Neutron Kinematics Reconstruction in the Upgraded Near Detector of the T2K Experiment

DPF-PHENO 2024

Abraham Teklu, May 16th 2024

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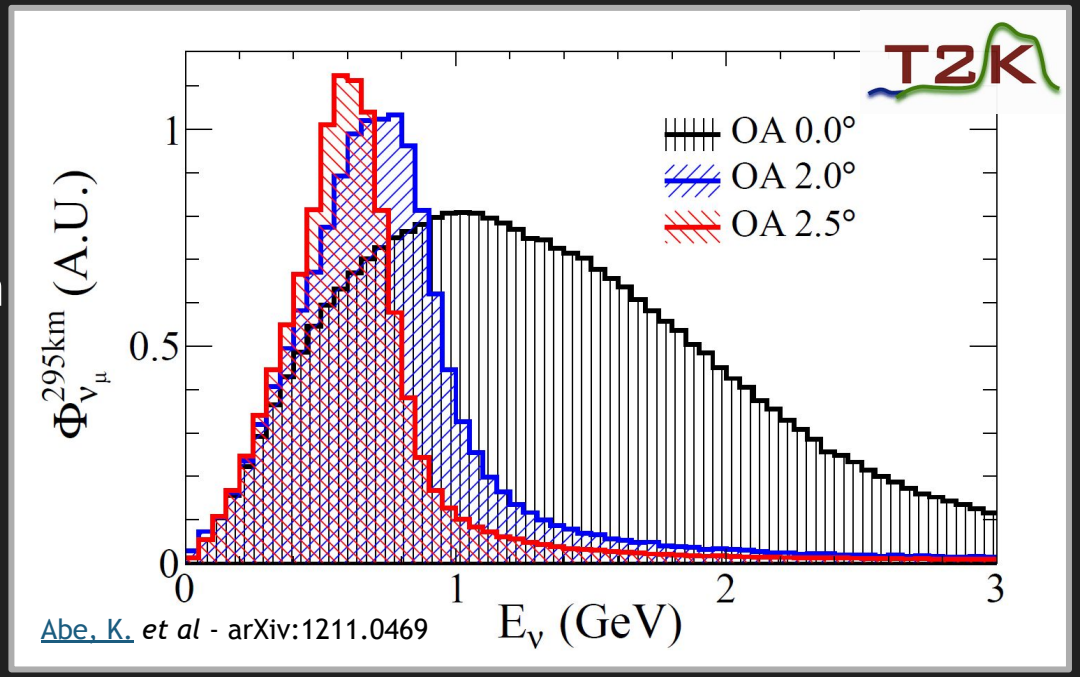
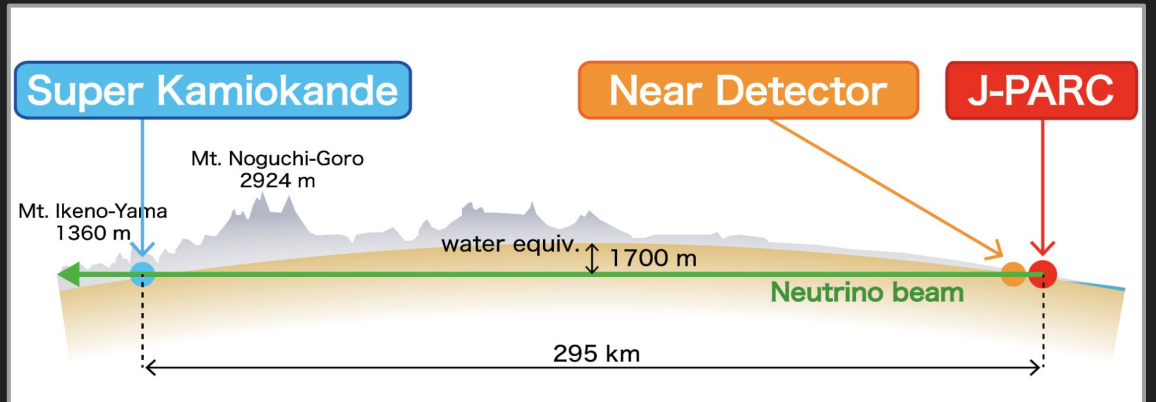
Overview

- Overview of the T2K Experiment as a whole.
- A look into the effect neutrons have on Long-Baseline neutrino experiments
- The ND280 Upgrade and the SuperFGD
- Progress we have made with neutrons in the SuperFGD

T2K Experiment

- Long baseline neutrino oscillation experiment in Japan
- Main oscillation channels of T2K are $\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- The ν_μ beam has peak energy of 600 MeV with 2.5° off-axis angle.
- 295 km away from Super-Kamiokande





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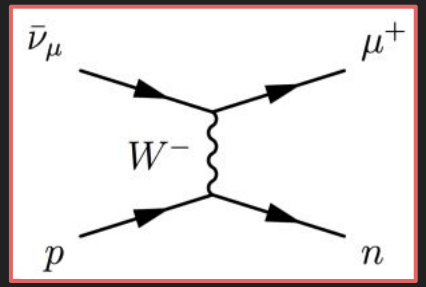
Neutrons in Long-Baseline Neutrino Experiments

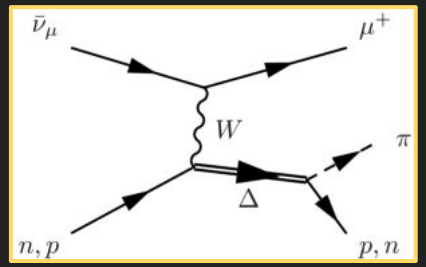
Neutrino Interactions, Minerba Betancourt, Lepton Photon, 2019

- Neutrons are produced in many neutrino interaction channels
- Previously our detectors did not have a low enough energy threshold to detect these neutrons
- This will affect the neutrino energy resolution for these interactions which will directly affect the error on the oscillation parameters.

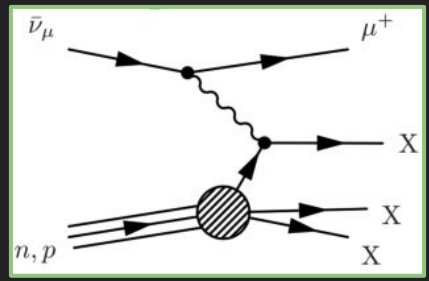
Charge Current Quasi-Elastic



Charged Current Resonant



Charged Current Deep Inelastic Scattering



$$N(E_\nu) = \int \Phi(E_\nu, t) \times \sigma(E_\nu) \times \epsilon_{det} \times P_{osc}(E_\nu, \Theta, L) dt$$

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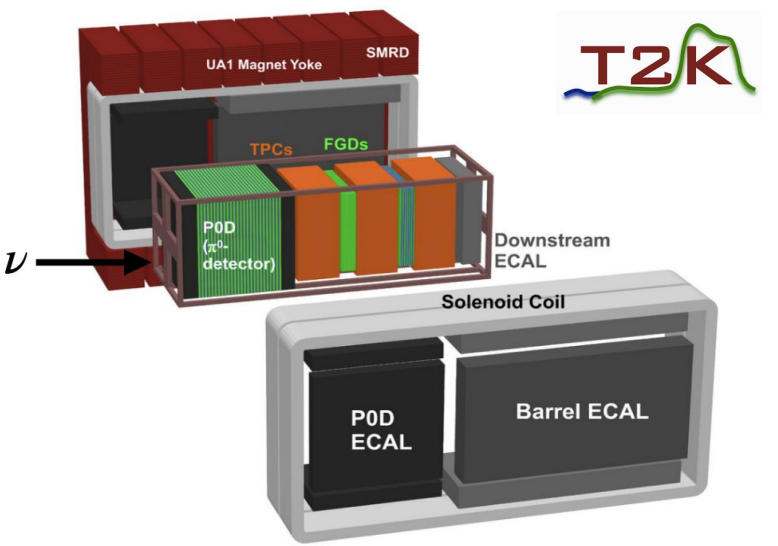
The ND280 Upgrade

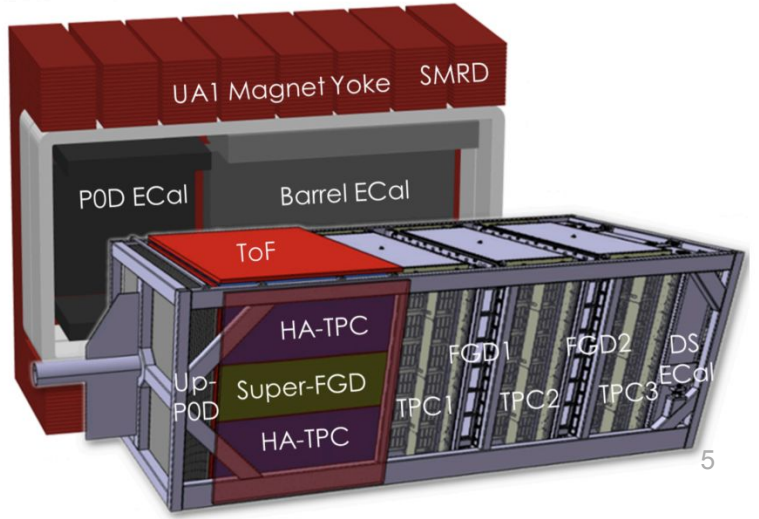
- The ND280 upgrade replaced part of the P0D with a **SuperFGD** sandwiched between two HA-TPCs

- The ND280 Upgrade is **currently installed** and preliminary data taking has commenced!

Before ND280 Upgrade



After ND280 Upgrade



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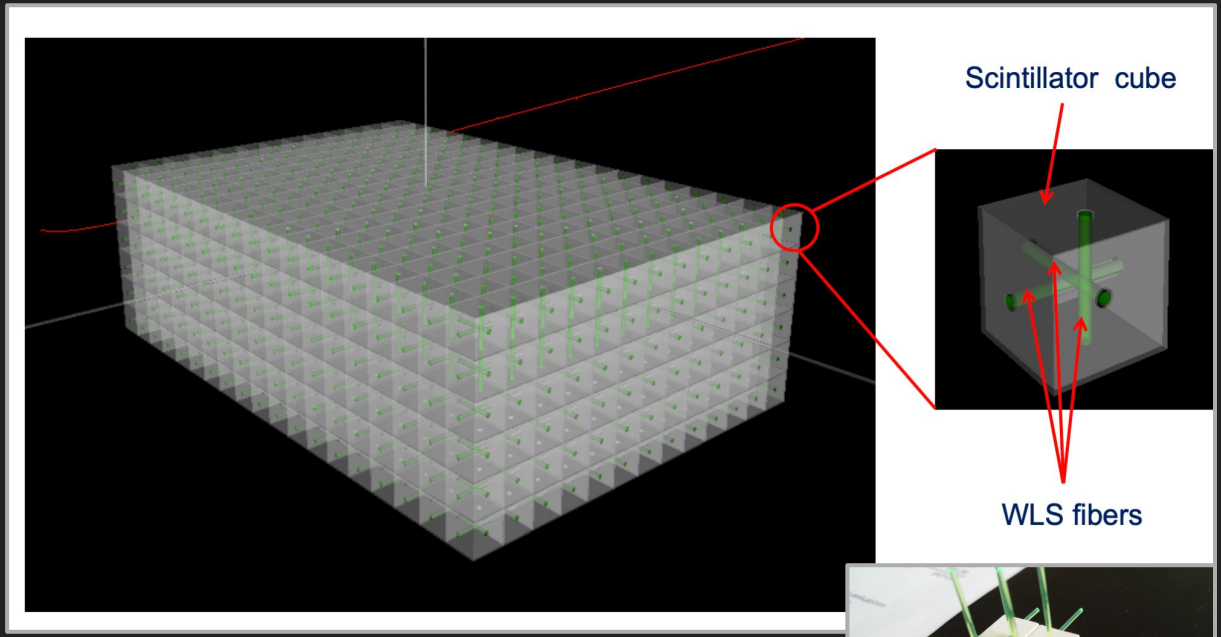
The SuperFGD

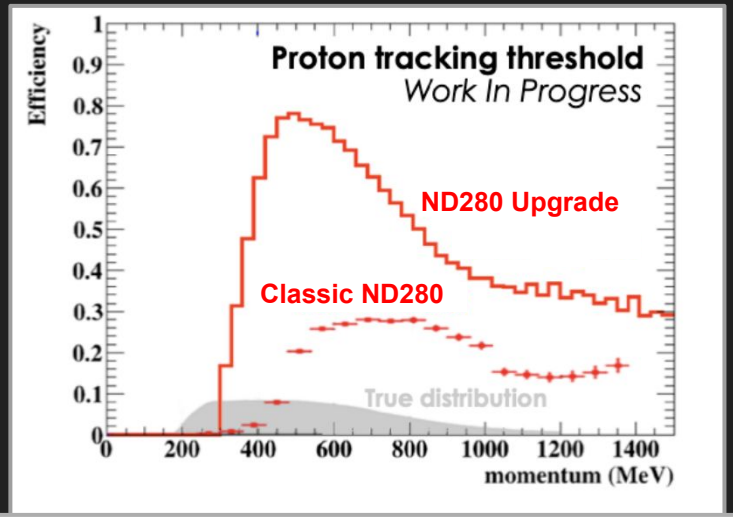
- Each cube is optically isolated, so light produced in each scintillator cube stays in that cube until it goes down the wavelength shifting fiber.
- The light is readout at the end of the fiber by an MPPC.



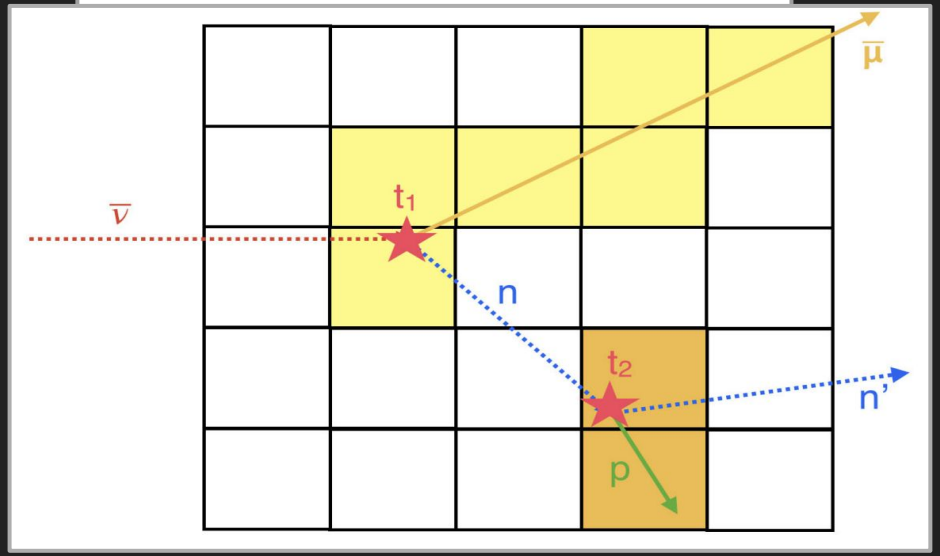
Cube: 1 cm x 1 cm x 1 cm
With 3 WLS Fibers along X Y Z

The SuperFGD

- Pseudo 3D readout that gives fine granularity, good timing resolutions, fully active, uniform acceptance and **has low energy threshold**
- **Reconstruct neutron kinematics event-by-event for the first time!** Gives a more complete picture of the neutrino interaction



Ulysse VIRGINET, NuInt, 2024



Physical Review D, 101(9), 092003. (2020).

SuperFGD Assembly

- The SuperFGD assembly took place in fall of 2022
- We managed to assemble and align 2 million scintillator cubes pre-assembled in 56 xy layers.
- Fiber insertion and electronics were also added and it is now been commissioned!
- It has been a worked on by tons of people in T2K for many years and SuperFGD is currently taking data!

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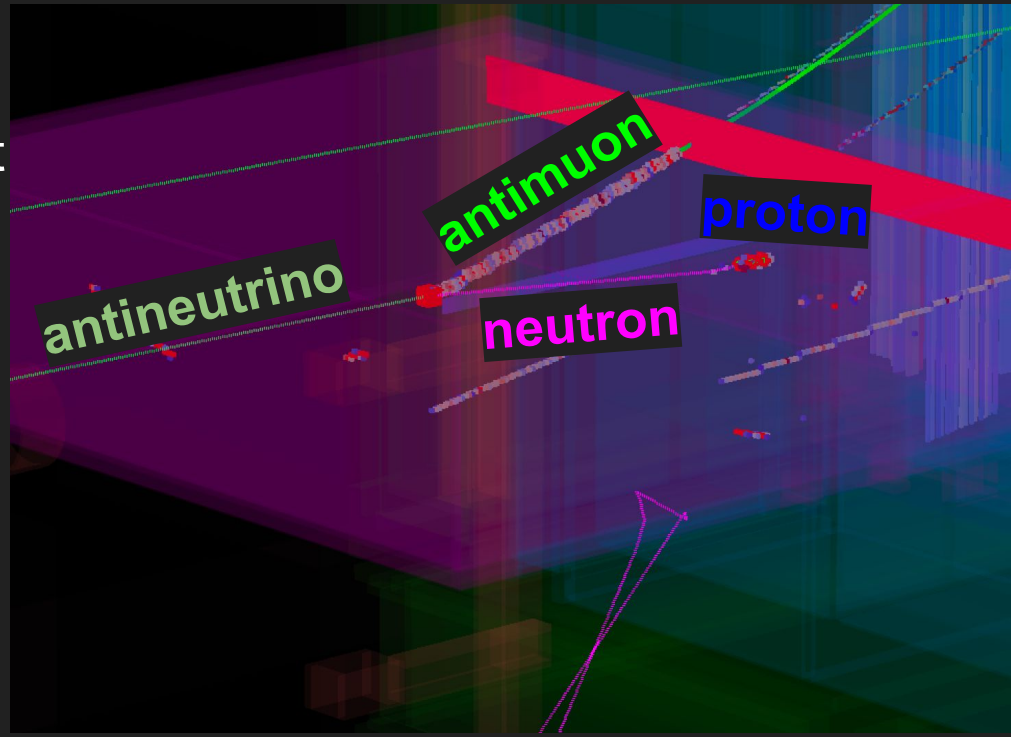
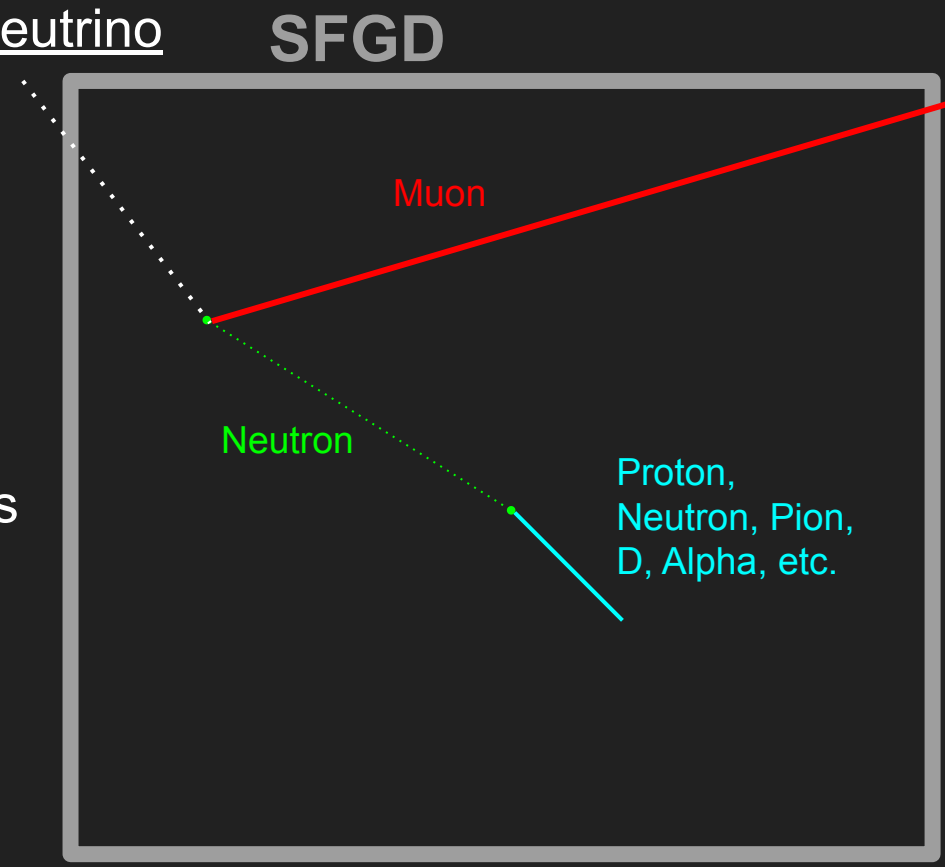
Antineutrino CCQE Selection with the SuperFGD

- Since CCQE is the dominant interaction in our energy range this should be the most significant and clean source of neutrons, even with FSI and 2p2h.
- Currently I am working on producing a high purity and efficiency selection. This can give us a lot of information about neutron kinematics in the SFGD.



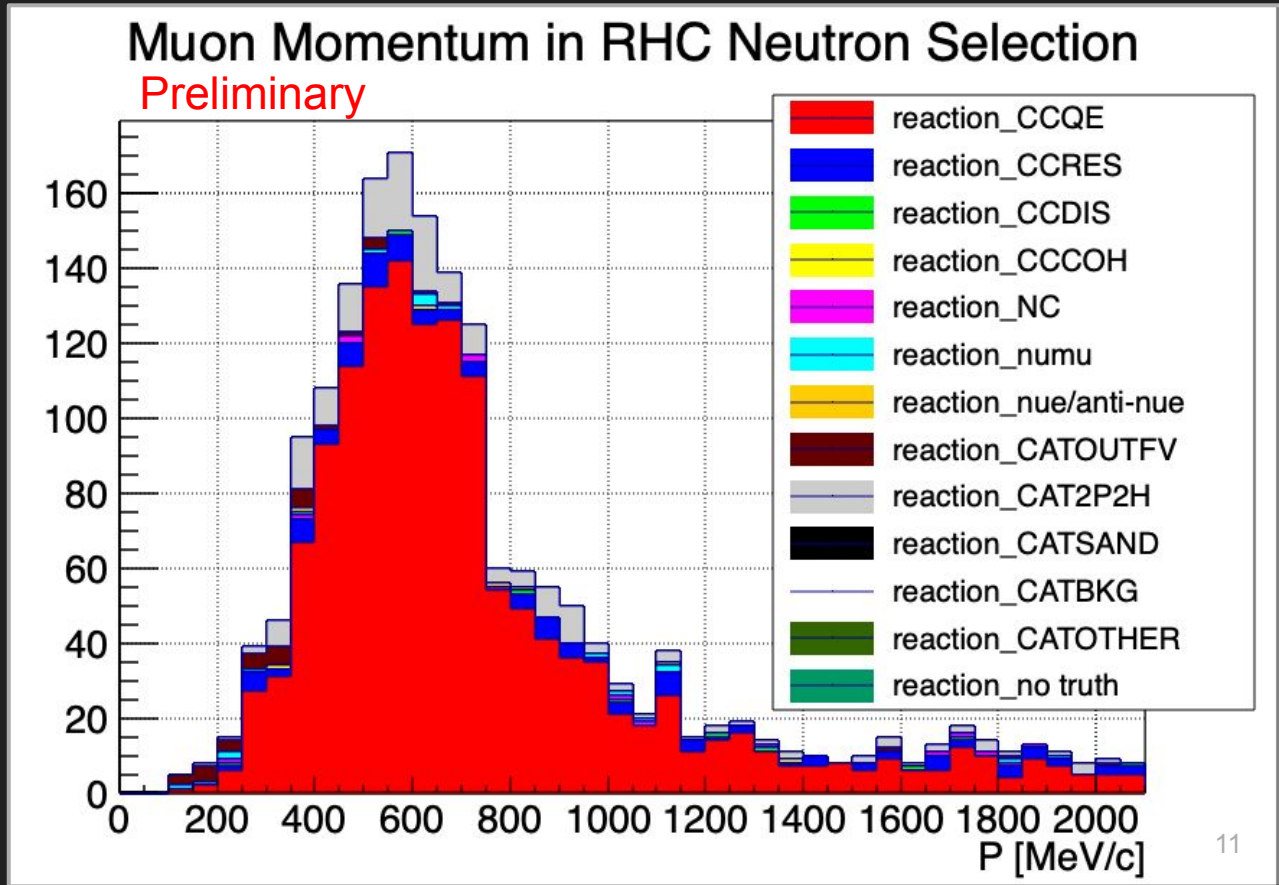
Antineutrino CCQE Selection with the SuperFGD

- Look for a lone muon track and another tracks or clusters in the SFGD
- Check that a neutron from the neutrino vertex could produce the neutron candidate. If not remove it as a candidate.
- Make sure all neutron candidates came from a single neutron vertex



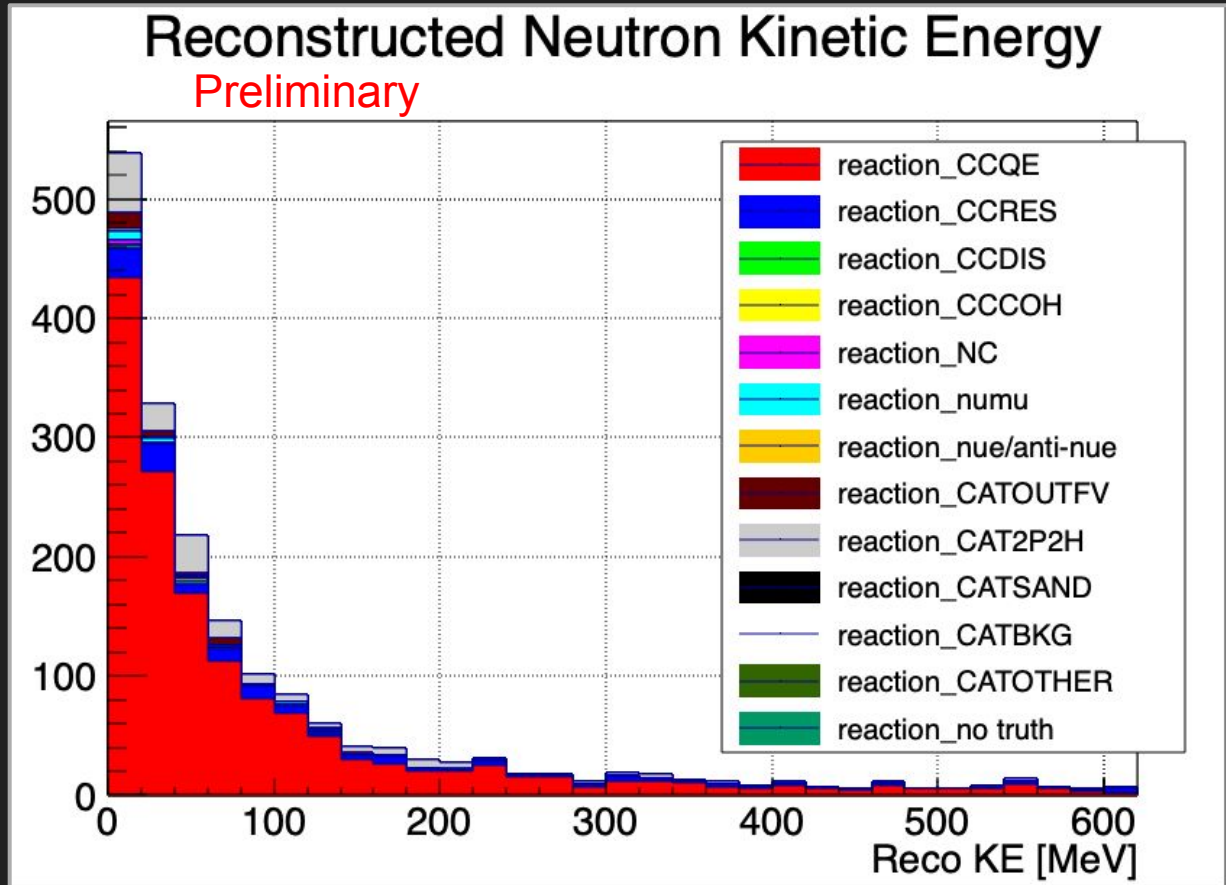
Antineutrino CCQE Selection with the SuperFGD

- This is a distribution of the muon momentum associated with these events.
- As you can see the majority of the selection is CCQE.



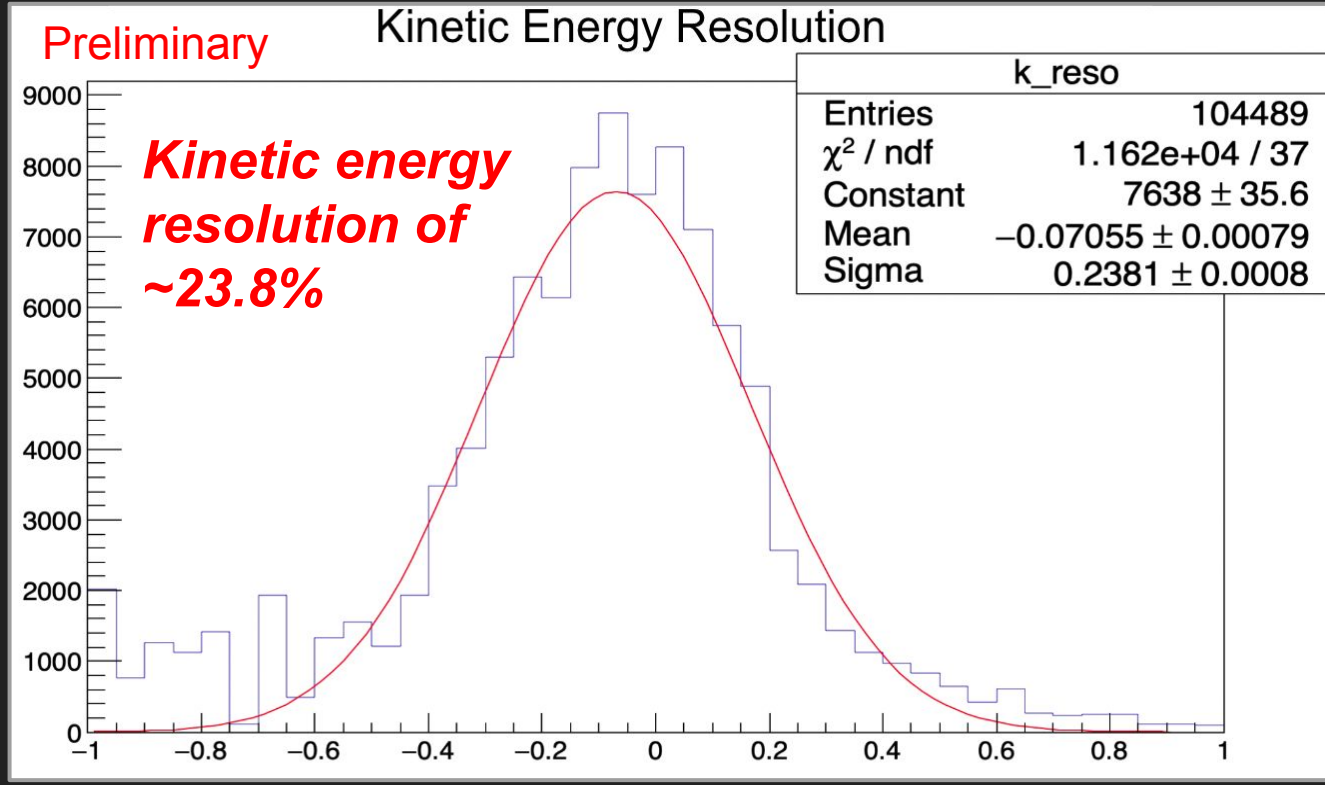
Antineutrino CCQE Selection with the SuperFGD

- This is a distribution of the neutron candidate kinetic energy associated with these events.
- This selection has a Purity: ~67% Efficiency: ~9% *PRELIMINARY*



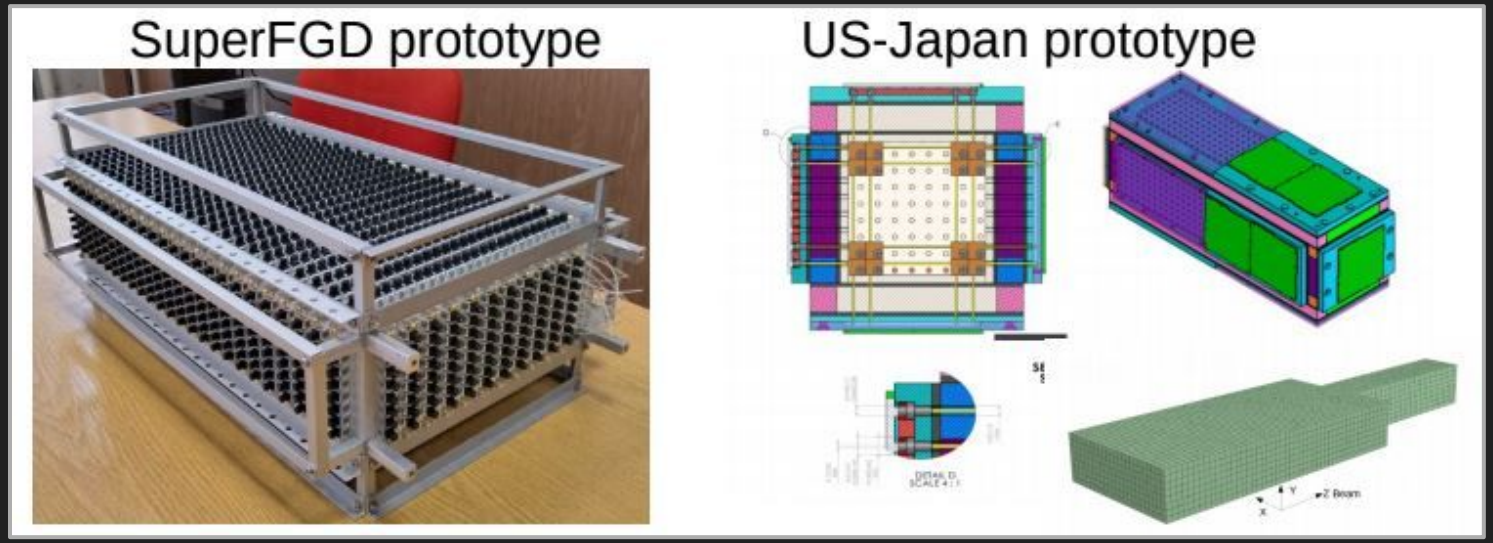
Neutron Reconstruction Studies with SuperFGD

This plot is showing the kinetic energy resolution of a neutron particle gun simulation in the SuperFGD. Neutrons with uniform energy from 0 to 1 GeV were sent in the z direction starting from the center of the SuperFGD.



Neutron test beam with SuperFGD Prototypes

We have also done studies with prototypes of the SuperFGD that looked a charge particle beam at CERN in 2018 and a neutron beam at LANL in 2019 and 2020. You will see more about this from Haowie Zheng.



Total neutron cross section measurement on CH with a novel 3D-projection scintillator detector *Mr Haowei Zheng*

David Lawrence Hall 107, University of Pittsburgh 17:15 - 17:30

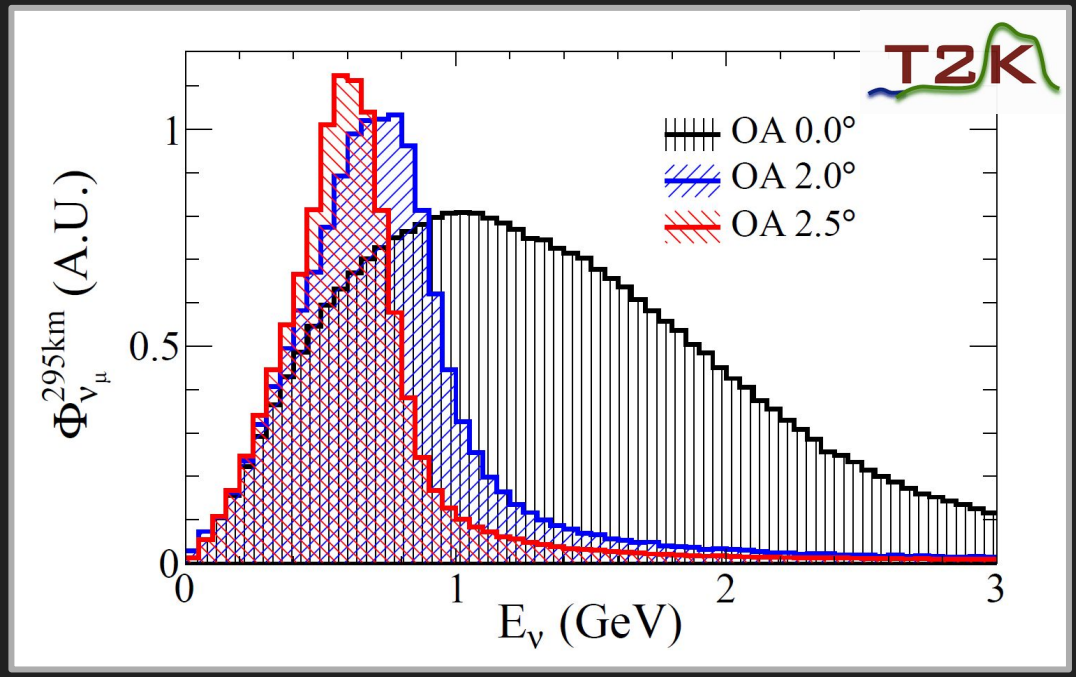
Summary

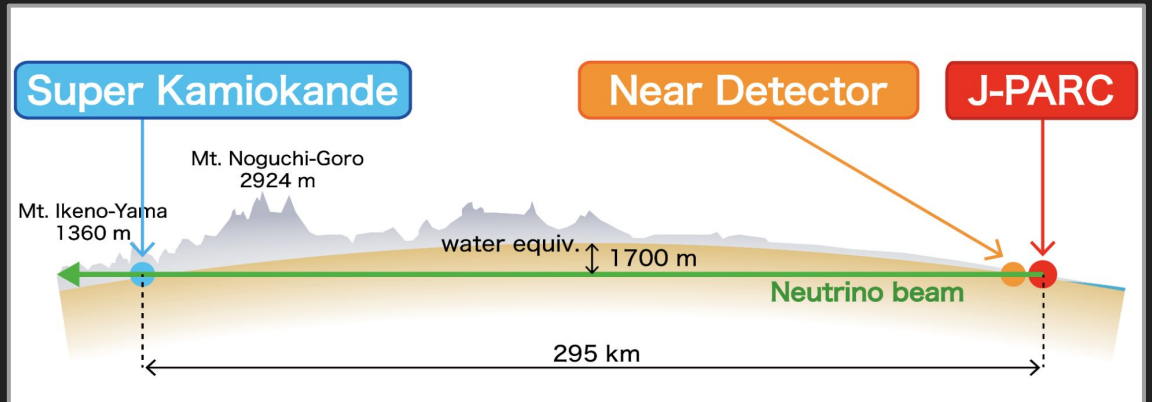
- The ND280 Upgrade, which includes the SuperFGD, has been fully installed and data taking should commence in late May. We have also taken commissioning data last December and February.
- Because of the SuperFGD we can now reconstruct neutron kinematics event-by-event, which is a novel development.
- Neutron reconstruction studies show kinetic energy resolutions as small as ~23.8%.
- The set of interactions with neutrons is quite a lot. And the selection power of the SuperFGD, gives us access to so many more analyses which are currently being studied by a dedicated group of analysers in T2K.

Backup

T2K Experiment

- A.U. : Arbitrary Units
- Scaled to have same area under the curve
- Meant to show energy distribution for different of-axis angles, ignoring reduction in flux.





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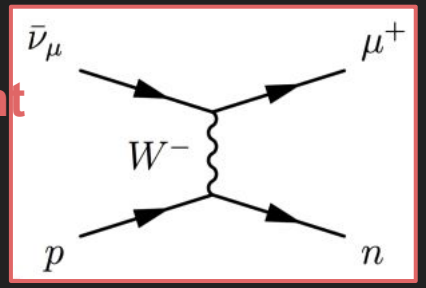
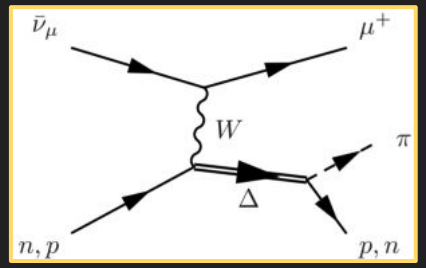
Delta CP left out

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{32} L}{4E} \right)$$

Charge Current Quasi-Elastic



Charged Current Resonant



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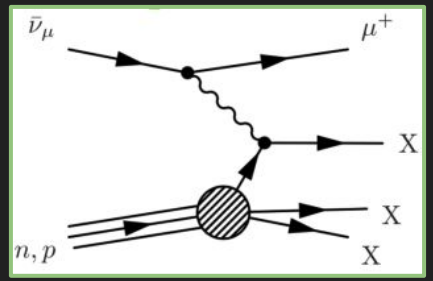

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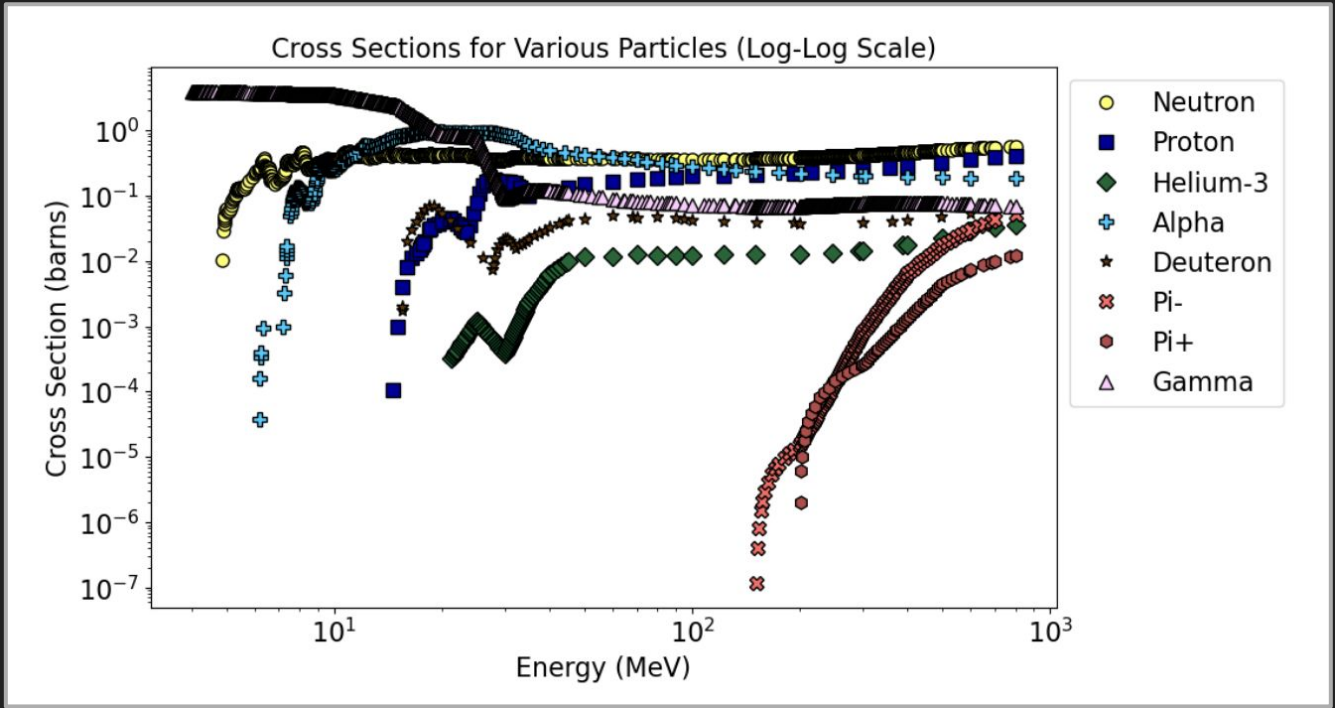
Neutron Studies with the SuperFGD

Analysis of Outgoing Particle Kinematics from Monte Carlo Simulations of Neutron Interactions on Hydrocarbon, a Master's thesis by Kuunal Kelash Mahtani, Department of Physics & Astronomy, Stony Brook University, May 2023.



"We have used ENDF data to obtain the total neutron cross sections as a function of incident neutron kinetic energy for inelastic scattering on carbon, organized by produced particle type as seen in Fig. 3.7."

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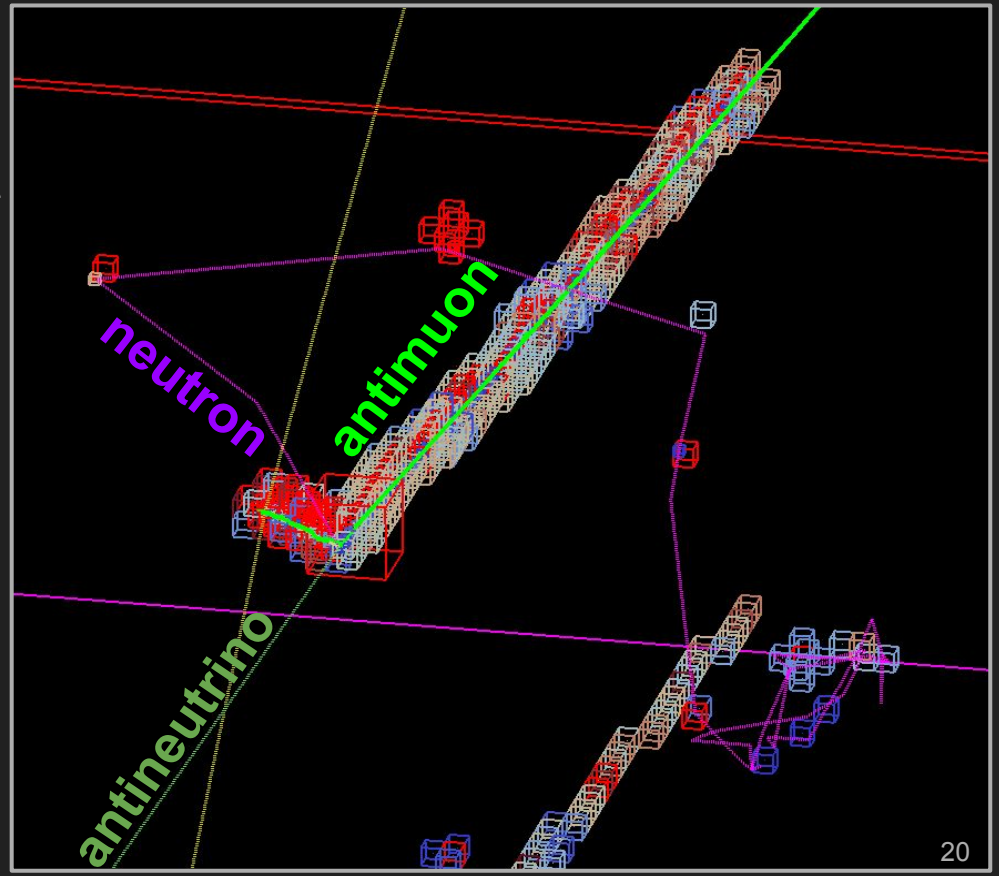
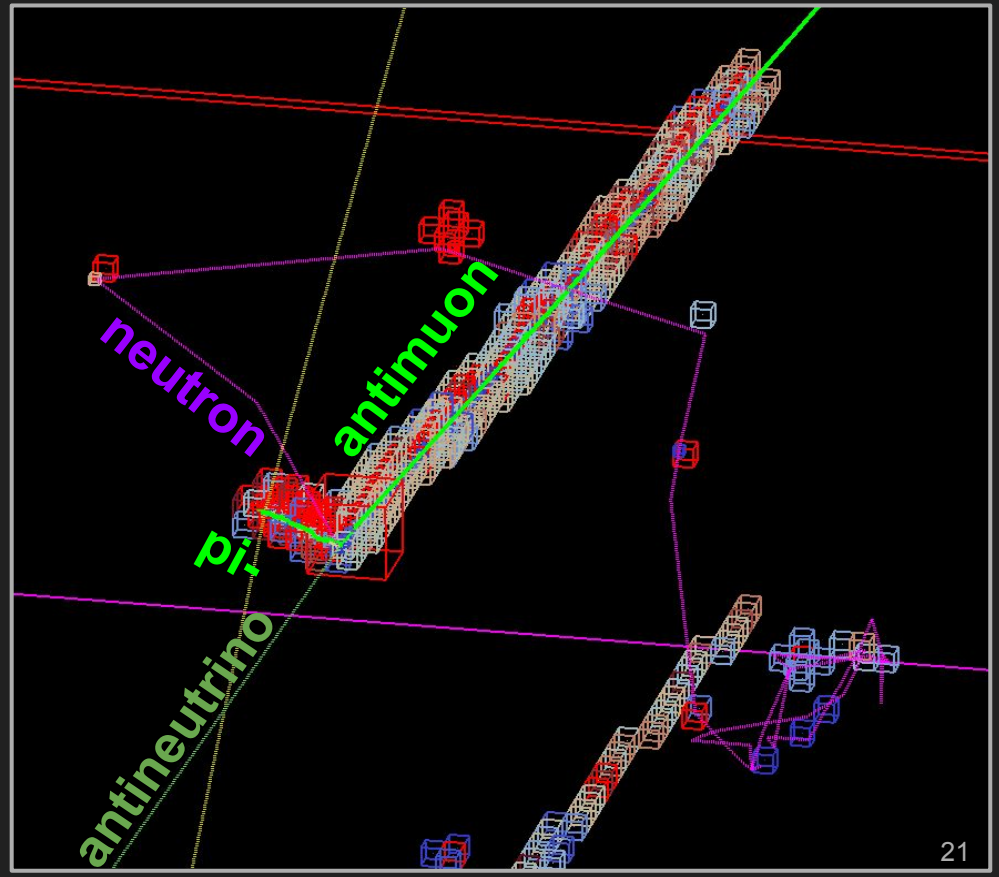


Antineutrino CCQE Selection with the SuperFGD

- This interaction shows a 3500 MeV antineutrino striking C13 to produce mu+, pi-, and a neutron.



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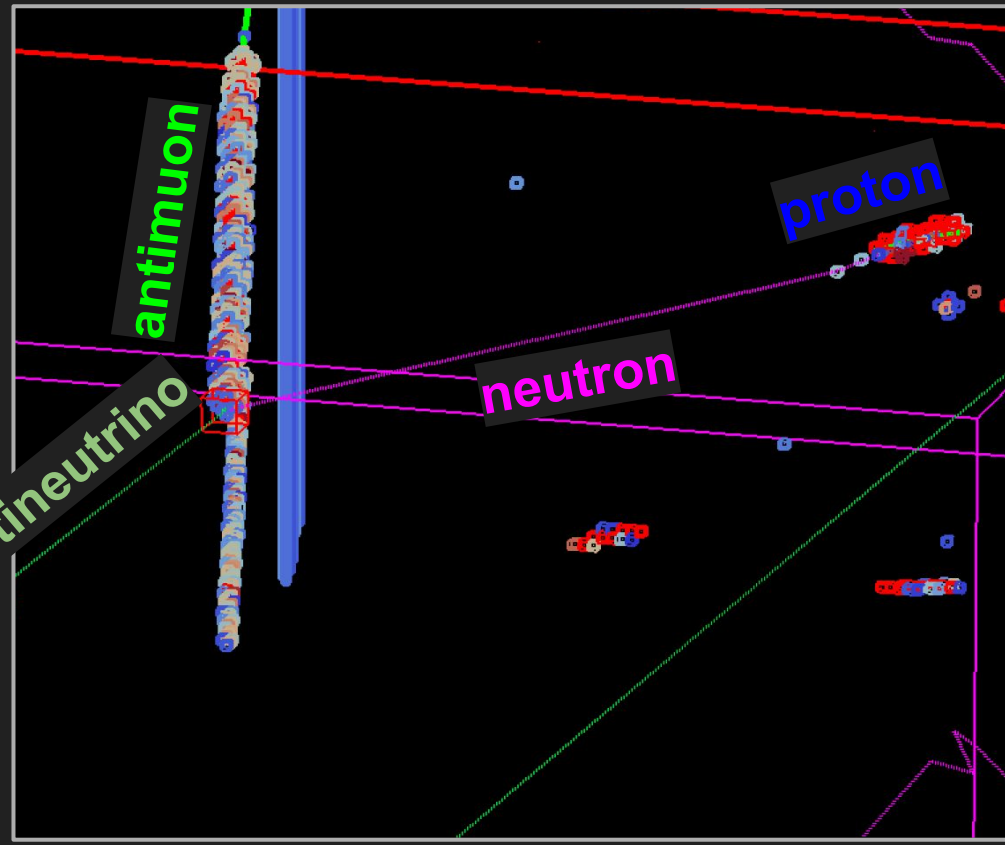

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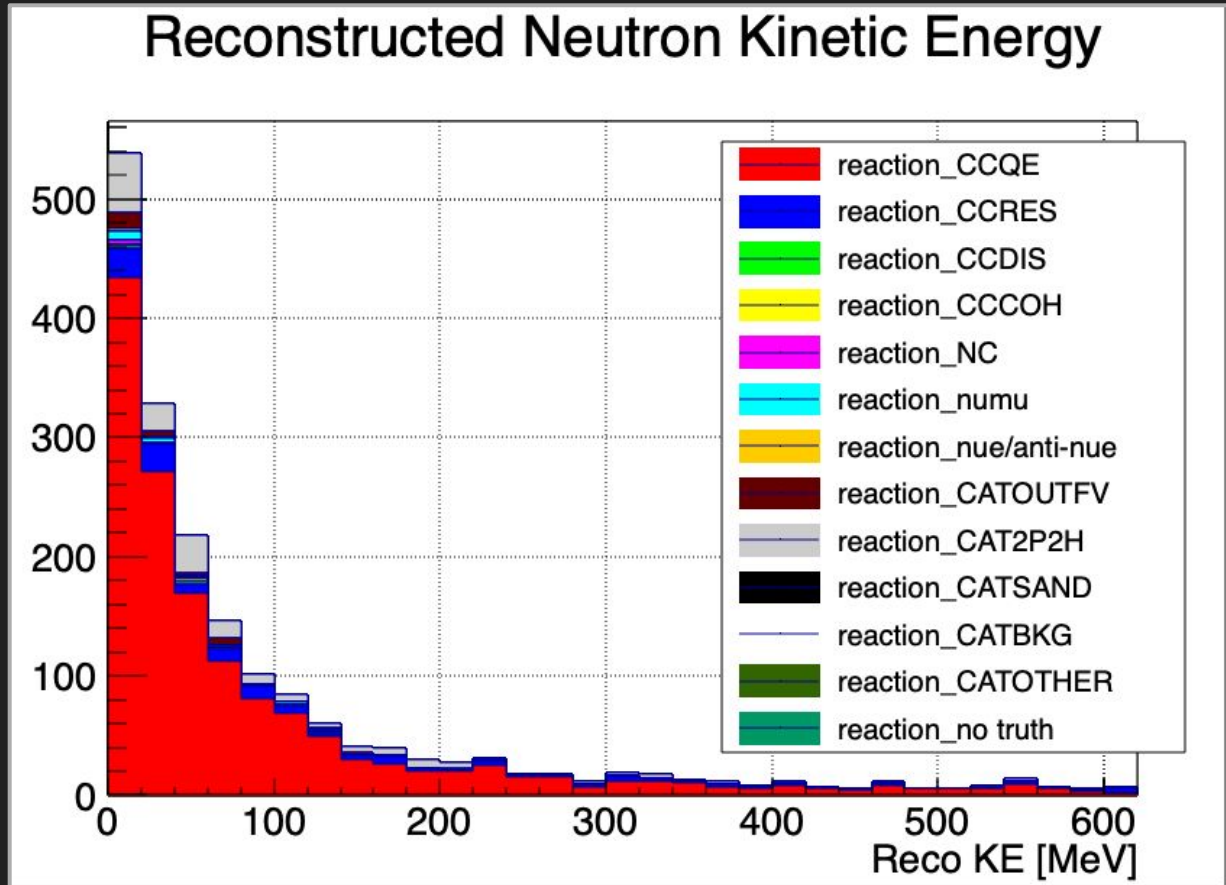
Antineutrino CCQE Selection with the SuperFGD

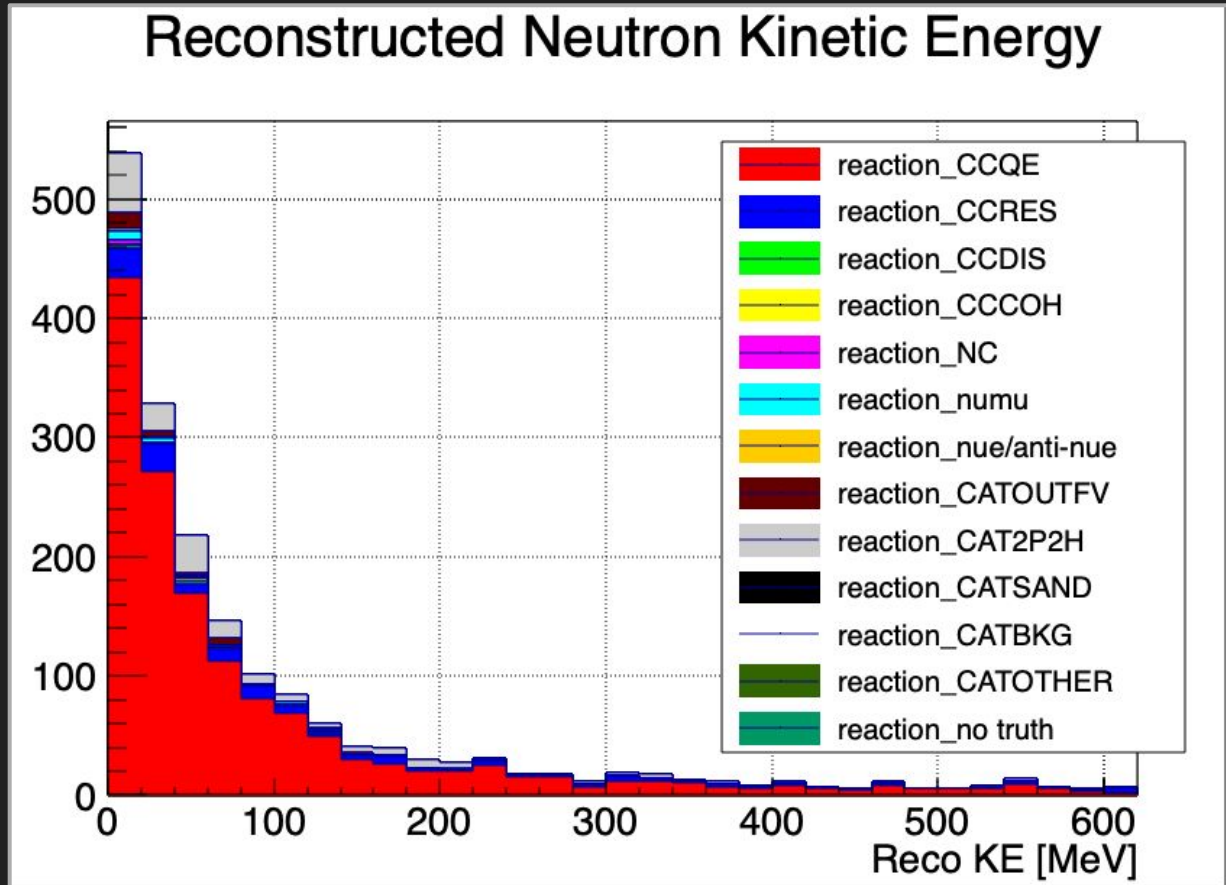
"The 10 mm cube size chosen for the SuperFGD is a natural granularity scale corresponding to the range of 200 MeV/c protons in plastic, a high probability momentum for protons arising from neutrino interactions at T2K."

A. Blondel et al 2020 JINST 15 P12003



Antineutrino CCQE Selection with the SuperFGD

195 MeV/c neutron momentum corresponds to 20 MeV kinetic energy. The lowest energy bin. This combined with smearing is why we don't see a threshold here.



Previous event by event neutron detection techniques

- Inverse kinematics measurements involve accelerating radioactive ion beams and directing them through a neutron target. This allows studying neutron-induced reactions on short-lived nuclei by reconstructing the kinematics of the reaction products.
- In neutron-neutron scattering experiments, the direction and energy of one neutron determines the kinematics completely, allowing prediction and measurement of the second neutron's three-momentum.