Study and improvement of the trigger system in ICARUS

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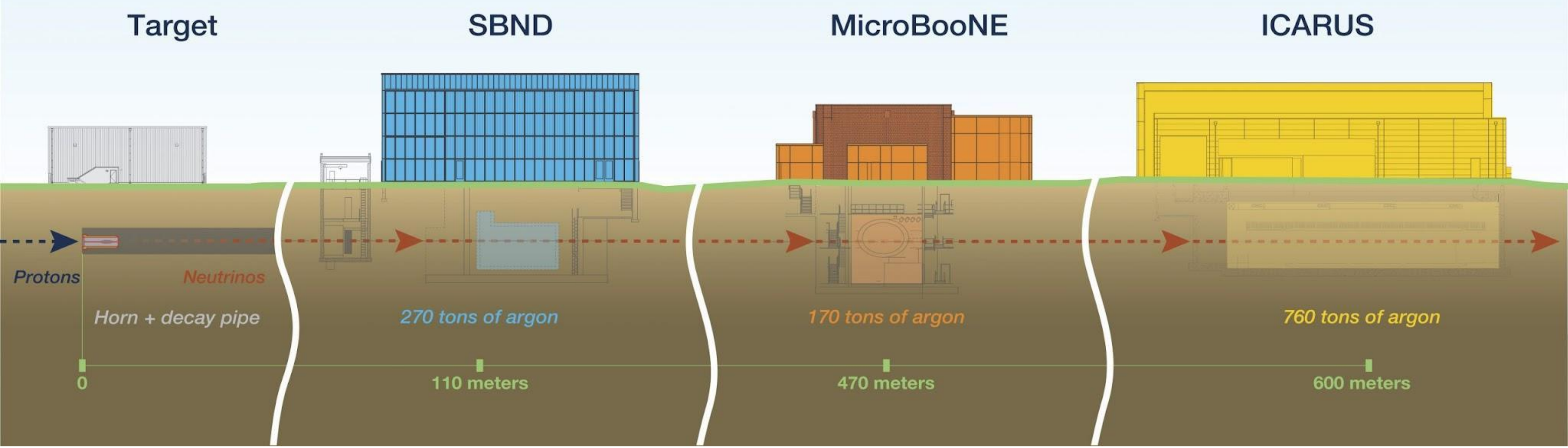
Short-Baseline Neutrino Program at Fermilab

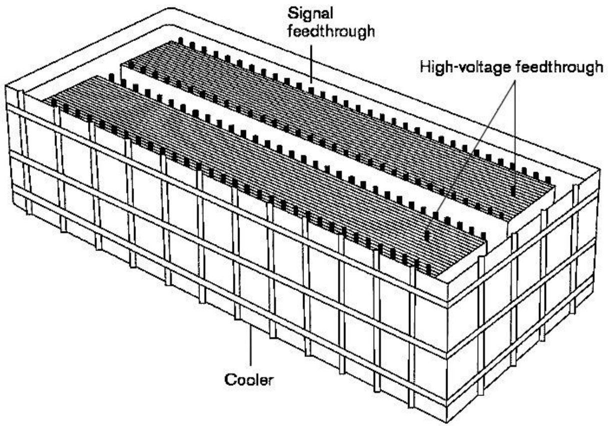


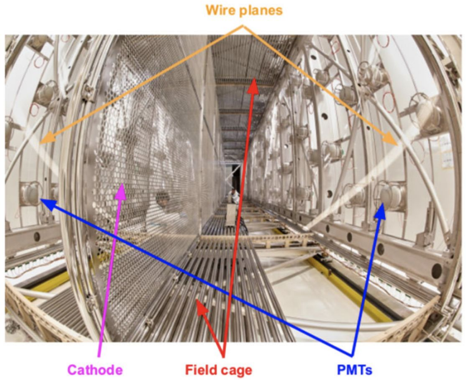
Short-Baseline Neutrino Program at Fermilab was set up:

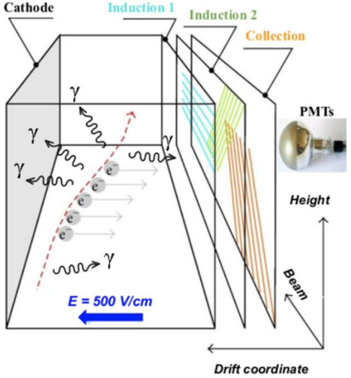
- to investigate **short-baseline neutrino oscillations**
- to further develop the LAr-TPC technology
- to measure σ(ν-Ar) in the *GeV region*
- to search for hints of physics **beyond Standard Model**

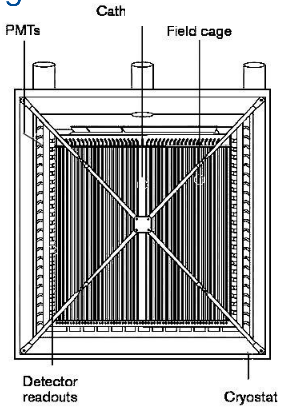
Icarus T600 Detector

- the *largest* of SBN detector and the *most distant* from neutrino source
- **760 tons** of liquid argon (476 tons of active volume) keeped at 89K
- *cryostat* split into two adjacent and identical modules (EAST and WEST)
- each module hosts two TPCs with a *drift field* of E = 500 V/cm
- exposed to the *on-axis neutrinos* from BNB and *off-axis neutrinos* from NuMI
- ionization charge continuously read non-destructively by **three wire planes**
- three-dimensional track reconstruction with 1 mm^3 spatial resolution
- scintillation light read by 360 PMT 8” TPB coated for wavelength shifting





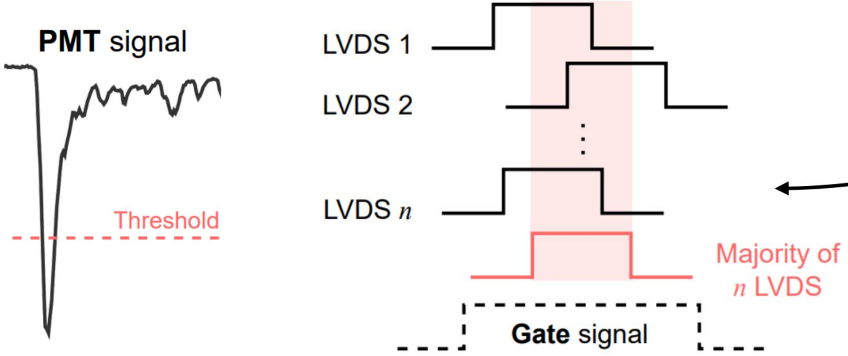




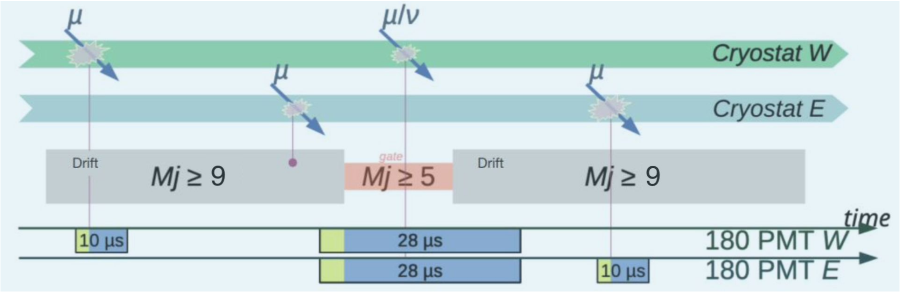
IMAGING COSMIC AND RARE UNDERGROUND SIGNALS

Trigger working principle

PMT signals are *digitized* at 500 MHz and *discriminated* with a 13 photoelectrons threshold (400 ADC) to produce a set of LVDS output signals, one every pair of adjacent PMT combined in OR. Each cryostat is then divided in three 6m-long windows with 60 PMT each: with a coincidence of at least 5 LVDS in the same window, a **majority trigger** is generated.

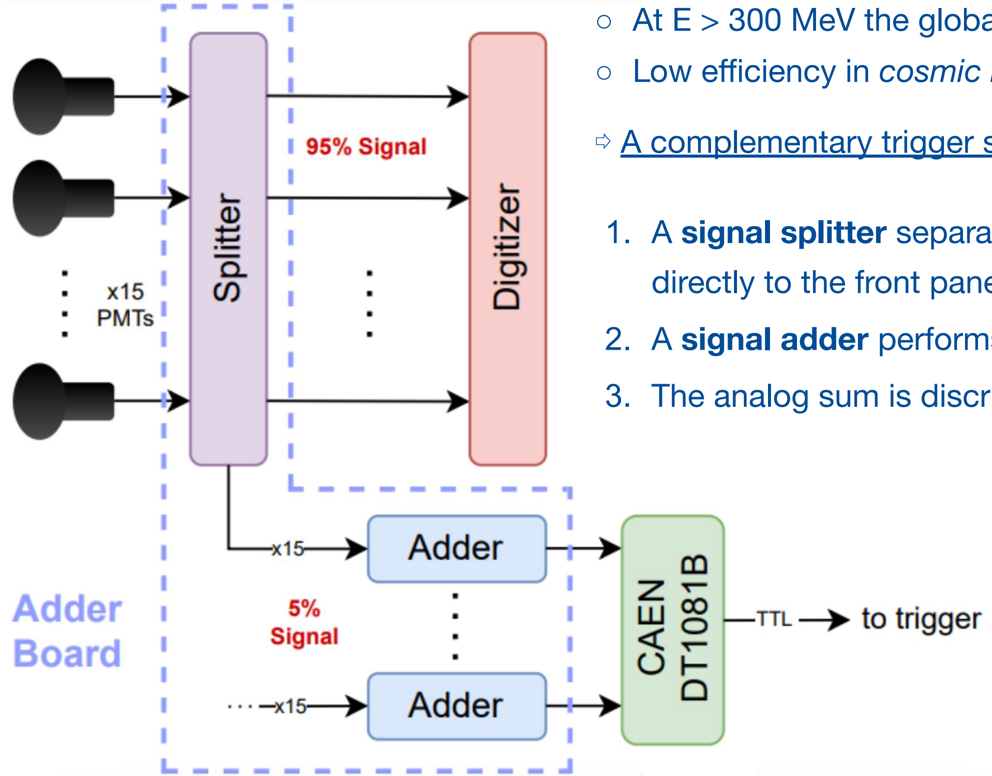


Global trigger = majority-5 trigger primitive coincident with the beam gate signal; PMT waveforms are recorded in a 28 μs acquisition window around trigger time in the beam spill and also TPC waveforms are recorded in a 1.5 ms window



Local trigger = PMT waveforms are recorded in a 10 μs acquisition window outside of the beam spill, in presence of a majority-9 trigger primitive (this allows to record CRs activity during TPC drift time).

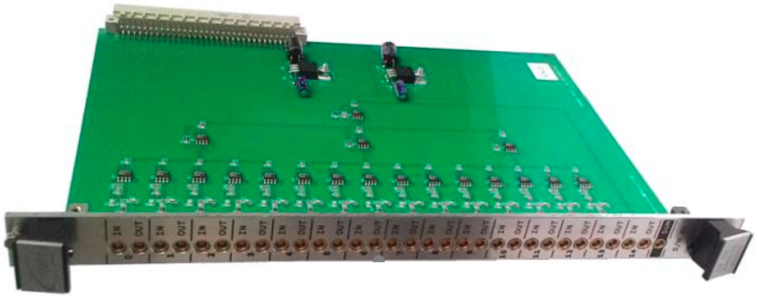
Adders trigger system



- At E > 300 MeV the global trigger efficiency is 97% but *decreases at lower energies*
- Low efficiency in *cosmic ray detection* for out-of-time PMT triggers

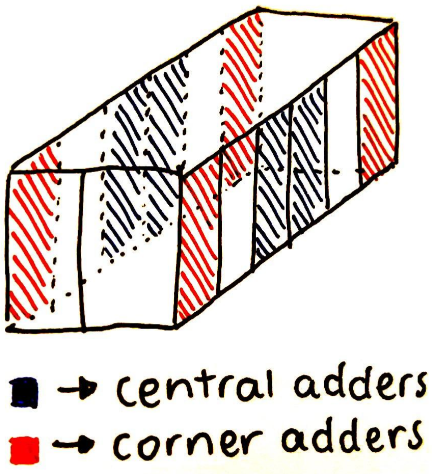
➪ A complementary trigger system based on adder boards may be exploited!

1. A **signal splitter** separates the PMT input signal into two parts: the 95% of it goes directly to the front panel as output, the 5% of it continues to stay in the board.
2. A **signal adder** performs the analog sum of the 15 scaled PMT signals.
3. The analog sum is discriminated with an external module that produces the output.



Why implementing adders trigger and what we can do with that

1. Adders can provide a complementary *information on the light yield*, totally independent from the majority logic;
2. Adders can be used in OR with the majority system to increase global trigger efficiency below 300 MeV.



In order to integrate the adders in the trigger system of ICARUS, we need to:

- studying the **adder trigger rate** in function of the threshold, to quantify the contribute of this new trigger system to the total trigger rate, and investigate what is the *optimal threshold range* where to take data;
- quantifying how adder trigger can record track undetected by standard majority trigger, focusing in particular on **cosmic rays** and **"neutrino-like" events.**
- computing the standalone adder efficiency on an unbiased sample, in a similar way to what has been studied to compute majority trigger efficiency;
- implementing *software emulation* for adder trigger, starting from single PMT waveforms, and analyzing adder waveform to check if emulation performs well.

Analysis of adder trigger rate

This analysis aims to study adder trigger rates in order to check if they perform as expected.

We analyzed data from two different data sets, one runned on the corner adder boards and one on the central adder boards; for each configuration we took data with 3 different threshold values (namely 60, 100, 200 mV).

What we want to study is:

- stability of trigger rate over time;
- trigger rate-threshold relationship;
- characterization of each cryostat;
- characterization of each board.

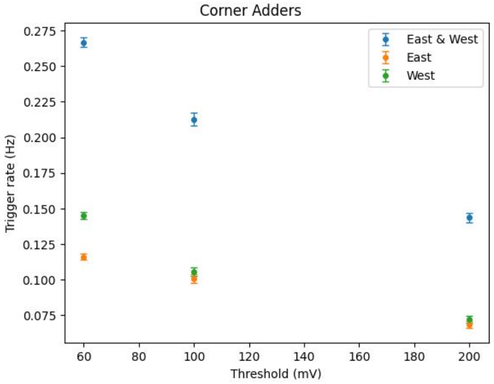
Once checked the stability of adder trigger rate over time, and verified that data match with the expected trend (exponential decreasing of rate in function of threshold) we characterized each cryostat and each adder board.

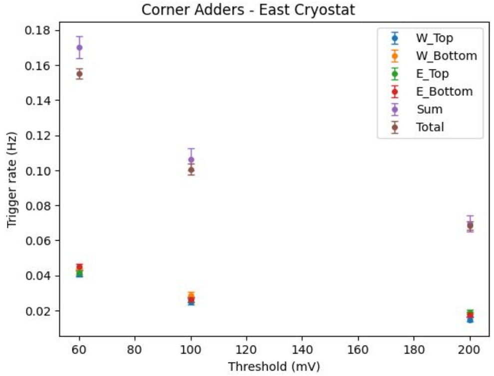
Plots are shown in the following slide.

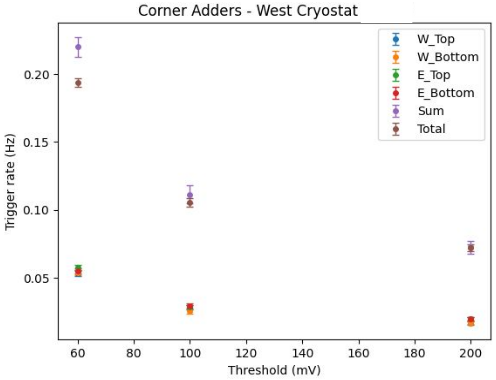
⇨ west cryostat rate **higher** than east cryostat rate (probably due to cryostats structural differences)

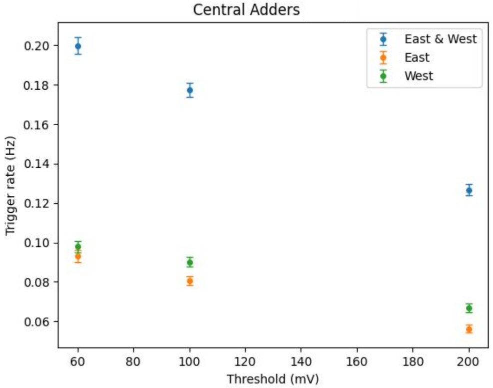
⇨ **multiple trigger** more frequent in central adders (due to geometrical configuration of boards)

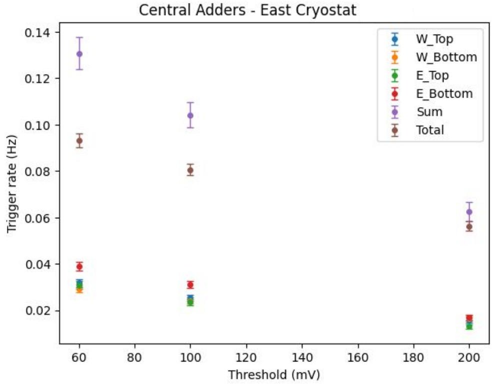
Characterization of each cryostat and each adder board

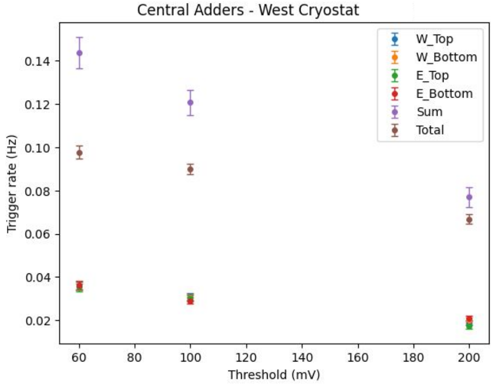










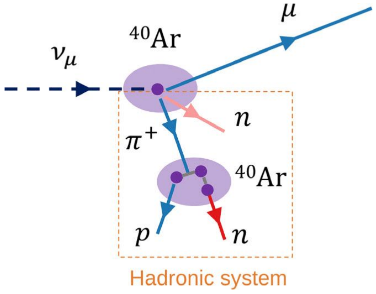


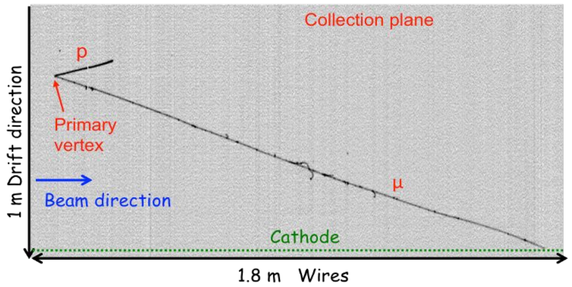
Selection of neutrino-like events

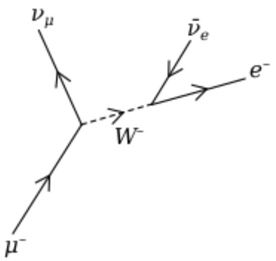
This analysis aims to provide an algorithm of neutrino-like events selections among all the events detected by ICARUS, in order to get an estimate of the efficiency of (central) adder trigger with respect to majority-5 trigger.

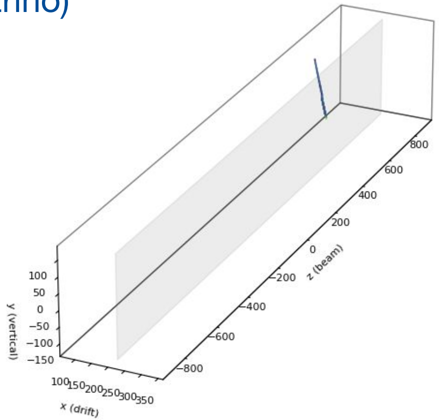
Since we are currently looking at cosmic rays, we are looking for particle interactions whose topology is very similar to *neutrino-Argon interaction*; the most frequent are:

- **stopping muons** (i.e. muons that enters the detector and lose all their energy without leaving the detector anymore)
- **muon decays** (i.e. muons that at a certain point decay into a *Michel electron* and a neutrino)









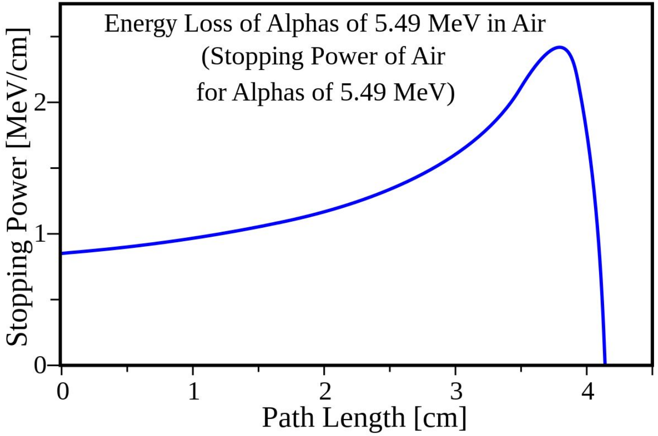
Selection cuts

In order to develop an algorithm to select *stopping muons*, we decided to impose the following selection cuts:

- both the starting and the ending points of a track must be located within 5 cm of the detector fiducial volume;
- track length must be greater than 30 cm;
- dQ/dr distribution must present the **Bragg peak**.

Bragg peak should occur just before the particle comes to rest.

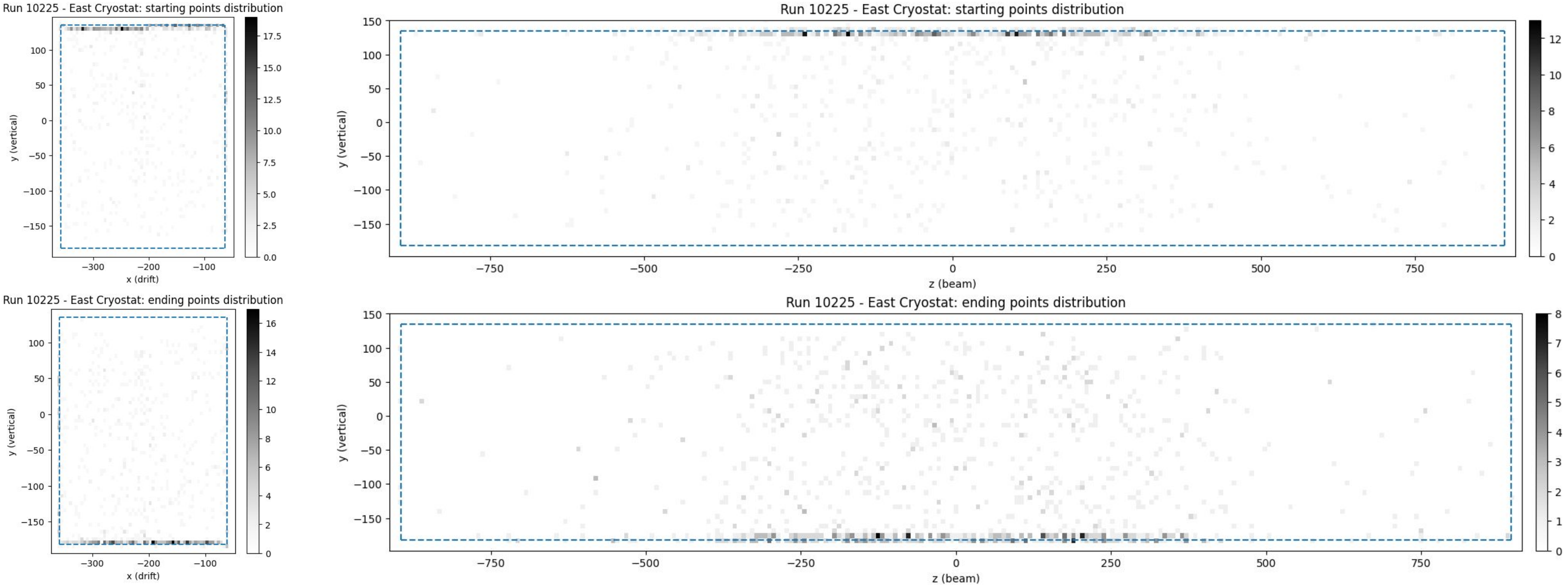
We computed the *most probable value* of dQ/dr by fitting the dQ/dr distribution with a convolution of Gaussian and Landau, and we ask for the mean dQ/dr value in the last 5 cm of the track to be greater than two times the most probable value.



Plots and results are shown in the following slide.

Checking fiducial volume coordinates

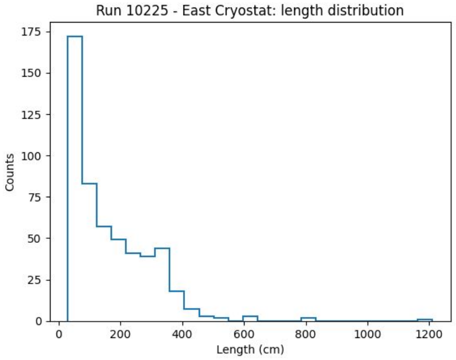
We plotted the *2D distribution of starting and ending points* of track to cross-check if they are contained in the fiducial volume and at the same time if the nominal values of the fiducial coordinates are right.

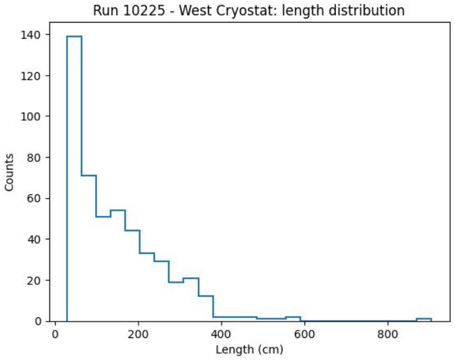


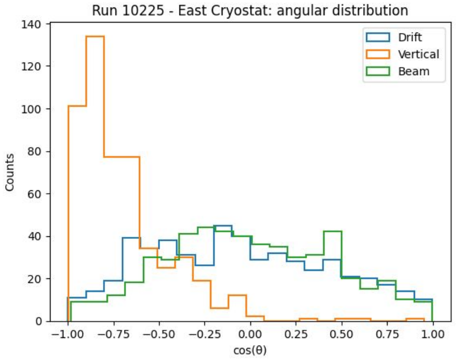
Length and angular distribution

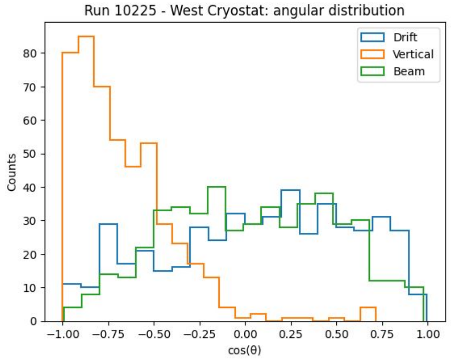
Second cross check: we plotted the length and the angular distribution of tracks which passed the first two cuts, in order to verify if they match with the expected trend:

- ✓ length distribution should *exponentially decrease* with the length;
- ✓ drift and beam angular distribution should be *isotropic*;
- ✓ vertical angular distribution should be *anisotropic* (<u>cosmic rays mainly come from above</u>).





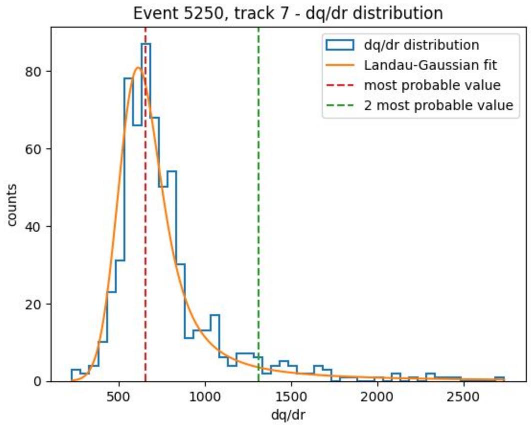


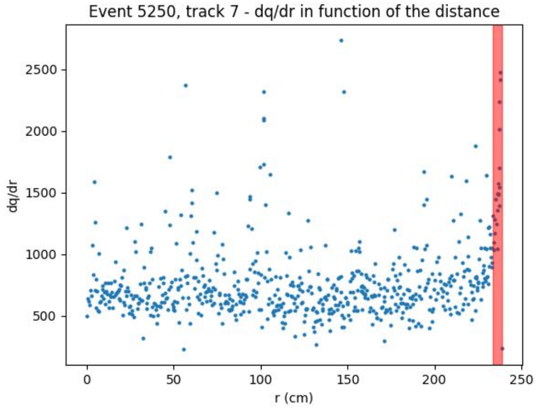


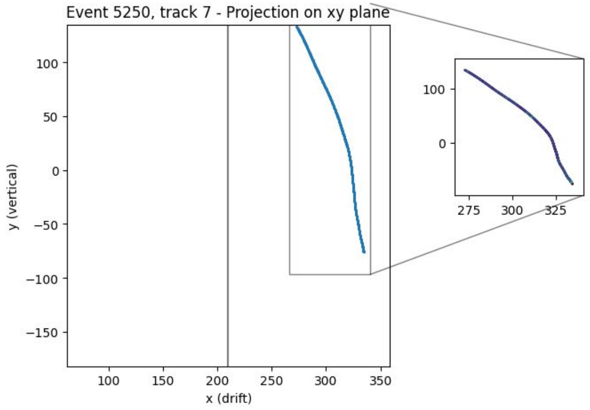
Final selection of stopping muons

Once having imposed all the selection cuts, we are finally dealing only with tracks which enter (but don’t leave) the fiducial volume of the detector, whose dQ/dr distribution fit a *convolution of Landau and Gaussian* and whose dQ/dr profile shows a Bragg peak just before the end of the track: clear evidence of **stopping muons**.

It is possible to *display events* to double-check if it is a stopping muon or (more rarely) a *muon decay*, but the important thing is that this algorithm reaches to filter all the tracks with a similar topology of neutrino interactions.



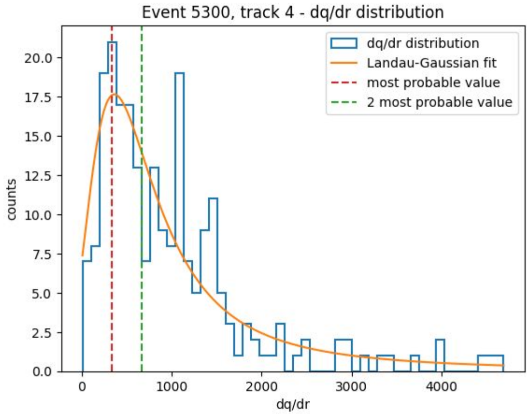


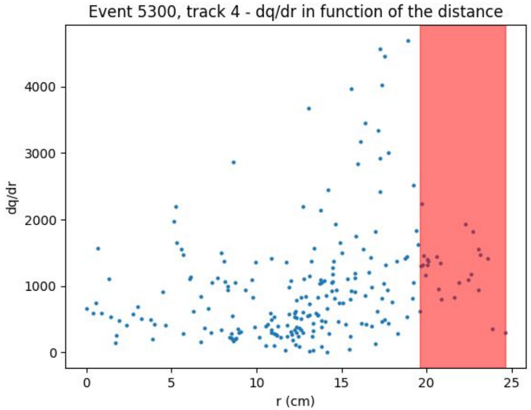


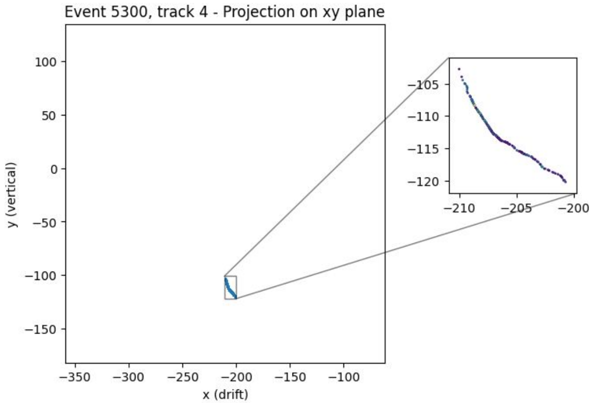
Do really adder boards improve trigger efficiency?

What emerges from this study is that almost 100% of tracks selected with this algorithm are triggered both from the majority trigger and the adder trigger: <u>only 1 track out of 48 total selected tracks triggers adders but not the majority.</u>

threshold of *60 mV* (run #10225)			threshold of *100 mV* (run #10226)			threshold of *200 mV* (run #10227)		
total	selected	majority-5	total	selected	majority-5	total	selected	majority-5
100*	1	1 (~**100%**)	446*	15	15 (~**100%**)	2044	32	31 (~**97%**)



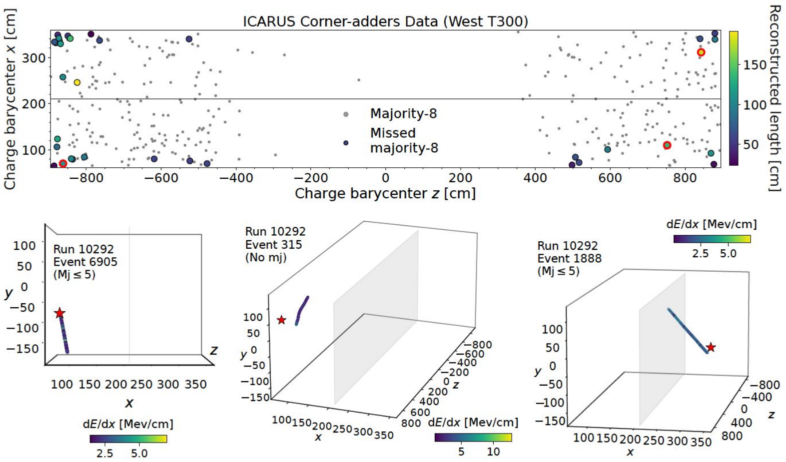




Conclusion

We observed that implementing adder boards in the central region is not so convenient: a majority-5 inefficiency of 2% is still too low to make it a significant result and a good reason to implement a new trigger system.

However, we have evidence from other ongoing studies by Riccardo Triozzi that *corner adders* do improve the global trigger efficiency in selecting cosmic events with a small detector occupancy. Plot is shown below.



In light of these results, it is reasonable to propose that we can implement only adder boards in the corner region, in order to improve efficiency in detecting cosmic events, and not also in the central region.

THANK YOU FOR YOUR ATTENTION!

REFERENCES

1) R. Triozzi. Studies of the trigger performance of the ICARUS T600 detector at Fermilab, 2022.
2) P. Abratenko et al. ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation, 2023.
3) R. Acciarri et al. A proposal for a three detector Short-Baseline Neutrino oscillation program in the Fermilab BNB, 2015.