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Measuring Muon Antineutrino Charged-Current Interactions Without Mesons in the Final State, in the NOvA Near Detector

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on behalf of the NOvA Collaboration

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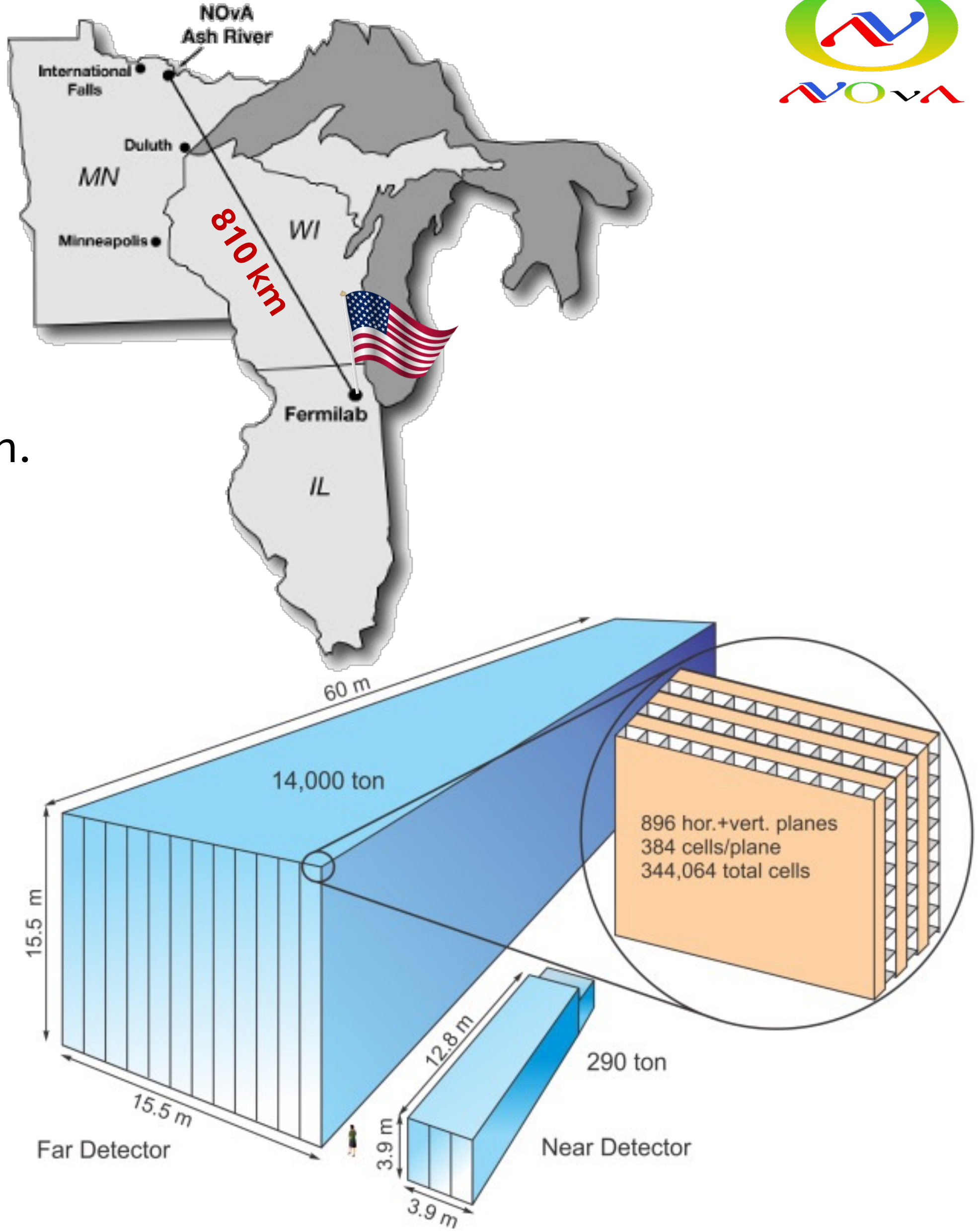
The NOvA Experiment

- Long baseline neutrino experiment, consisting of:
  - High purity (anti)neutrino beam produced at Fermilab, Illinois.
  - Forward horn current (FHC) mode for a muon neutrino (ν_μ) beam.
  - Reverse horn current (RHC) mode for a muon antineutrino ($\overline{\nu}_\mu$) beam.
  - Near Detector: 1km from the source.
  - Far Detector: 810km from the source, at Ash River, Minnesota.

- The two detectors are both 14.6 mrad off-axis and are functionally identical, which helps to reduce systematic uncertainties.

- Primary goals:
  - Observe and measure the oscillation of muon neutrinos to electron neutrinos.
  - Determine the neutrino mass ordering.
  - Investigate the matter / antimatter asymmetry.



Why are Cross Sections Important in Oscillation Analyses?

To understand neutrino oscillations, we need to make precision measurements of the neutrino mixing angles (e.g. θ_{23} and θ_{13}) and mass splittings (e.g. Δm^2_{32}):

Oscillation probability (electron neutrino appearance)

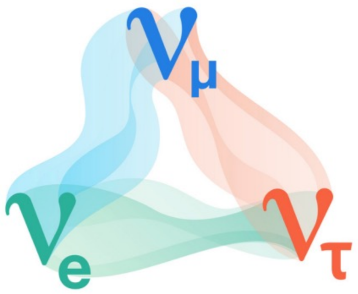
$$P(\nu_\mu \to \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{1.27\, \Delta m^2_{32}\, L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]}$$

L Distance between detectors
E Mean neutrino beam energy

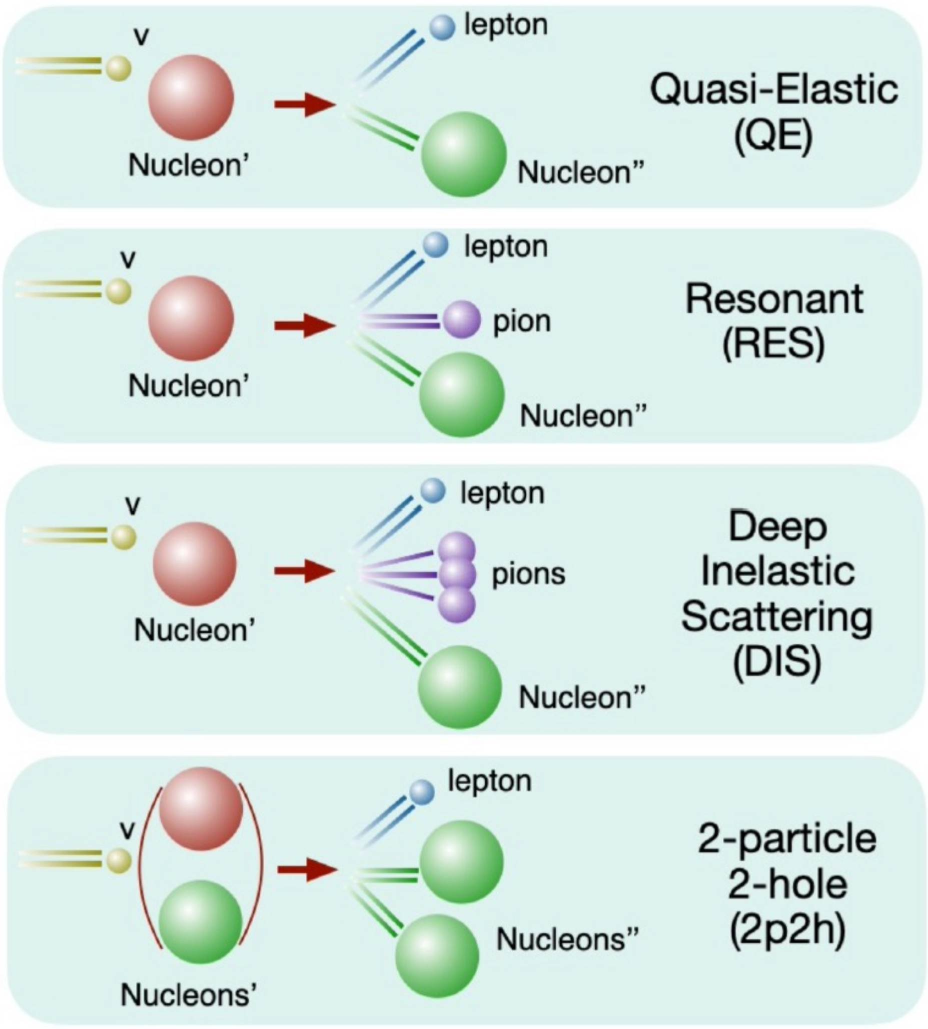
Measured event rate

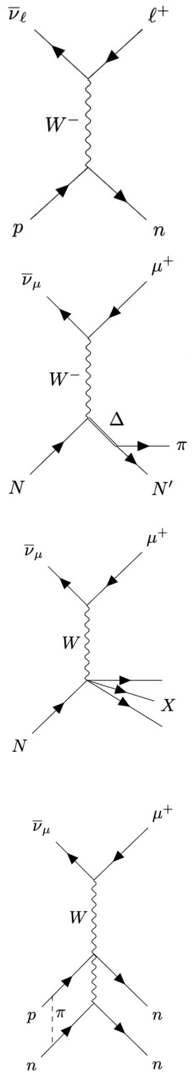
$$R(\vec{x}) = \int_{E_{\min}}^{E_{\max}} \Phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_\mu \to \nu_e)$$

$\Phi(E_\nu)$	Neutrino flux
$\sigma(E_\nu, \vec{x})$	Cross section (probability of neutrino-nucleus interaction)
$\epsilon(\vec{x})$	Detector response / efficiency



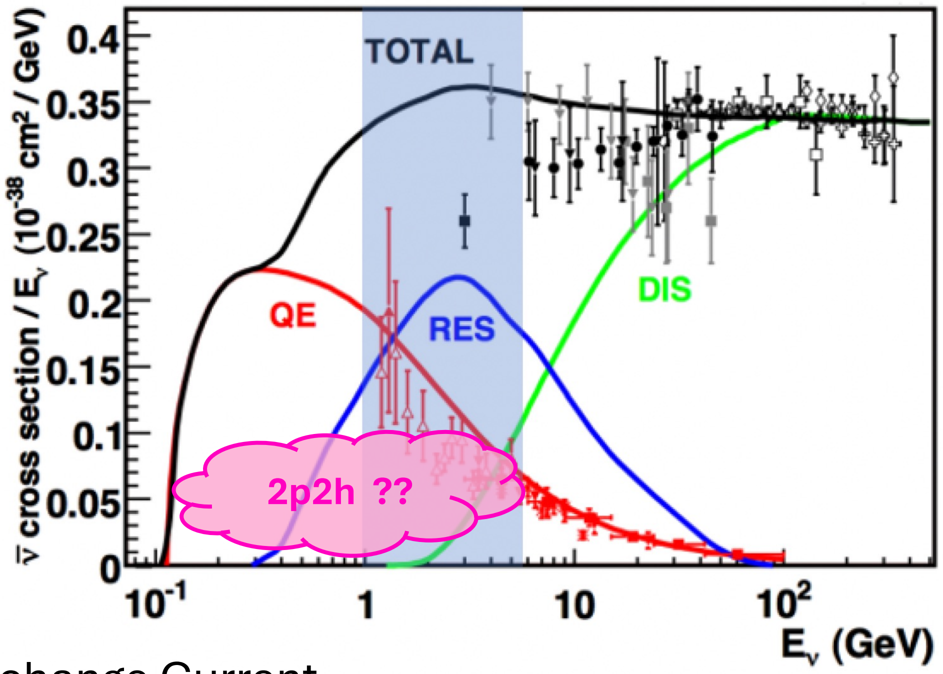
Neutrino Interactions





L. Cremonesi
(Neutrino 2020)

NOvA's neutrino flux lies in the transition region between the main interaction processes.



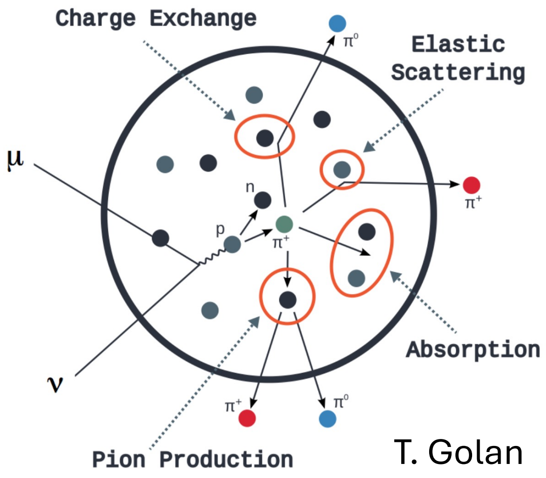
J. Formaggio and G. Zeller
(arxiv:1305.7513) *(adapted)*

The Meson Exchange Current (MEC) model is a leading model to describe the 2p2h process.

Why is a Zero-Meson Antineutrino Analysis Interesting?

- We can achieve a high sample purity: charged-current (CC) ν_μ events generally produce protons (easily misidentified as pions), but CC $\overline{\nu}_\mu$ events mainly produce neutrons (largely go unseen in NOvA's detectors).
- Study 2p2h processes in the antineutrino sector and compare different QE and MEC models.
- Antineutrino cross sections are smaller by a factor of ~ 2 – 3, but NOvA has high statistics, and we can keep statistical uncertainties reasonably small.
- In probing the low energy region close to the nucleus, we may also gain some insight into final-state interactions.

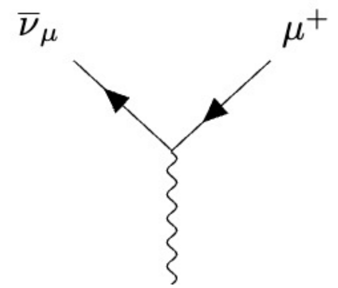
Final state interactions due to re-scattering inside the nucleus can change the kinematics of the outgoing hadrons.



T. Golan

Zero-Meson Antineutrino Analysis

- Signal: CC $\overline{\nu}_\mu$ event with no true mesons (e.g. pions or kaons) above a threshold energy of 100 MeV (at lower energies, NOvA's pion reconstruction has a low efficiency).



- Background:
    - Neutral Current interactions.
    - Interactions from wrong-sign (ν_μ) component of the beam.
    - All events that contain mesons with energy > 100 MeV in the final state.

- Deliverables:
    - Double-differential measurement of muon kinematics (longitudinal / transverse momentum).
    - Single-differential measurements in the derived variables Q^2 (four-momentum transfer squared) and E_ν (incoming neutrino energy).

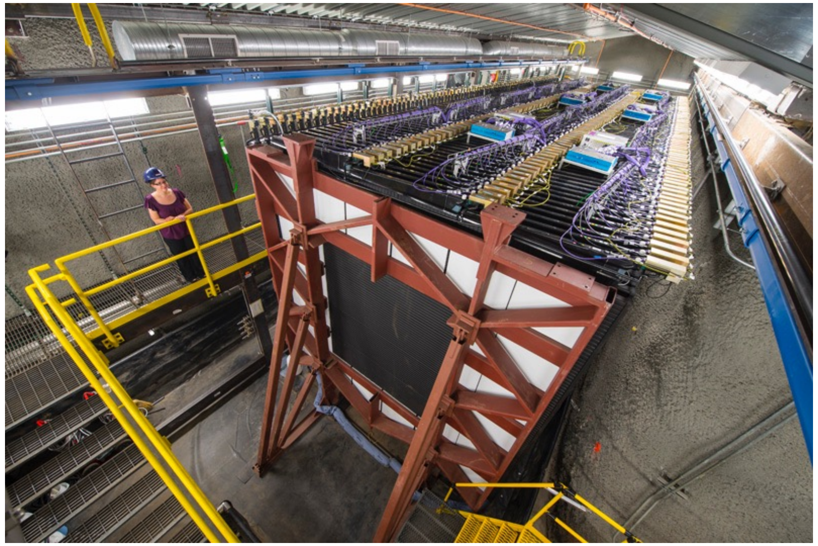
- This is a blind analysis, and we have not yet looked at data.

Measuring a Cross Section

$$\left(\frac{d^2\sigma}{dP_L\, dP_T}\right)_i = \frac{\sum_j U_{ij}\left[N^{sel}(P_L, P_T)_j\, P(P_L, P_T)_j\right]}{\epsilon(P_L, P_T)_i (\Delta P_L)_i (\Delta P_T)_i\, N_{targets}\, \phi}$$

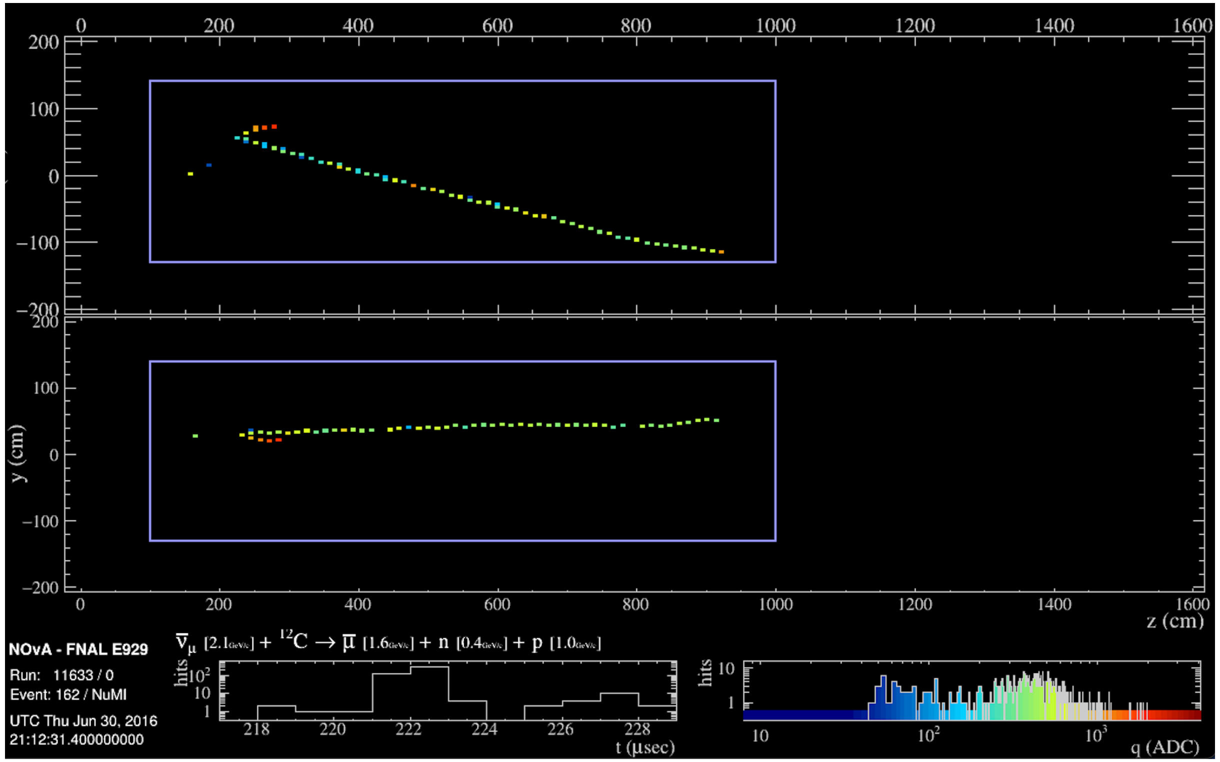
$N^{sel}(P_L, P_T)_j$	Number of selected events
$P(P_L, P_T)_j$	Purity of sample
U_{ij}	Unfolding Matrix – to migrate from reconstructed to truth space
$\epsilon(P_L, P_T)_i$	Efficiency of sample
$(\Delta P_L)_i(\Delta P_T)_i$	Bin width of each variable
$N_{targets}$	Number of targets in the detector
ϕ	Incoming neutrino flux

NOvA Near Detector

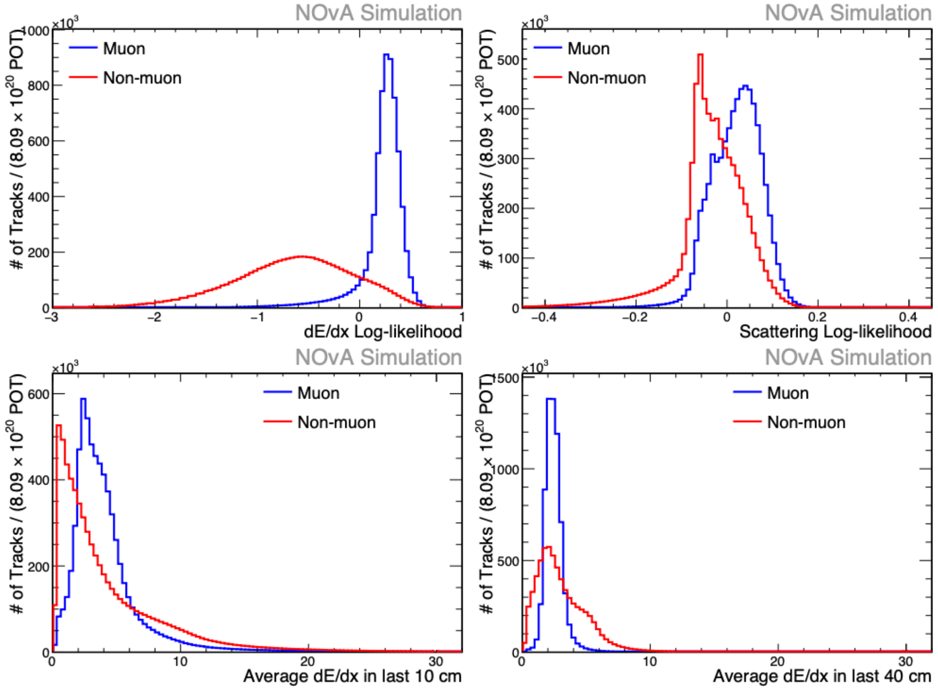


Machine Learning in NOvA

NOvA uses **Convolutional Visual Networks** (CVNs) to classify particles and events based on the topology, without the need for a detailed reconstruction. Particle CVNs are trained on single particles, to reduce model dependence.



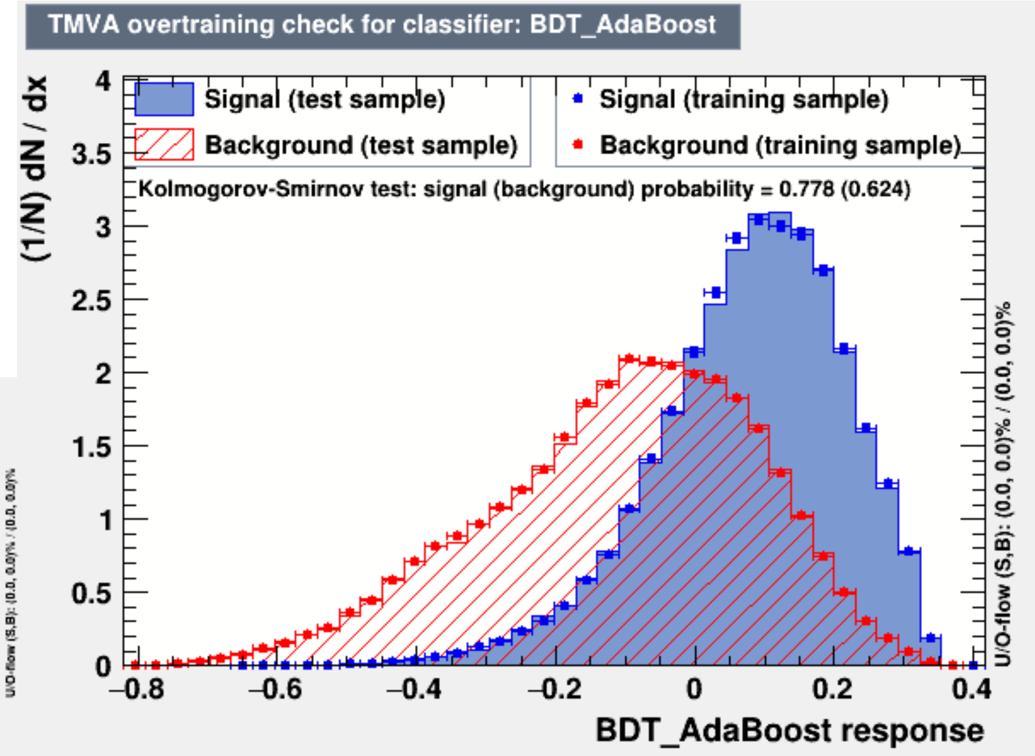
MuonID is a boosted decision tree (BDT) used to identify the likelihood of a track being a muon, with the inputs being the the dE/dx log-likelihood, scattering log-likelihood and average dE/dx near the end of the track.

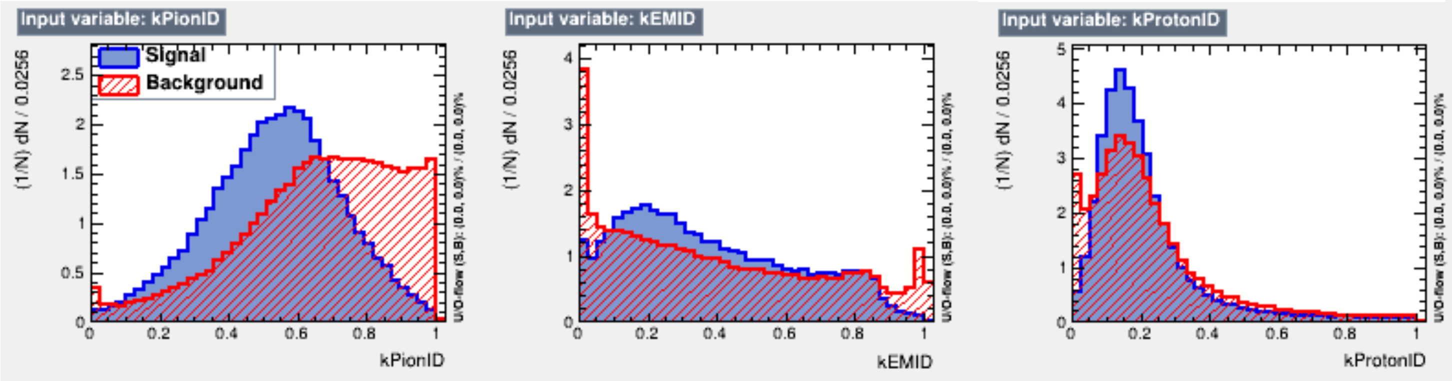


MERMAID: Identifying Events without Mesons

- **Machine-Enhanced RHC Meson Abolition ID** – a novel BDT trained to identify events without mesons. It is trained on events which have more than one reconstructed track (muon + hadron).

- Inputs include: the CVN likelihood scores for a particle in the event being a pion, proton or electromagnetic (sum of the electron and gamma likelihoods), the width of any identified shower and the gap between the interaction vertex and the shower.



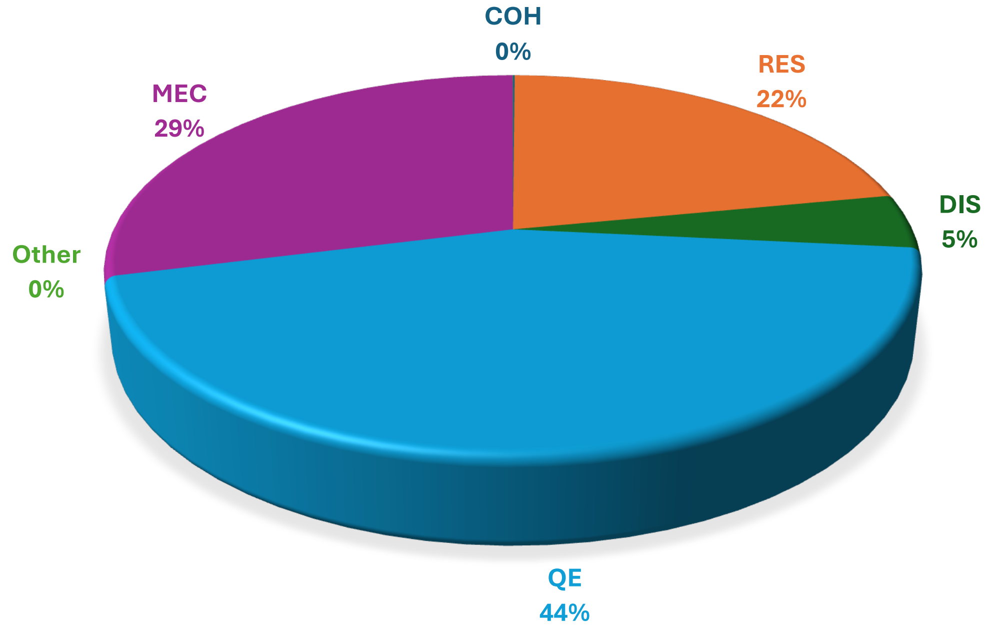


Selection Criteria

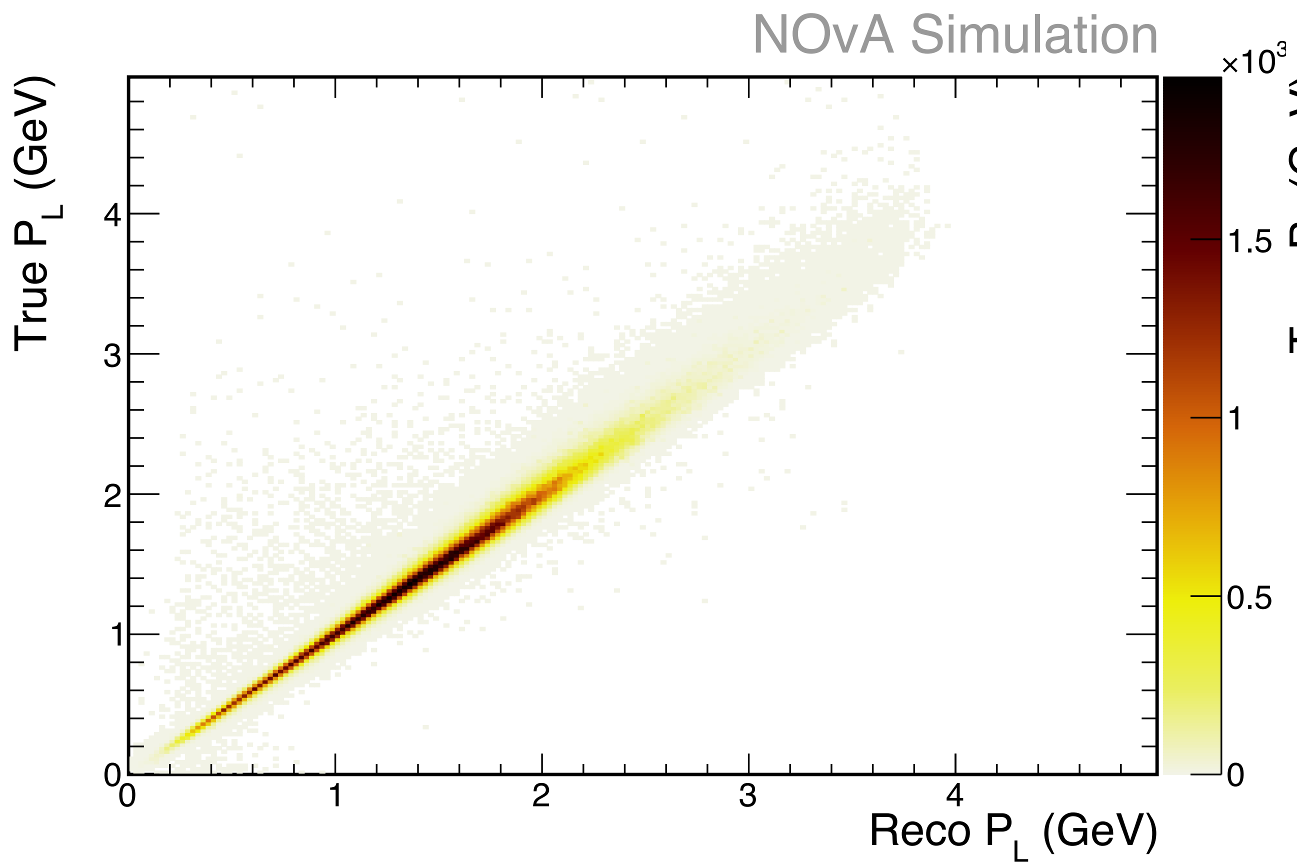
- Data quality, e.g. an event must contain a minimum number of hits in the detector.
- The muon track must be fully contained in the detector to allow for energy estimation, and the interaction vertex must lie in the fiducial volume of the detector.
- Optimised cut based on the MuonID score, to ensure that it is a CC event.
- The event must contain either one track (the muon) or, if there are multiple tracks, it must pass the MERMAID selection (BDT score of ≥ 0.04).

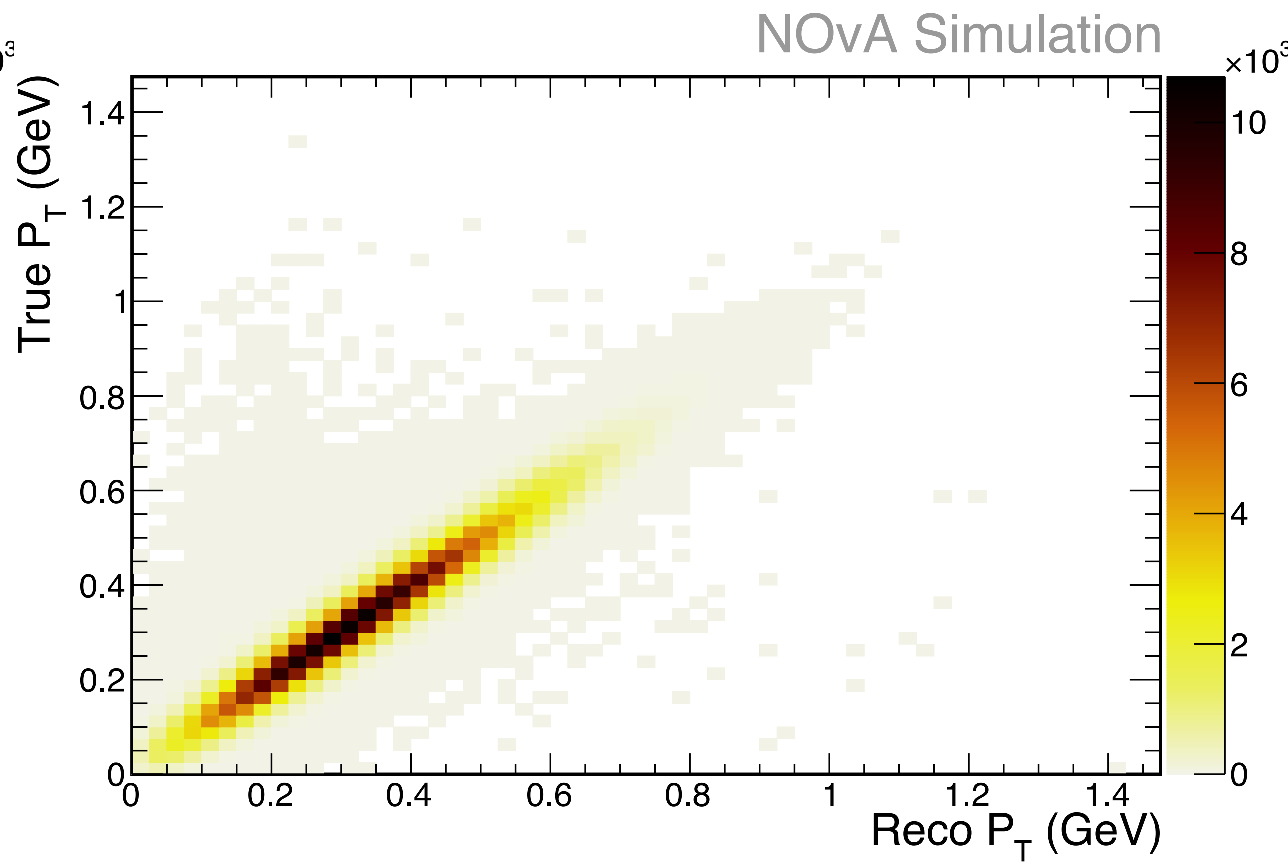
Signal Events: 542,576
Background Events: 165,217

Purity: 76.7%
Efficiency: 27.6%



Muon Longitudinal and Transverse Momentum



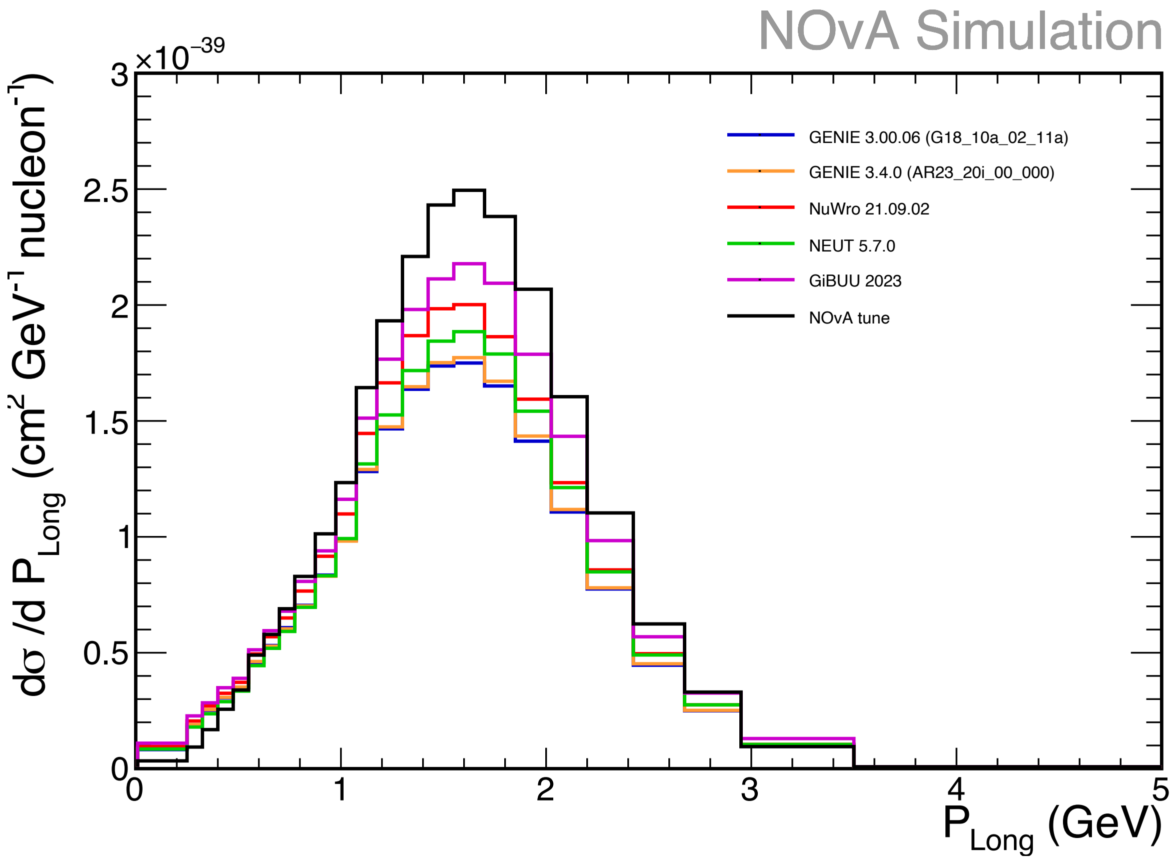


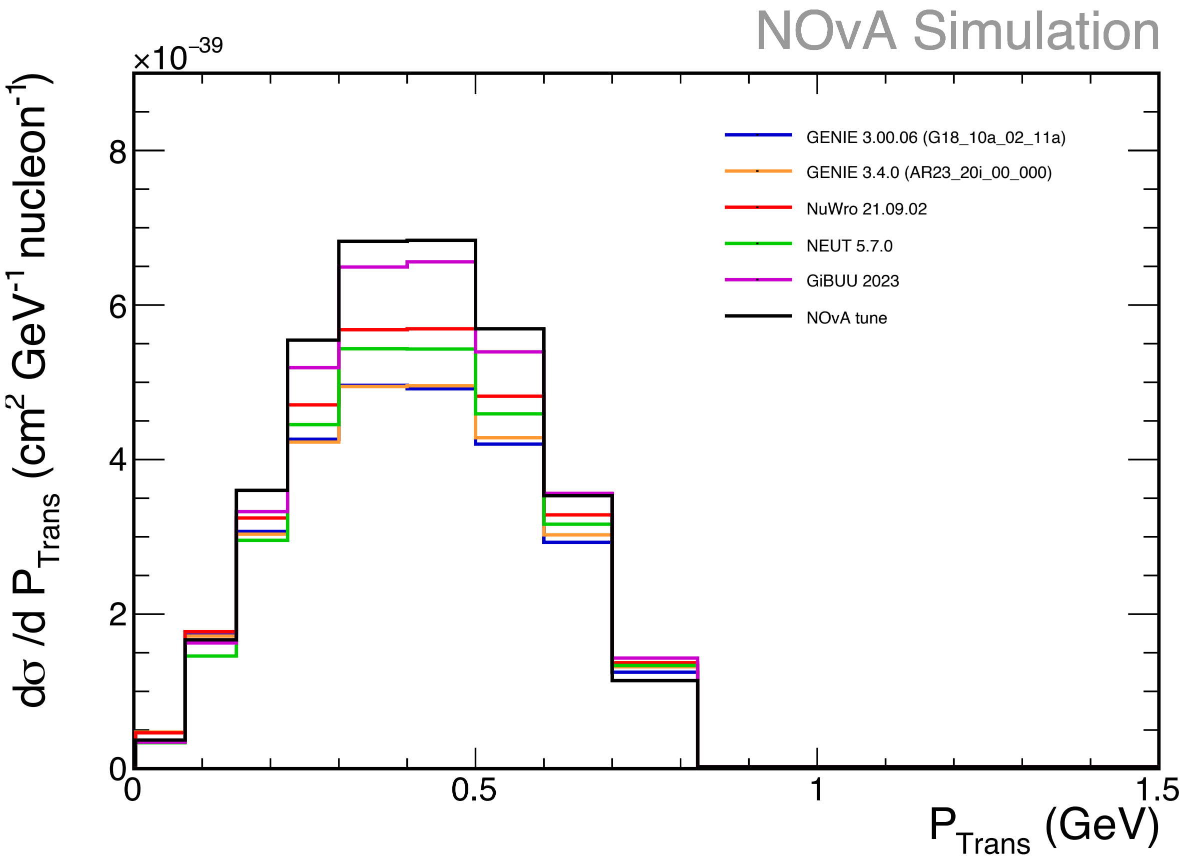
- Migration matrices for these variables are strongly diagonal, with good resolution.
- We will therefore be able to report results in a large number (~215) of 2-dimensional bins as a double-differential cross section.

Neutrino Event Generators

Generator	Initial State	QE	MEC	RES/COH	DIS	FSI
GENIE 3.00.06 **G18_10a_02_11a**	Local Fermi Gas (LFG)	Valencia	Valencia	Berger-Sehgal (BS)	Bodek-Yang (BY)	hA
GENIE 3.4.0 **AR23_20i_02_11b**	Spectral function LFG	Valencia	SuSAv2	BS	BY	hA
NuWro 21.09.02	LFG	Llewellyn-Smith (LS)	Valencia	NuWro RES model	BY	NuWro FSI model
NEUT 5.7.0	LFG	Valencia	Valencia	BS / Rein-Sehgal	BY	Custom semi-classical intranuclear cascade (INC)
GiBUU 2023	Modified LFG	Dipole Form Factor, RPA corrections	Semi-inclusive electron scattering data	MAID (electromagnetic form factors)	Data-driven GiBUU model	BUU transport model

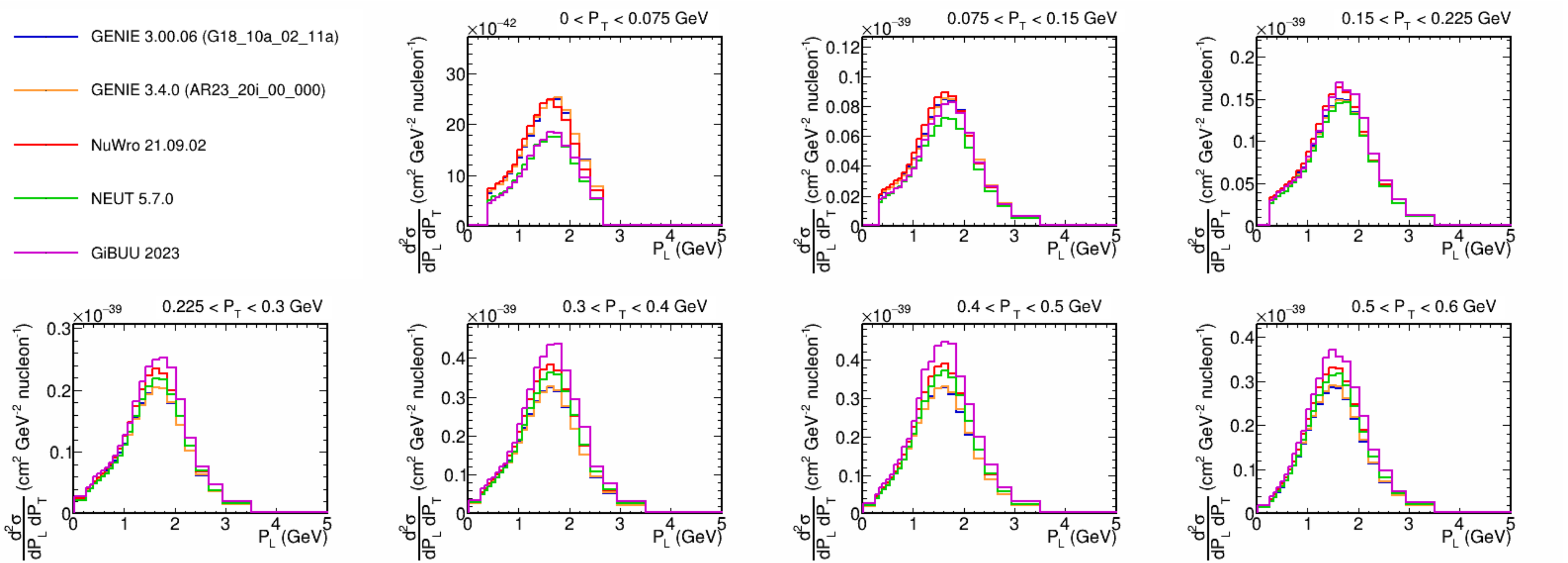
Muon Longitudinal and Transverse Momentum

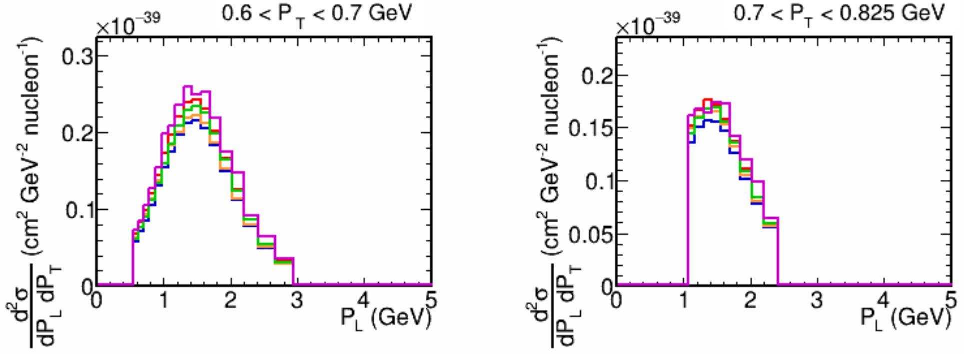




- Consistent shape, but the NOvA-tuned GENIE simulation generally has slightly larger cross sections.
- This is consistent with NOvA's inclusive analyses for both neutrino and antineutrino mode.
- GiBUU, followed by NuWro, appear closest to the NOvA-tuned MC.
- It will be fascinating to see what the real data will show!

Double Differential Cross Section





- The largest discrepancy between models is at low P_T, where NEUT and GiBUU predict lower cross sections than GENIE and NuWro.
- At medium P_T, GiBUU predicts a noticeably larger cross section, with other generators showing similar performance.
- Generators appear to have a similar performance at higher P_T.

Conclusions

- New measurement of Zero-meson antineutrino charged-current interactions in the NOvA near detector.

- We will report a double-differential cross section in muon kinematics (longitudinal and transverse momentum), as well as single-differential cross sections in the derived variables Q^2 and E_ν.

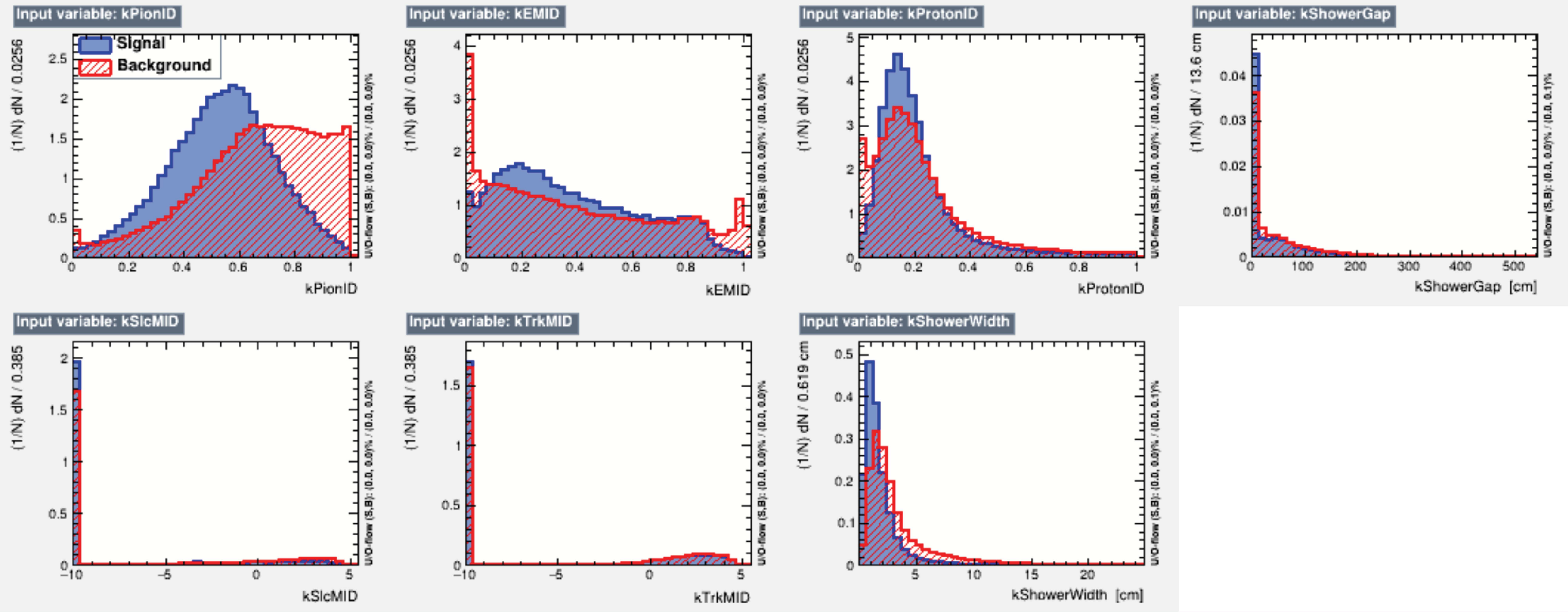
- A range of FSI, QE and MEC models used by different generators can be tested and evaluated with this measurement.

- Next Steps:
  - Unfolding and Fake Data Studies
  - Detailed study of Systematic Uncertainties
  - Unblinding – finally look at the real data!
  - Model comparisons

Thank you, on behalf of The NOvA Collaboration

Backup

MERMAID: Input Variables



Incoming Neutrino Energy and 4-momentum transfer