

Physics Modeling, Data-driven Optimization and Systematics

SLAC neutrino group
Future planning 2024

Physics modeling and systematics

— Mainline (accelerator) neutrino analyses

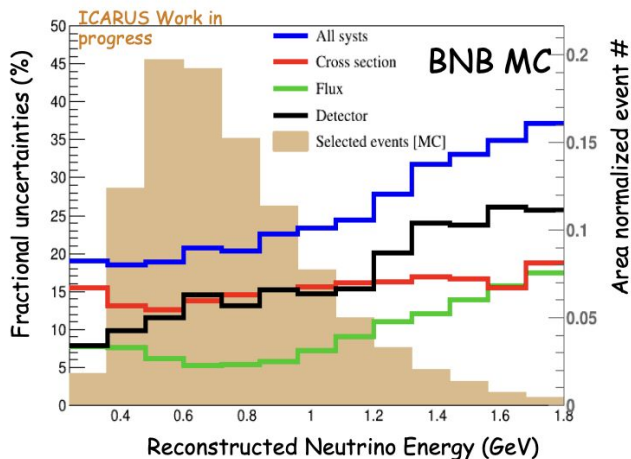
Flux

Neutrino interaction

Secondary interaction

Detector

ICARUS Example: BNB $\nu\mu\text{CC}$ $1\mu\text{Np}$ Pandora selection



Reconstruction

Physics modeling difficulties and model optimization

Flux

- Hadron cross section (nuclear effect)
- Hadron production (geometry, material)
- Horn focusing
- Alignment

- Near and far detectors joint analyses
- PRISM
- Flux related experiments:
 - Hadron production with thin and replica targets (NA61, EMPATHETIC)
 - Beam monitoring (ENUBET)

Neutrino interaction

- No ab-initio calculation of neutrino-nucleus interaction
- Different processes are modeled separately and glued together
- No global consensus among models
- Comparison to data is not straightforward
- Underfunded field (neutrino interaction modeling)
- Neutrino scattering data
 - Topology vs. neutrino interaction channels
 - Model independent extraction
 - Data-data comparison(!)
- Electron scattering data
 - How to relate to ν scattering
- Generator tuning
- Model development
- PRISM

Secondary interaction

- Hadron cross section with a lot similar difficulties

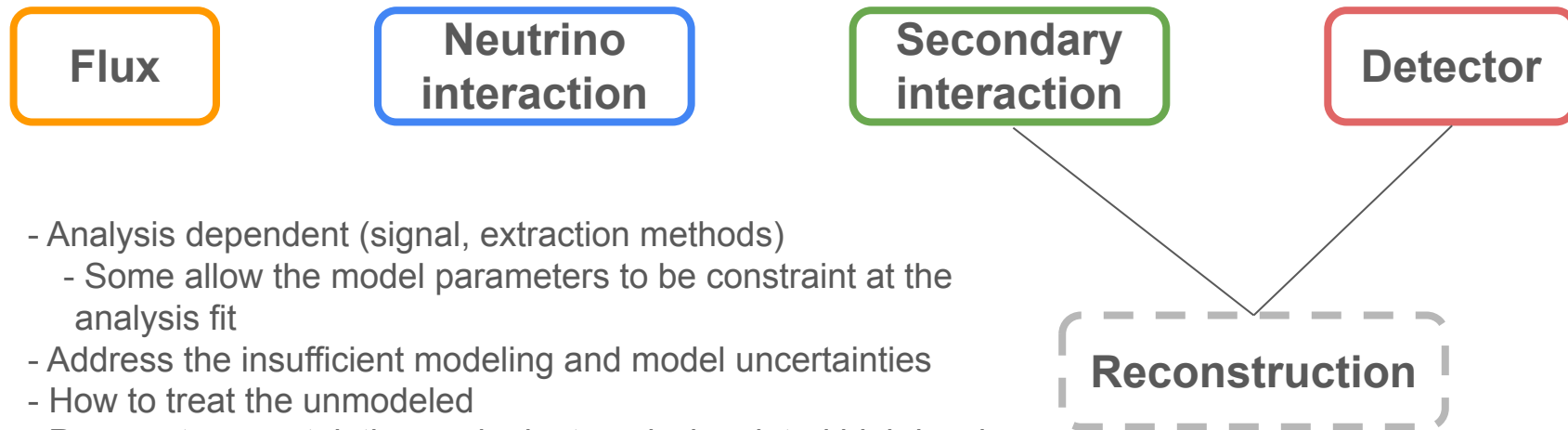
- Hadron cross section measurements with test beam (relevant energy ranges)
 - FSI and G4
 - Model tuning

Detector

- Energy deposition to charge signal
- Model charge drift, light signals and electronic readout

- Calibration
 - Different processes are entangled in the readout
 - Some measurements are old, some are wildly different
 - Light propagation: G4 in LUT
 - Would it improve the same experiment?

Physics modeling and systematics



- Analysis dependent (signal, extraction methods)
 - Some allow the model parameters to be constraint at the analysis fit
- Address the insufficient modeling and model uncertainties
- How to treat the unmodeled
- Propagate uncertainties vs. look at analysis related high level variables directly
- Correlation between systematics
- Event/bin weight responses of the change (splines, universes...)
- “Sidebands” (background control samples) to constrain background modeling

Physics modeling: Implementation

Flux

Neutrino
interaction

Secondary
interaction

Detector

- We are working on detector simulation implementation (DUNE ND)
 - Plans to improve the simulation logic
- Future concern: unified implementation across experiments or different parts of the experiment
- Simulation efficiencies:
 - Surrogate model (detector: light propagation, neutrino interaction: FSI calculation)
 - Rock muon simulation
 - Fake data sample: Generator-to-generator mapping
- Any interests working on physics modeling (simulation) for the other parts of the pipeline?

Physics model optimization and systematics

Flux

- Hadron cross section (nuclear effect)
- Hadron production (geometry, material)
- Horn focusing
- Alignment

- In general, it seems there's not much (not enough) effort on flux modeling
- Potential use of differentiable detector simulation: horn focusing, beam alignment (Geant4 simulation)
- Potential ML use: PRISM
- Tuning the hadron production (differentiable simulation?)
- Our group is not very connected to this effort at the moment.

- Near and far detectors joint analyses
- PRISM
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Physics model optimization and systematics

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 - Generator tuning
 - Model calculation
 - PRISM
- Neutrino cross-section measurements are generally towards the direction of better neutrino interaction modeling and systematics.
 - Unclear path from measurements to model optimization
 - Generator tuning is not ideal if we care about the underlying physics (as we know we probably mismodel) However, the process can be largely improved.
 - Why don't we try to build a grand surrogate model to predict the global data? (we don't have a lot of data)

Physics model optimization and systematics

Secondary interaction

- Hadron cross section with a lot similar difficulties

- Hadron cross section measurements with test beam (relevant energy ranges)
- FSI and G4
- Model tuning

- Hadron cross-section measurements are supporting better secondary interaction modeling and systematics.
- Measurements at relevant energies: p, pi, n, K...
 - Is it too late?
 - Suitable beams
- Model fitting (generator + Geant4)

Physics model optimization and systematics

Detector

- Energy deposition to charge signal
- Model charge drift, light signals and electronic readout
- Calibration
 - Different processes are entangled in the readout
 - Some measurements are old, some are wildly different
 - Light propagation: G4 in LUT
 - Would it improve the same experiment?
- Detector calibration is difficult
 - Detector physics processes are entangled in the readout
 - Control samples
 - Consistency, and whether the optimization is used in the same experiment
- Detector systematic is difficult
 - Uncertainty propagation? Control samples?
 - Coverage, double counting
 - How to build weight response efficiently?
- Differentiable simulation?
 - To cover simulation, calibration (low level reco) and systematics
 - The unmodeled?

Physics modeling optimization and systematics for BSM and others

- Similar logics and inherit the difficulties for the overlap parts
- Additional concerns
 - How to control the background unbiasedly
 - Signal background distinction for the control sample

Physics modeling, optimization, systematics: Timeline

Flux

**Neutrino
interaction**

**Secondary
interaction**

Detector

- Related to the sensitivity of an experiment (critical)
- Until the end of an experiment, should be continuous effort
 - However, we are building things on blocks that we don't know if the community will deliver (no clear path for solving the bottleneck)
 - For the breakthrough, the earlier, the better
- Scattered effort
- Recognition