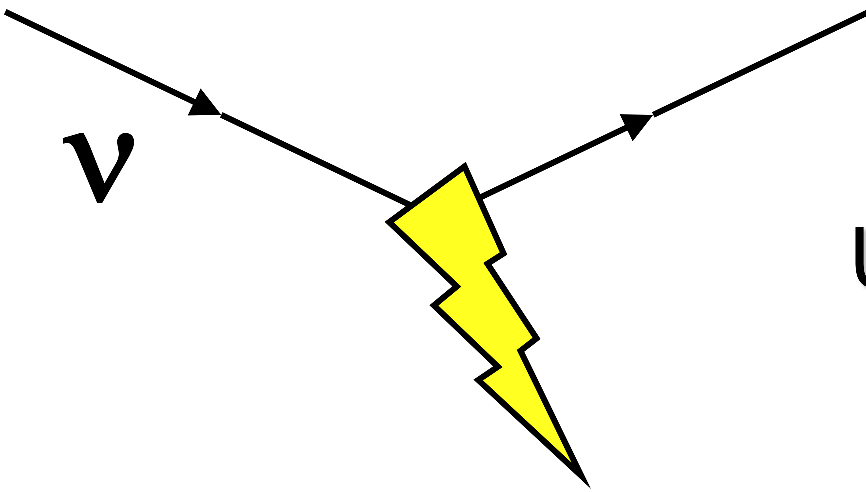
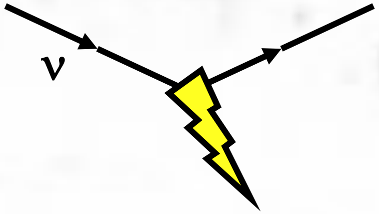
# *Neutrino Interaction Measurements and Oscillation Experiments*




Kevin McFarland
University of Rochester
19 November 2020

SnowMass2021

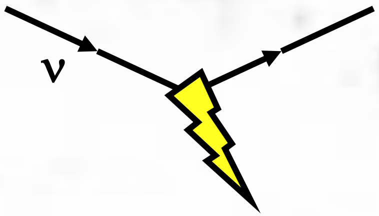



# *Relationships*

- I was asked specifically to speak about the *relationship* between neutrino interaction measurements and oscillation experiments.
- I've found this relationship to be complicated by the need for oscillation experiments to do their work with resources they control.
- Specifically, it's hard to argue you get to build a B$ class experiment without a clear path to controlling your own systematic uncertainties.
- And yet…

*Paul Verlaine and Arthur Rimbaud, both leaning to their right*

# Relationships *(cont'd)*

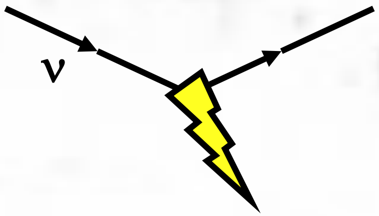



- Our current generation of precision oscillation experiments has not been able to do its work without significant investments in improving the interaction model.
- The data motivating or validating those model improvements or new uncertainties has mostly come from neutrino interaction measurements.
- So it's likely the relationship will continue, despite possible disapproval of our BFFs.

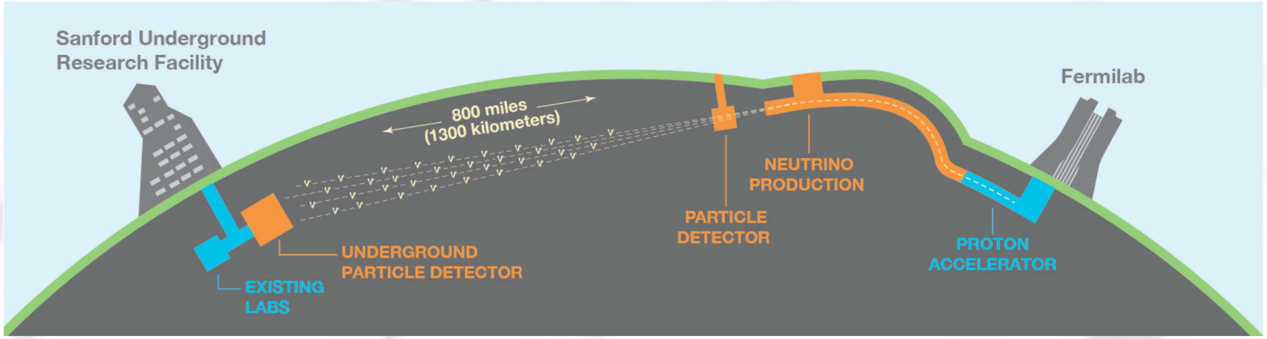
*Detail from "Un Coin de Table", by Henri Fantin-Latour. (On display for all to see, some year, at La Musée d'Orsay.) That's Rimbaud gazing at an annoyed Verlaine at the left and the rest of the table ignoring the clingy display.*

# *How Oscillation Experiments Use Interaction Models*

# Near Detectors and Oscillation Analyses

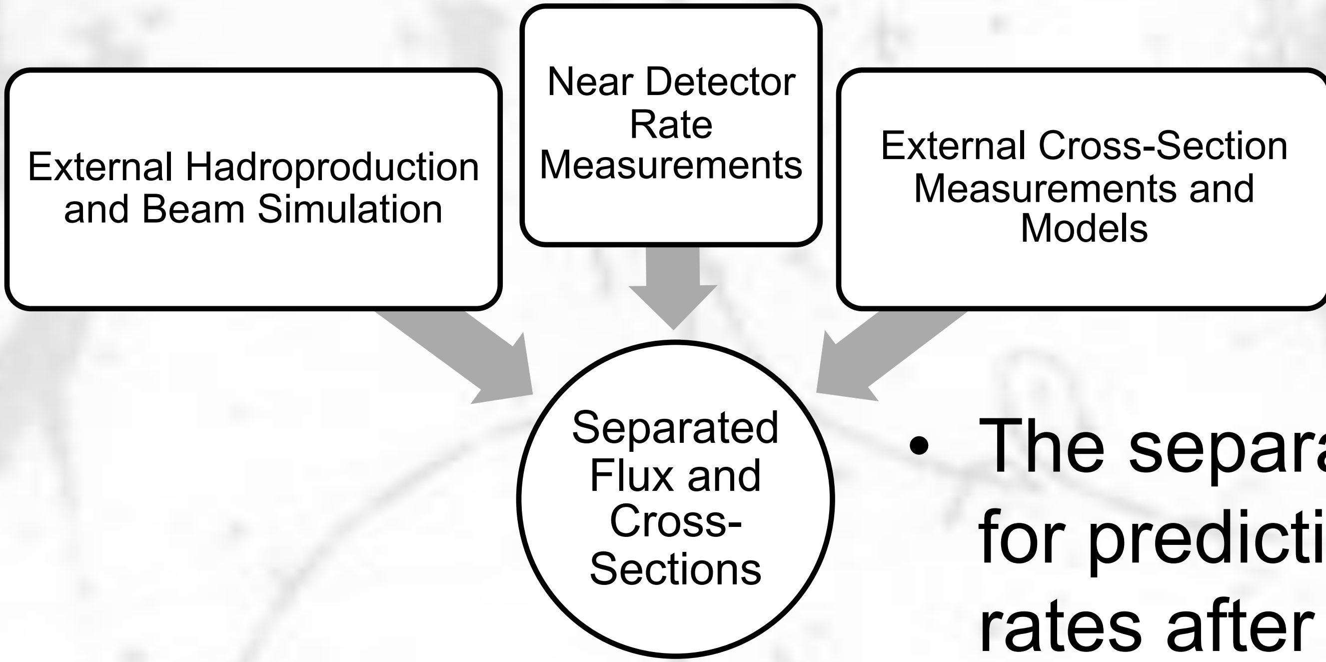



- Near detector sees beam near source, before significant oscillations.
- Goal is to measure flux and neutrino interactions, and to inform modeling of response of the far detector.
- Near detector rate = $\int$ flux$\otimes$cross-section$\otimes$detector response.
- Detector must provide methods to deconvolve these elements.



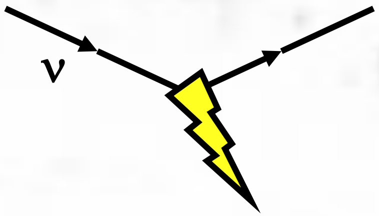
# *Oscillations: Near Detectors*

- Experiments have a, more or less, universal scheme for using the near detector data to constrain the flux and cross-section




- The separation is critical for prediction of event rates after oscillation.
- ∴ Reliance on models

# But, challenges

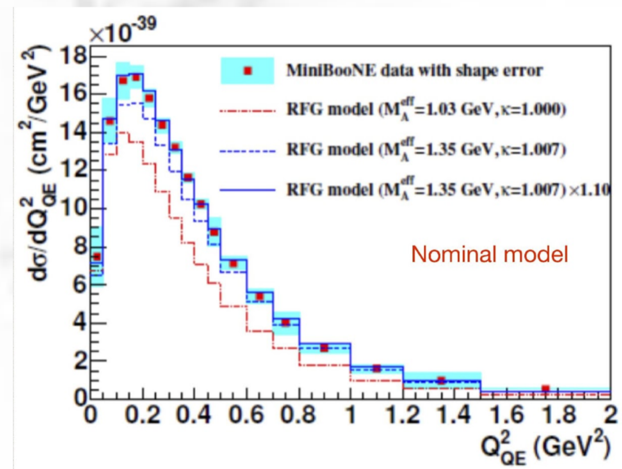



- Neutrino flux is difficult to measure independently.
  - "Standard candle" reactions are either dim or unreliable.  (Chose one.)
- Neutrino oscillation probability, $P(\nu_\mu \rightarrow \nu_\ell) = \mathcal{F}\left[parameters, \frac{L}{E_\nu}\right]$.
  - The detector measures $E_\nu$ from final state particles.
  - But the detector response in ionization to leptons, $\pi^0$, protons, $\pi^+$, $\pi^-$, neutrons, nuclear remnant are all different (rough ordering by visibility).
- Rate at the near detector is much higher than rate at far detector.
  - DUNE provides the extreme, but not the only example of the problem.
    - 1.5M $\nu_\mu$ CC events/ton/yr at the on-axis location in neutrino beam.
    - LAr readout by drifting ionization in a TPC is a slow detector technology. Pileup of neutrino interactions at near detector complicates the task.
- Deconvolution is an ill-posed problem.

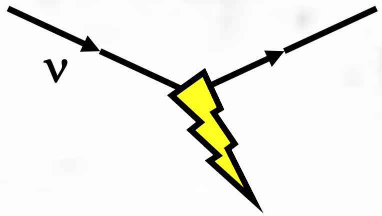
# *Historical example of a failure of deconvolution*

- MiniBooNE observed a discrepancy in its "CCQE" events vs $Q^2$.
  - Attributed to axial form factor and Pauli blocking, just an event distortion in $Q^2$.
  - We understand now this is, at least in part, due to multinucleon production with a different energy-momentum transfer relationship. More later on that.
- Attributing the difference in form factor meant misreconstructing $E_\nu$.
- Lesson: need multiple observables to diagnose an incorrect deconvolution.

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

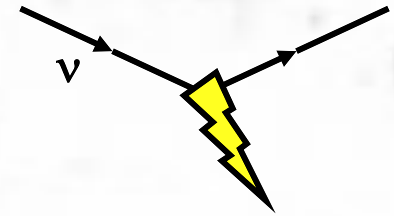



Phys.Rev.Lett. 100 (2008) 032301

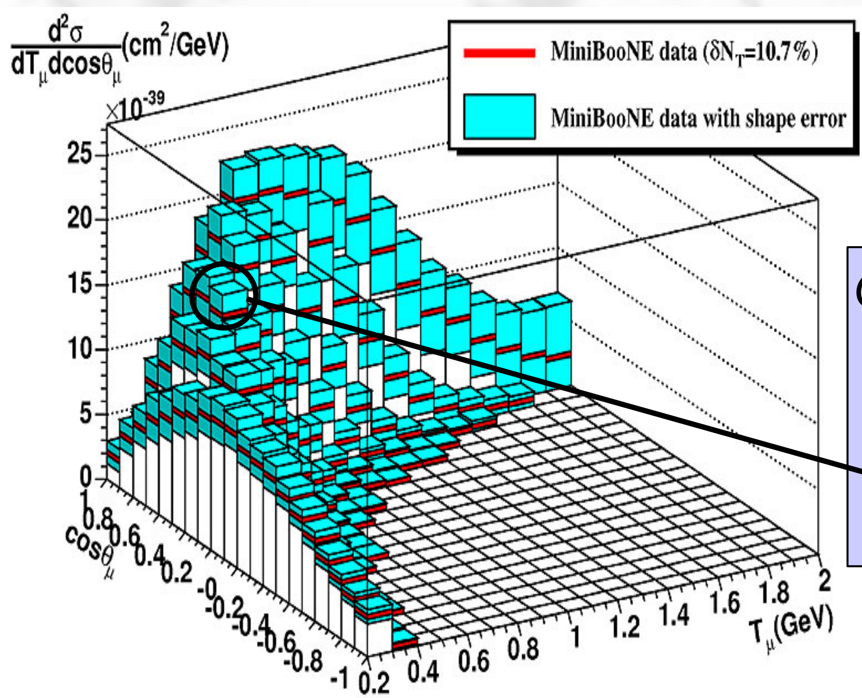



# General Comments on Measurements of Neutrino Interactions and Their Interpretations

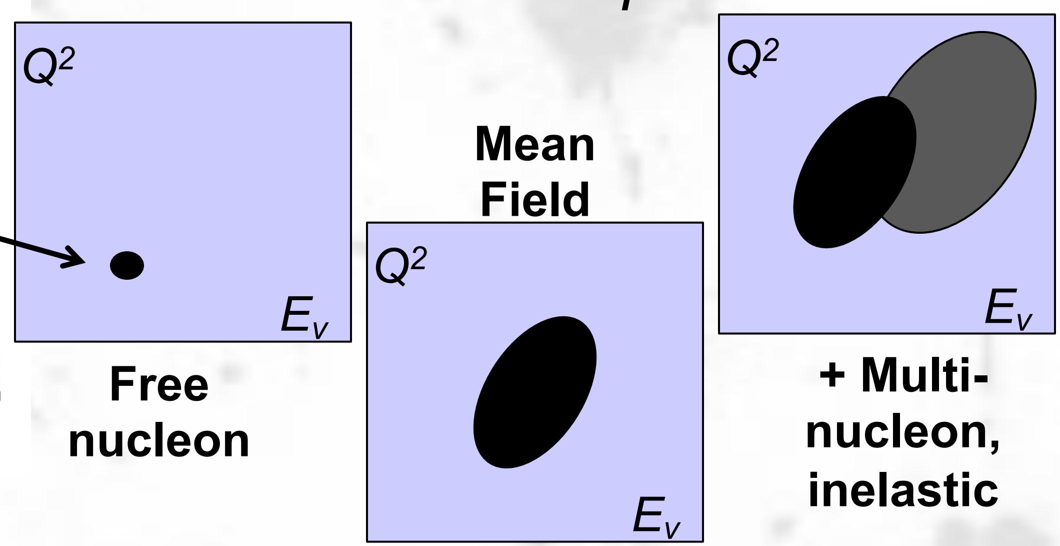
# *Importance and Limitations of Model-Independent Data*



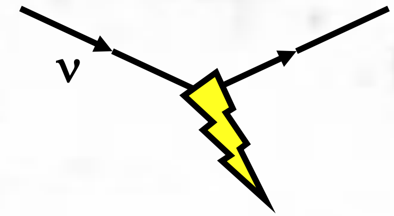

- MiniBooNE pioneered, and the rest of the field adopted, procedures for producing "model-independent" results.
- Meaning that they can be precisely compared with models.



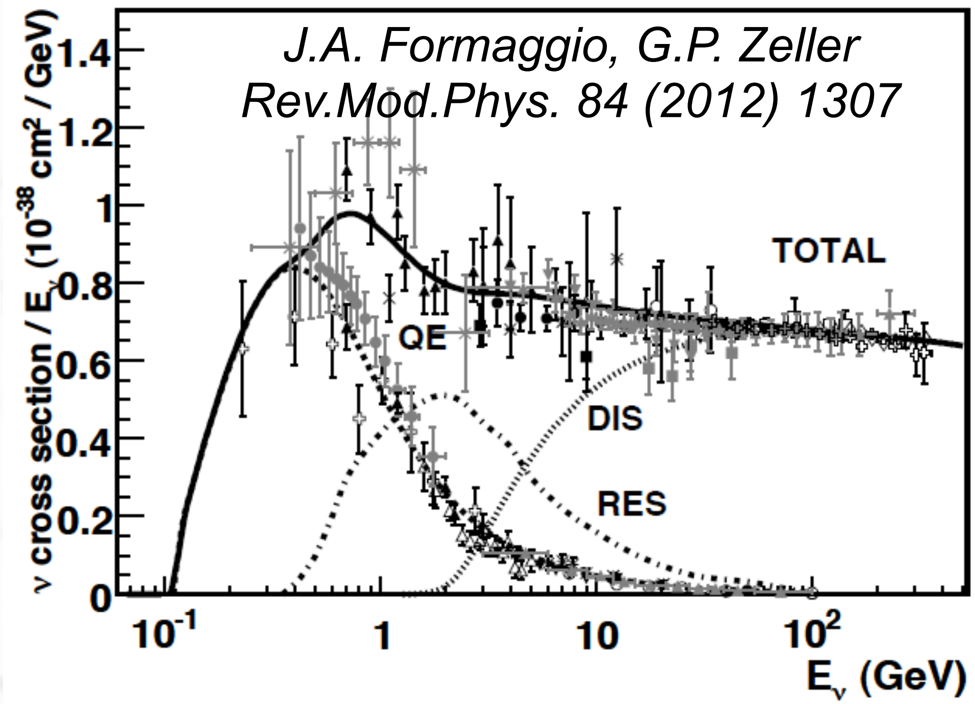

- *But inference of energy and momentum transfer information is not model independent.*



# *With that in mind, consider this plot we've all seen…*

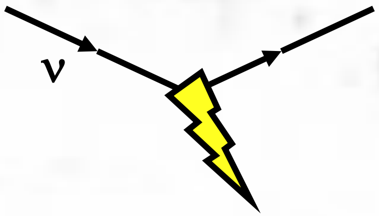



- What is this "data"?
  - At high energies, hadron multiplicites are large and can measure $E_{\nu}$ from "average" final state
  - Some of the "QE" data is on deuterium, a nearly free nucleon, where $E_{\nu}$ is well defined.

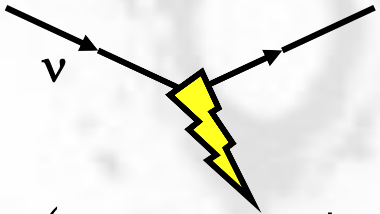



- But with those exceptions, this plot doesn't show measurements. It shows some model's interpretations of measurements.

# Leptons are Special



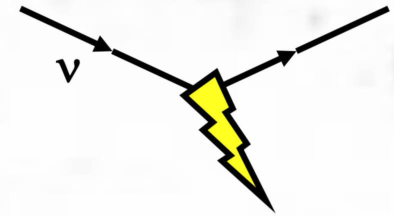

- Lepton measurement is special, even in very high performance detectors
  - Not subject to vagaries of hadronic final state response or hadronic physics
  - Easier to calculate
  - We will always want to know about relationship of lepton to incoming neutrino



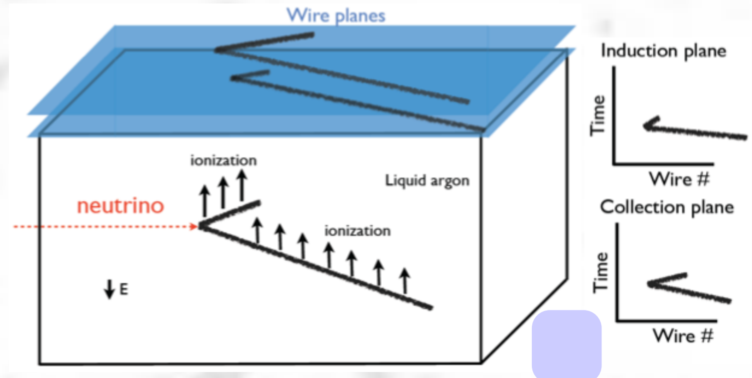

$$\left(E_\nu - E_\mu, \left|\vec{p}_\nu - \vec{p}_\mu\right|\right)$$

- For experiments using recoil information, want details and correlation with lepton response
  - Individual final states, calorimetric response, etc.

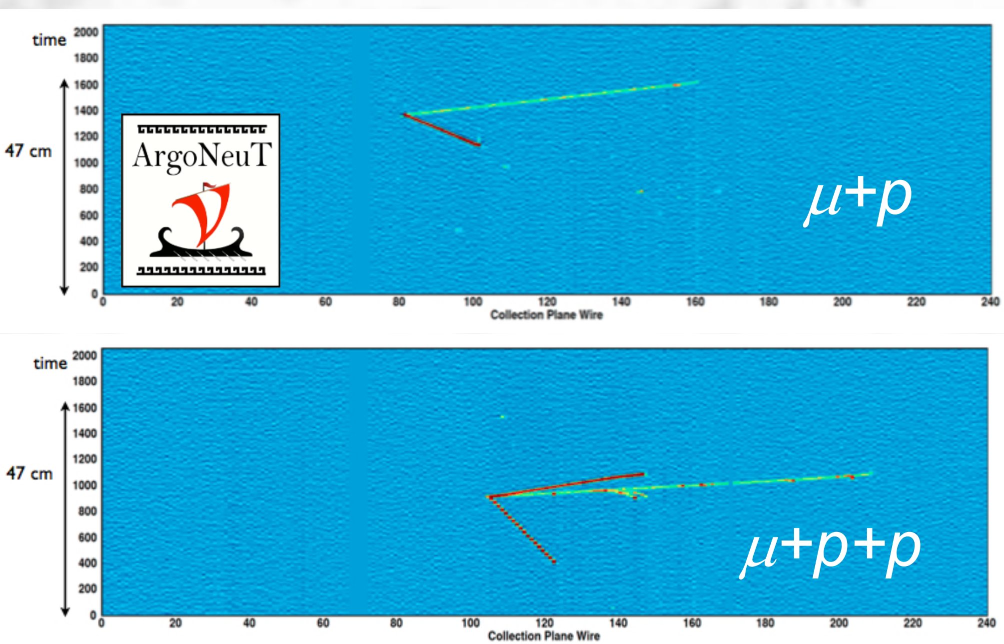
# *And the details of the final state are priceless…*




- Liquid argon has excellent resolution for final state
- Example: ArgoNeuT, a small liquid argon TPC test in NuMI beamline

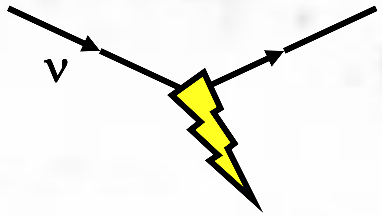



J. Spitz, arXiv: 1009.2515v1

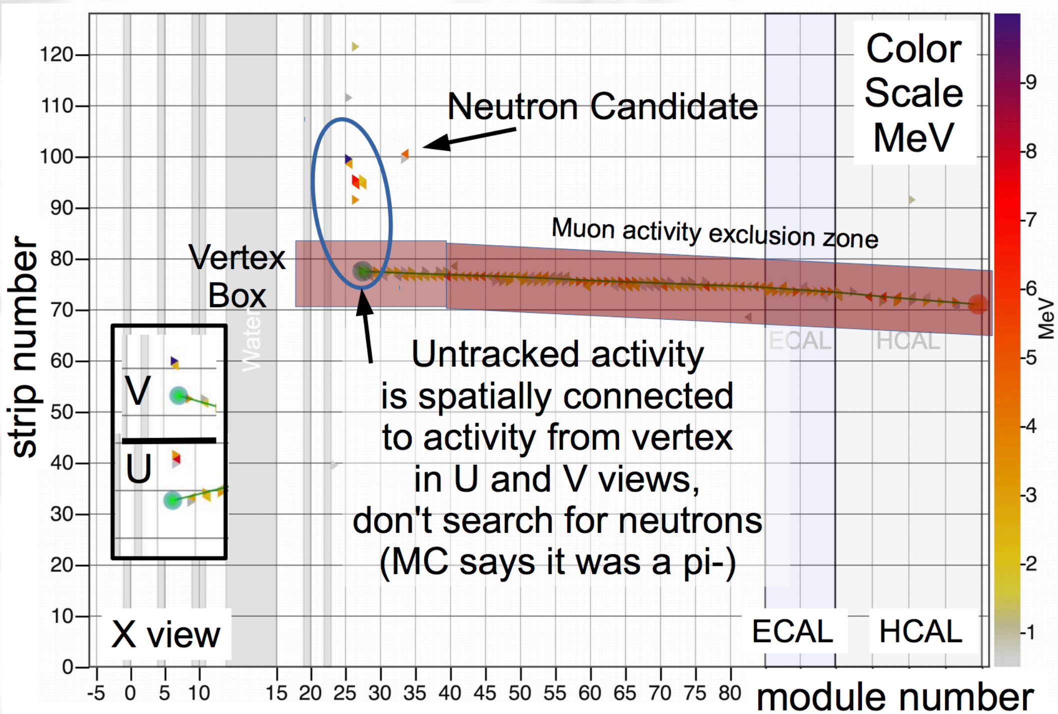



- Provides samples of events with multiple nucleons
- *Physics goals demand methods to separate final state interactions from initial state multi-nucleon correlations*

# But seeing the details might require multiple techniques

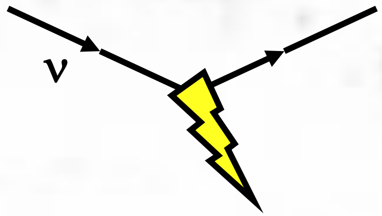



- It's difficult for slow LAr TPCs to find neutrons which interact far from other particles, particularly in the presence of pile-up.
- But that's not so difficult for fast detector (scintillator) that can use timing to associate the displaced recoil from the neutron, and even time of flight to infer momentum.

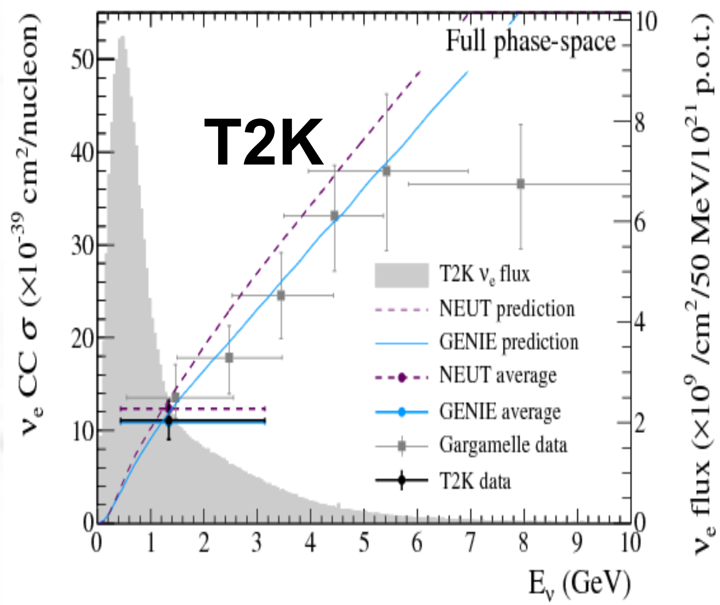



*Phys. Rev. Lett. 120, 221805 (2018)*

# *Another example: electron and muon neutrinos*

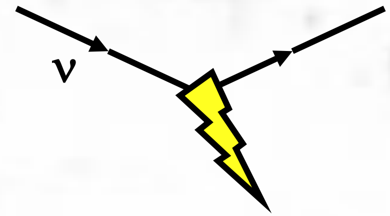



- T2K and NOvA control neutrino beam interactions with and $\nu_\mu$ (and $\bar{\nu}_\mu$), but measure both $\nu_e$ and $\nu_\mu$ interactions.
- The extrapolation is mostly straightforward, except unique phase phase (lepton mass), radiative corrections and other (small) effects.
- Challenging measurement since beam is ~1% $\nu_e$. Require high statistics and low backgrounds.
- Backgrounds will be worse at low neutrino energies.
- Magnetized detectors can directly measure $\gamma \rightarrow e$ fakes via wrong charge.
- Again, a single technology struggles to do this measurement alone.

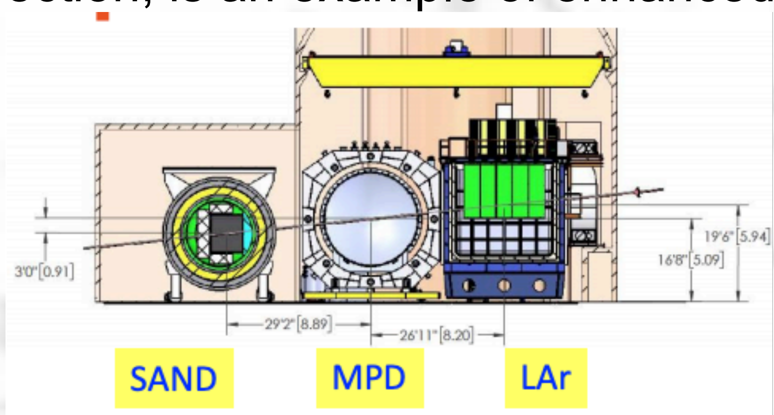


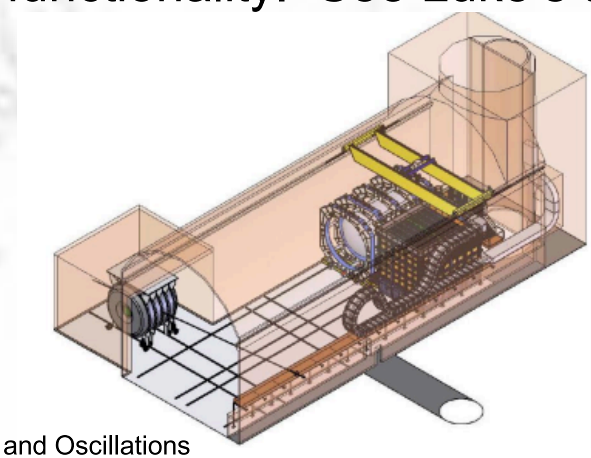

*Phys.Rev.Lett. 113 (2014) 24, 241803, where the e⁺ sample measures $\gamma \rightarrow e^+e^-$ background to $\nu_e$.*

# *And where is this interaction experiment?*

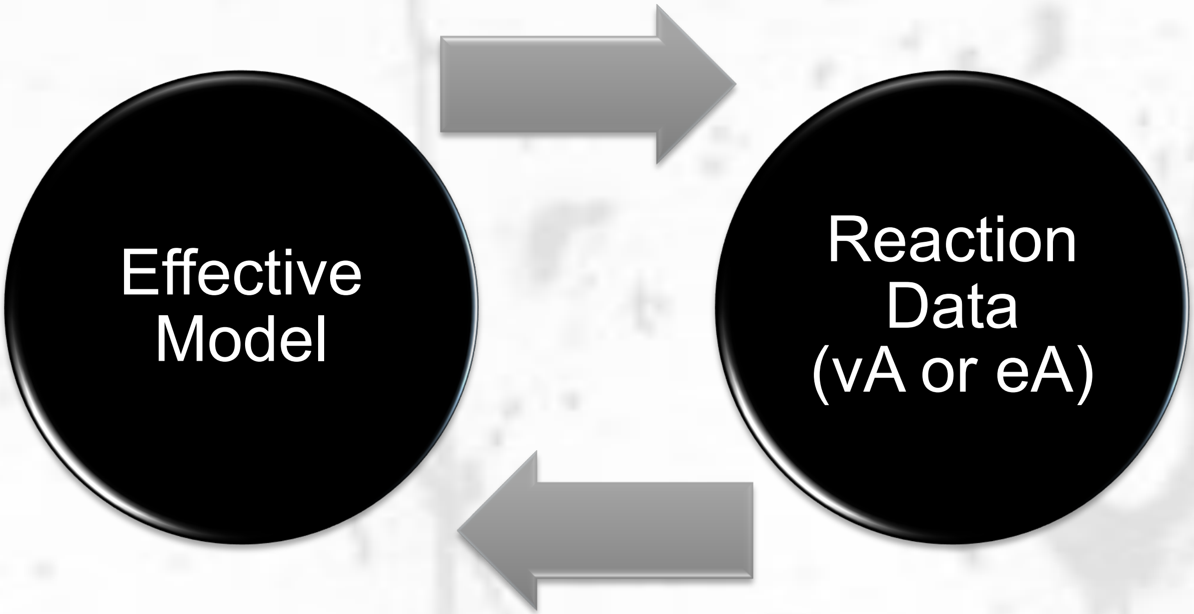



- Does that matter? If it does, we should acknowledge the possibility that the interaction experiment may itself be part of the oscillation experiment's infrastructure.
- The plans for the DUNE "near detector complex" are an excellent example. Because of the many functions beyond measuring an event rate, it is indeed "complex".
  - The "PRISM" capability, another way to separate flux and cross-section, is an example of enhanced functionality. See Luke's talk.



# *How Interaction data is Used*



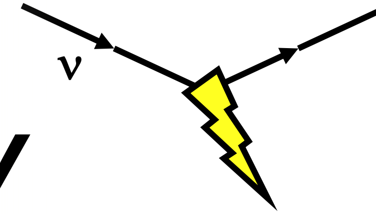

- Necessary because data can’t measure full phase space
- Iterative process, using data to improve models
- Models are usually effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions or limited kinematic reach.

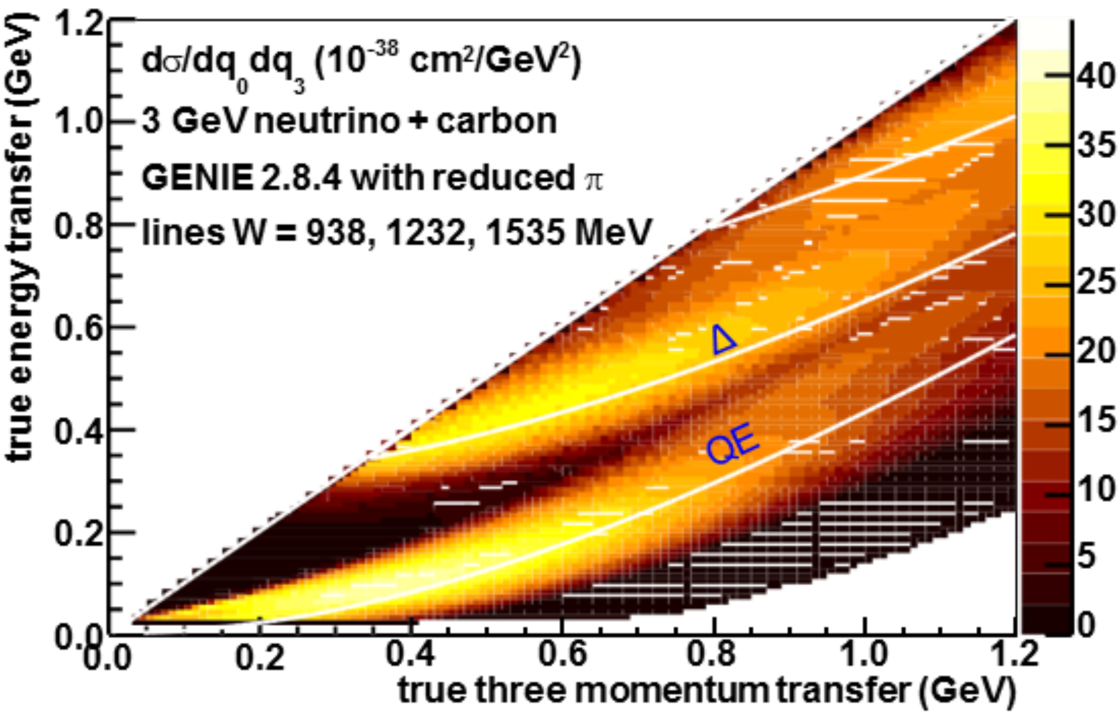
# *Improving Models by using Data is not Automatic*

- Treatments for modeling cross-sections vary in different oscillation experiments
  - Experiments are individually learning how to join effective models with constraints on data to produce uncertainties
  - A global generator effort like GENIE needs to draw contributions from these many sources
- Similarly, we need to do better to bring best models into generators used by experiments
  - Not even half as easy as it sounds.
  - Models are rarely “generator ready” because they are semi-inclusive or cover limited kinematics.

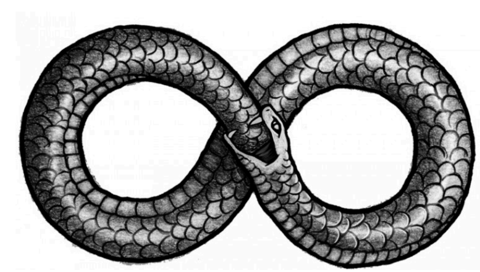
# *The Canonical Example…*
# *Multinucleon Effects at MINERvA*

# *What we'd measure if we knew initial neutrino energy*



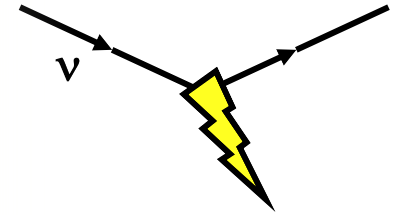




To do this in neutrino scattering, we have to use the final state observed energy since we don't know incoming neutrino energy.



*(See Kendall's talk on how electron scattering, which has this advantage, helps)*

# *Since we don't know neutrino energy…*




- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.
- *MINERvA uses calorimetry for all but the final state lepton*
  - *Don't measure energy transfer, $q_0$, but a related quantity dependent on the details of the final state, "available energy"*

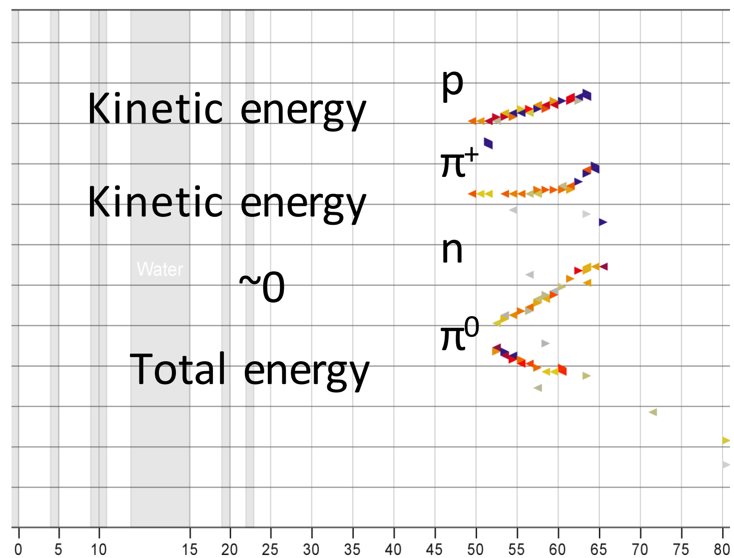
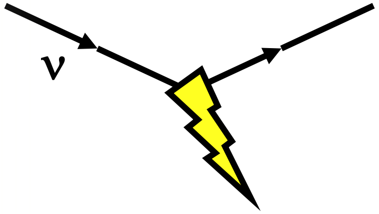
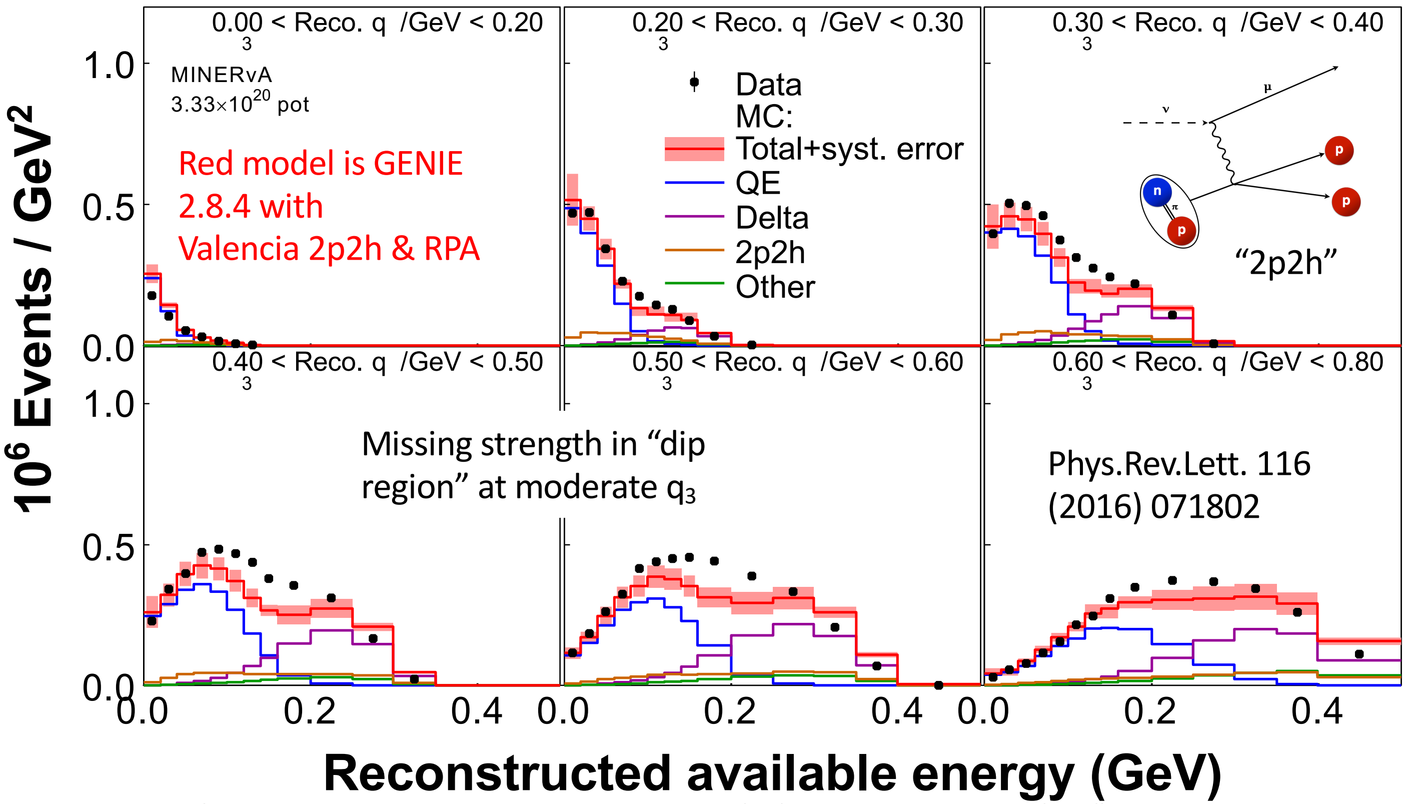



Figure courtesy P. Rodrigues

$$E_{avail} \equiv (\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{E of other particles except neutrons})$$

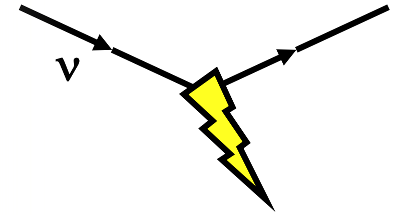
# *Missing moderate $|q_3|$ "Dip Region"*



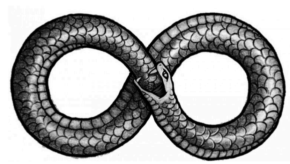




- Nieves 2p2h & RPA model added to GENIE prediction used by MINERvA.
- But it doesn't provide enough strength at moderate $|q_3|$.

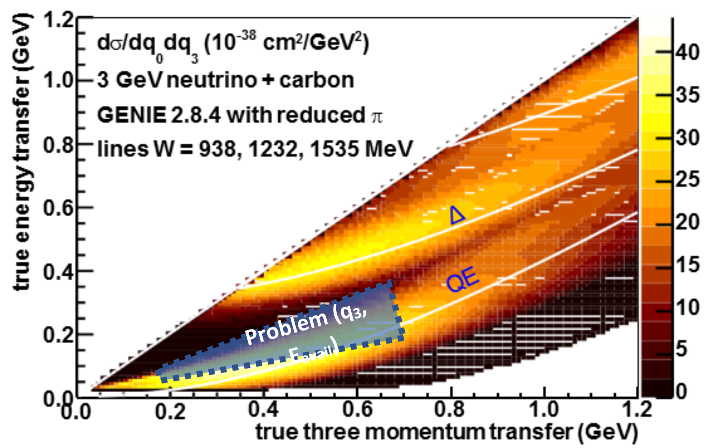
# *What can we do to fix it?*




- Identify the sources in this type of measurement is a problem.

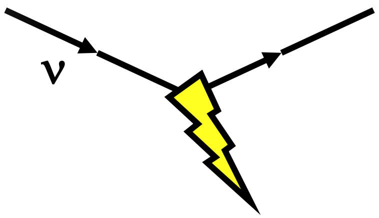


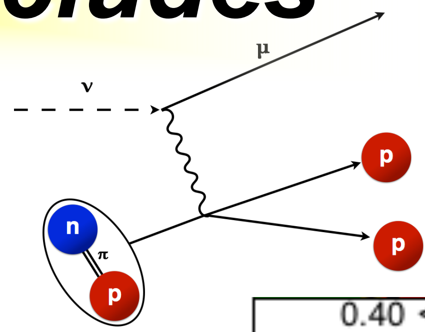
- But in this kinematic region, there are only so many possible contributing processes.



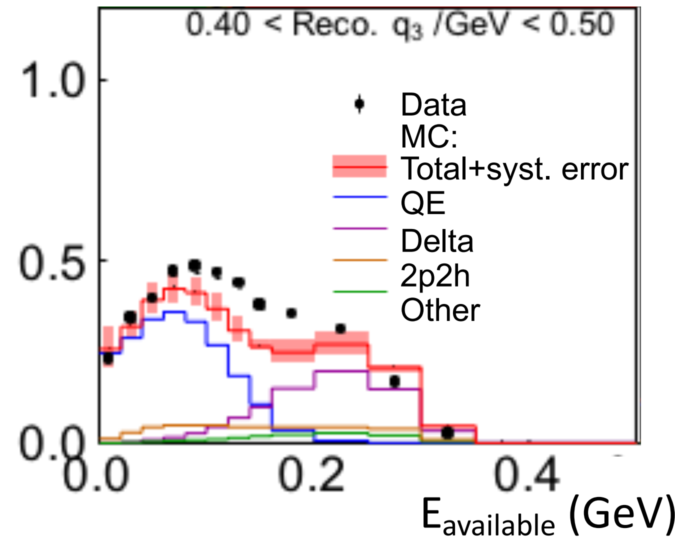

$E_{\text{avail}} \approx q_0 \underbrace{- \Sigma T_n - \Sigma m_{\pi^\pm}}_{\text{need \textasciitilde 200 MeV to migrate from } \Delta}.$ So, QE and 2p2h.

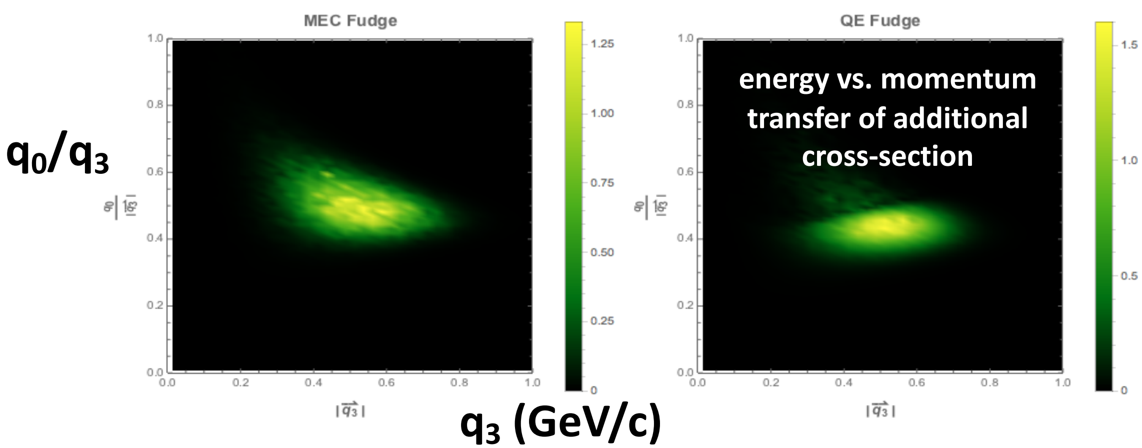
# What MINERvA concludes



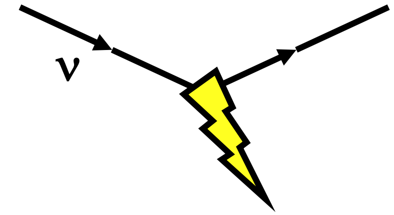




- MINERvA's low recoil data identifies missing strength, but it doesn't identify if $\nu_\mu A(n) \rightarrow \mu^- p A'$ or $\nu_\mu A(nn) \rightarrow \mu^- p n A'$ or $\nu_\mu A(np) \rightarrow \mu^- p p A'$ is the most likely source.
  - Different choices mean different $E_{\text{avail}}(q_0)$.
- Default tune augments ratio of 2p2h nn/np initial state as per Nieves' model of 2p2h.

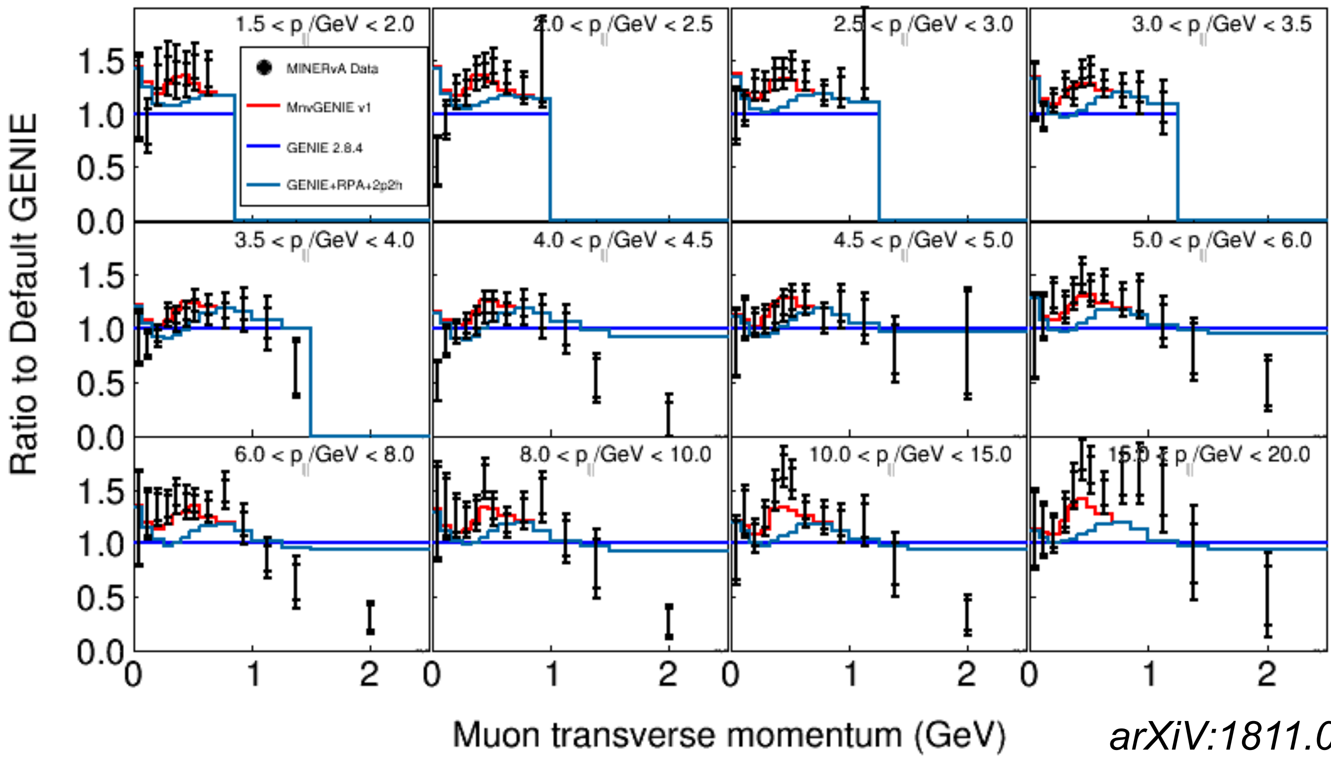


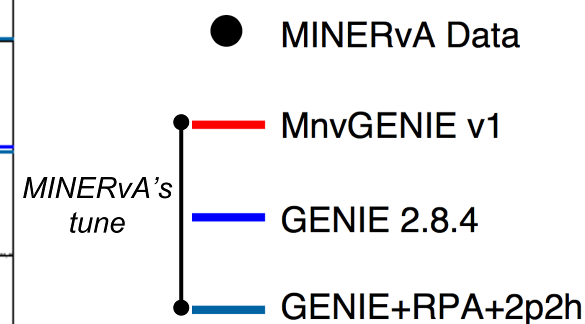
# MINERvA ν pionless events (CC0π)




- Tuned vs untuned in an exclusive channel

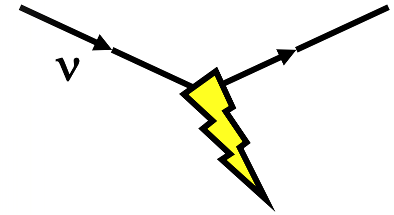



$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\|}} \quad \boldsymbol{\nu}$$



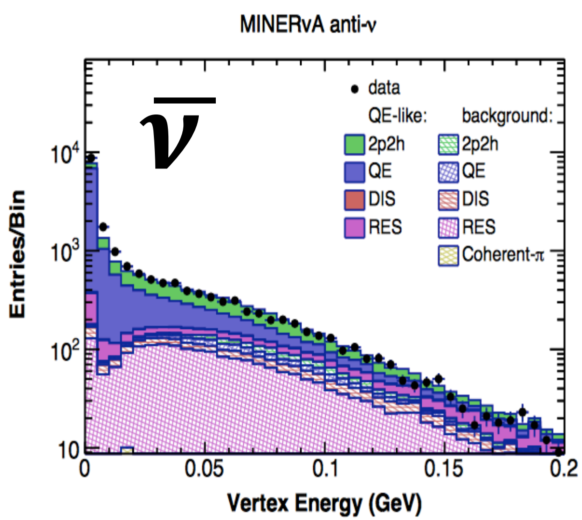

*arXiV:1811.02774*

# *Low energy protons in CC0π events*

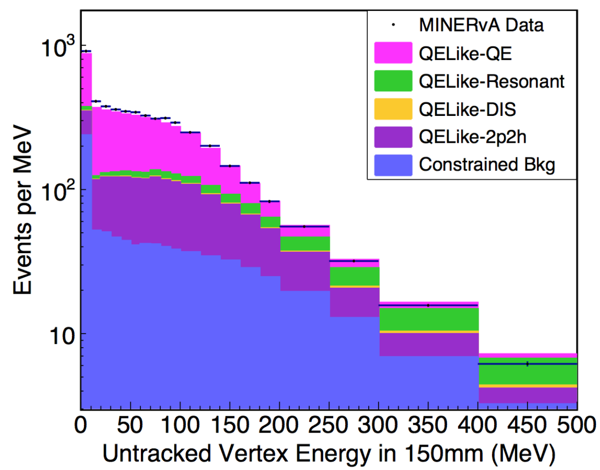


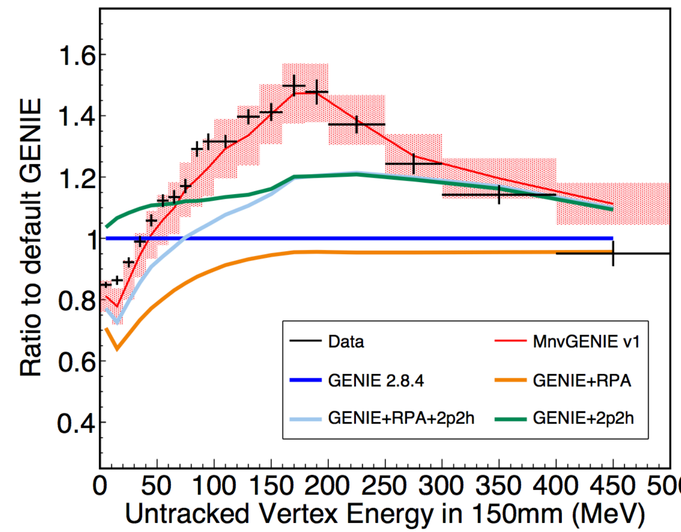

- Does this tune get details right, like energy from protons below tracking threshold ("vertex energy")?

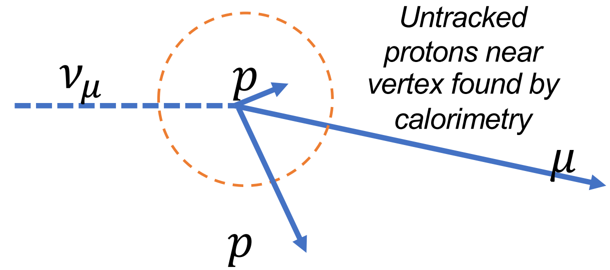
$\bar{\nu}$




$\nu$



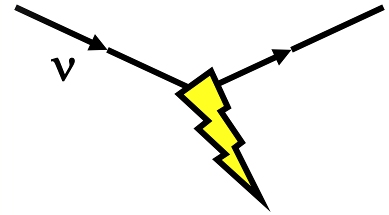



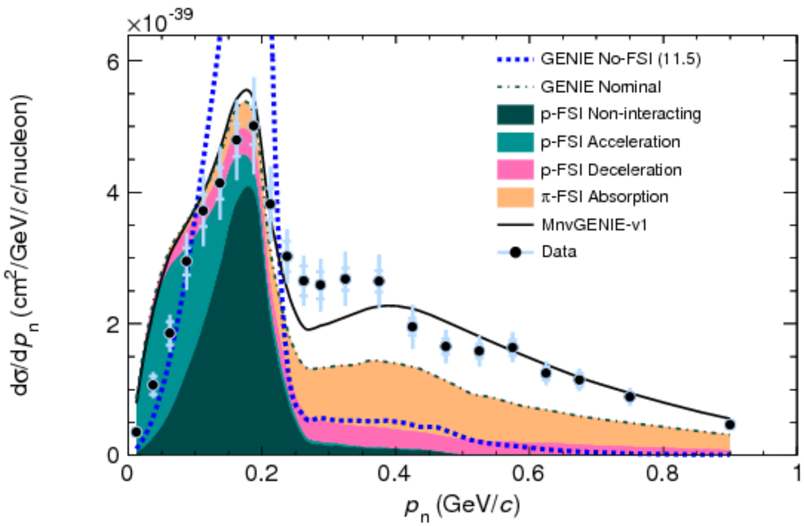




*Untracked protons near vertex found by calorimetry*

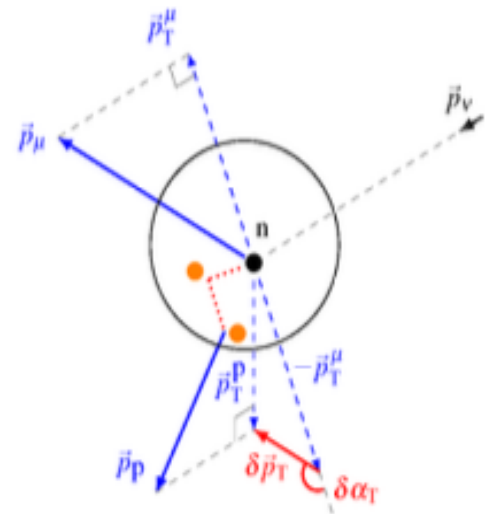
*Phys.Rev. D97 (2018), 052002 and arXiV:1811.02774*

# *Initial State and Final State in CC0π w/ proton*




*Phys. Rev. Lett 121 022504 (2018)*

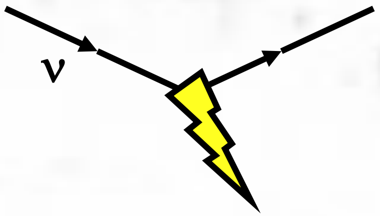



*Neutron momentum under exclusive μp hypothesis*

- MINERvA 2p2h tune helps with the tail!
- But by studying reconstructed neutron momentum and transverse variables in CC0$\pi$ events, we have evidence for deficiencies in the initial and final state models. (The most glaring is an FSI bug in GENIE, since fixed.)

# Lessons learned…

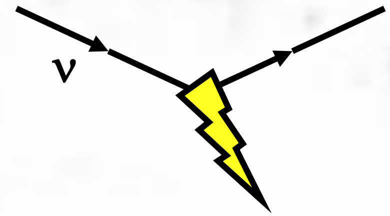
- MiniBooNE, the first to observe hints of the effect, didn't have access to sufficient observables to identify the source.
- Even a capable detector (MINERvA) required many complementary observables in the same events to reach a convincing understanding.  Capabilities matter, as does the creativity to find those observables.
  - Developing those observables was a collaboration between oscillation and interaction experiments, as it turned out.
- NOvA has used similar methods to derive a similar tune.
  - Maybe it's helpful that some key NOvA contributors were trained on a neutrino interaction experiment?
- T2K, interestingly, has not… perhaps because of energy dependence.  But the possibility of distortions of the multinucleon model is incorporated in their analysis.




# *Conclusions*

# What will the future needs be?

- Probably I don't have an accurate crystal ball, but…
- Energy lost to neutrons, which is different for neutrinos and antineutrinos, will be critical.
  - Current program will make some progress here.  Maybe not enough though because of the need to measure on argon for DUNE.
- Doing a similar analysis for the single pion low W region as was described here for ~elastic will be necessary.
  - Lower energy experiments (SBND?) may have an advantage because of the small feed-down from high W, which is a problem at higher energies for pion production./
- Electron and muon neutrino interaction differences.
  - At high precision, may require a program to study directly?
  - Or indirectly through auxiliary measurements of proxy processes to validate the theory behind small differences from nuclear effects, radiative corrections, etc.




# The End of the Affair

- Neutrino interaction measurements, wherever they are done, play a critical role in validating details of interaction models.
- Whatever the specifics, they play this role by exploiting capabilities not needed in extrapolation from a near to far detector.
- Even if infrequently, oscillation experiments are likely to be compelled to sometimes "swipe right" to accomplish their goals.

A. RIMBAUD

UNE

SAISON EN ENFER

PRIX : UN FRANC

BRUXELLES

ALLIANCE TYPOGRAPHIQUE (M.-J. POOT ET COMPAGNIE)

37, rue aux Choux, 37

1873

*Rimbaud's symbolist prose masterpiece, written while Verlaine was spending two years in prison for shooting him.*