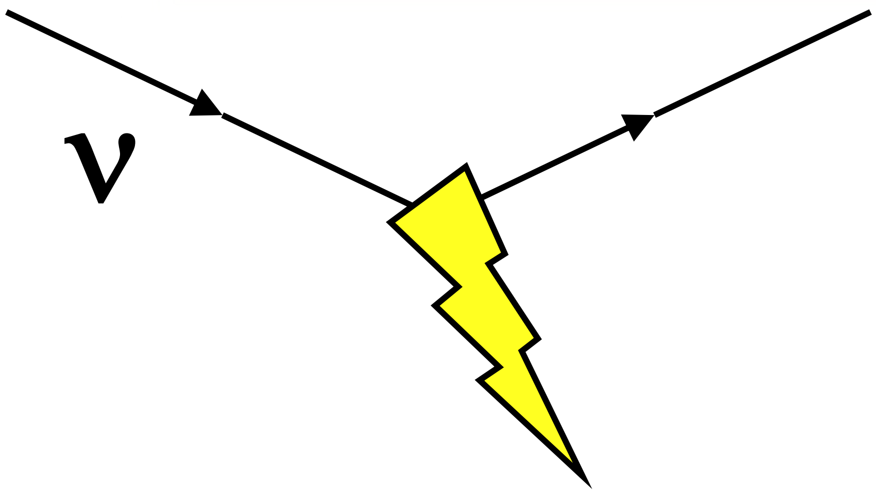
Neutrino Interactions: Puzzles and Progress



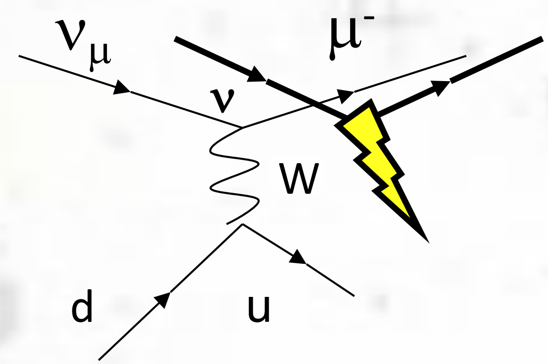
Kevin McFarland,
University of Rochester

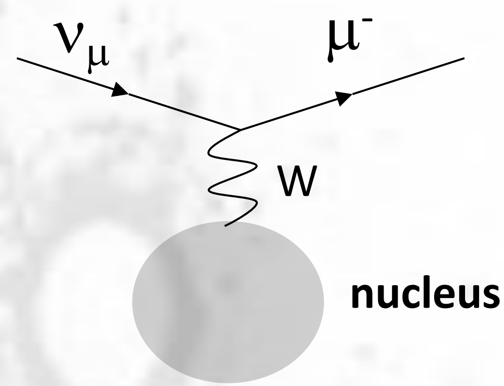
NOW 2022

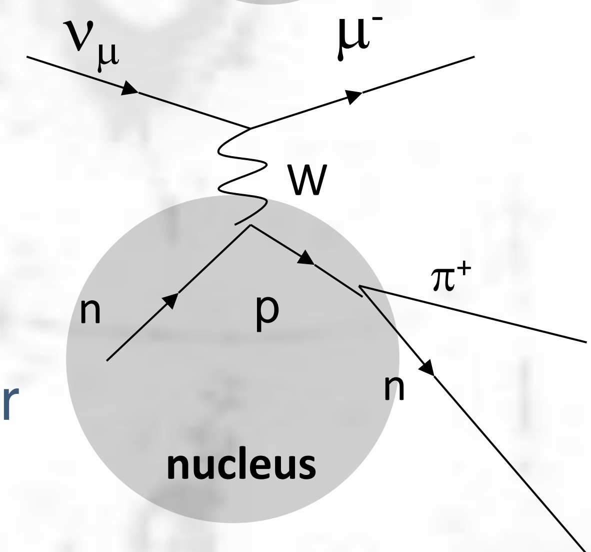
5 September 2022

ν Interactions: Scope

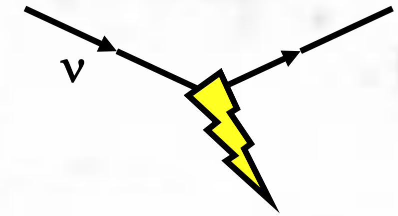
- We know a lot about neutrino interactions.
  - Weak interactions of quarks and leptons, and even neutrinos, have been extensively studied with $W^{\pm}$ and Z^0 boson precision production and decay measurements.
- Our quark targets are bound.
  - This is a problem, but not always a hard one.
  - Reactor experiments don't have interaction problems with small momentum transfers and therefore nearly static, elastic interactions.
- GeV neutrinos on nuclei are a special "pain point" that nature has gifted us at accelerator neutrino oscillation experiments.



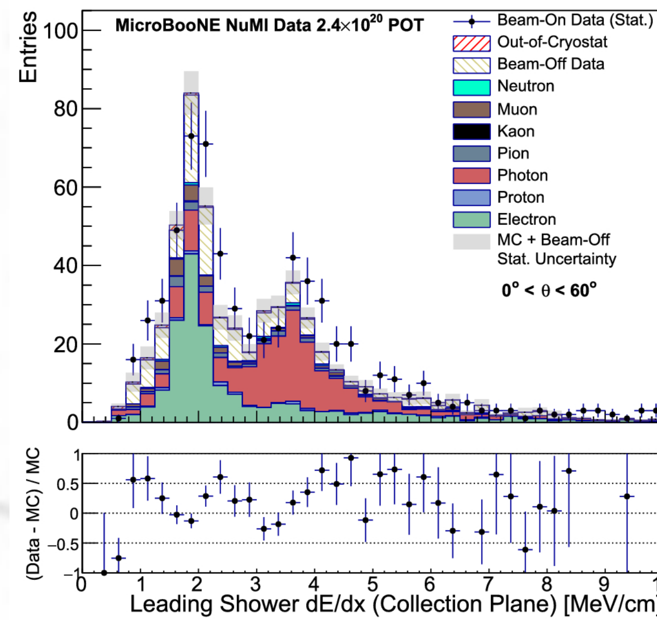




How do ν interactions matter for oscillation experiments?

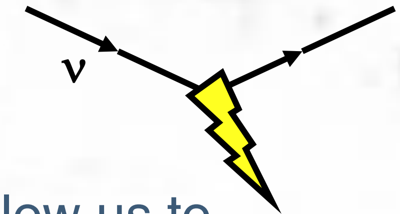


- A neutrino oscillation experiment infers the parameters of interest in a single event, neutrino flavor and energy, by measuring the final state.
- Energy: detectors are imperfect and lack uniform response:
  - Energy is lost to nuclear mass, excitation.
  - Response to an energetic neutron is scant and stochastic, but energetic protons steadily lose energy by ionization.
  - A π^- interacting in a detector tends to produce neutrons in its inelastic interactions, e.g., $\pi^- p \rightarrow \pi^0 n$. But a π^+ doesn't.
  - A π^0 cleanly deposits all its energy, including its rest mass.
- Flavor: photons, primarily from π^0, can't be perfectly separated from electrons.



The European Physical Journal Special Topics **volume 230**, pages4275–4291 (2021)

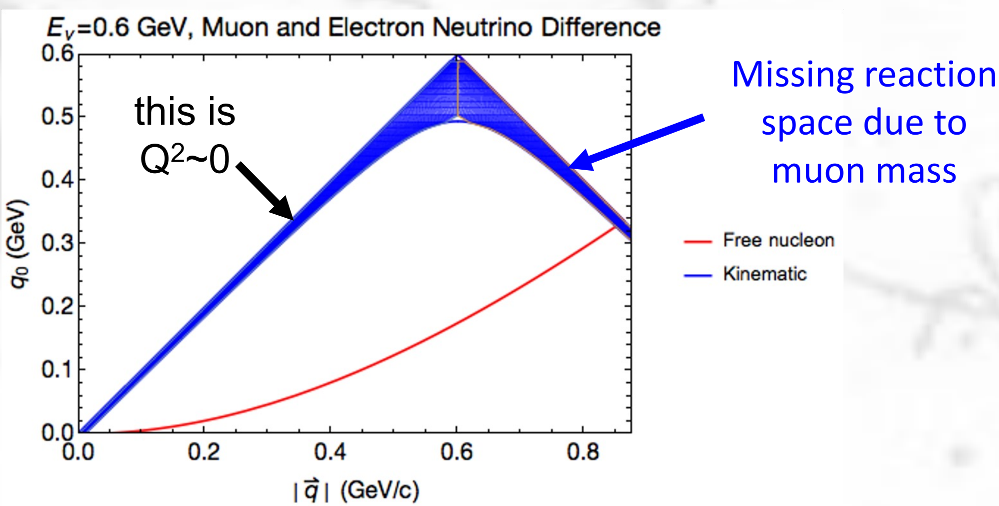
And the ν_e Problem…



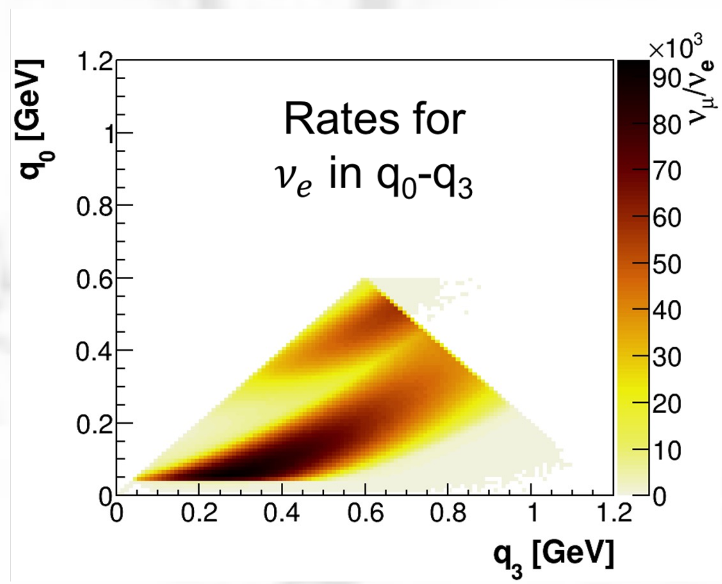
- By necessity, our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions.
- Therefore, we infer ν_e interactions from studies of ν_μ
  - But what we study can't give us the whole picture.
  - Phase space (below), radiative corrections, etc.

O. Tomalak et al, arXiV: [2105.07939](https://arxiv.org/abs/2105.07939)

energy transfer



3-momentum transfer

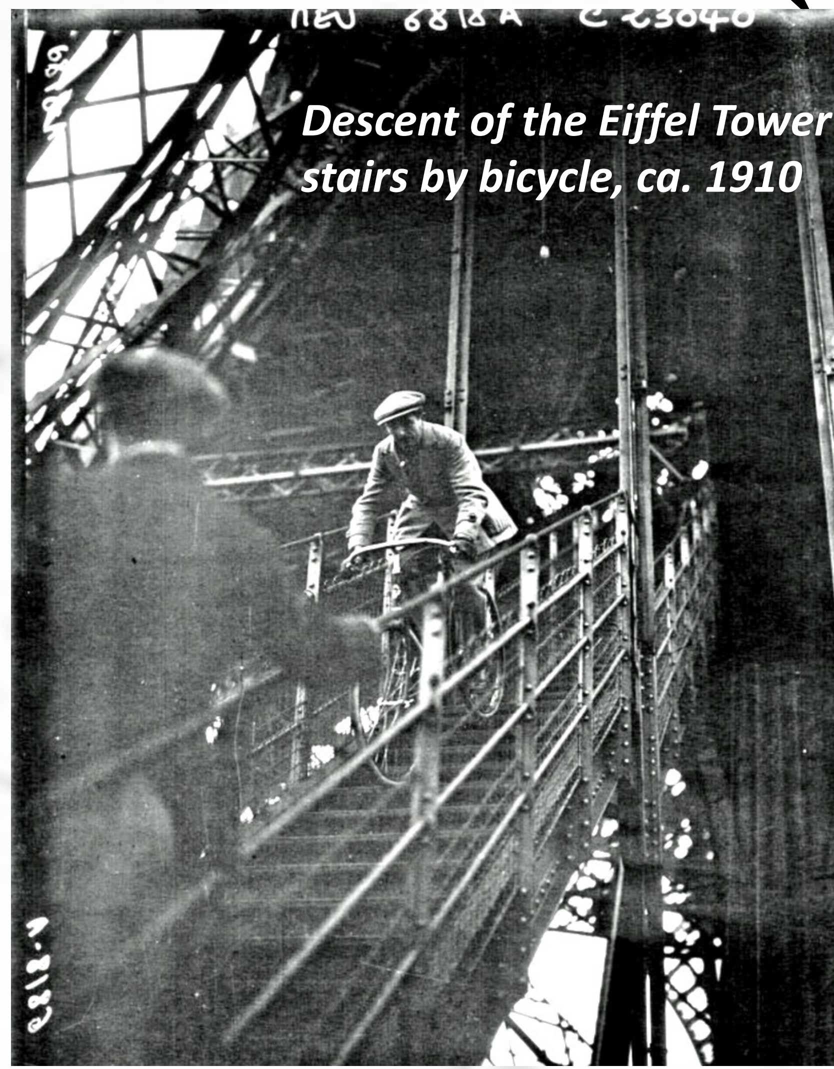


Theory and Experiment

Failed Multi-Scale Problems

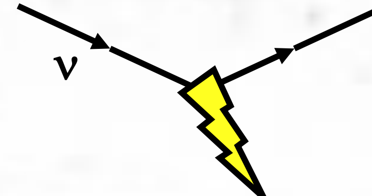
Consider a bicycle rider at right, descending the stairs of the Eiffel Tower

- A bicycle wheel is ~1m in diameter.
- If steps were ~1cm height or ~100m height, we could perfectly predict the cyclist’s trajectory.



Descent of the Eiffel Tower stairs by bicycle, ca. 1910

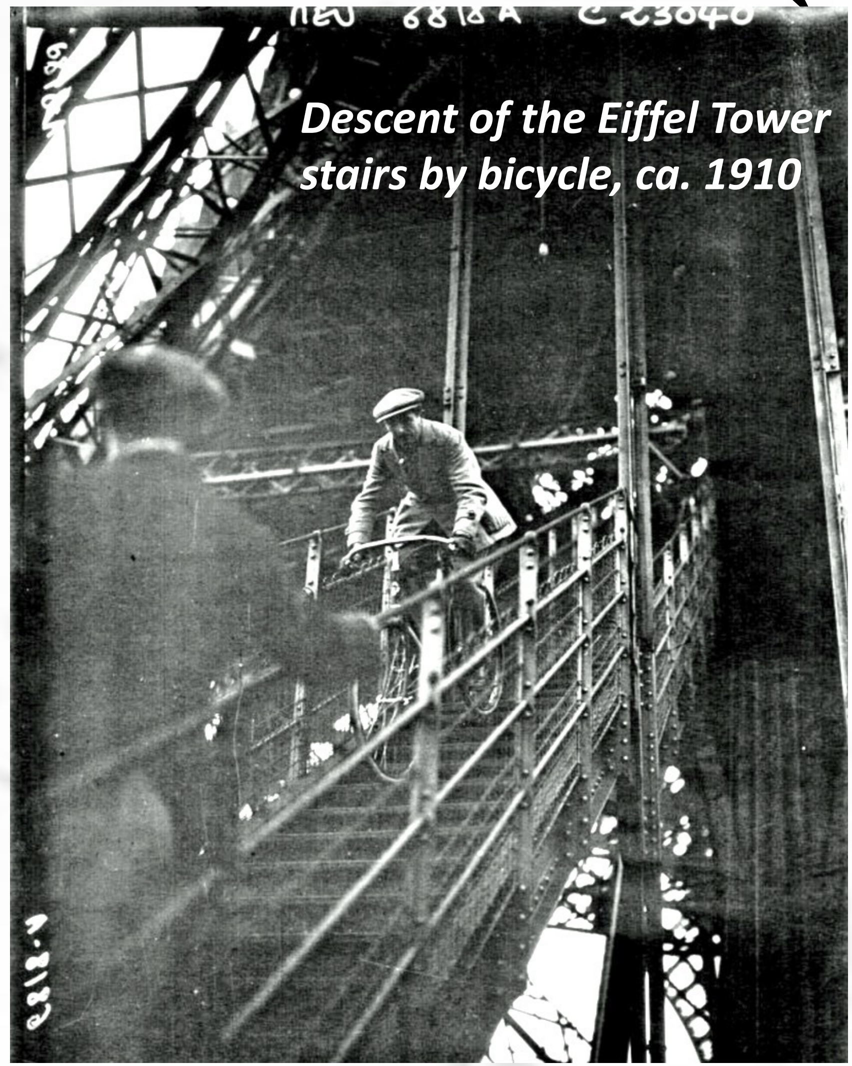
Failed Multi-Scale Problems



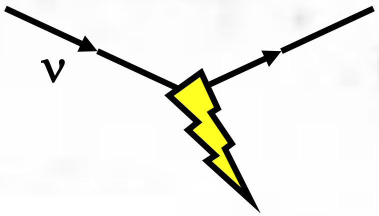
Consider a bicycle rider at right, descending the stairs of the Eiffel Tower

- A bicycle wheel is ~1m in diameter.
- If steps were ~1cm height or ~100m height, we could perfectly predict the cyclist's trajectory.

- *Since the wheel size is too close to the step size, the only reliable prediction is that it is going to be painful.*



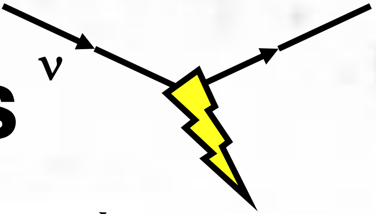
Our Failed Multi-scale Problem



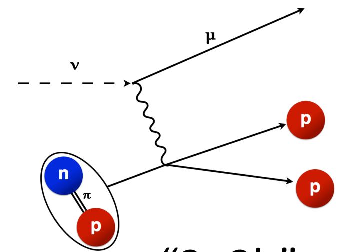
- We have $E_\nu \sim 500 - 5000$ MeV, and therefore energy transfers from nearly zero to $\mathcal{O}(1000)$ MeV.
- Nuclear response at these neutrino energies spans elastic, metastable excitations, quasielastic (knockout), and inelastic (new particles).
- But single nucleon separation energy in ^{40}Ar is ~ 30 MeV, and $m_\Delta - m_N \sim 250$ MeV.
- Processes cannot be cleanly separated, and models can't approximate away nuclear structure nor final state degrees of freedom.

- Exact modeling of nuclear response becomes akin to equation of motion for the system above if energy required to uncouple springs is comparable to energy required to break them.

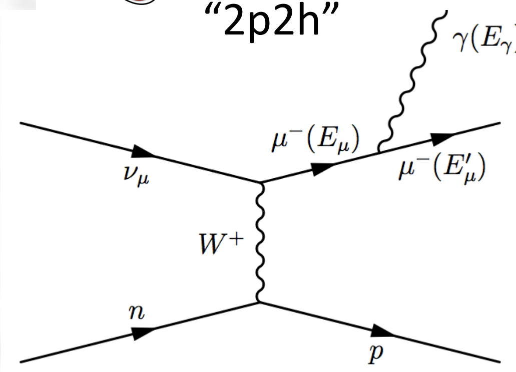
More Problems in ν Interactions

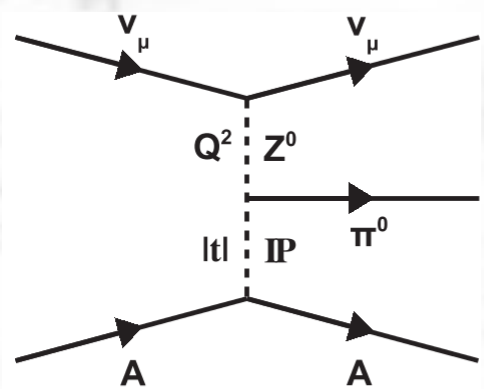


- There are other, subleading processes that are also difficult to model, but potentially important.
- Knocking out multiple nucleons (“2p2h”, two-particle-two-hole, or more) is surprisingly common and difficult to model.
- Radiative corrections to neutrino interactions will be different for muon and electron neutrinos.
- Coherent π^0 production produces very energetic photons with little else in the the event to warn it isn’t a ν_e.
- And so forth…



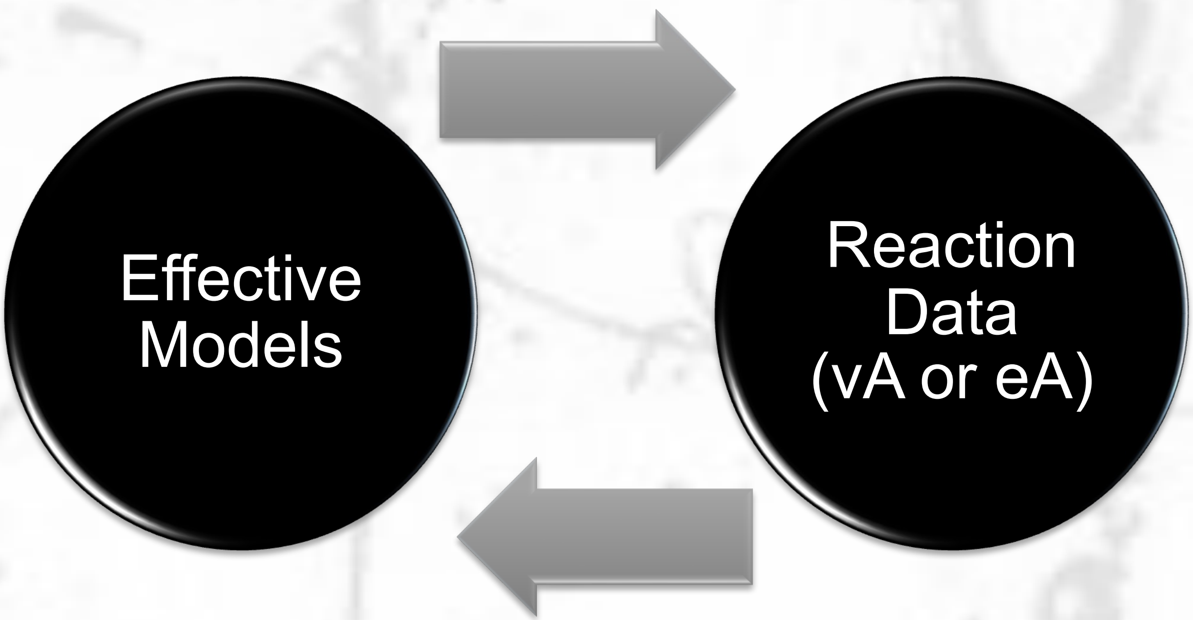
“2p2h”



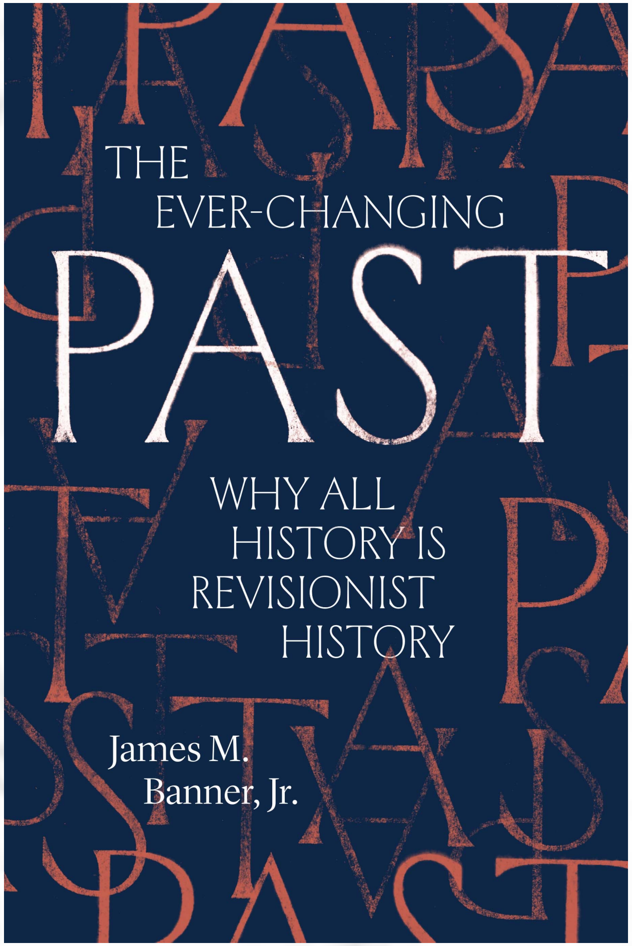


Theory and Experiment

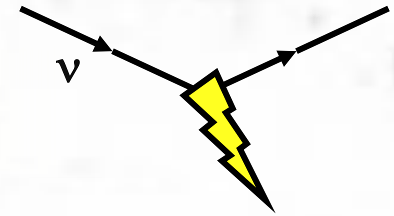
- Both are critical, and both are limited in what they can offer.
- Theory, as noted, uses necessary approximations, is limited in phase space, or calculates overly inclusive reactions ill suited to generator implementation.
- Data are good at pointing out modeling deficiencies, but often poor at pinpointing the problem.



A Revisionist History

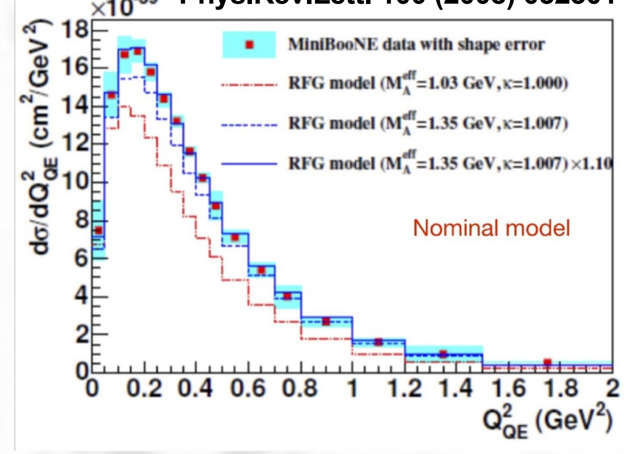


Hypothesis: Detector Capabilities Lead to Improved Models



- Canonical exhibit is MiniBooNE.
- Primary detector capability was (excellent) lepton detection and identification.
- Single detector experiment: observed a discrepancy in the transverse momentum of muons, related to "Q^2_{QE}".
- With the data in hand, there could have been many culprits. But it was interpreted as a change in the free nucleon cross-section, as seen through ^{12}C nuclei.
  - Large "axial mass".

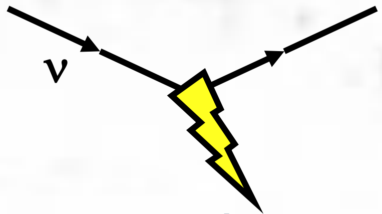
Phys.Rev.Lett. 100 (2008) 032301



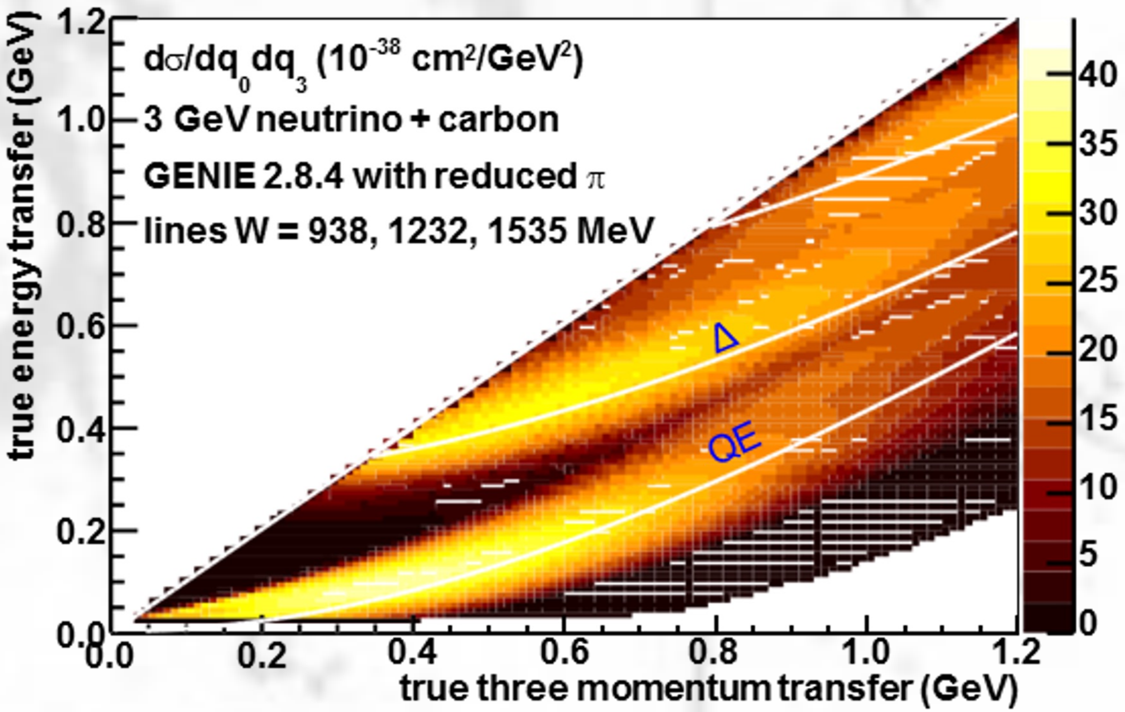
$F_A(Q^2)=F_A(0)/(1+Q^2/M_A^2)^2$

snarky poster courtesy of Teppei Katori

Why was this important?



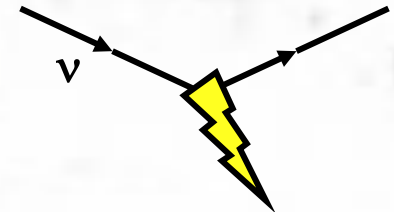
- Response of carbon (from a GENIE model) in momentum and energy transfer is below.
- Lepton detecting experiments, like MiniBooNE and T2K/Hyper-K rely on the relationship between transverse momentum transfer and energy transfer to estimate neutrino energy.



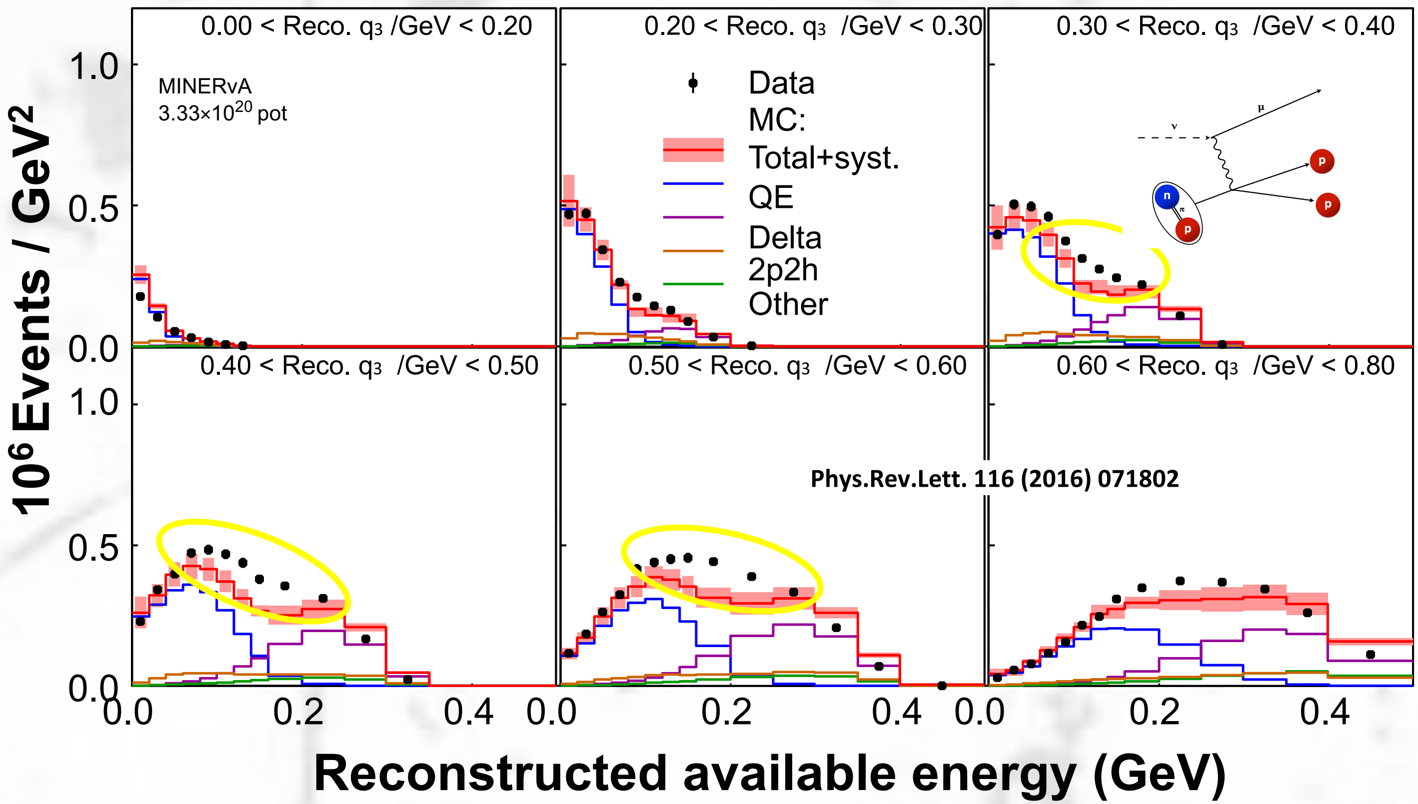
- W (recoil mass) is fixed in this space

  $W^2=(M+q_0)^2-q_3^2$
- Quasielastic band, at low W, is shown broadened by nuclear effects.
- MiniBooNE assumption was that the fix left interactions in the QE band.

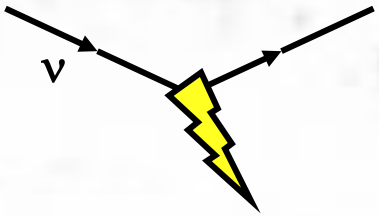
How to solve this puzzle



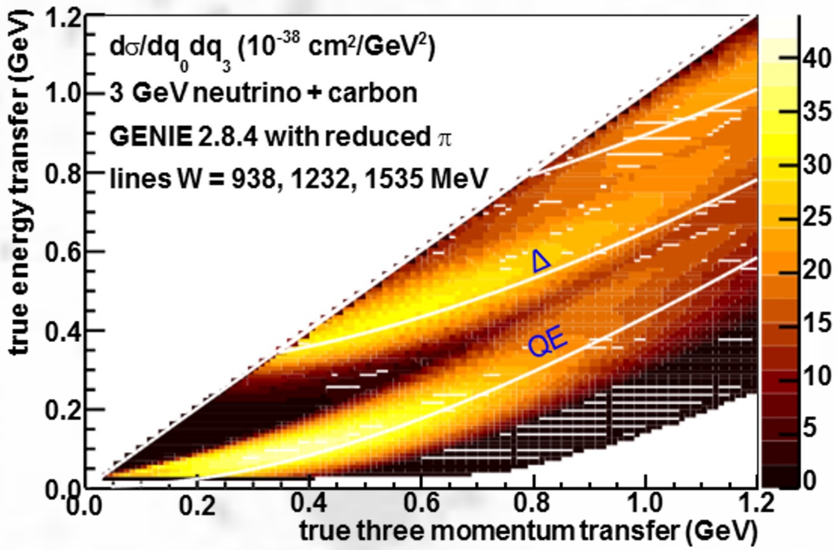
- Easy in retrospect… correlation of recoil and the lepton to try to mimic the measurement of energy and momentum transfer.
- Requires detector technology (scintillator calorimetry) and high statistics.



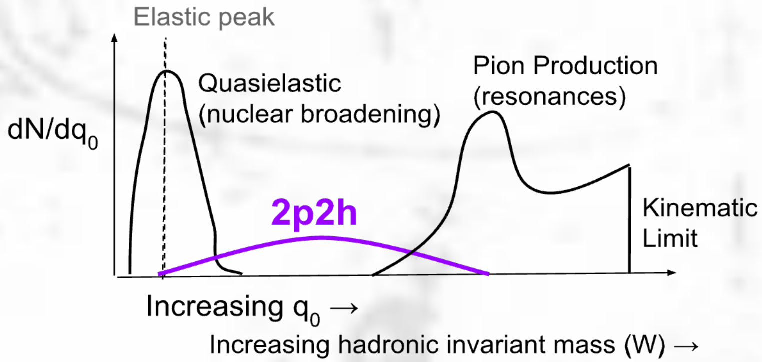
Interpretation: Multinucleon Knockout, a.k.a., “2p2h”



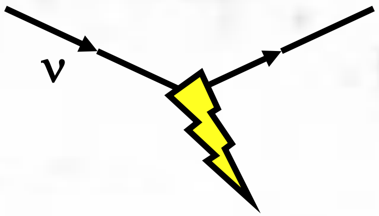
- In brief, this data was interpreted as significant evidence for a large “2p2h” event rate.
- And significantly larger than predicted by models.
- Why does it matter? 2p2h sits at higher energy transfer for fixed momentum transfer.
- Interpretation of this rate as quasielastic leads to the wrong neutrino energy reconstruction.



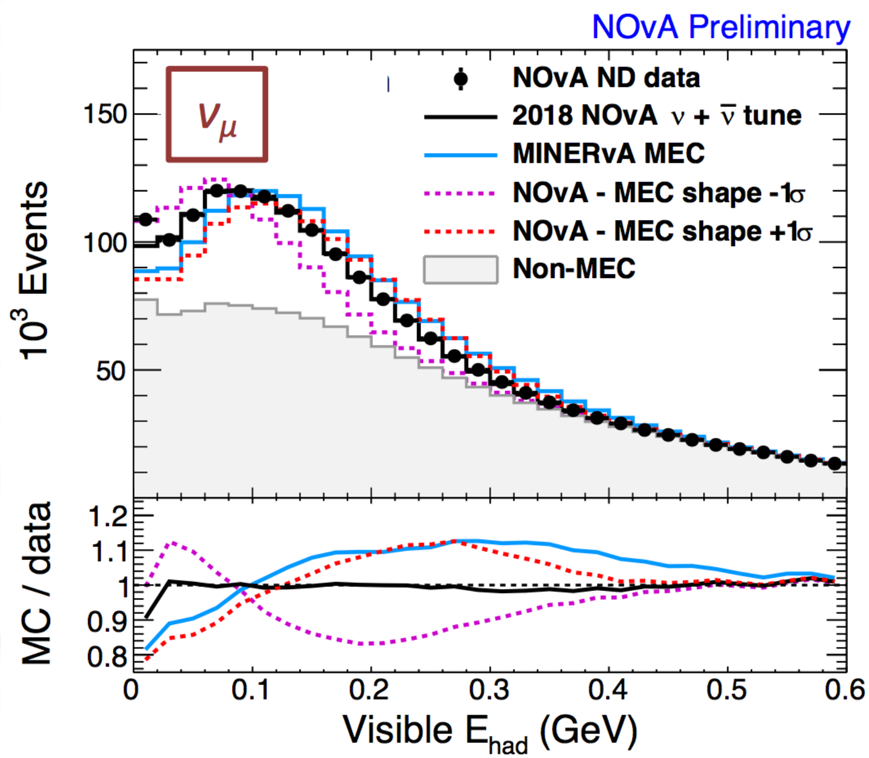
Fixed Three-Momentum Transfer



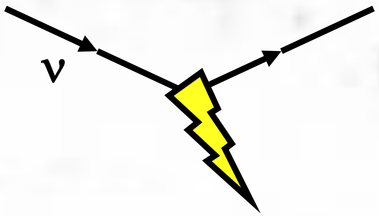
Interpretation: Multinucleon Knockout, a.k.a., “2p2h”



- “2p2h” interpretation was corroborated by other measurements of the recoil system, in correlation with the leptons.
- Technique now used by NOvA as an important part of their oscillation analysis.

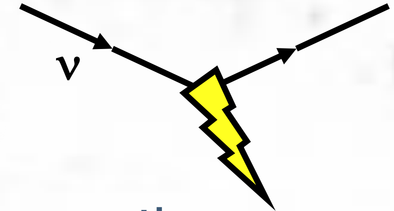


Alex Himmel, JETP Seminar, June 2018

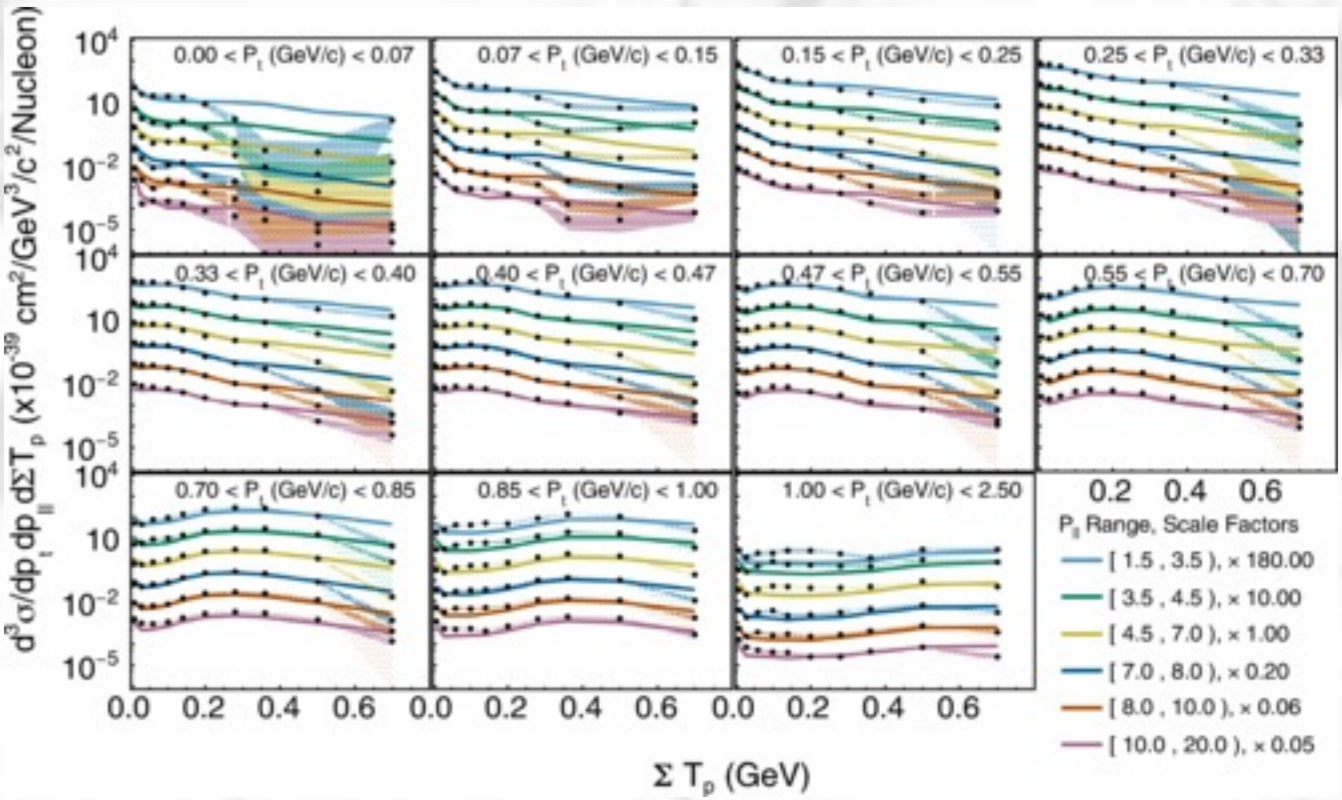


Some Recent Results…

Lepton-Hadron Correlations



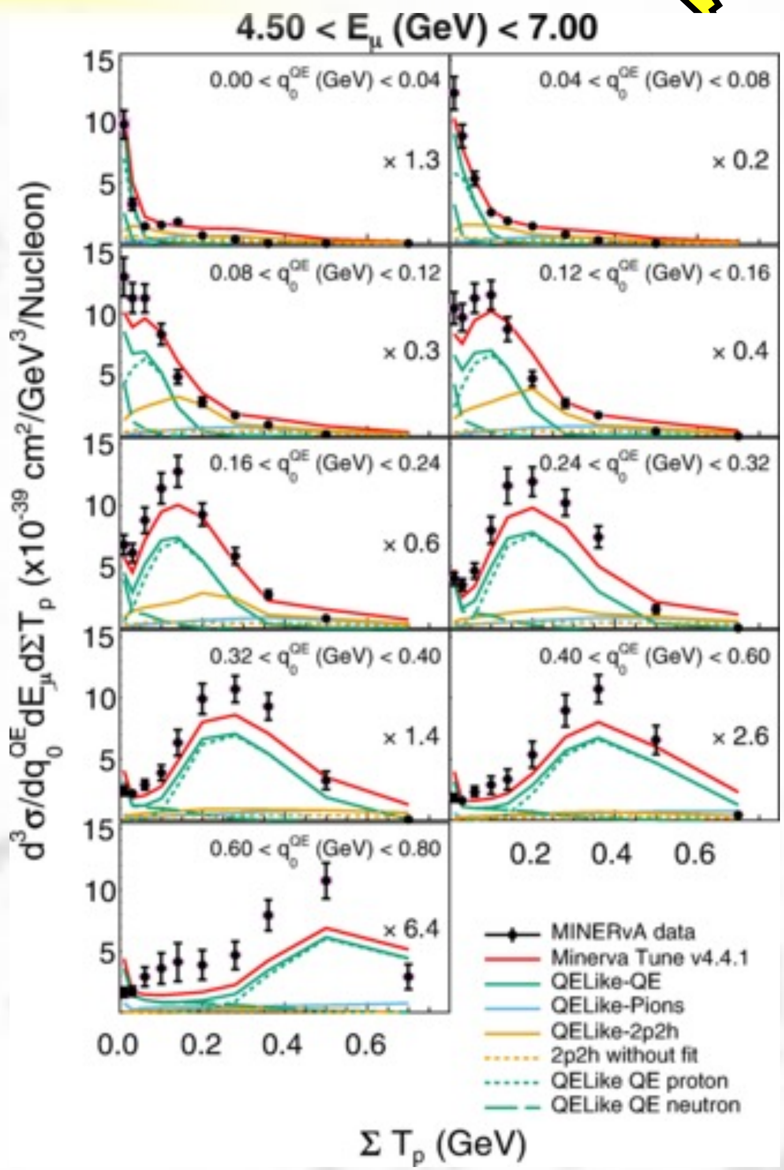
- New MINERvA result correlating recoil with lepton kinematics.
- Key technologies: control of backgrounds, to isolate final states with only nucleons, and overwhelming statistics.



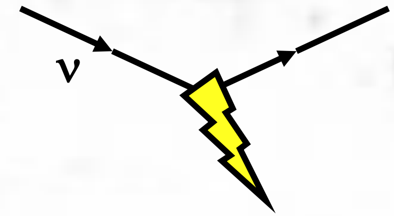
Simultaneous Measurement of Proton and Lepton Kinematics in Quasielastic like ν_μ-Hydrocarbon Interactions from 2 to 20 GeV
D. Ruterbories *et al.* (MINERvA Collaboration)
Phys. Rev. Lett. **129**, 021803 – Published 6 July 2022

Why it matters

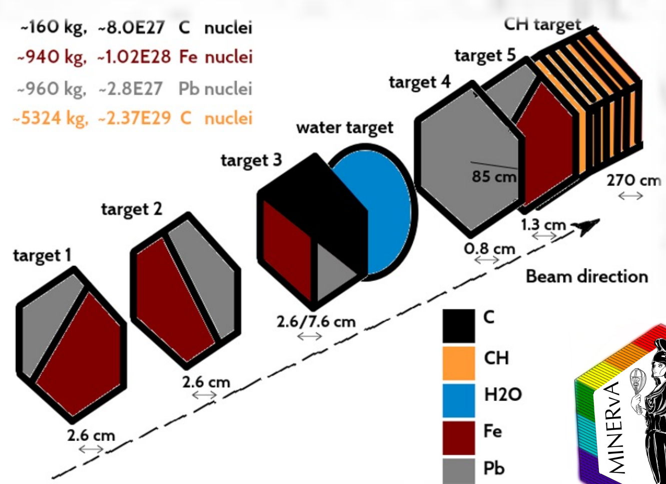
- Ability to compare lepton-only energy reconstruction (MiniBooNE, T2K) with calorimetric reconstruction (NOvA, DUNE) against a model, since both are accessible in this data.
- GENIE model has generally poor agreement on tails, and misses peaks by tens of MeV on recoil.
- This model can't simultaneously be (successfully) used to estimate neutrino energies in the two types of experiments.

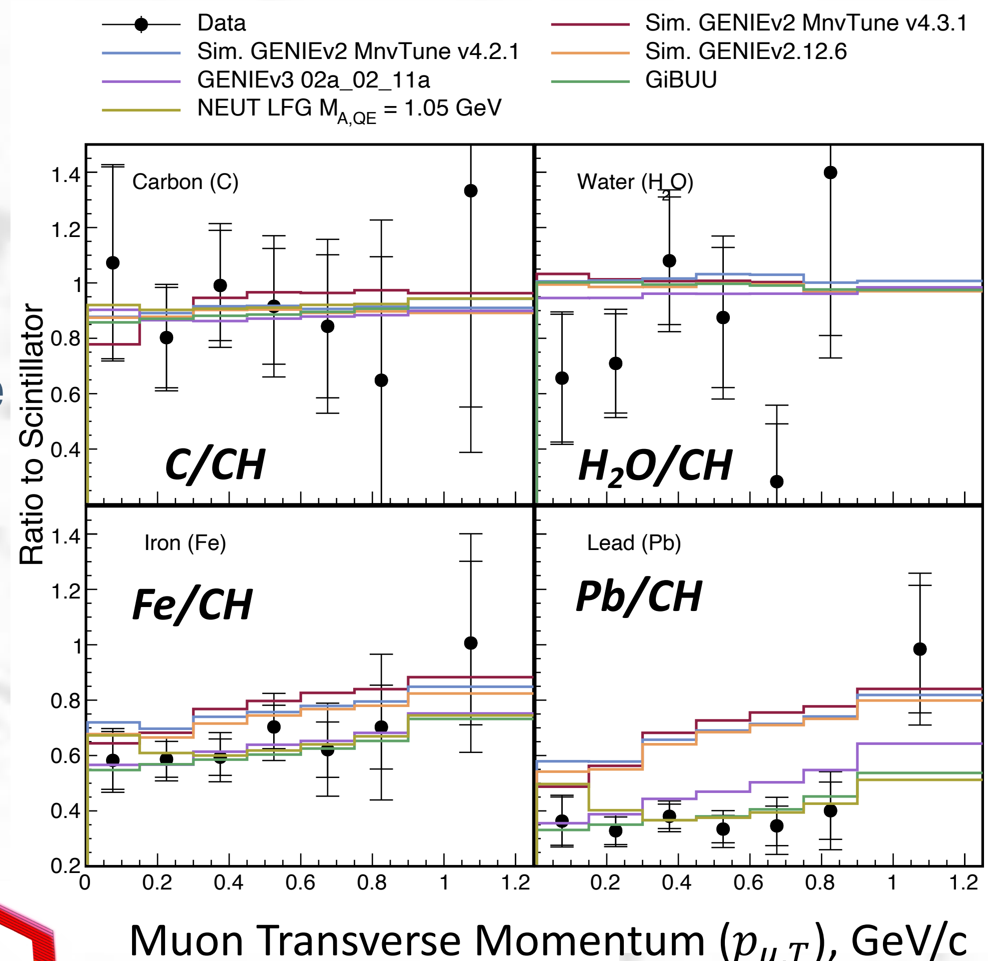


Exclusive Processes on Nuclei



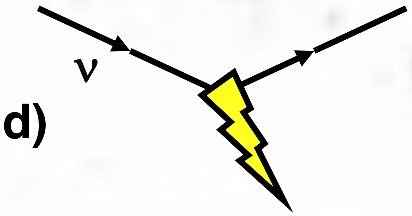
- MINERvA has studied exclusive processes on different nuclei, in the same beam and with the same reconstruction technique.
- Example, detection of single π^+ from the decay of the stopped $\pi^+ \rightarrow \mu^+ \rightarrow e\nu\bar{\nu}$.



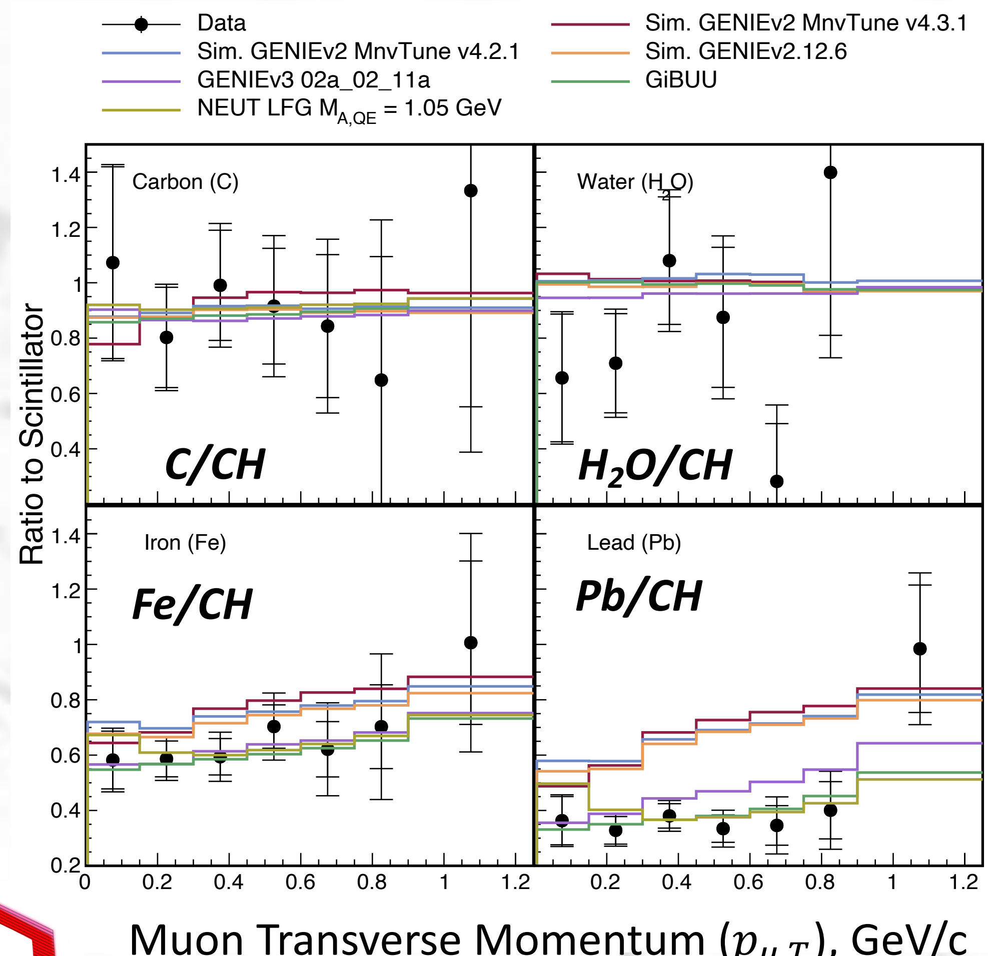


A. Bercellie, K. Kroma-Wiley et al. [MINERvA], appearing on the arXiv soon, arXiv:2209.????

Exclusive Processes on Nuclei (cont'd)



- Data is consistent with a universal scaling scaling factor for each nucleus.
  - Some models do better than others in predicting this scaling, GiBUU and NEUT.
- Striking because of large suppression at low $p_{\mu,T}$.



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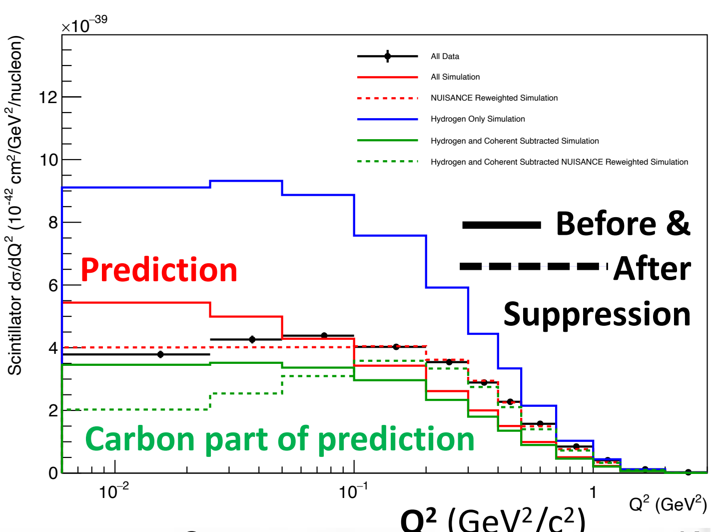
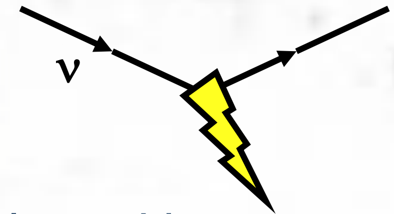


Why it matters



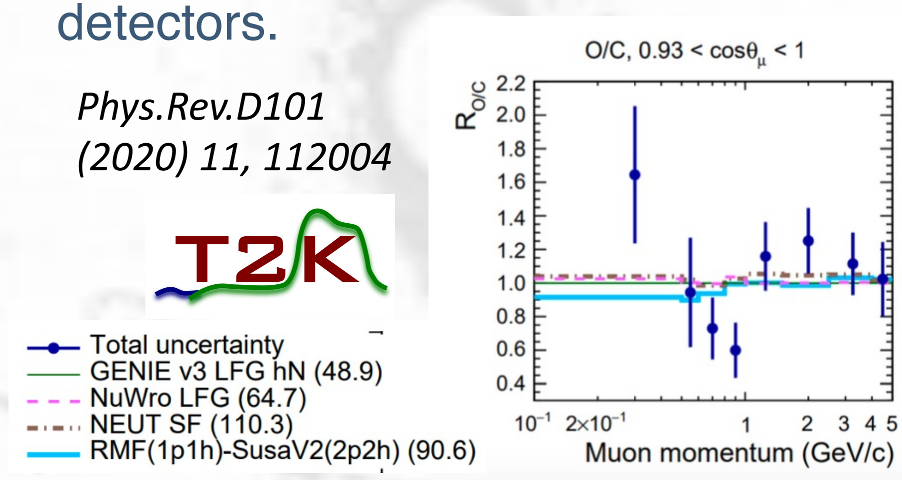
- The content of the final state is important to energy reconstruction, so accurate models of final state interactions are important.
- Wealth of data on carbon is useful for constraining oxygen (Hyper-K) and argon (SBN, DUNE) interactions.
- A model that can explain effects on multiple nuclei builds confidence, even if working with only one nucleus.

- MINERvA does this also, with higher statistics, in CCQE-like or CC0π events.

D. Harris, MINERvA (Tuesday)

- T2K also does this with scintillator to water comparisons in near detectors.

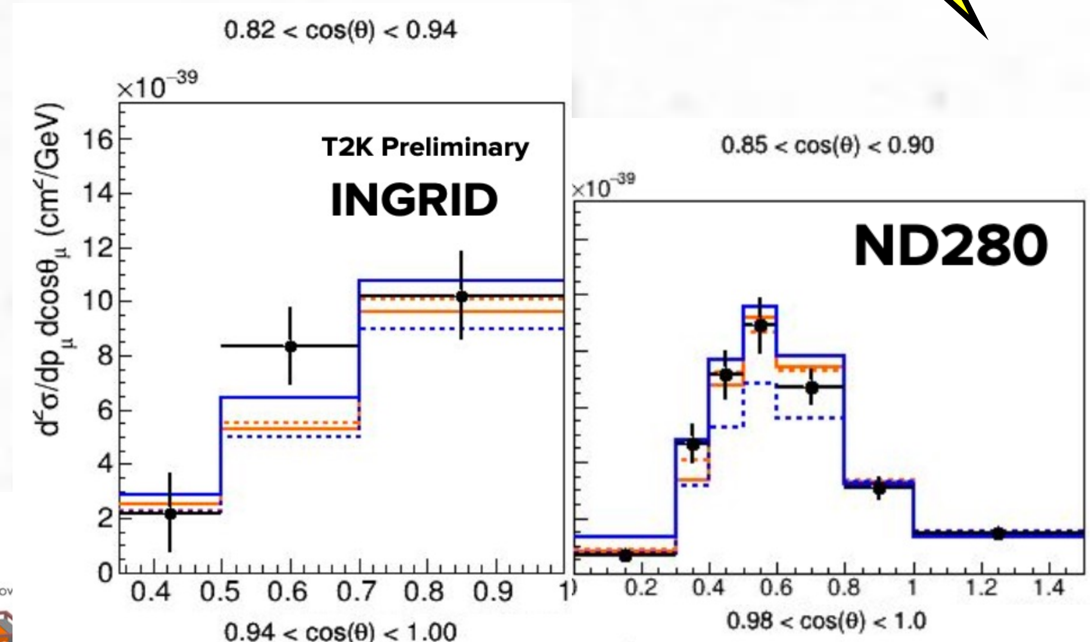
Phys.Rev.D101 (2020) 11, 112004

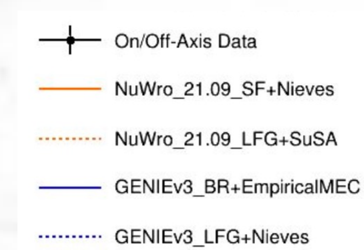


- This sample explores the CCQE-like or CC0π, and is sensitive to differences in pion absorption and to multinucleon production.

Neutrino Energy Dependence

- Near detectors may have a large spatial extent, or may be placed at different locations with respect to the beam axis.
- Results in different fluxes.
- T2K measures CC0π cross-sections.





Each detector is centered at a different on-/off-axis angle.

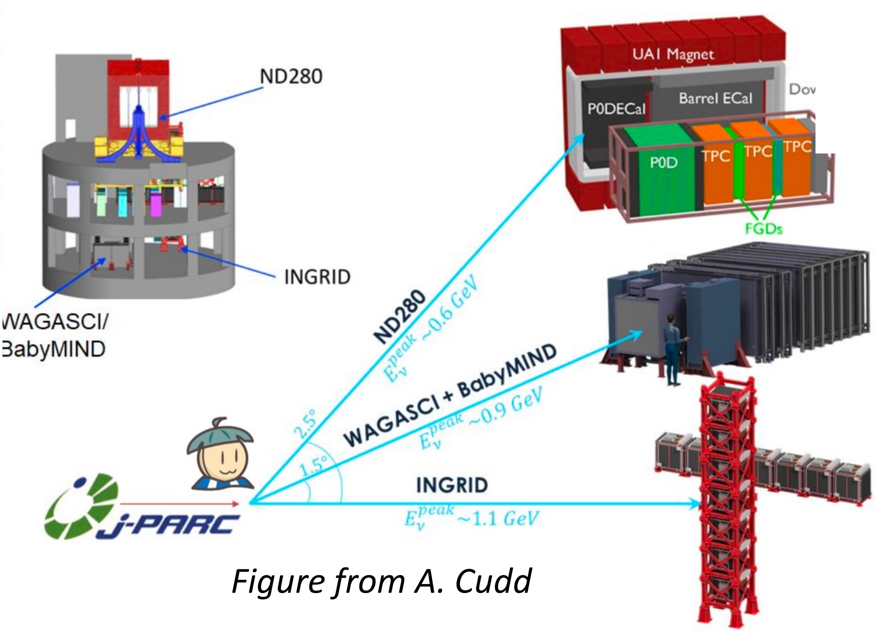
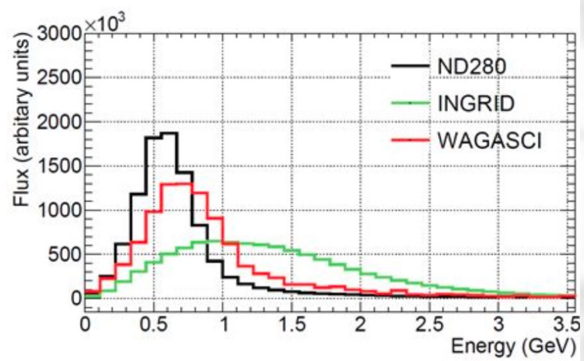


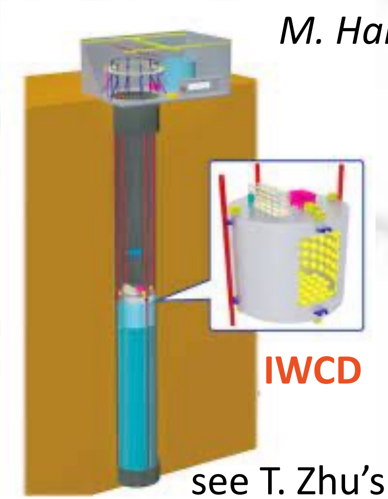
Figure from A. Cudd

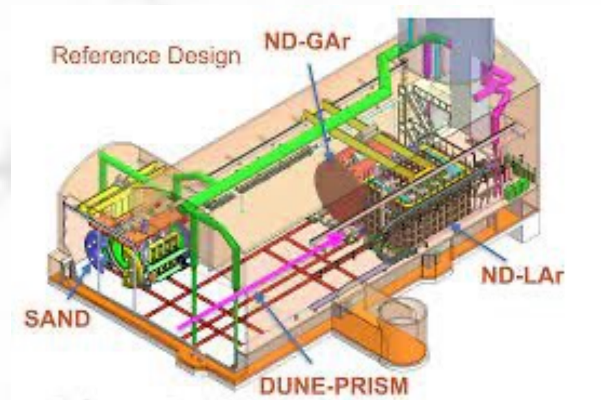


Why it matters

- Single experiments measure cross-sections integrated over the flux as a function of neutrino energy.
- Details of model become important, particularly near process thresholds, which are difficult to probe.
- Higher energy events, with invisible energy, i.e., kinetic energy in neutrons, may be indistinguishable from lower energy events without this.
- T2K analysis currently does model comparisons rather than cross-section extraction due to limited momentum range of INGRID.
- DUNE and Hyper-K both make this capability a design focus of their near detector.

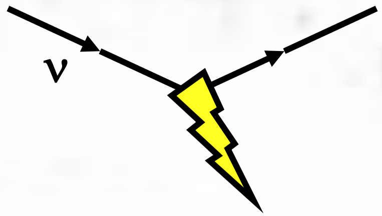
M. Hartz, JPS Conf.Proc. 8 (2015) 023013





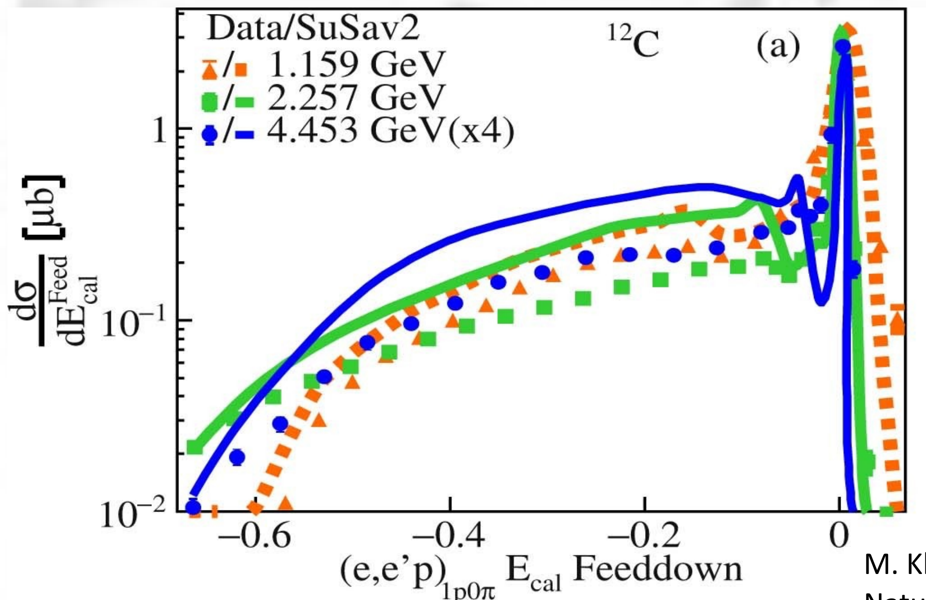
see T. Zhu's talk Tuesday

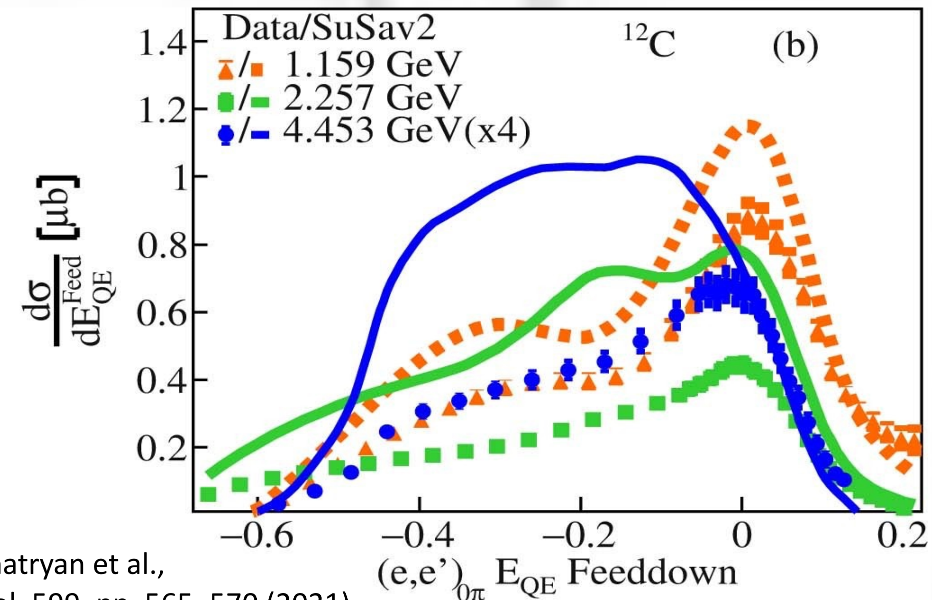
e4nu Energy “Feed-down”



- In electron scattering, knowledge of the true electron energy allows measurement of the difference between reconstructed and true energy.
- Model (SuSAv2 in this case) misses shape and rate in “feed-down” tail where electrons are reconstructed at much lower energy than reality, using neutrino reconstruction techniques.

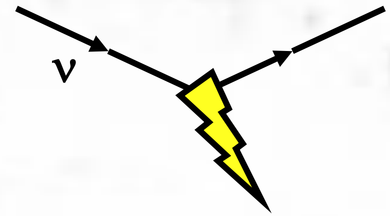
see A. Papadopoulou’s talk Friday





M. Khachatryan et al.,
Nature vol. 599, pp. 565–570 (2021)

Why it matters



- Although electron scattering doesn't probe all parts of the reaction, key features, the nuclear initial state, and final state interactions, are common to electron and neutrino scattering.
- Deficiencies in the models used in neutrino scattering, when they fail to predict electron scattering, point to deficiencies in the models used for E_ν reconstruction.

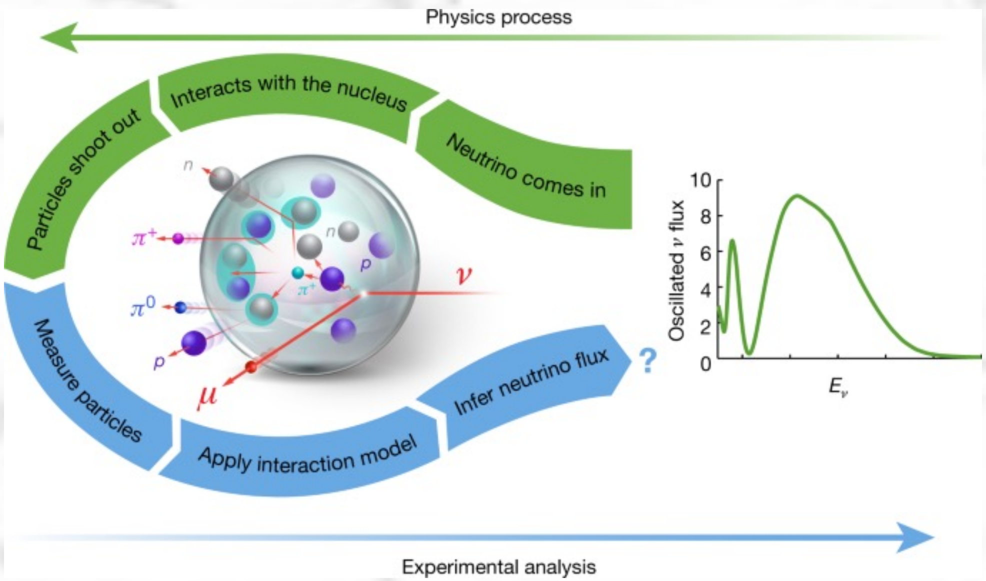
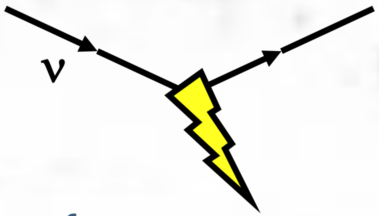


Figure from M. Khachatryan et al., Nature vol. 599, pp. 565–570 (2021)

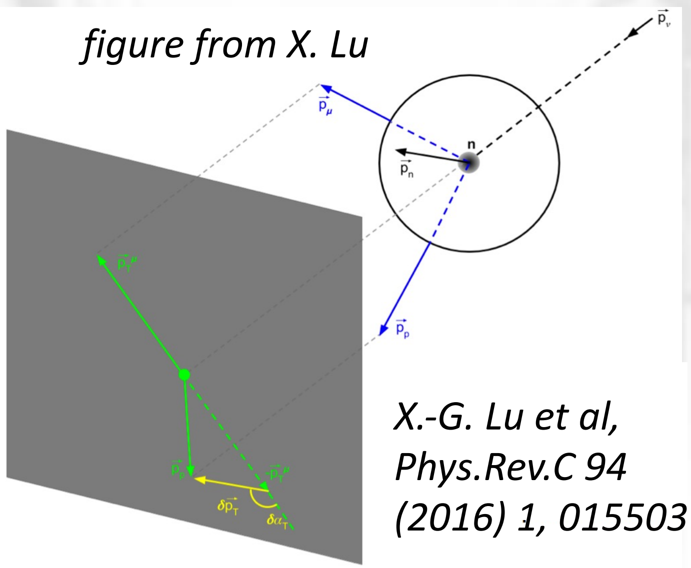
Transverse Kinematics at MicroBooNE



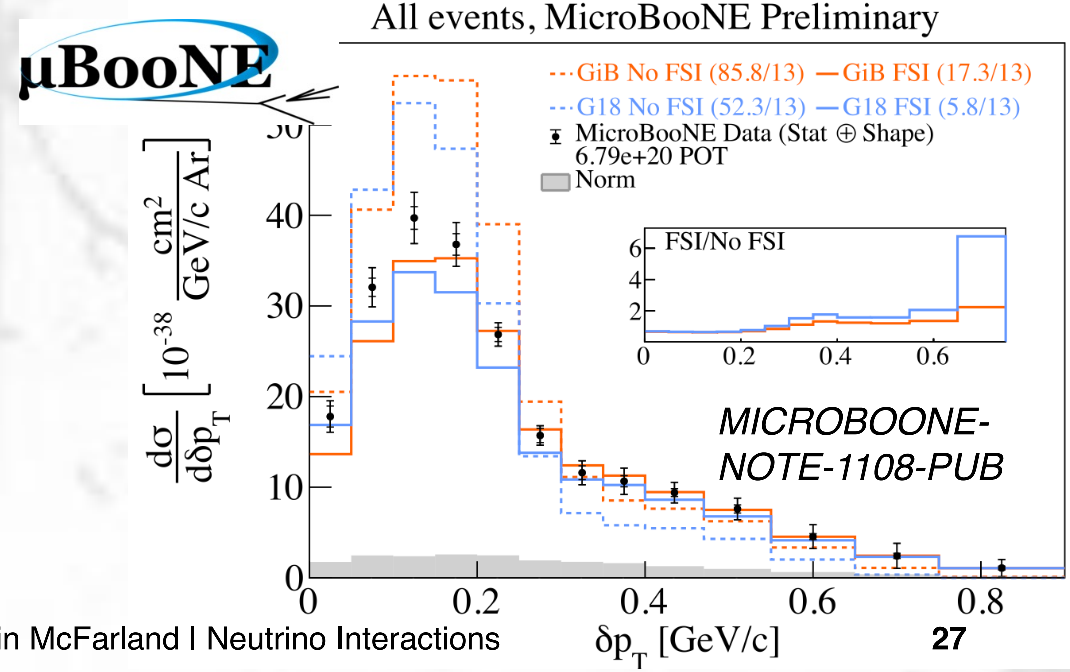
- Technique invented by T2K and MINERvA collaborators.
- Longitudinal momentum of incoming neutrino is unknown, but momentum transverse to the neutrino direction must balance.

- This is the magnitude of momentum imbalance from MicroBooNE.
  - Single knockout has imbalance characteristic of nucleon momentum ~200 MeV in nucleus.
  - Larger imbalance when there are other final state particles.

figure from X. Lu



X.-G. Lu et al, Phys.Rev.C 94 (2016) 1, 015503



MICROBOONE-NOTE-1108-PUB

Transverse Kinematics at MicroBooNE (cont'd)

- MicroBooNE also looks at angle between the momentum imbalance and the lepton, $\delta\alpha_T$.
- Correlation analysis can separate this for the large imbalance (inelastic) events to isolate differences from single knockout and inelastic processes.

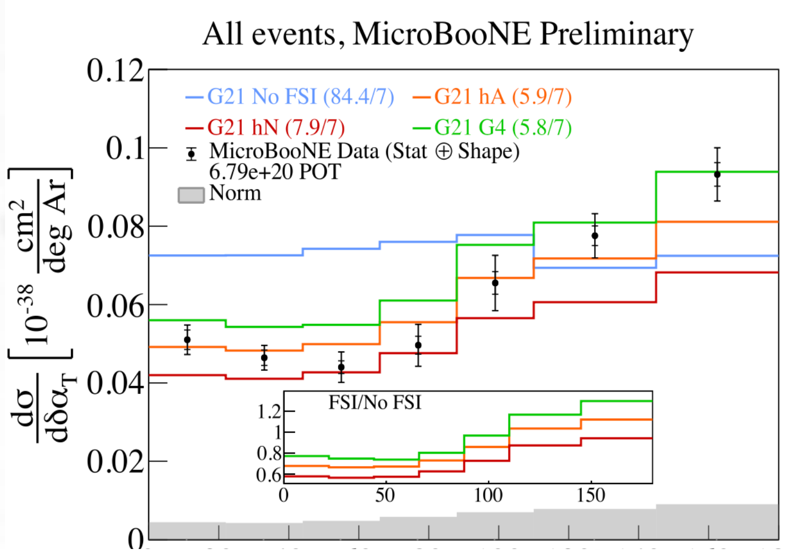
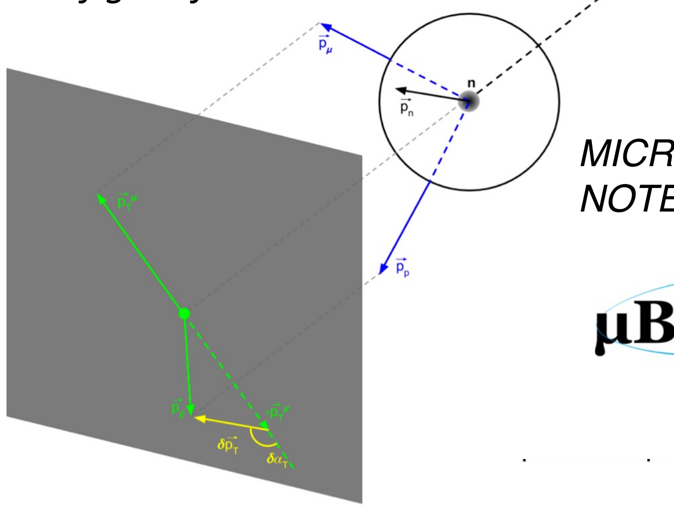


figure from X. Lu



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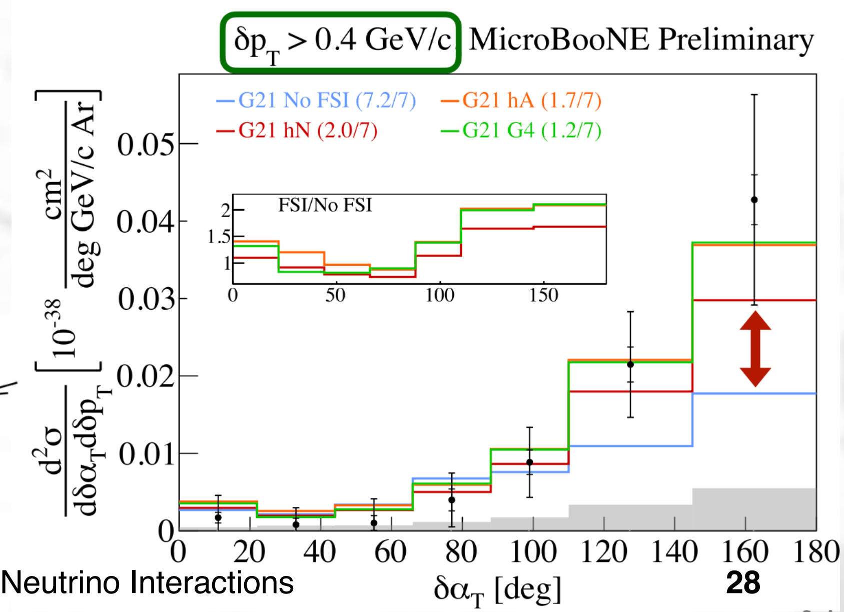
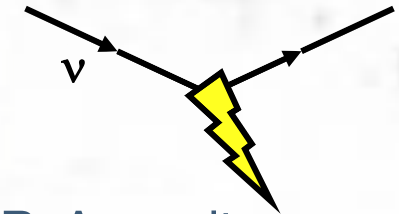
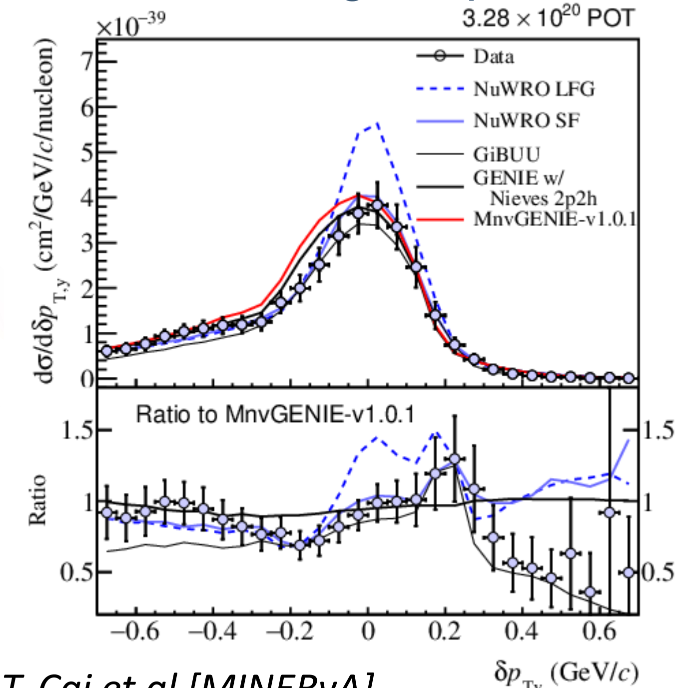


Why it matters



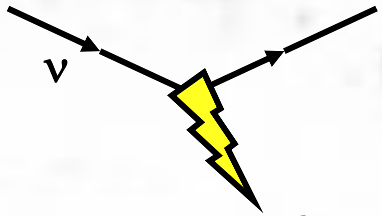
- These transverse kinematic measurements provide ways to disentangle nuclear effects.
- Can separate effects of final state interactions from initial state effects.
- Ultimately these tests will help nuclear models in neutrino interactions to the point where we get beyond downselection (MicroBooNE) to improvements.
- This is an area where studies in scintillator have already made progress; measurements in argon test model in revealing ways when both are high statistics.

- Related MINERvA result: imbalance projected into the reaction plane.
- Sensitive to binding and momentum of initial nucleon. Note wide range of predictions.



T. Cai et al [MINERvA], Phys.Rev.D 101 (2020) 9, 092001

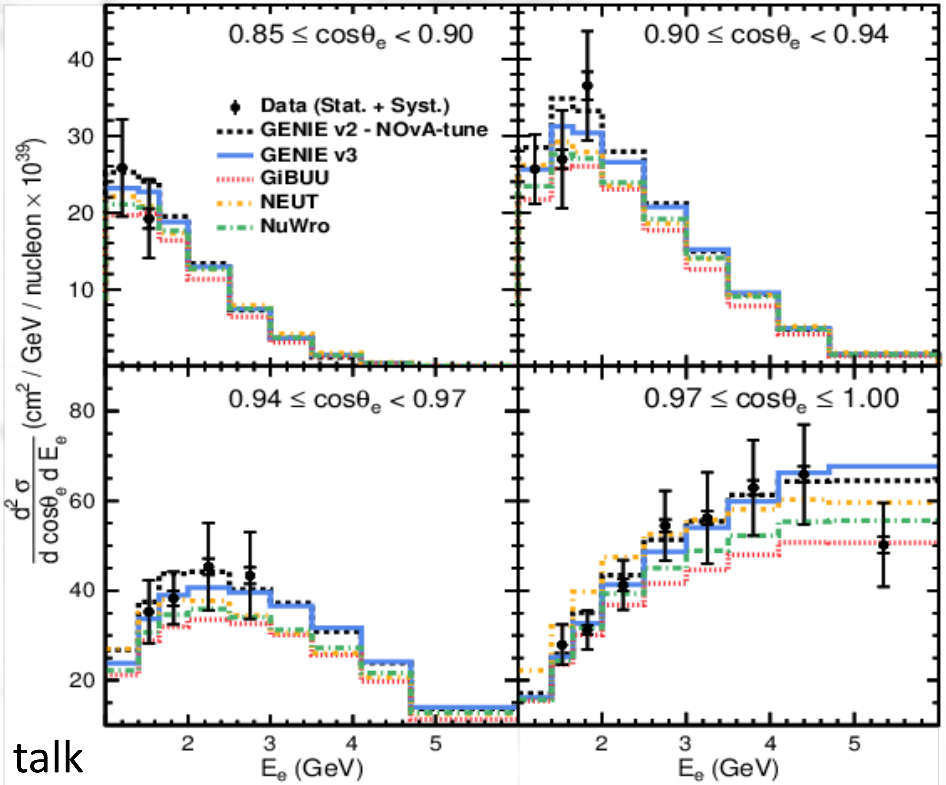
ν_e interactions at NOvA



- We noted the theoretical problem with extrapolating from muon to electron neutrino interactions. A solution is to measure directly!
- Challenging because photons from π^0 decays are a large background.
- Separation by dE/dx near start of “electron” track has been demonstrated in scintillator and liquid argon TPCs.

NOvA, arXiv: 2206.10585

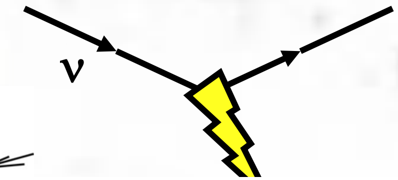
- Lepton energy-angle correlations for candidates in NOvA.
- Note very small statistical errors; refining background control techniques is critical to the analysis.

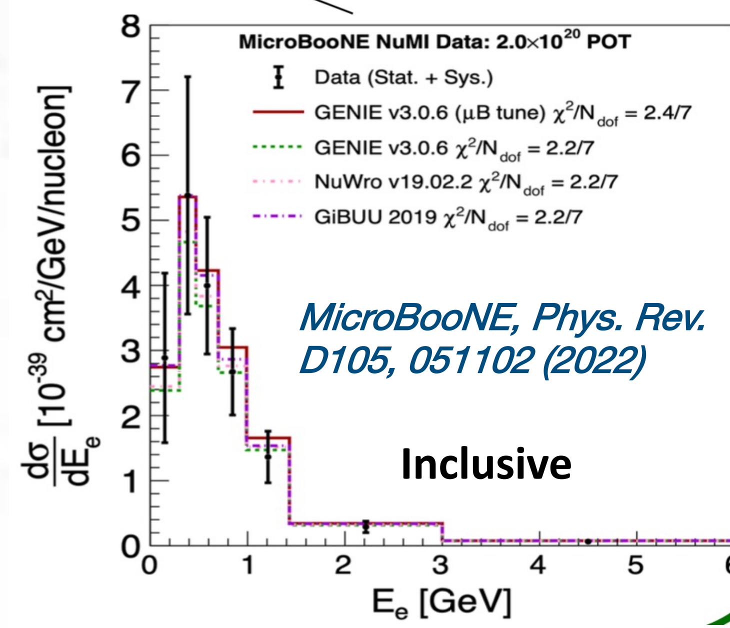


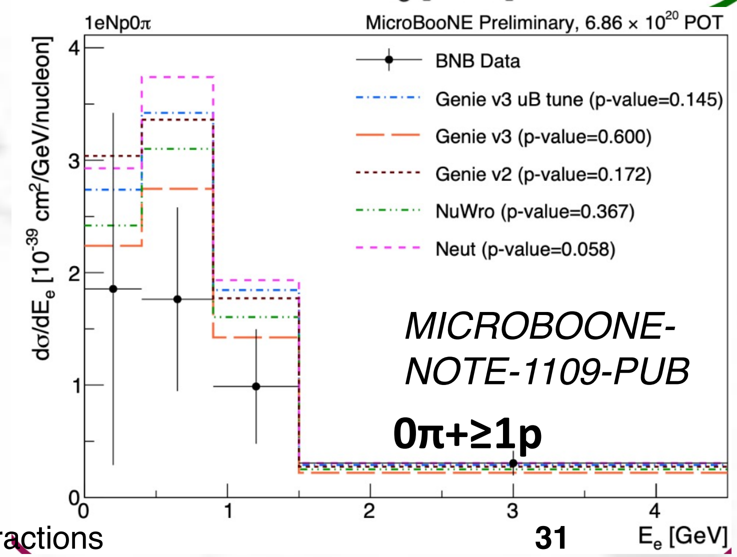
see also J.-M. Carceller’s talk

Why it matters

- While the measurements are challenging, ultimately this is the test that gives us confidence in percent level predictions of the ratio from theory.
- Tests can focus on possible differences, such as threshold effects and radiative photons, and so don't literally need %-level control in every bin of each variable.
- Controlling systematics with electron to muon ratios will be essential.
- Other experiments also think it matters and are prioritizing this measurement: MicroBooNE, T2K, and MINERvA.







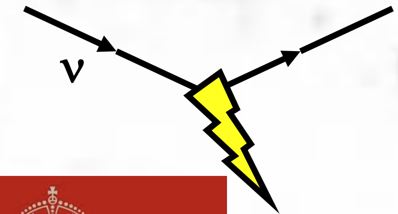
Closing Thoughts

Interactions: Progress on Puzzles

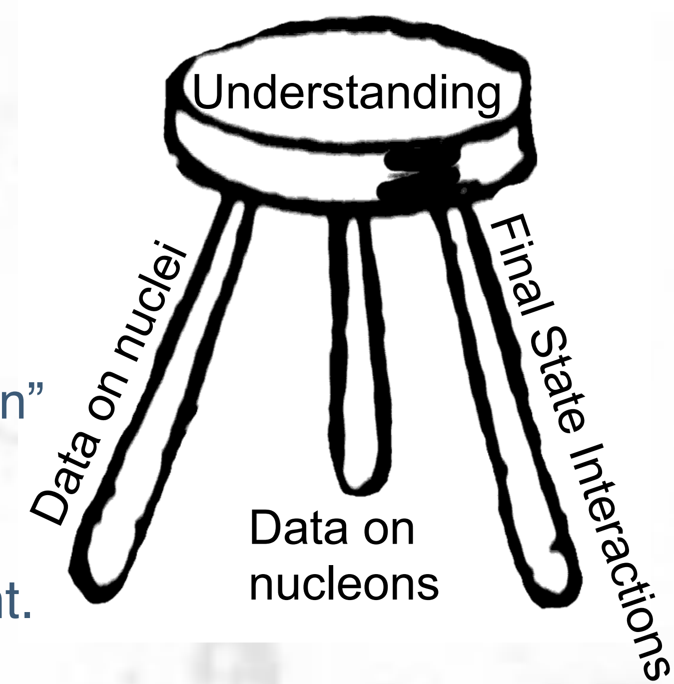
- Both theory (*see L. Alvarez-Ruso's talk Tuesday, S. Dolan's talk Wednesday and S. Gardiner's talk Friday*) and data are required to make progress on the understanding of neutrino interactions needed for precision oscillation experiments.
- New capabilities in neutrino experiments…
  - improved detectors, high statistics, creative analysis concepts,
- … have led to improvements in models which have proved critical for interpretation of oscillation data at T2K and NOvA.
- Future needs of DUNE and Hyper-K will benefit from new capabilities, such as DUNE PRISM & IWCD and high statistics ν_e samples at upgraded beams, that we will use to explore neutrino interactions.

Backup

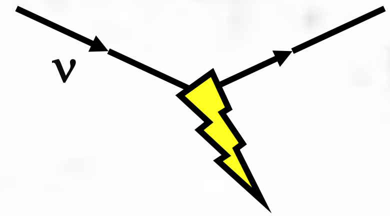
Measurements on Nucleons



- As the MiniBooNE story illustrates, a challenge data on nuclei is whether we are seeing a nucleAR effect, or a neutrino-nucleON effect.
- Mine safety considerations means we are unlikely to have significant new datasets using hydrogen targets, and nature doesn’t give us free neutrons.
- Measurements that can measure scattering on hydrogen by comparing carbon to hydrocarbon will may fill the gap.
- MINERvA is on the cusp of publishing its effort to measure $\bar{\nu}_\mu H \rightarrow \mu^+ n$.
  - DUNE and Hyper-K can try similar “subtraction” approaches
- Dedicated hydrogen experiments are challenging, but would be qualitatively different.



MINERvA low Q^2 Suppression of Single π^+ Production



- Scintillator sample Q^2 distribution is very poorly predicted.
- Hypothesis is that this is because of mistakes in the carbon prediction. Analysis assumes suppression is universal in all nuclei, and agrees with $p_{\mu,T}$ measured distributions.
- $Q^2 \approx p_{\mu,T}^2\left(1+{}^{\nu}/_{E_\nu}\right) \approx p_{\mu,T}^2$ at MINERvA energies for this sample.