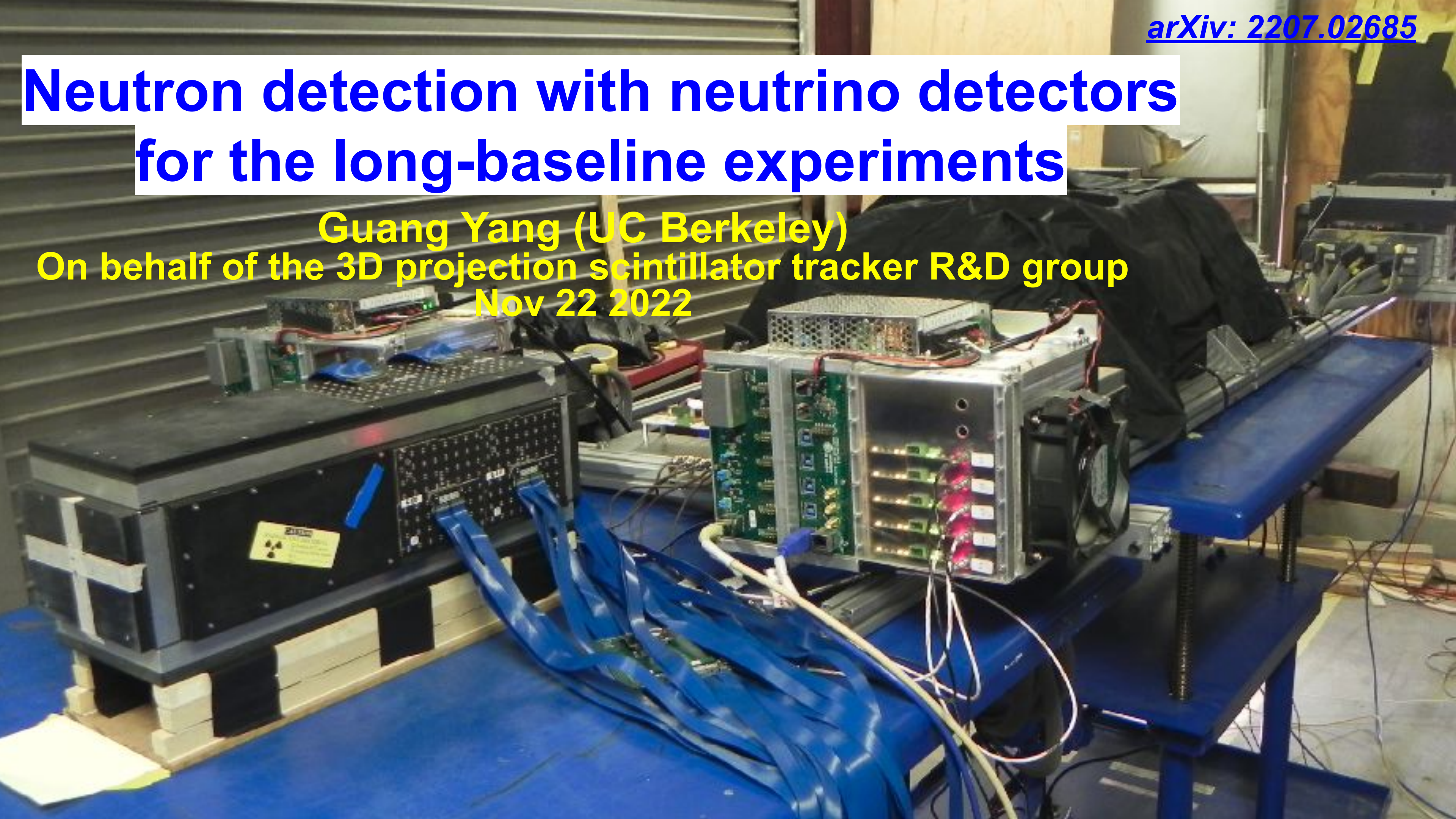


arXiv: 2207.02685

Neutron detection with neutrino detectors for the long-baseline experiments

Guang Yang (UC Berkeley)
On behalf of the 3D projection scintillator tracker R&D group
Nov 22 2022

3D projection scintillator tracker R&D group

CERN
Chung-Ang University, South Korea
ETH Zurich, Switzerland
University of Geneva, Switzerland
KEK, Japan
IFAE, Spain
Imperial College, UK
Institute for Nuclear Research (INR), Russia
University of Kyoto, Japan
Louisiana State University, USA
University of Pennsylvania, USA
University of Pittsburgh, USA
South Dakota School of Mines and Tech., USA
Stony Brook University, USA
University of Tokyo, Japan

Why neutrinos

Fundamental: Neutrinos are fundamental particles in the standard model.

Abundant: Neutrinos are by far the most abundant particles in the universe. About 100 trillion neutrinos pass through your body every second without interacting with any of the particles in your body.

Elusive: Extremely small cross section through the weak interaction.

Massive: Neutrino has mass, in contradiction to the standard model.

CP violation: Neutrino and antineutrino do not behave the same.

Measured through the neutrino oscillation

Important questions

https://sites.slac.stanford.edu/neutrino/research/neutrino-oscillations

Do neutrinos and antineutrinos oscillate in the same way? Or do they exhibit "CP violation", an asymmetry between matter and antimatter?

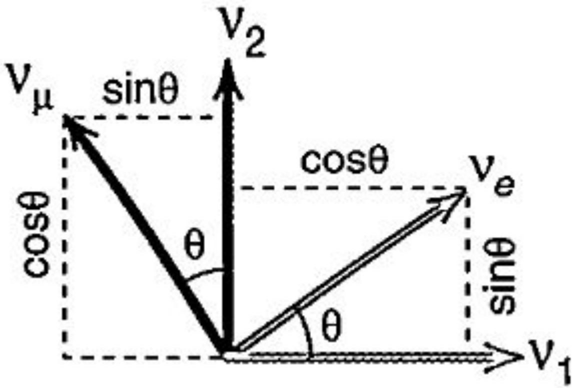
What role do neutrinos have in the evolution of the Universe? Are they the reason for why the universe is matter dominated?

Is there a pattern in the fundamental parameters which relate the neutrino flavor and mass states that point to new symmetries or physics?

What is the pattern of neutrino masses and why are they so small, more than a million times smaller than the electron, the next lightest particle? Do they get masses from a different source than other particles (e.g. the Higgs mechanism)?

Are there additional species of neutrinos than those we know about? Do they have exotic properties that can't be explained by the Standard Model?

Neutrino oscillation



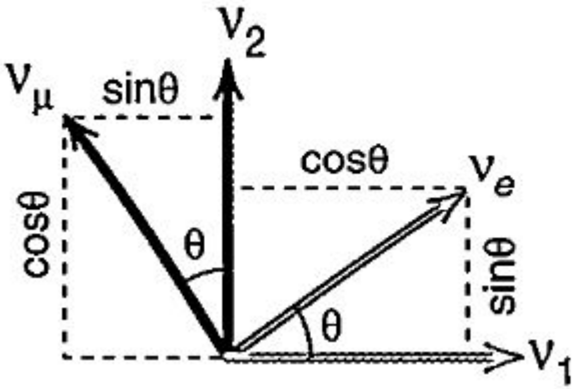
Neutrinos interact in the flavor states (ν_e, ν_μ, ν_τ).

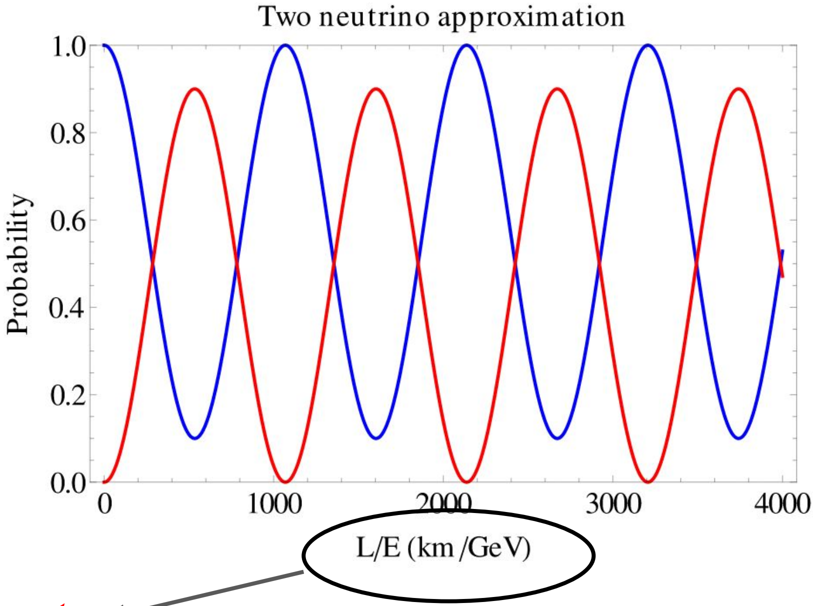
Neutrinos propagate in the mass states (ν_1, ν_2, ν_3).

Angle between the two states indicate the strength of the oscillation.

The mass split between the mass states indicates the frequency of the oscillation.

Neutrino oscillation





Measured in experiments

Accelerator-based long-baseline experiments : T2K

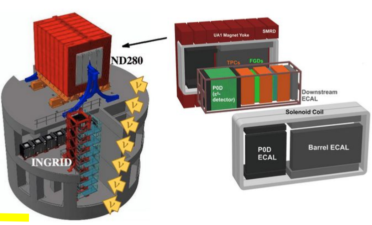
Neutrinos generated from hadron decays caused by proton hitting targets

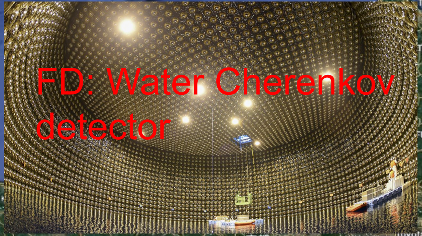
Two opposite horn currents changing focused hadron charge resulting in neutrino (FHC) and antineutrino (RHC) modes

A FD (far detector) with a very long baseline and a ND (near detector) close to the beam

Quite often, FD off-axis to reduce the high energy background

ND: Magnetized hybrid tracking system

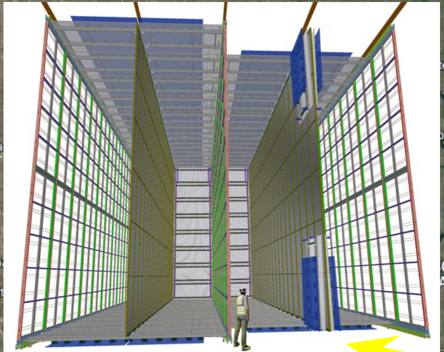




FD: Water Cherenkov detector

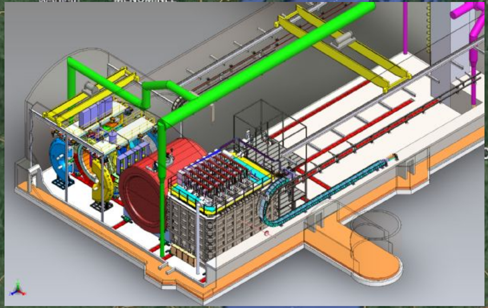
295 km baseline

Accelerator-based long-baseline experiments : DUNE



FD: 40-kt total mass; At least two 10-kt scale liquid argon modules

ND: Movable hybrid detector system



1300 km baseline

Powerful beam to deliver unprecedented amount of neutrinos and antineutrinos

Optimized long-baseline setting

Broader band beam to cover more than one oscillation maxima with 1300 km baseline

LArTPC sensitive to different particle topologies

There are more long-baseline experiments. I am showing these two only to demonstrate the idea.

Main Goal: measuring oscillation probability

Ideally

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu)}$$

Observable

$$\frac{dN_\nu^{det}}{dE_\nu} = \phi_{\nu_\mu}^{det}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu)$$

Even more

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}(E_\nu) * T_{\nu_\mu}^{det}(E_\nu, E_{rec})\, dE_\nu$$

Cancel them?

$$\frac{dN_{\nu_e}^{far}}{dE_\nu} \Big/ \frac{dN_{\nu_\mu}^{near}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma_{\nu_e}^{Ar}(E_\nu)}{\sigma_{\nu_\mu}^{Ar}(E_\nu)} * F_{far/near}(E_\nu)$$

It turns out

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\, dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\, dE_\nu}$$

Highly degenerate

Even more, there are neutrinos and antineutrinos.

Tackling the systematic uncertainties

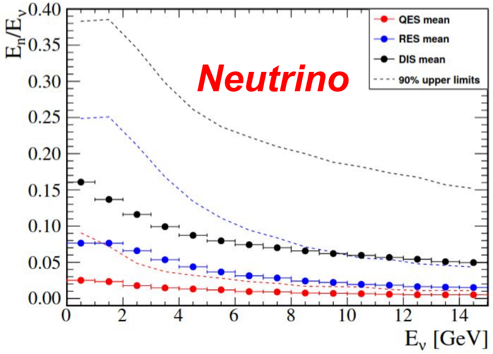
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\to\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}\,(E_\nu) * \sigma^{Ar}_{\nu_e}\,(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\,dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}\,(E_\nu) * T^{near}_{\nu_\mu}(E_\nu, E_{rec})\,dE_\nu}$$

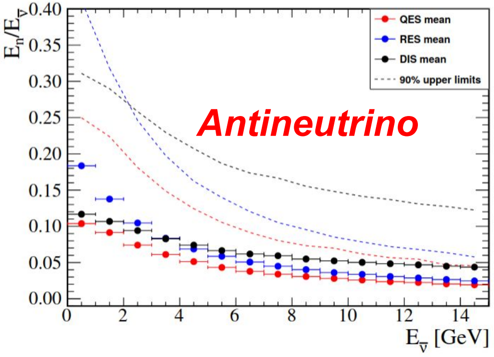
Philosophy:

- Measuring absolute flux at near detector with the channels that have well-known cross sections (nu-e elastic scattering, nuclear effect free etc.) -> target independent
- Measuring as many exclusive differential cross sections as possible to fine tune the interaction models
- Designing similar near and far detectors to cancel as much detector systematic uncertainty as possible

Affected by missing neutrons!

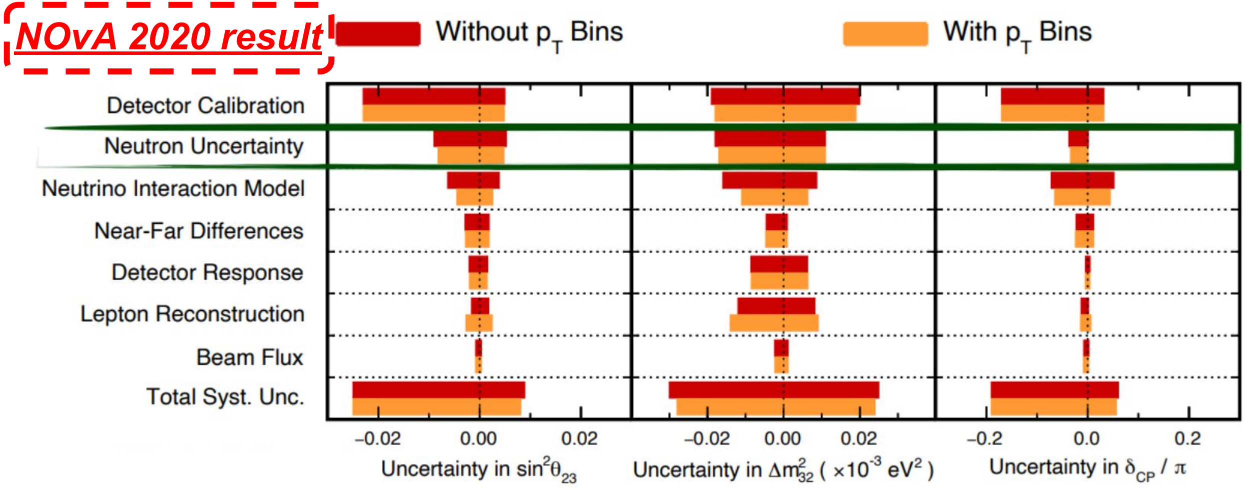
Systematic uncertainty induced by missing neutron





Neutrons carry substantial amounts of energy from the neutrino interaction.

The neutron information strongly depends on models.


NOvA 2020 result

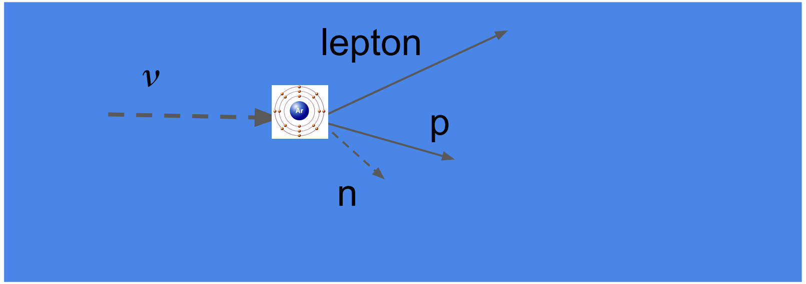
More problematic: potential bias induced by missing neutrons

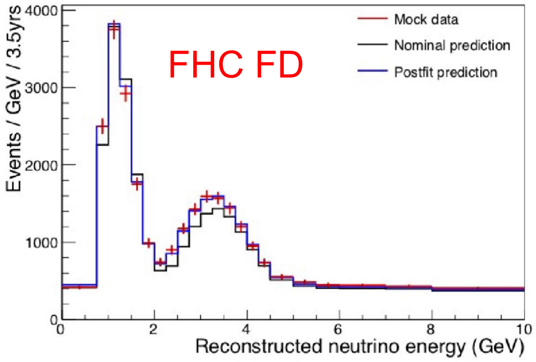
20% of the proton kinetic energy assigned to neutrons

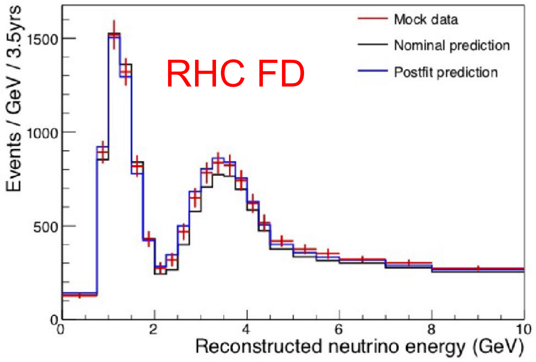
Absence of the proton/neutron kinetic energy dials in the systematic pulls

Near detector postfit predictions matching mock data through other systematic pulls

Far detector postfit predictions matched mock data through both systematic pulls and the oscillation parameters





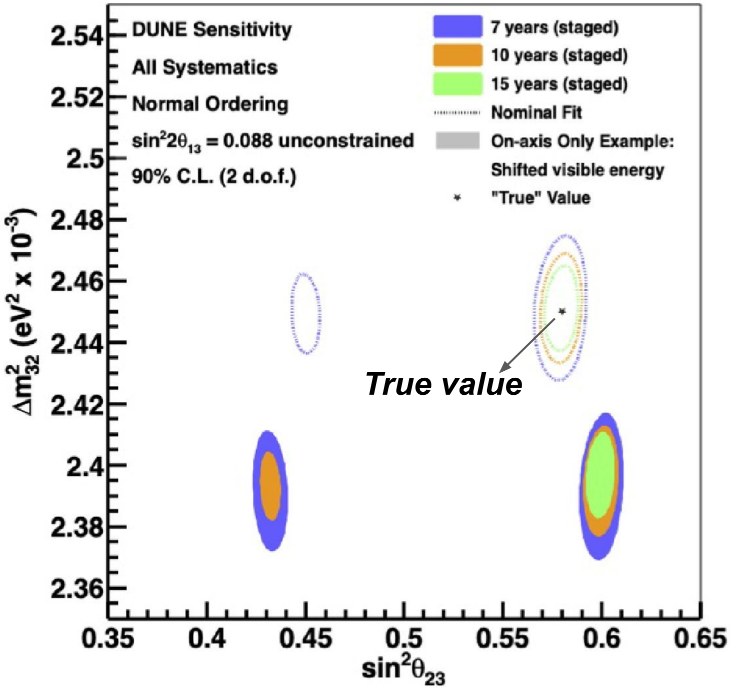


More problematic: potential bias induced by missing neutrons

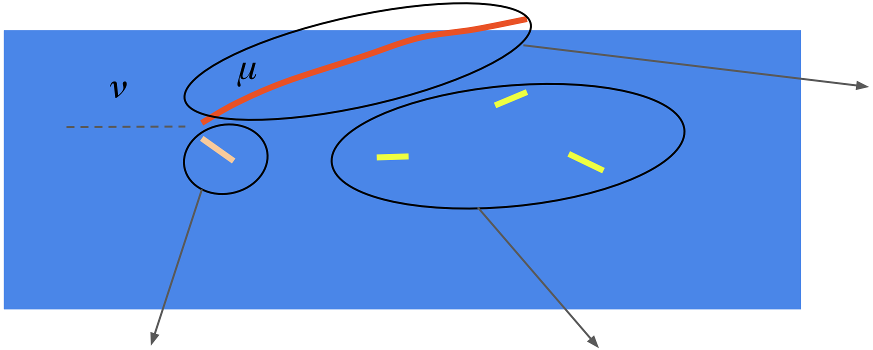
The systematic uncertainties are highly constrained by the ND.

Due to the lack of proton/neutron kinetic energy systematics, other systematics are forced to change.

The oscillation parameters must be shifted to make FD prediction and mock data match.



How to detect neutron kinematics event-by-event?

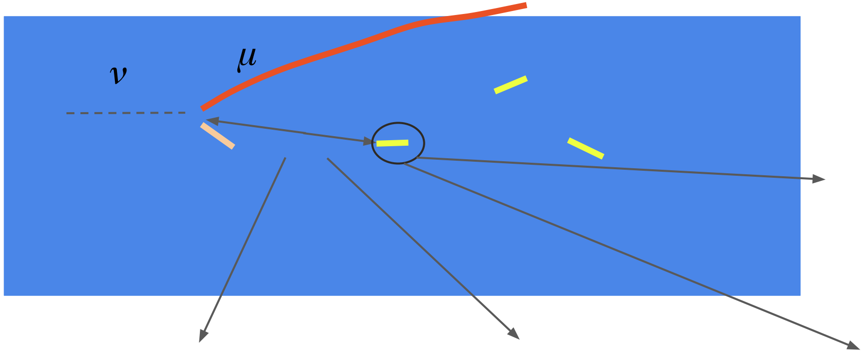


Muon track can be identified and momentum and sign can be determined with a magnetized tracker; neutrino interaction vertex also identified

Proton can be identified and energy can be measured with a low-threshold detector

In order to detect neutrons, need to look at all isolated clusters

How to detect neutron kinematics event-by-event?



Fine granularity and fast timing needed to identify the first isolated objects

High light yield to enable the visible low energy neutron-induced deposit

Fully active volume to avoid neutron interaction in passive material -> change ToF and lever arm

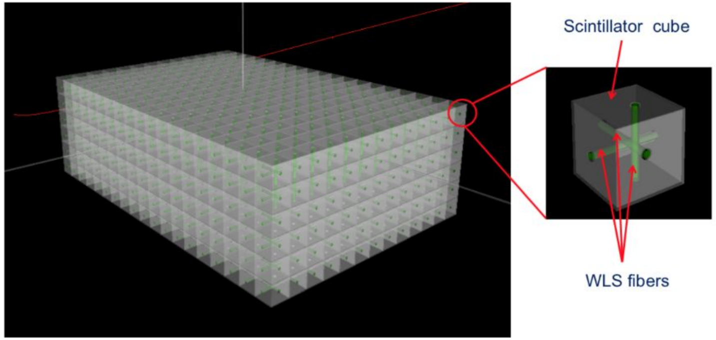
Fast timing and fine granularity needed to measure the time-of-flight and drift distance

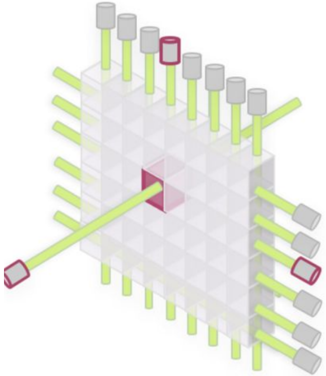
Fully active!
Fast timing!
Fine granularity!
High light yield!

3D-projection scintillator tracker

3D array of 1 cm^3 optically isolated scintillator cubes

3D readout with 3 WLS fibers passing through each cube and connected to MPPCs (multi-pixel photon counters)



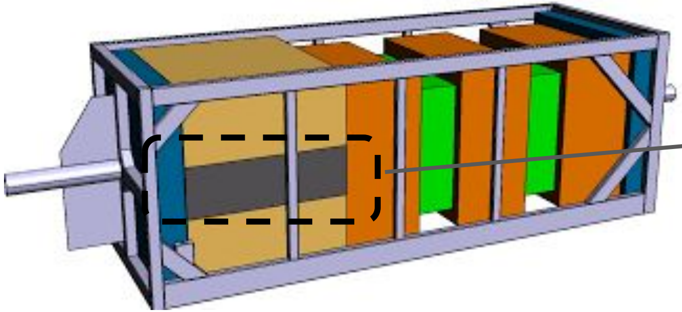


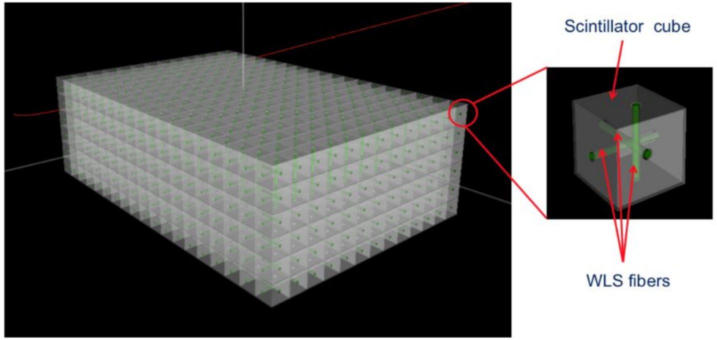
2018 JINST 13 P02006 NIM A936 (2019) 136-138

No dead material:
Fully active!
Single fiber 0.9 ns timing resolution: Fast timing!
1-cm-scale size:
Fine granularity!
>50 PE/MeV each readout: High light yield!

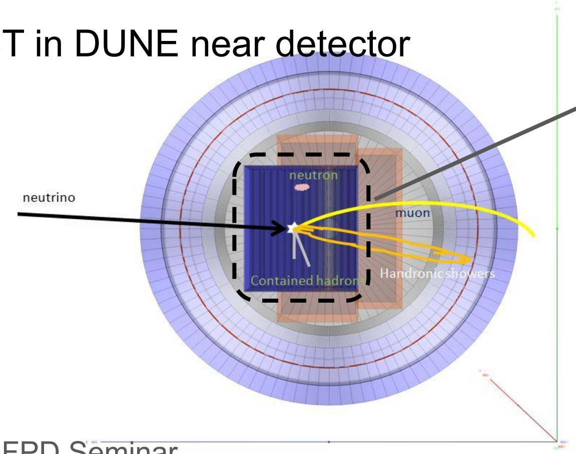
Neutron detection on an event-by-event basis

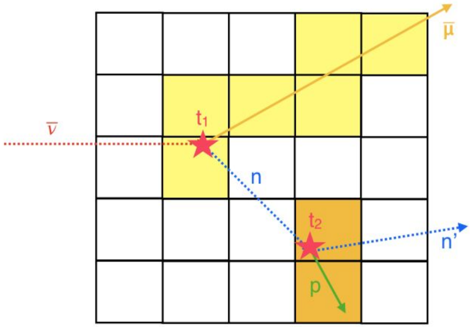
ND280 upgrade in T2K





3DST in DUNE near detector



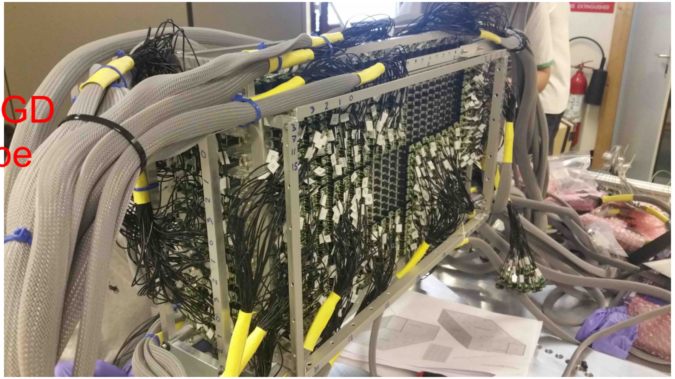


Not only tagging, SuperFGD can measure the neutron kinematics!

Demonstration of the neutron detection capability

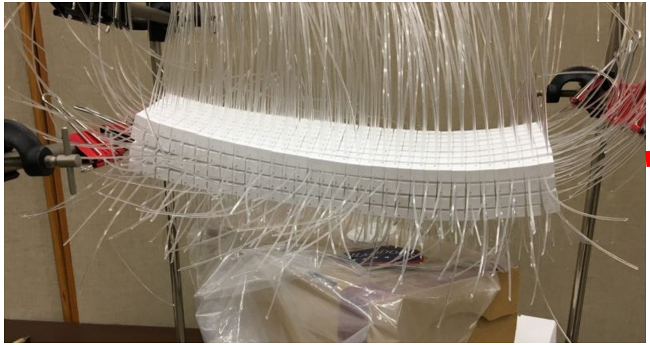
Using prototypes to prove it => two prototypes with 1cm x 1cm x 1cm cube size

- SuperFGD prototype (SFGD) been used for a charged particle beam test at CERN (size 24 x 8 x 48): *JINST* 15 (2020) P12003
- US-Japan prototype (USJ) with new designs that will be used in the T2K upgrade (size 8 x 8 x 32).



SuperFGD prototype

US-Japan proto.
Assembled
In Stony Brook



US-Japan prototype

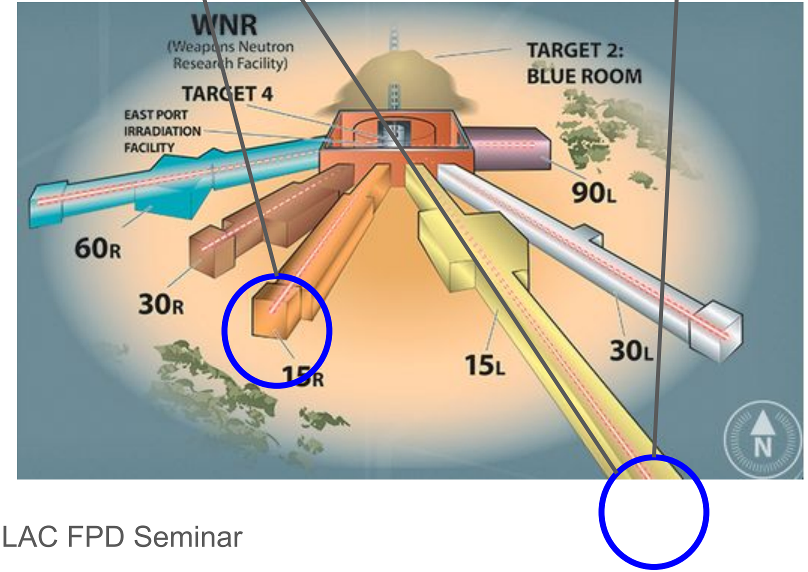
At LANL

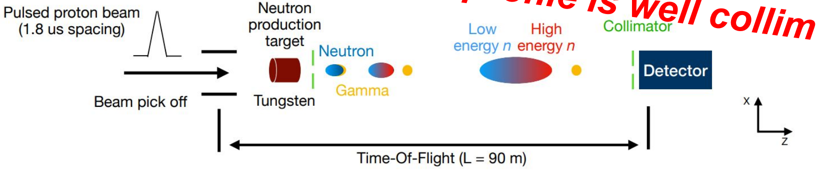
Neutron beam facility

Los Alamos National Lab LANCSE facility provides neutron beam ranged up to 800 MeV.

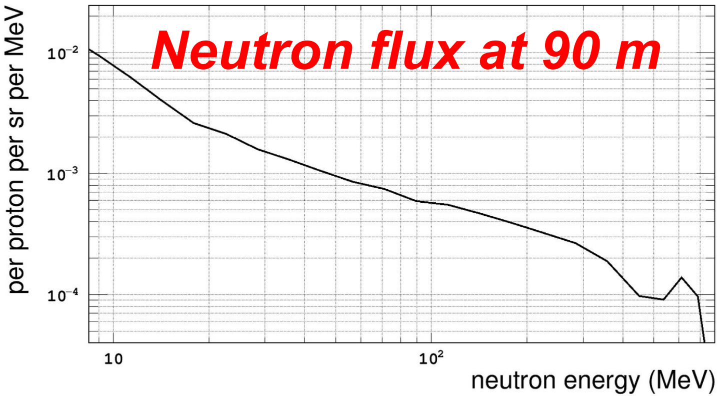
2019: 15R 20 m 3 days (SFGD+USJ) + 15L 90 m 2 weeks (SFGD only)

2020: 15L 90 m 2 weeks (SFGD+USJ, various collimator, pulse spacing, detector configuration settings.)





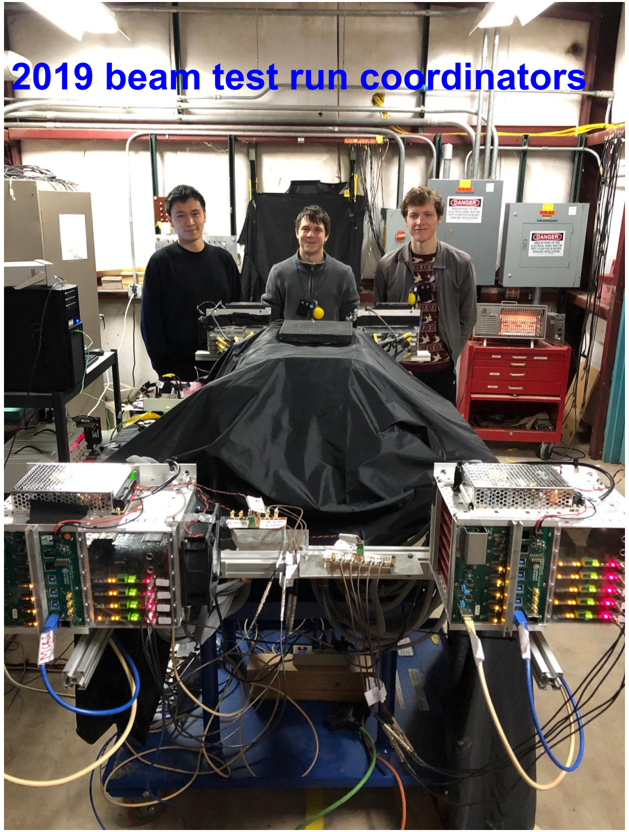
Beam profile is well collimated!



Neutron flux at 90 m

Let’s install the detector in the beamline, but before that, say hi to the crew members.

2019 beam test run coordinators



2020 beam test onsite team

Detectors at the beamline

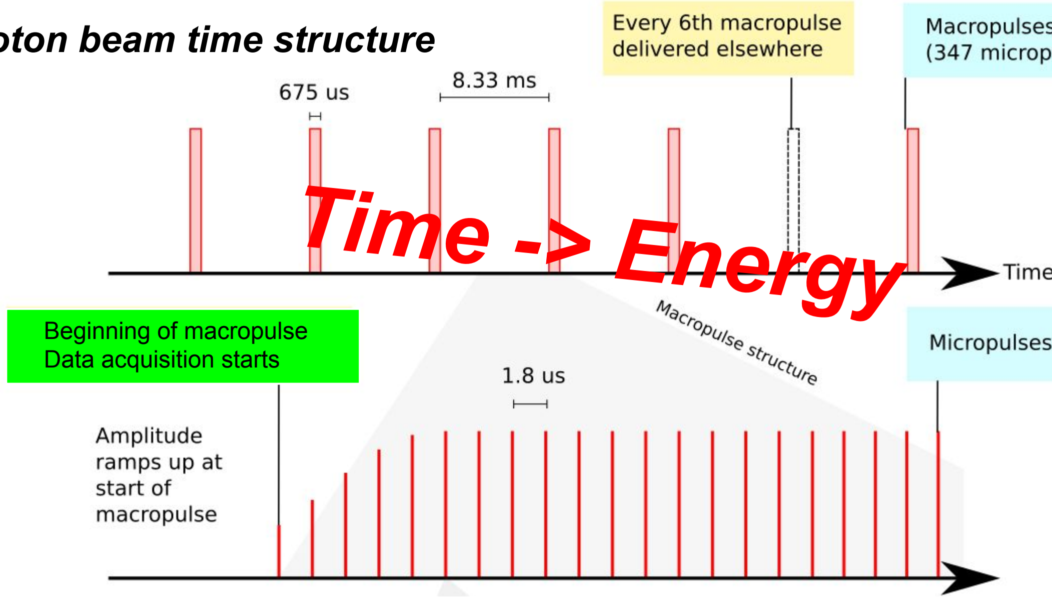
Neutron beam time structure

Neutrons are from protons hitting a tungsten target.

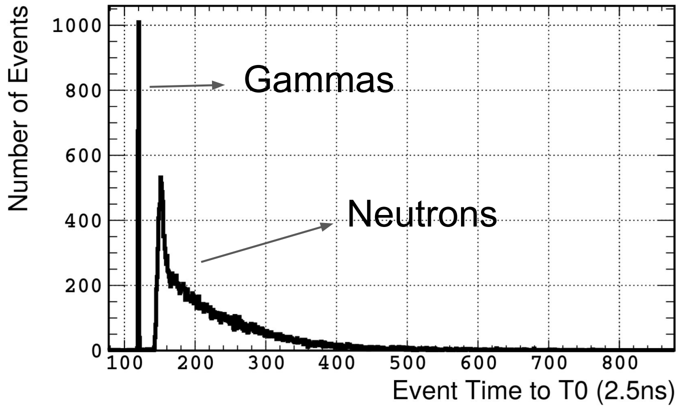
Micropulse very short (sub-ns) => able to measure the neutron energy

Gamma flash and t0 available for micropulses

Proton beam time structure



Time -> Energy

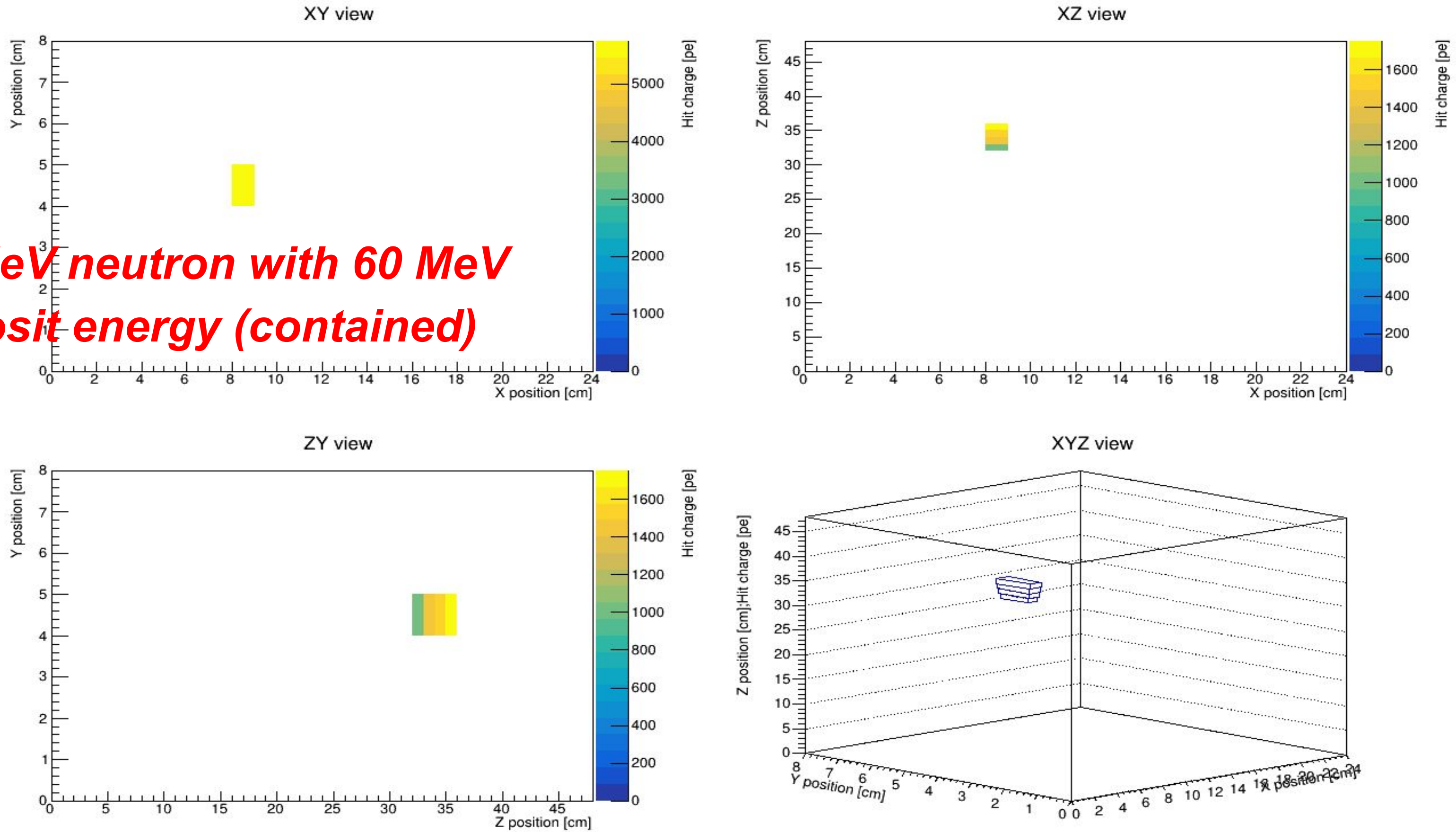


In each micropulse, neutrons following gamma flashes

Two micropulse spacing of 1.8 μs and 3.6 μs

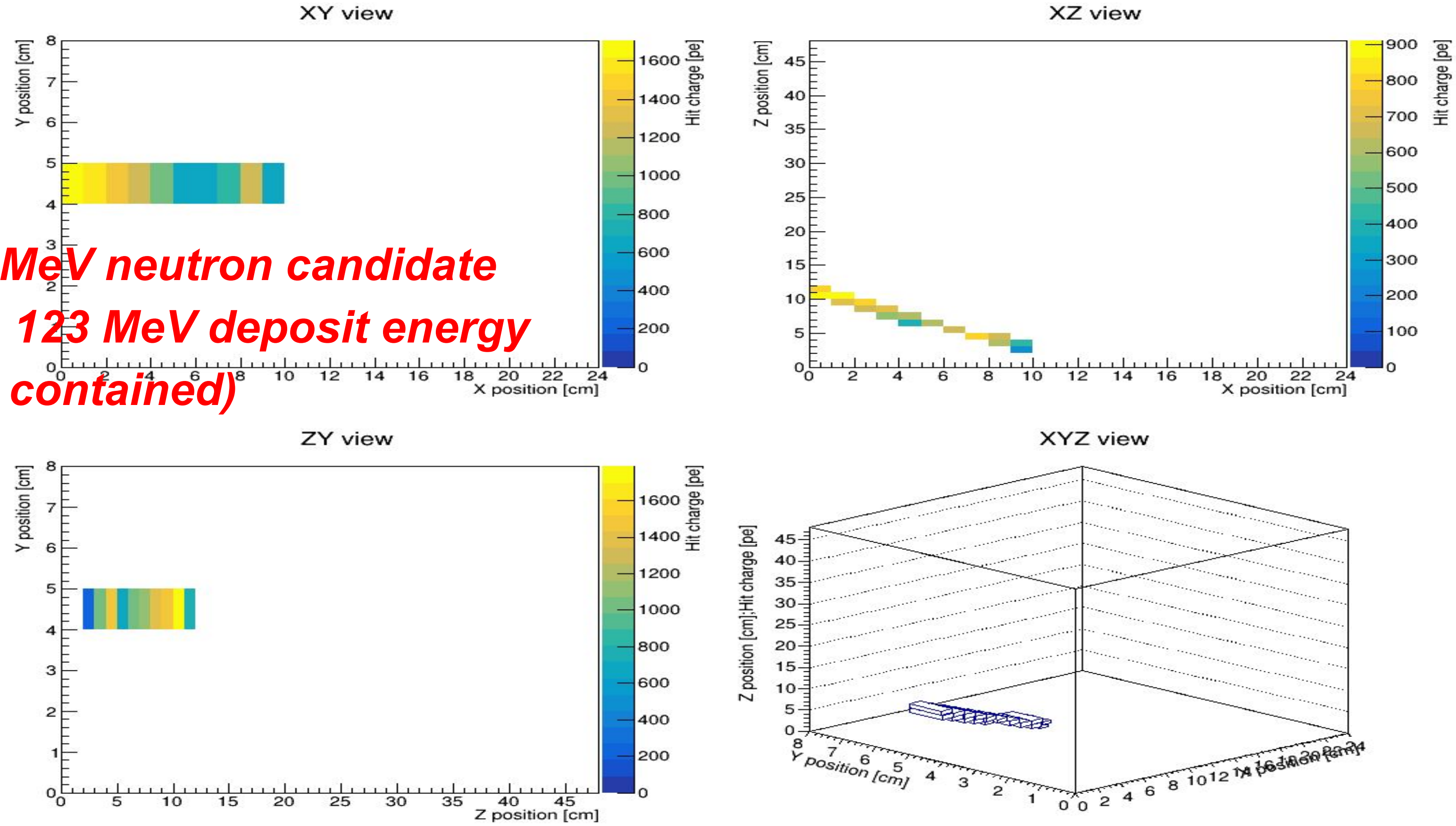
Only 2020

Neutron candidates



65 MeV neutron with 60 MeV deposit energy (contained)

Neutron candidates



193 MeV neutron candidate with 123 MeV deposit energy (not contained)

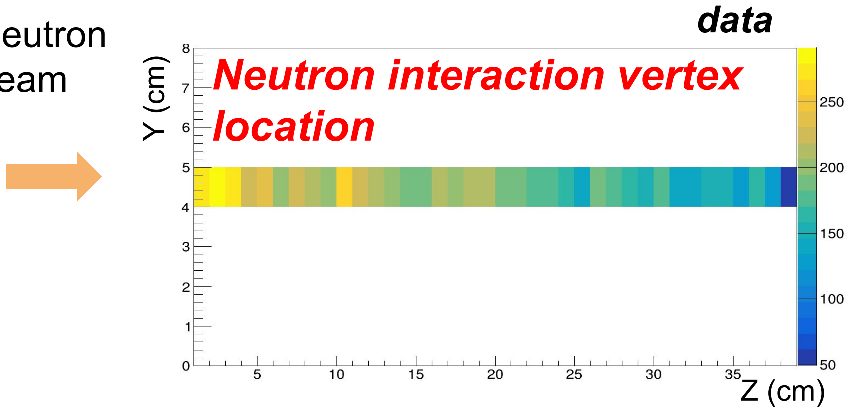
First physics result

Neutron-CH total cross section from 98 MeV to 688 MeV

- Aim for demonstrating that SuperFGD is able to detect neutron interactions as expected.
- Provide a useful measurement for energy above 500 MeV region, which is not well-known in the nuclear community.
- Region where neutron KE below 98 MeV does not form clear topologies.
- Region where neutron KE above 688 MeV has less statistics and contains gammas.

A total cross-section measurement

Neutron beam



The extinction method needs a relative measurement of event rate at each layer along the beam.

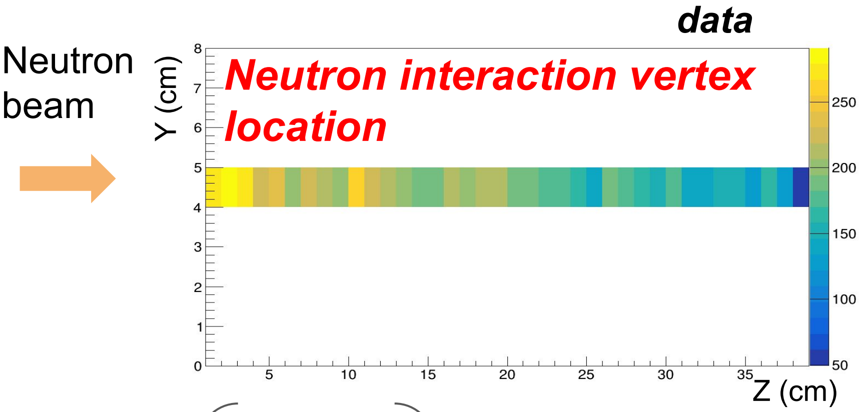
$$N(z) = N_0 \cdot \exp(-T \cdot \sigma_{total} \cdot z)$$

Nuclear density total xsec depth along the beam, i.e. layer

Measurement of event rate at each layer indicates a total cross section

The first result of the neutron total cross-section measurement only takes the 2019 SuperFGD prototype data.

A total cross-section measurement



Event rate ratio for any two layers with certain topology (e.g. single-track) is equal to the event rate ratio for any two layers with all topologies-> any topology can be used

$$N_{e,z} = \sum \begin{pmatrix} N_{\text{single-track},e,z} \\ N_{\text{invisible},e,z} \\ N_{\text{two-track},e,z} \\ .. \\ N_{\text{100-track},e,z} \end{pmatrix} = \sum \begin{pmatrix} N_{\text{single-track, }e,z} \\ N_{\text{single-track, }e,z} \times \varepsilon e \\ \\ \end{pmatrix}$$

Energy Layer

ε is the cross section
Ratio between "non-single-track" and single-track, it only depends on energy, regardless of layer

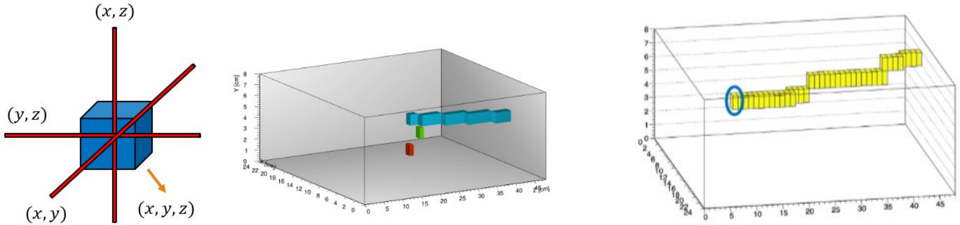
$$N_{e,l} / N_{e,m} = N_{\text{single-track},e,l} / N_{\text{single-track},e,m}$$

Layer l Layer m

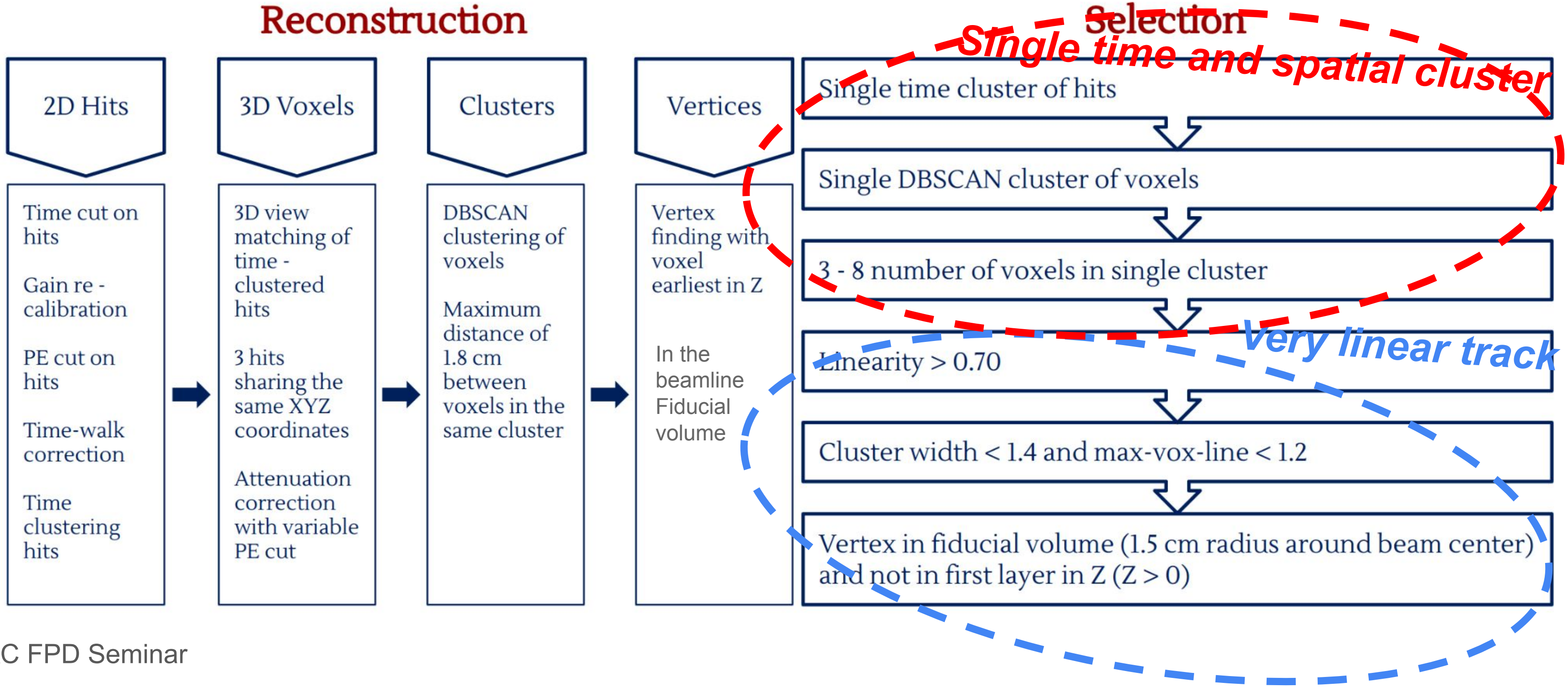
Single track attenuation indicates a total cross-section

Single track defined as a single temporal and spatial cluster with at least three voxels and good linearity

Single track recon.



Voxel: 3D reconstructed cube



Reconstruction

2D Hits

- Time cut on hits
- Gain re-calibration
- PE cut on hits
- Time-walk correction
- Time clustering hits

→

3D Voxels

- 3D view matching of time-clustered hits
- 3 hits sharing the same XYZ coordinates
- Attenuation correction with variable PE cut

→

Clusters

- DBSCAN clustering of voxels
- Maximum distance of 1.8 cm between voxels in the same cluster

→

Vertices

- Vertex finding with voxel earliest in Z
- In the beamline Fiducial volume

Selection

Single time and spatial cluster

1. Single time cluster of hits
2. Single DBSCAN cluster of voxels
3. 3 - 8 number of voxels in single cluster

Very linear track

4. Linearity > 0.70
5. Cluster width < 1.4 and max-vox-line < 1.2
6. Vertex in fiducial volume (1.5 cm radius around beam center) and not in first layer in Z (Z > 0)

Systematic uncertainty included

Dominating !

Detection systematic: Cube, MPPC and passive material non-uniformity

Invisible scattering: Invisible primary interaction vertex

Geometric acceptance: Location dependent acceptance due to limited detector size

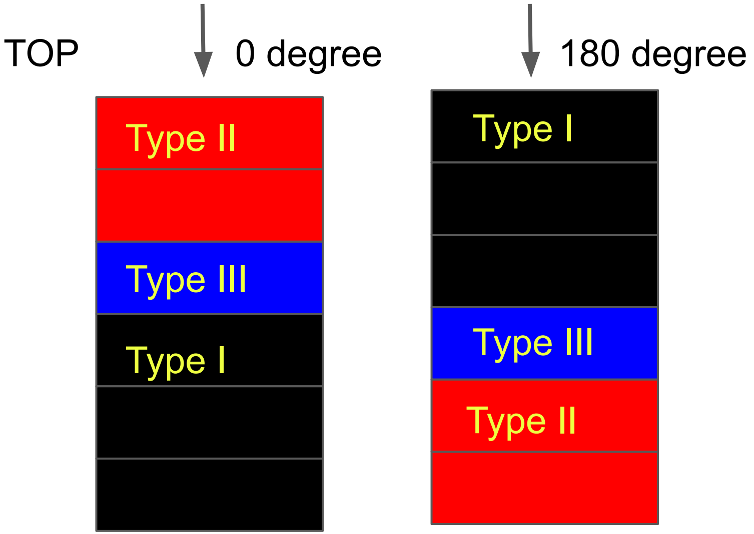
Light yield: Light yield variation for each channel

Time resolution: Events shifting across different energy bins

Collimator interaction: Events interacting with the collimator before entering the detector

Major Systematics: Detection

- When compare the event rates of 0 degree and 180 degree configurations, the difference is up to 10% across the z layers.
- **MPPC anisotropy:** Relatively small as the results without the top view are very similar.
- Ruled out the hypothetical reasons of **calibration, beam tilting and reconstruction**.
- **Cube misalignment:** In simulation, systematically shifting every 5 layers by 1 mm makes the events rate at z changes up to 10% -> **this is the culprit of our best understanding.**



TOP

0 degree

Type II

Type III

Type I

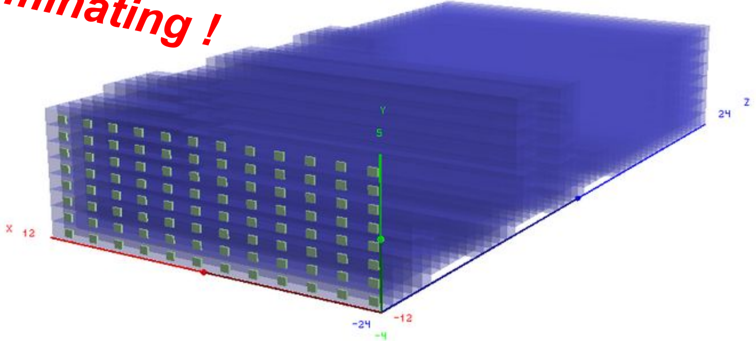
180 degree

Type I

Type III

Type II

Dominating !



Major Systematics: Detection

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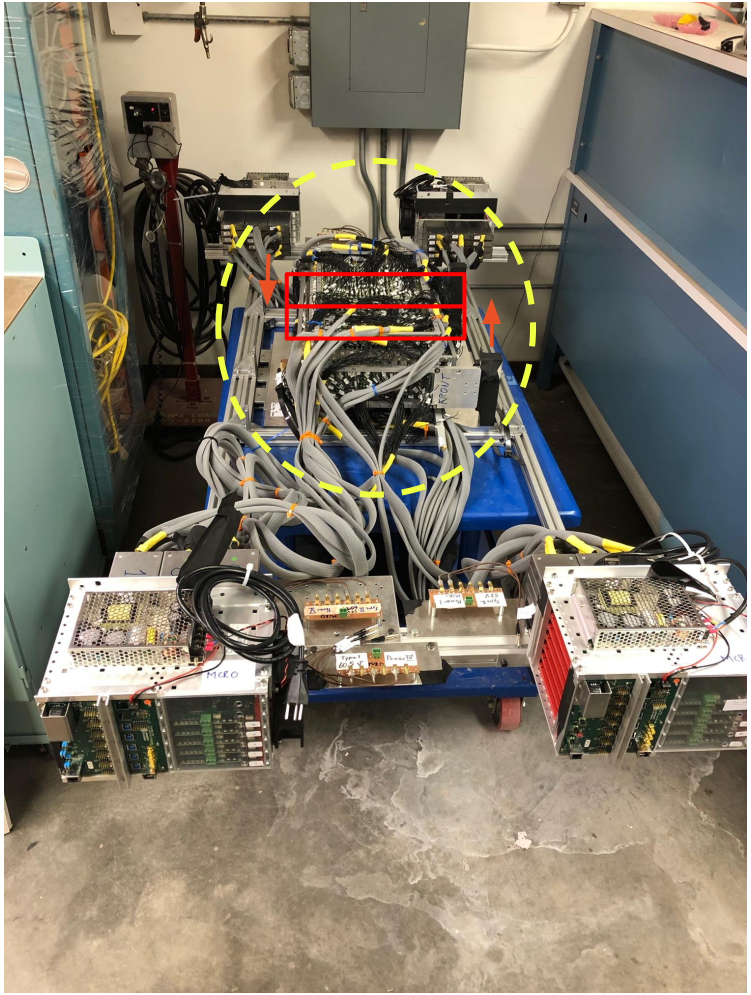
- **MPPC anisotropy:** Relatively small as the results without the top view are very similar.
- Ruled out the hypothetical reasons of **calibration, beam tilting and reconstruction**.
- **Cube misalignment:** In simulation, systematically shifting every 5 layers by 1 mm makes the events rate at z changes up to 10% -> **this is the culprit of our best understanding.**
- ***May be less a problem in the neutrino interaction. Still, dedicated alignment study is needed in the future.***



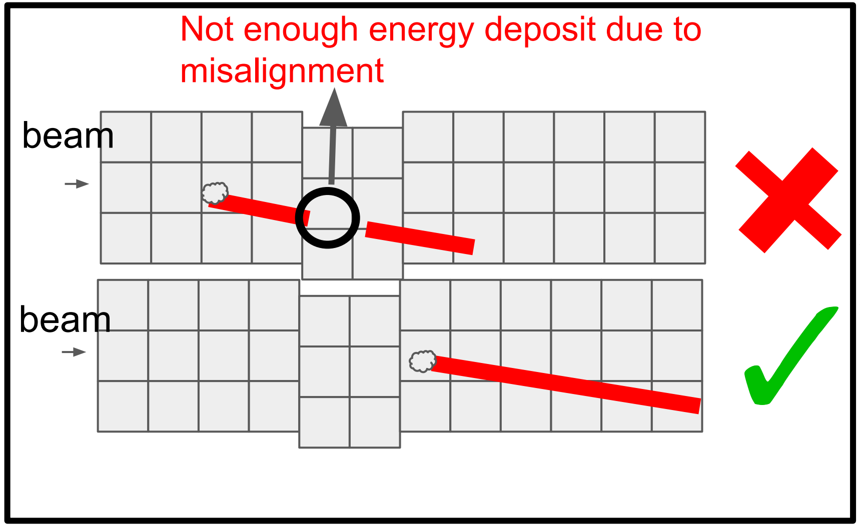
Major Systematics: Detection

Dominating !

A certain topology along z results in a total cross section measurement, compare

- Single-track
- Everything above threshold

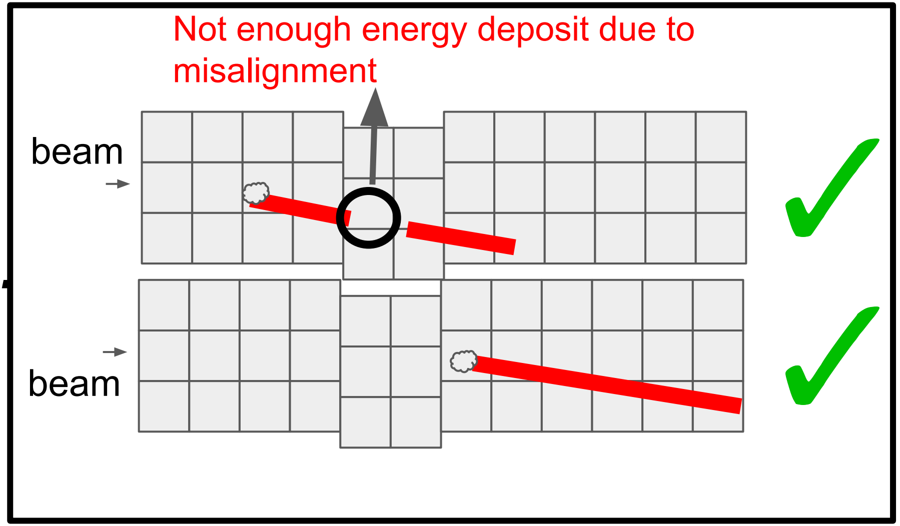
Single-track



Not enough energy deposit due to misalignment

VS.

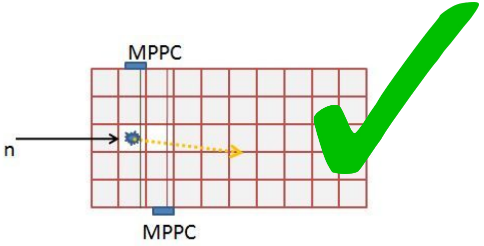
Everything above threshold (called “no-cut”)

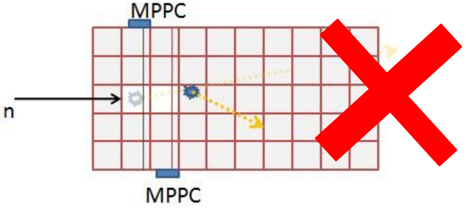


Not enough energy deposit due to misalignment

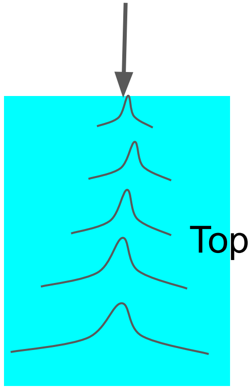
Major Systematics: Invisible scattering

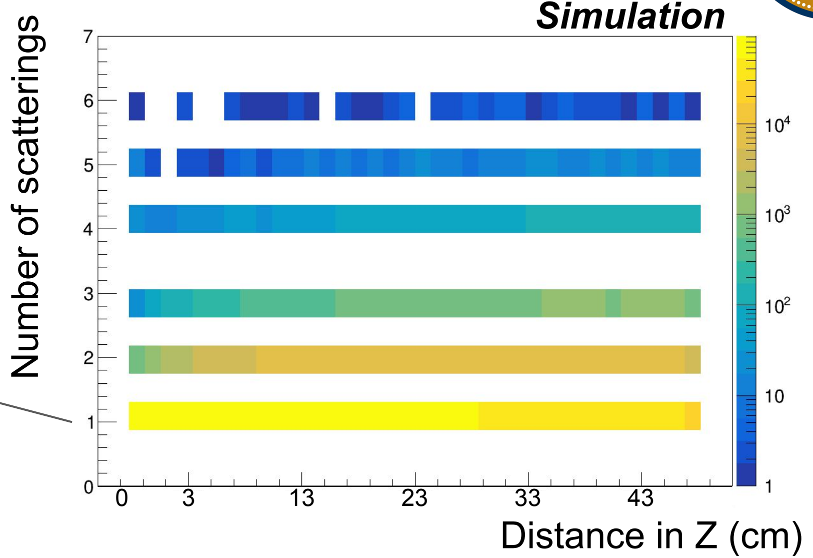
What we want to measure:
neutron-induced single track =>
requiring no scattering before the
visible one that induces single tracks





No invisible scattering

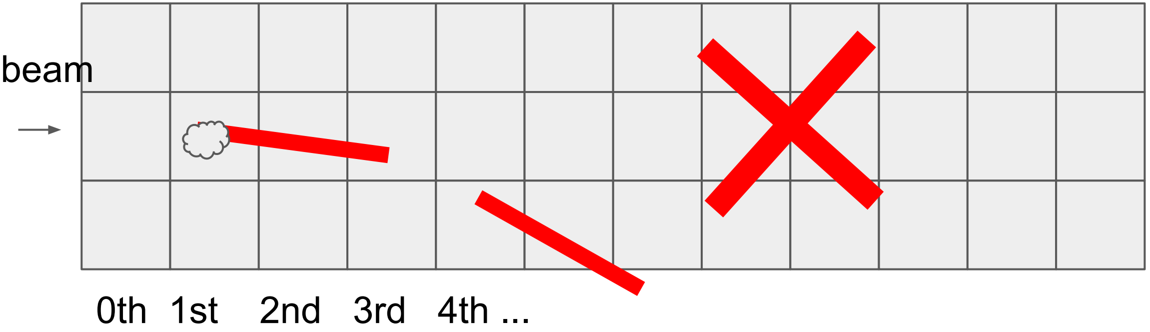


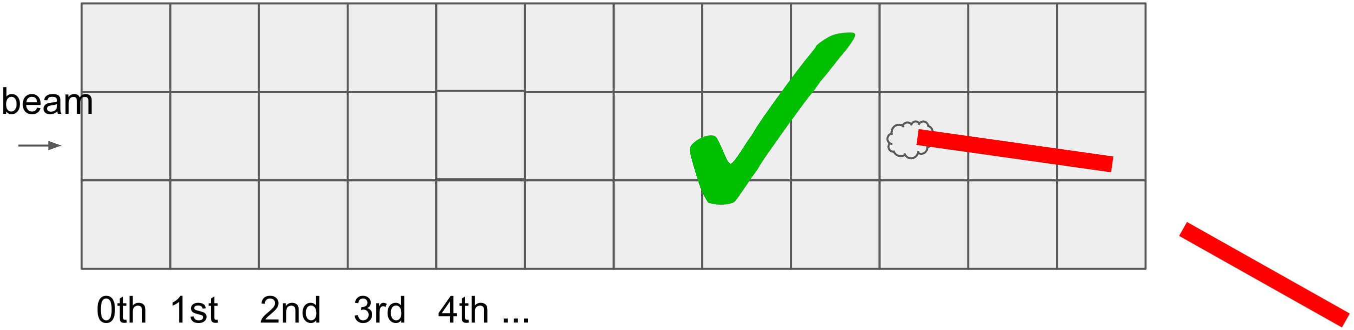


1. ***Tune MC transverse spread to data by weighting invisible scattering.***
2. ***Invisible scattering fraction can be extracted from the tuned MC -> It is taken as the systematic uncertainty.***

Major Systematics: Geometric acceptance

The same topology may have different selection acceptance depending its z location.

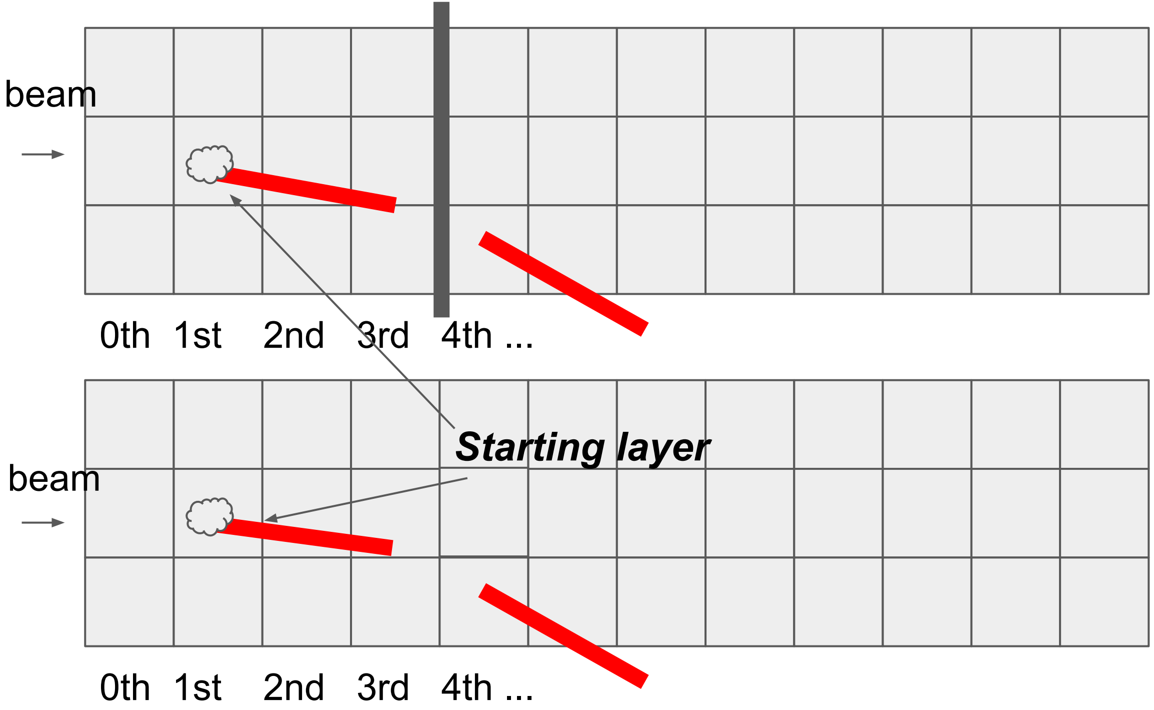




To reduce the model dependency, try to use a data-driven approach.

Major Systematics: Geometric acceptance

Shifting detector z boundary: Remove hit beyond layer m, m is from 47th, 46th to 1st.



Shifting boundary effectively expands the detector!

Ratio between with and without boundary shows the acceptance change due to limited detector size!

Used 2-8 layers as the starting layers and the variations among them is taken as systematics.

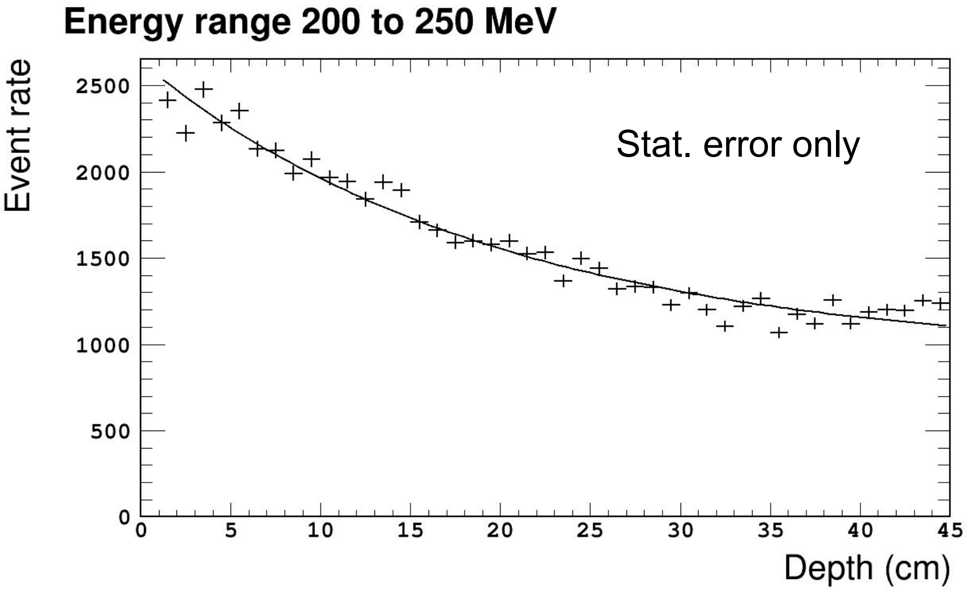
Cross-section fitter

Single-track event selection with known incident neutron energy from ToF

Applying the relative detection acceptance correction to all z layers for each energy range

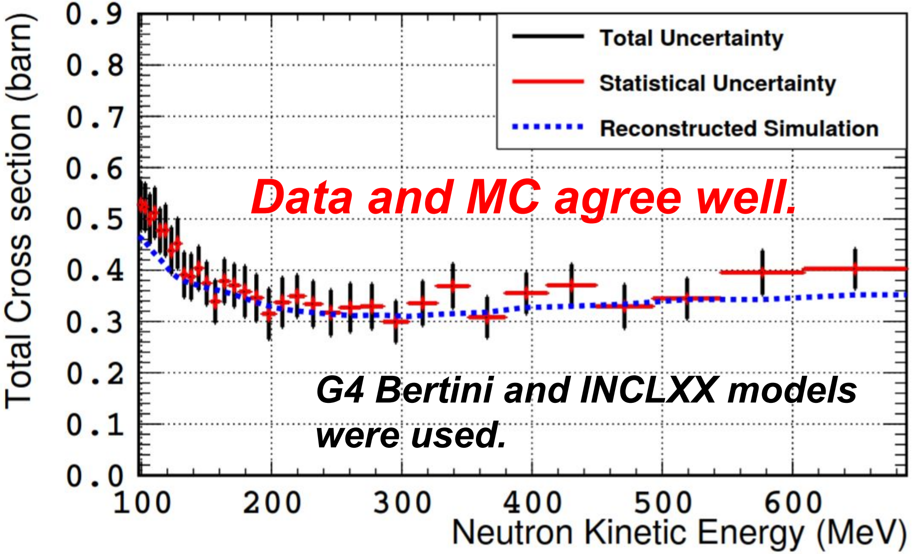
Fitting an exponential function to the Z layer distribution for each energy range.

For each energy, number of events in each z ha
a combined uncertainty from invisible scattering
detection, acceptance correction, light yield, timing resolution, collimator interaction -> The event rate randomly varied based on that uncertainty.



Total cross-section measurement result

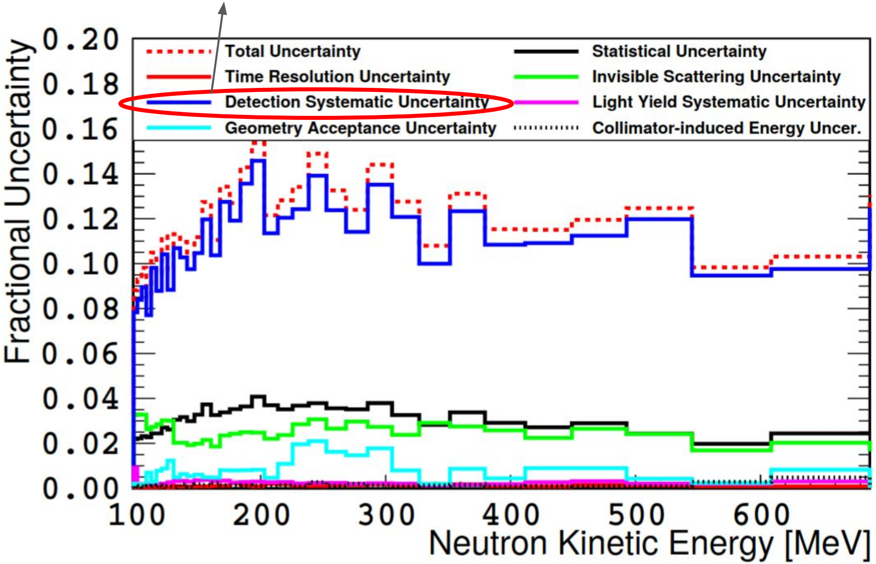
arXiv: 2207.02685



Data and MC agree well.

G4 Bertini and INCLXX models were used.

Main systematic



Other ongoing effort

Exclusive n-CH cross-section measurements such as proton production and pion production

Neutron secondary scattering model tuning (e.g. inelastic and elastic fraction of the neutron interaction)

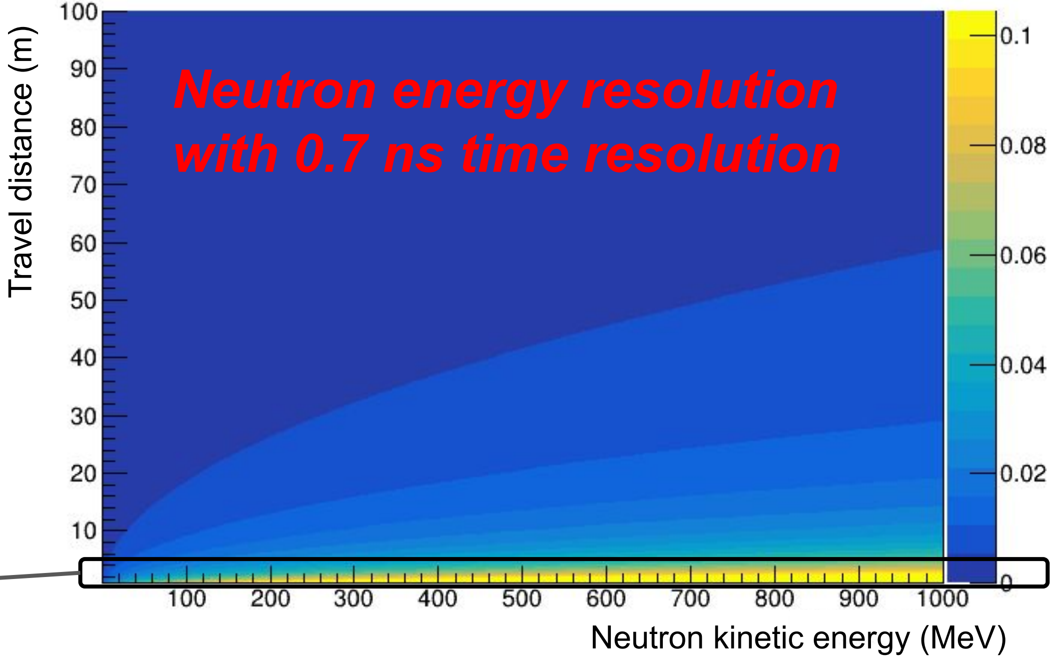
Exclusive neutron detection efficiencies

Nuclear modeling probe

Not the end -> Neutron detection in the neutrino interaction

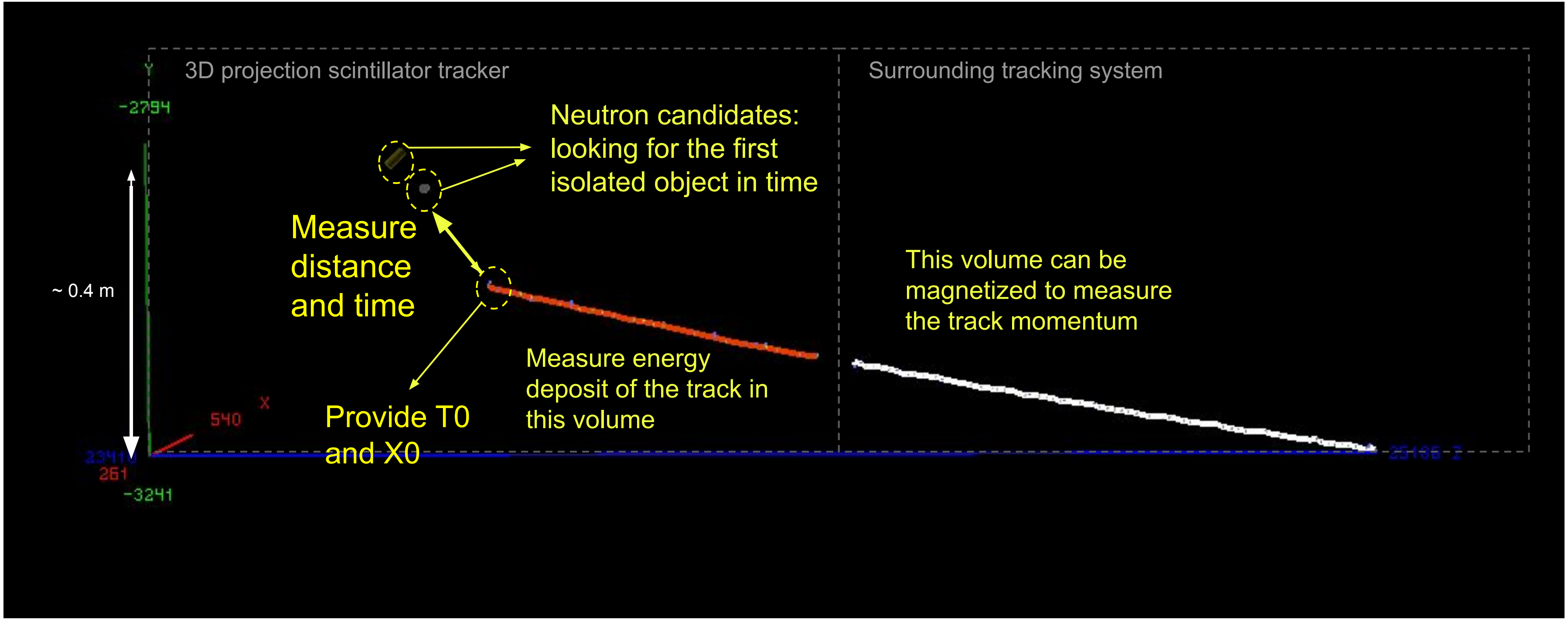
Eventually we need to move this effort to the neutrino interaction.

In the neutrino detector, the travel distance of neutrons will be less than 1 or 2 meters.



We need to come down to this region

Neutron detection in the neutrino interaction



Neutron candidates: looking for the first isolated object in time

Measure distance and time

Provide T0 and X0

Measure energy deposit of the track in this volume

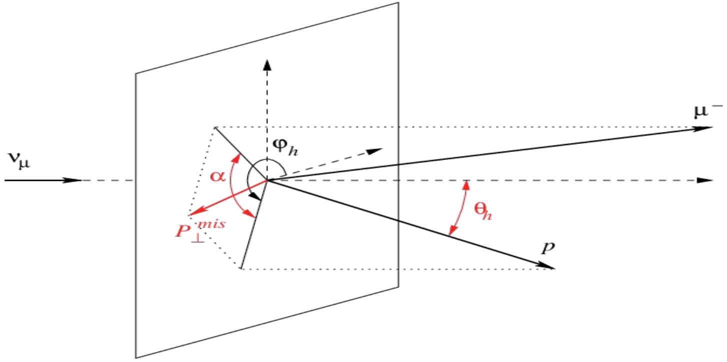
This volume can be magnetized to measure the track momentum

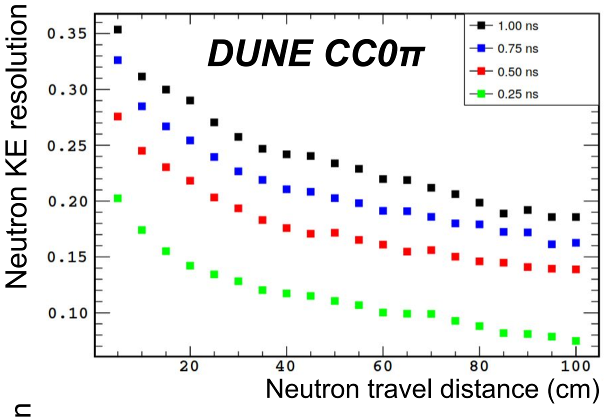
Neutron detection in the neutrino interaction

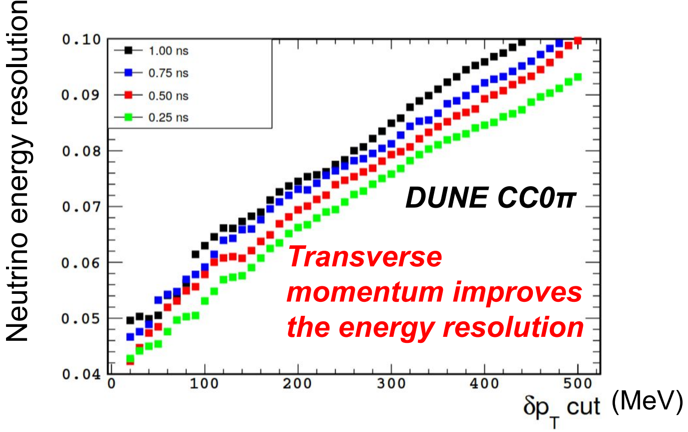
The main parameter we can control is the ***timing resolution***.

The individual neutron measurement opens a new era of utilizing transverse plane variables.

A lot effort are ongoing.







Transverse momentum improves the energy resolution

Summary

A lot of neutron interaction data with SuperFGD and US-Japan prototypes have been taken in 2019 and 2020.

A total n-CH cross-section measurement has been completed and ***it demonstrated that the 3D-projection scintillator tracker is capable of detecting neutrons.*** ***arXiv: 2207.02685***

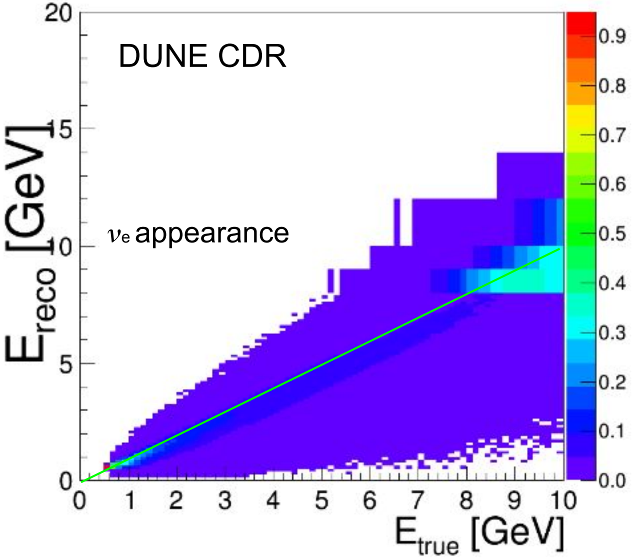
Lessons learned are being propagated to the SuperFGD physics studies and rich physics topics will be studied in the near future.

More importantly, the individual neutron detection fills the big hole in the puzzle of neutrino interaction-> opens a new era utilizing new variables.

Backups

Biased reconstructed energy

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\, dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * T^{near}_{\nu_\mu}(E_\nu, E_{rec})\, dE_\nu}$$



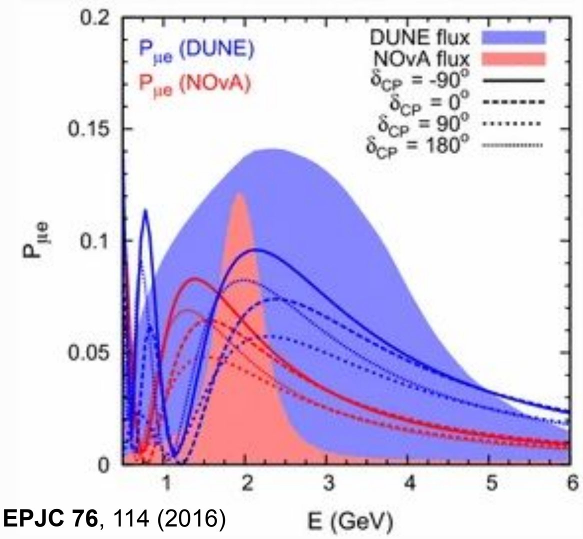
Calorimetrically reconstructing neutrino energy leads to a “feed-down” due to threshold, neutrons etc.

ND and FD are different.

The “feed-down” effects are different in neutrino and antineutrino due to different final state particles.

Wide band beam

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\, dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * T^{near}_{\nu_\mu}(E_\nu, E_{rec})\, dE_\nu}$$



EPJC 76, 114 (2016)

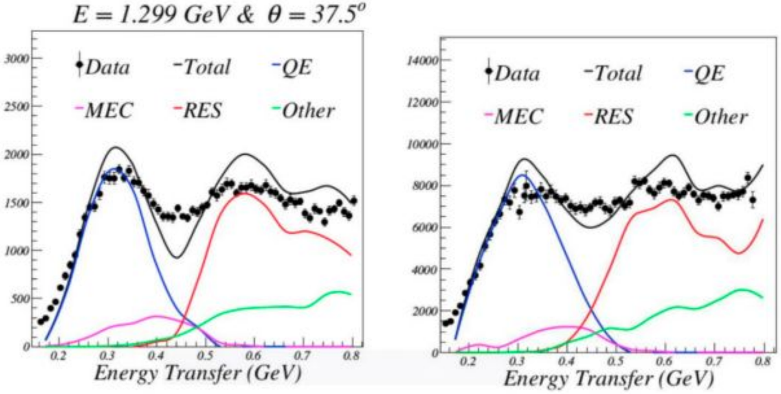
A broad band beam in DUNE => complicating the reconstructed to true energy mapping

The fluxes at ND and FD different => Aforementioned “feed-down” cannot be cancelled between ND and FD

Convoluted effects

$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\, dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * T^{near}_{\nu_\mu}(E_\nu, E_{rec})\, dE_\nu}$$

^{12}C Electron scattering ^{56}Fe



*Genie R-2_12_10

Neutrino interaction modeling is not satisfactory even with simpler nuclear target-> DUNE has a rather complicated nuclear target.

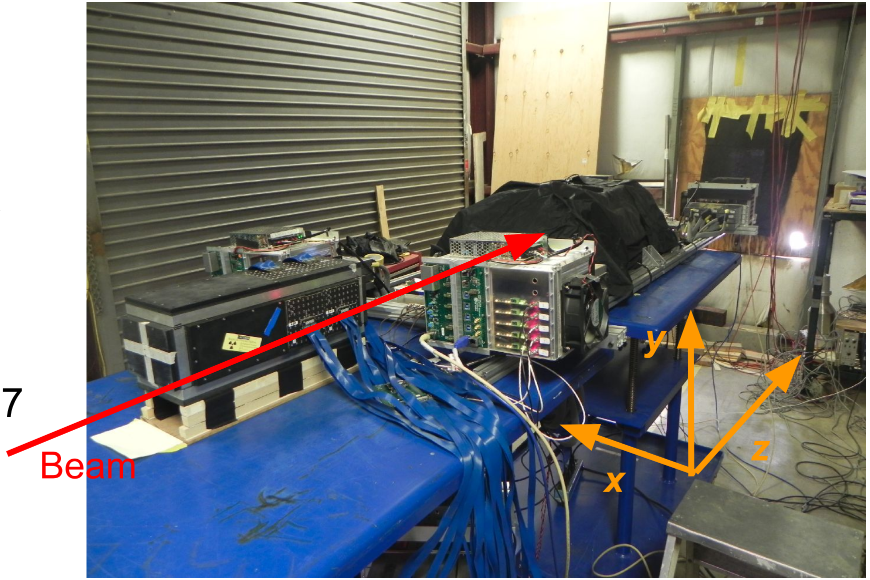
All the effects above are convoluted in an integral.

Again, it is different in neutrino and antineutrino.

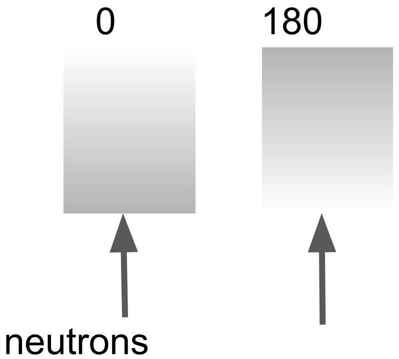
Experimental setup in 2019

Two orientation used in 2019, 0 degree and 180 degree along Y (height) -> to understand the detector anisotropy

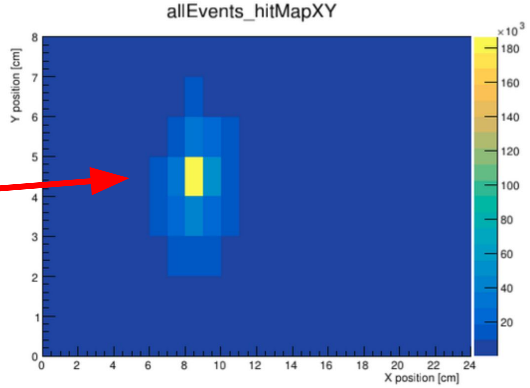
The time sampling tick size 2.5 ns, dominating the timing resolution -> single channel time resolution 1.37 ns including t0 resolution (~1.0 ns for single channel)



Top view



Beam profile collimated to 8 mm or 1mm (only for 2020) diameters



Calibration

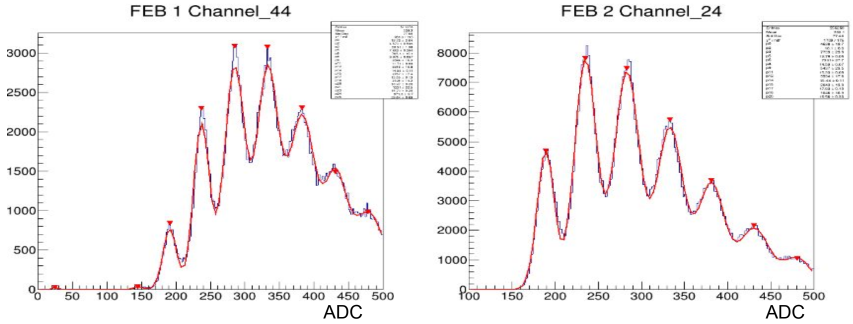
Gain calibration

- LED runs taken at LANL in 2019
- Gain extracted for each channel and temperature variance included

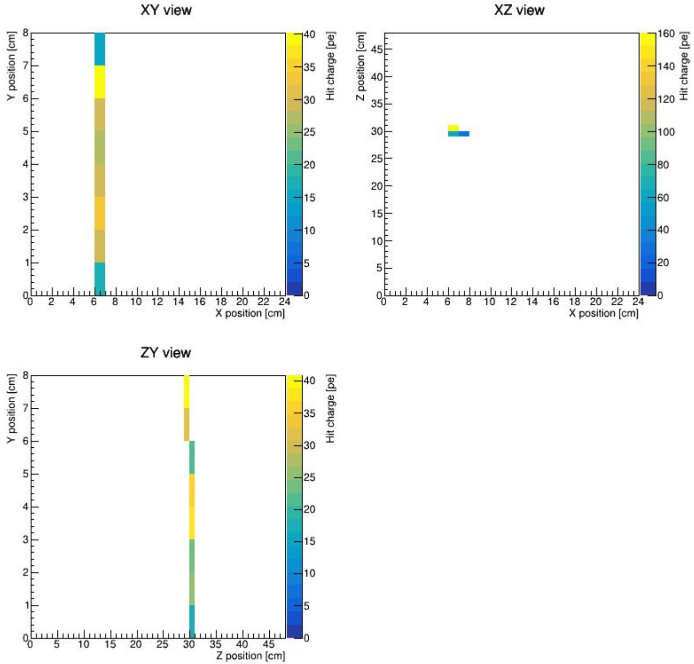
Light yield calibration

- Dedicated cosmic samples selected
- PE per MeV obtained for each channel

PE peaks finding

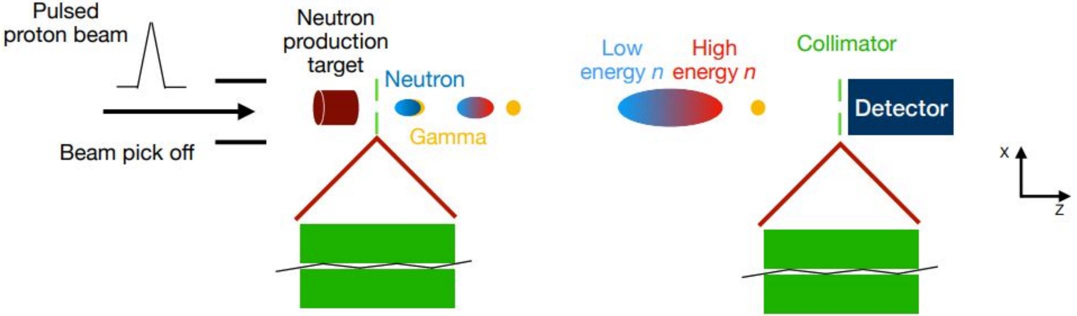


Cosmics candidate

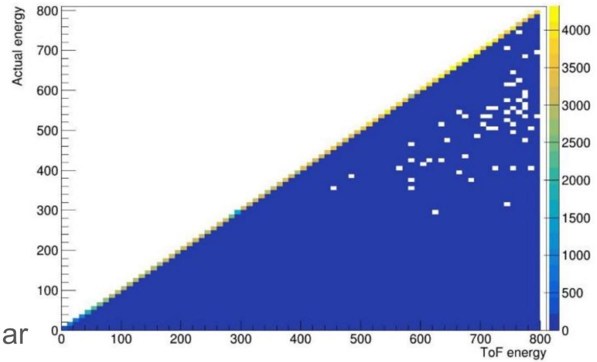


Systematics: collimator and light yield

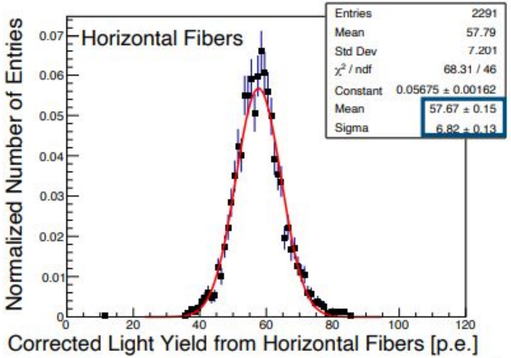
Collimator interaction reduces neutron energy, in particular those interactions at 90 m may bias the neutron energy

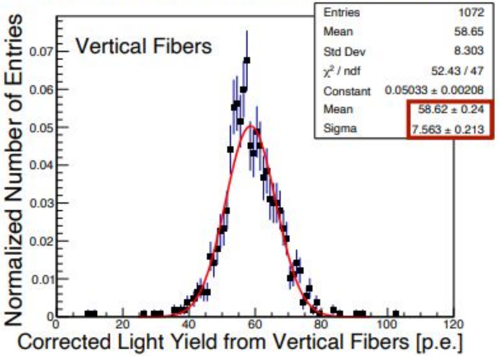


Actual energy vs. ToF energy



Light yield systematic originated from the cosmic calibration



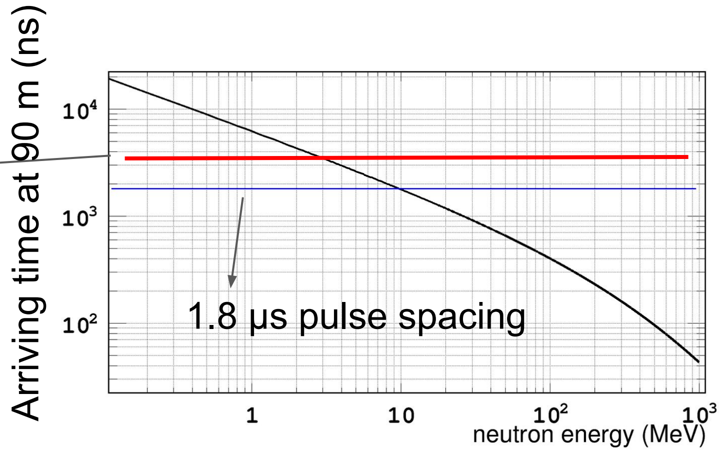


Outstanding new configurations in 2020

1 mm and 1 cm collimator in 2020 while only 1 cm collimator in 2019: Provide a better understanding of the invisible scattering before visible energy deposit.

3.6 μs pulse spacing

- It pushed to a lower wrap-around threshold, i.e. low energy and high energy neutrons can be understood better



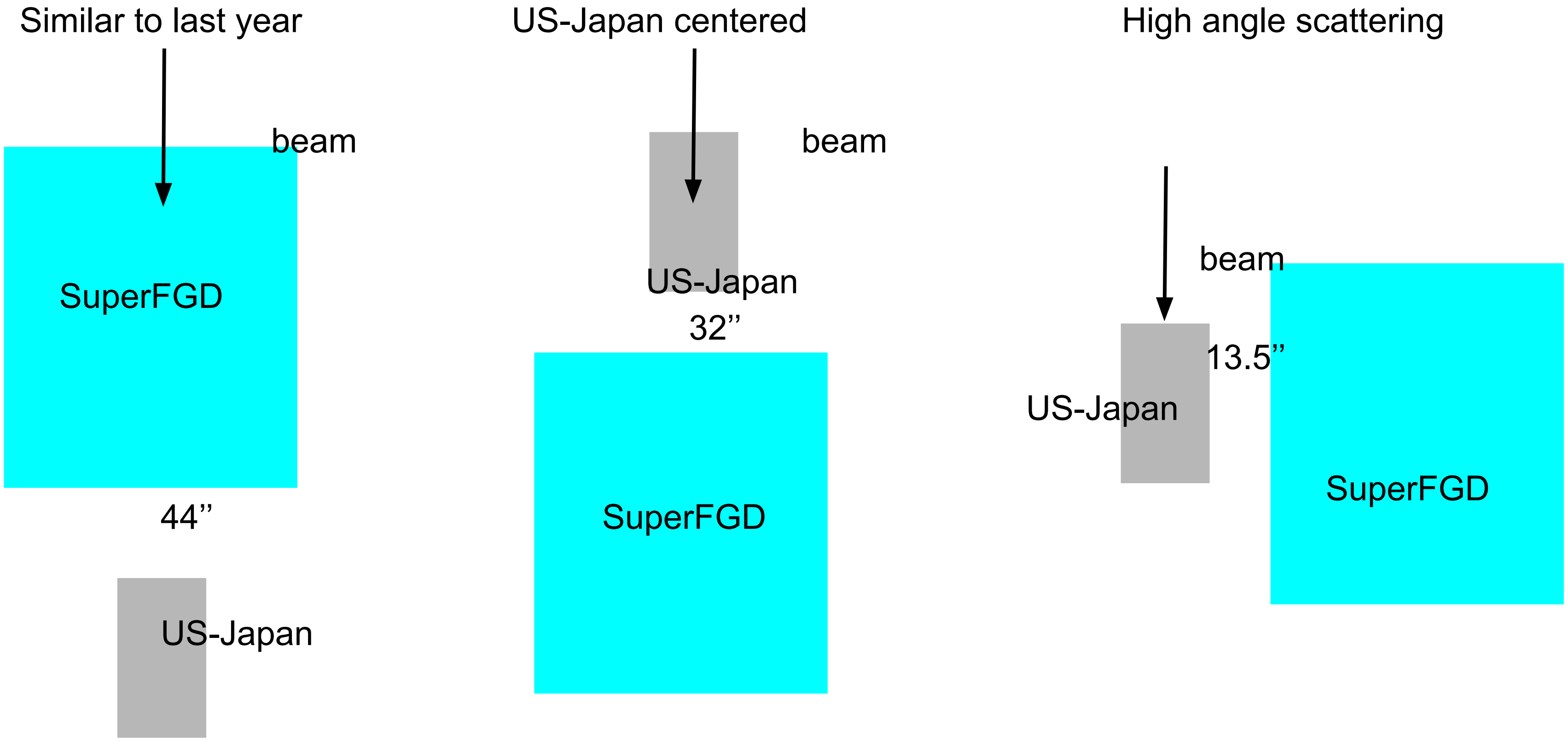
1.8 μs pulse spacing

US-Japan prototype in combination with SuperFGD

- A good extension to understand neutron detection in a larger scale

Detector configurations in 2020

All in top view



Even more: with neutron kinematic information

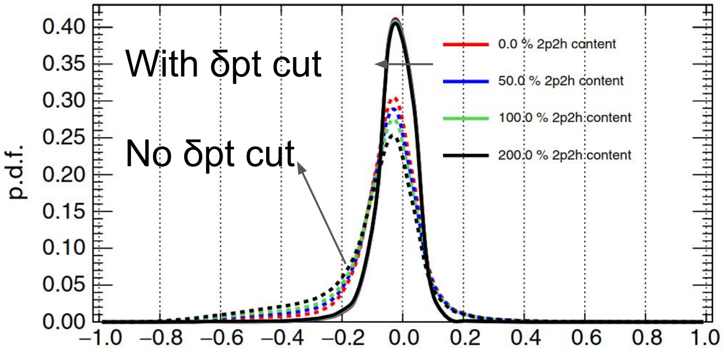
Neutron opens a new era of using transverse kinematics space to understand the neutrino interaction.

A transverse momentum cut can result in a sample relatively free of nuclear effect.

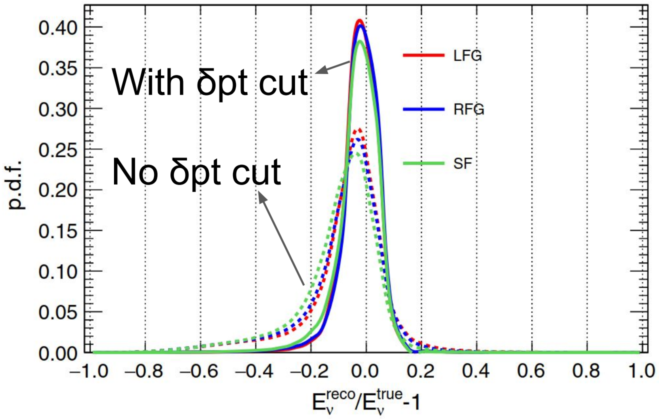
The transverse momentum cut is relatively independent from the nuclear modeling.

Several studies have shown the promising results benefit from using neutron information:

- *Phys.Rev.D* 101 (2020) 9, 092003
- *Phys.Rev.D* 105 (2022) 3, 032010



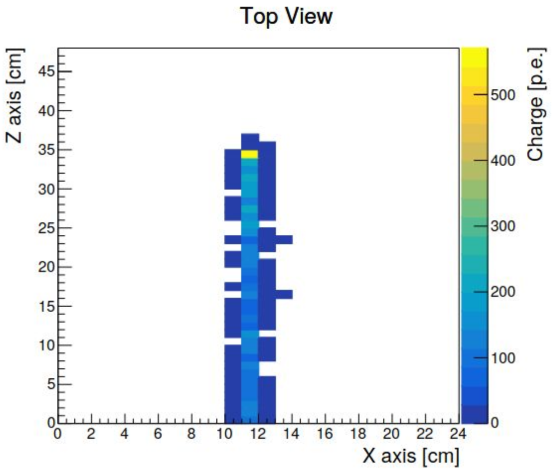
Phys. Rev. D 101, 092003



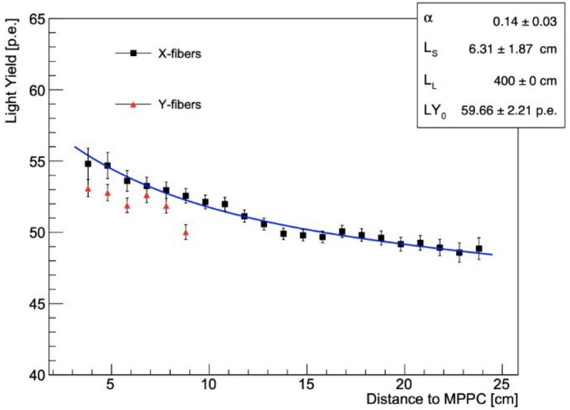
SuperFGD prototype at CERN charged beam facility

A thorough understanding of the detector response to charged particles such as proton, muon, pion, gamma conversion: *JINST* 15 (2020) 12, P12003

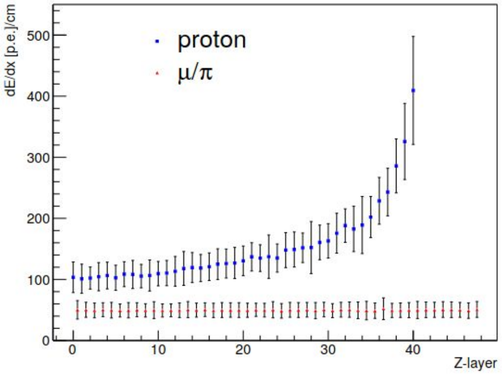
Stopping proton



Light yield and attenuation



PID



Well-motivated neutron detection capability

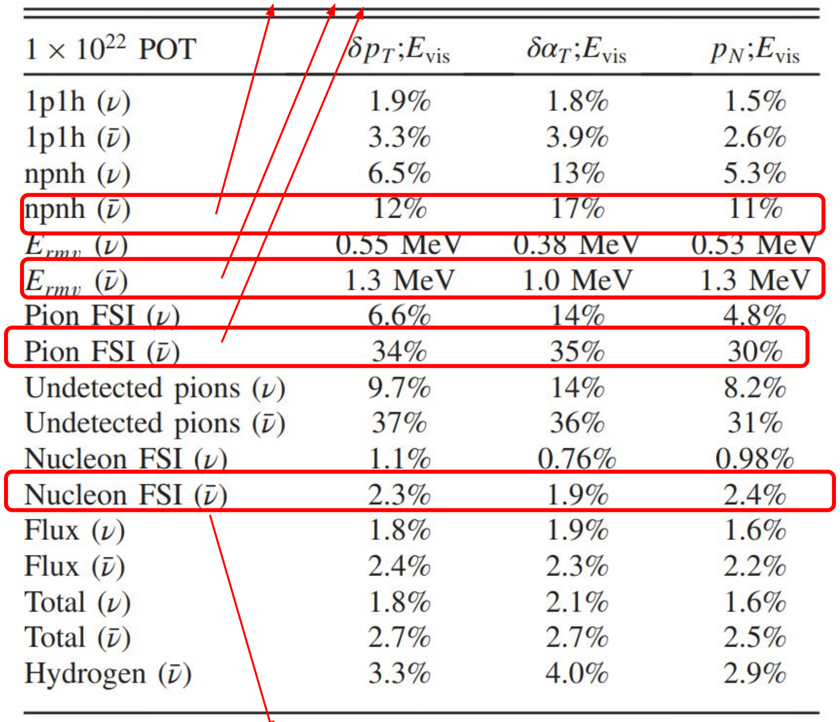
A ND280 fit with the transverse space variables provide direct constraints on nuclear modeling parameters.

Several studies have shown the promising results benefit from using neutron information:

- *Phys.Rev.D* 101 (2020) 9, 092003
- *Phys.Rev.D* 105 (2022) 3, 032010

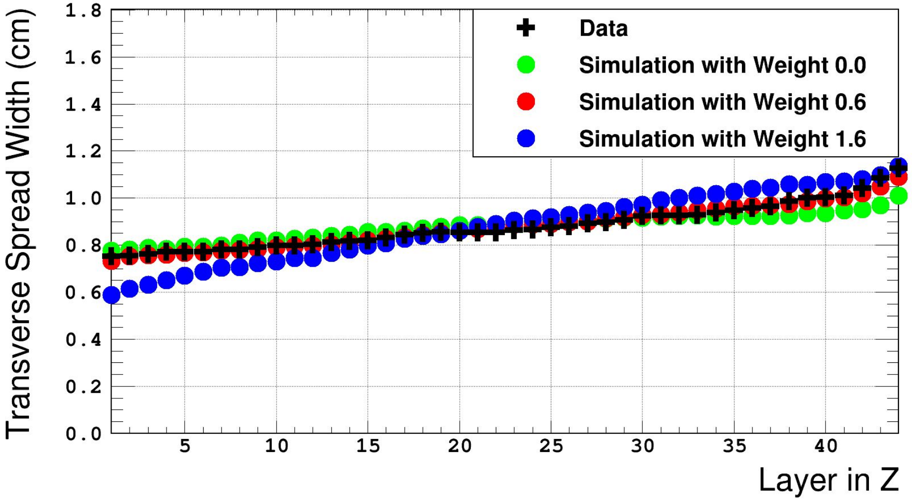
Phys. Rev. D 105, 032010

Unconstrained pre-fit

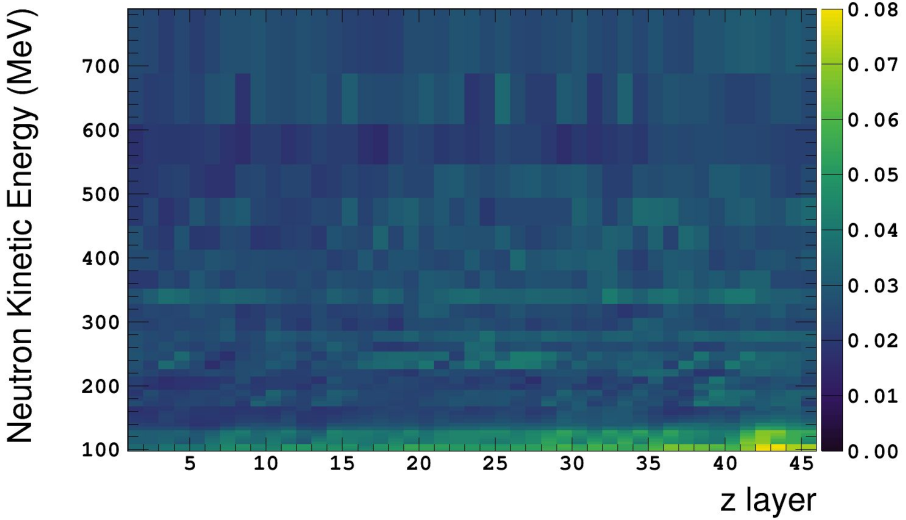


1×10^{22} POT	$\delta p_T;E_{\text{vis}}$	$\delta\alpha_T;E_{\text{vis}}$	$p_N;E_{\text{vis}}$
1p1h (ν)	1.9%	1.8%	1.5%
1p1h ($\bar{\nu}$)	3.3%	3.9%	2.6%
npnh (ν)	6.5%	13%	5.3%
npnh ($\bar{\nu}$)	12%	17%	11%
E_{rmv} (ν)	0.55 MeV	0.38 MeV	0.53 MeV
E_{rmv} ($\bar{\nu}$)	1.3 MeV	1.0 MeV	1.3 MeV
Pion FSI (ν)	6.6%	14%	4.8%
Pion FSI ($\bar{\nu}$)	34%	35%	30%
Undetected pions (ν)	9.7%	14%	8.2%
Undetected pions ($\bar{\nu}$)	37%	36%	31%
Nucleon FSI (ν)	1.1%	0.76%	0.98%
Nucleon FSI ($\bar{\nu}$)	2.3%	1.9%	2.4%
Flux (ν)	1.8%	1.9%	1.6%
Flux ($\bar{\nu}$)	2.4%	2.3%	2.2%
Total (ν)	1.8%	2.1%	1.6%
Total ($\bar{\nu}$)	2.7%	2.7%	2.5%
Hydrogen ($\bar{\nu}$)	3.3%	4.0%	2.9%

30% pre-fit



Invisible scattering uncertainty



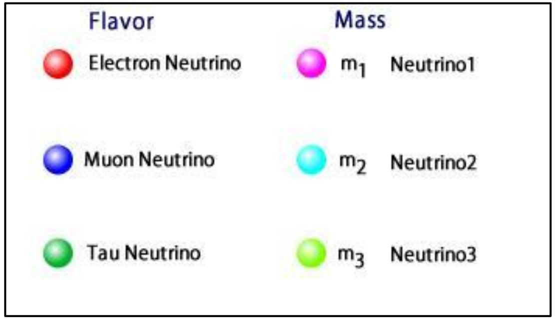
Important questions to be answered

- Facts about neutrino oscillation that we know
  - Neutrinos interact in flavor states and propagate in mass states→ oscillation nature
  - All three mixing angles are none zero→ room for a CP violation phase measurement
- Key questions to be answered by DUNE long-baseline program
  - How well we know about the CP violation phase? Very confident that CP is not conserved?
  - How well we can determine the mass hierarchy? Normal or Inverted?

Mono-flavor neutrino flux

Both neutrino and antineutrino

Measure unoscillated Flux and interaction



Controllable: L and E

Measure oscillated Flux and interaction

CP violation phase measurement

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

What we measure

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Small

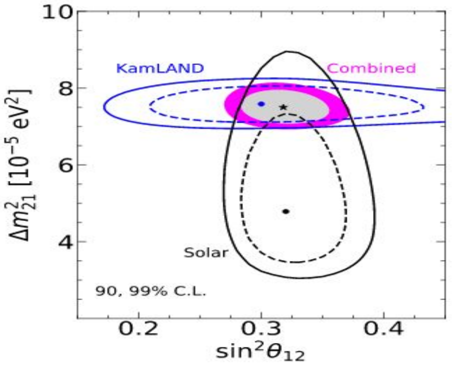
ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

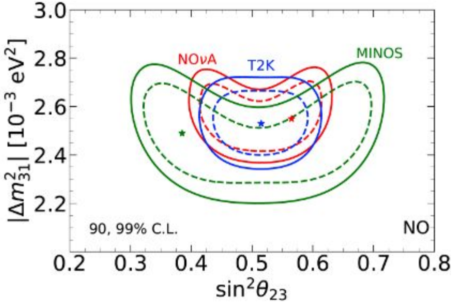
Proportional to L

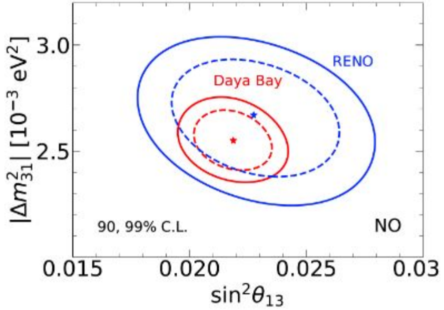
CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\; s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

What we want

with $A = 2\sqrt{2}G_F n_e E = 7.6\times 10^{-5}\,\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$







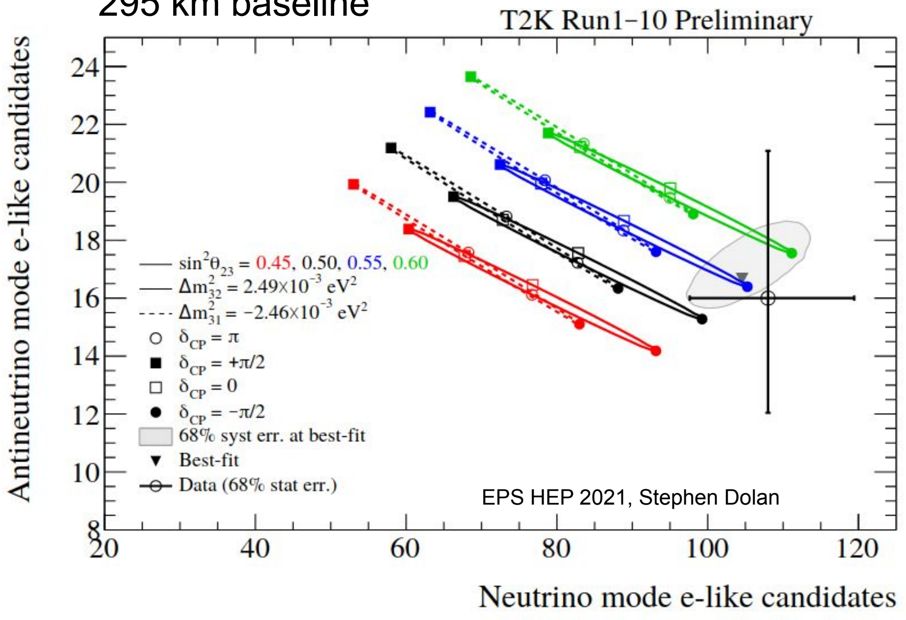
All mixing angles non-zero and being measured

CP violation phase to be measured by comparing neutrino and antineutrino muon flavor to electron flavor oscillations

What we know from current long-baseline experiments?

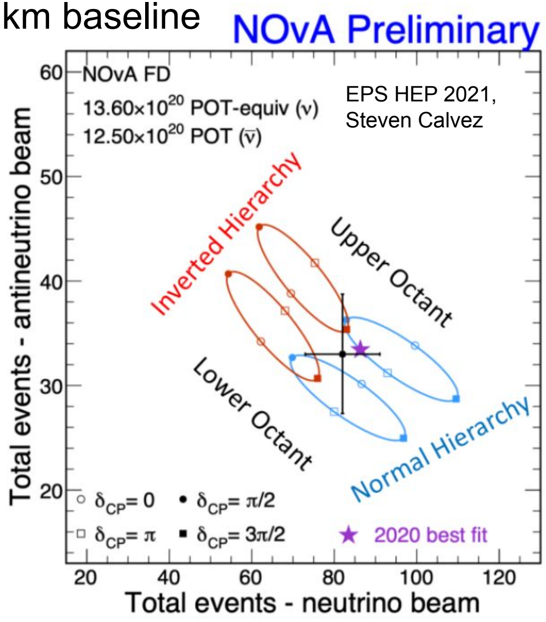
- T2K and NovA have great sensitivity to the CP violation measurement → not enough to conclude, yet

295 km baseline



EPS HEP 2021, Stephen Dolan

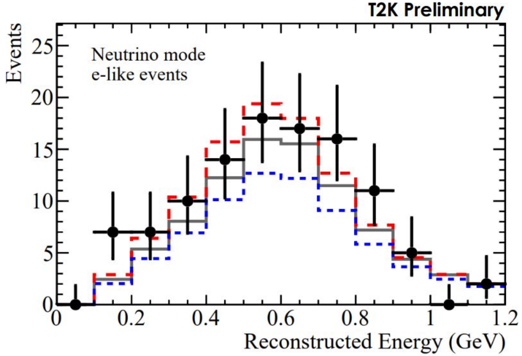
810 km baseline



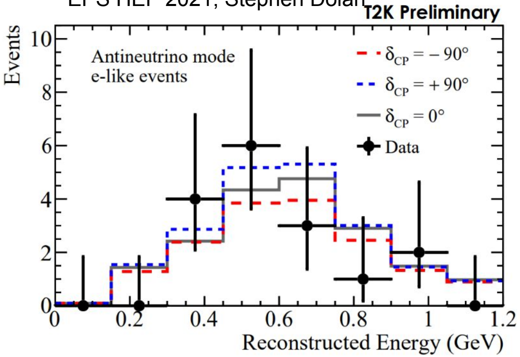
EPS HEP 2021, Steven Calvez

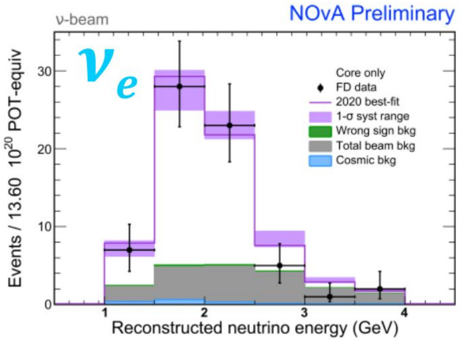
What we know from current long-baseline experiments?

- Both T2K and NOvA are largely rate-based measurement on the CP violation phase.
- Bi-event plot shows almost the full power of T2K and NOvA, but not for those with capability of spectral measurement.

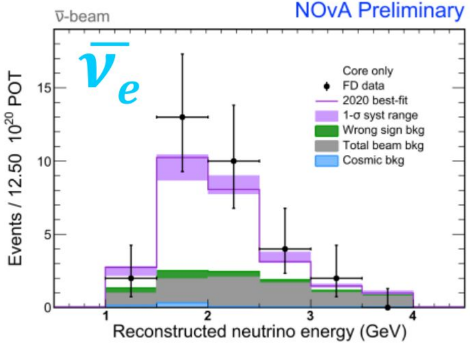


EPS HEP 2021, Stephen Dolan



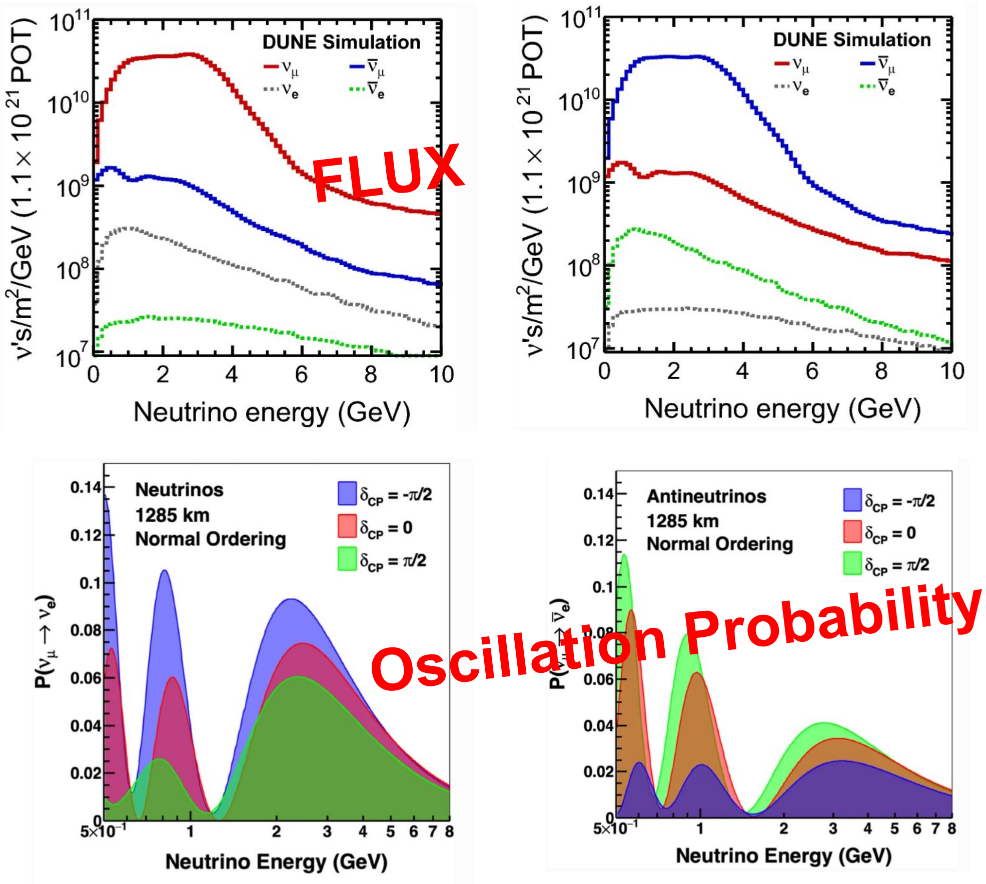


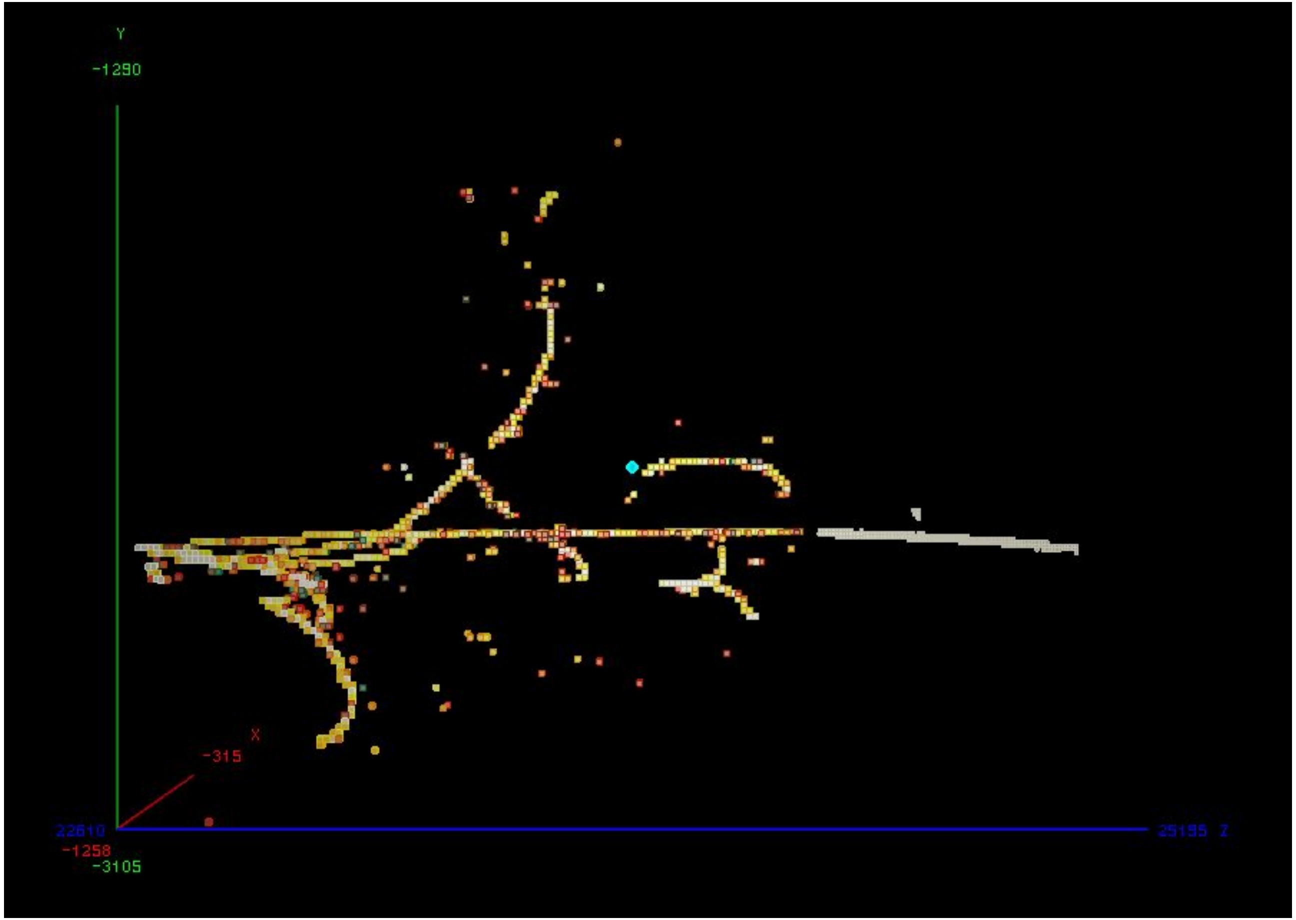
EPS HEP 2021,
Steven Calvez



What we know from current long-baseline experiments?

- Both T2K and NOvA are largely rate-based measurement on the CP violation phase.
- Bi-event plot shows almost the full power of T2K and NOvA, but not for those with capability of spectral measurement.
  - DUNE will utilize a wide-band beam covering more than 1 oscillation maxima.

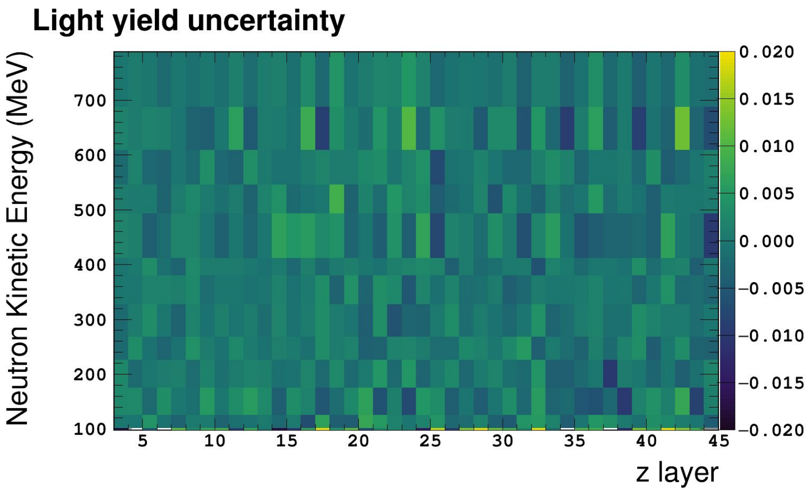


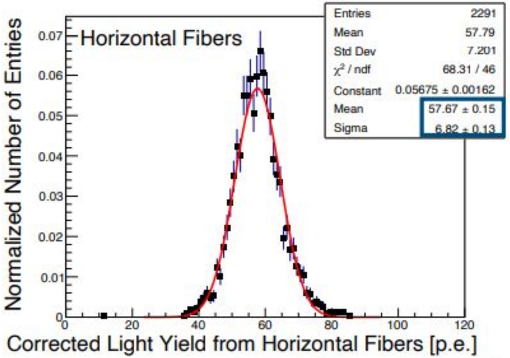

Y
-1290
X
-315
22610
-1258
-3105
25195 Z

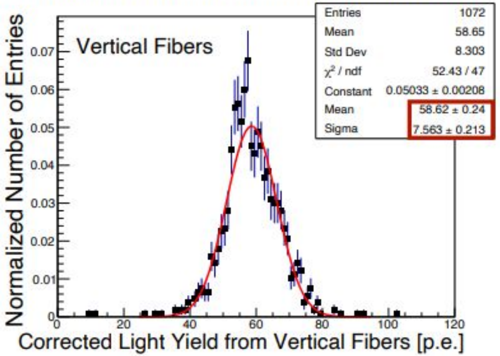
Light yield

Light yield obtained using cosmic data taken at LANL

Random fluctuation of light yield from nominal propagated as the uncertainty of the event rate in each energy bin and layer





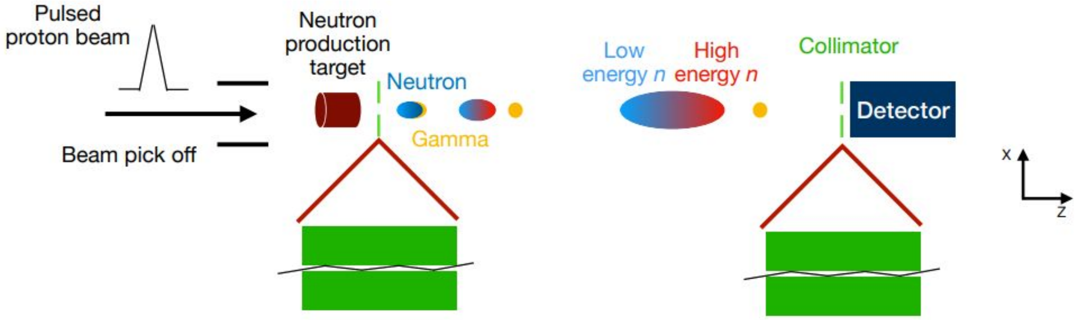


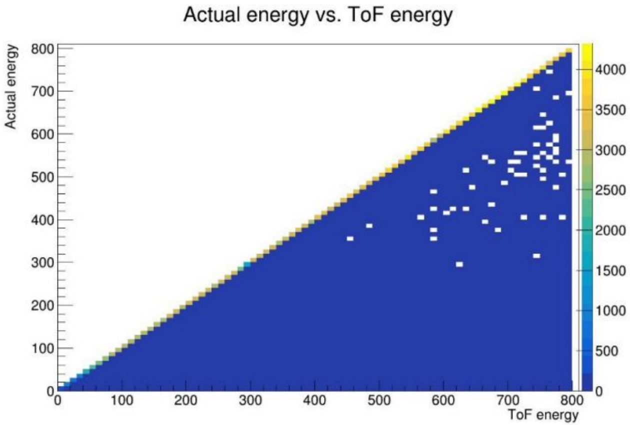
Collimator interaction

Multiple interactions inside the collimators

None of which interacts in first collimator arrive to the detector while the second can contribute to energy smearing (feed-down bias)

Smearing the neutron energy using MC estimations of the energy lost by neutrons showed minimal impact





Invisible scattering

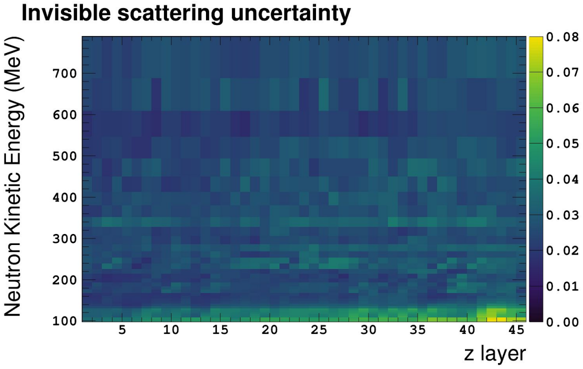
Undetected neutron interactions introduce a smearing to the neutron energy estimation

The invisible scattering mainly cause a displacement of the vertex

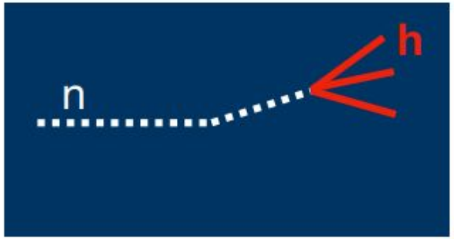
Transverse spread of the beam used to characterize such scattering

Tuned transverse spread in MC (Geant4 Bertini and INCLXX lists) to data assuming it was all due to invisible scattering (very conservative)

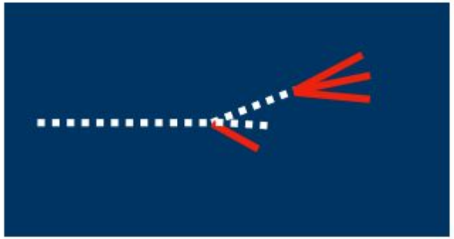
2% of invisible scattering for energy > 98 MeV is taken as systematic error



Elastic scattering and inelastic scattering later



Inelastic scattering with charged particles undetected

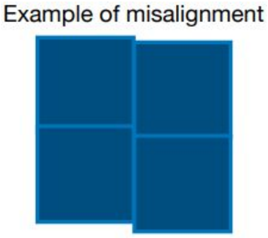


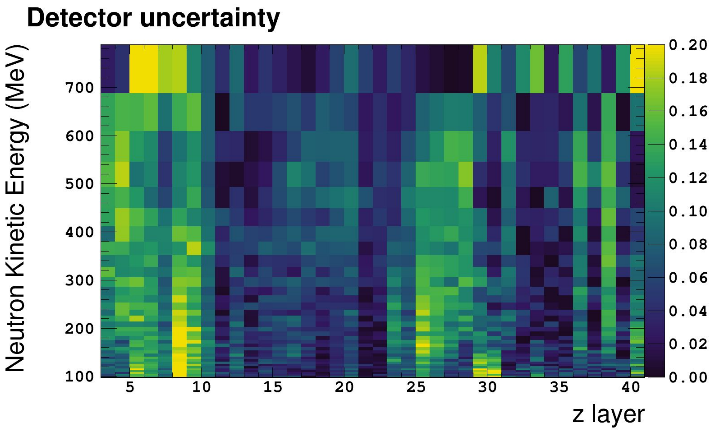
Detection uncertainty

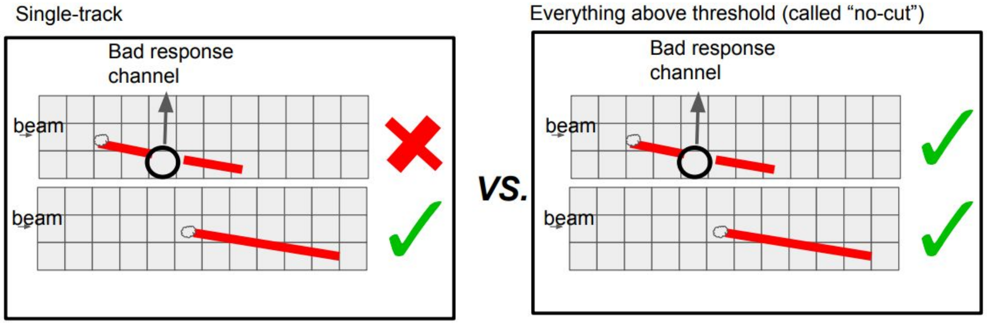
Cube mis-alignment plays a big role: vertical shift of every 5 cube layers by 1 mm causes up 10% difference in event rate between Z layers

Relatively small contribution from MPPC type differences

Difference between single-track selection and "no-cut" case propagated as the uncertainty to the event rate in each energy bin and layer







Geometric acceptance

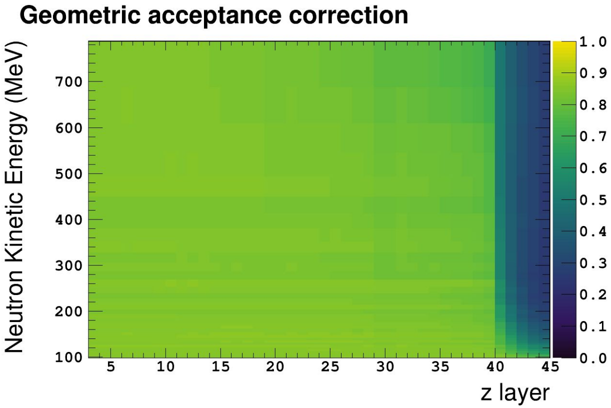
Geometric acceptance:

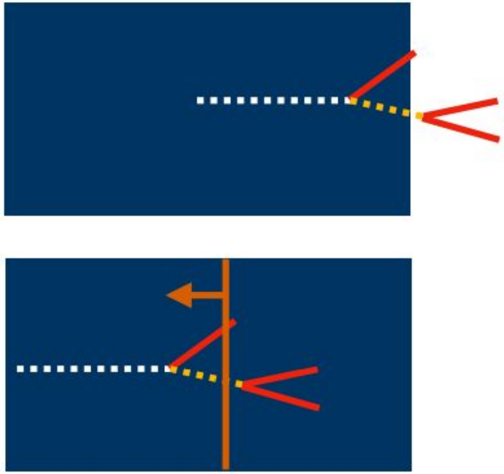
Limited size of our detector can introduce a bias in the single track selection:

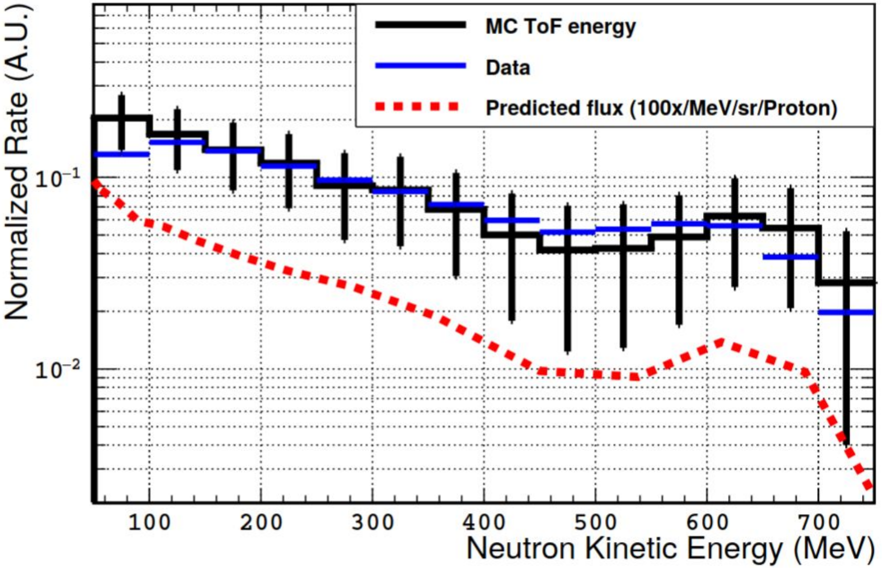
- A multiple-track event can be selected as single track
- Cut on number of voxels and upper limit on the fitting range (layer 40) used to mitigate this effect

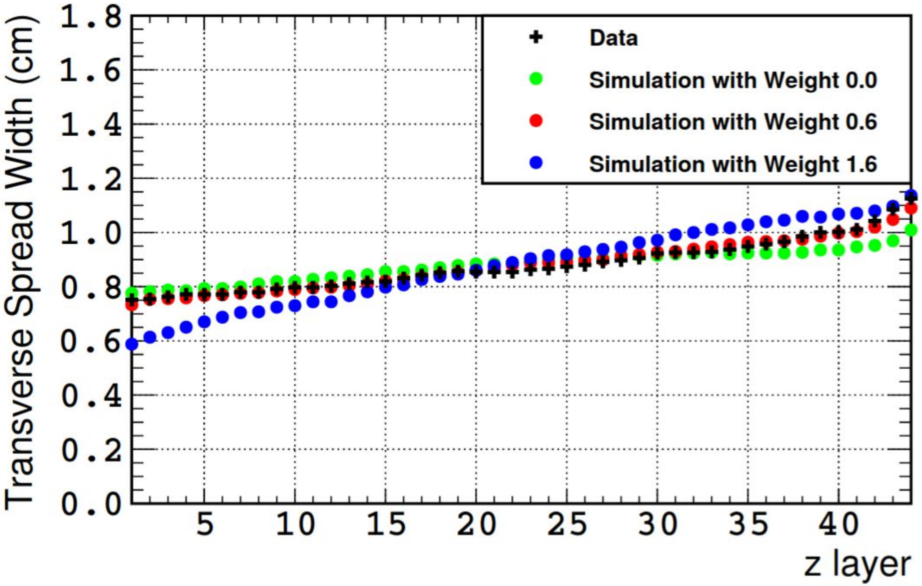
Data driven method used to estimate such uncertainty:

- Expand or reduce the detector size by shifting hits boundary
- Ratio between event rate (energy vs z-layer) with and without boundary is taken as systematic error






MC ToF energy
Data
Predicted flux (100x/MeV/sr/Proton)
Normalized Rate (A.U.)
10^{-1}
10^{-2}
100
200
300
400
500
600
700
Neutron Kinetic Energy (MeV)


Data
Simulation with Weight 0.0
Simulation with Weight 0.6
Simulation with Weight 1.6
Transverse Spread Width (cm)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
5
10
15
20
25
30
35
40
z layer