FERMILAB-POSTER-24-0083-PPD

New RES and DIS uncertainties for NOvA cross-section model

Maria Martinez-Casales
Fermilab, mcasales@fnal.gov

Michael Dolce
Wichita State University,
michael.dolce@wichita.edu

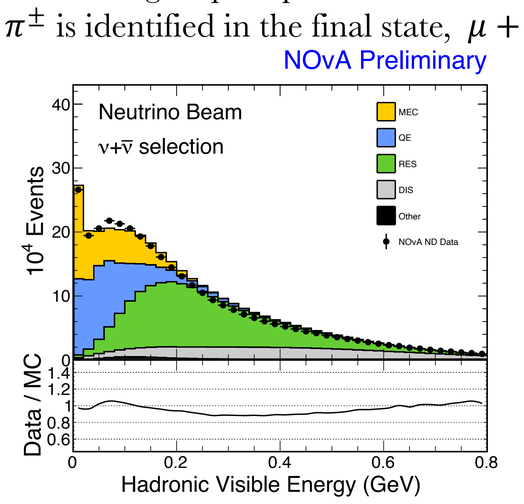
1. Interaction model

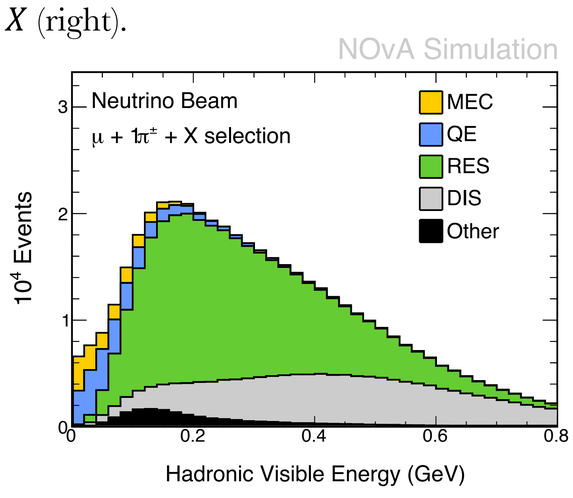
- NOvA is a long-baseline neutrino oscillation experiment with its Near Detector (ND) at Fermilab.
- Designed to constrain oscillation parameters Δm^2_{32}, $\sin^2\theta_{23}$, and δ_{CP}.
- Use simulations based on the GENIE neutrino event generator to extrapolate ND data into oscillated predictions in the Far Detector (FD).
- GENIE 3.0.6 with Comprehensive Model Configuration N18_10j_00_000.
- We present refinements in pion-production uncertainties with new parameters not previously captured in GENIE.

Neutrino - free nucleon interactions	
Quasi-Elastic (QE)	Valencia 1p1h Z-expansion axial form facror
Resonance (RES)	Berger-Sehgal
Deep inelastic Scattering (DIS)	Bodek-Yang
Multinucleon interactions	
Meson exchange current (MEC)	Valencia MEC custom adjustment to NOvA data for 2p2h
Interactions with the nuclear environment	
Final State Interactions (FSI)	hN Semi Classical Cascade Custom fit to external pion scattering data.

2. ND selection

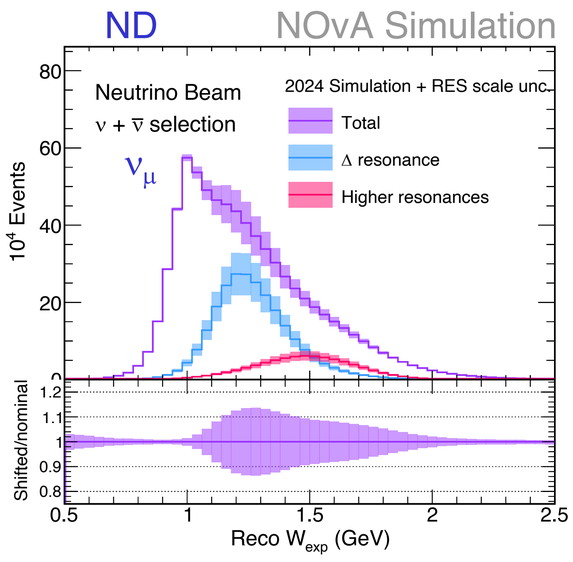
- RES and DIS interactions modes are leading contributors to pion production at larger hadronic visible energy.
- RES interactions are a significant fraction of the inclusive NOvA ND selection (left).
- We investigate pion production modeling with a subset of interactions where a single $\pi^{\pm}$ is identified in the final state, $\mu + \pi + X$ (right).

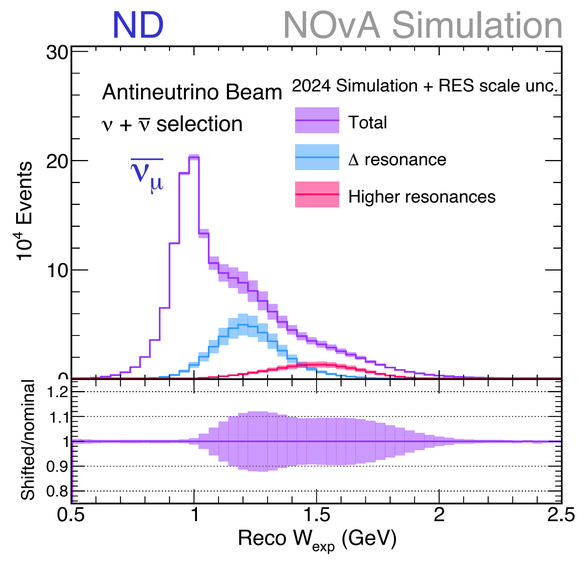




3. RES Scaling Uncertainty

- NOvA has several RES-focused uncertainties, however none that address Δ and higher order resonances directly.
- Major contribution of Δ resonance production, and non-trivial contribution of higher mass resonances in the ND selection (right).
- Introduce two new uncertainties:
  - Delta Resonance scale: interaction is reweighed by ± 20% at $\pm1\sigma$.
  - Higher Resonances scale: interaction is reweighed by ± 20% at $\pm1\sigma$.
- Motivated by past NOvA cross section measurements that observed excess of RES events.





4. RES $\frac{\sigma(\nu p)}{\sigma(\nu n)}$ Uncertainty

- Relative resonance contributions of $\sigma_{RES}(\nu p)$ and $\sigma_{RES}(\nu n)$ scatters are not exactly known – uncertainty created to account for this.
- Adjusts $\sigma_{RES}(\nu p)$ / $\sigma_{RES}(\nu n)$ ratio by ±5% at ±1σ, linearly up to $\pm3\sigma$.
- Parameters change expected FS hadrons NOvA observes, impacting hadronic visible energy (table, right).

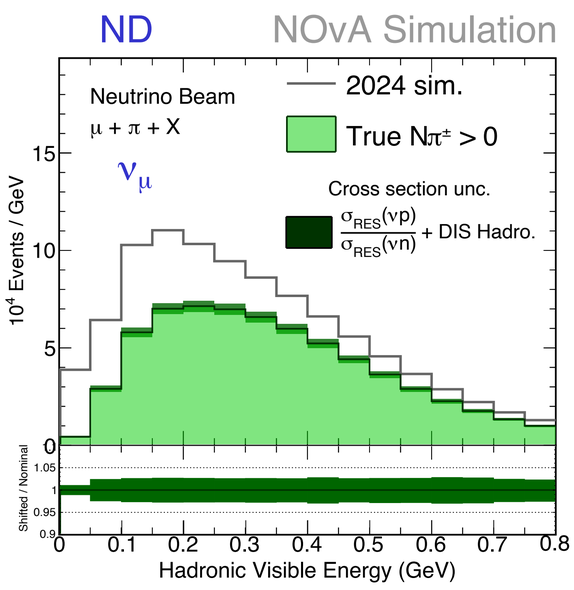
ν Interaction	Δ Decay
$\nu + p \to \mu^- + \Delta^{++}$	$\Delta^{++} \to p + \pi^+$
$\nu + n \to \mu^- + \Delta^+$	$\Delta^+ \to \pi^+ + n$ $\Delta^+ \to \pi^0 + p$
$\bar{\nu} + p \to \mu^+ + \Delta^0$	$\Delta^0 \to \pi^0 + n$ $\Delta^0 \to \pi^- + p$
$\bar{\nu} + n \to \mu^+ + \Delta^-$	$\Delta^- \to n + \pi^-$

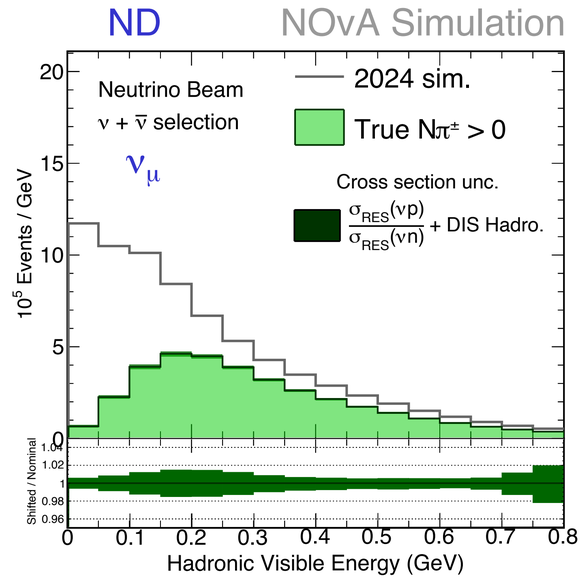
- **Below**: Combined $\pm1\sigma$ error from the RES $\frac{\sigma(\nu p)}{\sigma(\nu n)}$ and DIS hadronization uncertainties:
  - Inclusive sample (right): error on true charged pions – minimal impact, 2%.
  - Pion-rich sample (left): approximately 5% due to interference between the two systematics.

5. DIS Hadronization Uncertainty

- Probabilities for FS hadron pairs in GENIE are **fixed** for ν (of charge Q=1) and $\bar{\nu}$ (of charge Q=0) :
  - $P(p + \pi^0) = \frac{1}{3}$, $P(n + \pi^+) = \frac{2}{3}$.
  - $P(p + \pi^-) = \frac{2}{3}$, $P(n + \pi^0) = \frac{1}{3}$.
- Two parameters allow the probabilities of the FS hadronic pairs (1 pion + 1 nucleon) to vary in DIS interactions.
- For ν, one limit of the uncertainty predicts an entirely $(p + \pi^0)$ FS; the other is entirely $(n + \pi^+)$ (table, below).

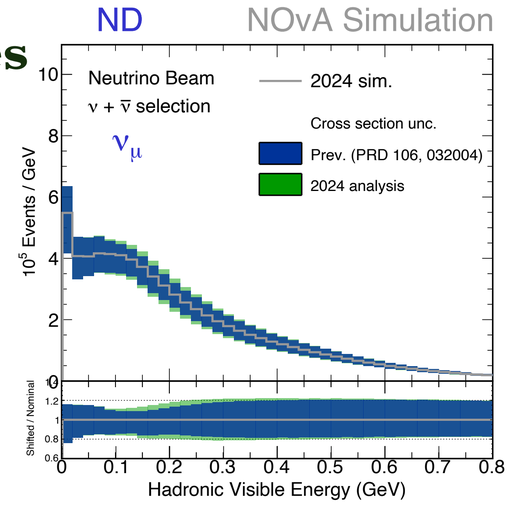
Feature	ν	$\bar{\nu}$
struck nucleon	n	p
final state charge, Q	+1	0
hadron combinations	$(1p + 1\pi^0)$, $(1n + 1\pi^+)$	$(1n + 1\pi^0)$, $(1p + 1\pi^-)$
default GENIE	p=1/3, n=2/3	p=2/3, n=1/3
uncertainty limits	2σ, -1σ	1σ, -2σ

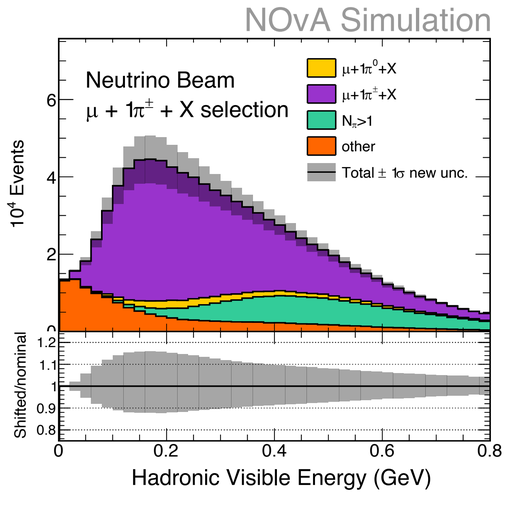




6. Impact on Analyses

- These systematics are added to NOvA's cross section uncertainty budget for 2024 oscillation analysis.
- RES $\frac{\sigma(\nu p)}{\sigma(\nu n)}$ and DIS hadronization systematics produce roughly 5% impact on the inclusive ND ν_μ sample – effects are observed in pion-rich samples.
- RES Scaling uncertainties have the largest impact.





- NOvA's extrapolation procedure minimizes the effect of cross section systematics in the oscillation analysis (left).
- In the pion-rich sample, these parameters are important degrees of freedom, and may be important in pion-sensitive cross section measurements (right).

7. Conclusion

- NOvA's simulation contains a large fraction of pion-producing events.
- Three new degrees of freedom associated with pion production were created:
  - The RES $\frac{\sigma(\nu p)}{\sigma(\nu n)}$ and DIS hadronization degrees of freedom do not substantially impact the NOvA inclusive sample, and produce an approximate 5% effect in $\mu + \pi + X$ sample.
  - The Δ scaling and higher resonances scale uncertainties are a larger effect on NOvA predictions.
- These uncertainties will prove important contributions to pion-sensitive cross section measurements.

U.S. DEPARTMENT OF ENERGY | Office of Science

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics. We would like to acknowledge the support of Department of Energy Office of Science Grant : DOE DE-SC0023362.

https://novaexperiment.fnal.gov