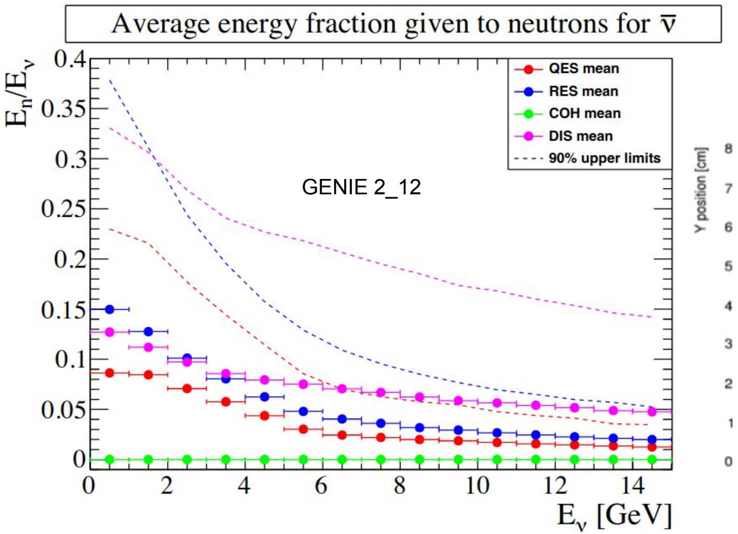
Total Neutron cross section measurement with a 3D projection scintillator tracker for long-baseline neutrino experiments

Guang Yang, Stony Brook University

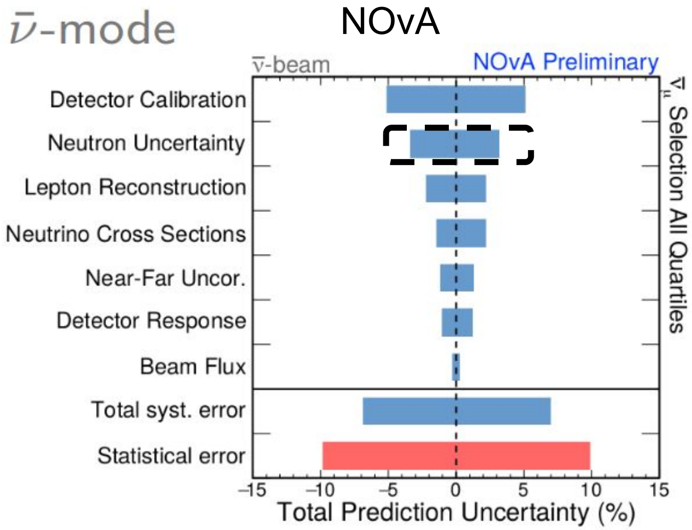
On behalf of the ***joint T2K-DUNE 3D Projection Scintillator R&D group***

Neutrons in the long-baseline neutrino experiments

- One of the major systematic uncertainties in the neutrino interaction modeling in the long-baseline neutrino experiments due to blindness to neutrons in the final state, especially in the RHC mode
- Neutron carrying out a large fraction of energy in antineutrino interaction



NOvA

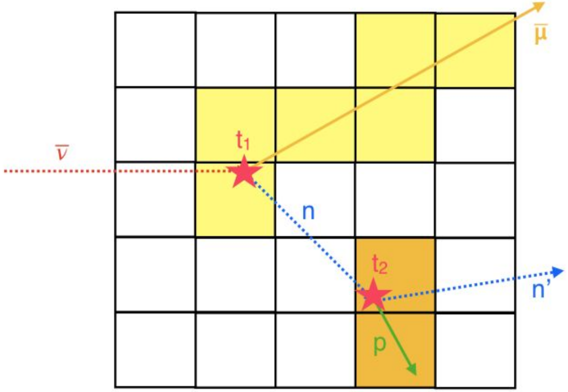


ICHEP 2020

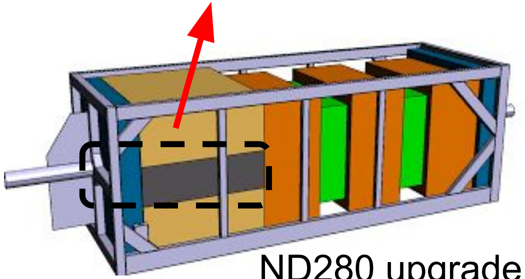
Neutron detection on an event-by-event basis

- Time of flight and travel distance between the vertex and first neutron induced hit cluster obtained and used to calculate the neutron kinetic energy
- A three-dimensional projection scintillator tracker (3DST), which is capable of neutron detection, as part of a Near Detector system proposed
- SuperFGD for T2K upgrade being built and 3DST for DUNE being proposed (3DST proposed to use the synergy with superFGD)
    - ***Not only tagging, we detect the neutron kinematics!***

Time-of-flight technique

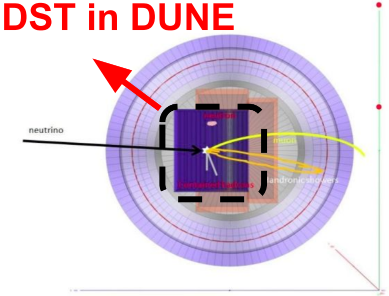


superFGD in T2K



ND280 upgrade

3DST in DUNE



DUNE SAND

A joint T2K-DUNE 3D Projection Scintillator R&D group

US institutions

- Louisiana state University
- University of Pennsylvania
- University of Pittsburgh
- University of Rochester
- Stony Brook University
- South Dakota School of Mines and Technology

International institutions

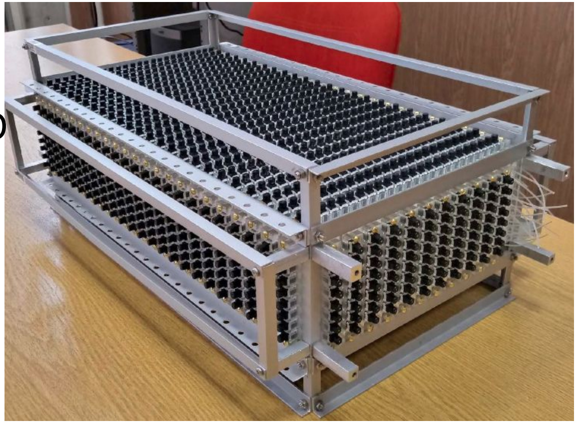
- CERN
- Chung-Ang University, South Korea
- ETH Zurich, Switzerland
- University of Geneva, Switzerland
- High Energy Accelerator Research Organization (KEK), Japan
- IFAE (Spain)
- Imperial College, UK
- Institute for Nuclear Research (INR), Russia
- University of Kyoto, Japan
- University of Tokyo, Japan

Demonstration of the neutron detection capability

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

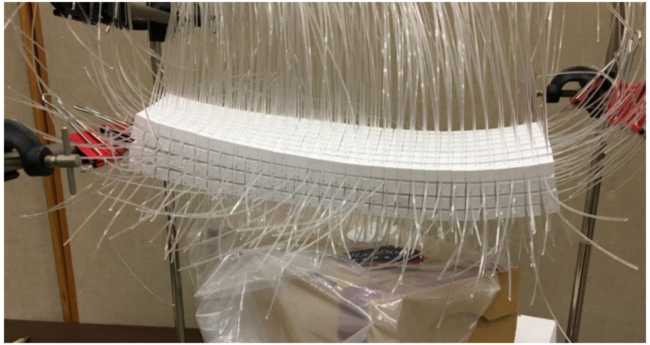
- SuperFGD prototype (SFGD) been used for a charged particle beam test at CERN (24 x 8 x 48): [*JINST* 15 (2020) P12003]
- US-Japan prototype (USJ) using some new designs that will be used in the T2K upgrade, probably 3DST (8 x 8 x 32).

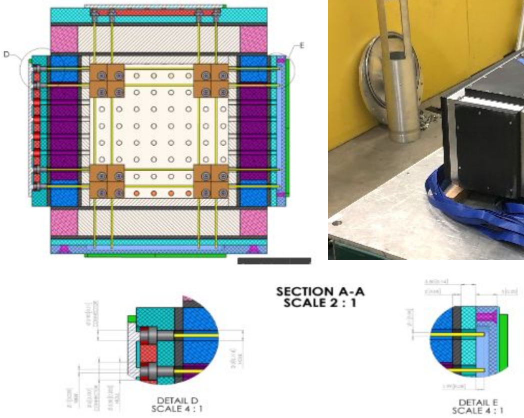
superFGD prototype



US-Japan prototype

US-Japan proto.
Assembled
In Stony Brook





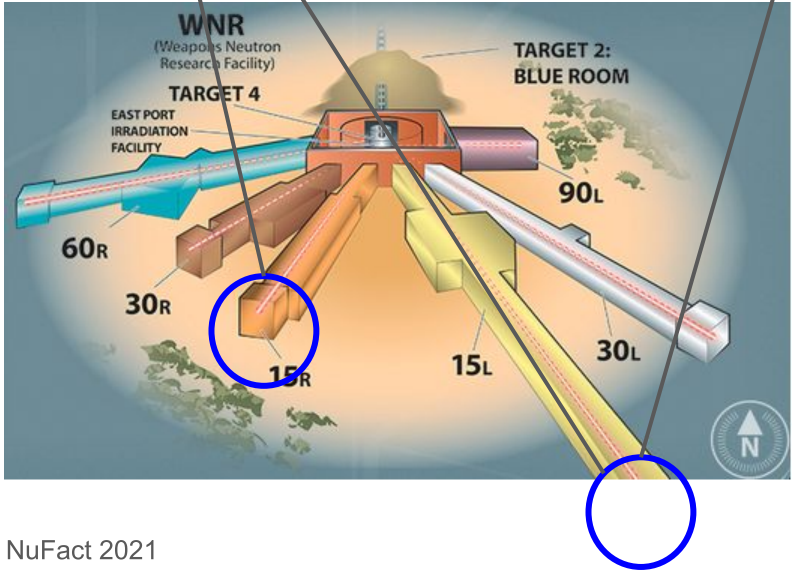
At LANL

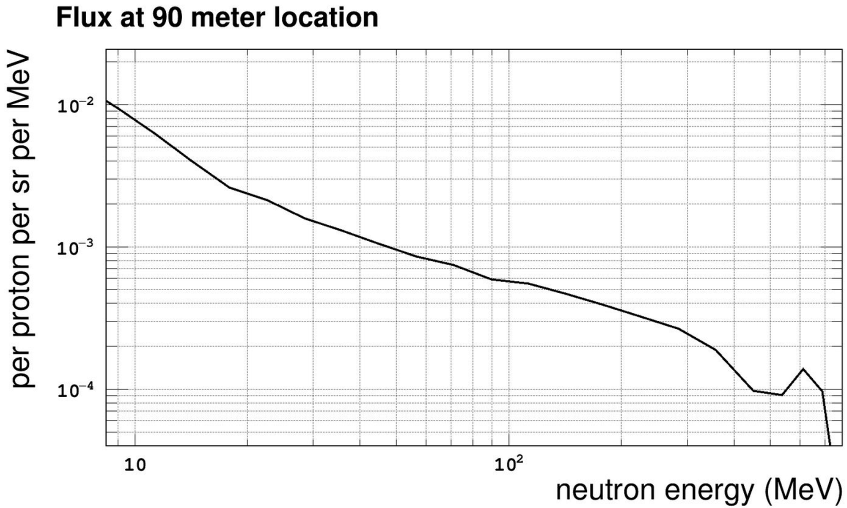
Neutron beam facility

Los Alamos National Lab LANCSE facility provides neutron beam ranged from 0 - 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.)

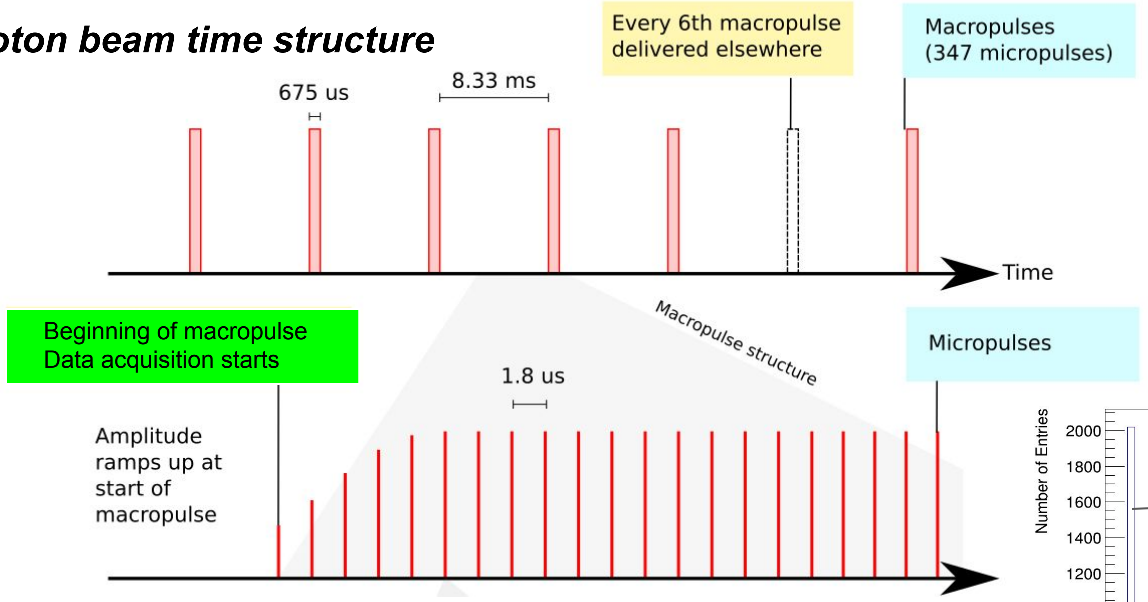




Neutron beam time structure

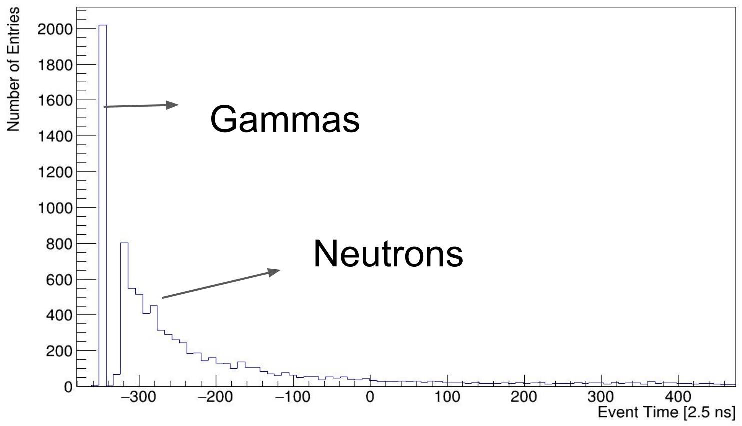
Neutrons are from protons hitting a tungsten target.

Proton beam time structure



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

Gamma flash and t0 available for micropulses



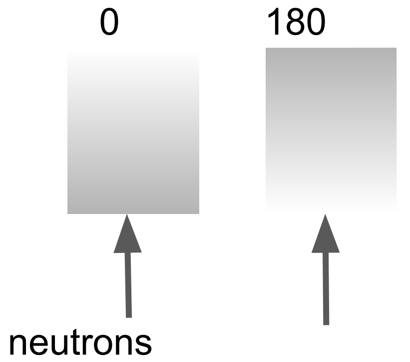
- In each micropulse, neutrons following gamma flashes
- Two micropulse spacing of 1.8 μs and 3.6 μs (only 2020)

Experimental setup

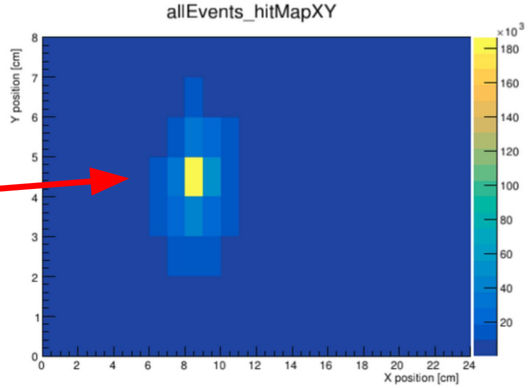
Two orientation used in 2019, 0 degree and 180 degree along Y (height) -> to understand the detector anisotropy

The time sampling tick size 2.5 ns, dominating the timing resolution -> single channel time resolution 1.37 ns including t0 resolution

Top view



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



Calibration

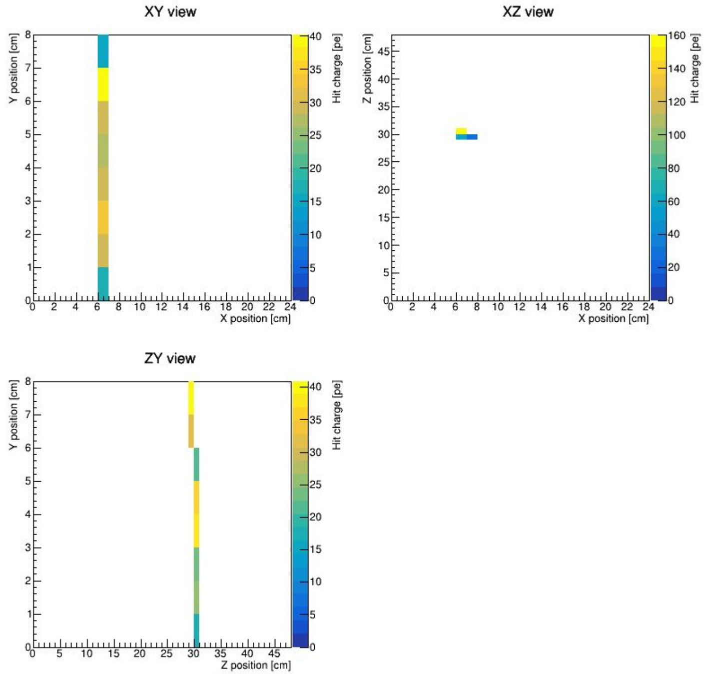
Gain calibration

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

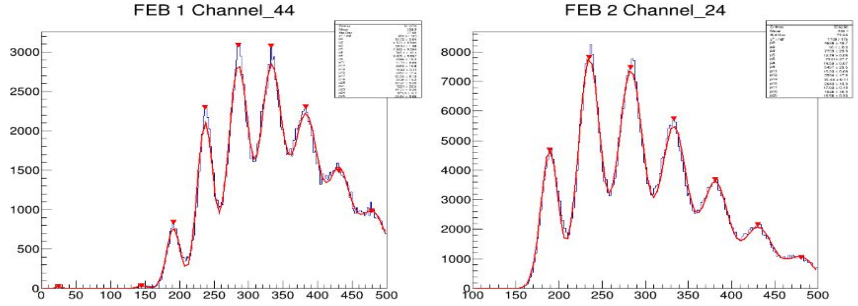
Light yield calibration

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

Cosmics candidate

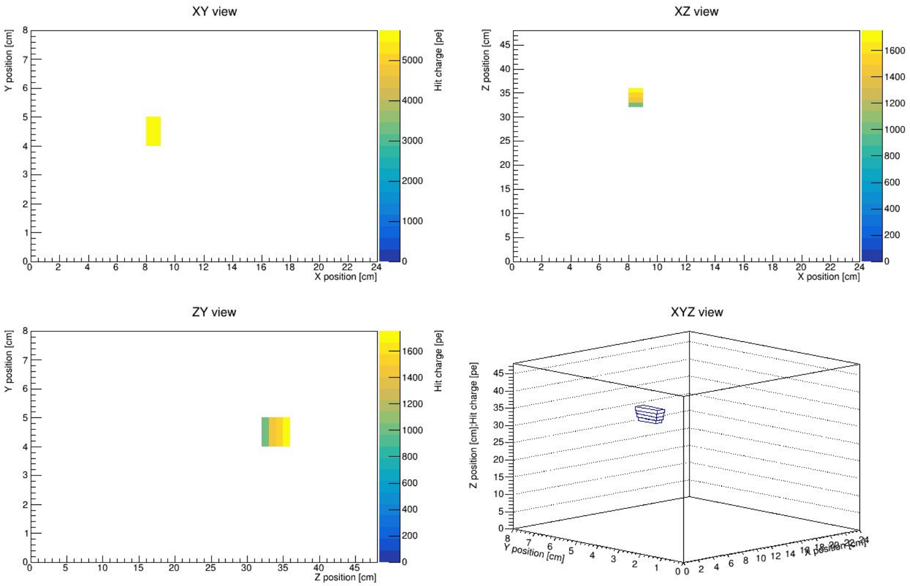


PE peaks finding

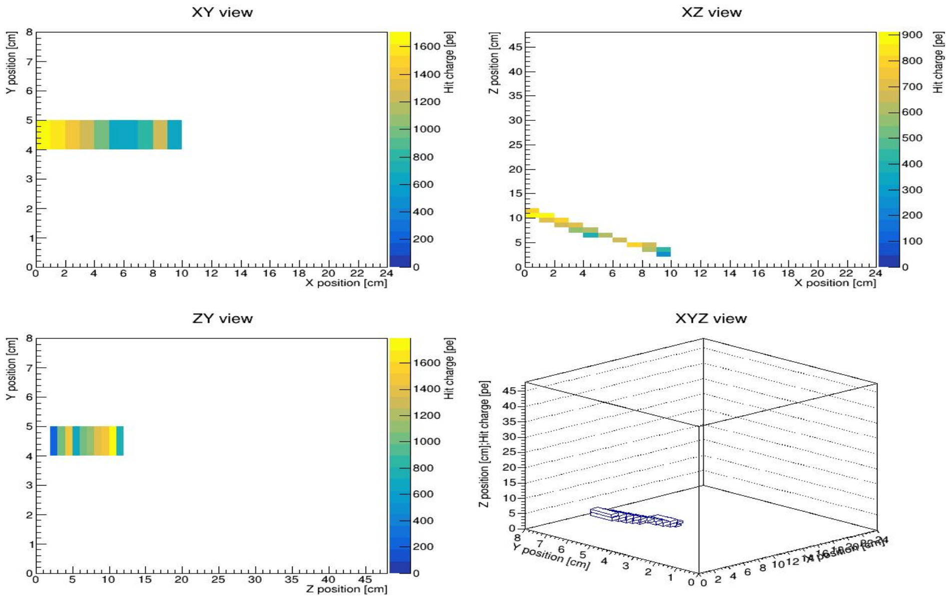


Individual neutron events

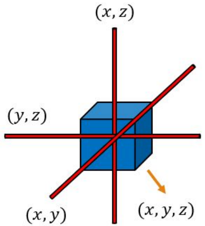
65 MeV neutron with 60 MeV deposit energy

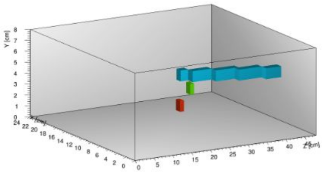


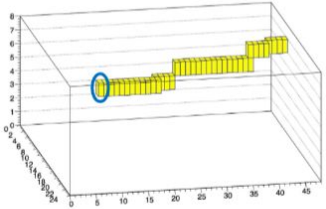
193 MeV neutron candidate with 123 MeV deposit energy



Reconstruction Chain







2D Hits

- Time cut on hits
- PE cut on hits
- Time clustering hits

3D Voxels

- 3D view matching of time - clustered hits
- 3 hits sharing the same XYZ coordinates

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

Voxel: 3D reconstructed cube

Analysis plans

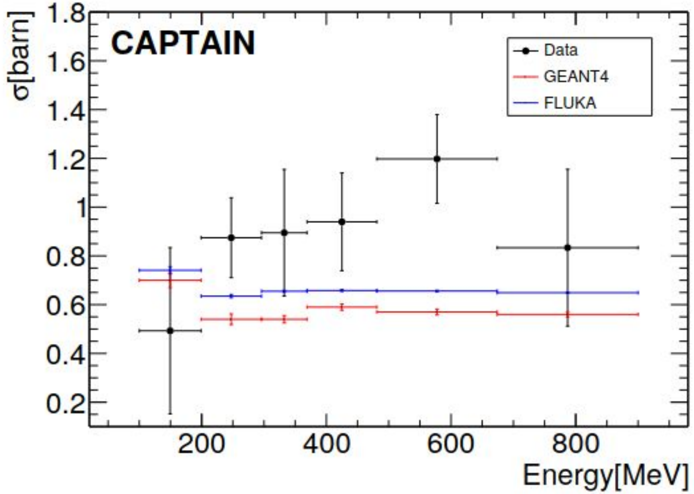
- First result will be on the total cross section measurement (with 2019 SFGD prototype data): validate our detector and demonstrate the neutron detection capability -> ***Main topic of this talk***
- Elastic scattering model tuning
- Neutron detection efficiency as a function of neutron energy
- Exclusive interaction cross section measurement
- Secondary scattering study : secondary scattering angle as a function of neutron energy etc.

A total cross section measurement

- Extinction method being used -> Looking at event rate at each layer and fitting the exponential to extract the cross section
- Used in the mini-CAPTAIN paper -> A certain topology being selected

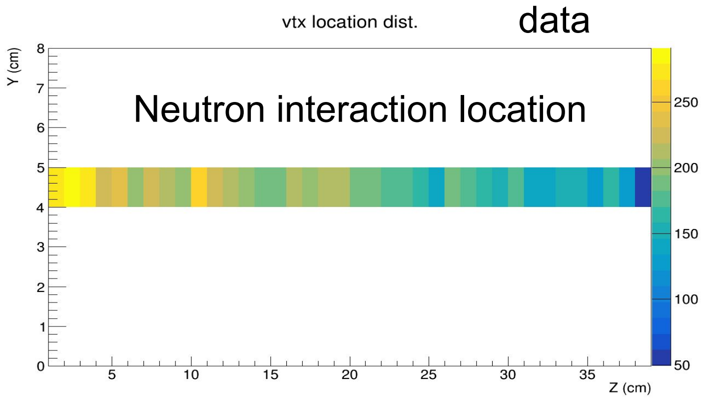
Phys. Rev. Lett. 123, 042502 (2019)

Our approach to measure the neutron cross section uses the fact that neutron flux decreases as a function of depth in the detector due to neutron interactions with argon. The attenuation of the beam dN_B/dx is proportional to the total neutron-argon cross section as seen in Equation 1. The attenuation can be measured by choosing a particular event topology and measuring the change in the rate of this particular process as a function of depth in the detector. Provided that the fraction of



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

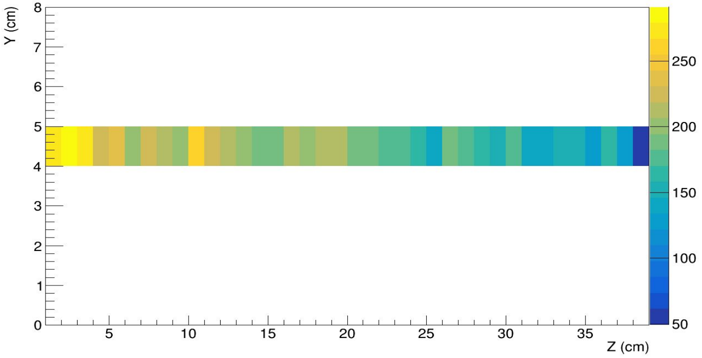
Nuclear density (T) — total xsec (σ_{total}) — depth along the beam, i.e. layer (z)

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

A total cross-section measurement

vtx location dist. data

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

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

Energy Layer

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

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

Layer l Layer m

Single track attenuation indicates a total cross-section

Single-track selection

1. Single time cluster of hits
2. Single DBSCAN cluster of voxels
3. More than 2 voxels in the cluster
4. Linearity cut that obtained from a Principle Component Analysis’ (PCA) eigenvalues
5. Cluster width cut with the eigenvalues from PCA
6. Vertex in fiducial volume

Systematic uncertainties

- Interaction: invisible scattering (primary interaction under detector threshold)
- Neutron energy: time resolution
- Detection/reconstruction: detector anisotropy due to geometry asymmetry and readout nonuniformity and event selection-induced uncertainty
- Light yield: with cosmic calibration
- External Background: negligible with the FV requirement

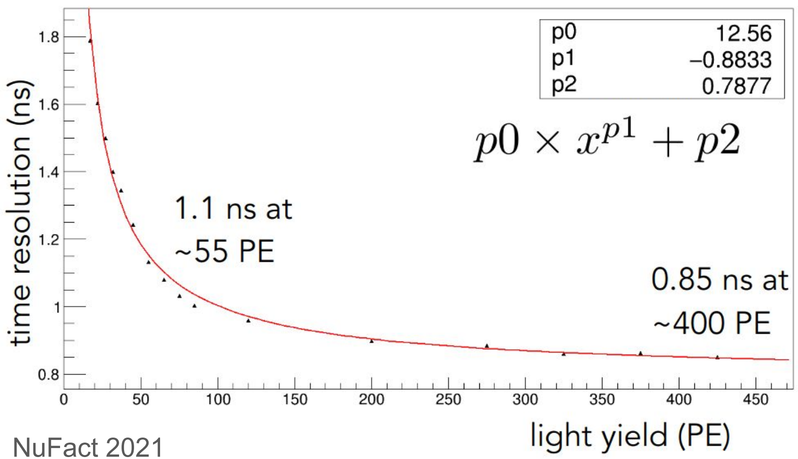
A few examples are shown here, a full systematic review will be presented in the paper, stay tuned!

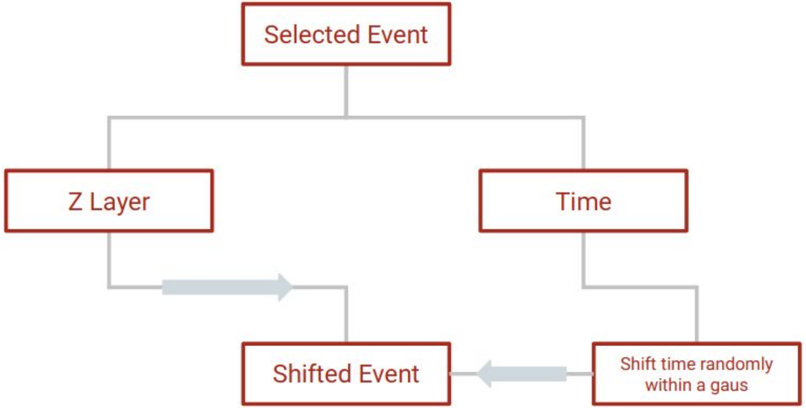
Energy uncertainty

Due to timing resolution -> selected event time resolution below 1 ns and PE dependent

Randomly shifting the measured timing based on the time resolution, the resulting Z layer distributions for each energy range forming an uncertainty band

Readout channel time resolution



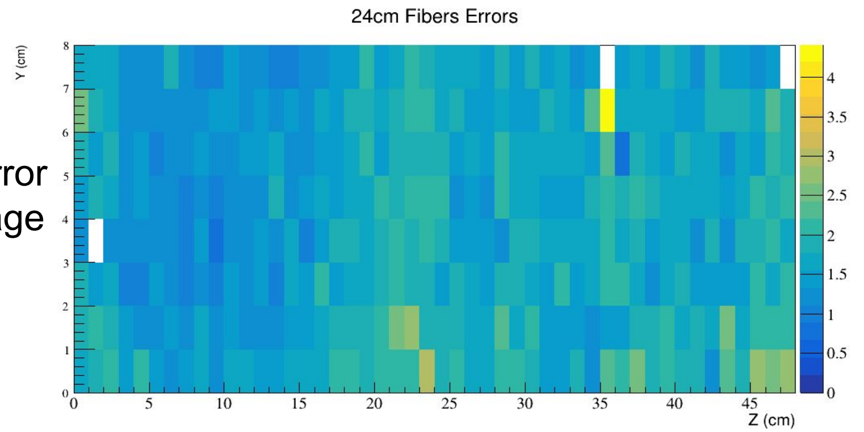


Light yield uncertainty

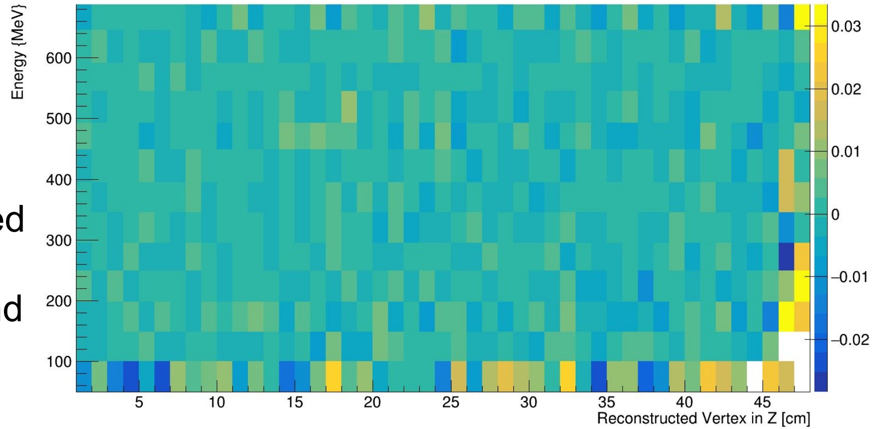
Light yield from cosmic muons with intrinsic fitting uncertainty

The fitting uncertainty for each channel propagated to the uncertainty on the energy and vertex z layer space

LY fitting error
In percentage



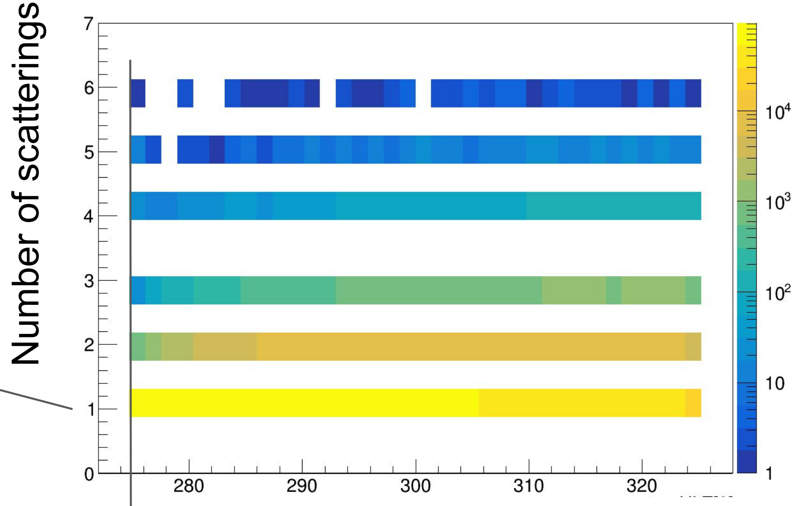
Propagated
Error on
Energy and
Vertex z



Invisible scattering in the detector

What we want to measure: neutron-induced single track => If using this to extract total cross section, requiring no scattering before the visible one that induces single tracks

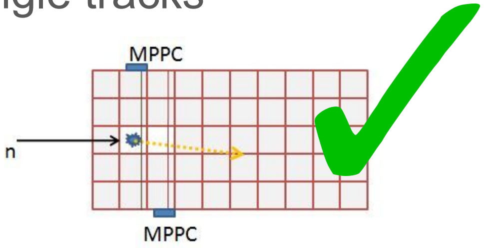
simulation

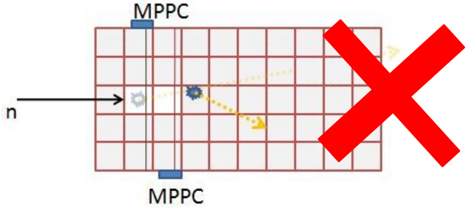


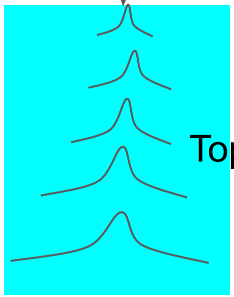
No invisible scattering

0 in z in detector coord.

Distance in Z (cm)







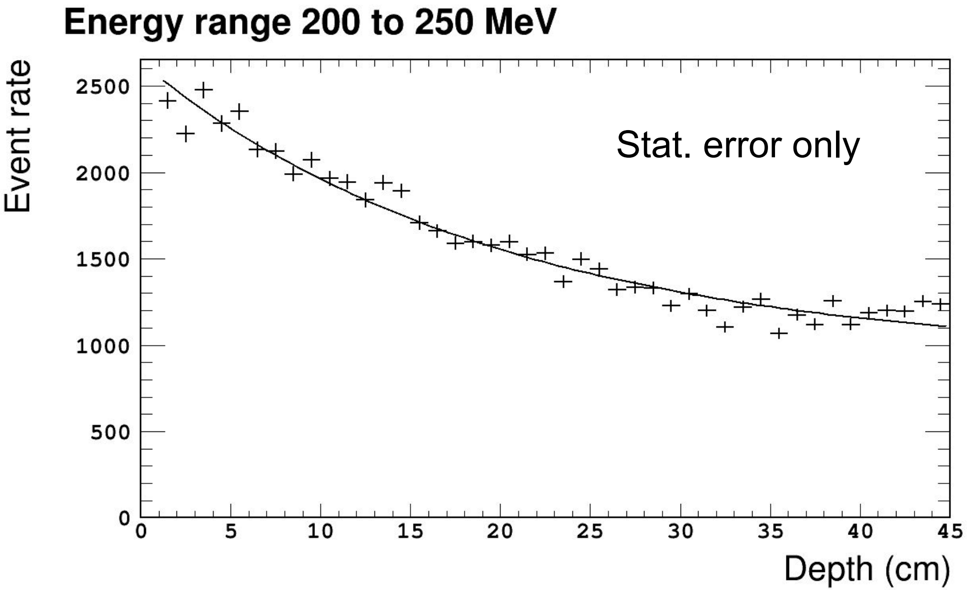
Top view

1. ***Tune MC spread to data by changing invisible scattering amount.***
2. ***Invisible scattering amount can be extracted from the tuned MC -> it will be used to correct for data.***

Cross section fitter

- Single-track event selection with known incident neutron energy from ToF
- Applying the relative detection efficiency correction to all z layers for each energy range
- Applying the invisible scattering correction to each z layer 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 having a combined uncertainty from energy scale, invisible scattering correction, detection and reconstruction-> The event rate randomly varied based on that uncertainty

10 m data, in total we have > 10 hours



Summary

Neutron kinematics reconstruction on an event-by-event basis in long-baseline neutrino oscillation experiments proposed

Two neutron beam tests with superFGD and US-Japan prototypes been completed successfully

- Sufficient (even the pion production at 700 MeV -> smallest sample size) and high-quality data been collected.

A full demonstration of the individual neutron detection capability ongoing

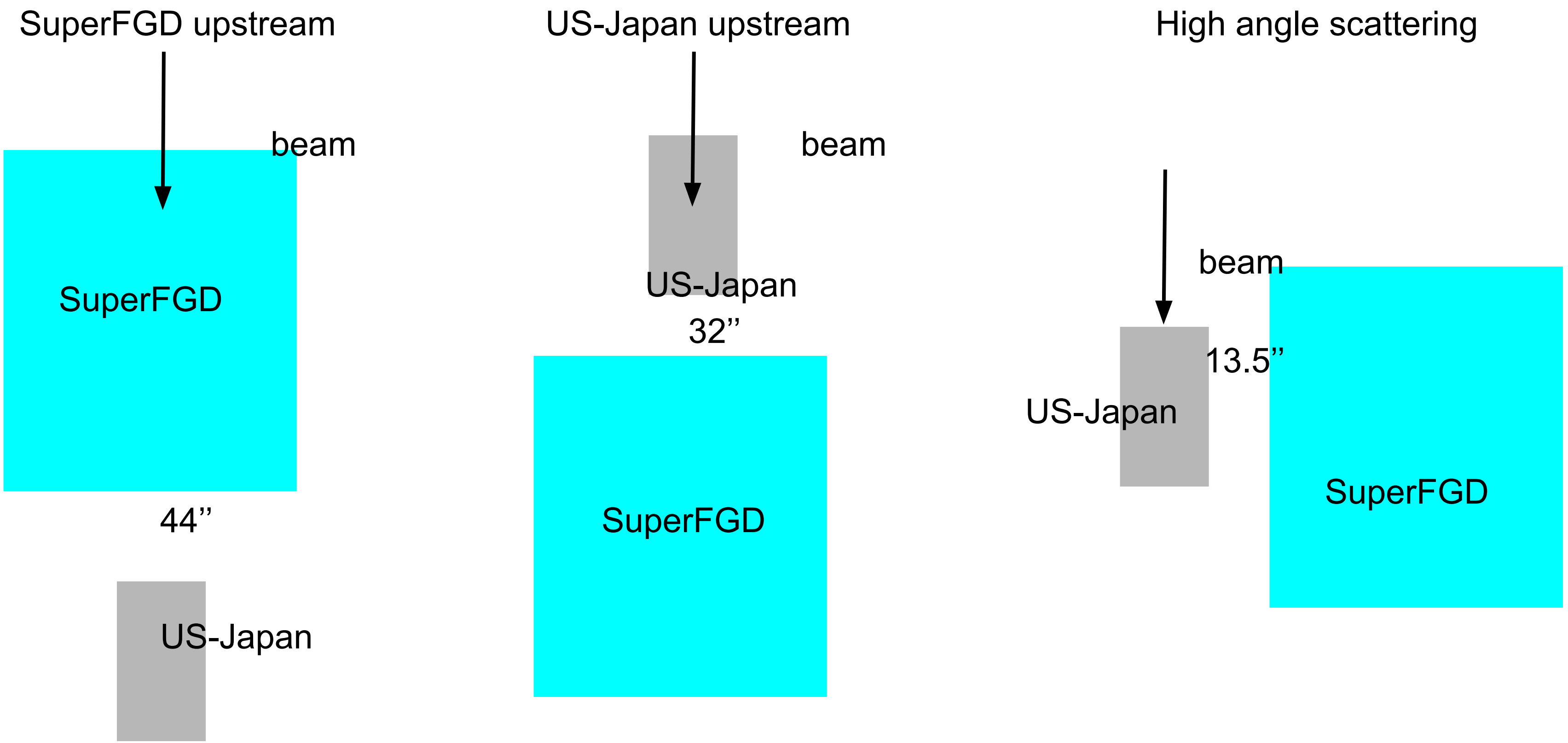
A total neutron-scintillator cross section measurement being finalized and prepared for publication

Backups

Detector configurations in 2020

In order to understand the systematic uncertainties, a number of new configurations have been developed in the 2020 beam test.

All in top view



Onsite team & remote shifters

2019: 3 run coordinators and more than 10 onsite shifters

2020: 4 onsite shifters (in two teams) and 20 remote shifters

One of the onsite shift team in 2019

Onsite shift team in 2020

Remote shifters in 2020

Date	Time (MT)	On-site Shifters	Restart Connection	Reboot PC	Power Cycle	Remote Shifter
12/02/2020	8:00 AM		8:00 AM	8:00 AM	8:00 AM	
	2:00 PM		2:00 PM			
	8:00 PM		8:00 PM			Kuribayashi
12/03/2020	2:00 AM		2:00 AM			Tatsuya Kikawa
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Michael Reh
	2:00 PM		2:00 PM			Jordi Capo
	8:00 PM		8:00 PM			Ki Young Jung
12/04/2020	2:00 AM		2:00 AM			Cesar Jesus-Valls
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Clark McGrew
	2:00 PM		2:00 PM			Alexander Paul-Torres
	8:00 PM		8:00 PM			Jairo Rodriguez
12/05/2020	2:00 AM		2:00 AM			Dana Douqa
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Marat Khabibullin
	2:00 PM		2:00 PM			Shih-Kai Lin
	8:00 PM		8:00 PM			Ki Young Jung
12/06/2020	2:00 AM		2:00 AM			Konstantin Limarev
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Alexander Paul-Torres
	2:00 PM		2:00 PM			Rachel Pellegrino
	8:00 PM		8:00 PM			Kuribayashi
12/07/2020	2:00 AM		2:00 AM			Sunwoo Gwon
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Robert Amarinei
	2:00 PM		2:00 PM			Ciro Riccio
	8:00 PM		8:00 PM			Alex Ramirez
12/08/2020	2:00 AM		2:00 AM			Loris Martinez
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Michael Reh
	2:00 PM		2:00 PM			Leonel
	8:00 PM		8:00 PM			Kuribayashi
12/09/2020	2:00 AM		2:00 AM			Dana Douqa
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Leonel
	2:00 PM		2:00 PM			Rachel Pellegrino
	8:00 PM		8:00 PM			Alex Ramirez
12/10/2020	2:00 AM		2:00 AM			Loris Martinez
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Ciro Riccio
	2:00 PM		2:00 PM			Shih-Kai Lin
	8:00 PM		8:00 PM			Cesar Jesus-Valls
12/11/2020	2:00 AM		2:00 AM			Sunwoo Gwon
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Marat Khabibullin
	2:00 PM		2:00 PM			Jairo Rodriguez
	8:00 PM		8:00 PM			Ki Young Jung
12/12/2020	2:00 AM		2:00 AM			Robert Amarinei
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Thorsten Lux
	2:00 PM		2:00 PM			Leonel
	8:00 PM		8:00 PM			Shih-Kai Lin
12/13/2020	2:00 AM		2:00 AM			Sunwoo Gwon
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Marat Khabibullin
	2:00 PM		2:00 PM			Rachel Pellegrino
	8:00 PM		8:00 PM			Kuribayashi
12/14/2020	2:00 AM		2:00 AM			Loris Martinez
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	2:00 PM		2:00 PM			Alexander Paul-Torres
	8:00 PM		8:00 PM			Alex Ramirez
12/15/2020	2:00 AM		2:00 AM			Sunwoo Gwon
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Clark McGrew
	2:00 PM		2:00 PM			Ciro Riccio
	8:00 PM		8:00 PM			Konstantin Limarev
12/16/2020	2:00 AM		2:00 AM			Cesar Jesus-Valls
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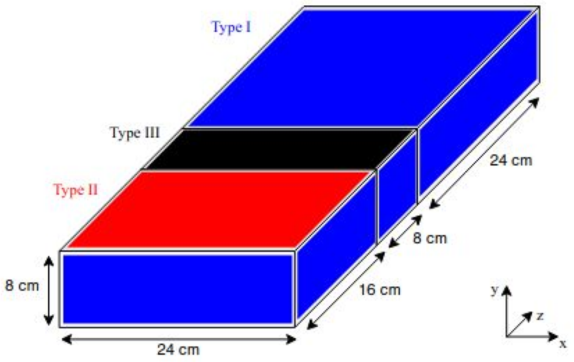
	2:00 PM		2:00 PM			Mark D'Souza
	8:00 PM		8:00 PM			Alex Ramirez
12/17/2020	2:00 AM		2:00 AM			Dana Douqa
	8:00 AM		8:00 AM	8:00 AM	8:00 AM	Mark D'Souza
	2:00 PM		2:00 PM			Jordi Capo
	8:00 PM		8:00 PM			Tatsuya Kikawa

MPPCs in SuperFGD prototype (sFGD)

Three types of MPPCs were used to test the detector response.

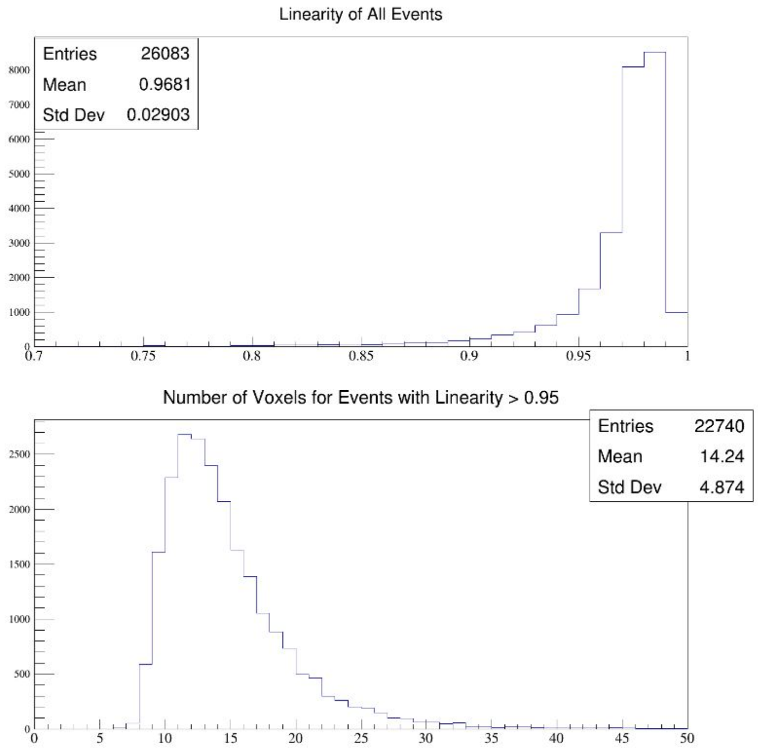
- Top (XZ) view has three types
- Side (YZ) and Beam (XY) view have only type I MPPCs.

Description	Type I	Type II	Type III
Manufacturer ref.	S13360-1325CS	S13081-050CS	S12571-025C
No. in Prototype	1152	384	192
Pixel pitch [μm]	25	50	25
Number of pixels	2668	667	1600
Active area [mm^2]	1.3×1.3	1.3×1.3	1.0×1.0
Operating voltage [V]	56–58	53–55	67–68
Photon detection eff. [%]	25	35	35
Dark count rate [kHz]	70	90	100
Gain	7×10^5	1.5×10^6	5.15×10^5
Crosstalk probability [%]	1	1	10



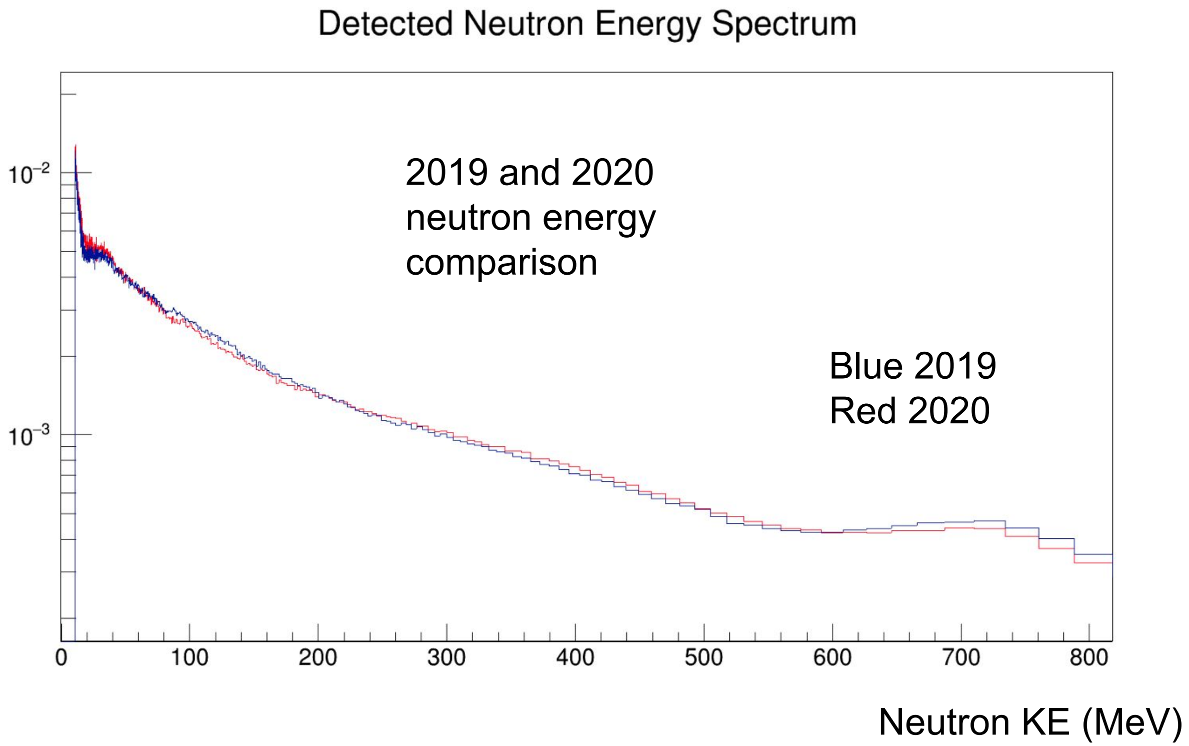
Cosmics sample selection

- 3D voxelization of hits
- Single spatial cluster
- PCA linearity > 0.95
- Number of voxels between 6-20
- Track must either pass through the top and bottom of detector or through side
- Minimum of 4 y-layers hit for event to be accepted
- Entry and exit points determined by the voxel positions with max and min y



2019 vs. 2020 spectrum

superFGD prototype 2019 and 2020 spectrum comparison



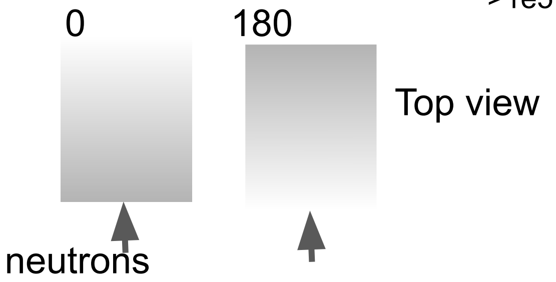
Data Rate Summary Table 2019 + 2020

Potential good data rate only, some data with bad alignment, bad t0 or a lot of missing channels etc. do not count.

Mins(>2e5* int. n per min)	8 mm + 1.8 us	8 mm + 3.6 us	1 mm + 1.8 us	1 mm + 3.6 us
SFGD upstream 19	~3600	NA	NA	NA
SFGD upstream 20	1055	1260	930	515
USJ upstream	1310	NA	3355	NA
High angle sct.	1095	325	NA	NA

* >1e5 for 3.6 us spacing

- In 2019, sFGD upstream data separated out to two orientations (0 and 180).



Selection Chain

- Similar to the reconstruction chain, the selection chain is developed specifically for selecting single track events

- A set of topological cuts are developed to select single track events:
  - Linearity
  - Cluster width
  - Max-vox-line

Principal Component Analysis (PCA) Overview

- Calculate the centroid for a distribution of points
- Calculate the covariance matrix with the centroid

$$[Cov]_{ij} = \frac{\sum_{l=1}^{N}(A_i - \overline{A_i}) \cdot (A_j - \overline{A_j})}{N}$$

- Perform eigen decomposition on the covariance matrix to obtain the eigenvalues of the covariance matrix
- Sort the obtained eigenvalues by $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$
- Evaluate the linearity, planarity and sphericity of the distribution of points

Linearity	$(\lambda_1 - \lambda_2)/\lambda_1$
Planarity	$(\lambda_2 - \lambda_3)/\lambda_1$
Sphericity	λ_3/λ_1

Cluster Width Overview

- 1D projection of voxels to the eigenvector with the second largest eigenvalue (from PCA calculation)

$$d_i = \boldsymbol{v_2} \cdot (\boldsymbol{r_i} - \bar{\boldsymbol{r}})$$

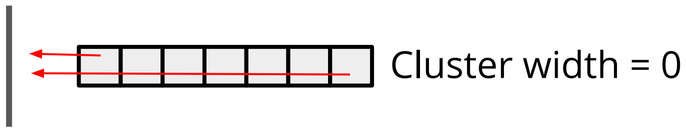
$\boldsymbol{v_2}$: *Eigenvector with the second largest eigenvalue*

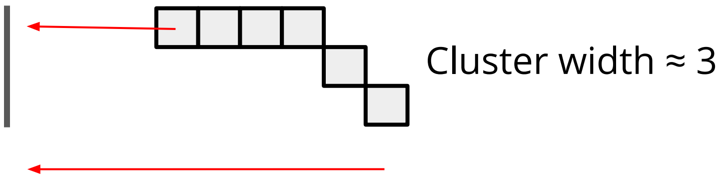
$\boldsymbol{r_i}$: *3D coordinate of voxel i*

$\bar{\boldsymbol{r}}$: *Mean 3D coordinate of voxels in the same cluster*

- Calculate the distance between the 2 voxels furthest away from each other in this eigenbasis (cluster width)

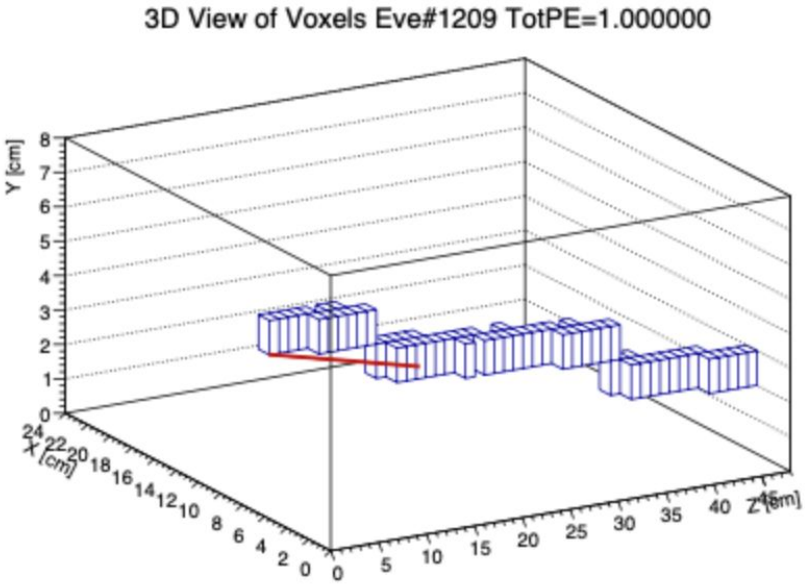
$$d = d_{max} - d_{min}$$ (Cluster width)





Max-Vox-Line Overview

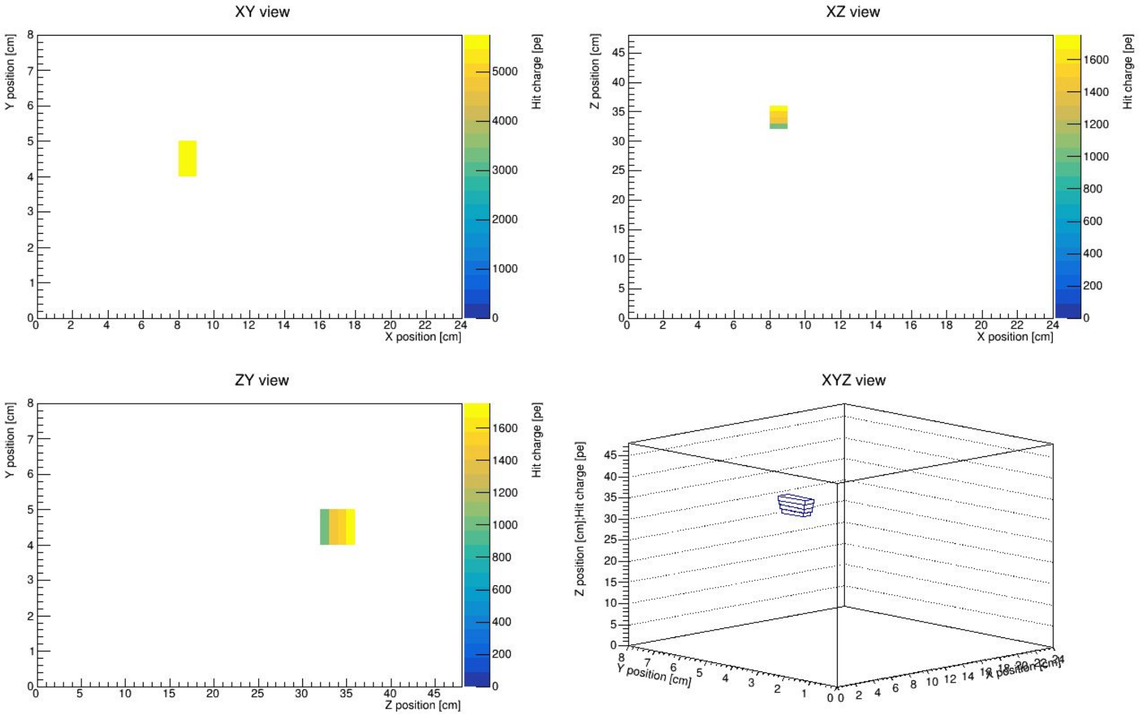
- Calculate the eigenvectors for a cluster of voxels using PCA
- Shift the origin of the eigenvectors from the centroid of the cluster to the vertex of the cluster
- Obtain the main eigenvector which is the eigenvector with the largest eigenvalue (red line in the figure)
- Compute the maximum distance between the voxels and the main eigenvector (max-vox-line)



Neutron interaction candidate gallery: DATA

65 MeV neutron with 60 MeV deposit energy

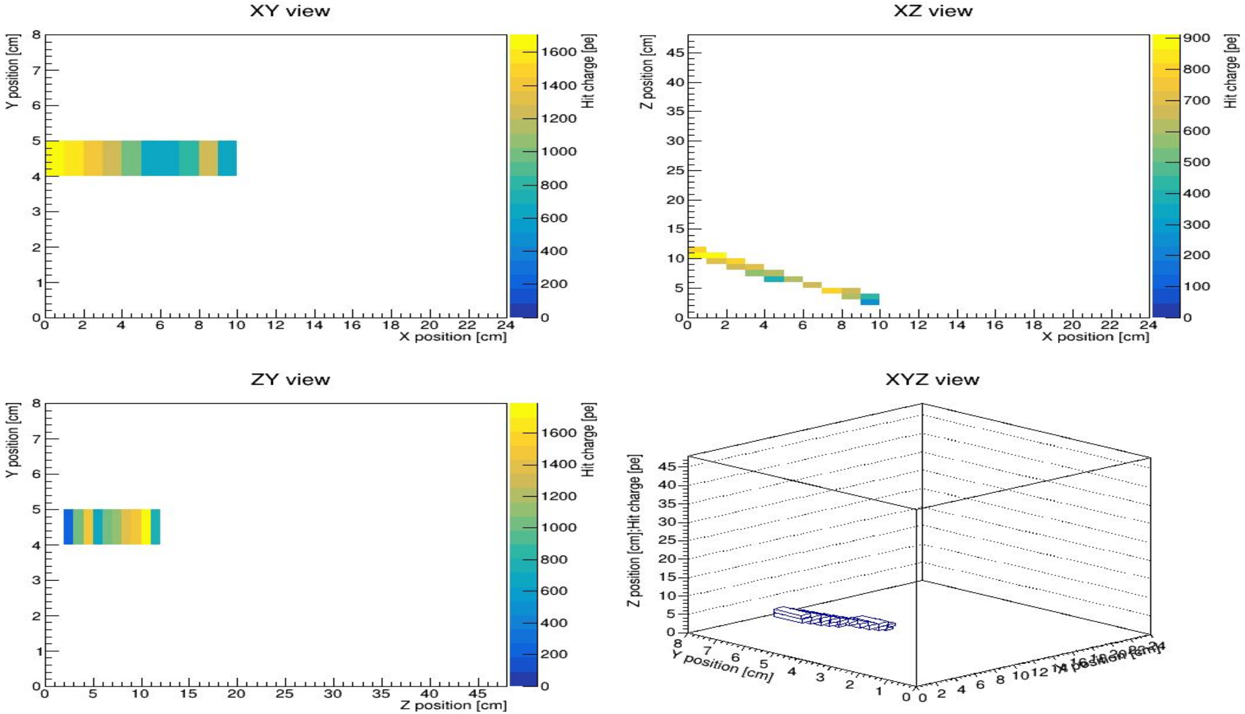
data



Neutron interaction candidate gallery: DATA

193 MeV neutron candidate with 123 MeV deposit energy

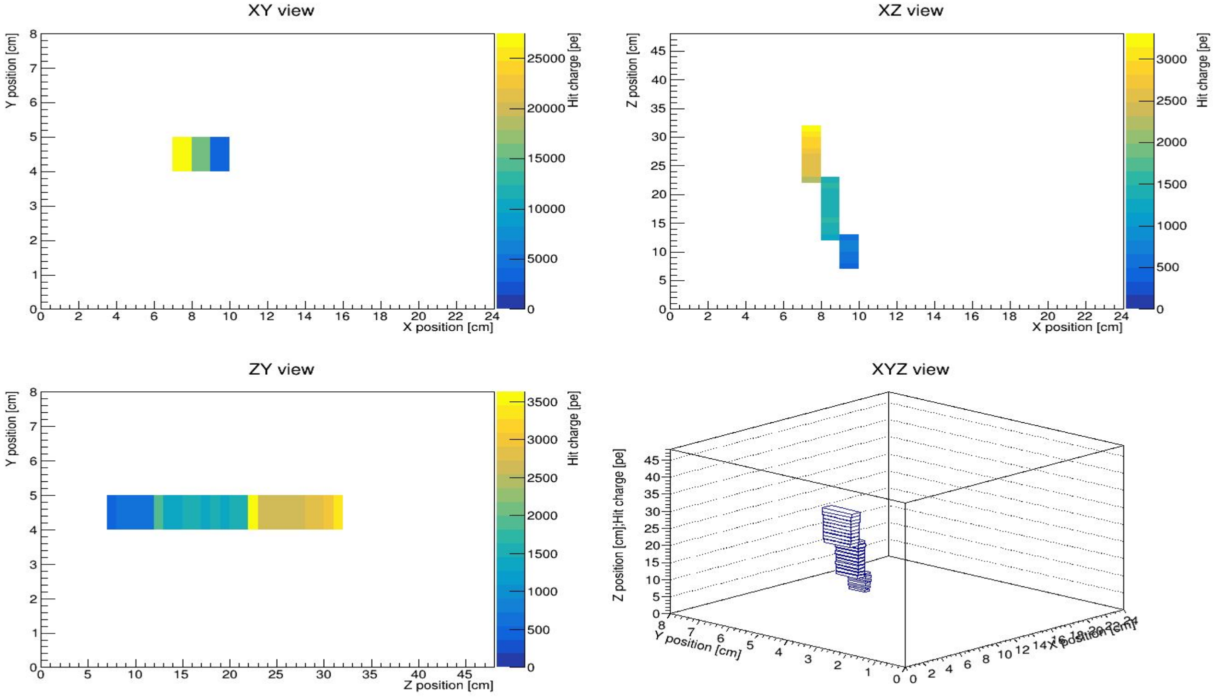
data



Neutron interaction candidate gallery: DATA

240 MeV neutron energy with 239 MeV deposit energy

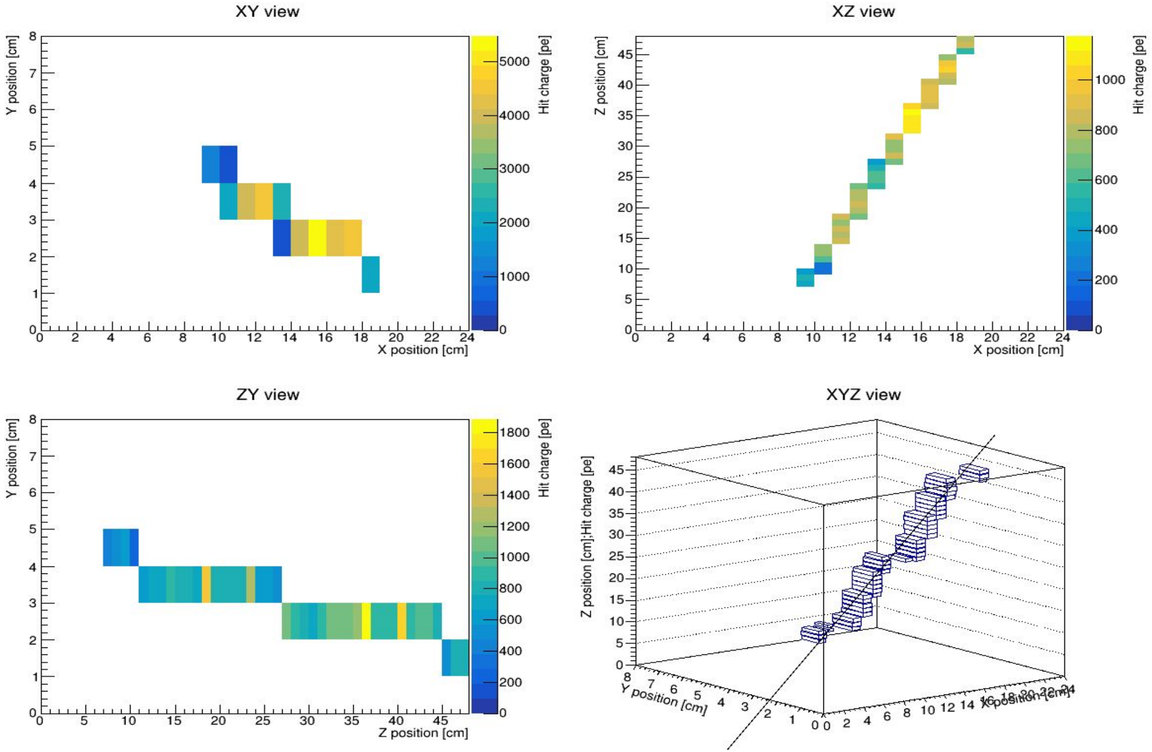
data



Neutron interaction candidate gallery: DATA

470 MeV neutron energy with 294 MeV deposit energy

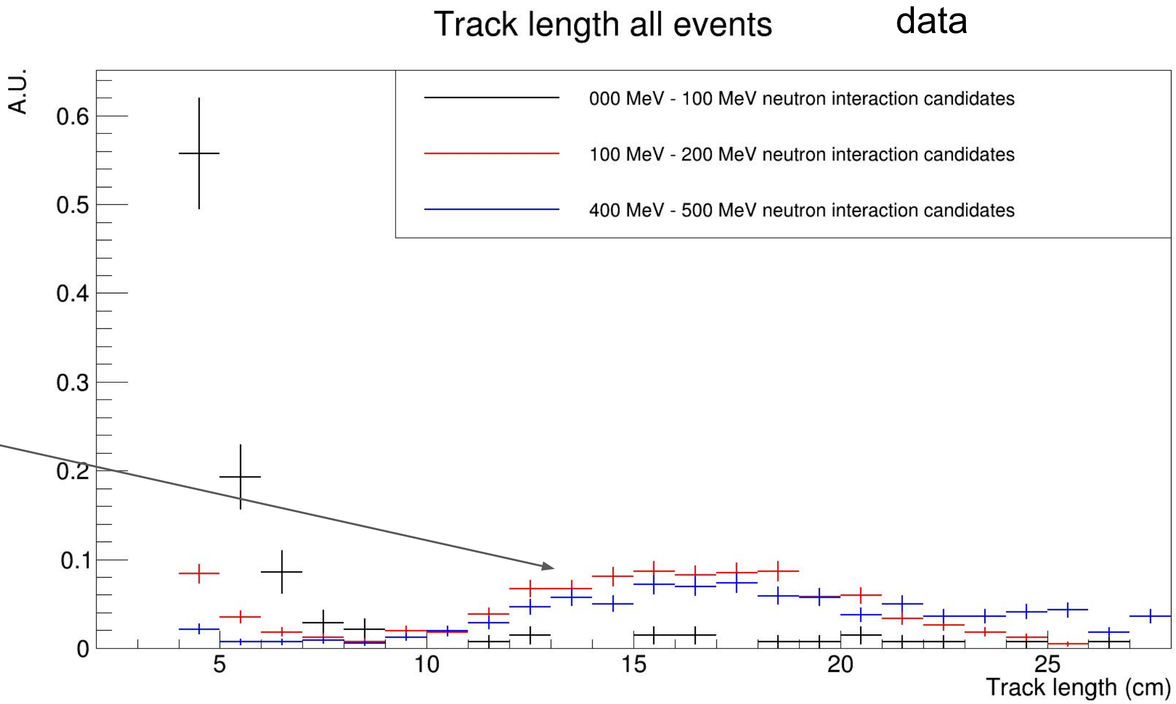
data



Neutron track length distribution

Higher energy neutron produces higher energy proton, i.e. larger length.

SFGD has a peaked containment of 100 -300 MeV protons.

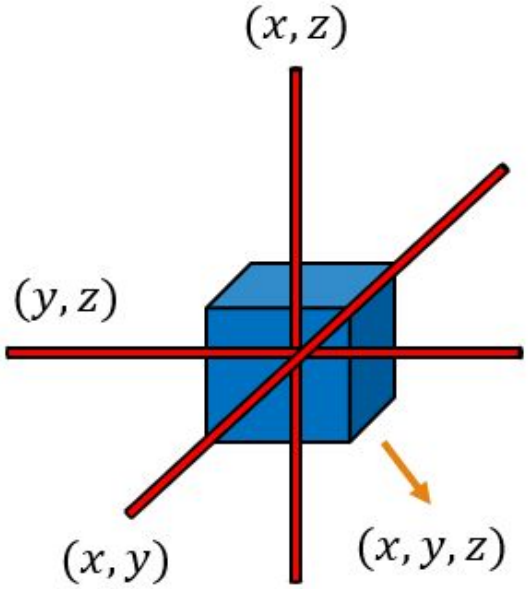


3D Voxels

3D Voxels

- 3D view matching of time - clustered hits
- 3 hits sharing the same XYZ coordinates

- Find 3 hits (3 different view) with the same X, Y, Z coordinates
- Construct a voxel with the X, Y, Z from the corresponding hits
- Attenuation correction:
  - Correct for the PE of the hits that make up the voxel
  - Remove the voxel if the corrected PE of any of the hits do not pass the PE cut

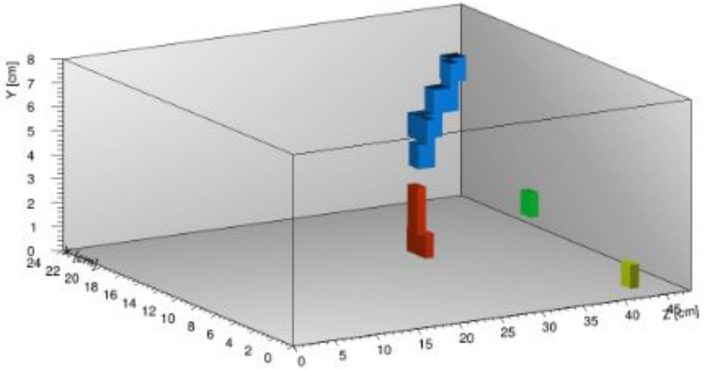


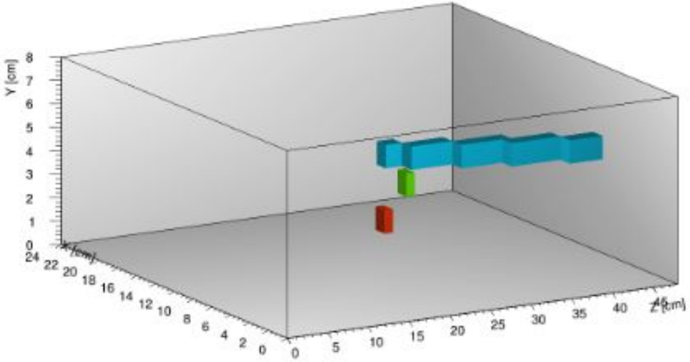
Clusters

Clusters

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

- DBSCAN clustering algorithm is used to group voxels into clusters
  - Any voxels within 1.8 cm (√3) cm of each other are grouped into the same cluster
  - 1 voxel by itself is considered a cluster





Vertices

Vertices

- Vertex finding with voxel earliest in Z

- The voxel with the smallest Z in the cluster is selected as the vertex of the cluster