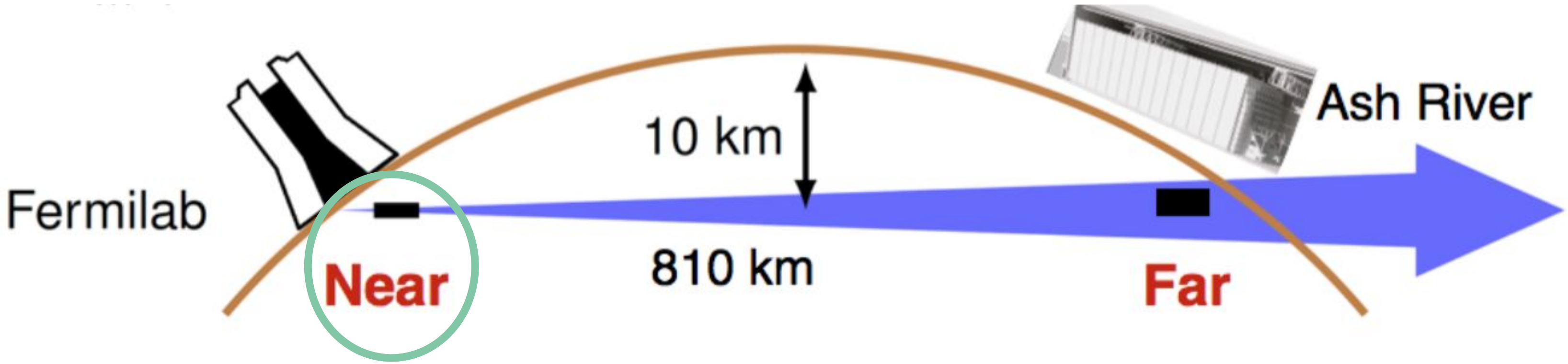
Is tuning the answer for new physics searches?

Nina Coyle
INT workshop
November 1, 2023

Accelerator neutrino experiments

Long-baseline accelerator neutrino experiments aim to measure oscillation probabilities using a near detector (ND) and a far detector (FD)



Near detectors interesting for new physics searches

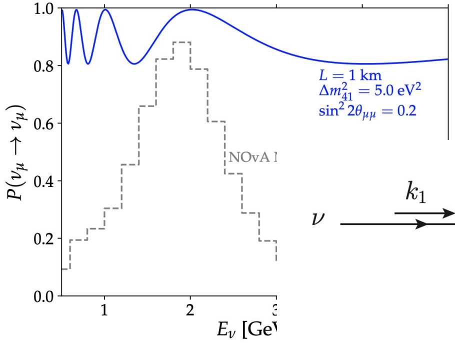
- Very high intensity
  - New physics typically has low rates => needs high intensity
- Weakly-interacting background
- Already built or are being built

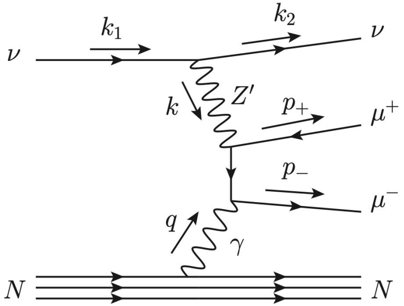
An excellent opportunity to extract as much physics from our experiments as we can

What kinds of new physics searches?

Some example models to search for:

- Light (eV-scale) sterile neutrinos (e.g. arXiv:1710.06488)
- Neutrinophilic scalars (arXiv:1901.01259)
- Trident production (arXiv:180710973)
- Light dark matter (arXiv:1107.4580)





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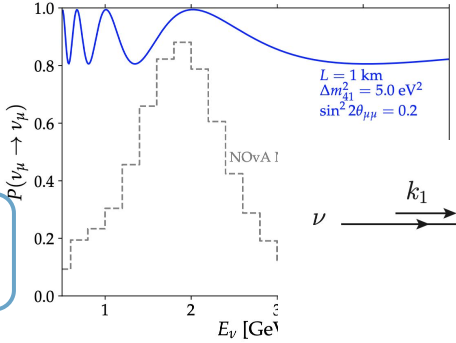
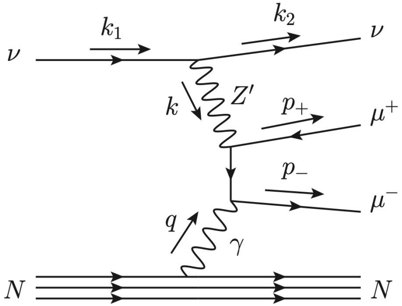




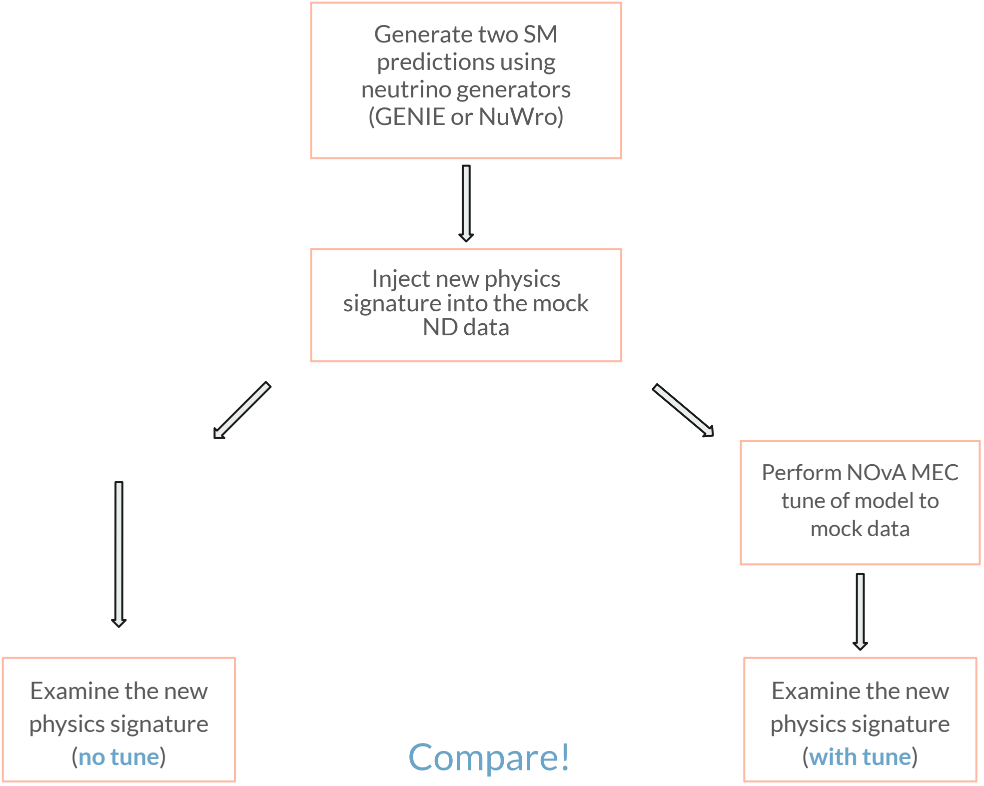
We know that our modeling of cross sections is not perfect, and we are looking for very small new physics signals.

How does this impact potential searches at the ND, and how might we deal with this issue?

Process

Goal:

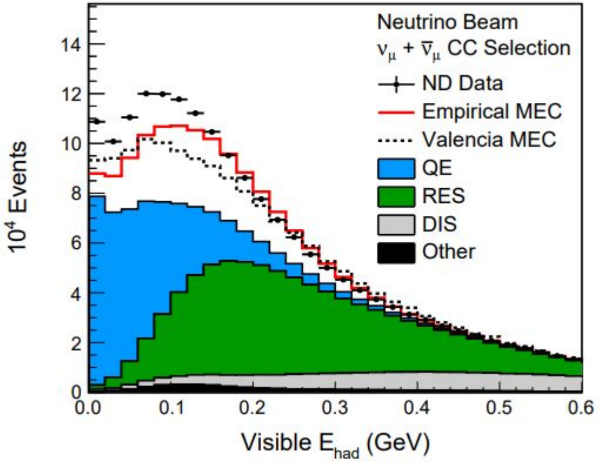
- Use two different generators as a tool to investigate impact of cross section modeling on new physics searches
- Test one potential approach to mitigating cross section uncertainties: ND tune

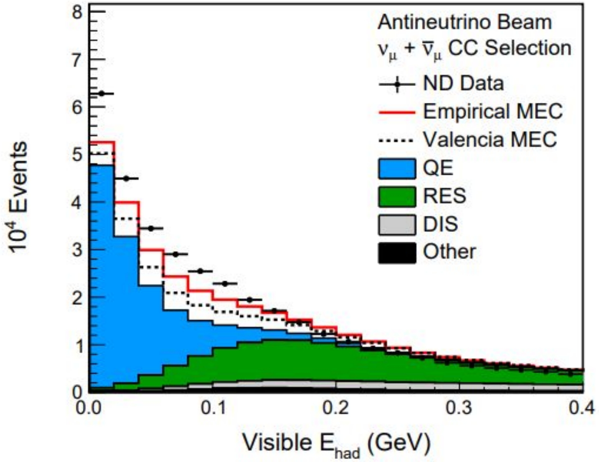


NOvA MEC tune

NOvA collaboration, arXiv:2006.08727

How to account for remaining discrepancy? Assume it's due to MEC mis-modeling and adjust the MEC contribution to match NOvA ND data





NOvA MEC tune

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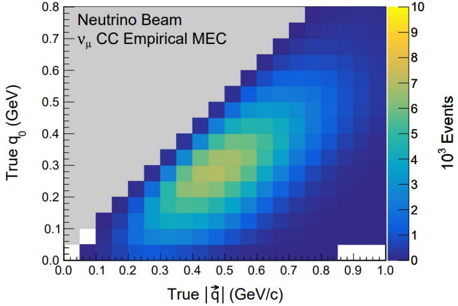
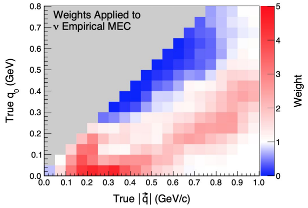
How to adjust for remaining discrepancy? Adjust the MEC contribution bin-by-bin





Migrate

Simulation binned in $|\vec{q}^{\,reco}|$ and q_0^{reco}

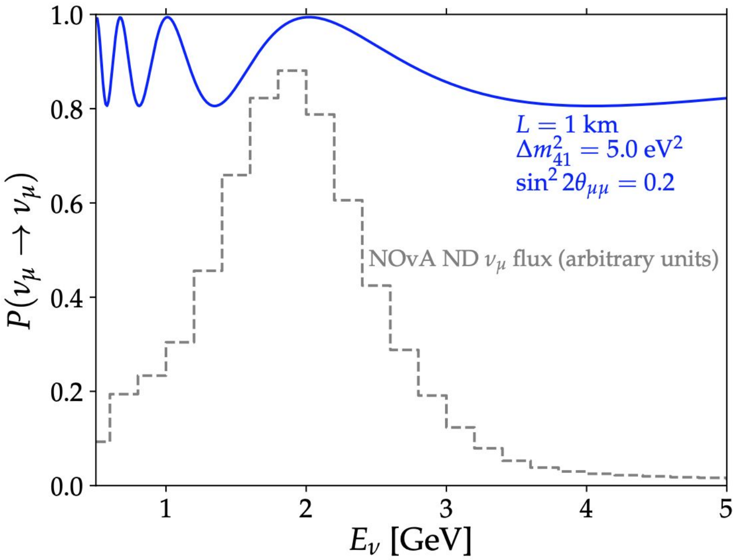
Fit

NOvA ND data binned in $|\vec{q}^{\,reco}|$ and q_0^{reco}

Sterile neutrino signal

Induce oscillations around L (km)/E (GeV) ~ 1

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$

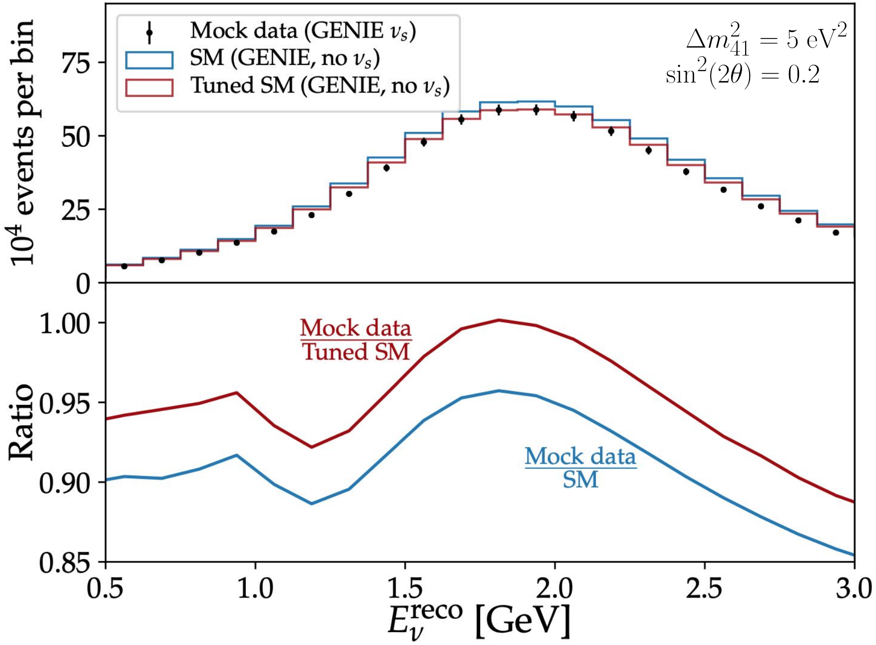


Existing near detectors can also search for sterile neutrinos

Sterile neutrino signal: same generator

- Use GENIE to generate both the mock data and the model
  - This allows us to see the effect of the tuning without other complications

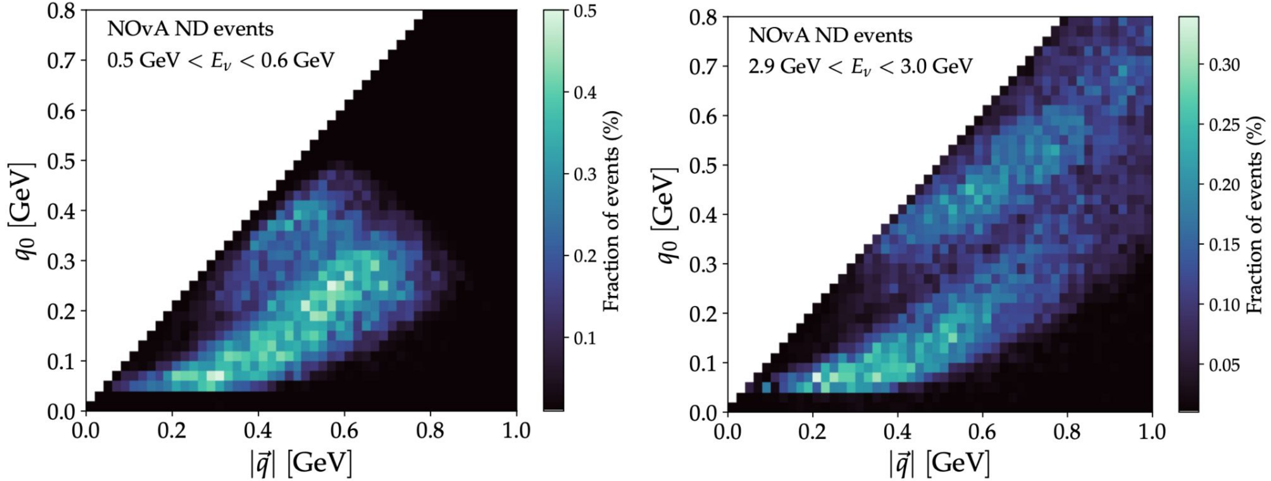
We find that we are not tuning away the oscillations



NC, Li, Machado, arXiv:2210.03753

Sterile neutrino: shape in the tune plane

Why doesn't the tuning procedure remove the oscillations? Neutrino energy isn't directly correlated with tune parameters



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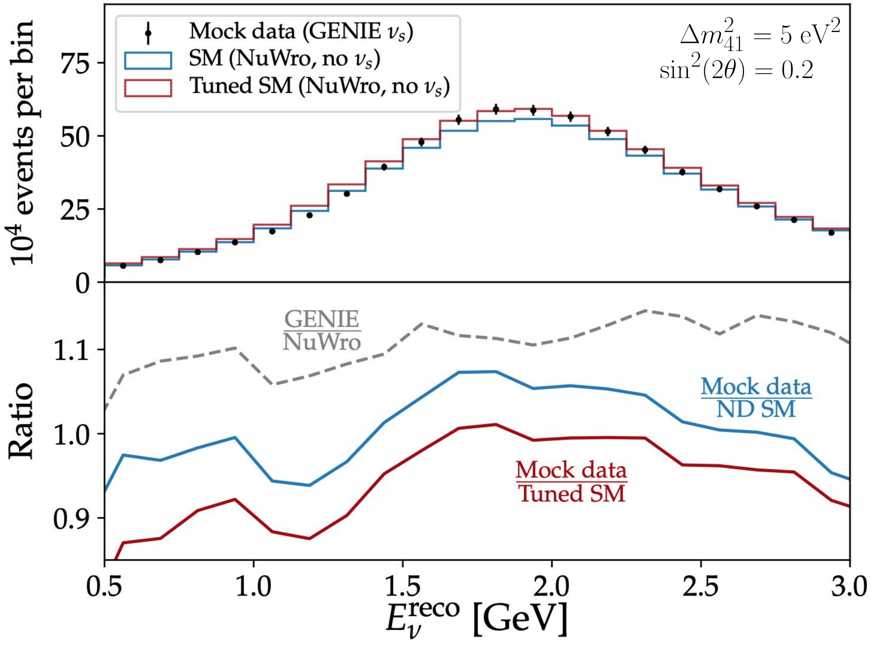
Sterile neutrino: mis-modeling impact

- More realistic: take a different generator for the model
  - This gives us a proxy for mis-modeling between our models and nature

Signature affected due to disagreement in generators



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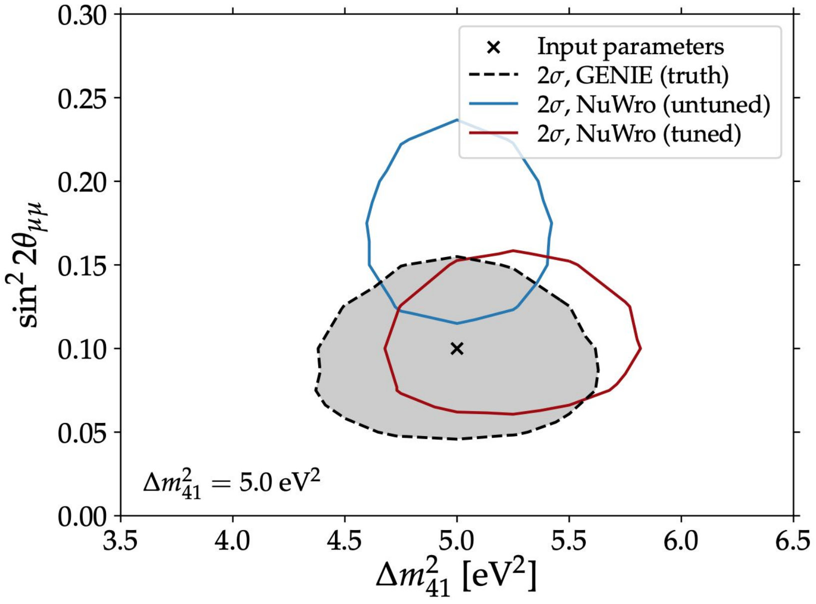
Sterile neutrino: sensitivity check

- Two cases:
  - Same generator for data and model (grey filled)
  - Different generators (color unfilled)
- Simultaneous fit and tune
- Chi-squared fit with a covariance matrix
- Systematic uncertainties:
  - Overall normalization: 20%
  - Near-to-far spectral correlated: 2%
  - Uncorrelated bin-to-bin: 2%



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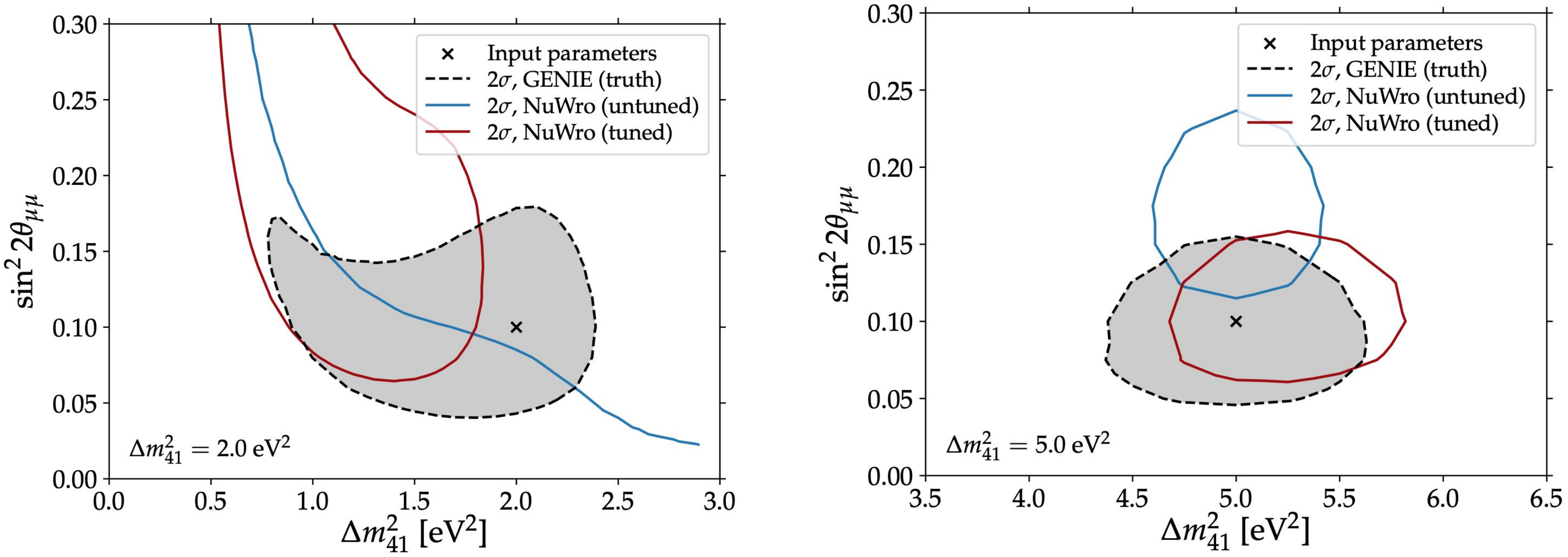

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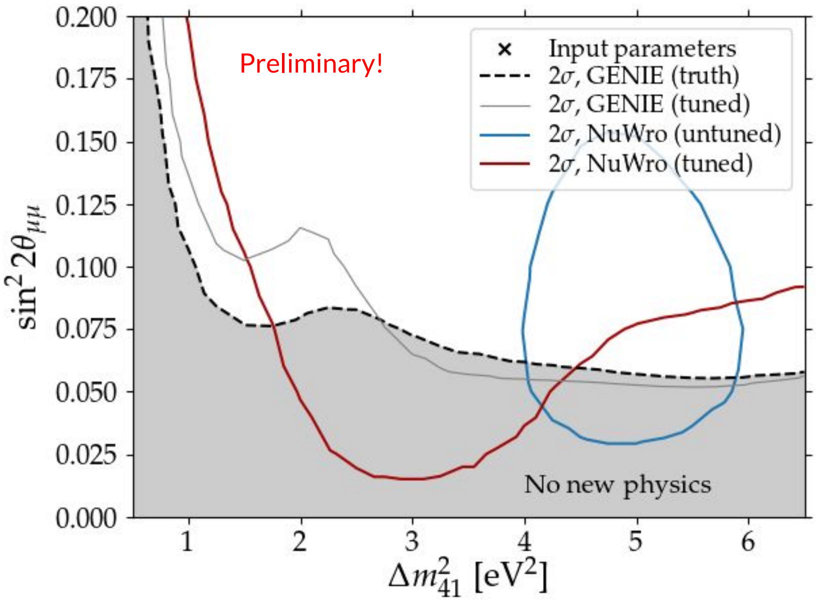
(No) sterile neutrino: sensitivity check (new!)

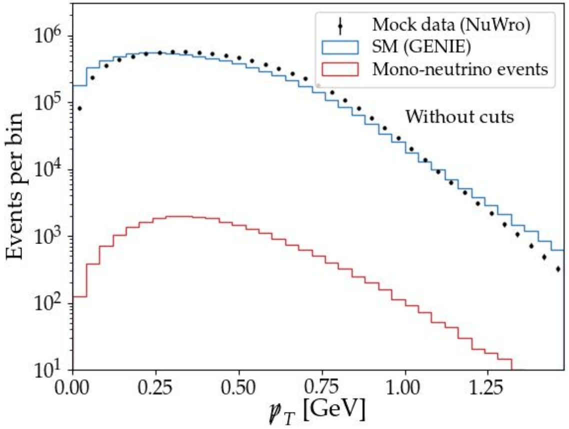


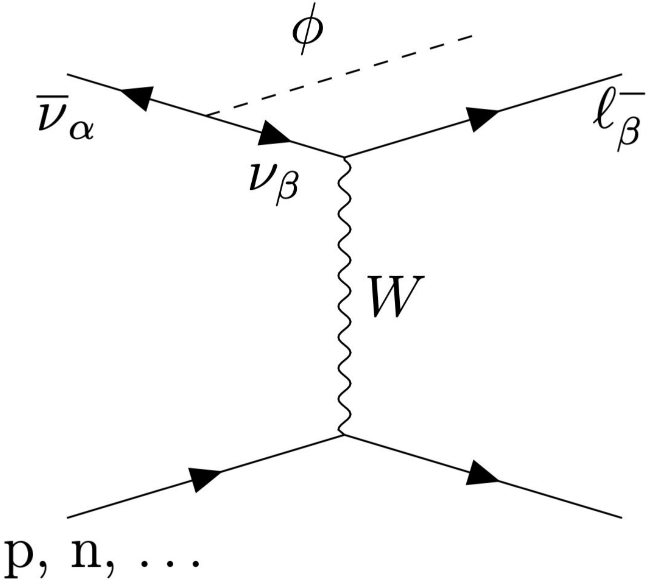
The untuned region infers the presence of new physics

But the tuned region is consistent with no new physics!

Mono-neutrino signal

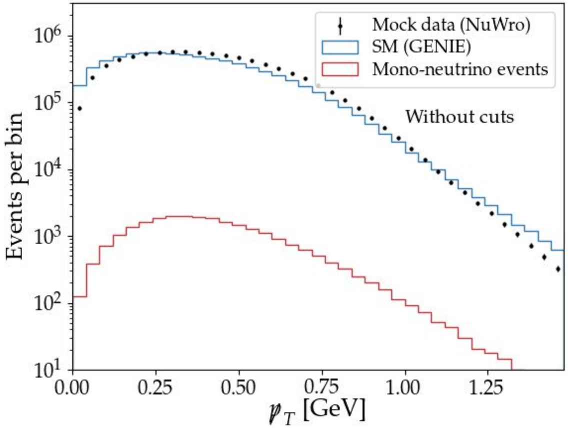
- Neutral scalar, showing up as missing pT
- Sub-percent-level fraction of events: requires cuts to see the signal

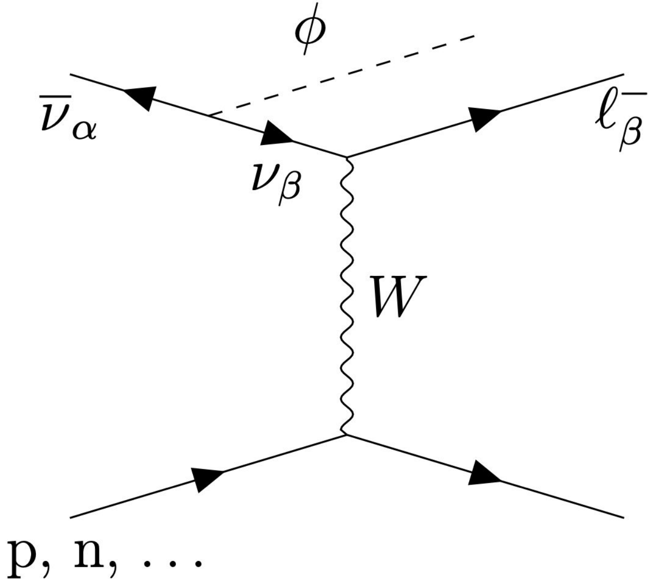




Mono-neutrino signal

- Neutral scalar, showing up as missing pT
- Cut on 0 pions, 1 proton, no neutrons (KE threshold of 100 MeV)





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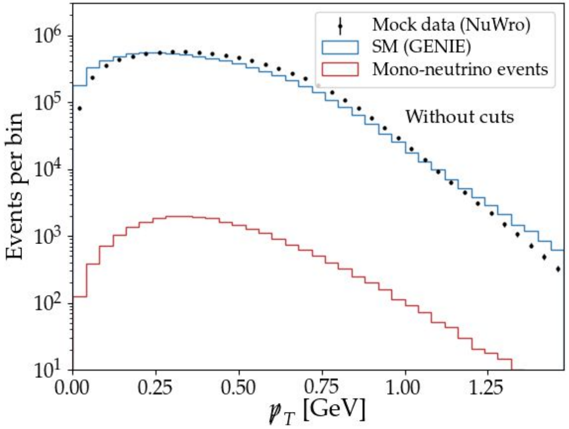
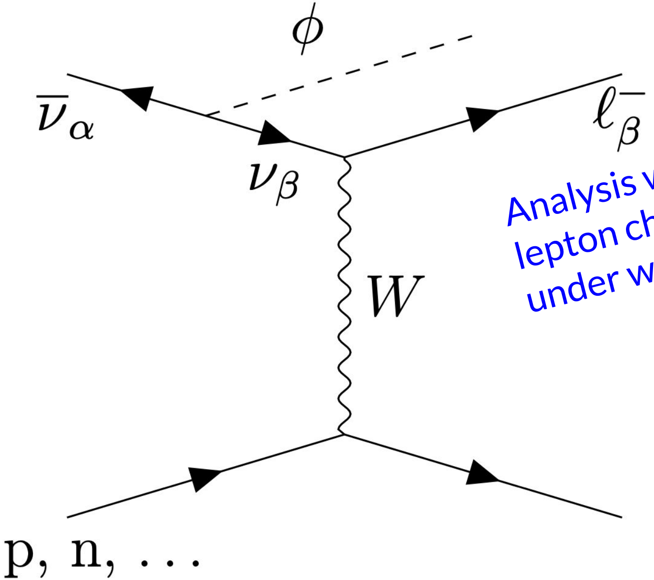
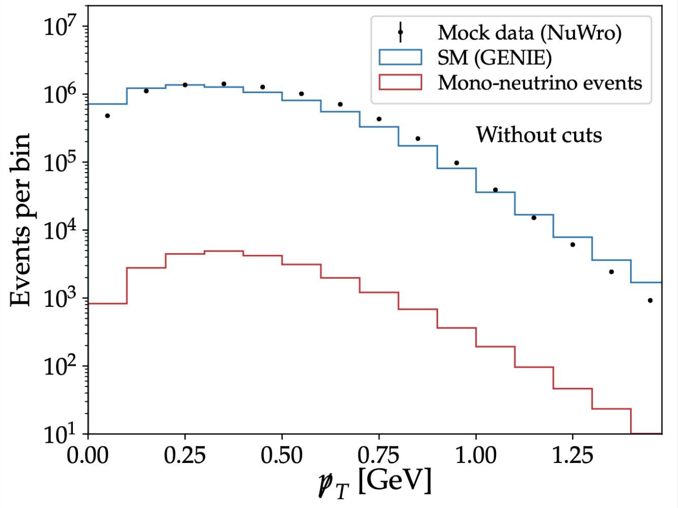


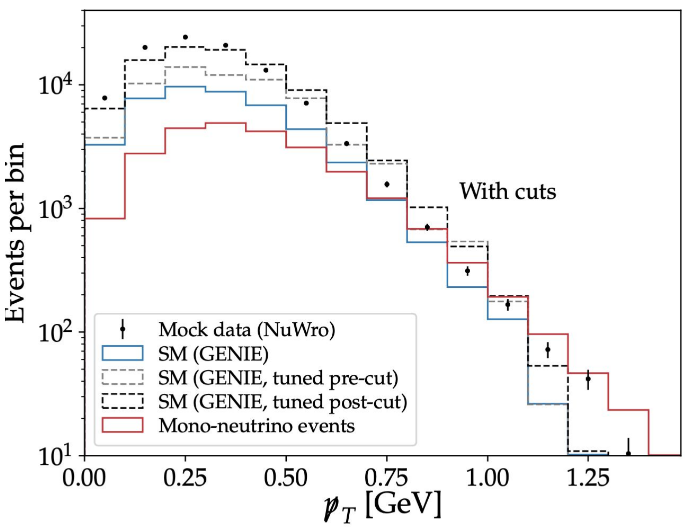


Analysis with lepton charge ID under way

Generators don't respond the same to cuts

NC, Li, Machado, arXiv:2210.03753

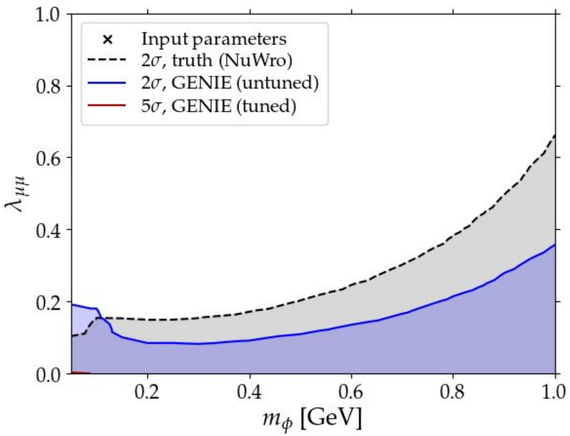


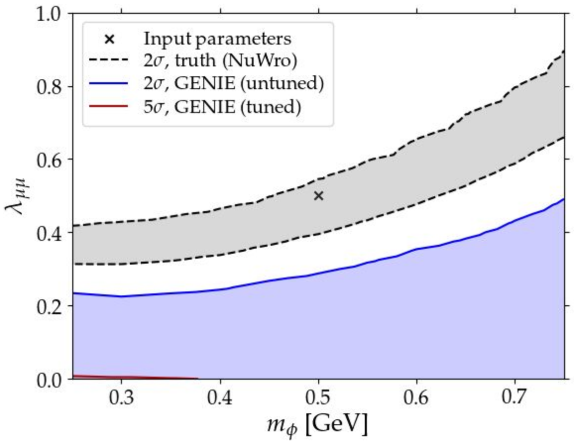


Mono-neutrino: (non)sensitivity plot

NC, Li, Machado, arXiv:2210.03753

- Different generators, simultaneous fit and tune, tuning after cuts
- Generator disagreement dominates over new physics



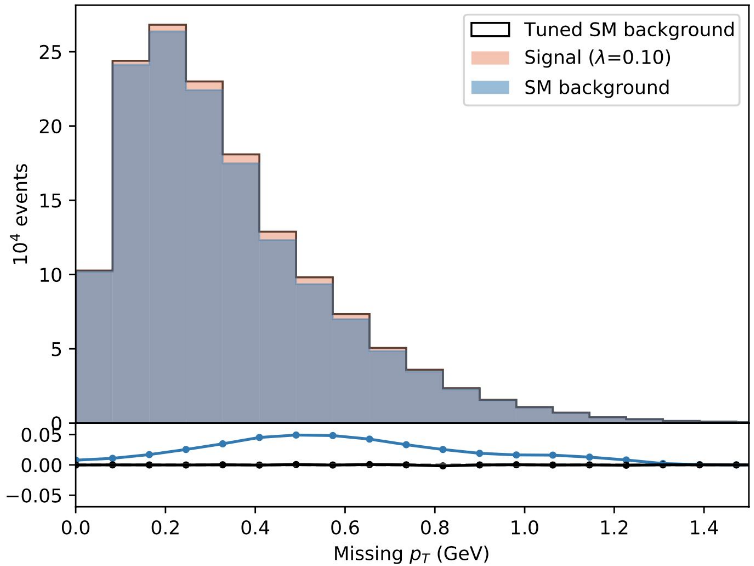


Could we tune away the new physics?

What if you tune in parameters that have a shape in the tune plane?

Example: perform the same tune, but with pT as one of your tune parameters

Answer: yes, you can tune away new physics... but only if we are being very uncareful



Conclusions

- Cross section mis-modeling can impact our interpretation of new physics searches
- A near detector tune does not entirely resolve these issues (perhaps not a surprise)
  - Interestingly, it can seem to help in the sterile neutrino analysis, but not for all searches
- It is difficult to disentangle shape differences arising from new physics from those arising from modeling
  - Plus when we cut on final states, discrepancies in individual processes becomes even more important (e.g. what if MEC is not the source of full remaining discrepancy?)
- A one size fits all solution seems unlikely. Consider specific solutions for individual new physics models, e.g. charge ID for mononeutrino

Thank you!

Tuning: NOvA

NOvA collaboration, arXiv:2006.08727

Start by implementing some changes to the base GENIE based on other experimental results

- Adjust CCQE M_A input value from neutrino-deuteron scattering data (arXiv:1603.03048)
- Adjust nuclear momentum distribution from MINERvA (arXiv:1705.0293)
- Reduction to non-resonant single pion production from bubble chamber data (arXiv:1601.01888)

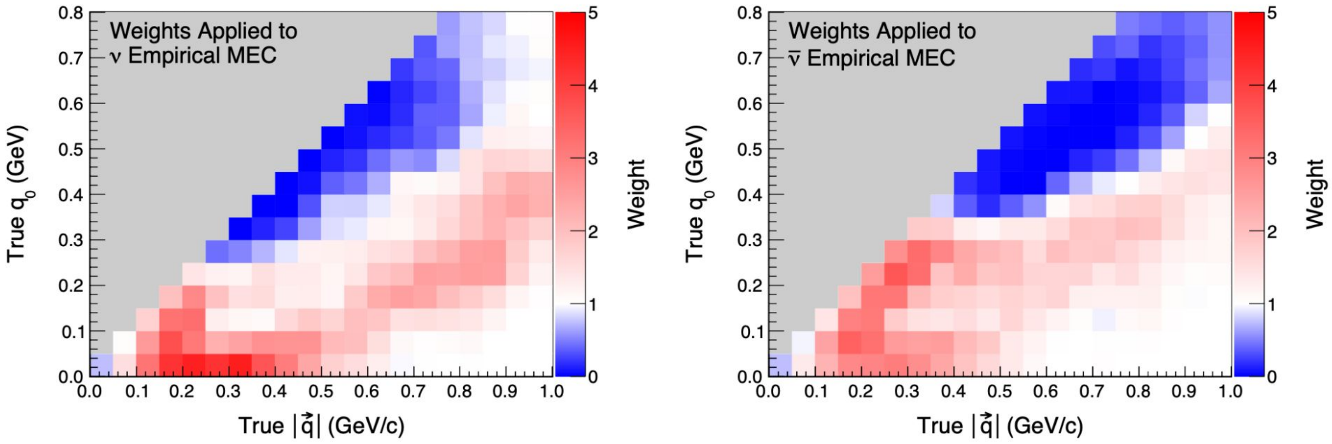


FIG. 4. The weights, in three-momentum and energy transfer, applied to simulated Empirical MEC interactions to produce the fitted NOvA 2p2h predictions described in the text, for neutrinos (left) and antineutrinos (right). Gray indicates kinematically disallowed regions, where no weights are applied.

NOvA collaboration, arXiv:2006.08727

Comparison of 2p2h predictions

NOvA collaboration, arXiv:2006.08727

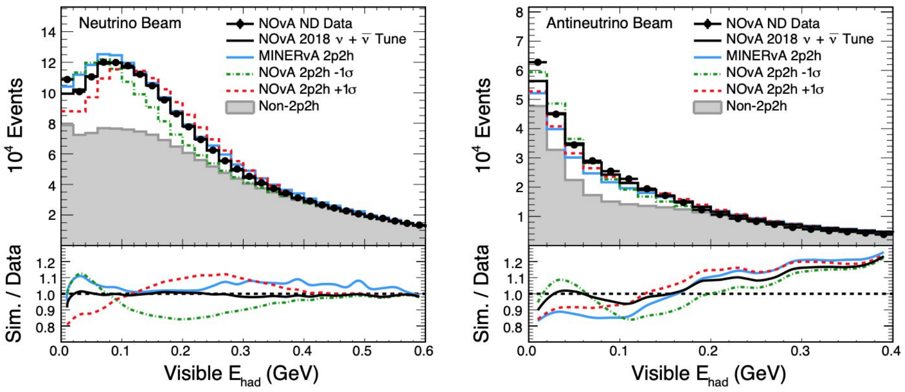
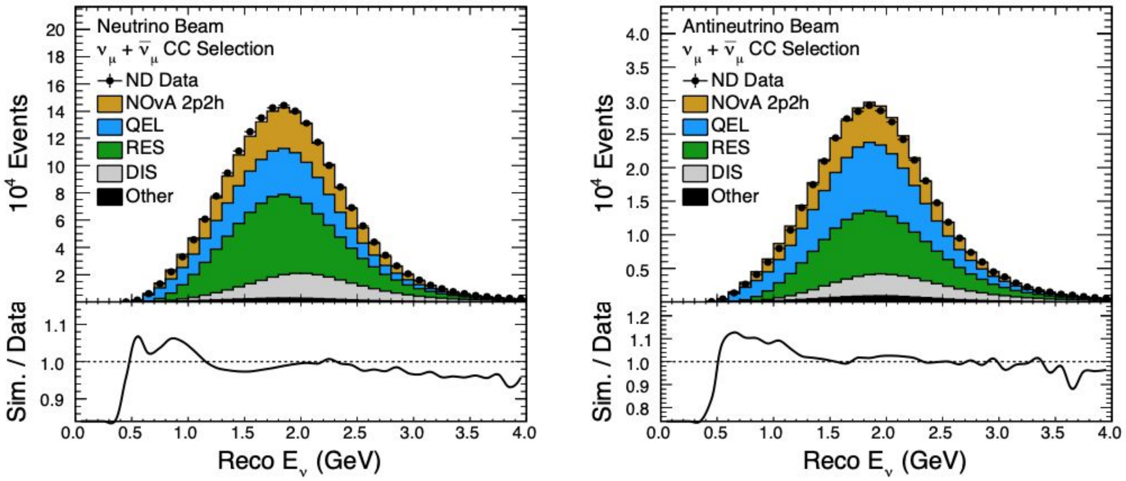
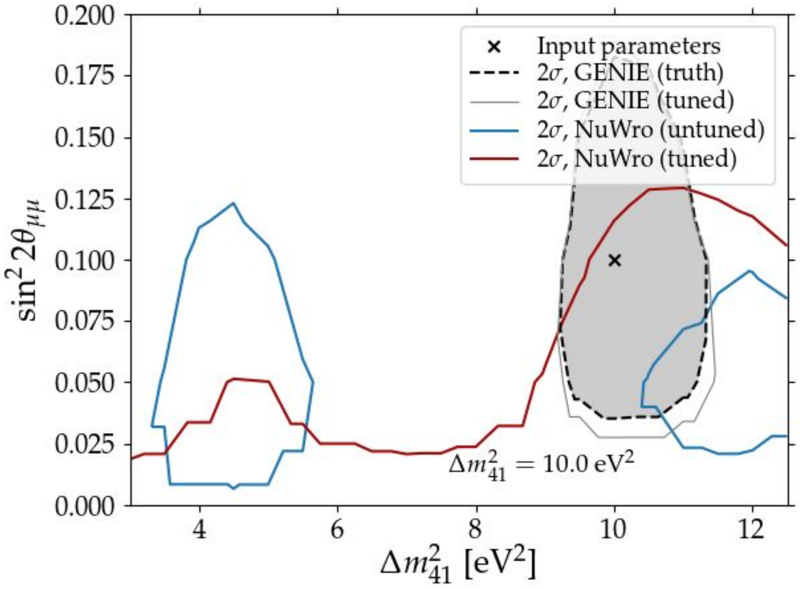


FIG. 13. Comparison of reconstructed visible hadronic energy distribution in ND data (black dots) to various simulations for neutrino beam (left) and antineutrino beam (right) running. The solid black curves correspond to GENIE predictions with the full set of adjustments described in this paper, while the red and purple dotted curves are the simulation with $+1$ and -1σ shifts from the 2p2h $(q_0, |\vec{q}|)$ response systematic uncertainty shown in Fig. 11, respectively. Also shown in solid blue is the result of replacing our tuned 2p2h with MINERvA's tuned 2p2h prediction. The shaded gray histogram represents the GENIE prediction for non-2p2h interaction channels.

Tuned E_reco distributions



An additional sterile mass squared splitting



Reco tune quantities

$$q_0^{\text{reco}} \simeq E_{\text{had}} = \sum_i^{\text{nucleons}} T_i + \sum_j^{\text{mesons}} E_j.$$

$$Q^2_{\text{reco}} = 2E_\nu \left(E_\mu - p_\mu \cos\theta_\mu\right) - m_\mu^2$$

$$|\vec{q}|_{\text{reco}} = \sqrt{Q^2_{\text{reco}} + E^2_{\text{had}}}$$