Impact of cross section uncertainties on NOvA oscillation analyses

on behalf of the NOvA collaboration

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NOvA: \(\nu\) oscillation physics

1. How are the mass eigenstates ordered?
2. Is there a symmetry governing mixing between \(\nu_\mu\) and \(\nu_\tau\)?
3. Is there CP violation in leptons?

Measuring key parameters in oscillation physics

(Most recent measurements discussed in J. Bian, plenary talk #12, Tues. 8/14)
NOvA: design considerations

Far Detector
14 kton, 810 km from source

Near Detector
300 ton, 1 km from source

Functionally identical detectors

Sampling calorimeter detectors

1 Channel
(4cm × 6cm)
How cross sections enter the story: energy reconstruction

- \( P(\nu_\alpha \rightarrow \nu_\beta) \) depends on \( E_{\text{true}} \), but detectors measure \( E_{\text{reco}} \)

- Detectors/reconstruction have different sensitivities to different processes, which have different \( E_{\text{true}} \leftrightarrow E_{\text{reco}} \)
How cross sections enter the story: energy reconstruction

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How cross sections enter the story: energy reconstruction

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Model building

**Theory work** and **other experiments' data** have shown that default GENIE 2.12 (our base model) needs some important adjustments...

(fuller discussion in J. Wolcott, FNAL Neutrino Seminar, Apr. 23 2018; paper forthcoming)

Nonresonant $1\pi^+$ production from neutrons needs to be reduced by $\sim$50% based on updated fits to free-nucleon data

[Europ. Phys. J. C76, 474]
**Model building**

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**Effective nuclear “screening”** from collective excitations:
treated with “**RPA**”.

We use Valencia group calculation for QE; also speculatively apply to RES based on hints in external data

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**València group’s RPA calculation**, ratio to GENIE nominal
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Effective nuclear “screening” from collective excitations: treated with “RPA”.

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Multinucleon knockout (2p2h)

We enable GENIE “Empirical MEC”, retune it based on our data
Evaluating cross section uncertainties

Depend heavily on GENIE's reweight system...

**Primary process uncertainties**

- **QE**: $M_A$, Vector FF, Pauli supp...
- **RES**: $M_A$, $M_V$, Δ decay isotropy...
- **DIS**: Bodek-Yang parameters, transition region (“non-resonant background” scale), ...
- **COH**: Rein-Sehgal $M_A$, $R_0$, ...

**Final-state model (hA) uncertainties**

- **Nucleon, pion** elastic, inelastic, chg ex., abs. reaction probabilities
- **Hadron mean free paths**

(~50 reweight knobs in all)

...and build custom knobs for our growing library of GENIE 'adjustments':

- **MEC model for 2p2h** (q$^\mu$ shape, $E_\nu$ shape, nn/np composition)
- **RPA-QE** (based on València treatment; histograms from R. Gran)
- **RPA-RES** (conservative “on” vs “off”)
In practice:

\[ \nu_\mu \text{ disappearance} \]

[a worked example]
νμ disappearance

\[ P_{\nu_\alpha \to \nu_\beta} \approx \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \]

Goal: measure the location and strength of the “oscillation dip” relative to no-oscillations prediction

Energy spectrum of your neutrino beam

How far away from the source you build your detector

Arbitrary units

Neutrino Energy (GeV)

Ratio to no oscillations

Neutrino Energy (GeV)

\[ \frac{\Delta m^2 L}{4E} = \frac{\pi}{2} \]

\[ \sin^2 2\theta \]
$\nu_\mu$ disappearance: energy reconstruction

$E_\nu = E_{\text{lep}} + E_{\text{had}}$

(3% resolution)

Calibrate muon track length to true $E_\mu$, then remaining visible energy to (true $E_\nu$ – reco $E_\mu$).

Calorimetric (not kinematic) energy reconstruction (more details in E. Smith's talk #182, Thur. 8/16, WG1)
ν_μ disappearance: energy reconstruction

Nominal resolution on E_ν ~ 9%.
νμ disappearance: energy reconstruction

Nominal resolution on $E_\nu \sim 9\%$; different by reaction
$\nu_\mu$ disappearance: energy reconstruction

Despite sculpting effect, calorimeter-style detectors ensure cross section systematics don't significantly degrade energy resolution

Nominal resolution on $E_\nu \sim 9\%$. 
Near detectors

Want to measure oscillation probability. Many other variables...

\[ N(E_{\nu}^{\text{rec}}) = \Phi(E_{\nu}^{\text{true}}) \times P_{\text{osc}}(E_{\nu}^{\text{true}}) \times \sigma(E_{\nu}^{\text{true}}, A) \times R(E_{\nu}^{\text{true}}) \times \epsilon(\ldots) \]
Near detectors

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Use the Near Detector to take advantage of high-stats measurement, free of oscillations, by exploiting correlations as much as possible.

\[ N^{ND}(E_{\nu}^{\text{rec}}) = \Phi(E_{\nu}^{\text{true}}) \times \sigma(E_{\nu}^{\text{true}}, A) \times R(E_{\nu}^{\text{true}}) \times \epsilon(\ldots) \]
$\nu_\mu$ disappearance: “extrapolation”

To produce a data-driven prediction at FD, based on ND:

True energy distribution is corrected so that reconstructed data & MC agree at the ND...
$\nu_\mu$ disappearance: “extrapolation”

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...modified true energy distribution is propagated through predicted geometric beam dispersion & acceptance ratio, oscillations...
νμ disappearance: “extrapolation”

To produce a data-driven prediction at FD, based on ND:

- True energy distribution is corrected so that reconstructed data & MC agree at the ND...
- ...modified true energy distribution is propagated through predicted geometric beam dispersion & acceptance ratio, oscillations...
- ...and “extrapolated” reconstructed energy distribution computed to compare to data
Illustrating XS systematics: MEC

Examine this procedure through the lens of reaction of interest:

2p2h via Meson Exchange Currents (GENIE 'Empirical MEC' w/ ND tuning)

Illustrate behavior through two different knobs:

- Neutrino energy dependence (brackets theoretical models)
- Four-momentum transfer dependence (bounds our fits)

NOvA Simulation

Neutrino Beam $\nu, \bar{\nu}$ CC MEC
- 2018 NOvA $\nu + \bar{\nu}$ Tune
- -1 $\sigma$
- +1 $\sigma$

Four-momentum transfer (q$_{0}$, |q|)
Illustrating XS systematics: MEC

Examine this procedure through the lens of reaction of interest:

**2p2h**

via

**Meson Exchange Currents**

(GENIE 'Empirical MEC' w/ ND tuning)

Illustrate behavior through two different knobs:

- Four-momentum transfer dependence (bounds our fits)
- Neutrino energy dependence (brackets theoretical models)

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* This one first

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**NOvA Simulation**

Neutrino Beam

$\nu_\mu$ CC MEC

- 2018 NOvA $\nu + \bar{\nu}$ Tune
- -1 $\sigma$
- +1 $\sigma$

Events

True $q_0$ (GeV)

$E_\nu$ (GeV)

Neutrino energy dependence (brackets theoretical models)
Testing extrapolation

To examine the effect of extrapolation:

Replace “ND Data” with “ND prediction under systematic shift”.
(Asks: “if data exhibits this effect, and we use baseline simulation, how well does extrapolation compensate?”)
Testing extrapolation

To examine the effect of extrapolation:

Transport “corrected” prediction through extrapolation process
Testing extrapolation

To examine the effect of extrapolation:

Compare “extrapolated” FD prediction to prediction obtained by varying FD directly.

③ If they match, extrapolation perfectly 'cancels' the effect.
Testing extrapolation
Only a few percent residual effect of this MEC syst after extrapolation: the rest was canceled by the procedure.
Testing extrapolation

Though extrapolation procedure can’t remove *all* effect of cross section uncertainties like MEC, extrapolation significantly reduces sensitivity to XS systs.

Only a few percent *residual* effect of this MEC syst after extrapolation.
Testing extrapolation

Far/Near extrapolation works best with *neutrino energy* systs, but we derive benefit from it for the other shape dependence as well.
Other important XS uncertainties

The story is similar for other important cross section uncertainties.
Other important XS uncertainties

The story is similar for other important cross section uncertainties. This illustrates how extrapolation responds to "unknown unknowns" in the data.

We do the "inverse" to handle "known unknowns" using our MC...
“Extrapolation” and uncertainties

We simulate the effect of our cross section systematics' residual effect after extrapolation by re-doing the entire analysis for each systematic and use the difference to extrapolated nominal MC as nuisance parameters in our oscillation fits.
Cross section systematics are not dominant systematic uncertainties due to detector design & power of extrapolation.

But... dedicated test beam program (see A. Sutton, poster #205) will drive detector response uncertainty down in the future, so soon enough cross sections will likely be atop the list...
Fig. 1 This task combines a worked example with a self-explanation prompt.

Eliza solved this problem correctly. Here is her work:

\[ 6 - k = -3 \]

- Why did Eliza subtract 6 from both sides of the equation?

Now: \( \nu_e \) appearance

Your Turn:

\[ -6 - k = 3 \]
ν_e appearance

\[ P^{(-)}(\nu_{\mu} \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A - 1)\Delta}{(A - 1^2)} \]

\[ + 2\alpha \sin \theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta \sin (A - 1)\Delta}{A} \frac{\sin \Delta}{(A - 1)} \]

\[ + 2\alpha \sin \theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta \sin (A - 1)\Delta}{A} \frac{\cos \Delta}{(A - 1)} \]

Where: \( \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \) \( \Delta = \Delta m^2_{31} \frac{L}{4E} \) \( A = \frac{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta} \)

Besides the dependence on the mixing parameters, we learn about the mass ordering (via \( \alpha \)) and \( \delta_{CP} \)
$\nu_e$ appearance

Added challenges:

- **Significant backgrounds** which oscillate differently
- **Beam $\nu_e$** oscillate very little over this L/E
- $\nu_\mu$ almost entirely disappear
- **NC** doesn't change due to oscillations (assume no steriles)

Need to disentangle ("decompose") before applying Far/Near makes any sense.

- **No signal at ND**
  - And difference $\nu_\mu$ ND vs. $\nu_e$ FD acceptance
$\nu_e$ appearance

Cross section systematics more important for signal here, but still under control for now. (Even more stat limited for $\bar{\nu}$.)

We expect to continue to benefit from ongoing work by this audience (and others) as well, to keep them that way...
Cross section uncertainties: future needs

- More certainty about **1p1h initial state**
  - **RPA treatments differ in sophistication** - how much detail do we need?
  - **Uncertainties** (from València) **still large**, not completely canceled by extrapolation
Cross section uncertainties: future needs

- **Nuclear models for inelastic processes** as well as QE
  - RPA-like effect for RES?
    - Suggested by data (MINERvA+MINOS ND+MiniBooNE+NOvA ND), but no theory guidance
    - “On-off” treatment for syst one of our largest
  - Inelastic continuum at low $E_\nu$
    - What does “shallow” inelastic scattering on carbon look like?
      - How does it interfere with RES? → GENIE uncertainties large
      - Free nucleon data helps only so much
    - Does diffractive scattering from H matter? How close are models?
- $\nu_e/\nu_\mu$ differences for inelastic processes
  - Current uncertainties are ad hoc

[NOvA has cross section measurements in progress which will help address some of these questions: see M. Judah, talk #71, Mon. 8/13, WG2]
Cross section uncertainties: future needs

- More/better **models for multinucleon knockout in GENIE**
  - València model agrees poorly with MINERvA, NOvA ND data; no alternatives in current versions (will change with 3.0?)
  - Empirical tuning procedure doesn't prescribe correlations between $\nu$ and $\bar{\nu}$ – so left uncorrelated...
Cross section uncertainties: future needs

- Much more $\bar{\nu}$ scattering data
  - Every issue mentioned above applies also for antineutrinos, only there are few data constraints
  - Abundance of fast neutrons an interesting challenge for calorimetry: final-state particle measurements especially helpful
Summary

• NOvA relies on strong internal constraints on cross section uncertainties for its oscillation program
  – Calorimeter design minimizes a priori impact
  – Functionally identical detectors enable major cancellation of residual errors in oscillation analyses

• Comprehensive program underway to ensure all relevant cross section issues are considered
  – Necessary ingredients in base model
  – Appropriate uncertainties

• We look forward to continuing the conversation:
  – Continued development of models & systematic treatments
  – New measurements of cross sections
  – Neutrino oscillation physics results!
Thank you for your attention!
Overflow
Rik Gran's work (originally for MINERvA) to extend the València RPA CCQE effect (PRC 70, 055503) to a correction for GENIE's central value and his work to extend the uncertainties in the model to higher energies (PLB 638, 325, PRD 88, 113007) naturally work reasonably well for NOvA.

Therefore, we apply using Rik's code.
Modeling the nucleus: collective effects (RPA)

- Should $\Delta$ production also be affected?
  - Seems likely for same reasons as elastic. No current attempts at calculation?
- Possible evidence: MiniBooNE, MINOS, MINERvA observations of apparent low-$Q^2$ suppression



MiniBooNE $1\pi^+$ Sideband, MINOS QE

\[ \text{Transition Sample} \]

\[ (\text{Events/0.04 GeV}^2) \times 10^{-3} \]

\[ Q^2 (\text{MeV}^2/c^4) \]

\[ \Delta \sigma/\Delta Q^2 \text{ (cm}^2/\text{nucleon}\cdot\text{GeV}^2) \]

\[ \text{Data} \]

\[ \text{True QE} \]

\[ \text{True RES} \]

\[ \text{True DIS + Other} \]

\[ \text{MINERvA} \]

\[ (\text{POT Normalized}) \]

\[ \text{Data (3.33e20 POT)} \]

\[ \text{GENIE w/ FSI} \]

\[ \text{NuWro} \]

\[ \text{Neut} \]

\[ \text{PRD 96, 072003} \]
Modeling the nucleus: collective effects (RPA)

- Should $\Delta$ production also be affected?
- Seems possible.

No current attempts at calculation?

"Quantiles" are divided by hadronic energy fraction: $\text{reco } E_{\text{had}} / \text{reco } E_\nu$.

Quantiles 3 & 4 are RES-rich regions of $\nu_\mu$ candidate sample.

We speculatively apply the $Q^2$-based RPA weight from QE to resonant production as well (w/ unmodified version as uncertainty variation).
Modeling the nucleus: tuning 2p2h-MEC

Our tuning is done in a two-dimensional space of the four-momentum transfer variables:

- energy transfer \( q_0 \)
- momentum transfer \( |q| \)

Fit in 2D space of nearest observables:
Visible \( E_{\text{had}} \) (~\( q_0 \)) and reco \( |q| \)

Fit a weight factor for each cell in this plot

Resulting MEC shape
MINERvA carried out a tuning procedure similar in spirit to ours (though with fewer degrees of freedom) using their data (PRD 116, 071802) which they kindly shared with us (private communication).

It is not dissimilar to the 1σ error band we arrive at (details on error construction next slide).
Modeling the nucleus: 2p2h-MEC uncertainties

Non-MEC base

Two alternate fits:
Choose combinations of uncertainties to push initial MC more towards QE or RES

| Knob            | "QE-like" shift | "RES-like" shift |
|-----------------|-----------------|------------------|
| QE MA           | +1σ (+5%)       | -1σ (-5%)        |
| QE RPA low-Q^2  | +1σ             | -1σ              |
| QE RPA high-Q^2 | +1σ             | -1σ              |
| QE Pauli Supp.  | -1σ             | +1σ              |
| RES MA          | -1σ             | +1σ              |
| RES MV          | -1σ             | +1σ              |
| RES RPA         | on (CV)         | off              |

Fitted MEC
Modeling the nucleus: 2p2h-MEC uncertainties

Cross section $E_\nu$ shape

Cross sections from three MEC models in the literature, plus Empirical MEC

(Renormalized to only show the shape difference since we're fixing the normalization to ND data via fitting)

Choose an envelope that more or less encloses the shapes of the predictions for our “±1σ” uncertainty
nn-np initial state composition

- Diagrams for $\nu$ CC 2p2h allow two nucleon “pairs” in initial state: nn or np ($\bar{\nu}$ has np or pp)
- Challenging to measure the real composition in data
  - LAr will help eventually?
  - MINERvA has made valiant efforts in the meantime, but not strong constraints on the value of the ratio (yet?)
- Stuck with theory for now
  - València prediction (via GENIE): $\sim$70% np/(nn+np).
  - SuSA prediction (PRC 94, 054610), detailed study: “The [np/nn] ratio is about 5-6 [i.e., np/(nn+np) ~ 80-90%] for a wide range of neutrino energies.”
  - Empirical MEC default is 80%

We choose $0.7 \leq \frac{np}{np+nn} \leq 0.9$ at 1$\sigma$. (It doesn't matter much; GEANT says we get ~similar response)
νμ disappearance: selection

kNN-based νμ CC classifier uses
4 inputs:
- Track length
- dE/dx
- Multiple scattering
- Fraction of track planes consistent with single particle dE/dx
$\nu_e$ appearance: selection

**Event selection** via a “Convolutional Neural Network”: energy deposition patterns treated as images, algorithm extracts representative abstract features by applying learned filters.
$\nu_e$ appearance: selection & reconstruction

**Convolutional neural network** selects events via transformations applied to energy deposits treated as images

Energy estimator is quadratic function of $E_e$ and $E_{\text{had}}$.

$\sim$11% resolution
\(\nu_e\) appearance: constraining beam \(\nu_e\) bknd

Assign discrepancies in ND \(\nu_\mu\) contained and uncontained samples to flux; derive corrections according to parent mesons (which also result in beam \(\nu_e\))

Pion-ancestor neutrinos are corrected in bins of parent \((p_z, p_T)\). Average \(\sim +2\%\)

Kaon-ancestor neutrinos get a single weight: -6.3%
\( \nu_e \) appearance: constraining \( \nu_\mu \) CC/NC ratio

Examine distribution of Michel electrons in each bin of ND \( \nu_e \) selected sample after beam \( \nu_e \) constraint (prev slide)

Fit these 18 distributions to determine \( \nu_\mu \) CC / NC corrections in each bin