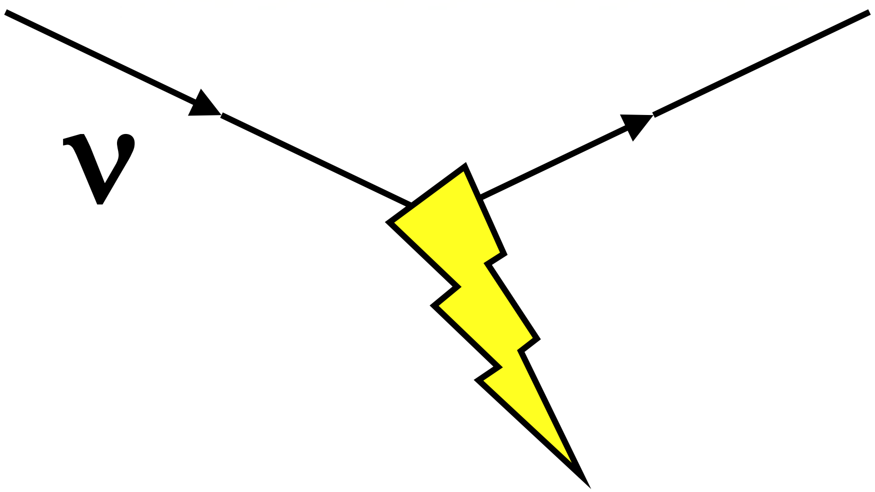
Recent Results on GeV Neutrino Interactions



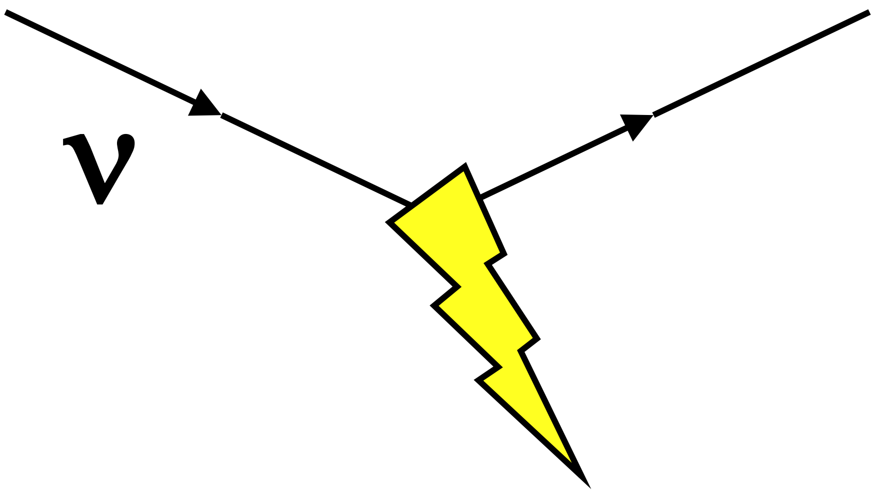
Kevin McFarland
University of Rochester

16 January 2018
ICRR

Outline

- Why progress on understanding GeV neutrino reactions is needed
- 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?

Recent ~~Results~~ Progress in Understanding GeV Neutrino Interactions



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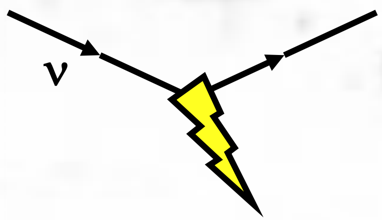
Why Study Neutrino Oscillations? And How?

Neutrino Interferometry



$$H|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

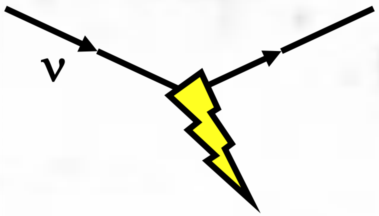
- So each neutrino wavefunction has a time-varying phase in its rest frame, $e^{-iEt/h}$
- Now, imagine you produce a neutrino of definite momentum but is a mixture of two masses, m_1, m_2

$$E_1 = \sqrt{p^2 + m_1^2} \approx p\left(1 + \frac{m_1^2}{2p^2}\right)$$
$$E_2 = \sqrt{p^2 + m_2^2} \approx p\left(1 + \frac{m_2^2}{2p^2}\right)$$

$$i(E_1 - E_2)\frac{\tau}{h} \approx i(m_1^2 - m_2^2)\frac{Lc}{2ph}$$

- they pick up a phase difference in lab frame

Neutrino Interferometry (cont'd)



- Phase difference $i(E_1 - E_2)\frac{\tau}{h} \approx i(m_1^2 - m_2^2)\frac{Lc}{2ph}$
- When phase difference is ~π radians, relative phase shift is large.
  - If $\nu_\alpha \propto \nu_1 + \nu_2$
    $\nu_\beta \propto \nu_1 - \nu_2$
  - then at π radians original ν_α would become ν_β

- How long does this take to happen?

$$\frac{L}{1\ \mathrm{km}} \approx \frac{E}{1\ \mathrm{GeV}} \times \left|\frac{1\ \mathrm{eV}^2}{\Delta m^2}\right|$$

↪ L is distance that neutrino travels

↪ $\Delta m^2 = m_1^2 - m_2^2$

- More generally, mixing need not be maximal

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

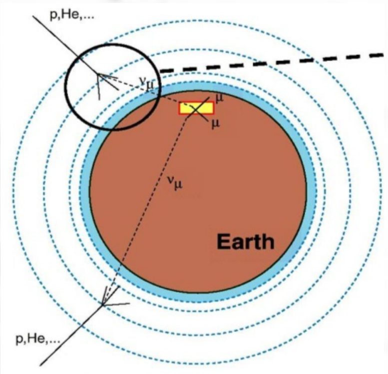
only two generations here!

Neutrinos are Lucky

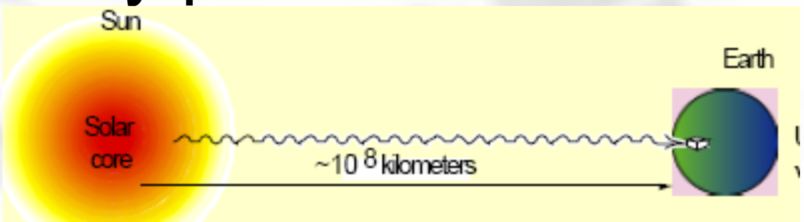
"We live in the best of all possible worlds"

– *Alvaro deRujula, Neutrino 2000*

- By which he meant…
  had not
  $E_{atm\ \nu}/R_{earth} < \delta m_{atm}^2 < E_{atm\ \nu}/h_{atm}$



  and had not solar density profile
  and δm_{sol}^2 been
  well-matched…



- *We might not have discovered ν oscillations!*

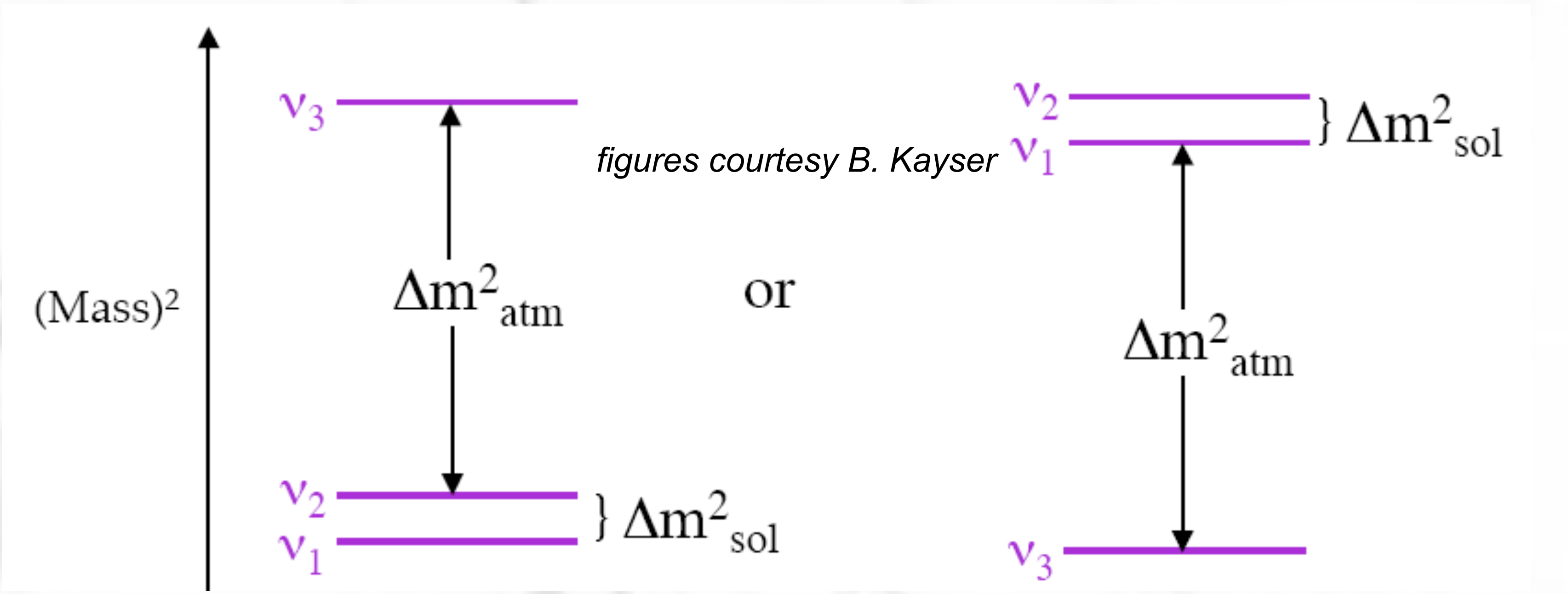
Neutrino Oscillation Goals

- Neutrino oscillation is a tool for discovery.

- Is there CP violation in the neutrino sector? And is it consistent with leptogenesis?
- Is there a symmetry to the pattern of masses or mixings?

- Answers to both of these probems require us to make precise measurements of neutrino oscillations

Two Oscillation Signatures fit into Three Neutrinos

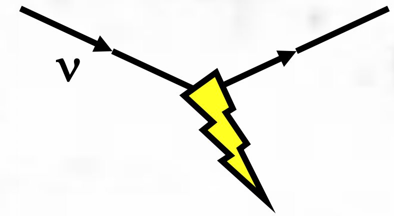


figures courtesy B. Kayser

$\delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8x10^{-5} eV^2$ $\delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5x10^{-3} eV^2$

- Oscillations have told us the differences in m^2, but nothing about the ordering (sometimes called "hierarchy")
- *The electron neutrino potential (matter effects) can resolve this in oscillations, however.*

Three Generation Mixing



- *As noted by Kobayashi and Maskawa in the quarks, a third generation of mixing admits the possibility of a complex phase → CP violation*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{ij} = cos\theta_{ij}$$
$$s_{ij} = sin\theta_{ij}$$

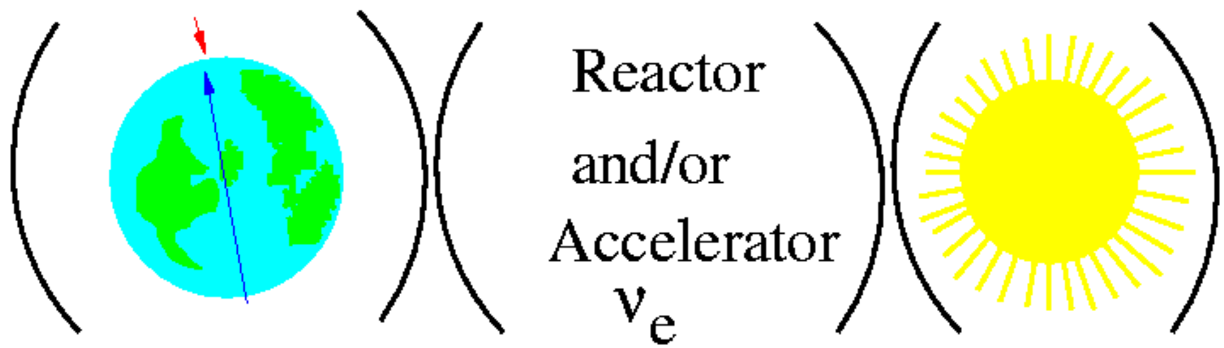
U=


Figure courtesy D. Harris

- Note the new mixing in middle, and the phase, δ

Are Two Paths Open to Us?

- If "reactor" mixing, θ_{13}, were small, but not too small, there is an interesting possibility

$$\nu_\mu \xrightarrow{\delta m_{23}^2,\ \theta_{13}} \nu_e$$

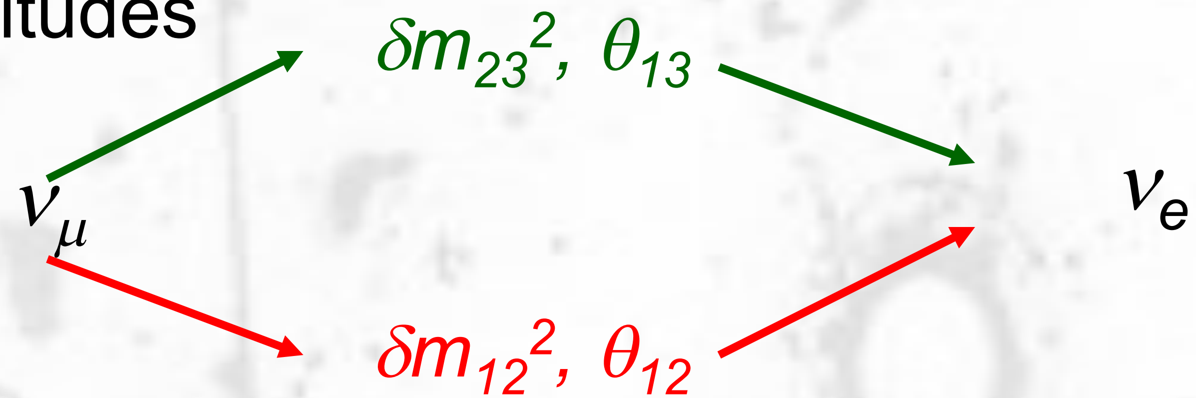
$$\nu_\mu \xrightarrow{\delta m_{12}^2,\ \theta_{12}} \nu_e$$

- At atmospheric L/E,

$$P(\nu_\mu \to \nu_e) = \sin^2 \underbrace{2\theta}_{\substack{\text{SMALL (green)} \\ \text{LARGE (red)}}} \sin^2 \left(\underbrace{\frac{(m_2^2 - m_1^2)L}{4E}}_{\substack{\text{LARGE (green)} \\ \text{SMALL (red)}}} \right)$$

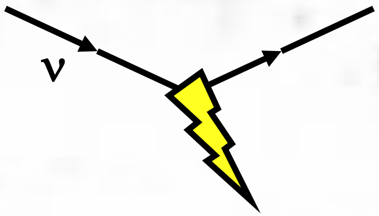
Implication of two paths

- Two amplitudes



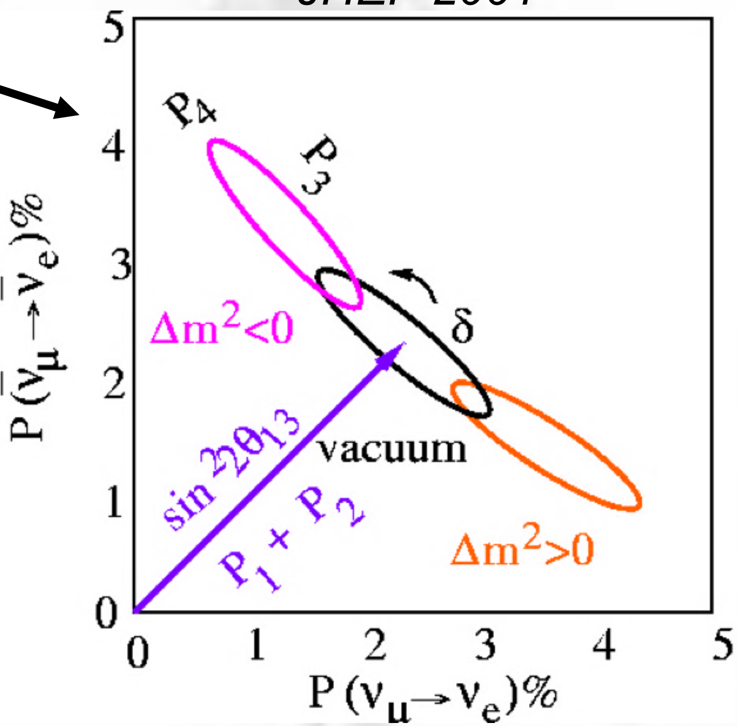
- If both small,
  but not too small,
  both can contribute ~ equally
- Relative phase, δ, between the paths can lead to CP violation (neutrinos and anti-neutrinos differ) in oscillations!

Observable Effects due to this Interference



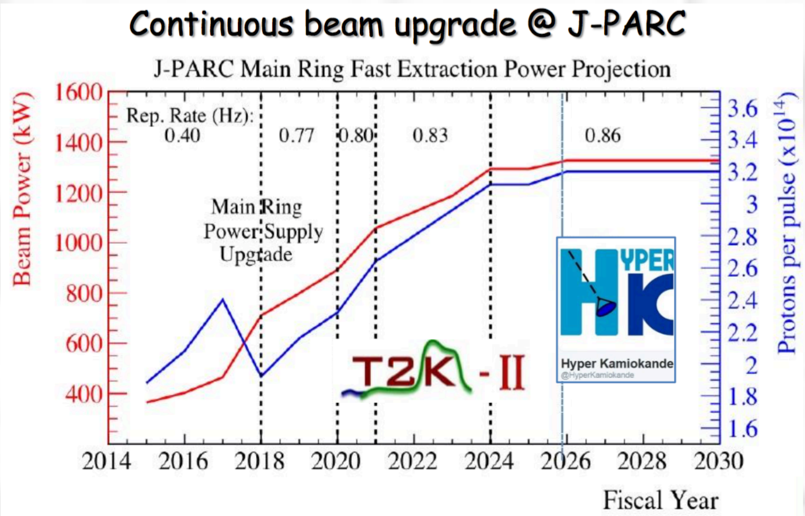
- "CP violation" (interference term) and matter effects lead to a complicated mix.
- Simplest case: first oscillation maximum, neutrinos and anti-neutrinos
- CP violation gives ellipse but matter effects shift the ellipse in a precision long-baseline accelerator experiment…

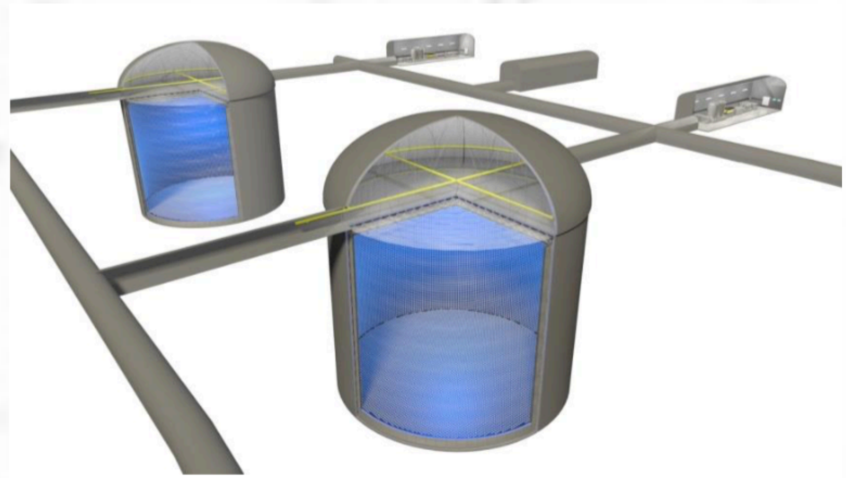
Minakata & Nunokawa JHEP 2001



One Path: Hyper-Kamiokande

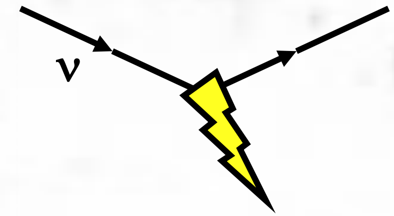
- Effectively an upgrade of the T2K experiment with more intense beam and larger detector at same sites



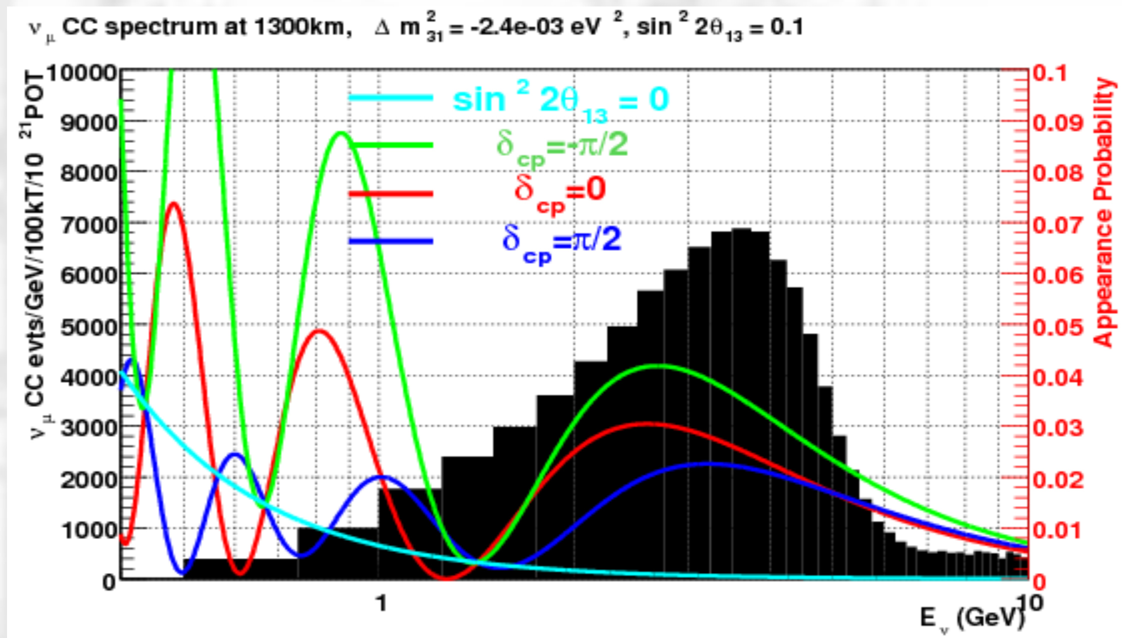


- *Greater than 1 MegaWatt of proton power (>2x current)*
- *Build two new detectors, each five times the size of Super-Kamiokande with 0.26 MegaTons of water*
- *Challenges in excavating cavern, photosensors, etc.*

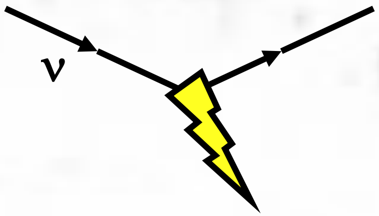
Another Path: DUNE



- Happy coincidence of location of Sanford lab (the former Homestake mine where solar neutrinos were discovered!) and location of high power multi-GeV proton sources

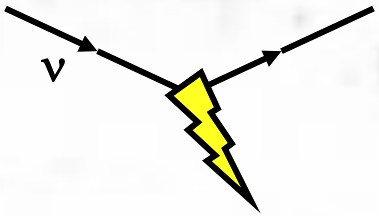


- *Wideband beam can study the oscillation effect across a range of energies. Requires good energy reconstruction!*

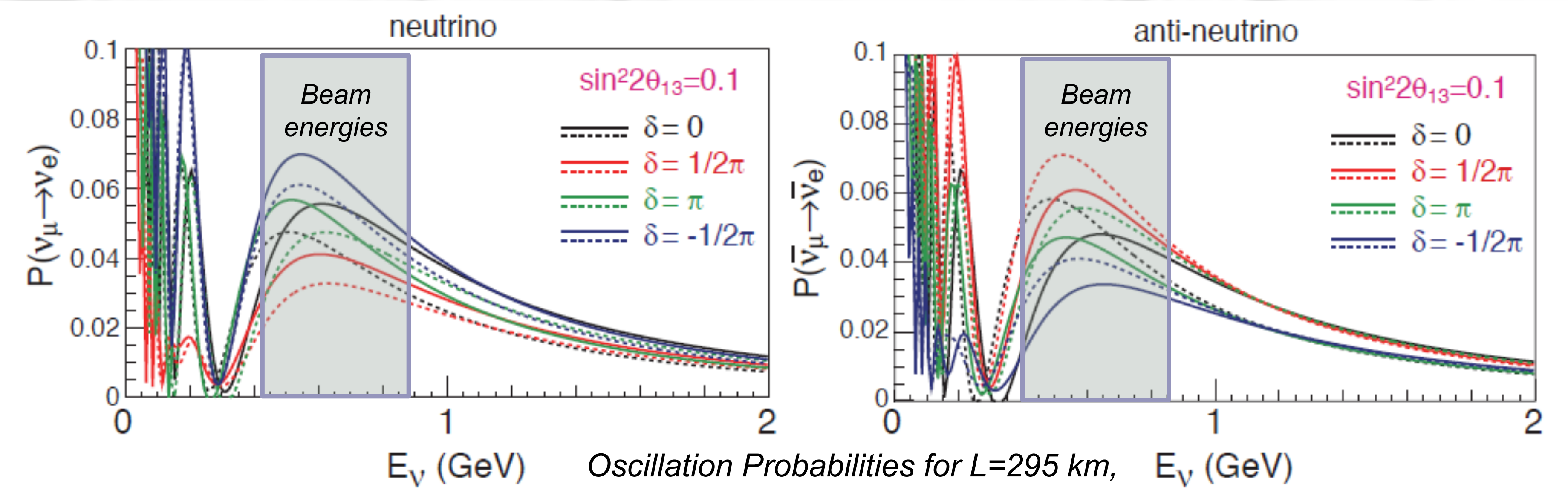


Progress is Difficult, but Necessary

Necessary: Energy Reconstruction

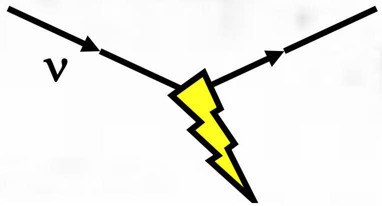


- Neutrino oscillation measurements require measurement of neutrino energy to determine oscillation probability.
- Even "narrow band" neutrino beams have an energy spectrum width that can't be ignored.
- Must estimate energy from the final state.



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.

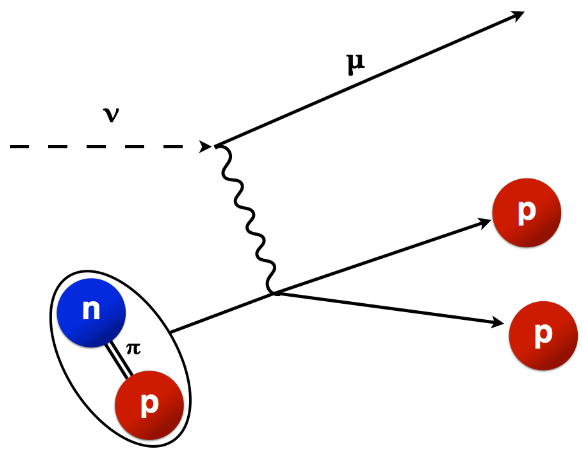
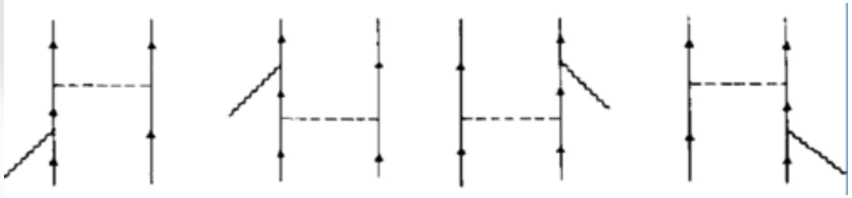
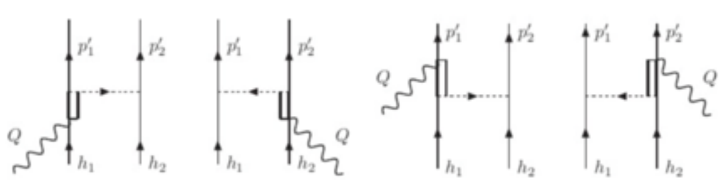


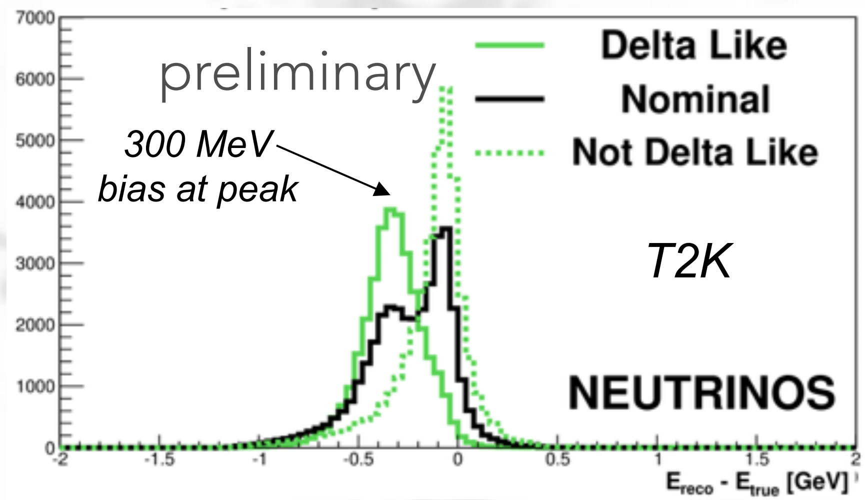
Figure courtesy M. DelTutto

Pair Correlation



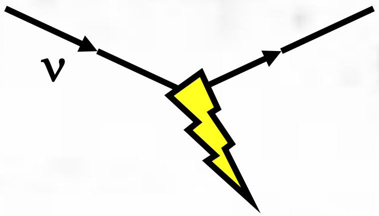
Delta absorption



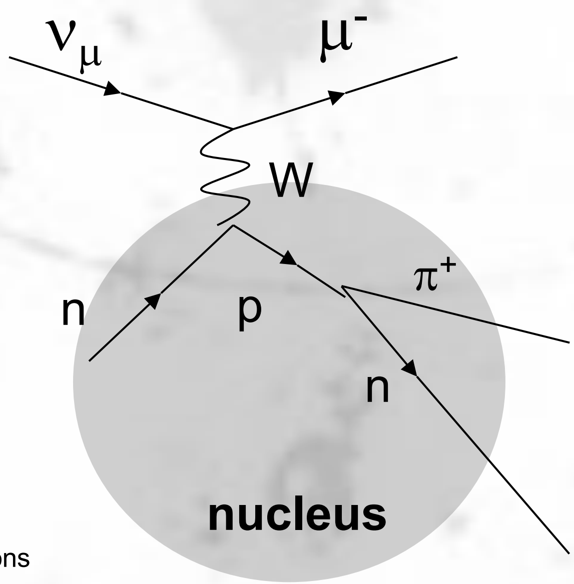


K. Nakamura @ NuFact 2017

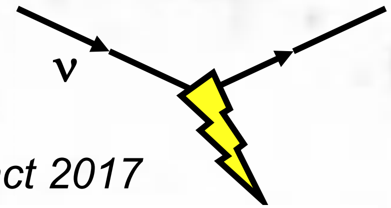
Necessary: Final States

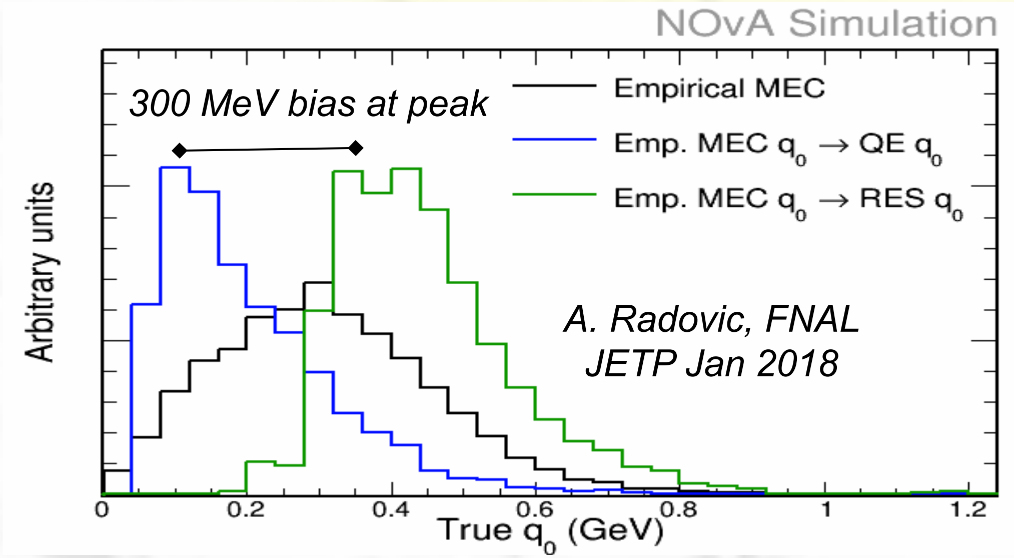


- Neutrino event selection is rarely inclusive
  - T2K selects events without visible pions in the final state, and that veto is nearly 100% efficient for π^0.
  - NOvA requires lepton energies large enough to identify muons and electrons efficiently among hadrons.
- Final state also affects energy reconstruction 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.

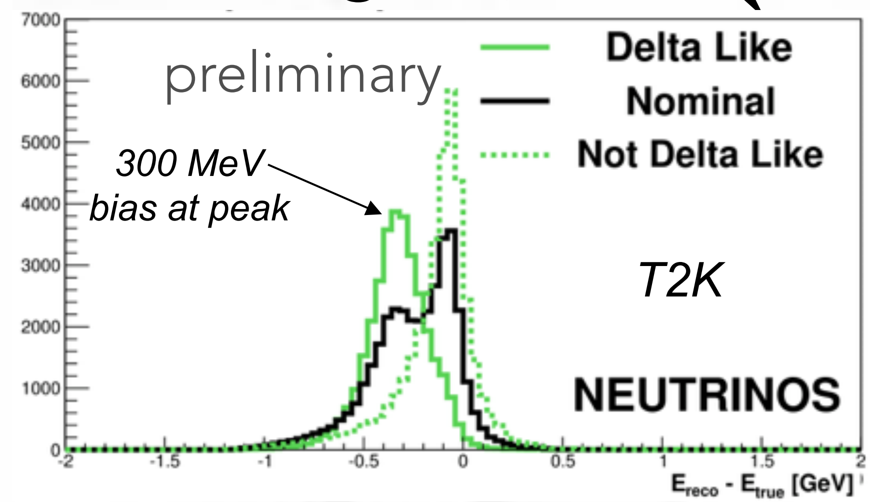


NOvA's Uncertainties

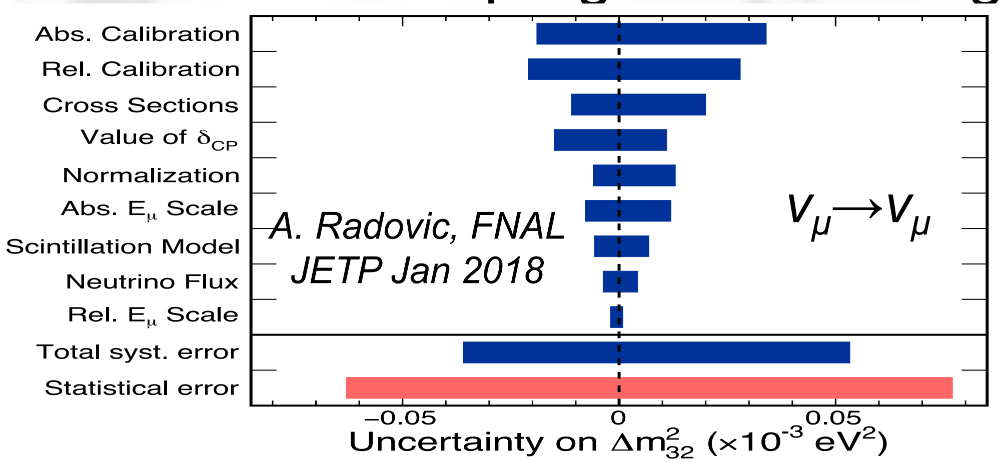


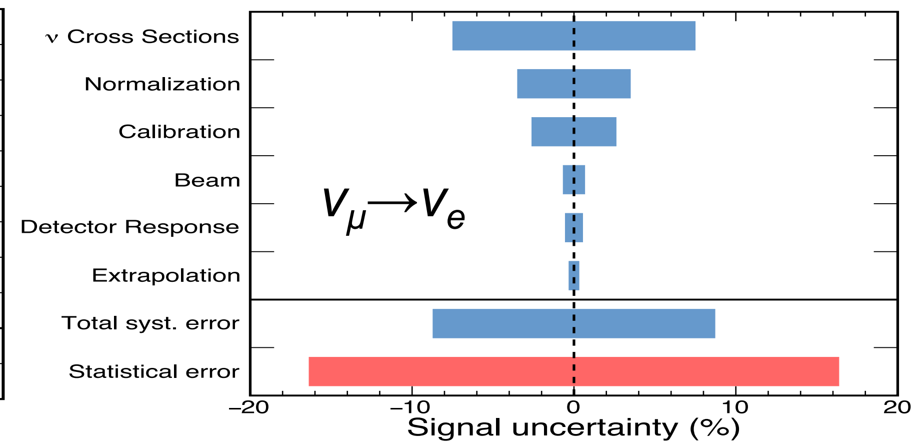


K. Nakamura @ NuFact 2017



- Multinucleon (2p2h) effect is large even at higher energies
- NOvA needs progress on energy and final state uncertainties

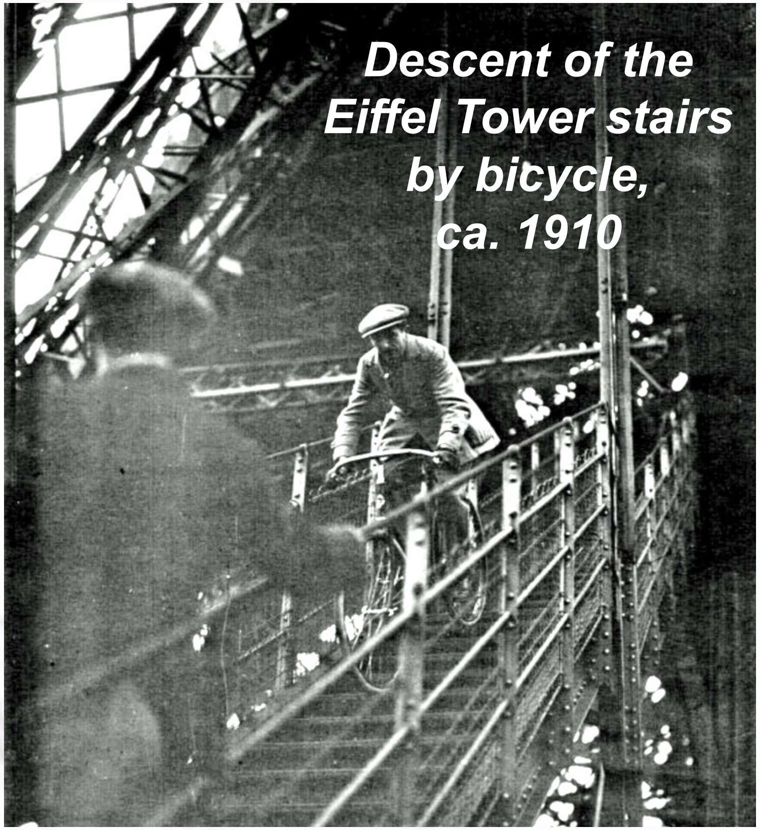




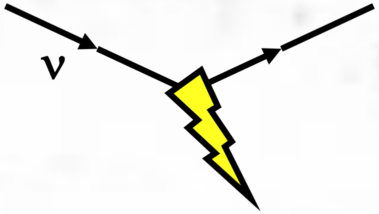
Tools for Progress

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



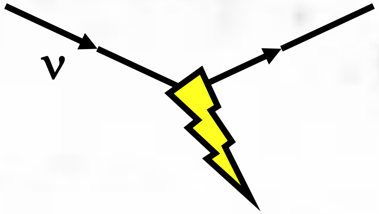
- *But since the wheel size is too close to the step size, all we know is that it is going to be painful.*



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.*

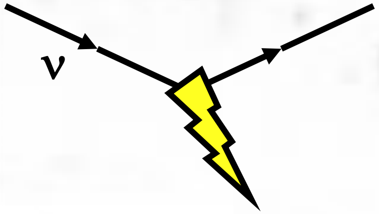
A Problem Hidden in Plain Sight for Neutrino Experiments

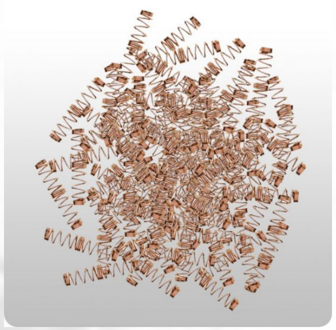


- What do we do when confronted with a problem we can't solve? We ignore it!
- This community started with modeling of neutrino interactions that was too naïve to support the precision needed for future experiments.
- People who had confronted charged lepton scattering data for decades told us what we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

Artist Liu Bolin, imitating the nucleus?

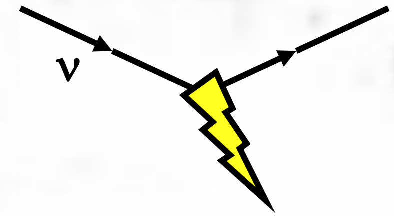
Tools: Theory





- Arguably our most important tool, my comments about the difficulties not withstanding.
- However, 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.

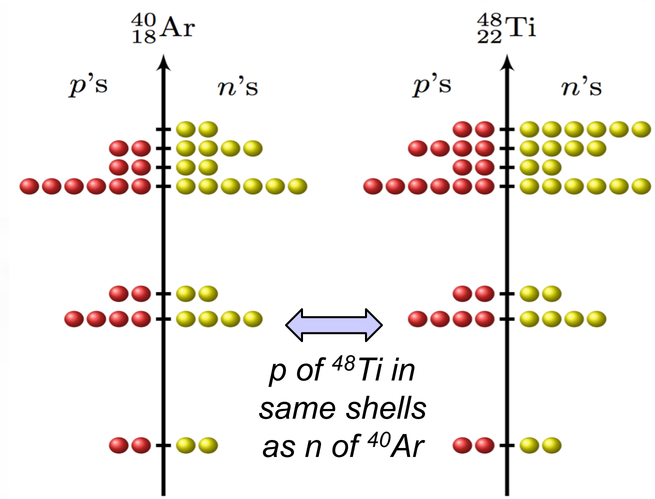
Tools: Electron Scattering

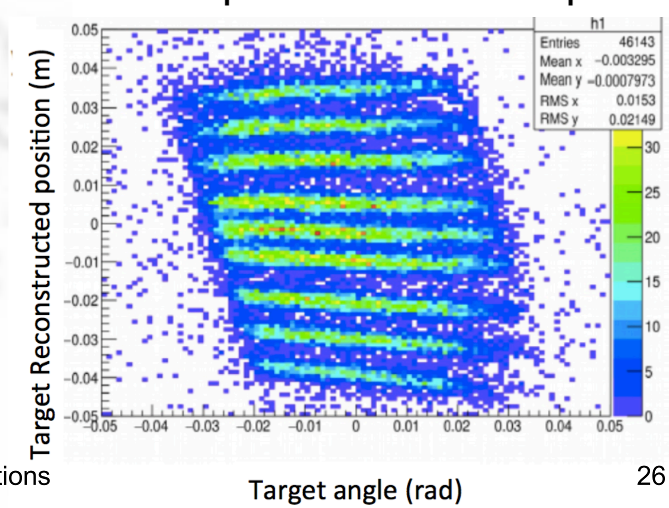


- There is a wealth of information available from electron/muon scattering experiments which cannot be matched with neutrino data.
  - Helpful for common effects, e.g., disappearance of energy into nucleus (spectral function), final state interactions
- But weak CC and EM NC are fundamentally different.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

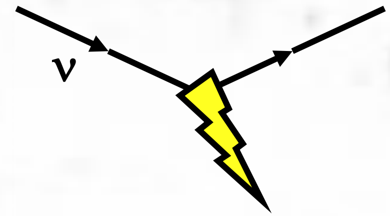
JLAB-E12-14-012

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



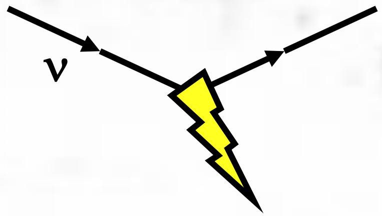


Tools: Neutrino Data

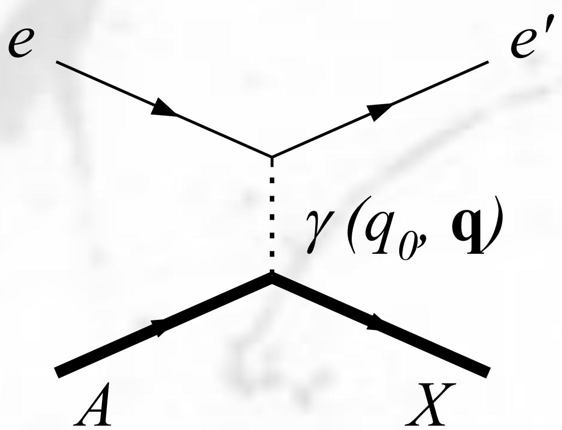


- Neutrino data has access to what we need. Just catalog reactions! But…
  - Experimentally challenging to get a capable detector and high statistics
  - Most neutrino sources (not muon decay sources) give us ν_μ, but also need ν_e.
    - Theory will get us most of the way there, but need to cleanly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

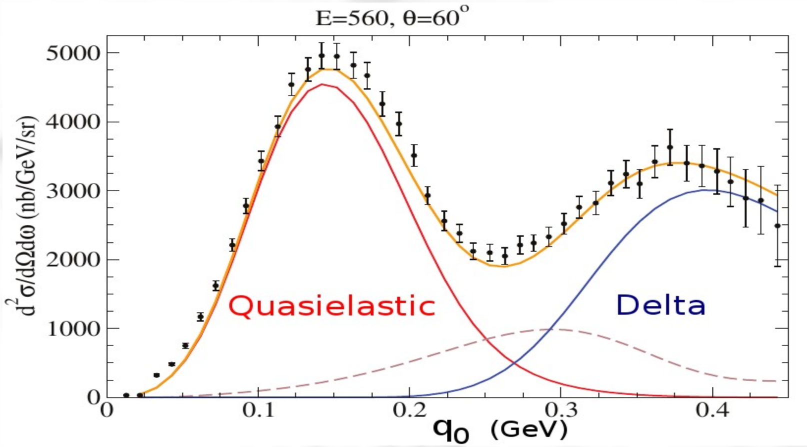
Tools: Neutrino Data



- Biggest limitation is the neutrino beam
  - 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.
  - If we had a tunable, high rate source of monochromatic neutrinos, we would repeat single arm electron scattering experiments and measure nuclear response.

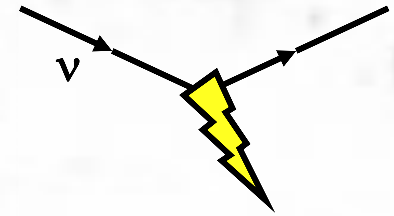


Adapted from G. D. Megias, NuFact 2015

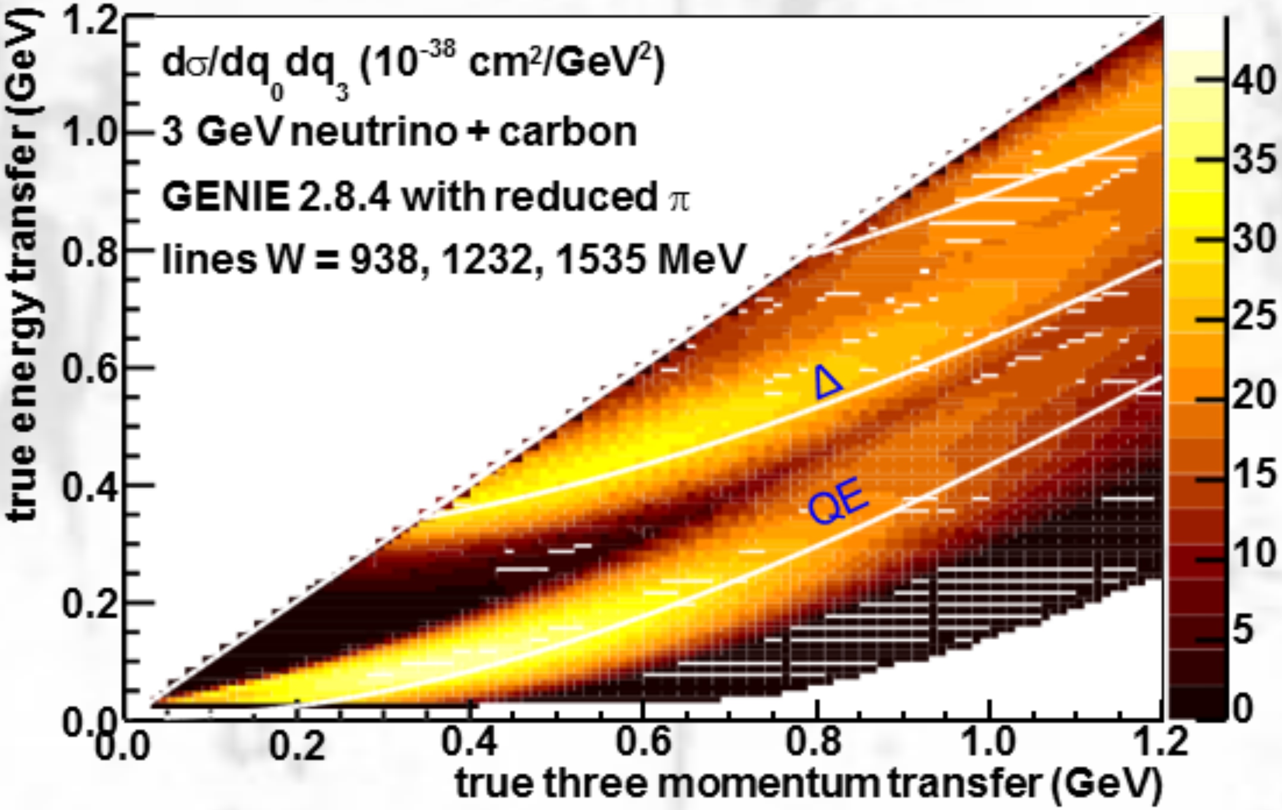


$$q_0 = E_e - E_{e'}$$

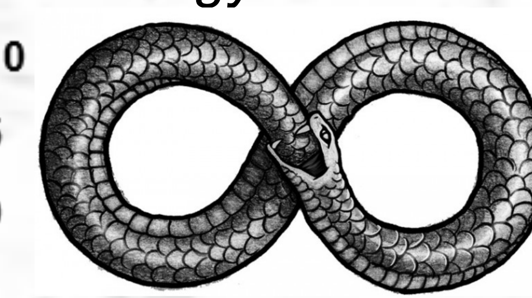
Tools: Neutrino Data



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

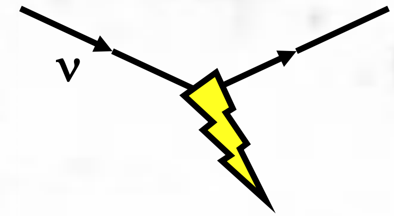


Unfortunately, we cannot do this without reference to the final state of the neutrino interactions to measure neutrino energy.

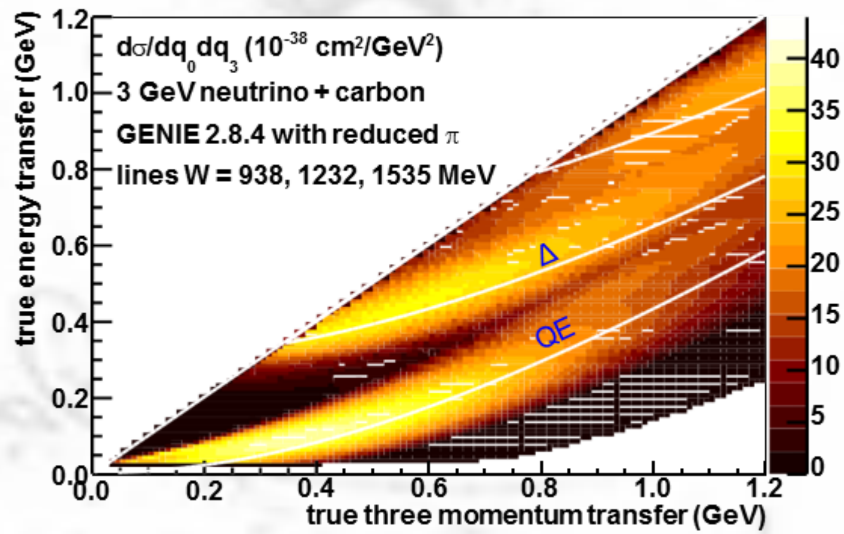


Neutrino Experiments that are Making Progress

First a Comment about Neutrino Energy



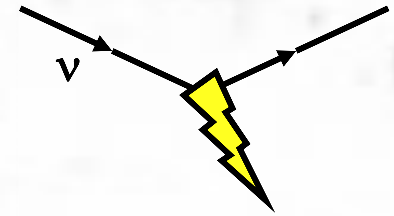
- Neutrino energy is not the most important criterion of usefulness of a data set, as long as the reaction(s) of interest are accessible
  - Response of the nucleus for a given final state is given by energy and momentum transfer. Not neutrino energy*.



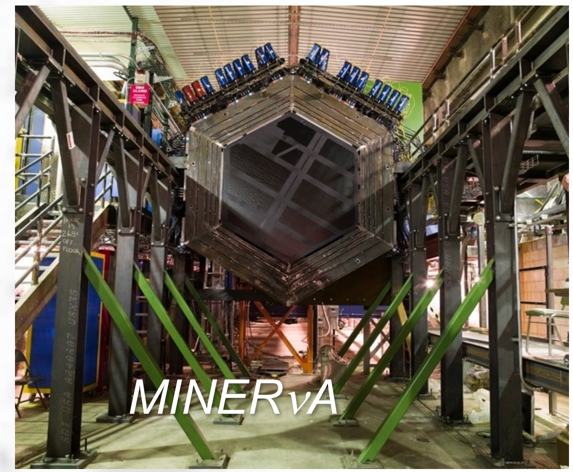
- Ability to measure a final state, get good statistics and measure kinematics are much more important.

* *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)
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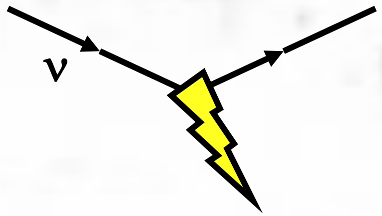

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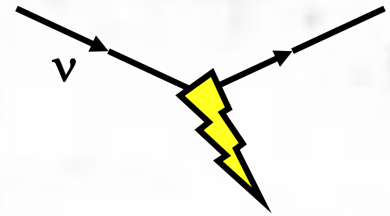
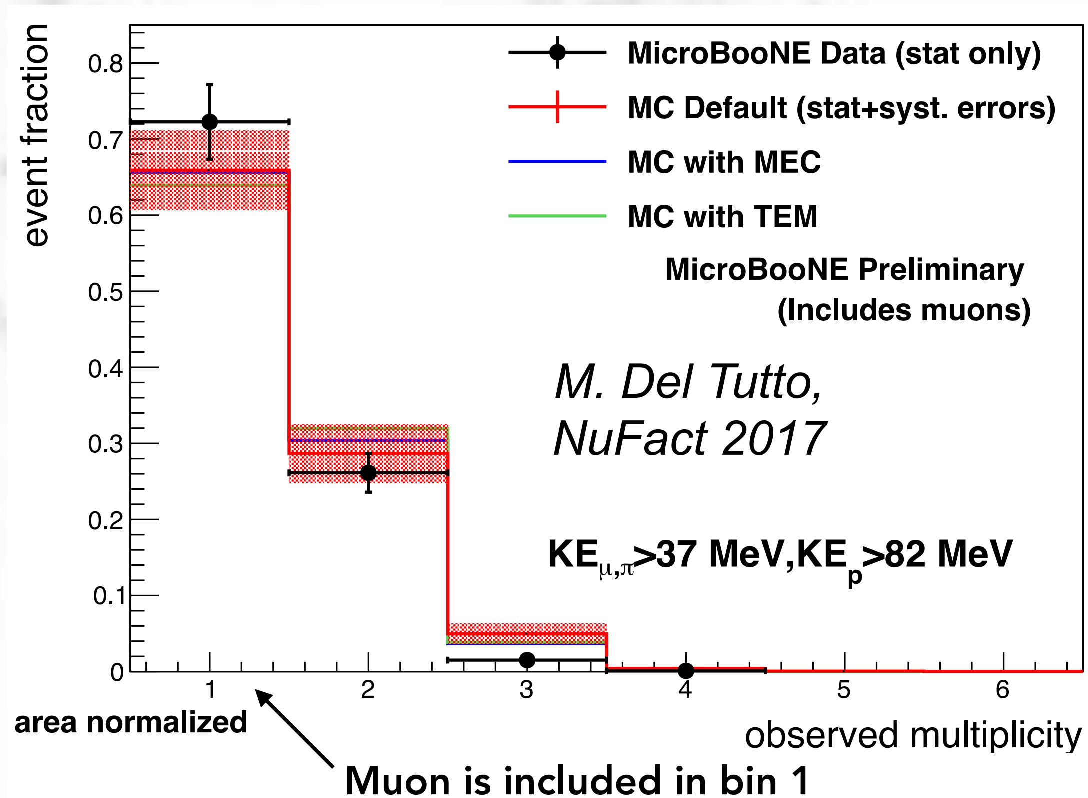
Some Highlights of Progress

Progress toward Low Threshold Multiplicities in Liquid Argon

Low Threshold Multiplicities

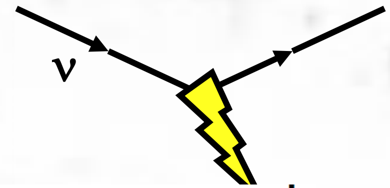


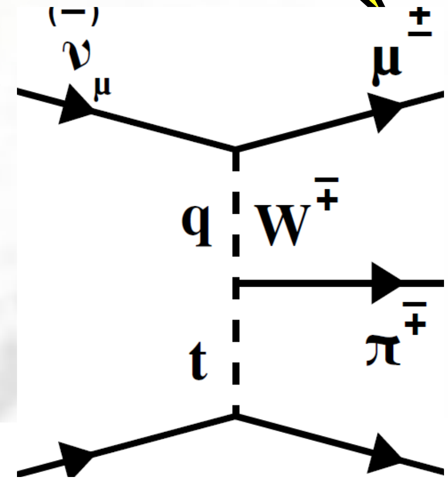
- Low energy particles, such as spectator nucleons and pions, are often degraded by final state interactions
  - Important for understanding LAr reconstruction
- Obviously, early days for MicroBooNE
- Want to reduce thresholds ($\div$ 1.5?) and add particle ID to get full power of these comparisons
- Scintillator tracker thresholds are (T_π>50 MeV, T_p>90 MeV)



Coherent Pion Production

A Very Strange Reaction…



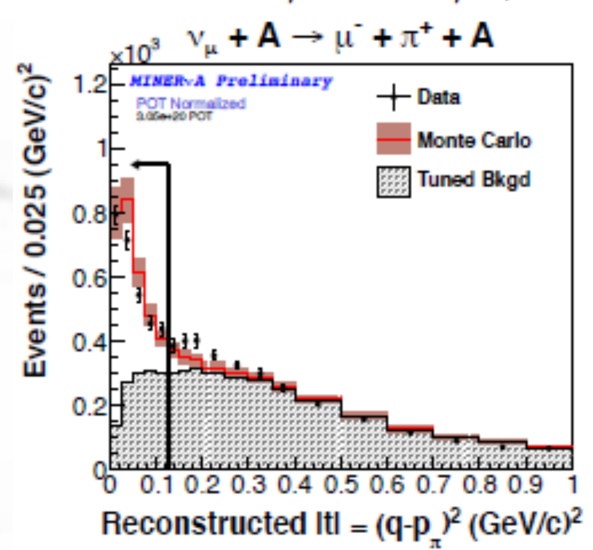


- Despite small binding energy of nucleus (few-10s MeV), a pion can be created from the off-shell W boson and leave the nucleus in its ground state
- Reaction has small 4-momentum transfer, t, to nucleus
- Can reconstruct |t| from final state
- Reconstruction of |t| gives a model-independent separation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

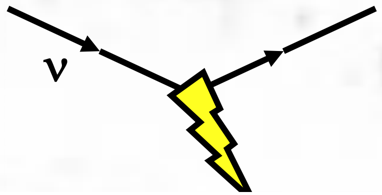
$$E_\nu = E_\mu + E_\pi$$

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

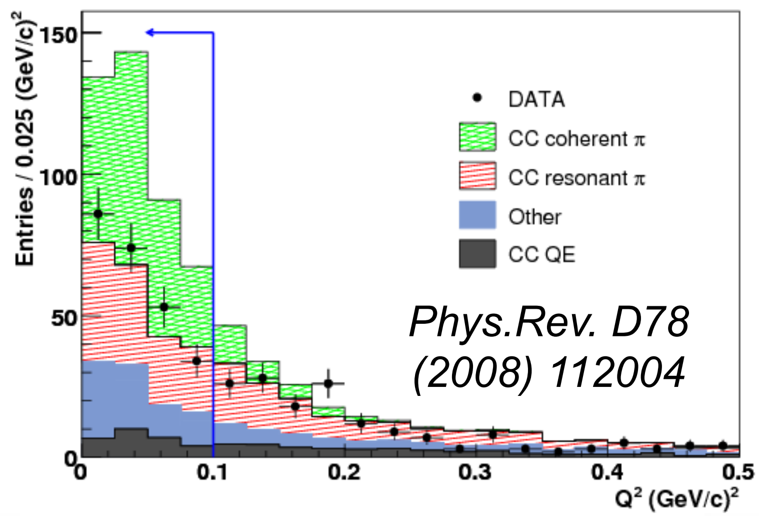
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$



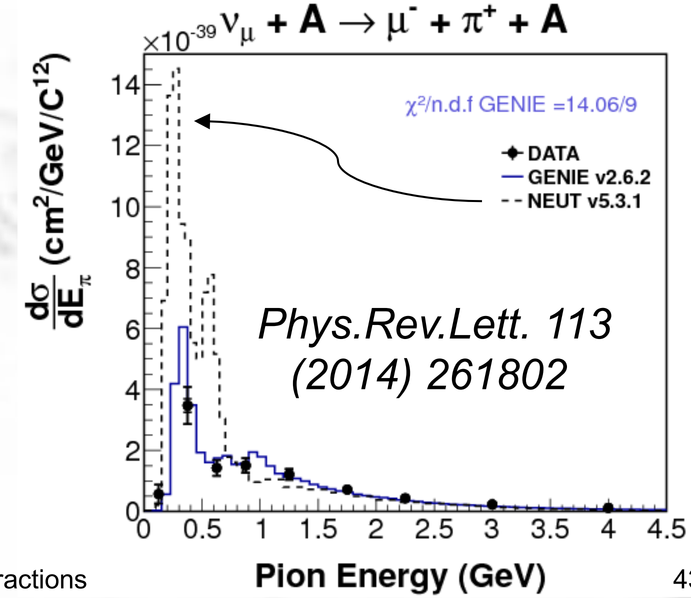
With a strange past…



- The SciBooNE experiment with a beam energy ~1 GeV didn't see this reaction at the expected level
  - This reaction has a special role in backgrounds for oscillations
  - It mimics "clean" single lepton events if pion is misreconstructed as a lepton and reaction is common.
- MINERvA showed that the expectation of the signal model was too generous at low energy.

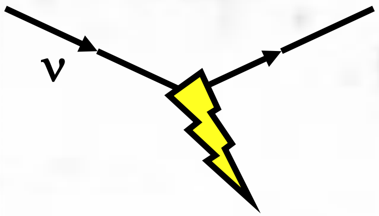


Phys.Rev. D78 (2008) 112004

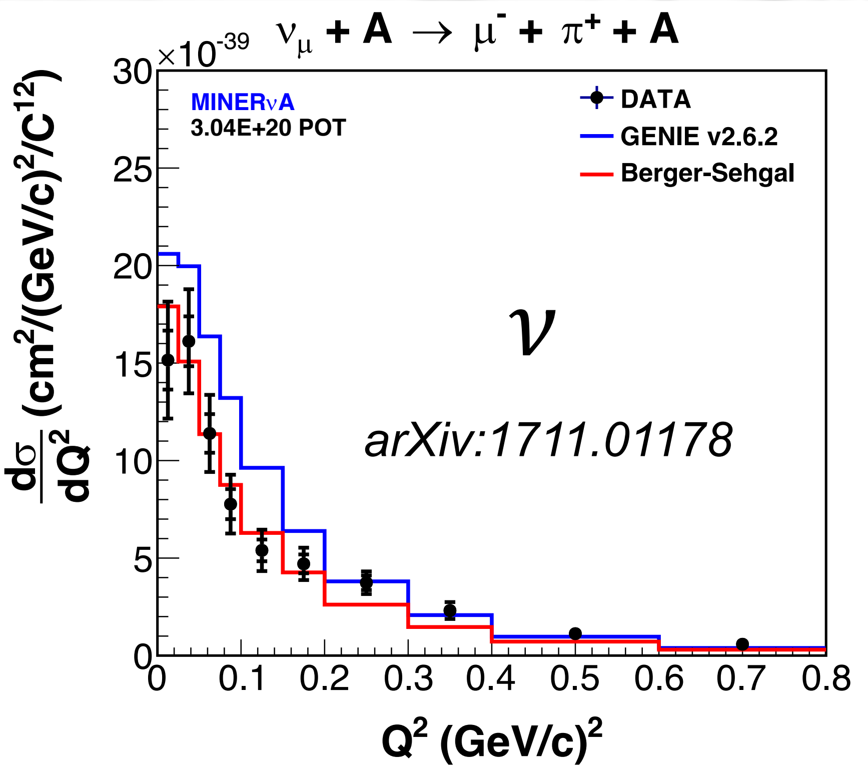


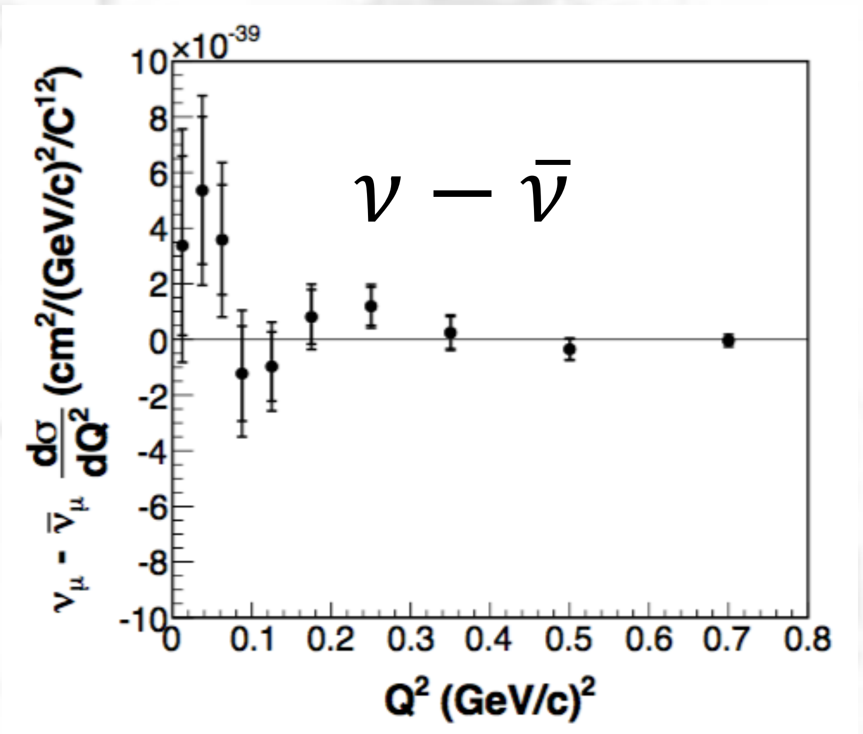
Phys.Rev.Lett. 113 (2014) 261802

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

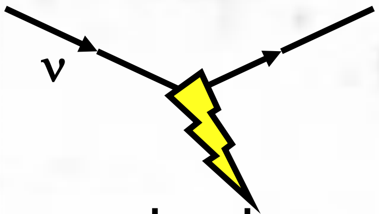


- Updated MINERvA results include $d\sigma/dQ^2$ and a direct check of the consistency of neutrino and antineutrino cross-section to check if process is purely axial vector.

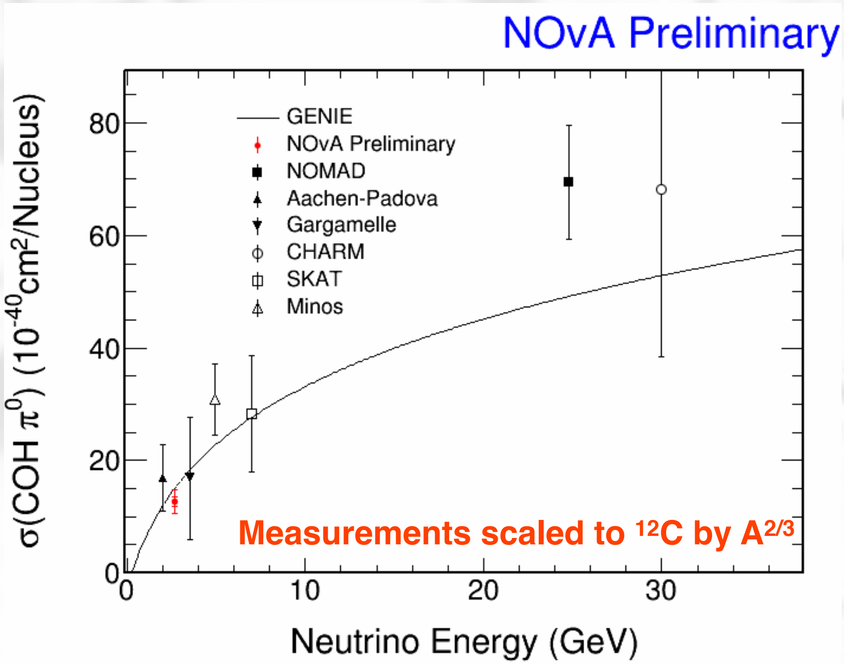


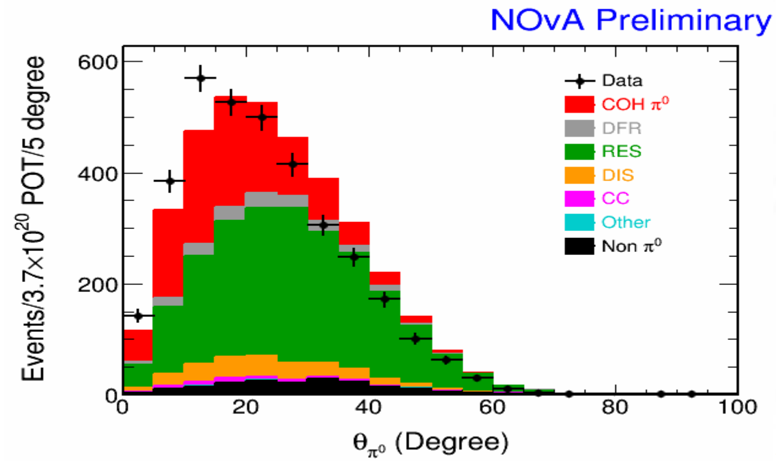


NOvA NC Coherent



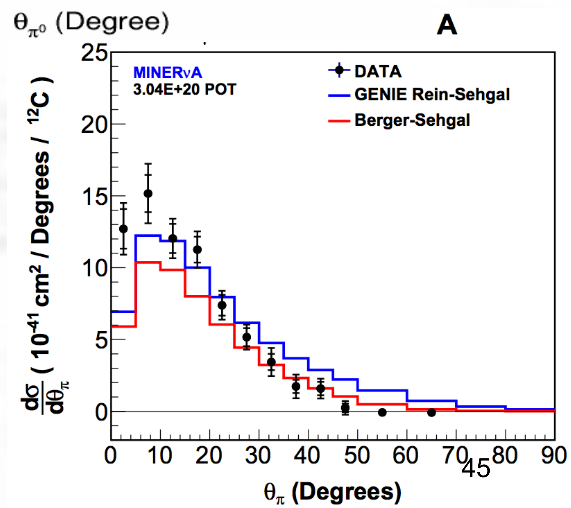
- NOvA has excellent π^0 reconstruction and has searched for this by looking at forward events
- Powerful check of model that works for charged current





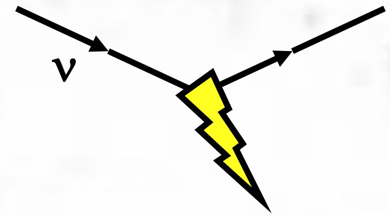
D. Hongyue, D. Pershey, FNAL JTEP Dec 2017

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



Resonance Pion Spectrum

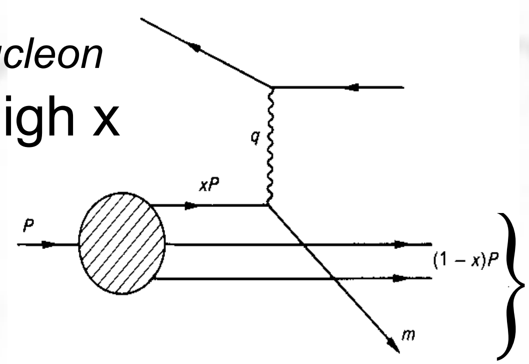
Low W, the Baryon Resonance Region



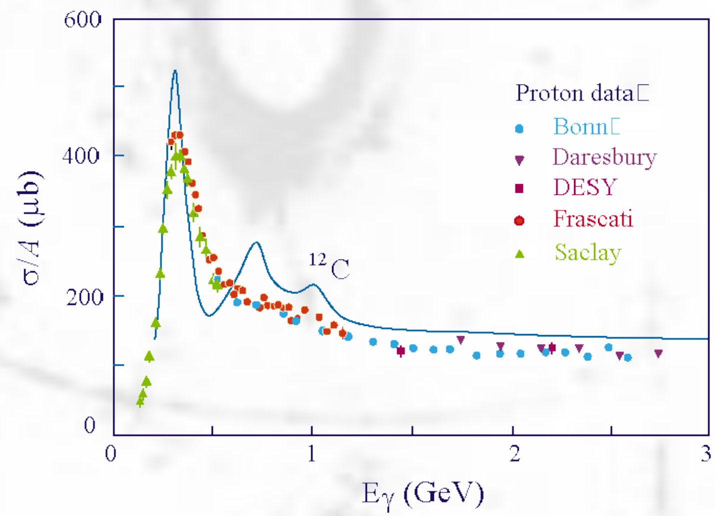
- ”Least inelastic” processes are dominated by baryon resonance production
  - Mass² of hadronic final state is given by

$$W^2 = M_T^2 + 2M_T\nu - Q^2 = M_T^2 + 2M_T\nu(1-x)$$

  - At low energy, nucleon-pion states dominated by N* and Δ resonances
- Leads to cross-section with significant structure in *W* just above $M_{nucleon}$
  - Low ν, high x



W^2



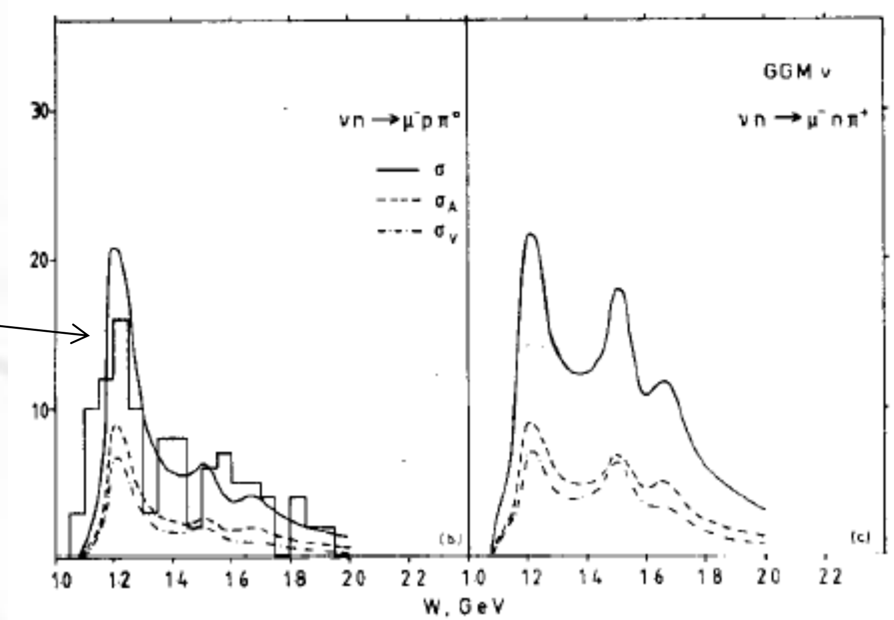
photoabsorption vs E_γ. Line shows protons.

Resonance Region Models

- Models of the resonance region are complicated
  - In principle, many baryon resonances can be excited in the scattering and they all can contribute
  - They de-excite mostly by radiating pions
- Most single pion production is from resonance decay

Nucleon Resonances below 2 GeV/c² according to Ref. [4]

Resonance Symbol[a]	Central mass value M [MeV/c²]	Total with Γ_0[MeV]	Elasticity $x_E = \pi\mathcal{N}$ branching ratio	Quark-Model/ SU_6-assignment
$P_{33}(1234)$	1234	124	1	${}^4(10)_{3/2}\ [56, 0^+]_0$
$P_{11}(1450)$	1450	370	0.65	${}^2(8)_{1/2}\ [56, 0^+]_2$
$D_{13}(1525)$	1525	125	0.56	${}^2(8)_{3/2}\ [70, 1^-]_1$
$S_{11}(1540)$	1540	270	0.45	${}^2(8)_{1/2}\ [70, 1^-]_1$
$S_{31}(1620)$	1620	140	0.25	${}^2(10)_{1/2}\ [70, 1^-]_1$
$S_{11}(1640)$	1640	140	0.60	${}^4(8)_{1/2}\ [70, 1^-]_1$
$P_{33}(1640)$	1640	370	0.20	${}^4(10)_{3/2}\ [56, 0^+]_2$
$D_{13}(1670)$	1670	80	0.10	${}^4(8)_{3/2}\ [70, 1^-]_1$
$D_{15}(1680)$	1680	180	0.35	${}^4(8)_{5/2}\ [70, 1^-]_1$
$F_{15}(1680)$	1680	120	0.62	${}^2(8)_{5/2}\ [56, 2^+]_2$
$P_{11}(1710)$	1710	100	0.19	${}^2(8)_{1/2}\ [70, 0^+]_2$
$D_{33}(1730)$	1730	300	0.12	${}^2(10)_{3/2}\ [70, 1^-]_1$
$P_{13}(1740)$	1740	210	0.19	${}^2(8)_{3/2}\ [56, 2^+]_2$
$P_{31}(1920)$	1920	300	0.19	${}^4(10)_{1/2}\ [56, 2^+]_2$
$F_{35}(1920)$	1920	340	0.15	${}^4(10)_{5/2}\ [56, 2^+]_2$
$F_{37}(1950)$	1950	340	0.40	${}^4(10)_{7/2}\ [56, 2^+]_2$
$P_{33}(1960)$	1960	300	0.17	${}^4(10)_{3/2}\ [56, 2^+]_2$
$F_{17}(1970)$	1970	325	0.06	${}^4(8)_{7/2}\ [70, 2^+]_2$

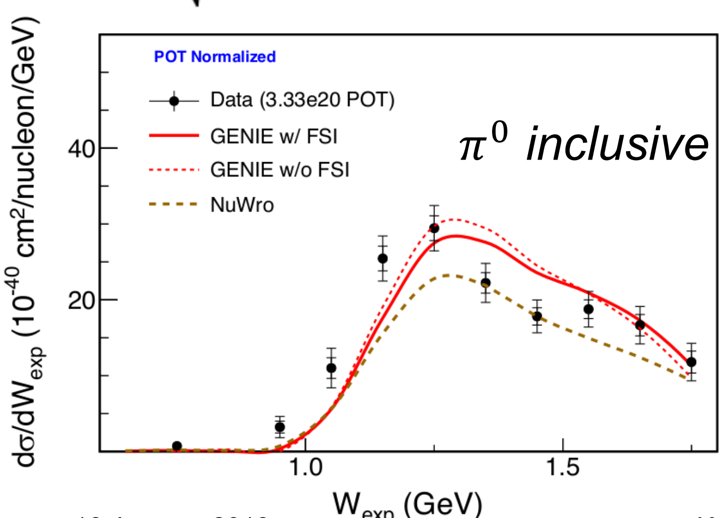


D. Rein and L. Sehgal, Ann. Phys. 133, 79 (1981)

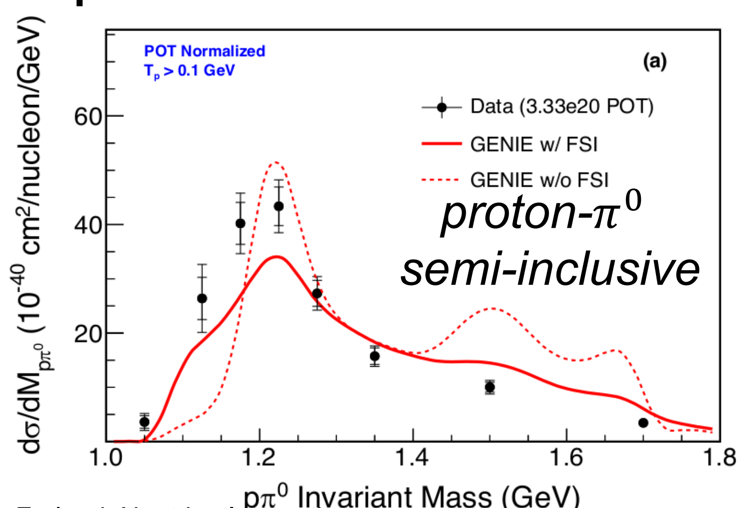
Δ Resonance Data on Nuclei

- Some confusing results in pion production nuclei at low momenta suggest unexpected features in pion production.
  - "MiniBooNE/MINERvA pion puzzle"
- Recent MINERvA results on proton-π^0 final states suggest a shift to lower *W* from expectation of Δ region.
- Likely because of deficiencies in resonance model.

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



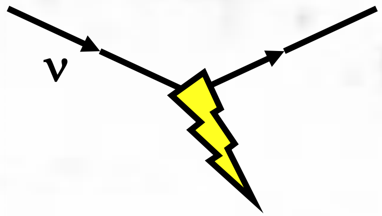
Invariant Mass calculated with proton and π^0 4-momentums



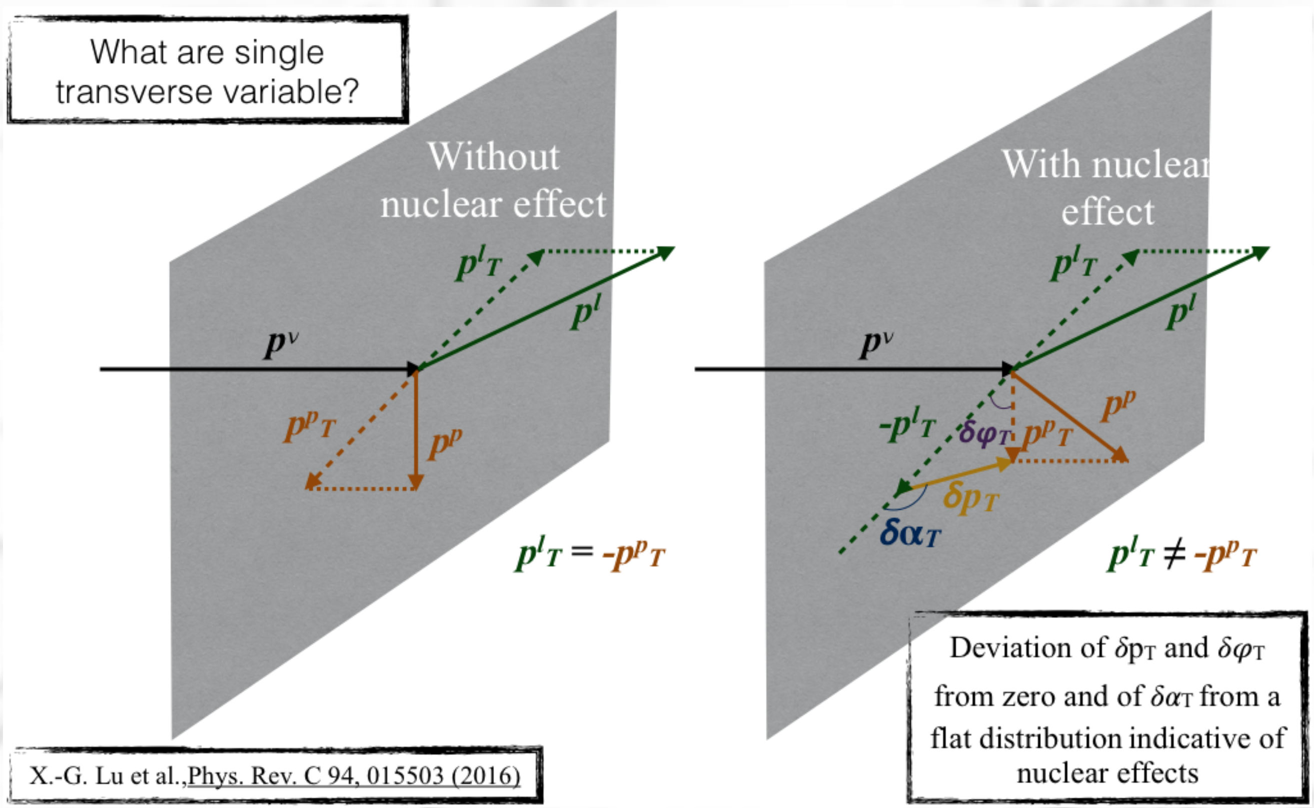
Phys.Rev. D96 (2017) 072003

Proton-Muon Correlations in Pionless Events (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 CC0π events! *Figure compiled by C. Riccio*



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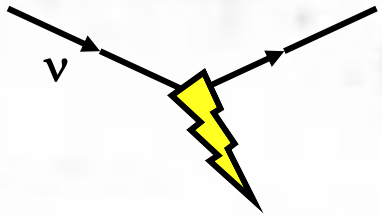
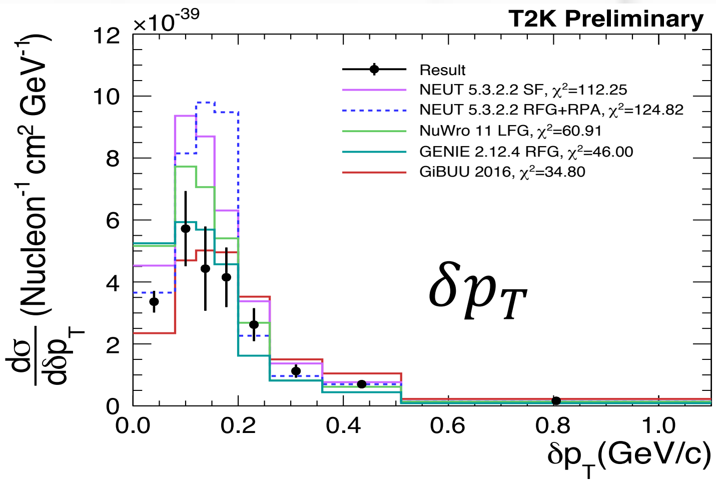
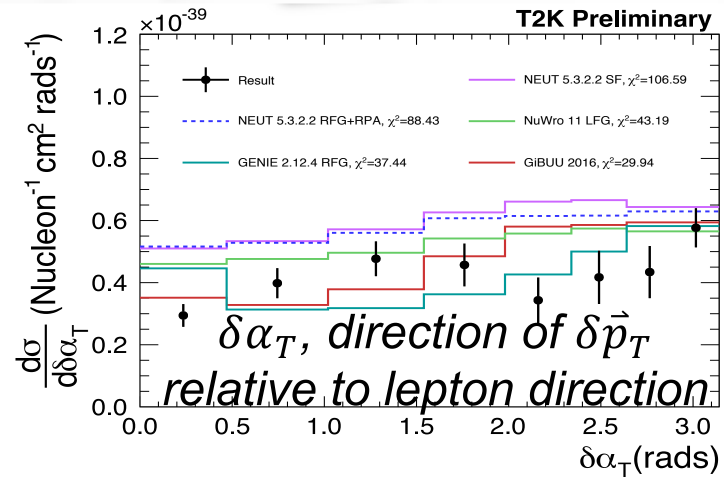
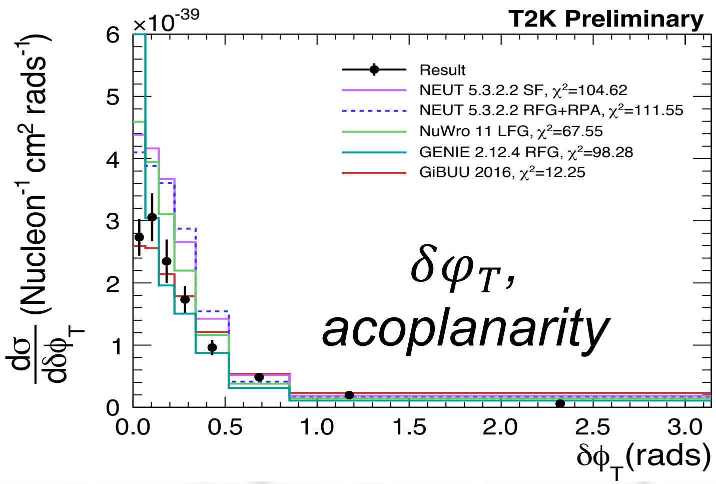




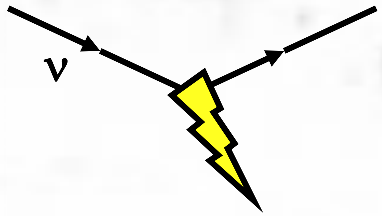




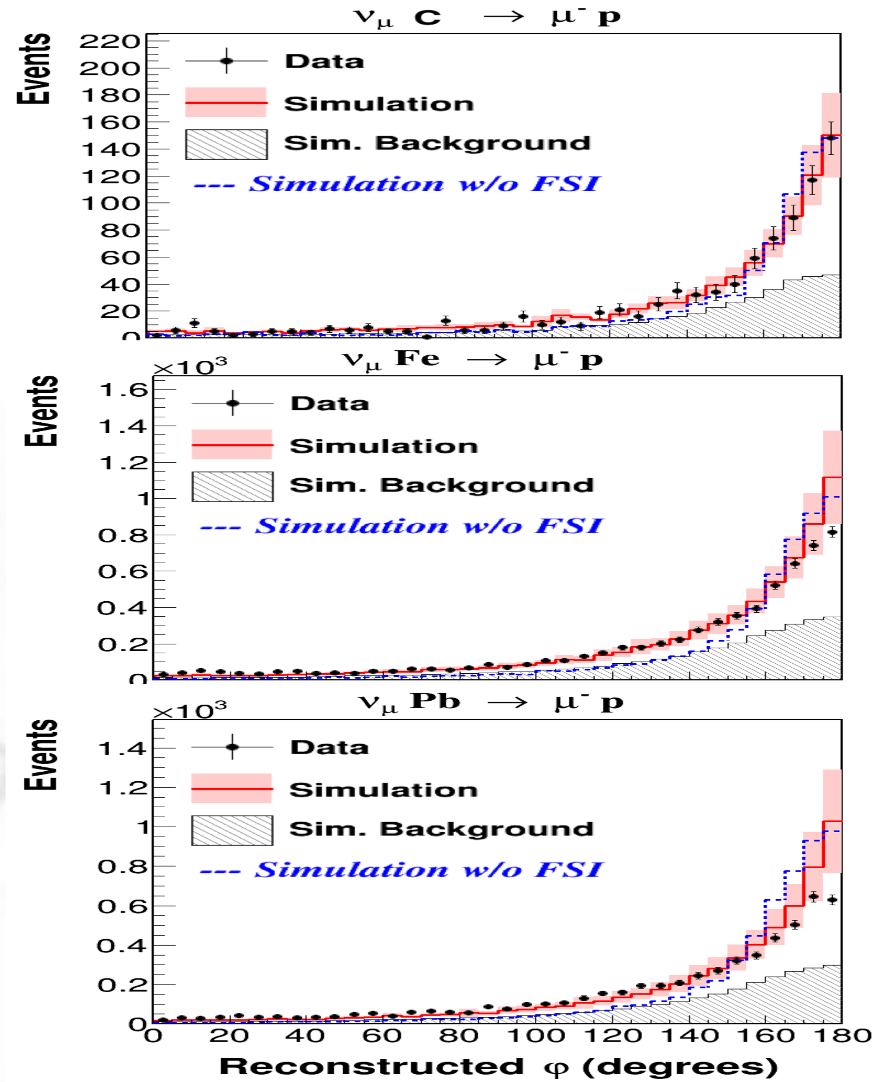
S. Dolan, Oxford D.Phil. thesis

- Current comparisons have initial state and final state effects together for different models.
- GENIE excess in first bins related to a feature of FSI model
- Data favors more realistic local Fermi Gas and Spectral function models over global Fermi Gas

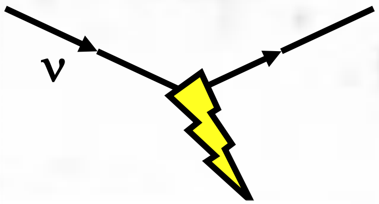
Proton-Muon Correlations on Different Nuclei



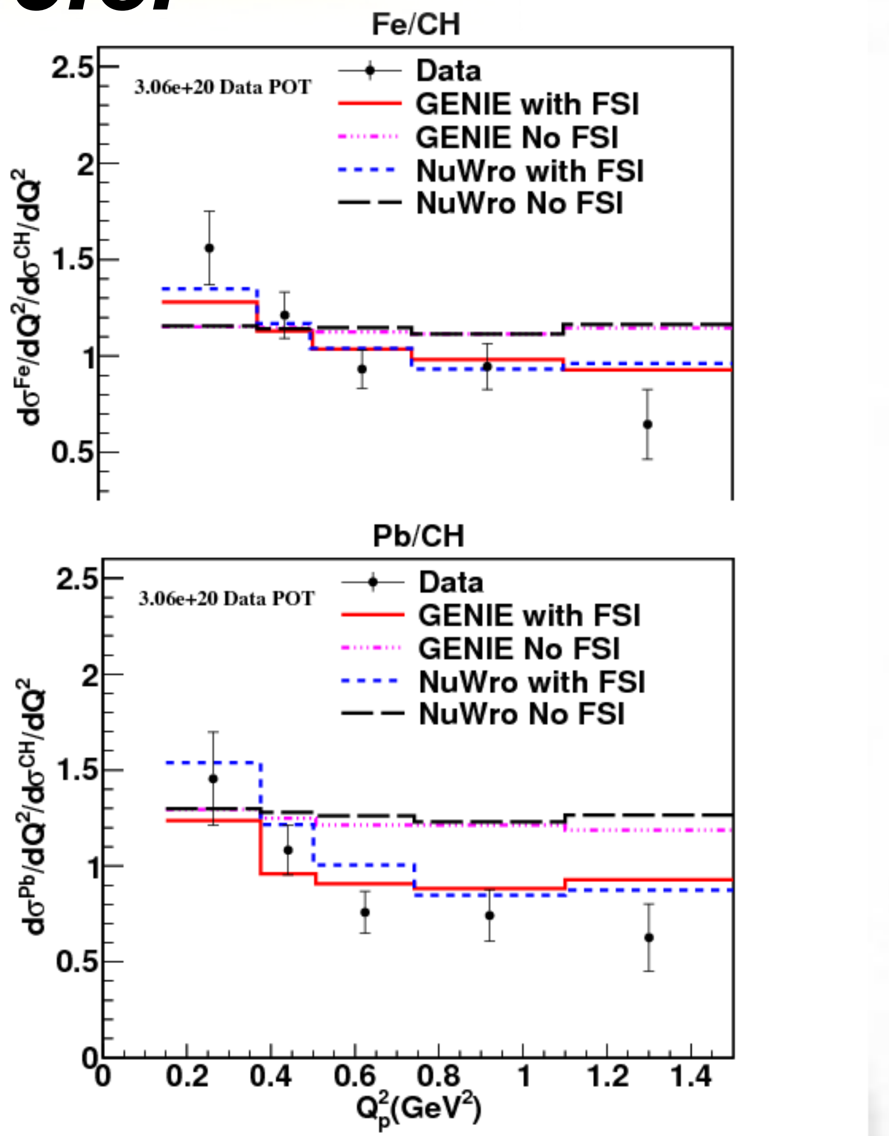
- MINERvA has done a similar analysis, but comparing scintillator (CH) to Fe and Pb
  Phys. Rev. Lett. 119 082001 (2017)
- This is one of the transverse variables from previous slide,
  $$\pi - \delta\varphi_T \rightarrow \varphi$$
- Model describes carbon, but fails to describe Fe, Pb



Proton-Muon Events on Different Nuclei

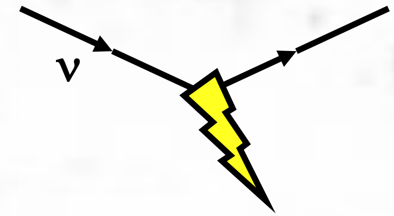


- Ratio of Fe and Pb to scintillator (CH) as a function of recoiling proton energy also shows model discrimination.
  Phys. Rev. Lett. 119 082001 (2017)
- Next steps are to follow T2K's lead of looking at complete set of correlations.

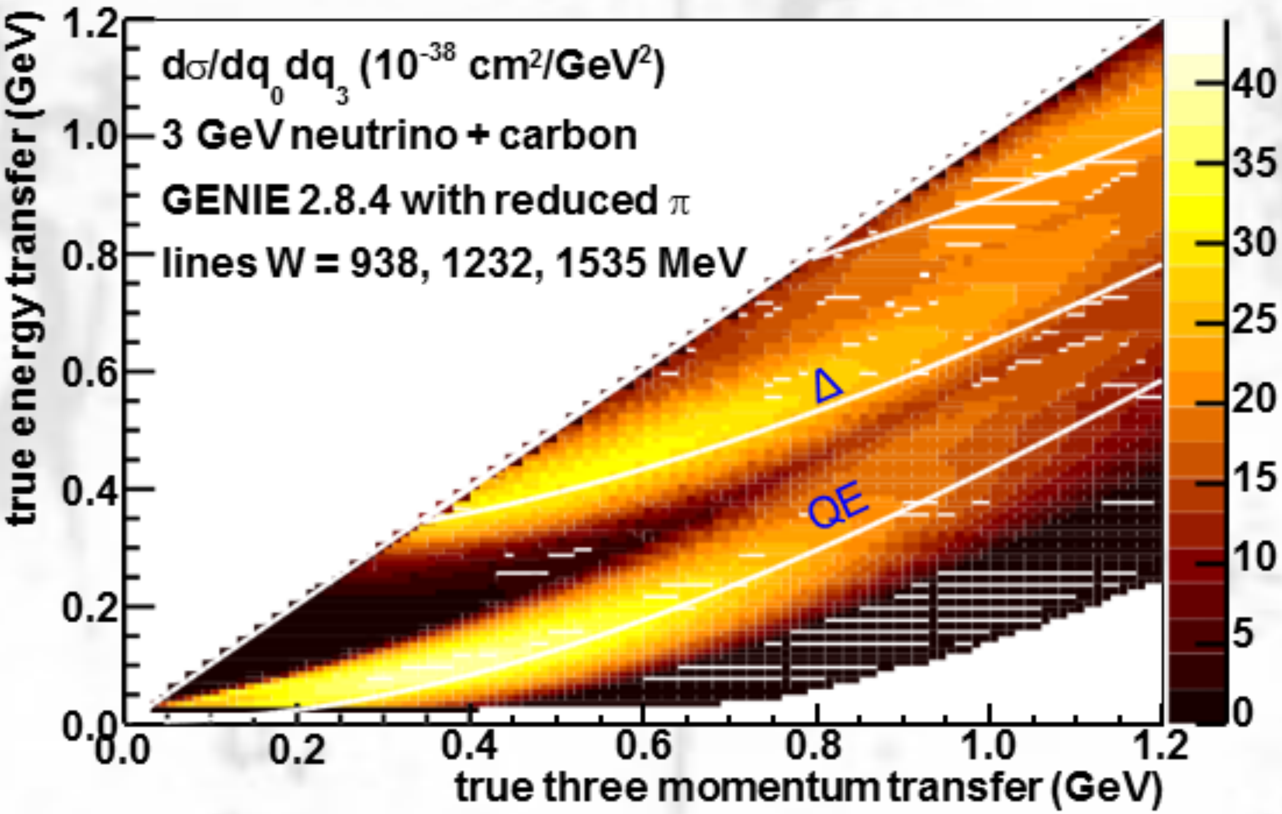


Progress Towards a Descriptive CC0π Model

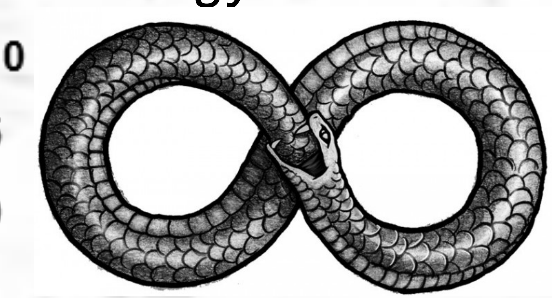
Recall… energy



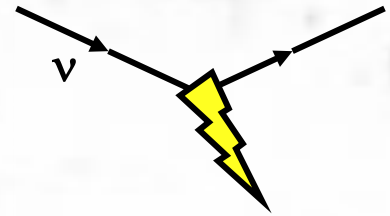
- More precisely, since single arm experiments would be wasteful ☺, we would measure these distributions of energy and momentum transfer.



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"*

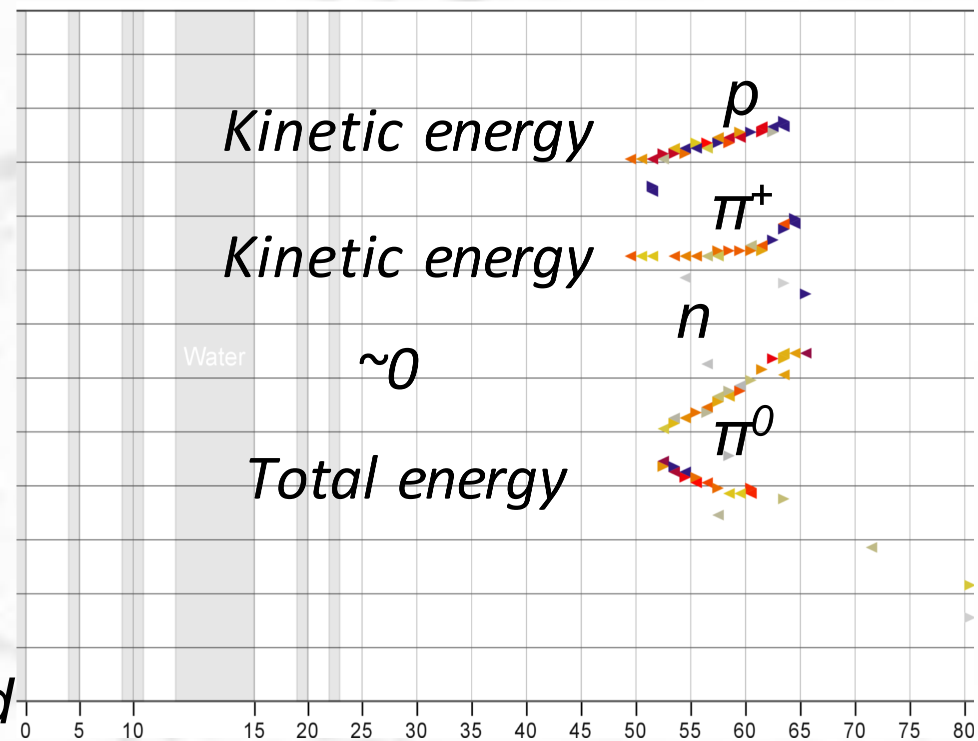
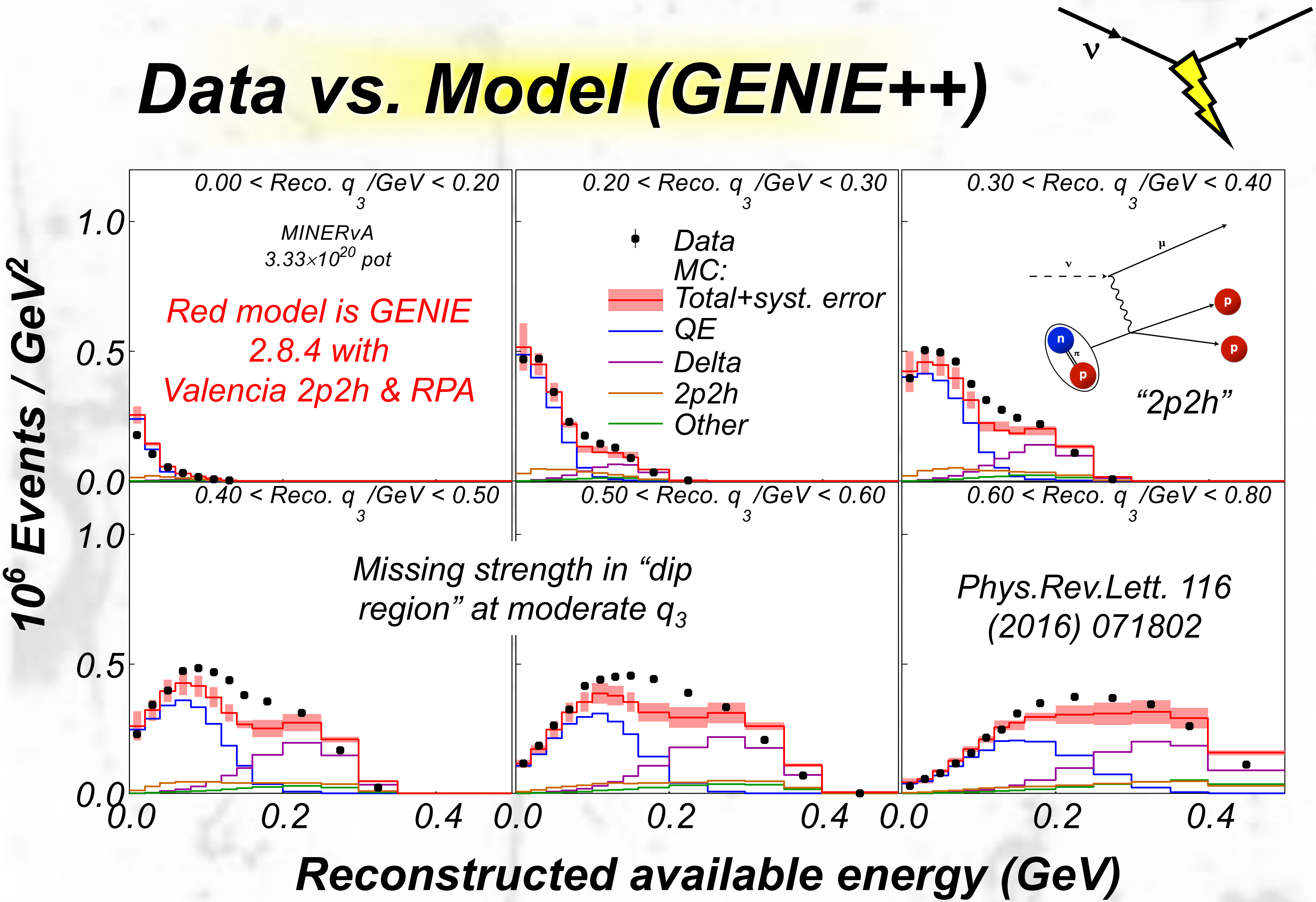


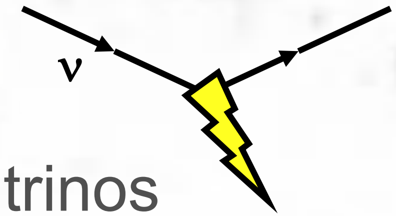
Figure courtesy P. Rodrigues

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

Data vs. Model (GENIE++)

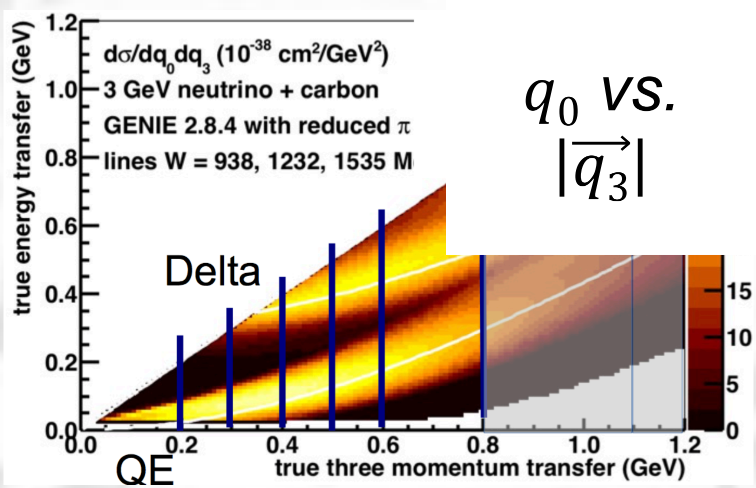


MINERvA ν_μ and anti-ν_μ "low q"

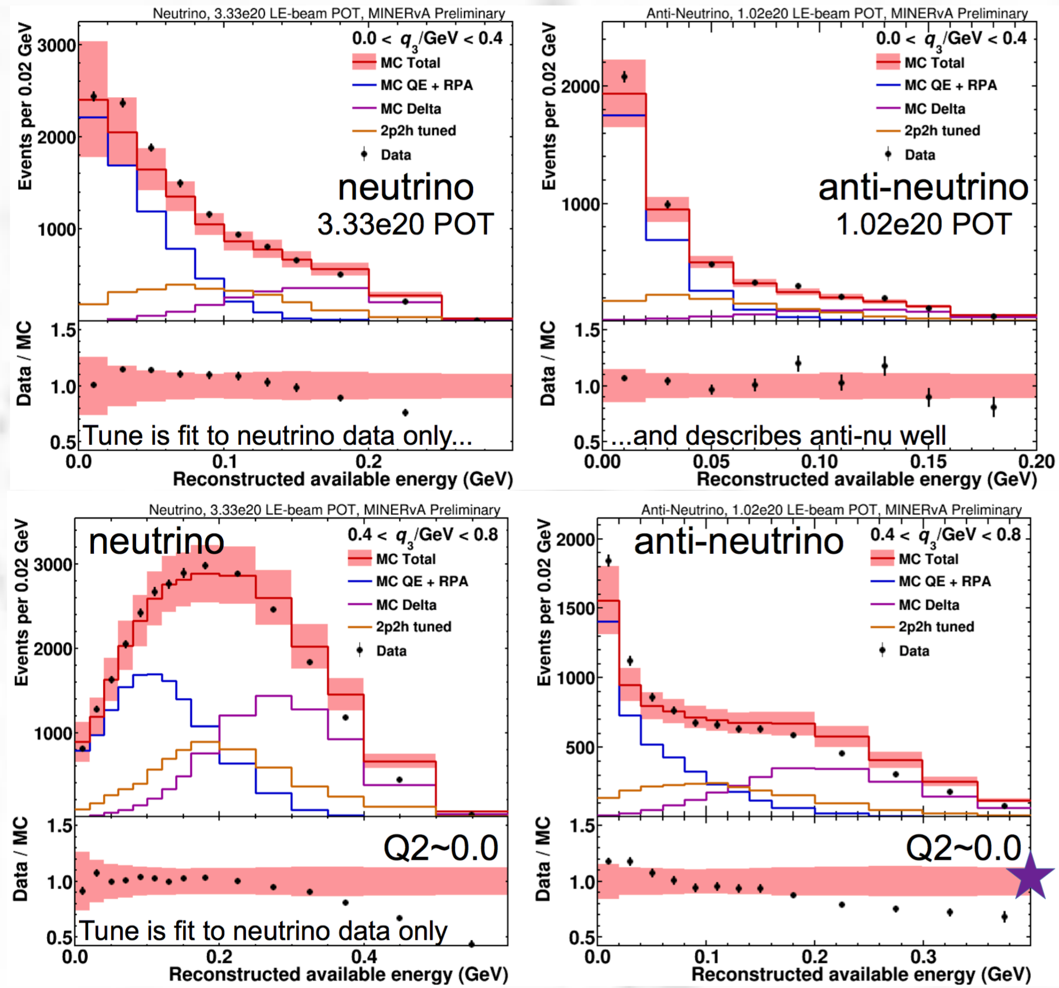


- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos

Phys. Rev. Lett. 116, 071802 (2016) and R. Gran FNAL JTEP seminar Nov 2017



q_0 vs. $|\overrightarrow{q_3}|$



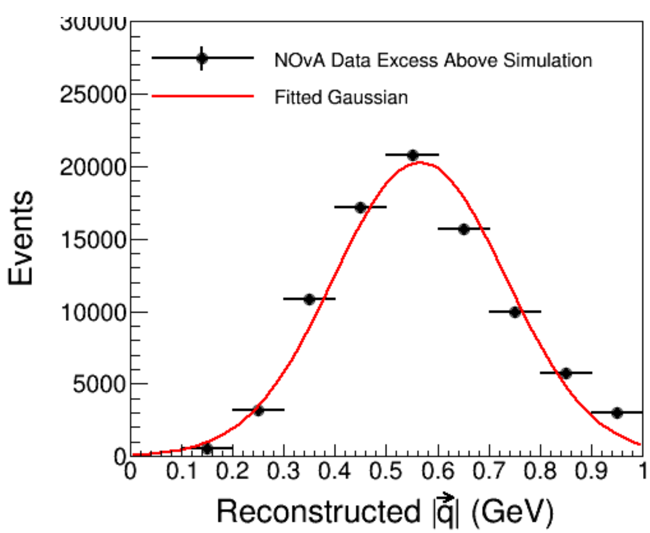
- *Tune model to fill in dip region between QE & Δ.*
- *This tune from neutrino data also agrees with antineutrino data!*

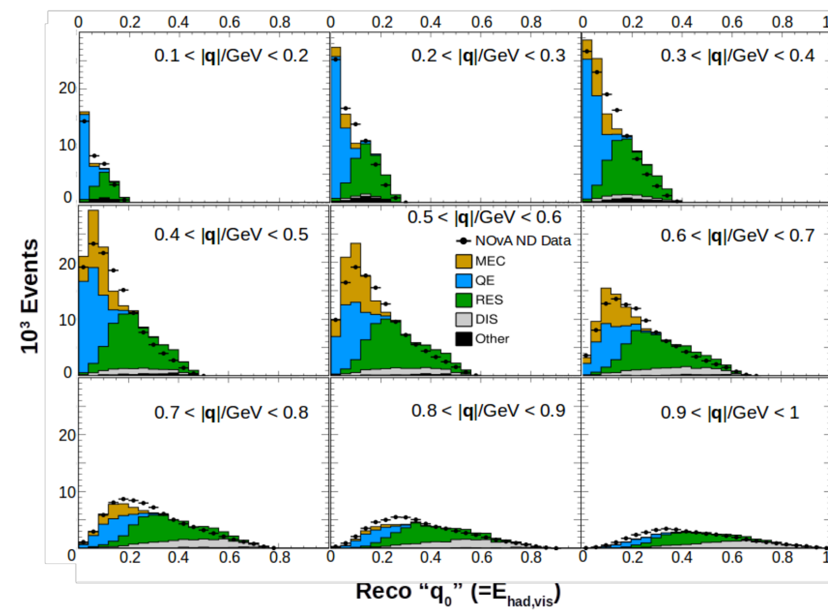
NOvA low-q Analysis

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

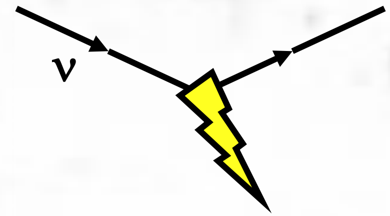
Second analyses (2016): *K. Bays @NuFact 2017*

- 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





NOvA low-q Analysis

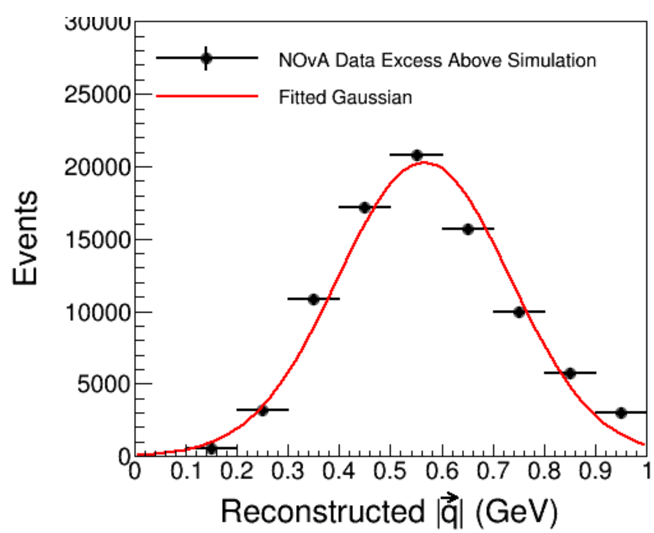


- NOvA is doing something very similar as part of its oscillation analysis evaluation of systematics

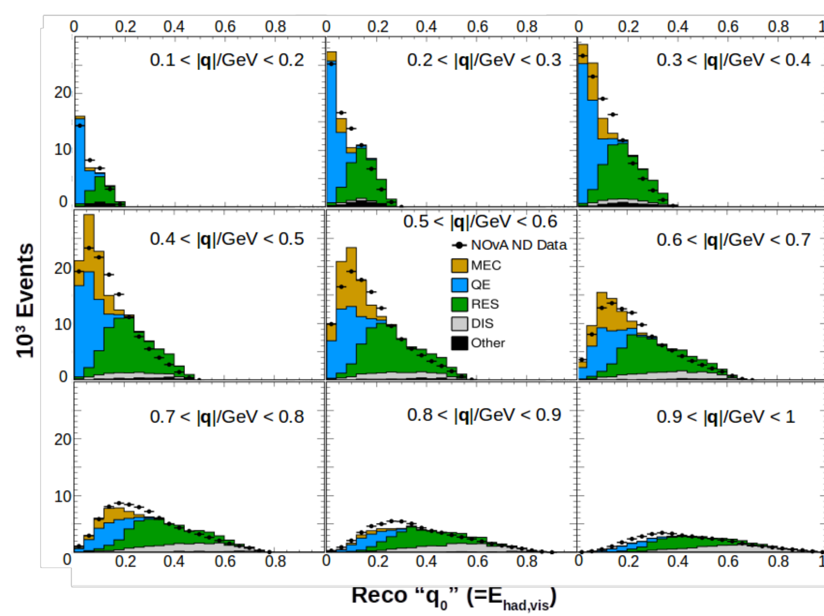
Third ~~Second~~ analyses ~~(2016)~~: (2018)

K. Bays @NuFact 2017

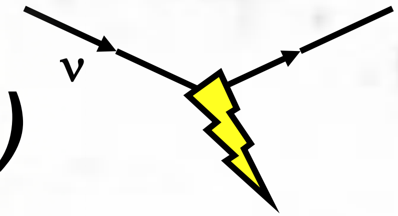
- Dytman 'empirical MEC' model is included in GENIE and used by NOvA
- Momentum transfer distribution fit to ND data; energy transfer set to match QE
- ~~A 50% normalization uncertainty is taken~~



Use Δ-like and non Δ-like energy transfer



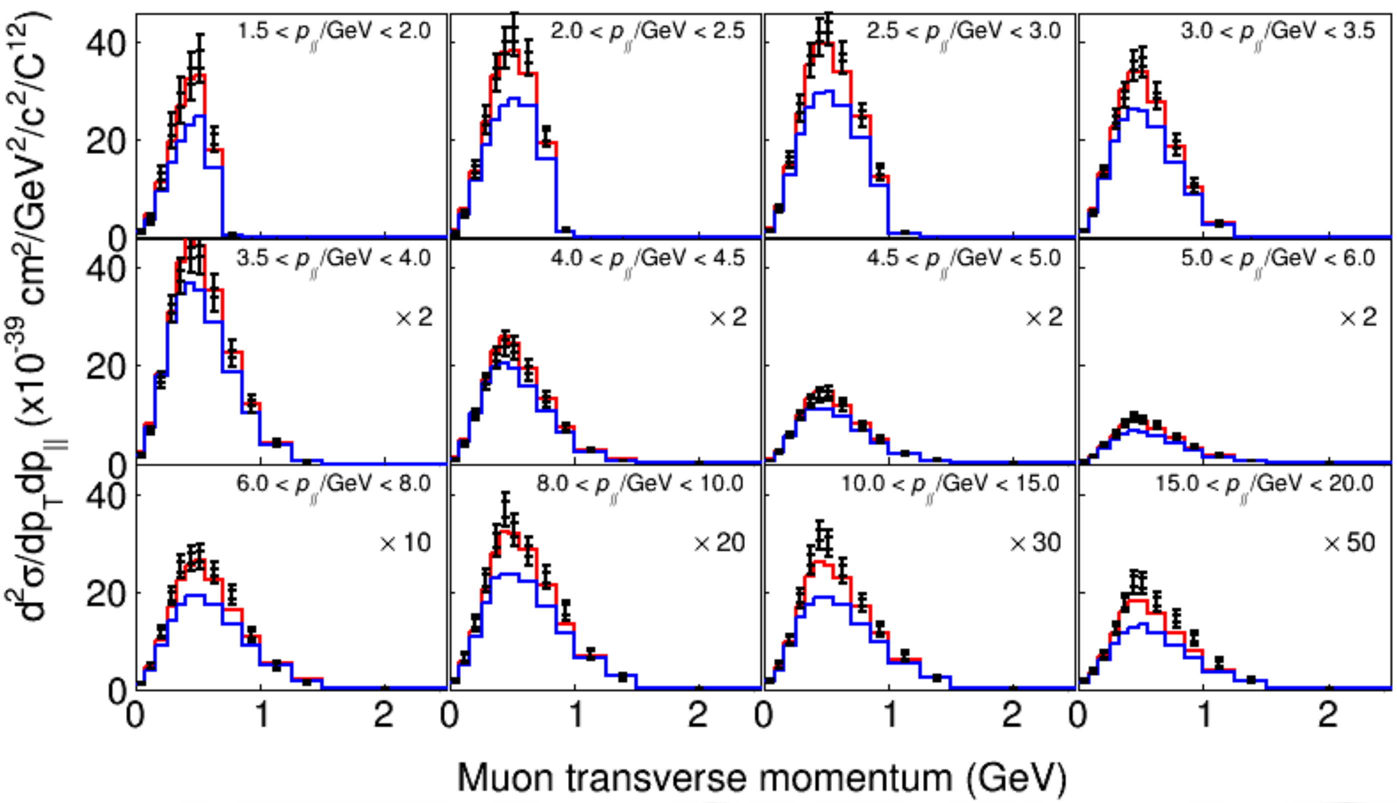
MINERvA ν pionless events (CC0π)

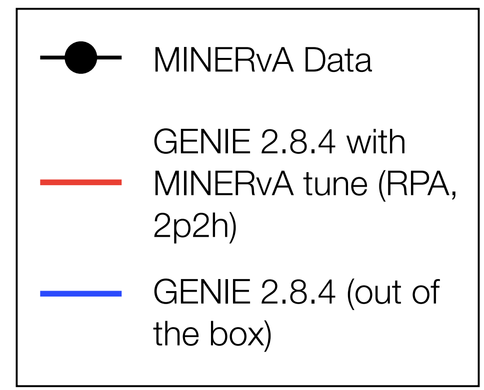


- What if we take tune to inclusive data and feed it back to predict muon distributions in an exclusive channel?

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

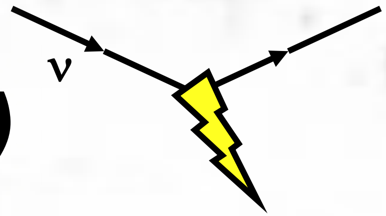
ν





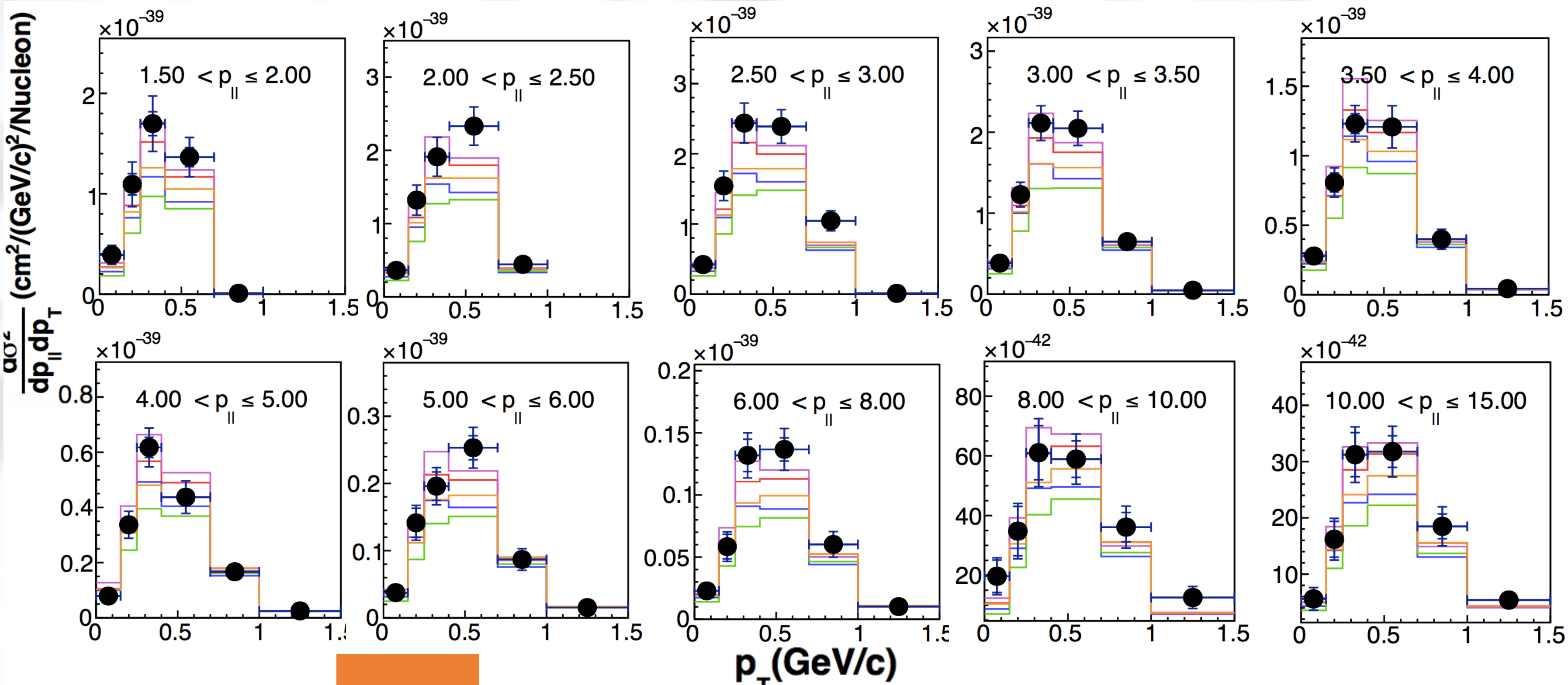
D. Ruterbories @NuINT2017, C. Patrick @NuFact2017

MINERvA $\bar{\nu}$ pionless events (CC0π)



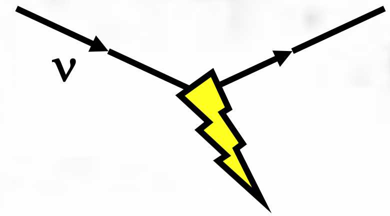
- What if we take tune to inclusive data and feed it back to predict muon distributions in a different exclusive channel?

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



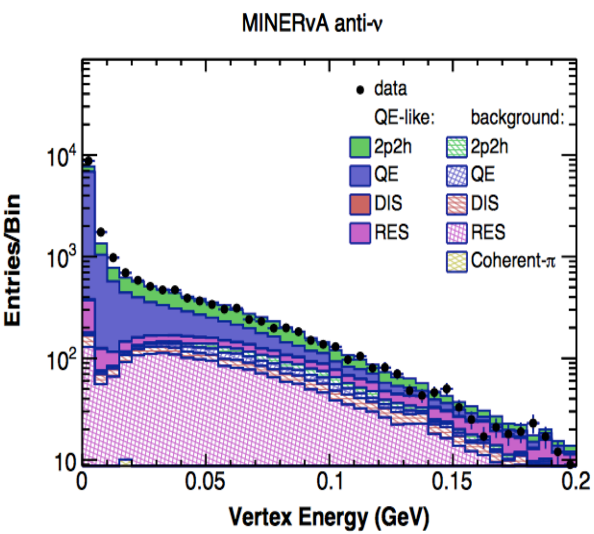
arxiV:1801.01197

Low energy protons in pionless events (CC0π)

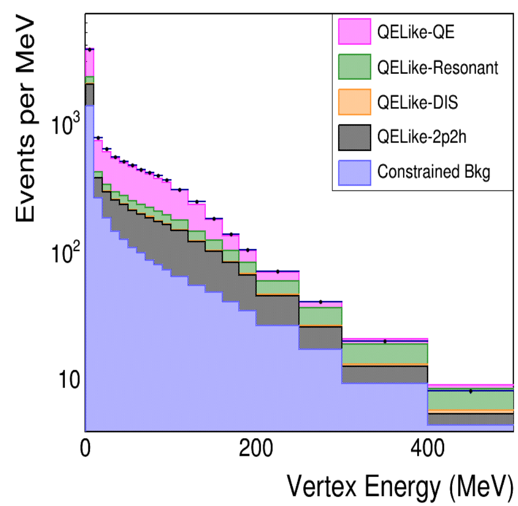


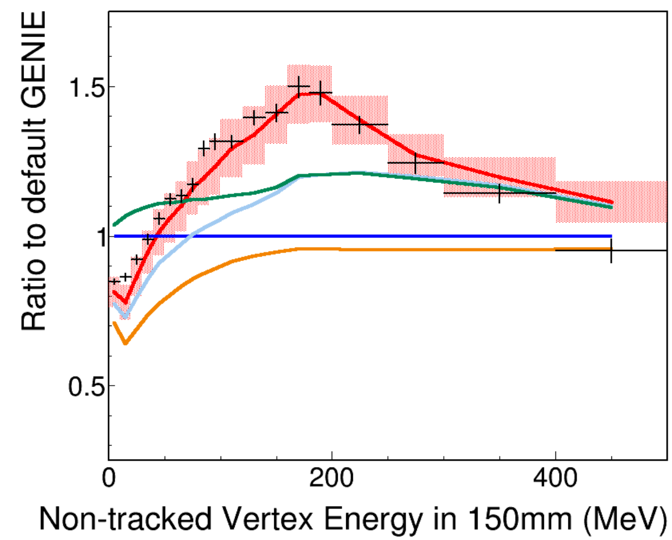
- Does this tune get details right, like energy from protons below tracking threshold? "Vertex energy"

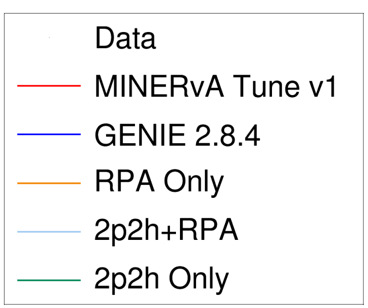
$\bar{\nu}$



ν

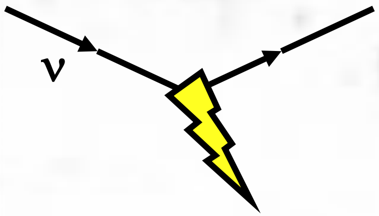






C. Patrick @NuFact2017 and D. Ruterbories @NuINT2017
arxiV:1801.01197 (antineutrino)

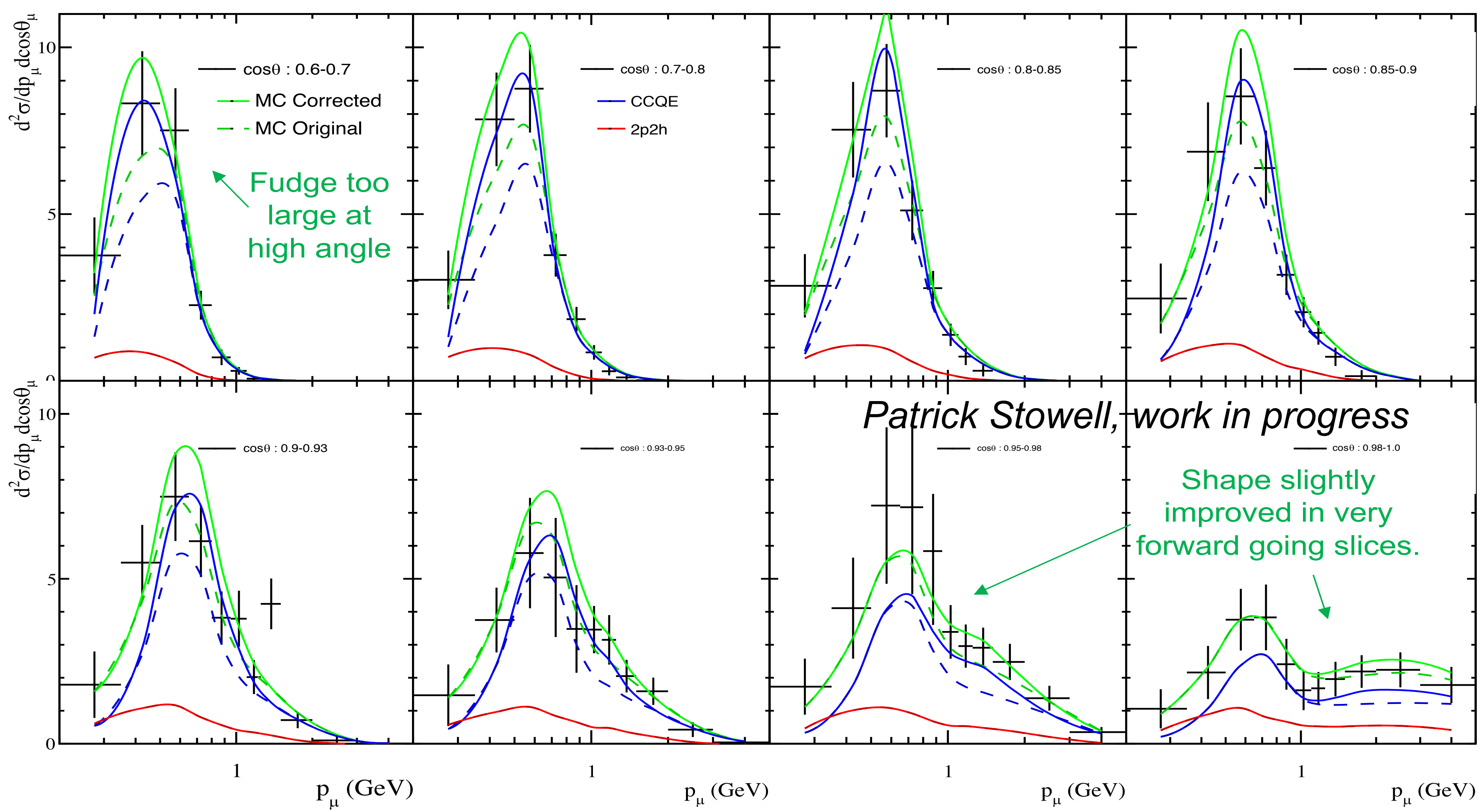
Summary of CC0π Model



- 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

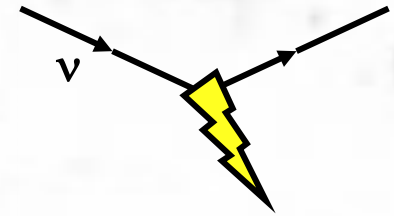
- “Model” is tuned to inclusive data which suggest an additional 2p2h (and/or some ”regular” 1p1h) at moderate, ~0.4 GeV, three-momentum transfer
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.
- Can it be applied to T2K, MicroBooNE energies?

Apply to T2K CC0π… fails

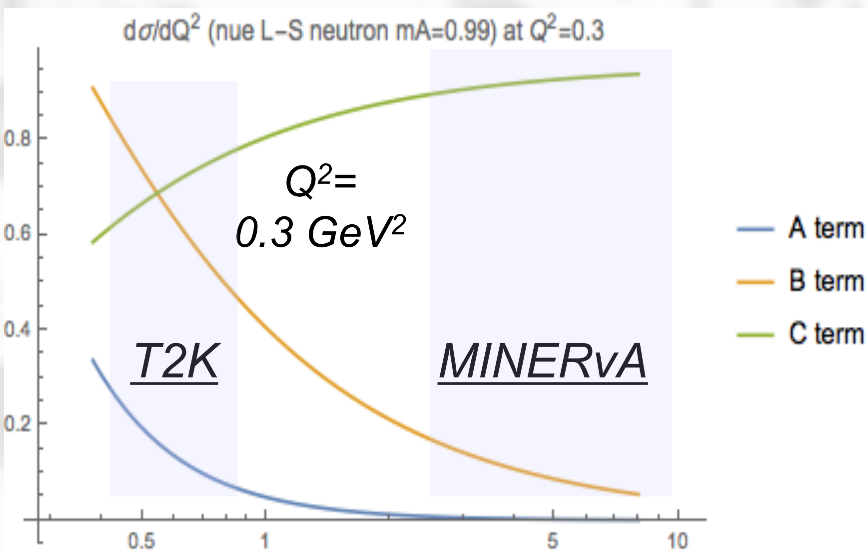


Phys. Rev. D93, 112012 (2016)

Could the "MINERvA tune" be Energy Dependent?



- At MINERvA energies, should we expect any? Not much.



CCE on free neutrons E_ν *(GeV)*

- *What are the A, B, C terms?*

- It turns out that there is a general form for energy dependence in exclusive and inclusive reactions on nucleons

$$E_\nu^2 \frac{d\sigma}{dQ^2 d\nu} = \breve{A} + \breve{B} E_\nu + \breve{C} E_\nu^2$$

  - *This holds for QE, 2p2h, etc.*

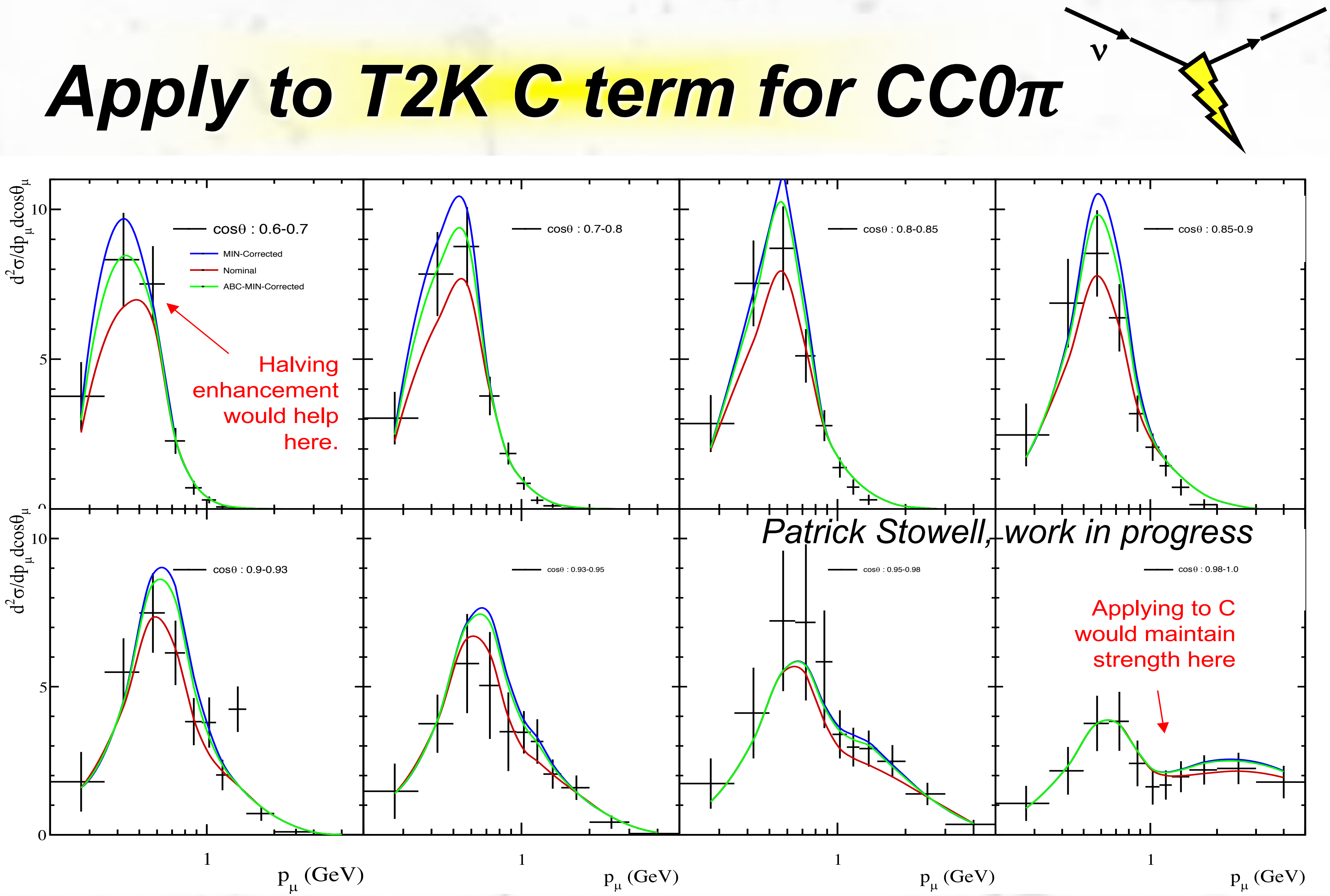
An expansion similar to eq. (2.5) holds for $\overline{\sum}\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

$$\overline{\sum}\sum m_{\mu\nu} \;\; \overline{\sum}\sum W^{\mu\nu} = A + B\,k\cdot P + C(k\cdot P)^2\,, \qquad (2.7)$$

a quadratic polynomial in the laboratory energy $E_{\bar\nu} = k\cdot P/M$ whose coefficients A, B and C depend on ν, q^2, and the reaction in question [L14, P2], It follows that if the interaction is of the current-current form *then* $E_\nu^2\, d^2\sigma/dq^2 d\nu$ *is a quadratic polynomical in* E_ν (cf. eqs. (2.10) and (2.11)) and therefore *only three combinations of structure functions are obtained if the final lepton polarization is not observed*. An alternative way to obtain the same result is to note that

C.H. Llewellyn Smith, Phys. Rep. 3 261-379 (1972), p. 280

Apply to T2K C term for CC0π



Phys. Rev. D93, 112012 (2016)

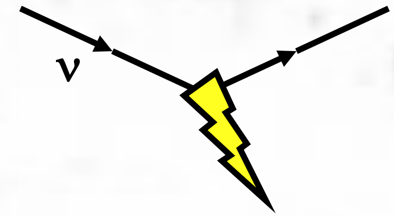
Conclusions

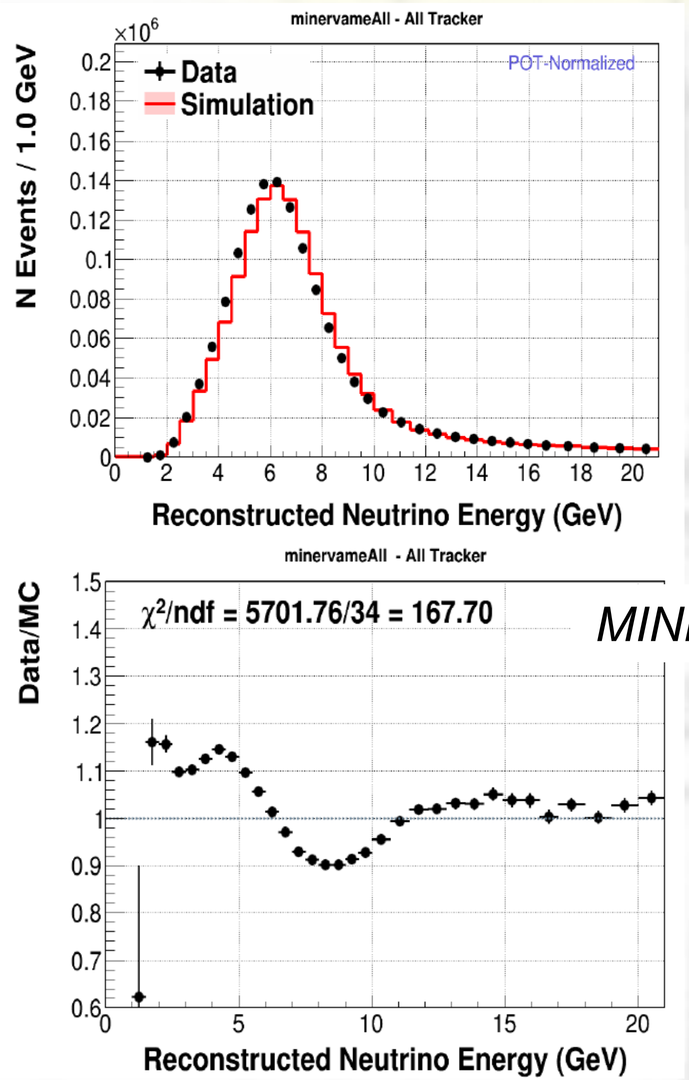
Conclusions

- We are approaching a plausible, data-driven description of the zero pion reactions that are most/much of T2K/NOvA and HK signals.
  - Theory has some work to do to catch up.
- Single pion is ~ready for same approach.
- We have a longer, more difficult, path to follow to reach the understanding necessary for all DUNE final states, but we have demonstrated techniques.

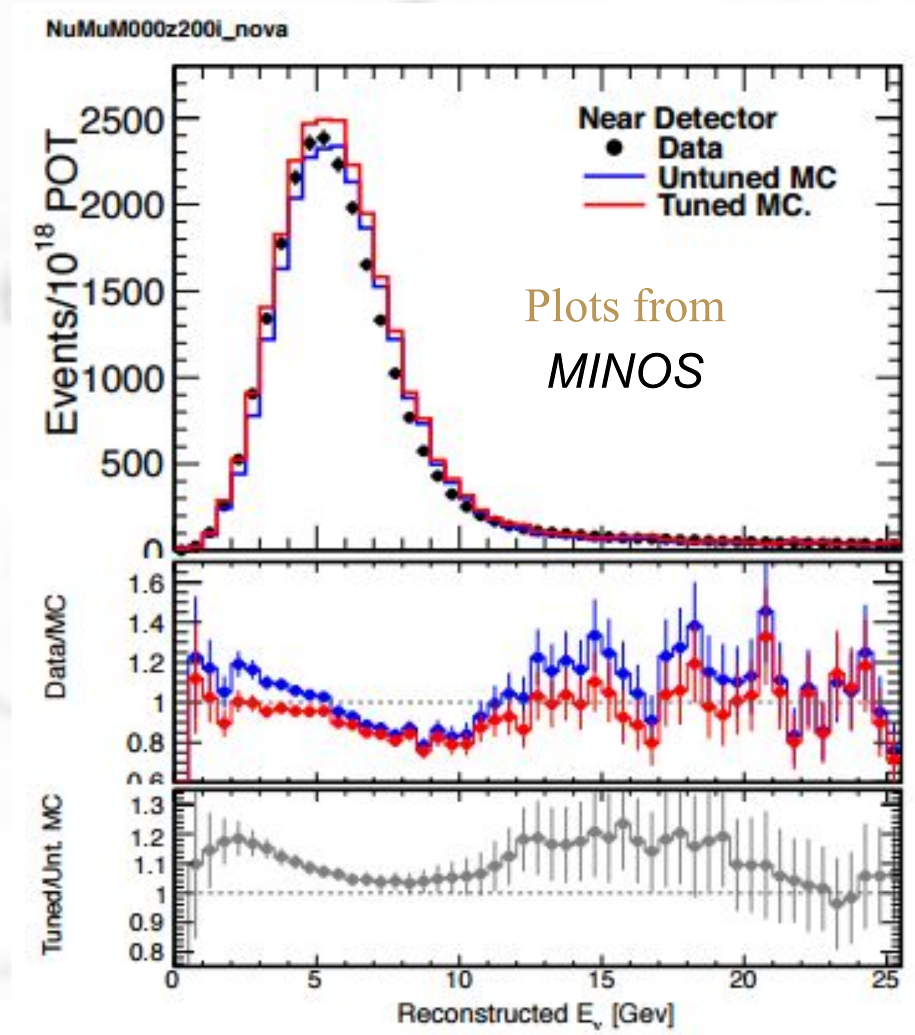
Backup

NuMI Flux Puzzle





MINERvA



Plots from

MINOS

MINERvA's neutrons