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Event-by-event neutron kinematics detection with neutrino detectors for long-baseline experiments

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On behalf of the 3D-projection scintillator tracker R&D group

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Queen Mary University of London Seminar

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
University of Rochester, USA
South Dakota School of Mines and Tech., USA
Stony Brook University, USA
University of Tokyo, Japan

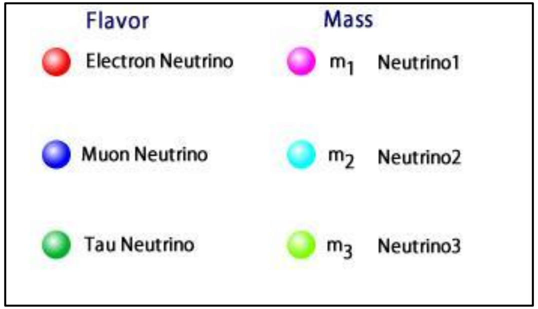
Important questions to be answered

- 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 long-baseline programs
  - How well we know about the CP violation phase?
  - How well we can determine the mass hierarchy?

Mono-flavor neutrino and antineutrino flux

Near site

Measure unoscillated Flux and interaction



Controllable: L and E

Far site

Measure oscillated Flux and interaction

Accelerator-based long-baseline experiments : T2K

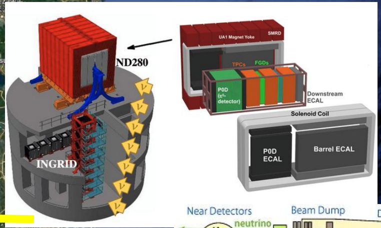
Neutrinos generated from hadron decays caused by proton hitting targets

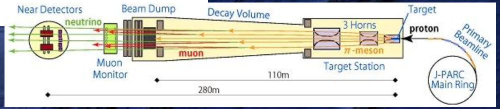
Two opposite horn currents changing focused hadron charge resulting in neutrino (FHC) and antineutrino (RHC) modes

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

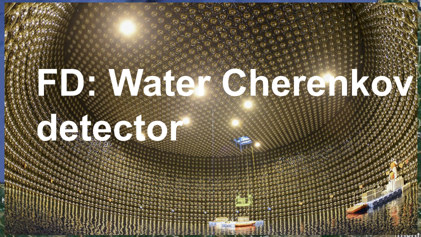
ND: Magnetized hybrid tracking system





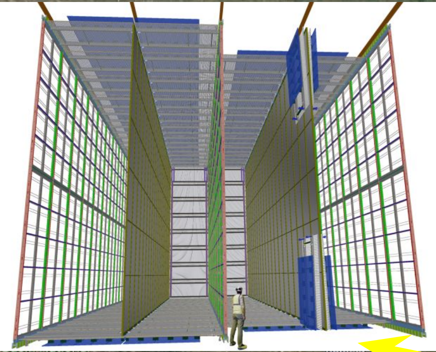
JPARC beam

295 km baseline



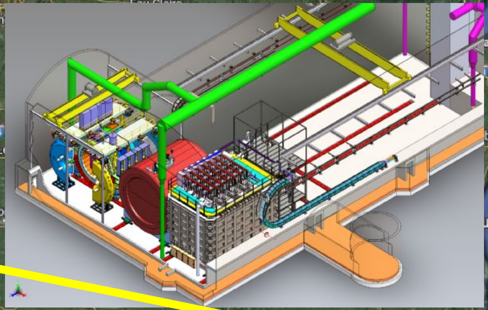
FD: Water Cherenkov detector

Accelerator-based long-baseline experiments : DUNE

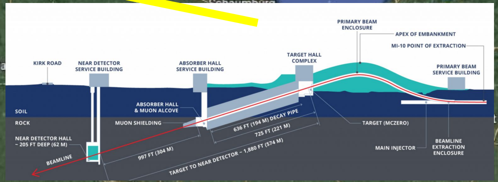


FD: 40-kt total mass; At least two 10-kt scale liquid argon modules

ND: Movable hybrid detector system



Beam facility



1300 km baseline

Powerful beam to deliver unprecedented amount of neutrinos and antineutrinos

Optimized long baseline

Broad-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.

Why we want to measure neutron kinematics?

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

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

Highly degenerate and not directly cancellable

For Neutrino and antineutrino separately, it turns out to be

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

Why we want to measure neutron kinematics?

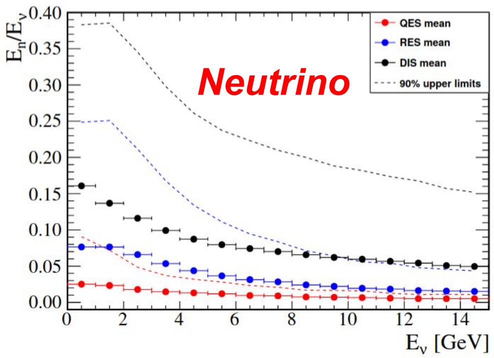
$$\frac{dN_{\nu_e}^{far}}{dE_{rec}} = \int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\, dE_\nu$$

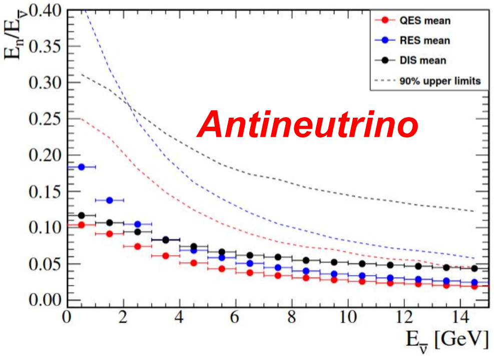
Philosophy at near detector:

- 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!

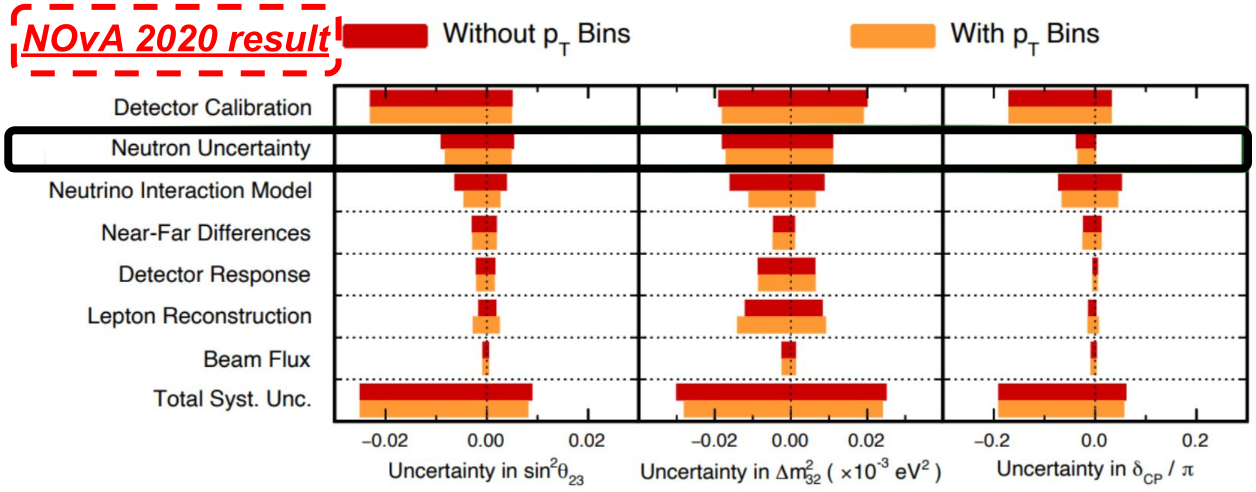
Necessity of event-by-event neutron detection





Neutrons carry substantial amounts of energy from the neutrino interaction.

The neutron information strongly depends on models.



Additional consideration: potential bias induced by missing neutrons

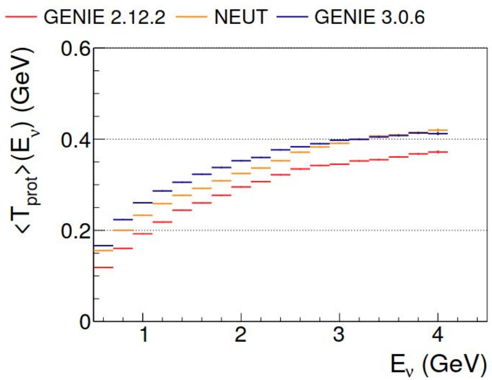
Toy model in DUNE

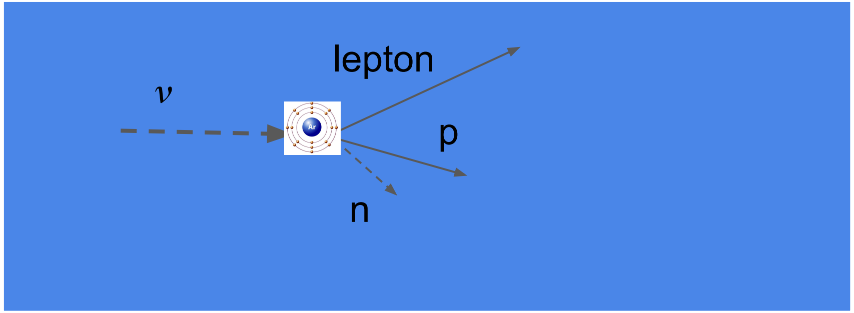
20% of the proton kinetic energy assigned to neutrons

Absence of the proton/neutron kinetic energy systematic pulls

At near detector: flux, interaction and near detector systematic pulls variable

At far detector: flux, interaction, far detector systematic pulls and ***oscillation parameters*** variable

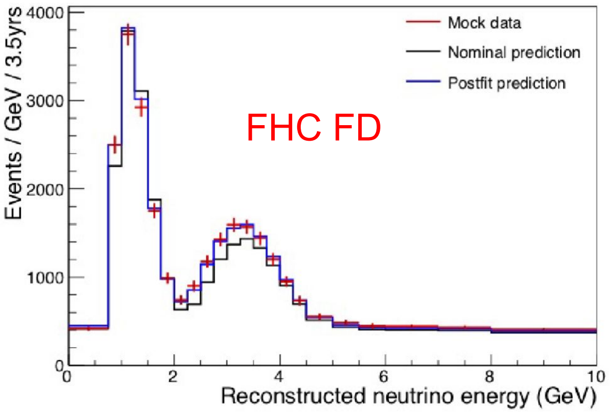


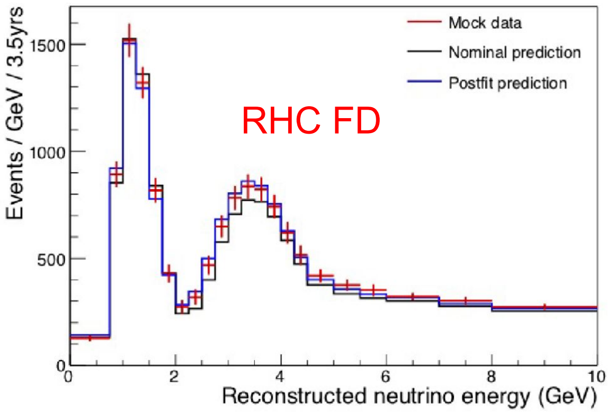


Additional consideration: potential bias induced by missing neutrons

The systematic uncertainties are highly constrained by ND.

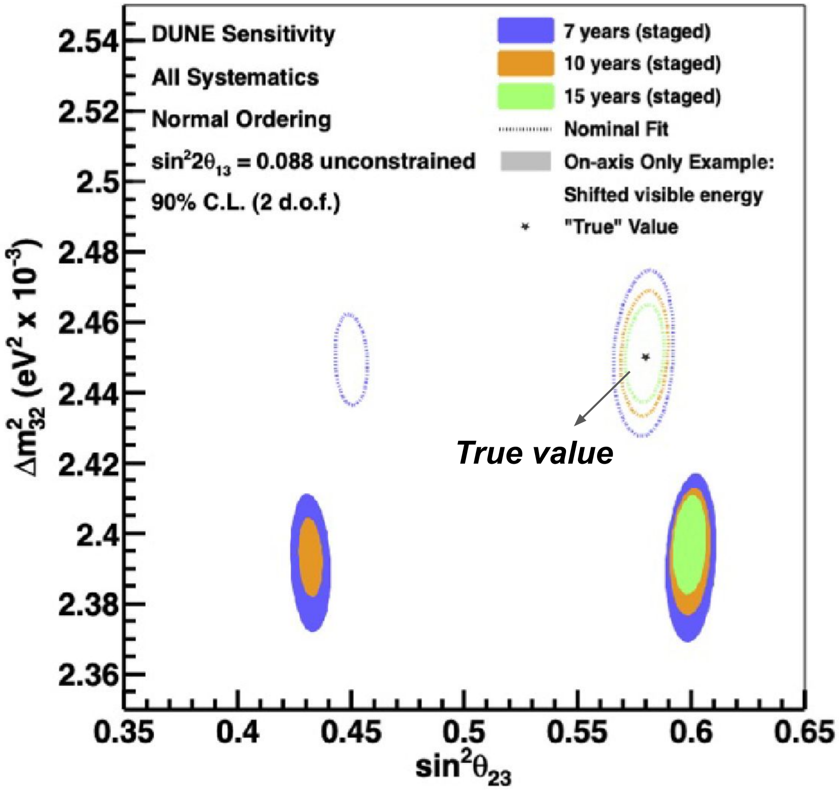
In the absence of proton/neutron kinetic energy systematic pulls, other systematics are forced to change.



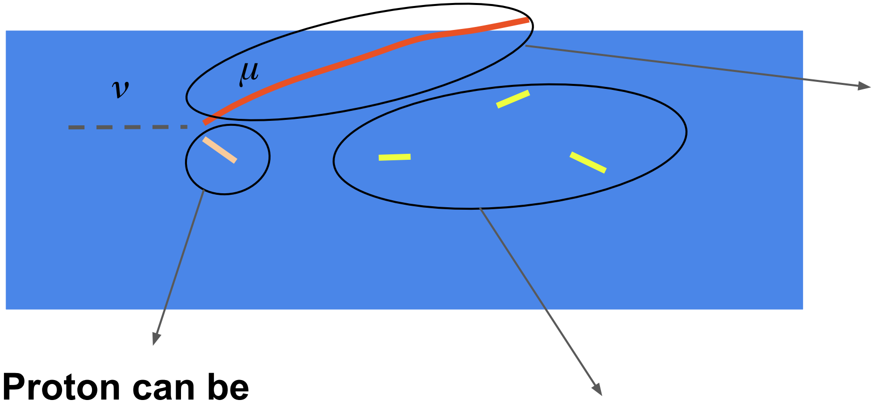


Additional consideration: potential bias induced by missing neutrons

At the same time, the oscillation parameters are shifted to make FD prediction and mock data match.



How to detect neutron kinematics event-by-event?

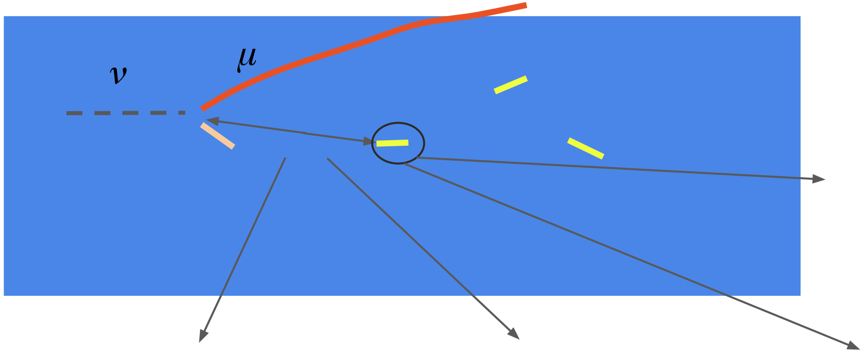


Muon track can be identified and momentum and sign can be determined with a magnetized tracker; neutrino interaction vertex also identified

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

Neutrons can’t be detected directly. Only neutron-induced objects can be seen -> In order to detect neutrons, need to look at isolated clusters

How to detect neutron kinematics event-by-event?



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

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

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

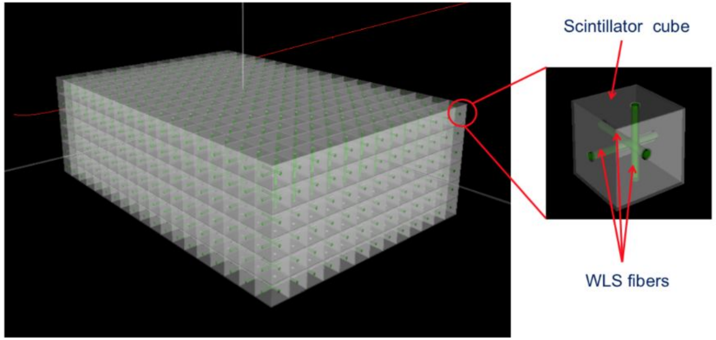
Fully active!
Fast timing!
Fine granularity!
High light yield!

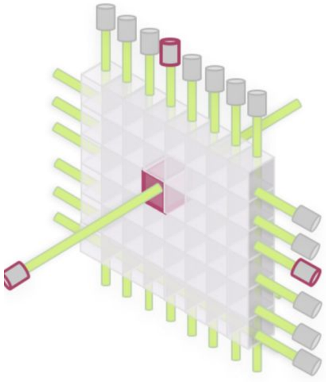
Must be at the same time!

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)



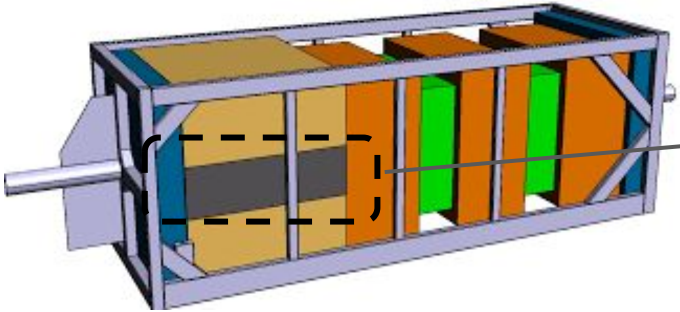


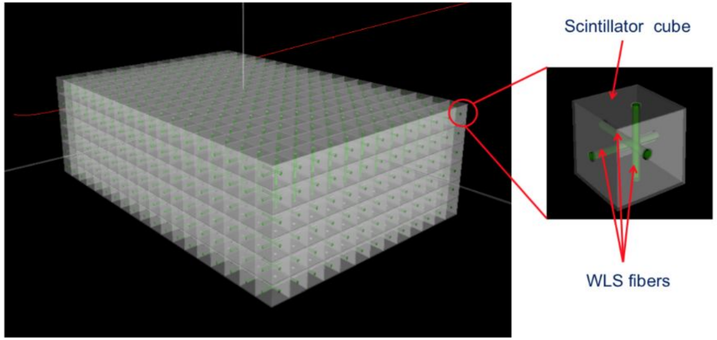
Fully active!
Single fiber 0.9 ns timing resolution: Fast timing!
1-cm-scale size: Fine granularity!
>50 PE/MeV each readout: High light yield!

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

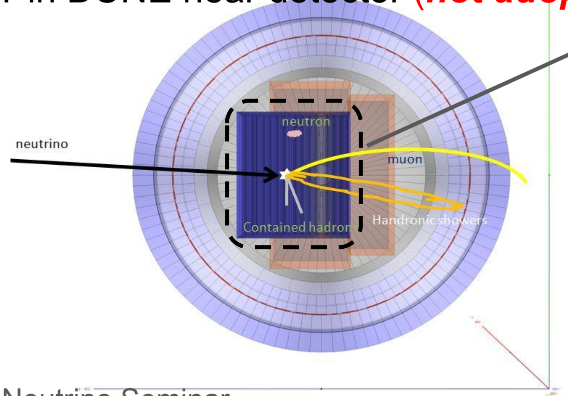
Neutron detection on an event-by-event basis

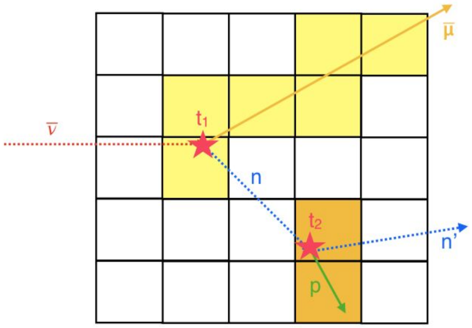
ND280 upgrade in T2K ***(being built)***





3DST in DUNE near detector (***not adopted***)



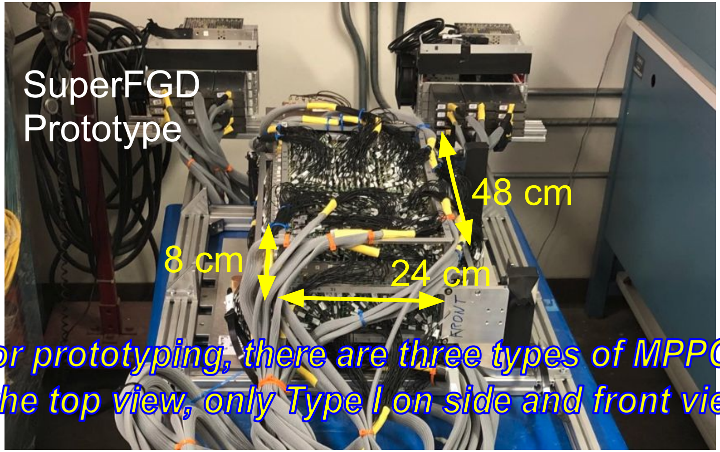


Not only tagging, SuperFGD can measure the neutron kinematics!

Demonstration of the neutron detection capability

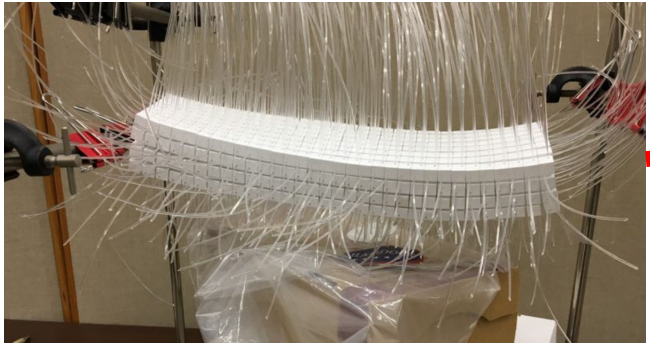
Using prototypes to prove it => two prototypes with 1cm x 1cm x 1cm cube size

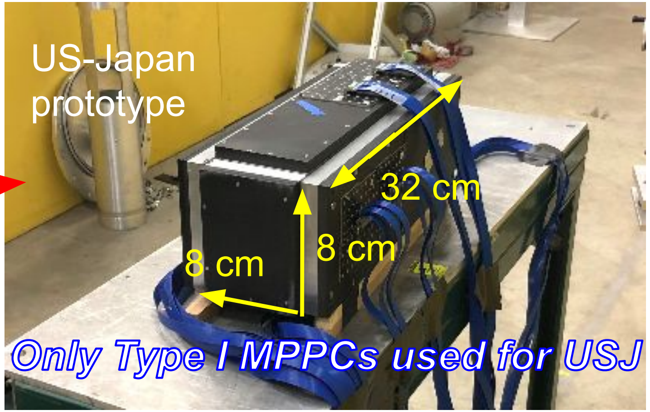
- SuperFGD prototype (SFGD) been used for a charged particle beam test at CERN (size 24 x 8 x 48): *JINST* 15 (2020) P12003
- US-Japan prototype (USJ) with new designs used in the T2K upgrade (size 8 x 8 x 32).



At LANL

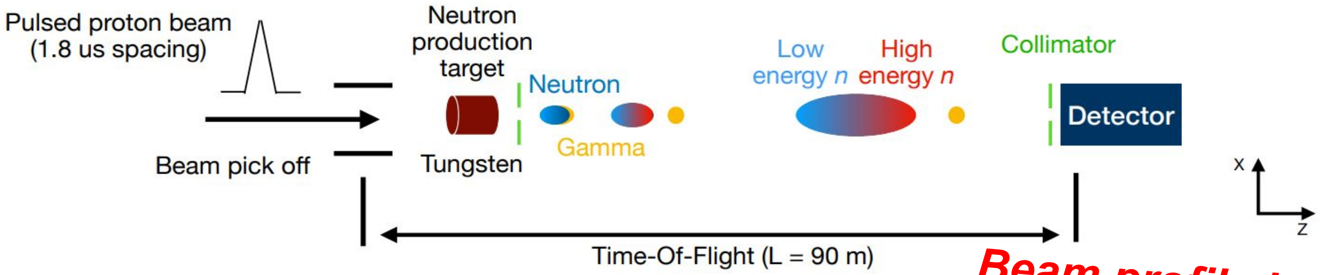
US-Japan proto.
Assembled
In Stony Brook



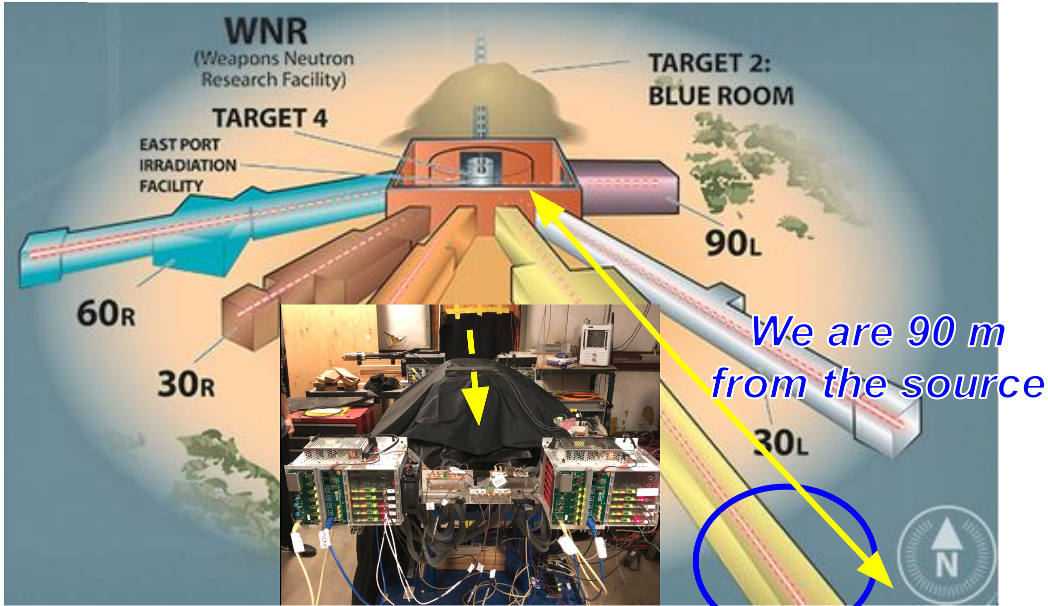


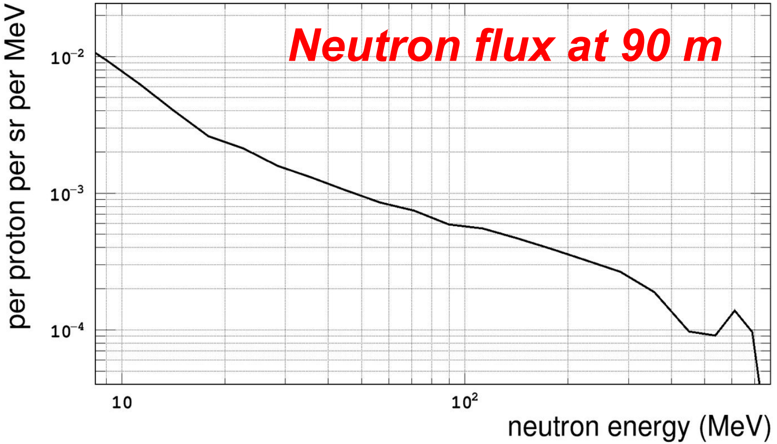
Neutron beam test facility

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



Beam profile is well collimated!

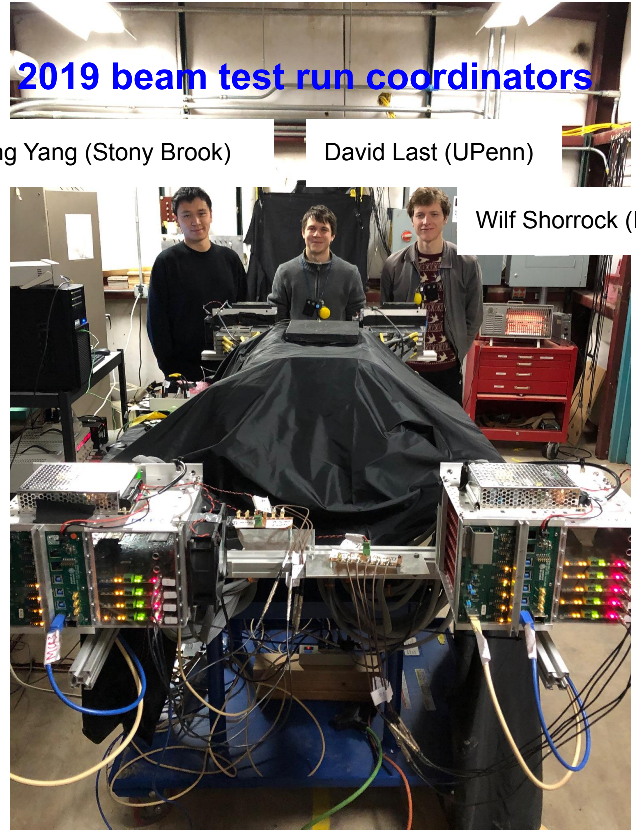




Onsite installation and operation team

SuperFGD only in 2019

2019 beam test run coordinators



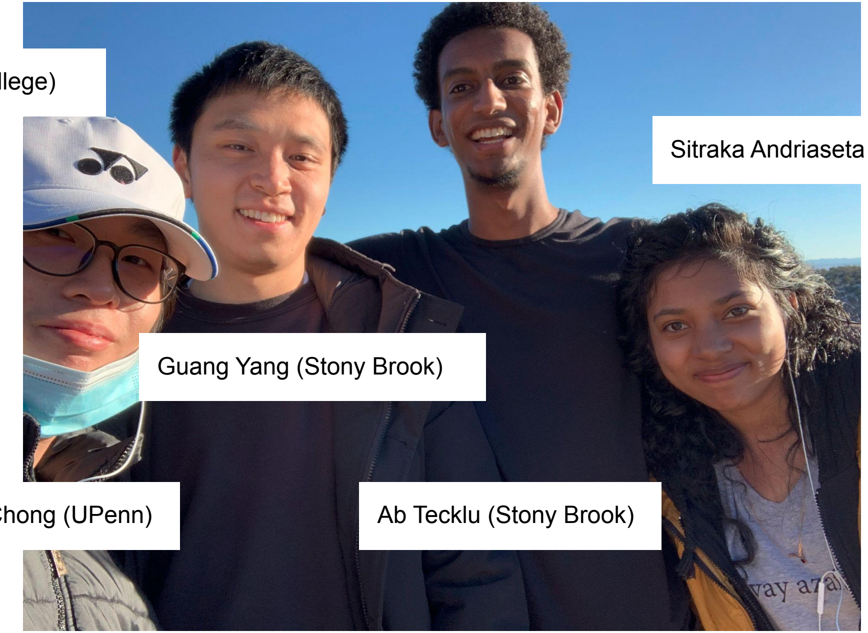
Guang Yang (Stony Brook)

David Last (UPenn)

Wilf Shorrock (Imperial College)

SuperFGD+US-Japan in 2020

2020 beam test onsite team



Sitraka Andriaseta (SDSMT)

Guang Yang (Stony Brook)

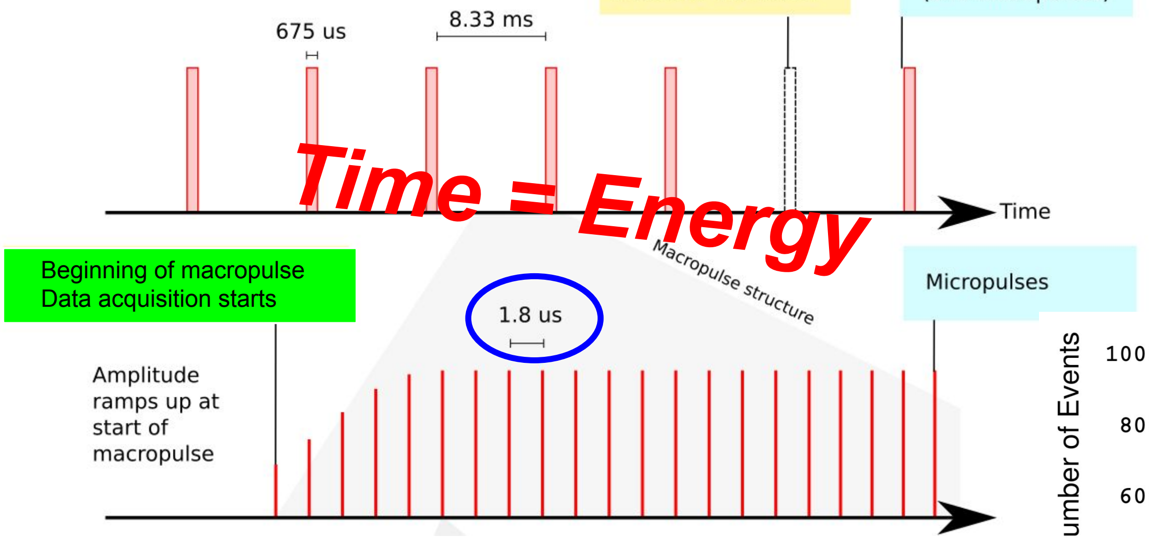
Eric Chong (UPenn)

Ab Tecklu (Stony Brook)

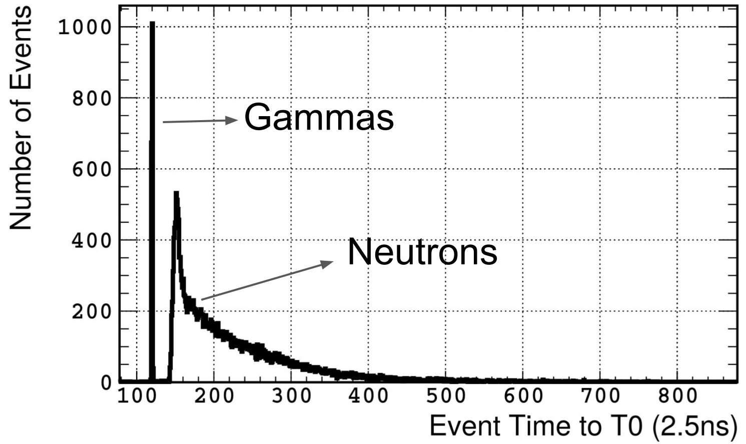
Detectors at the beamline

Neutron beam time structure

Proton beam time structure



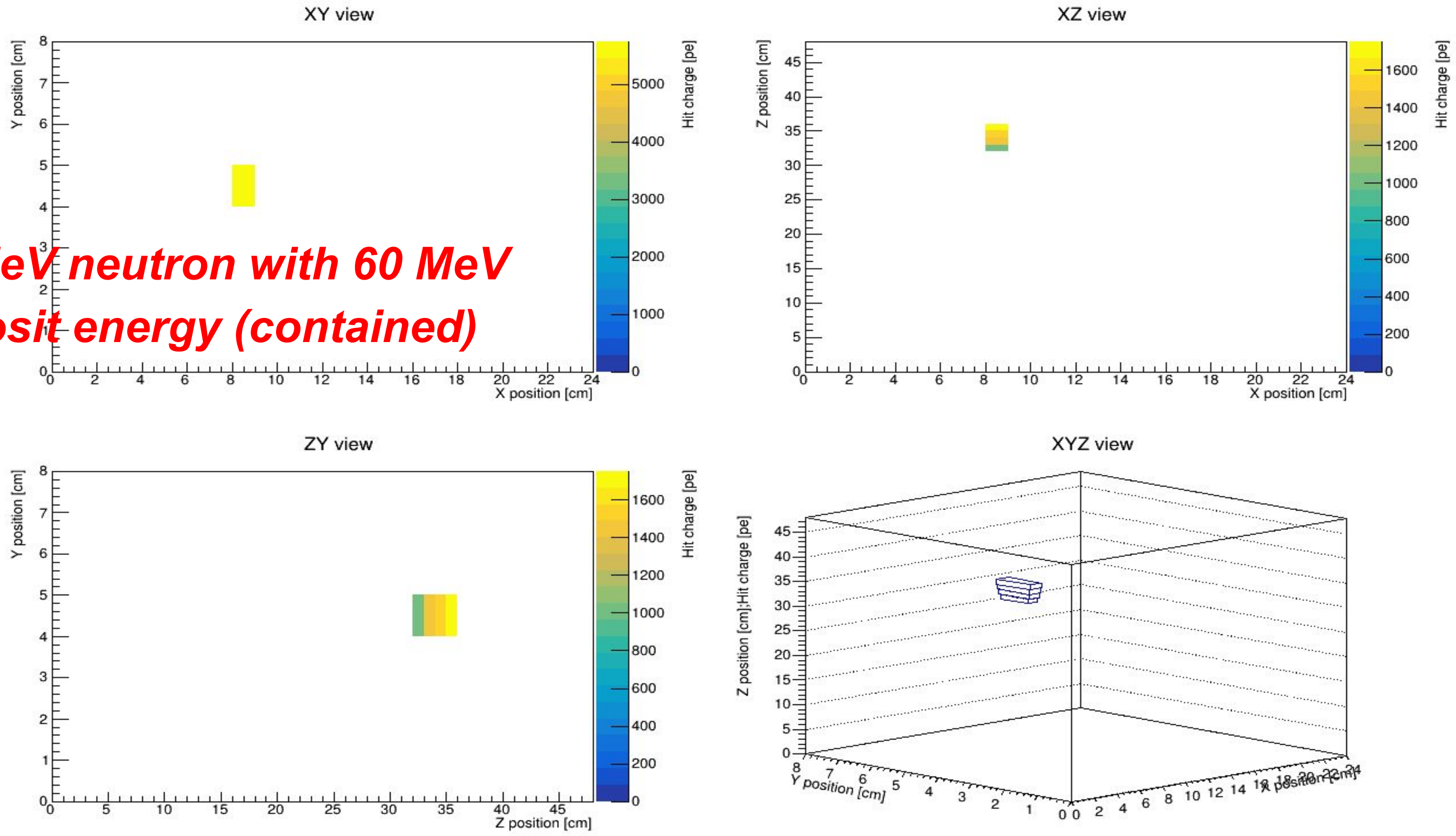
Gamma flash and t0 available for micropulses



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

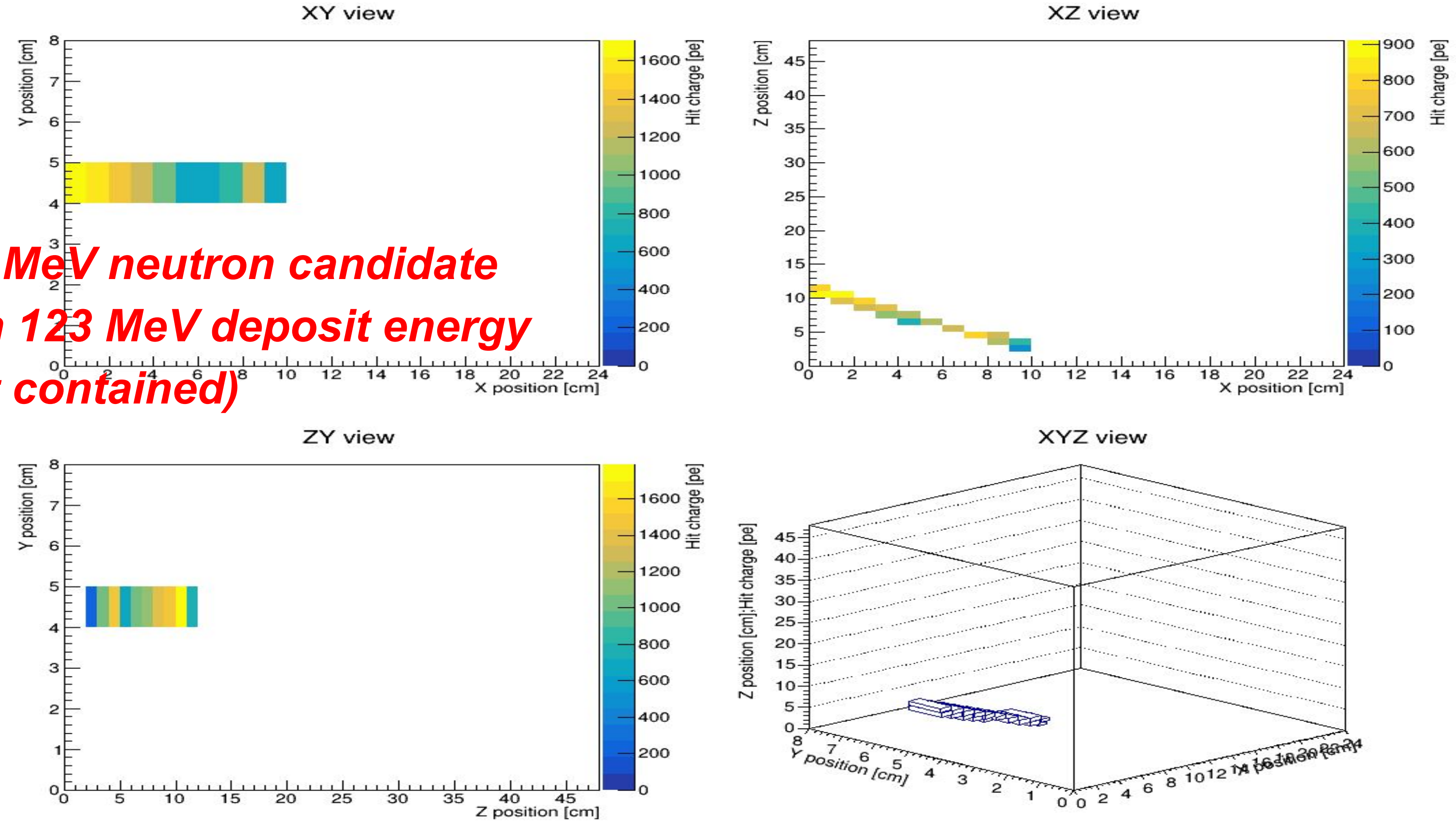
Spacing between micropulses -> 1.8 μs

Neutron candidate in SFGD prototype



65 MeV neutron with 60 MeV deposit energy (contained)

Neutron candidate in SFGD prototype



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

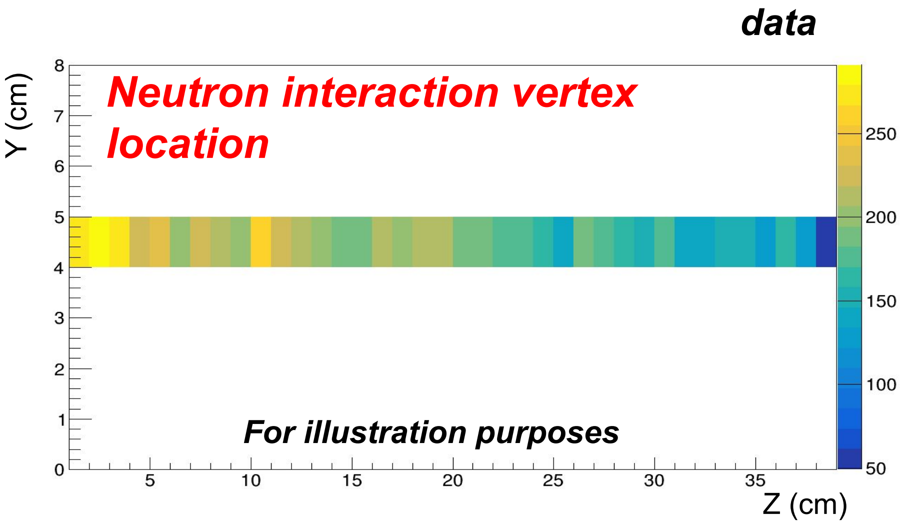
First physics result

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 insufficient statistics and contains gammas.

Only the 2019 SuperFGD prototype data used for this total cross-section measurement

A total cross-section measurement



Neutron beam

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

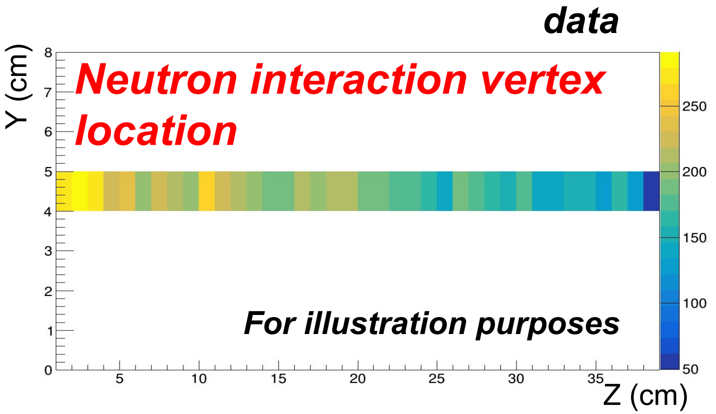
$$N(z) = N_0 \cdot \exp(-T \cdot \sigma_{total} \cdot z)$$

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

- T: Nuclear density
- σ_{total}: total xsec
- z: depth along the beam, i.e. layer

A total cross-section measurement

Neutron beam



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

$$\mathbf{N}_{e,z} = \sum \begin{pmatrix} \mathbf{N}_{\text{single-track},e,z} \\ \mathbf{N}_{\text{invisible},e,z} \\ \mathbf{N}_{\text{two-track},e,z} \\ .. \\ \mathbf{N}_{\text{100-track},e,z} \end{pmatrix} = \sum \begin{pmatrix} \mathbf{N}_{\text{single-track},\,e,z} \\ \mathbf{N}_{\text{single-track},\,e,z} \times r_e \end{pmatrix}$$

Energy Layer

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

$$\mathbf{N}_{e,l} / \mathbf{N}_{e,m} = \mathbf{N}_{\text{single-track},e,l} / \mathbf{N}_{\text{single-track},e,m}$$

Layer l Layer m

Single track attenuation indicates a total cross-section

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

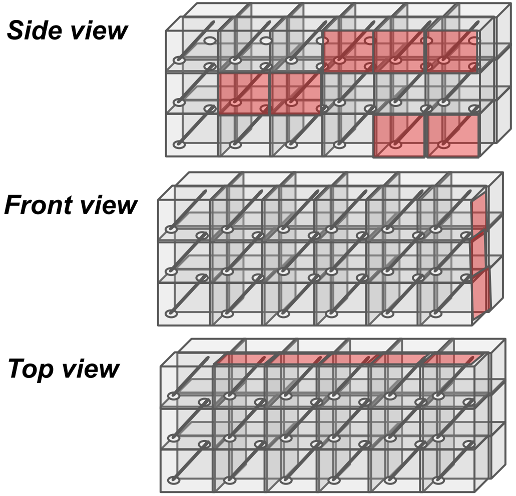
Event reconstruction

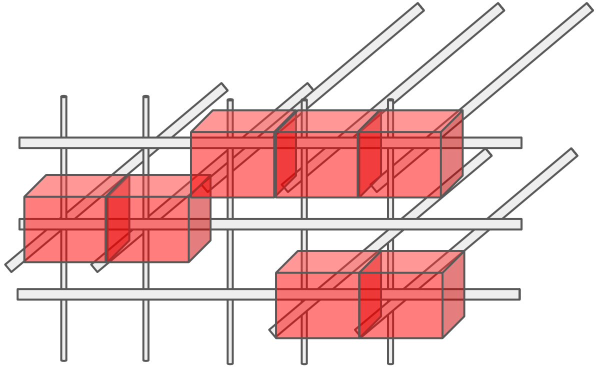
2D hits → **3D voxels** → **Clustering and vertex**

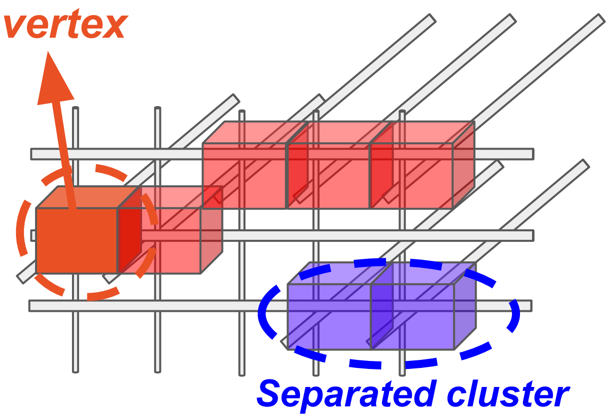
1. Time range selection
2. Gain calibration
3. PE cut
4. Time-walk correction
5. Time clustering

1. 3D voxel matching
2. Hit number
3. Attenuation corr.

1. Spatial clustering
2. Vertex: first voxel in z in fiducial volume



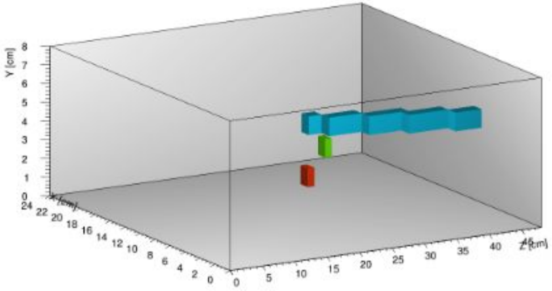




Single-track event selection

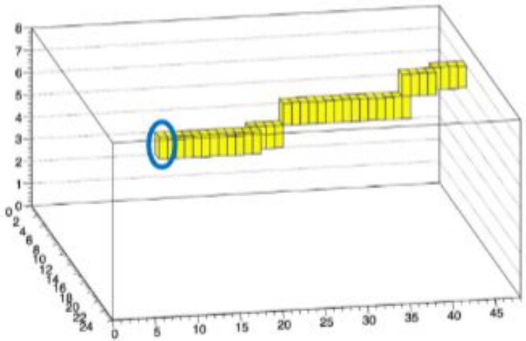
Single cluster in time and space

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



Linear track

1. Not in first layer
2. Linearity > 0.70
3. Cluster width < 1.4 and max-vox-line < 1.2
4. Vertex in fiducial volume (1.5 cm radius around beam center)



Systematic uncertainty

Event rate = Flux x cross section

Cross section ~ Event rate ratio at layers

Sources largely:

- **Flux**
- **Detector uniformity**
- **Detection efficiency**

Make a guess!

Systematic uncertainty included

Dominating !

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

Invisible scattering: If the first interaction is **elastic scattering or inelastic scatterings below the threshold**, we can't see the primary vertex.

Geometric acceptance: Limited detector size

Light yield: Light yield variation for each channel

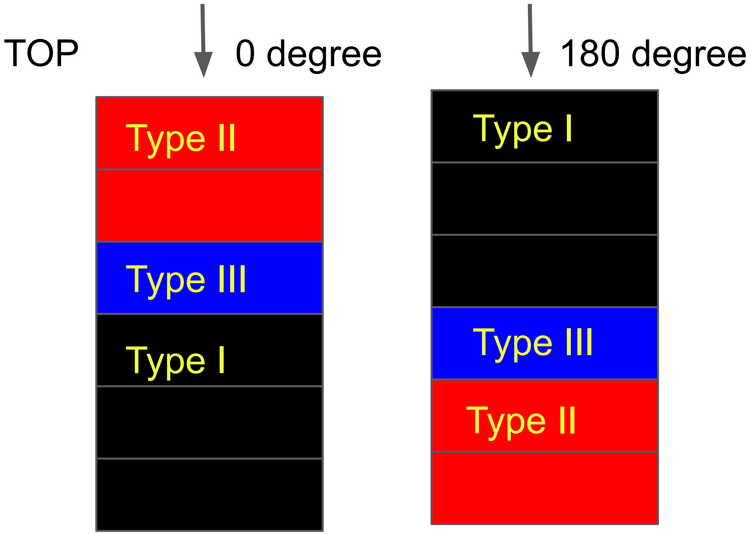
Time resolution: Events shifting across different energy bins

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

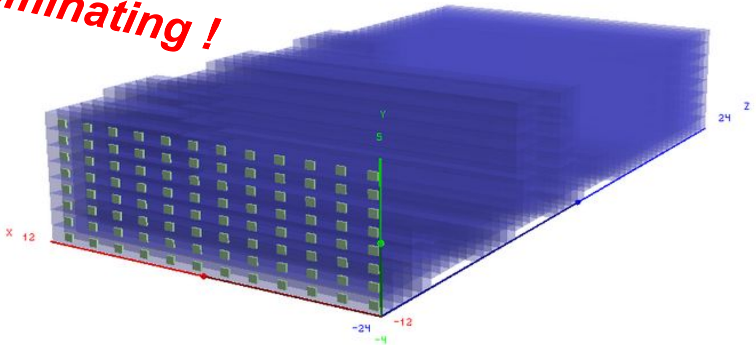
Major Systematics: Detection

- 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.**

Guessing but can be realistic



Dominating !



Major Systematics: Detection

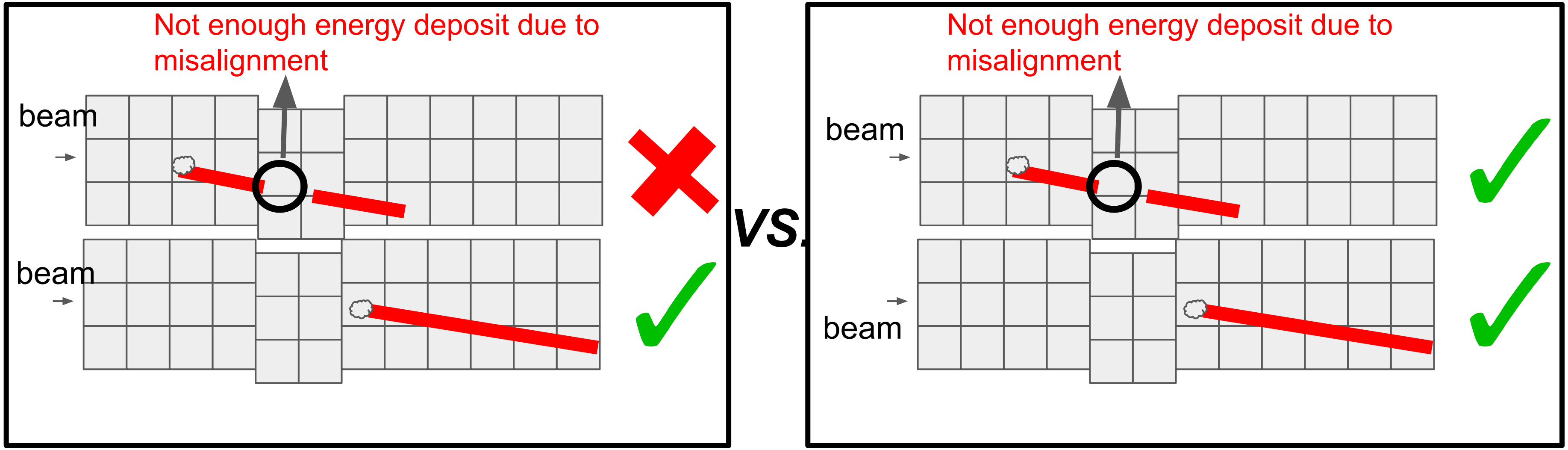
Dominating !

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

- Single-track
- Everything above threshold

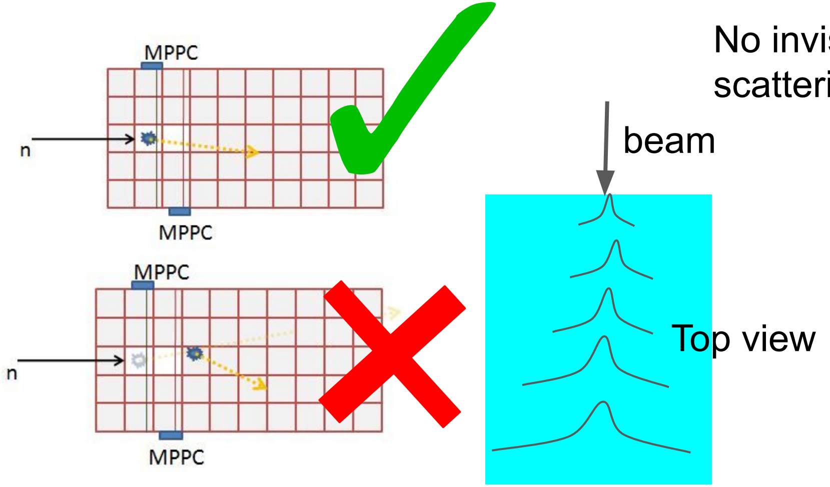
Single-track

Everything above threshold (called “no-cut”)

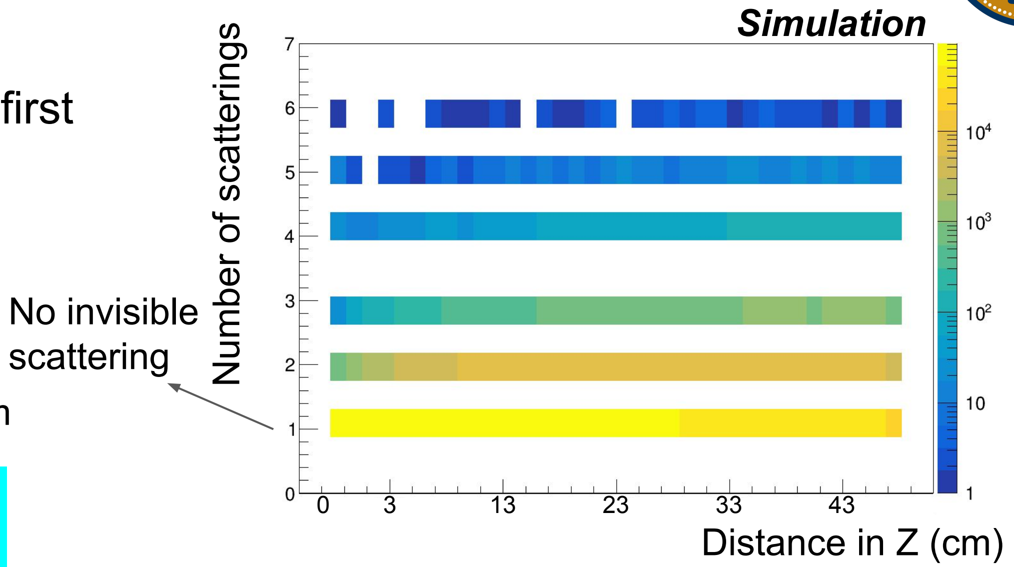


Major Systematics: Invisible scattering

What we want to measure:
neutron-induced single track as the first interaction => requiring no invisible scattering before the visible one



Transverse spread increase along beam caused by 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.***

Cross-section fitting

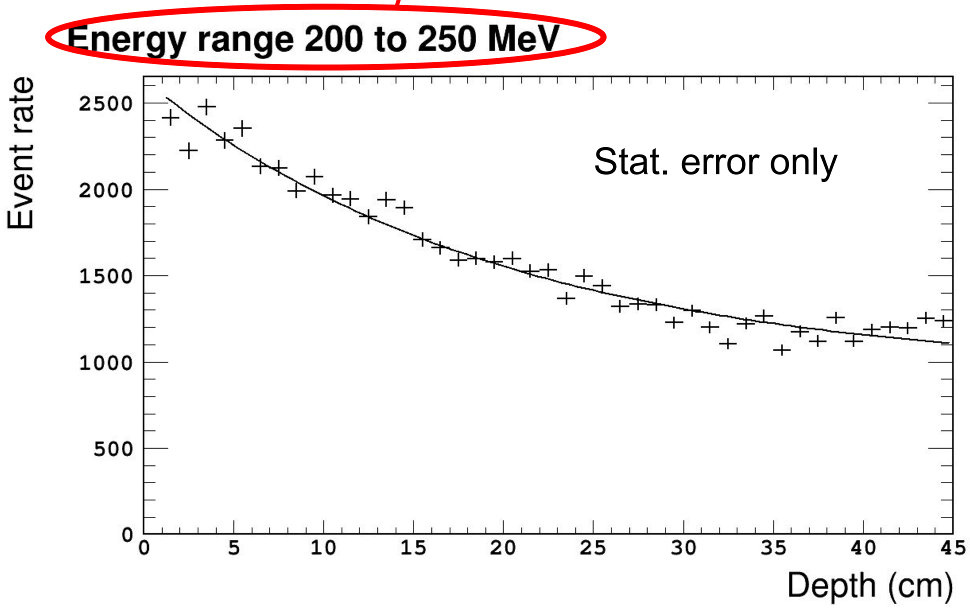
Single-track event selection with known incident neutron energy from ToF

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.

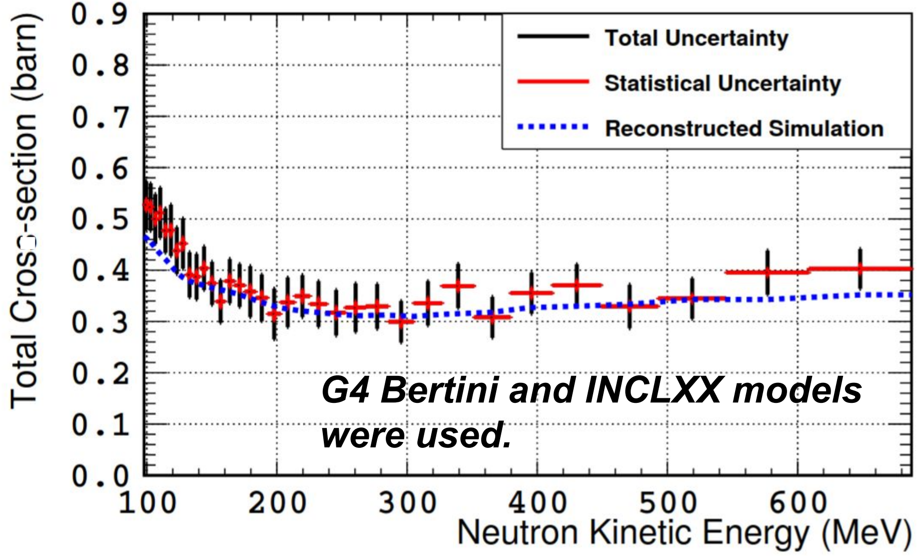
The event rate randomly varied based on all uncertainties.

This can be any energy ranges.



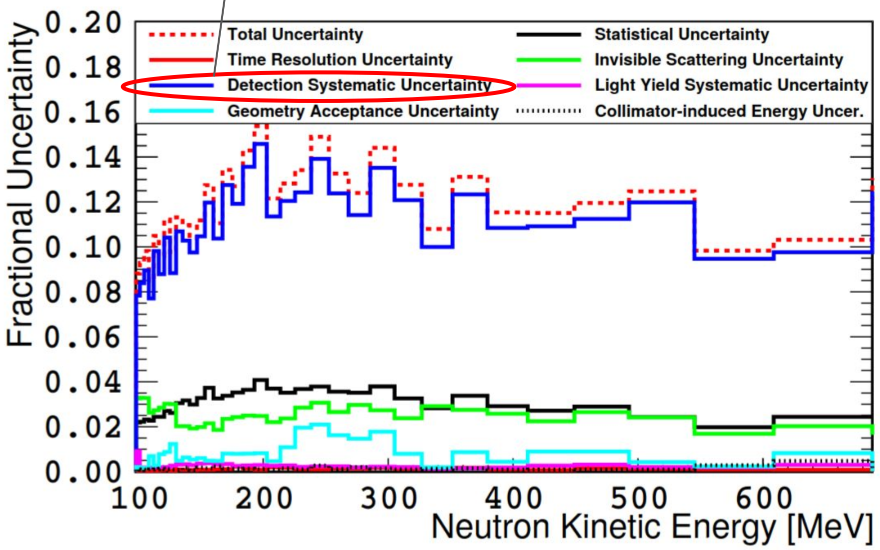
Total cross-section measurement result

arXiv: 2207.02685



G4 Bertini and INCLXX models were used.

Main systematic



χ^2/d.o.f. below 150 MeV: 15.2/11
χ^2/d.o.f. Below 200 MeV: 16.1/18

Other ongoing effort

Detection systematic uncertainty reduction

Data taken in 2020 with additional configurations of the beam structure, collimator setting and combination of the two prototypes

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)

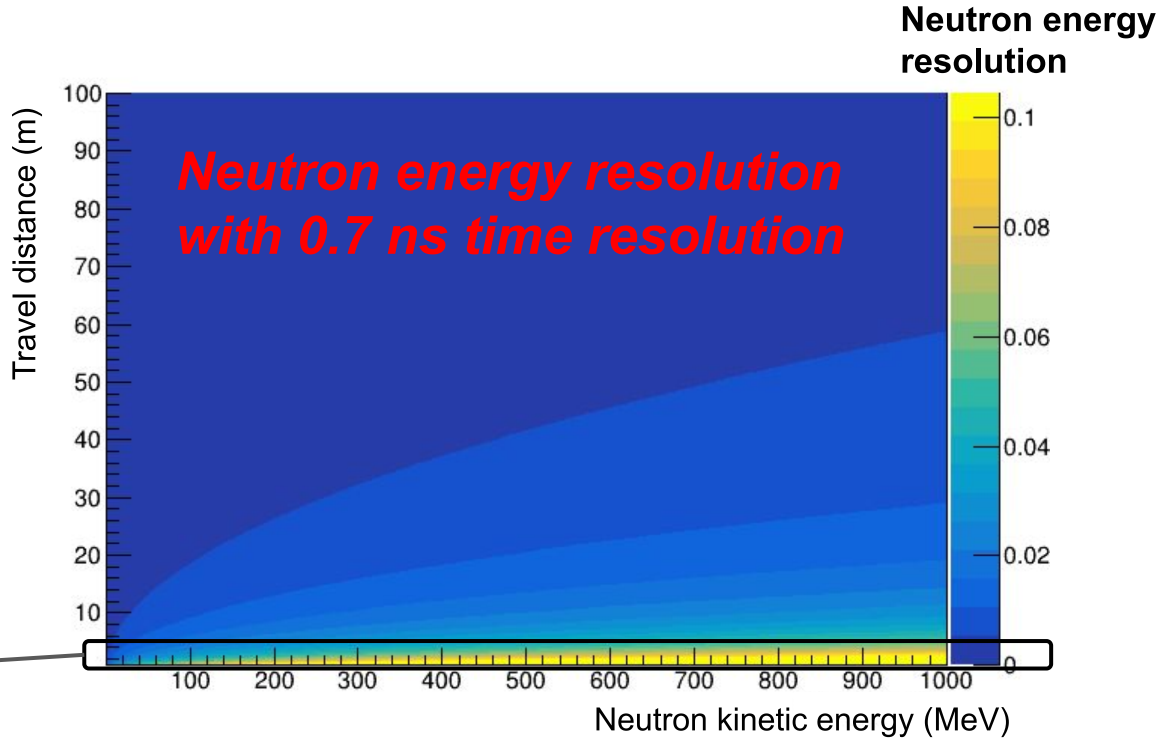
Exclusive neutron detection efficiencies

Nuclear modeling probe

MOVE FORWARD:
Event-by-event neutron detection in the neutrino interaction

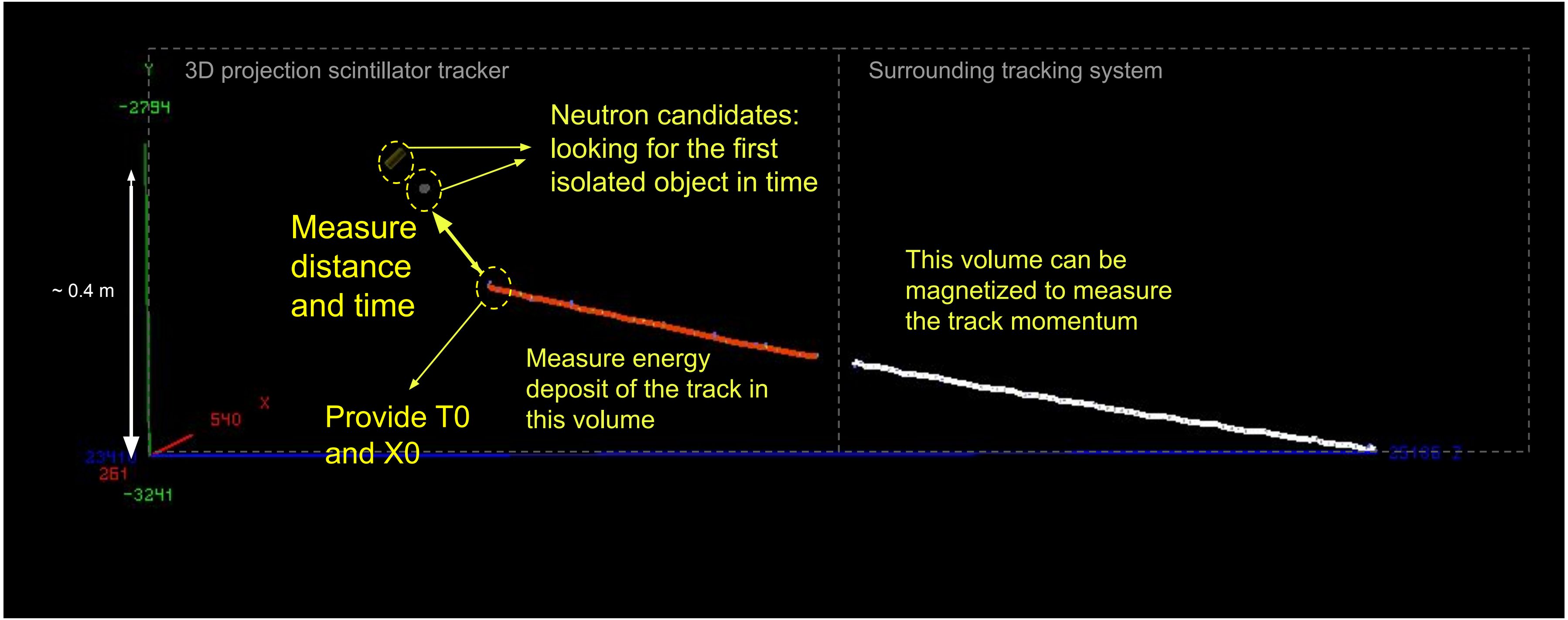
Eventually we need to move this effort to the neutrino interaction.

In SFGD and 3DST, 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 detection in the neutrino interaction

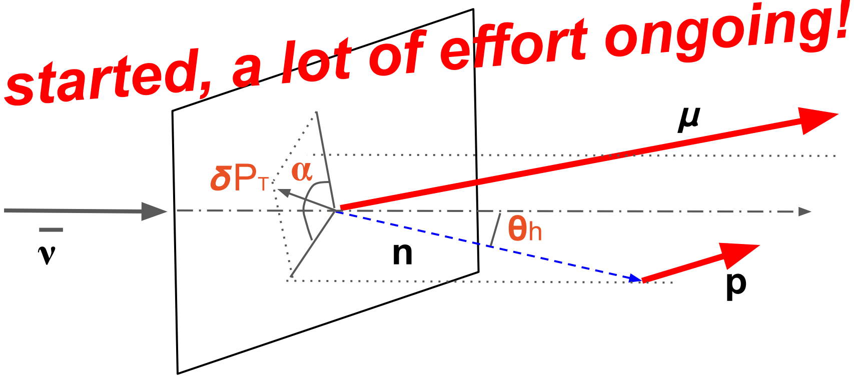
Main controllable parameter: ***timing resolution***

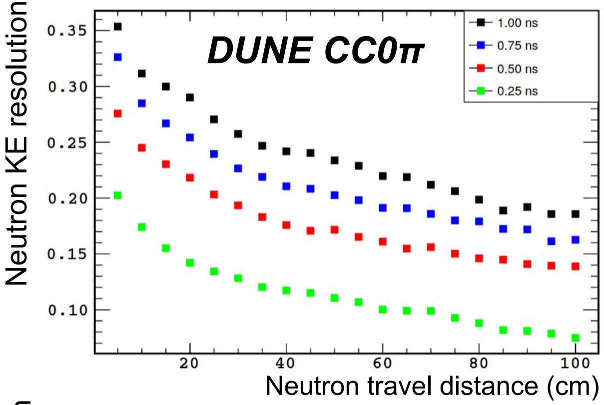
So far, targeting at events with single neutrons

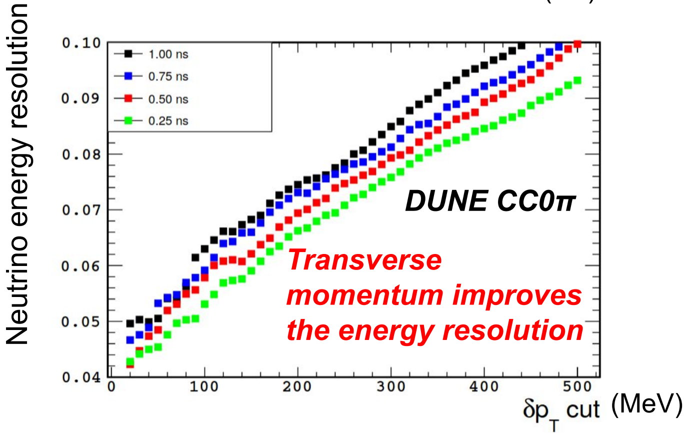
- External and internal backgrounds being studied: ***arXiv:2211.17037***

Individual neutron measurement to significantly enhance the utilization of transverse plane variables

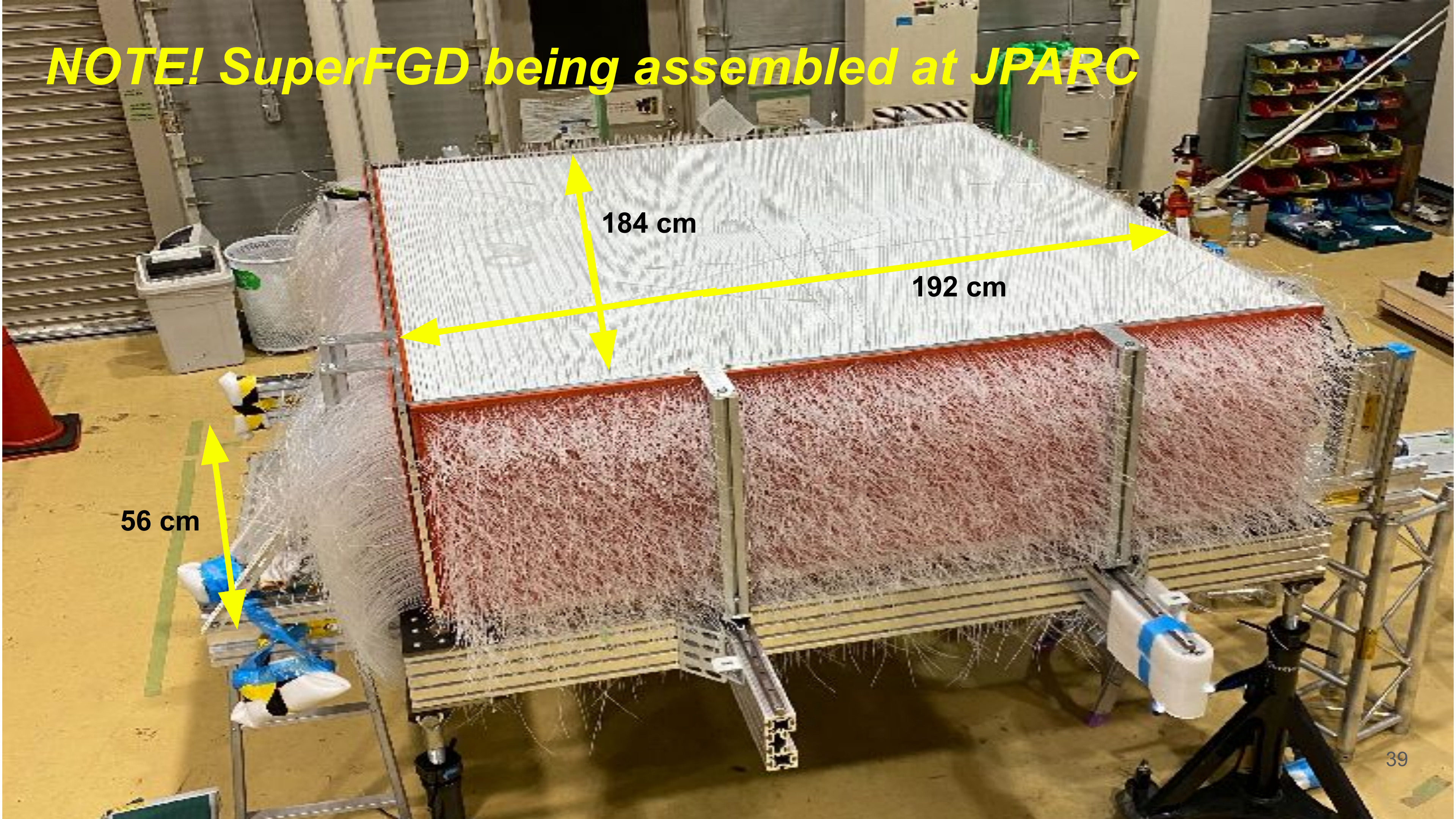
Just started, a lot of effort ongoing!







NOTE! SuperFGD being assembled at JPARC



NOTE! SuperFGD being assembled at JPARC

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Summary

More than 10^7 neutron interactions 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 kinematics detection attempts to fill the hole in the puzzle of neutrino interaction-> utilizing transverse variables more effectively.