Experience Implementing GiBUU in SBND Simulation

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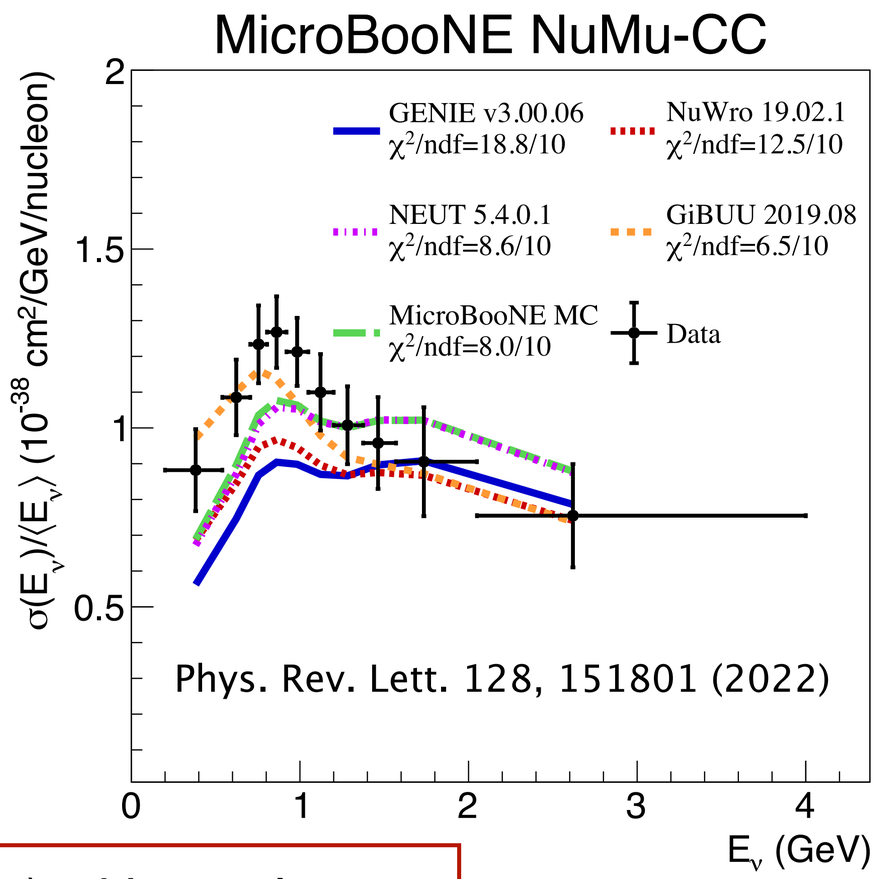
Introduction

Motivation

» The GiBUU project provides a unified theoretical and simulation framework for particle interactions with nucleus in a wide energy range (MeV-GeV)

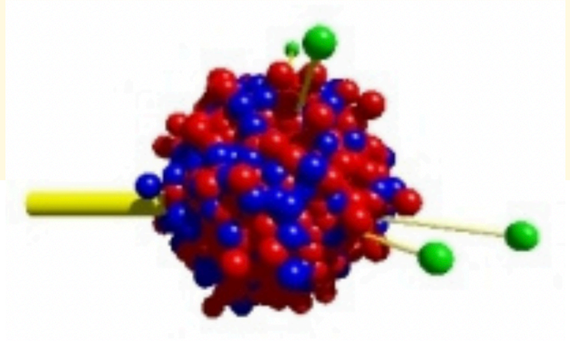
- Based on first-principles interactions

» GiBUU propagates particles from the initial interactions using a transport model (the BUU equation) which describes the time evolution of the Wigner transform of the real-time Green's function



GiBUU showed good agreement (shape and normalization) with results from many neutrino experiments, including Ar targets (MicroBooNE)

Motivation



» Not implemented as an event generator yet

- Our plan is to implement GiBUU as an alternative generator, event by event, in Larsoft.

» Our first application is the SBN physics program

Advantages

- *An **independent account for corrections** coming from simulations: purity (signal-to-bkg migrations), efficiency, neutrino energy reconstruction, etc.*
- ***Crucial for extrapolations in oscillation analysis** (model dependent analysis) and **important for model independent measurements** (such as neutrino-Ar cross sections) and to **understand in BSM searches***

GiBUU weighted events

» The GiBUU's output is a list events

These weights

- *Each event has a weight*
- *can have negative values (if destructive interference terms, such as some resonances which are relevant for higher energies)*
- *have to be added to obtain the cross section for any variable (neutrino, FS, etc)*

These cross sections have to be converted into a generated event-by-event interaction and propagated through the detector

General approach

» The first step is to generate GiBUU events with (reasonable) high statistics and store them in a standard format we can use. We produce two libraries, one for positive and one for negative weights

- For negative weights we take the absolute value to produce events.

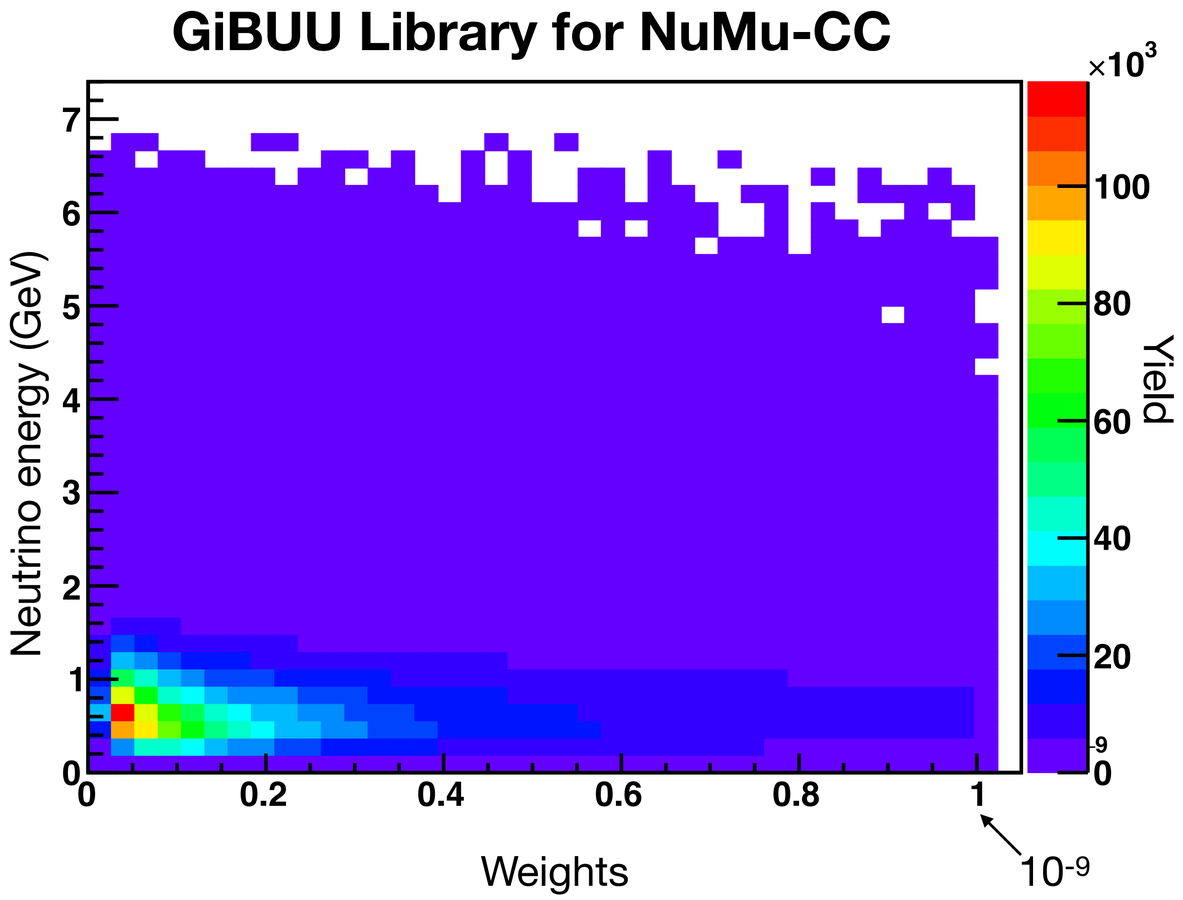
» We made two productions (one corresponding to a negative and one for positive weights). The final results can be calculated by subtracting both.

» We use the flux and geometry GENIE infrastructure to propagate those GiBUU events in the detector geometry (SBND).

GiBUU weights

» GiBUU weights have a wide distribution that span over several orders of magnitude

- *Not only depend on the neutrino energy but the different processes.*



GiBUU weights

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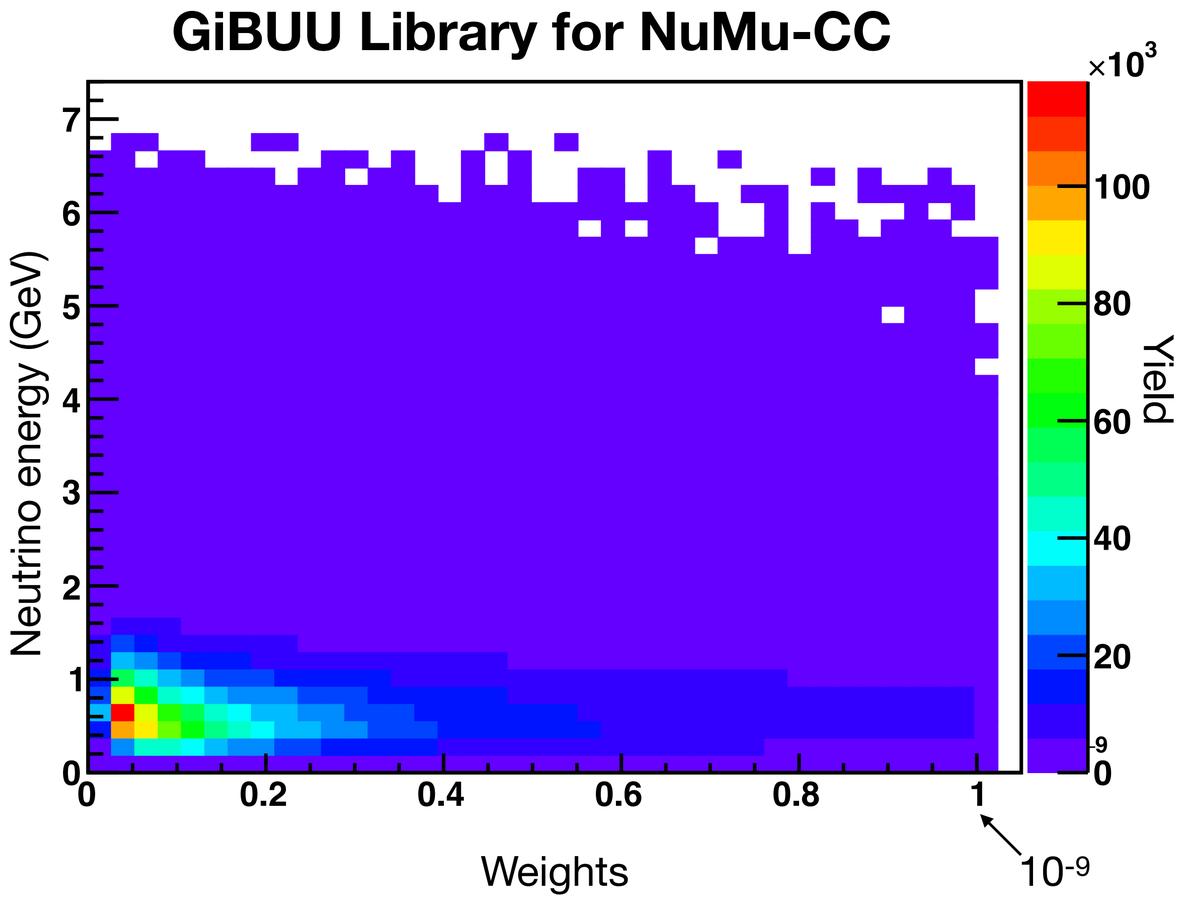
» In a first approach, we tried to use the event Library Interface (**EvtLib**) from GENIE (available in version >= 3.2)



» Unfortunately the **EvtLib** does not **handles weighed library inputs** and **does not propagate the interaction mode of external generators**)

Libraries

» A standalone code to generate GiBUU events and create the libraries

- We use the most recent GiBUU version (2021)
- Only interactions in Ar40 are produced for now. We need to expand to other materials for completeness
- The library contains all neutrino interaction flavors (ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, and NC and CC).

Each entry has:

- *Neutrino energy, weight, process ID (QE, 2p2h, etc)*
- *Array of final state particles: ID and kinematics*

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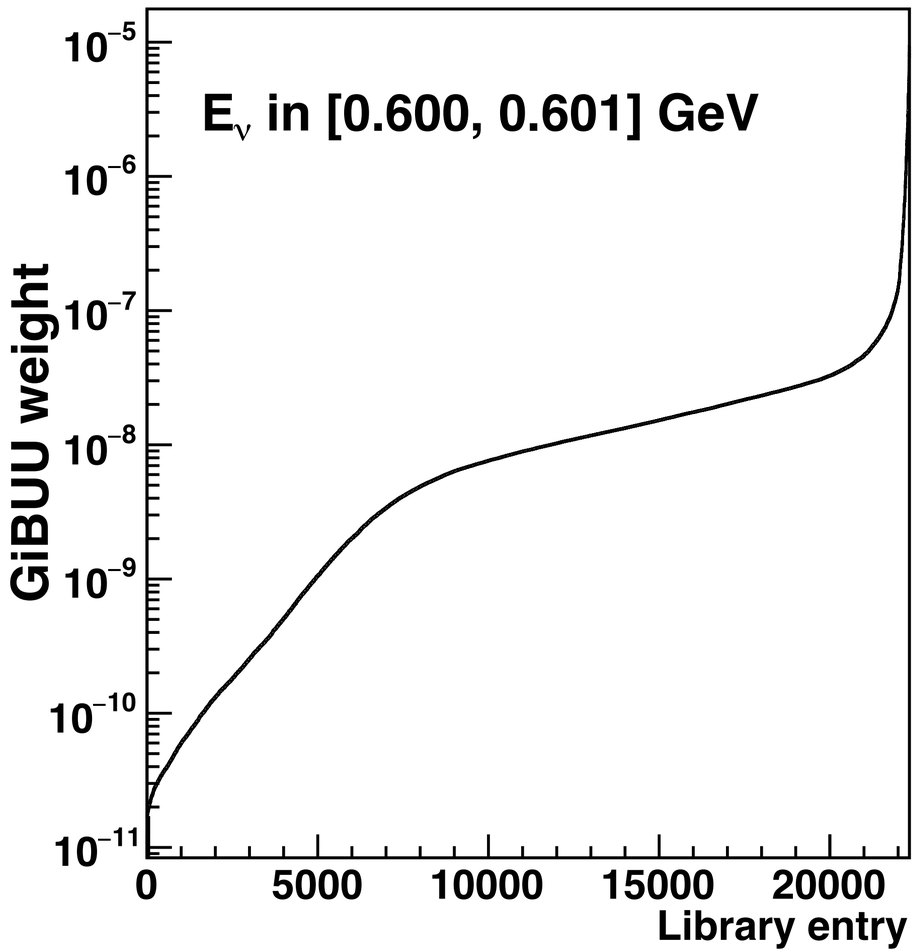
» A code (ART module based on **GENIEGen**) generates and replaces GENIE events with GiBUU events

- We keep the interaction vertices and use the neutrino information to find an event in the GiBUU library
- We calculate and propagate a weight to account for the difference between the inclusive GENIE vs GiBUU cross section. For instance: $\mathbf{w = \sigma^{GiBUU}_{\nu\mu CC} / \sigma^{GENIE}_{\nu\mu CC}}$

Choosing the GiBUU entry

» The GiBUU entry is chosen given the distributions of weights

- This distribution is made using a narrow neutrino energy: $\Delta = 0.001$ GeV
- An entry from the library from a random selection.
- Given the wide span of the weights, the challenge is not repeating multiple times entries with very large weights



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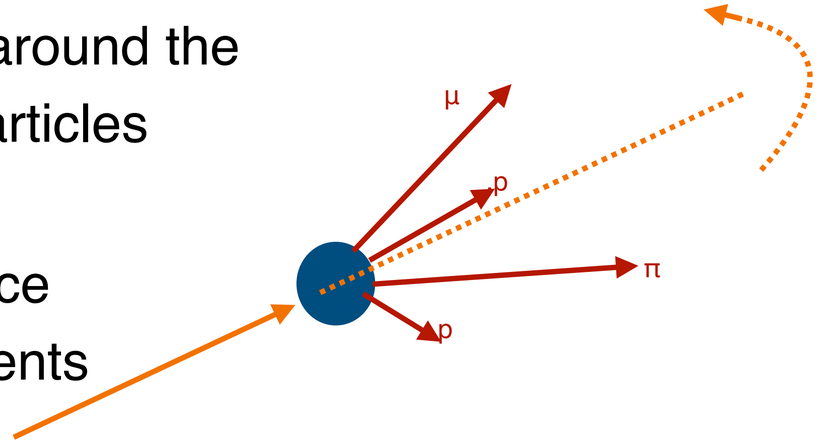
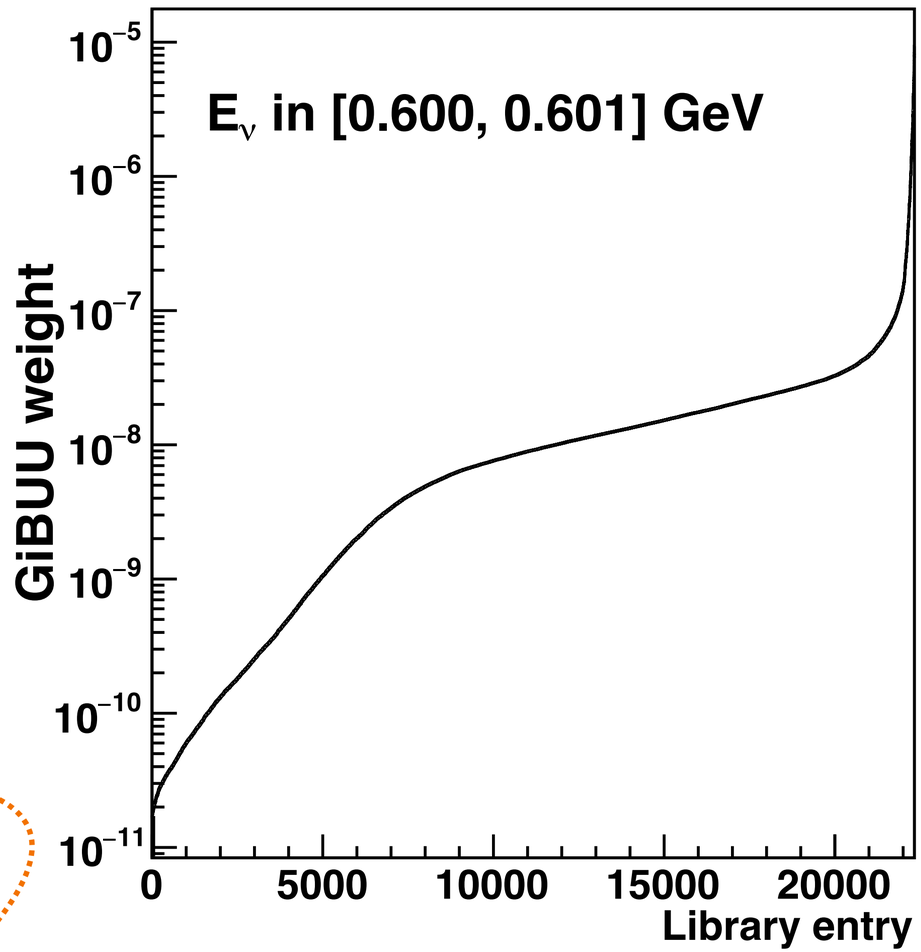
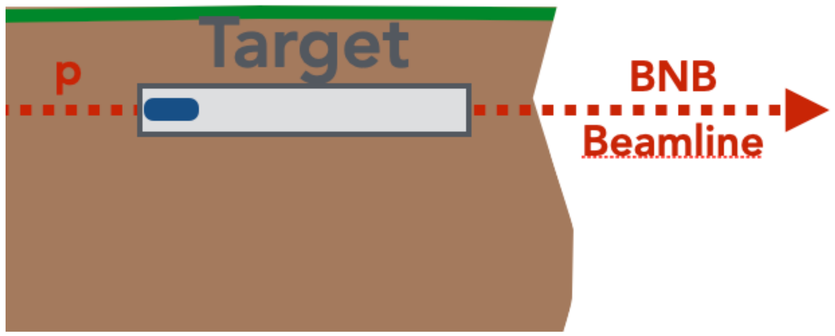
- We add a random rotation around the neutrino axis for the final particles
  - This introduces some randomization and reduce the cost of repeating events

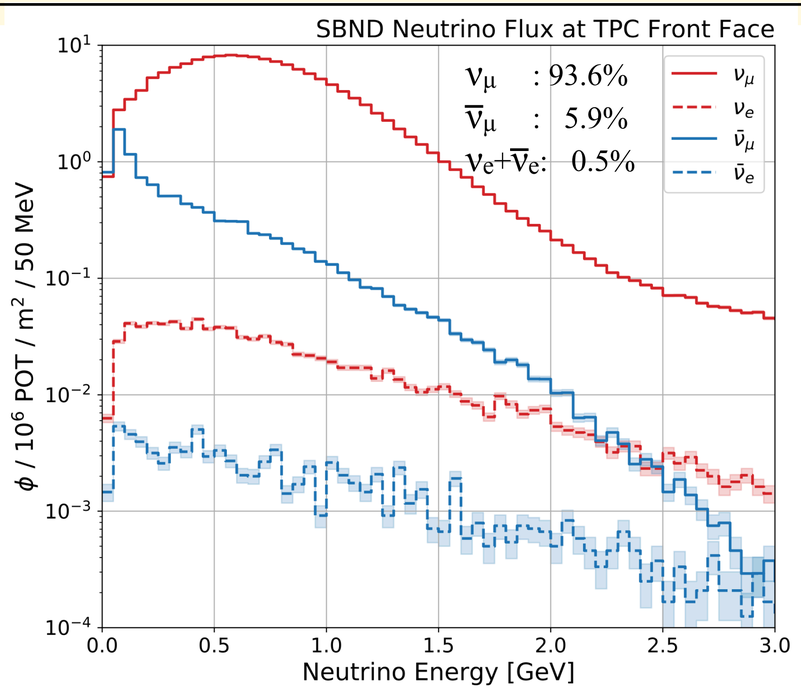


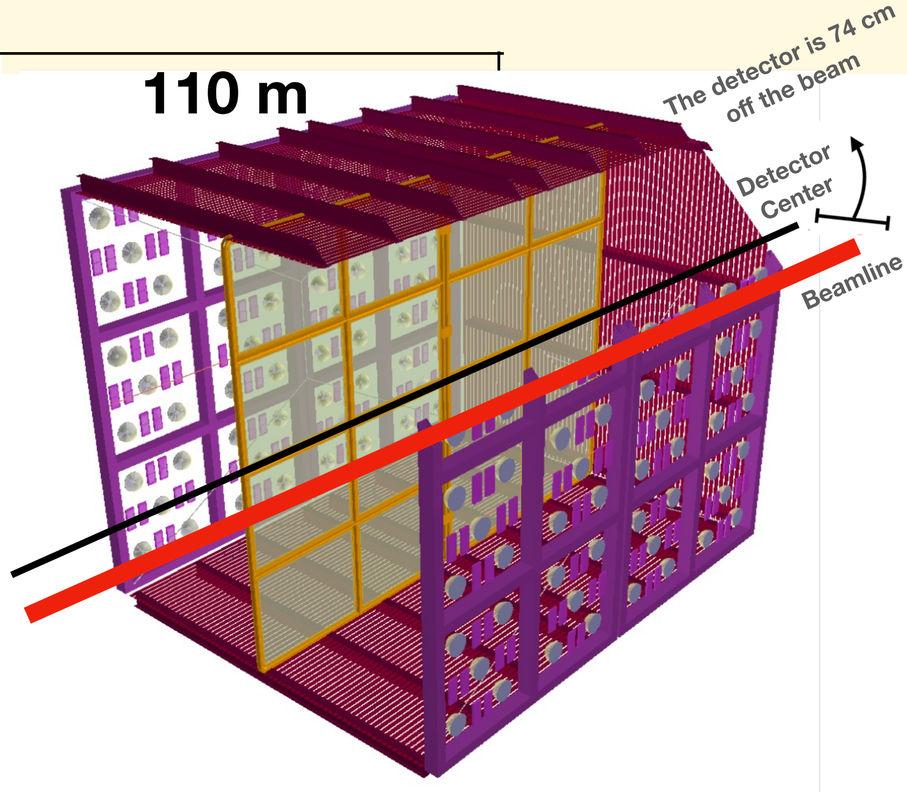


Prof-of-principle:
Full implementation for SBND

Short-Baseline Near Detector







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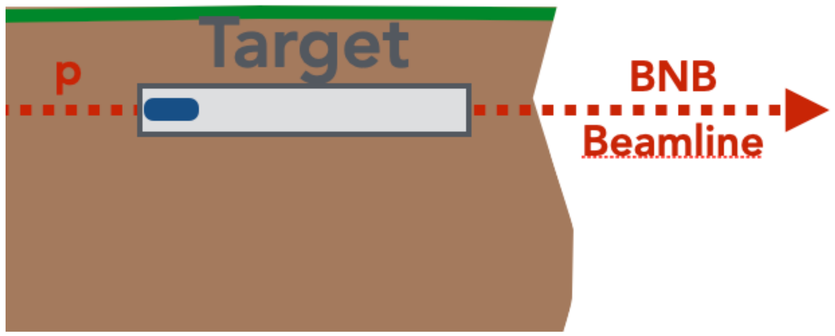
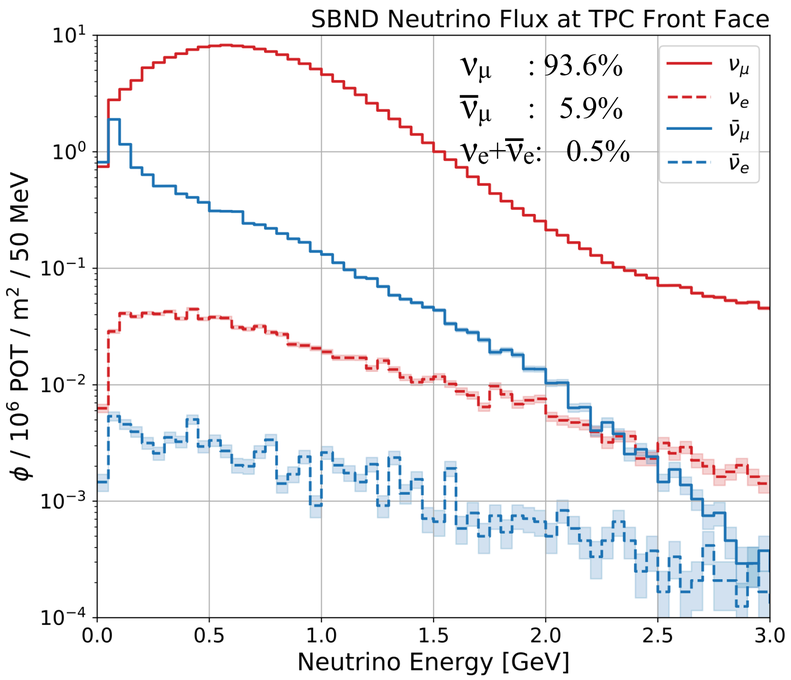
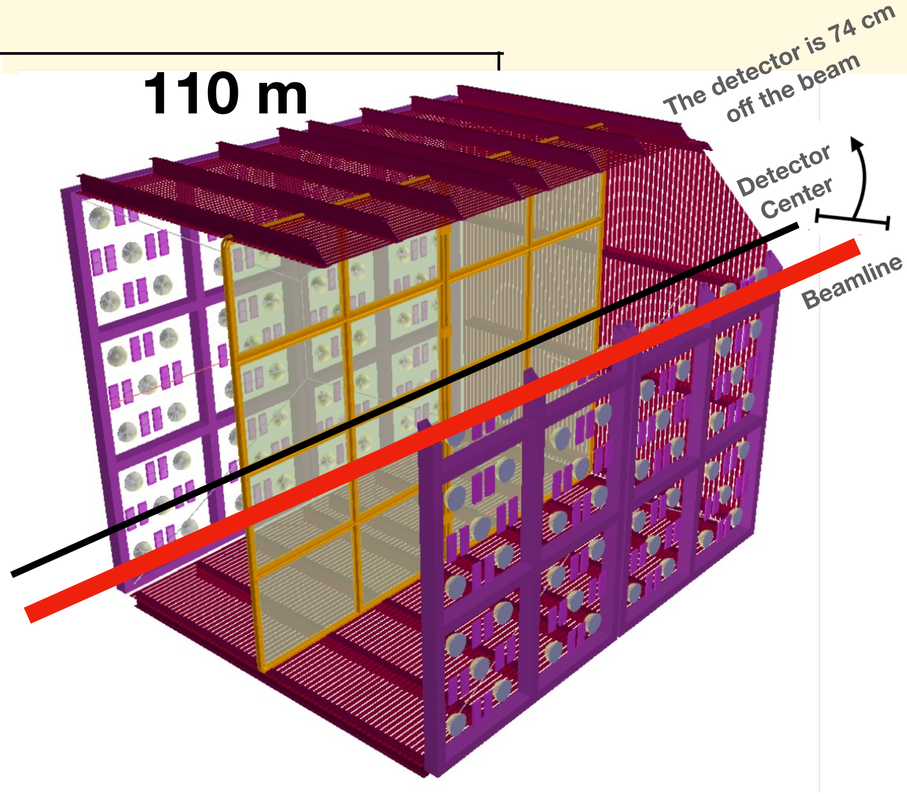






Two-detector analyses for sterile neutrino analysis:

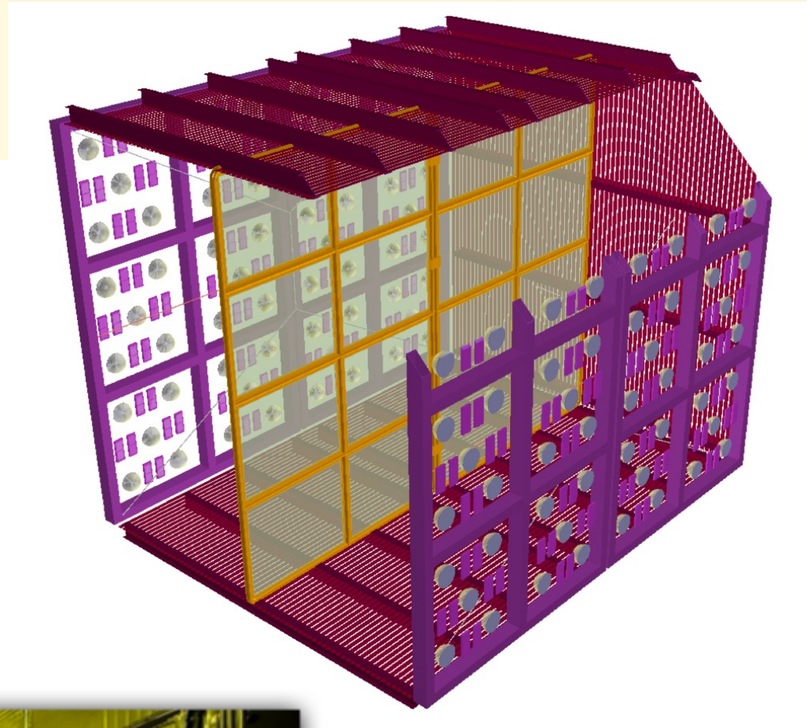
- » **Near Detector: SBND**
- » **Far Detector : ICARUS**

Same neutrino beam, nuclear target and detector technology (LAr TPC detectors) to reduce systematic uncertainties to the % level.

ν-Ar interactions: with an order of magnitude more data than is currently available (**5000 ν events/per day)**

In addition to the sterile and cross-section programs, the SBND large detector mass and proximity to intense beams enable a broad physics program such BSM searches

Short-Baseline Near Detector

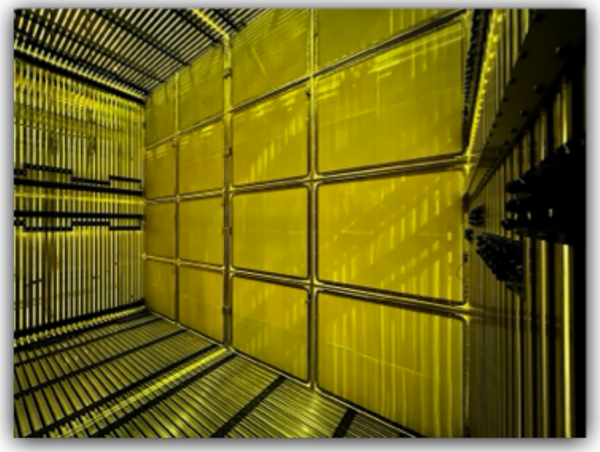


Large-mass Liquid Argon Time Projection Chamber (LArTPC)

- » *3D reconstruction with a mm position resolution*
- » *Fine-granularity calorimetry*
- » *Excellent particle identification with dE/dx information*
- » *Low energy thresholds: few MeV*

Photon Detection System (PDS)

- » *Novel technology of PMTs and X-Arapucas.*
- » *Scintillation & reflected light => high and uniform light yield and excellent timing resolution*



Cosmic Ray Tagger (CRT)

- » *Timing and position resolution allows for triggering on entering/exiting particles*

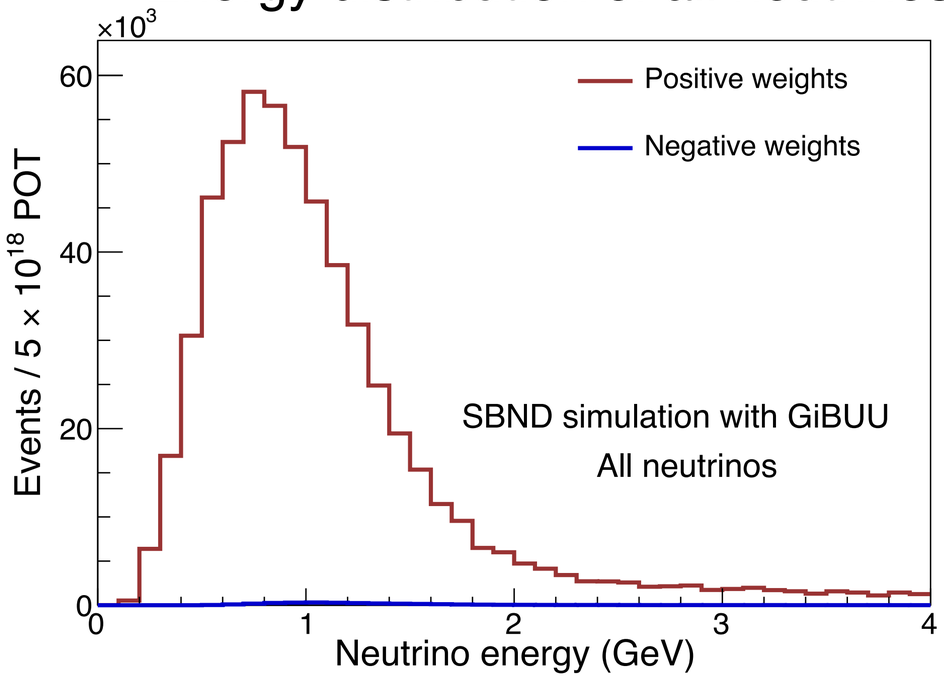
Cold commissioning - Summer 2023

Implementation

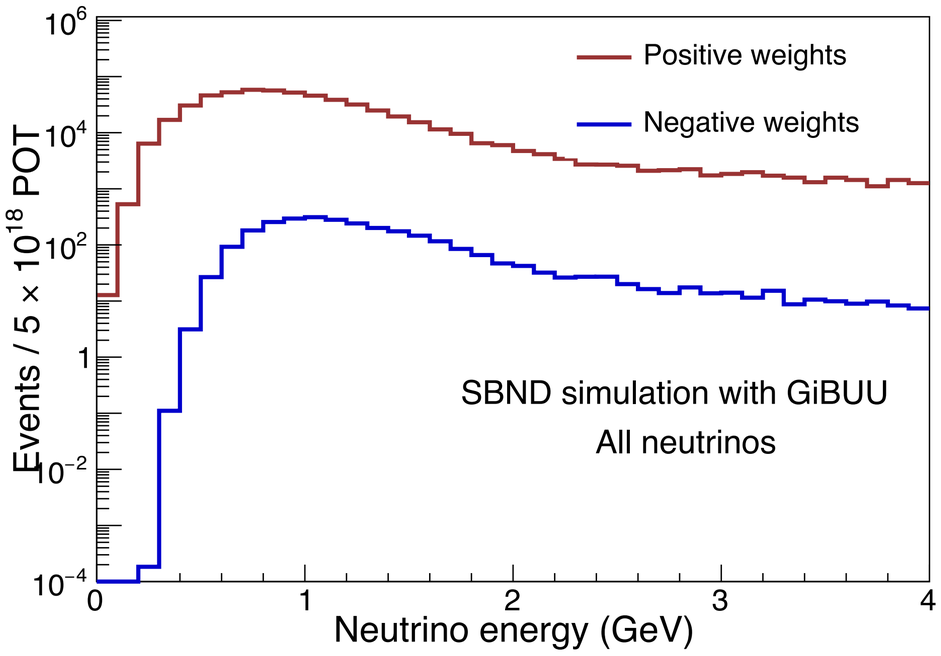
» We have implemented GiBUU into LarftSoft

- We generate GiBUU events and propagate them through the full simulation, including the final analysis framework (CAFAna)

Energy distribution of all neutrinos



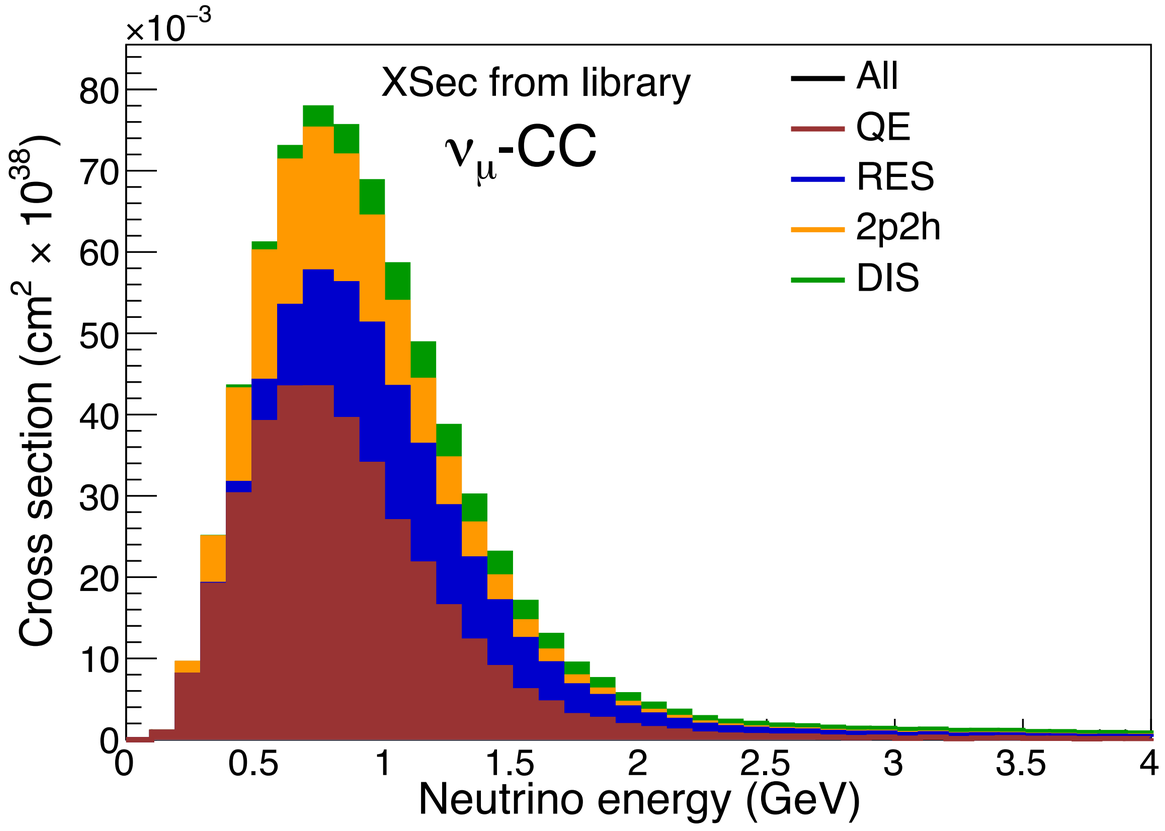
Log-scale version

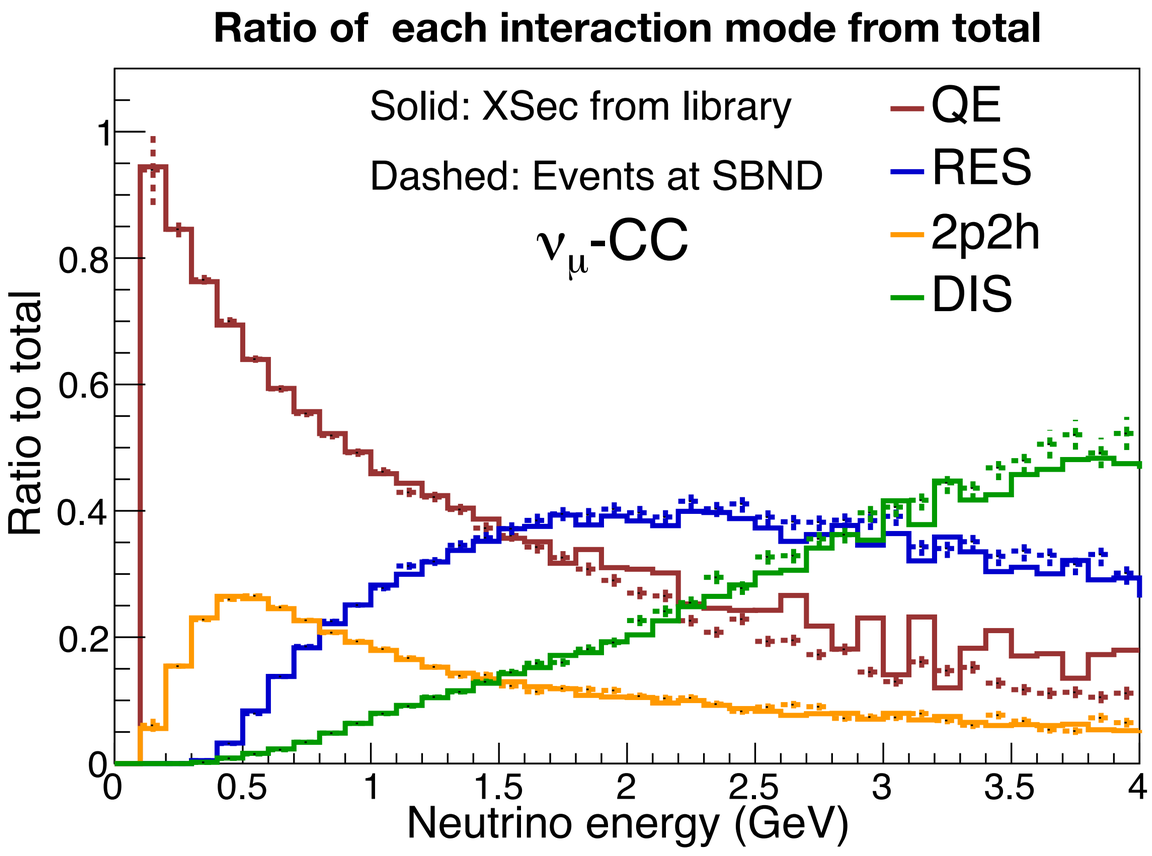


Interaction modes

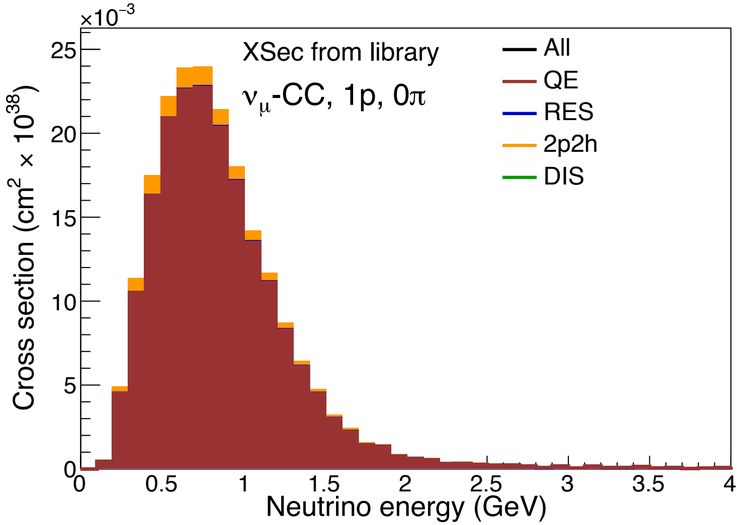
» We also propagate the GiBUU process ID through the simulation

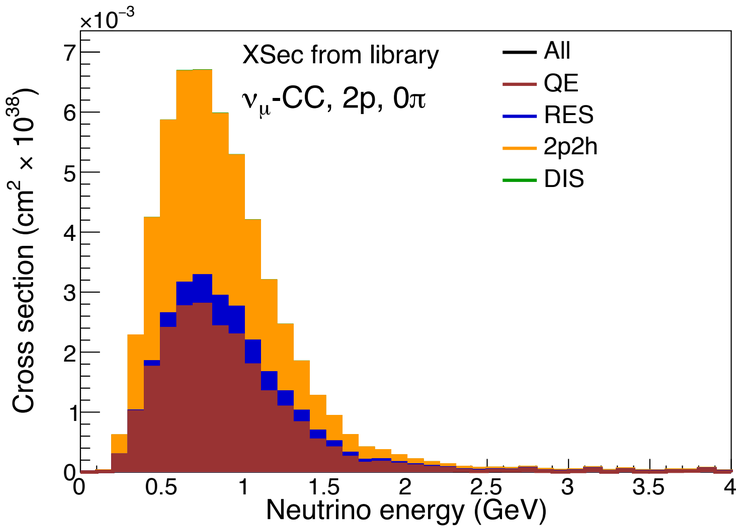
- This information is crucial to calculate the neutrino interaction systematics.





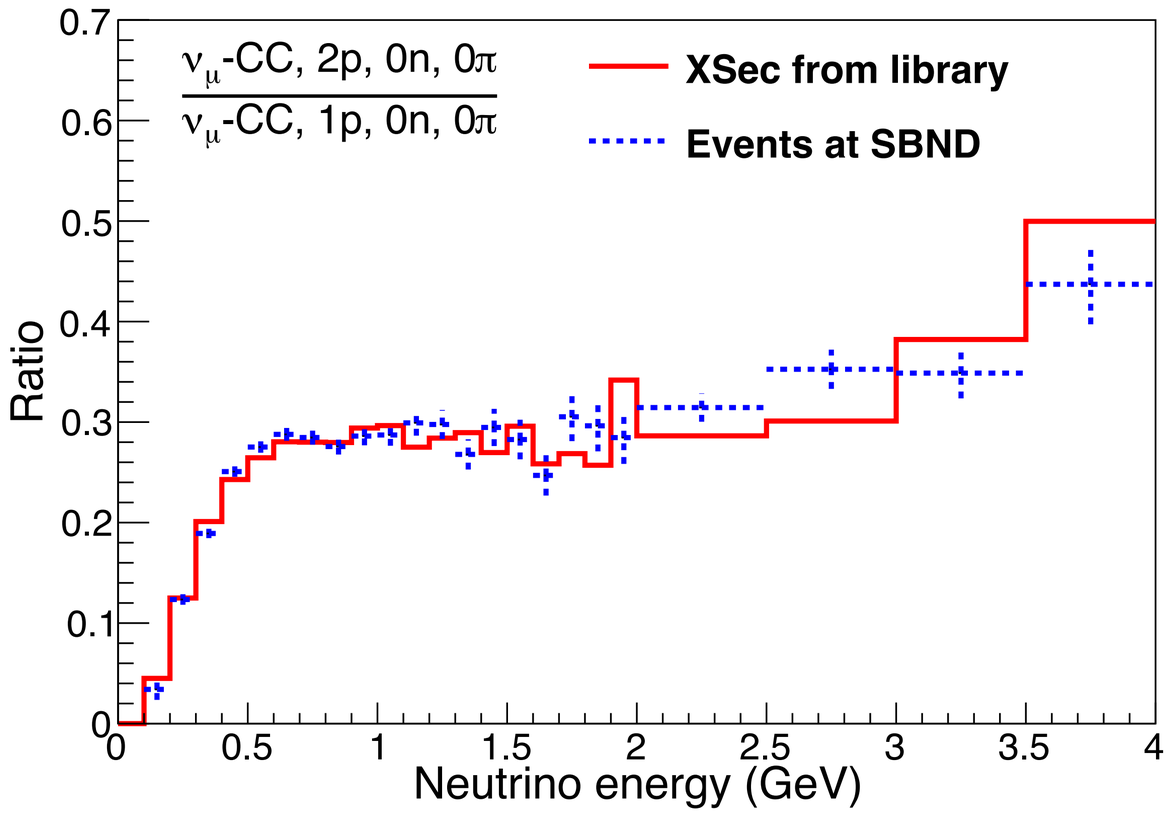
Other checks: enhanced QE and 2p2h





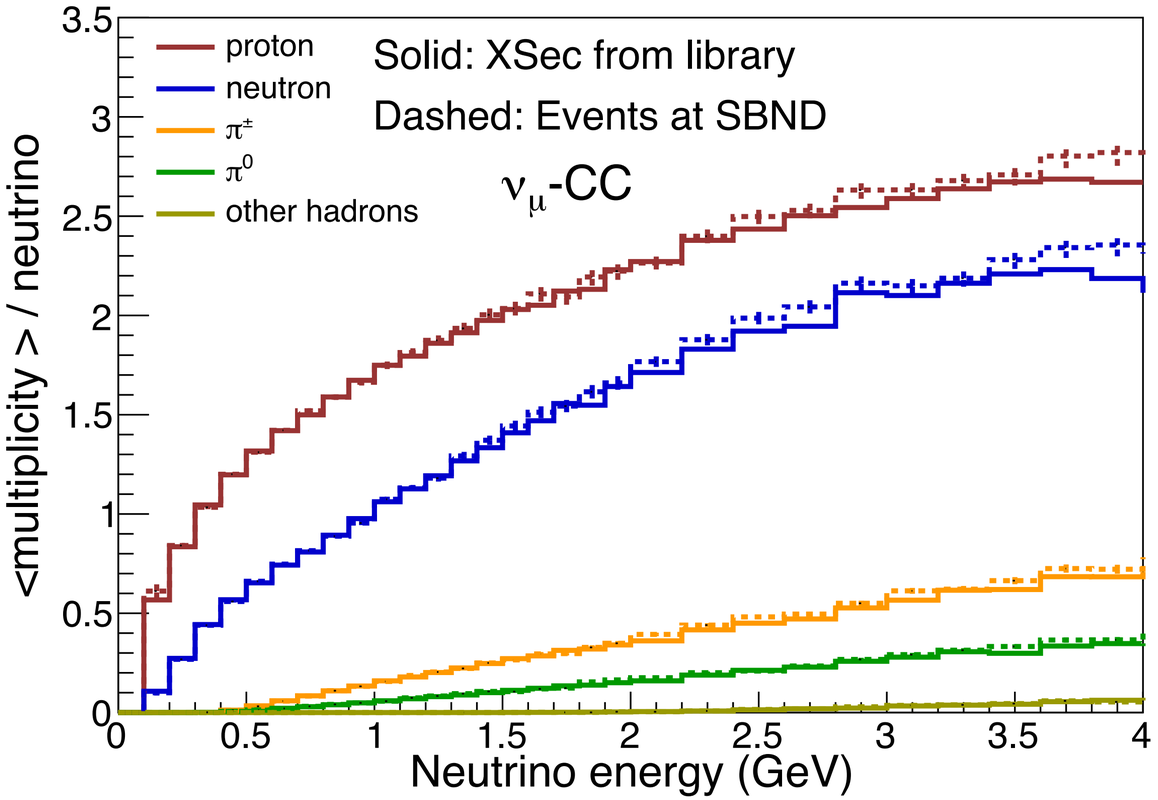
» NuMU-CC interactions with:

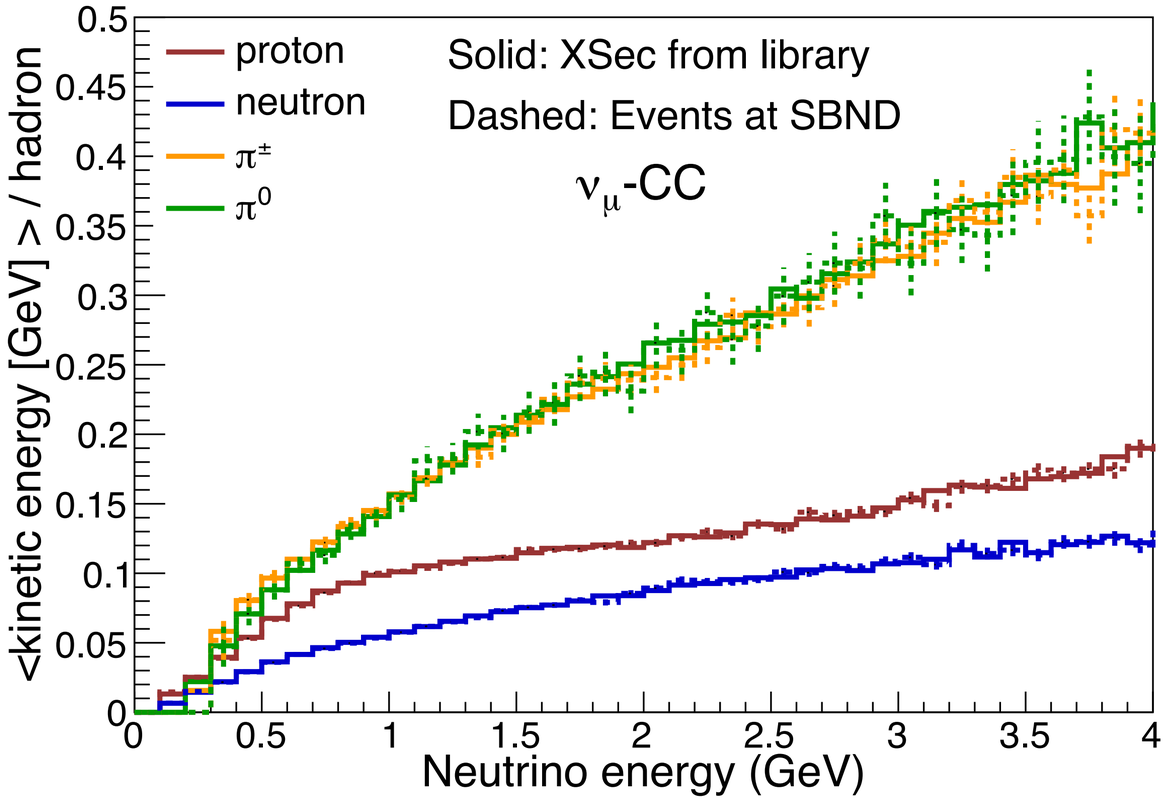
- 1p, 0n and 0pi: enhanced QE
- 2p, 0n and 0pi: enhanced 2p2h



Other checks: hadron production

» Average multiplicity per neutrino interaction and the average kinetic energy of hadrons in NuMu-CC interactions



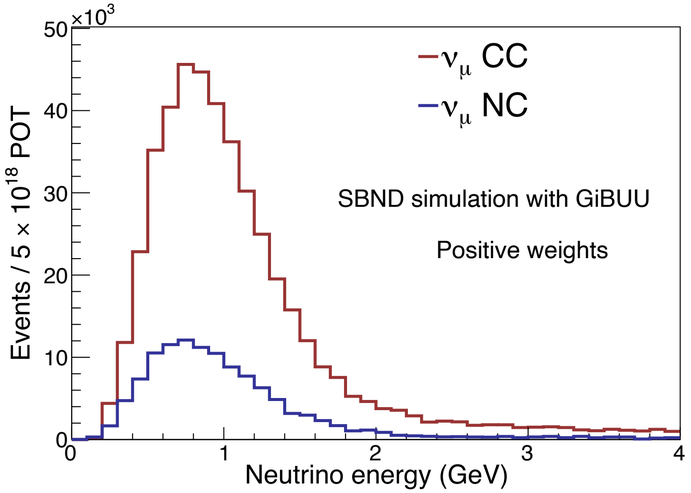


Neutrino Energy

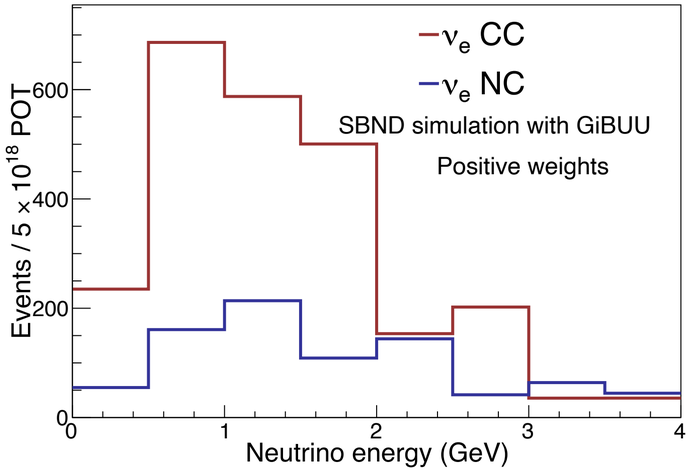
» Distributions for the neutrino energy per current and neutrino type

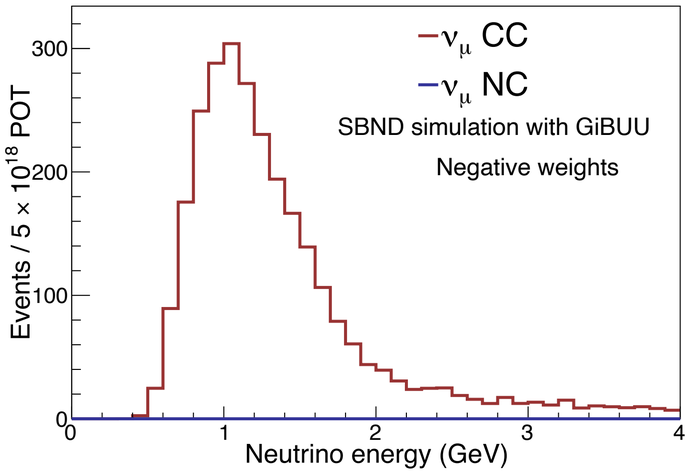
» Negative amplitudes only appear in CC

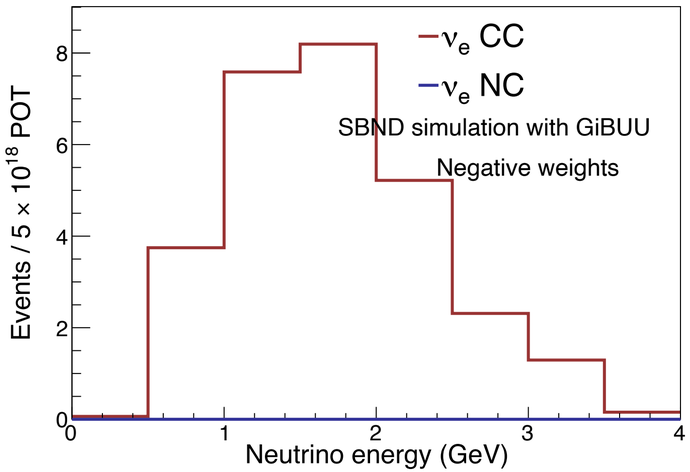
Muon neutrino



Electron neutrino



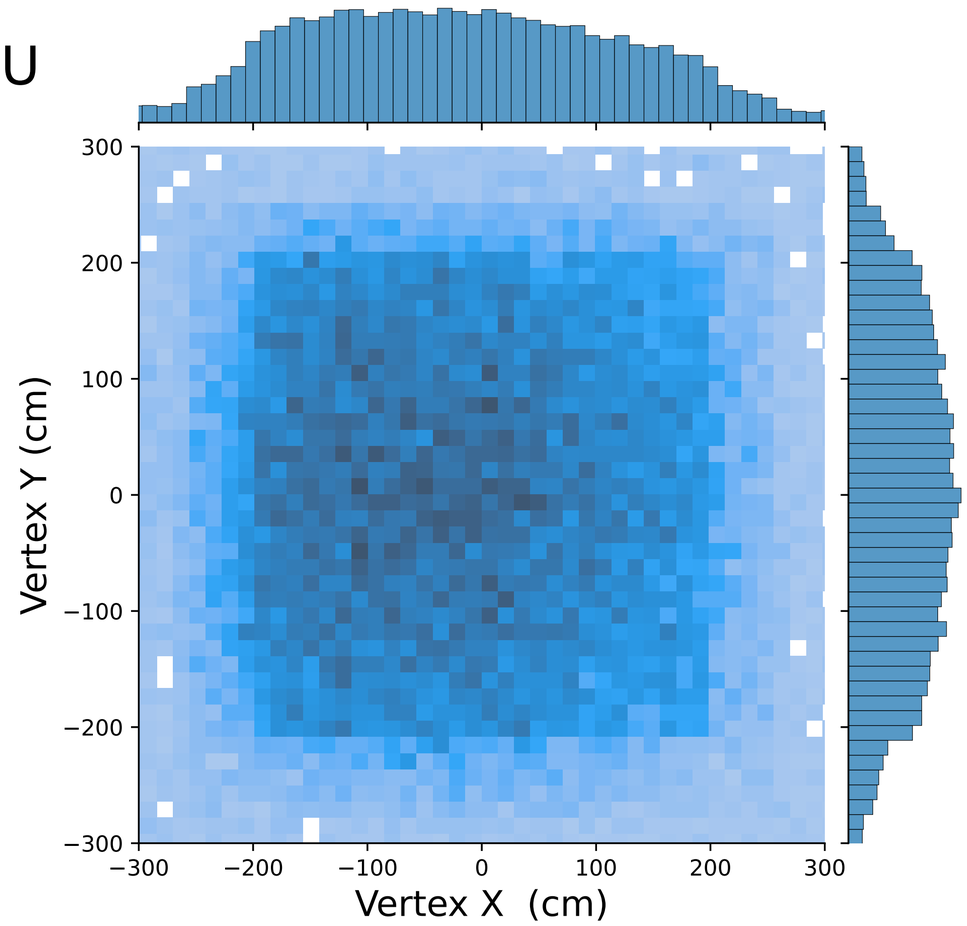




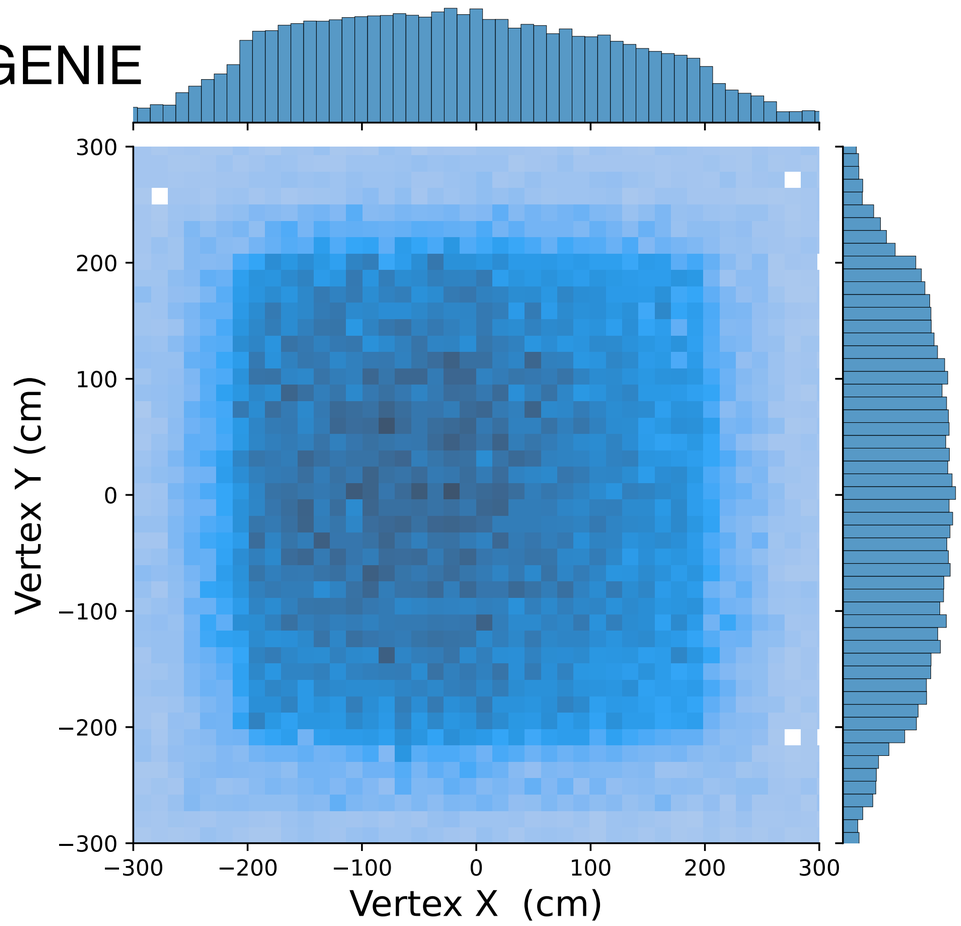
Interaction vertex distributions

Transverse view

GiBUU



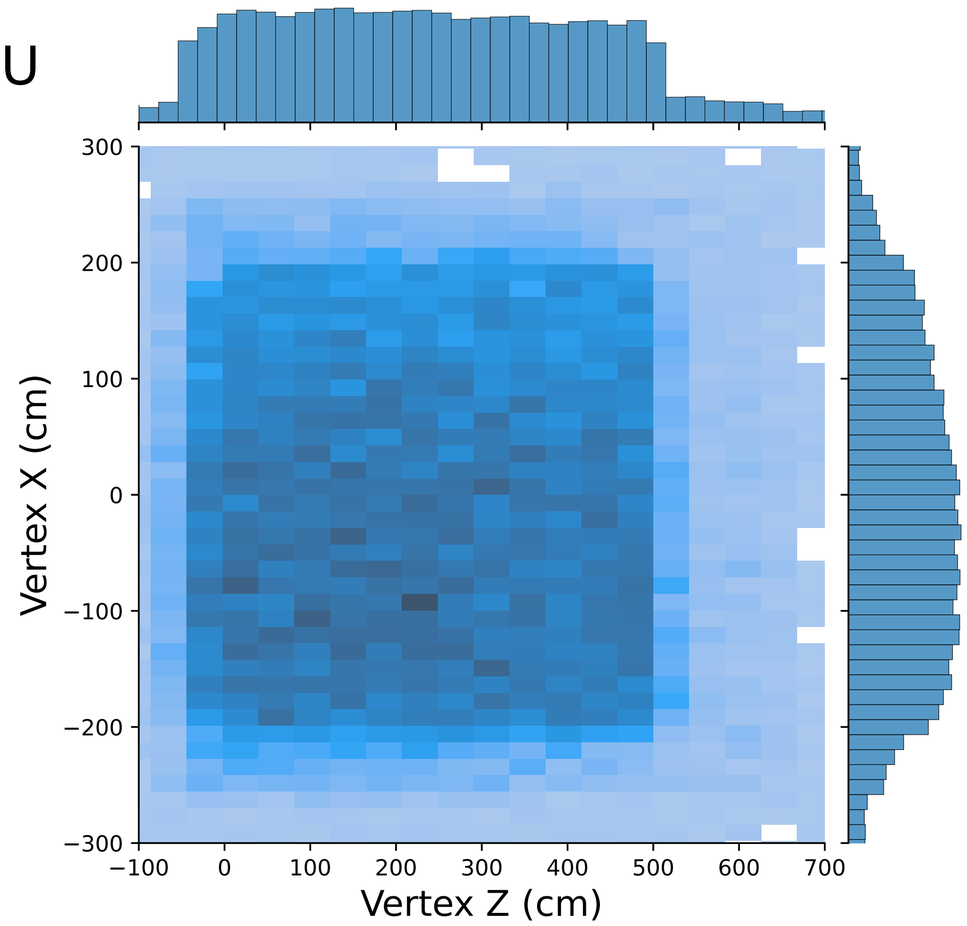
GENIE



Interaction vertex distributions

Longitudinal view

GiBUU



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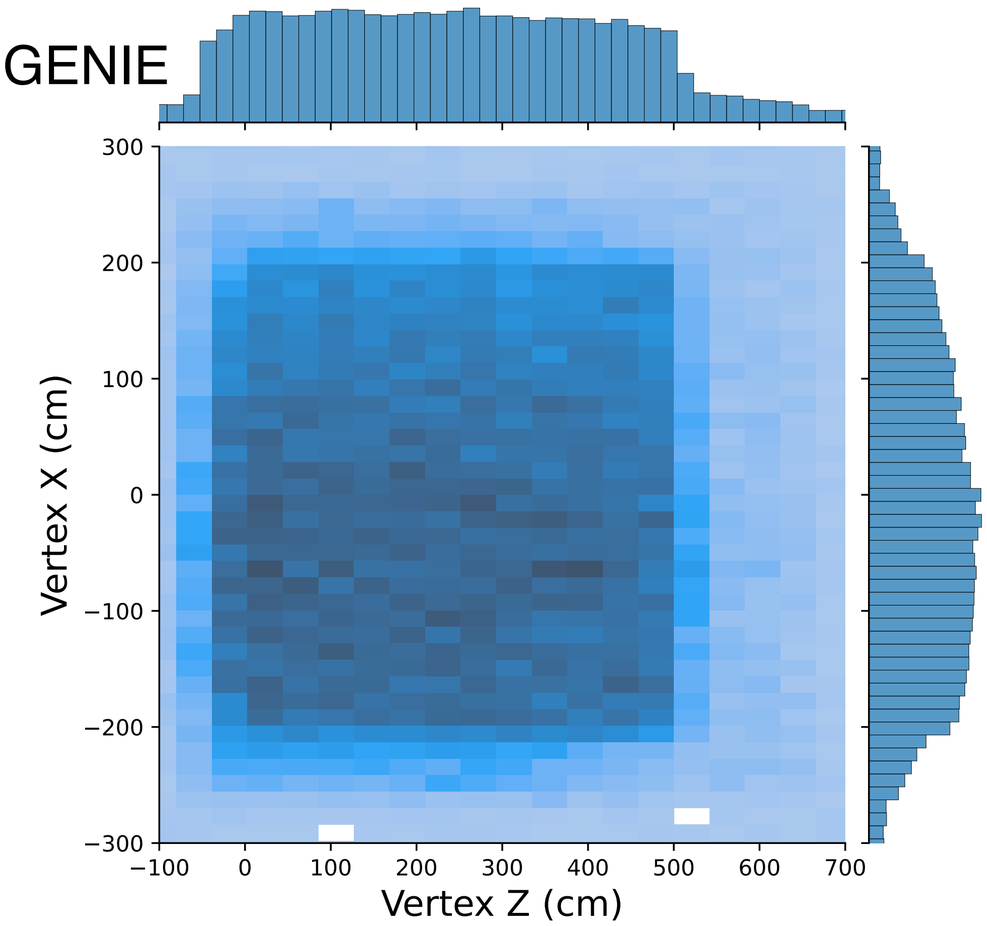
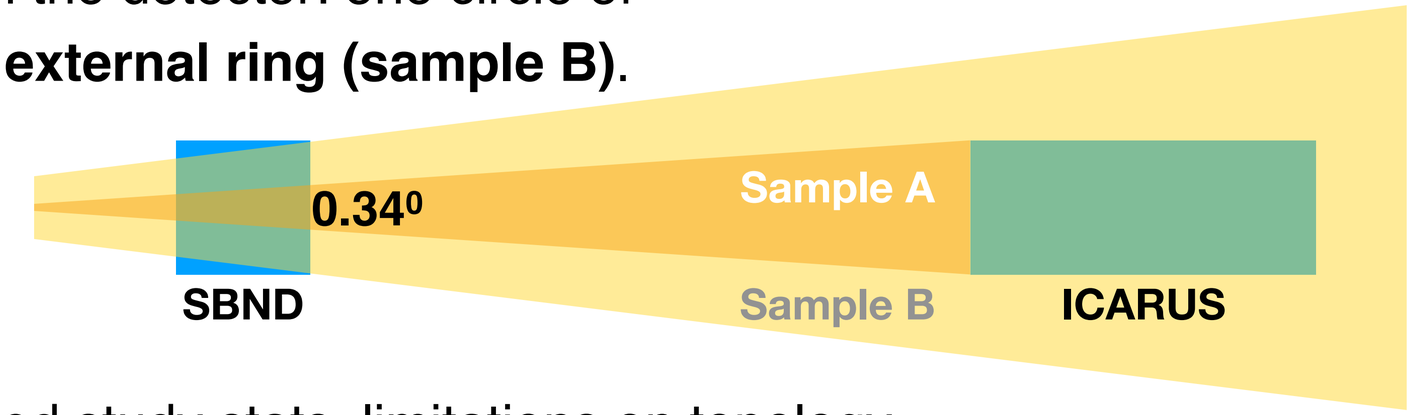


Plan for uncertainties

Principle

» Split the SBND sample into 2 regions in the detector: one circle of **ICARUS' projection (sample A)** and an **external ring (sample B)**.



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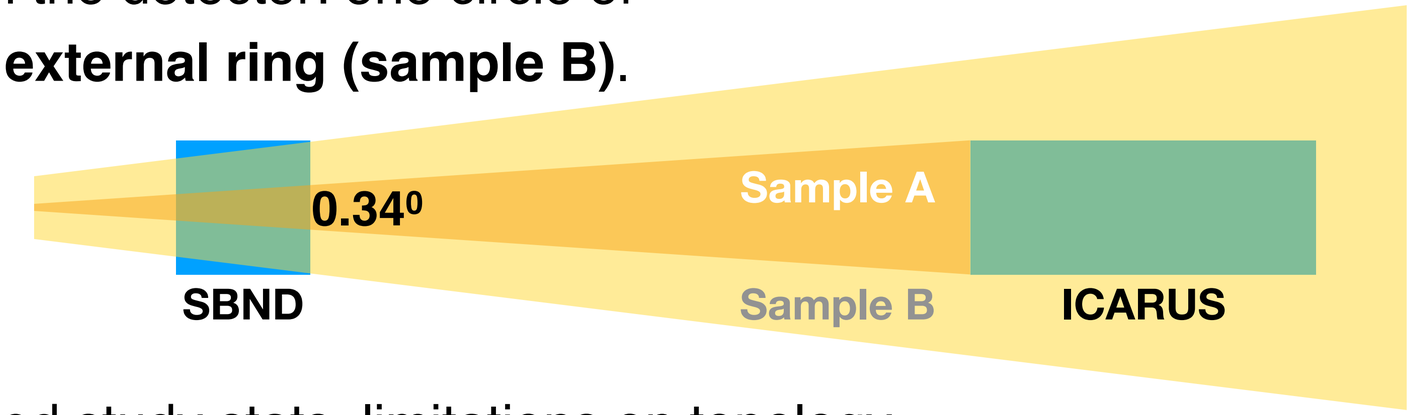

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» Uncertainties will come from two sources:

External e- and hadron scattering

Neutrino scattering in sample B

» Event selections in sample B will be done with our own detector efficiencies, signal definitions, and enhancing the sensitivity to the parameters we want.

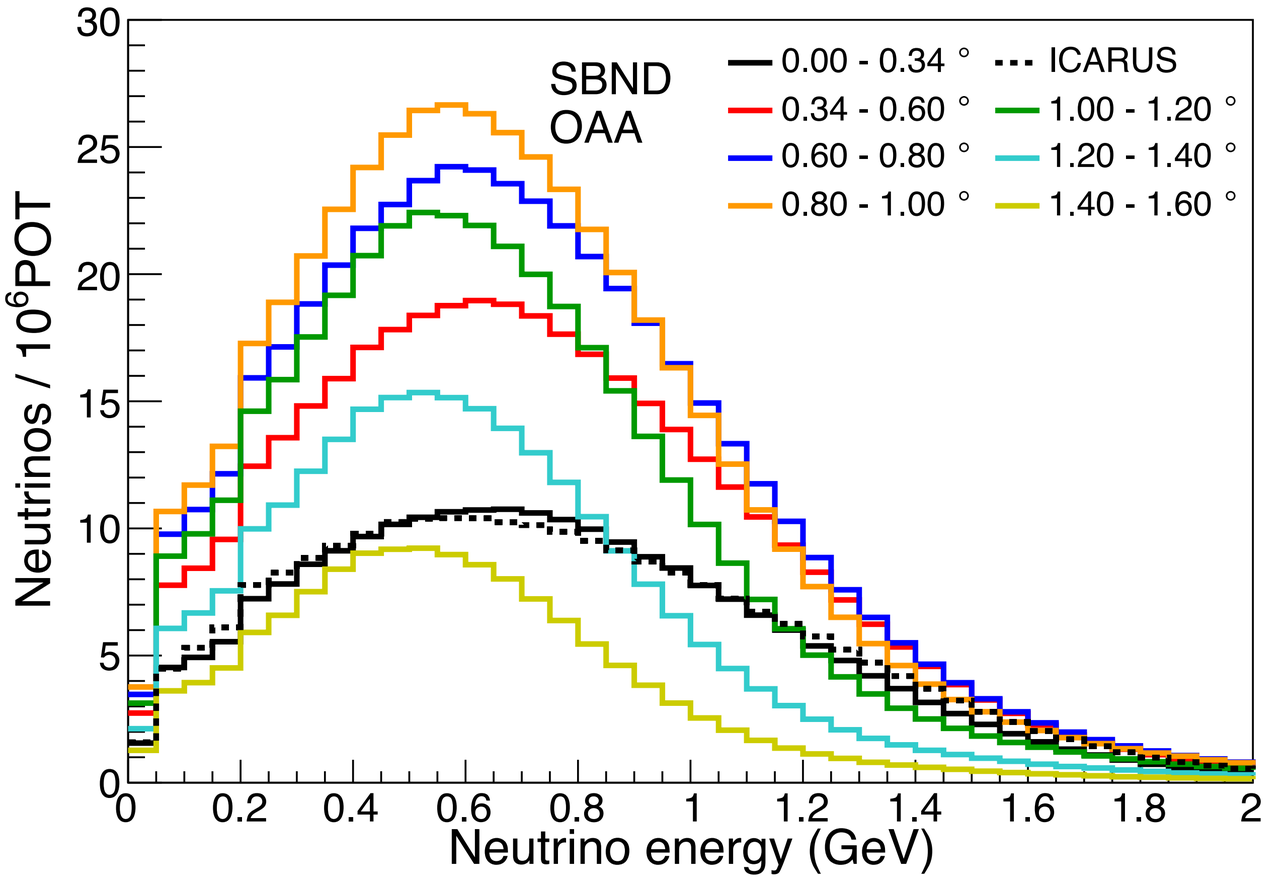
Principle

Pros

» it can provide a robust model extrapolation and let us target desired sample for oscillation and error estimation.

» Beam uncertainties when comparing sample A and B should be small, so we expect better error precision

» Will reduce to its minimum flux uncertainties in the osc measurement.



Outgoing studies on selection efficiency, statistics, etc. Final answer till we look at the data.

Conclusions

» Having an alternative generator has the advantage of an independent account for all corrections coming from simulations.

- GiBUU has shown good agreement with neutrino-nucleus data, even in Ar.

» We have implemented GiBUU as an alternative generator, event by event, in LarSoft.

- This includes the propagation through the full chain till the analysis stage.

» We are focused to incorporate realistic systematics coming from our own neutrino-Ar data.

- We are collaborating with **Ulrich Mosel** and **Kai Gallmeinster** (GiBUU authors) to be loyal to the physics.
- We are exploring using GENIE-Reweight to propagate systematics. We are learning from the experience of **Costas Andreopoulos** and **Marco Roda.**

Backup

GiBUU interaction modes

GiBUU modes:

- 1: nucleon (QE)
- 2-31: non-strange baryon resonance
- 32: pi neutron-background (e.g. $\nu + n \rightarrow \mu + \pi^+ + n$)
- 33: pi proton-background (e.g. $\nu + n \rightarrow \mu + \pi^0 + p$)
- 34: DIS
- 35: 2p2h QE
- 36: 2p2h Delta
- 37: two pion background

Link here

Comparison to GENIE

Neutrino energy for muon- and electron-neutrinos