Neutron Total Cross Section Measurement on Plastic Scintillator Using 3D Projection Scintillator Tracker Prototype

Eric Chong
University of Pennsylvania
Joint T2K-DUNE 3D Scintillator R&D Group
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Joint T2K-DUNE 3D Scintillator R&D Group Institutions

CERN

Louisiana State University, USA

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Stony Brook University, USA

ETH Zurich, Switzerland

University of Pennsylvania, USA

University of Geneva, Switzerland

Imperial college, UK

University of Rochester, USA

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Chung-Ang University, South Korea

High Energy Accelerator Research Organization (KEK), Japan

South Dakota School of Mines and Technology, USA

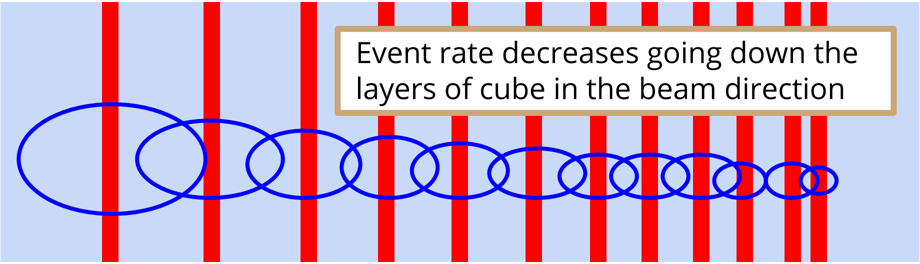
Introduction

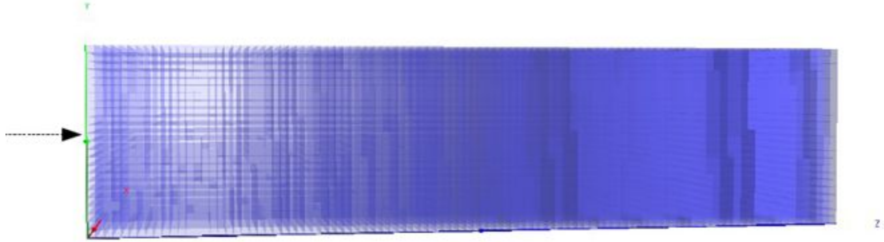
- Following the talk from Sitraka (South Dakota School of Mines and Technology), large amount of neutron beam data has been taken with two 3D projection scintillator tracker prototypes in 2019 and 2020 both in Los Alamos National Laboratory

- The main goal of the beam test is to characterize the neutron detection capability for SuperFGD and 3DST (3D projection scintillator tracker)
=> a number of measurements can be done including neutron cross section, detection efficiency, threshold, double scattering signature etc

Neutron Total Cross Section Measurement

Neutron beam





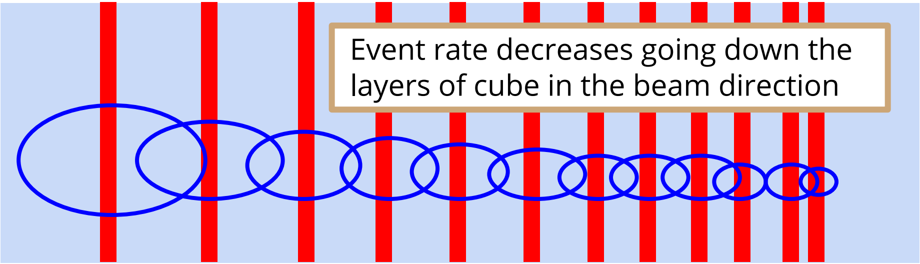
$N(l) = N_0 \cdot \exp(-T \cdot \sigma_{total} \cdot l)$

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

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

Neutron Total Cross Section Measurement

Neutron beam



Chosen event topology for the measurement: Single track events

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

Energy Layer

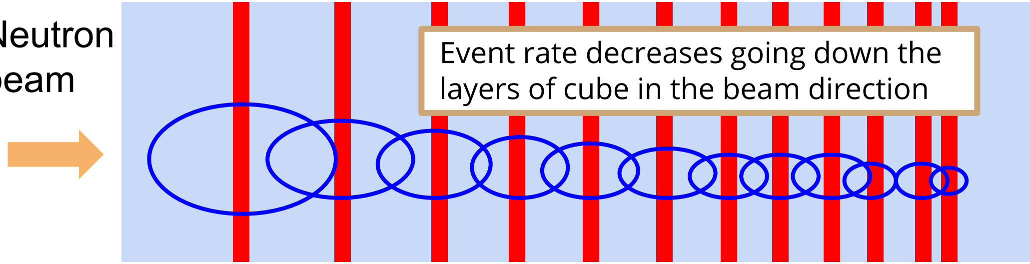
ε is the cross section Ratio between “other-than single track” and single-track, it only depends on energy, regardless of layer

$\mathbf{N}_{e,l} / \mathbf{N}_{e,m} = N_{\text{single-track},e,l} / N_{\text{single-track},e,m}$ Single track attenuation indicates a total cross-section

Layer l Layer m

Neutron Total Cross Section Measurement

Neutron beam



Presence of **invisible scattering of neutrons** in the detector:
*Elastic and inelastic scattering of neutrons **without visible energy deposit** in the detector*

$$\mathbf{N}_{e,l} = \sum \left(\begin{array}{l} \mathbf{N}_{\text{single-track},e,l} \\ \mathbf{N}_{\text{invisible},e,l} \\ \textbf{Others} \end{array} \right)$$

Energy Layer

They are always combined due to threshold and..
$N_{\text{invisible}} / N_{\text{single-track}}$ is **Layer-dependent !**

A correction for the invisible scattering is needed and it should be data-based.

Total Cross Section Measurement Systematics

- Interaction : invisible scattering
- Flux : energy scale uncertainty
- Detection : detector anisotropy due to geometry asymmetry and readout nonuniformity
- Reconstruction : selection-induced uncertainty

- Detector and reconstruction systematics will be combined
- A detector geometry correction will be applied

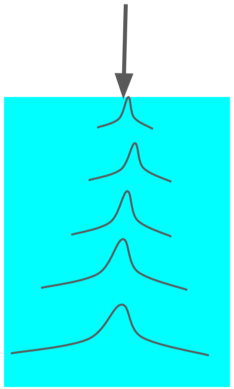
Interaction: Invisible scattering

$$N_{e,l} = \sum \begin{pmatrix} N_{\text{single-track},e,l} \\ N_{\text{invisible},e,l} \\ \textbf{Others} \end{pmatrix}$$

Energy Layer

Always appear together, need to correct for the invisible component

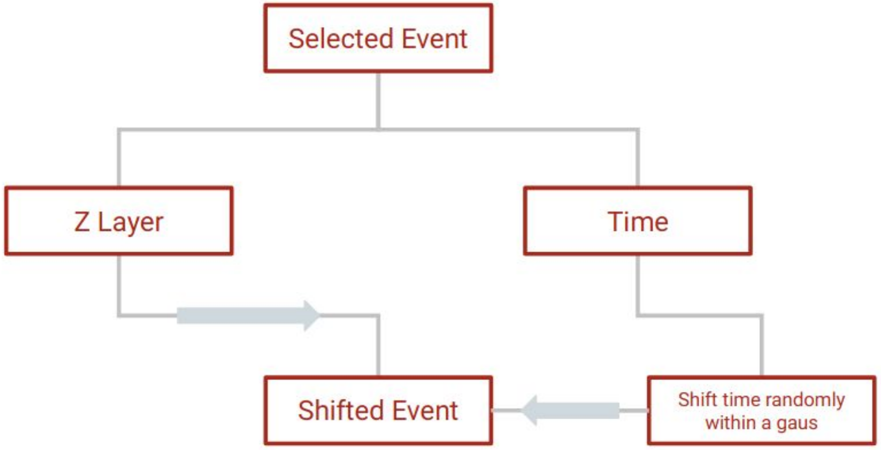
Top view



- Mainly due to threshold of the detector
- MC (Geant4 -> Bertini model) can provide a correction map to correct for the invisible component
  => MC needs to be tuned to data
- Use transverse spread of events to tune MC with data

Flux: Energy scale uncertainty

- Due to timing resolution (~1.1ns [arXiv:2008.08861])
- Randomly shift the measured timing based on the time resolution, the resulting Z layer distribution for each energy range will have an uncertainty band



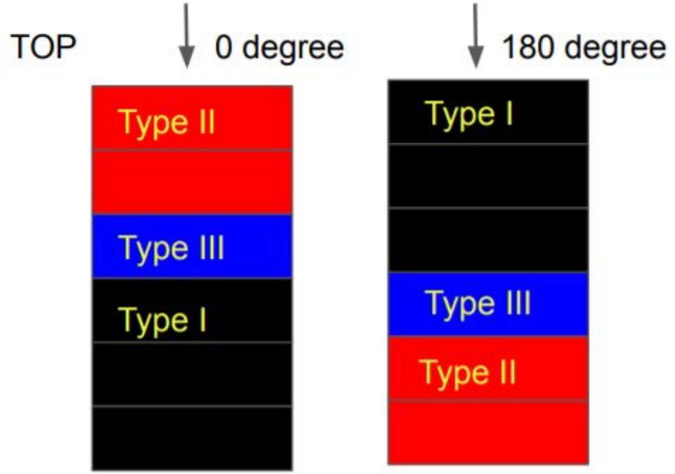
Readout nonuniformity, geometry asymmetry and reconstruction

-> Work in progress

- Selection cuts optimized by minimizing the difference between 0 degree and 180 degree runs (rotated by Y)

- A geometry correction based on the proton MC will be applied:
  our detector is not geometrically symmetric

- We will use 0 degree configuration data for our first result (180 degree configuration data used for systematic evaluation)



Cross Section Fitter: Workflow

- Fill an histogram (number of events vs z-layer) for every energy bin
- Correct this distribution for the invisible scattering
- Propagate the systematic in the following way:
  - Fit an exponential ($N_0e^{-\lambda z}$) for every variation of a systematic uncertainty
  - Fill an histogram with every value of the cross-section computed as λ/N_{target}
  - The systematic uncertainty will be the RMS of this distribution
- Statistical uncertainty: Fit the nominal distribution and vary the number of events using a Poisson distribution

Cross Section Fitter: Workflow

- The source of systematics uncertainties are:
  - Time resolution: ~1.1ns
  - Invisible scattering: 100%
  - Detector inhomogeneity: overall 10% normalization (preliminary)

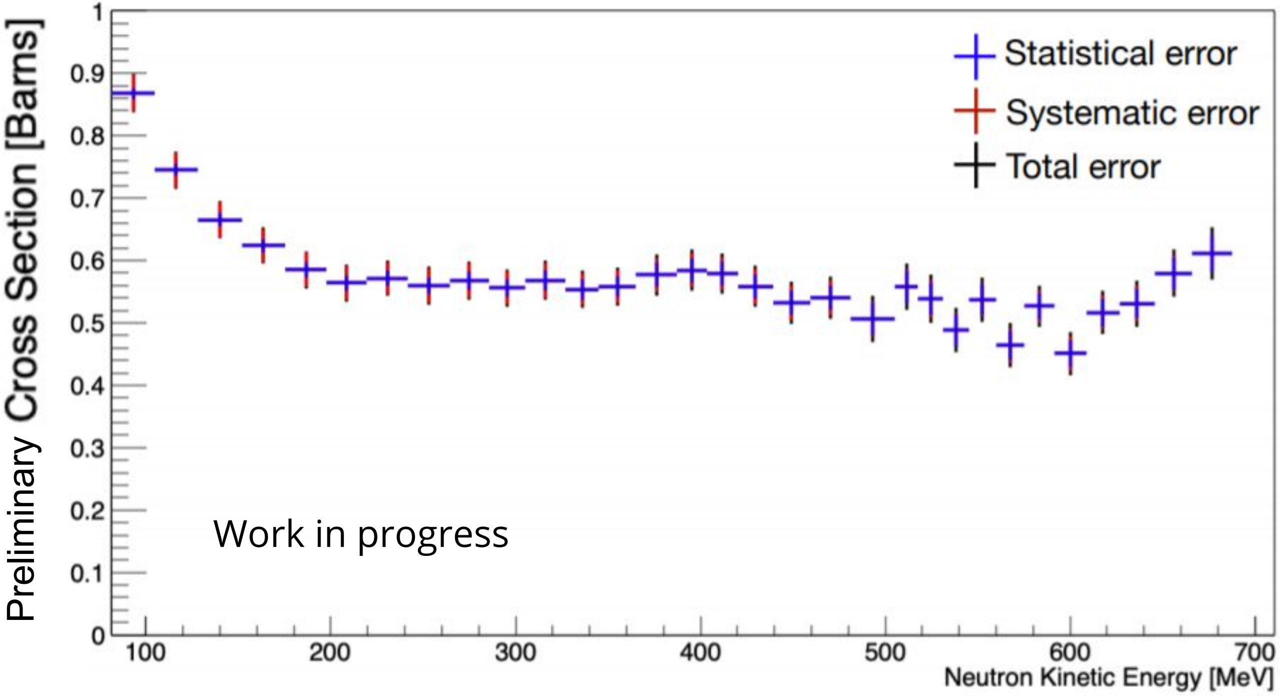
- Time resolution will change the energy distributions

- Invisible scattering and detector inhomogeneity will vary the event normalization in each layer

Cross Section Fitter: Workflow Test

Caveat:

Only 16 minutes of data used



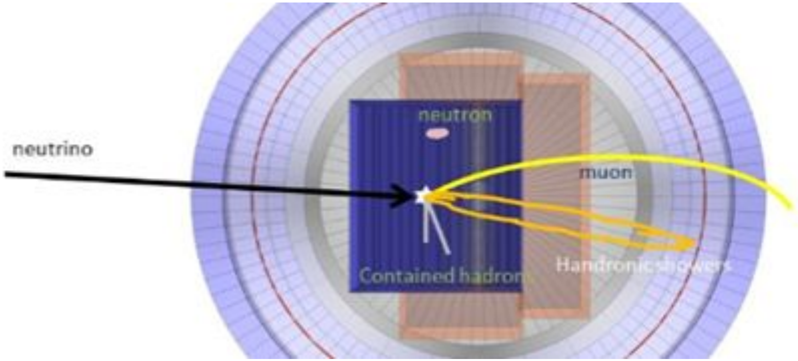
Summary

- Expected neutron detection potential is observed from preliminary analysis on the neutron data taken
- A number of results can be expected in the next few years
- A neutron total cross section measurement on plastic scintillator publication is expected by this summer

Backup Slides

Introduction

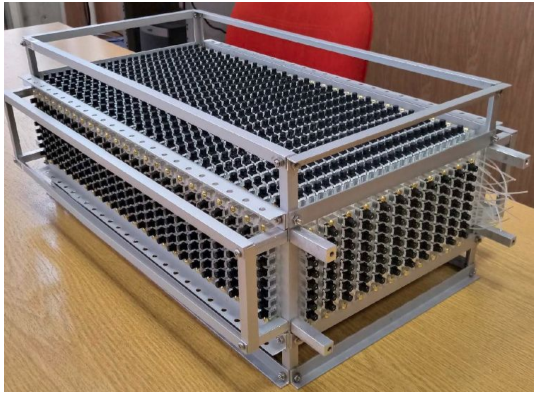
- Missing neutron energy is one of the dominant systematic uncertainties in long-baseline neutrino oscillation analyses.
- Neutron information desired in the near detectors of the long-baseline experiments in the precision era.
- Neutrons kinetic energy can be measured in 3DST (3D Projection Scintillator Tracker) with time-of-flight technique.
- Neutron detection capability, efficiency, backgrounds etc. can be studied with analysis on the neutron beam test data taken in LANL.



Prototype Detectors

- SuperFGD prototype being used for the charged particle beam test at CERN and both 2019 + 2020 neutron beam tests (24 x 8 x 48)
- US-Japan prototype being fully used for the 2020 beam test (8 x 8 x 32)

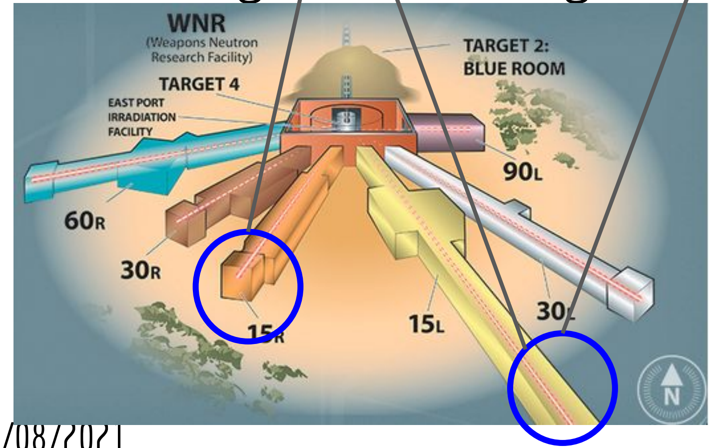
superFGD

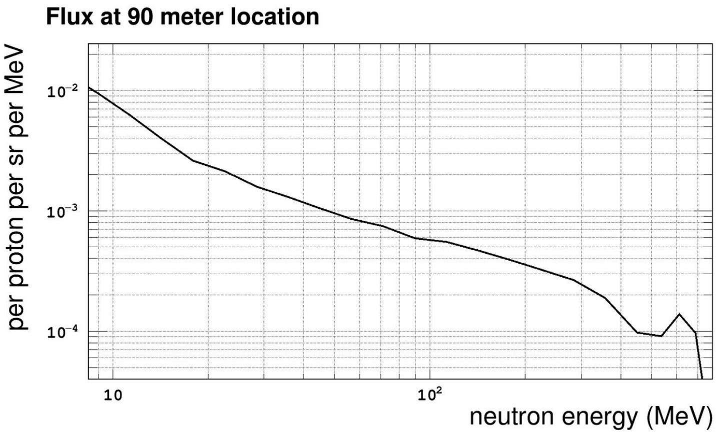


US-Japan

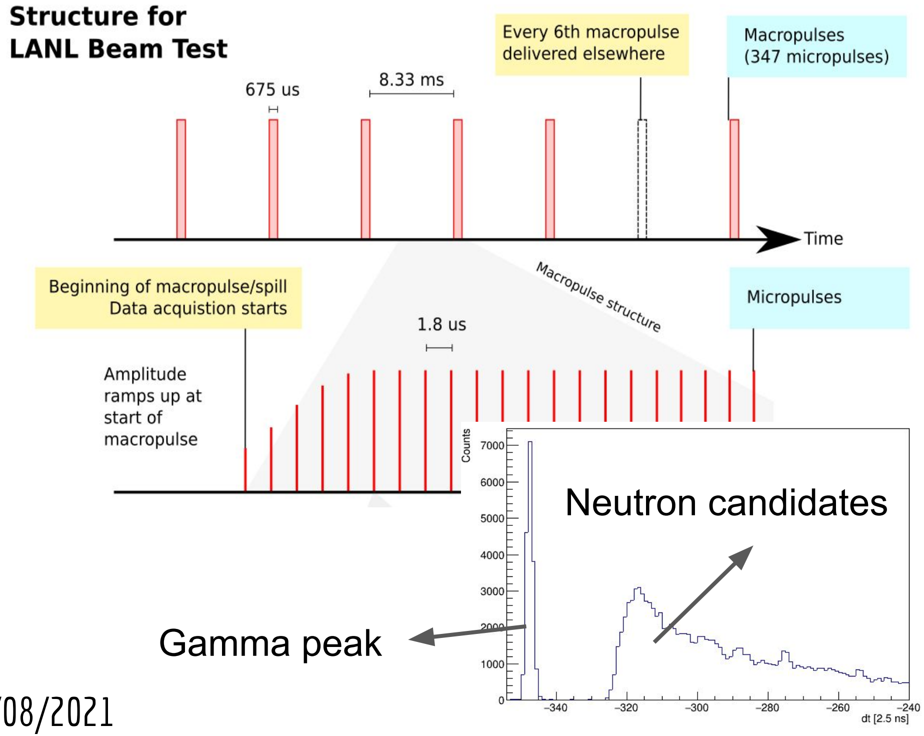
Neutron Beam Test Facility

- Los Alamos National Lab LANCSE facility provides neutron beam ranged from 0 - 800 MeV.
- 2019: 15R 20 m 3 days + 15L 90 m 2 weeks
- 2020: 15L 90 m 2 weeks (various collimator, pulse spacing, detector configuration settings.)



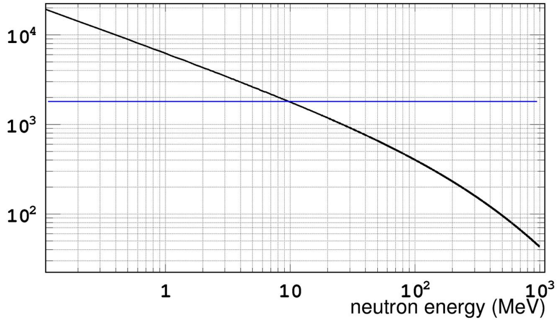


Neutron Beam Time Structure



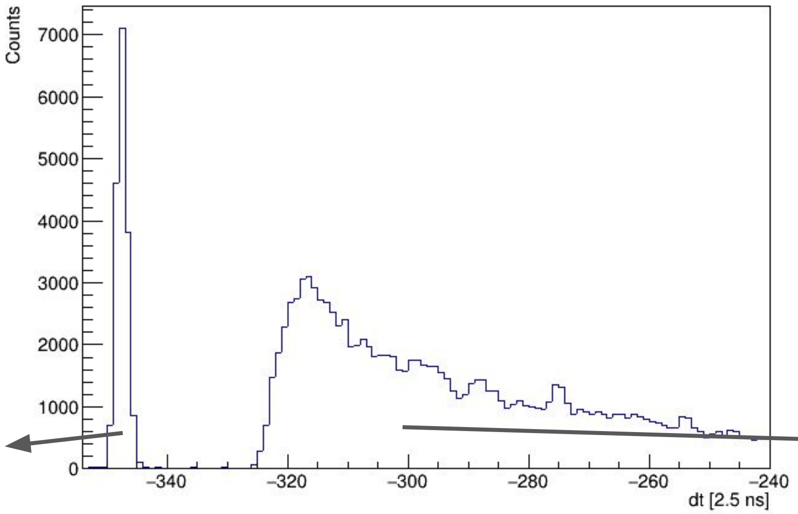
- Beam pulse is narrow enough to provide single neutron energy by time-of-flight
- We have 675 us trigger window to cover each macropulse
- Gamma flash and t0 are available for micropulses

neutron energy vs time diff. at 90 m location



Neutron Beam Data

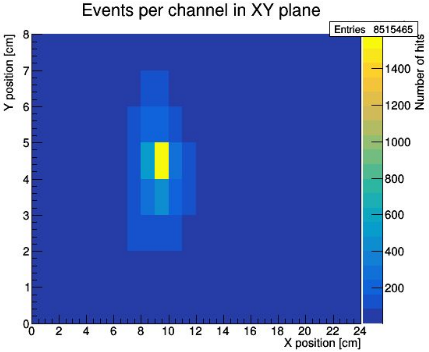
Gamma peak

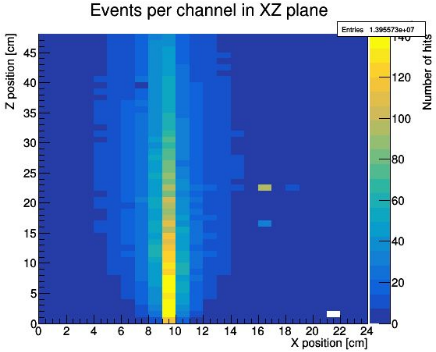


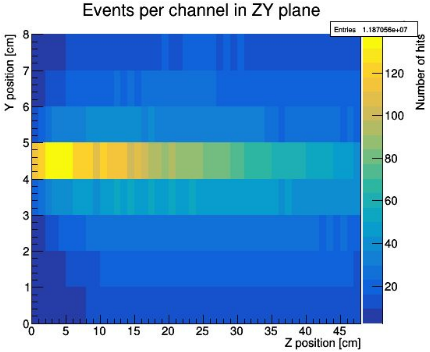
Neutron candidates

Neutron Beam Data

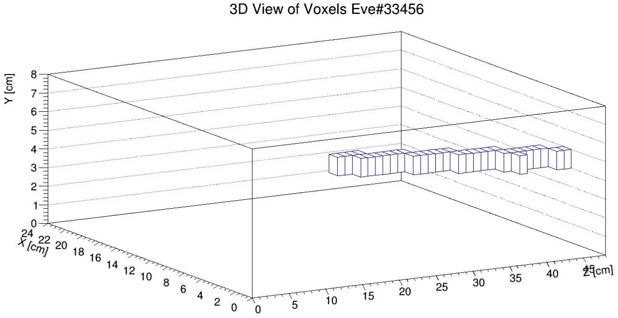
- Neutron beam observed in SuperFDG prototype detector

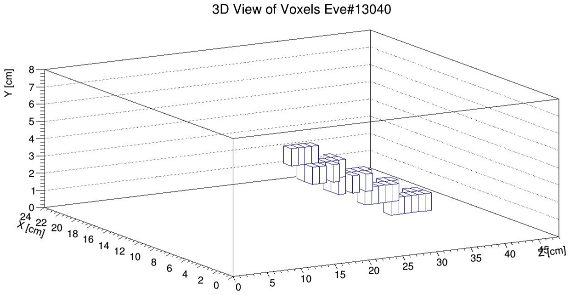






- Neutron events in SuperFDG prototype detector





Neutron Total Cross Section Measurement

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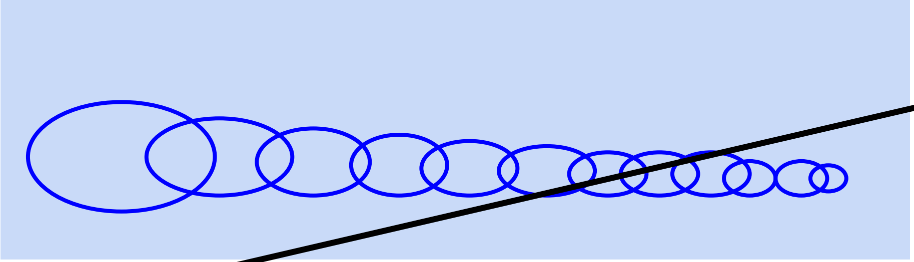
Neutron beam



$\mathbf{N}_{e,l} = \sum$ ($\mathbf{N}_{\text{single-track},e,l}$, $\mathbf{N}_{\text{invisible},e,l}$, $\mathbf{N}_{\text{two-track},e,l}$, .., $\mathbf{N}_{100\text{-track},e,l}$)

Energy Layer

$\mathrm{N}_{\text{single-track},e,l}$ can be any topological selection, e.g

- Single time cluster of hits
- Single DBSCAN cluster of voxels
- Number of
- Vertex in fi Z (Z > 0)
- Linearity > 0.8
- Cluster width < 1.5 and maximum distance between voxels and principal vector < 1.5

Topological selection cuts

$\mathbf{N}_{e,l} = \sum$

Single time cluster of hits
Single DBSCAN cluster of voxels
Number of voxels > 2 in single cluster
Vertex in fiducial volume (1 cm radius around beam center) and not in first layer in Z (Z > 0)
Linearity > 0.8
Cluster width < 1.5 and maximum distance between voxels and principal vector < 1.5

Single time cluster of hits
Single DBSCAN cluster of voxels
Number of voxels > 2 in single cluster
Vertex in fiducial volume (1 cm radius around beam center) and not in first layer in Z (Z > 0)
Linearity > 0.8
Cluster width < 1.5 and maximum distance between voxels and principal vector < 1.5

$\times\ \epsilon_e$

layer independent

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)

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

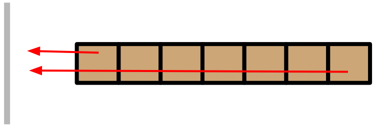
$\boldsymbol{v_2}$: *Eigenvector with the second largest eigenvalue*

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

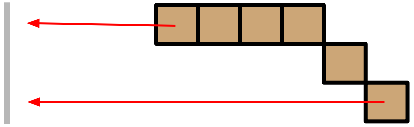
$\bar{\boldsymbol{r}}$: *Mean 3D coordinate of voxels in the same cluster*

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

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



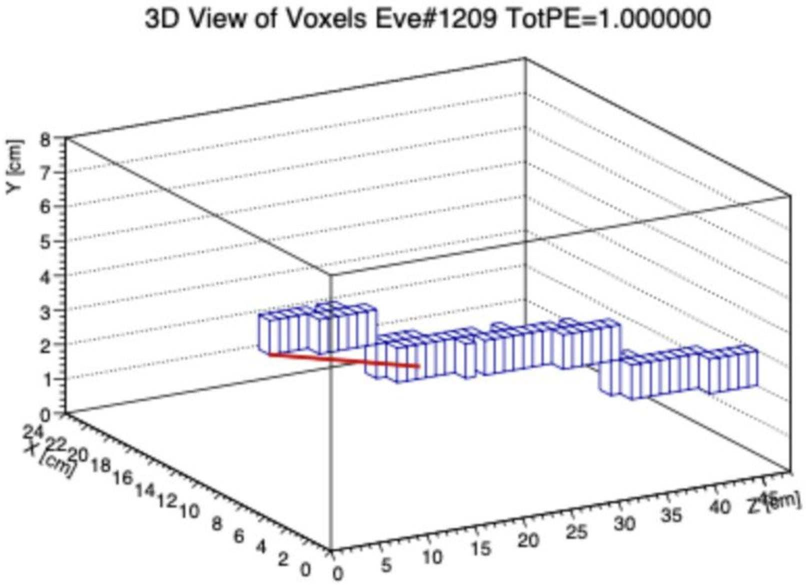
Cluster width = 0



Cluster width ≈ 3

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)



Single Track Events Selection (MC)

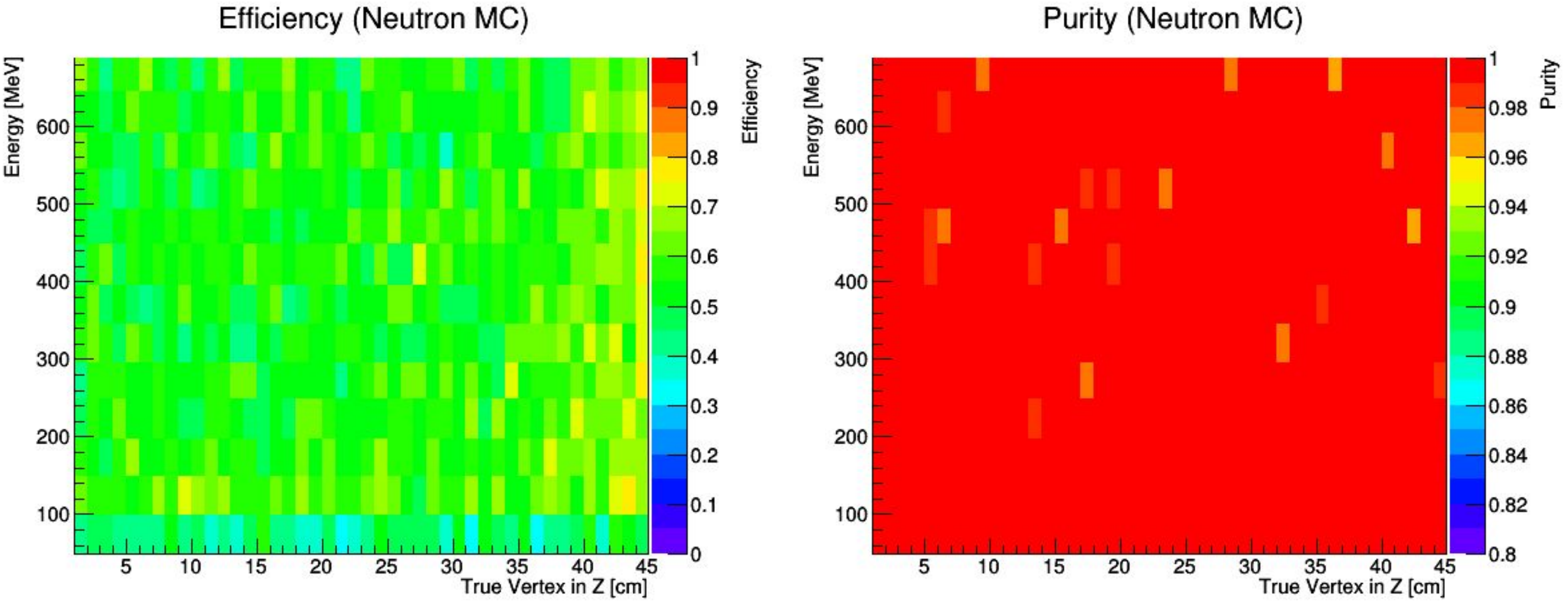
- Definitions:

$$Efficiency = \frac{Number\ of\ true\ single\ track\ events\ that\ got\ reconstructed\ as\ single\ track\ events}{Number\ of\ true\ single\ track\ events}$$

$$Purity = \frac{Number\ of\ reconstructed\ single\ track\ events\ that\ are\ true\ single\ track\ events}{Number\ of\ reconstructed\ single\ track\ events}$$

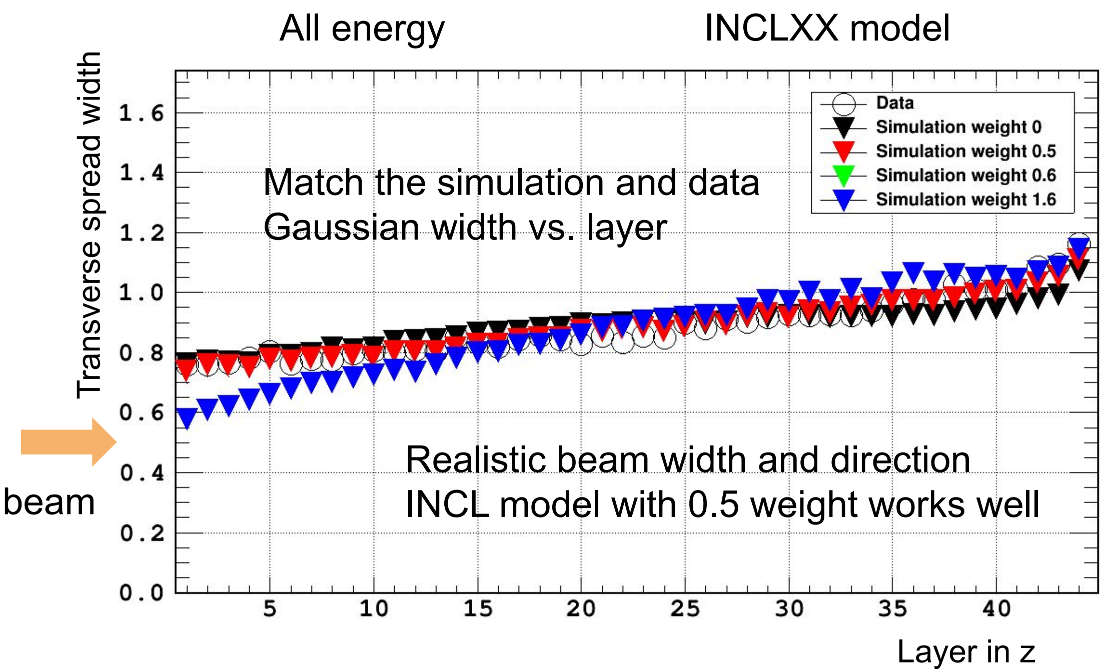
- Neutron MC sample
  - Selected a sample of events that got tagged as either true single track events or true multi track events in the MC file
  - True single track events: Only 1 proton as the final state particle (≥ 2 MeV energy deposit)
  - True multi track events: At least 3 final state particles (each one ≥ 2 MeV energy deposit)

Single Track Events Selection (MC)



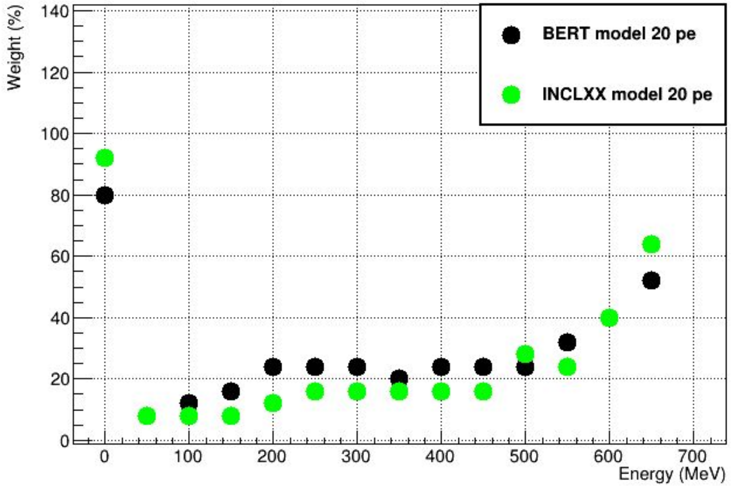
Looking at the transverse spread => our “control sample”

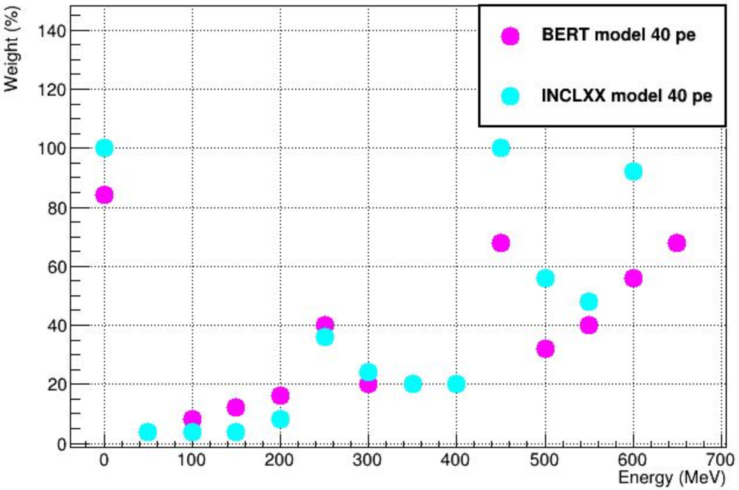
- Along beamline, the interaction spread increases => assume this merely comes from the invisible scattering.
- Invisible scattering in simulation can be weighted to match data.
- Best matched weight can be found and this weight can be applied to simulation => simulation will be tuned.
- It is implemented for each energy range with multiple G4 models.
- Uncertainty comes from the correction discrepancy between two models.



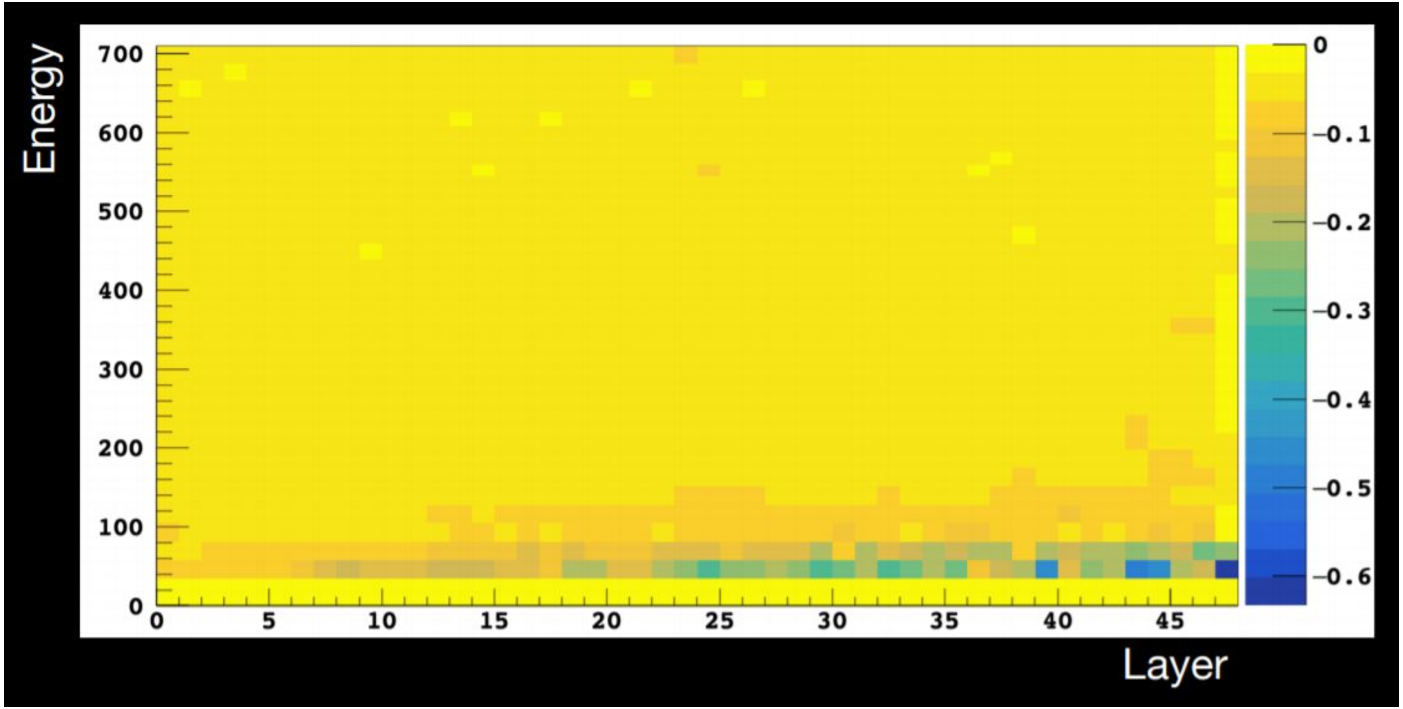
Invisible scattering reweight in various cases

- Two models (BERT and INCLXX) were used to check the correction -> difference can be a systematic uncertainty source.
- Two pe cuts were used to check the correction stability -> systematics from pe cut will be included in the detection+reconstruction uncertainty

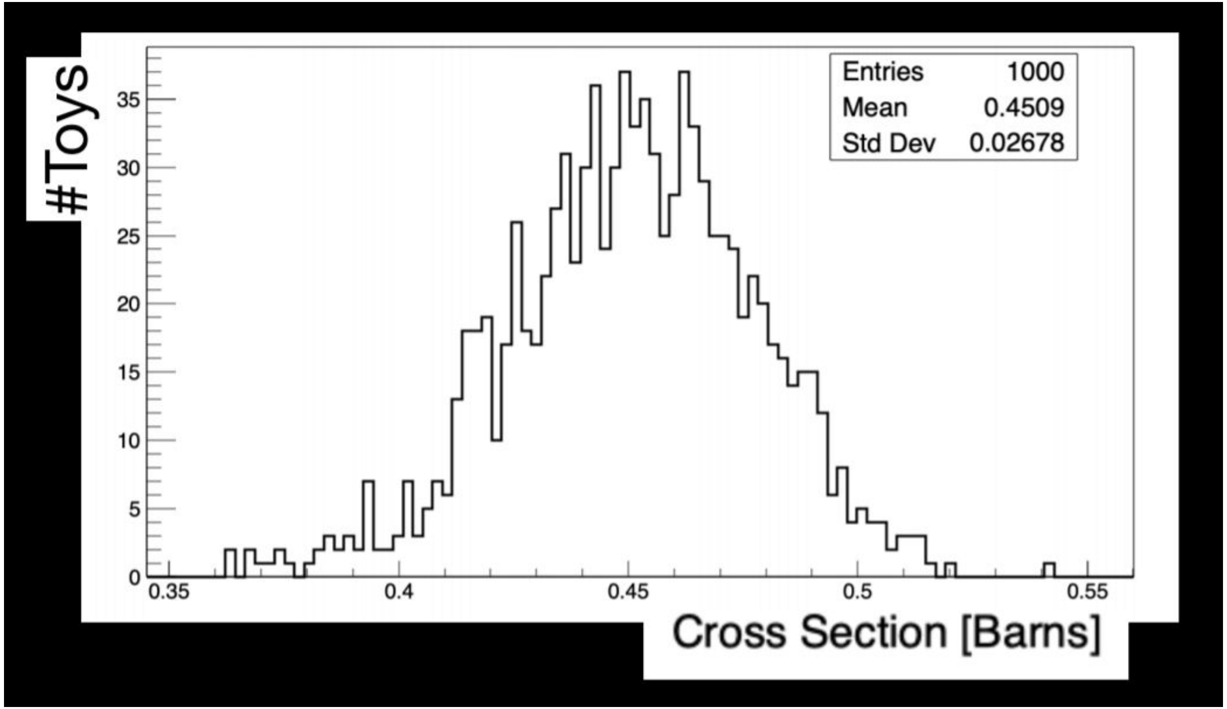




Invisible Scattering Correction

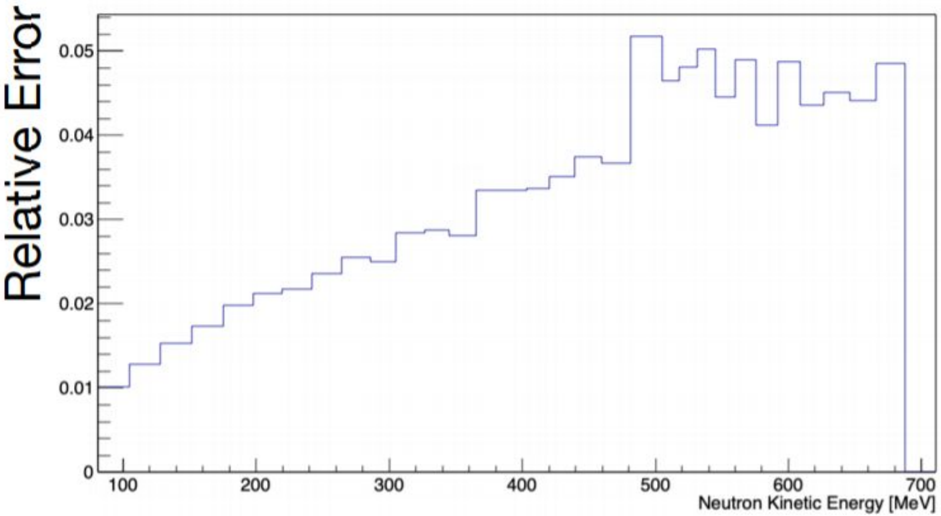


Details about Uncertainty Propagation

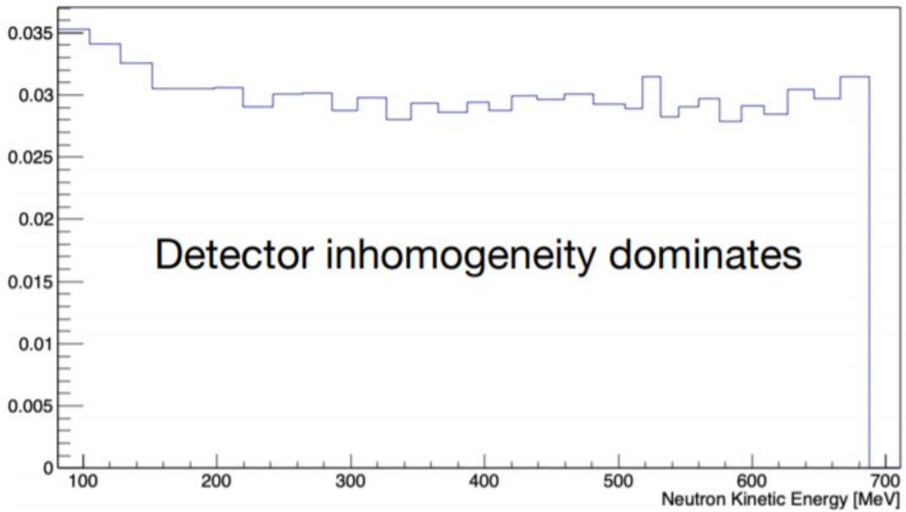


Cross Section Fitter: Initial Result

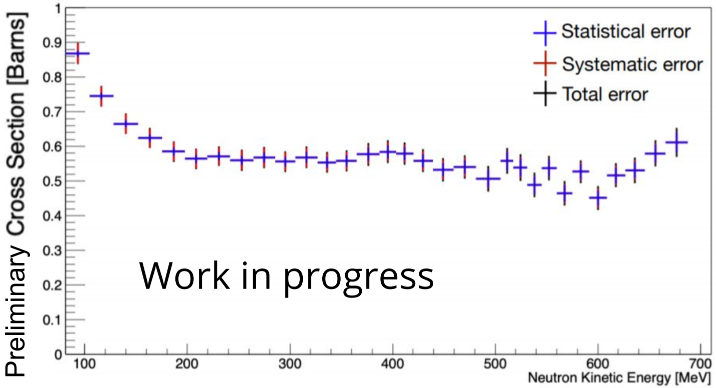
Statistical uncertainty



Systematic uncertainty



Caveat: Only 16 minutes of data used



DOI: 10.1103/PhysRevC.47.237

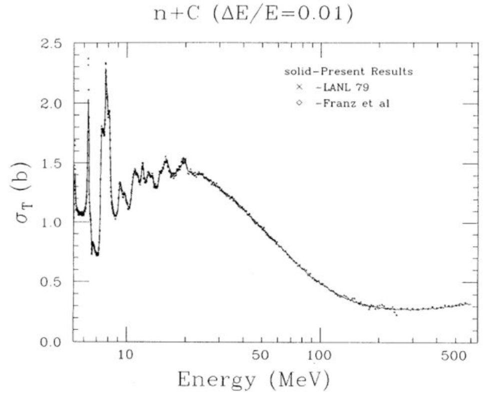


FIG. 8. Present results for carbon (solid line) compared with earlier work from Refs. [3] and [23]. The seemingly better resolution of the 1979 data is a consequence of the choice of binning function for the present work. The resolution of the unbinned raw data is a factor of 2 better than the 1979 work.

DOI: 10.1103/PhysRevC.63.044608

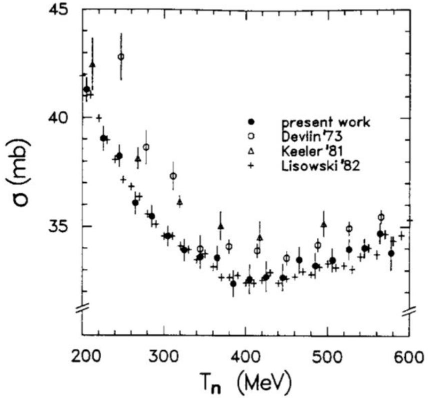


Fig. 2. Total neutron–proton cross sections between 200 and 600 MeV.

DOI: 10.1016/0370-2693(85)90729-4

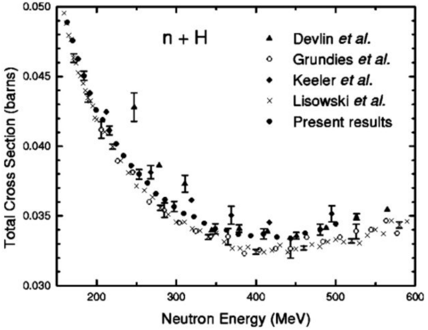


FIG. 8. Results are shown for the H cross section extracted from the two CH_2 samples combined with those from the C_8H_{18} sample.