Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Analysis of Neutrino Interaction Models Using SBND-PRISM

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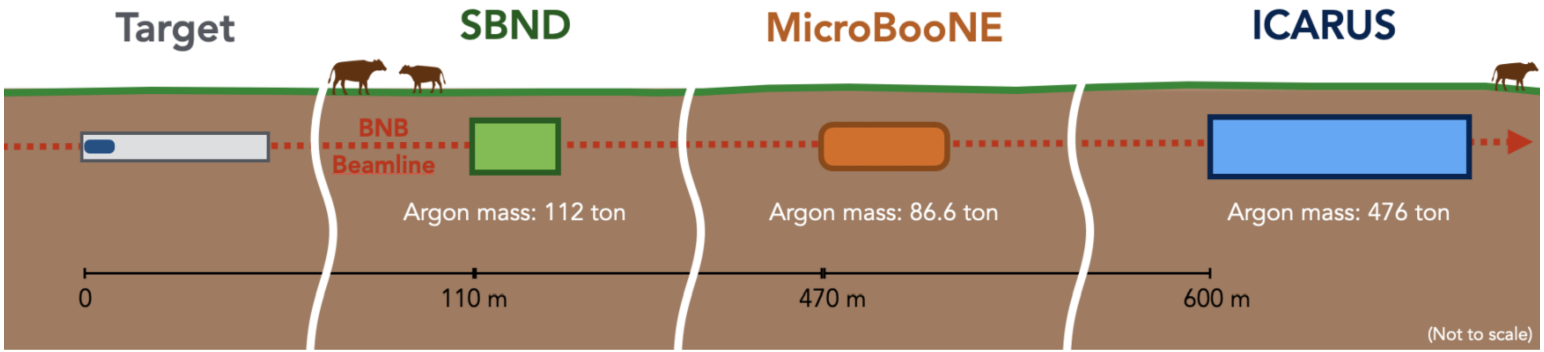
SULI Fall 2022 Presentation

7 December 2022

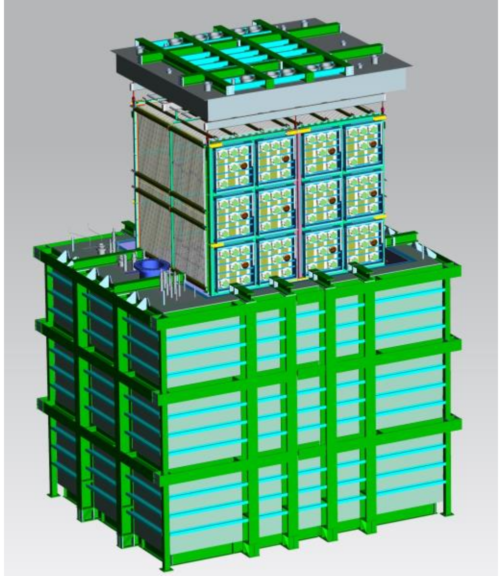
SBND Introduction

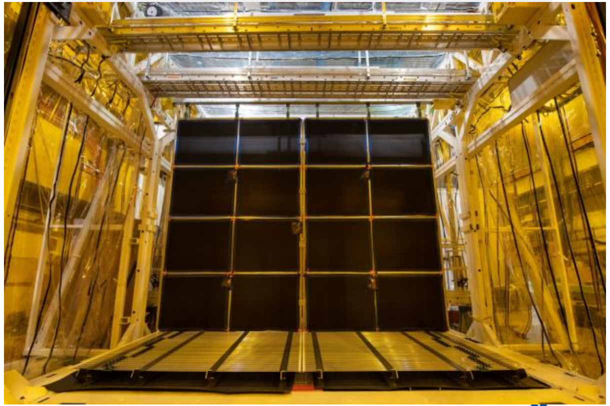
- SBND is a Liquid Argon Time Projection Chamber (LArTPC) detector and is part of the Short Baseline Neutrino (SBN) program
- Closest of the three LArTPC detectors part of the SBN program
  - 110m from the Booster Neutrino Beam (BNB) neutrino source
  - Currently under assembly; operating by 2023



SBND Introduction

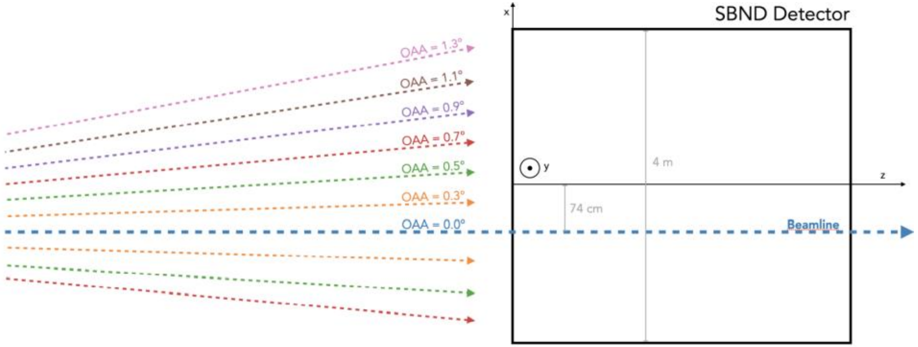
- Will record an unprecedented number of un-oscillated neutrino interactions per year
  - Will allow for unprecedented precision in measurements of neutrino-argon interaction cross sections
    - Crucial for neutrino LArTPC experiments
- Goals of SBND:
  - Search for eV mass-scale sterile neutrinos
  - Study GeV scale neutrino-argon interactions
  - Search for new and rare physics



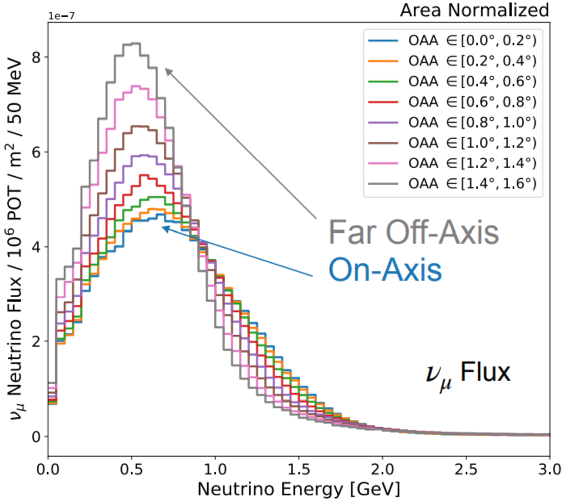


SBND-PRISM

- Close proximity to neutrino beam leads to a prism effect
  - Neutrino beams come in at different angles and lead to different fluxes
- Gives an additional degree of freedom for constraining systematic uncertainties
  - Allows for a linear combination of fluxes
  - Isolates different neutrino-nuclei interactions for research
  - Can replicate fluxes at far detectors



Images courtesy of Dr. V. Pandey



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CRPA/SuSAv2 Hybrid Model

- GENIE is an event generator that uses the Monte-Carlo method to simulate neutrino interactions
- The CRPA/SuSAv2 Hybrid model is currently not being used for SBND
- Combines the CRPA and SuSAv2 to model GeV scale neutrino interactions
  - CRPA describes QE interactions at low energy scales well
  - SusAv2 describes QE interactions at high energy scales well
  - Can be combined by interpolating both model's results at intermediate momentum transfers

Implementation of the CRPA model in the GENIE generator and an analysis of nuclear effects in low-energy transfer neutrino interactions

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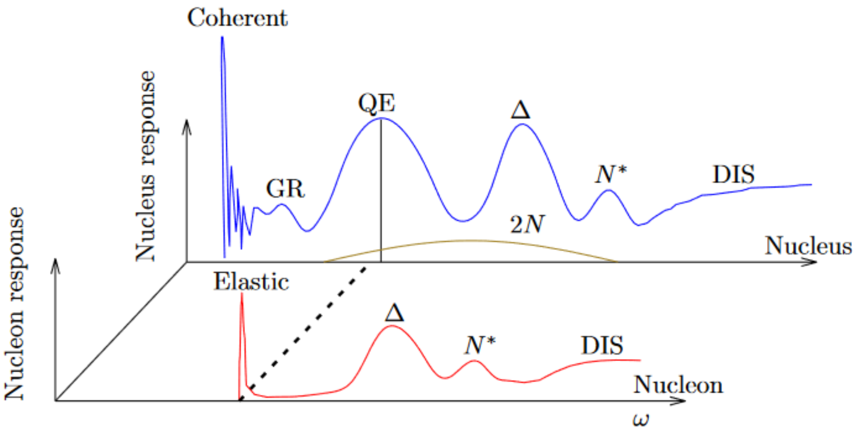
(Dated: November 2, 2022)

arXiv:2110.14601

Quasi-elastic Interactions

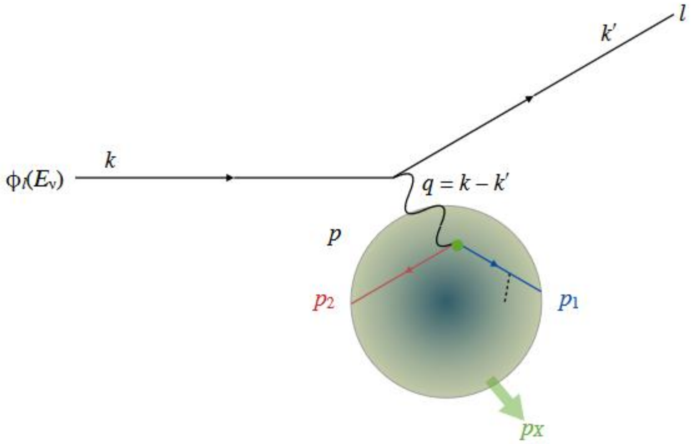
- We can only detect neutrinos off their interactions with nuclei
- Results in a number of different types of interactions
- Focused mainly on on QE interactions; most prevalent type in GeV range



biblio.ugent.be/publication/8517218

Quasi-elastic Interactions

- Charged-Current Quasi-Elastic interactions (CCQE)
  - Muon and nucleon in the final state with no pions
  - Incident neutrino is converted into a charged lepton
- CCQE-like interactions
  - Incident neutrino also converted into a charged lepton
  - Muon in the final state with no pions
  - Interactions that mimic the CCQE signal



arXiv:1706.03621

Goals

The goals of our research were to:

- Explore how SBND-PRISM can be used to constrain neutrino-nucleus interactions
- Set up a framework to analyze Monte-Carlo simulations of predictions within models for different off-axis fluxes in the SBND detector
- Find experimentally measurable observables which are as optimized as possible to discriminate between different models

CRPA/SuSAv2 Hybrid Model Analysis

We take the linear combination of flux-averaged cross sections obtained with different fluxes.

- Removes the high energy tail
- Isolates different neutrino interactions
- Can be used to find differences in models
- Same thing as taking the linear combination of the flux and then calculating the flux-averaged cross section with this new flux (works because only flux changes)

CRPA/SuSAv2 Hybrid Model Analysis

The event rate is the flux-averaged cross rate:

$$Rate = \int dE\, \Phi(E_\nu) \cdot \frac{\sigma(E_\nu)}{dE_\mu\, d\, cos(\theta_i)}$$

Letting *a* and *b* be arbitrary factors,

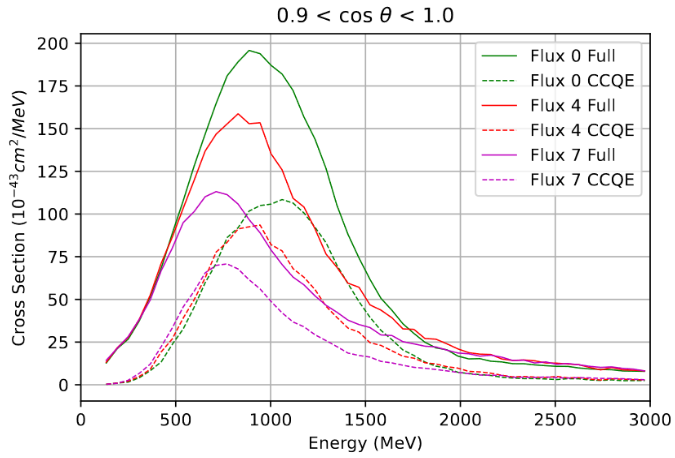
$$a \cdot Rate_1 + b \cdot Rate_2 = \int dE\, (a \cdot \Phi_1 + b \cdot \Phi_2)(E_\nu) \cdot \frac{\sigma(E_\nu)}{dE_\mu d\, cos(\theta_i)}$$

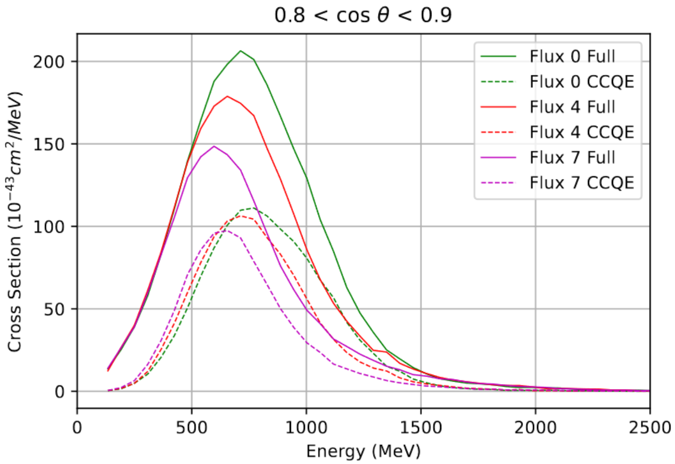
The linear combination used for our research:

$$\Phi_7 - 0.3 \cdot \Phi_0$$

CRPA/SuSAv2 Hybrid Model Analysis

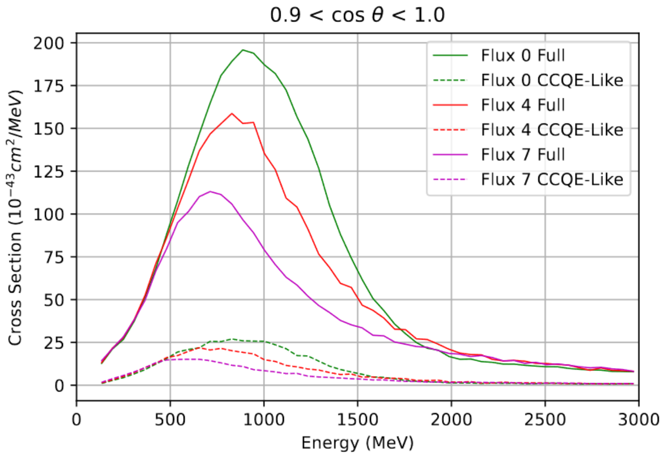
- CCQE contributions to the energy distribution as a function of lepton energy and scattering angle
- Shape of plots share similarity
- At peak differential cross-section, CCQE's make up ~60% of energy distribution (cross-section increases at $0.8 < \cos\theta < 0.9$)
- Energy spectrum and diff. cross-section decreases at larger scattering angles

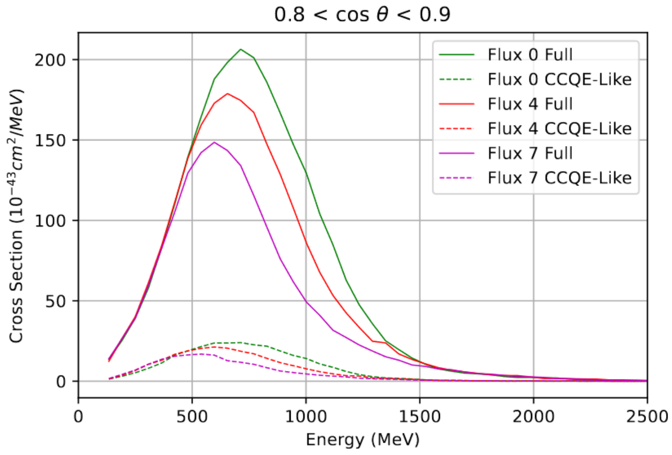




CRPA/SuSAv2 Hybrid Model Analysis

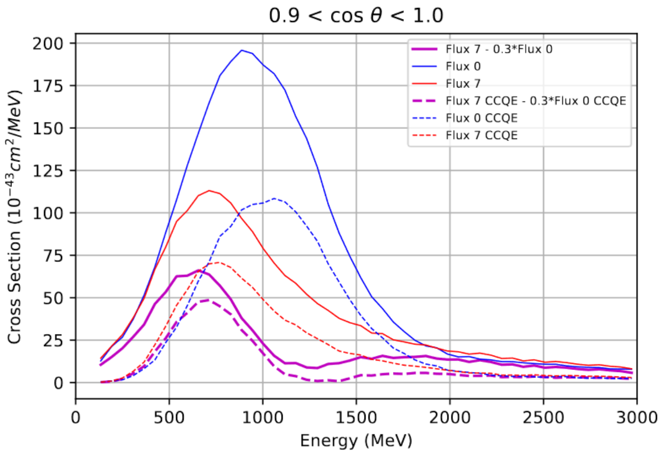
- CCQE-like contribution to full energy distribution as a function of lepton energy and scattering angle
- CCQE-like interactions occur more frequently at lower energy
- Peak diff. cross-section and energy spectrum decreases at larger scattering angles

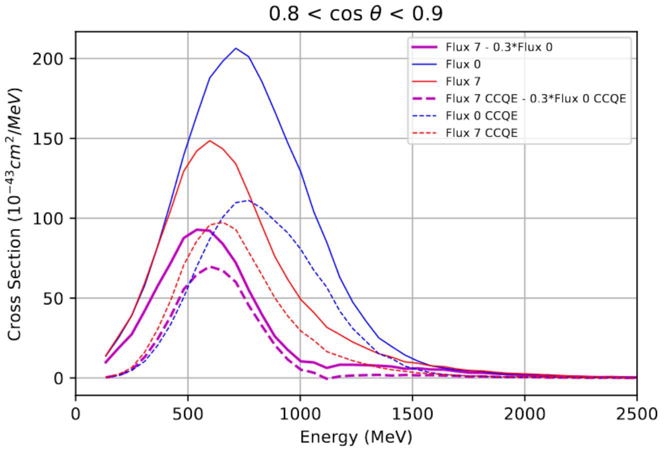




CRPA/SuSAv2 Hybrid Model Analysis

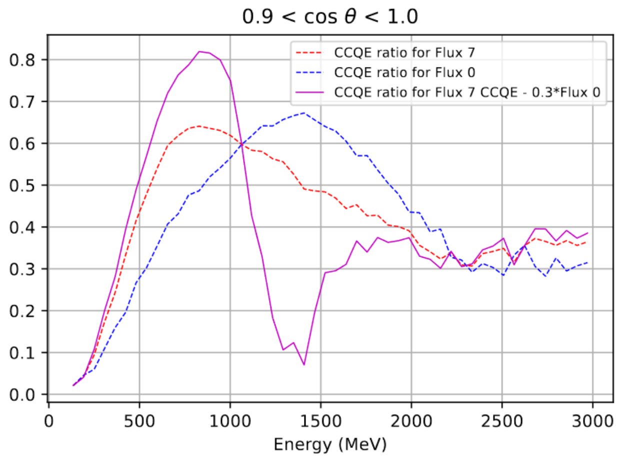
- CCQE contribution to the energy distribution after linear combination as a function of lepton energy and scattering angle
- CCQE interactions make up more of the new distribution (at peak ~70 %)
- Energy spectrum and peak diff. cross-section decreases overall with larger scattering angles (cross-section increases at 0.8< cos θ < 0.9)

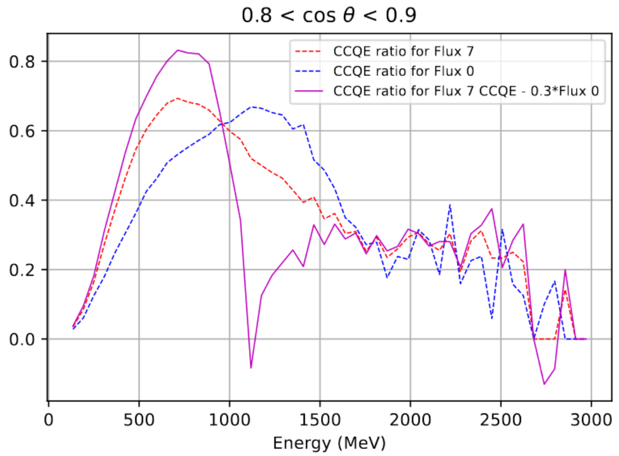




CRPA/SuSAv2 Hybrid Model Analysis

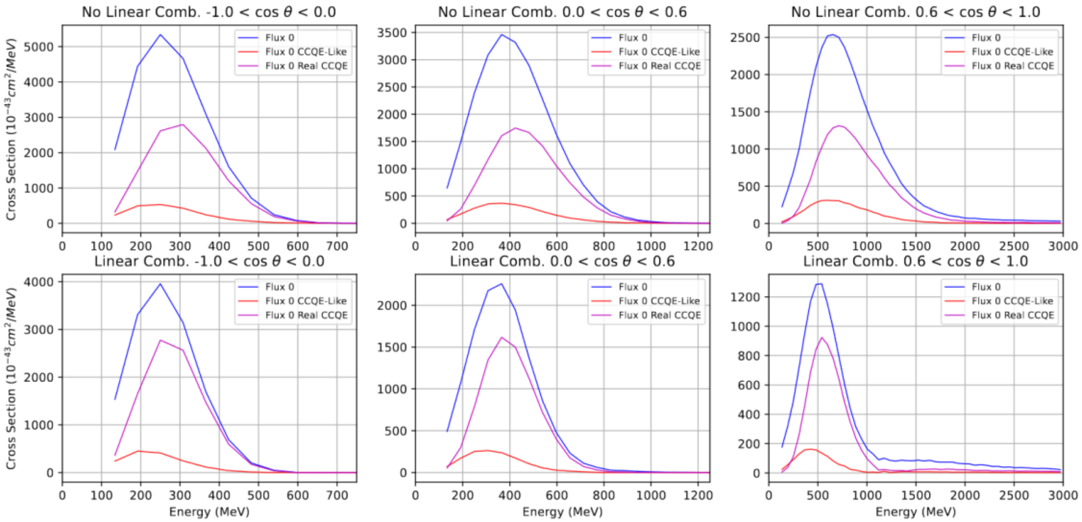
- Ratio of CCQE contribution to full energy distribution as a function of lepton energy and scattering angle
- Shape of ratio is consistent between 0 - 1500 MeV; shape of linear combination is also narrower
- Ratios are consistent at larger scattering angles
- Larger percentage of CCQE interactions below 1000 MeV





CRPA/SuSAv2 Hybrid Model Analysis

- Separation of lepton energy distributions in larger scattering bins
- CCQE-like interactions found more in front end of full signal and CCQE interactions dominate full signal up to 1 GeV
- Additional neutrino interactions occur only at more on-axis scattering angles



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Conclusion and Future Work

- By using SBND-PRISM, the information from different fluxes can be used together to better isolate different interaction channels
- We've applied it to the CRPA/SuSAv2 interaction model implemented into GENIE and have shown that CCQE contributions can be better isolated
- Further work is needed using the same framework to:
  - compare different models
  - utilize different parameters
  - estimate statistical uncertainties to see if observed rates can be used to differentiate models

Acknowledgements

I would like to give a huge thanks to my supervisors Dr. Vishvas Pandey and Dr. Alexis Nikolakopoulos for guiding me throughout this period, for advising me on my work, for teaching me about concepts and researching, for providing me with resources, and for being endlessly patient with me.

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Collaborations / Partnerships / Members [19.5pt Bold]