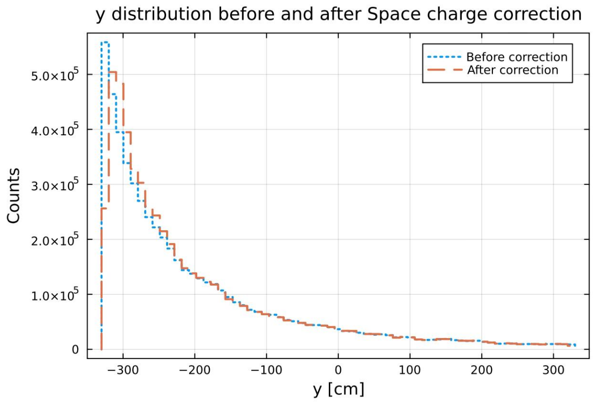
For each surface, Δy shows a shift toward the center

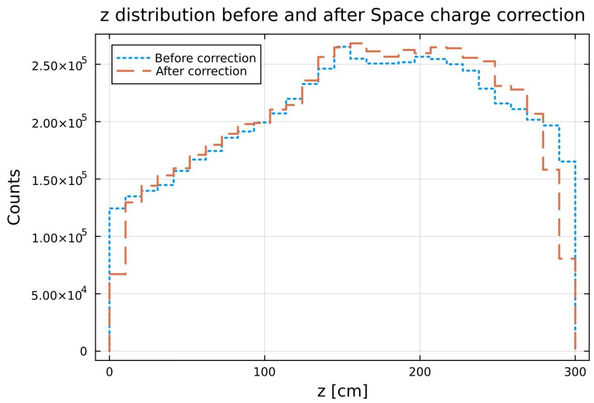
Higher values near the cathode plane

Asymmetry between Top and Bottom volumes (not very clear with low statistic)

Application of Space Charge Effect on PNS







PNS position → x = -30, y = -580, z = 190

- At first, the ES energy reconstruction is poor
  - Compute the θ angle to improve this reconstruction
  - The angular distribution is too imprecise to reconstruct correctly the energy

- Realistic fitting method to compute the angle

- Implementation of a "sun" mode in Marley to launch neutrino according to the Sun's position

- It is possible to distinguish neutron background and ES electrons by using the cos(θ) distribution
  - ES electrons will be directed according to the position of the Sun
  - cos(θ) distribution for neutron capture in LAr is uniform

- With nominal shielding, discrimination method applied, and the forward peaked cos(θ) distribution of ES electrons (cos(θ) ≈ 1), the background can be strongly suppressed

Cosmic muon tracks allowed us to do a first characterization of Space Charge effect in PDVD

- Anode-Cathode-Anode tracks show Space Charge Effect pushing horizontally the hits towards the center of the active volume
- The vertical differences are less uniform and smaller

The study has been then extended to Anode crosser tracks

- Same trend in the horizontal axis
- Average vertical differences show different trends compared to Anode-Cathode-Cathode tracks

→By looking at the track hits near the cathode plane, different regions of the detector are considered according to the type of tracks

→ Improvements are planned (Matching light, tracks that cross each other)

→First application of the Space Charge Effect deviations on PNS simulation