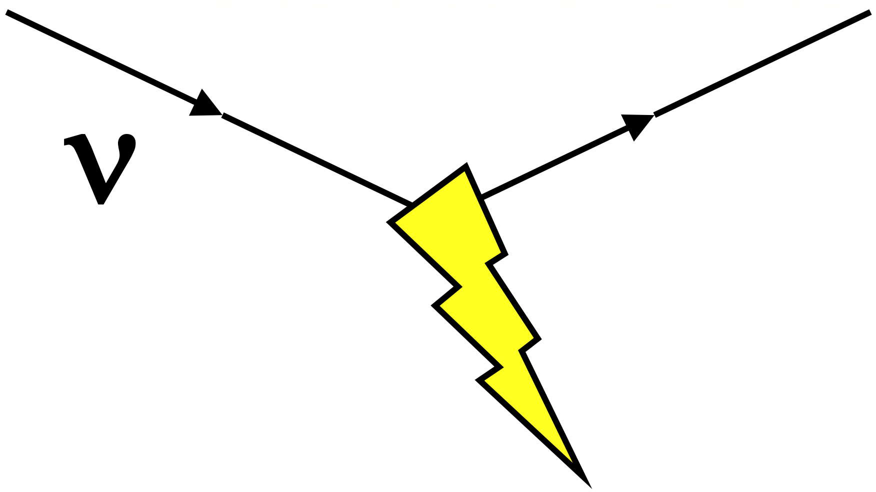
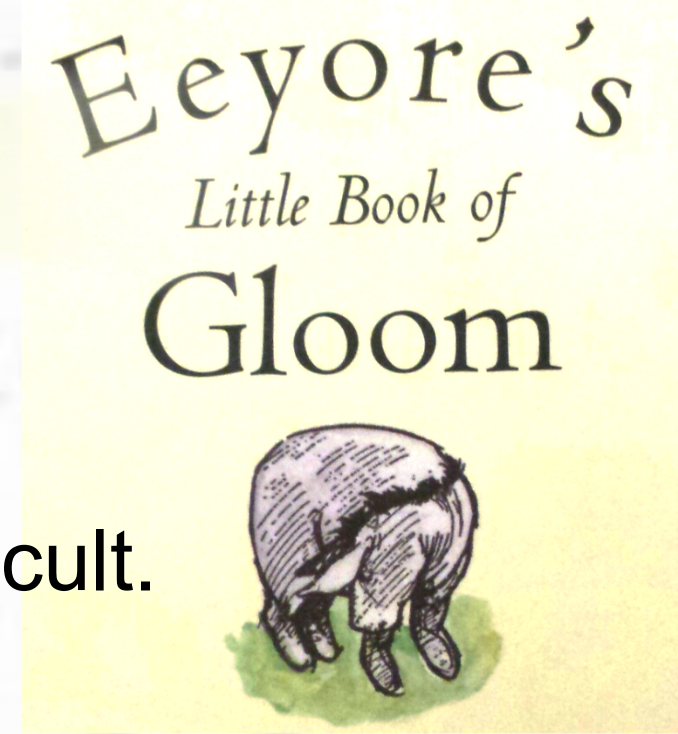
Experimental Progress in Neutrino Interactions



Kevin McFarland
University of Rochester

27 September 2017
NuFACT 2017 Uppsala

Outline

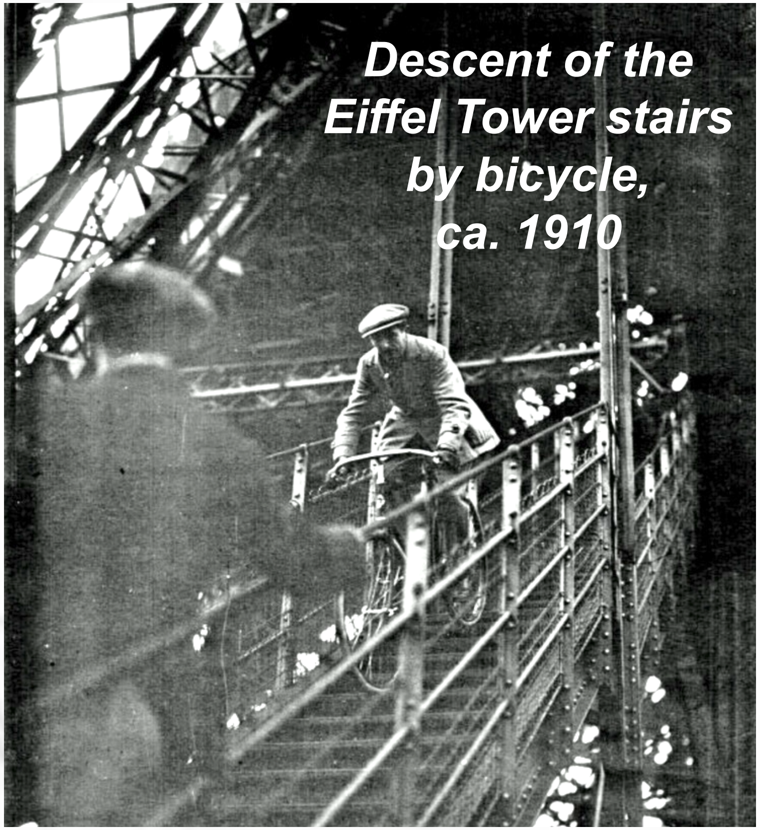


- ?? Famously pessimistic Kevin said "progress"!??
- Why progress has been difficult.
- Why progress is necessary.
- Tools for progress: theory, electron scattering and neutrino scattering
- Neutrino experiments that make progress.
- Highlights of progress.
- Did I mention progress?

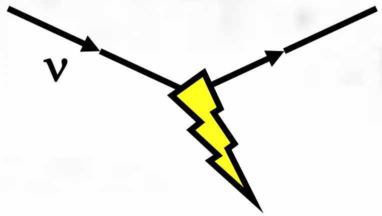
Progress is Difficult, but Necessary

Difficult 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



- *But since the wheel size is too close to the step size, all we know is that it is going to be painful.*

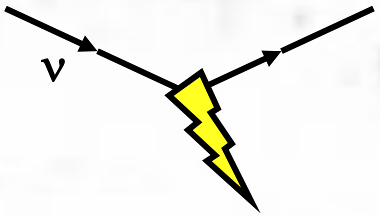


Failed Multi-Scale Problem

- Similarly, we have $E_\nu \sim 300 - 5000\ GeV$, $m_\Delta - m_N \sim 250\ MeV$, $E_{\text{Binding}} \sim 30\ MeV$ in ^{12}C
- Nuclear response at these neutrino energies spans elastic, quasielastic and inelastic
- And even the last two cannot be cleanly separated since the effect of binding of nucleons cannot easily be factored from inelastic excitations of nucleons

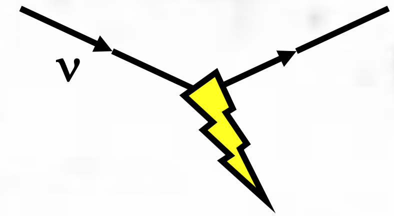
- *Exact prediction of nuclear response becomes akin to equation of motion for the system at the right if energy required to uncouple springs is comparable to energy required to break them.*

A Problem Hidden in Plain Sight for Neutrino Experiments



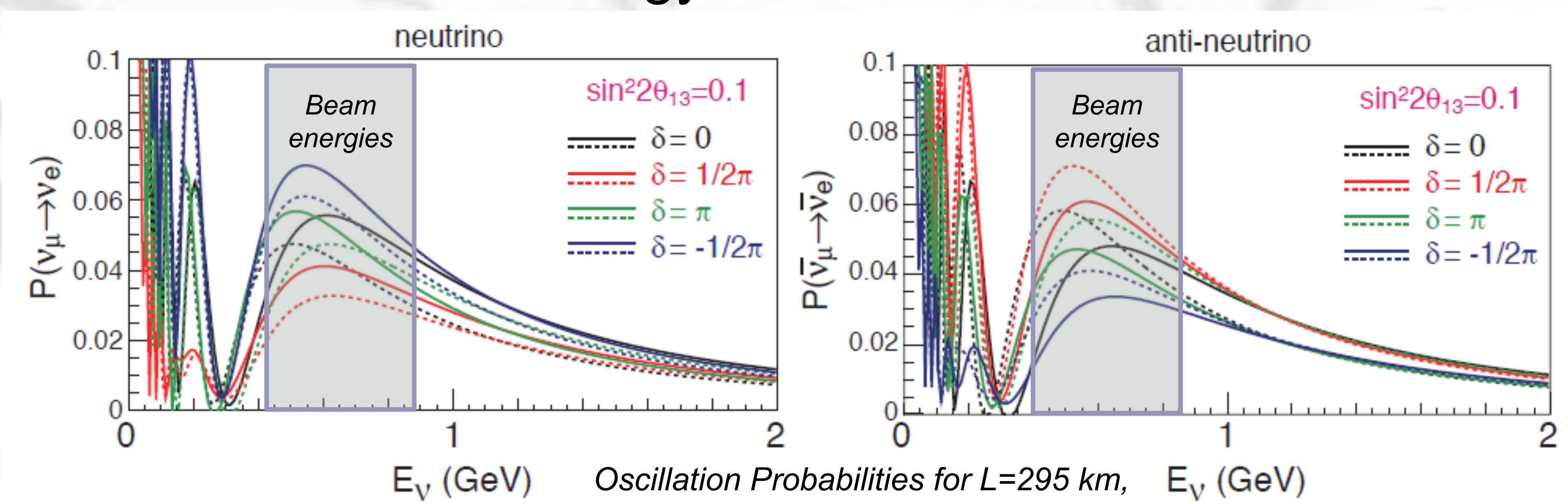
- What do we do when confronted with a problem we can't solve? We ignore it!
- This community started with modeling of neutrino interactions that was too naïve to support the precision needed for future experiments.
- People who had confronted charged lepton scattering data for decades told us what we were facing.
- Gradually, and painfully, we have learned to listen…

Artist Liu Bolin, imitating the nucleus?



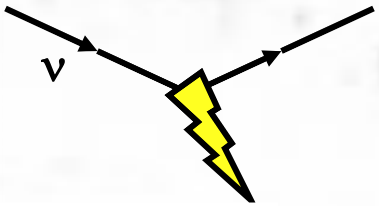
Necessary: Energy Reconstruction

- Neutrino oscillation measurements require measurement of neutrino energy to determine oscillation probability.
- Even "narrow band" neutrino beams have an energy spectrum width that can't be ignored.
- Must estimate energy from the final state.



Oscillation Probabilities for L=295 km, Hyper-K LOI

Necessary: Energy Reconstruction



- Now consider the effect of multinucleon (2p2h) processes on energy reconstruction from leptons as in T2K and HyperK.

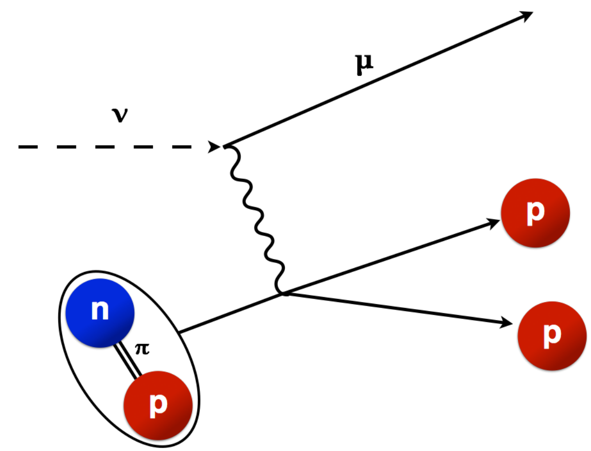
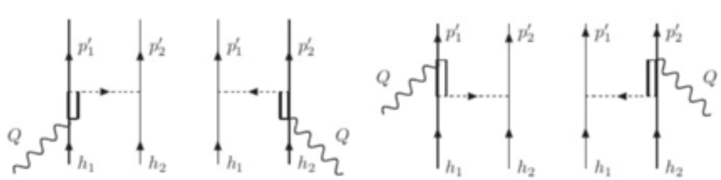
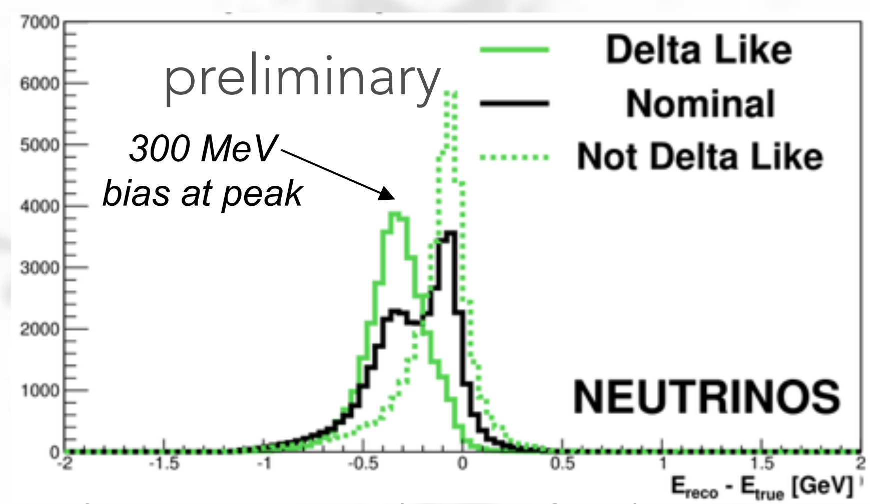


Figure from M. DelTutto (Tues, WG2)

Pair Correlation

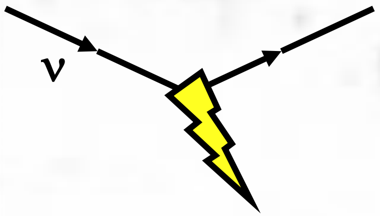
Delta absorption



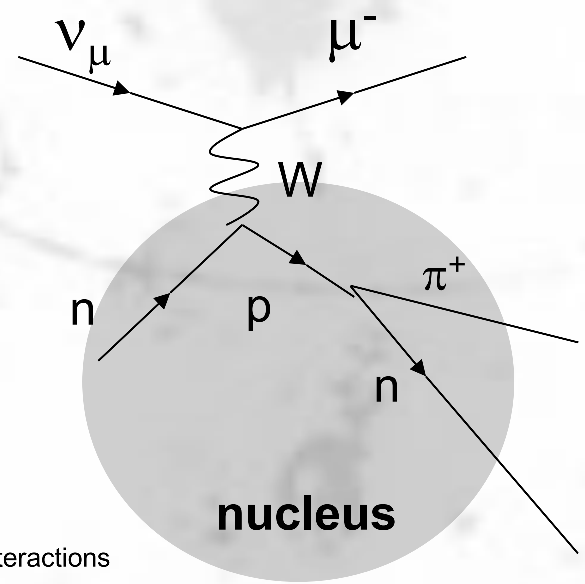


Figures from K. Nakamura (Tues, WG1+2)

Necessary: Final States

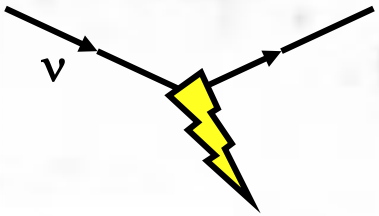


- Neutrino event selection is rarely inclusive
  - T2K selects events without visible pions in the final state, and that veto is nearly 100% efficient for π^0.
  - NOvA requires lepton energies large enough to identify muons and electrons efficiently among hadrons.
- Final state also affects energy reconstruction in some detectors (scintillator, LAr)
  - Response to neutrons is not the same as to protons is not the same as to $\pi^{\pm}$ is not the same as to π^0…
- Now consider modification of the final state in the nucleus.
- This must be understood.

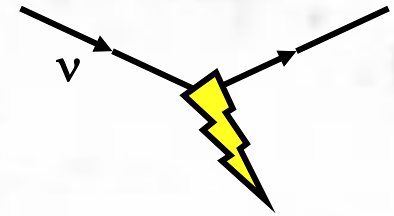


Tools for Progress

Tools: Theory



- Arguably our most important tool, my comments about the difficulties not withstanding.
- Luis Alvarez-Ruso will summarize status.
- Suffice it to say that it is difficult to create reliable theory on nuclei over the full range of targets, kinematics and final states relevant for oscillation experiments.
- And consequently, framework for interpretation of data is incomplete. The results of incorporating new neutrino data are not always predictive.
  - One might instead learn about failings of the model.

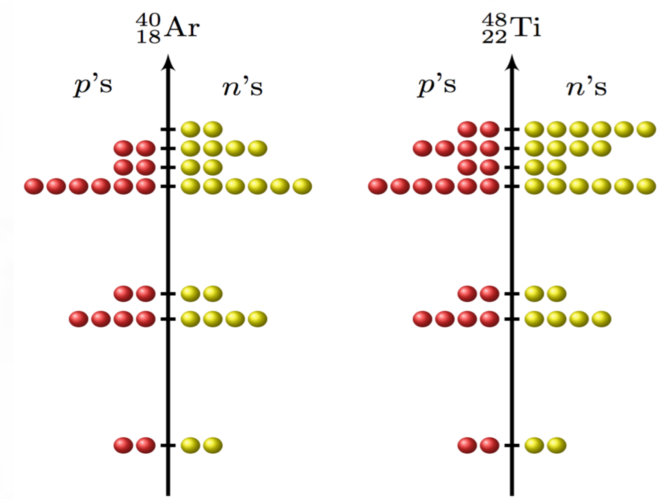


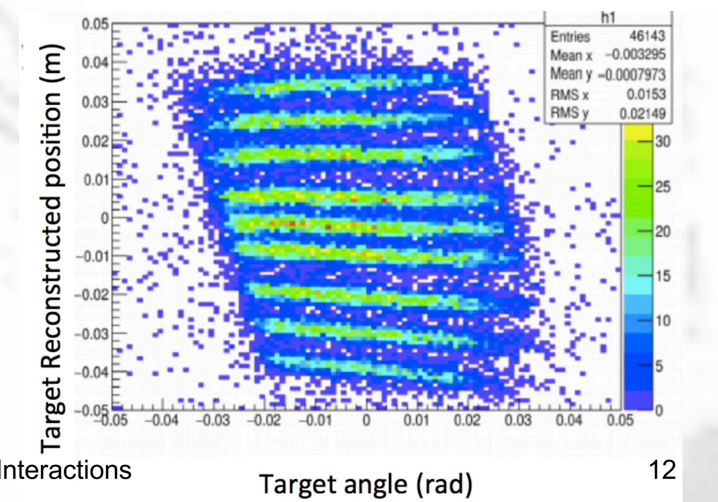
Tools: Electron Scattering

- There is a wealth of information available from electron/muon scattering experiments which cannot be matched with neutrino data.
  - Helpful for common effects, e.g., disappearance of energy into nucleus (spectral function), final state interactions
  - But weak CC and EM NC are fundamentally different.
    - o New form factors
    - o Charge change (isospin rotation)
- New data arriving!

JLAB-E12-14-012

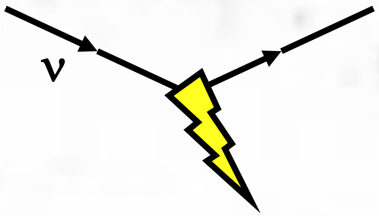
$$e + A \to e' + p + (A-1)$$





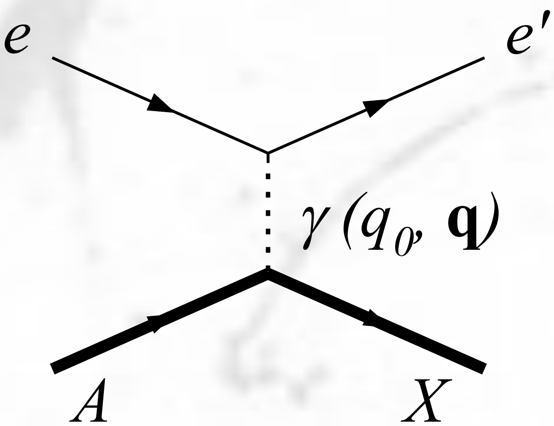
Tools: Neutrino Data

- Neutrino data has access to what we need. Just catalog reactions! But…
  - Experimentally challenging to get a capable detector and high statistics
  - Most neutrino sources (not NuSTORM or other muon decay source) are ν_μ but also need ν_e.
    - o Theory will get us most of the way there, but need to cleanly separate lepton mass parts of cross-section and reactions in phase space missing for muon neutrinos
    - o An open question is how much more we would learn from NuSTORM and what systematics are without it. Needs work!
    - o E.g., M. Day and KSM, Phys. Rev. D 86, 053003 (2012) works this out for CC elastic on free nucleons.

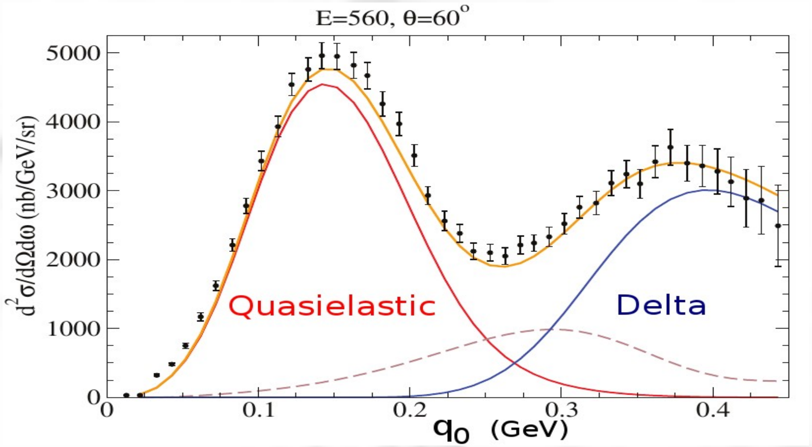


Tools: Neutrino Data

- Biggest limitation is flux.
  - As Alex just told us, flux as a function of energy may not be well constrained, despite *in situ* and *ex situ* work.
  - But even if flux as a function of neutrino energy is understood, still don't have event-by-event neutrino energy.
- This is trouble.
- If we had a tunable, high rate source of monochromatic neutrinos, we would repeat single arm electron scattering experiments and measure nuclear response.

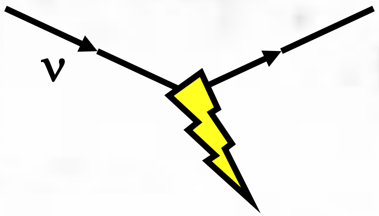


Adapted from G. D. Megias, NuFact 2015

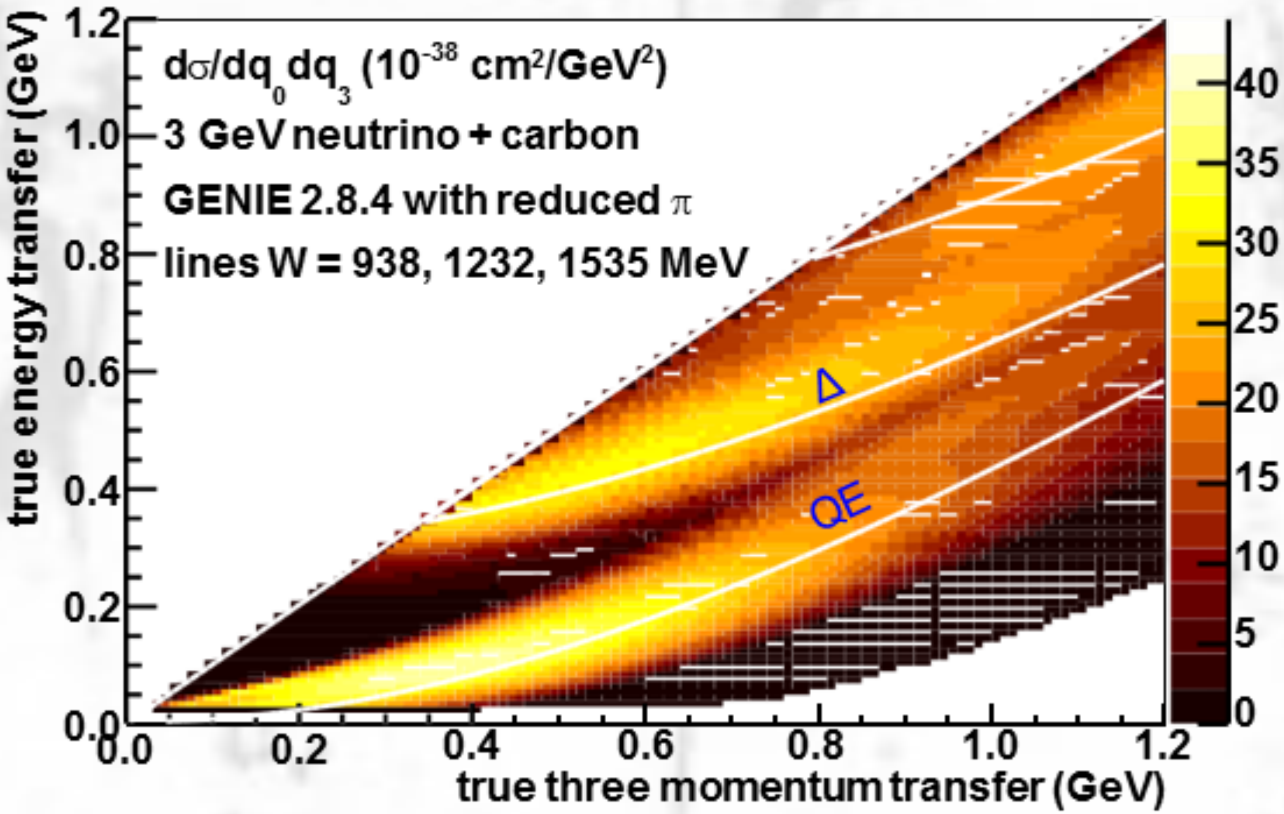


$q_0 = E_e - E_{e'}$

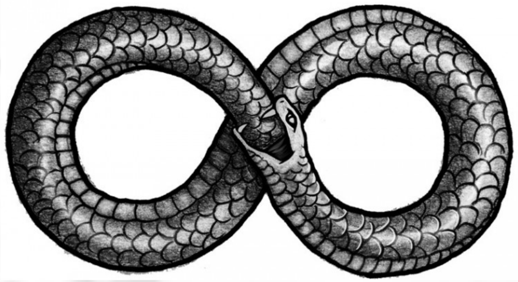
Tools: Neutrino Data



- More precisely, since single arm experiments would be wasteful ☺, we would measure these distributions of energy and momentum transfer.

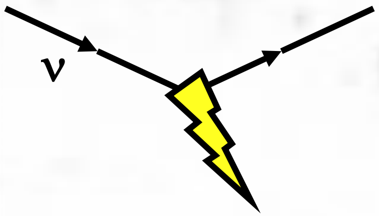


Unfortunately, we cannot do this without reference to the final state of the neutrino interactions to measure neutrino energy.

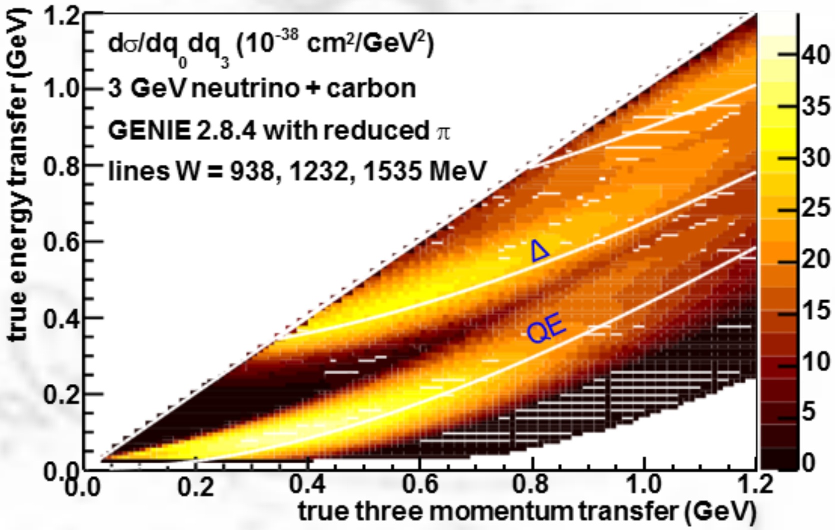


Neutrino Experiments that are Making Progress

First a Comment about Neutrino Energy



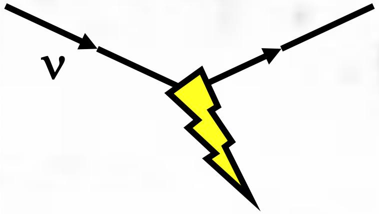
- Neutrino energy is not the most important criterion of usefulness of a data set, as long as the reaction(s) of interest are accessible
  - Response of the nucleus for a given final state is given by energy and momentum transfer. Not neutrino energy*.



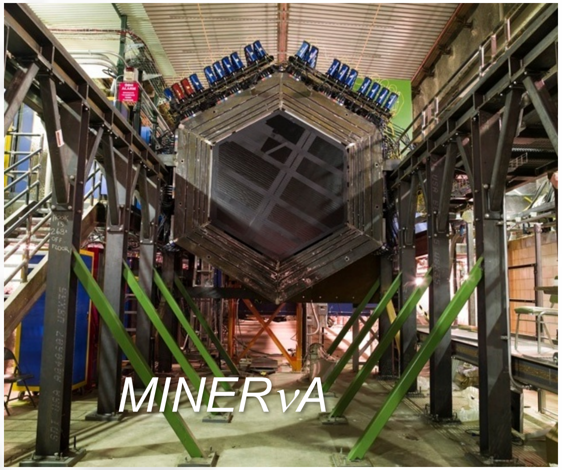
- Ability to measure a final state, get good statistics and measure kinematics are much more important.

** near q_0 boundary, lepton mass effects become important. Often predictable.*

Current Experiments



- MINERνA: in NuMI at Fermilab
  - Fine-grained scintillator detector
  - Nuclear targets of He, C, H_2O, Fe, Pb
- T2K 280m Near Detector at J-PARC
  - Fine-grained scintillator, water, and TPC's in a magnetic field
- NOνA near detector: running, early results
  - Segmented Liquid scintillator in off-axis beam
- MicroBooNE: running, early results
  - Liquid Argon TPC in FNAL Booster Beam
  - Some data from ArgoNeuT, a test in NuMI



Strengths and Weakness of Experiments *(warning: opinions)*

- MINERvA. Strengths: established and publishing on high statistics sample. Multiple nuclear targets in same beam. ν-e scattering for flux. Neutron reconstruction. Weakness: wideband w/ flux puzzles. relatively high tracked/IDd particle thresholds (T_p>90 MeV, T_π>50 MeV)
- MicroBooNE. Strength: lower particle thresholds (T_p>80 MeV, T_π>35 MeV done, hope for factor of 1.5 lower), excellent PID if particles don't hadronically interact. Weakness: statistics >order of magnitude lower than MINERvA (SBND will be ~MINERvA), cosmic ray backgrounds.
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- NOvA Strengths: narrow band beam, albeit with some flux worries, factors of two better statistics than MINERvA, neutron reconstruction?. Weaknesses: higher thresholds than MINERvA, all plastic so containment is not great, "cocktail" not easily compared to other results.

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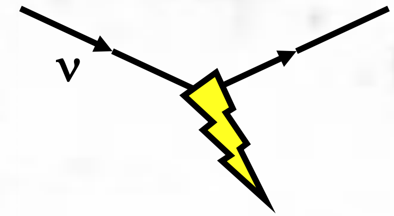

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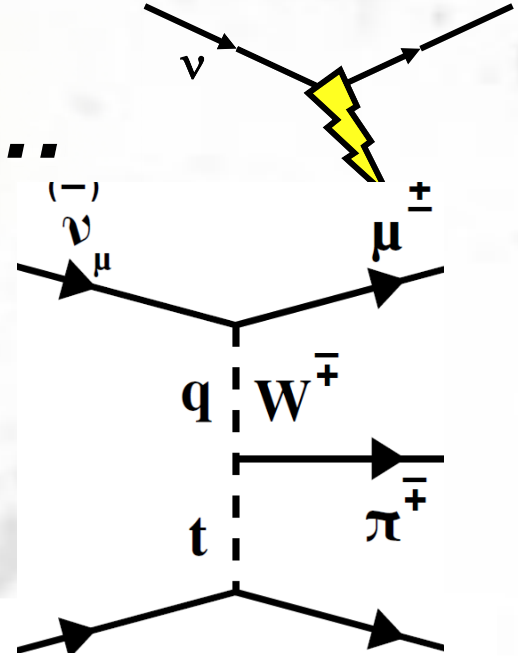
Some Highlights of Progress

Coherent Pion Production

A Very Strange Reaction…

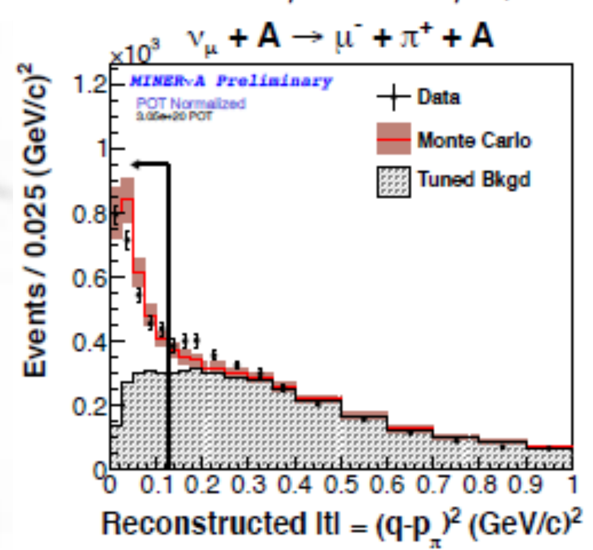


- Despite small binding energy of nucleus (few-10s MeV), a pion can be created from the off-shell W boson and leave the nucleus in its ground state
- Reaction has small 4-momentum transfer, t, to nucleus
- Can reconstruct |t| from final state
- Reconstruction of |t| gives a model-independent separation of coherent signal and background
  - Tune background at high |t|
  - Measure signal
- MINERvA, T2K and ArgoNeuT have all measured this in charged current.

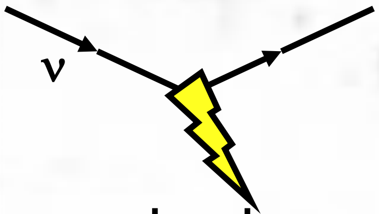
$$E_\nu = E_\mu + E_\pi$$

$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

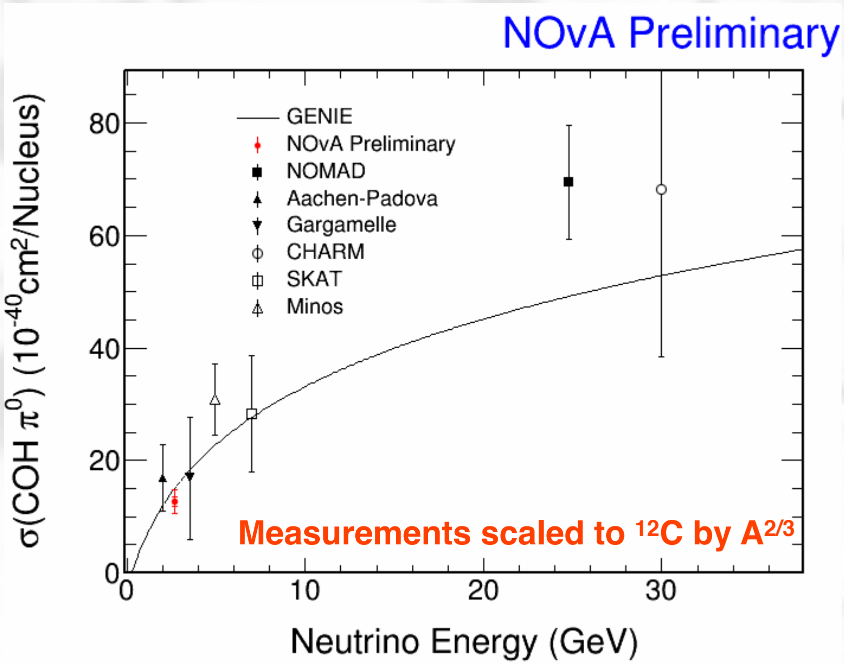
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$



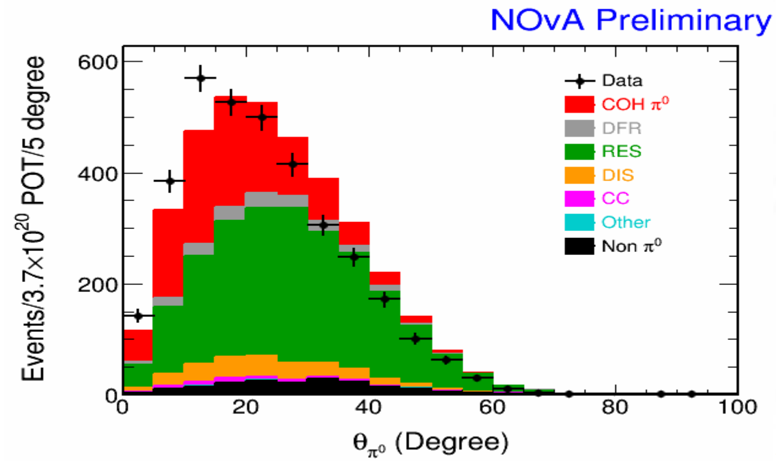
NOvA NC Coherent



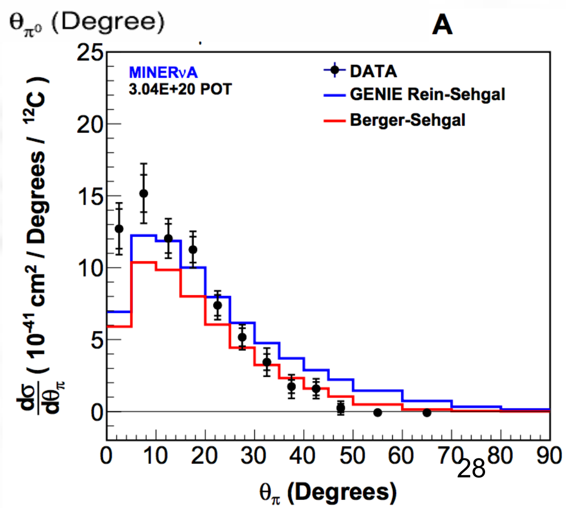
- NOvA has excellent π^0 reconstruction and has searched for this by looking at forward events
- Powerful check of model that works for charged current



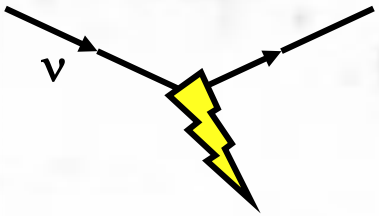
L. Cremonesi, Monday WG2



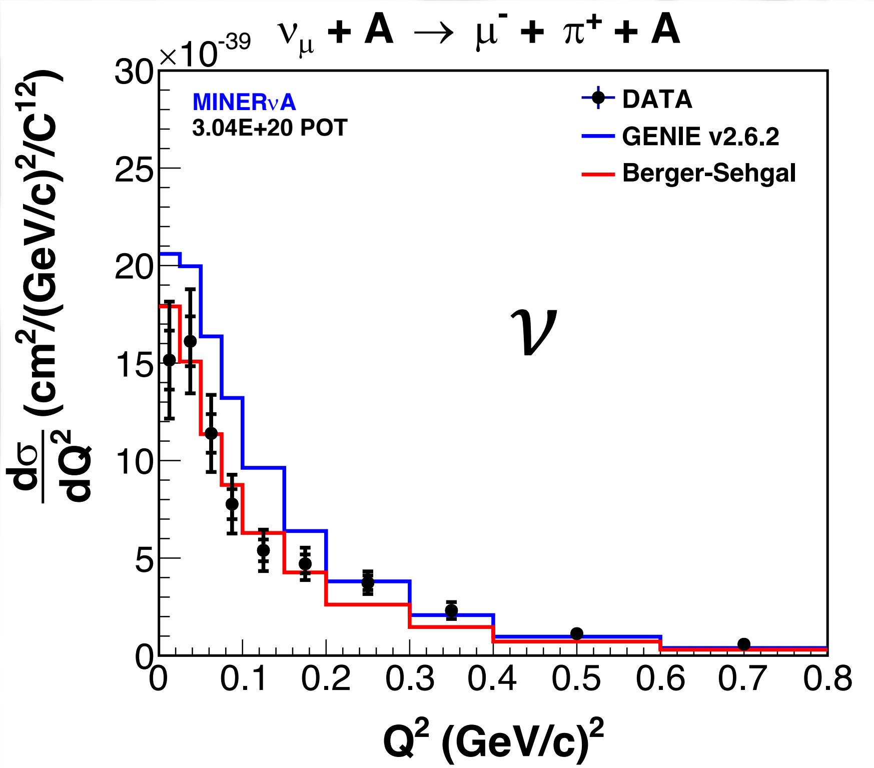
Note that MINERvA sees the similar shift to forward π in charged current!

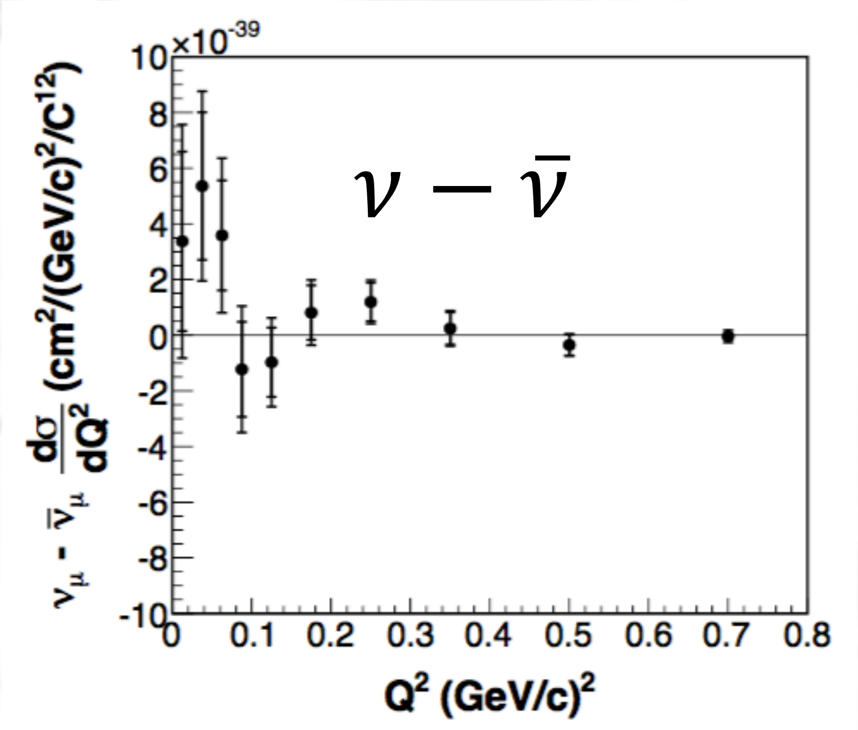


Comparison of Neutrinos and Antineutrinos, and $d\sigma/dQ^2$



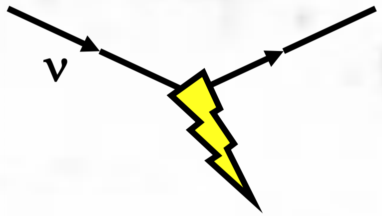
- Updated MINERvA results include $d\sigma/dQ^2$ and a direct check of the consistency of neutrino and antineutrino cross-section to check if process is purely axial





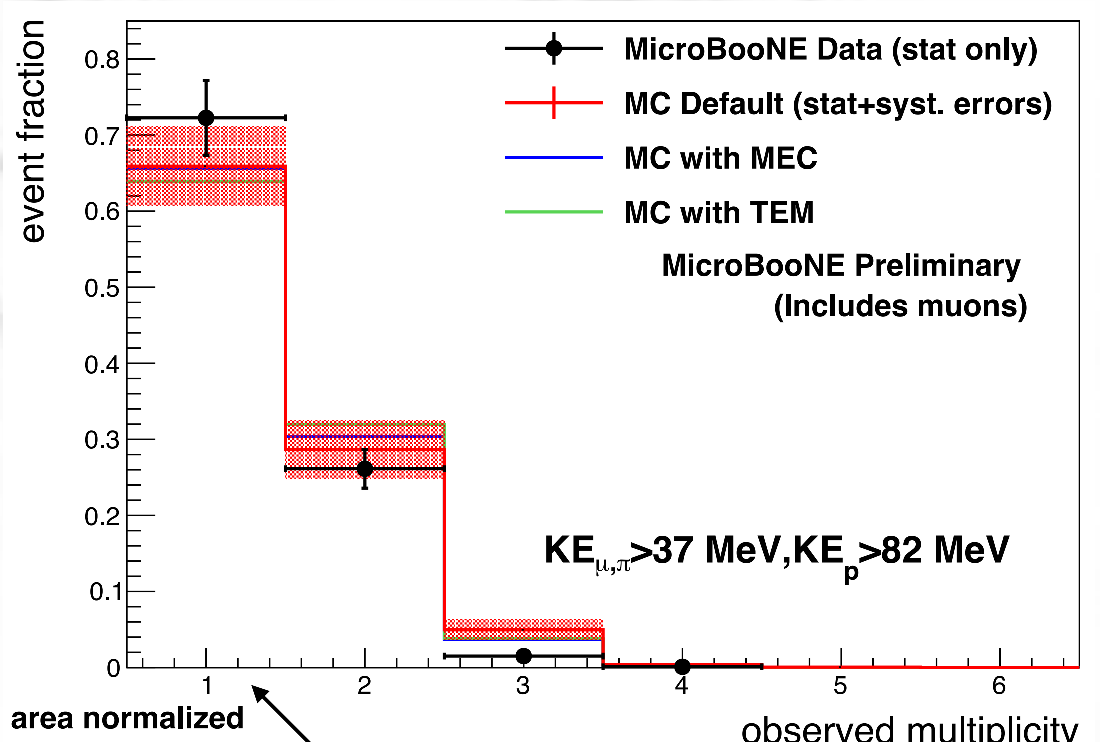
Low Threshold Multiplicities in Liquid Argon

Low Threshold Multiplicities



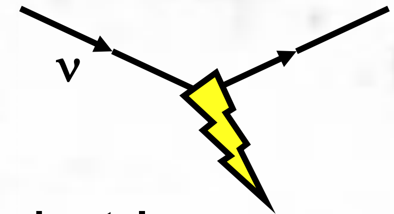
- Model check of low energy particles, such as spectator nucleons and pions degraded by final state interactions
- Important for understanding LAr reconstruction
- Obviously, early days for MicroBooNE
- Want to reduce thresholds (÷ 1.5?) and add particle ID to get full power of these comparisons

M. Del Tutto, Monday WG2



Muon is included in bin 1

Resonance Spectrum

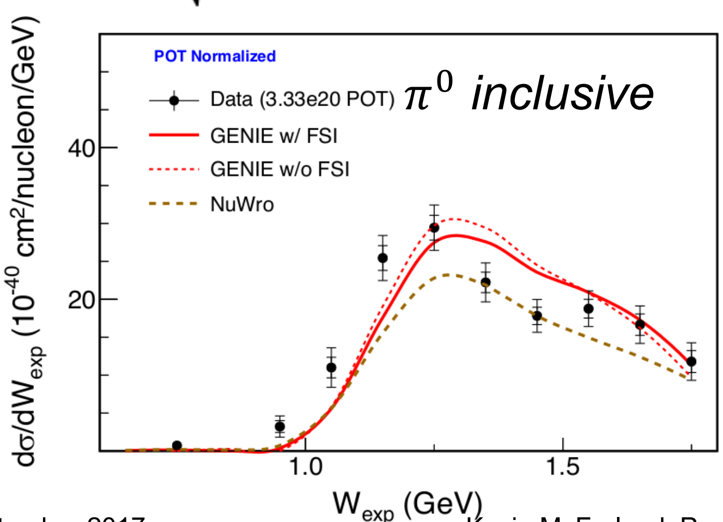


Δ *Resonance in Nuclei*

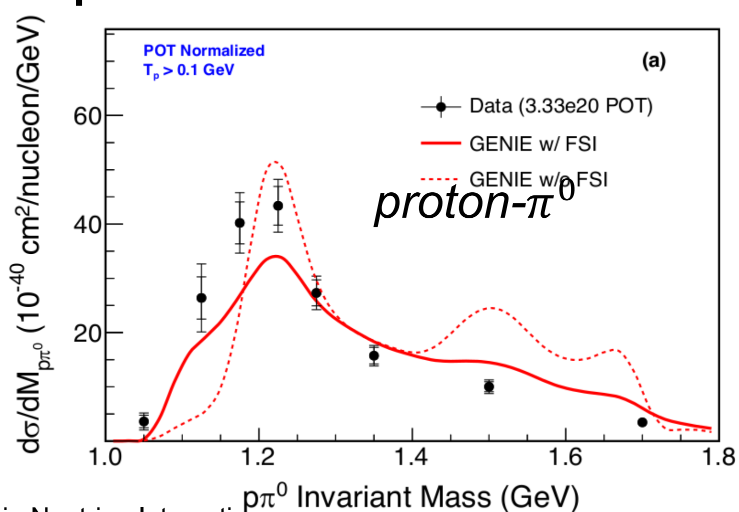
- Some confusing results in pion production nuclei at low momenta suggest unexpected nuclear effects
  - "MiniBooNE/MINERvA pion puzzle"
- Recent MINERvA results on proton-π^0 final states have some interesting effects
- More evidence of oversimple pion model?

E. Valencia, Monday WG2

$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$

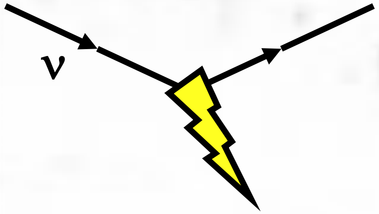


Invariant Mass calculated with proton and π^0 4-momentums

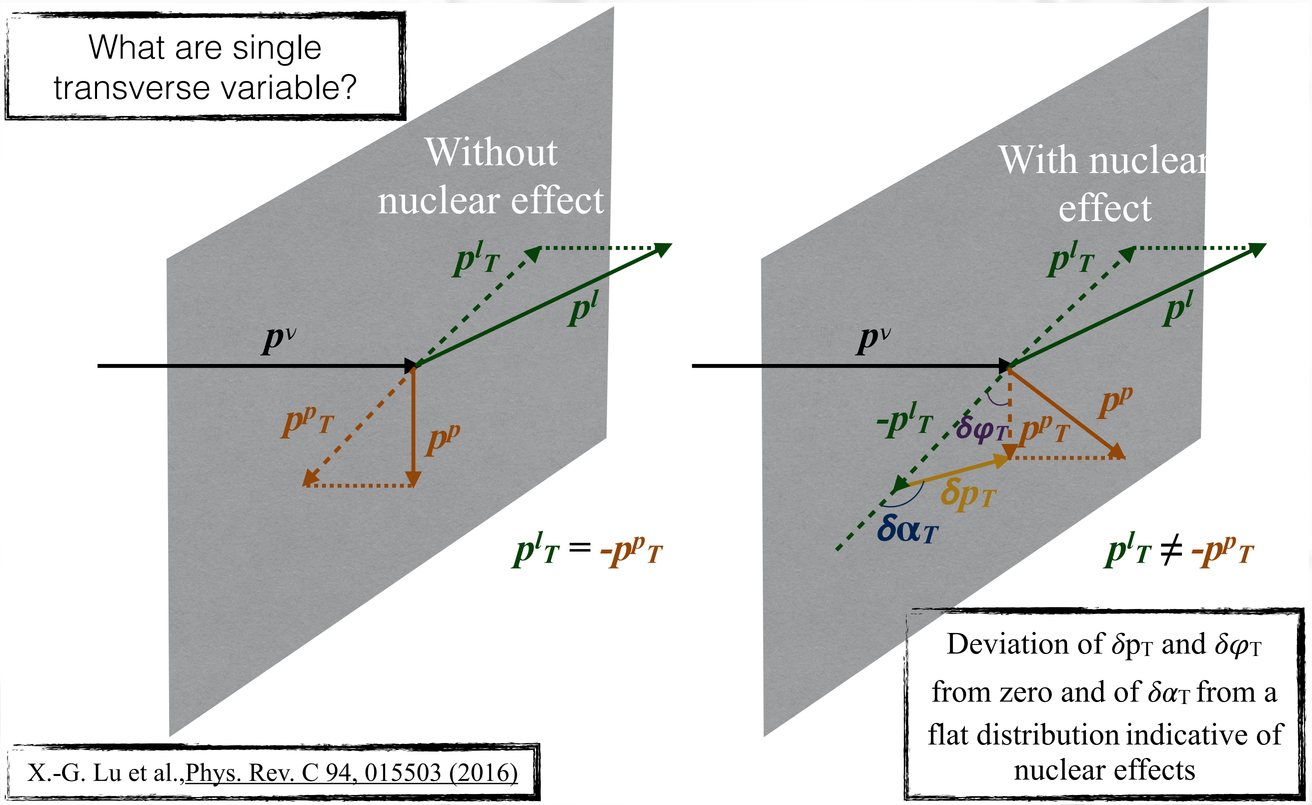


Proton Muon Correlations in CC0π

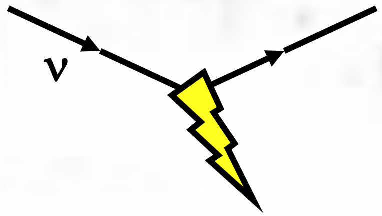
How to pick apart different nuclear effects?

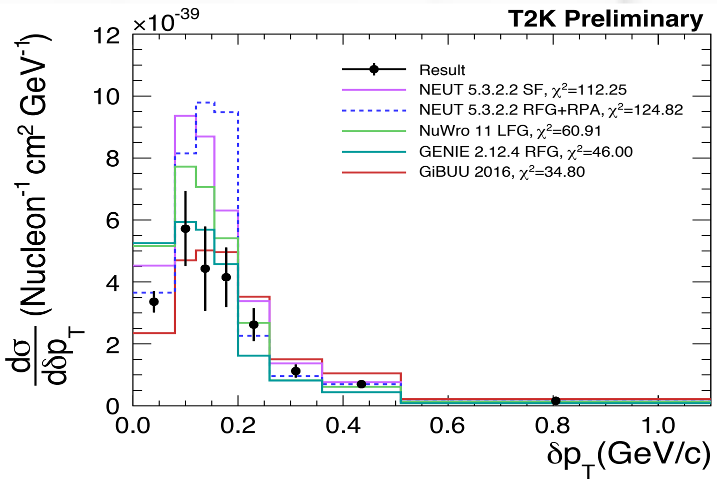


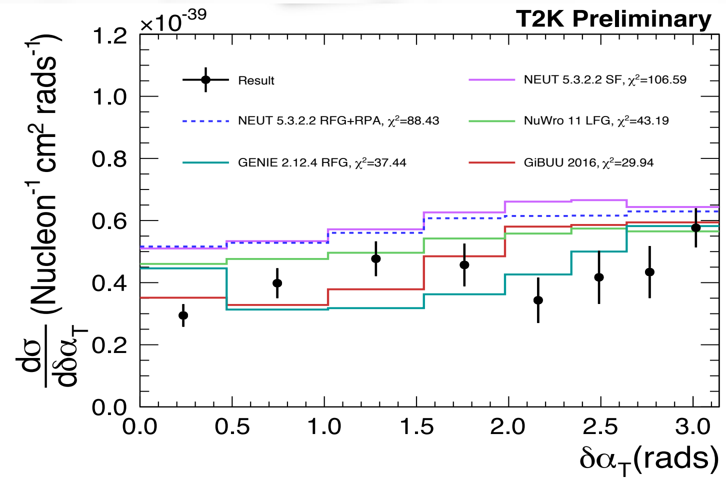
- Often it is very difficult to separate initial state (Fermi motion, in medium modifications) from final state (rescattering) effects
- Need new observables… correlations between protons and muons in CC0***π*** events! *C. Riccio, Monday WG2*

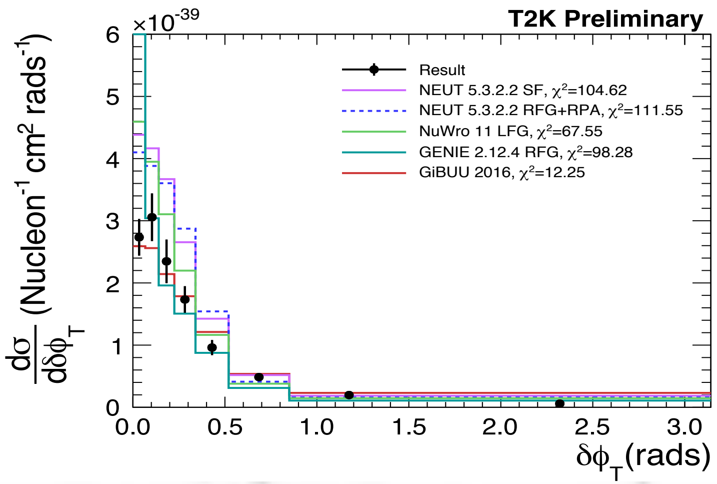


How to pick apart different nuclear effects?









Data strongly disfavor RFG in favor of LFG and Spectral Function

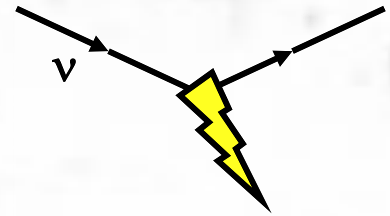
GIBUU with very different FSI seems close to data

GENIE shape in first bin of each STV related to FSI model ("hA")

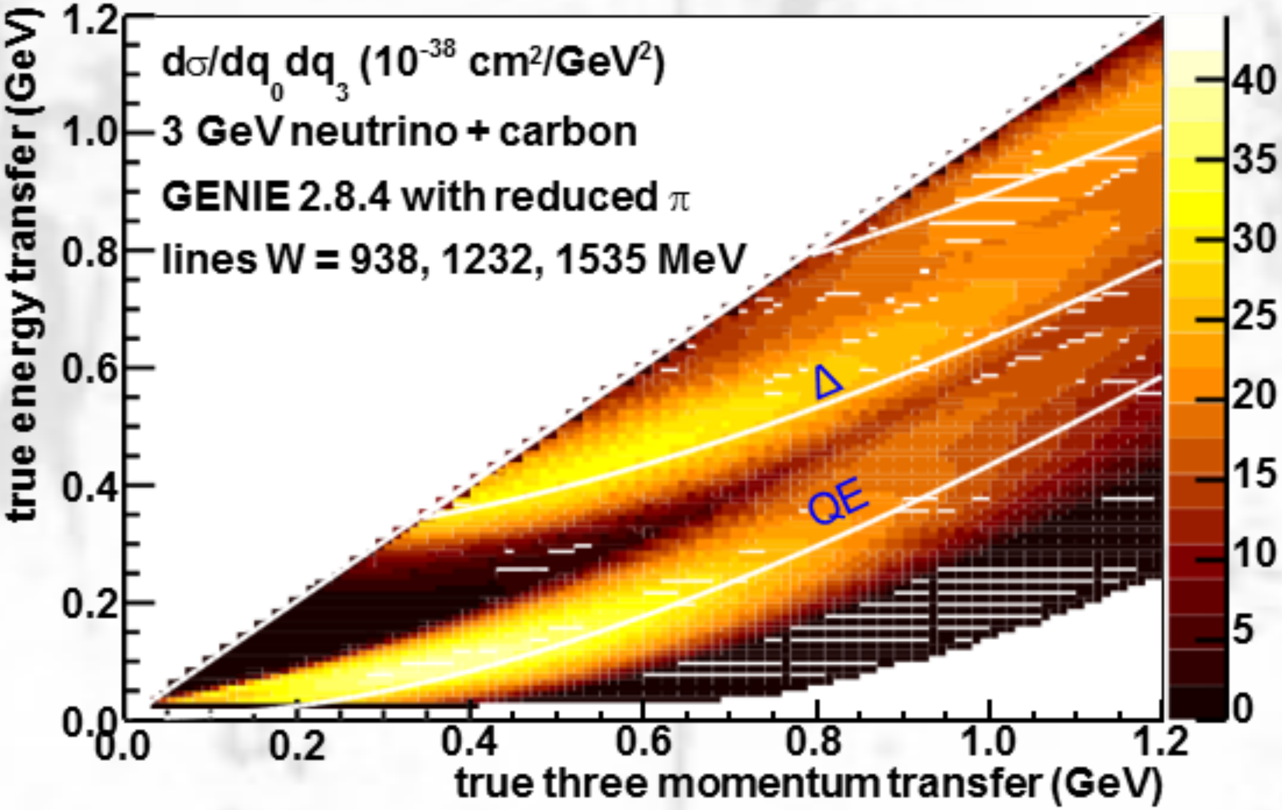
C. Riccio, Monday WG2

Progress Towards a Descriptive CC0π Model

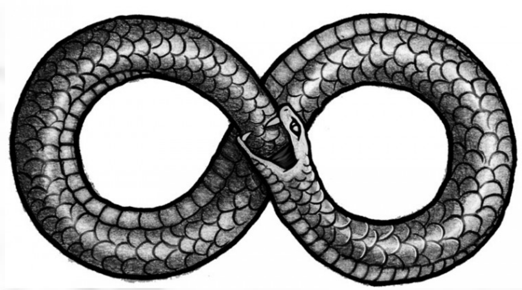
Recall… energy



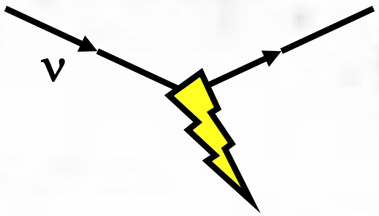
- More precisely, since single arm experiments would be wasteful ☺, we would measure these distributions of energy and momentum transfer.



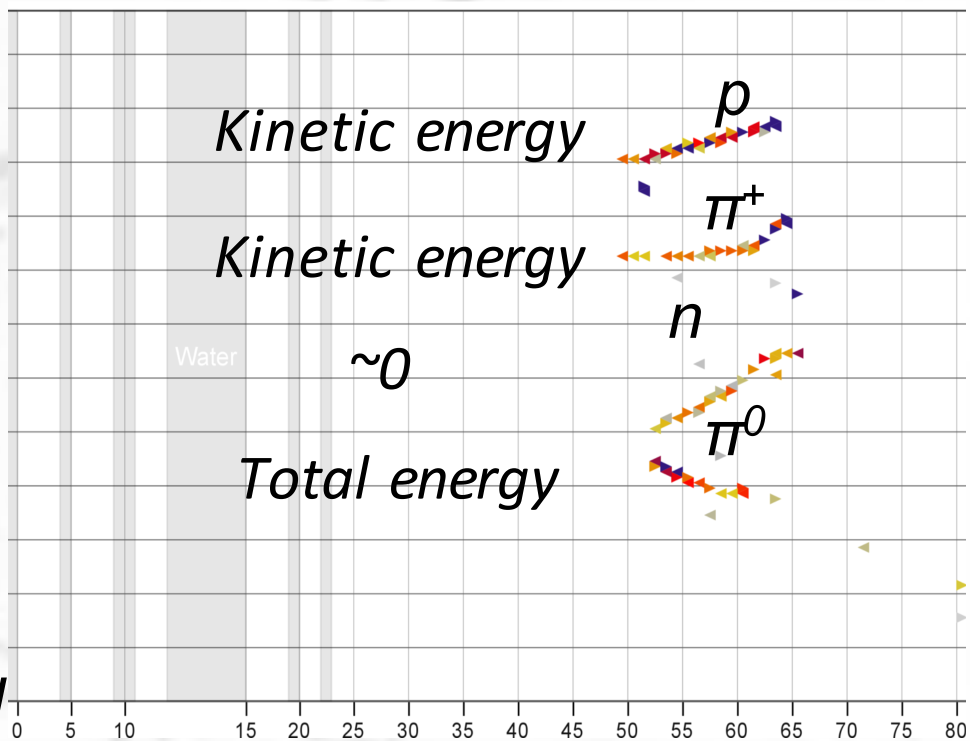
Unfortunately, we cannot do this without reference to the final state of the neutrino interactions to measure neutrino energy.



If we can't measure energy…

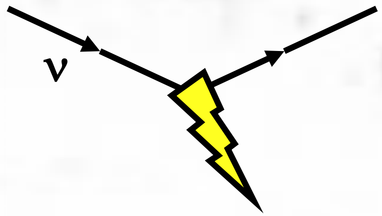


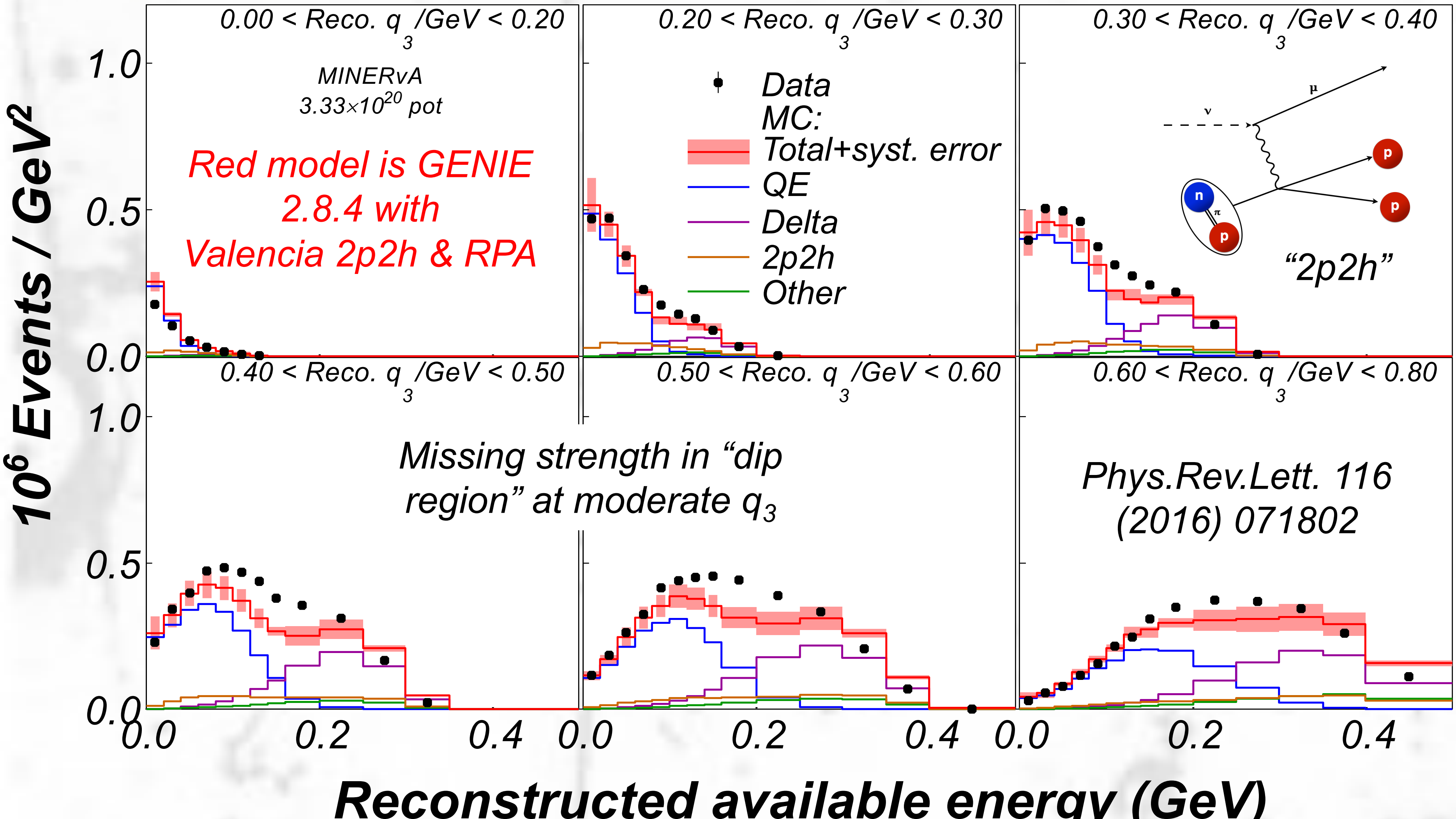
- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.
- *MINERvA's approach is to use calorimetry for all but the final state lepton*
  - *Don't measure energy transfer, q_0, but a related quantity dependent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



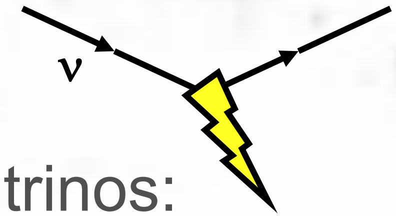
$$E_{avail} \equiv (\text{Proton and } \pi^{\pm}\ KE) + (E \text{ of other particles except neutrons})$$

Data vs. Model (GENIE++)

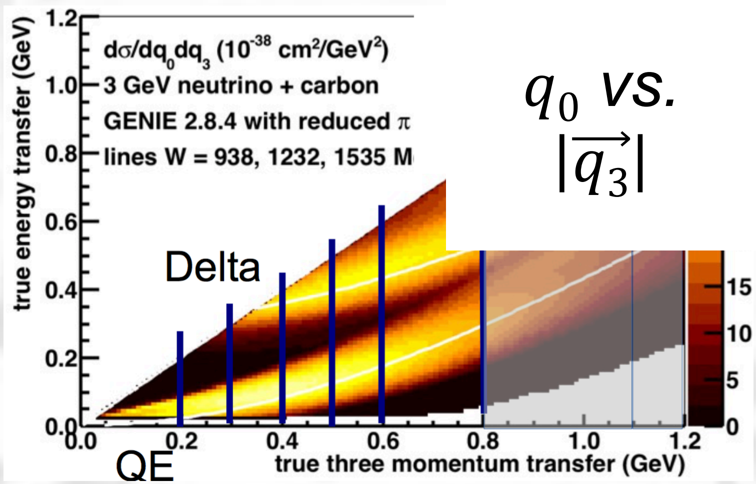


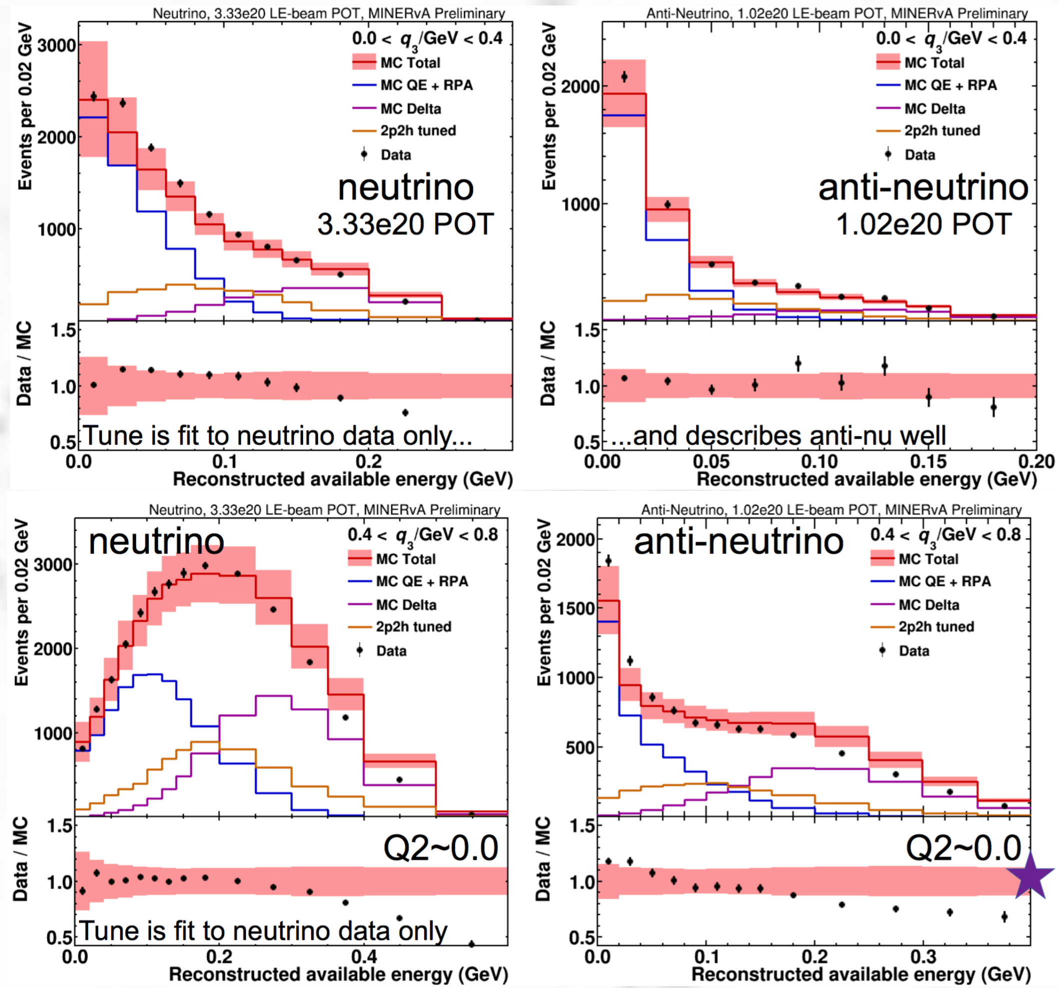


MINERvA ν_μ and anti-ν_μ “low q”



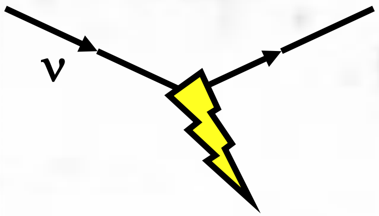
- Low recoil “Inclusive” ν_μ cc interactions in antineutrinos: MINERvA (A. Bravar)





- *Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.*
- *This tune from neutrino data also agrees with antineutrino data!*

NOvA low-q Analysis

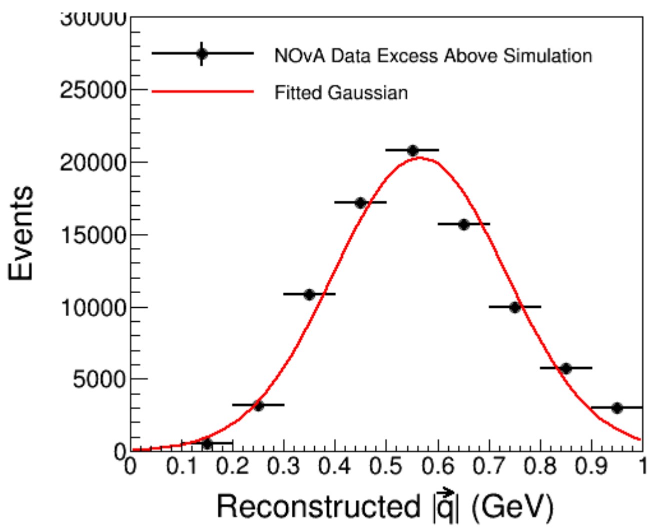


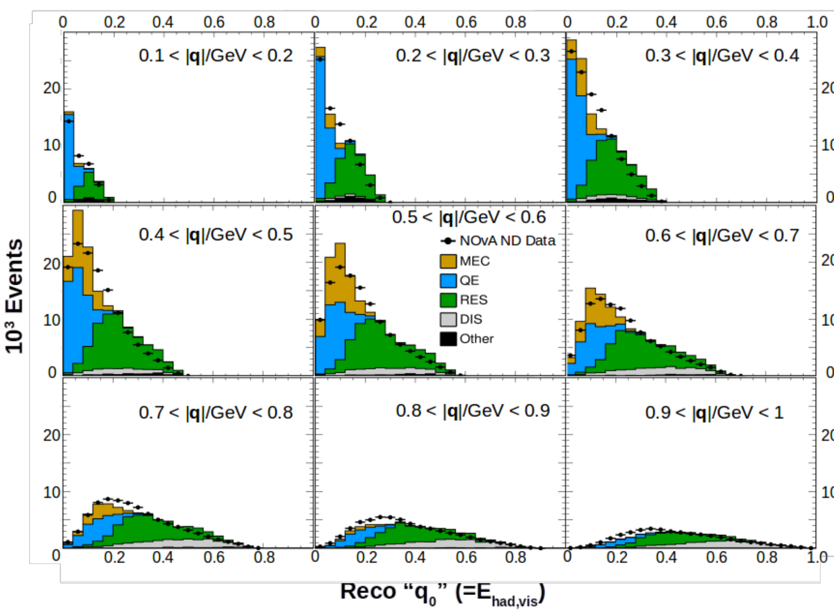
- NOvA is doing something very similar as part of its oscillation analysis evaluation of systematics

Second analyses (2016):

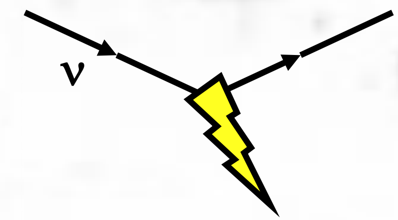
K. Bays, Tues WG1+2

- Dytman 'empirical MEC' model is included in GENIE and used by NOvA
- Momentum transfer distribution fit to ND data; energy transfer set to match QE
- A 50% normalization uncertainty is taken





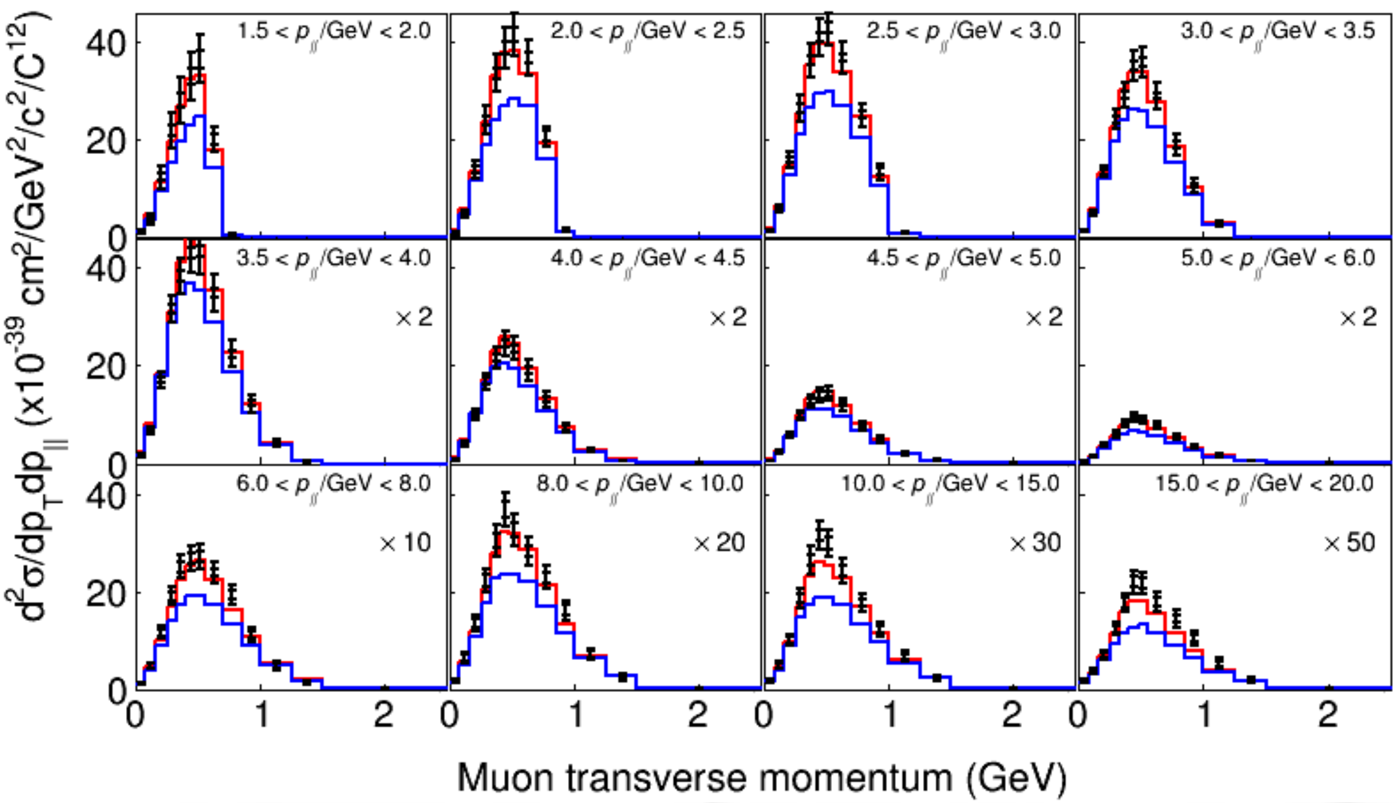
ν pionless events (CC0π)



- What if we take tune to inclusive data and feed it back to predict muon distributions in an exclusive channel?

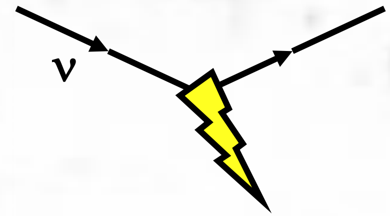
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\parallel}}$$

ν



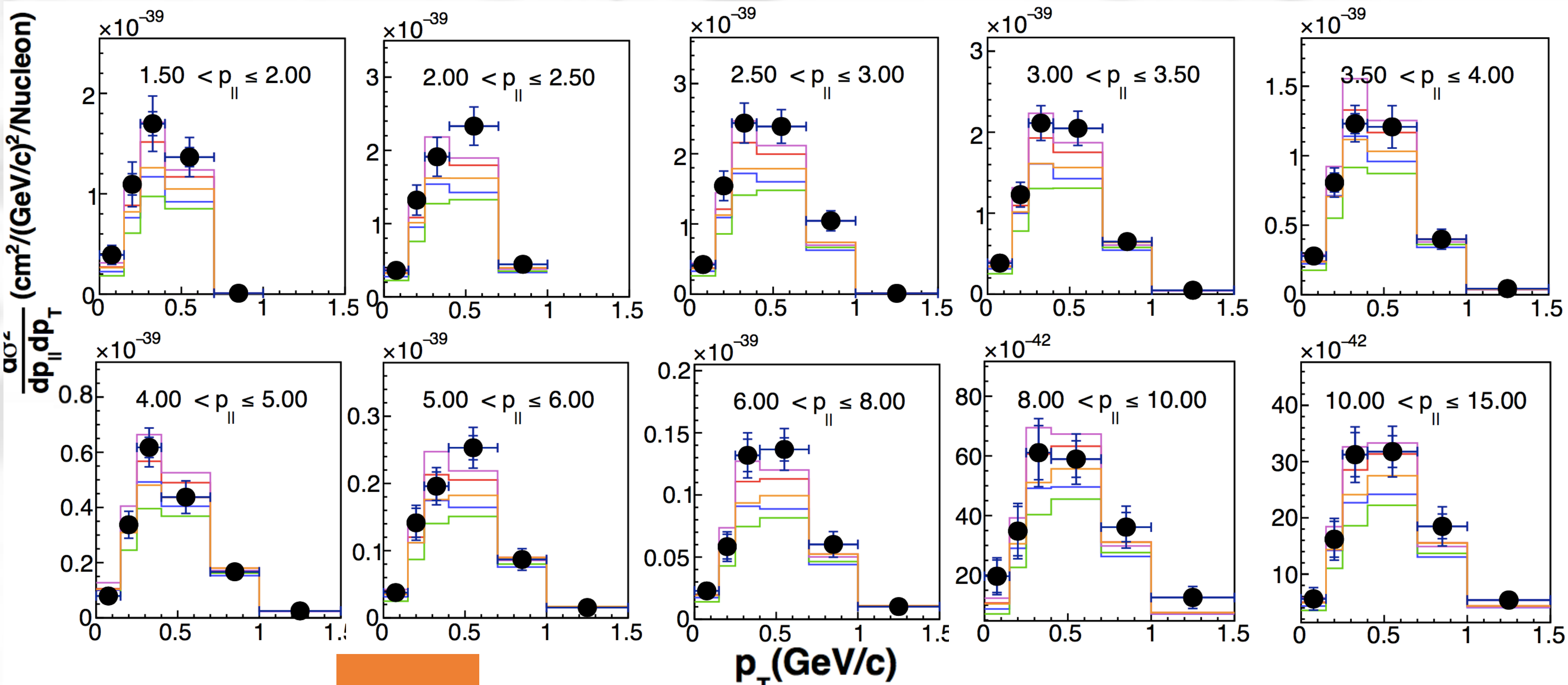
C. Patrick, Friday WG2

$\bar{\nu}$ pionless events (CC0π)



- What if we take tune to inclusive data and feed it back to predict muon distributions in a different exclusive channel?

$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\parallel}}$$



$\bar{\nu}$

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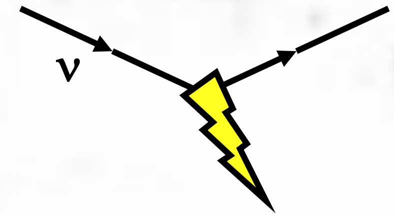
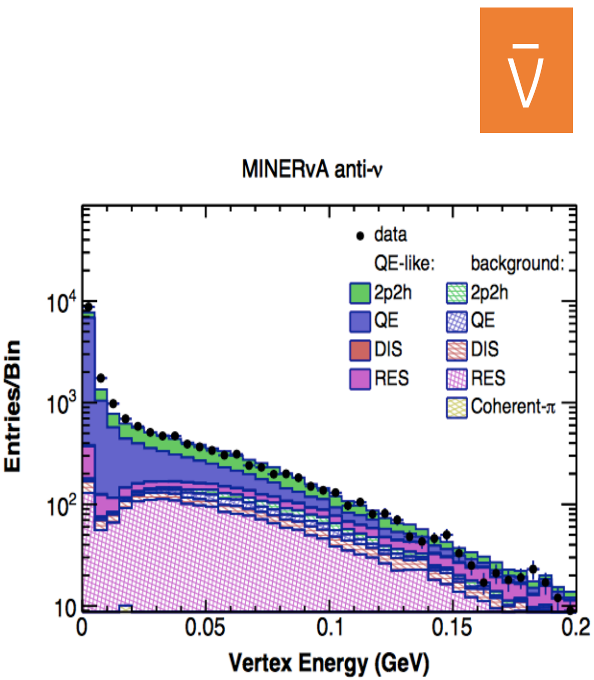
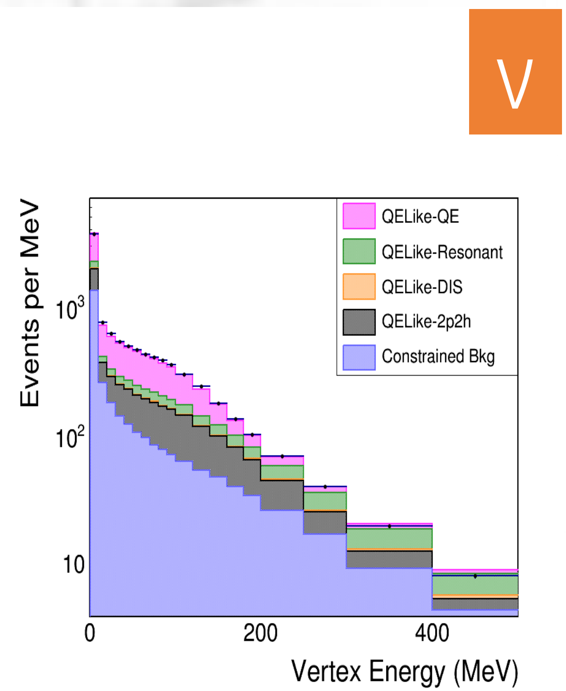
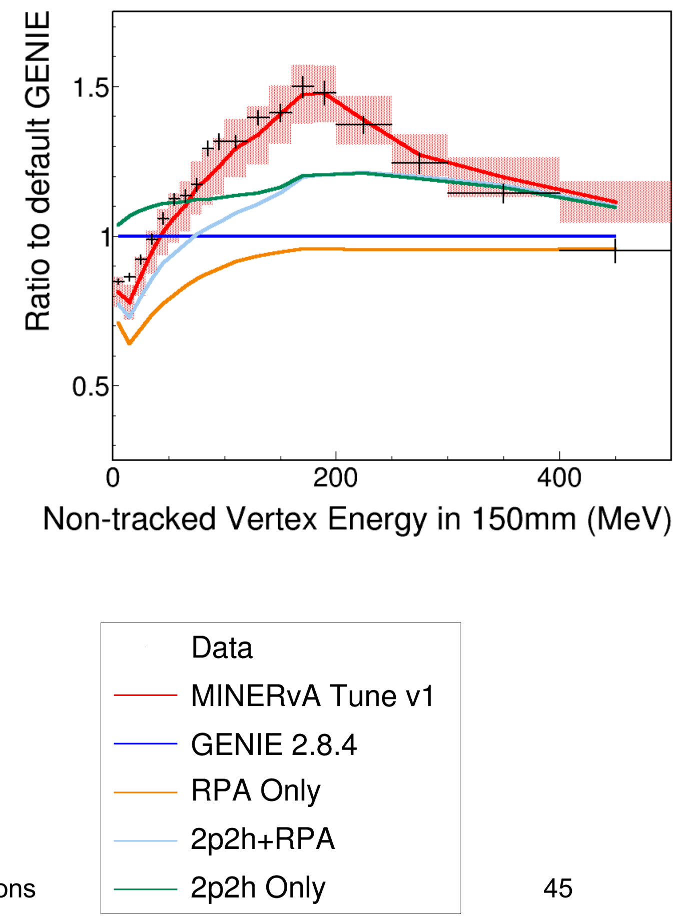
Low energy protons in pionless events (CC0π)



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







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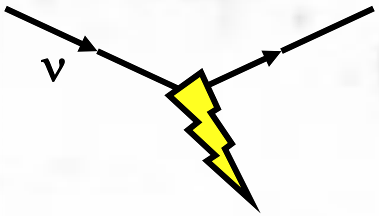
Summary of CC0π Model

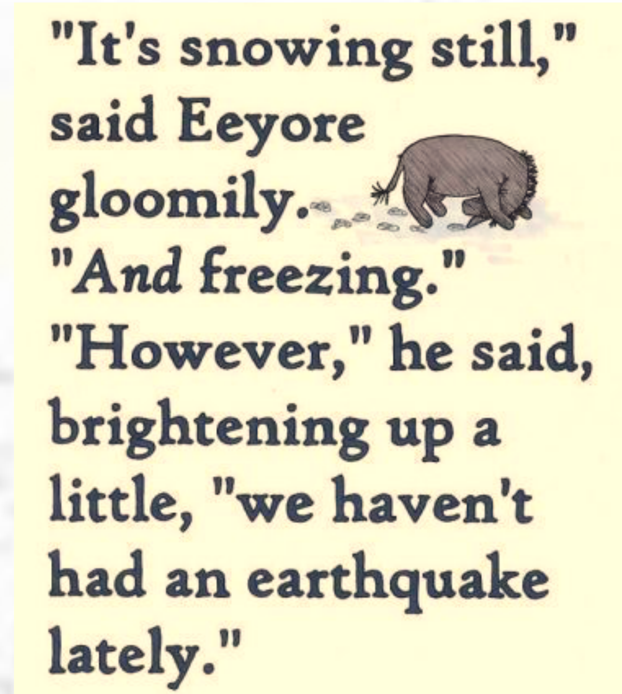


- For these “least inelastic” events, we seem to have found a model which explains
  - Lepton energy distributions over MINERvA flux
  - Details of proton (visible) recoil
  - Neutrino and antineutrino

- “Model” is tuned to inclusive data which suggest an additional 2p2h (and/or some ”regular” 1p1h) at moderate, ~0.4 GeV, three-momentum transfer
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.
- Interesting to test against T2K, MicroBooNE, etc.

Conclusions

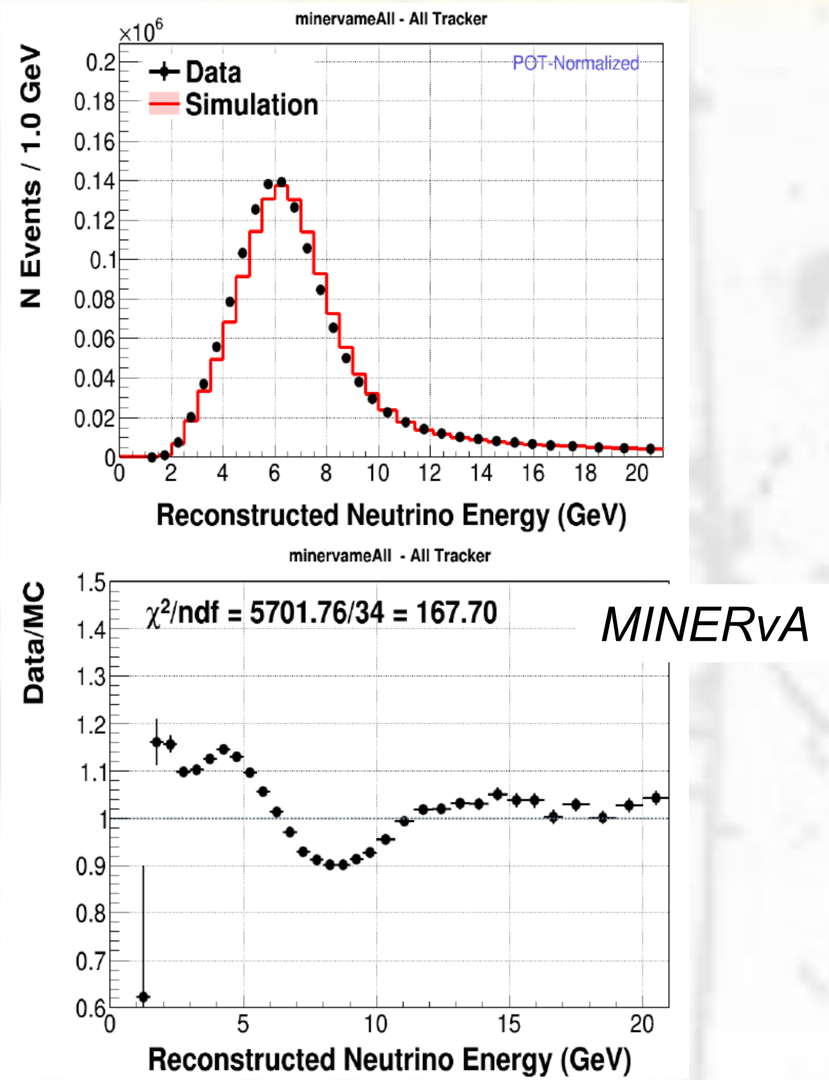
Conclusions

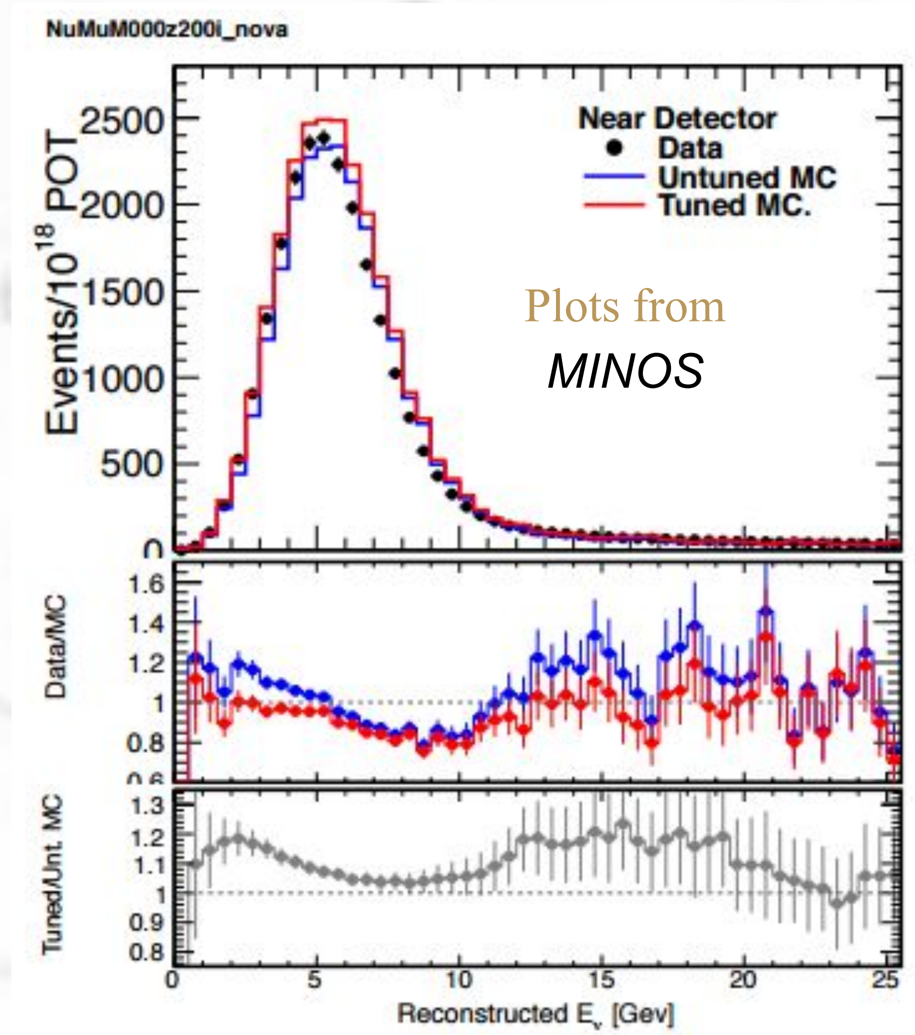


- Did I mention progress?
- We are approaching a plausible description of the zero pion reactions that are most/much of T2K/NOvA signals.
  - Theory may have some catching up to do.
- Single pion is ~ready for same approach.
- We have a longer, more difficult, path to follow to reach the understanding necessary for DUNE.

Backup

NuMI Flux Puzzle





MINERvA's neutrons