OK, this still needs work…

- Months ago I had planned a few days off, preceding immersion into a cult-like (read: sixteen hour days) meeting of a private foundation I'm entangled with.

- I'm in a superposition of an apologetic and not apologetic state.

Neutrino Interactions: Puzzles and Progress

Kevin McFarland, University of Rochester
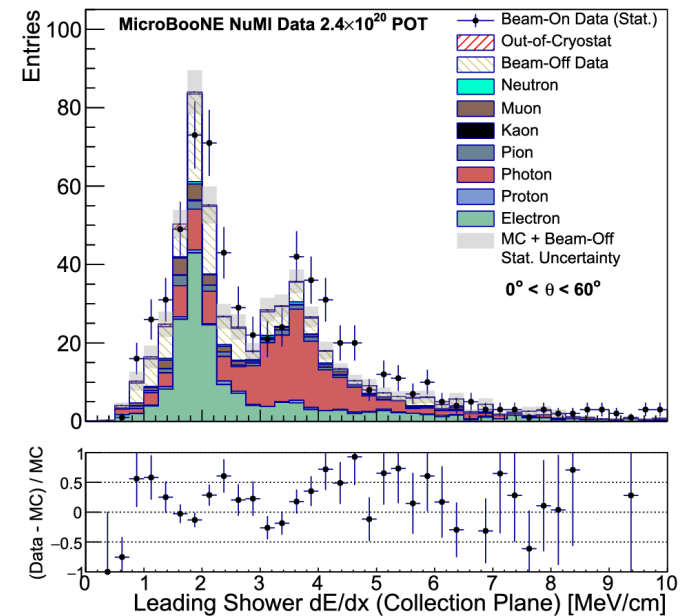
Snowmass Summer Meeting

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.
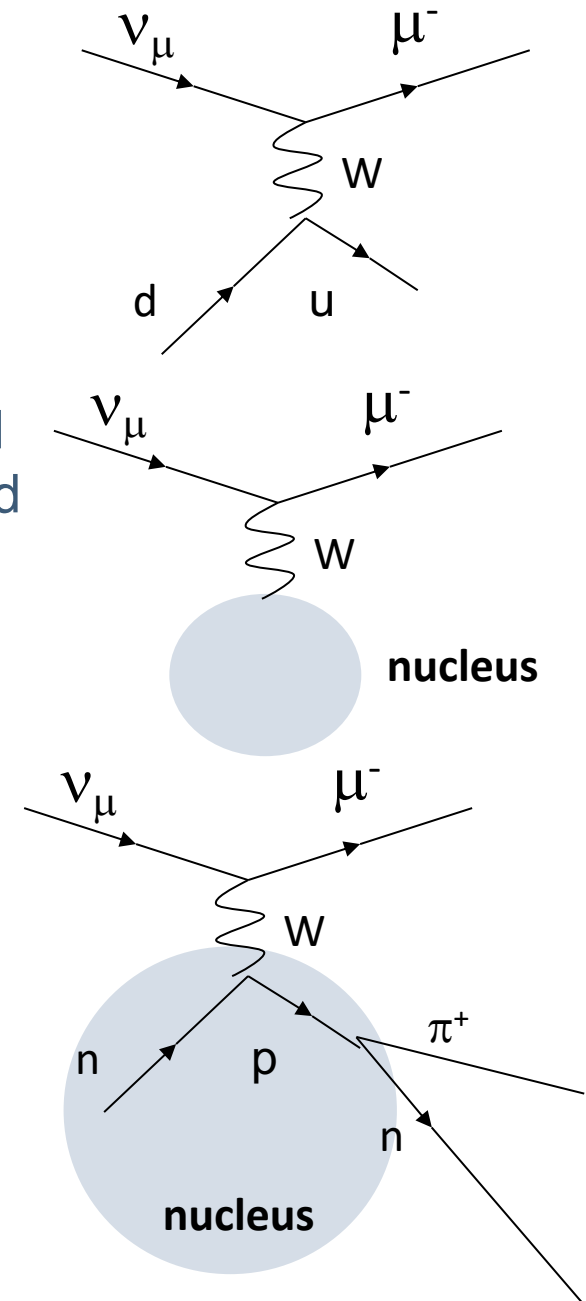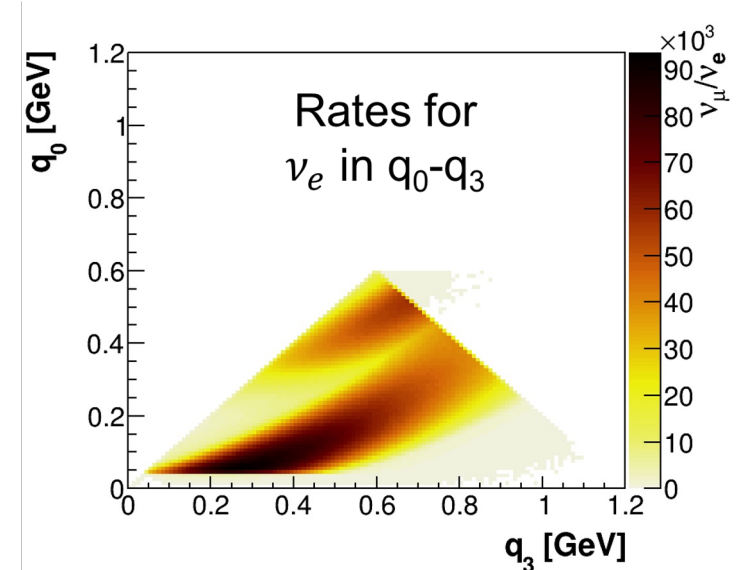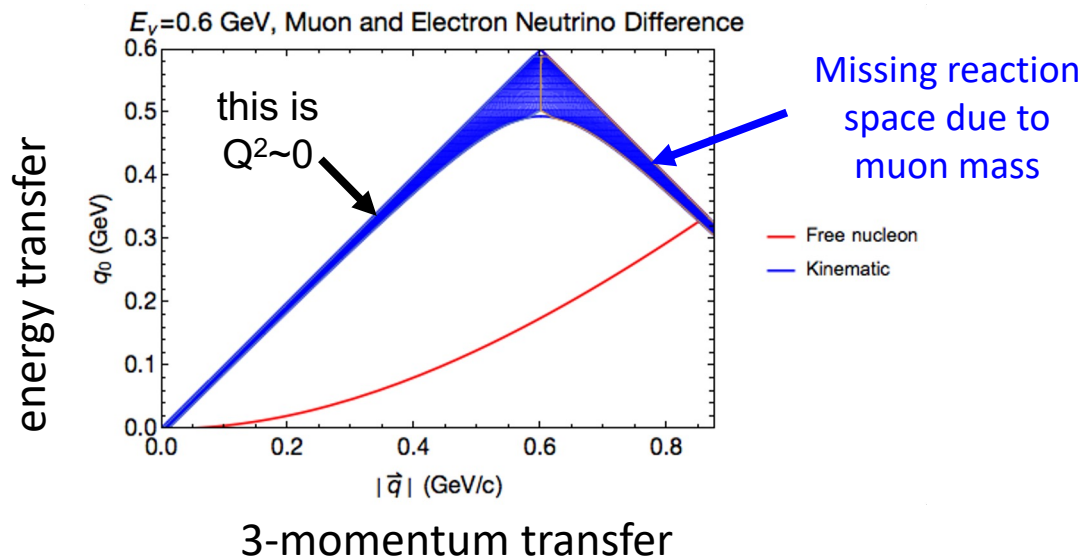
How do ν interactions matter?

- 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., $\pi^- p \rightarrow \pi^0 n$. 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.

MicroBooNE NuMI Data 2.4×10^{20} POT

Legend: Beam-On Data (Stat.), Out-of-Cryostat, Beam-Off Data, Neutron, Muon, Kaon, Pion, Photon, Proton, Electron, MC + Beam-Off Stat. Uncertainty

$0° < \theta < 60°$

Entries

(Data - MC) / MC

Leading Shower dE/dx (Collection Plane) [MeV/cm]

UNIVERSITY of ROCHESTER   DU(V)E

And then 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.

this is $Q^2 \sim 0$

Missing reaction space due to muon mass

energy transfer
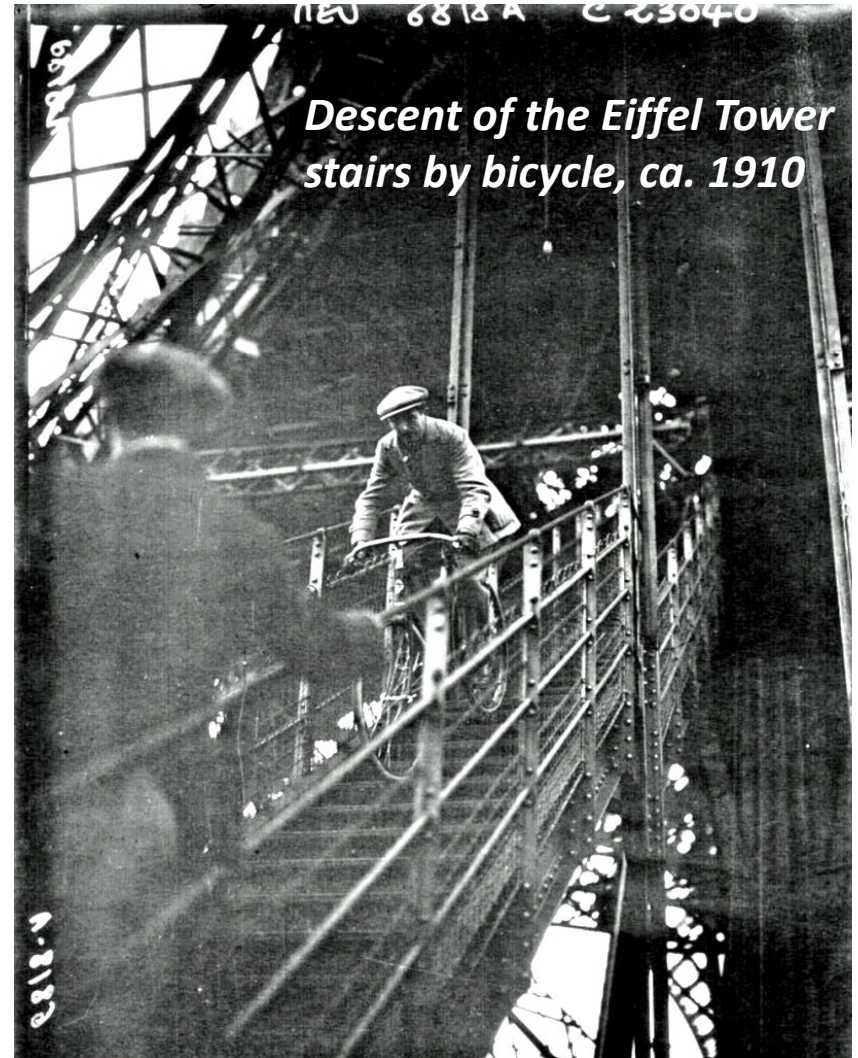
3-momentum transfer

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

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

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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 simple result is that it is going to be painful.*

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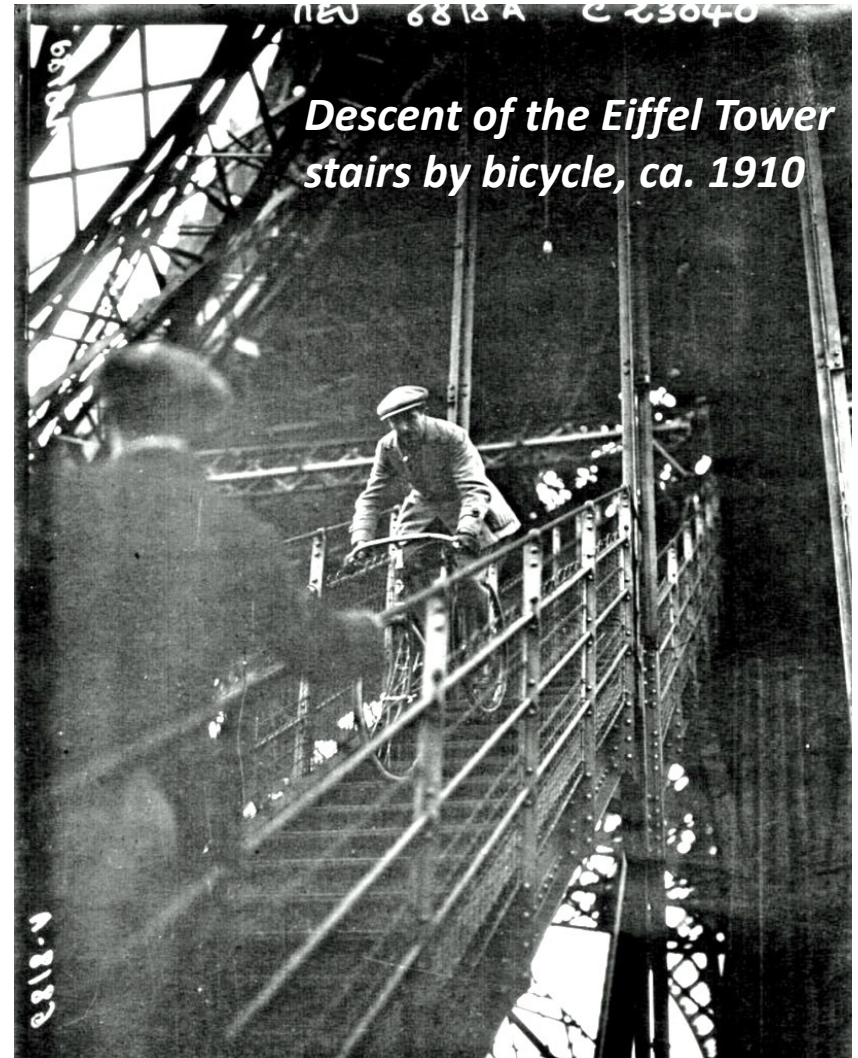
Our Failed Multi-scale Problem

- We have $E_\nu \sim 500 - 5000$ GeV, and therefore energy transfers from nearly zero to $\mathcal{O}(1)$ GeV.

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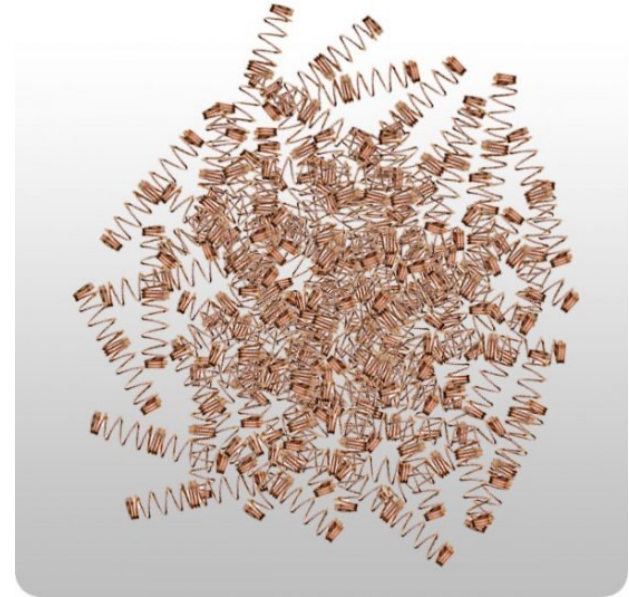
- Exact modeling of nuclear response becomes akin to equation of motion for the system above if energy required to uncouple springs is comparable to energy required to break them.
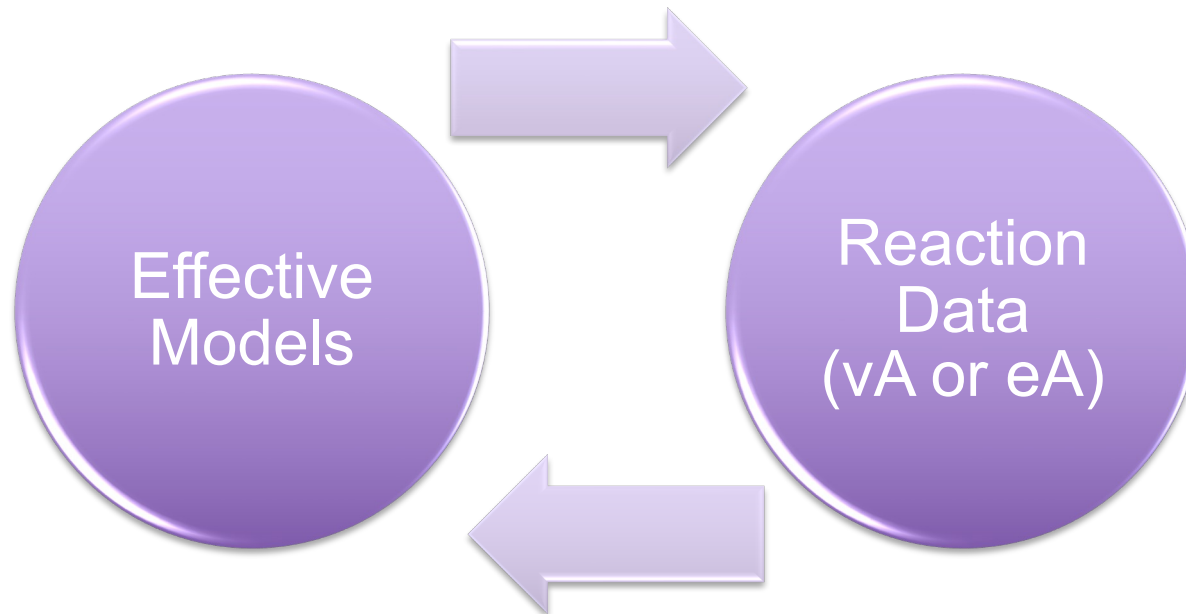
More Problems in ν Interactions

- 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 event to warn it isn't a ν_e.
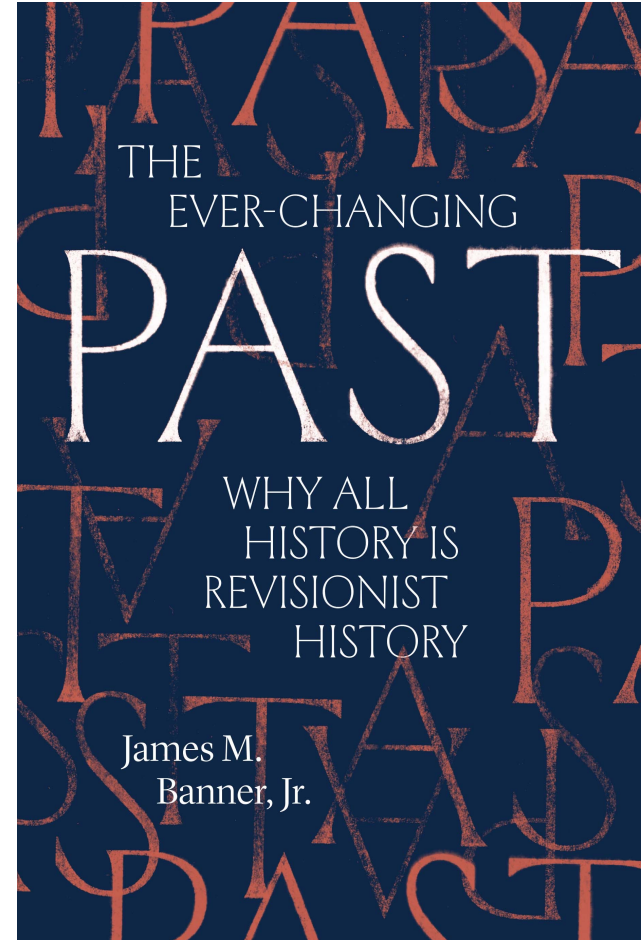
- And so forth…

"2p2h"
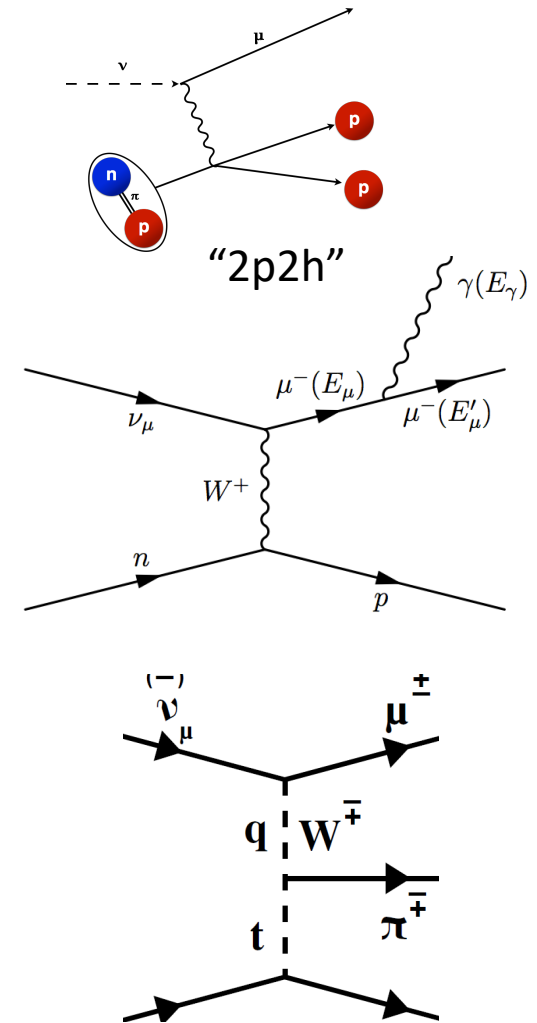
Theory and Experiment

- 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 is good at pointing out modeling deficiencies, and often poor at pinpointing the problem.

Effective Models

Reaction Data (vA or eA)

Some Revisionist History

THE EVER-CHANGING PAST

WHY ALL HISTORY IS REVISIONIST HISTORY

James M. Banner, Jr.

Kevin McFarland l Neutrino Interactions

UNIVERSITY of ROCHESTER

DUNE

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_{QE}^2".

- 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.
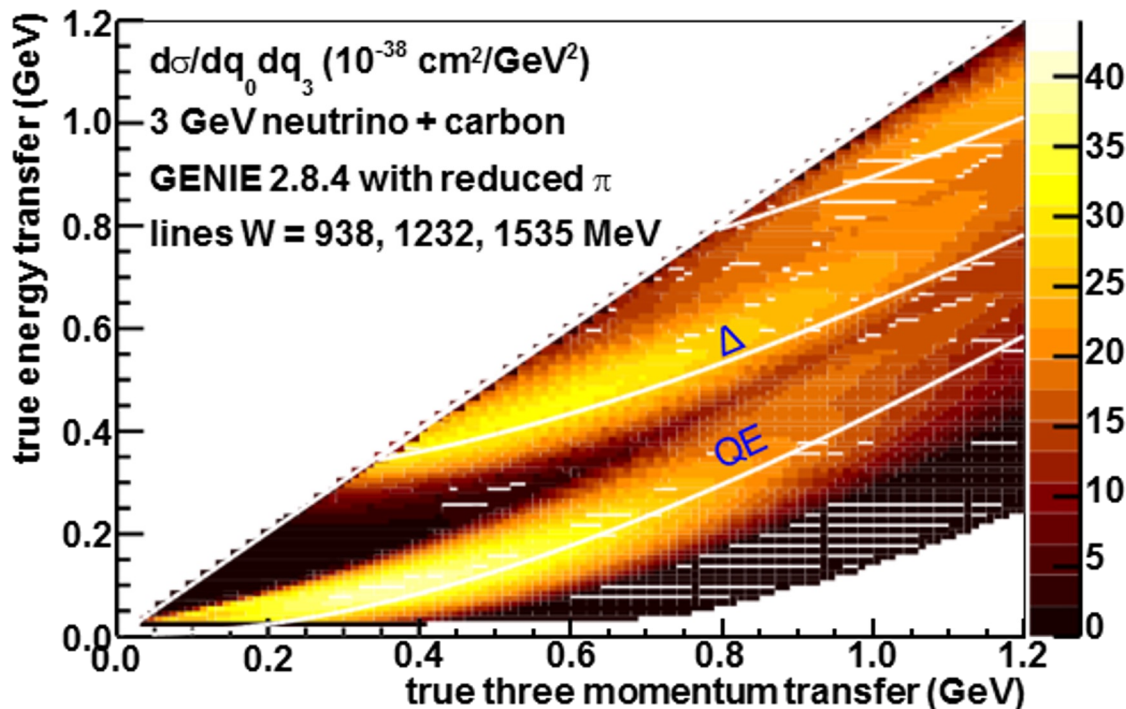
  – Large "axial mass".

$$F_A(Q^2) = F_A(0)/(1 + Q^2/M_A^2)^2$$
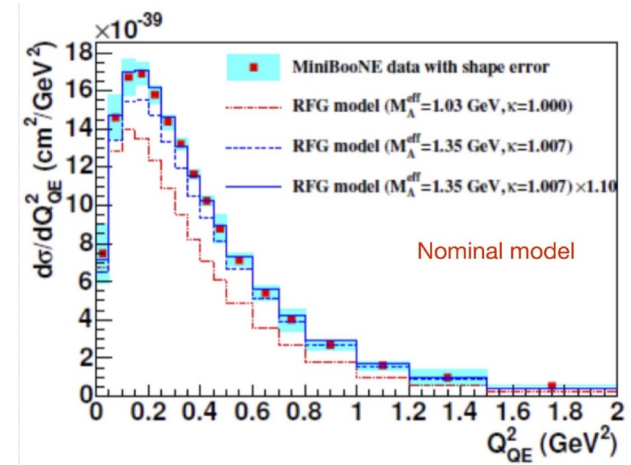
Phys.Rev.Lett. 100 (2008) 032301

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.

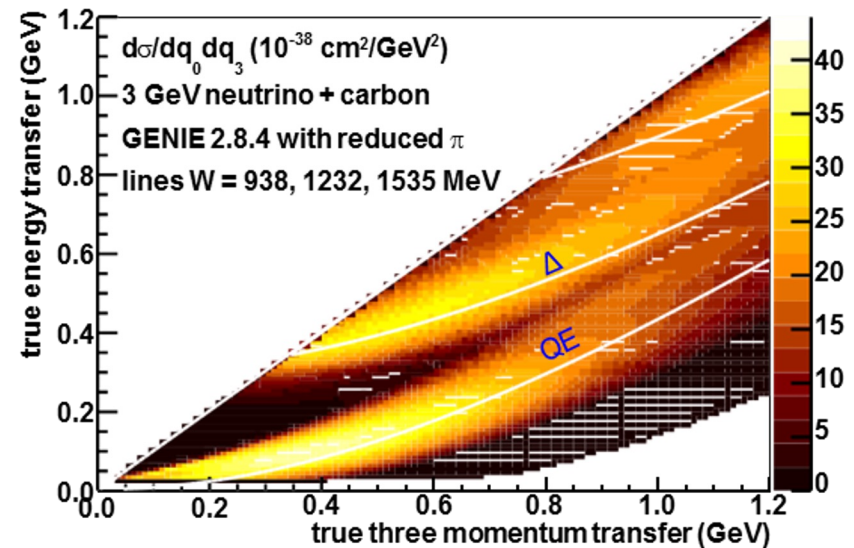- MiniBooNE assumption was that the fix left interactions in the QE band.

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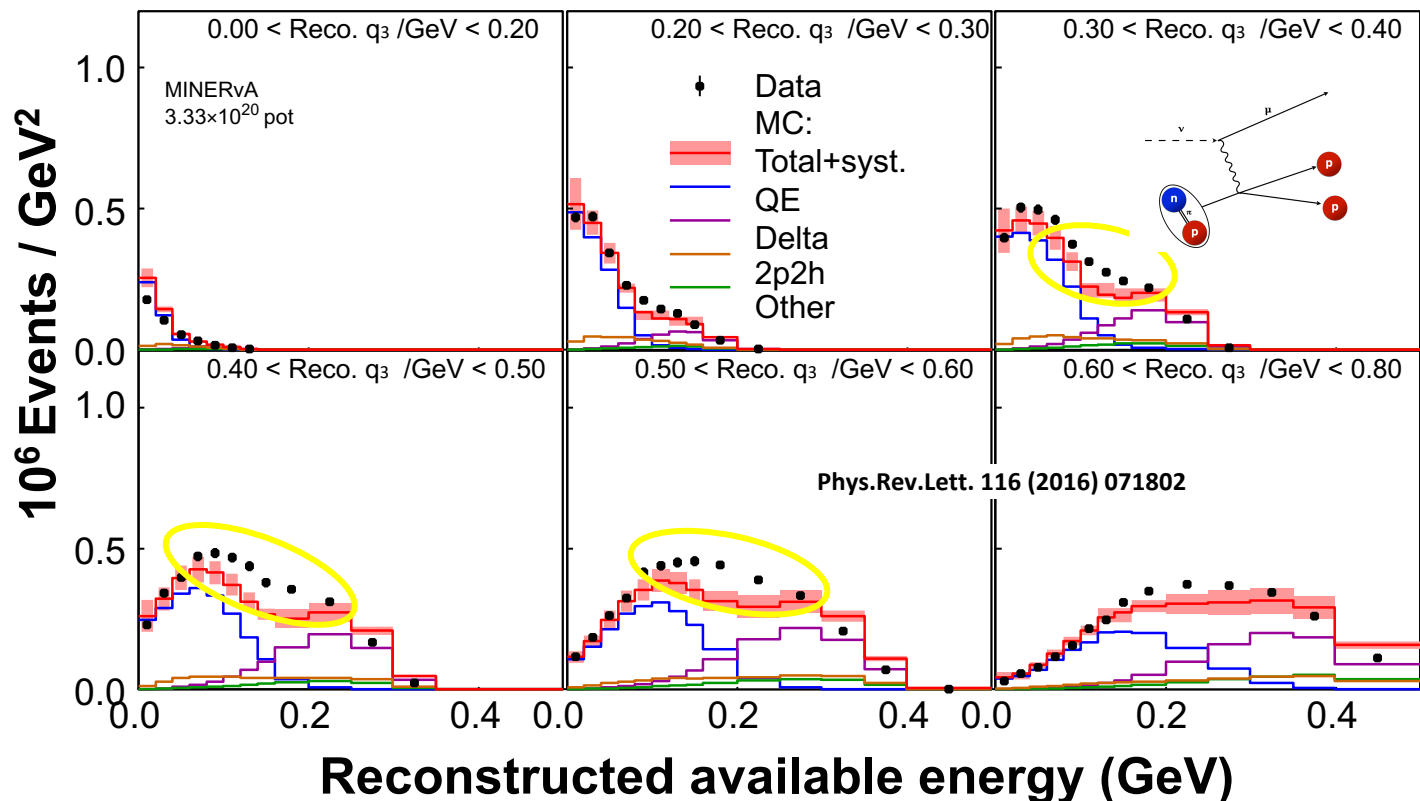
# Interpretation: Multinucleon Knockout, a.k.a., "2p2h"

- 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 energy hypothesis.

$d\sigma/dq_0 dq_3$ (10^{-38} cm²/GeV²)
3 GeV neutrino + carbon
GENIE 2.8.4 with reduced π
lines W = 938, 1232, 1535 MeV
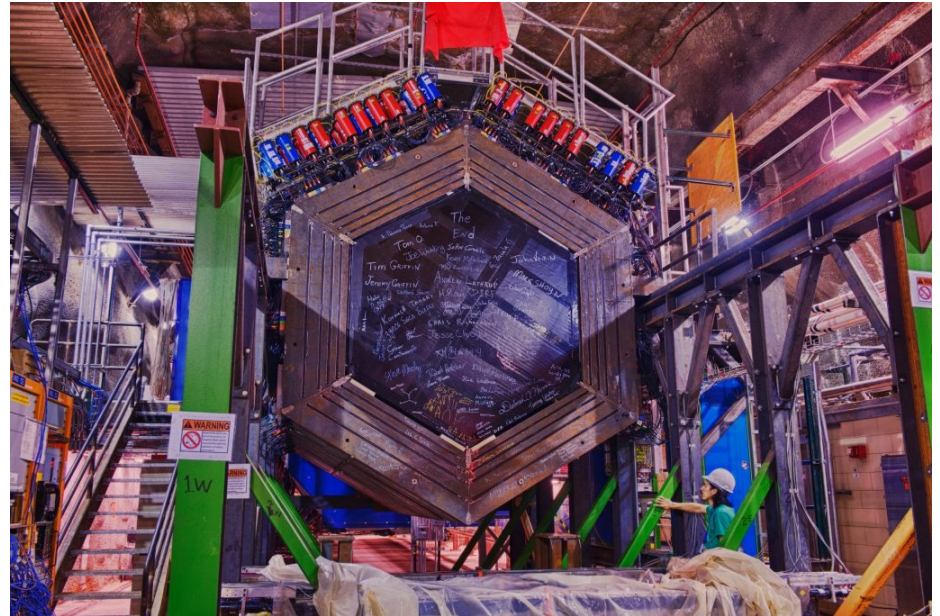
missing schematic here

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

- "2p2h" interpretation was corraborated by other measurements of the recoil system, in correlation with the leptons.

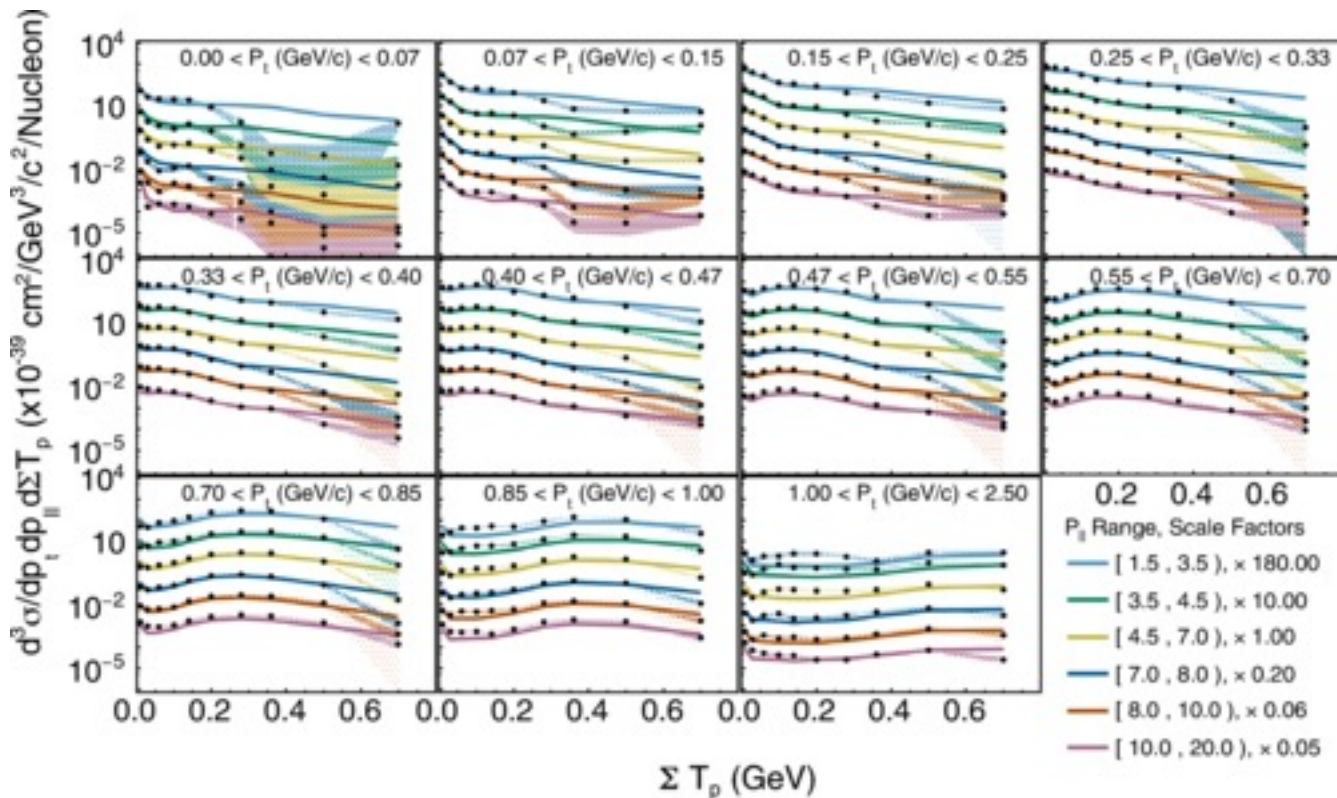- Technique now used by NOvA as an important part of their oscillation analysis.
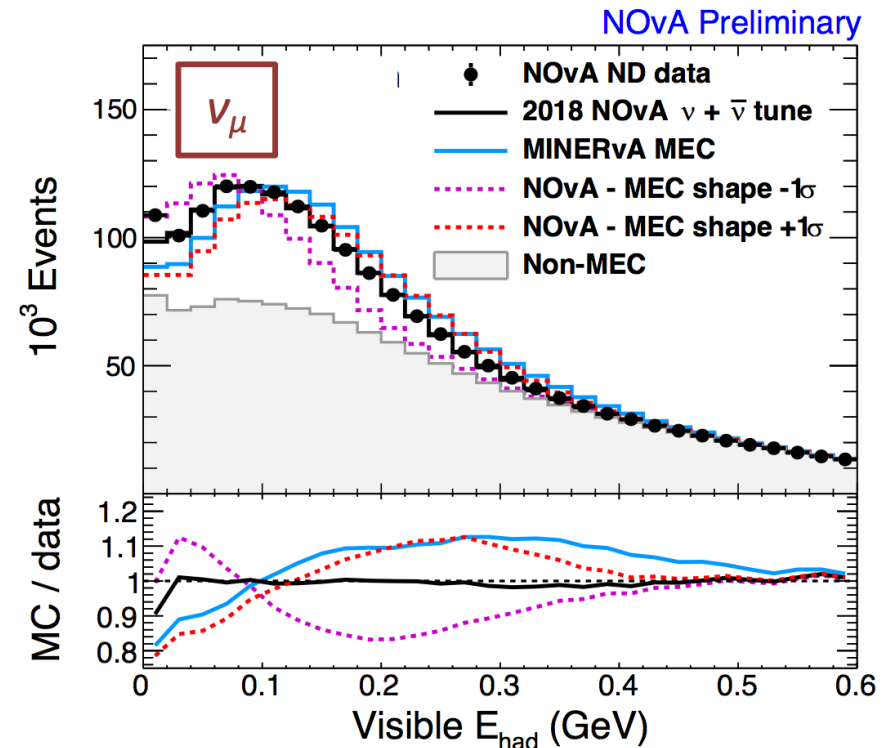
Alex Himmel, JETP Seminar, June 2018

# New 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.
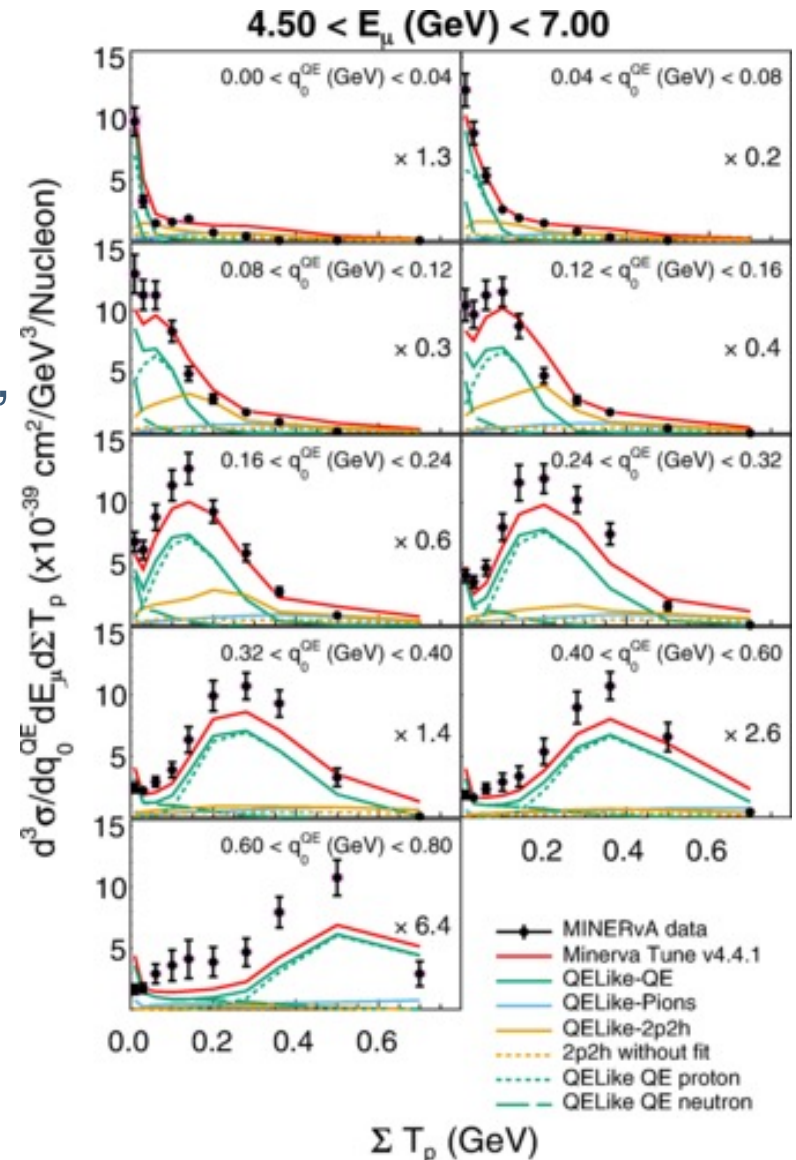
Low Q² Pion Production

- Want to add a description of this, and have not finished.

- May not have time.

missing figure here

- Point is that result shows (unexplained) large suppression and also that it seems to scale with A for C, Fe, Pb.

Forecasting…

19 July 2022   Kevin McFarland | Neutrino Interactions

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 essentially add determination of the true neutrino energy to the existing capabilities of lepton and recoil measurement will generate data that solves puzzles critical for DUNE.

missing figure here

Closing Thoughts

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 that we will use to explore neutrino interactions.

Backup

Measurements on Nucleons

Coherent Pion Production Data

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