First Neutrino Candidates and Hadron Scattering in ProtoDUNE: Preparing for DUNE Far Detector Analysis

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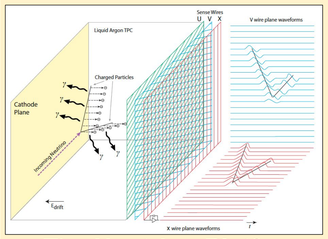
ProtoDUNE



- The **Neutrino Platform** at CERN hosts and operates two **ProtoDUNE** modules to test the LArTPC technologies for the DUNE Far Detectors. [1]
- A **LArTPC drifts the ionisation electrons** with a uniform electric field towards the anodes that read the number of electrons moving over time.

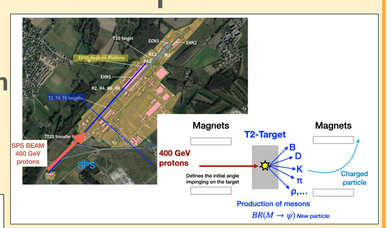
Motivation

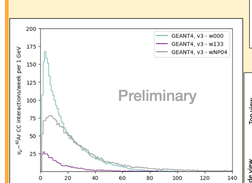
The goal of this work is to use the ProtoDUNE data to prepare for the DUNE Far Detector operations:

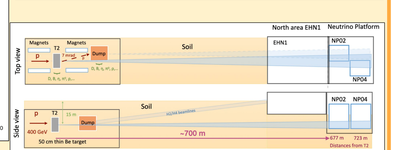
- First observation of **neutrino** events with the FD technology:
  - Real neutrino interaction **data to test and improve** reconstruction software and DAQ.
  - Pathfinder for other possible **rare event searches** with ProtoDUNE.
- Exclusive cross section of **pions** in Ar:
  - **Probe the nuclear structure** of the target
  - **Reduce the systematic uncertainties** for all future analyses.

Beam Complex

The **SPS beam** hits the T2 target **~700 m before the ProtoDUNE area**.







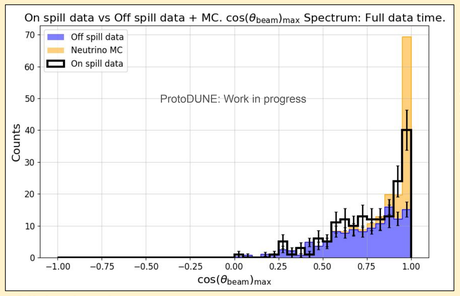
The ProtoDUNE detectors are **almost perfectly on axis** with the collision, and therefore we **parasitically** benefit from a beam of long living neutral particles (neutrinos, maybe BSM). [2]

Neutrino Search

A number of cuts are applied to remove events, based on both standard reconstruction objects and custom variables derived from low-level hits.

Cut	Beam-off Events/h	Beam-on Events/h	Beam On/Beam Off Ratio
Before cuts	1950.26 ± 6.61	2383.98 ± 12.01	1.22
Max $\cos(\theta_{\text{beam}})$	106.34 ± 1.54	217.53 ± 3.63	2.05
Tail Length Density	23.09 ± 0.72	28.96 ± 1.32	1.25
Cut on $C_{140-150}$	6.65 ± 0.39	9.92 ± 0.77	1.49
ROI Z close to vertex	1.79 ± 0.20	3.87 ± 0.48	2.16
N daughter particles	0.81 ± 0.13	2.84 ± 0.41	3.53
Vertex fiducial volume	0.65 ± 0.12	2.48 ± 0.39	3.82
Cut on C_{40-50}	0.56 ± 0.11	2.36 ± 0.38	4.21
ROI Z size 10 cm	0.49 ± 0.10	2.12 ± 0.36	4.30
Cut on C_{0-10}	0.45 ± 0.10	1.87 ± 0.34	4.19

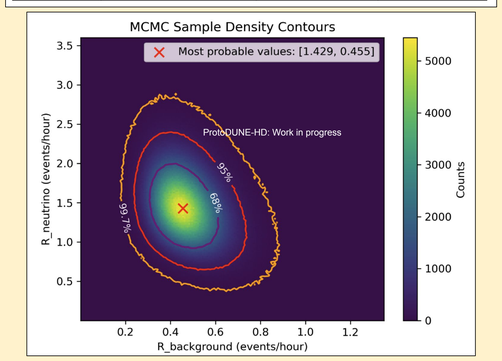
After the selection, the $\cos(\theta_{\text{Beam}})_{\text{max}}$ distribution is plotted with the **beam on and off**.



An excess is visible in the final bin.

With the beam on, the events are concentrated in the **lower part** of the detector, as expected considering the shape of the neutrino beam.

	Number of events	Time (hours)	Hourly rate
Beam-on	31	16.53	1.88
Beam-off	20	44.688	0.45



The log-likelihood is sampled using an MCMC method, and the observed excess is significant.

Pion-Argon studies

A **dedicated beamline** can deliver **charged pions** inside the ProtoDUNE's active volume.

$$N_{\nu_\beta}(E_\nu^{reco}) = P_{\nu_\mu \to \nu_\beta}(E_\nu^{true}) \Phi(E_\nu^{true}) \sigma(E_\nu^{true}) \epsilon(E_\nu^{true}) S(E_\nu^{true}, E_\nu^{reco}) \quad \beta = e, \mu$$

Systematic uncertainties

Oscillation parameters · Neutrino flux · Interaction cross-section · Detection efficiency · Energy smearing matrix

Many factors impact the visible energy:

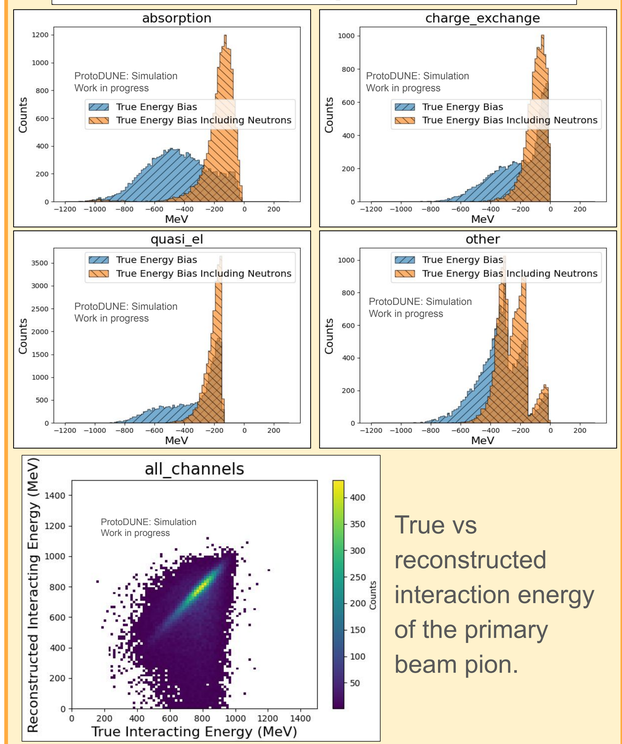
- **Binding energy** smears all peaks by O(50 MeV)
- **Charged pion masses** (decay to neutrinos)
- **Neutrons** (invisible energy)

After Final State Interaction (FSI):

- Increased contributions from **neutrons**
- Pion absorption (-> **neutrons** emitted)

To validate nuclear models and reduce systematic uncertainties for physics analyses, we study the **invisible energy** produced in π+-Ar interactions via the energy bias.

$$\text{Energy bias} = \sum T_{\pi^\pm,p} + \sum E_{\pi^0,\gamma} - T_{\pi^\pm}^{ini}$$



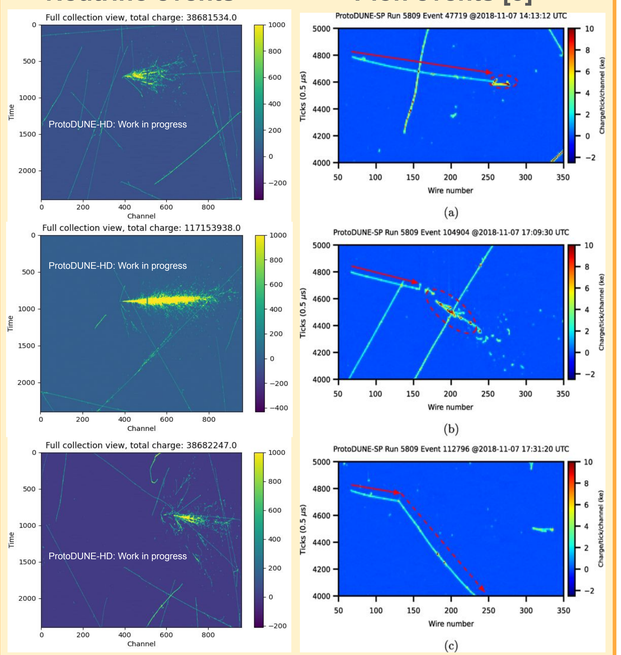
True vs reconstructed interaction energy of the primary beam pion.

Validation is ongoing to establish what information is available and what needs to be expanded.

Event Displays

Neutrino events

Pion events [3]



Time vs channel event displays for neutrino and pion interactions from **real ProtoDUNE data**.

Conclusion

The new generation of long-baseline experiments will soon begin operations, and we need to prepare for it.

- A full selection pipeline has been developed to select neutrino candidates from **real ProtoDUNE data**. Other studies are following, looking for rare events in both ProtoDUNE modules (more in Biao Wang's poster).
- Reducing the systematic errors is a **key requirement** for achieving the physics goals of DUNE. **Studies are ongoing** to measure the energy bias in pion-argon interactions with ProtoDUNE, to validate and improve the existing nuclear models and allow for more precise measurements.

[1] The DUNE Collaboration, June 2017 DOI:10.48550/arXiv.1706.07081
[2] P. Coloma, J. López-Pavón, L. Molina-Bueno and S. Urrea, JHEP 01 (2024), 134 doi:10.1007/JHEP01(2024)134
[3]Measurement of exclusive π+-argon interactions using ProtoDUNE-SP. doi.org/10.1103/nm5s-4cnw