Constraining Backgrounds for Non-Oscillation Physics

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Path to Dark Sector Discoveries at Neutrino Experiments
Colorado State University 6th June 2023

THE UNIVERSITY OF TEXAS AT ARLINGTON

A very specific (& ambitious) title: Constraining Backgrounds for Non-Oscillation Physics!

Let's start with this premise: it is unlikely to have a background-free experiment.

How do we constraint backgrounds?

Model Constraint

Data Constraint

Model Constraints

- **Signals are model dependent**. You define your signal in your analysis using a definition according to a model (can be New Physics BSM, a neutrino-nucleus scattering process, a calibration signal,…). We want to measure that model.

- **Backgrounds constraints can (and should) be as model-independent as possible**. But to be fully-model-independent is usually impossible.

- **Models are necessary for both**, signal and background, at different level depending on your analysis strategy, but still unavoidable.

Backgrounds need to be corrected or subtracted in the data analysis. No matter your approach, you need a robust background model and its systematics.

Non-oscillation physics at ν experiments

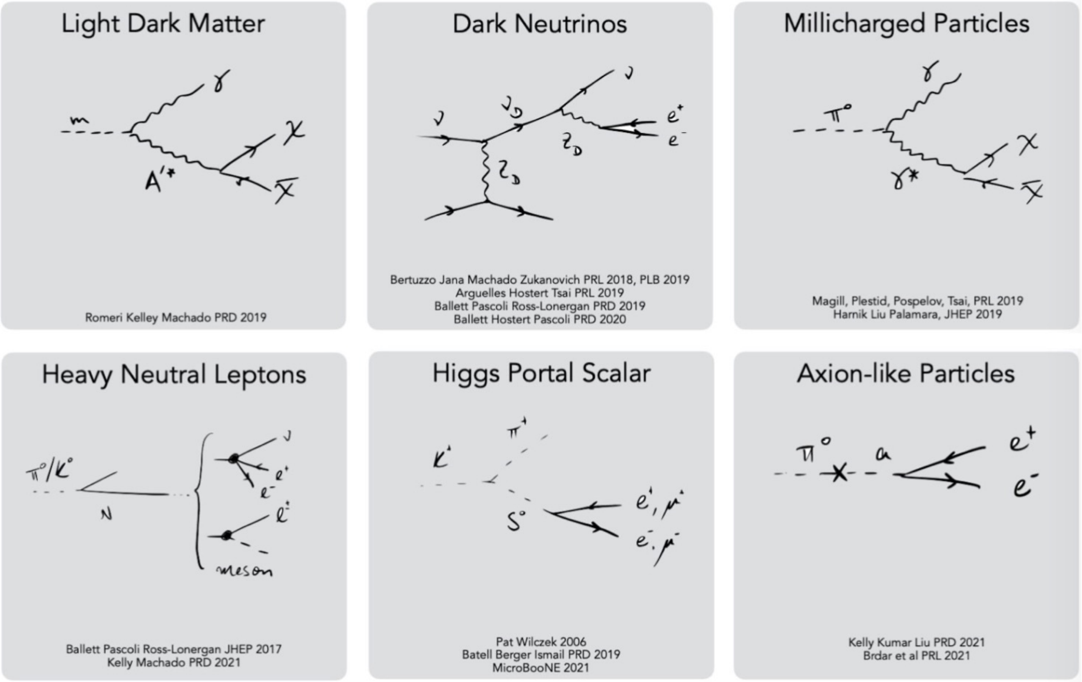


Image credit: Pedro Machado & Marco del Tutto.

A limited but very informative list of possible signals.

Non-oscillation physics at ν experiments

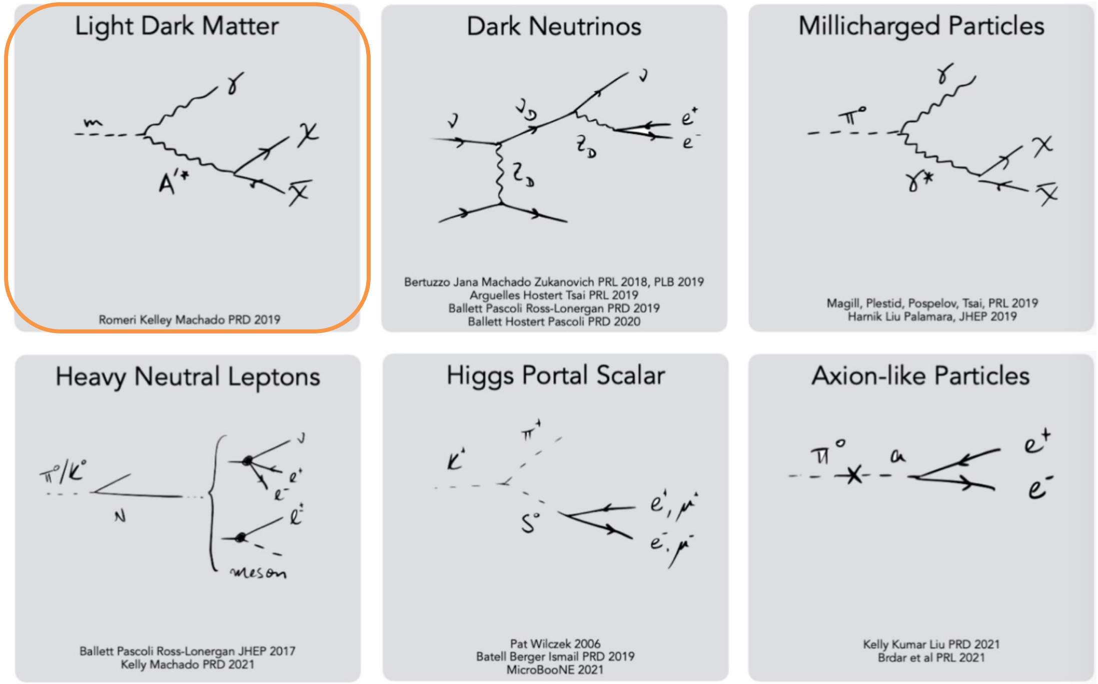
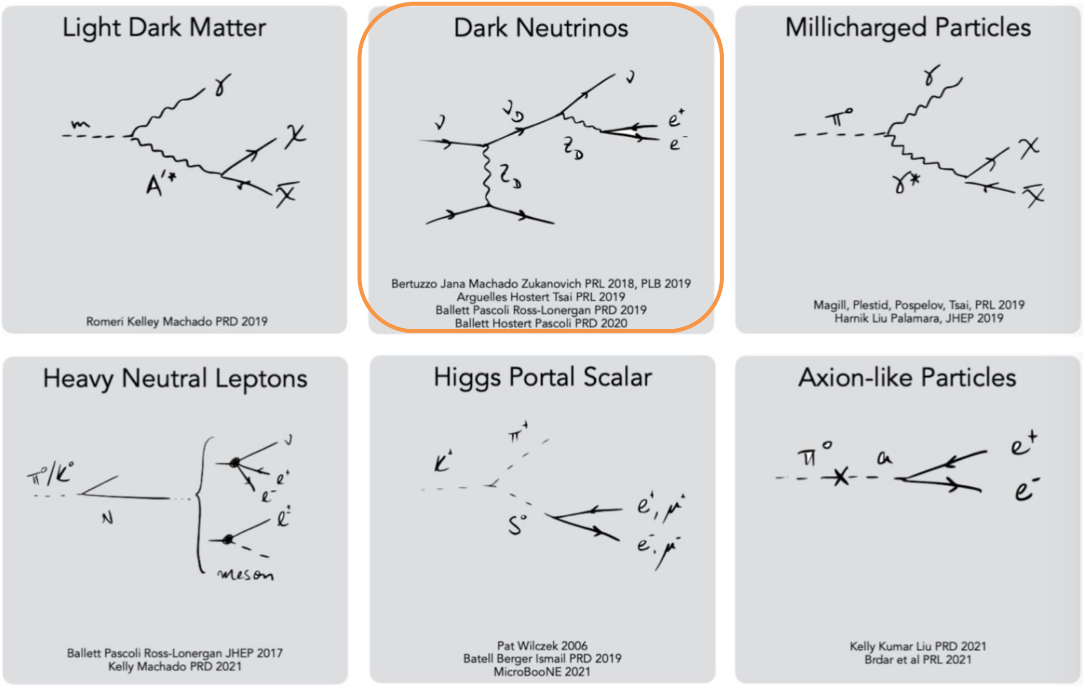


Image credit: Pedro Machado & Marco del Tutto.

Potential backgrounds:

1. $NC\gamma$: not constrained & discrepancy between models.
2. $NC\pi^0$: poorly constrained & very few measurements& discrepancy between models.
3. ν_e $CC0\pi$: constrained via $\nu_\mu CC$ & discrepancy between models.
4. ν-e: this is the best modeled from this list.

Non-oscillation physics at ν experiments



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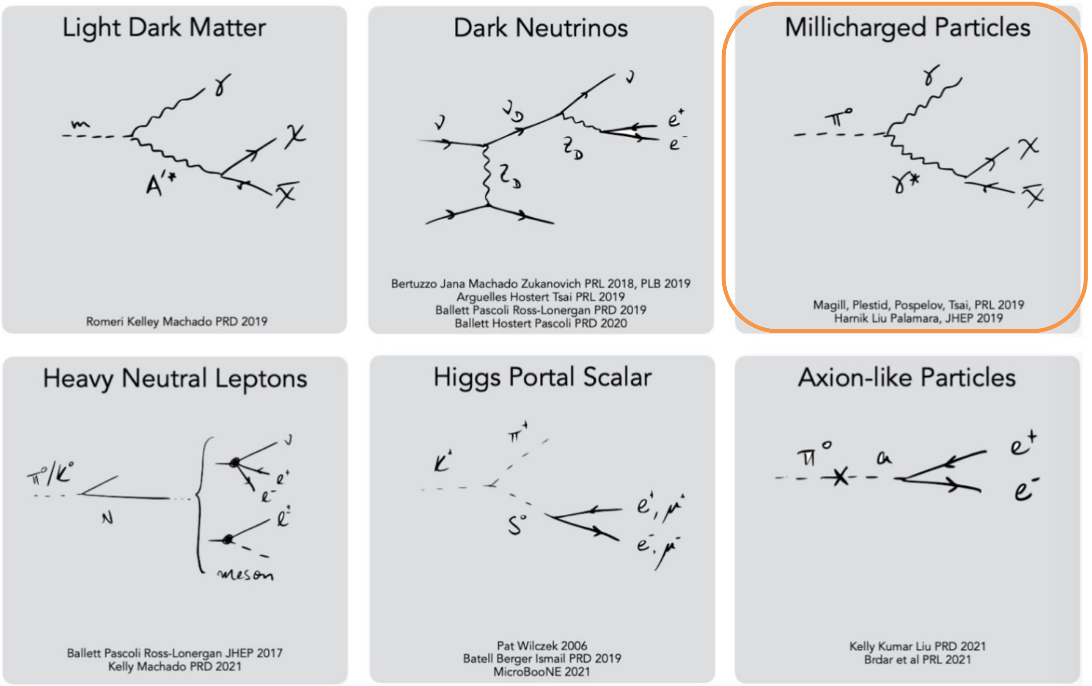

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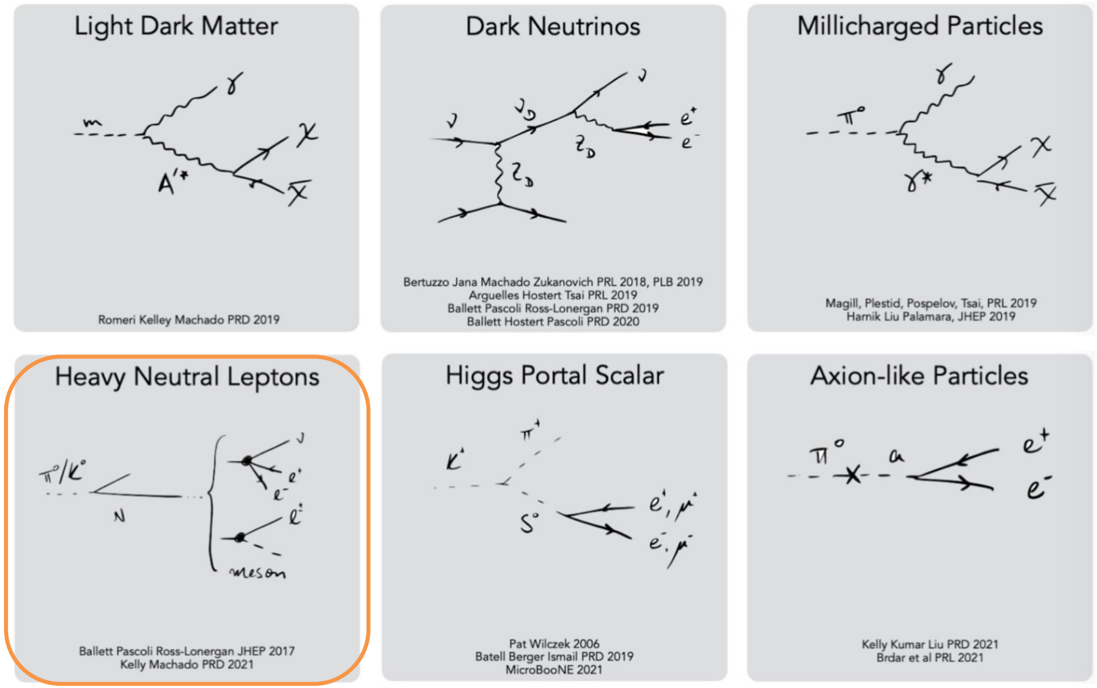

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3. $\nu_\mu||\nu_e$ CC$\pi^{+/-/0}$: poorly constrained & scarce data & discrepancy between models.

Non-oscillation physics at ν experiments

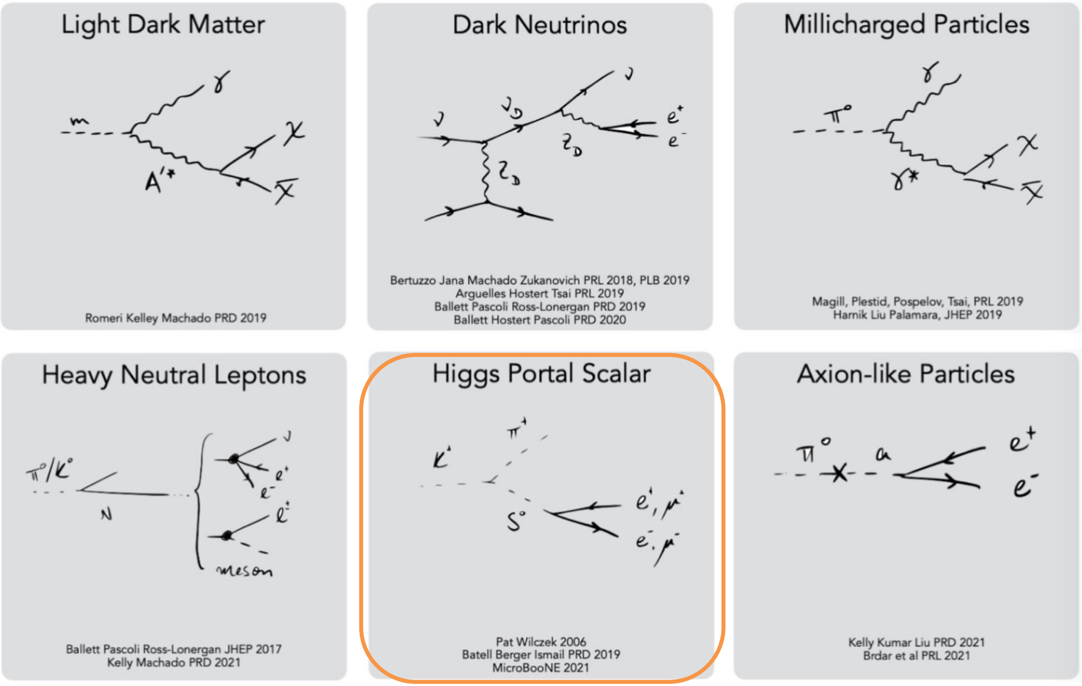

Image credit: Pedro Machado & Marco del Tutto.

Potential backgrounds:

1. $\nu_\mu || \nu_e$ CC||NC multi-$\pi^{+/-}$: poorly constrained & scarce data & discrepancy between models.

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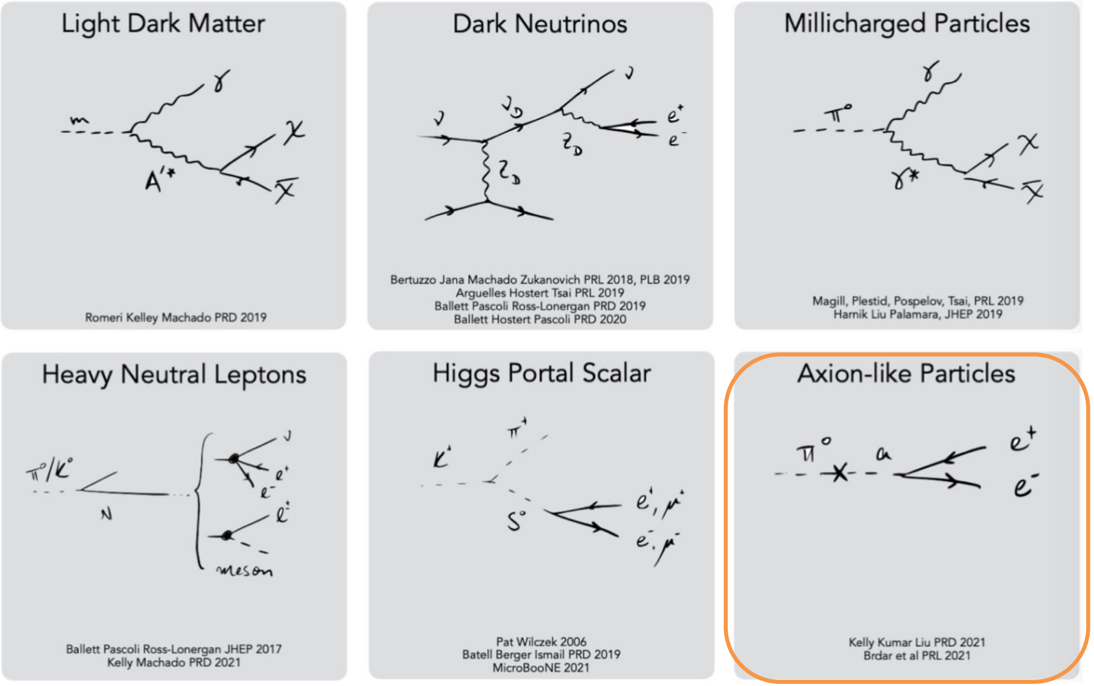
Non-oscillation physics at ν experiments



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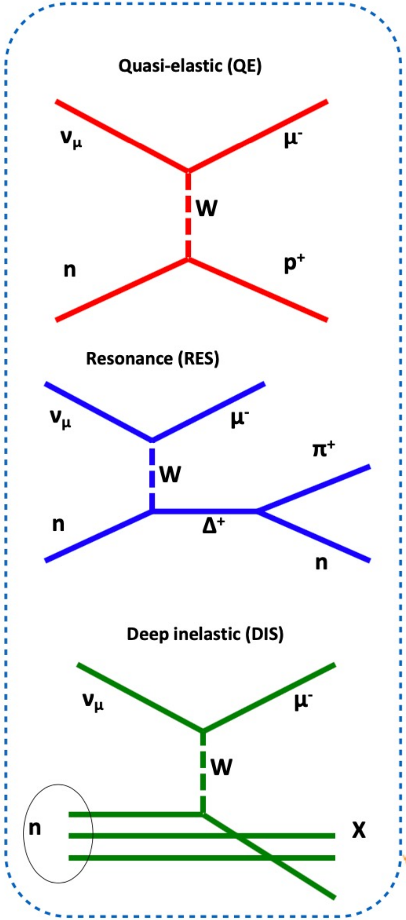
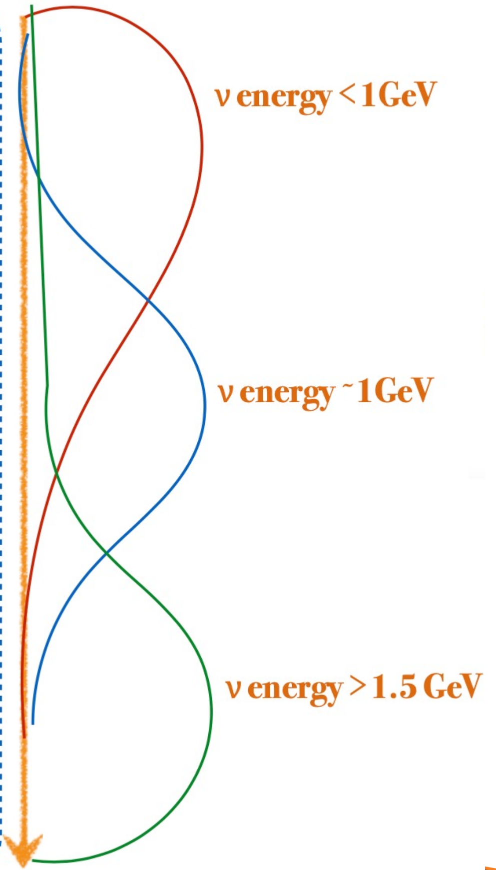
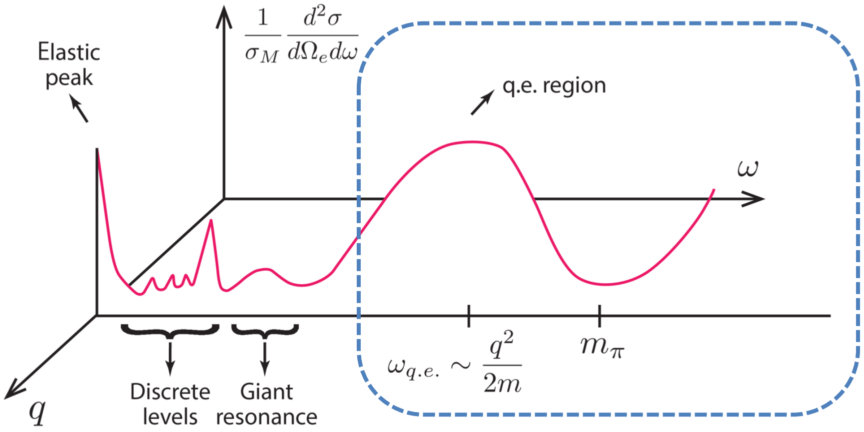
Let’s focus on backgrounds: neutrino-nucleus scattering

Neutrino-nucleon scattering

0.1-10 GeV



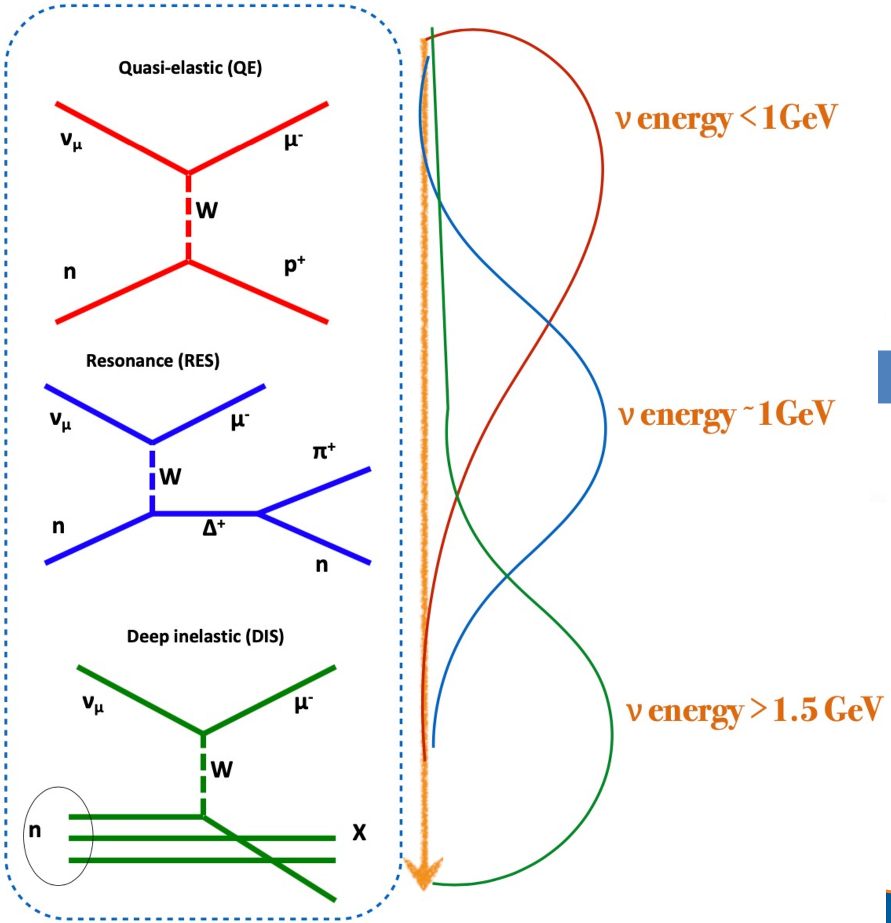




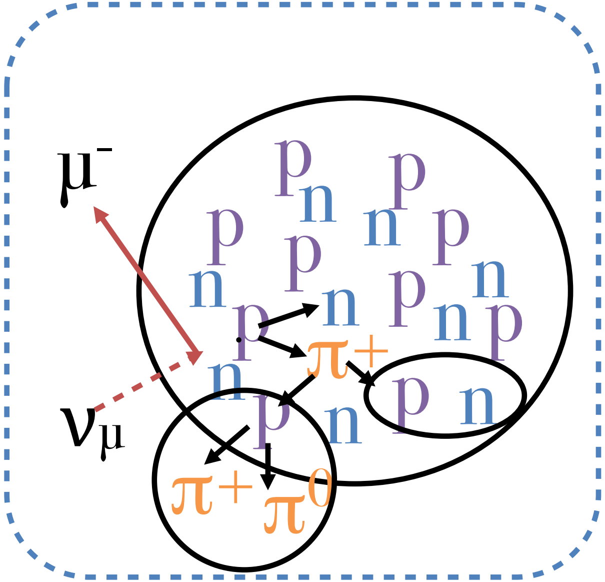
ω~10² MeV: accelerator neutrinos
ω~10¹ MeV: EM decay, Beta decay
ω<~10¹ MeV: nuclear rates for astrophysics

Neutrino-nucleus scattering

0.1-10 GeV



Is a many-body problem!



Empirical Models

Most of the current simulations being used by experiments are **empirical models**, even if originally implementing theory models, they have gone through **several iterations of fits to neutrino data**:

- GENIE
- NEUT
- NuWro

One can even choose which *tuning* to use, or use available tools for DIY (i.e. NUISANCE).

While *tunning* can be powerful, is **not trivial how to fit to the data -** neutrino energy being unknown and the Final State of the Interaction (FSI) being the observable, **we cannot uniquely associate a mechanism to the event**.

- Are we using the same data in the fits and the uncertainty estimations?
- How do we calculate the accuracy of these *tunings*?
- How can we extract information from cross-section data (which has been corrected to these MC) to learn about the theory?

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Some Known Weaknesses

Neutrino-induced pion production remains with large tensions data/MC and large systematics:

- ν_μ CCπ^+: there are strong disagreements among models and to the data, particularly at low momentum pions.

- ν_μ CCπ^0: very scarce data, we use same models as for charged pions, but many of these events comes from charge ex-change from charged pion production.

- NCπ^0: even less data and kinematical resolution worsens since only depends on the pi0 for the vertexing.

Meson Ex-change Current (MEC):

- CCMEC has been implemented using several approaches, still with the larger uncertainties.
- Current commonly used event generators don't have a NC-MEC besides the so-called *phenomenological MEC*. In some experiments, MEC has been used in tuning almost as a free parameter.

There is no clear approach to treat **nuclear binding energy**, which is being approximated by one parameter per nucleus, modelling its variations have shown to account for some discrepancies. But these variations are not incorporated in the model, but in the uncertainty budget (i.e. T2K, see arXiv:2303.03222).

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Unfortunately this list can continue…

A first-principles-based simulation: GiBUU

The success of rare event searches at neutrino experiments depends critically on a good knowledge of neutrino-nucleus interactions to characterize backgrounds and produce reliable systematics.

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

GiBUU provides a realistic treatment using the **same nuclear theory to describe many different nuclear reactions with the same set of parameters and physics assumptions.**

GiBUU uses a full relativistic formalism, neutrino interactions are treated as a two-step process:

- Interaction of the neutrino with a bound nucleon.
  - Simulates MEC for both CC and NC using the same model.
- Produced particles are **propagated through the nucleus** using the **BUU transport model**, including a full coupled-channel treatment of final-state interactions, this influences in particular the low-energy part of the hadron spectra by side-feeding (cannot be achieved by simple absorption models).

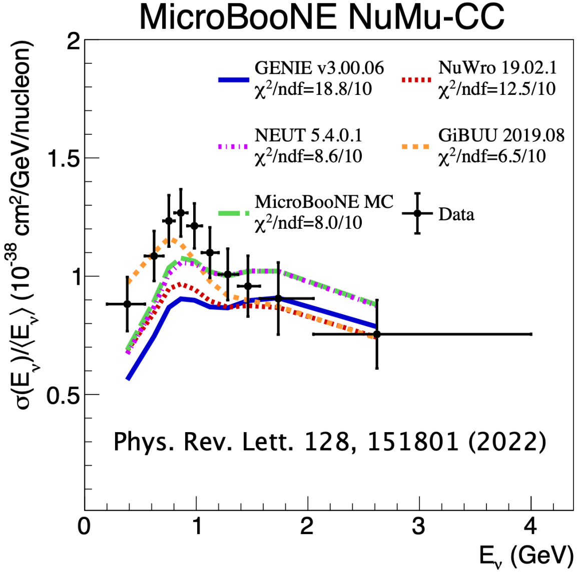
A first-principles-based simulation: GiBUU

The BUU equation describes the space-time evolution of a many-particle system under the influence of a mean-field potential and a collision term.

Originally developed to describe heavy-ions collisions, GiBUU has been extended **to describe interactions of pions, photons, electrons, and neutrinos.**

It has been successfully **tested against photon and electron interactions with nuclei data**, both are important prerequisites to describe neutrino scattering.

Without tuning any parameter to neutrino-nucleus data it has been compared well to very diverse neutrino data.



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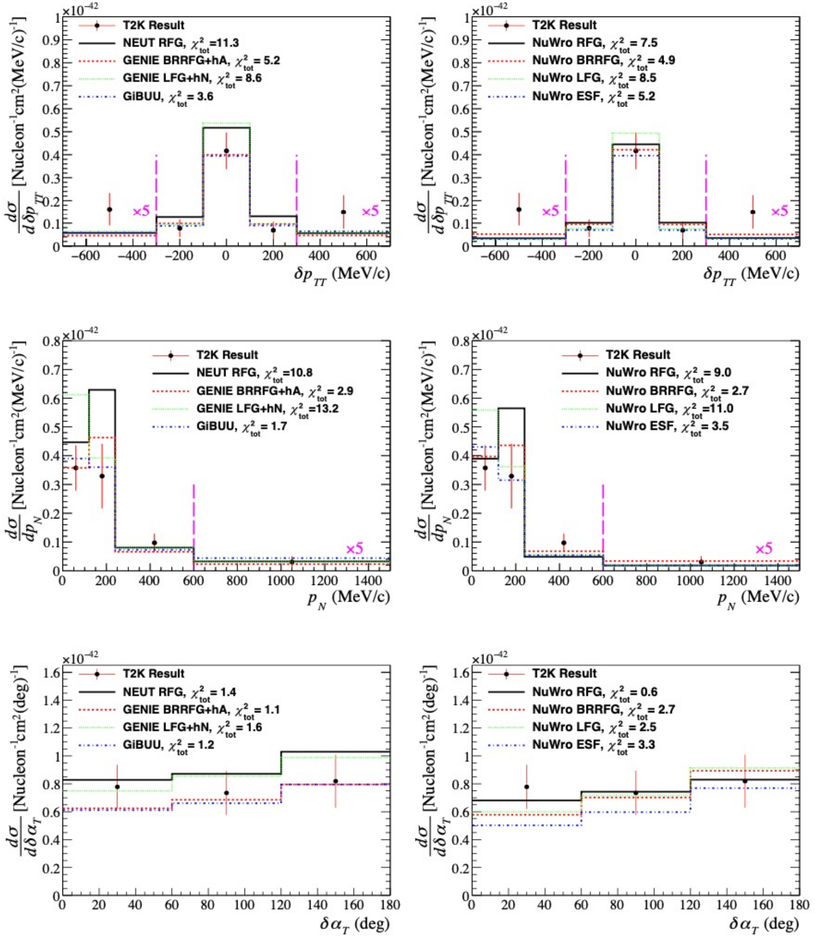
A first-principles-based simulation: GiBUU

First T2K measurement of transverse kinematic imbalance in the muon-neutrino charged-current single-π+ production channel containing at least one proton. Phys. Rev. D **103**, 112009.



Implementing GiBUU as an event generator

We have been working to implement GiBUU as an event generator in LArSoft (main framework to simulate LArTPC detectors), with the first application being the SBN program and closely collaborating with GiBUU developers.

Advantages:

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

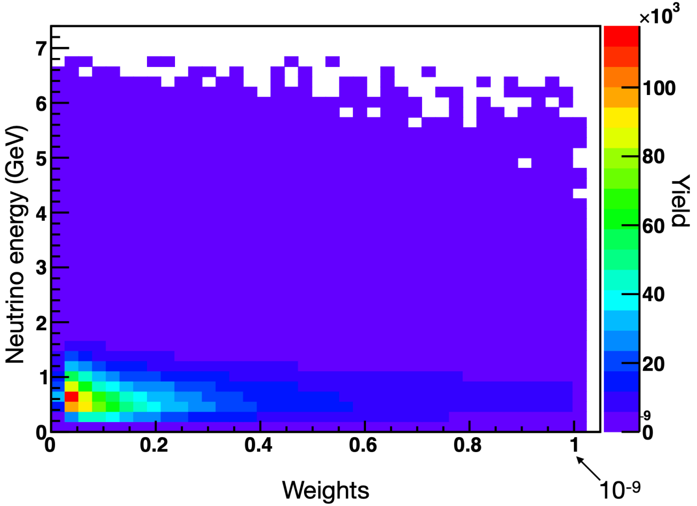
We converted the calculated cross-sections into event-by-event Monte Carlo, using acceptance-and-rejection method, and propagated through the detector using existing drivers from GENIE.

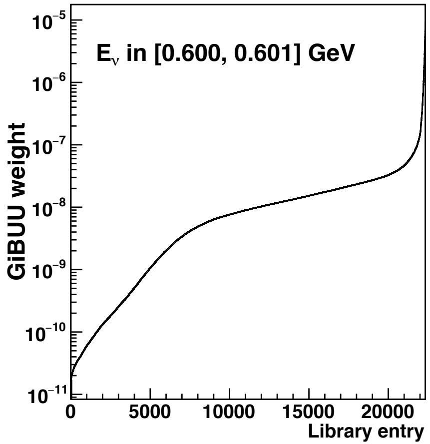
- The output comes as a weighted simulation with positive and negative terms (destructive interferences, relevant for higher resonances).

Implementing GiBUU as an event generator

Our approach:

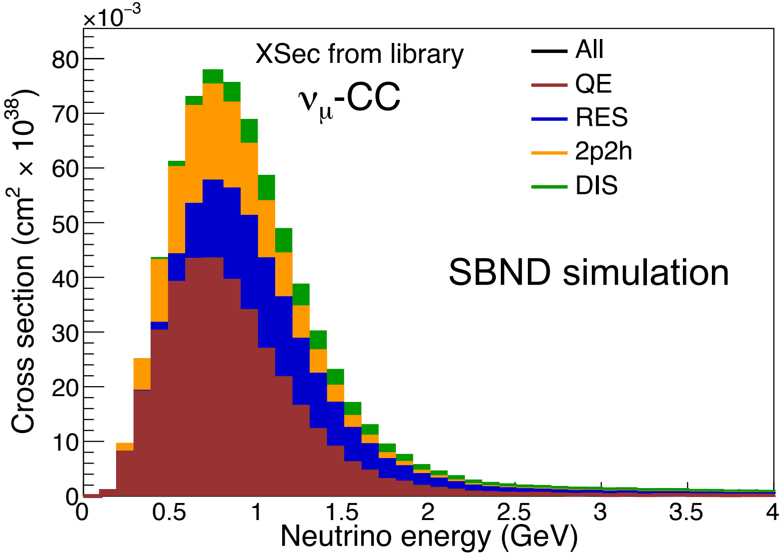
- We produced libraries from GiBUU using the flux (SBND) we were interested on.
- We used the flux and geometry drivers from GENIE to propagate those GiBUU events in the detector geometry.
- Since GENIE EvtLib does not handle weighted libraries and does not propagate the interaction mode of external models we developed our own EvtLib in an standalone code (can be used to implement other models and keep its interaction mode).

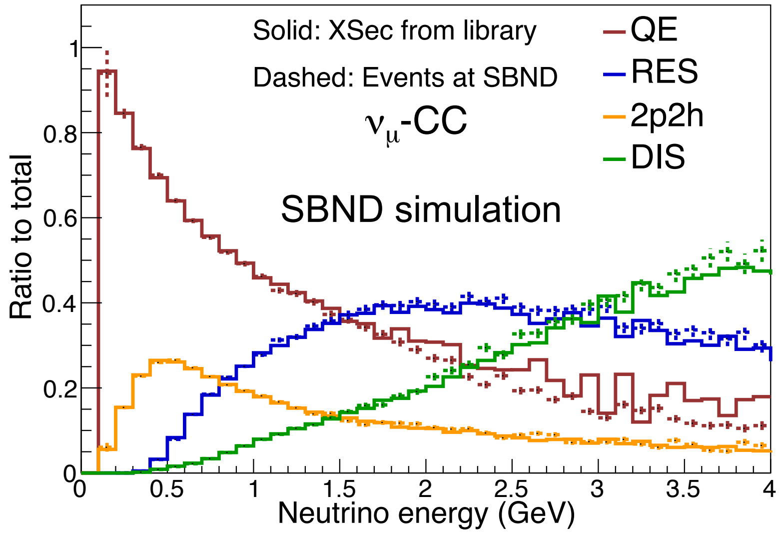




Implementing GiBUU as an event generator

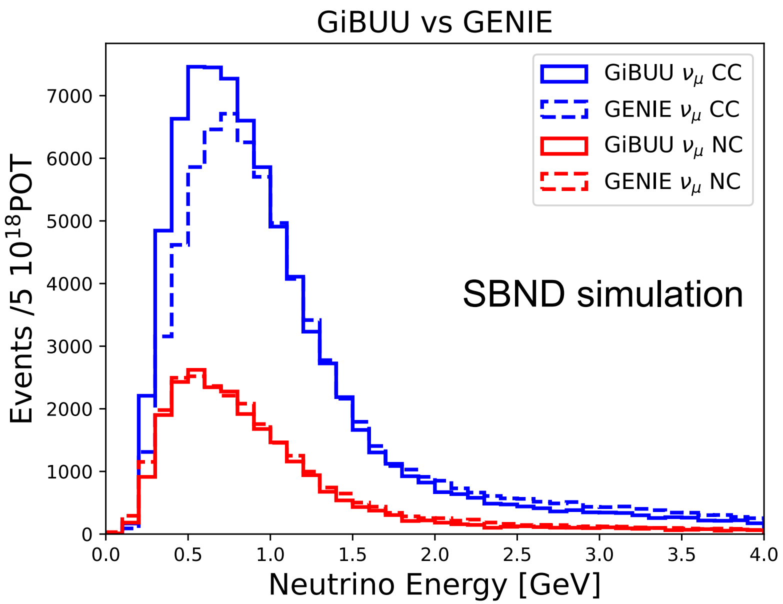
- The simulated events in ART have been propagated through the detector simulation, detector reconstruction and the analysis files (CAF files).
- Within the approach we follow it doesn't require more time that other generators.

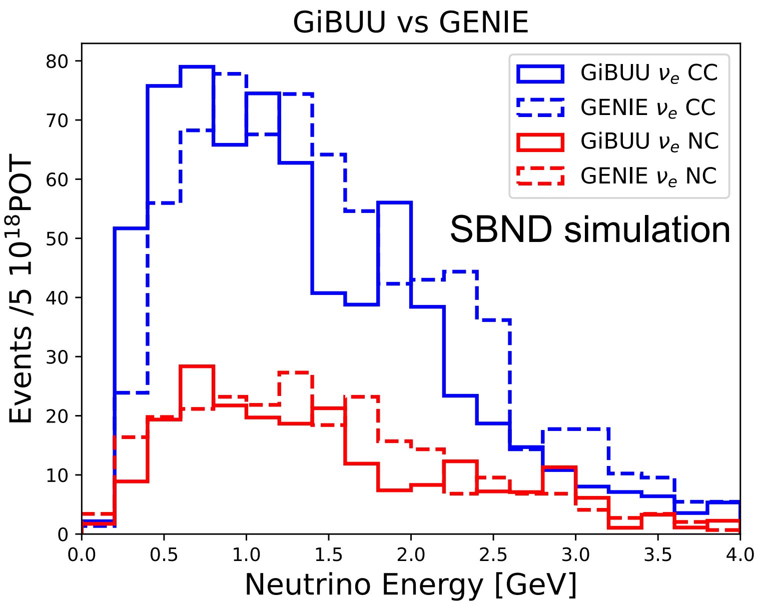




GiBUU vs GENIE

- Differences between GENIE and GiBUU models are visible in the inclusive samples, and can be very important for specific exclusive topologies.
- Currently we are working on the uncertainties in GiBUU.





Model constraints

- A first-principles event generator is very much needed to account for neutrino interactions produced by the beam and to have robust uncertainties.
- In a nucleus like argon, around 3x carbon, nuclear transport cannot be neglected.
- Isospin in argon has two units difference with respect to the most traditional neutrino-nucleus scattering data, accounting for it is critical as these effects will show up.
- We proved our approach using GENIE drivers to propagate GiBUU events can be a good solution to unify infrastructures.
- The EvtLib developed can be used to also propagate other models as BSM keeping their interaction mode, which would make substantial improvement on the robustness of event selection for rare signals.

Data Constraints

- For oscillations in Far Detector analyses (FD) there has been two different approaches followed:
- Simultaneous fits- NOvA
- Sequential fits – T2K

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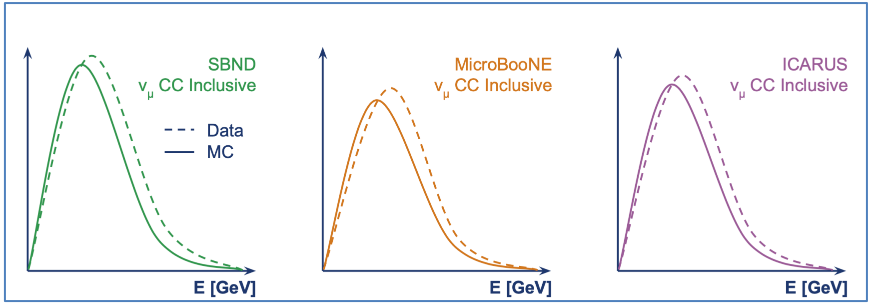

Image credit: Rhiannon Jones

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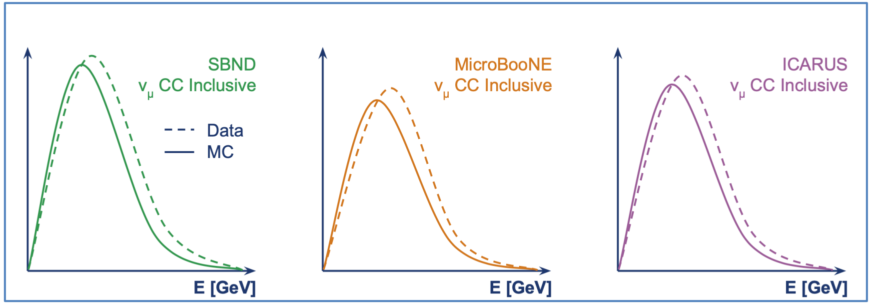
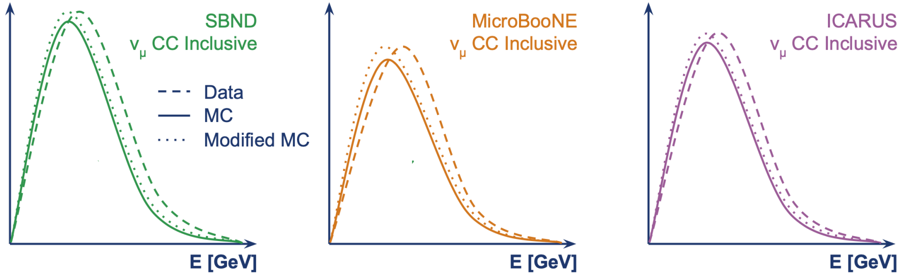


Image credit: Rhiannon Jones

Simultaneous fit



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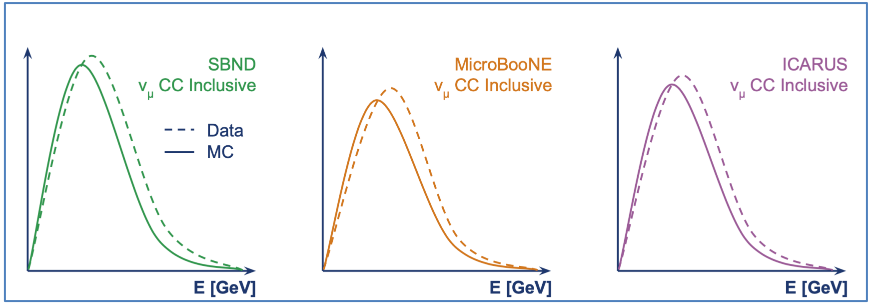
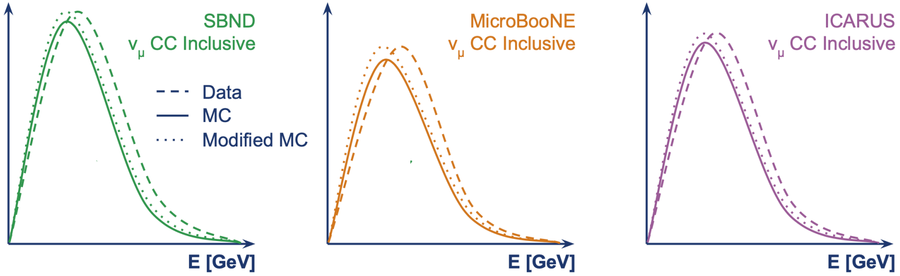


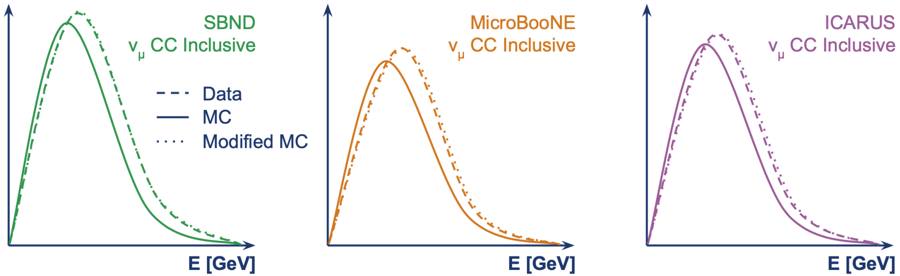
Image credit: Rhiannon Jones

In sequential fits, a new MC (post-fit) is produced and then used for the anomaly search at FD.

Simultaneous fit



Sequential fit



Data Constraints

While the same procedure will be difficult to use in BSM searches, data constraints should be developed.

- For **BSM searches at FD**, a good data constraint should incorporate near detector (ND) data extrapolation (event rates & covariance).
    - A sequential fit would be a good approach.
    - Fitting techniques and kinematical variables to fit at each detector can be different.

- For **BSM searches at ND**:
    - A set of data side-bands should be used in simultaneous fit with the signal sample.

There is no reason to use the same event selection at ND (for sequential and/or simultaneous fit) than in Oscillations.

- the constraint should enhance the topologies that are signal-like and background.

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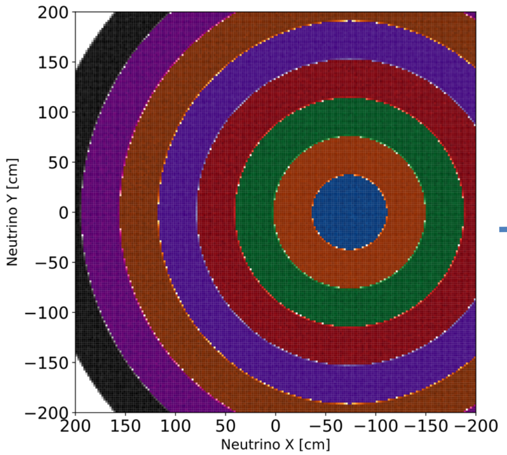
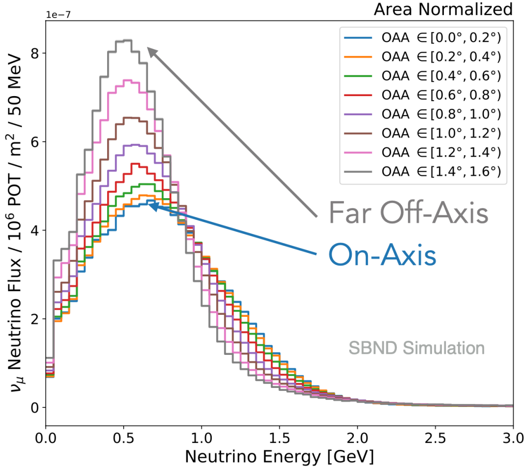
Data Constraints

Some of the current experiments present features that should be exploited in the data constraints, as the PRISM configuration (SBND for SBN, ND-LAr for DUNE, IWCD for HK). Important to exploit all design advantages.

Slightly off-axis SBND allows to perform measurements with large off-axis angles.





Larger off-axis angle produce narrower beams with lower mean energy.

Less resonant production expected at the higher OAA.

I won't talk on PRISM feature as this is already being covered by many colleagues

Summary

- Background constraints have a large dependency on how good is the background model:
  - Empirical models can be useful but they limit the robustness of anomaly searches and their uncertainties.
  - We currently don't have any metric to assess the goodness of any of these tunings or cannot explain why the different parameters of the models need to change experiment-to-experiment.
  - Implementing alternative models, such a GiBUU, provides critical information about neutrino-nucleus scattering and offers an unify description of the scattering processes with an unify model.

- Data constraints are essential in any data analysis,
  - It is however critical to define data samples (similarly as we don in oscillation analyses) to provide a background model before we compare to the signal selection.
  - Searches at ND and FD doesn't need to follow the same approach.

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