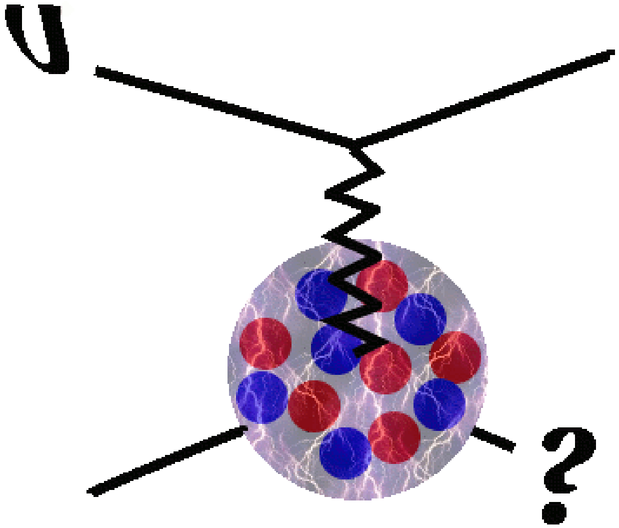
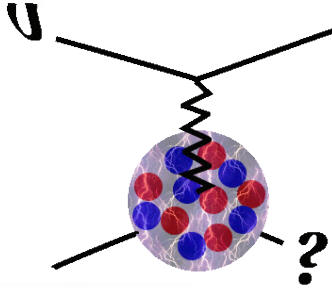
NEUTRINO SCATTERING



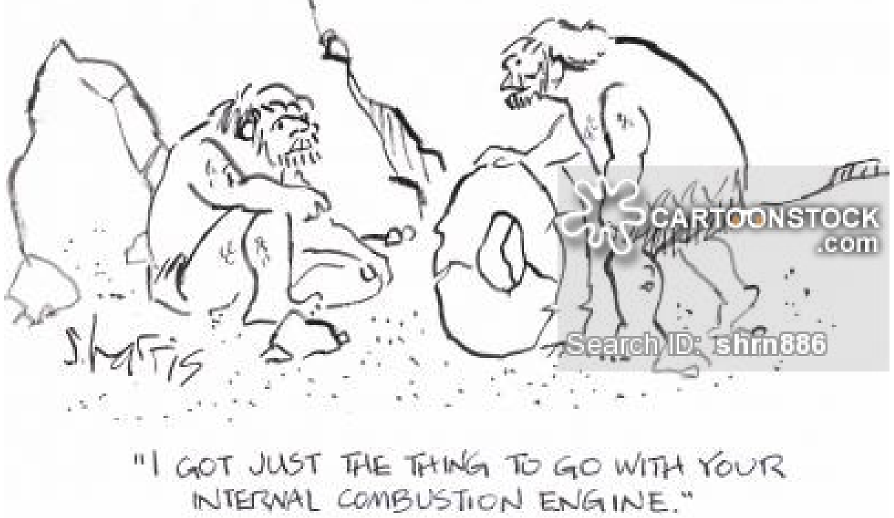
Kevin McFarland
University of Rochester
HiX Workshop, Frascati
18 November 2014



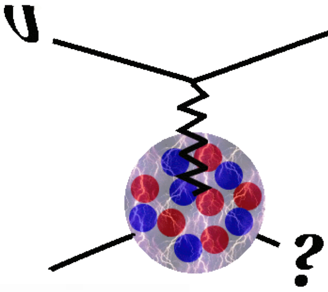
Neutrino Scattering is not like Electron Scattering

- I always feel somewhat inadequate at meetings with JLab people

“I got just the thing to go with your internal combustion engine”



Neutrino Scattering is not like Electron Scattering

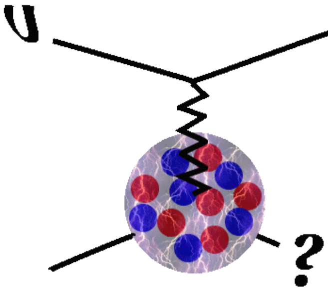


- I always feel somewhat inadequate at meetings with JLab people

- The technology and capabilities of neutrino experiments are less advanced

"I got just the thing to go with your internal combustion engine"

- Nevertheless, as has already been discussed at this meeting, there are some reasons that one might want to go through the difficulties of working with neutrinos

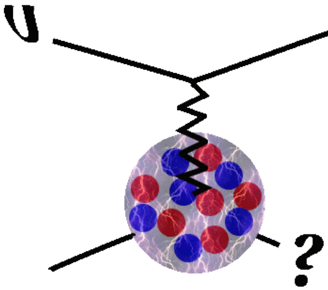


But first, more complaining…

- Working with neutrinos is really, really painful

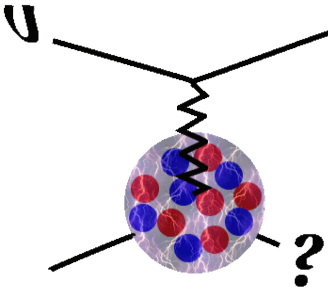
- Typical neutrino experiment algorithm:
  1. *Decide what experiment you want to do*

But first, more complaining…



- Working with neutrinos is really, really painful

- Typical neutrino experiment algorithm:
  1. *Decide what experiment you want to do*
  2. *Build the same crude detector over and over and over again until you can't stand it anymore. Then build more of it.*



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  1. *Decide what experiment you want to do*
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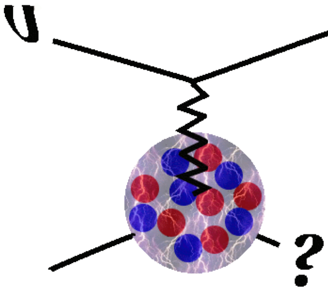
  3. *Operate your detector for tens of years because the rate is so low. Then ask for run extensions because, after all, you went to all that work to build the thing.*



But first, more complaining…

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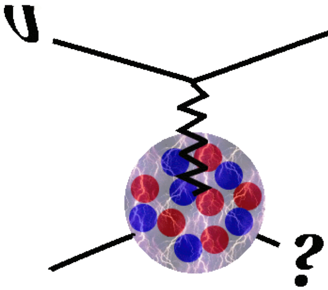
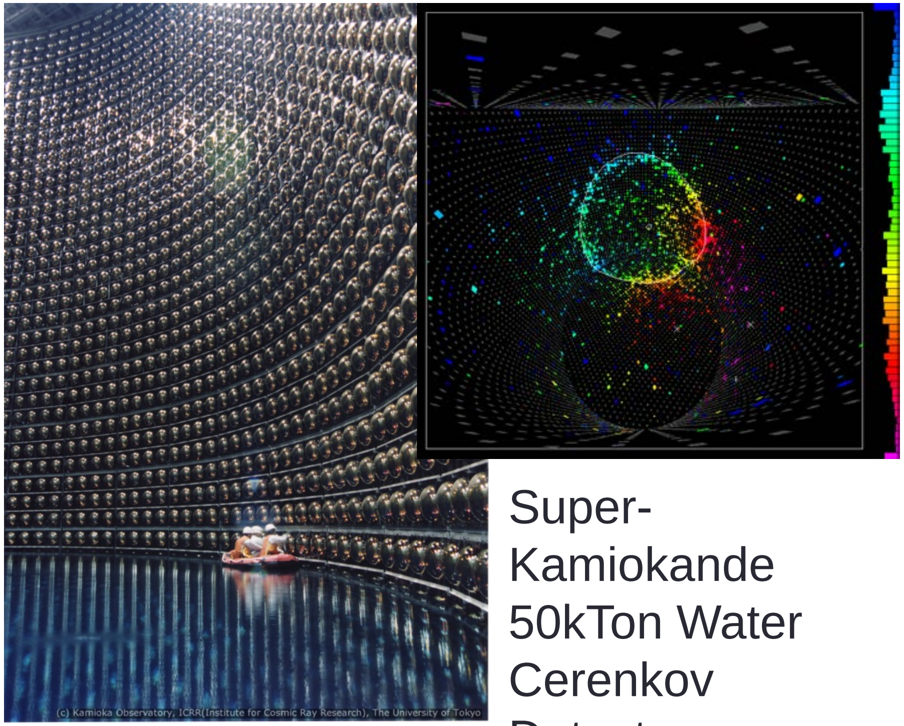
- Typical neutrino experiment algorithm:
  1. *Decide what experiment you want to do*
  2. *Build the same crude detector over and over and over again until you can't stand it anymore. Then build more of it.*
  3. *Operate your detector for tens of years because the rate is so low. Then ask for run extensions because, after all, you went to all that work to build the thing.*
  4. *Profit!* (South Park *taught me all I know about science)*

Masatoshi Koshiba (Rochester Ph.D. 1955): "The secret to winning a Nobel Prize is to live a very long time."

The Difficulties

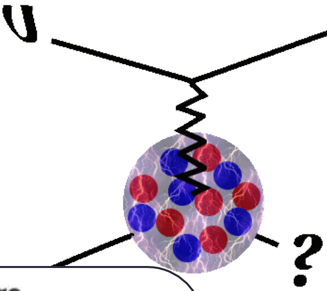


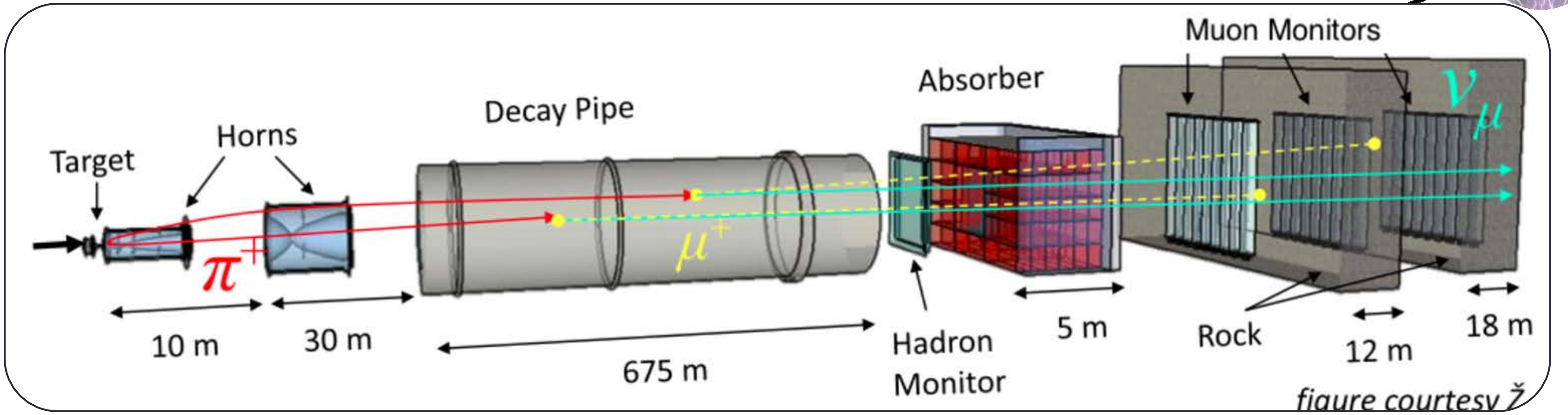
- Neutrinos interact only weakly, so the interaction cross-sections are very low. A comparison to PVES is illustrative:
  - $\sigma=|A_{PC}|^2+2\mathrm{Re}A_{PC}^{*}A_{PV}$+negligible. The last term is the neutrino part.
  - But A_{PV} for neutrinos is the entire amplitude instead of $\sim10^{-6}$
- That means in turn, that your target has to be your entire detector, since interactions occur everywhere.
- This means your target is a moderate or heavy nucleus that is cheap
- And the capabilities of the detector are limited



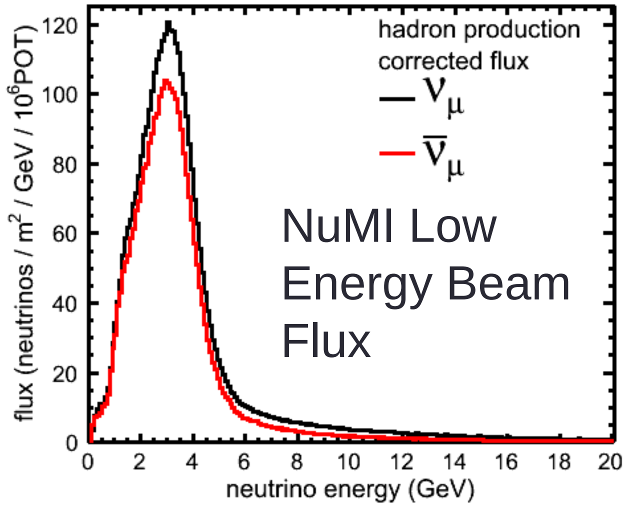
Super-Kamiokande 50kTon Water Cerenkov Detector

The Difficulties

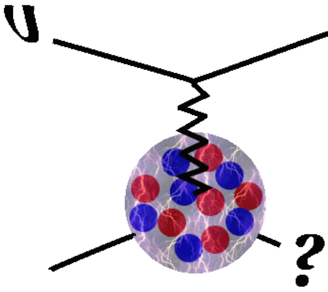




- Finally, to make enough neutrinos, even over the scope of your career, you give up control over your beam.
- You need to create, collect and focus all the pions you can to decay into neutrinos
- So your beam is poorly known and broadband. And you reconstruct energy from the final state.



Why bother?



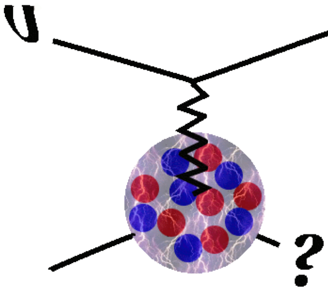
- Neutrino interactions have, of course, some desirable properties in the context of this meeting
- Flavor selection

$$2xF_1^{\nu p,CC} = x\left[d_p(x) + \overline{u_p}(x) + s_p(x) + \overline{c_p}(x)\right]$$

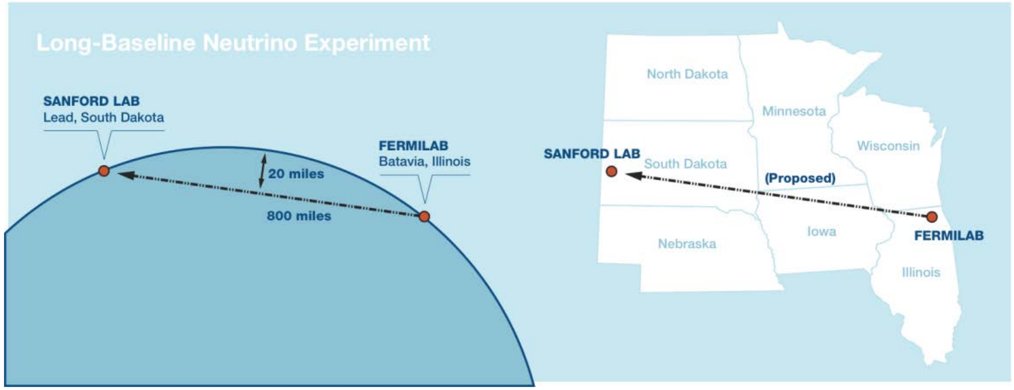
$$xF_3^{\nu p,CC} = x\left[d_p(x) - \overline{u_p}(x) + s_p(x) - \overline{c_p}(x)\right]$$

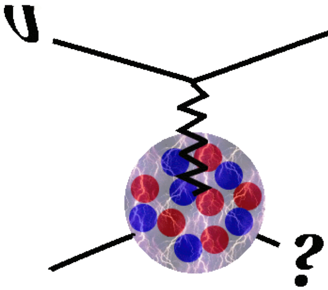
  - e.g., charged-current reactions select only charge -1/3 or -2/3 in the initial state for neutrinos and +1/3 or +2/3 for anti-neutrinos
  - strange quarks “promoted” to charm and easier to detect
- Nuclear dependence
  - Models for nuclear effects would benefit from more challenges from data, e.g. EMC → “every model’s copacetic”
  - Likely that because of flavor dependence or dynamics that neutrinos will observe different nuclear effects

Recent, Current and Future Experiments



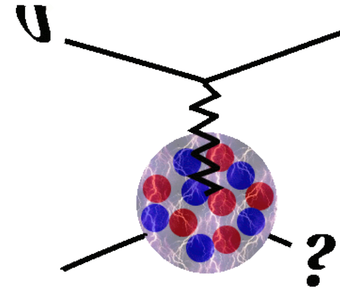
- In the 1970s, ’80s and even ’90s, studies of weak interactions and measurements of structure functions on (bound) nucleons were major drivers for neutrino physics
  - Consequently, experiments pushed to higher energy at SPS, Tevatron, etc. Interactions dominated by high Q^2, high W.
- But the physics we are discussing at this meeting is not currently driving the field of neutrino physics
  - CP violation in neutrino oscillations requires experiments with L/E_ν of 400 km/GeV. Since L is limited by diverging beam, E_ν is small.





A Selection of Older, but still Interesting, Neutrino Results

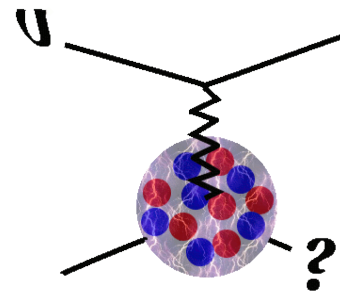
A Brief Observation…



- I came to this conference expecting to hear little or no mention of the old results I planned to highlight
  - Measurement of strange quarks
  - CTEQ calculation of neutrino "Nuclear Effects" from NuTeV and CHORUS
  - NuTeV NC/CC ratio

- I am pleasantly surprised that everyone wants to steal my thunder. Great! Perhaps I can finish on time. ☺

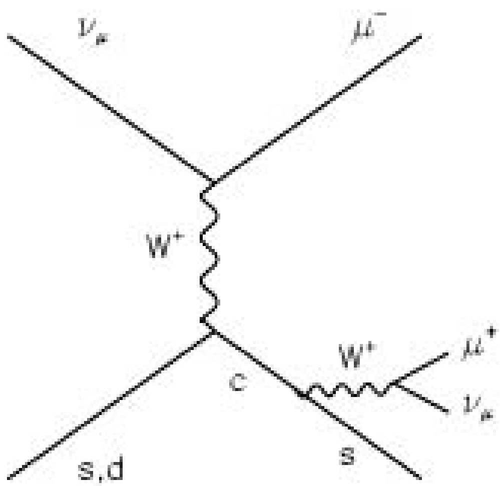
Strange Sea from Neutrinos



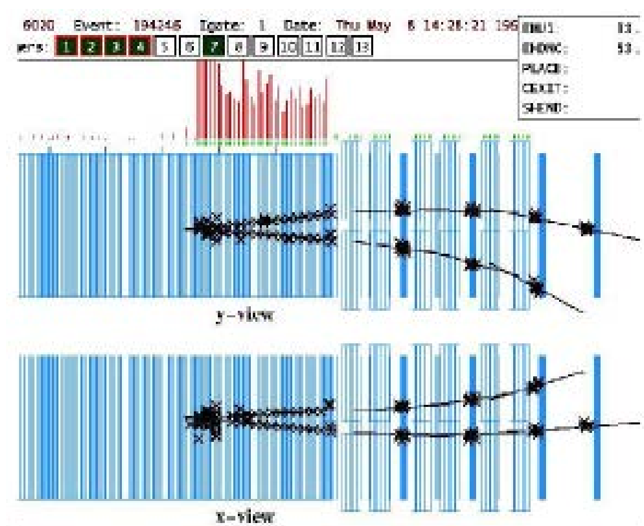
- Neutrino induced charm production has been extensively studied
  - Emulsion/Bubble Chambers (low statistics, 100s of events). Reconstruct the charm final state, but limited by target mass. E.g., CHORUS
  - “Dimuon events” (high statistics, ~10000 events). E.g., CCFR, NuTeV and NOMAD

$$\nu_\mu + \begin{pmatrix} d \\ s \end{pmatrix} \rightarrow \mu^- + c + X, \qquad c \rightarrow \mu^+ + \nu_\mu + X'$$

$$\bar{\nu}_\mu + \begin{pmatrix} \bar{d} \\ \bar{s} \end{pmatrix} \rightarrow \mu^+ + \bar{c} + X, \qquad \bar{c} \rightarrow \mu^- + \bar{\nu}_\mu + X'$$

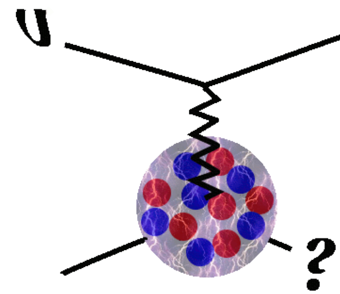


NuTeV dimuon event



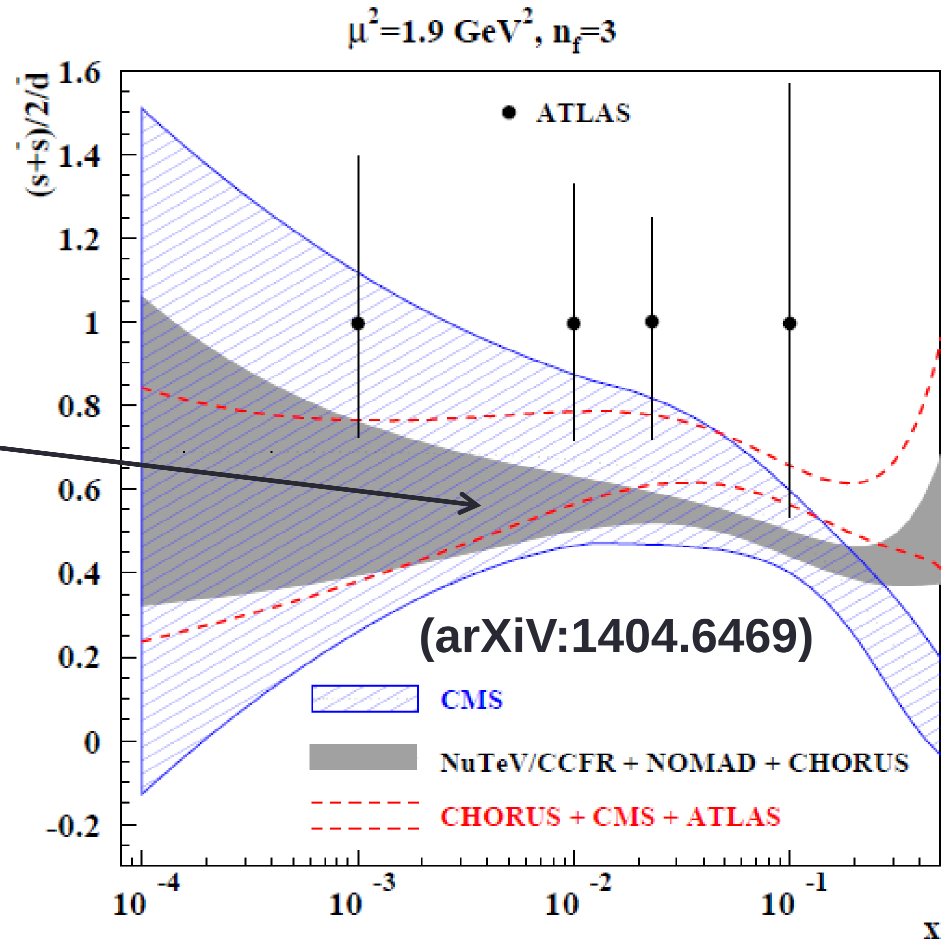
Phys.Rev. **D64**, 112006 (2001) [NuTeV]
Nucl.Phys. **B876**, 339 (2013) [NOMAD]
New J.Phys. **13**, 093002 (2011) [CHORUS]

Constraining the Sea



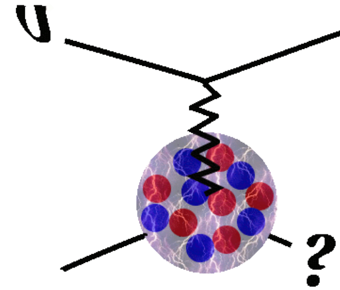
- Recent comprehensive analysis by Alekhin and collaborators essentially closes the book on extracting strange sea information

Neutrino data

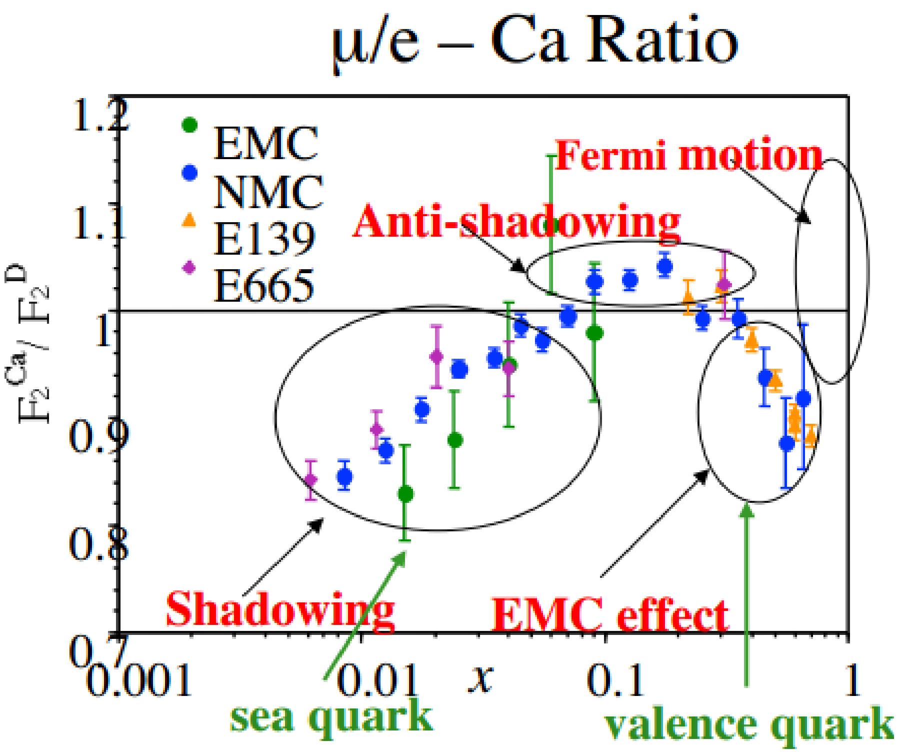


- Of course, this is still on heavy targets
- Last comment: collider techniques are promising, but still are sensitive to charm fragmentation models

Charged Lepton Nuclear Ratios



Charged lepton data show structure function F_2 effectively changes when nucleon bound in nucleus



Physics Letters B123,
Issues 3–4, 31 March 1983, Pages 275–278

Abstract:
"Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2(Fe)/F_2(D)$ is presented.
The observed x-dependence of this ratio is in disagreement with existing theoretical predictions. "

… and after much experimental and theoretical effort to explain this …

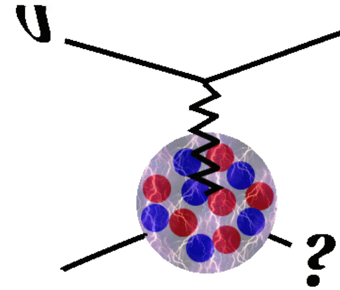
CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years

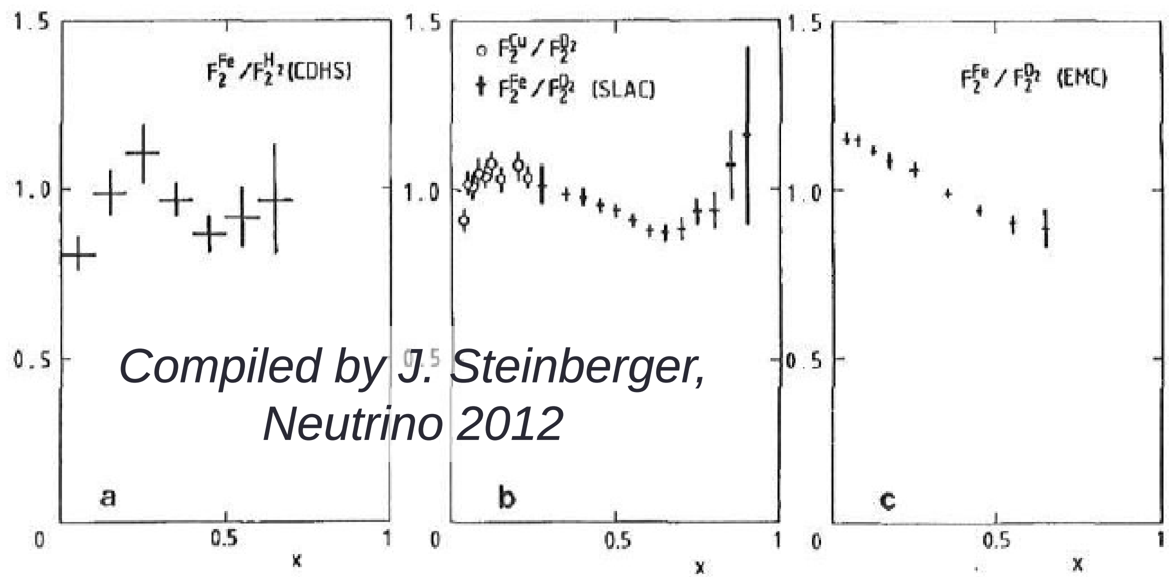
Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

No Comparable Neutrino Data Currently Exists



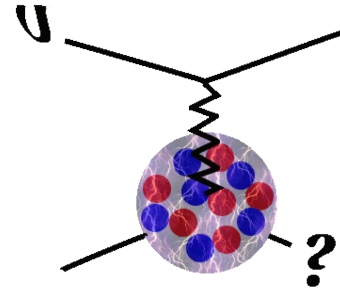
- There is good motivation for neutrino data to exist
  - Neutrinos sensitive to structure function xF_3
    - (Charged leptons are not)
    - Gives neutrinos ability to separate valence and sea
  - Neutrinos sensitive to axial piece of structure function F_2
    - (Charged leptons are not)
    - Axial effect larger at low x, low Q^2

- Here's the only measurement I am aware of with a comparison to contemporary data

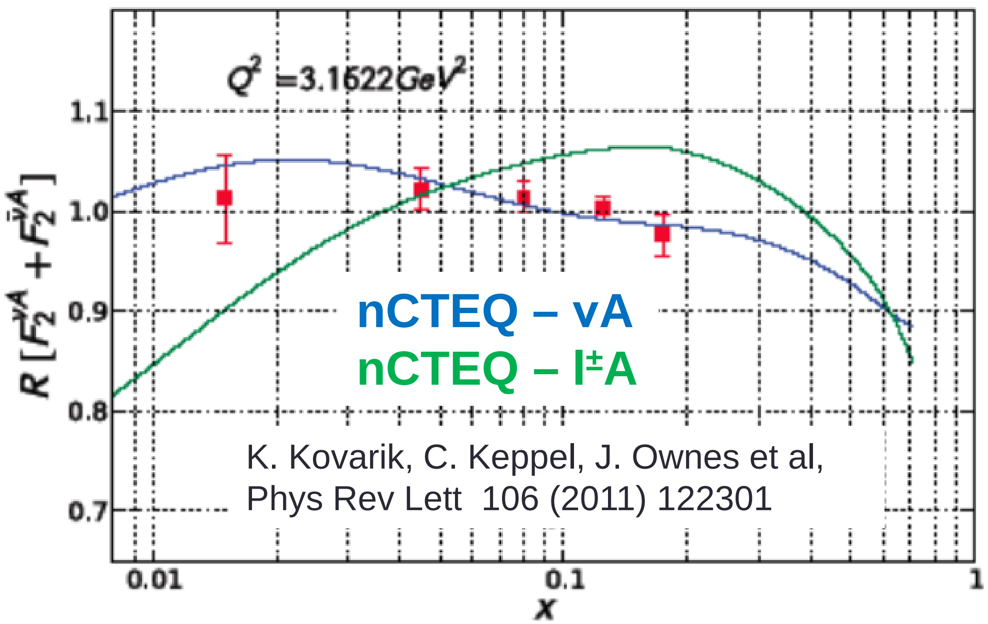


Compiled by J. Steinberger, Neutrino 2012

What can one do?

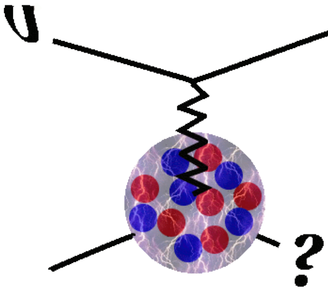


Compromise approach is to compare a theoretical calculation of free nucleon F_2 to, e.g., NuTeV (ν-Fe) data, and fit. Compared to fits to charged lepton data.

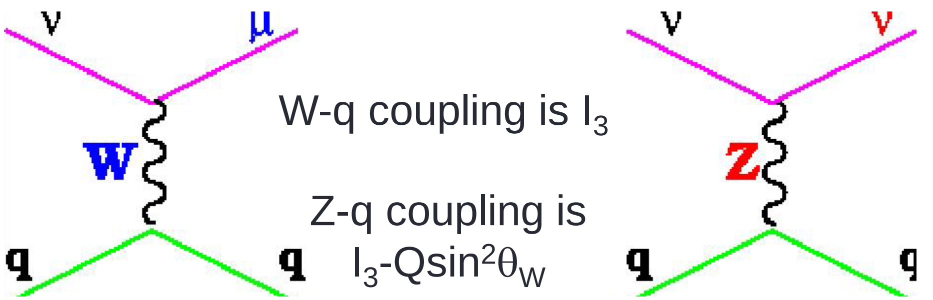


- *This approach is "what one can do" given the data*
- *But this theoretical construction of a "free nucleon F_2" is fraught with peril: heavy flavor, lepton mass effects, radiative corrections, isoscalar corrections of iron, etc.*
- *I agree with Stan's comment that "NuTeV sees no evidence of anti-shadowing". But possibly not for the same reason Stan believes it…*

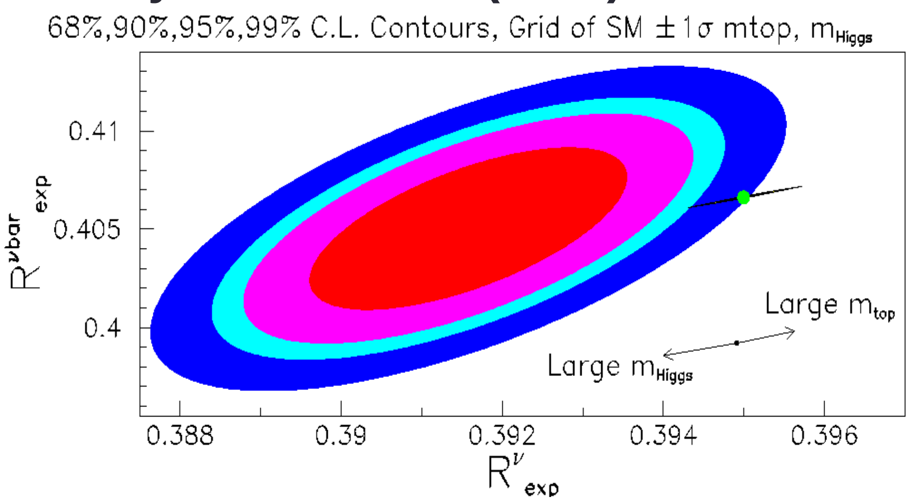
And of course, my favorite subject… NuTeV NC/CC



- The idea of NuTeV was to measure NC/CC in neutrinos and anti-neutrinos as an electroweak test

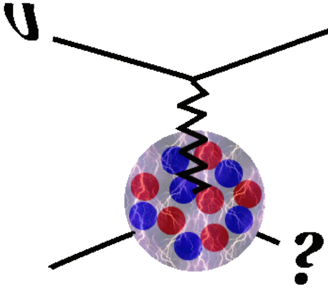


Phys Rev Lett 88 (2002) 091802



- This interpretation makes some assumptions
  - That nuclear effects in Fe are the same for W and Z exchange
  - That charge symmetry holds for the PDFs in iron at the ~% level
- Several authors have built plausible models for these effects and have helpfully calculated corrections to NuTeV's data

Tony has kindly cited this work from time to time over the years…



- 1) Shadowing corrections and the precise determination of electroweak parameters in neutrino-nucleon scattering
- By Gerald A. Miller, Anthony William Thomas.
- hep-ex/0204007.
- 10.1142/S0217751X0502121X.
- Int.J.Mod.Phys. A20 (2005) 95-98.

- 2) Nuclear shadowing at low Q**2 and the extraction of sin**2 Theta(W)
- By W. Melnitchouk, Anthony William Thomas.
- hep-ex/0208016.
- 10.1103/PhysRevC.67.038201.
- Phys.Rev. C67 (2003) 038201.

- 3) Charge symmetry violating contributions to neutrino reactions
- By J.T. Londergan, Anthony William Thomas.
- hep-ph/0301147.
- 10.1016/S0370-2693(03)00267-3.
- Phys.Lett. B558 (2003) 132-140.

- 4) Charge symmetry violation corrections to determination of the Weinberg angle in neutrino reactions
- By J.T. Londergan, Anthony William Thomas.
- hep-ph/0303155.
- 10.1103/PhysRevD.67.111901.
- Phys.Rev. D67 (2003) 111901.

- 5) Neutrino physics without oscillations
- By Anthony William Thomas.
- hep-ex/0311029.
- 10.1063/1.1627727.
- AIP Conf.Proc. 689 (2003) 53.

- 6) Constraints on parton charge symmetry and implications for neutrino reactions
- By J.T. Londergan, Anthony William Thomas.
- hep-ph/0407247.

- 7) Nucleon and hadron structure changes in the nuclear medium and impact on observables
- By K. Saito, Kazuo Tsushima, Anthony William Thomas.
- hep-ph/0506314.
- 10.1016/j.ppnp.2005.07.003.
- Prog.Part.Nucl.Phys. 58 (2007) 1-167.

- 8) Experimental tests of charge symmetry violation in parton distributions
- By J.T. Londergan, D.P. Murdock, Anthony William Thomas.
- hep-ph/0507029.
- 10.1103/PhysRevD.72.036010.
- Phys.Rev. D72 (2005) 036010.

- 9) Implications of current constraints on parton charge symmetry
- By J.T. Londergan, Anthony William Thomas.
- 10.1088/0954-3899/31/11/003.
- J.Phys. G31 (2005) 1151-1163.

- 10) Testing the standard model by precision measurement of the weak charges of quarks
- By Ross Daniel Young, Roger D. Carlini, Anthony William Thomas, Julie Roche.
- arXiv:0704.2618 [hep-ph].
- 10.1103/PhysRevLett.99.122003.
- Phys.Rev.Lett. 99 (2007) 122003.

- 11) Moments of Nucleon's Parton Distribution for the Sea and Valence Quarks from Lattice QCD
- By M. Deka, T. Streuer, T. Doi, S.J. Dong, T. Draper, K.F. Liu, N. Mathur, A.W. Thomas.
- arXiv:0811.1779 [hep-ph].
- 10.1103/PhysRevD.79.094502.
- Phys.Rev. D79 (2009) 094502.

- 12) Quark distributions in nucleons and nuclei
- By Wolfgang Bentz, Ian C. Cloet, Takuya Ito, Anthony W. Thomas, K. Yazaki.
- PoS CONFINEMENT8 (2008) 090.

- 13) Isovector EMC effect explains the NuTeV anomaly
- By I.C. Cloet, W. Bentz, A.W. Thomas.
- arXiv:0901.3559 [nucl-th].
- 10.1103/PhysRevLett.102.252301.
- Phys.Rev.Lett. 102 (2009) 252301.

- 14) Charge Symmetry at the Partonic Level
- By J.T. Londergan, J.C. Peng, A.W. Thomas.
- arXiv:0907.2352 [hep-ph].
- 10.1103/RevModPhys.82.2009.
- Rev.Mod.Phys. 82 (2010) 2009-2052.

- 15) Positrons at Jefferson Laboratory
- By Anthony W. Thomas.
- arXiv:0907.4748 [nucl-ex].
- 10.1063/1.3232031.
- AIP Conf.Proc. 1160 (2009) 3-7.

- 16) Reassessment of the NuTeV determination of the weak mixing angle
- By W. Bentz, I.C. Cloet, J.T. Londergan, A.W. Thomas.
- arXiv:0908.3198 [nucl-th].
- 10.1016/j.physletb.2010.09.001.
- Phys.Lett. B693 (2010) 462-466.

- 17) Symmetries and the search for physics beyond the standard model
- By Anthony W. Thomas.
- 10.1016/j.nuclphysa.2010.05.008.
- Nucl.Phys. A844 (2010) 19C-25C.

- 18) An Overview of Meson-Nuclear Physics
- By Anthony W. Thomas.
- arXiv:1011.3884 [nucl-th].
- 10.1063/1.3647113.
- AIP Conf.Proc. 1374 (2011) 145-150.

- 19) Charge Symmetry Breaking in Parton Distribution Functions from Lattice QCD
- By R. Horsley, Y. Nakamura, D. Pleiter, P.E.L. Rakow, G. Schierholz, H. Stuben, A.W. Thomas, F. Winter et al..
- arXiv:1012.0215 [hep-lat].
- 10.1103/PhysRevD.83.051501.
- Phys.Rev. D83 (2011) 051501.

- 20) The Determination of $\sin^2 \theta_W$ in Neutrino Scattering: no more anomaly
- By A.W. Thomas.
- arXiv:1111.0122 [hep-ph].
- 10.1063/1.3667317.
- AIP Conf.Proc. 1418 (2011) 147-153.

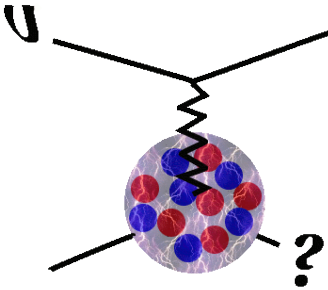
- 21) Parity-violating DIS and the flavour dependence of the EMC effect
- By I.C. Cloet, W. Bentz, A.W. Thomas.
- arXiv:1202.6401 [nucl-th].
- 10.1103/PhysRevLett.109.182301.
- Phys.Rev.Lett. 109 (2012) 182301.

- 22) Charge symmetry breaking from a chiral extrapolation of moments of quark distribution functions
- By P.E. Shanahan, A.W. Thomas, R.D. Young.
- arXiv:1303.4806 [nucl-th].
- 10.1103/PhysRevD.87.094515.
- Phys.Rev. D87 (2013) 9, 094515.

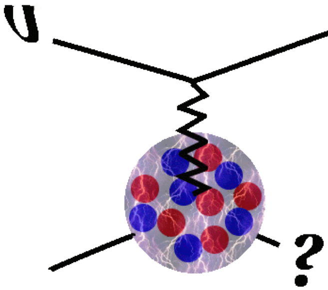
- 23) Progress in resolving charge symmetry violation in nucleon structure
- By R.D. Young, P.E. Shanahan, A.W. Thomas.
- arXiv:1312.4990 [nucl-th].
- 10.1142/S0218301314610102.

… and I'm happily returning the favor.

Thoughts about NuTeV…



- To interpret NuTeV's results as an anomalous electroweak coupling, one would have to cautiously modify only neutrino couplings.
  - Only at the fraction of a % level, but still this is theoretically ugly.
- It's clear that there are plausible models for nuclear effects and nucleon charge symmetry violation which could explain what NuTeV sees
- It's not clear how to provide evidence for which of these models are correct from the NuTeV data itself
  - *Snarky but true comment: if we put them all in, we'd still have to modify electroweak couplings, just in the opposite direction*
  - Experiments that could shed light on the same nuclear and nucleon physics with other observables would be well motivated

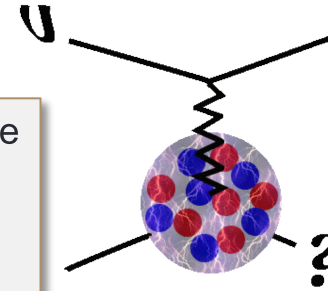


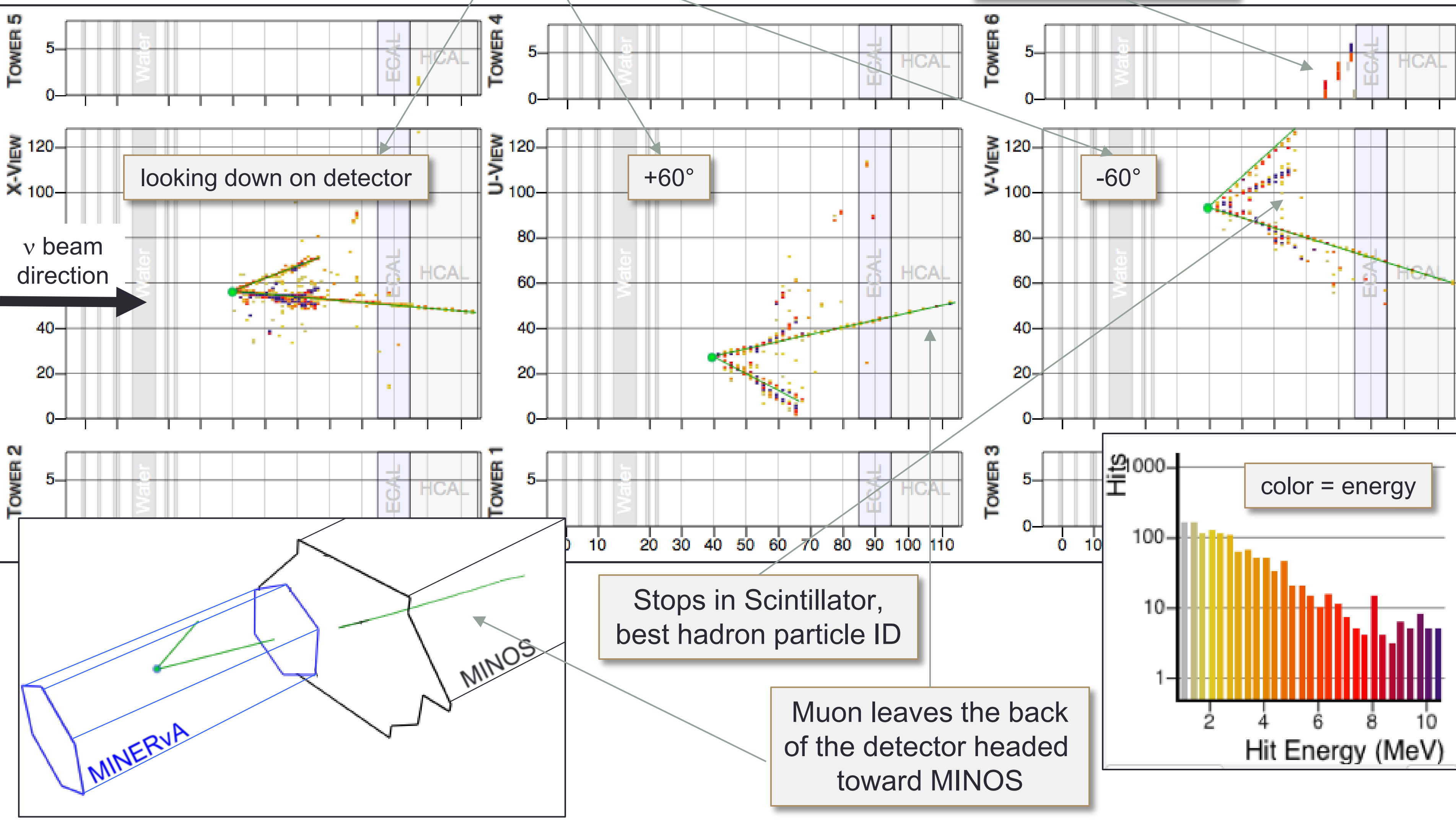
Results and Prospects from the MINERvA Experiment

Events in MINERvA

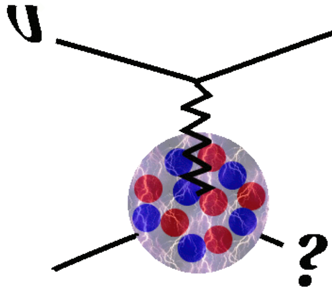
3 stereo views, X—U —V , shown separately

Particle leaves the inner detector, stops in outer iron calorimeter

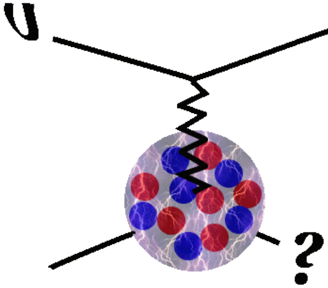




Things to remember about working with neutrinos



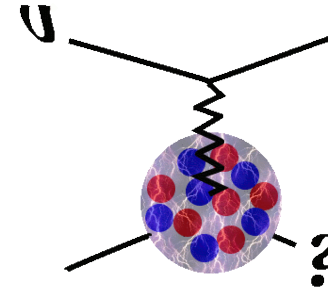
- In any given event, we don't know anything about the neutrino energy
  - Except by reconstruction of the final state
  - And we don't even know the integrated flux in our beam with any decent precision
- Events are hard to come by
  - In rough numbers, our 2010-2012 exposure had ~5E5 reconstructable neutrino interactions in our 8 ton scintillator target
  - Our future higher energy exposure in parallel with NOvA experiment is estimated to give us ~5E6 such interactions
- Our detector is a reasonable compromise between rate, granularity and cost, but still has limitations
  - ~80 MeV kinetic energy threshold for tracking protons, for example
  - Calorimetric response not uniform to pions, protons, neutrons at the relevant energies



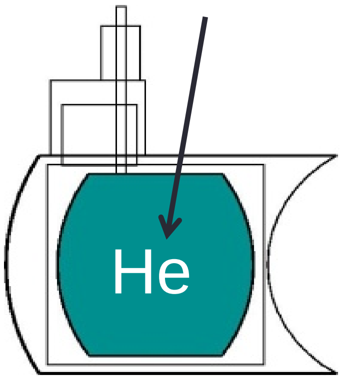
Nuclear Target Ratios

Phys. Rev. Lett. 112, 231801 (2014)

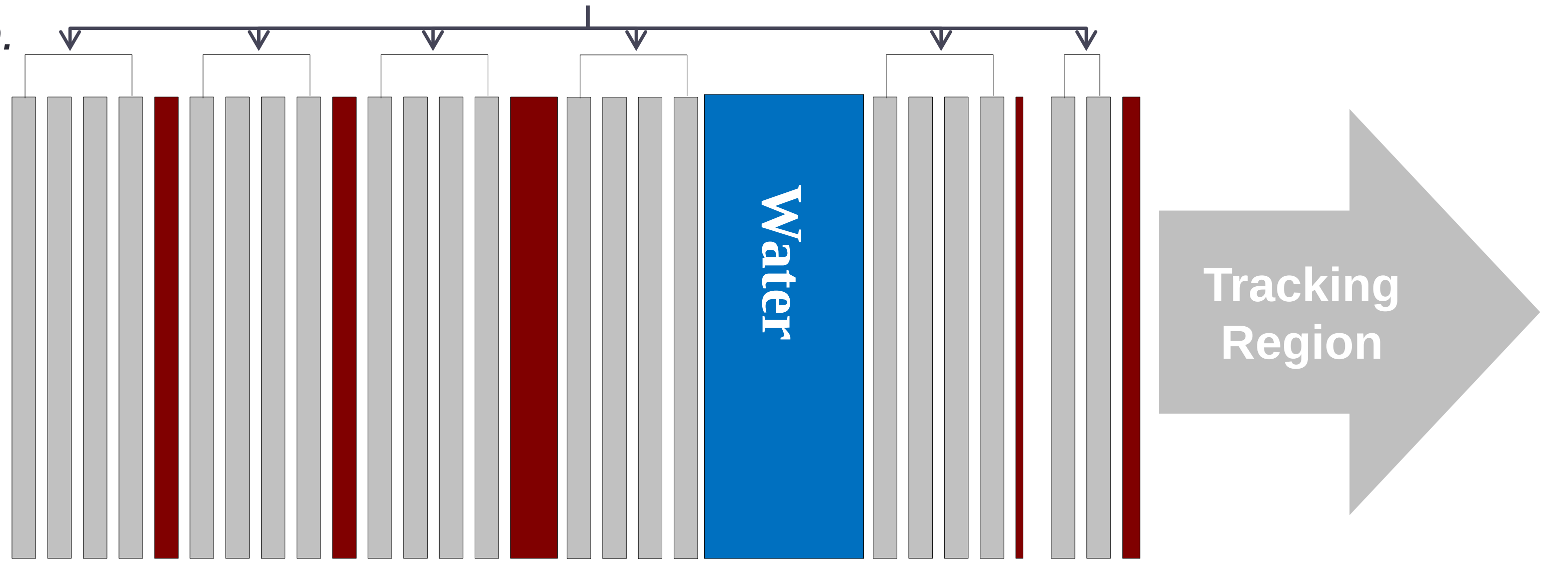
Passive Nuclear Targets



Why ^{4}He? You can get 2500 liters of it and it doesn't ignite.



Scintillator Modules



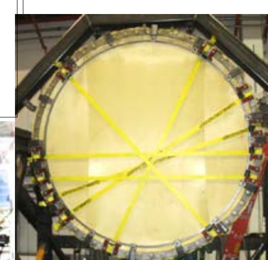
250 kg
Liquid He

1" Fe / 1" Pb
323kg / 264kg

1" Pb / 1" Fe
266kg / 323kg

3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg

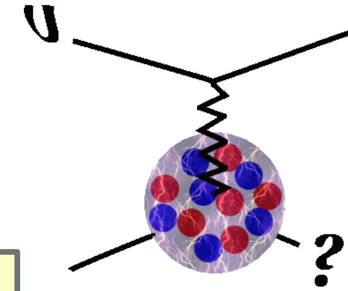
6" 500kg Water

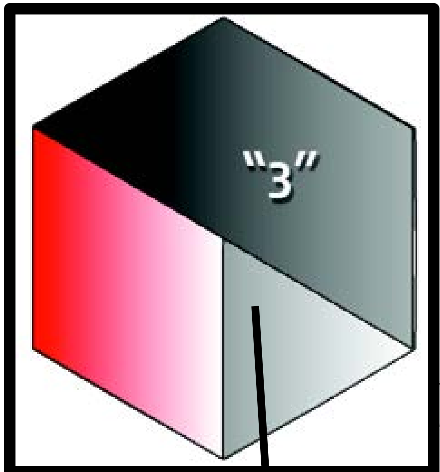


0.3" Pb
228kg

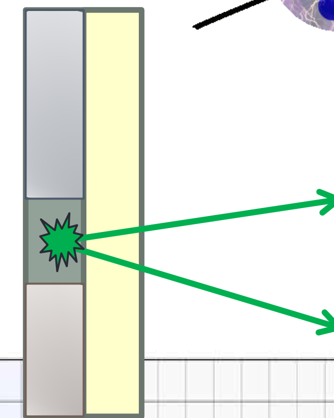
.5" Fe / .5" Pb
161kg/ 135kg

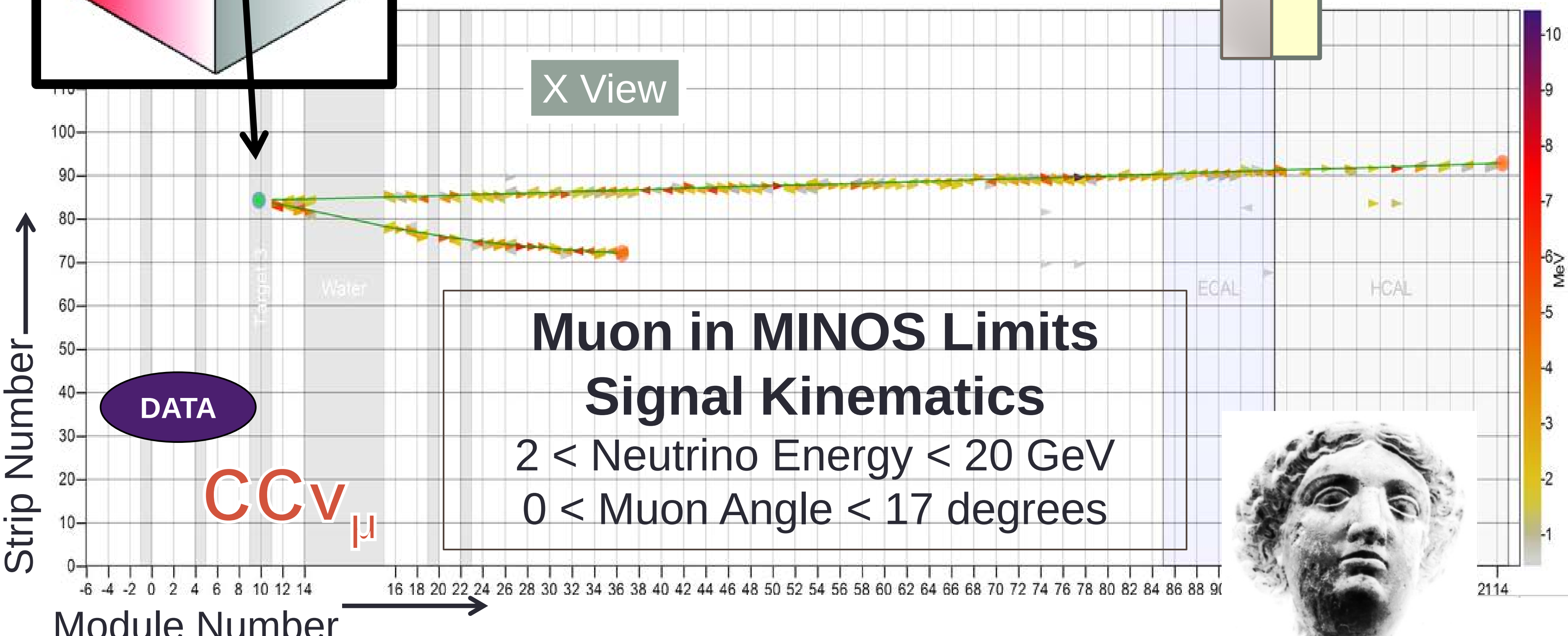
MINERvA Pb Candidate





- Two track event can often be projected back unambiguously to target
- But this is not most of data…



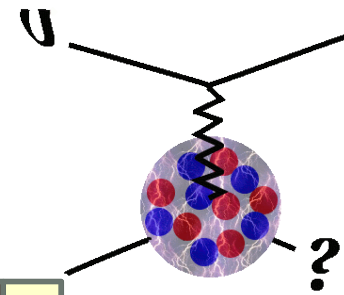


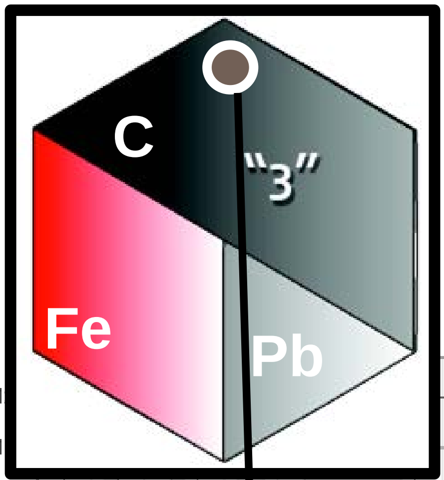
Muon in MINOS Limits Signal Kinematics

2 < Neutrino Energy < 20 GeV

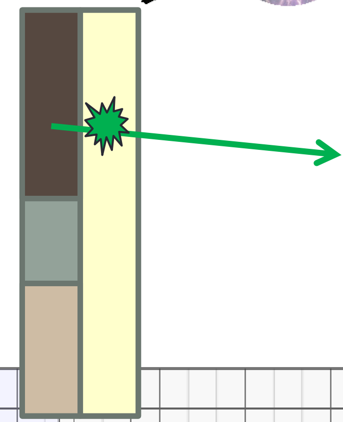
0 < Muon Angle < 17 degrees

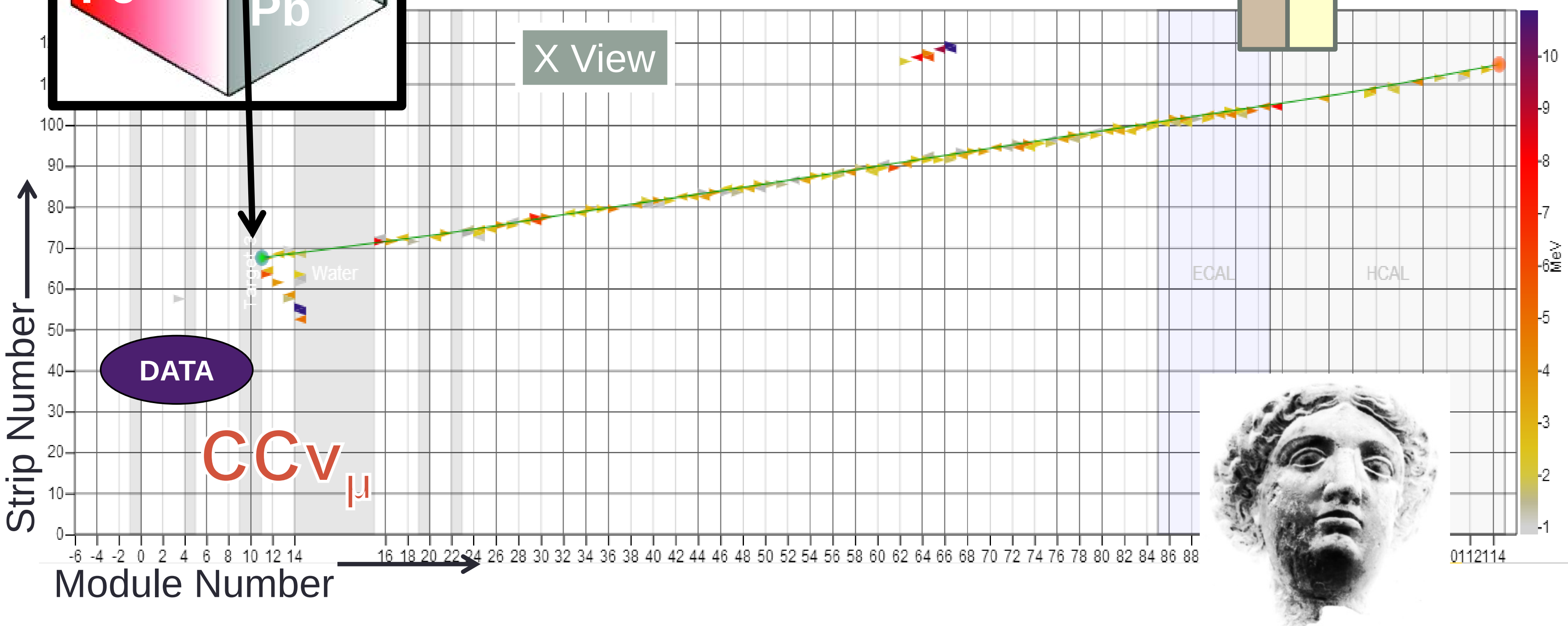
MINERvA 1-track C Candidate



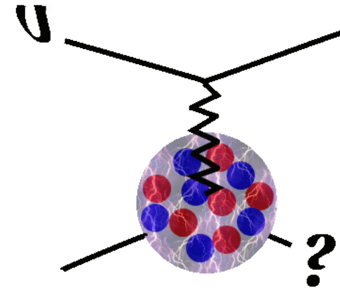


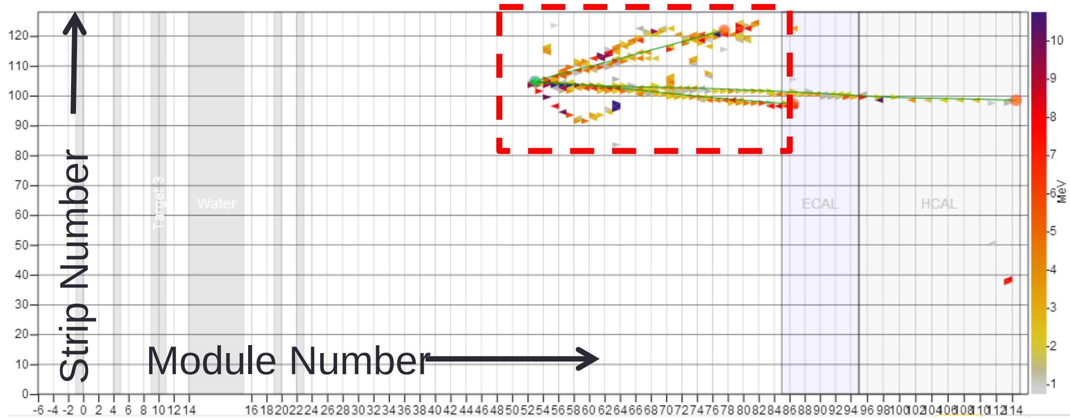
- One track candidates may originate from passive target or from downstream scintillator
- Source of background



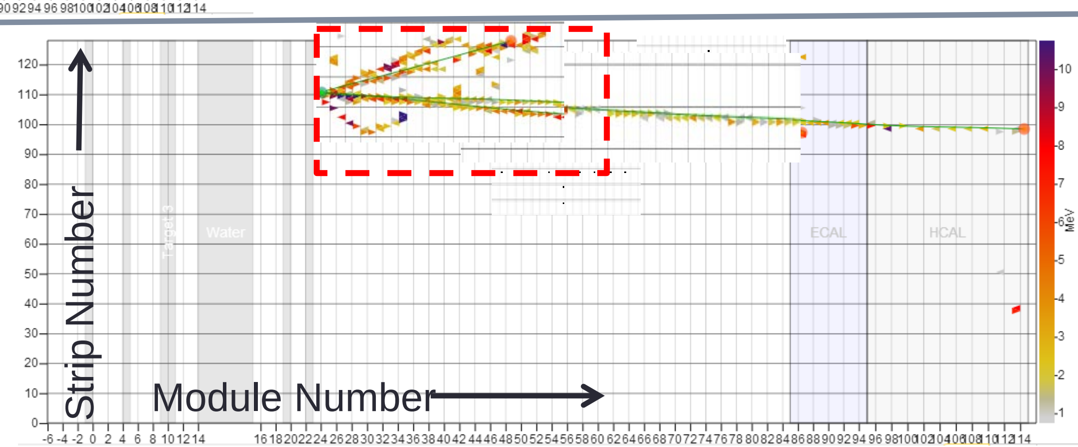


Predicting Scintillator Background



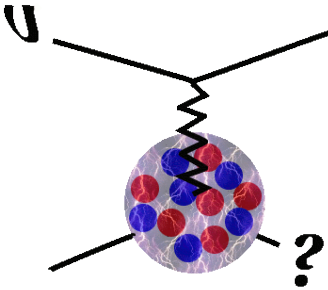


1. Find an event in scintillator of tracker
2. Move to a passive nuclear target

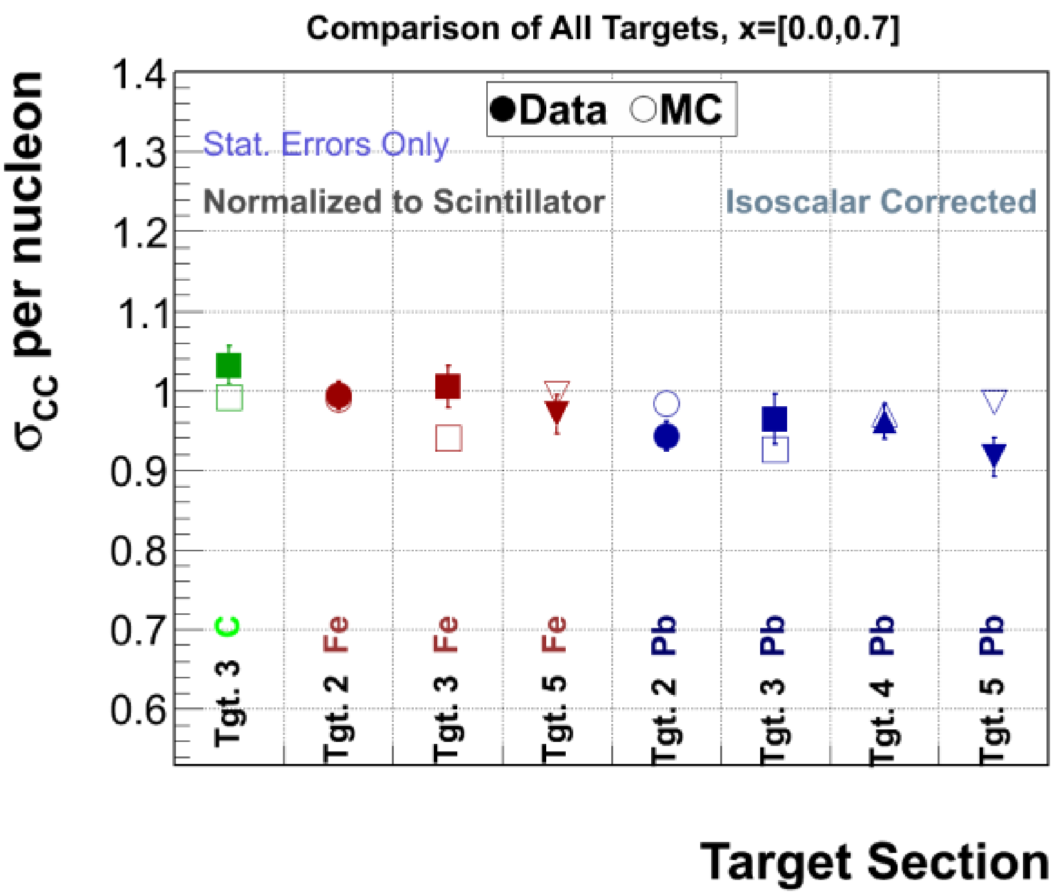


3. Use simulation to predict probability of track(s) being obscured by recoil shower
4. Evaluate uncertainties by comparing simulation procedure (and variants) against true event

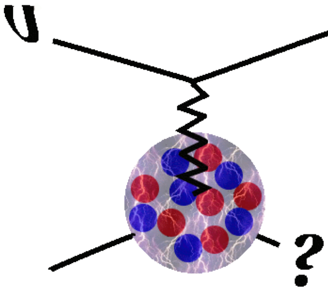
Result of Subtraction

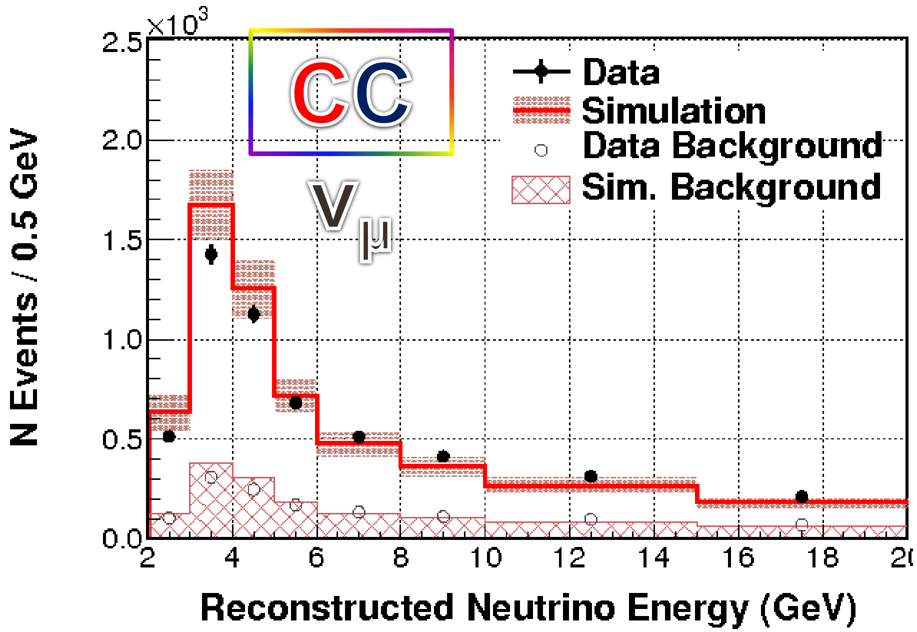


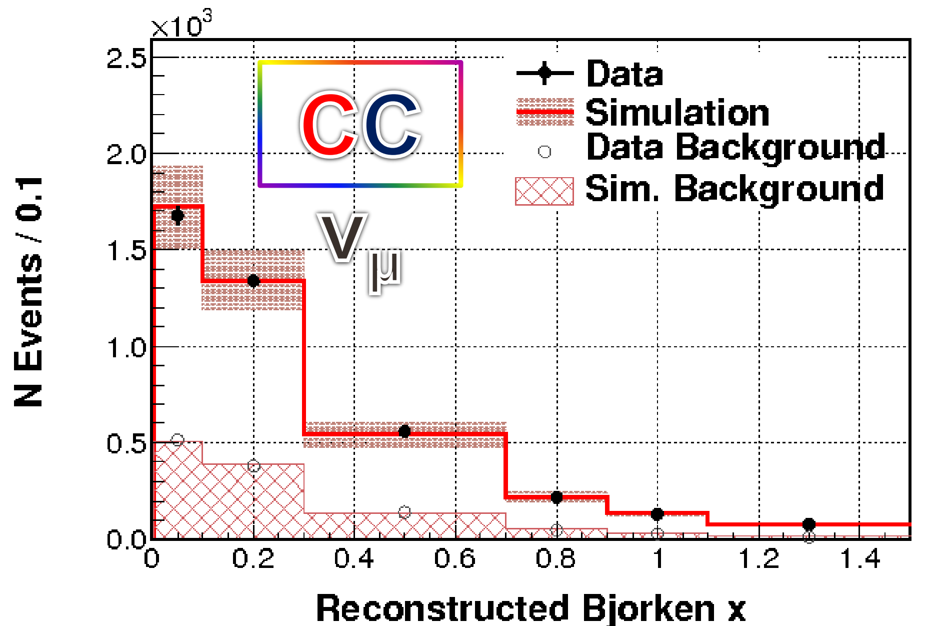
- Multiple iron and lead targets
- Can compare consistency among these
- Well within statistical uncertainties



Kinematic Reconstruction: Fe of Target 5







$$\nu = E_{recoil} = \alpha \times \sum_{i}^{hits} \frac{E_i}{f_i}$$

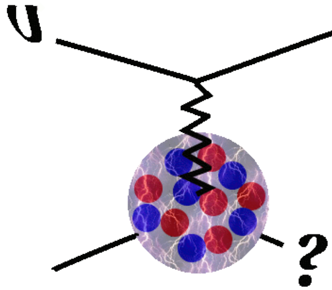
$$E_\nu = \nu + E_\mu$$

$$Q^2 = 2E_\nu \left(E_\mu - p_\mu cos\left(\theta_\mu\right)\right)$$

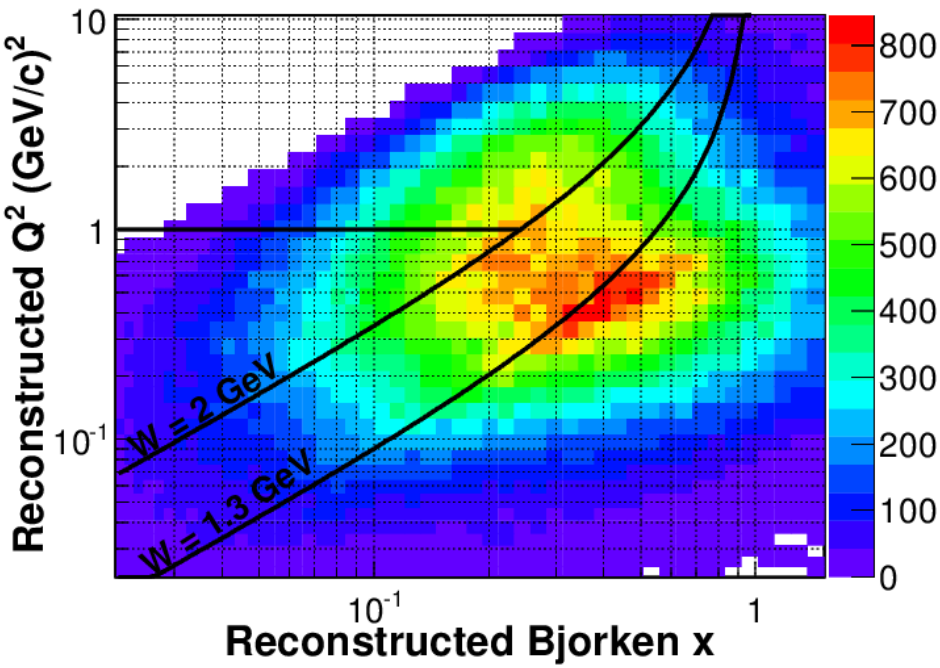
$$x = \frac{Q^2}{2M\nu}$$

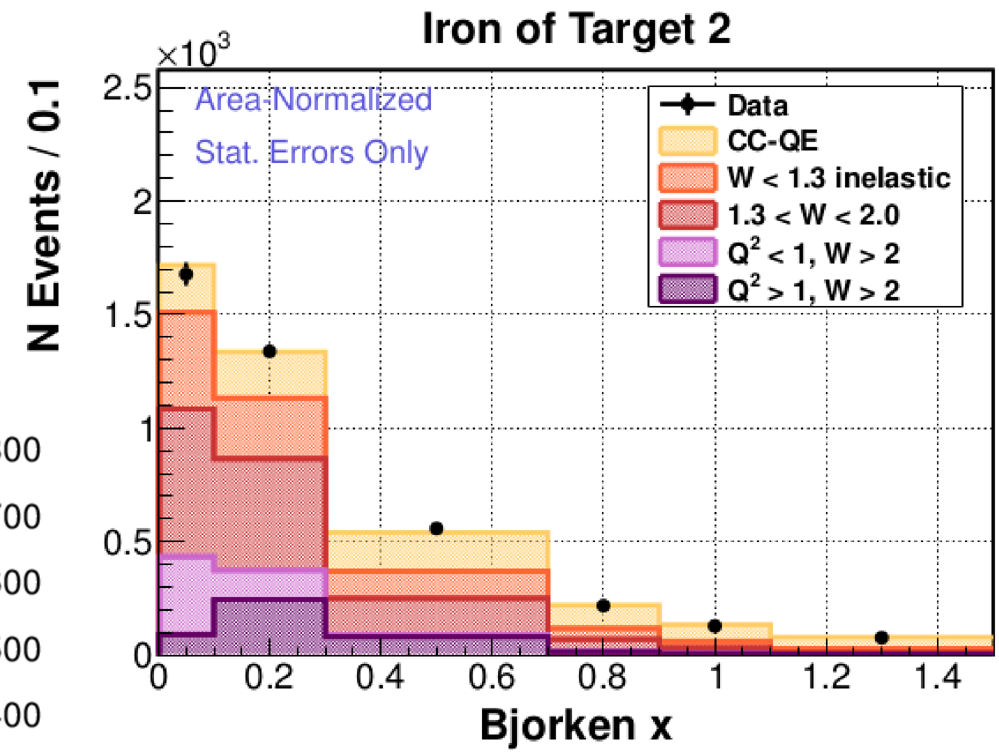
Simulation scaled to data by total number of events passing selection.
Shading on simulation is systematic uncertainty.

Kinematics of Events in MINERvA Low Energy Beam



- Events are a blend of elastic, resonance region and DIS
- Mostly NOT DIS



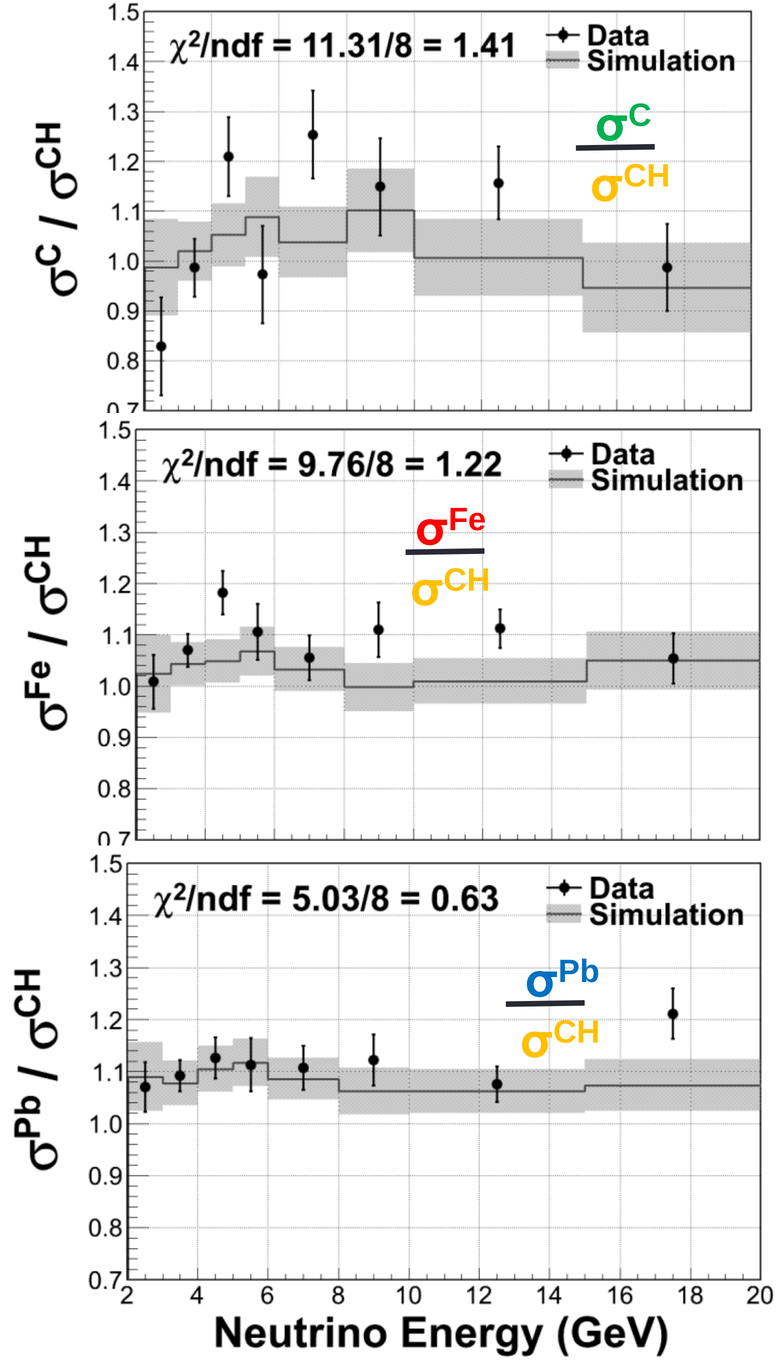


Invariant hadronic mass

$$W = \sqrt{M^2 + 2M\nu - Q^2}$$

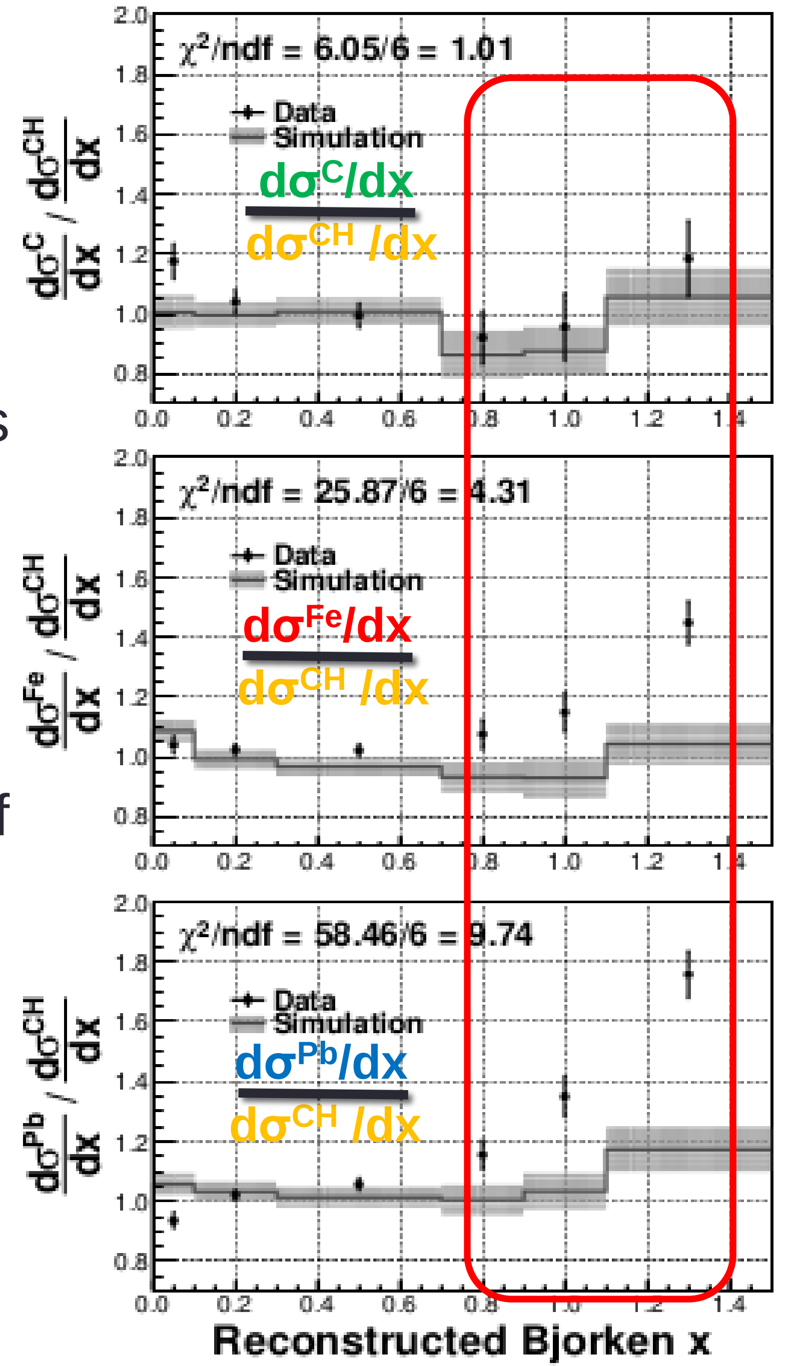
Neutrino Energy

- Ratio plotted is cross-section per nucleon
- Within statistical uncertainties, no evident variation of ratio with energy
- Gray band of prediction is the uncertainty in the ratio from varying parameters in GENIE 2.6.2 neutrino generator
  - Not unity because, e.g., quasielastic cross-section is a function of number of neutrons, not nucleons



High x Region

- At x=[0.7,1.1], we observe a **excess** that grows with the size of the nucleus
- This effect is not observed in simulation.
- But is due to not understanding physics of elastic processes, or that of inelastic processes?
  - ~2/3 of the events in this region in our simulation are due to quasi-elastic events
  - There is significant migration of these events from bin-to-bin because of poor recoil resolution at small recoil

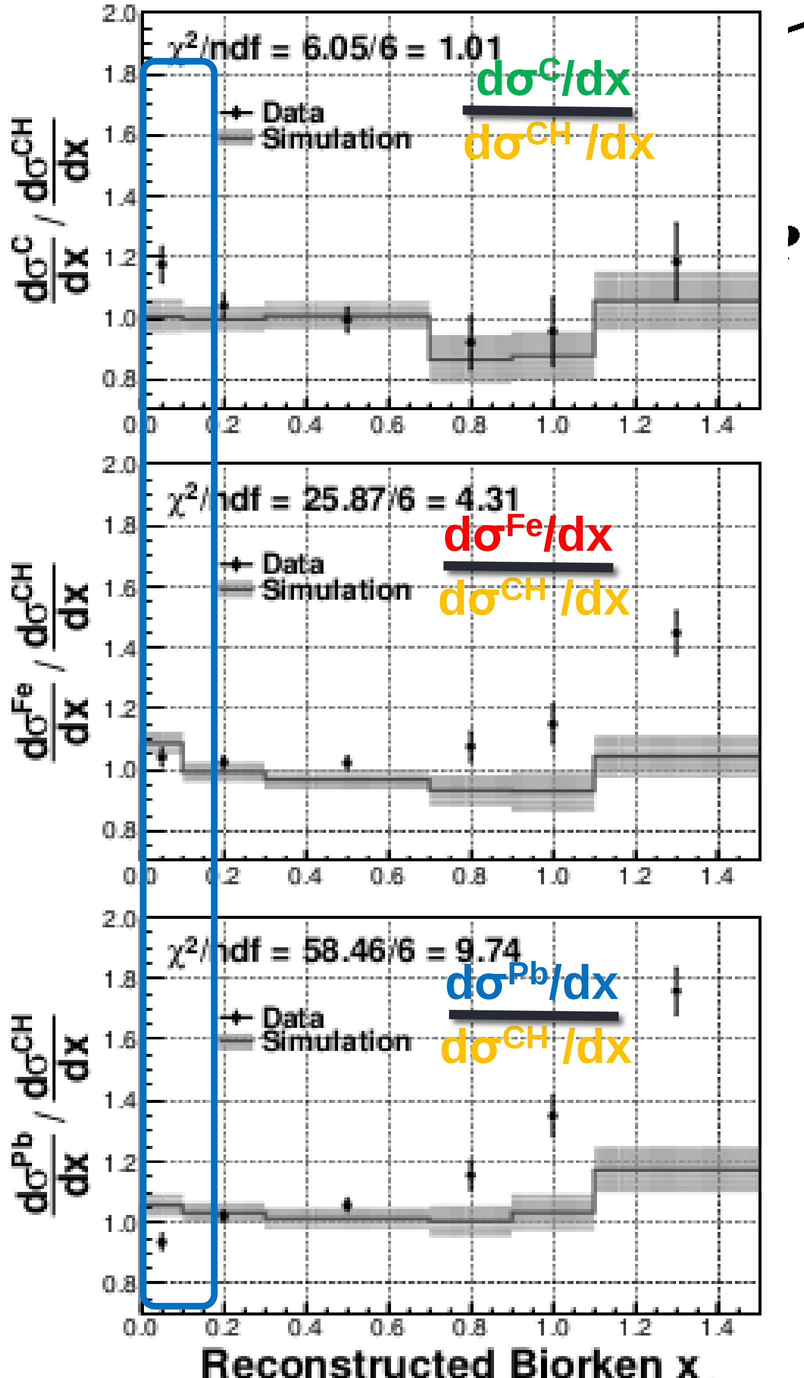


Low x Region

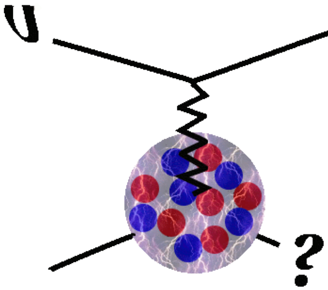
- At x=[0,0.1], we observe a **deficit** that increases with the size of the nucleus
- These events are mostly resonance (1<W<2) region. ~10% quasielastic
- Data show effects not modeled in simulation. Why?

Neutrinos sensitive to structure function xF_3

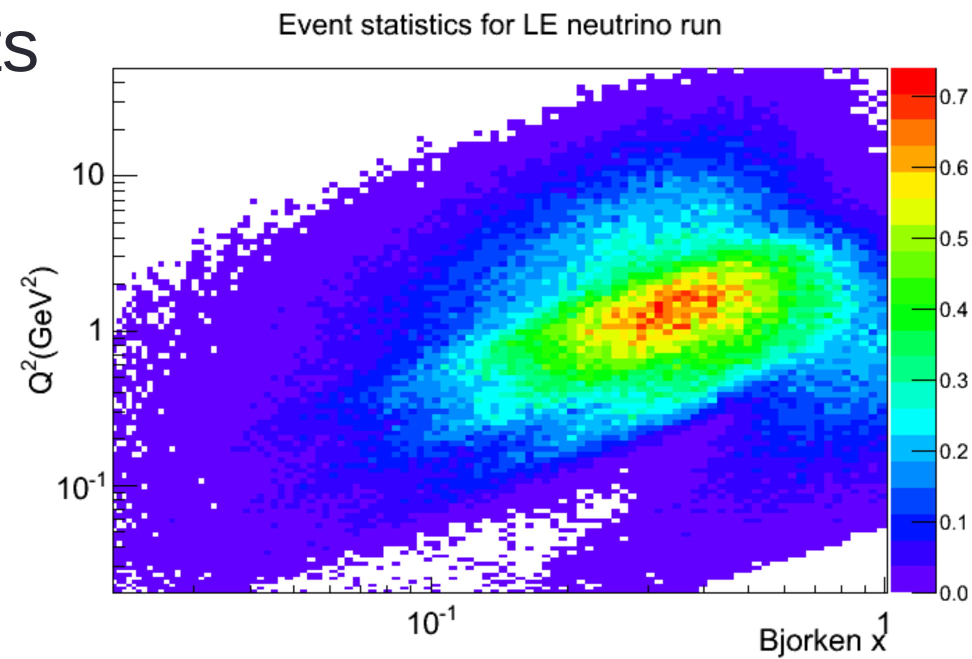
Neutrinos sensitive to axial piece of structure function F_2



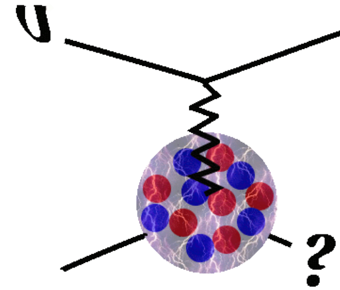
Nuclear Target Ratios



- MINERvA observes behavior not found in “standard” interaction generators
- There initial results are interesting, but also difficult to compare to physics of EMC effect because high x effects, at least, may be in elastic or nearly elastic events
- New running in NOvA beam tune will help kinematic reach and statistics and will add anti-neutrinos



Nuclear Target Ratios



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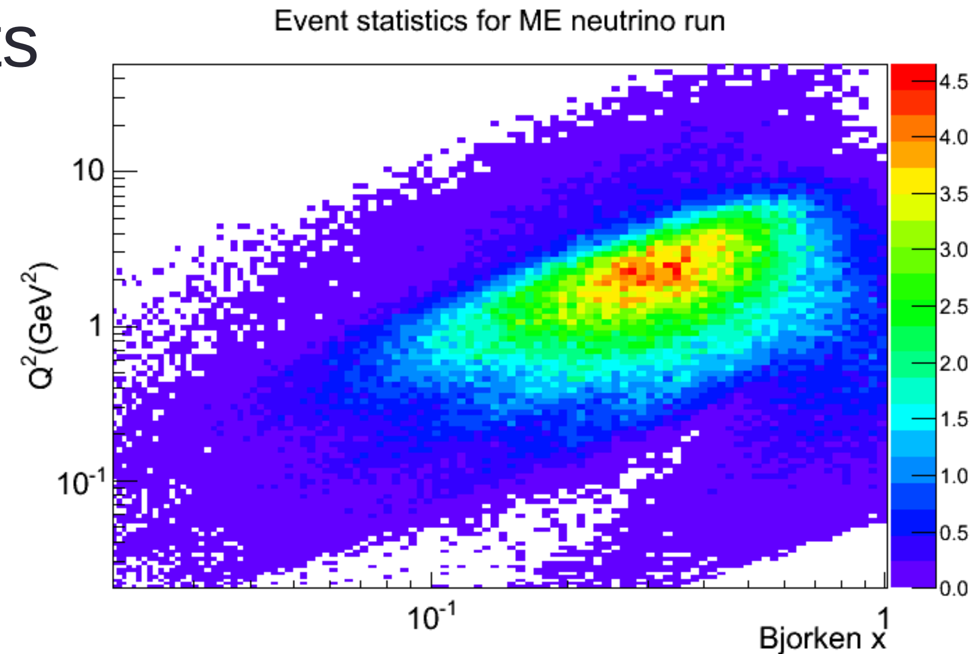
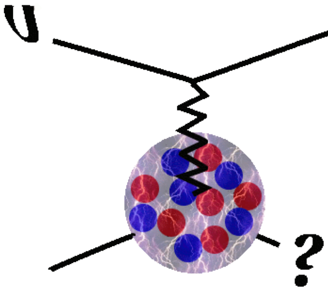


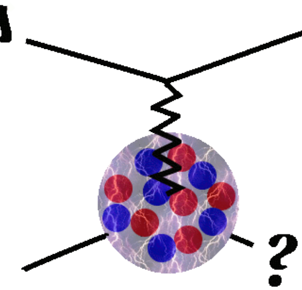


Quasi-Elastic Scattering

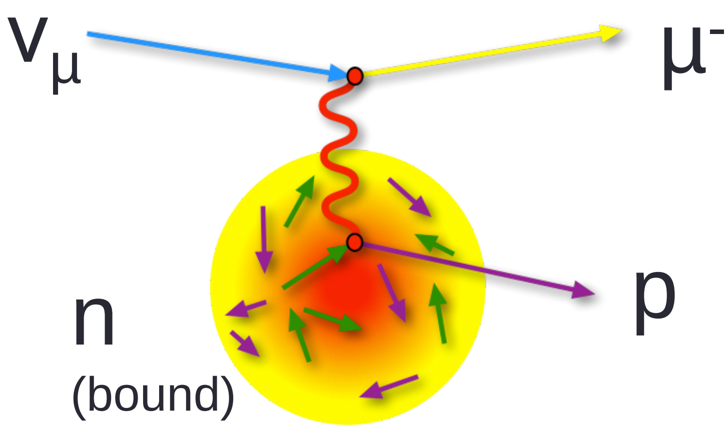
(it’s high x, right?)

Phys. Rev. Lett. 111, 022502 (2013), Phys. Rev. Lett. 111, 022501 (2013), arXiV:1409.4497

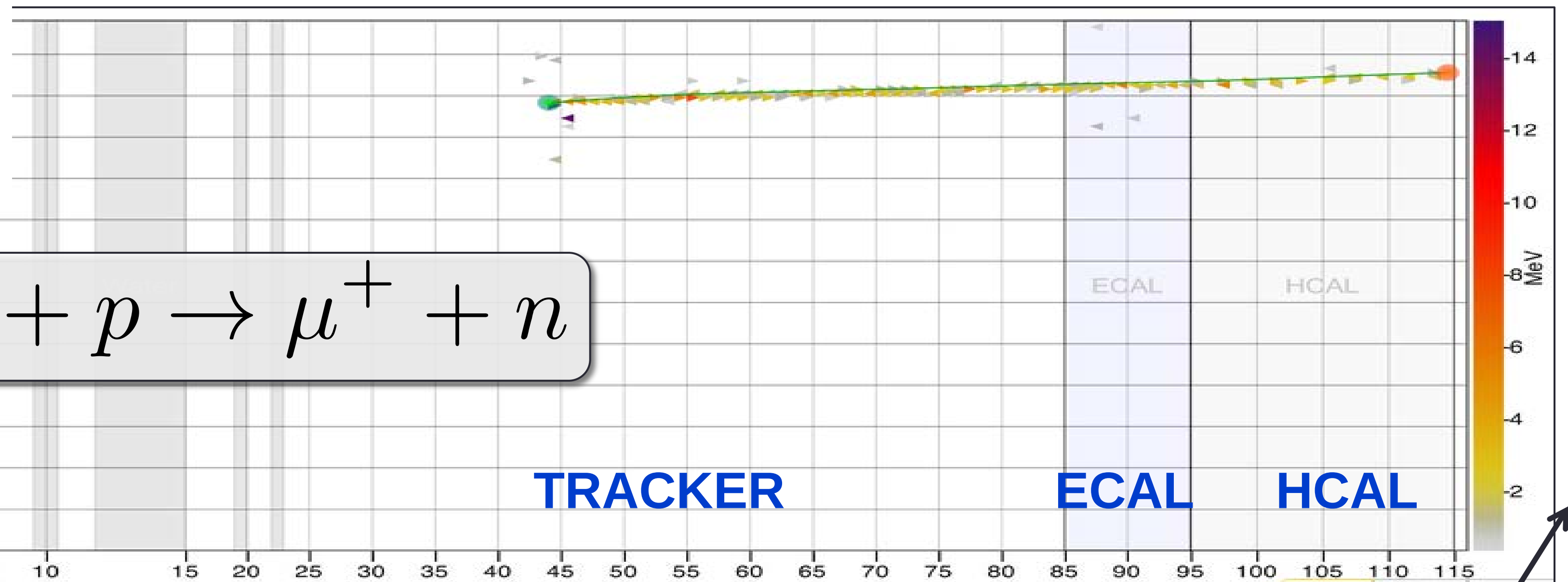
Quasi-Elastic Scattering



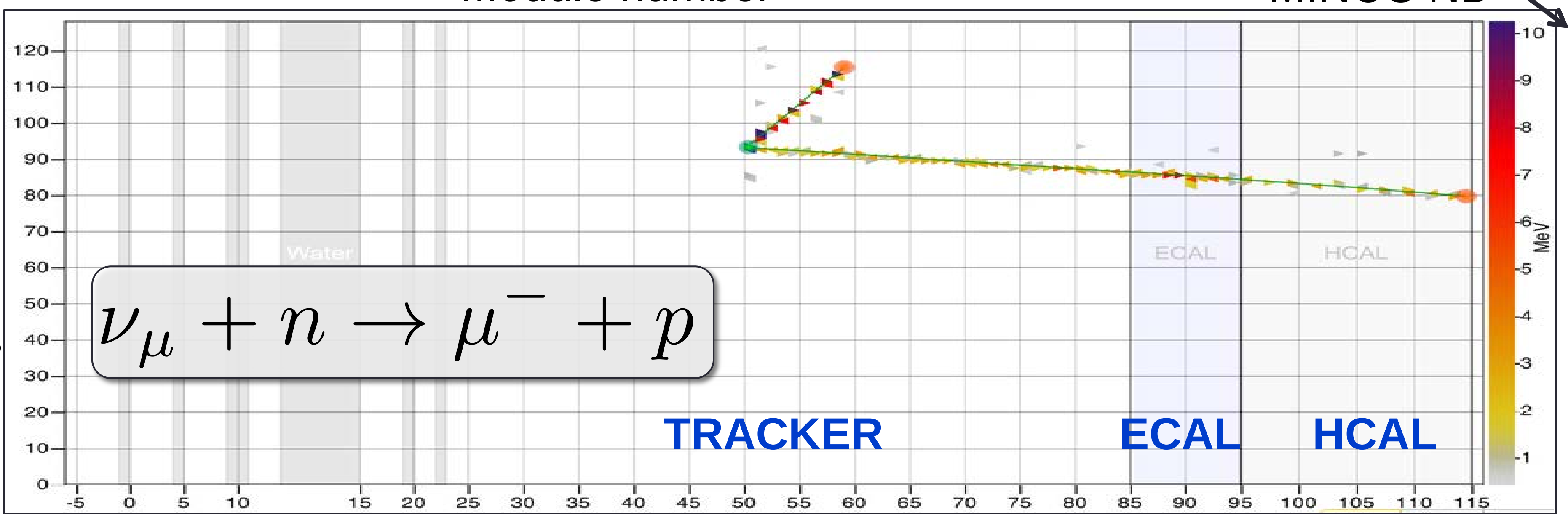
- Signature of quasi-elastic scattering is production of no mesons, photons or heavy baryons
- Breakup of nucleus or hadron reinteraction may produce additional protons and neutrinos in final state. Allow those as signal.



- Veto events with energy from pions (leading background)
- "1-track" analysis identifies these calorimetrically as energy distant from vertex
  - Can also identify of recoil proton or veto on Michel electrons from decay chain of π^+

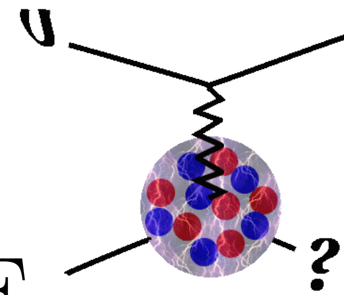


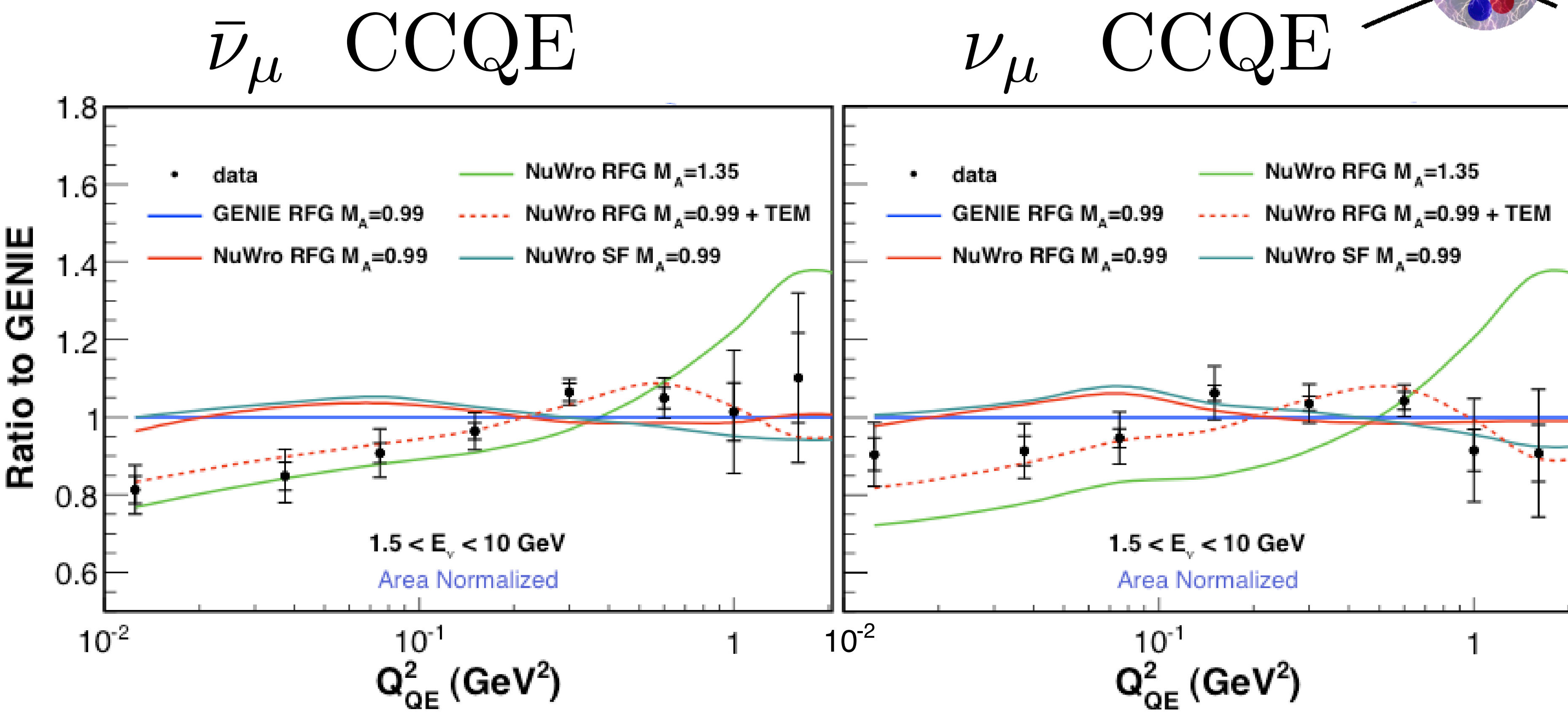
$$\bar{\nu}_\mu + p \to \mu^+ + n$$



$$\nu_\mu + n \to \mu^- + p$$

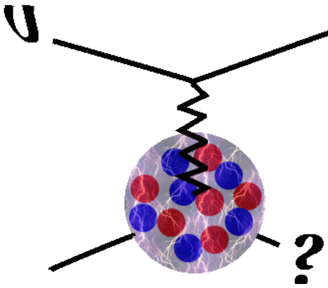
dσ/dQ² Shape

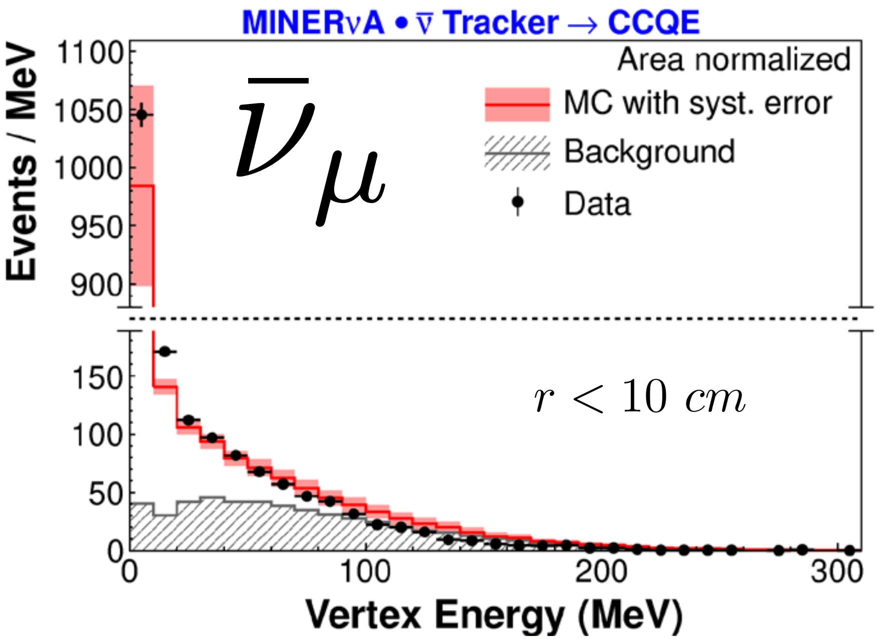


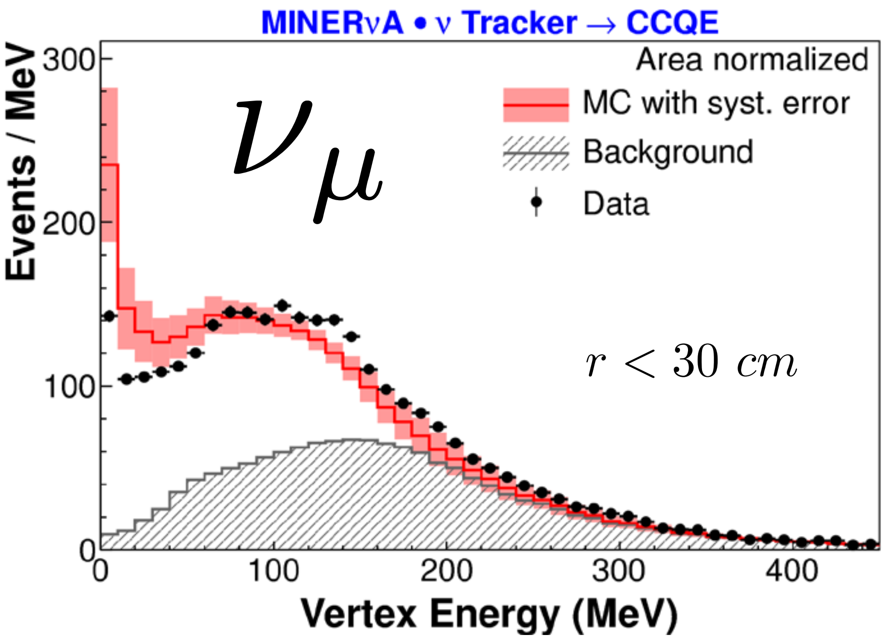


- Model used by MiniBooNE in oscillation analysis is the green line (enhance "effective" axial form factor at high Q^2)
- Best fit prefers data-driven multi-nucleon model

Extra Protons at Vertex?

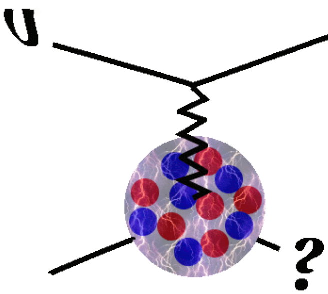




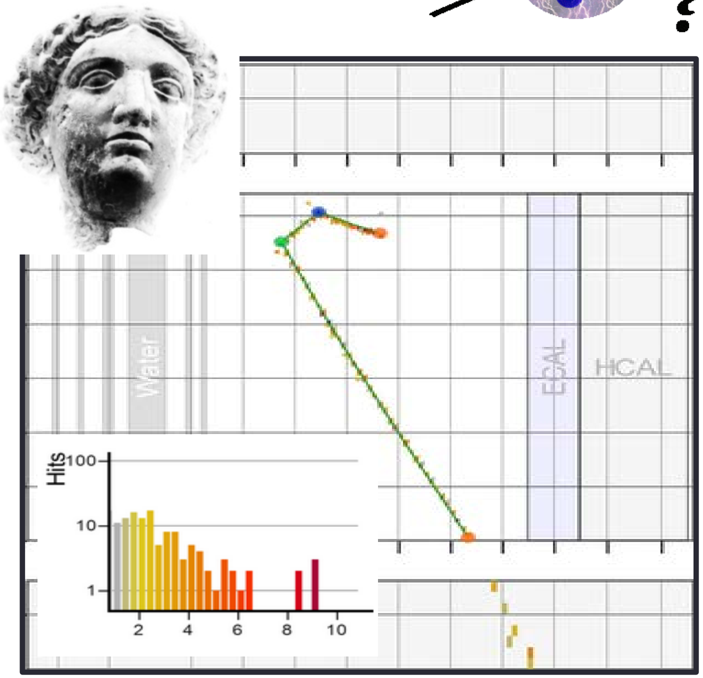


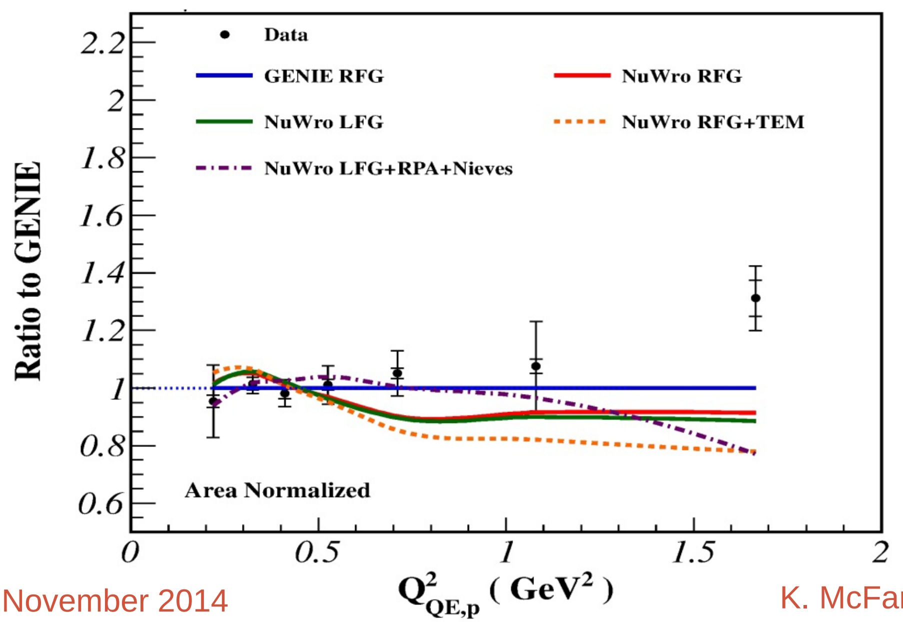
- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- If we make the ***assumption*** that the additional vertex energy per event in data is ***due to protons***, it would require

Exclusive Proton+Muon Result



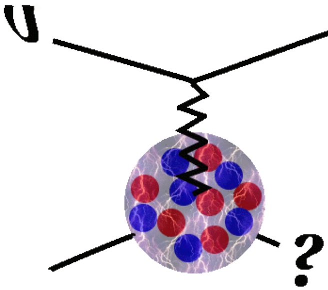
- Sample includes events where muon is fully contained and events where only muon angle is well measured
- Muon kinematics of sample are compatible with μ+X(0π) sample



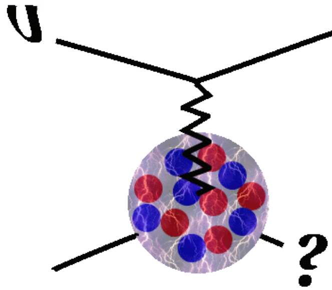


- Measure $Q^2_{QE,p}$ assuming quasi-elastic kinematics from the bound nucleon at rest
  - A model-independent quantity, $Q^2_{QE,p}(T_p,\theta_p)$, sensitive to final state interaction model

Quasi-Elastic: Discussion

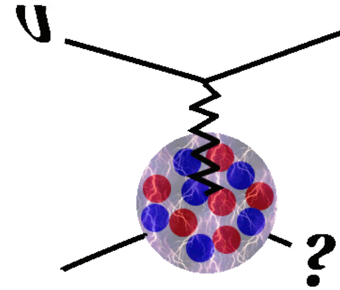


- Selected events that had muons and nucleons, but without pions
- Enhancement at moderate Q^2, consistent with other experiments, does not persist at high Q^2
  - Consistent with dynamical models of multi-nucleon processes
  - Not consistent with “standard” modification of nucleon form factors
- Also see presence of additional energy near vertex in neutrinos, but not anti-neutrinos
  - Consistent with interpretation of leading multi-nucleon correlations as an “np” state… so pp in neutrinos, but nn in anti-neutrinos
- Exclusive muon+proton has compatible muon kinematics, but some disagreements in proton kinematics

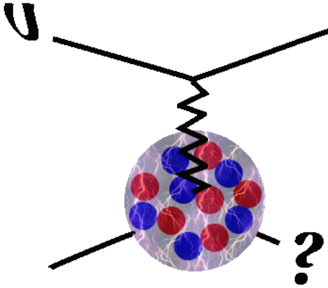


Concluding Comments

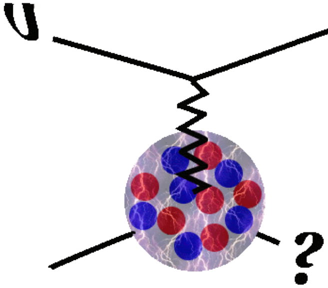
Neutrinos @ HiX



- I was really pleased to see all the continuing interest in neutrino DIS data. Sadly, however, there is little new high energy data on the horizon.
- Several experiments or proposed experiments (T2K, MINERvA, CAPTAIN-MINERvA) will make direct measurements of ratios on different nuclei at 1-10 GeV
  - What will be our strategy to make the best use of this data in the transition region between resonance and DIS?
  - Can we get some collaboration from this community to add H_2 and D_2 targets to some neutrino experiment? This is a non-trivial effort because of the volume of cryogenic flammable material.
- Look for many more results on inclusive and exclusive processes in the near future from these efforts

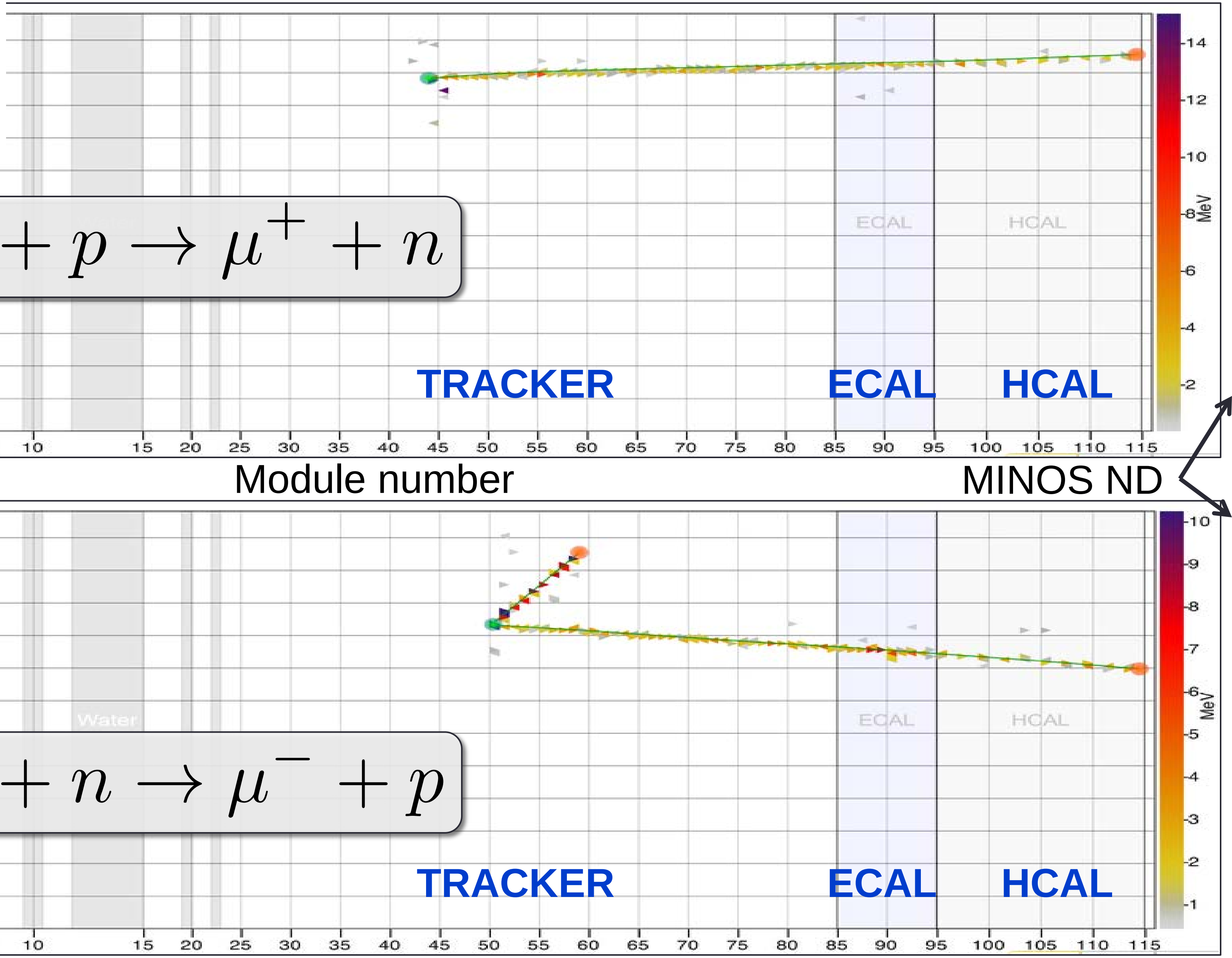


Backup



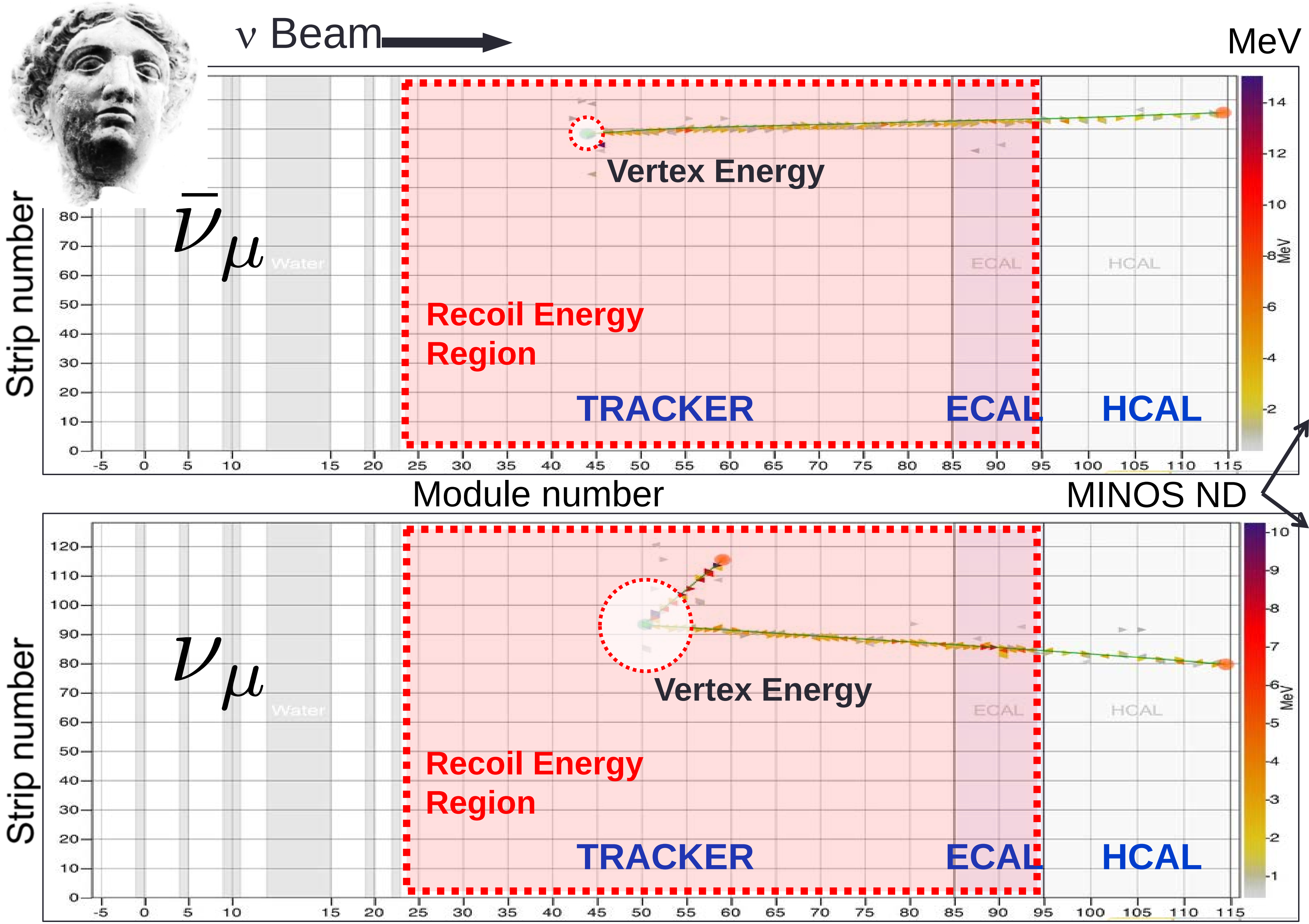
More on Quasi-Elastic Scattering

ν Beam

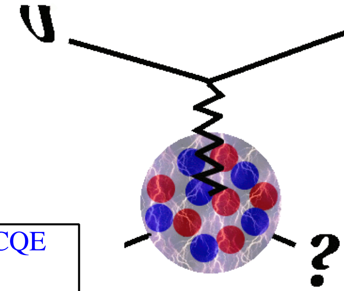


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

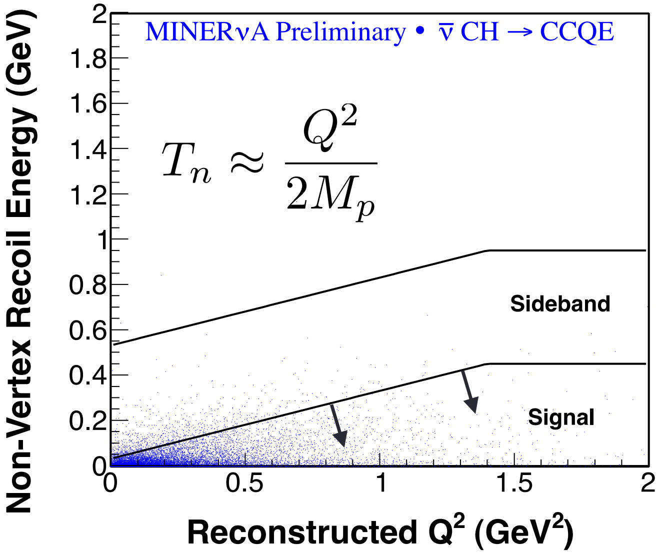
$$\nu_\mu + n \rightarrow \mu^- + p$$

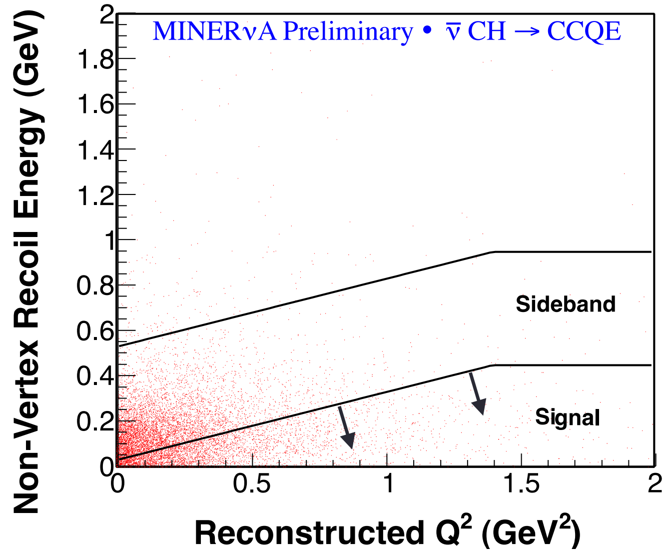

ν Beam
MeV
Vertex Energy
$\bar{\nu}_\mu$
Water
ECAL
HCAL
Recoil Energy
Region
TRACKER
ECAL
HCAL
Strip number
Module number
MINOS ND
ν_μ
Vertex Energy
Water
ECAL
HCAL
Recoil Energy
Region
TRACKER
ECAL
HCAL
Strip number

Recoil Energy Distributions



$\bar{\nu}_\mu$

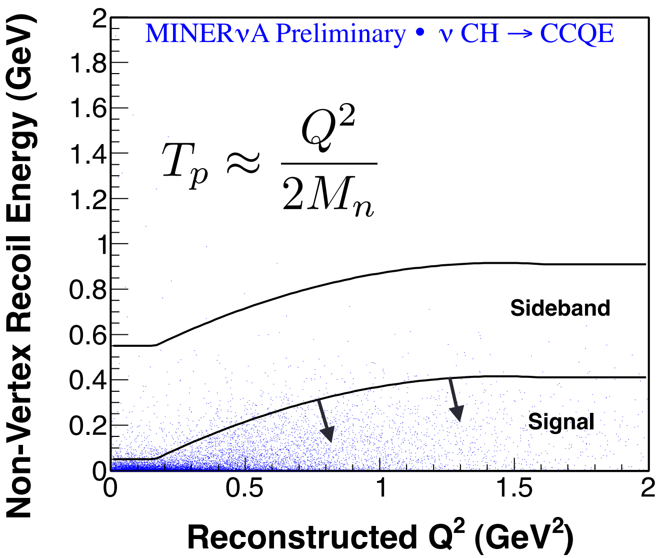


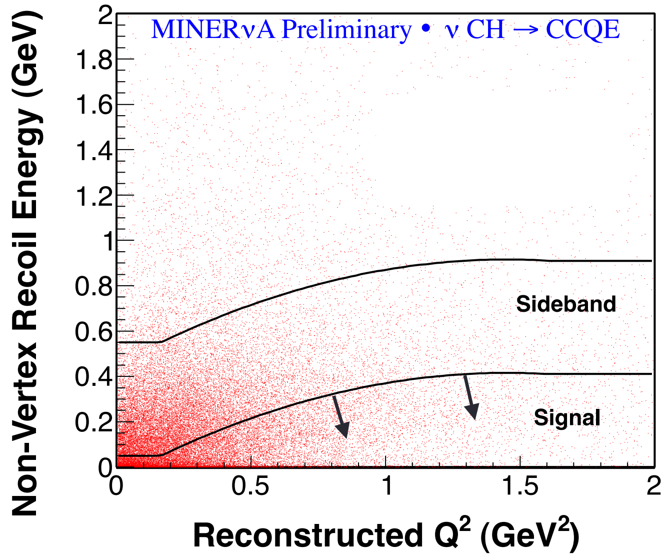


QE

QE

ν_μ

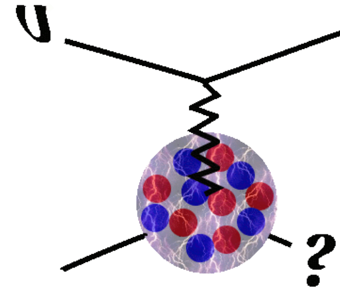




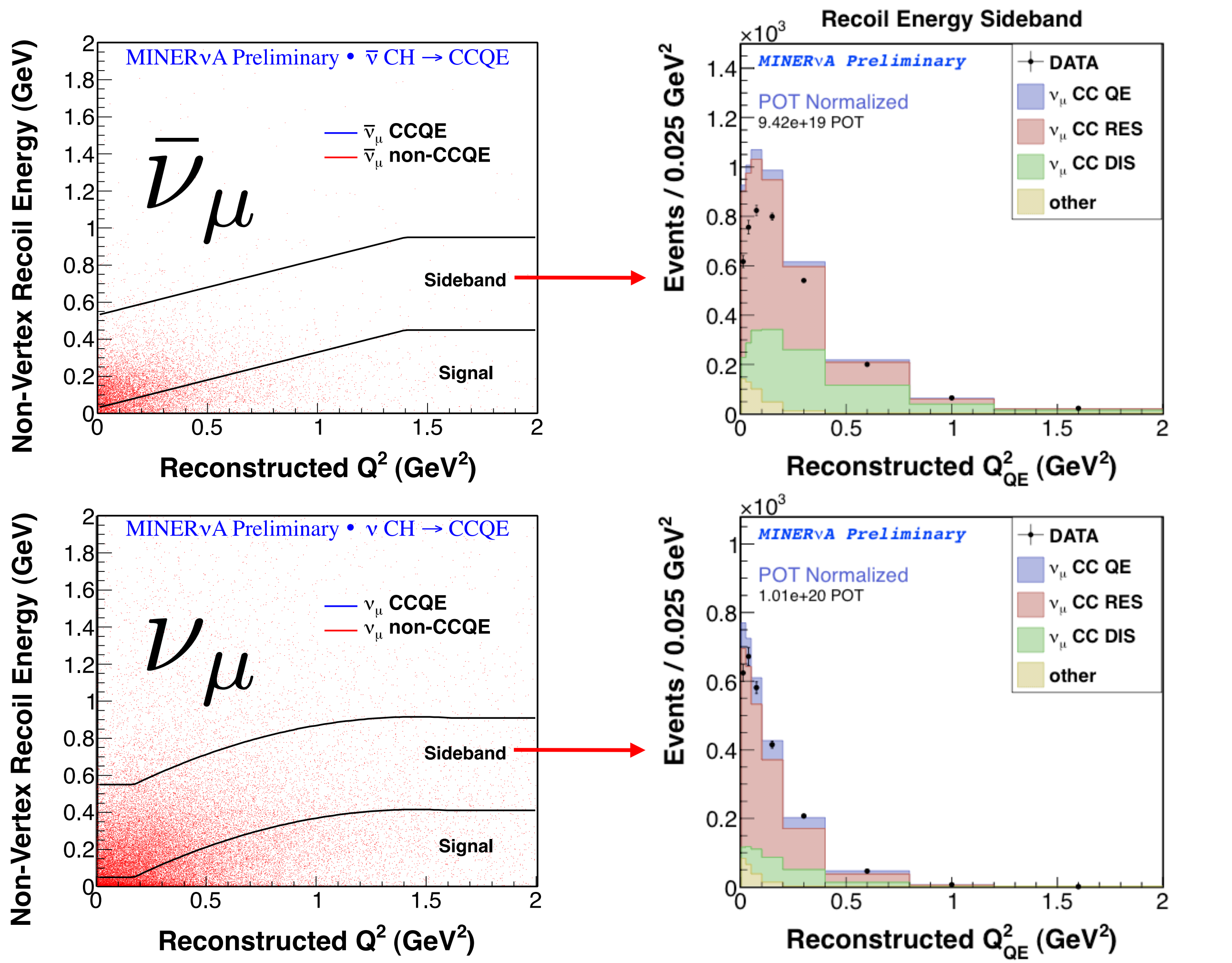
Estimate of 4-momentum transfered to nucleon

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

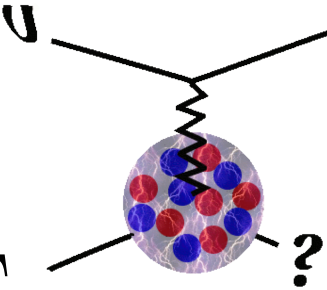
Constraint on Background

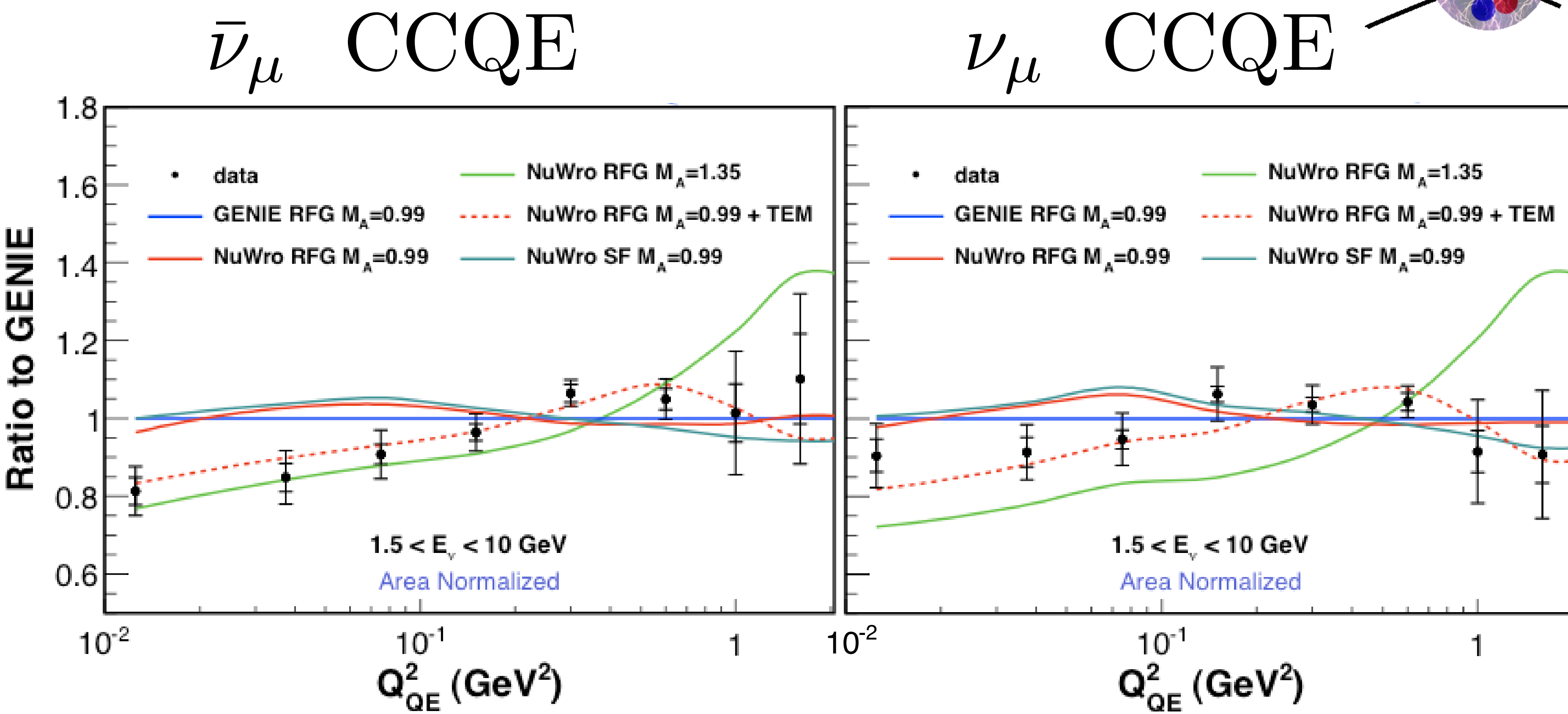


- Large uncertainties on background cross-section models
- Complicated by reinteraction inside nucleus "Final State Interactions" (FSI)
- Use high recoil events to study



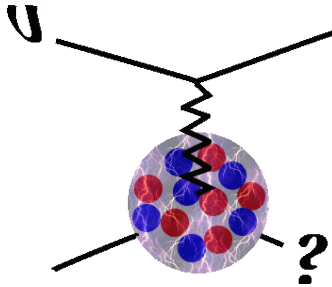
dσ/dQ^2 Shape

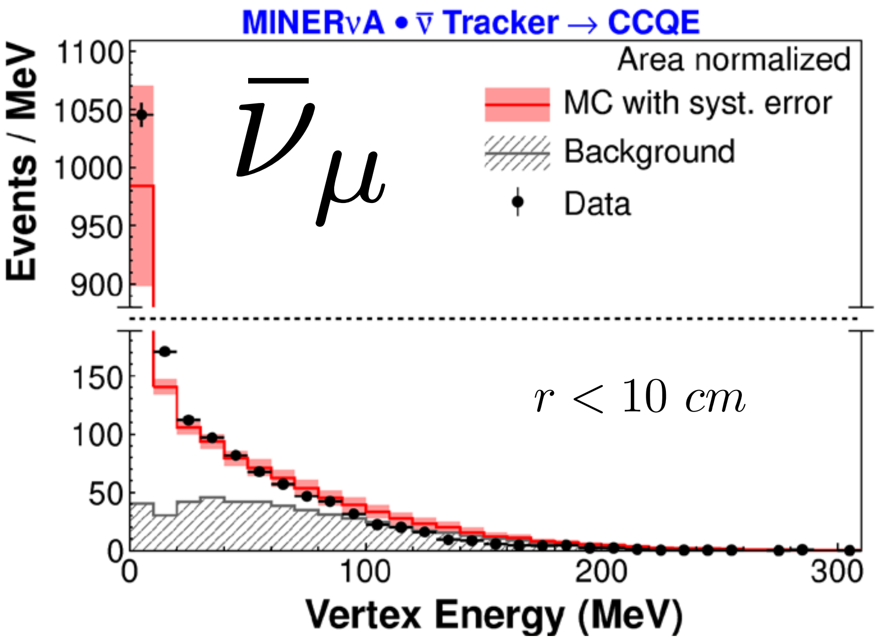


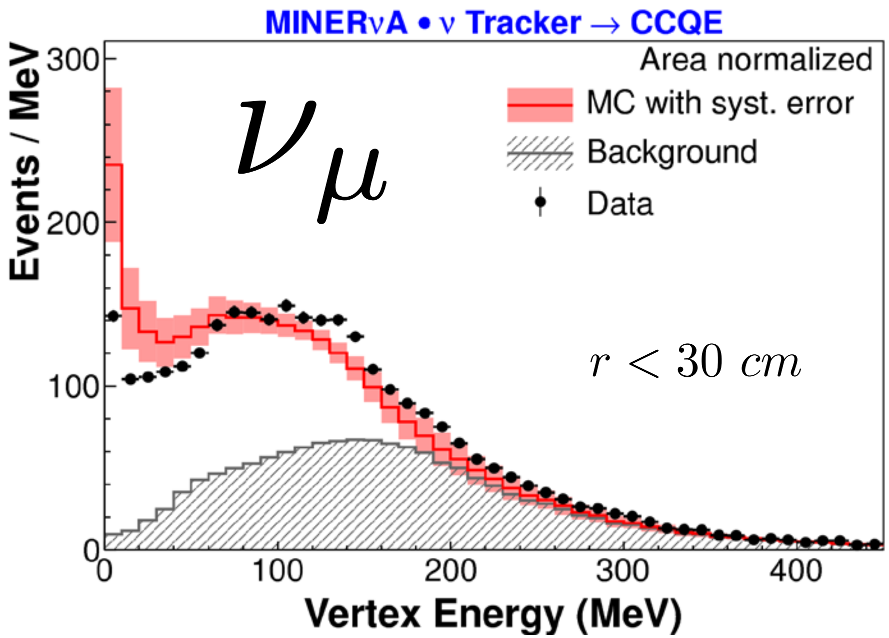


- Model used by MiniBooNE in oscillation analysis is the green line (enhance “effective” axial form factor at high Q^2)
- Best fit prefers data-driven multi-nucleon model

Vertex Energy

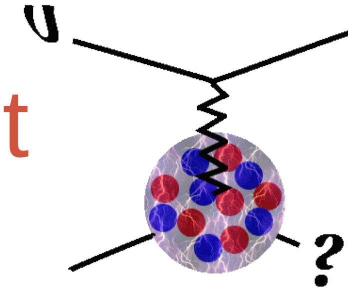


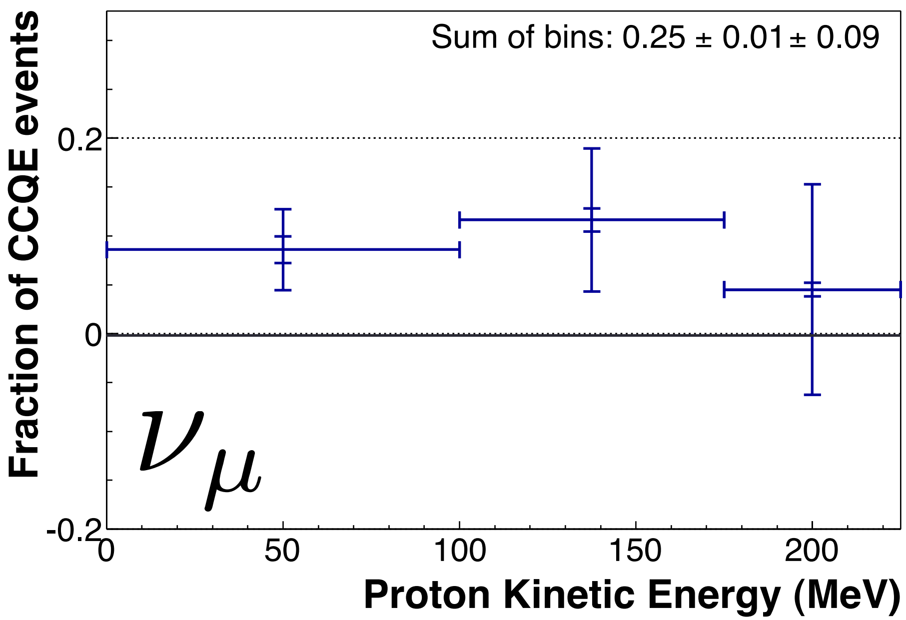


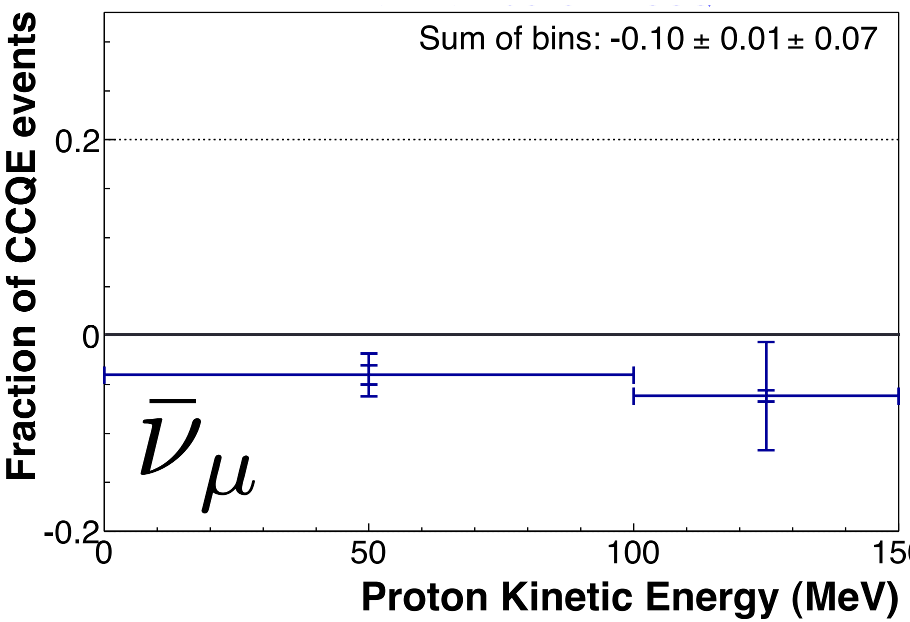


- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the ***working assumption*** that the additional vertex energy per event in data is ***due to protons***

Vertex Energy – Proton Content



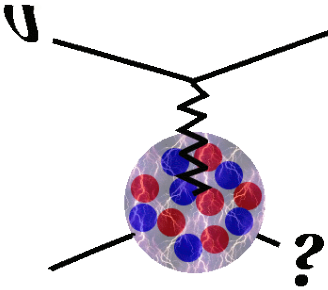




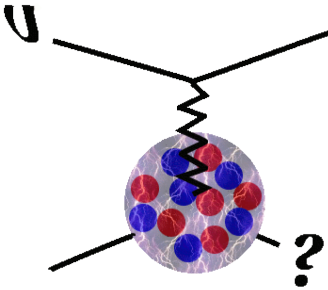
We find that adding an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events** improves agreements with data

No such addition required for antineutrinos. Slight reduction if anything.

(-10 ± 7)% of QE events



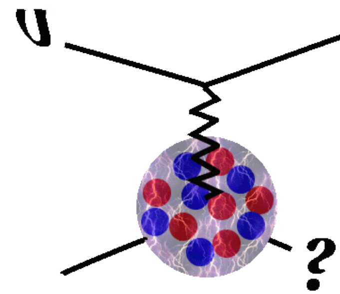
Things you don't care about at HiX, but I think are awesome



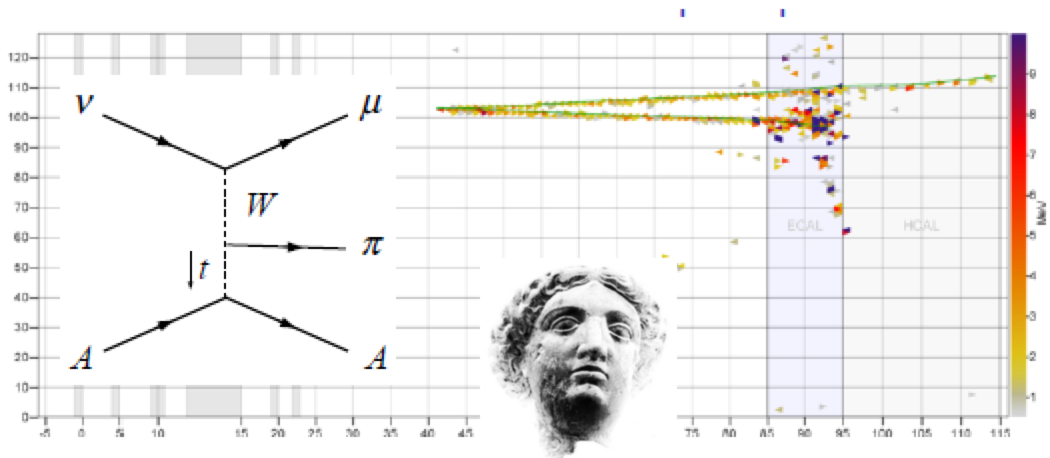
Coherent Pion Production

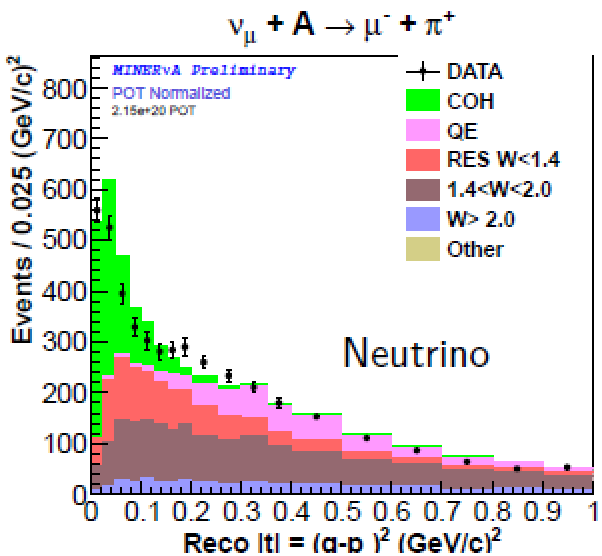
arXiV:1409.3835, to appear in Phys. Rev. Lett.

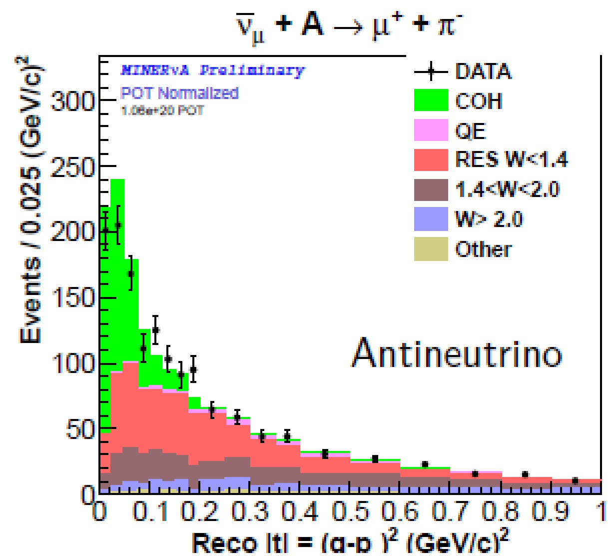
Coherent Pion production from Nuclei



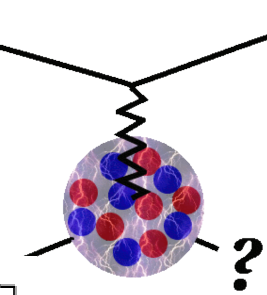
- Signature is low |t| transfer to the nucleus
- Dangerous for neutrino expts if pion fakes a lepton
- Models disagree
- MINERvA has clear evidence



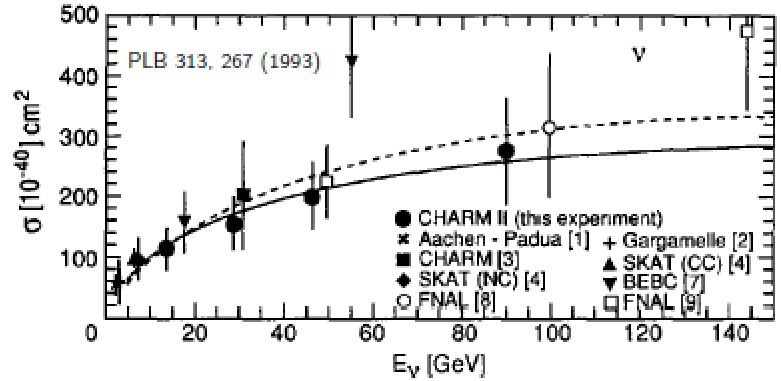




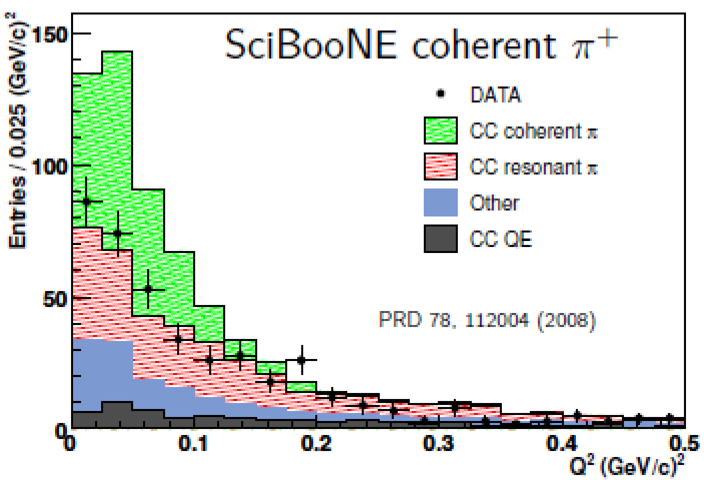
Puzzle at GeV energies?

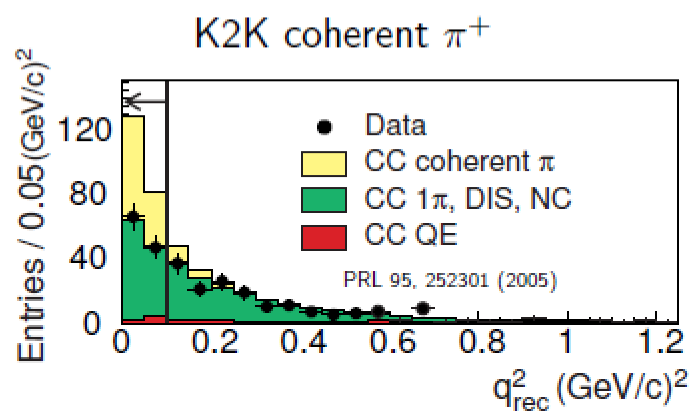


- Process has been well measured at high energy neutrino experiments

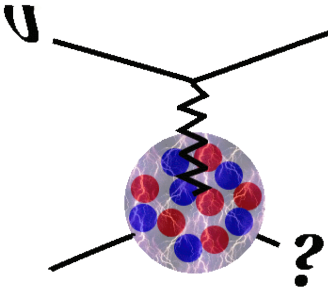


- Previous low energy experiments did not find process
- Possible problem was background model? Those experiments we unable to measure |t| directly.

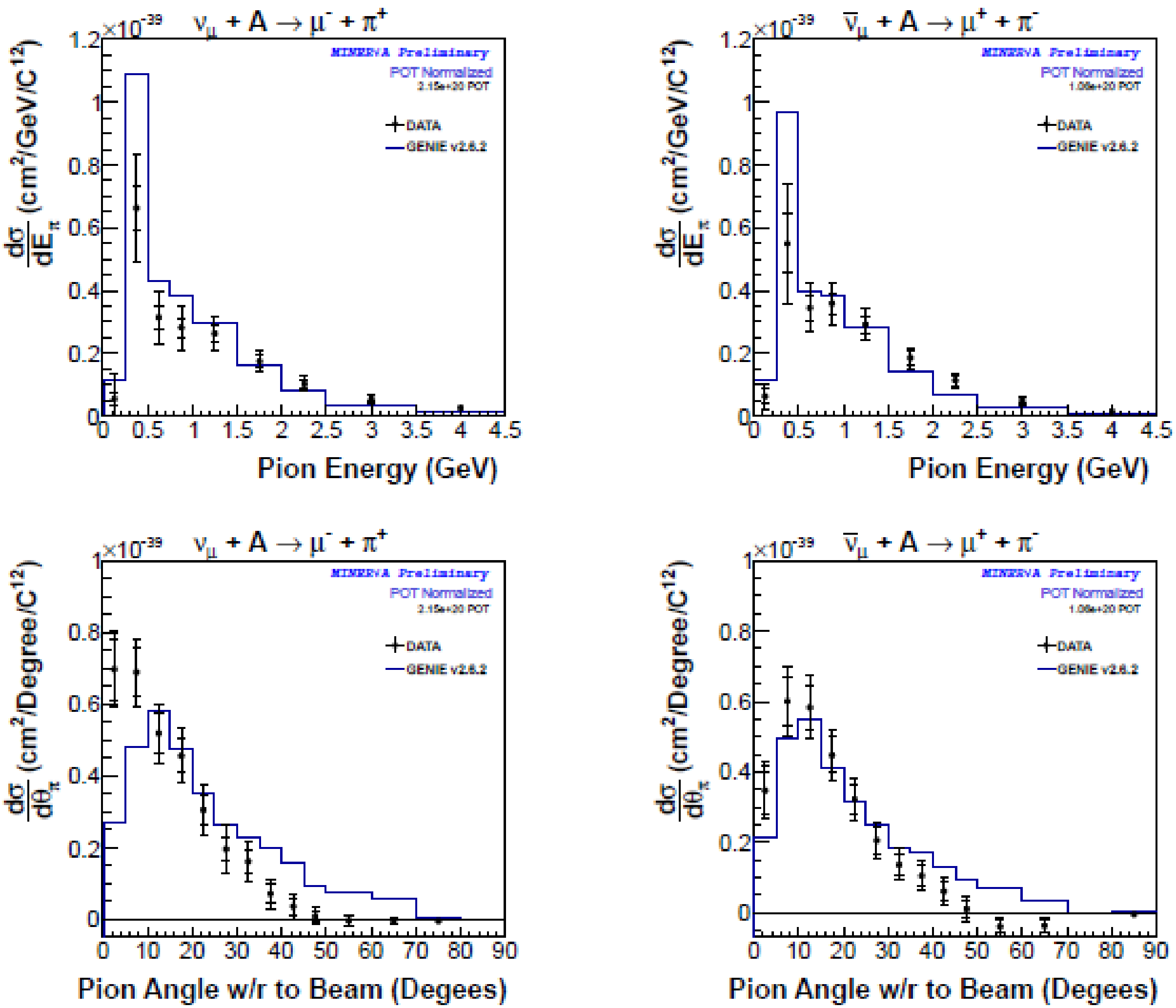


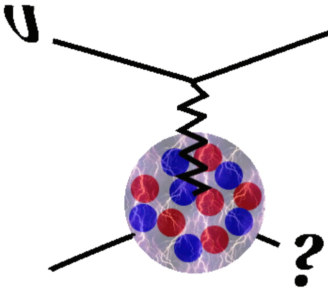


MINERvA Measures: Usual Rein-Sehgal Model is Lacking



- In particular, see problems at high pion angles and low energies
- This data can now be used to down-select from the plethora of available calculations

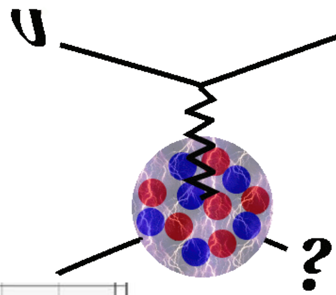




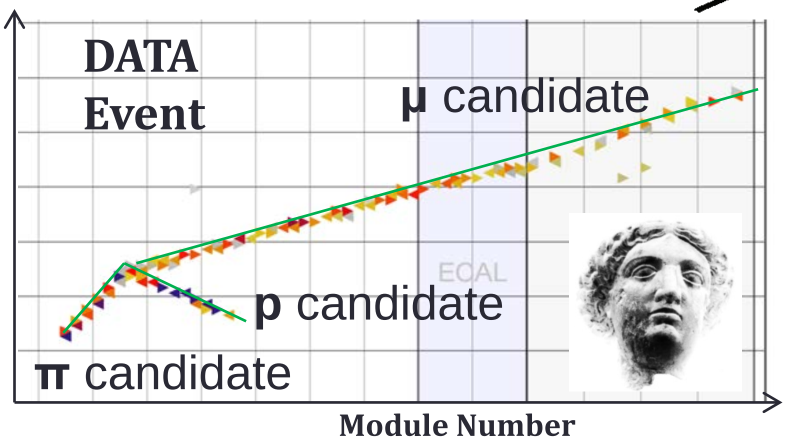
“Resonance” Pion Production

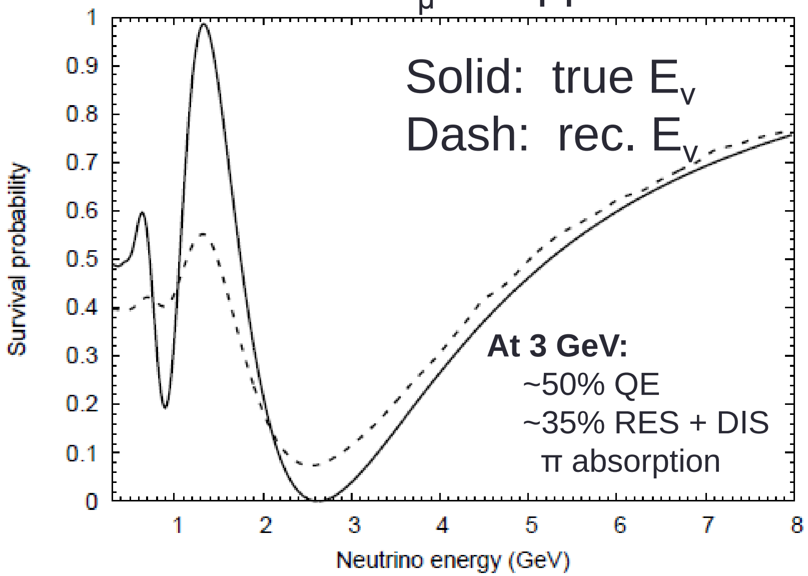
arXiV:1406.6415

Charged Pion Production

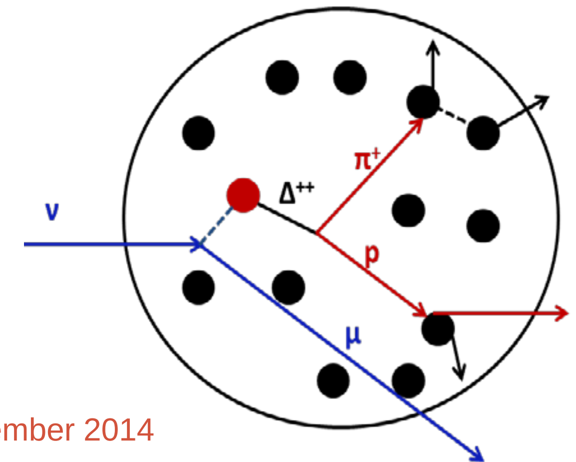


- Most common inelastic interaction at low energies
- Oscillation experiments that don't identify the pion suffer an energy bias
- Produced pions strongly interact inside nucleus before emerging

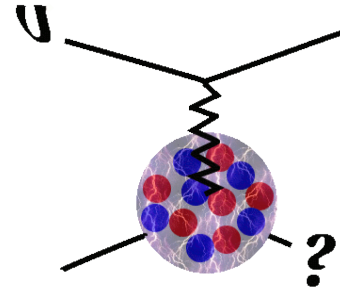




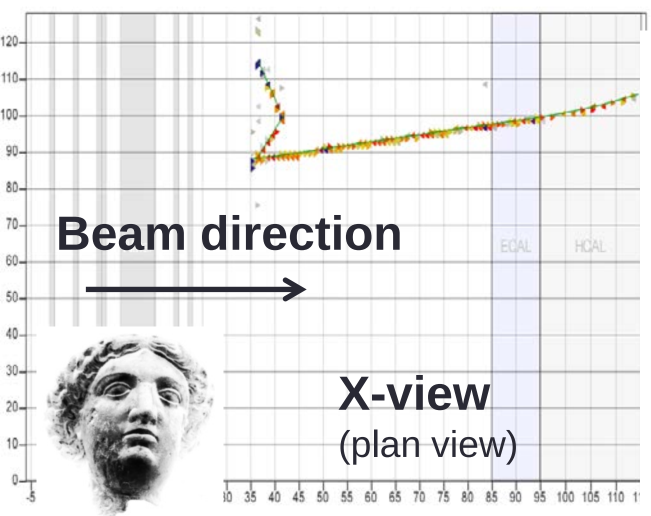
Mosel *et al*: arxiv 1311.7288

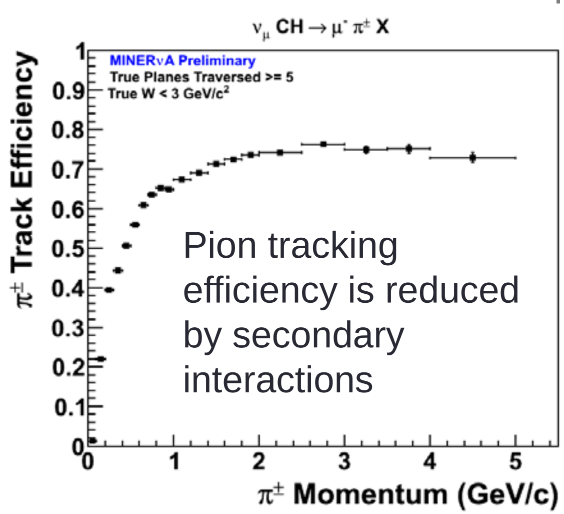


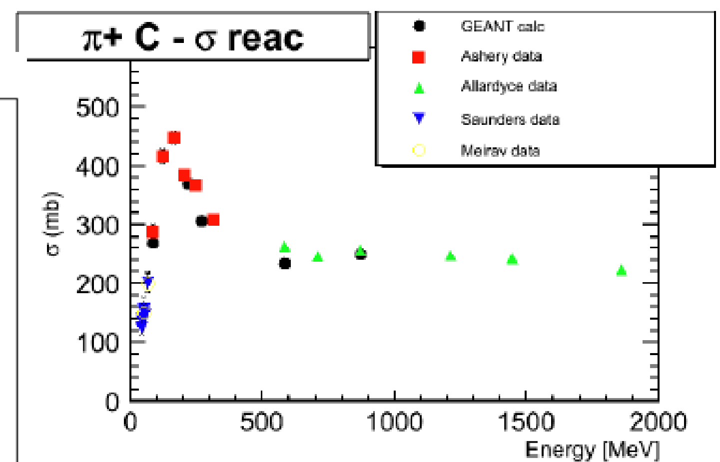
Pion Reconstruction



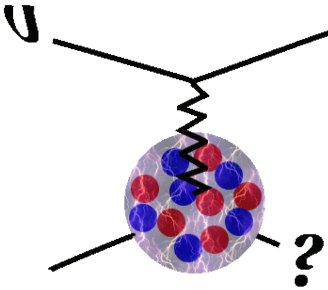
- Key is identification of a track as a pion by energy loss as a function of range from the vertex
- Confirmed by presence of Michel electron, π→μ→e
- Elastic or inelastic scattering in scintillator is a significant complication of reconstruction
  - Study uncertainties by varying pion reactions, constrained by data



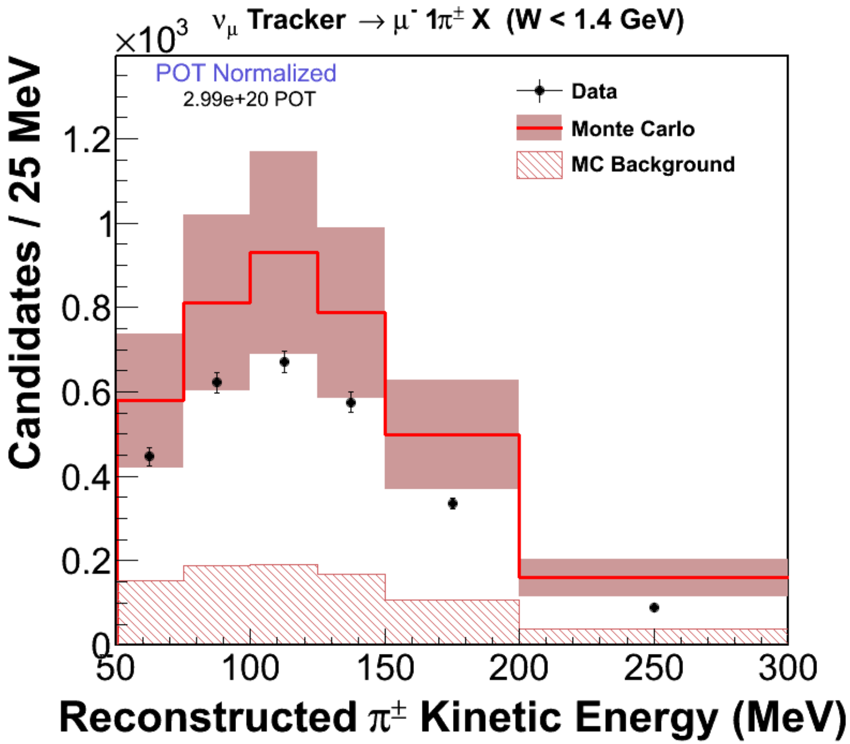


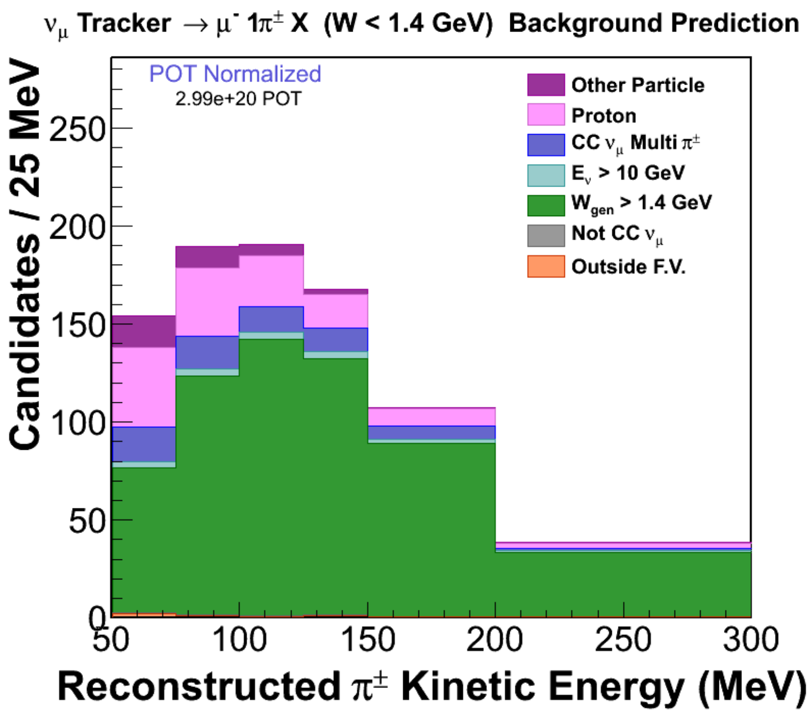


Signal and Background

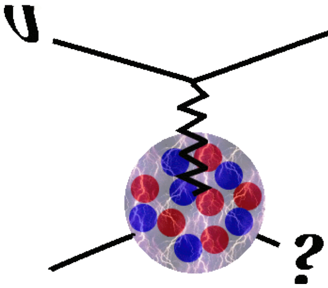


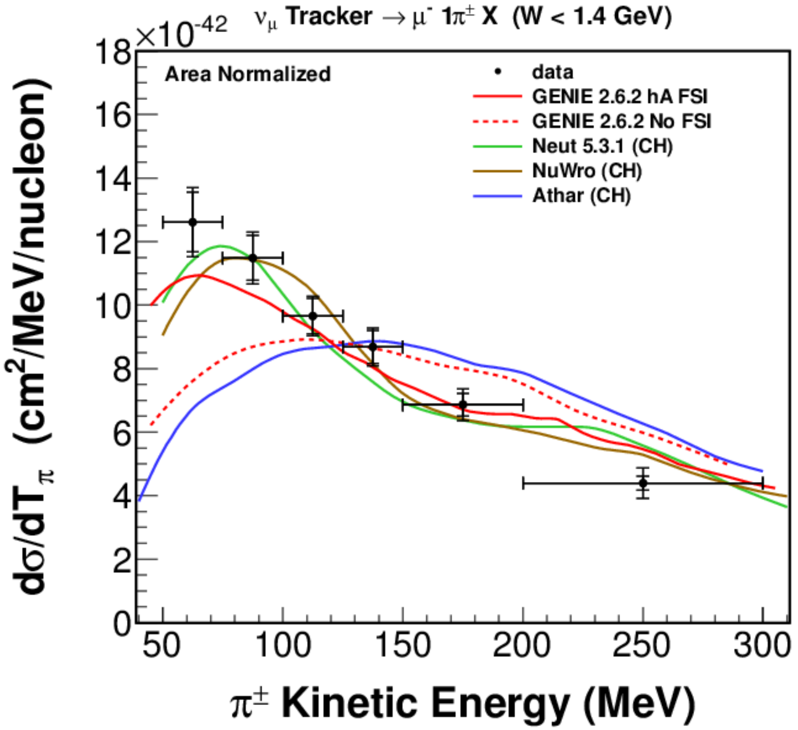
- Define signal as W<1.4 GeV… mostly single pions
- Pion KE w/ background prediction (before sideband tune)
  - Green and blue are high W backgrounds
  - Pink (proton) and purple are non-pion events

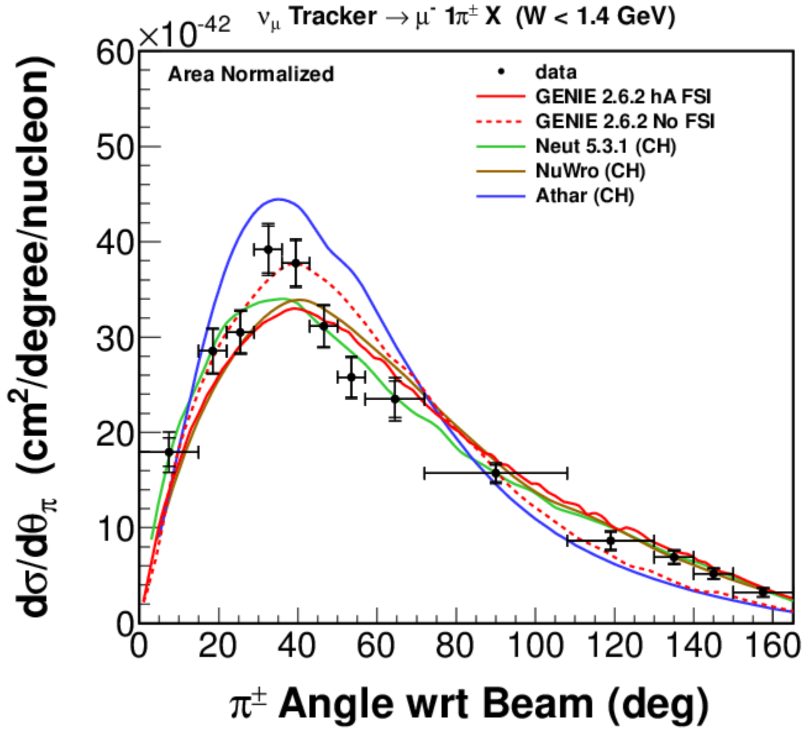




Pion Kinematics (Flux integrated) and Final State Interactions

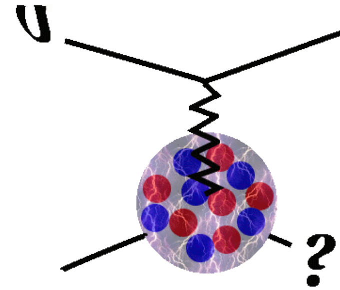


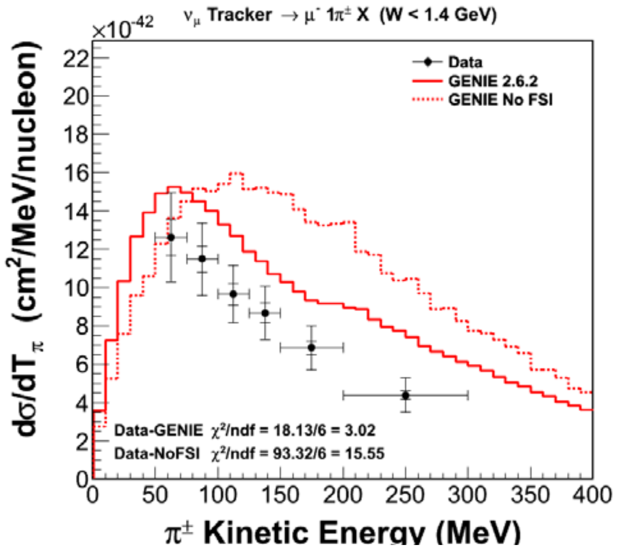


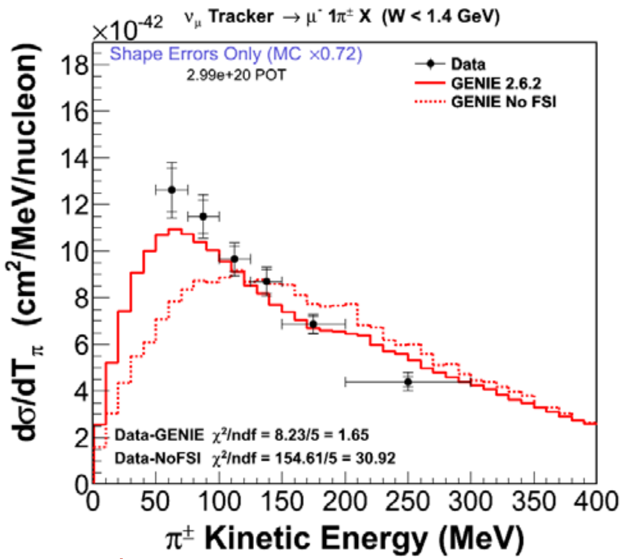


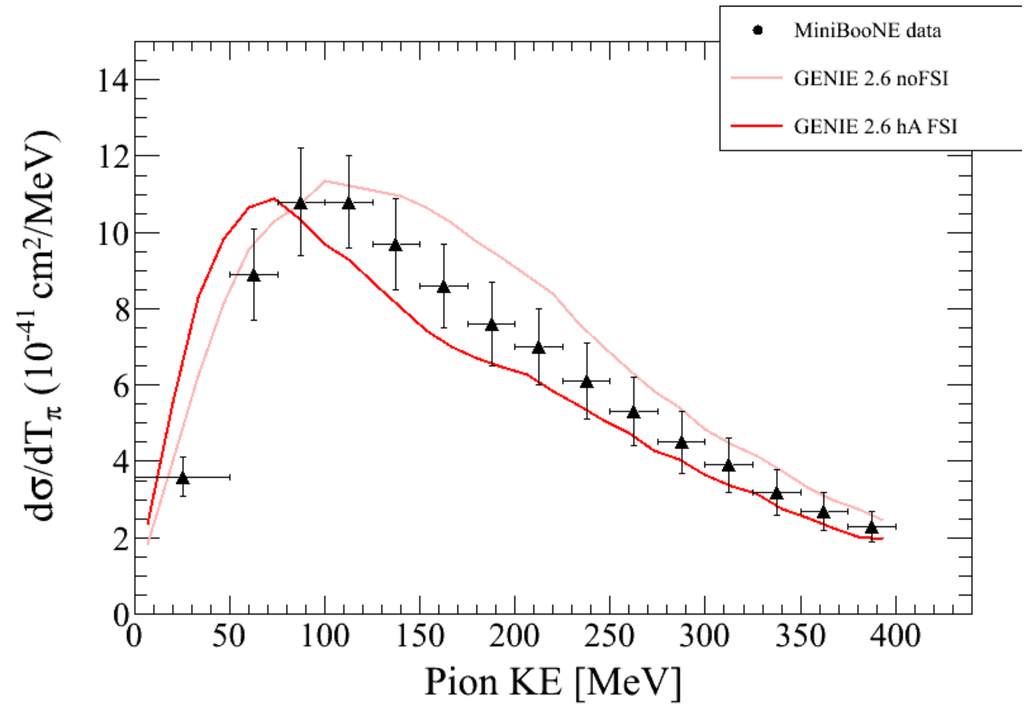
- **Conclusion:** NuWro, Neut, and GENIE all predict the data shape well
- **Conclusion:** Data insensitive to the differences in pion absorption shape between GENIE, NuWro, and Neut
- **Conclusion:** Athar, the sole theoretical calculation, does not agree with data. Likely due to an insufficient FSI model

Comparison to MiniBooNE









- Even with ~10% flux uncertainties from both experiments, there is ~2σ tension between MINERvA and MiniBooNE
- Some shape tension also