Neutrino Interactions: Puzzles and Progress

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Snowmass Summer Meeting

19 July 2022
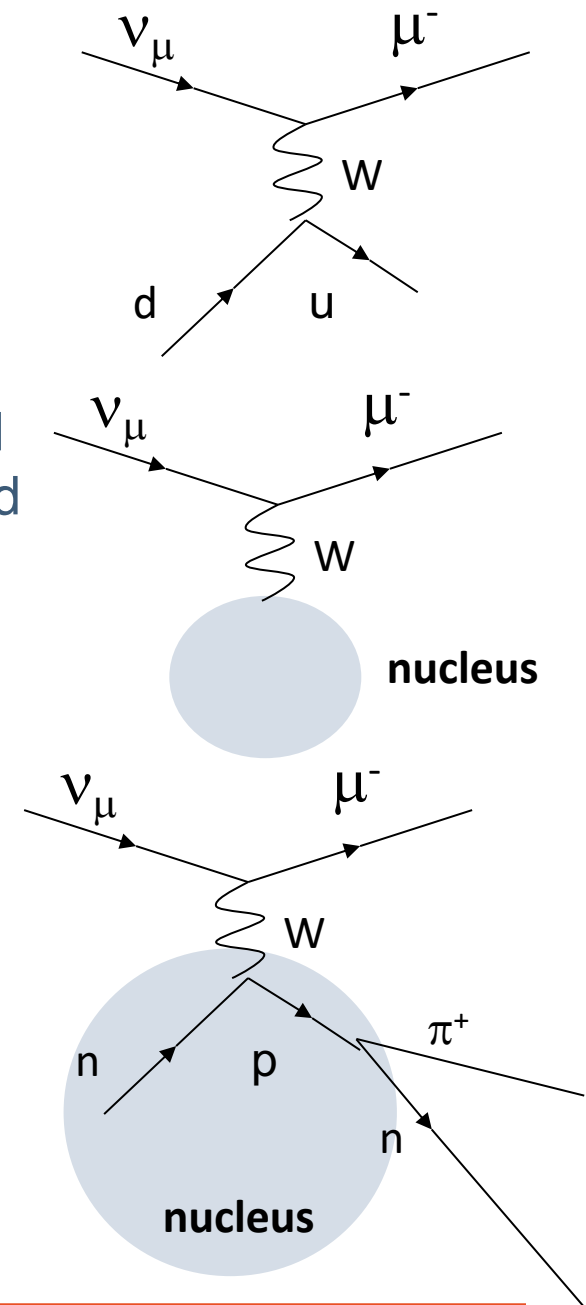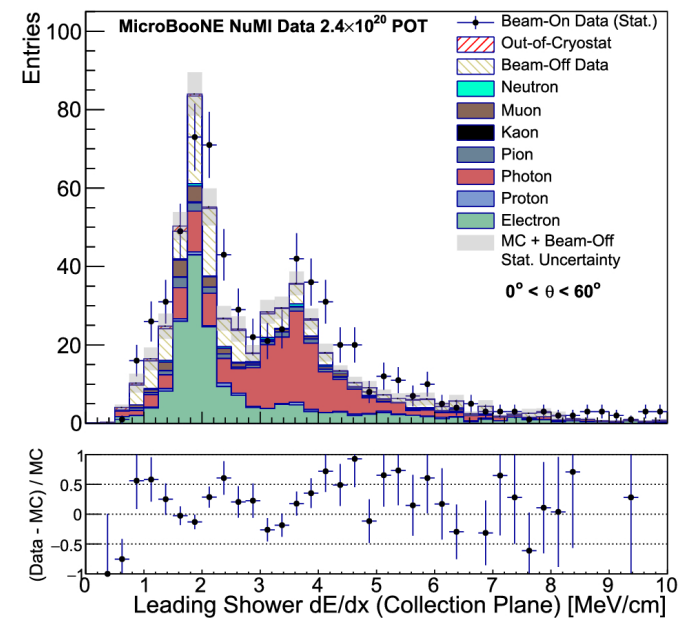
ν Interactions: Scope

- 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?

- 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., $\pi^- p \to \pi^0 n$. But a π^+ doesn't.

  - A π^0 cleanly deposits all its energy, including its rest mass.

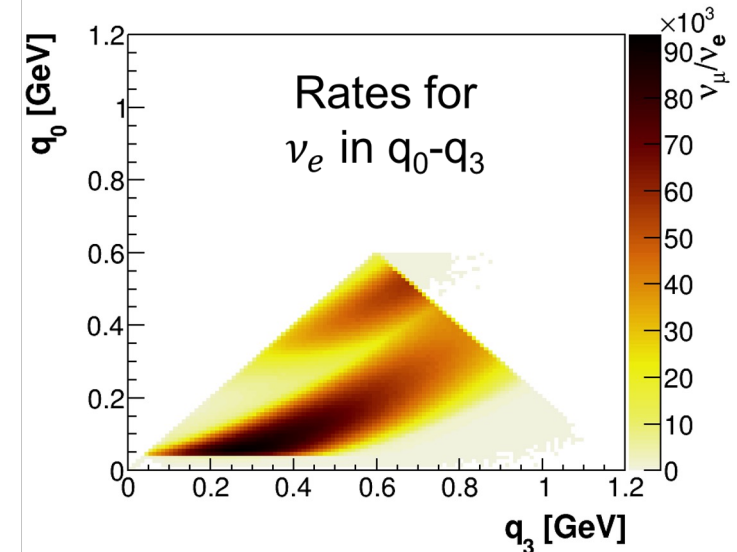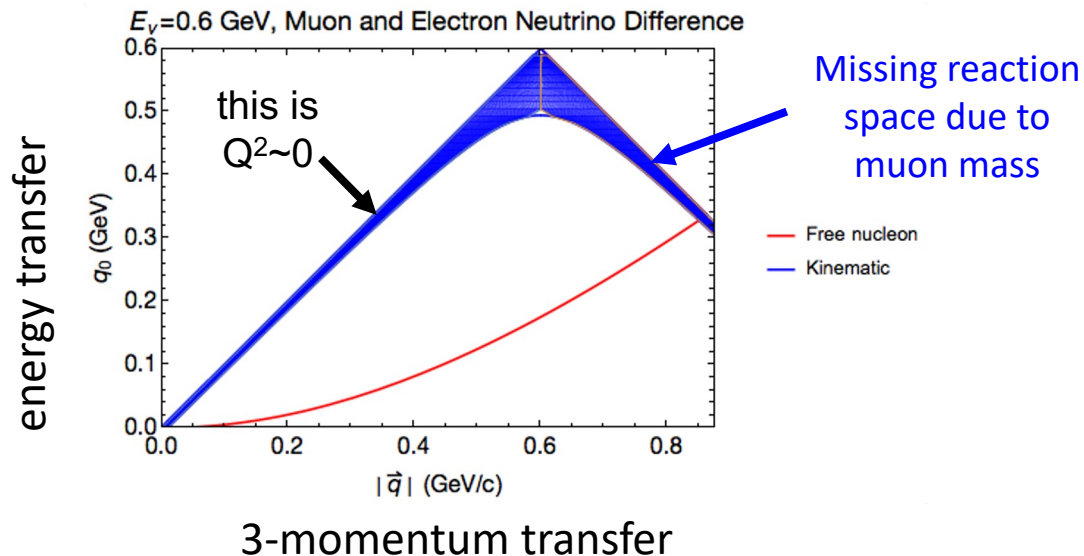- Flavor: photons, primarily from π^0, can't be perfectly separated from electrons.

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

this is $Q^2{\sim}0$

Missing reaction space due to muon mass

energy transfer

3-momentum transfer
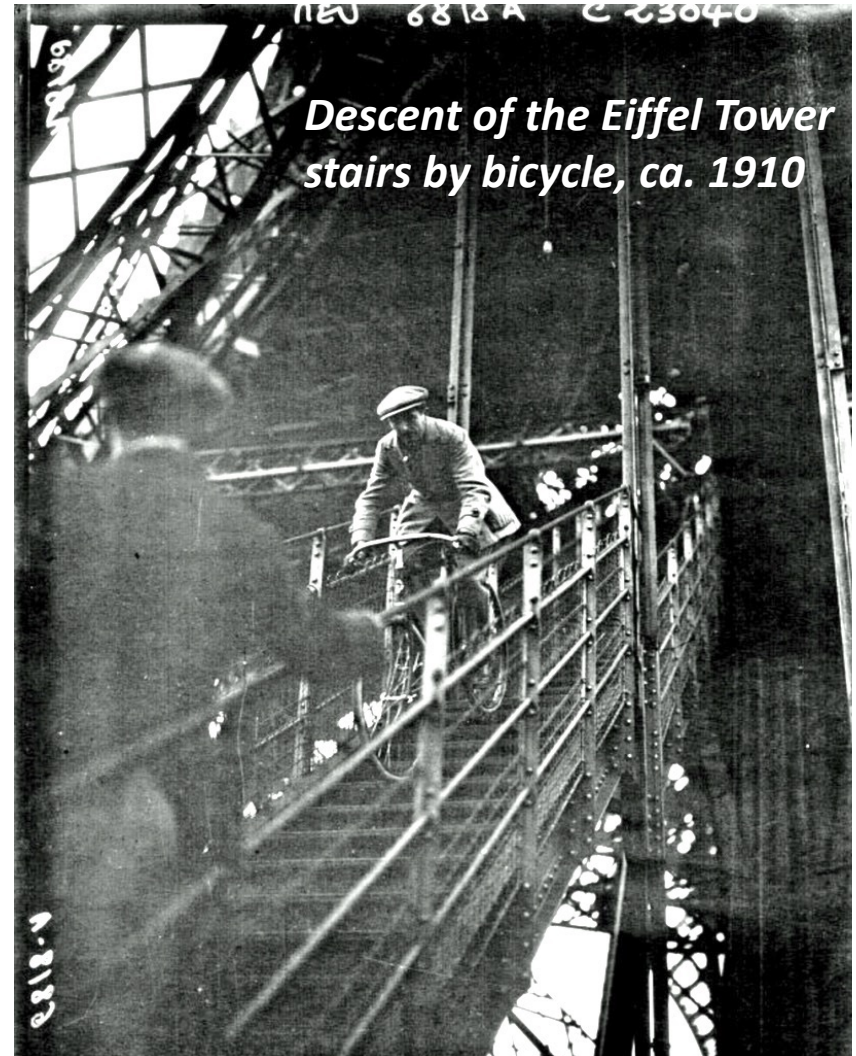

Rates for ν_e in q_0-q_3

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 the steps were ramps of ~100m, we could predict the cyclist's trajectory.
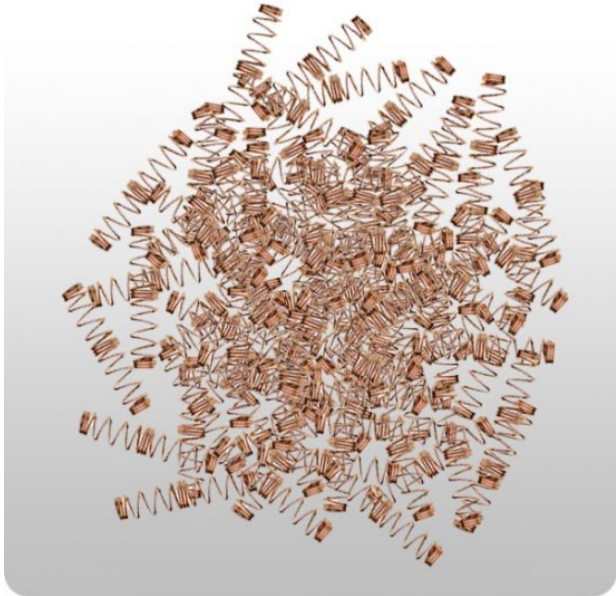

Descent of the Eiffel Tower stairs by bicycle, ca. 1910

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 the steps were ramps of ~100m, we could 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.*

*Descent of the Eiffel Tower stairs by bicycle, ca. 1910*
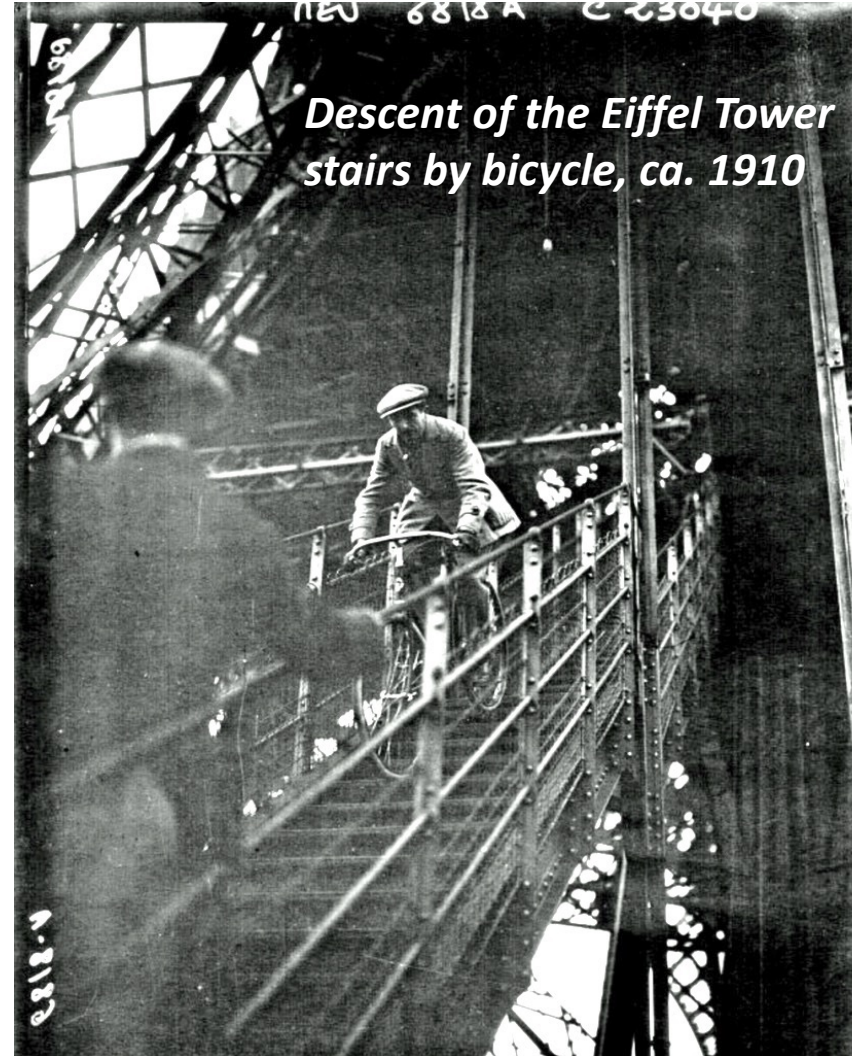
Our Failed Multi-scale Problem

- 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.

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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 event to warn it isn't a ν_e.

- And so forth…

"2p2h"
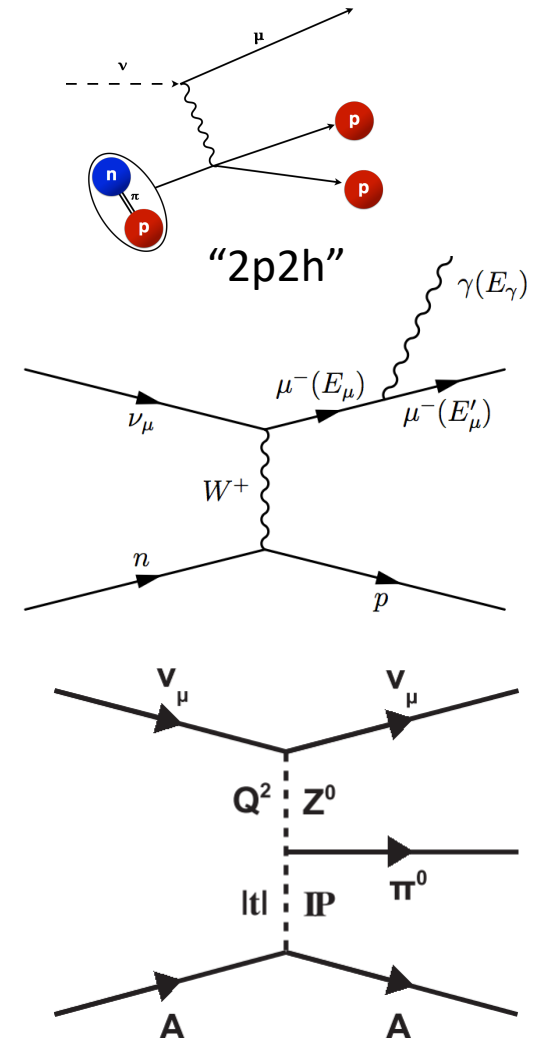
Theory and Experiment

- 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.
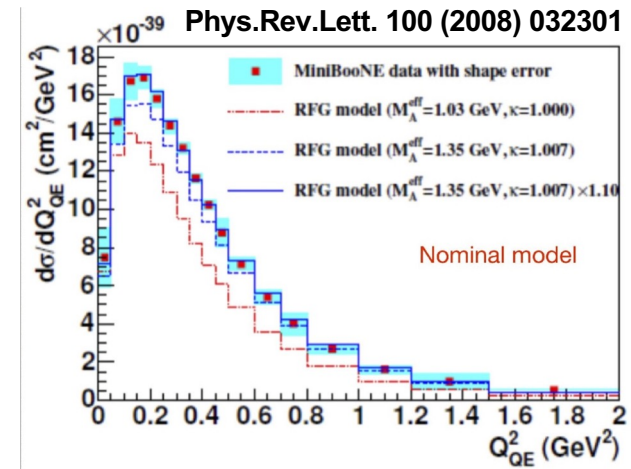
Effective Models

Reaction Data (vA or eA)

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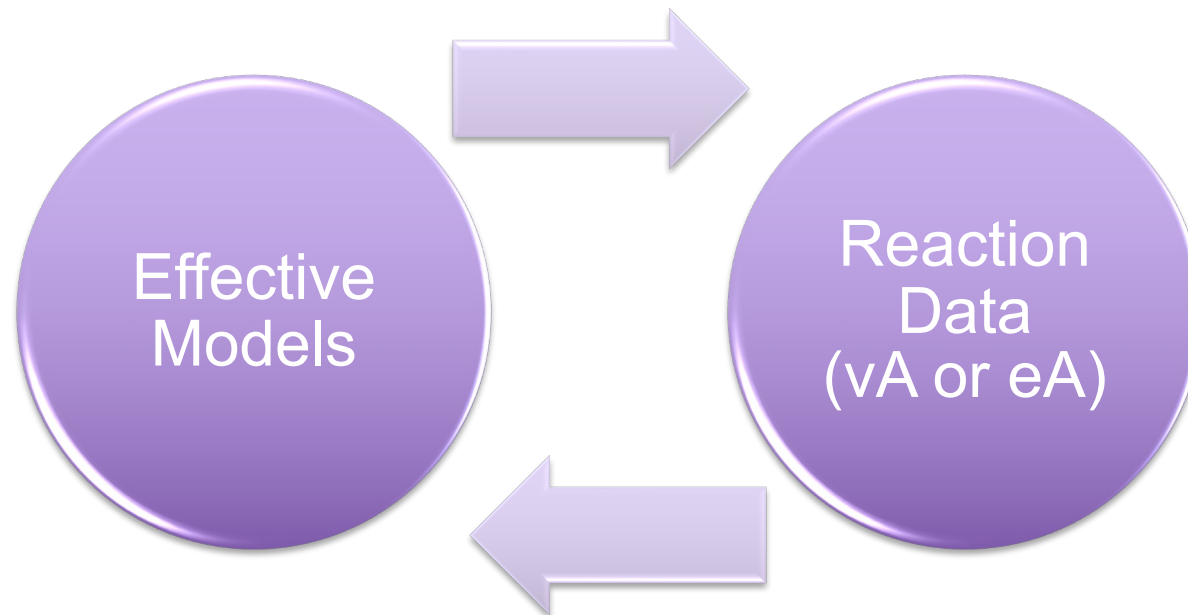
Some Revisionist History
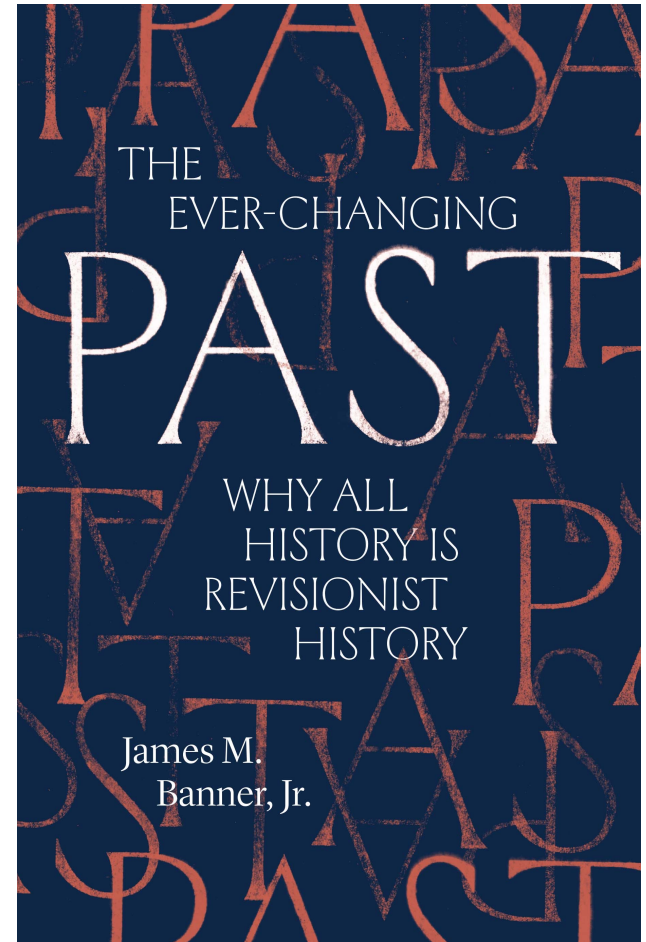
Hypothesis: Detector Improvements Lead to Improved Models

- 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

Legend:
- MiniBooNE data with shape error
- RFG model (M_A^{eff}=1.03 GeV, κ=1.000)
- RFG model (M_A^{eff}=1.35 GeV, κ=1.007)
- RFG model (M_A^{eff}=1.35 GeV, κ=1.007)×1.10

Nominal model

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

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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.

$d\sigma/dq_0 dq_3$ $(10^{-38}$ $cm^2/GeV^2)$
3 GeV neutrino + carbon
GENIE 2.8.4 with reduced π
lines W = 938, 1232, 1535 MeV
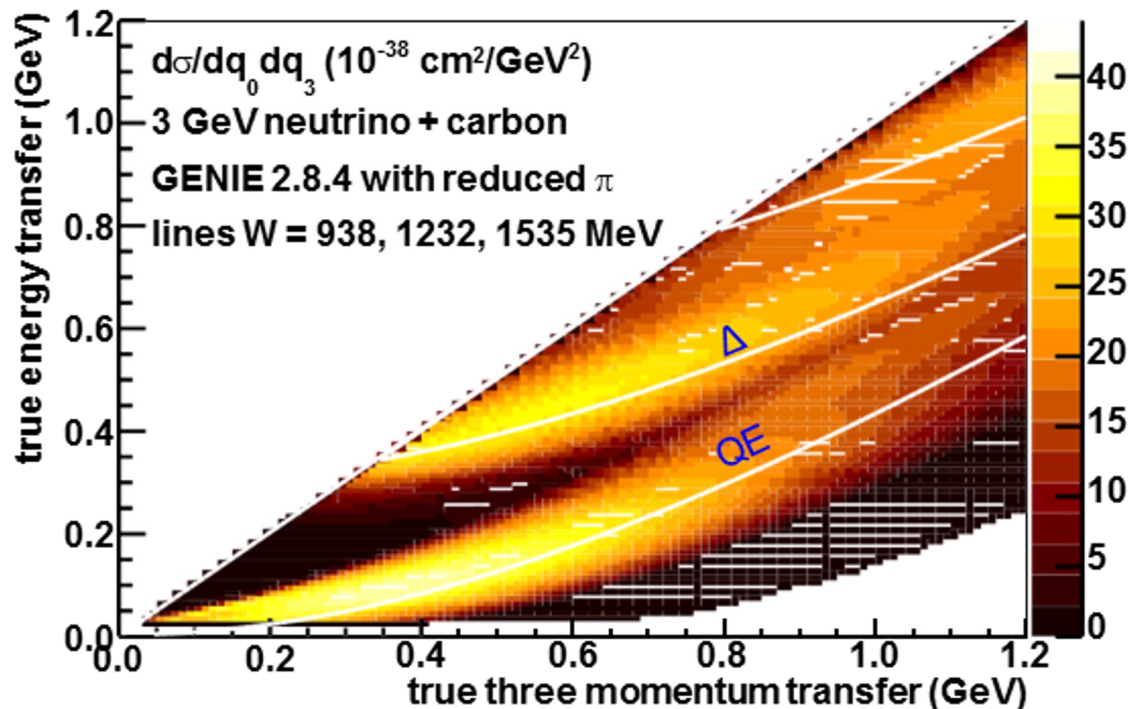
- W (recoil mass) is fixed in this space
  $$W^2=(M+q_0)^2-q_3^2$$
- Quasielastic band, at low W, is shown broadened by nuclear effects.
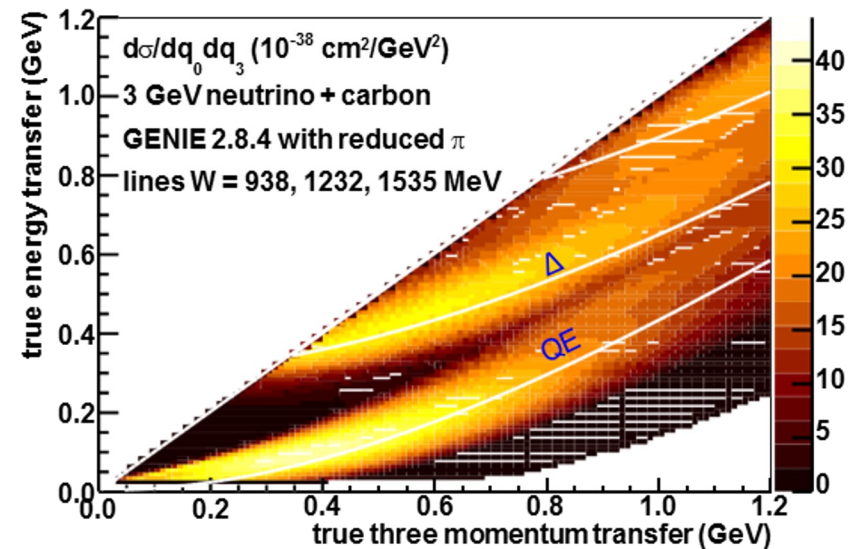- MiniBooNE assumption was that the fix left interactions in the QE band.

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.
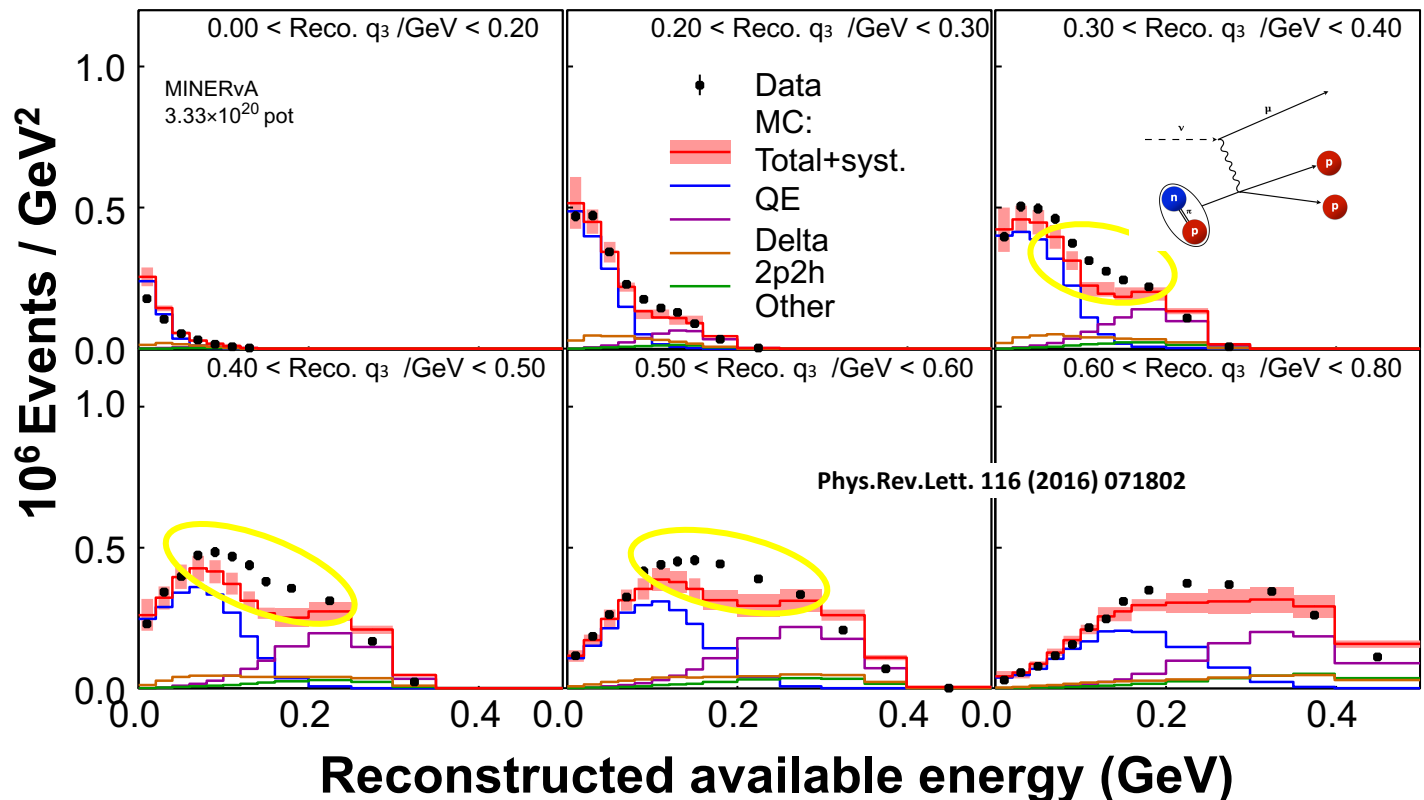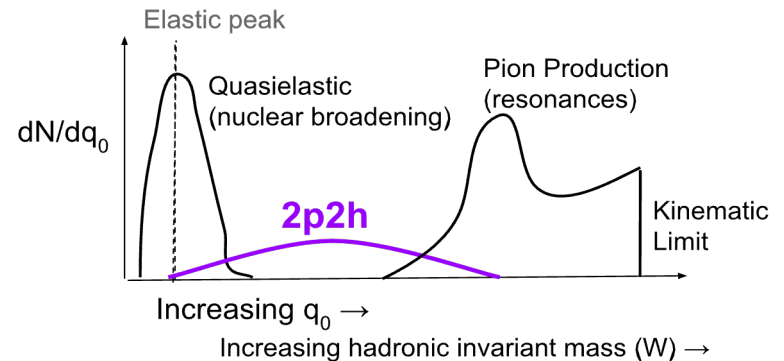
Interpretation: Multinucleon Knockout, a.k.a., "2p2h"

- 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.

$d\sigma/dq_0 \, dq_3 \; (10^{-38} \text{ cm}^2/\text{GeV}^2)$
3 GeV neutrino + carbon
GENIE 2.8.4 with reduced π
lines W = 938, 1232, 1535 MeV

true energy transfer (GeV)

true three momentum transfer (GeV)

Δ
QE

Fixed Three-Momentum Transfer

Elastic peak
Quasielastic (nuclear broadening)
Pion Production (resonances)
dN/dq_0
2p2h
Kinematic Limit
Increasing $q_0 \rightarrow$
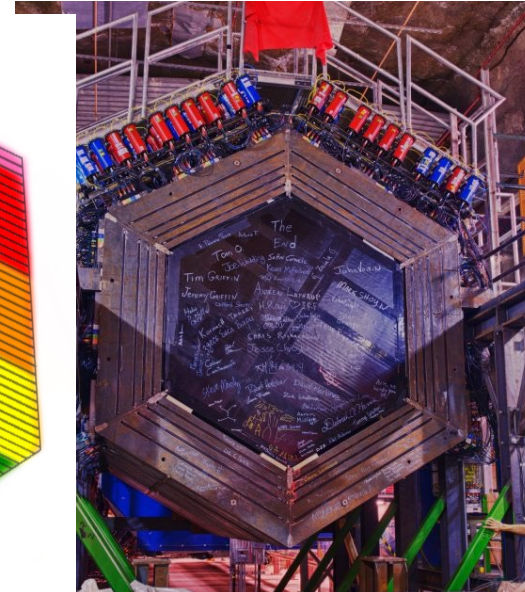Increasing hadronic invariant mass (W) $\rightarrow$

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.
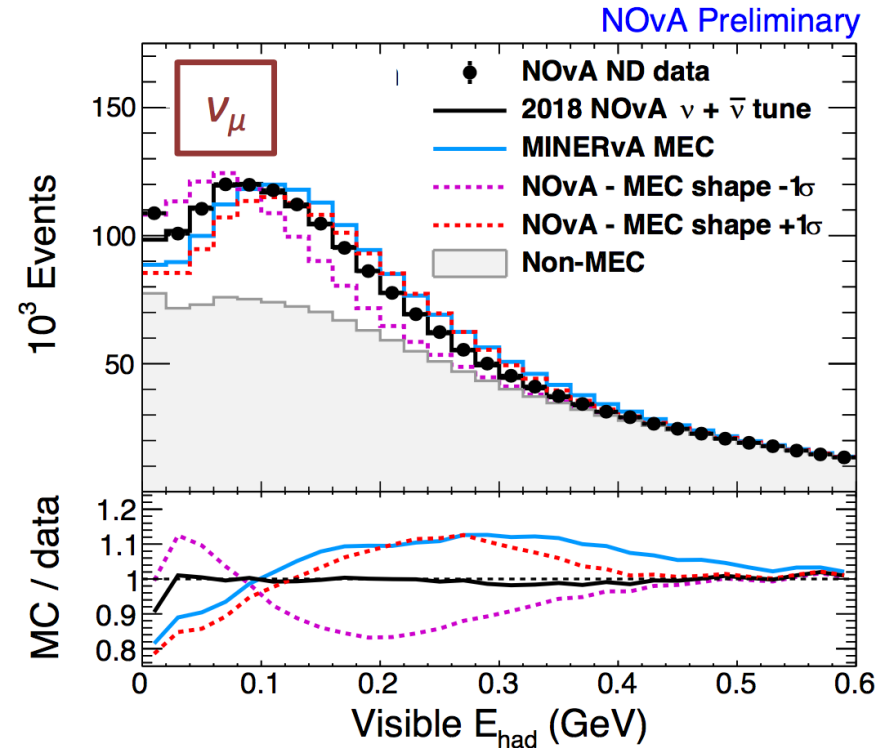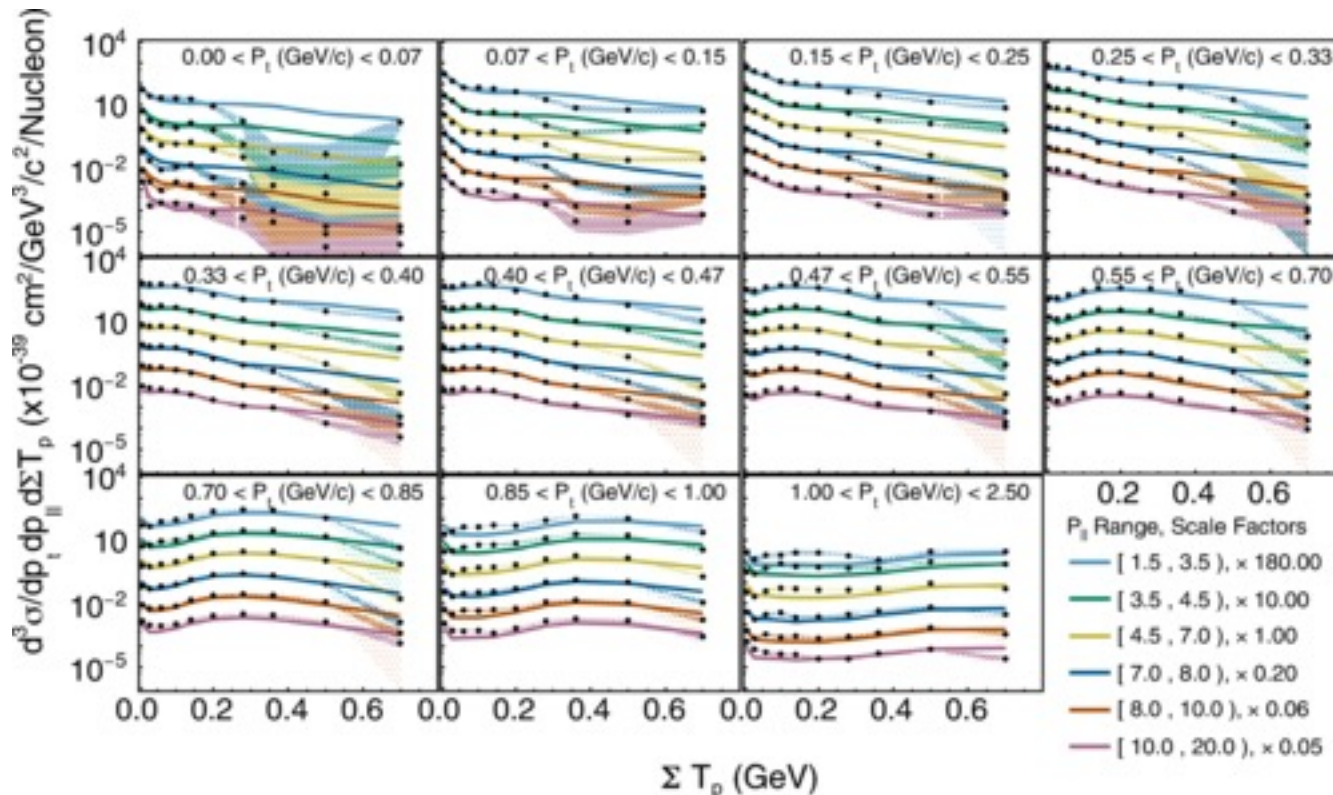

Alex Himmel, JETP Seminar, June 2018

Some Recent Results…

Result and Enabling Technology

- 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.
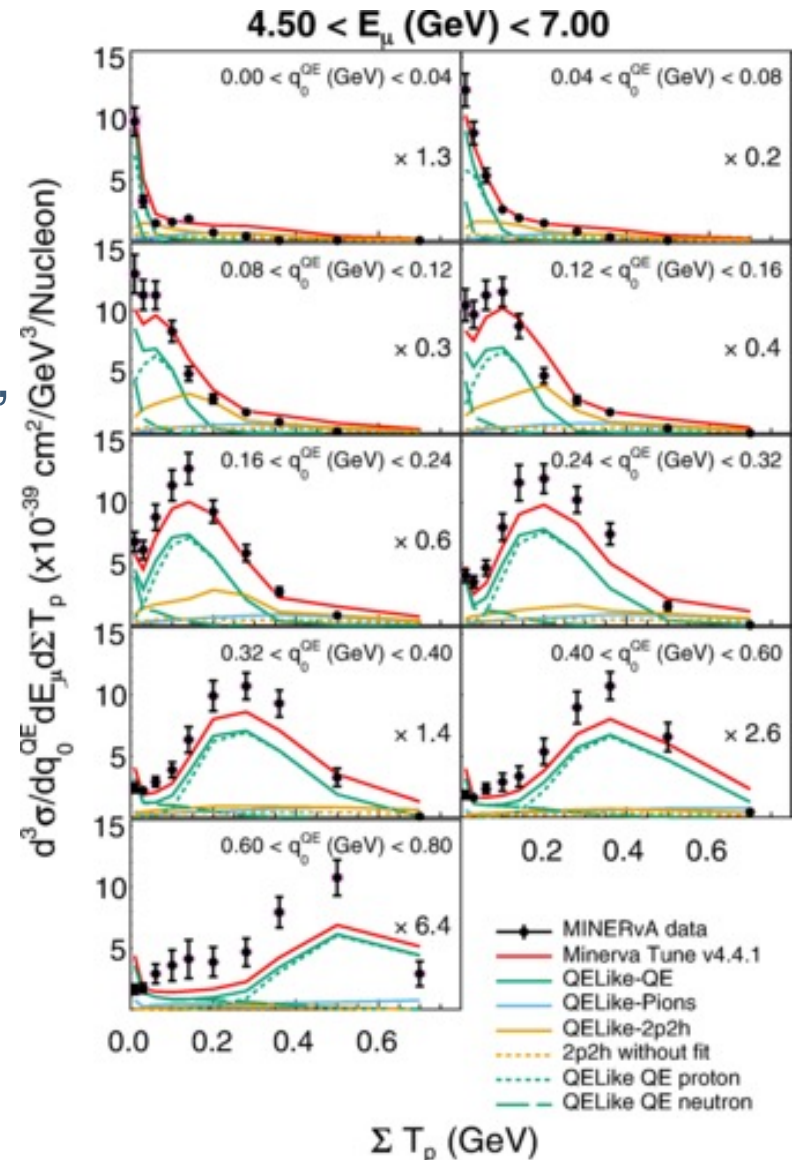
e4nu Energy "Feed-down"

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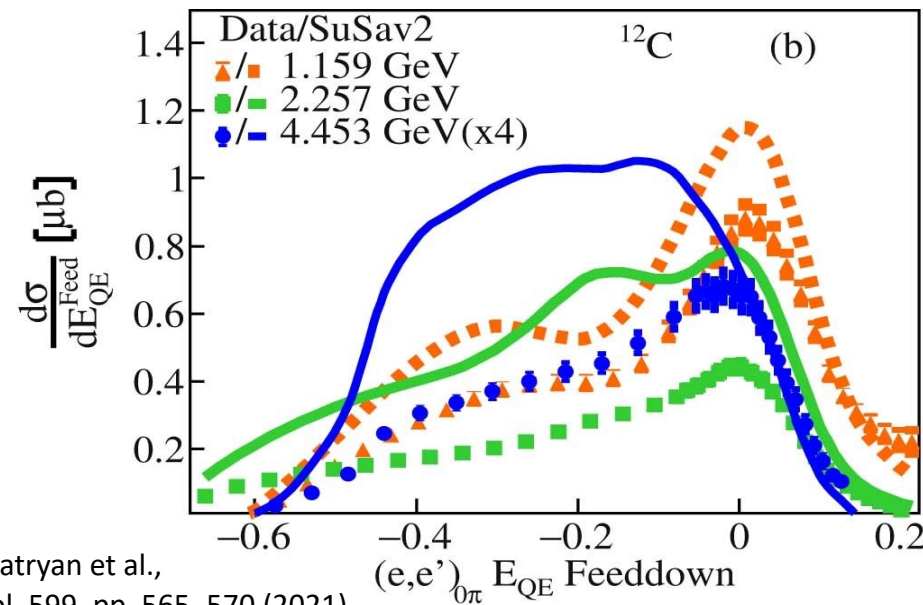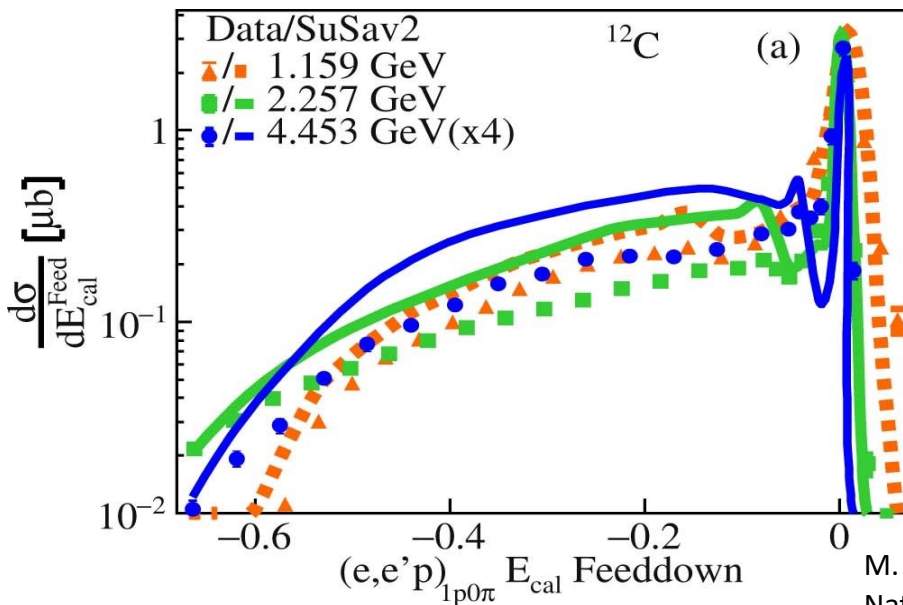
M. Khachatryan et al.,
Nature vol. 599, pp. 565–570 (2021)

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 squarely at deficiencies in the models used for E_ν reconstruction.
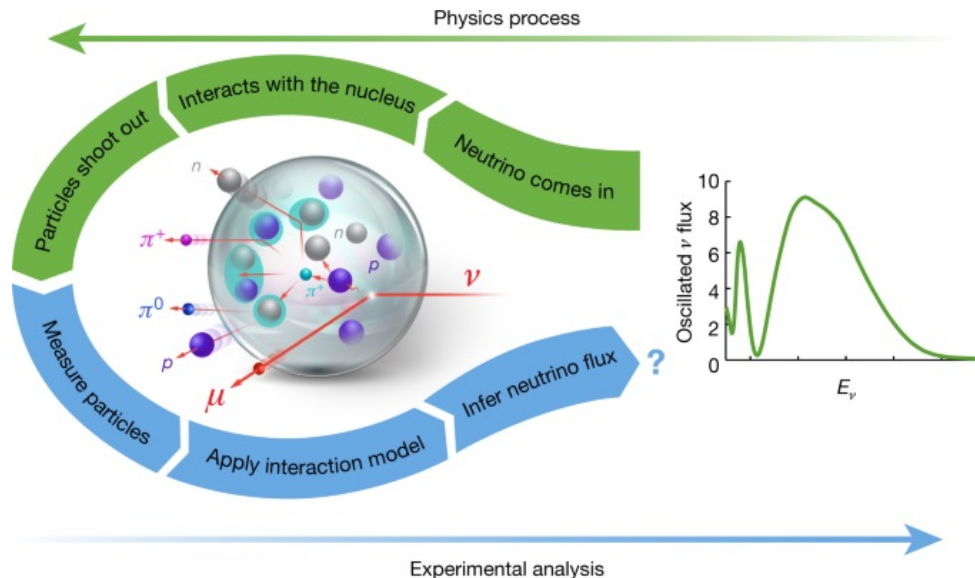

Figure from M. Khachatryan et al., Nature vol. 599, pp. 565–570 (2021)

Forecasting…

What can we expect before and during DUNE?

- SBN experiments are in an excellent position to exploit LAr TPC capabilities in lower energy, broadband beams.

  – Parallel to, and complimentary to MINERvA.

- Narrowband beams (off-axis) at NOvA and T2K will continue to make quasi-single energy measurements on carbon.

- Prediction: PRISM, with its ability to add information from the true neutrino energy, will generate data that solves puzzles critical for DUNE.

- Prediction: DUNE's overwhelming near detector statistics will provide important constraints on ν_e interactions.

neutrino fluxes at different DUNE PRISM locations

Closing Thoughts
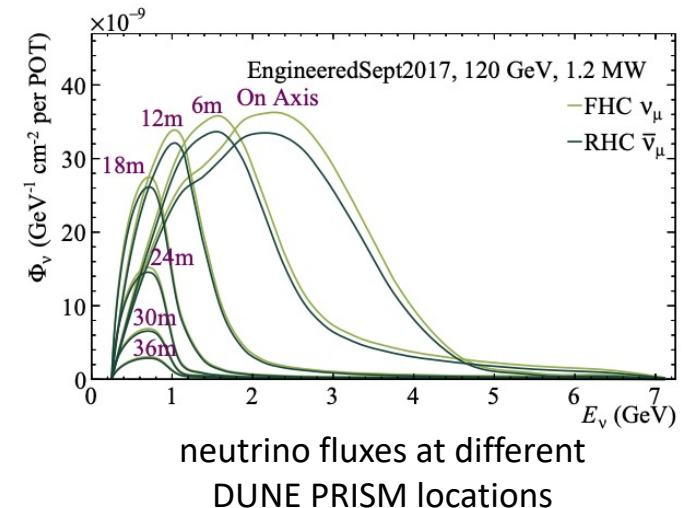
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Interactions: Progress on Puzzles

- Both theory 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 ideas,

- … have led to improvements in models which have proved critical for correct interpretation of oscillation data.

- Precision needs of DUNE will benefit from new capabilities, such as DUNE PRISM and electron neutrinos at high statistics, that we will use to explore neutrino interactions.

Backup

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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 $\bar{\nu}_\mu H \rightarrow \mu^+ \, n$.

- Capable DUNE near detectors with CH will have overwhelming statistics to exploit.

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Understanding

Data on nuclei

Final State Interactions

Data on nucleons

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