# $\nu$ Cross Sections: *Renaissance*


Ben Messerly


*Neutrino Oscillation Workshop*

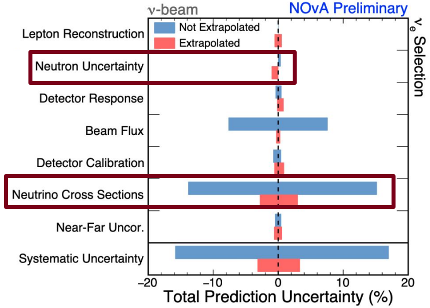
*Ortanto*
*September 6, 2024*

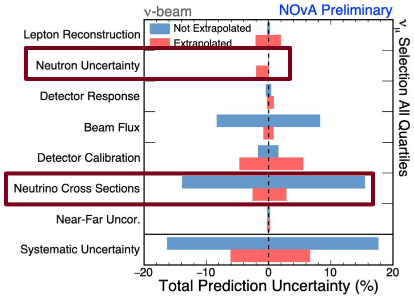
*The Annunciation* - Fra Angelico
1445 - Early Renaissance

*Last Supper* - Jacopo Tintoretto
1594 - Late Renaissance, early Baroque


UNIVERSITY OF MINNESOTA

# Cross Section Knowledge:
## A Challenge for *Current* Oscillation Experiments

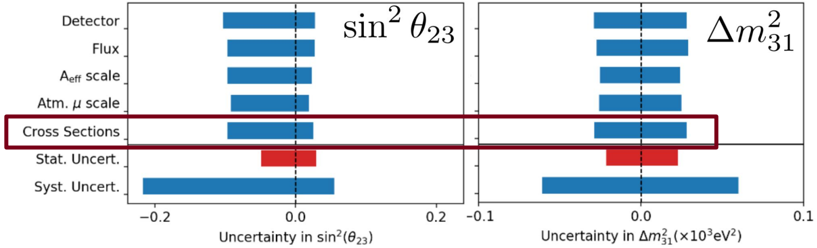



**NOvA** Talk from Tuesday (Liudmila Kolupaeva, NOW 2024)

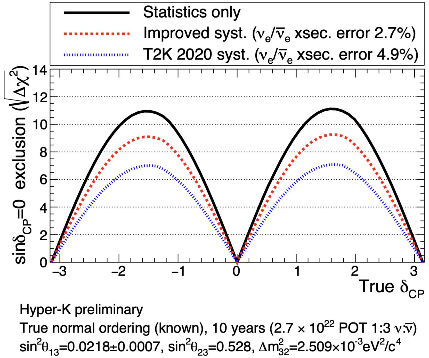
| Sample | | Uncertainty source (%) | | | Flux⊗Interaction (%) | Total (%) |
|---|---|---|---|---|---|---|
| | | Flux | Interaction | FD + SI + PN | | |
| 1R$\mu$ | $\nu$ | 2.9 (5.0) | 3.1 (11.7) | 2.1 (2.7) | 2.2 (12.7) | 3.0 (13.0) |
| | $\bar{\nu}$ | 2.8 (4.7) | 3.0 (10.8) | 1.9 (2.3) | 3.4 (11.8) | 4.0 (12.0) |
| 1R$e$ | $\nu$ | 2.8 (4.8) | 3.2 (12.6) | 3.1 (3.2) | 3.6 (13.5) | 4.7 (13.8) |
| | $\bar{\nu}$ | 2.9 (4.7) | 3.1 (11.1) | 3.9 (4.2) | 4.3 (12.1) | 5.9 (12.7) |
| 1R$e$1de | $\nu$ | 2.8 (4.9) | 4.2 (12.1) | 13.4 (13.4) | 5.0 (13.1) | 14.3 (18.7) |

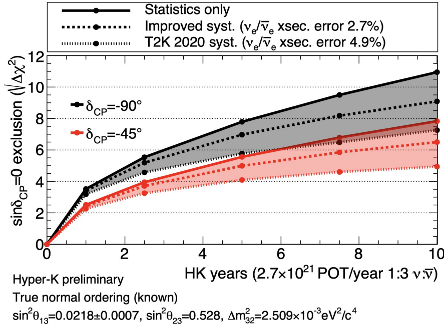
**T2K** Oscillation Analysis. 2303.03222v 2023.



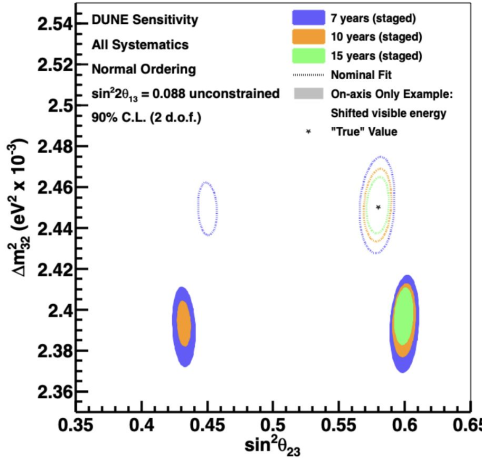

**IceCube** Talk from Tuesday (Andrii Terliuk, NOW 2024)

# Cross Section Knowledge:
## A Challenge for *Upcoming* Oscillation Experiments




**HK $\nu_e/\bar{\nu}_e$ systematic:** [HK Talk from Tuesday](#) (Jeanne Wilson, NOW 2024)




**DUNE p/n response:** plausible consequence of an alternative interaction model that shifts 20% of proton energy into neutrons. [DUNE TDR](#).

# Cross Section Knowledge:
## A Challenge for *Upcoming* Oscillation Experiments

- LBL oscillation experiments *will* be systematics limited.
- Cross section knowledge will need to improve for the success of these (imminent) programs.

| Sample | T2K | NOvA | Hyper-Kamiokande | DUNE |
|---|---|---|---|---|
| $N_\mu^{rec}$ FHC | 318 | 211 | 10000 | 7000 |
| $N_\mu^{rec}$ RHC | 137 | 105 | 14000 | 3500 |
| $N_e^{rec}$ FHC | 108 | 82 | 3000 | 1500 |
| $N_e^{rec}$ RHC | 16 | 33 | 3000 | 500 |

Wret @ NuINT 2024

- There has been a full Renaissance of measurement techniques and technologies to challenge generators/models/theories.

# Outline

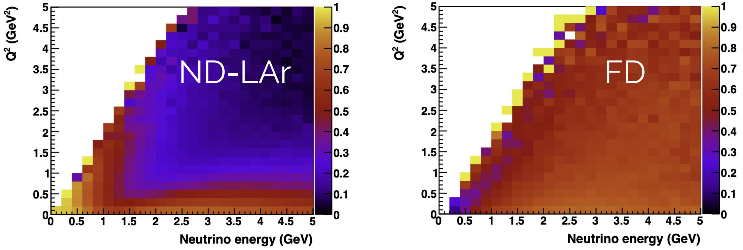
1. Motivate cross section challenges
   a. Theory challenges
   b. Experimental needs
   c. Measurement renaissance
2. Highlighting some of LBL's biggest cross section challenges in the context of an ongoing experimental **renaissance**
   a. Neutrons
   b. $\nu_e / \bar{\nu}_e$
   c. TKI
   d. Shallow Inelastic Scattering
   e. Generators
   f. Data Preservation

# How Xsec Uncertainty Impacts Oscillation Experiments

$$N_\mu^{ND} = \Phi_\mu^{ND}(E_\nu) \otimes \sigma_\mu(E_\nu) \otimes \epsilon_\mu^{ND}(\vec{x})$$

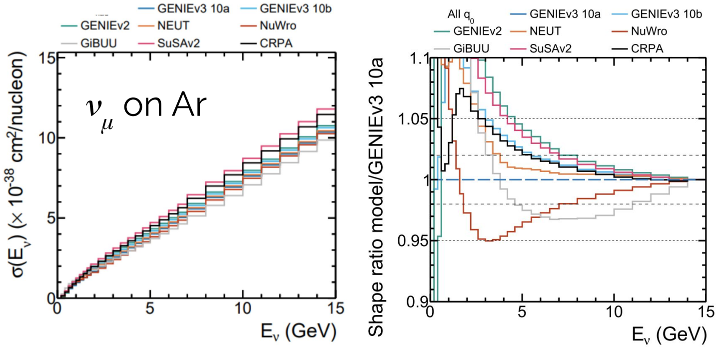
$$N_\mu^{FD} = \Phi^{FD}(E_\nu) \otimes \sigma_\mu(E_\nu) \otimes \epsilon_\mu^{FD}(\vec{x}) \otimes P_{\nu_\mu \to \nu_\mu}(E_\nu)$$

- ND constraints mitigate flux and xsec uncertainties.
- But correlations don't fully cancel:
  - $\Phi_{\nu e}^{ND} \neq \Phi_{\nu\mu}^{ND} \times P(\nu_\mu \to \nu_e)$
  - Need precise knowledge of $\sigma_{\nu\alpha}/\sigma_{\nu\beta}$, $\sigma(E_\nu)$ shape
- Rely heavily on models for ND→FD extrapolation, efficiency, and energy smearing.
- Harder when ND and FD have different A




DUNE $\mu$ acceptance.

DUNE CDR.

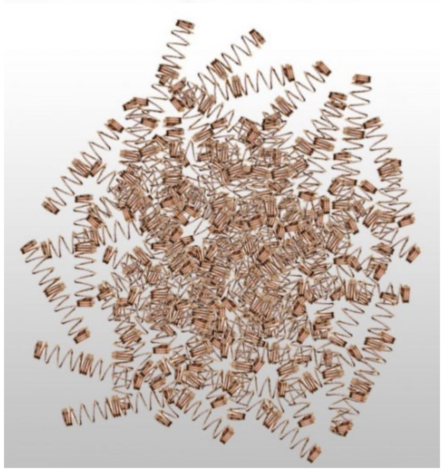



2203.11821

# What's so hard about xsecs? Nuclear environment

- Unfortunate coincidence that LBL beam energies (0.1 - 20 GeV) and energy transfers of $\lesssim$ 1 GeV effect multiple nuclear response modes
  - Elastic, metastable excitations, quasielastic (knockout), and inelastic (new particles)
  - And single nucleon separation
  - And subleading processes like 2p2h
- Nuclear modeling nightmare – processes can't be cleanly separated, and models can't approximate away nuclear structure nor final state degrees of freedom.

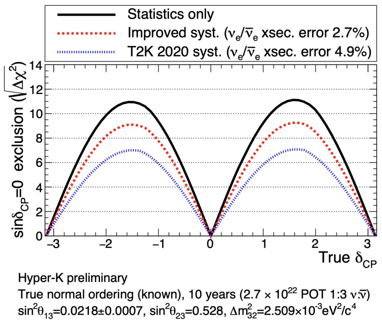
See Noah Steinberg's talk on Saturday afternoon



Like solving this equation of motion where the energy to uncouple springs ~ energy to break them.

From K. McFarland

# What's so hard about xsecs? $\nu_e, \bar{\nu}_e, \bar{\nu}_\mu$

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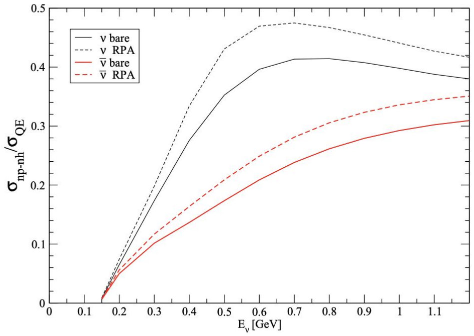
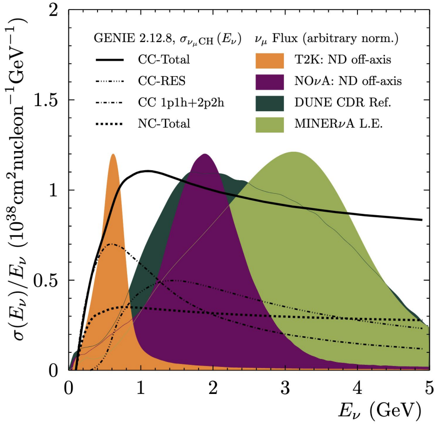



- Beams are primarily $\nu_\mu$. So $\nu_e$ and $\bar{\nu}$ harder to study, and measurements lack.
- Can infer a lot of knowledge of $\nu_e$ interactions from $\nu_\mu$, but never the whole picture.
- $\nu_\mu$ / $\nu_e$ impacted by radiative corrections 2105.07939 and nuclear medium effects
- $\nu$ vs $\bar{\nu}$ interaction theory still developing, e.g. different 2p2h rates 1002.4538, RPA effects

See Nikolakopoulos, Belocchi, and Dordei talks on Saturday afternoon

# What's so hard about xsecs? **Experiment**

- Need event-by-event energy and flavor.
- Overlapping interaction channels
  - Problem when we make energy or flavor conclusions from erroneous reco interaction channel.
- Cannot take flavor for granted (e.g. $\pi^0$ photons ↔ $\nu_e$)
- Energy is smeared (e.g. lost neutral energy)
- Cross section effects could overlap with osc parameter effects
  - E.g. Incorrect $\pi^0$ background model → increased $\nu_e$ rate → larger $\delta_{CP}$ and $\theta_{13}$
  - Wrong neutral energy → move peak → different $\Delta m_{32}^2$

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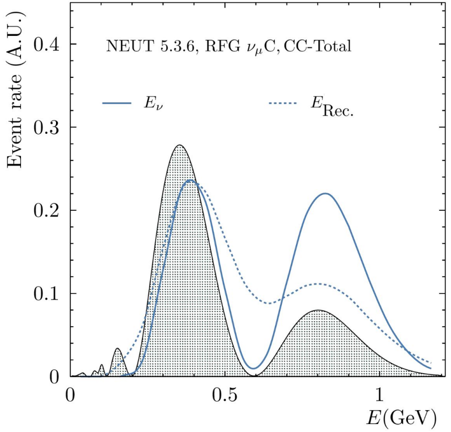
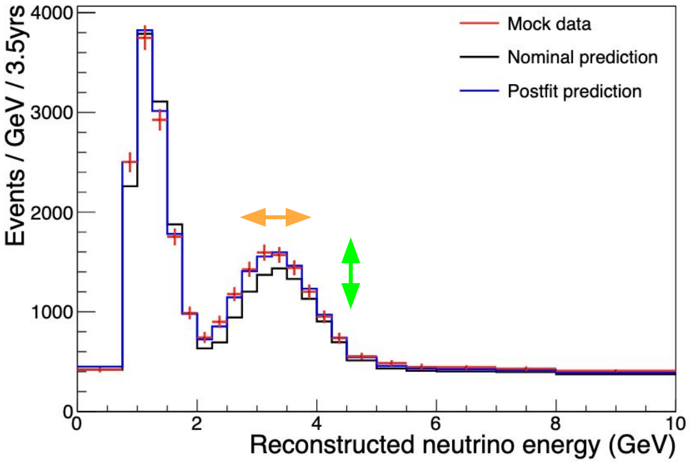


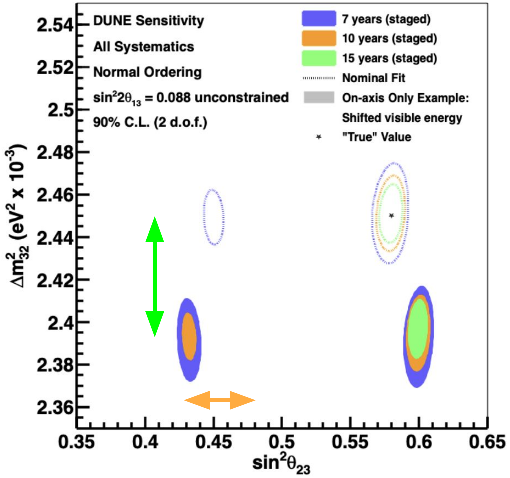

L. Pickering

# Energy mismodeling at DUNE

Shift 20% of proton energy to neutrons while keeping $p_p$ distribution same

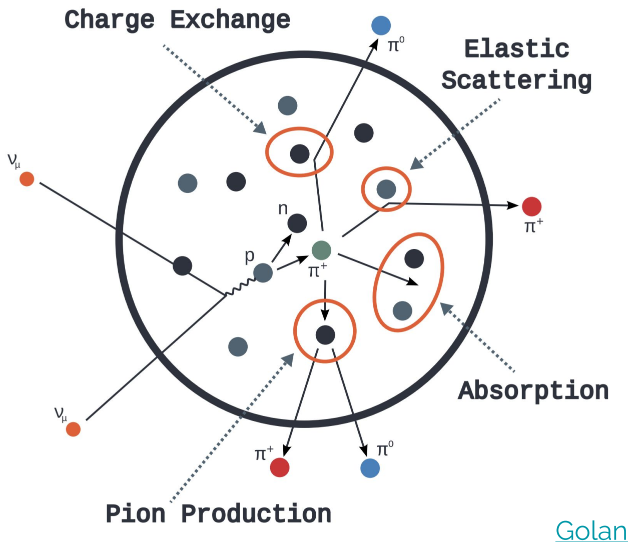
Consequences of a plausible alternative model.



# More energy smearing and flavor determination

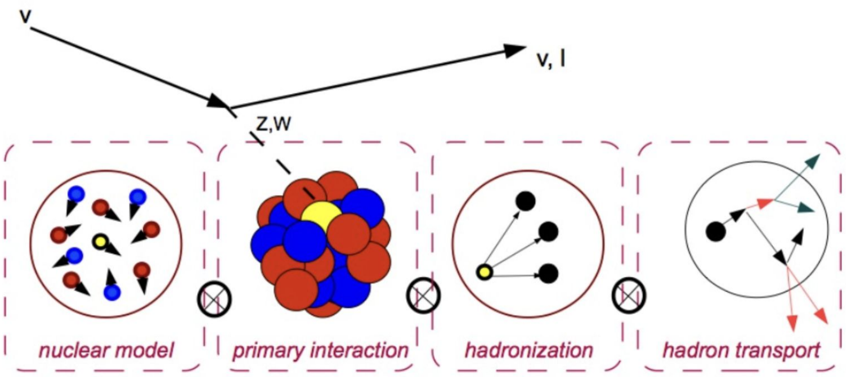
- Experimental signature asymmetry where there is isospin symmetry:
  - Protons look different from neutrons
  - Inelastic $\pi^-$ produce neutrons
  - $\pi^0$ deposits KE and mass vs $\pi^+$ deposits KE (at best)
- Energy lost to…
  - Initial nuclear state momentum
  - Nuclear mass
  - Excitation
  - Hadronization
  - Detector thresholds
- FSIs mask interaction channel and smear E.




Golan

# What's so hard about xsecs? **Technically**

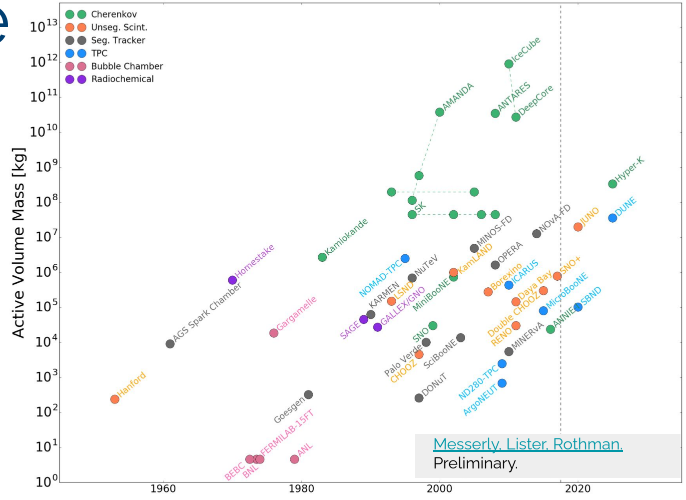
- Neutrino experiments strongly bound to generators.
- Generators encode physics, models for experimental use.
- Experimentally critical for model to resemble data.
- Theory and generator development is extremely difficult.
  - Use necessary approximations, limited phase spaces, overly inclusive reactions.
  - Data points out model deficiencies, but can't answer why.




# The last 15 years: the renaissance

"Most of our knowledge of neutrino cross sections in this intermediate energy range comes from early experiments that collected relatively small data samples (tens- to-a-few-thousand events). These measurements were conducted in the 1970's and 1980's using either bubble chamber or spark chamber detectors…"

– *From eV to EeV: Neutrino Cross-Sections Across Energy Scales*, Zeller, Formaggio, 2013




First high statistics measurements begin with NOMAD and MiniBooNE.

**Next**: focus on explosion of novel/revived/matured measurement techniques used to fill in swathes of phase space across interaction channels.

## $\nu_\mu CC1\pi^+$ Event Count

| FNAL 15' BC (1978) | MINERvA (2015) | MINERvA (2024) |
|---|---|---|
| ~300 | ~3,000 | ~100,000 |

# The Latest in Interaction Measurement Techniques and Technologies

- Explosion of new (revived) techniques enabling novel and more robust measurements
  - Multi-dimensional xsecs
  - Transverse Kinematic Imbalance
  - Adler Variables
  - H separation from CH
  - Correlated/cross-chiral/multi-channel measurements
  - Not to mention ML

- New experimental technologies
  - Nuclear Target Cross Section Ratios
  - Low-threshold measurements
  - Neutron Detection
  - PRISM flux technique

- Other best practices are maturing
  - Model Independence (topology-based, fiducial signal definitions)
  - Model tuning
  - Full covariance matrix reporting
  - Unfolding strategizing
  - Peelle's Pertinent Puzzle, Log $\chi^2$ comparisons
  - Data Preservation

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Finely segmented phase space, mitigate biases of efficiency sim

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Decoupling nuclear initial state from final state

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Low A measurement in high A

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Decouple flux effects, $\nu$ vs $\bar{\nu}$ , $\nu_\mu$ vs $\nu_e$, probe nuclear effects

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Vertex reconstruction, PID, …

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Probe nuclear scaling

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Energy smearing/loss, new areas of phase space

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Critical component of DUNE and HK. Decouple flux effects.

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Model independence

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Better uncertainty estimation, better background estimation, more robust results

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More responsible statistics practices

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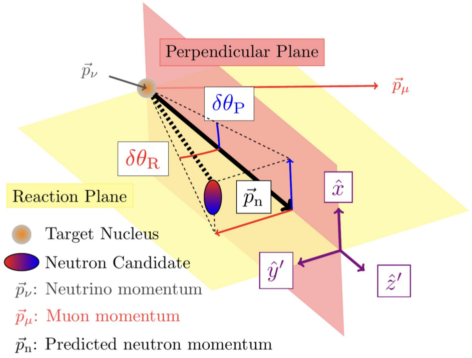
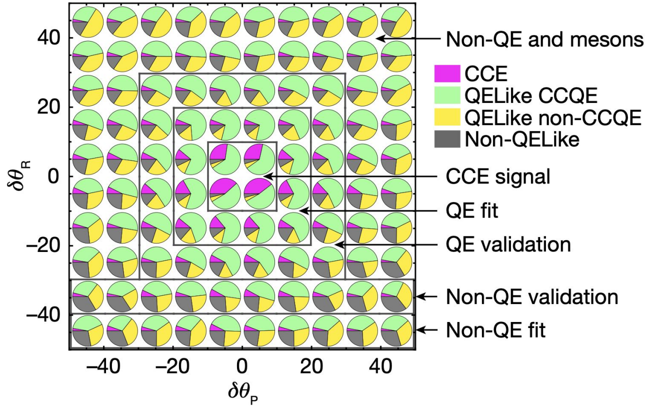
Open science!

# Neutron Measurements (MINERvA, etc)

- Impacts on $\bar{\nu}$-$\nu$ separation, energy loss
- Measurement of $\bar{\nu}_\mu$H $\rightarrow \mu$N on a CH target
  - 2-body neutron kinematics in $\bar{\nu}_\mu$H unlike on $\bar{\nu}_\mu$C.
  - Use deviation from predicted two-body $p_N$ to select $\bar{\nu}_\mu$H events among CH.
  - Calculate cross section and extract $F_A$.
  - Unique probe of weak sector, direct comparison to lQCD computations.
- MINERvA multi-neutron cross section (CH target, 6 GeV beam). First of its kind. 2310.17014.
- SNO (2019), T2K (2022), and uBooNE (2024) neutron tagging results. And SuperFGD soon!



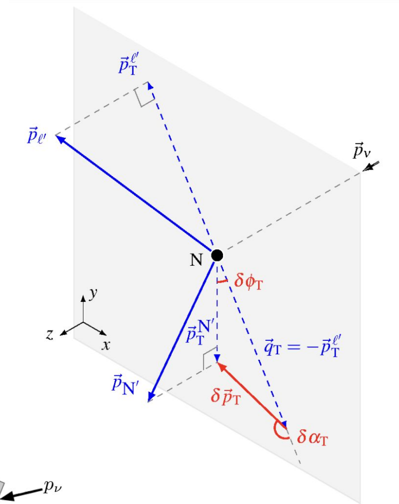



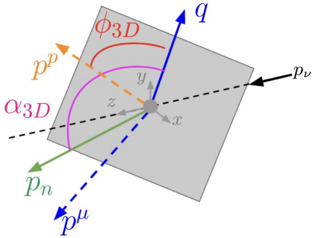

10.1038/s41586-022-05478-3

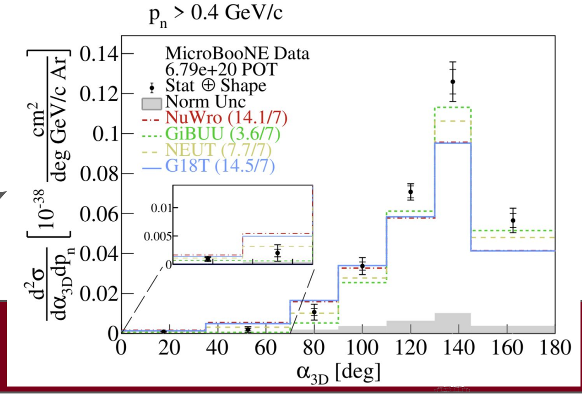
# Transverse Kinematic Imbalance

- Effects of nuclear motion can be separated from FSI and MEC contributions to the cross section
- $\delta_{pT}$ is missing transverse momentum (momentum of struck nucleon w/o FSIs)
  - Low $\delta_{pT}$ → minimal FSI occurred.
  - High $\delta_{pT}$ → missing hadronic energy
- New results from MINERvA[1] , T2K[2][3], and uBooNE [4][5].

uBooNE uses alternate coordinate system more sensitive to FSI effects

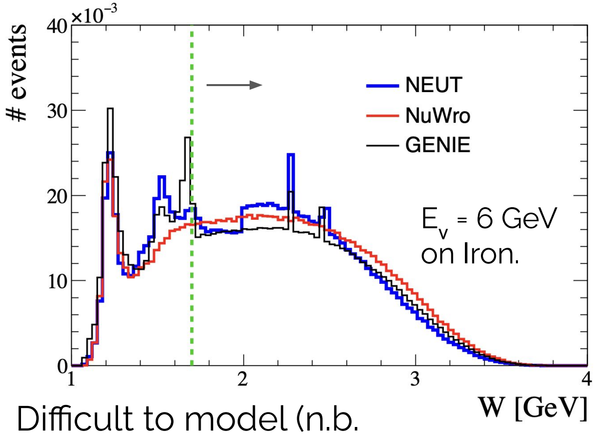


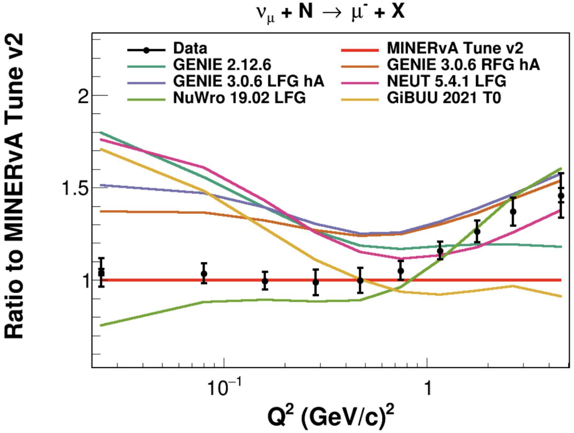
# Shallow Inelastic Scattering

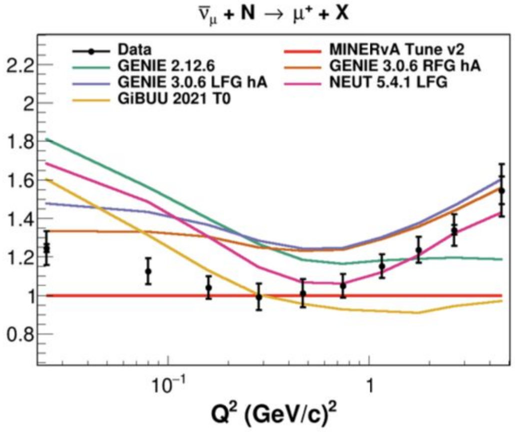
- Meson production “in between” res and DIS.
- Significant fraction (50%+) of DUNE events are in SIS kinematic region.
- MINERvA (2024) First SIS measurement since bubble chambers.

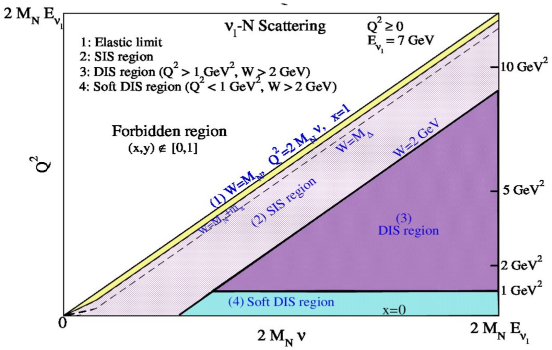



Difficult to model (n.b. discontinuities). Generators have very different predictions in this region. 1608.02716v1.

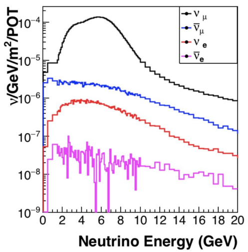
Includes resonant and non-res meson production. 2006.08603.

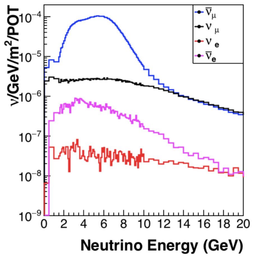


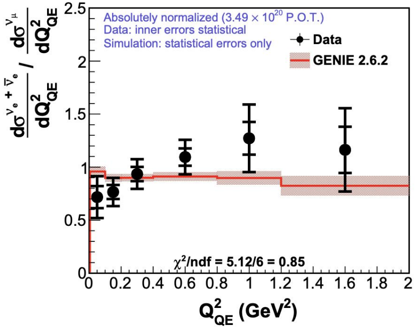



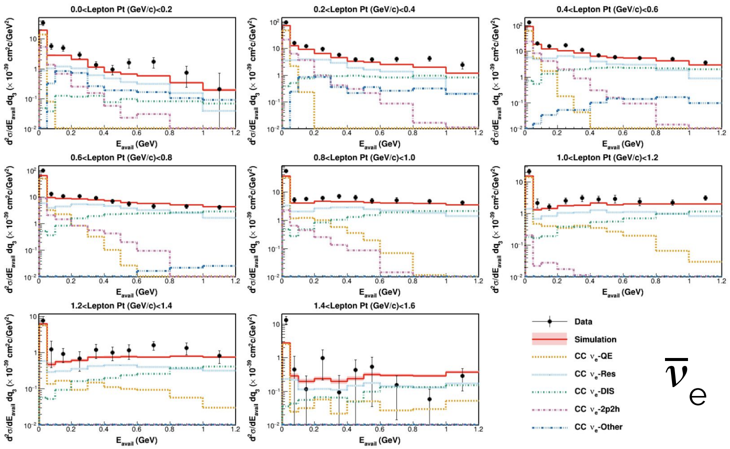
# $\nu_e$ & $\bar{\nu}_e$



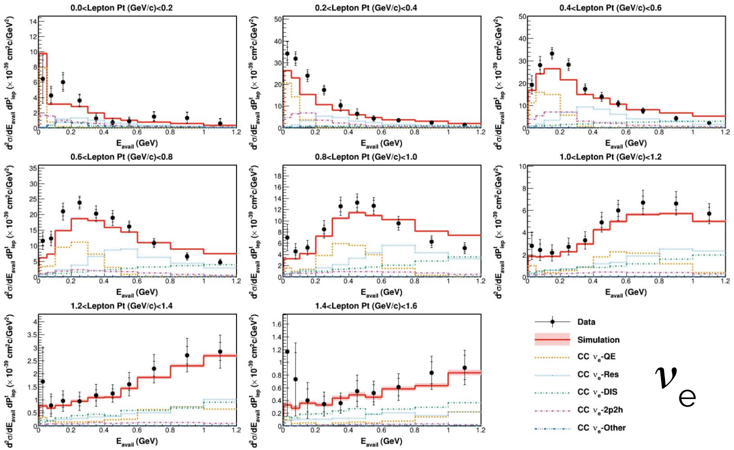




- MINERvA has two results
- 2016, Inclusive $\nu_e + \bar{\nu}_e / \nu_\mu$ ratio, 2000 events, 1509.05729
- 2024, separate $\nu_e$ and $\bar{\nu}_e$ measurements. 2312.16631. Ratio in progress.



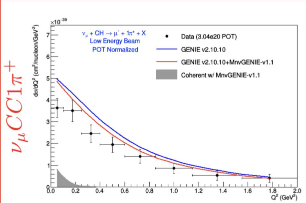

$\bar{\nu}_e$



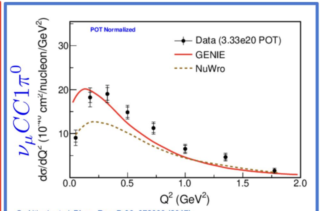

$\nu_e$

# "Correlated" Measurements

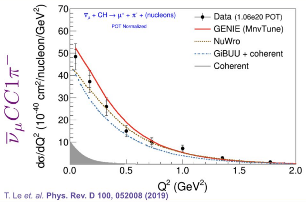
- Loose definition of "correlated"
  - "Intra-experimental"
  - Hold (an aspect of) the experiment constant to isolate an effect.
- MINERvA:
  - Nuclear Target Ratios
  - Pion suite ($\nu_\mu$ & $\bar{\nu}_\mu$ $1\pi^X$)
  - $\nu_e$ & $\bar{\nu}_e$ (prev slide)
- T2K:
  - $\nu$-$\bar{\nu}$
  - on- and off-axis
  - nuclear targets
  - $\nu$-$\bar{\nu}$ + nuclear targets



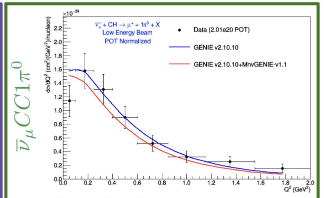
B. Eberly et al. Phys. Rev. D 92, 092008 (2015)



O. Altinok et al. Phys. Rev. D 96, 072003 (2017)



T. Le et. al. Phys. Rev. D 100, 052008 (2019)



T. Le et al. Phys. Lett. B 749 (2015)

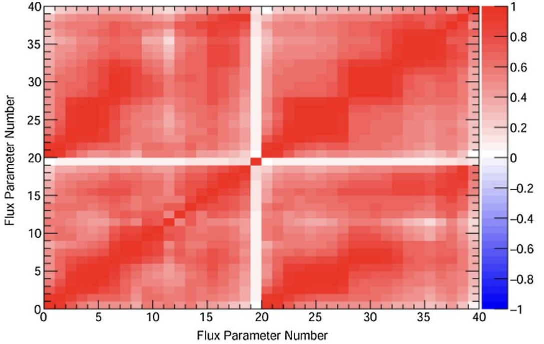


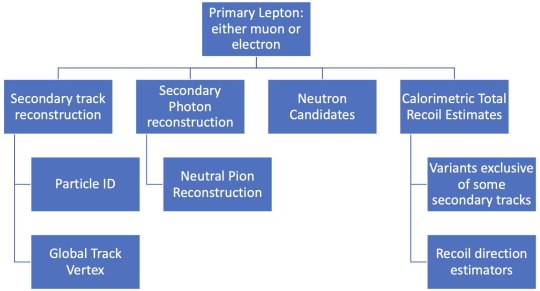
FIG. 13. Input flux correlation matrix binned in neutrino energy for both ND280 and INGRID. The flux is highly correlated both across the energy spectrum and between the detectors.

# Data Preservation

- CERN, HEPData, IRIS-HEP - resources invested into data preservation, open science infrastructure.
- The neutrino community (at FNAL, at least) is far behind.
- MINERvA's data preservation program provides data and the (experiment agnostic) toolkit to analyze it.
- MINERvA has a rich dataset that could be mined for nonstandard interactions, nuclear wisdom, some continued relevance to LBL experiments.

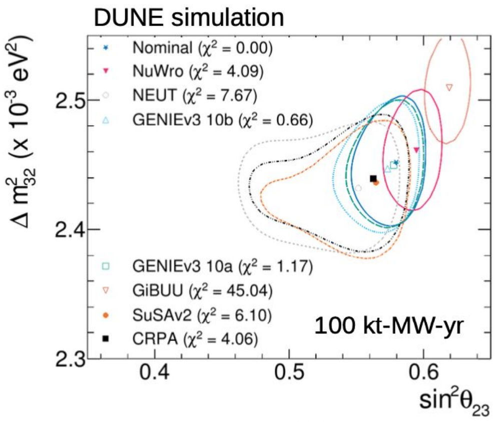
HEPData

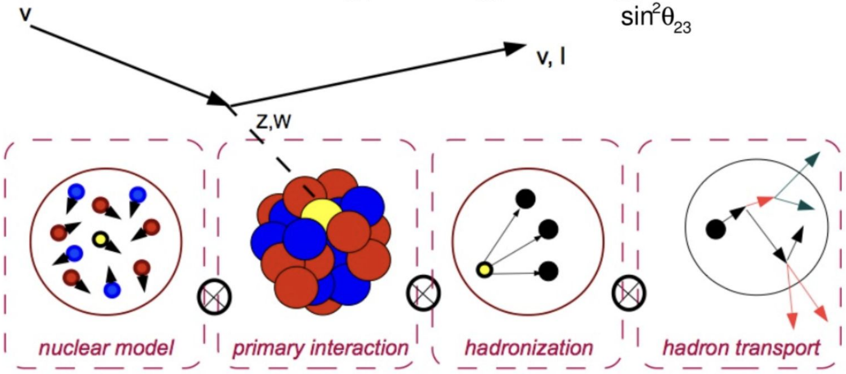
- 2009.04548
- 2103.08677



# BONUS: Generators

- We will not have a “correct” model for the imminent LBL oscillation experiments.
- One big problem: serial nature of interaction simulation.
- One current effort [1][2]: tune existing generators/models to match data.
  - Will involve stuffing mismodeled physics into whichever knob can handle it.
  - Could we encode the serial simulation in an uncertainty?
  - Could we extricate ourselves from them?




Strong need for generator flexibility, resources (funding), and more sympathetic experimentalists.

# Conclusions

- Cross section knowledge still a critical path for success of oscillation program.
- Explosion of novel and matured experimental techniques and technologies in the last 15 years to challenge models.
- Highlighted recent results that address LBL's biggest concerns using new tools
  - Neutron final state interactions
  - Kinematic imbalance
  - SIS/Transition Region
  - $\nu_e$ & $\bar{\nu}_e$ and other correlated measurements
  - (Heavy targets)
  - Data preservation
  - Generator development

# Thank you!

Thanks to the usual suspects and these general references:

- L. Pickering
- C. Wilkinson
- L. Munteanu
- C. Wret
- S. Dolan
- K. McFarland