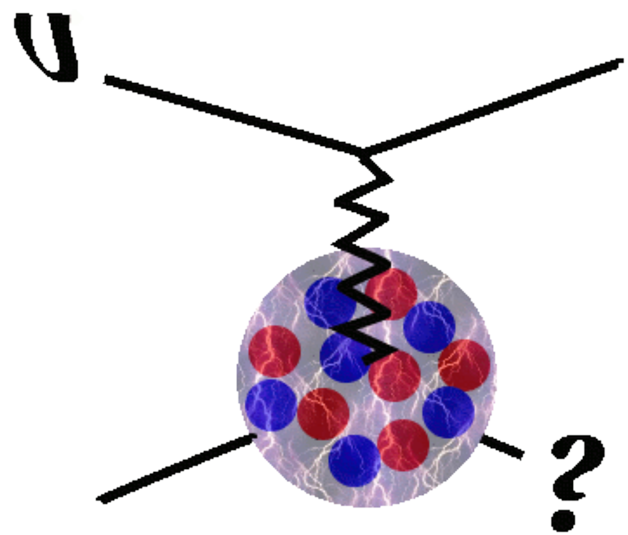
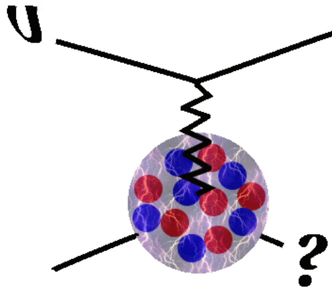
PRECISION NEUTRINO PHYSICS AND THE "REDISCOVERY" OF THE NUCLEUS

Kevin McFarland, University of Rochester
Frontiers of Electroweak Interactions of Leptons and Hadrons
Muslim Aligarh University
2 November 2016

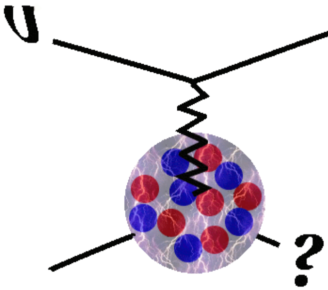




Outline

- Why the nucleus is important for precision neutrino physics
- An awkward introduction: NuINT 2001
- Puzzles in Neutrino Interactions
- Some Results from the MINERvA experiment
  - Low Recoil Scattering
  - Coherent Pion Production
  - Production of Kaons by Neutrinos

Neutrino Oscillation Goals

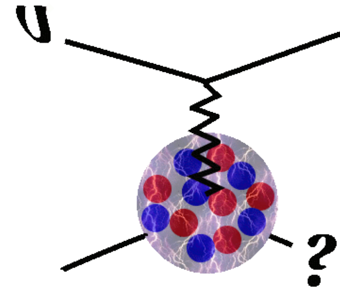


- Now that we have the wonderful tool of neutrino oscillation available to us…
- Of course we want to understand more!

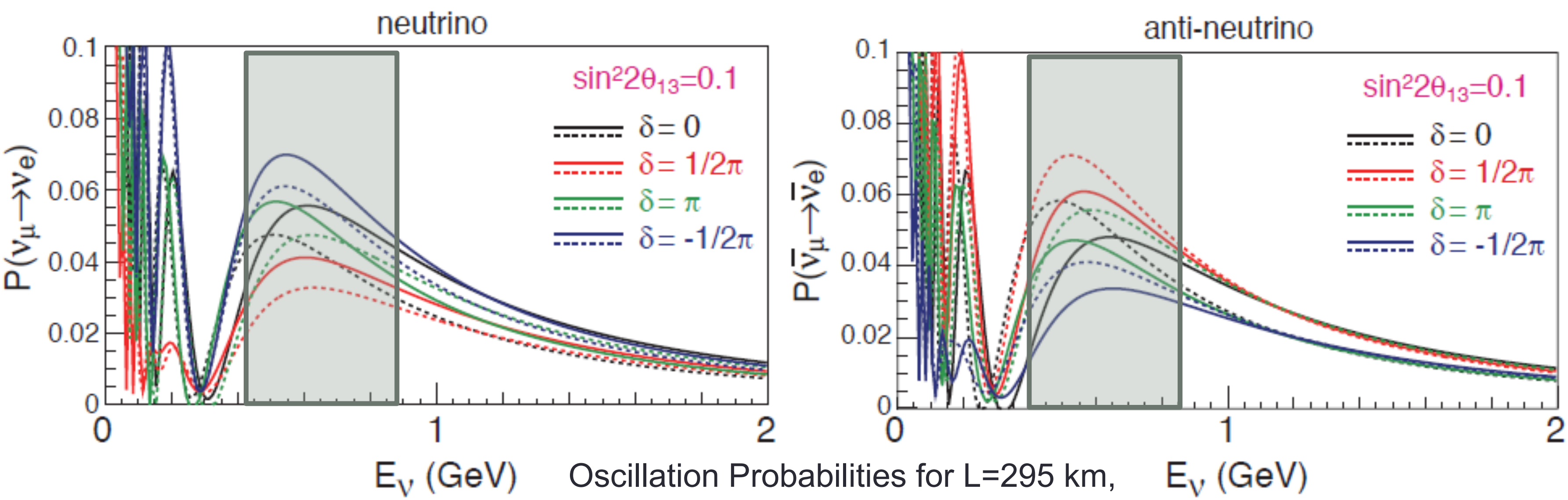
- Is there CP violation in the neutrino sector? And is it consistent with leptogenesis?
- Is there a symmetry to the pattern of masses or mixings?

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

Oscillations: Needs
(J-PARC to Hyper K)

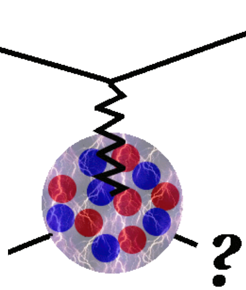


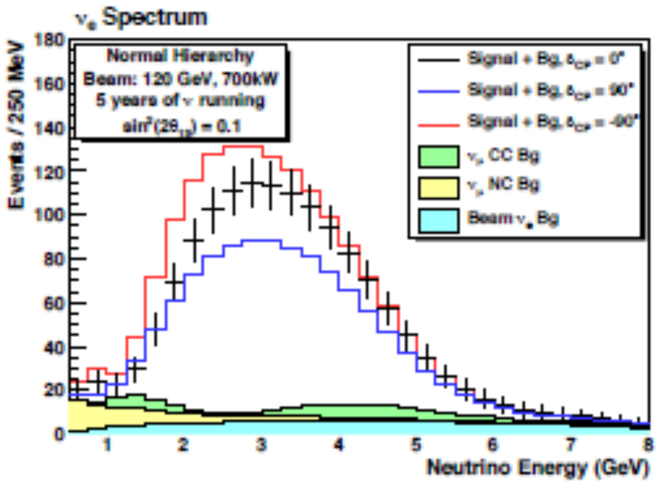
- Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy
- Even in a narrow band beam, one can see that energy distortions will be important

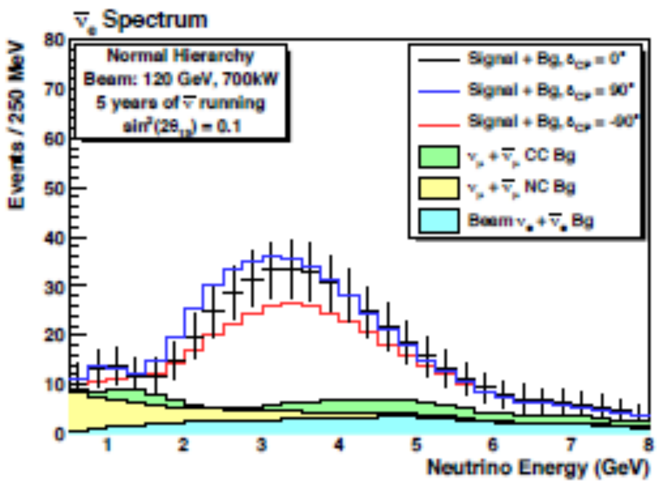


Oscillation Probabilities for L=295 km, Hyper-K LOI

Oscillations: Needs (DUNE)

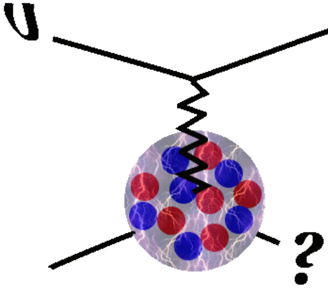




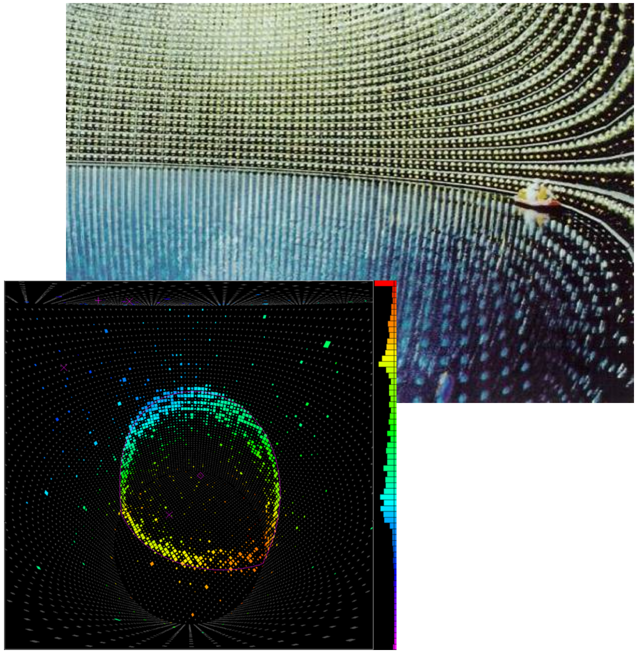


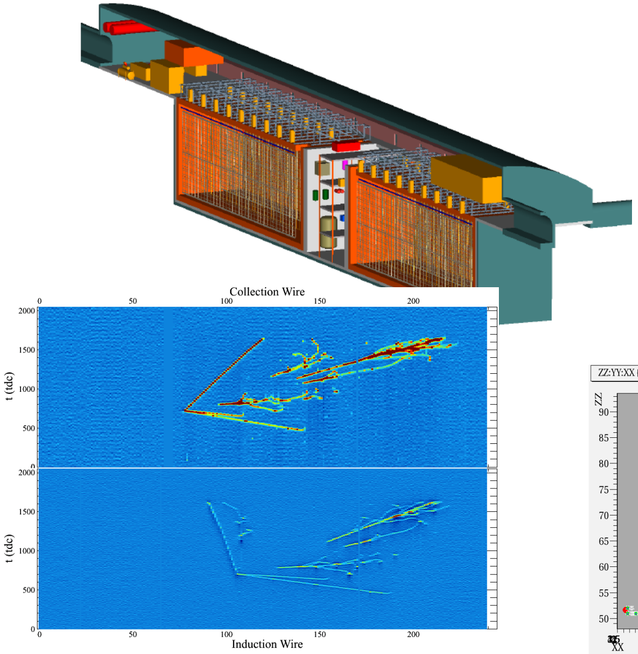
- Maximum CP effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Pileup of backgrounds at lower energy makes 2nd maximum only marginally useful, even in an optimized design
- Spectral information plays a role
  - CP effect may show up primarily as a rate decrease in one beam and a spectral shift in the other

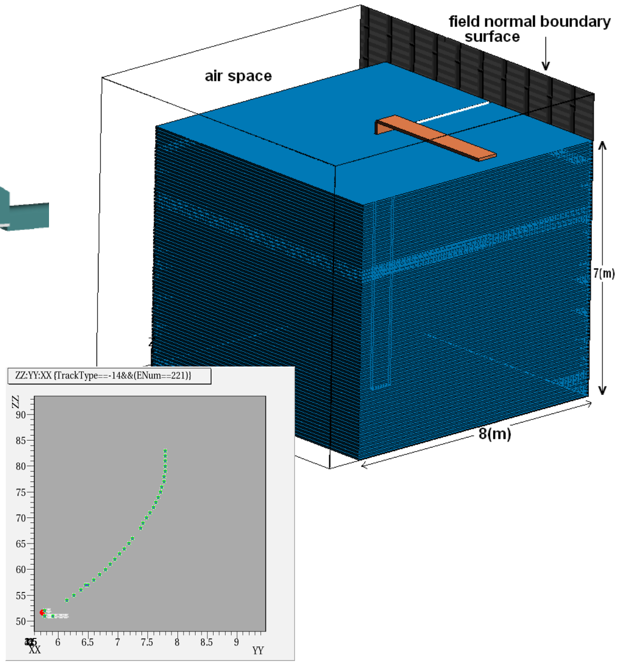
Heavy Targets

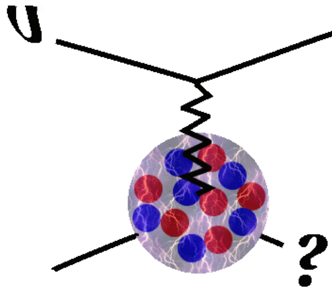


- Next generation neutrino discovery experiments are made with heavy nuclear targets in order to see enough neutrino interactions
- Water (and Ice) Cerenkov, Argon TPCs, Magnetized Iron



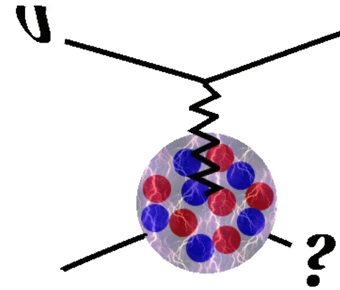






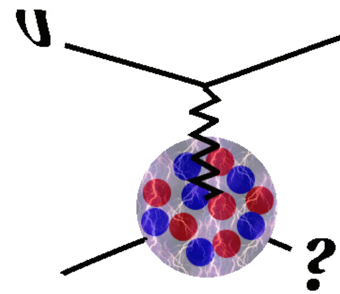
NuINT 2001

What was formative about NuINT 2001?



- Meeting organized by Jorge Morfin and Makoto Sakuda
- Goal was to bring together theoretical and experimental physicists who understood developments in nuclear physicists with the neutrino physicist setting the goals for the future generations of oscillation experiments
- Recall that this was
  - Three years after the Super-Kamiokande discovery
  - Before SNO had results, when the “SMA solution” was still viable
  - When T2K was a group of people in a room with powerpoint drawings of detectors and J-PARC was still “JHF”
  - When NOvA hadn’t even gotten to the stage of “is the cheapest hydrocarbon absorber dried corn kernels?”
  - And no one had dreamt of Hyper-K, DUNE, INO…

NuINT 2001 Papers



Neutrino Scattering Physics Opportunities with the NuMI Beam at Fermilab

(MINERvA!)

Jorge G. Morfín[a] *

[a]Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL, 60510

The NuMI Facility at Fermilab will provide an extremely intense beam of neutri oscillation experiment. The spacious and fully-outfitted MINOS near detector hal high statistics (anti)neutrino-nucleon/nucleus experiments. The experiment describe the cross sections, measured nuclear effects and detailed neutrino beam composition neutrino oscillation experiments, but will also address a wide variety of open neutrino p without the NuMI beam intensity.

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NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS

www.elsevier.com/locate/npe

Neutrino oscillation stud...

Paolo Lipari
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and I.N.F.N., Sezione di Roma 1, P. A. Moro 2, I-00185 Roma, Italy

The present uncertainties in the knowledge of the neutrino cross sections for $E_\nu \sim 1$ GeV, that is in the e range most important for atmospheric and long baseline accelerator neutrinos, are large. These uncertaint not play a significant role in the interpretation of existing data, however they could become a limiting fac future studies that aim at a complete and accurate determination of the neutrino oscillation parameters. New data and theoretical understanding on nuclear effects and on the electromagnetic structure functions at low Q^2 and in the resonance production region are available, and can be valuable in reducing the present systematic uncertainties. The collaboration of physicists working in different subfields will be important to obtain the most from this available information. It is now also possible, with the facilities developed for long baseline beams, to produce high intensity and well controlled ν–beams to measure the neutrino interaction properties with much better precision that what was done in the past. Several projects and ideas to fully exploit these possibilities are under active investigation. These topics have been the object of the first ν–interaction (NUINT01) workshop.

Electroweak Form Factors

S. K. Singh* [a]

[a]Department of Physics, Aligarh Muslim University, Aligarh-202 002, India.

The present status of electroweak nucleon form factors and the $N - \Delta$ transition form factors is reviewed. Particularly the determination of dipole mass M_A in the axial vector form factor is discussed.

Neutrino Interactions at Low and Medium Energies

E.A. Paschos[a]*

[a]Institut für Physik, Universität Dortmund
D-44221 Dortmund, Germany

We discuss the calculations for several neutrino induced reactions from ... attention is paid to nuclear corrections when the targ... ratios of neutral to charged cu... ratios are useful

Inclusive Quasielastic ν Reaction in ^{16}O

S. K. Singh and M. Sajjad Athar[a]*

[a] Department of Physics, Aligarh Muslim University, Aligarh-202 002, India

We calculate the inclusive quasielastic ν_μ cross sections in ^{16}O. The calculations are done in t Approximation(LDA) and take into account Pauli blocking, Fermi motion and the effect of renormaliz... weak coupling constants in the nuclear medium.

Results from Low-Energy Neutrino-Nucleus Scattering Experiments

Makoto Sakuda [a]*

...KEK, Institute of Particles and Nuclear Studies., ...ba,305-0801, Japan

...cleus interactions in the few-GeV region are reviewed. We comment on ...ctions using the existing data of electron-nucleus interactions. ...lastic reaction.

Precise determination of the oscillation parameters: need to understand low energy neutrino interactions

A. Para Fermilab
Pine St. , PO Box 500, Batavia IL60510, USA

Precise measurements of the neutrino oscillation parameters will be an important part of the experimental program of high energy physics in the years to come. High intensity conventional beams and/or neutrino factories will be necessary to attain the ultimate precision. Measurements of the oscillation parameters performed at low neutrino energies, below 10 GeV, may suffer for systematic uncertainties caused by relatively poor knowledge of neutrino physics at low energies and by nuclear effects. Dedicated new experiments are necessary to constrain modeling of neutrino interactions necessary for the precise fit of the oscillation parameters.

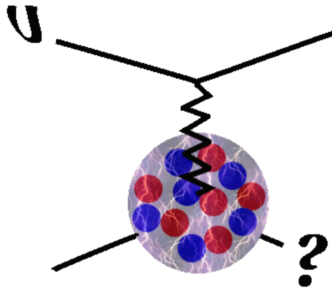
Neutrino and Anti-Neutrino Cross Sections and CP Phase Measurement

Yoshihisa OBAYASHI [a] *

[a]Institute for Particle and Nuclear Studies, KEK 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan

Intense neutrino beam and large detector such as second phase of JHF neutrino beam and Hyper-Kamiokande ...ill enable us to measure CP phase of lepton term. The treatment of fake asymmetry in CP measurement due cross section difference of neutrino and anti neutrino is reported. Expected CP phase measurement sensitivity ...d required improvement of experiments are reported as well.

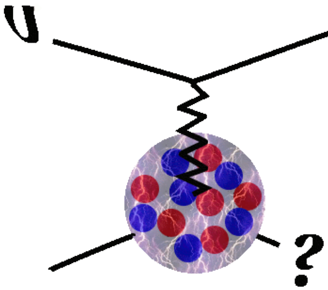
A Problem Hidden in Plain Sight for Future Neutrino Experiments



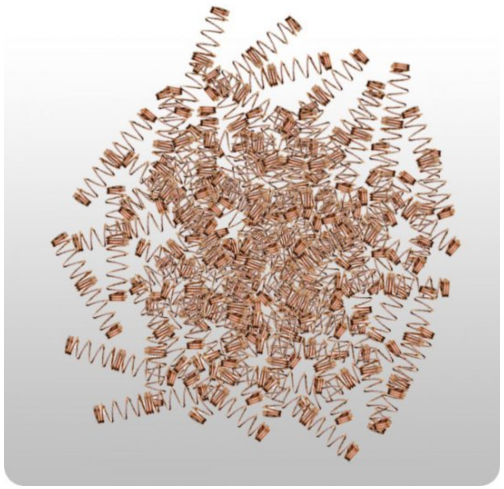
- In retrospect, of course it was obvious
- Neutrino experiments needed the precision I just described for reactions on nuclear targets
- But the community's knowledge of neutrino interactions was too naïve to support this precision
- People who had confronted lepton scattering data for decades told us what we were facing
- And gradually, we learned…

Artist Liu Bolin, imitating the nucleus?

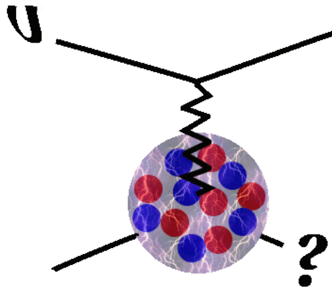
Failed Multi-Scale Problem



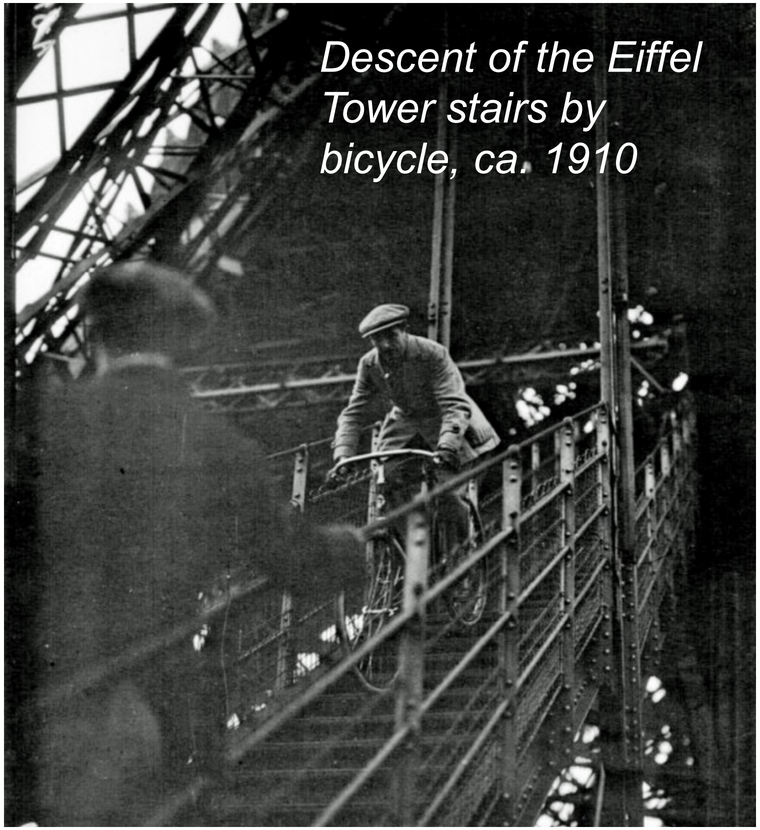
- Accelerator oscillation experiments require beam energies of 0.3-5 GeV
- Not large compared to the scale for inelastic excitations of baryons, $m_{\Delta} - m_{N} \sim 250\ MeV$
- Which is in turn not large compared to the scale for binding of nucleons, $\sim 30\ MeV$ in ^{12}C



Failed Multi-Scale Problem

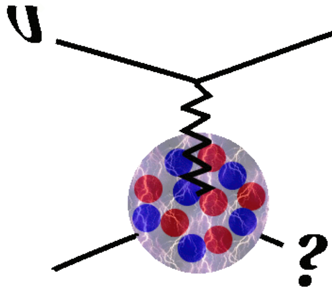


- Consider a bicycle rider at right, descending the stairs of the Eiffel Tower
- A bicycle wheel is 1m in diameter
- If the steps were 1cm or the steps were ramps of 100m, we could predict the cyclist's trajectory

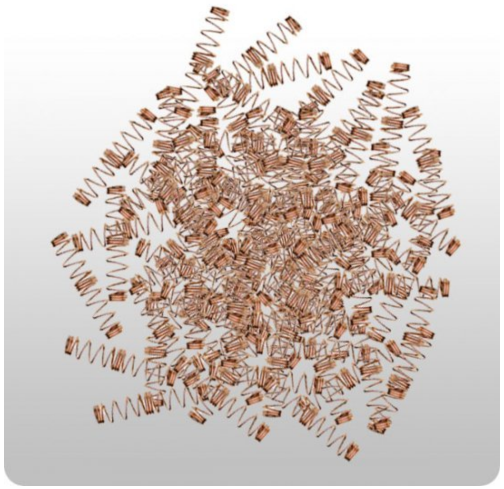


- But since the wheel size is too close to the step size, all we know is that it is going to be painful

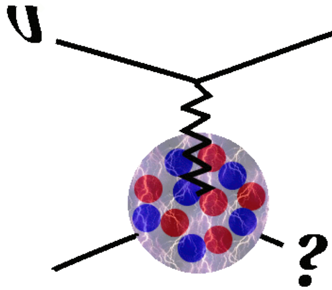
Failed Multi-Scale Problem

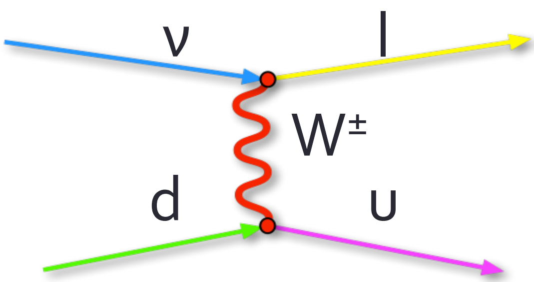


- $E_\nu \sim 300 - 5000\ GeV$, $m_\Delta - m_N \sim 250\ MeV$, $E_B \sim 30\ MeV$ in ^{12}C
- Nuclear response at these neutrino energies spans elastic, quasielastic and inelastic
- And even the last two cannot be cleanly separated since the effect of binding of nucleons cannot easily be factored from inelastic excitations of nucleons
- Exact prediction of nuclear response becomes akin to equation of motion for the system at the right if force required to uncouple springs is comparable to force required to break them
- Prize to the first student with an exact solution!

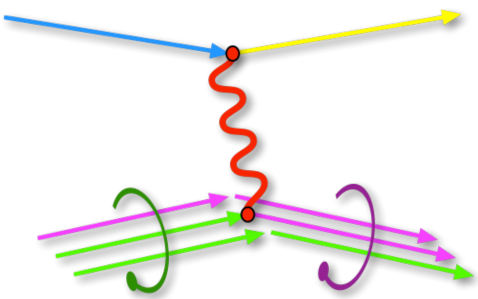


The same problem in high energy physics language





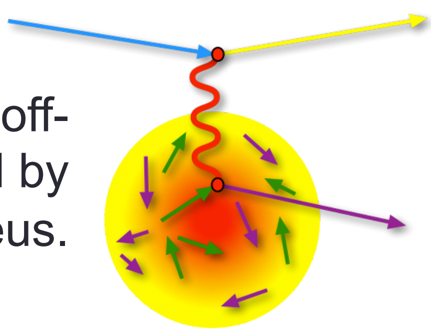
Leptonic current is perfectly predicted in SM…
…as is the hadronic current for free quarks.



For inclusive scattering from a nucleon, add PDFs for a robust high energy limit prediction

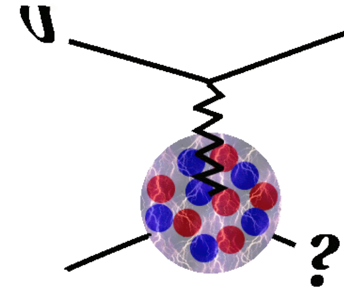
For exclusive, e.g., quasi-elastic scattering, hadron current requires empirical form factors.

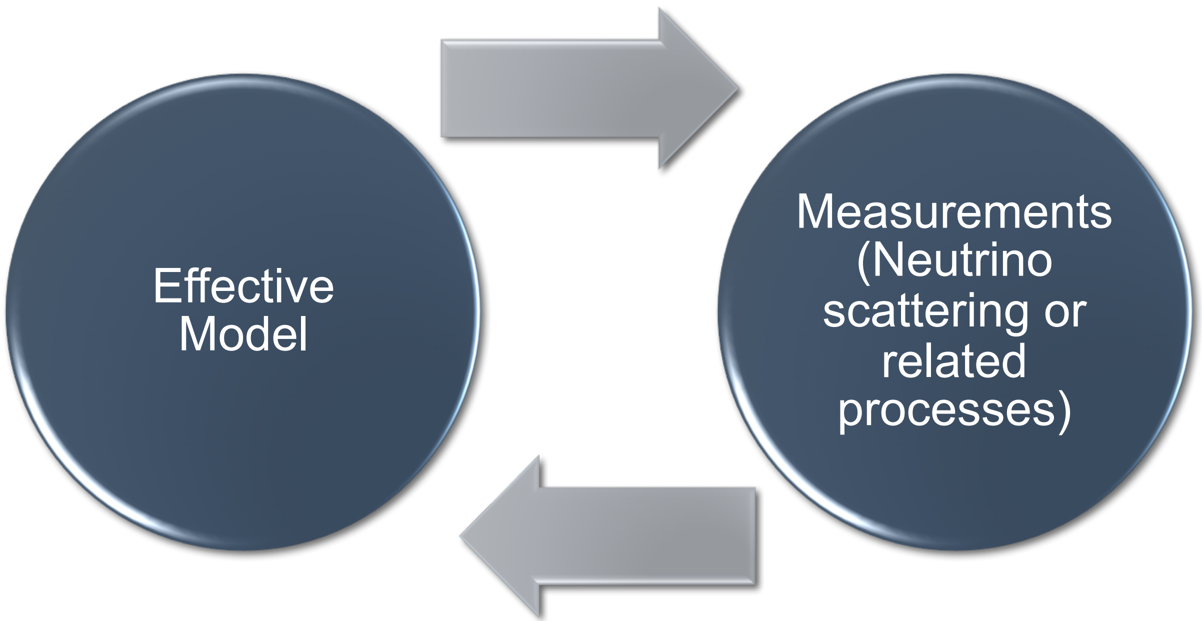
(drawings courtesy G. Perdue)



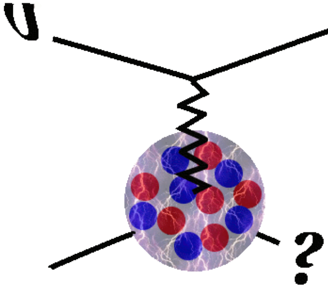
If the nucleon is part of a nucleus, it may be modified, off-shell, bound, etc. Also, exclusive states are affected by interactions of final state hadrons within the nucleus.

Thriving in the face of Failure



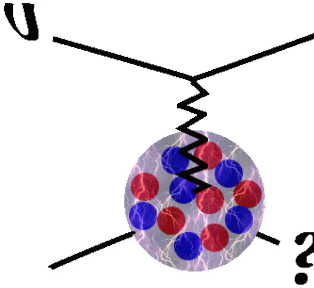


- Iterative process, using data to improve models
- Models are effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions.

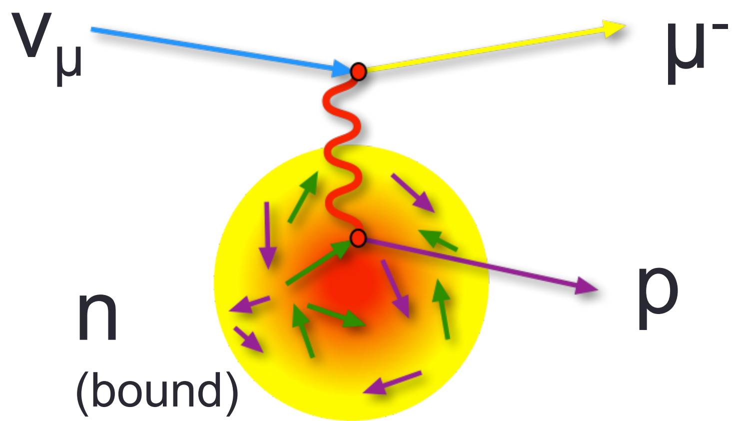


Early Experiences (and failures) with Neutrino Interactions

Charged Current Quasielastic Scattering



- In a simple model of the nucleus, the quasielastic reaction allows neutrino energy to be estimated from only the outgoing lepton:

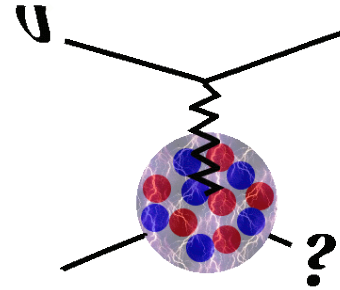


$$E_\nu^{\rm rec} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e\cos\theta_e)};$$

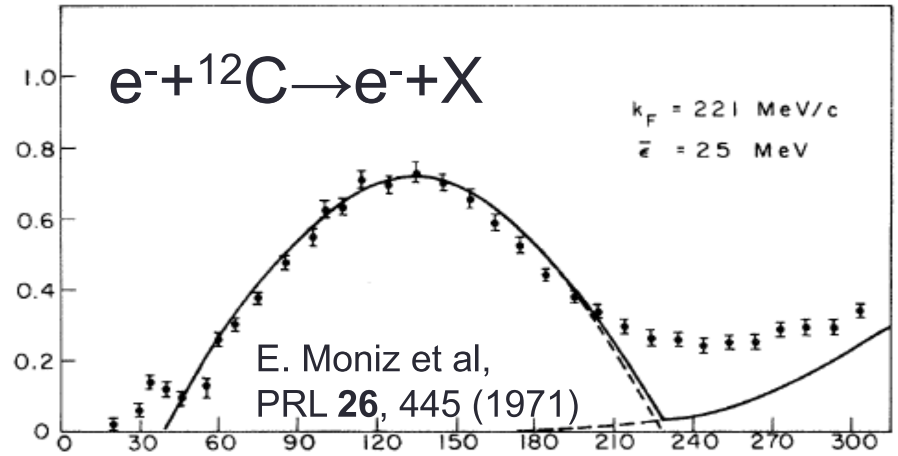
When things are too complicated, sometimes you give up trying!

- This assumes:
  - A single target nucleon, motionless in a potential well (the nucleus)
  - Smearing due to the nucleus is typically built into the cross-section model since it cannot be removed on an event-by-event basis

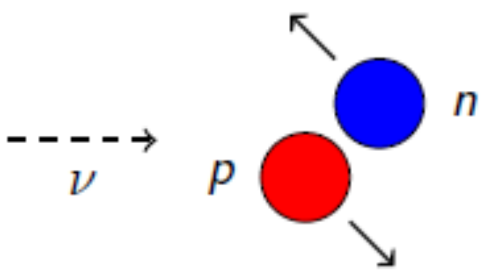
Simple Model of the Nucleon in a Nucleus



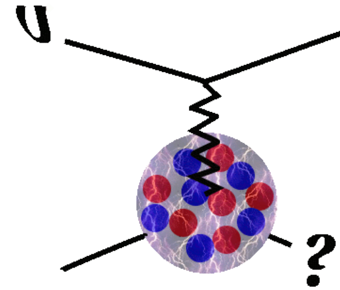
- Our models come from theory tuned to electron scattering
- Generators usually use Fermi Gas model, which takes into account effect of the mean field.
- Corrections to electron data from isospin effects in neutrino scattering.
- Hmmm… between elastic peak and pion production rise looks bad.



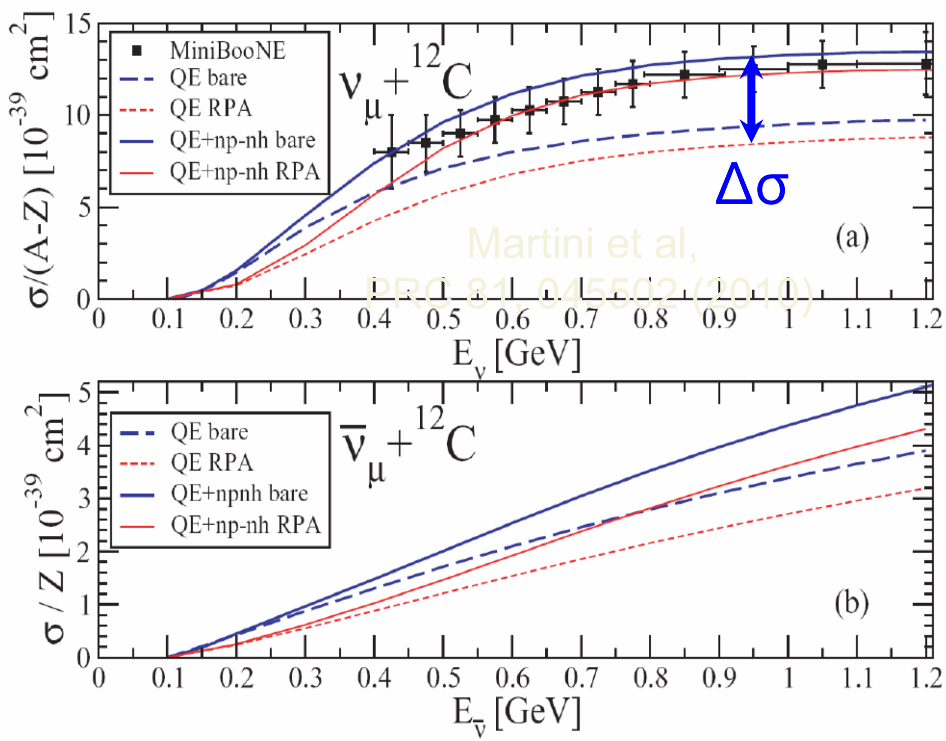
- This approach of quasi-free nucleons in a mean field neglects processes involving closely correlated nucleons



MiniBooNE's Large Quasi-Elastic Cross-Section



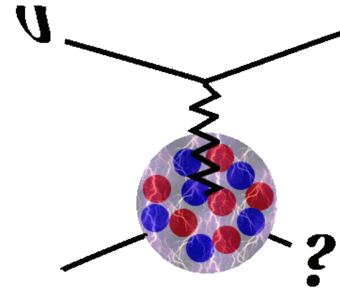
- Gradually it became clear that the large cross-section measured at MiniBooNE on ^{12}C was likely due to production from correlated pairs of nucleons not in a mean field model: $\nu_\mu n \rightarrow \mu^- p \quad + \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$



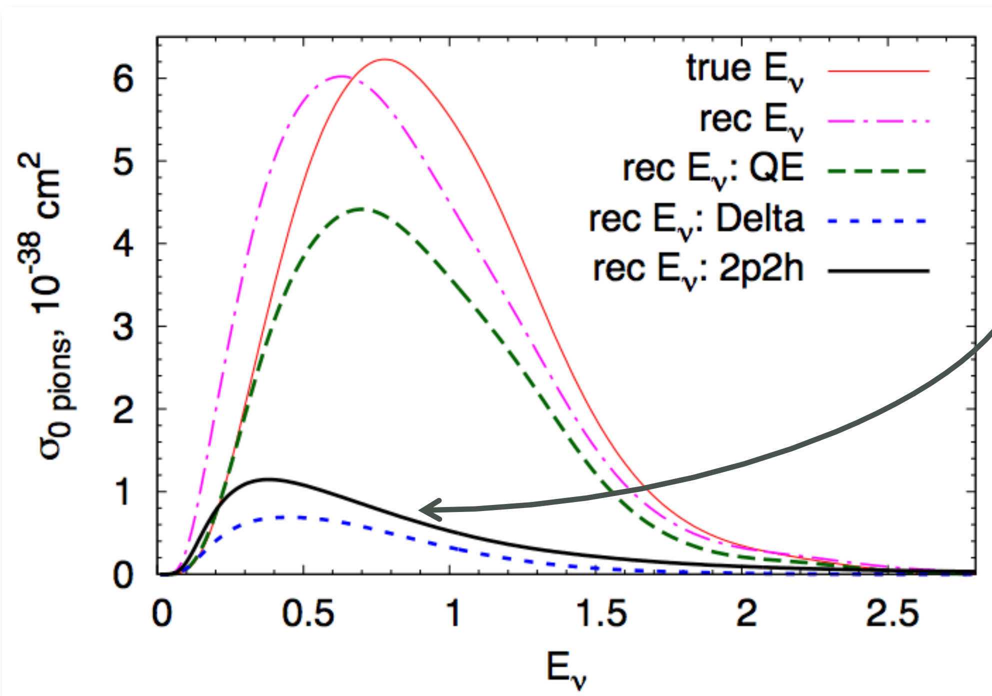
Early work applying this to neutrinos

Nieves et al., arXiv:1106.5374 [hep-ph]
Bodek et al., arXiv:1106.0340 [hep-ph]
Amaro, et al., arXiv:1104.5446 [nucl-th]
Antonov, et al., arXiv:1104.0125
Benhar, et al., arXiv:1103.0987 [nucl-th]
Meucci, et al., Phys. Rev. **C83**, 064614 (2011)
Ankowski, et al., Phys. Rev. **C83**, 054616 (2011)
Nieves, et al., Phys. Rev. **C83**, 045501 (2011)
Amaro, et al., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]
Martinez, et al., Phys. Lett **B697**, 477 (2011)
Amaro, et al., Phys. Lett **B696**, 151 (2011)
Martini, et al., Phys. Rev **C81**, 045502 (2010)
[compilation by G.P. Zeller]

Energy Reconstruction: Quasi-Elastic



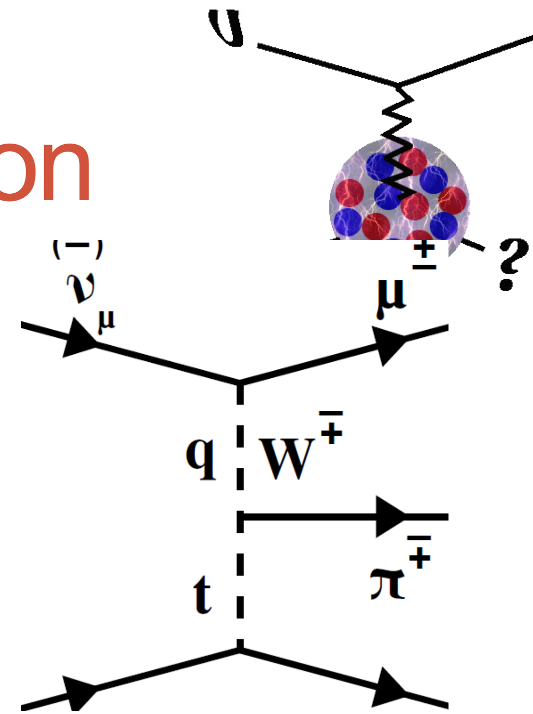
- Does it quantitatively matter if we model this effectively (e.g., alter nucleon form factors) or microphysically?
- Inferred neutrino energy changes if target is multinucleon.



Effect at MiniBooNE calculated by Lalakulich, Gallmeister, Mosel,1203.2935

ex: Mosel/Lalakulich 1204.2269, Martini *et al.* 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

Coherent Pion Production



- 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

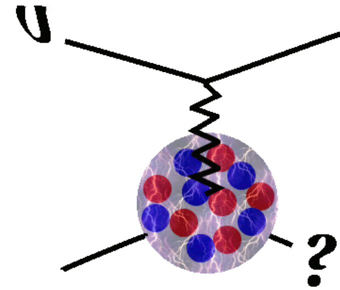
$$E_\nu = E_\mu + E_\pi$$

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

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

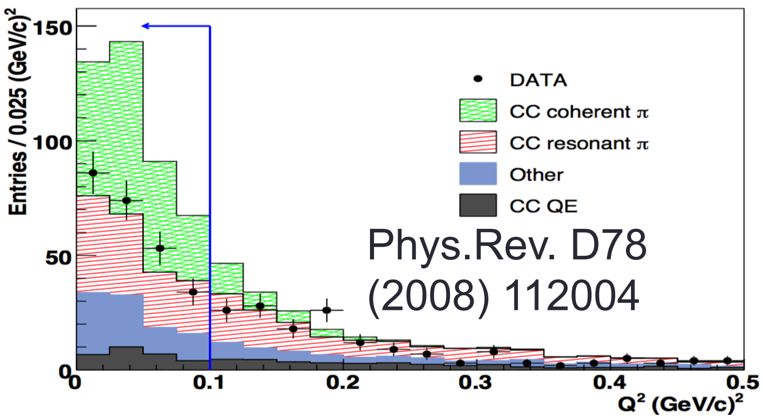
$$|t| = \sum_{\pi,\mu}(E - p_L)^2 + \left|\sum_{\pi,\mu}\overrightarrow{p_T}\right|^2$$

- Low $|t|$, among other necessary conditions, requires that $E_\pi^2(1 - cos\theta_\pi)^2$ and Q² both be small, so sometimes experiments look for forward pions and low Q²



Missing Coherent Pions?

- Coherent pion production had definitely been observed at high energies, back as far as the bubble chamber experiments of the 1980s
- Primary analysis of the SciBooNE experiment, ~1-2 GeV neutrinos, looked for an excess at low Q^2
  - No rise at low Q^2!
- SciBooNE had other hints that the process was probably in the data, e.g., angular distributions, but couldn't use their model to find the process



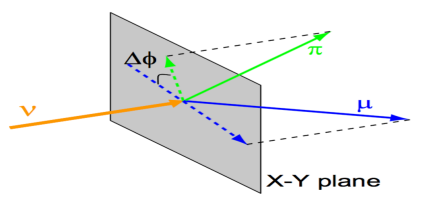
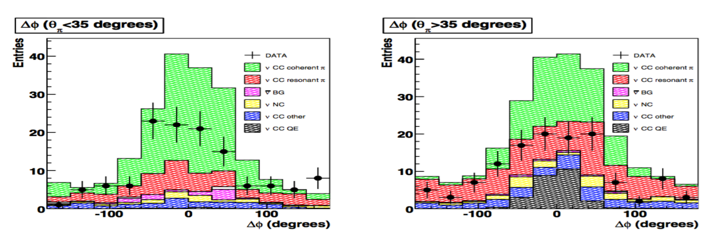
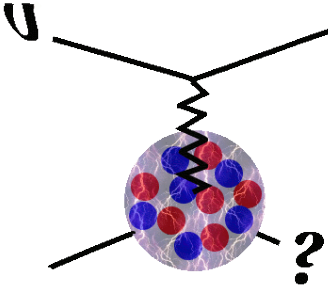


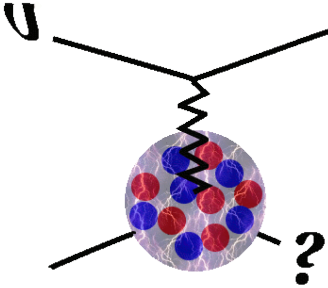
FIGURE 5. Definition of the kinematic variable $\Delta\phi$.



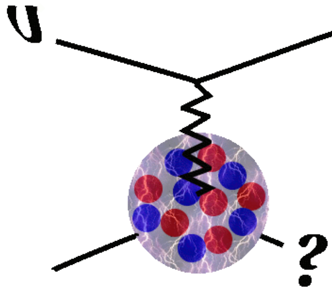


Some of what we are learning at MINERvA

Why MINERvA?



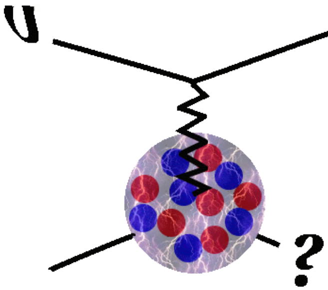
- Many other experiments have studied or are studying neutrino-nucleus scattering at the relevant energies
  - K2K, NOMAD, MiniBooNE, MINOS, SciBooNE, T2K, ArgoNeuT, NOvA, MicroBooNE…
- But MINERvA is my experiment
  - and I left home after dinner 33 hours ago to arrive this morning to give this talk, with stops in Toronto and Istanbul, so I get to choose?
- MINERvA also has
  - A relatively well understood flux of neutrinos (~8% uncertainties)
  - An excellent compromise between detector granularity and statistics
  - Multiple nuclear targets for direct study of A dependence (see Deborah Harris' talk)
  - The benefit of experience of previous experiments and the theoretical work of the NuINT community



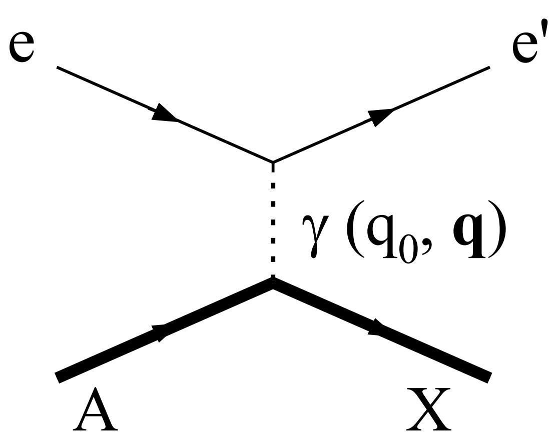
Low Recoil Nuclear Response with Neutrinos

published as Phys.Rev.Lett. 116 (2016) 071802

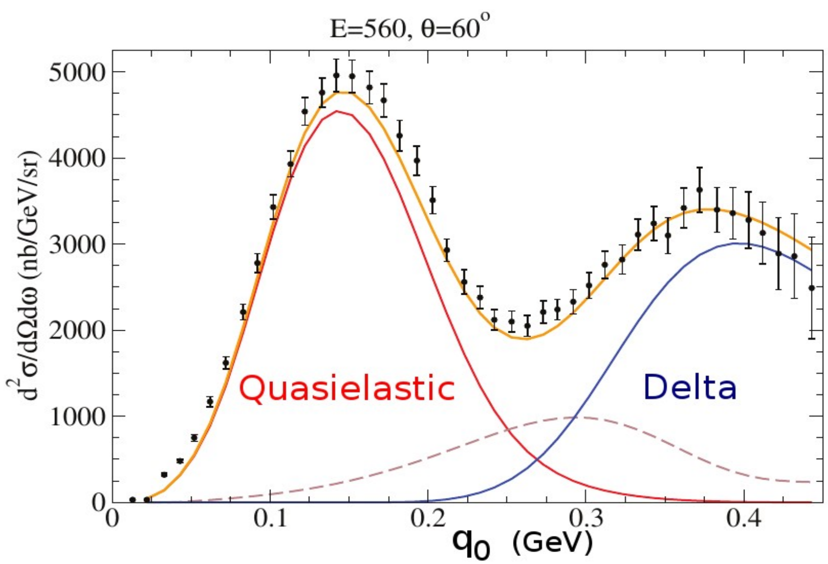
How we would like to measure nuclear response



- If we had a tunable, high rate source of monochromatic neutrinos, we would repeat single arm electron scattering experiments

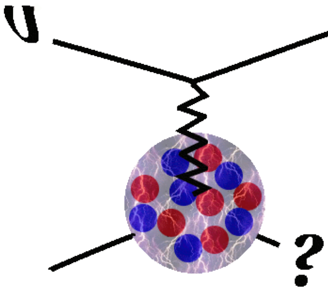


Adapted from G. D. Megias, NuFact 2015

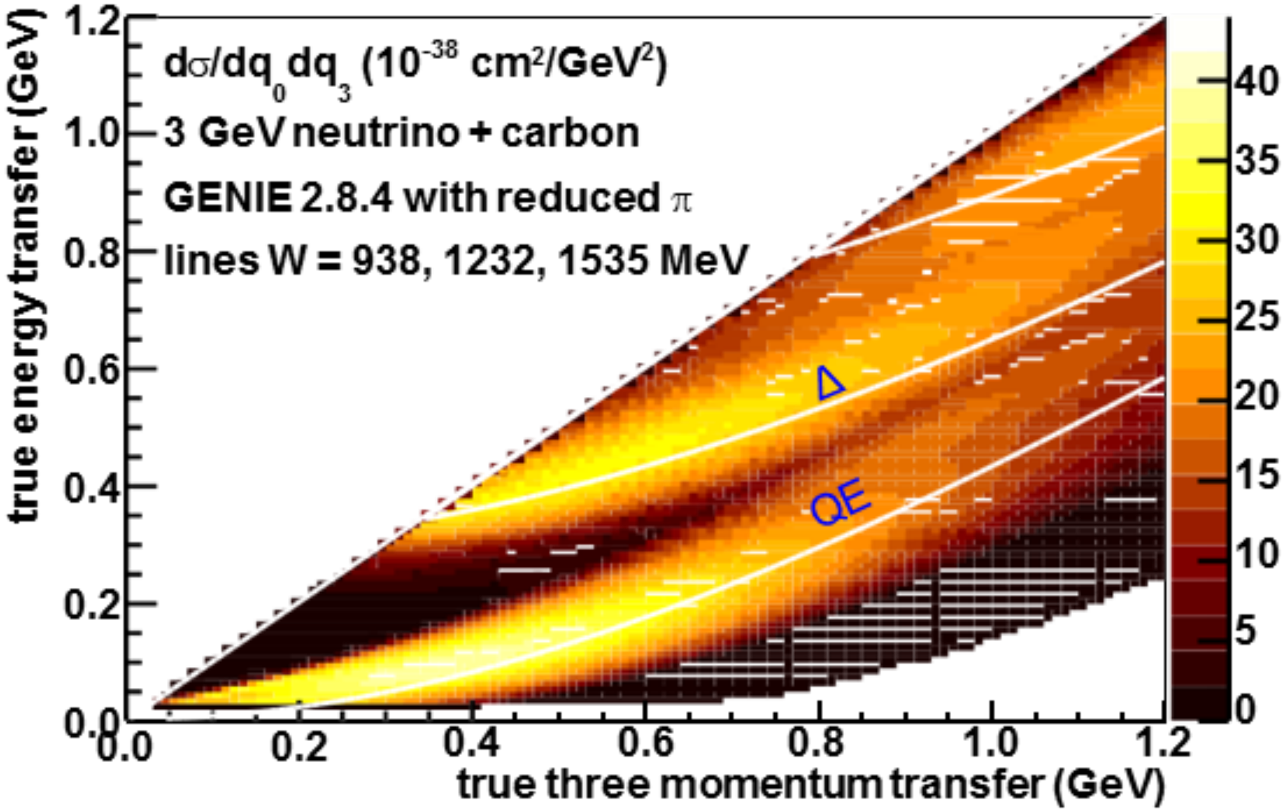


$$q_0 = E_e - E_{e'}$$

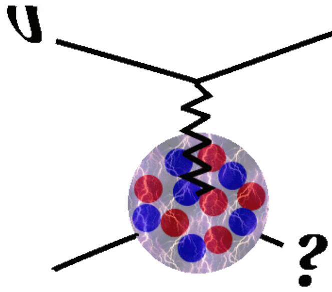
Ideal Neutrino Nuclear Response



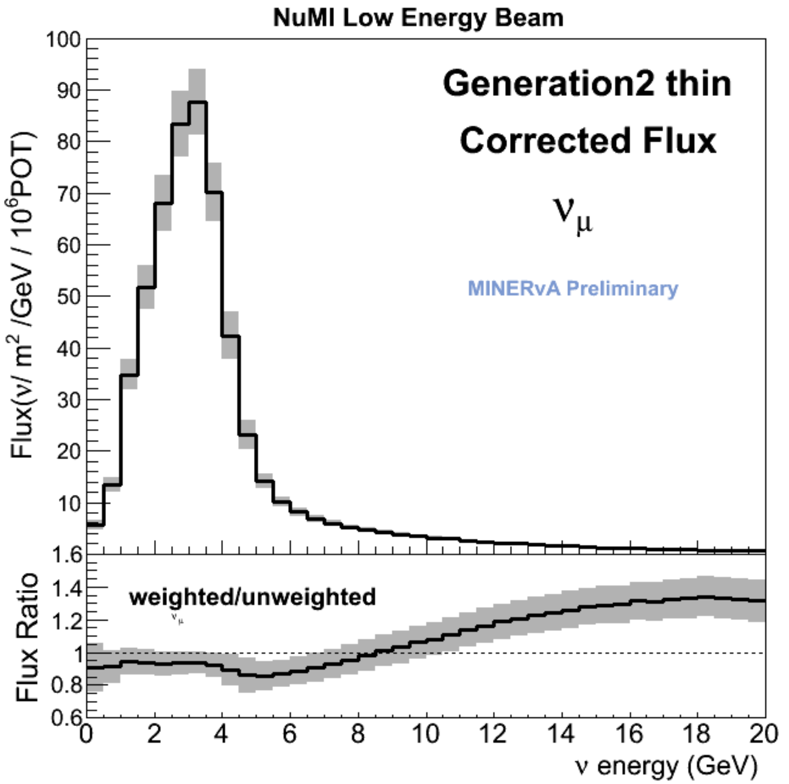
- More precisely, since single arm experiments would be wasteful ☺, we would form these distributions



Why can't we do this?

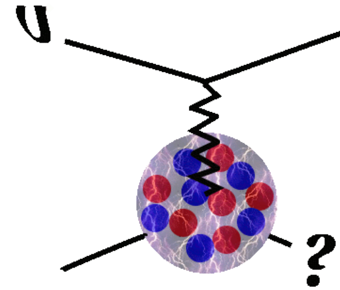


- The compromises to make a neutrino beam lead to two sources of evil
  - The neutrinos come to us with all different energies with no tagging possible
  - We don't even predict the distribution of energies well
- On the latter point, after several physicist-decades of work and a combination of *in situ* and *ex situ* data, σ_{Φ}/Φ~8%

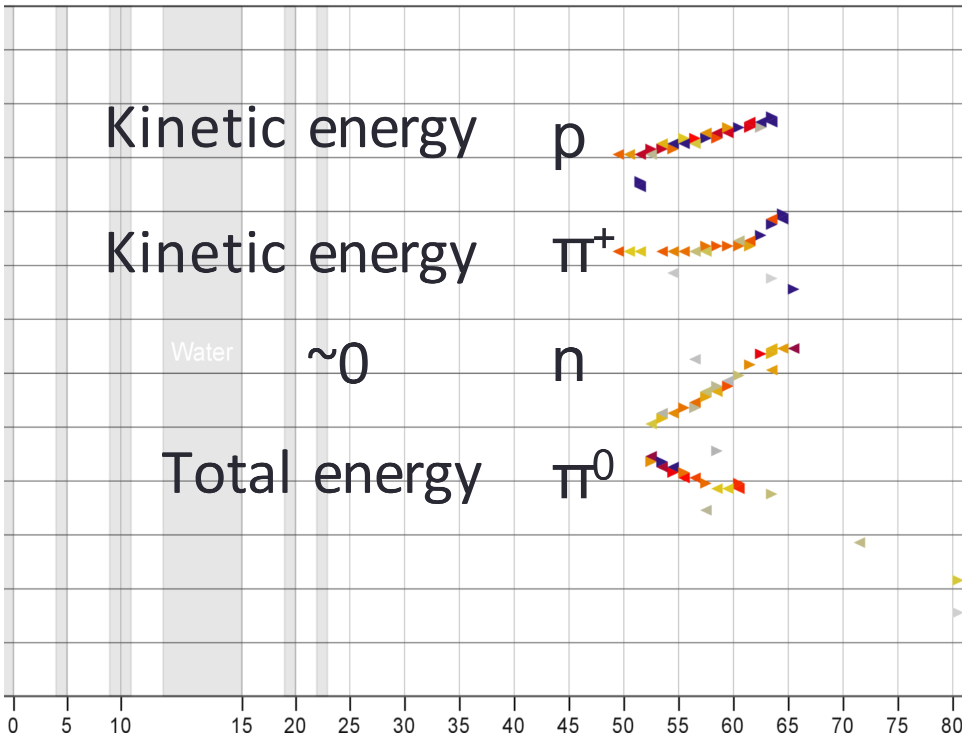


The best known high rate accelerator beam flux on earth: at NuMI

So what may we do instead?

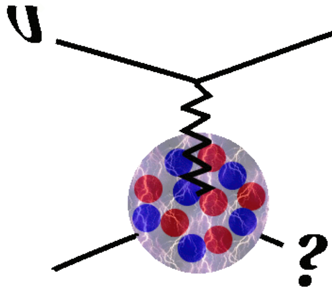


- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.
- *MINERvA's approach is to use calorimetry for all but the final state lepton*
  - *We therefore don't measure q_0 but a related quantity dependent on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

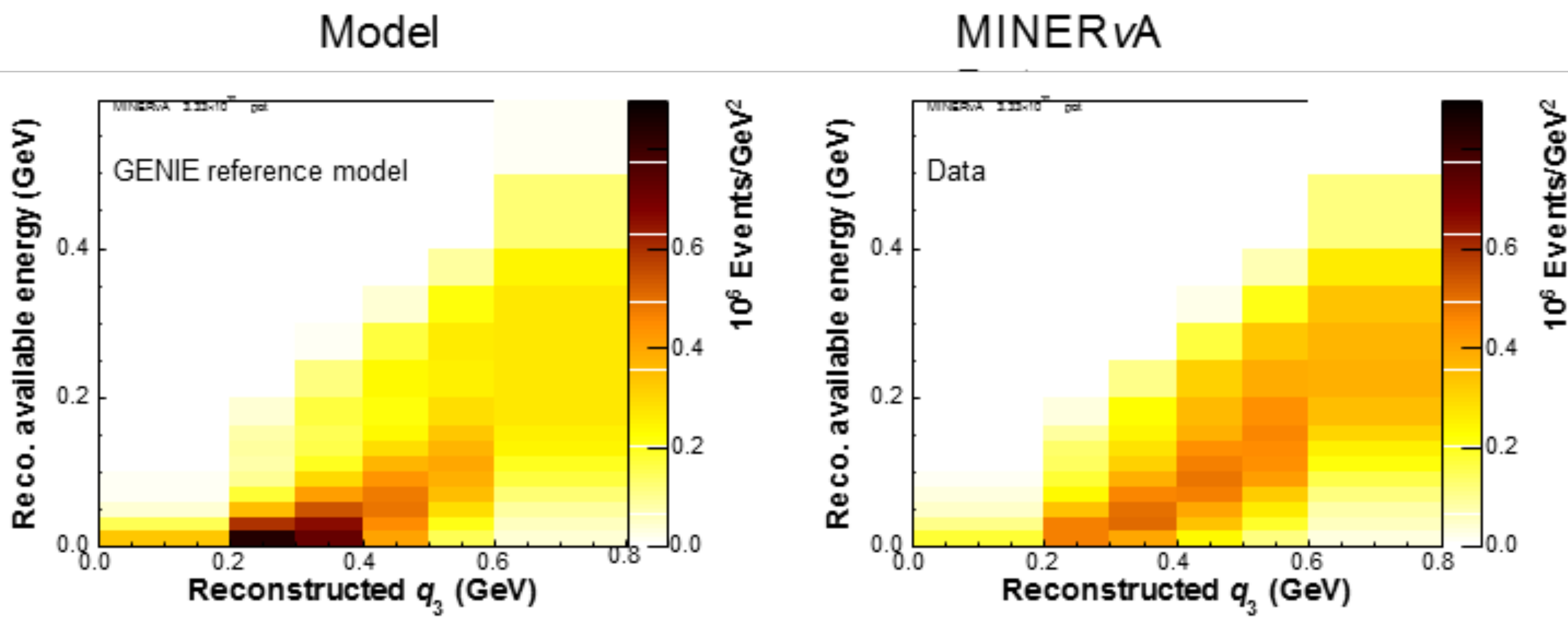


$$E_{avail} \equiv (\text{Proton and } \pi^{\pm}\ KE) + (E \text{ of other particles except neutrons})$$

Agreement with reference impulse approximation model (GENIE*)?

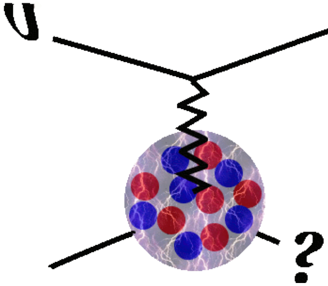


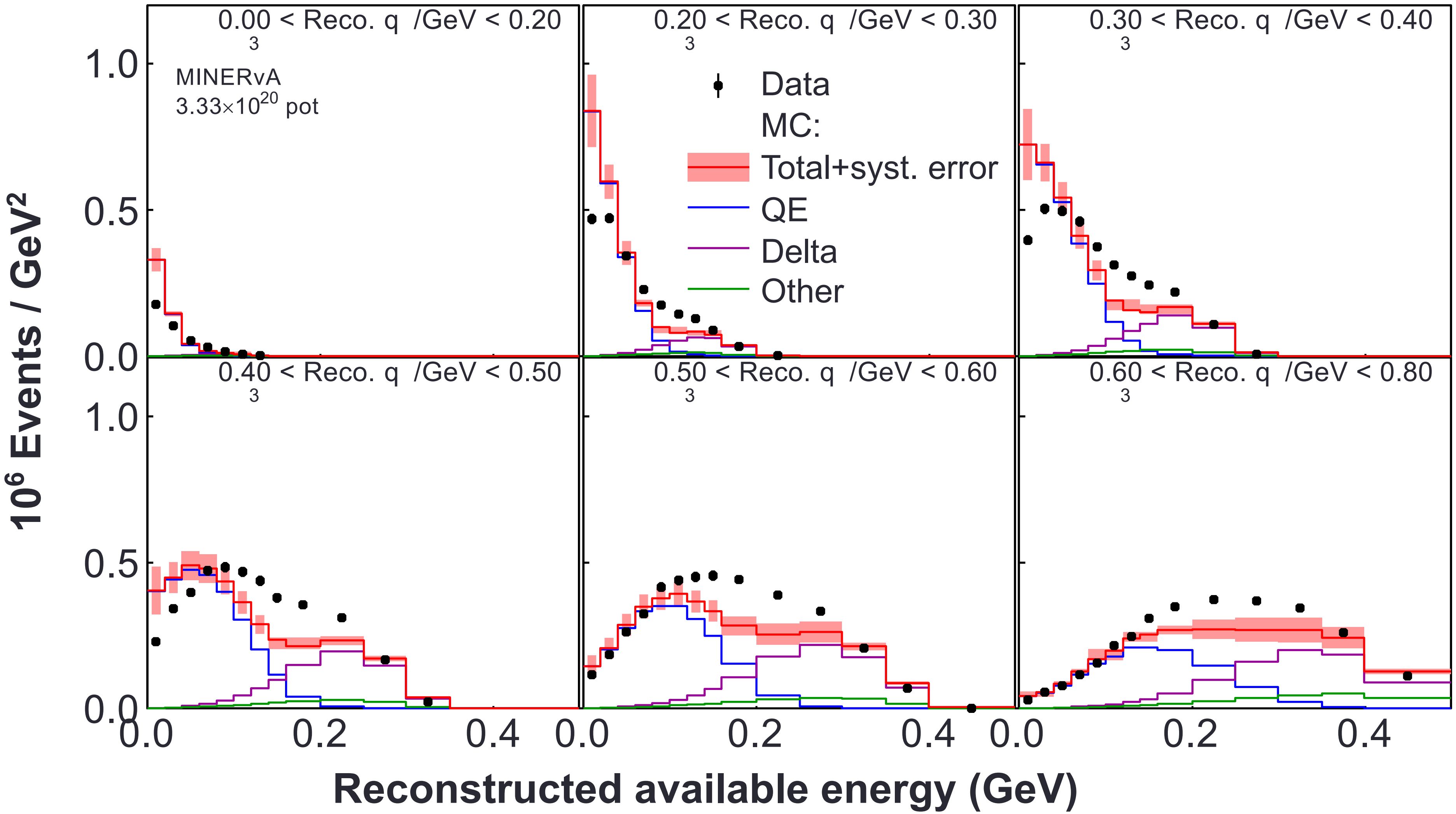
- No, of course not. It's the nucleus!



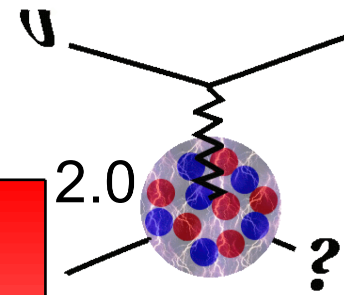
* GENIE 2.8.4 with no RPA or Valencia 2p2h model and MINERvA's pion tuning applied to Rein-Sehgal model

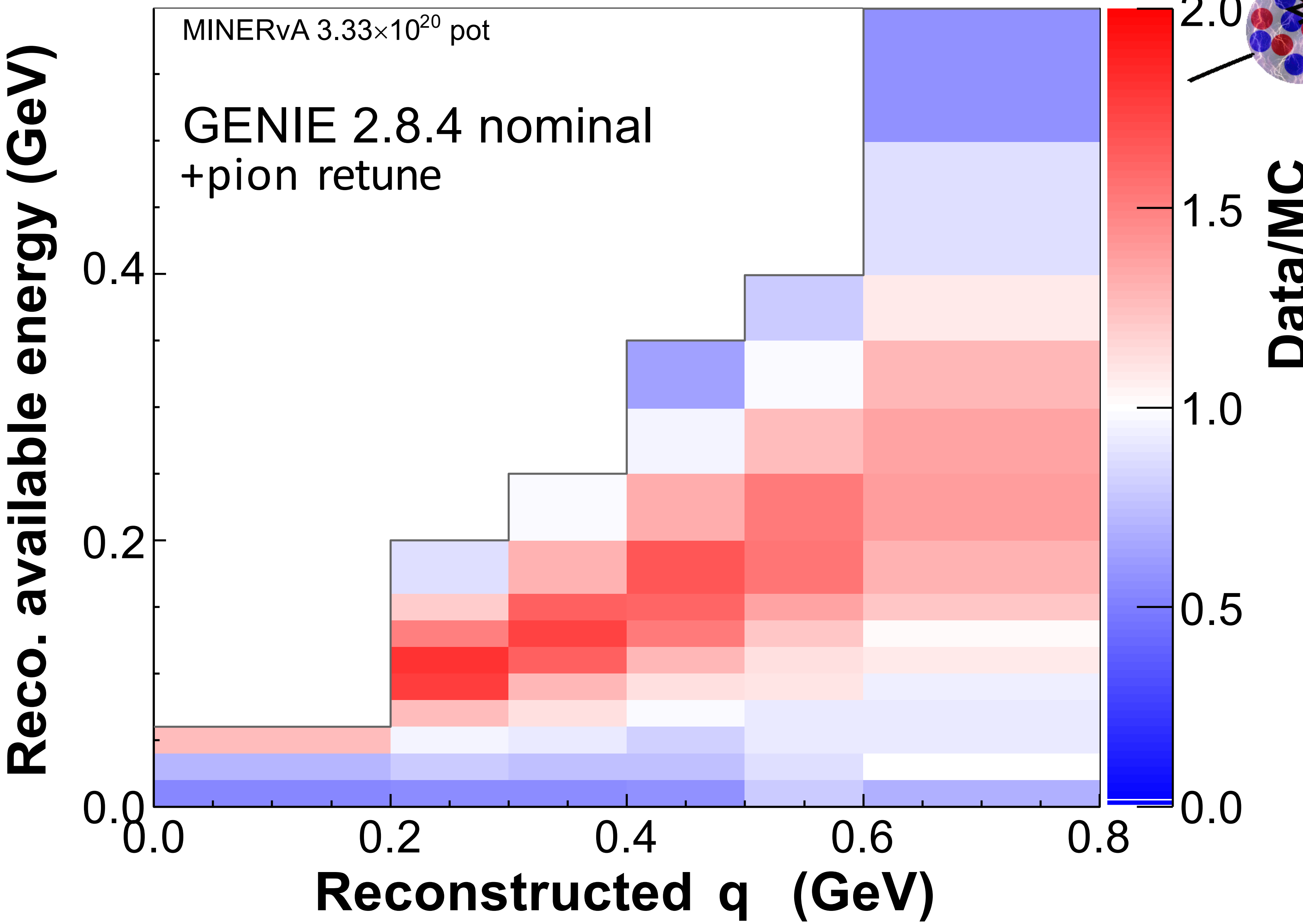
Agreement with reference model (GENIE*)?



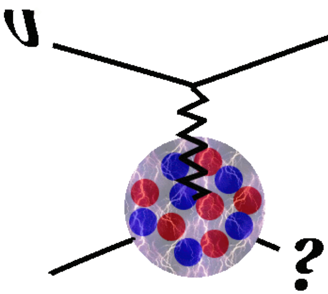


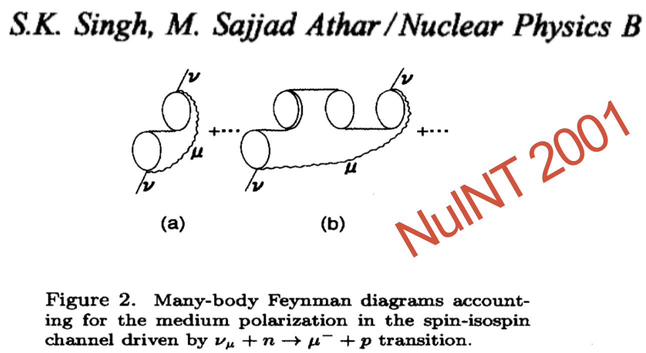
Data/MC ratio

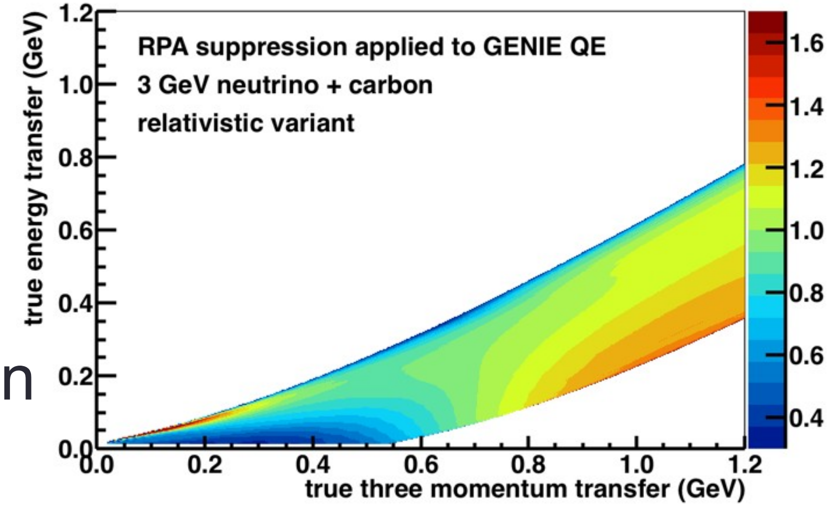




Adding Screening and Multinucleon Processes

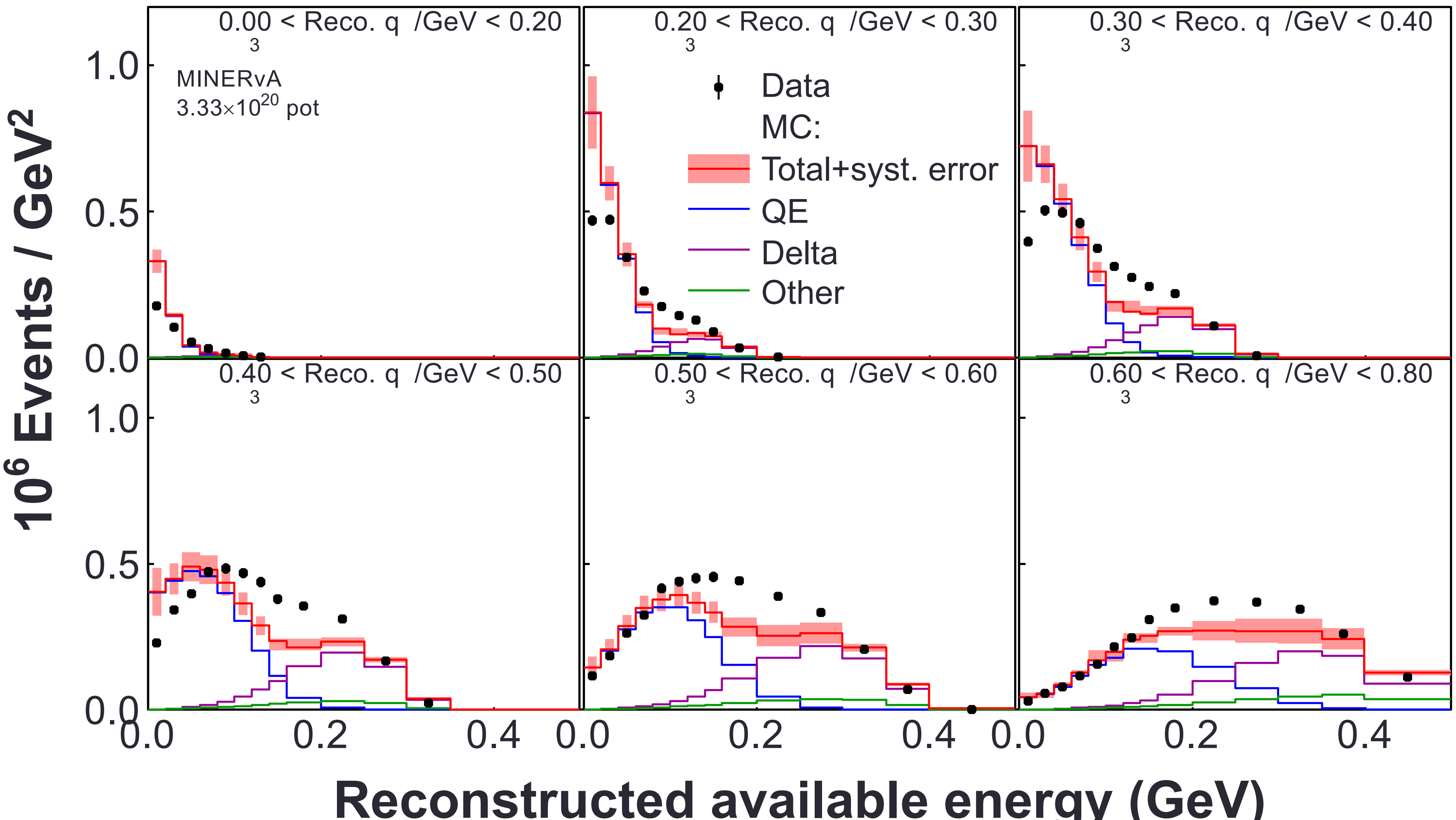






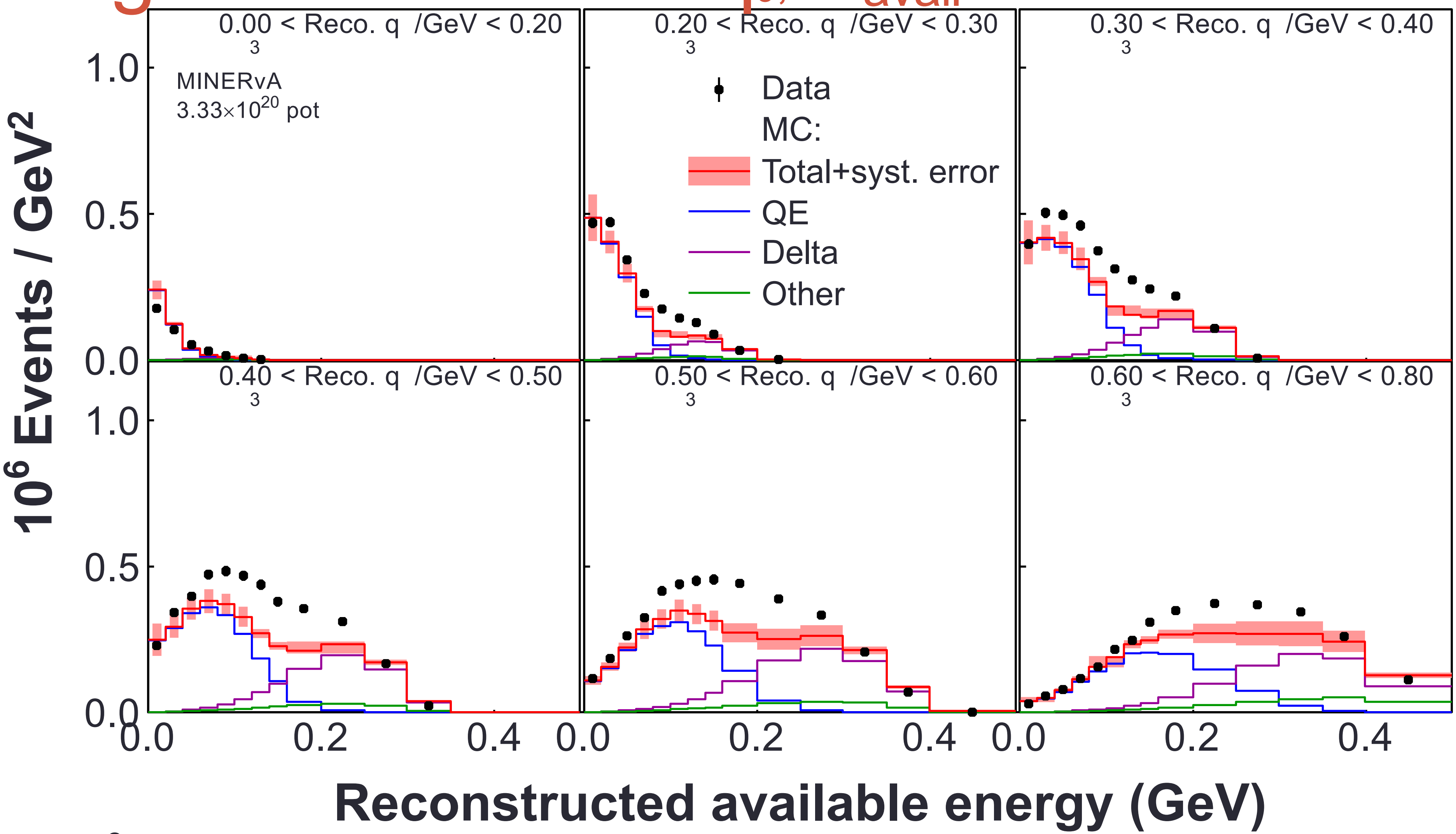
- Can add scenning correction
  - Valencia model
    RPA/no RPA prediction
    (Nieves, Ruiz Simo, Vicente Vacas, Phys.Rev. C83 (2011) 045501)
- Also added Valencia 2p2h multinucleon model
  - High q_3 dealt with by cutoff
    (Gran, Sanchez, Nieves, Vicente Vacas, Phys.Rev. D88 (2013) 113007)=
- Note that these are in GENIE 2.12, more or less as we have implemented them for MINERvA

That default prediction again



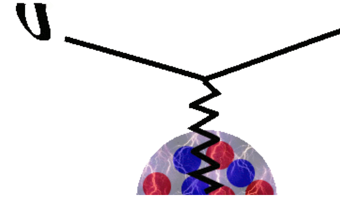
…, $\chi^2 = 896$ (stat+syst, 62 dof)

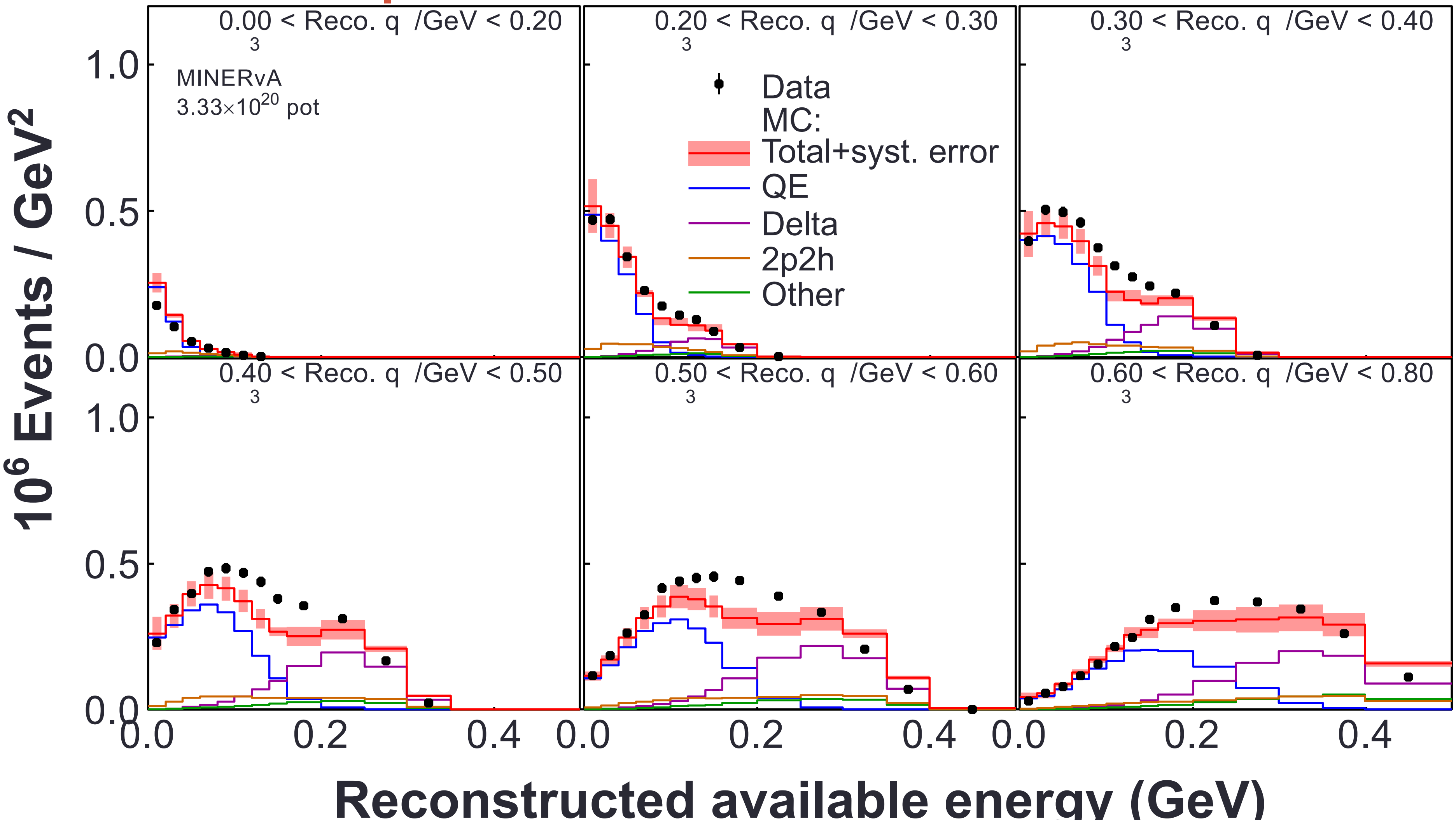
RPA screening improves agreement at low q_3, E_{avail}



$\chi^2 = 540$ (stat+syst, 62 dof)

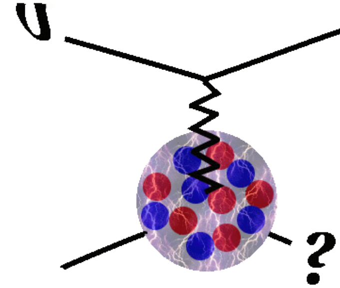
Adding multinucleon 2p2h is a smaller improvement



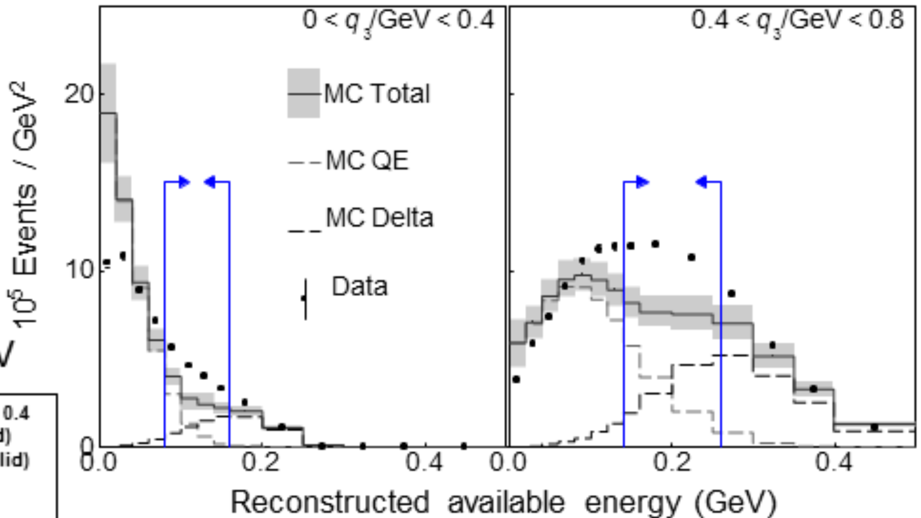


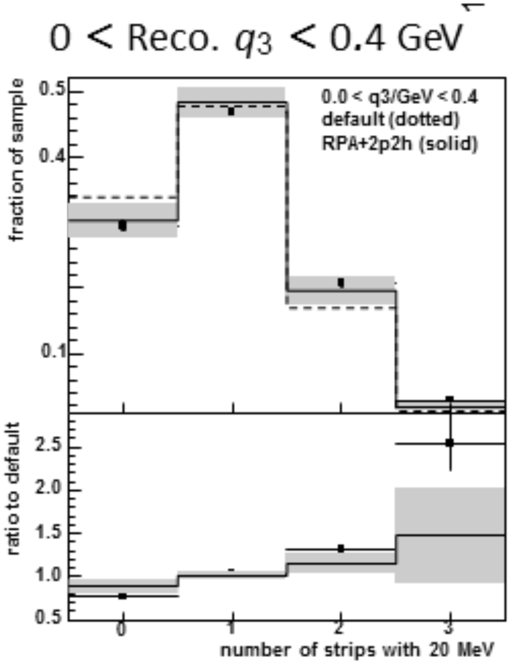
χ^2 = 498 (stat+syst, 62 dof)

See extra protons with excess

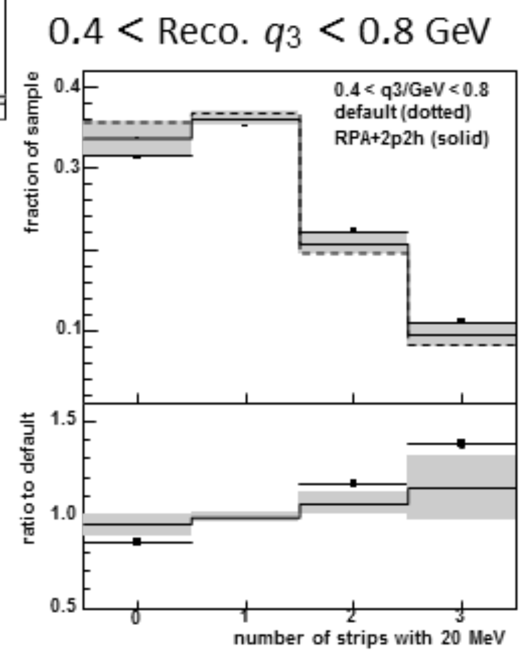


- MINERvA tags final state protons by Bragg peak

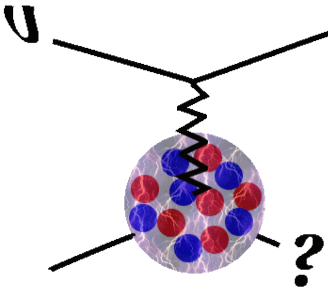




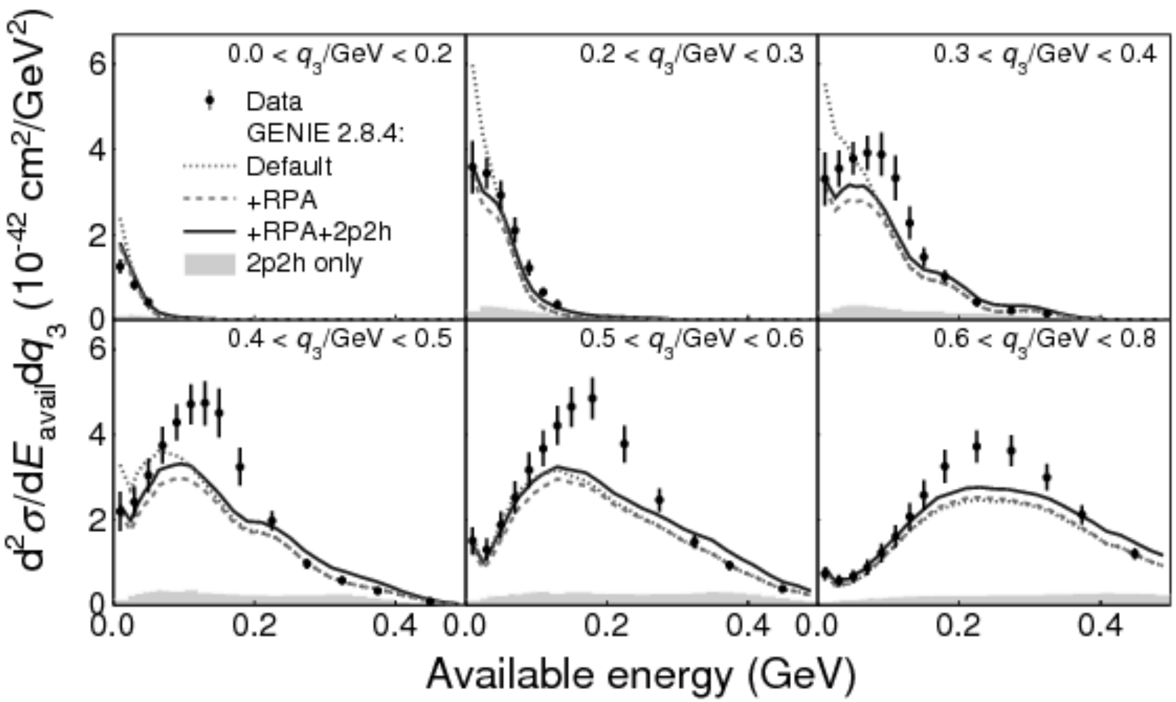
- Adding Valencia 2p2h improves agreement, but not “enough”

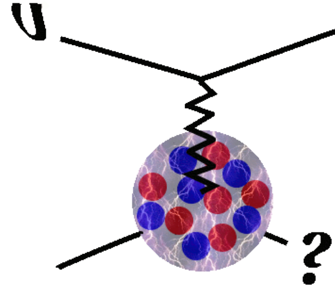


Result has been “unfolded” to be compared with theory



- Corrected to true E_{avail} and q_3 by unfolding
- A model that can predict the final state (by whatever means), can try to reproduce this
  - All generators in principle could do so (and should)

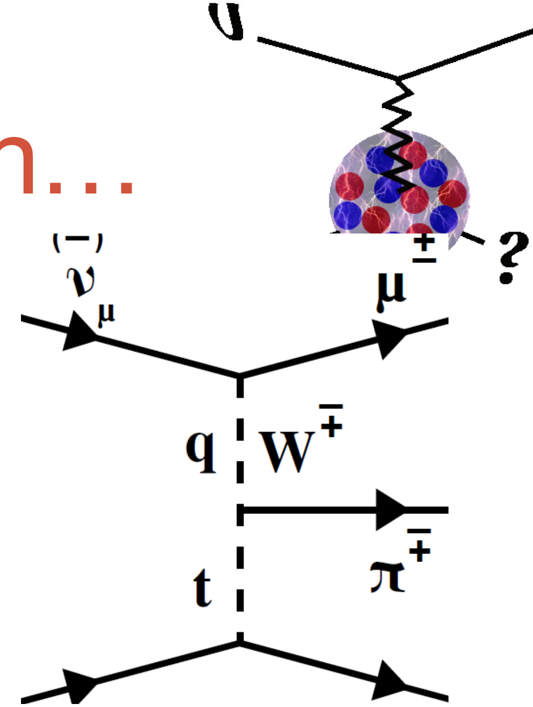




Coherent Pion Production

Published as Phys.Rev.Lett. 113 (2014) 261802 and manuscript describing $d\sigma/dQ^2$ in preparation for Phys. Rev. D

A Very Strange Reaction…



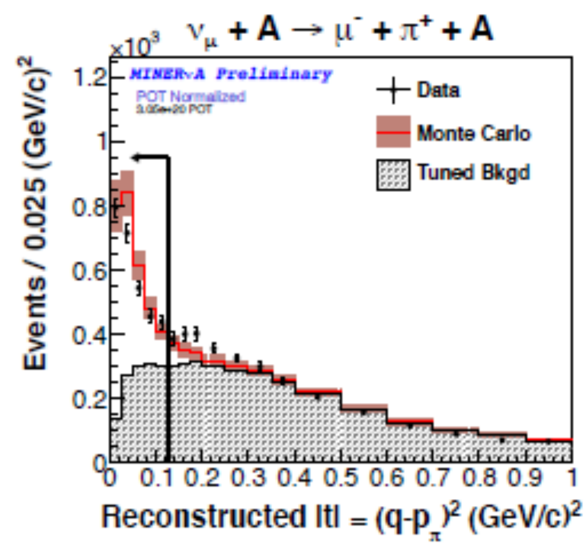
- Despite small binding energy of nucleus (few-10s MeV), a pion can be created from the off-shell W boson and leave the nucleus in its ground state
- Reaction has small 4-momentum transfer, t, to nucleus
- Can reconstruct |t| from final state

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

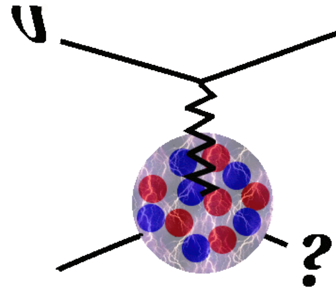
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

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

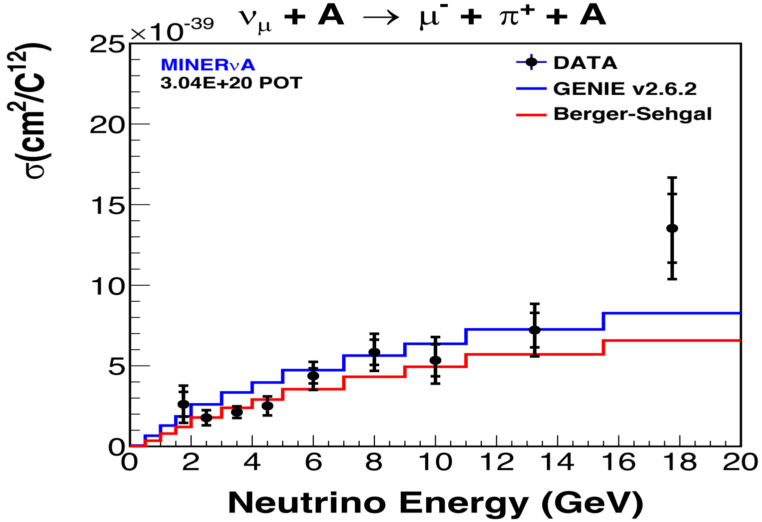
- Reconstruction of |t| gives a model-independent separation of coherent signal and background
  - Tune background at high |t|
  - Measure signal

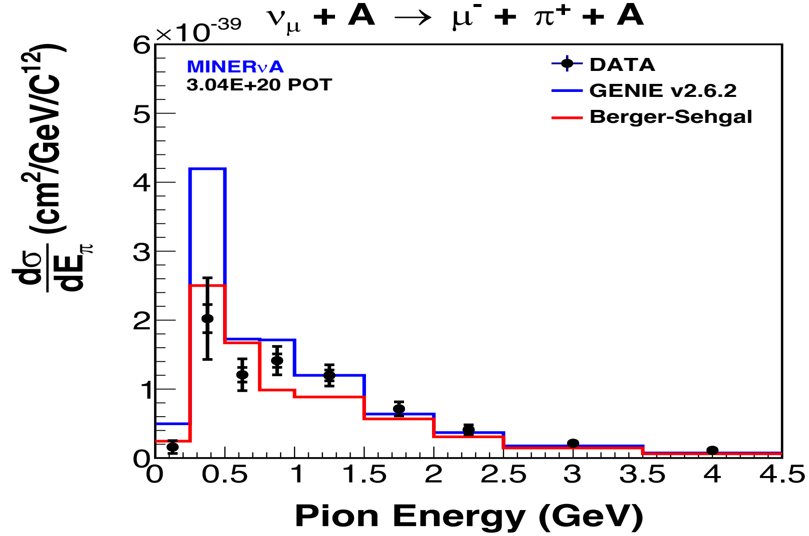


MINERvA Result

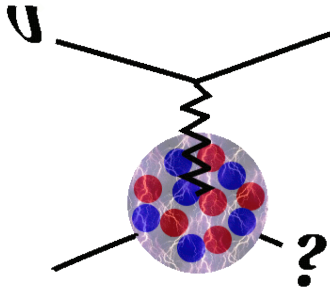


- Measure in both neutrinos and anti-neutrinos (signal cross-section should be the same)
- NEUT, GENIE and Berger-Sehgal Models differ in treatment of one input (pion-nucleus elastic scattering cross-section) and in treatment of mass effects
- Neither NEUT nor GENIE generators do well, particularly at low pion energy
  - Improved πA form factors in Berger-Sehgal calculation provide a better description

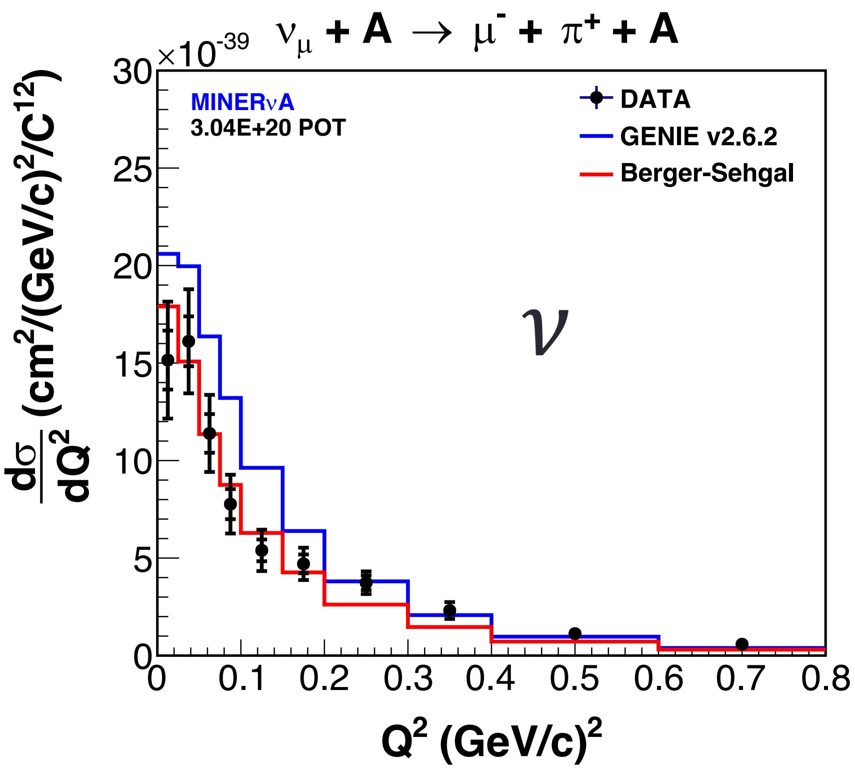


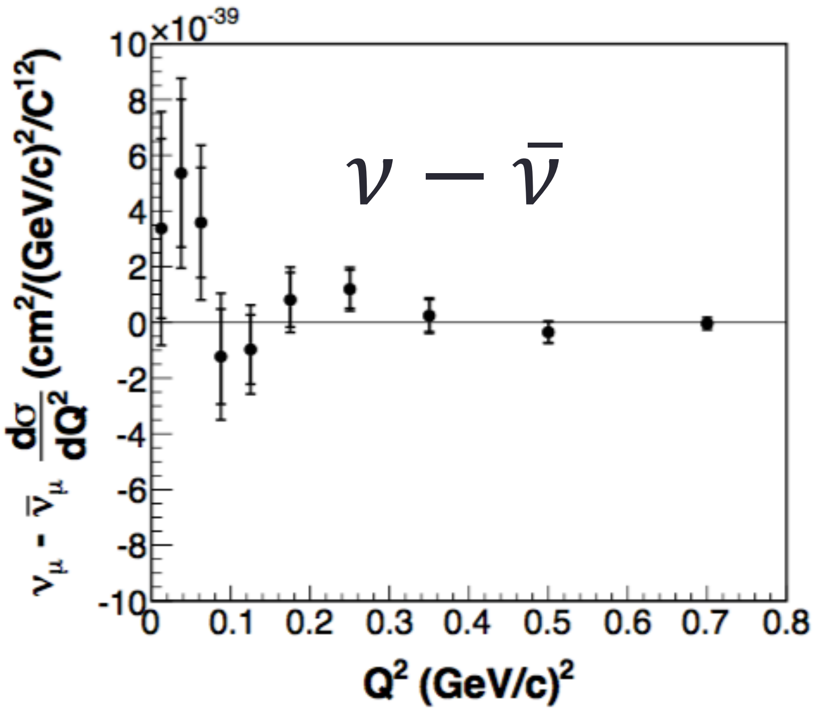


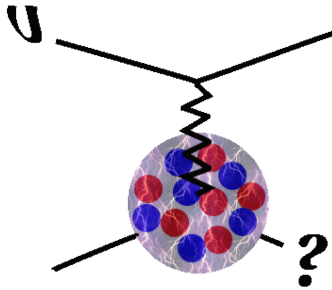
Comparison of Neutrinos and Antineutrinos, and $d\sigma/dQ^2$



- 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



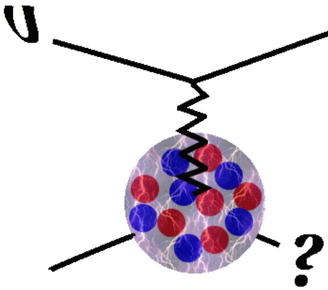




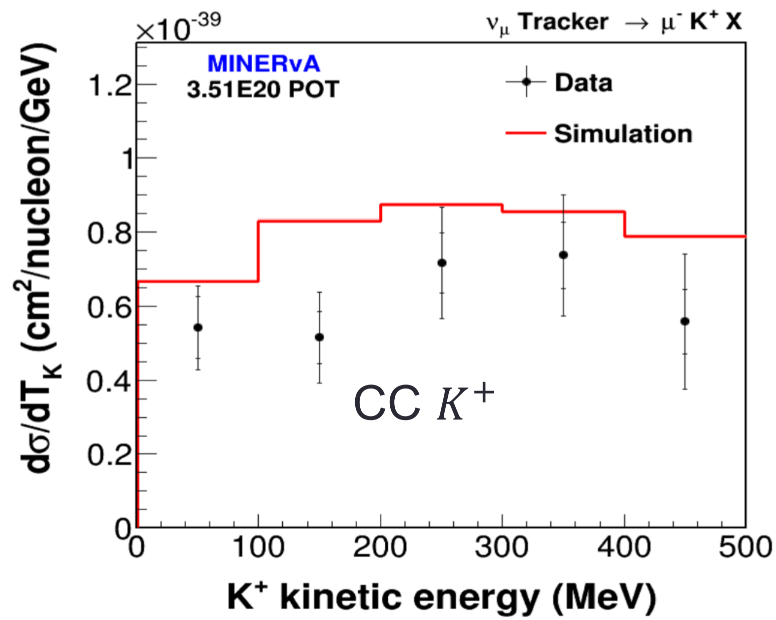
Kaon Production

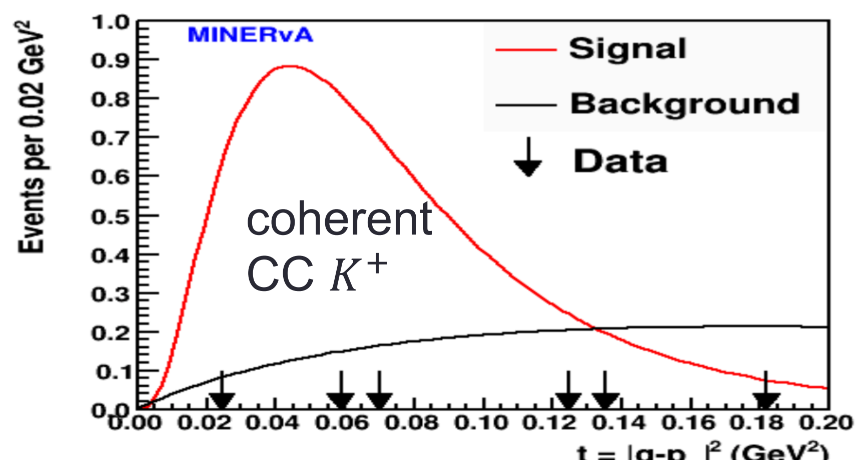
Published in Phys.Rev.Lett. 117 (2016) 061802 and Phys.Rev. D94 (2016) no.1, 012002 and manuscript describing NC process and proton decay backgrounds in preparation for Phys. Rev. Lett.

A basket of kaon results

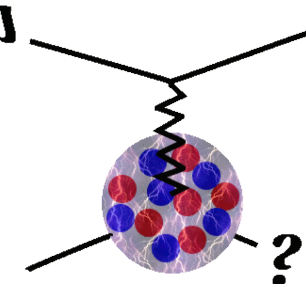


- One we had established the basic technique of identifying K^+, by the time delayed decay products from decay-at-rest…
  - CC K^+ to study FSI of K^+
  - Discovery of the rare[2] coherent CC K^+ production
  - NC K^+
- The latter, the last of our results, is particularly interesting in that we can look at events that could produce backgrounds to $p \rightarrow K^+\nu$

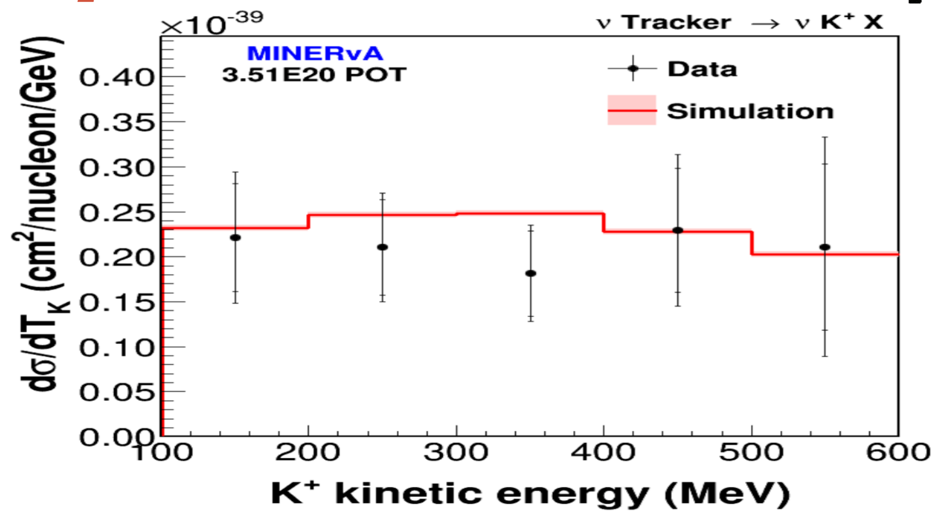


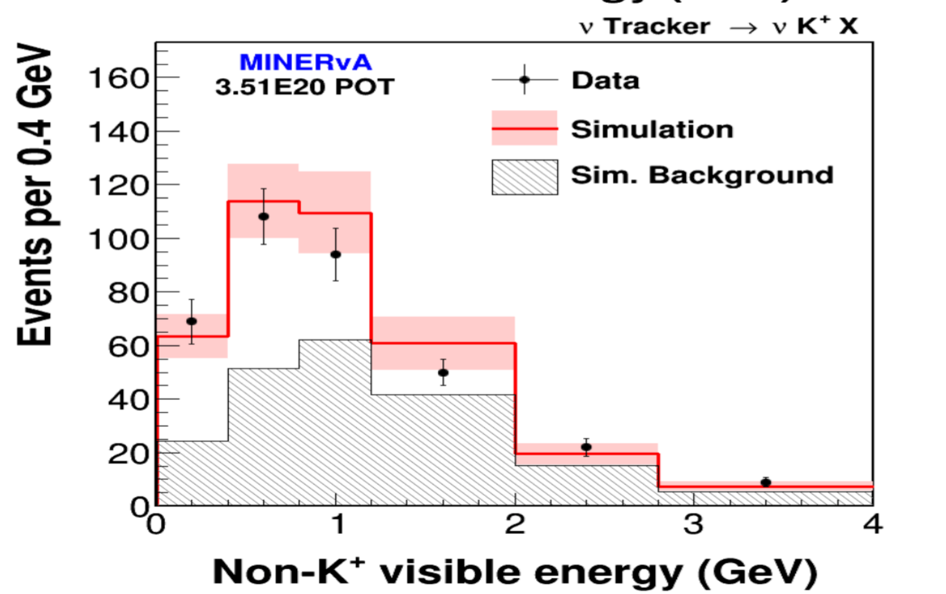


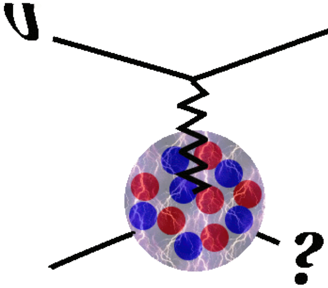
Atmospheric Neutrino Backgrounds to $p \to K^+\nu$



- Flux is 100s of Mton-year exposure equivalent
- The total rate of NC production of low energy kaons is consistent with GENIE (tuned fragmentation) prediction
- We see some modest difference in final state particle content in the events with the least non-K energy
  - In particular, fewer π^0
  - Could interpret the latter as suggesting more K^+K^- pairs then expected
- Provides a framework for assessing uncertainty of background

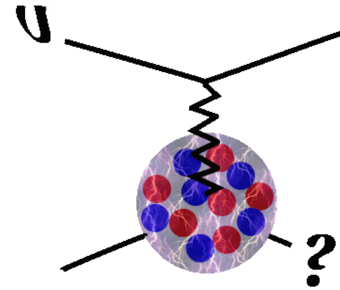






Conclusions

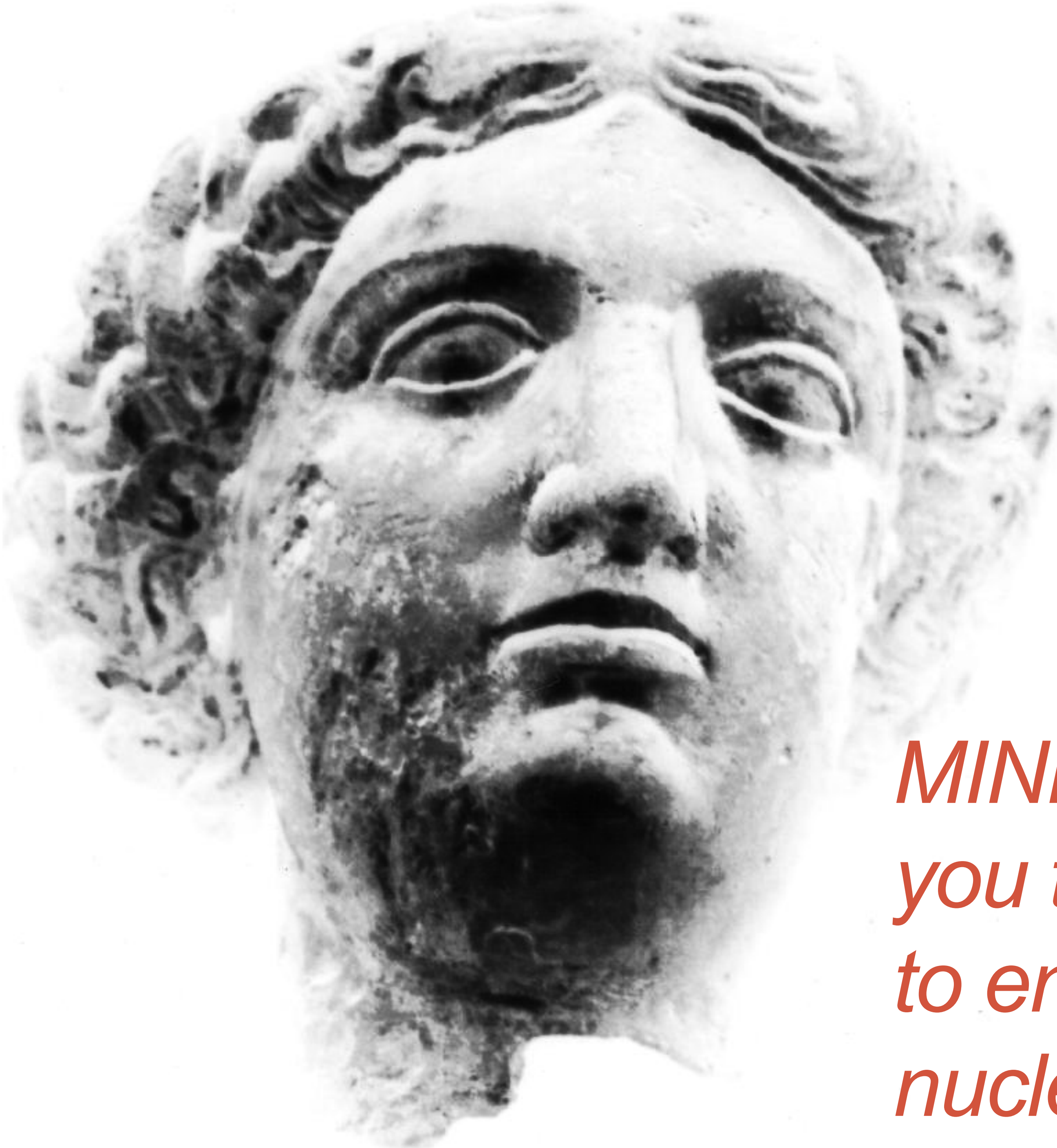
Neutrino Physicists are Learning to find the Nucleus!



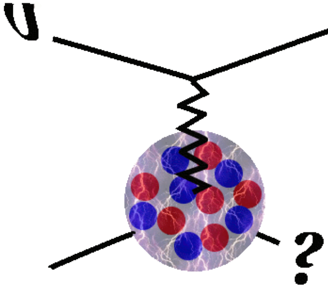
- Neutrino interaction experiments are beginning to reveal nuclear effects
  - Sometimes in good agreement with theory (coherent and kaon) and sometimes not (multinucleon processes)
- New collaborations between nuclear physics and neutrino physics have emerged and flourished
- Neutrino interaction modeling is growing more sophisticated (C. Andreopolous talk)
- Prospects for control of uncertainties from neutrino scattering on nuclei are good for DUNE, INO ICAL, Ice Cube and Hyper-K if we continue to learn together

Liu Bolin

We can find the nucleus together!

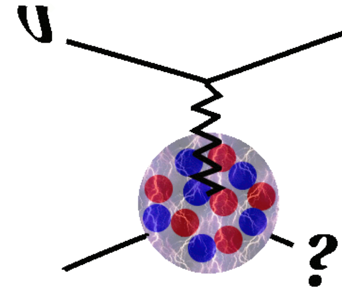


MINERvA invites you to continue to enjoy the nucleus!

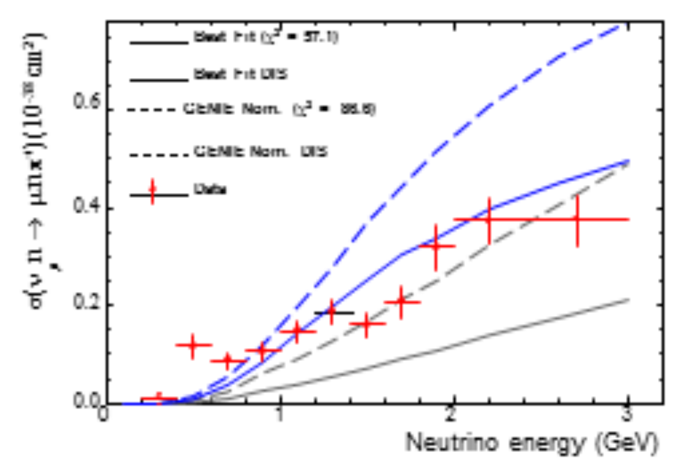


Backup

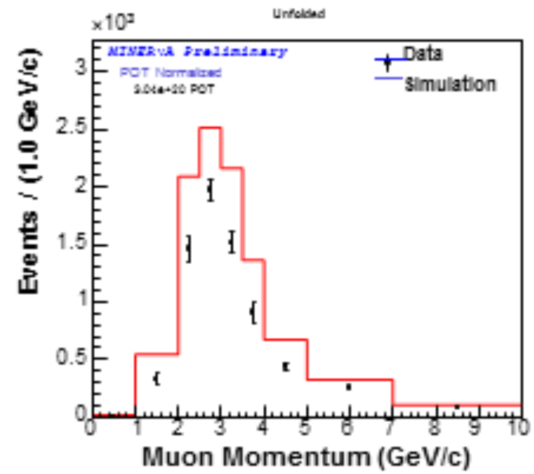
What is that pion modification to GENIE in the low recoil analysis?



BNL D_2 $\nu_\mu n \rightarrow \mu^- n \pi^+$

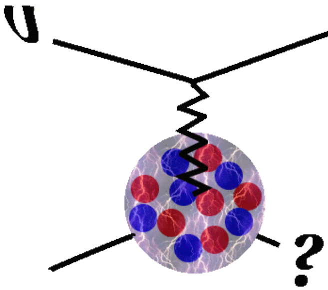


MINERVA $\pi^\pm$ production

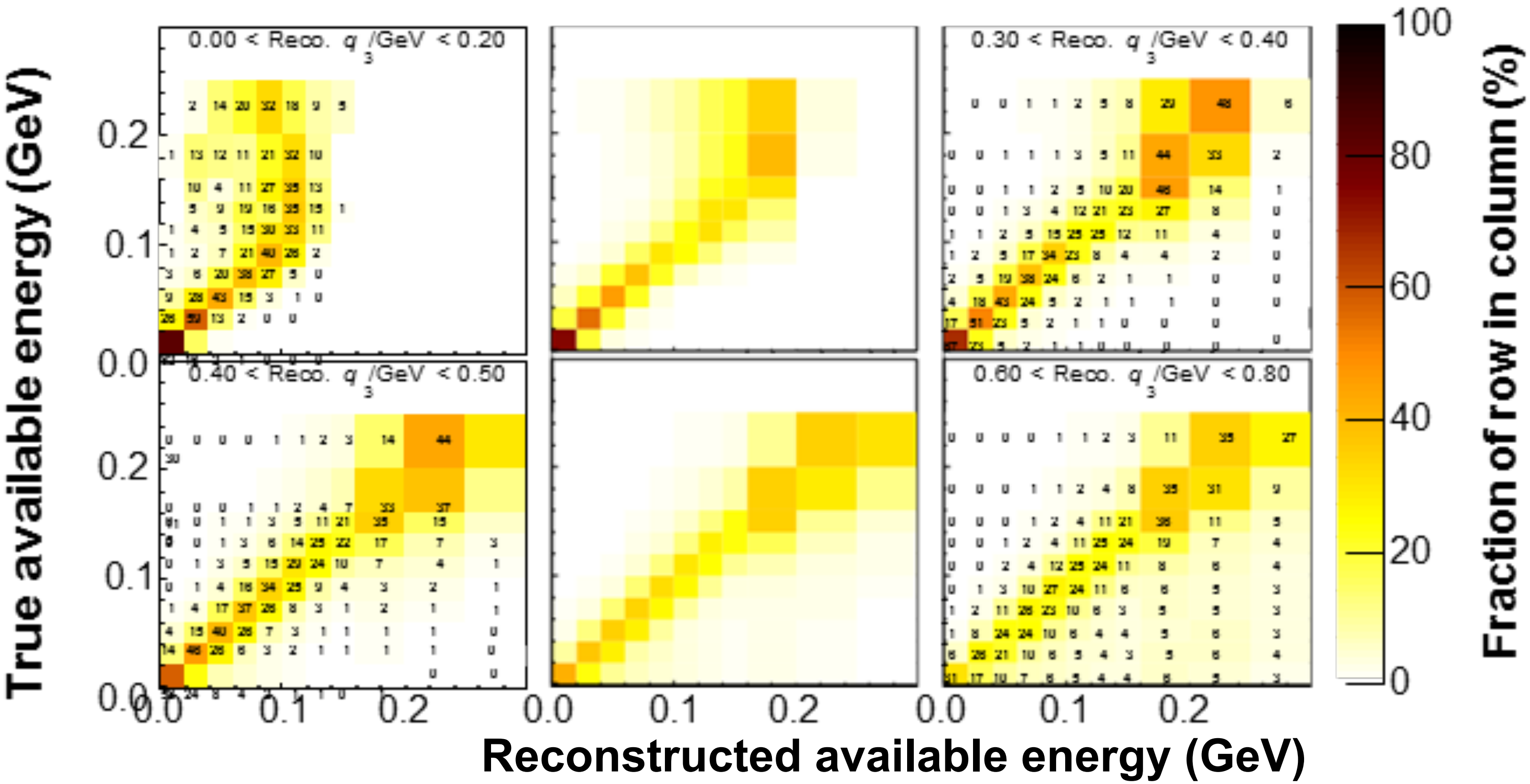


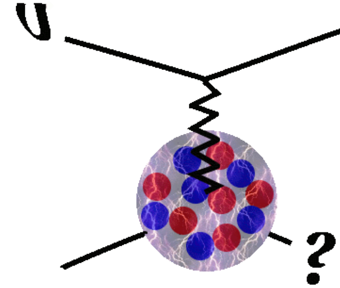
- Use reanalyzed ANL/BNL deuterium data (Wilkinson et al. PRD 90, 112017)
  - Scale down nonresonant production (): GENIE's NonRESBGvnCC1π) by 75% (1.5σi w/ 50% fractional uncertainty (Wilkinson et al. arXiV:1601.01888)
- Further scale down pion production with W < 1.8 GeV by 10% based on comparison with MINERvA data
- From comparison with MINERvA CC coherent π^+, reduce coherent with E_π < 450 MeV by 50%

How well does it work?



- Do we reconstruct E_{avail} correctly? Yes.





How well does it work?

- Here is the same plot for a 2p2h model
- Very slightly different. E_{avail} is a sound choice.