

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

IOP Joint APP, HEPP and NP Annual Conference 2024

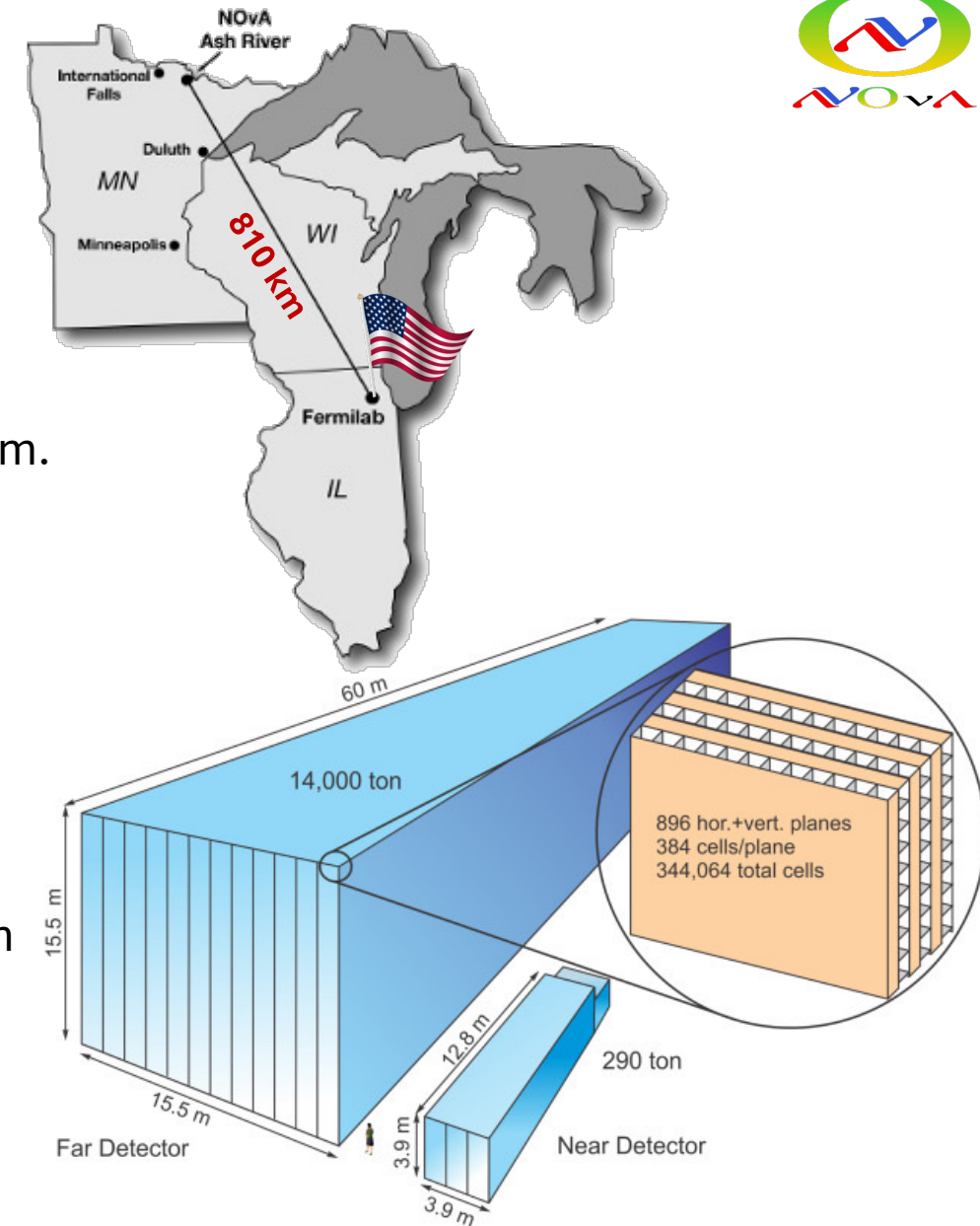
Kevin Vockerodt
on behalf of the NOvA Collaboration

Supervisor: Dr Linda Cremonesi

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 ($\bar{\nu}_\mu$) 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_{32}^2):

Oscillation probability
(electron neutrino appearance)

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{1.27 \Delta m_{32}^2 L [\text{km}]}{E [\text{GeV}]}$$

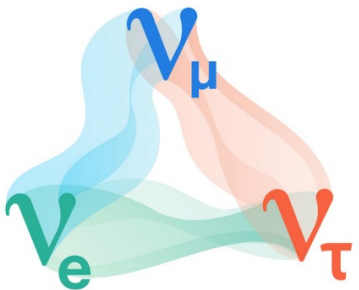
L Distance between detectors
 E Mean neutrino beam energy

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

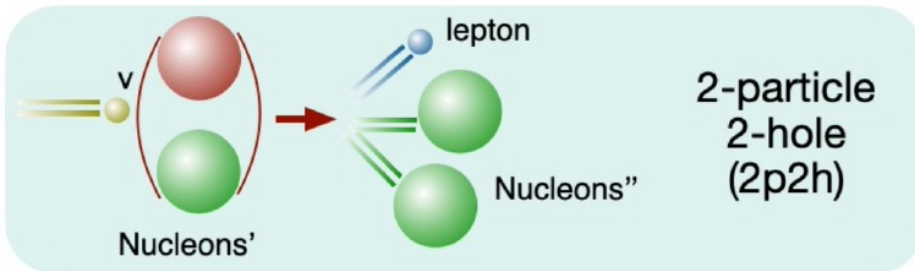
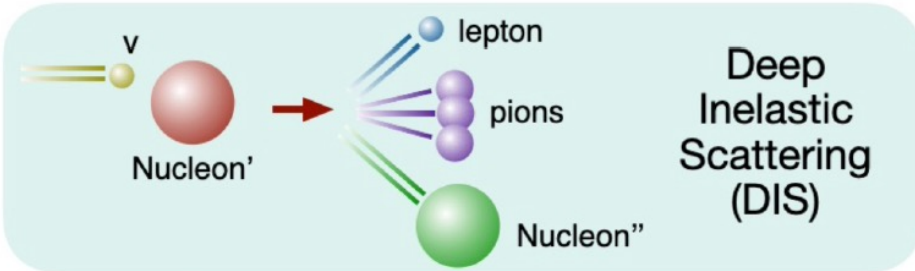
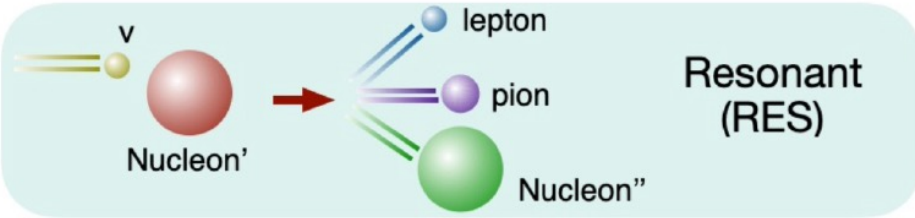
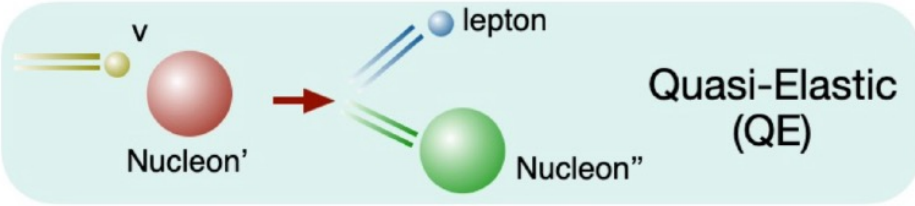
$\Phi(E_\nu)$ Neutrino flux

$\sigma(E_\nu, \vec{x})$ Cross section (probability of neutrino-nucleus interaction)

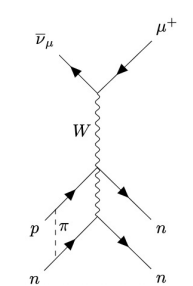
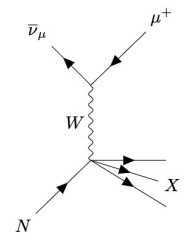
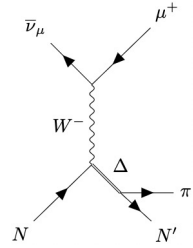
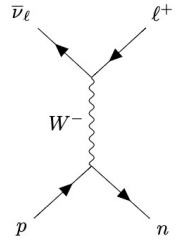
$\epsilon(\vec{x})$ Detector response / efficiency



Neutrino Interactions

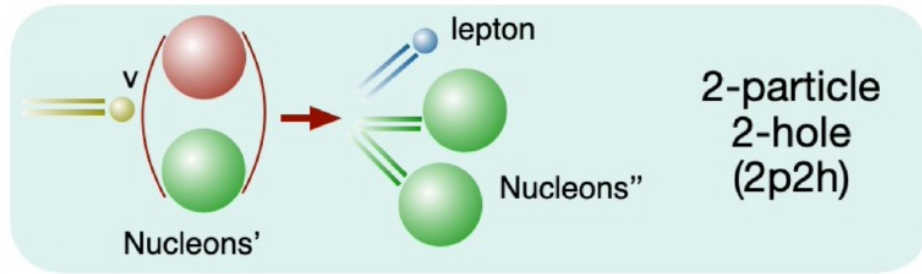
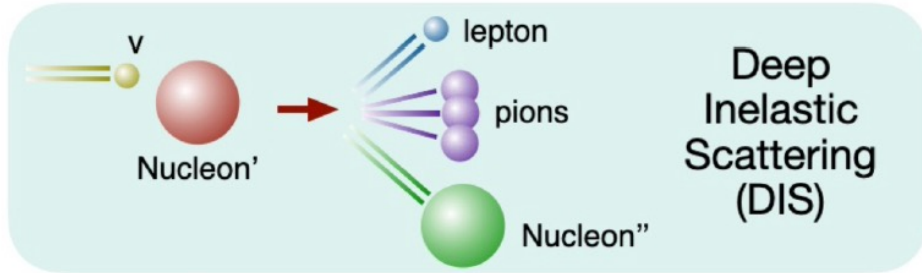
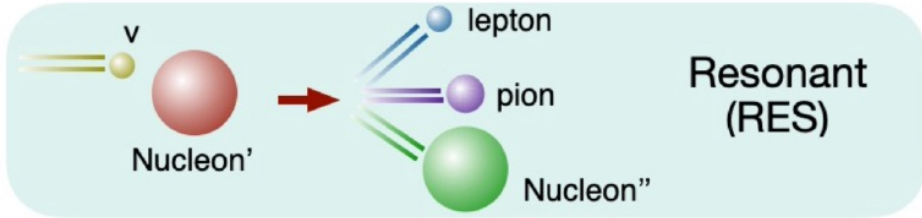
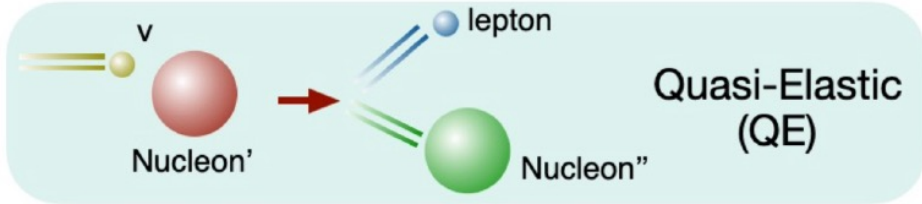


L. Cremonesi
([Neutrino 2020](#))

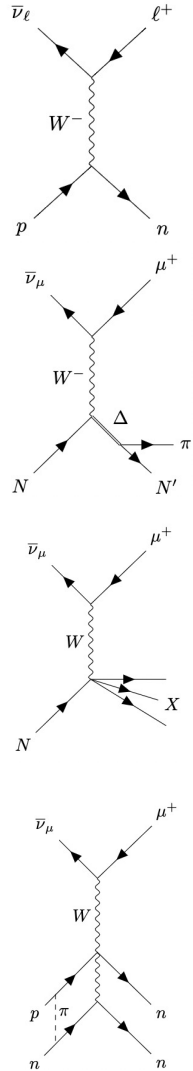


The Meson Exchange Current (MEC) model is a leading model to describe the 2p2h process.

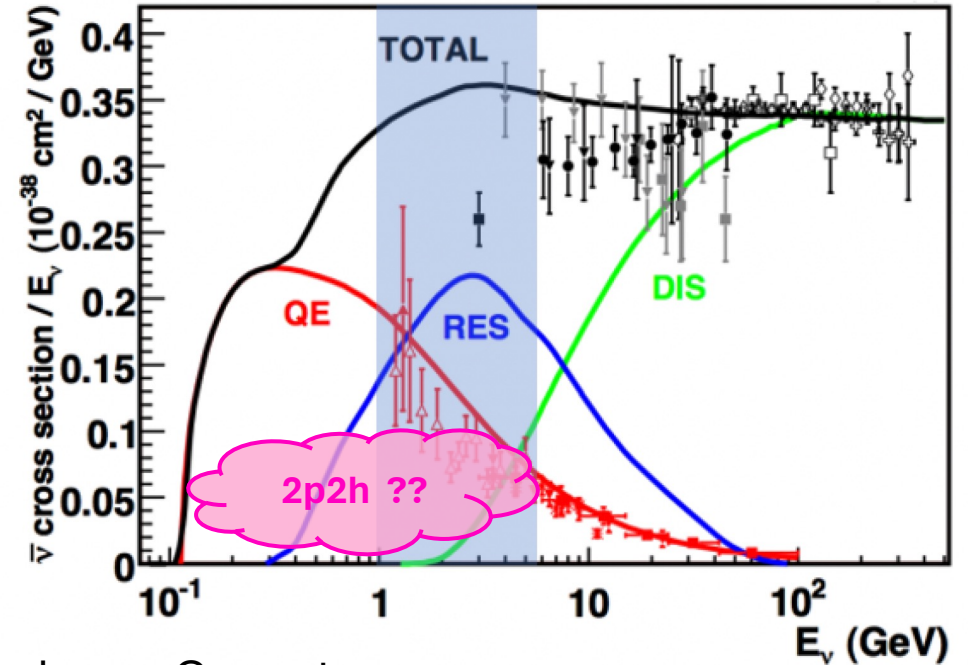
Neutrino Interactions



L. Cremonesi
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NOVA's neutrino flux lies in the transition region between the main interaction processes.



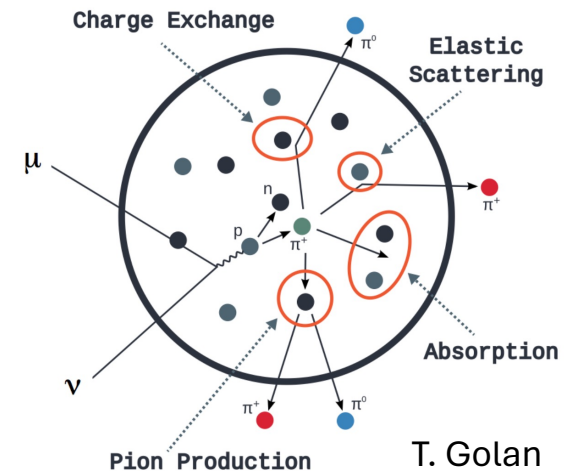
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J. Formaggio and G. Zeller
([arxiv:1305.7513](#)) (adapted)

Why is a Zero-Meson Antineutrino Analysis Interesting?

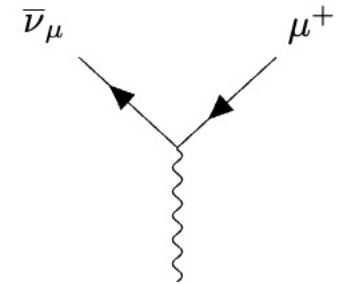
- We can achieve a high sample purity: charged-current (CC) ν_μ events generally produce protons (easily misidentified as pions), but CC $\bar{\nu}_\mu$ events mainly produce neutrons (largely go unseen in NOvA's detectors).
- Study 2p2h processes in the antineutrino sector and compare different QE and MEC models.
- Antineutrino cross sections are smaller by a factor of $\sim 2 - 3$, but NOvA has high statistics ($\sim 12 \times 10^{20}$ POT), 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.



Zero-Meson Antineutrino Analysis

- Signal: CC $\bar{\nu}_\mu$ 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).
- NOvA's analyses are blinded, and we have not yet looked at data.



Measuring a Cross Section

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

i truth space
 j reco space

$N^{sel}(P_L, P_T)_j$

Number of selected events

$P(P_L, P_T)_j$

Purity of sample

U_{ij}

Unfolding Matrix – to migrate from reco 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

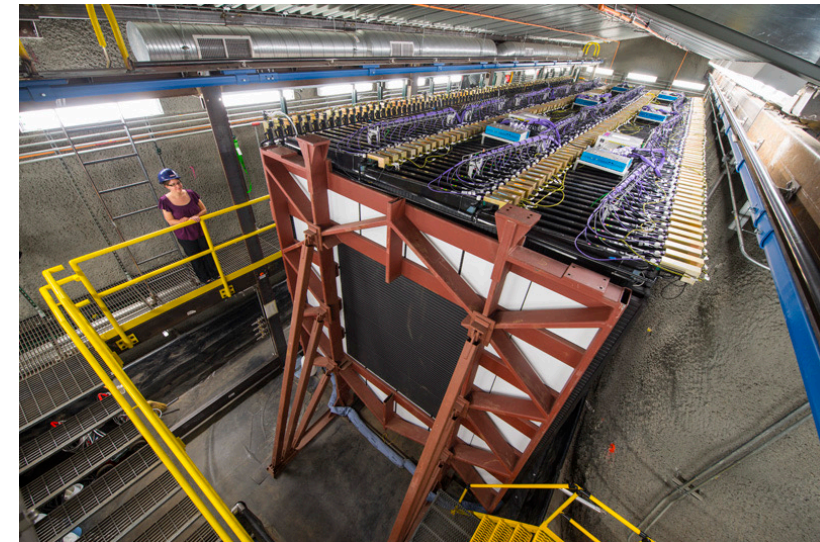
N_{targets}

Number of targets in the detector

Φ

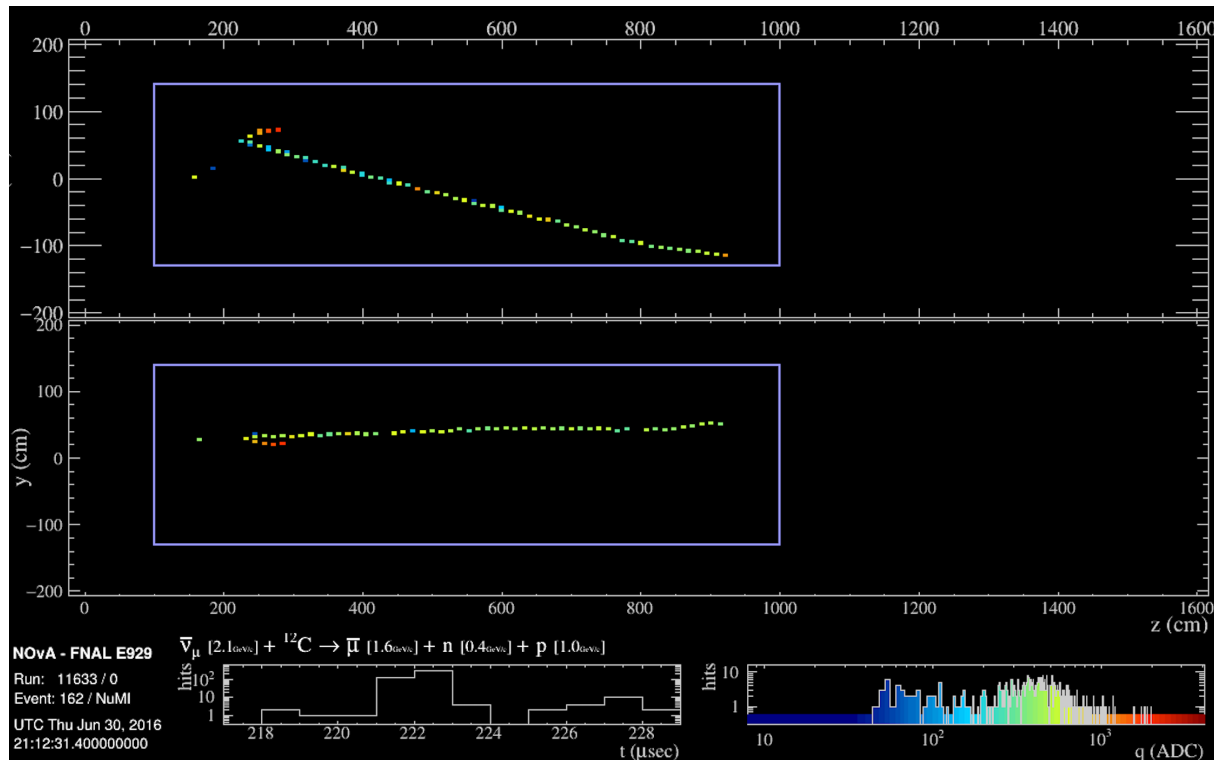
Incoming neutrino flux

NOvA Near Detector



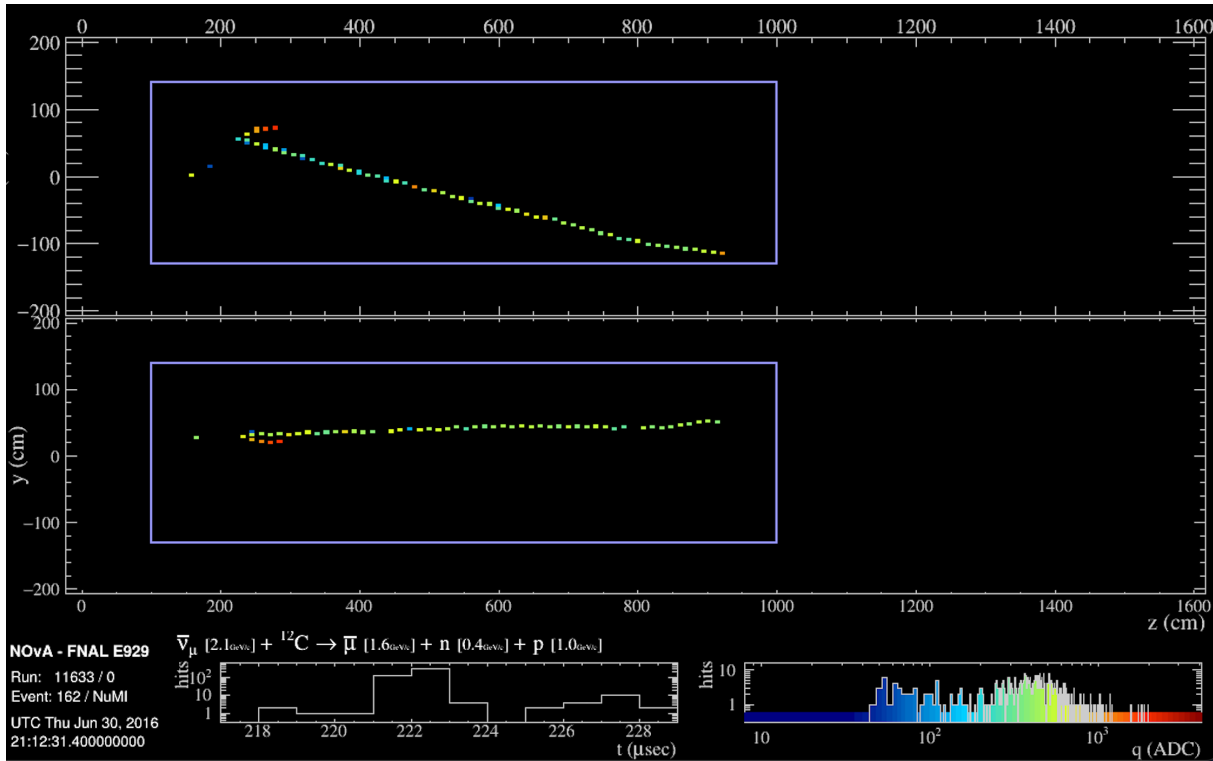
Machine Learning in NOvA

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.

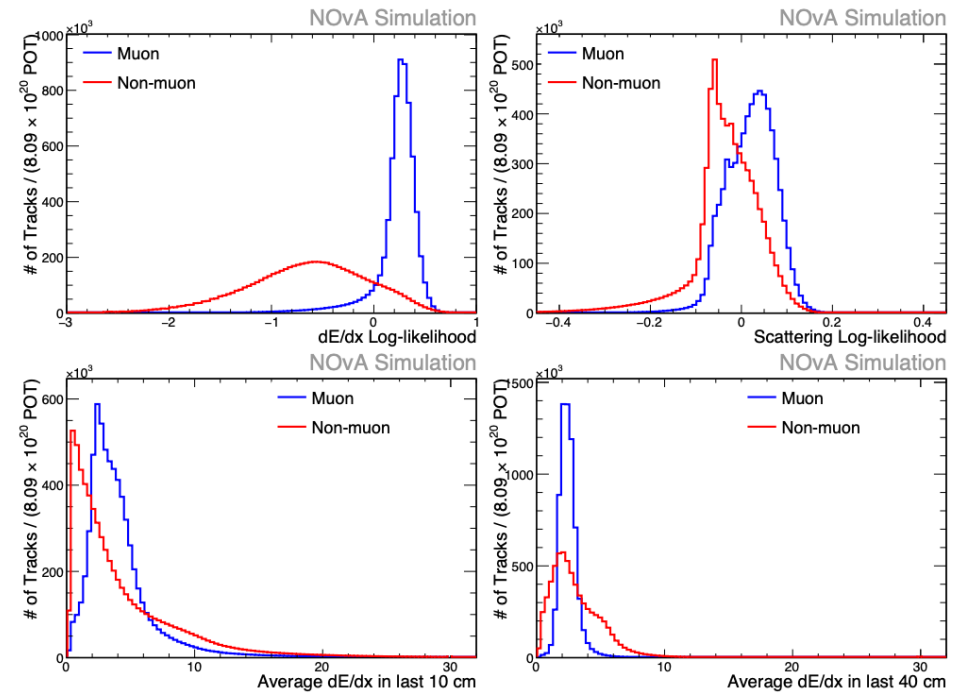


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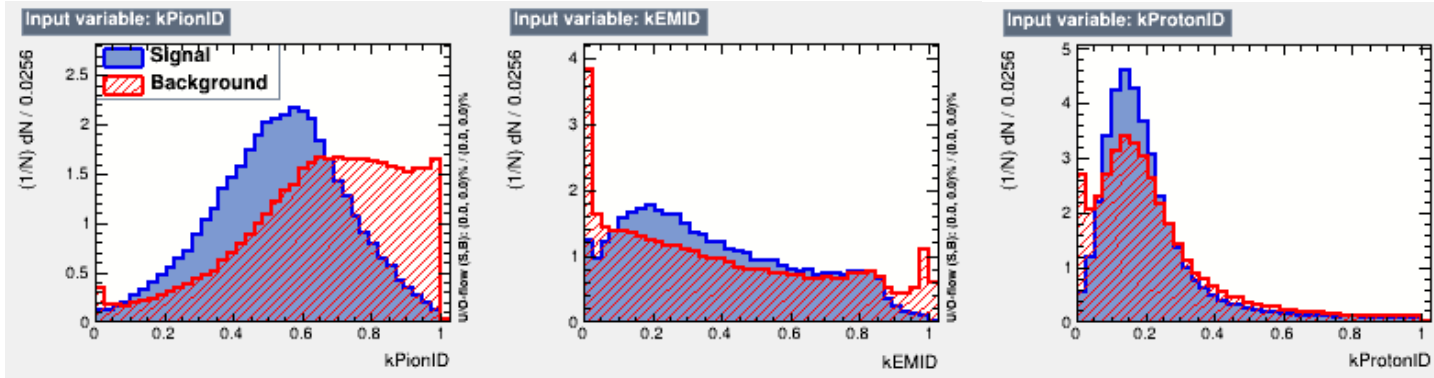
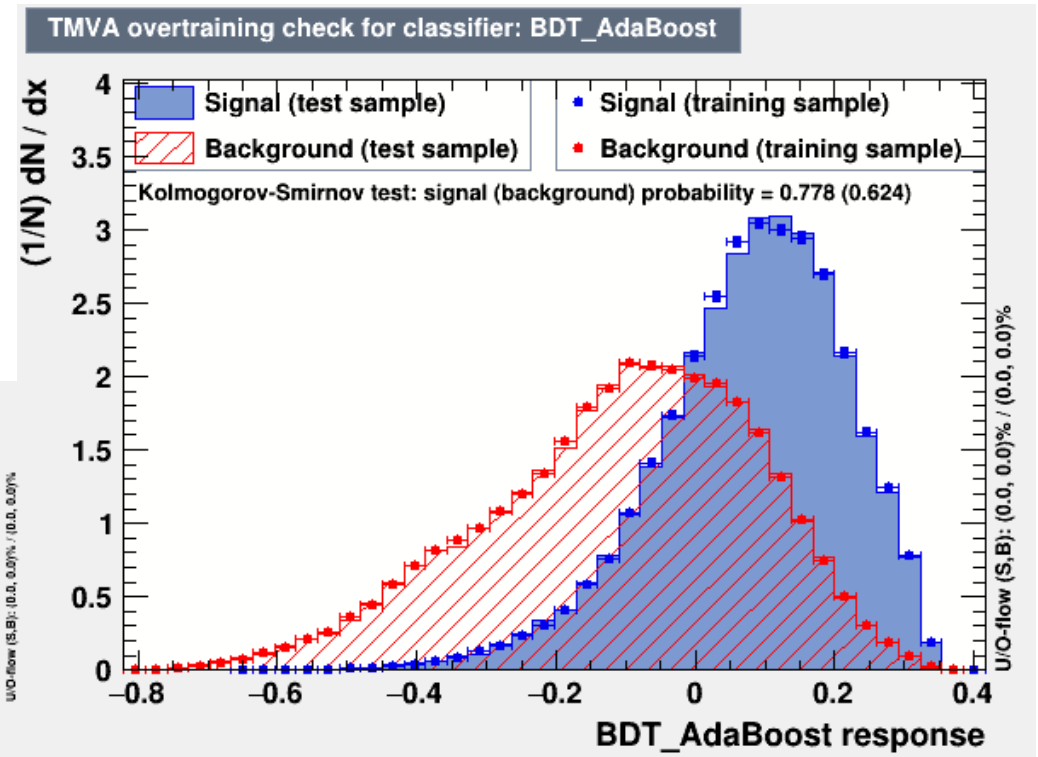


MuonID is a boosted decision tree (BDT) used to identify the likelihood of a track being a muon, with the inputs being the the energy deposition (dE/dx) log-likelihood, scattering log-likelihood and average dE/dx near the end of the track.



MERMAID: Identifying Events without Mesons

- **Machine-Enhanced RHC Meson Abolition ID** – a novel BDT 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.

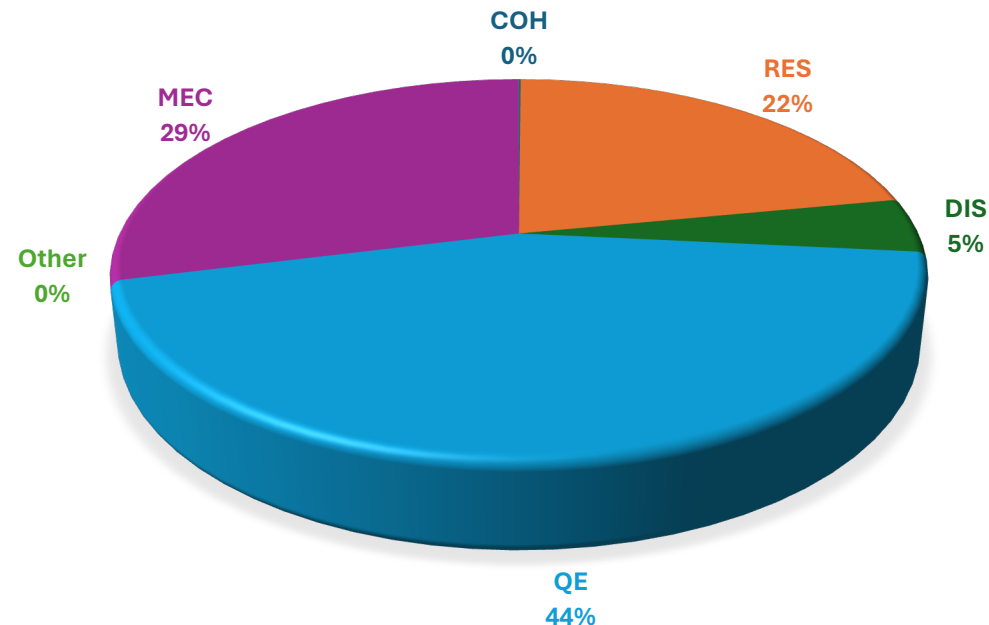


Selection Criteria

- 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 criterion (BDT score of ≥ 0.04).

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

Purity: 76.7%
Efficiency: 27.6%





Neutrino Event Generators

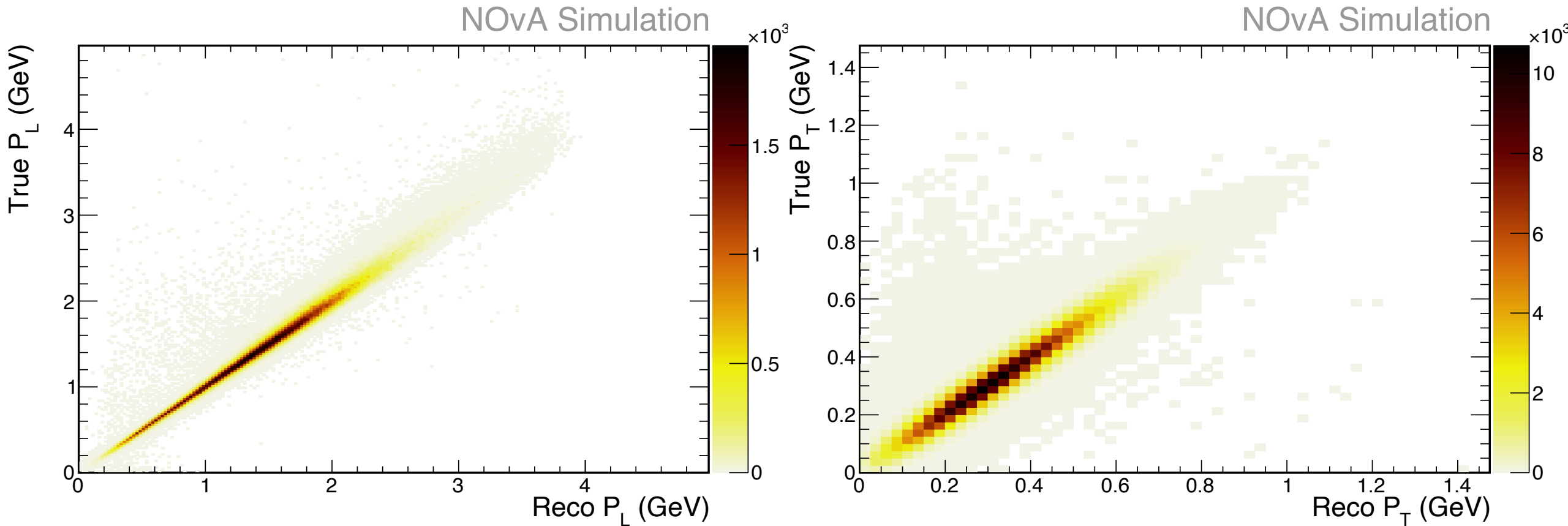
- Main MC generator for this analysis is GENIE 3.00.06, using the G18_10a_00_000 comprehensive model configuration (CMC), and with MEC and FSI tuned to NOvA data.
- Comparisons are also being made to a number of other generators and GENIE CMCs.

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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

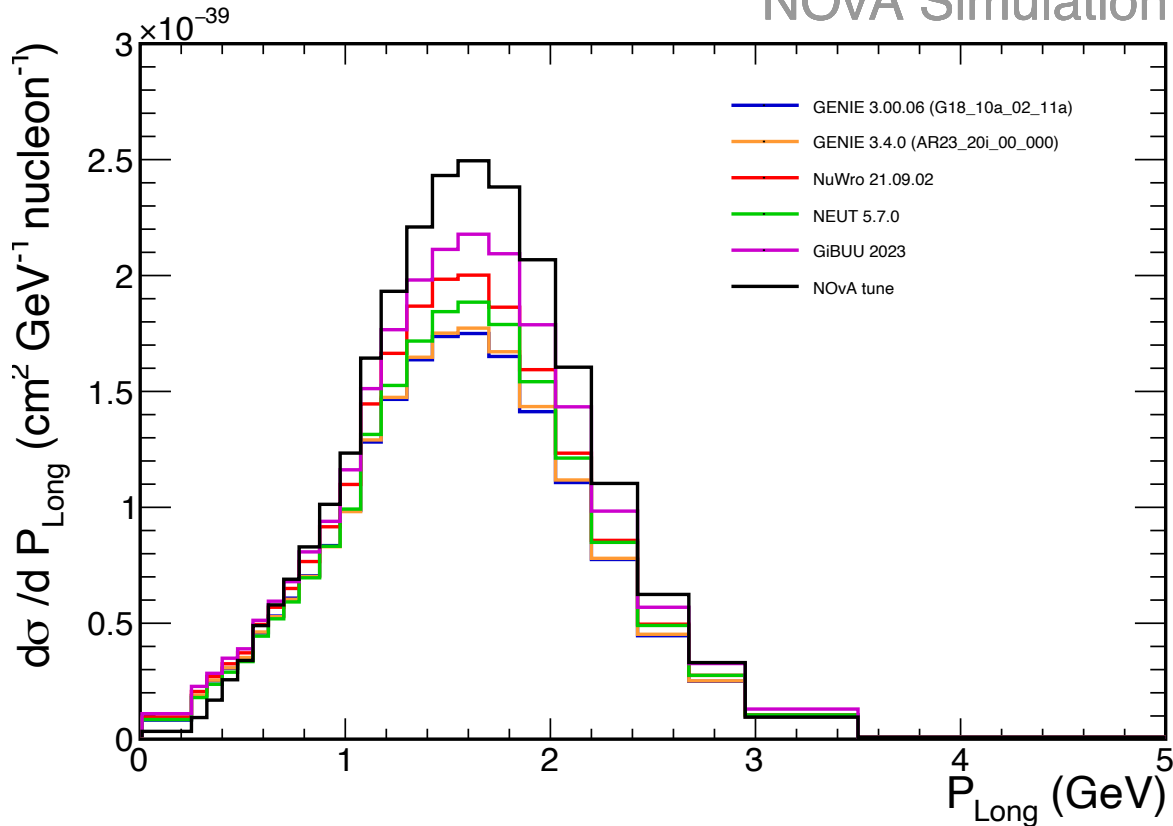


- Migration matrices for these variables are strongly diagonal, with good resolution.
- We will therefore be able to report results in a large number (~ 215) of 2-dimensional bins as a double-differential cross section.

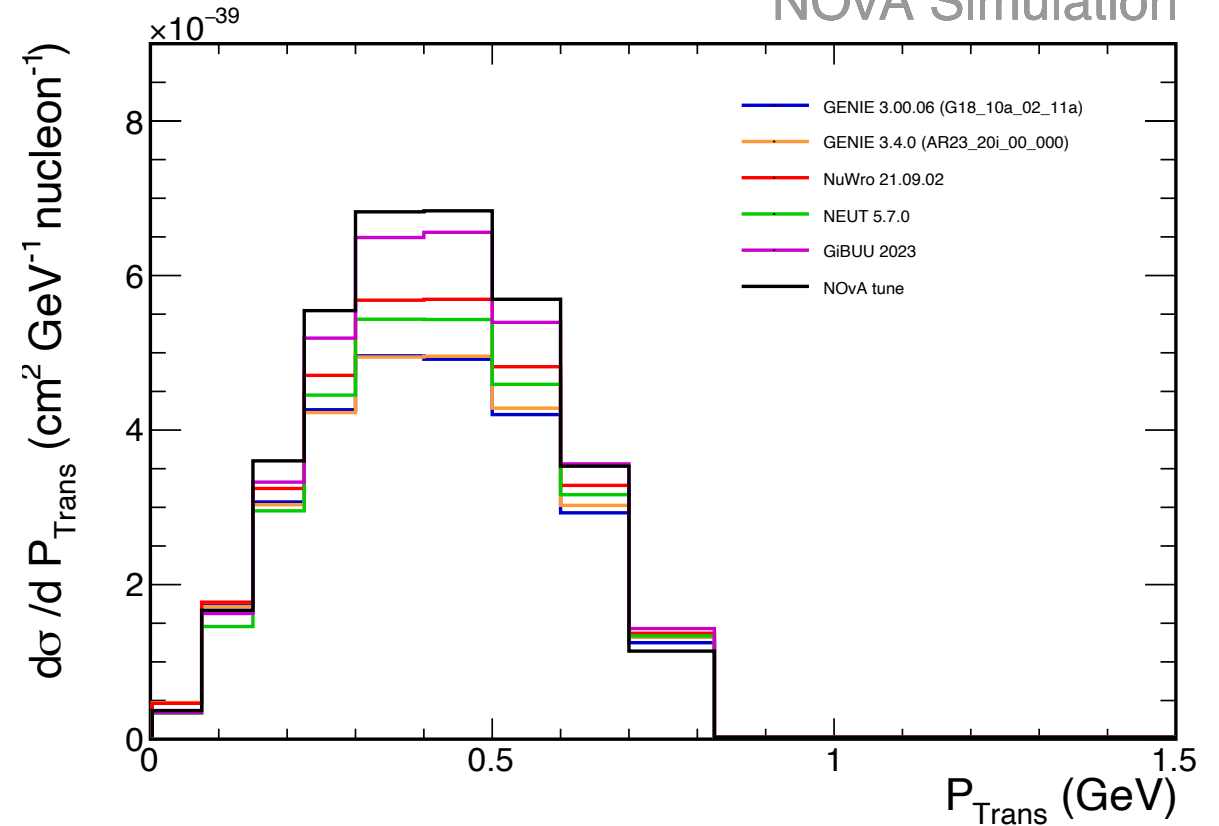
Muon Longitudinal and Transverse Momentum



NOvA Simulation



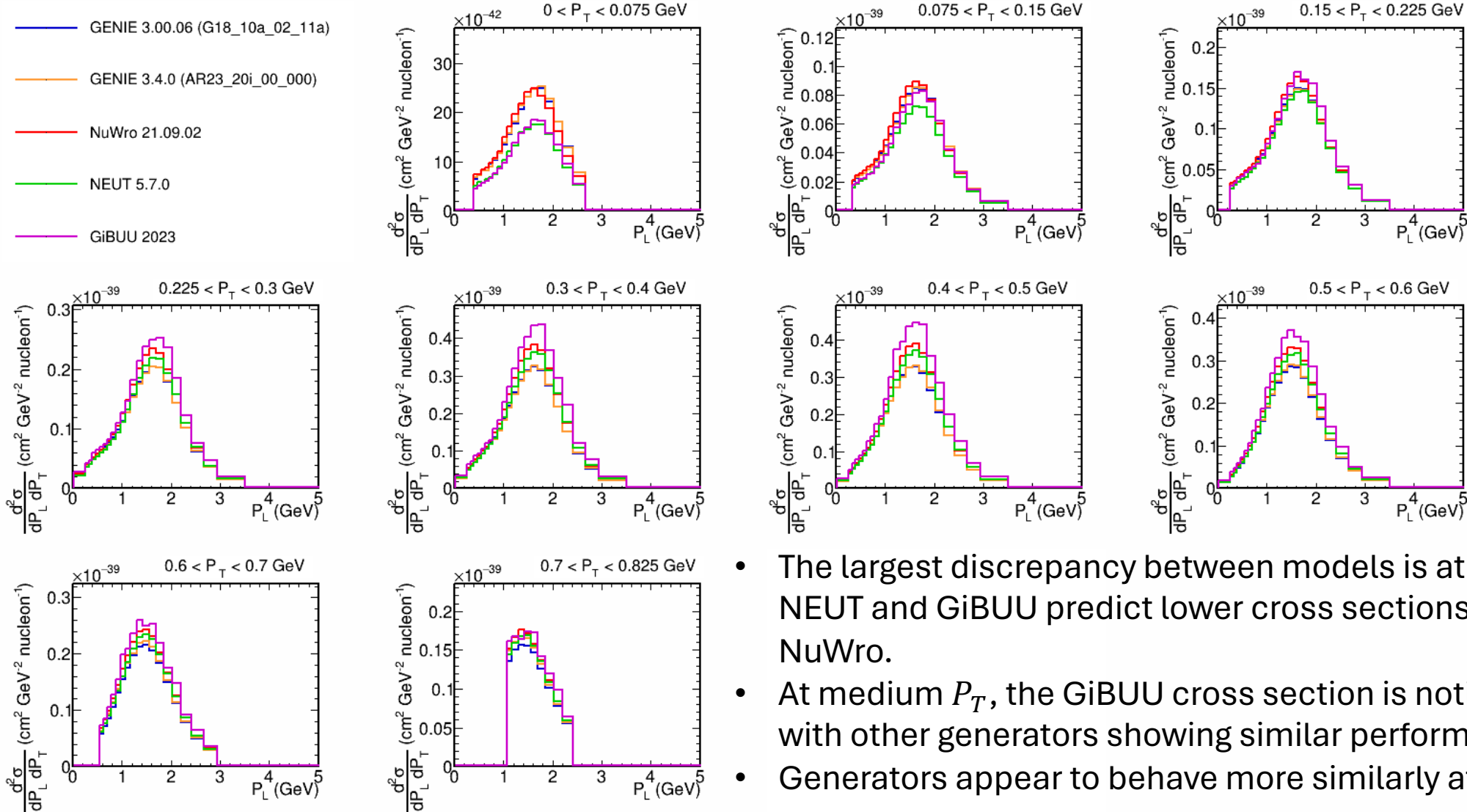
NOvA Simulation



- 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

- GENIE 3.00.06 (G18_10a_02_11a)
- GENIE 3.4.0 (AR23_20i_00_000)
- NuWro 21.09.02
- NEUT 5.7.0
- GiBUU 2023



- 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 , the GiBUU cross section is noticeably larger, with other generators showing similar performance.
- Generators appear to behave more similarly 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

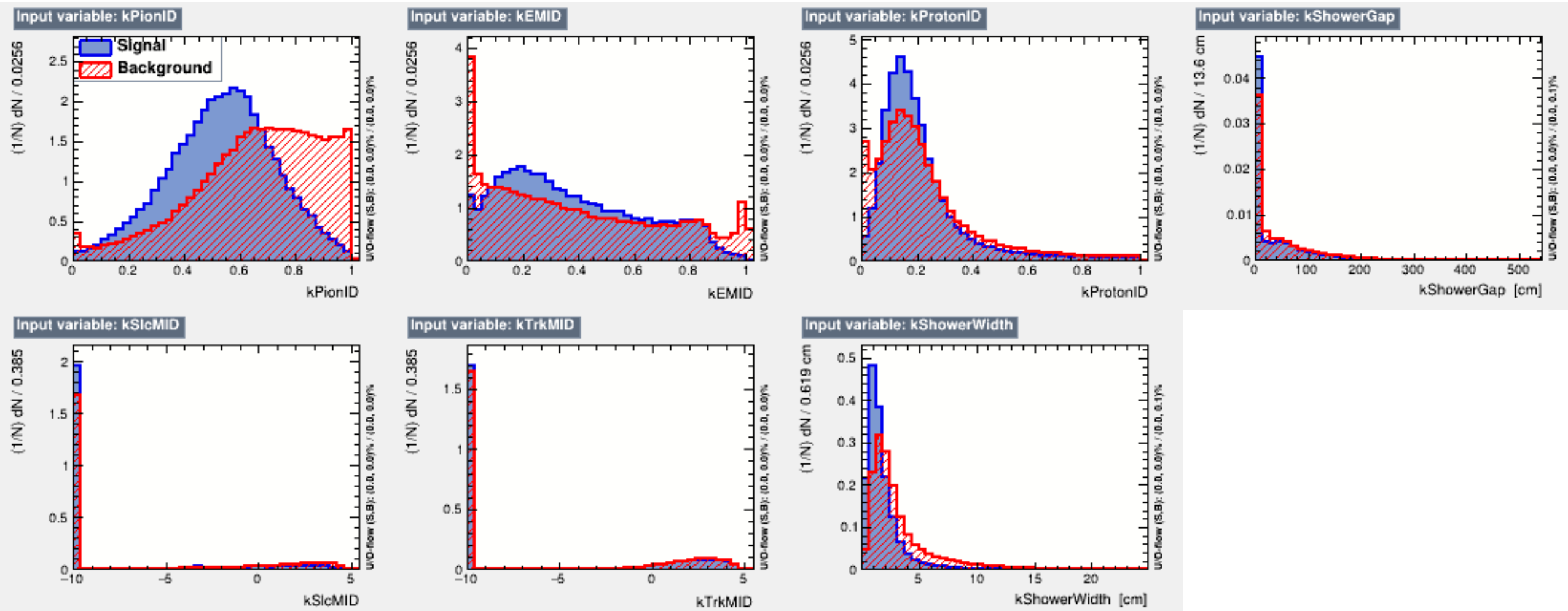
Thank you, on behalf of The NOvA Collaboration



Backup



MERMAID: Input Variables



Incoming Neutrino Energy and 4-momentum transfer

