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

Maël Martin

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Directors :
Dominique Duchesneau
Luis Manzanillas Velez

CSI committee :
Mathieu Bongrand
Francisco Jose Iguaz Gutierrez
Iro Koletsou

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 have mass

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i} |\nu_i\rangle$$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

PMNS Matrix

Oscillation parameters :

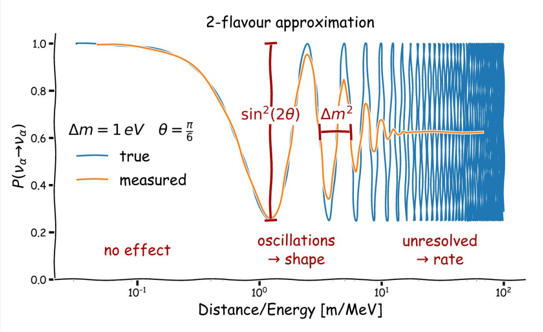
- Mixing angle θ_{ij} ⇒ Oscillation amplitude
- Mass differences Δm² ($m_i^2 - m_j^2$) ⇒ Oscillation frequency
- Oscillations are expressed as a function of a probability ⇒ Depends on the energy and the distance

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

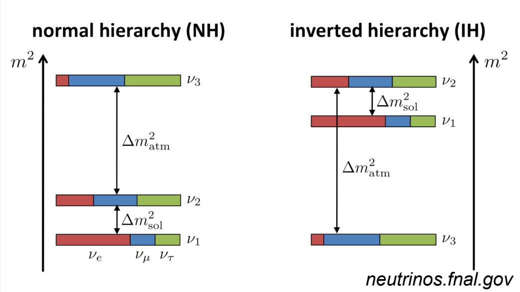
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2_{ji} L}{4E}\right)$$

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

Oscillation probability and survival probability for a 2 flavors case



Survival probability as a function of the distance L and the energy E (1906.01739)



Different neutrino mass orderings : normale (NO) or inverted (IO)

The DUNE experiment

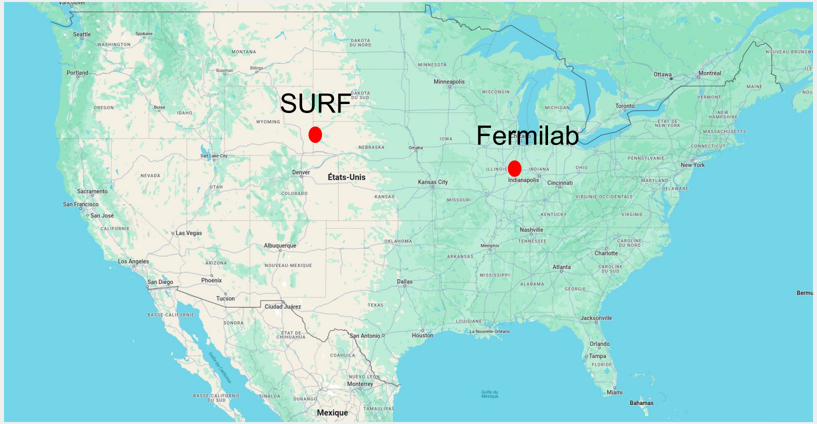
- DUNE ⇒ Deep Underground Neutrino Experiment
- Located in the United States (Fermilab and SURF)

DUNE's physics goals :

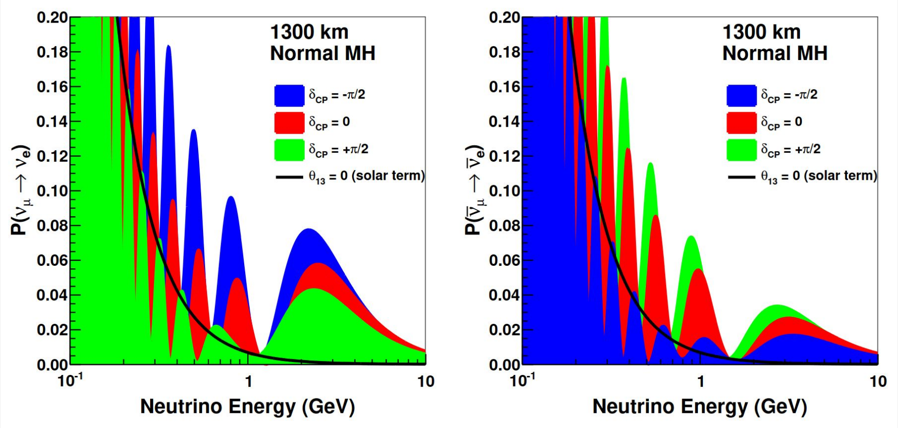
- Matter–antimatter asymmetry ⇒ δ_{CP}
- Neutrino mass ordering ⇒ Δm^2
- Solar neutrinos and Supernovae neutrinos

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{\Delta_{31}-aL}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

Oscillation probability of electron neutrinos for the DUNE experiment



Location of laboratories used by DUNE

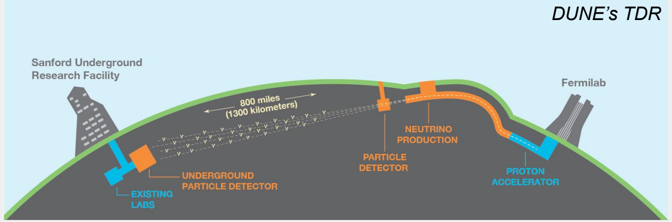


Oscillation probability of electron neutrinos as a function of the energy (2002.02967)

DUNE's detectors

The facilities :

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

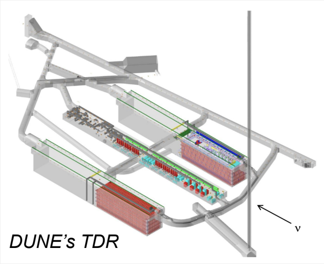


DUNE's facilities

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



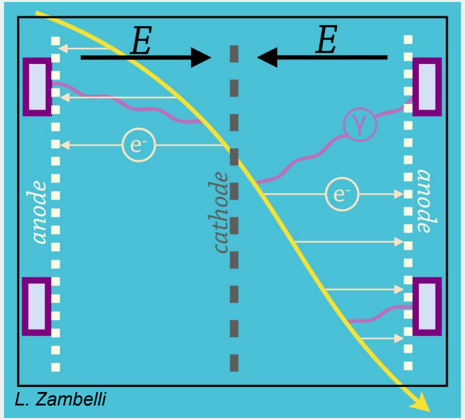
DUNE's cavern

Use of LArTPC for the first two modules :

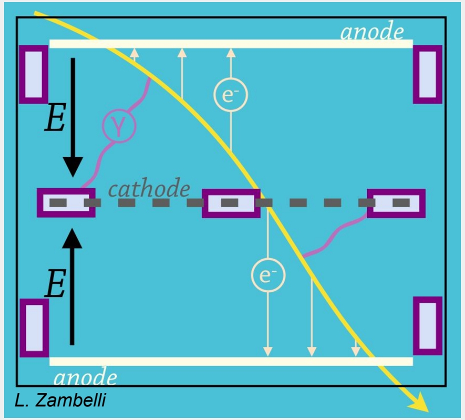
- Ionization e- produced after particle-Argon interaction
- Drift of ionization e- towards the detection systems thanks to an electric field of 0.5 kV/cm
- Recombination of electrons produces the emission of a light signal detected by an ARAPUCA

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



Horizontal Drift

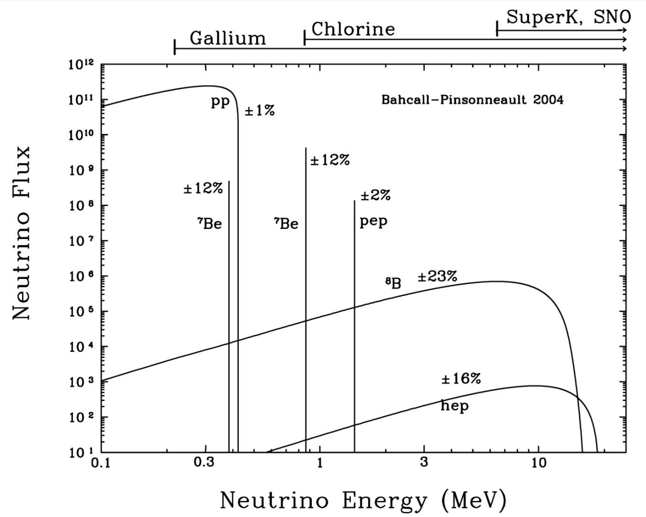


Vertical Drift

Solar neutrinos

Main purpose of DUNE ⇒ Study neutrinos at GeV-scale

This experiment has also the capacity to observe MeV-scale neutrinos→Supernovæ neutrinos and **solar neutrinos**



Solar neutrino fluxes (astro-ph/0412440)

Solar neutrinos→65 billions per cm² per second on Earth

→ Study the inner layers of the Sun which can't be observed with optical measurements
→ Understanding of thermonuclear reactions
→ Comparison of different solar models

Measurement of two different flux with DUNE :

^{8}B :

- Highest flux above 2 MeV
- Gives information on the sun temperature

Hep :

- Most energetic flux
- Never observed before

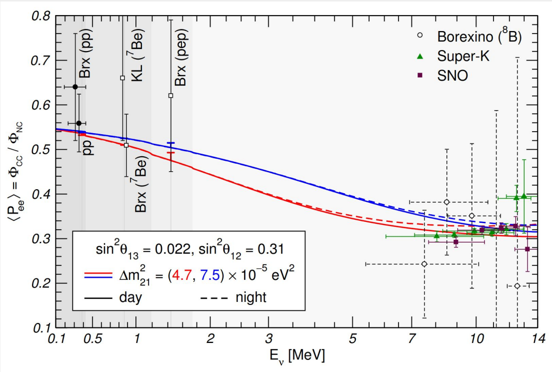
Solar neutrinos

⇒ Possibility to measure oscillation parameters directly with solar neutrinos

- Mixing angles θ_{12} et θ_{13}
- Mass differences Δm^2_{21}
- Matter effect with day/night asymmetry

Survival probability P_{ee} :

$$P_{\nu_e \to \nu_e} = \frac{1}{2} \cos^4 \theta_{13} [1 + \cos 2\hat{\theta}_{12} \cos 2\theta_{12}] + \sin^4 \theta_{13}$$

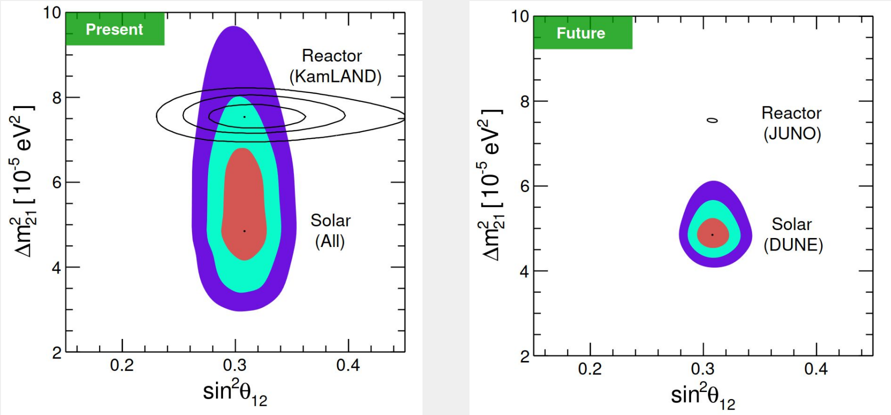


Survival probability P_{ee} (1507.05287)

Reactor neutrino experiments are also able to measure these parameters ⇒ Discrepancy of ~ 2σ between reactor and solar neutrino measurements

The JUNO experiment will shortly determine these parameters with a high precision

There is a necessity to measure precisely solar neutrinos to compare the obtained values of the oscillations parameters



Measurements of θ_{12} and Δm^2_{21} (current and future) (1808.08232)

Solar neutrino spectrum

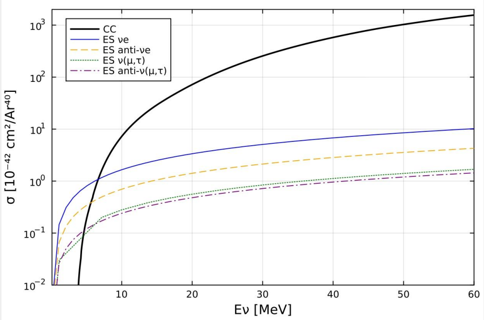
$N_{CC/ES} = \Sigma\, \phi_\nu * \sigma_{CC/ES} * n_{Ar/e-}$

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

$$\sigma(E_\nu, T_e^{\rm th}) = \frac{\sigma_0}{m_e}\left[(g_1^2+g_2^2)\,(T_e^{\rm max}-T_e^{\rm th}) - \left(g_2^2 + g_1 g_2\,\frac{m_e}{2\,E_\nu}\right)\left(\frac{T_e^{\rm max2}-T_e^{\rm th^2}}{E_\nu}\right) + \frac{1}{3}\,g_2^2\left(\frac{T_e^{\rm max3}-T_e^{\rm th^3}}{E_\nu^2}\right)\right]$$

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

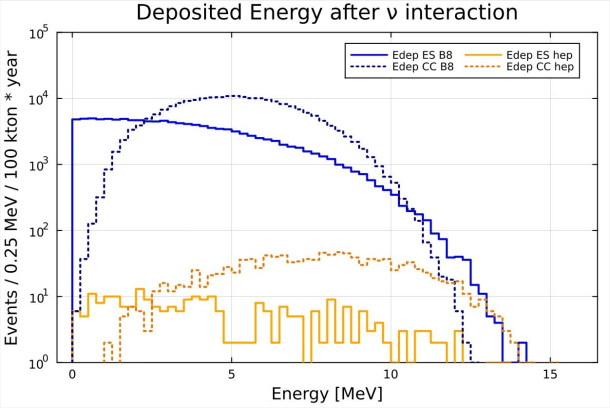


Charge-Current and Elastic-Scattering cross sections

DUNE's advantages :

- Huge detection volume ⇒ 40 kilotons with 4 modules (Super-Kamiokande is approximatively 20 kilotons)
- 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 ⇒

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



Solar neutrino spectrum in DUNE

	^{8}B	*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

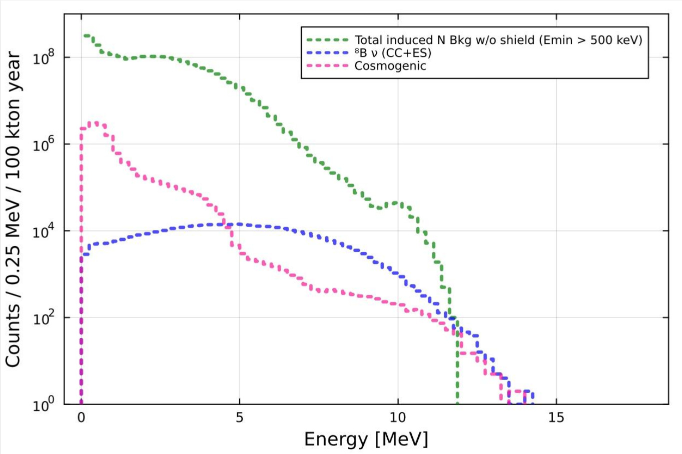
^{36}Ar ⇒ 8.8 MeV

^{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 creation and energy reconstruction

The different contributions are simulated with Geant4

→ Clustering of the deposits in the liquid argon
→ The reconstructed energy corresponds to the most energetic cluster
→ The clustering distance is selected according to the difference between the initial energy and the reconstructed energy

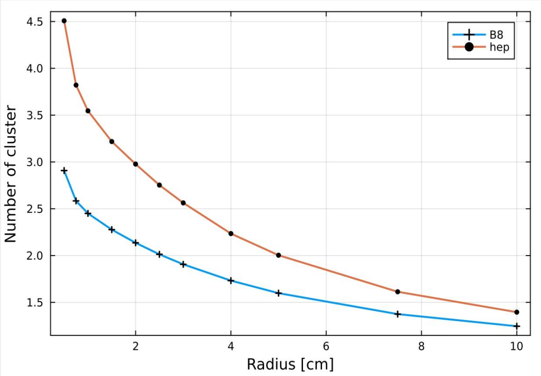
- Electron interaction (MeV) in argon :

→ Linear and continuous
→ Can be contained in one cluster

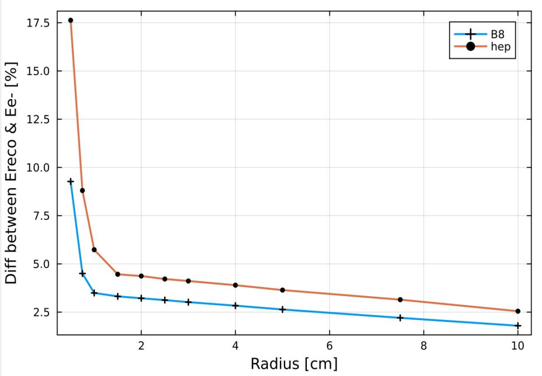
- γ interaction in argon :

→ Several dispersed deposits
→ Several clusters created

⇒ Use of a 2.5 cm radius for the future analyses



Average number of clusters as a function of the clustering radius (ES interaction)

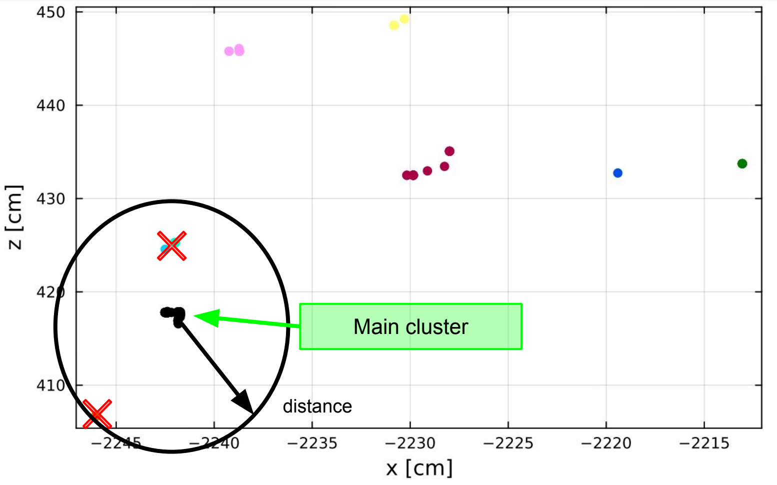


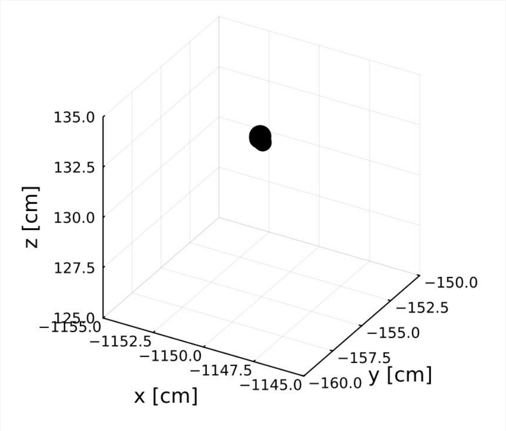
Difference between initial energy and reconstructed energy (ES interaction)

Cluster discrimination for ES events

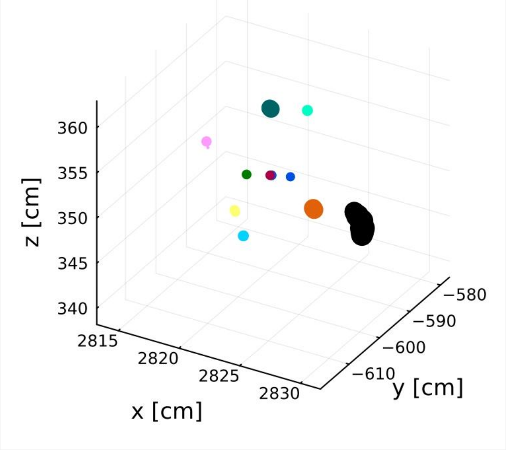
Application of a new method to further reduce neutrons → Using neutron capture signatures to reject neutrons

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





Event kept



Event that can be rejected

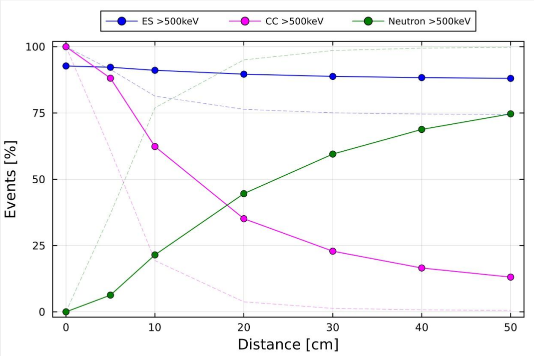
Influence of energy threshold on discrimination

Discrimination method depends on threshold energy

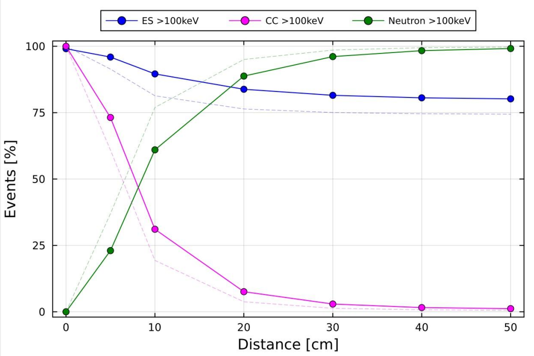
→ Less energetic clusters will be not take into account

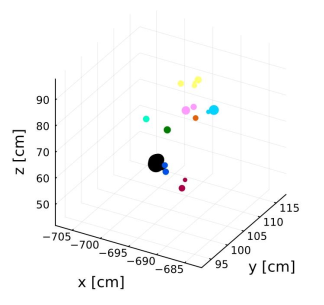
→ A rejected event can be saved

- At 500 keV : More ES events saved **but the neutron background removal is less important**
- At 100 keV : Less ES events saved **but the neutron background removal is very efficient**

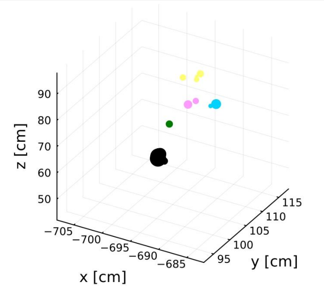


Percentage of events saved (blue and pink) or rejected (green) for different types of interaction

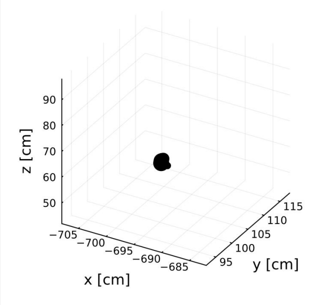




No threshold



100 keV threshold



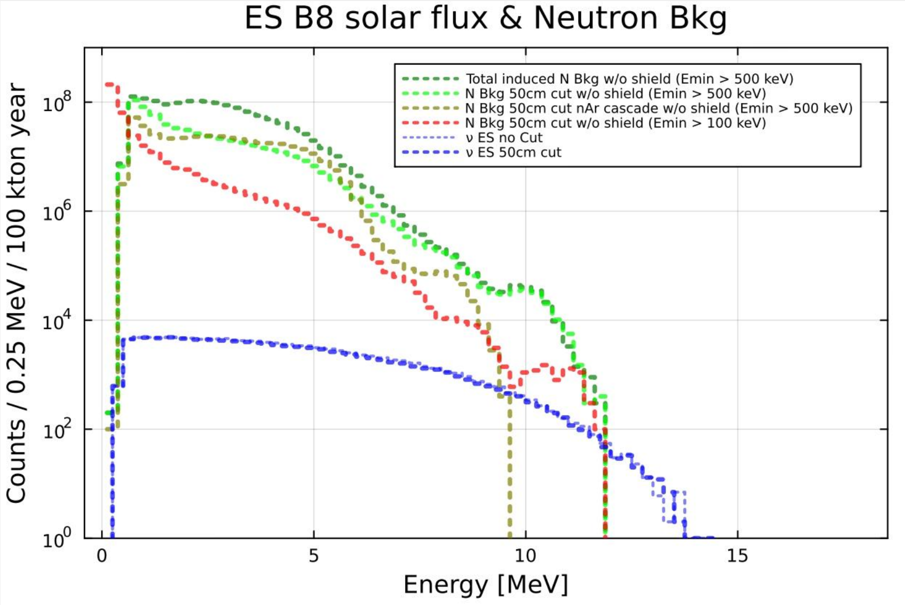
500 keV threshold

Energy spectrum : 1st case

Most pessimistic case :

→ No shielding
→ No fiducialization
→ Energy threshold at 500 keV

- **The neutron background is very important !!**
  - More than **a factor 10^4** compared to the ^8B flux
- ES solar neutrinos observation is difficult **until 12 MeV**
- Discrimination method inefficient with an energy threshold of 500 keV
  - The red curve shows the efficacy of this method with a lower energy threshold (100 keV)



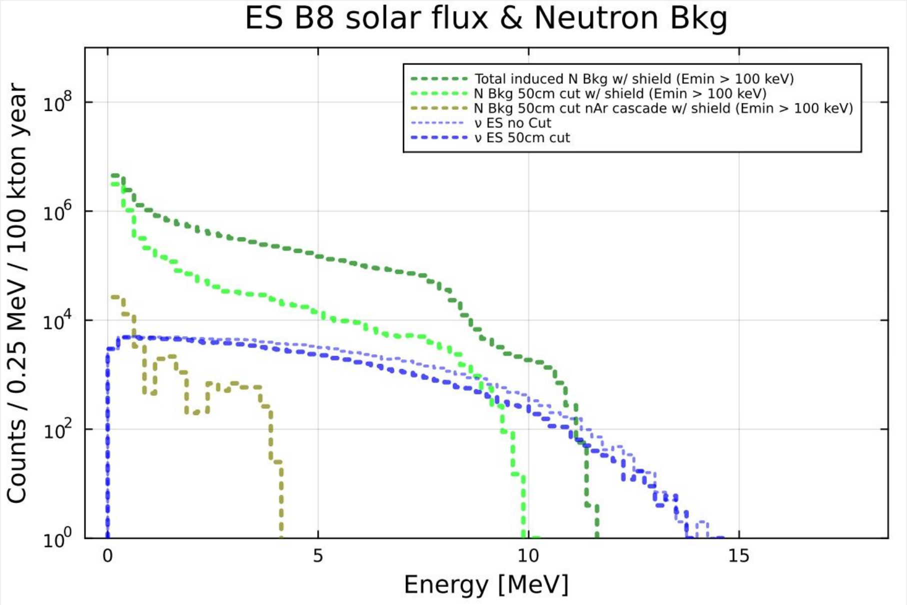
Energy spectrum : 2nd case

Nominal shielding : 30 cm borated HDPE at the bottom & 23 cm water on the sides

Use of different reduction methods :

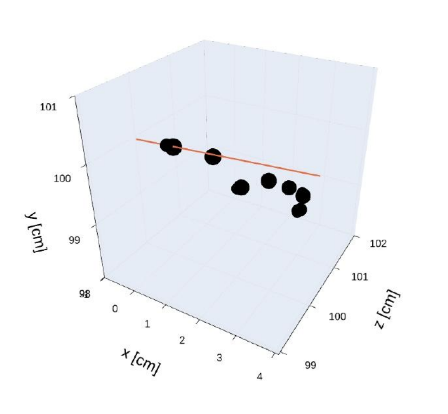
→ Shielding
→ Fiducialization cut
→ Energy threshold reduced to 100 keV

- **The neutron background is clearly less important thanks to the shielding**
  - It has been reduced by more than a factor 10
- **Discrimination method is very efficient** with an energy threshold of **100 keV**
  - There is a factor 10 difference between the case with and the case without the discrimination method
  - There is no more background above 10 MeV



Angle cut for ES events

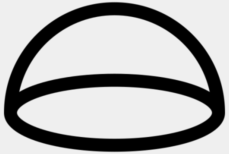
The direction of the ES outgoing electron is correlated with the initial direction of neutrino

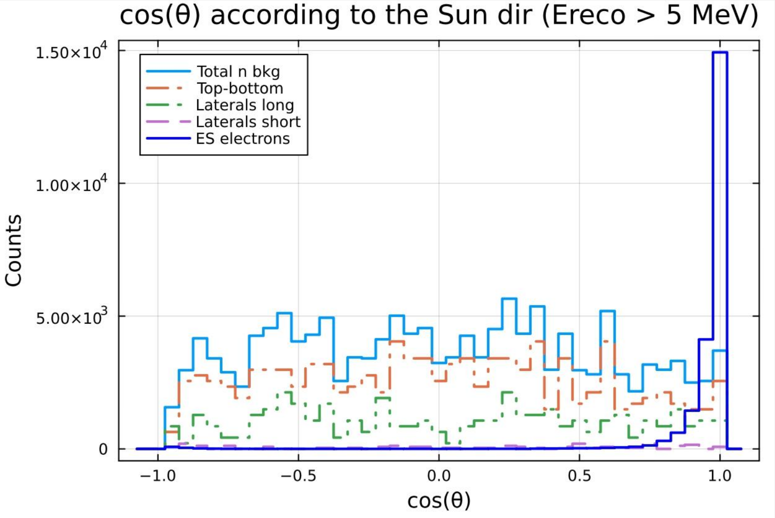


A straight line (orange) is fitted with the first 3 deposits to compute the outgoing electron direction

→ One angle is then determined between these two directions

→ Doing the same with neutrons launched from outside with a half sphere random direction towards detector wall

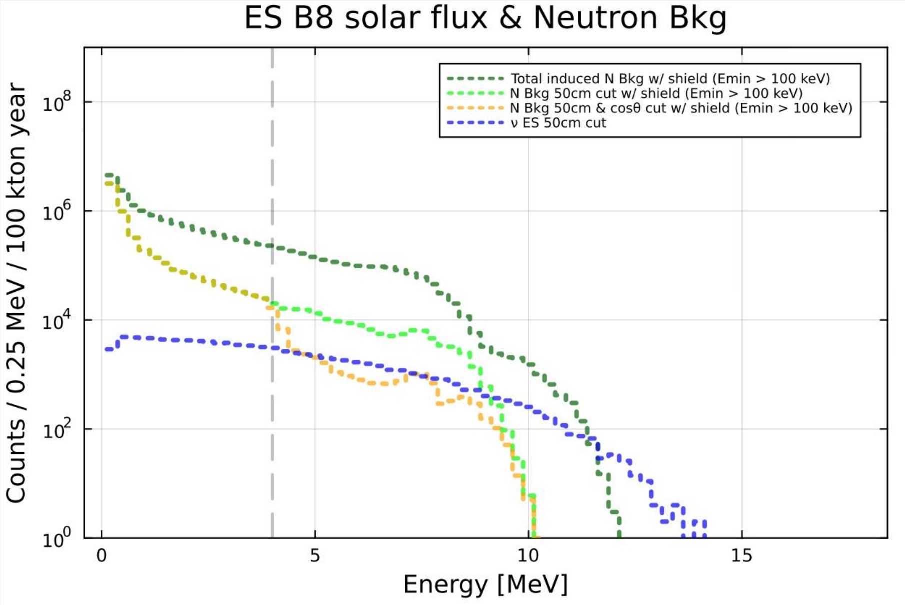




ES events become more dominant compared to background when cos(θ) > 0.7

Energy spectrum : 3rd case

Nominal shielding : 30 cm borated HDPE at the bottom & 23 cm water on the sides



Use of different reduction methods :

→ Shielding
→ Fiducialization cut
→ Energy threshold reduce to 100 keV
→ **Events with cos(θ) > 0.7**

- **There is a clear improvement by applying the angle cut**
  - **The neutron background becomes inferior to the ES signal above 5 MeV**

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

Neutron background reduction

→ This analysis shows at first the necessity to put a shielding around the detector to thermalise and capture neutrons

→ Application of a fiducialization cut to reject events close to the edges of the active volume

→ Application of a discrimination method to remove events by taking into account the signature of a neutron capture

→ Use of a low-energy threshold to make this method efficient

→ Application of an angle cut to remove events with no directionality

→ It is essential to know the capability of the detector at this energy scale

→ Data analysis of *ProtoDUNE-HD* located at the neutrino platform at CERN

Data analysis of *ProtoDUNE-HD*

Bring a new study of the Low-Energy features of the ProtoDune-HD by using different tools :

- LARDON as the data reconstruction software
- ULALAP as our internal Geant4 Simulation

Use of the Bismuth sources and radiological elements in structures to :

- Characterize the resolution
- Compute the recombination factor

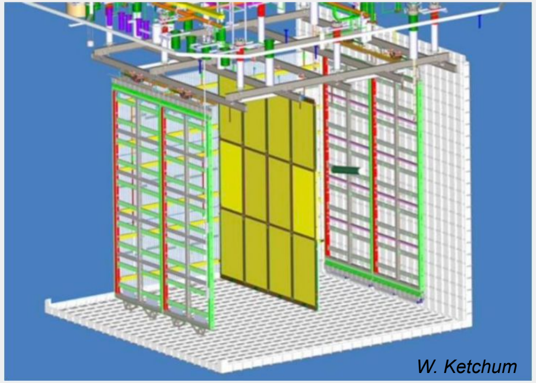
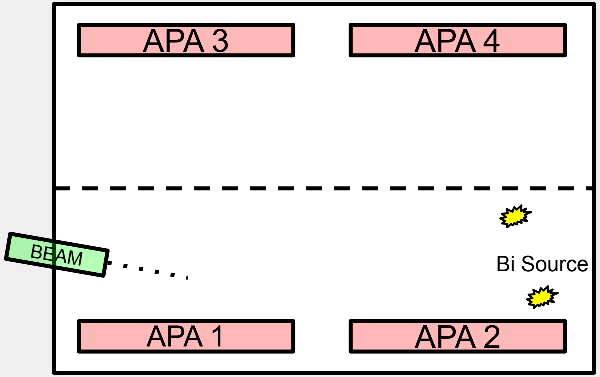


Illustration of ProtoDUNE-HD geometry

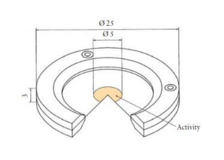
ProtoDUNE-HD :

→ One cathode in the center and two anodes at the edges
→ An anode is made of two APAs
→ The APAs are the detection systems

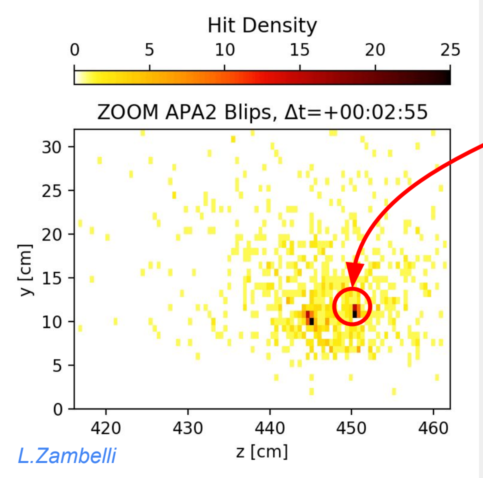


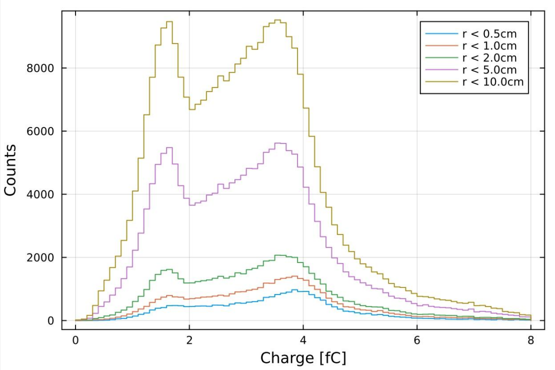
Zoom on the anode Bismuth source

The active deposit is a 5mm diameter circle in a 25mm diameter ring

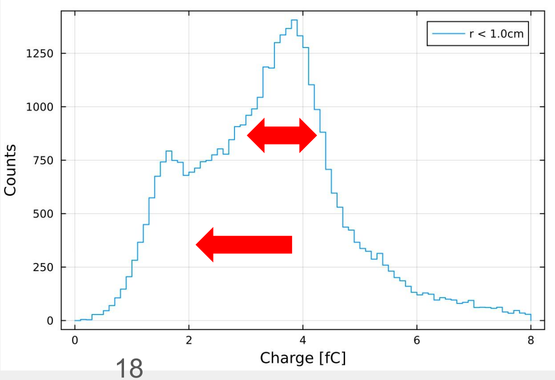


The source is localised only in a **few centimeters !**





Gammas contribution is more significant with a larger radius
⇒ Radius chosen for the next analysis = 1cm



Next step :

Resolution of the charge

Conversion factor to MeV unit

Chi2 test between data and MC

⇒ Chi2 = $\sum \frac{(Hist_{data} - Hist_{MC})^2}{Hist_{data}}$

⇒ Parameters :

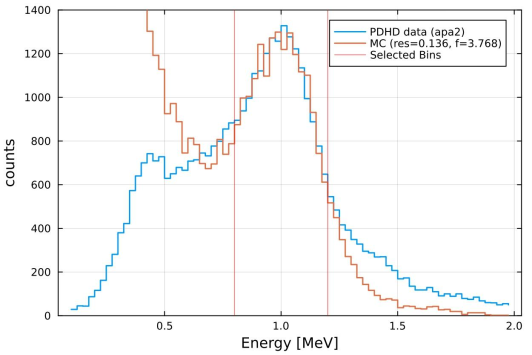
- selected bins = 0.8 : 0.025 : 1.2
- tested factors = 3.6 : 0.012 : 3.9
- tested resolution = 0.10 : 0.004 : 0.20

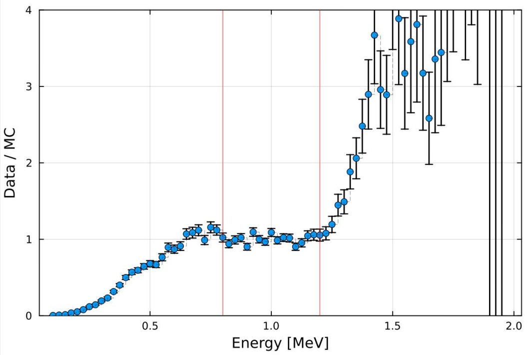
Minimum chi2 for :

- **f = 3.768 fC/MeV**
- **σ = 0.136**

Comparison of data & MC :

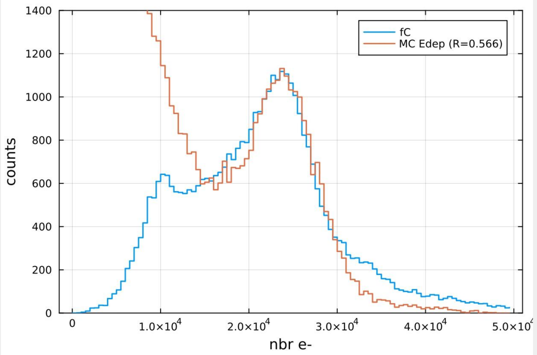
- Application of **resolution** and **fCtoMeV factor** show a **good match** between data and MC
- The Data/MC **efficiency is near 1** in the tested bins





→Estimation of the recombination factor R by calculating the number of electrons in two different ways

The best fitting is obtained when :
R = 0.566



For the cathode Bi source, the obtained values are :

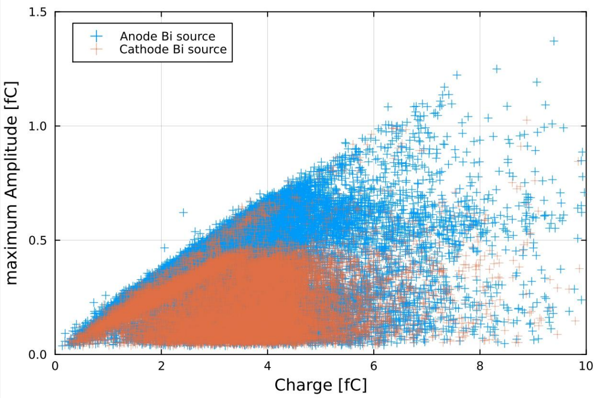
- **f = 4.102 fC/MeV**
- **σ = 0.145**
- **R = 0.608**

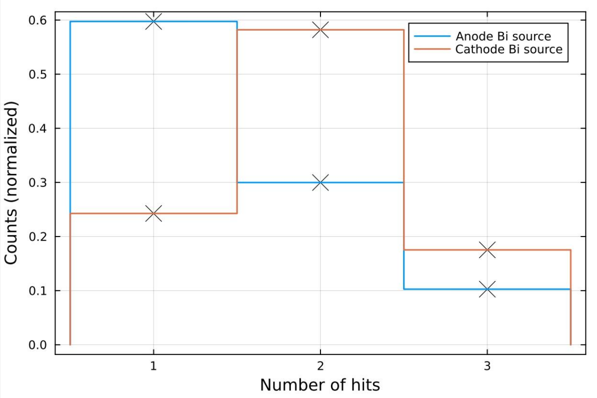
There are some differences between the two sources but the results are consistent between each other

Differences between the two sources

⇒ The two sources present **noteworthy differences** regarding some parameters

- The **anode single hits** have **a higher maximum amplitude** compared to the **cathode single hits**
- The **anode single hits** have **fewer concerned wires** compared to the **cathode single hits**

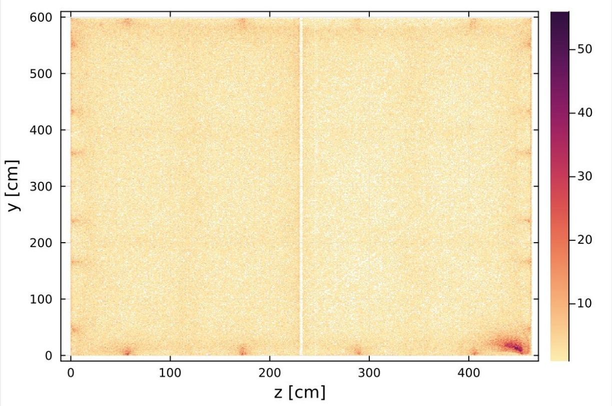




⇒ These differences may be caused by the diffusion of the electron cloud

This can be a way to separate events close to the anode or the cathode !

Radiogenics in *ProtoDUNE-HD*

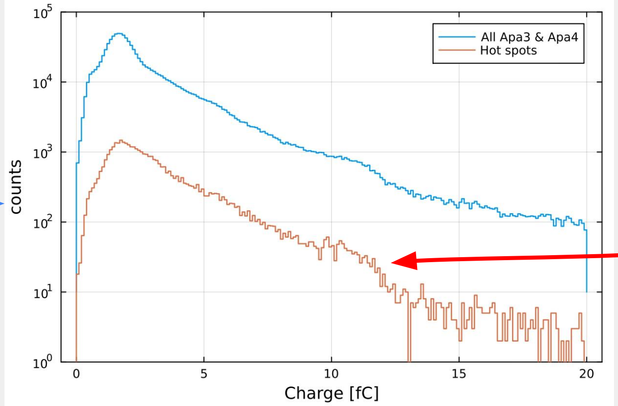


Thorium Contamination (^{232}Th) in the detector structure :

→ Field cage bars
→ Cathode structure

Possibility to estimate the recombination factor at a different energy

Use of Monte-Carlo simulation (^{212}Pb) to compare with the data



2.614 MeV γ-ray after β decay of 208-Tl

Compare the position of the drop of the signal with simulation instead of the shape of the signal

chi2 = $\sum \frac{\left(\frac{dN_{data}}{dx} - \frac{dN_{mc}}{dx}\right)^2}{\left(\frac{dN_{data}}{dx} + 0.1\right)}$

minimum chi2 for : **f = 4.76 fC/MeV**

→ **R = 0.701**

The obtained value is different because the recombination factor depends on the energy and the electric field

Data analysis of *ProtoDUNE-HD*

→ Analysis of the Bismuth sources :

- In a region of 1cm around the source, we found :
  - **An energy resolution of ~15 %**

- We estimated the recombination factor and it seems to be in agreement with Aprile's results

- The use of the two Bismuth sources allows to compare the signal at two different positions
  - It will help us study the diffusion and the space charge effect

→ Analysis of the Thallium contamination :

- We found a new value for the recombination factor (R = 0.701)

Conclusion & perspectives

→ Background reduction thanks to :

- A shielding
- A fiducialization cut
- A discrimination method, efficient with a low threshold
- An angle cut by taking into account the ES events directionality

Then :

- Add these modifications to the Solar fitter of *A.López-Moreno* to estimate the oscillation parameters
- Develop a second discrimination method for CC interaction

→ *ProtoDUNE-HD* analysis :

- Estimate the energy resolution
- Estimate the recombination factor

Then :

- Compare the analysis with one done with the LArSoft software
- Data analysis on *ProtoDUNE-VD*

→ Scientific production during the first year :

- Two talks given during collaboration meeting and participation in two workshops. Attended the Summer School on Neutrino Physics Beyond the Standard Model in Strasbourg this summer.

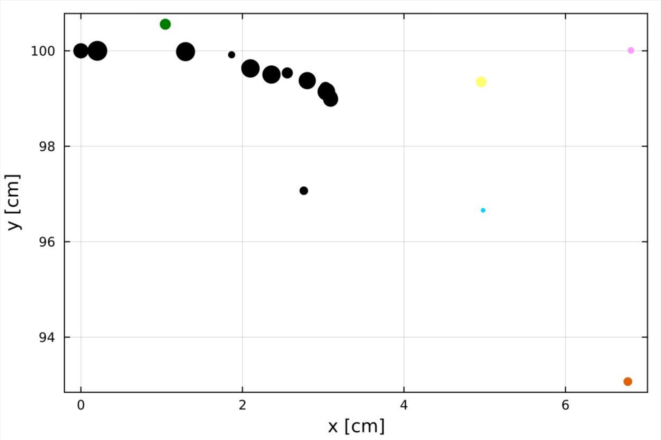
Thank you for your attention !

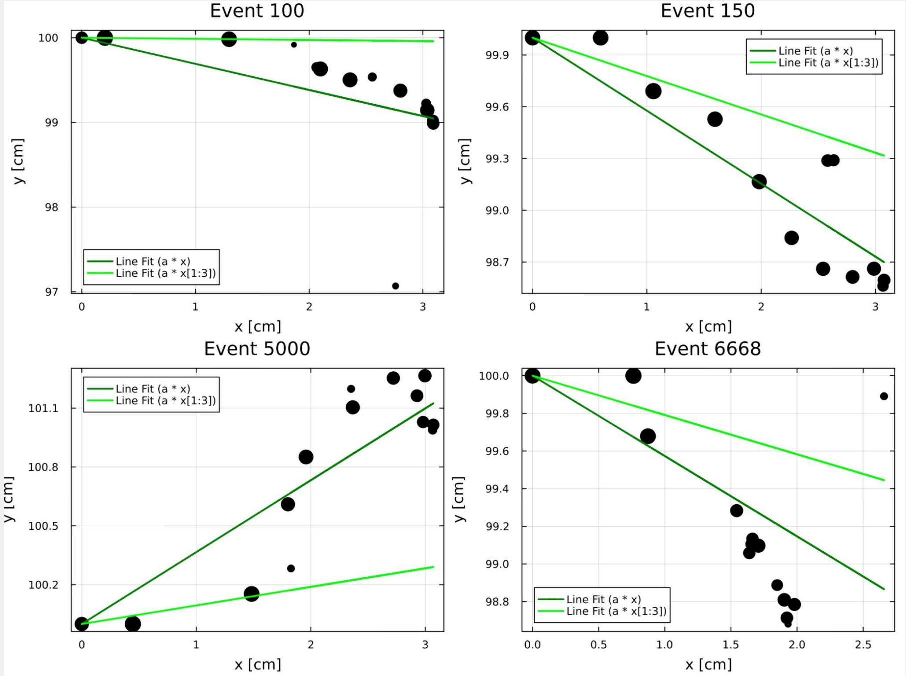
Backup

10 MeV electron simulation

Launch of 10 MeV electrons in LAr on the X axis

Example of an event :





→ One main cluster with close deposits

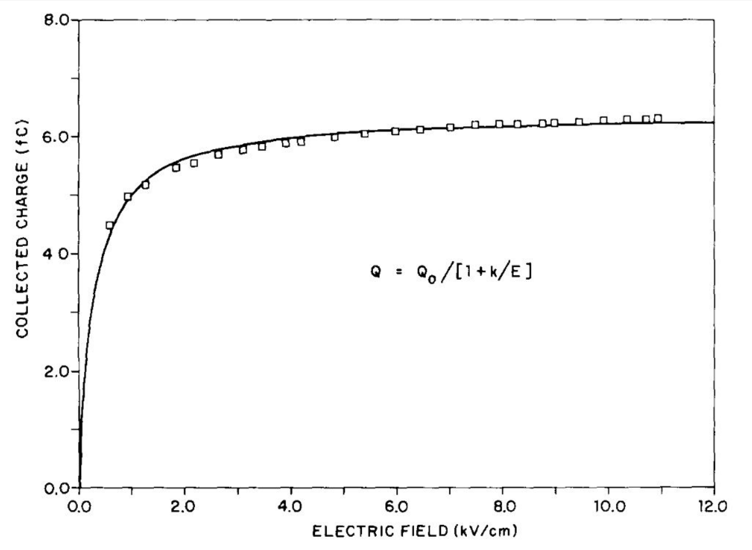
→ Some deposits that are further away due to bremsstrahlung

Focus on the main cluster for the analysis

- The first deposits of the track have in them the direction of the electron
  - Fit a straight line with the first three deposits
- Obtaining a coefficient : f(x) = x * a

Comparison with Aprile data

Energy resolution studies of liquid argon ionization detector : Measurement of the energy resolution in liquid argon at different drift fields, with a Bi-207 radioactive source and a small gridded ionisation chamber

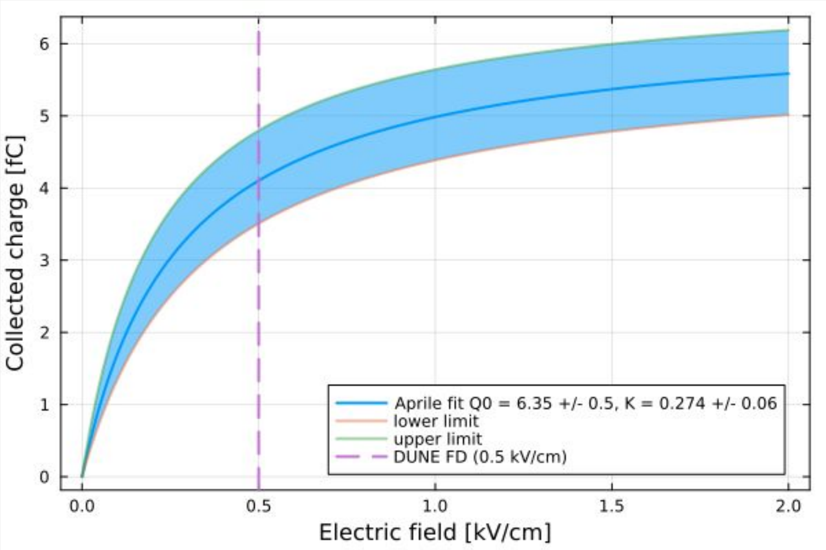


Aprile fit values :

- Q_0 = 6.35 +/- 0.5 fC
- K = 0.274 +/- 0.06 kV/cm

Thanks to their experimental conditions, they can distinguish the two conversion electron peaks.

⇒ Their fit is then made with the most dominant peak which correspond to the 976 keV electron.



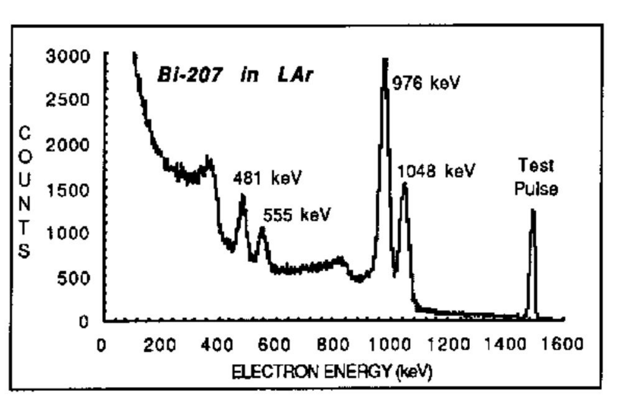
Goal : Add values at 0.5 kV/cm with the two Bi sources by finding the mean collected charge Q of the 976 keV peak with our data

Fit with two gaussians and an exponential

Use BAT.jl package to do a bayesian fit with our histograms

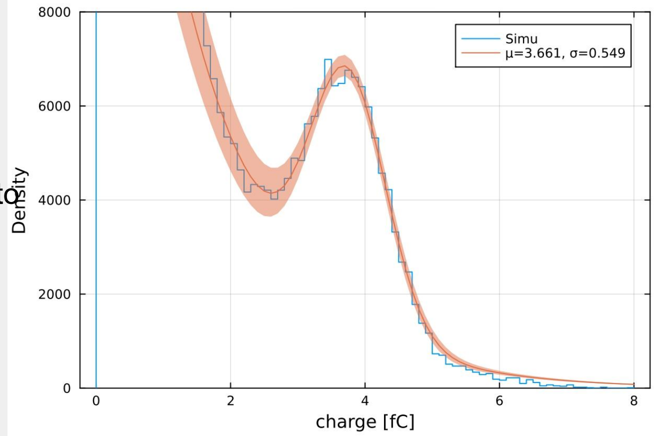
Initial parameters :

- Two gaussians separated by a factor 1.07, corresponding to the quotient between the two peaks (976 & 1048 keV)
- The density between the two peaks is the quotient of the number of counts for these two

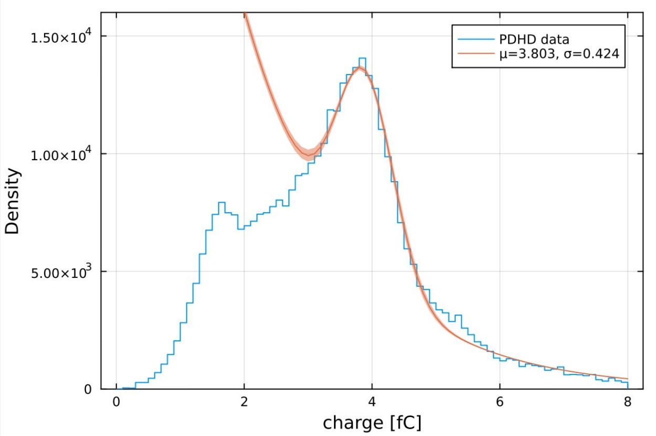


Delta electron production and the ultimate energy resolution of liquid argon ionization detectors PDF

Firstly ⇒ Fit our simulation histogram with the functions to obtain the parameters of the exponential



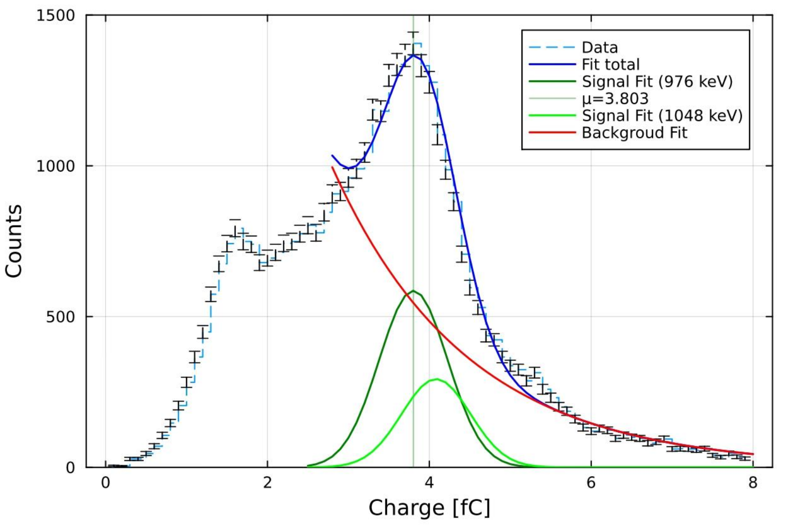
Second ⇒ Apply these exponential parameters and find the gaussian parameters with our data histogram

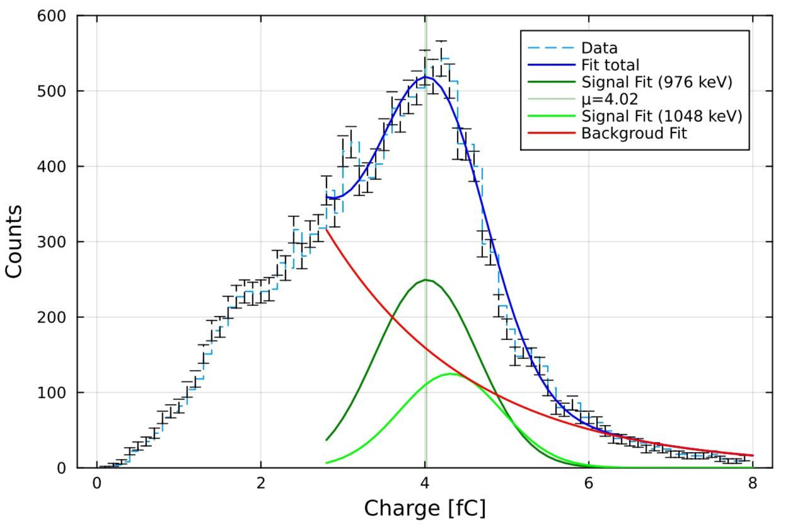


Fit with two gaussians and an exponential

If we look in detail the contribution of each function :

- Exponential ⇒ Background coming from gammas emitted by the source
- Two gaussians ⇒ Signal coming from the electrons (976 & 1048 keV)





Anode Bi source :

- Mean value of **3.803 fC for the 976 keV peak**, with an electric field of **0.5 kV/cm**

Cathode Bi source :

- Mean value of **4.020 fC for the 976 keV peak**, with an electric field of **0.5 kV/cm**

Comparison with Aprile data

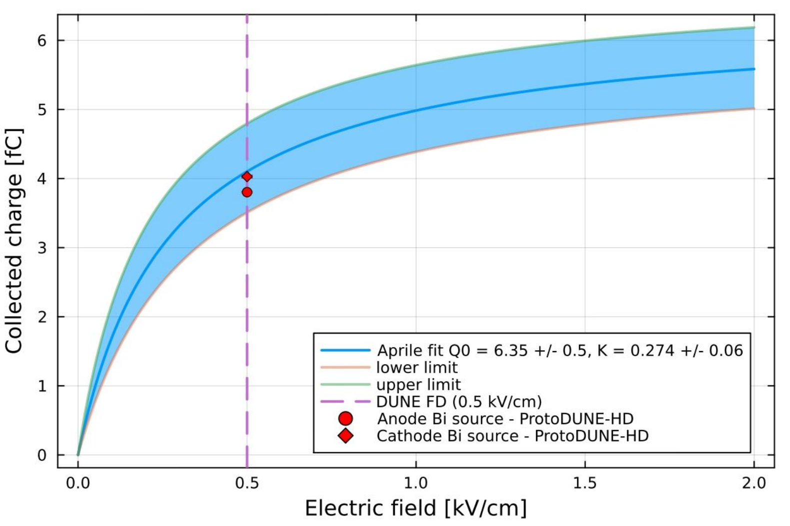
Anode Bismuth source : **Q = 3.803 fC**

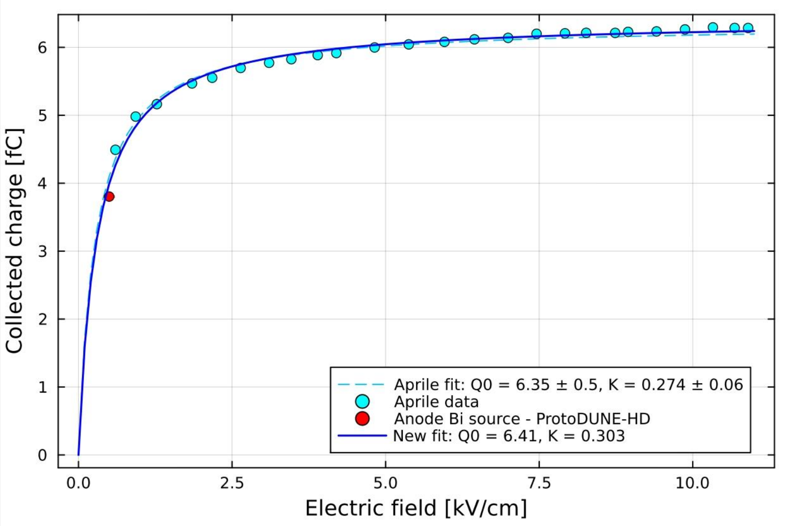
Cathode Bismuth source : **Q = 4.020 fC**

Addition of our values and recalculation of the fit

Parameters found with a fit taking into account our values :

Q_0 = 6.41
K = 0.303





Our study allowed to add values at low electric field and to redefine the function parameters