MINERvA and its "Medium Energy" Program

Kevin McFarland
University of Rochester
on behalf of the MINERvA collaboration

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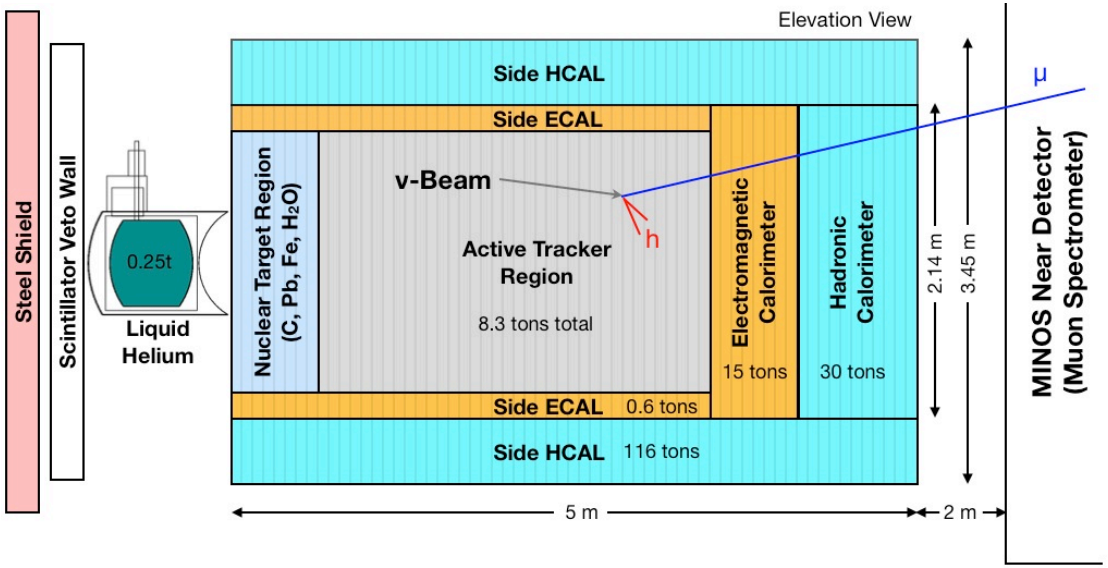
What is MINERvA?

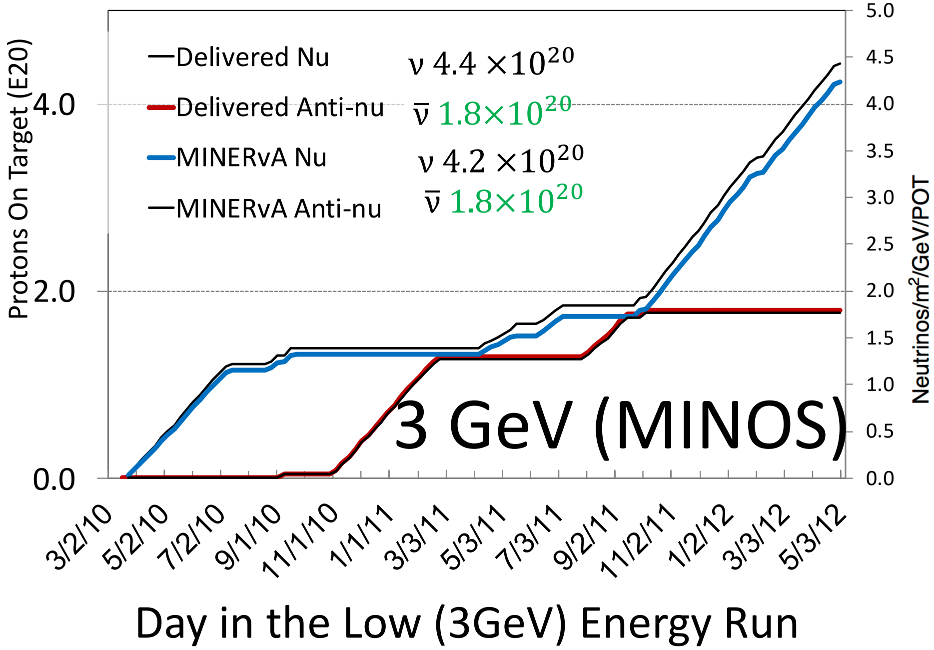
- MINERvA is a dedicated neutrino scattering experiment in the NuMI beamline at Fermilab.
- Primary goal is to characterize neutrino interactions for oscillation experiments.
  - Identification of nuclear effects and tests of models of those at low energy transfer.
  - Measure exclusive final states, and correlations of those with leptons.
  - Demonstrate techniques for oscillation expeirments.
- Secondary goals are measurements of nuclear effects, e.g. neutrino "EMC" effect.

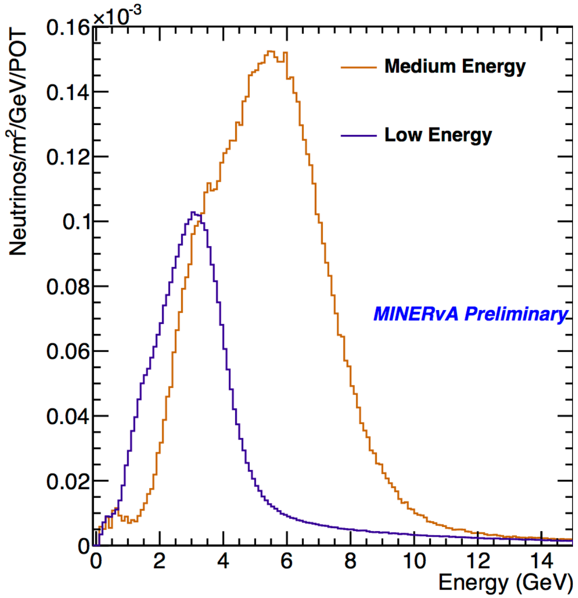


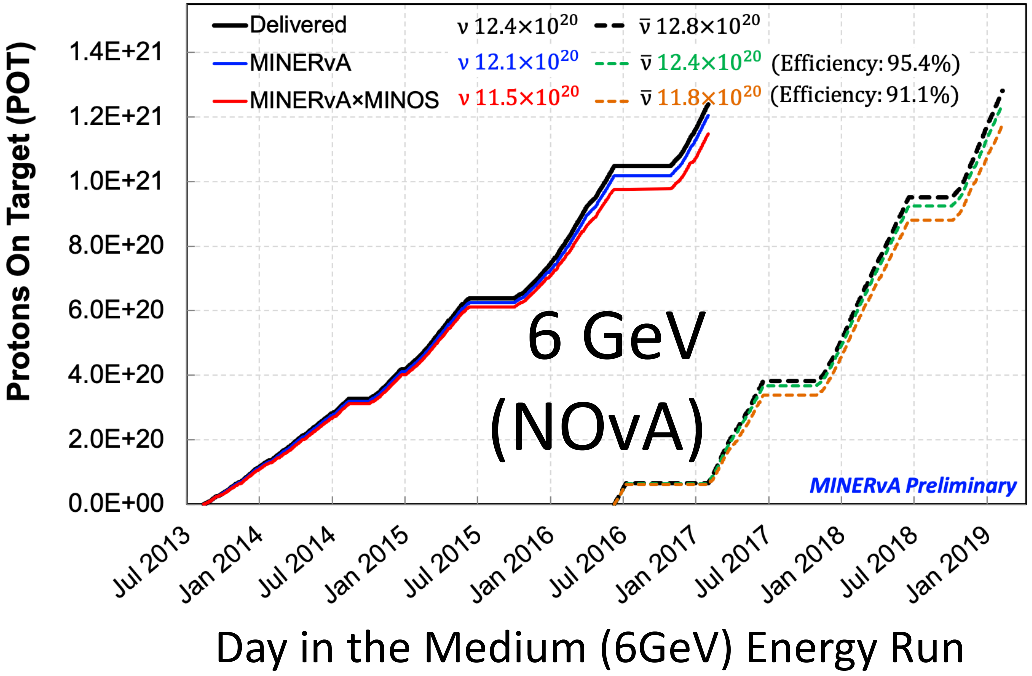
- Detector has a large "active tracker" of segmented solid scintillator
- Upstream of the MINERvA tracker is a region of He, C, H_2O, Fe, and Pb targets.
  - Masses of 0.25-0.8 ton, statistics limited.
- Downstream and side calorimeters

MINERvA's Neutrino Exposures

- Exceptional and enviable performance of FNAL accelerator and NuMI.
- Two beam exposures: 3 GeV (concurrent with MINOS), 6 GeV (NOvA)
- Most results to date on MINERvA from 3 GeV beam. 6 GeV beam has statistics gain of 8 (low W) to 15 (high W) for ν, and factors of 20 to 40 in $\bar{\nu}$.



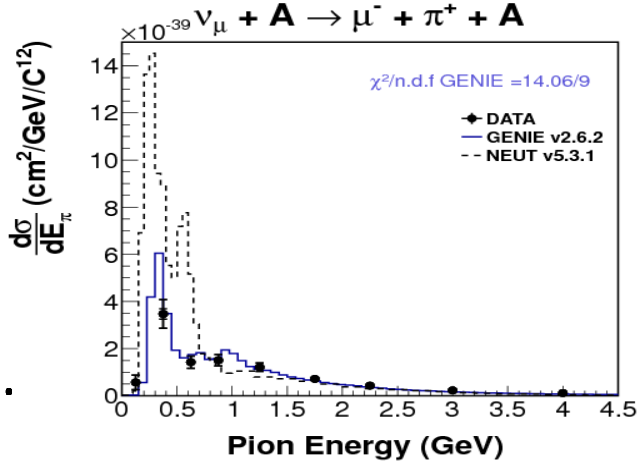




Summary of MINERvA's 3 GeV Results

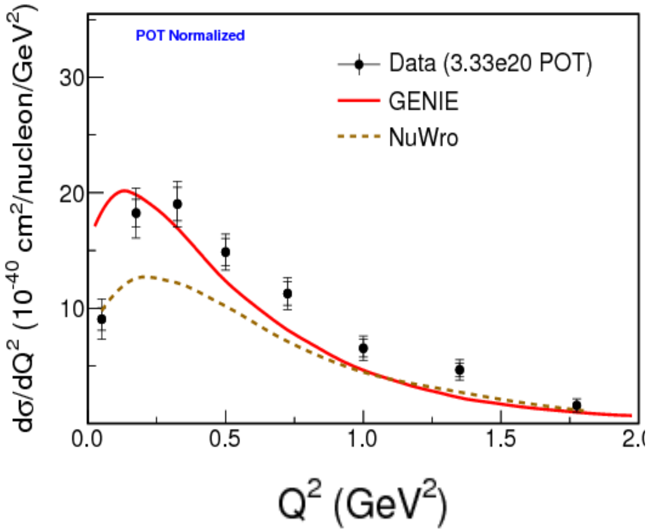
1. "Measurement of anti-νμ charged-current single pi- production on hydrocarbon in the few GeV region using MINERvA" arXiv:1906.08300, submitted for publication
2. "Constraint of the MINERvA Medium Energy Neutrino Flux using Neutrino-Electron Elastic Scattering" arXiV:1906.00111, submitted for publication
3. "Tuning the GENIE Pion Production Model with MINERvA Data" arXiV:1903.01558, submitted for publication
4. "Neutron measurements from anti-neutrino hydrocarbon reactions" arXiV:1901.04892, accepted by Phys. Rev. D.
5. "Measurement of Quasielastic-Like Neutrino Scattering at ⟨Eν⟩~3.5 GeV on a Hydrocarbon Target" Phys. Rev. D 99, 012004 (2019)
6. "Reducing model bias in a deep learning classifier using domain adversarial neural networks in the MINERvA experiment" Journal of Instrumentation, Vol. 13 (2018)
7. "Measurement of final-state correlations in neutrino muon-proton mesonless production on hydrocarbon at ⟨Eν⟩ = 3 GeV" Phys. Rev. Lett. 121, 022504 (2018)
8. "Antineutrino charged Current charged-current reactions on scintillator with low momentum transfer" Phys. Rev. Lett. 120, 221805 (2018)
9. "Measurement of the muon anti-neutrino double-differential cross section for quasi-elastic scattering on hydrocarbon at~Eν~3.5GeV" Phys. Rev. D 97, 052002 (2018)
10. "Measurement of Total and Differential Cross Sections of Neutrino and Antineutrino Coherent π± Production on Carbon" Phys. Rev. D 97, 032014, (2018)
11. "Measurement of νμ charged-current single π0 production on hydrocarbon in the few-GeV region using MINERvA" Phys. Rev. D 96, 072003 (2017)
12. "Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA" Phys. Rev. Lett. 119, 082001 (2017)
13. "Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon" Phys. Rev. D 95, 072009 (2017)
14. "Measurement of neutral-current K+ production by neutrinos using MINERvA" Phys. Rev. Lett. 199, 011802 (2017)
15. "Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method" Phys. Rev. D 94, 112007 (2016)
16. "Neutrino Flux Predictions for the NuMI Beam" Phys. Rev. D 94, 092005 (2016)
17. "First evidence of coherent K+ meson production in neutrino-nucleus scattering" Phys. Rev. Lett. 117, 061802 (2016)
18. "Measurement of K+ production in charged-current νμ interactions" Phys. Rev. D 94, 012002 (2016)
19. "Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA"Phys. Rev. D 94, 052005 (2016).
20. "Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon" Phys. Rev. Lett. 117, 111801 (2016)
21. "Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering", Phys. Rev. D 93, 112007 (2016)
22. "Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA", Phys. Rev. D 93, 071101 (2016).
23. "Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer", Phys. Rev. Lett. 116, 071802 (2016).
24. "Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Eν of 3.6 GeV", Phys. Rev. Lett 116, 081802 (2016).
25. "Single neutral pion production by charged-current anti-νμ interactions on hydrocarbon at average Eν of 3.6 GeV", Phys. Lett. B749 130-136 (2015).
26. "Measurement of muon plus proton final states in νμ Interactions on Hydrocarbon at average Eν of 4.2 GeV" Phys. Rev. D91, 071301 (2015).
27. "MINERvA neutrino detector response measured with test beam data", Nucl. Inst. Meth. A789, pp 28-42 (2015).
28. "Measurement of Coherent Production of π± in Neutrino and Anti-Neutrino Beams on Carbon from Eν of 1.5 to 20 GeV", Phys. Rev. Lett. 113, 261802 (2014).
29. "Charged Pion Production in νμ Interactions on Hydrocarbon at average Eν of 4.0 GeV" , Phys. Rev. D92, 092008 (2015).
30. "Measurement of ratios of νμ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV", Phys. Rev. Lett. 112, 231801 (2014).
31. "Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022502 (2013).
32. "Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013).
33. "Design, Calibration and Performance of the MINERvA Detector", Nucl. Inst. and Meth. A743 (2014) 130.
34. "Demonstration of Communications using Neutrinos", Mod.Phys.Lett. A27 (2012) 1250077
35. "The MINERvA data acquisition system and infrastructure", Nucl.Instrum.Meth. A694 (2012) 179-192
36. "Arachne – A web-based event viewer for MINERvA", Nucl.Inst.Meth. 676 (2012) 44-49

Some of MINERvA's 3 GeV Results



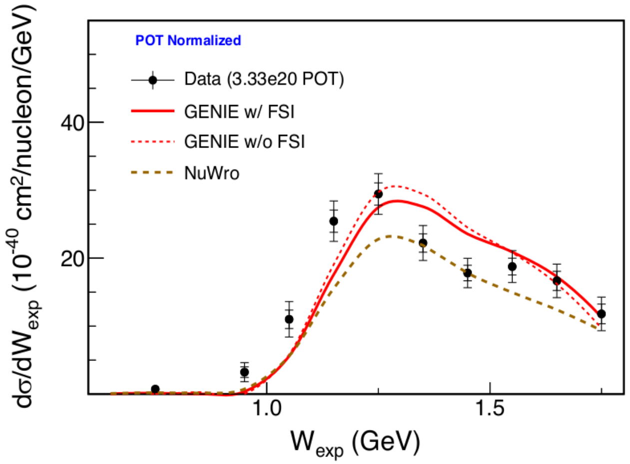
Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802

- Solved coherent pion "puzzle".
  - Low energy (K2K, SciBooNE) null results were because of overprediction at low E_π.
  - Discovered coherent kaon production.



Phys.Rev. D96 (2017) 072003

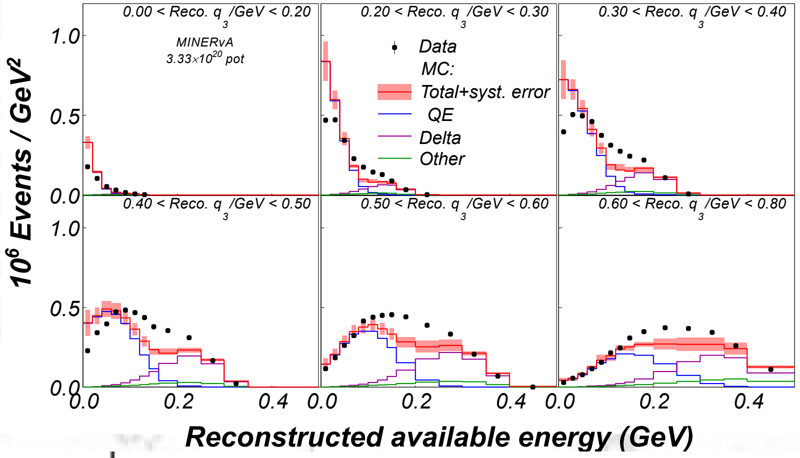
$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$



- Strong evidence for low Q^2 suppression in some pion production events.
- MINERvA sees a shift in pion spectra to lower energies, also consistent with an apparent shift in the $\Delta(1232)$ peak.
  - Maybe from the resonant-non resonant interference that is absent from model?

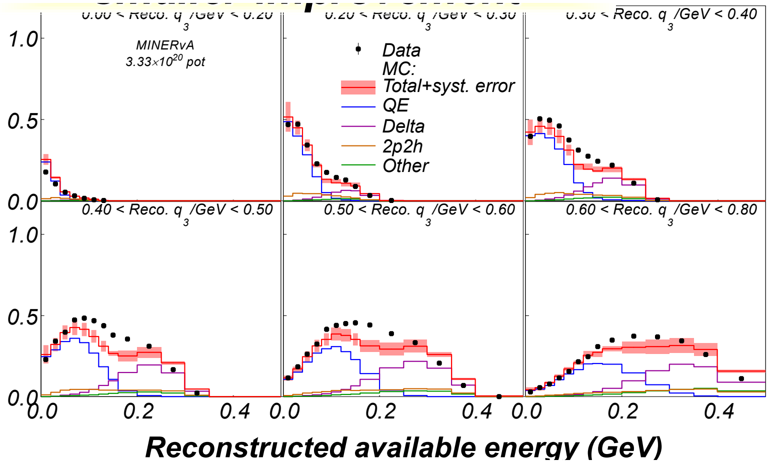
Some of MINERvA's 3 GeV Results

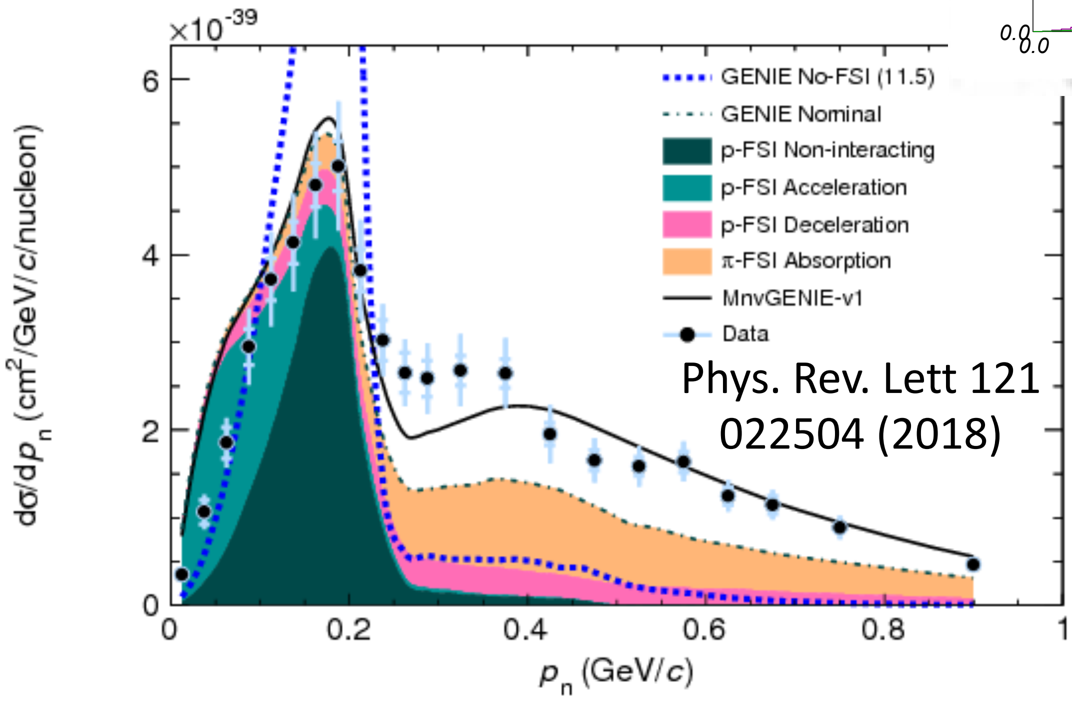
- Experimental demonstration of "RPA" low Q^2 suppression and events with multinucleon kinematics



Phys.Rev.Lett. 116 (2016) 071802

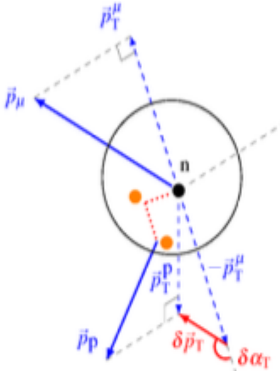
Add RPA, 2p2h to model





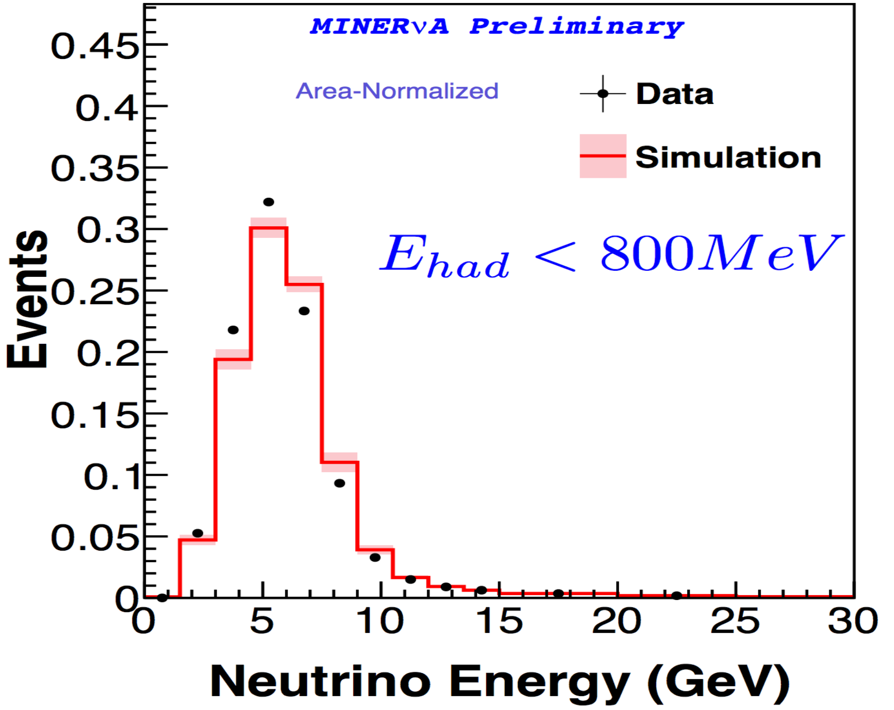
Phys. Rev. Lett 121 022504 (2018)

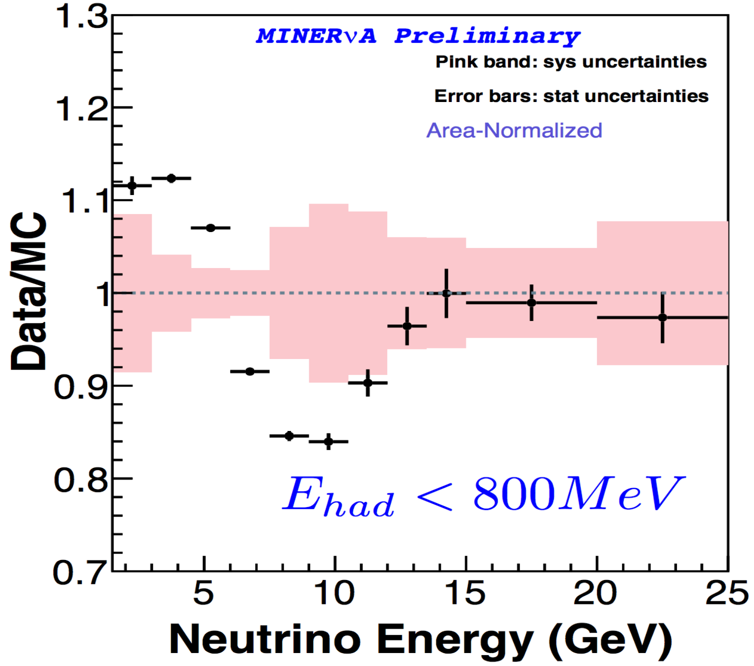
Neutron momentum under exclusive μp hypothesis



- Development of techniques to probe nuclear model with lepton-hadron correlations
  - Disagreement in region of FSI "acceleration" is a model bug.

Slowdown: 6 GeV Flux Puzzle





low recoil events

systematic band at right includes flux and GENIE's (unconstrained) estimate of low recoil cross section.

normalization uncertainties not shown

- Results of fits to low recoil flux measurement in different regions of the detector give two equally valid solutions.

muon energy scale needs to be pulled by 1.8σ.

target position in z or horn currents far out of measured tolerance.

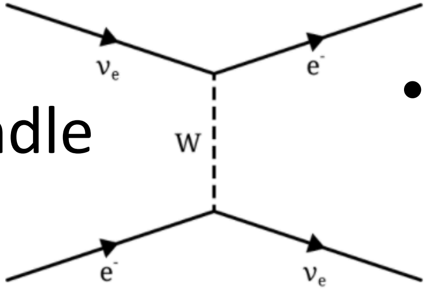
Surprisingly, this indicates NuMI's focusing peak is *a priori* more precise than our detector calibration!

So far, we consider the full range of both solutions as uncertainties.

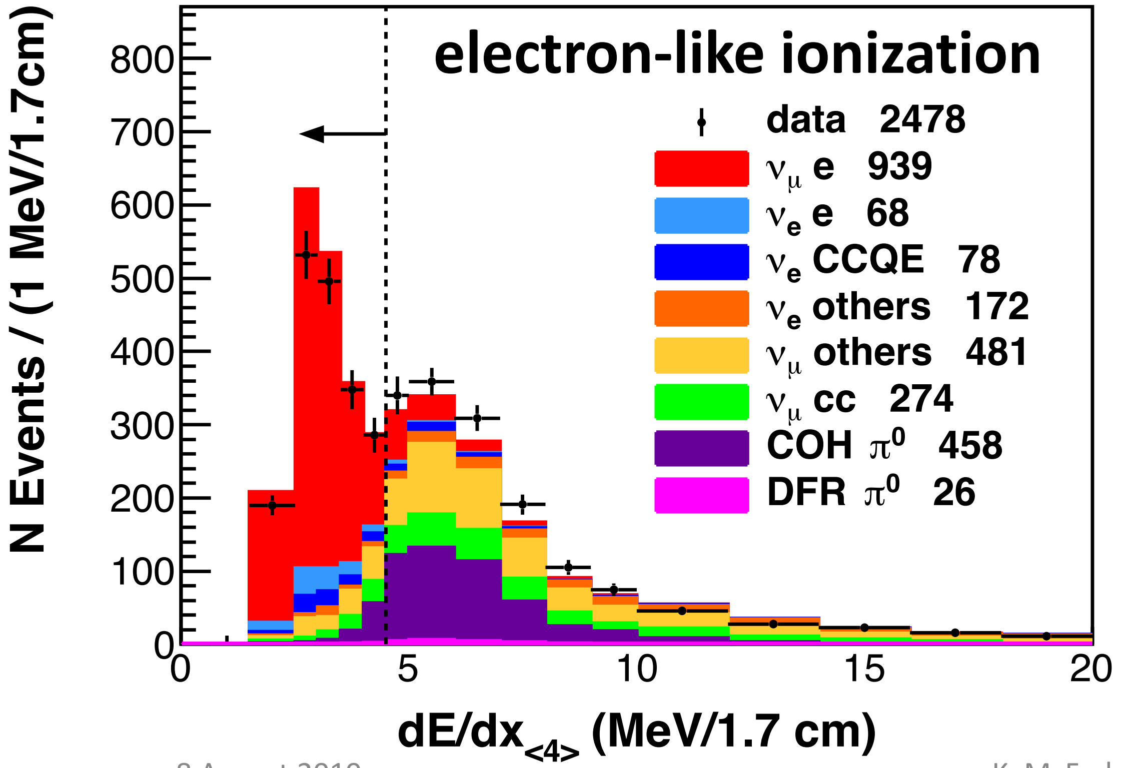
6 GeV ("Medium Energy") Flux from Neutrino-Electron Scattering

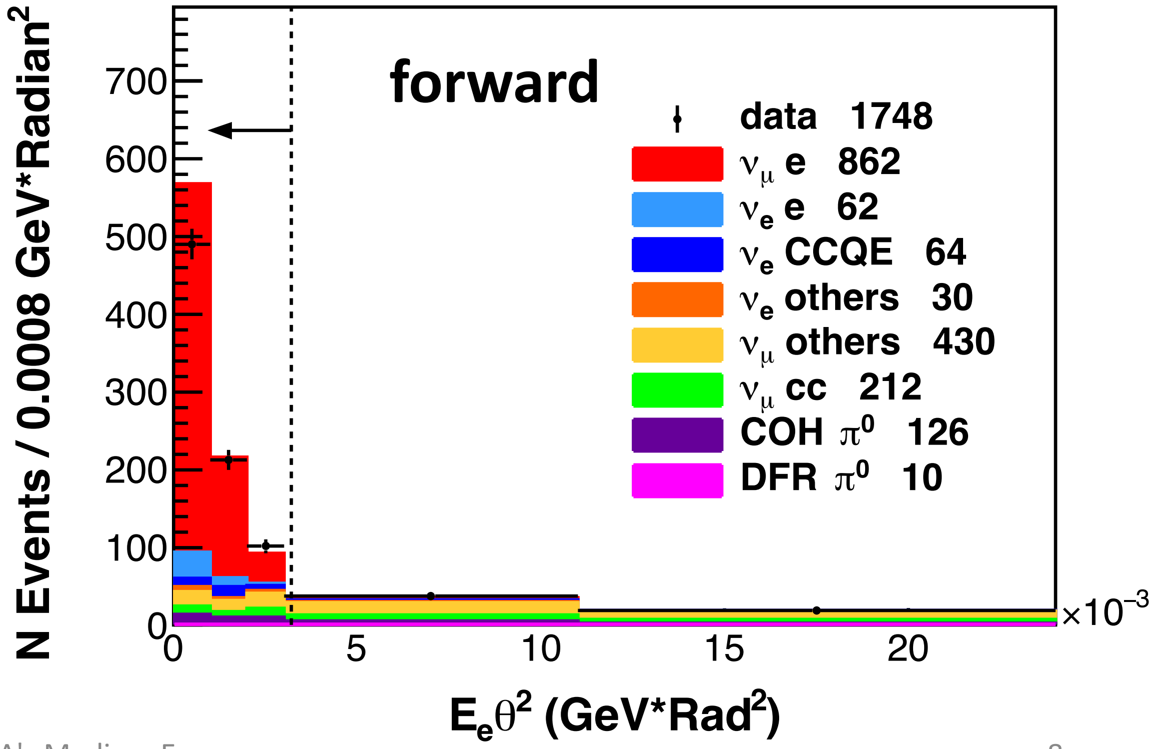
arXiv:1906.00111

- Neutrino-electron elastic scattering is a standard candle for neutrino interactions.



- Experimentally, a forward going energetic electron with nothing else in event.
  - Backgrounds are primarily from ν_e interactions and photons from π^0 decays.

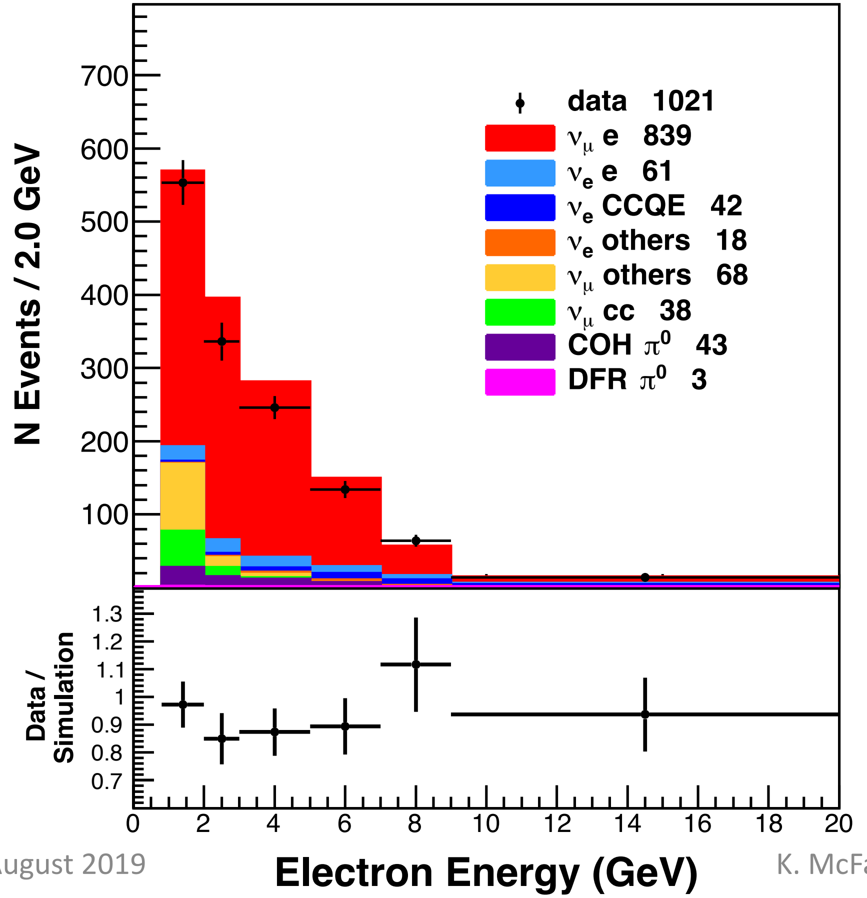


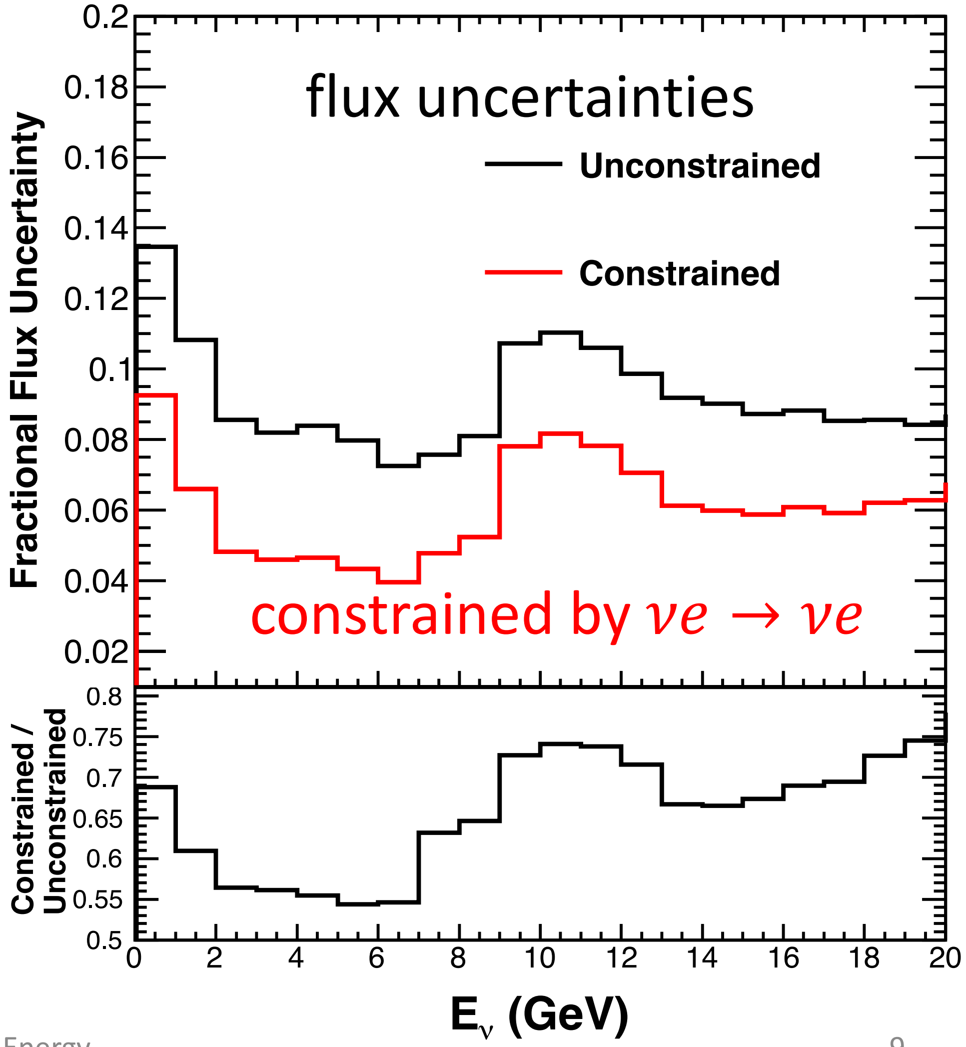


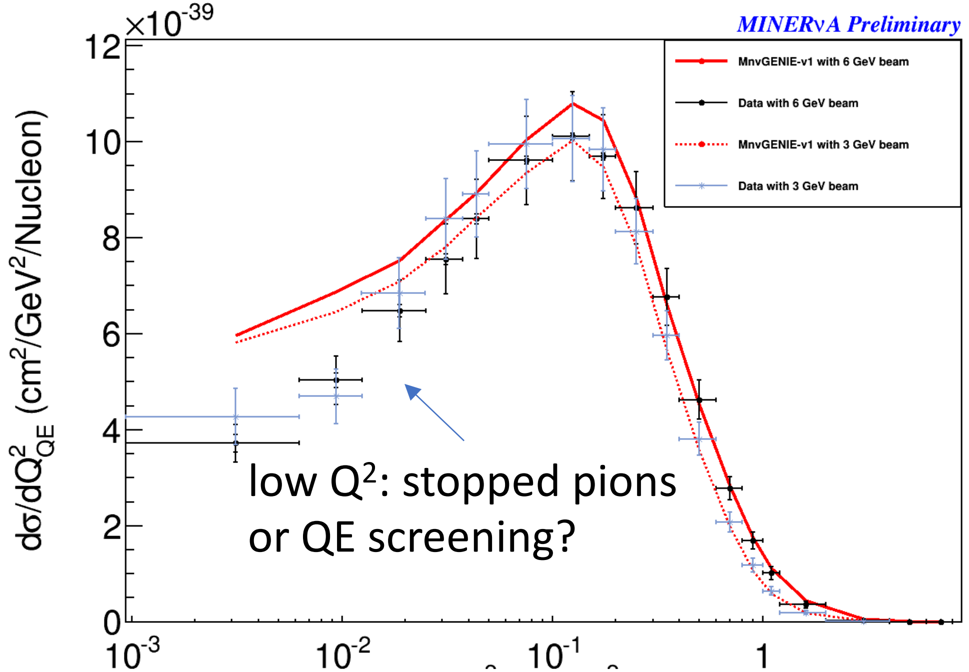
6 GeV ("Medium Energy") Flux from Neutrino-Electron Scattering

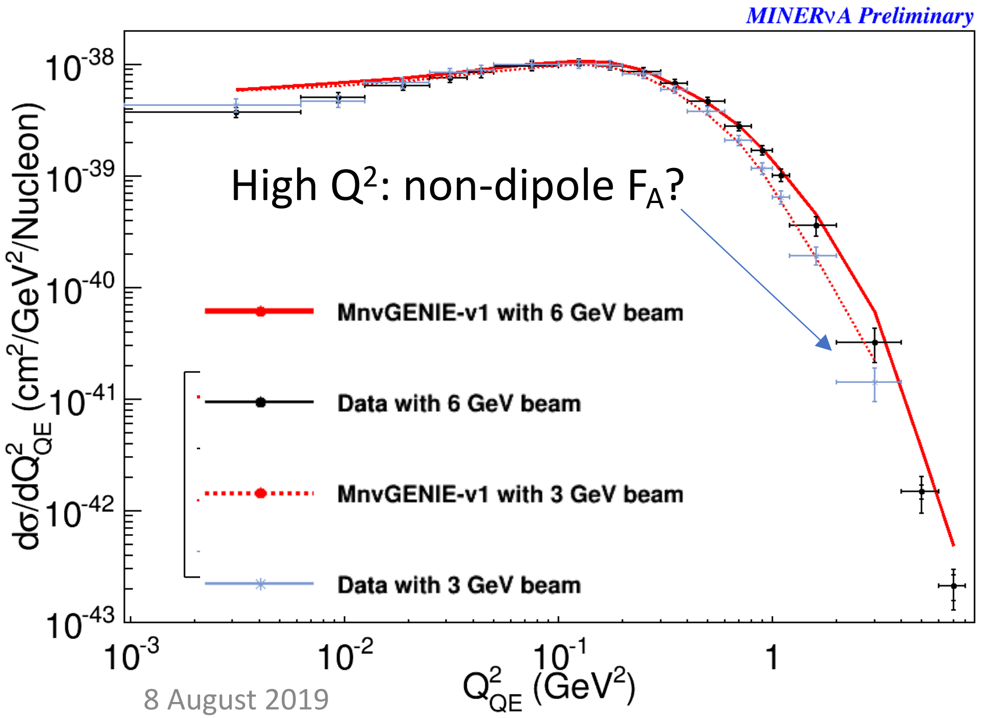
arXiv:1906.00111

- 1021 events in data with a predicted background of 212. S/N~4 for a process that is 0.02% of total interaction rate.







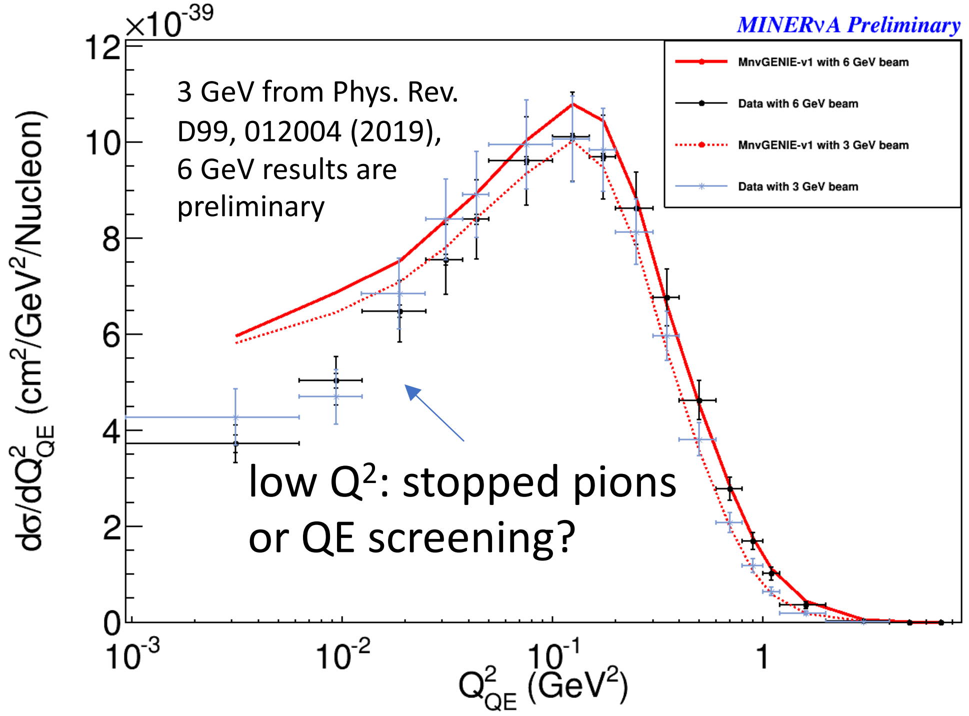


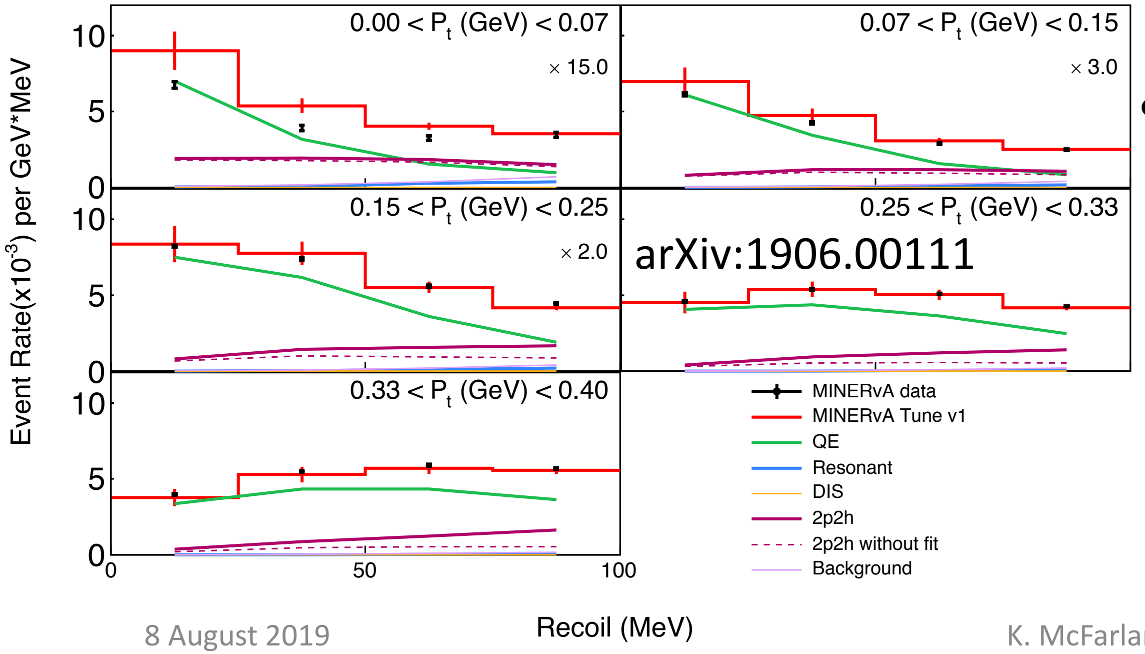
6 GeV CC0π

- We have a CC0π sample from the NOvA era analysis.
  - Higher statistics by a factor of 10.
  - Higher energy means more reach in Q^2.
  - Even with more inelastic processes at higher energies, backgrounds after selection are comparable! Surprising, but true.
  - Flux and muon energy scale uncertainties set conservatively in this preliminary result.
- See consistent discrepancies at low and high Q^2 in both data sets.

3 GeV from Phys. Rev. D 99, 012004 (2019), 6 GeV results are preliminary

More 6 GeV CC0π

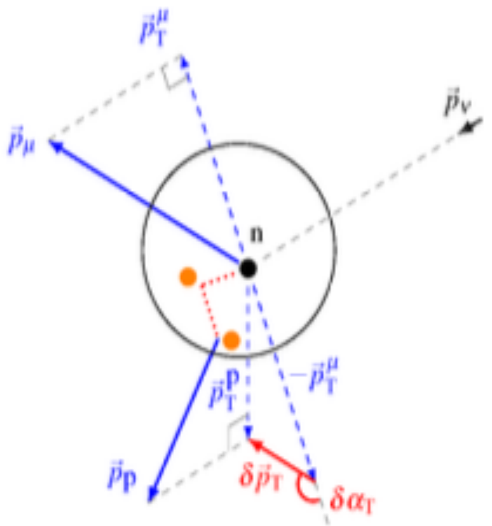




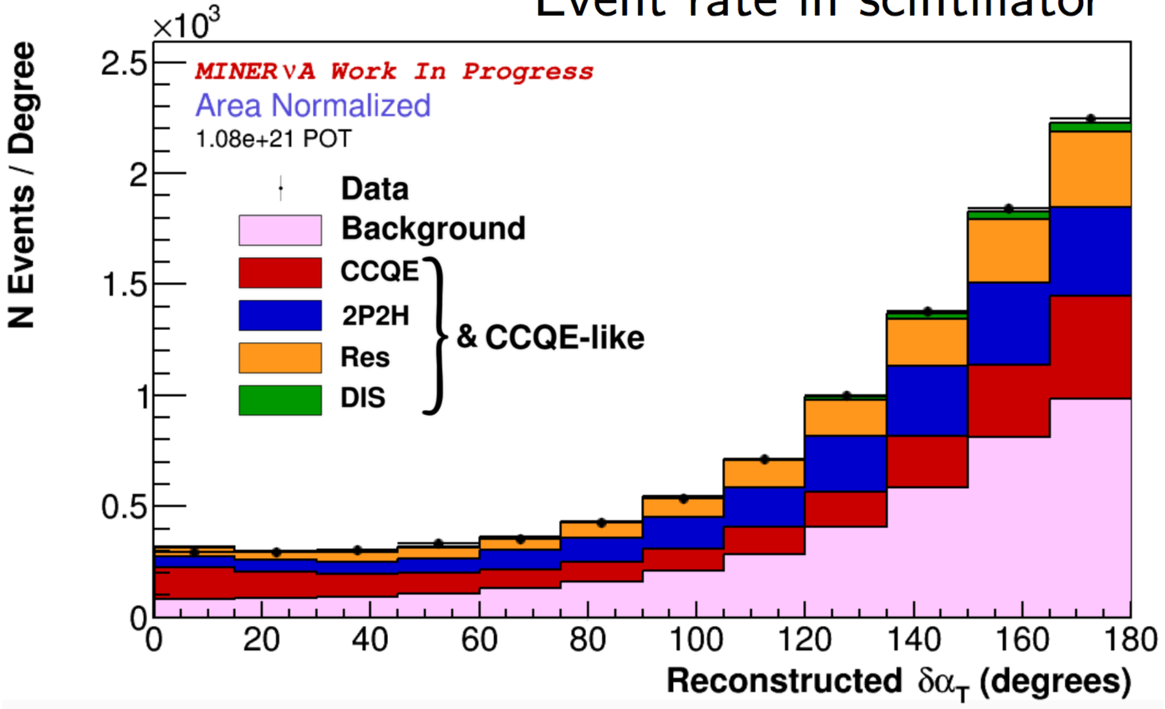
- The "?" on the previous slide had to do with the source of the low Q^2 discrepancy.
- 10x statistics means we can look at visible energy (proton kinetic energy in in CC0π events) in the low Q^2 events.
- A small fraction of the discrepancy appears to be "quasielastic" in origin.
  - Quasielastic events are low "recoil" energy in plots at left. Discrepancy is mostly off scale, in regions dominated by pion production.
  - Quasielastic ν_e events are a background to $\nu e^- \rightarrow \nu e^-$, so we had to tell the world. ☺

6 GeV CC0π in Targets

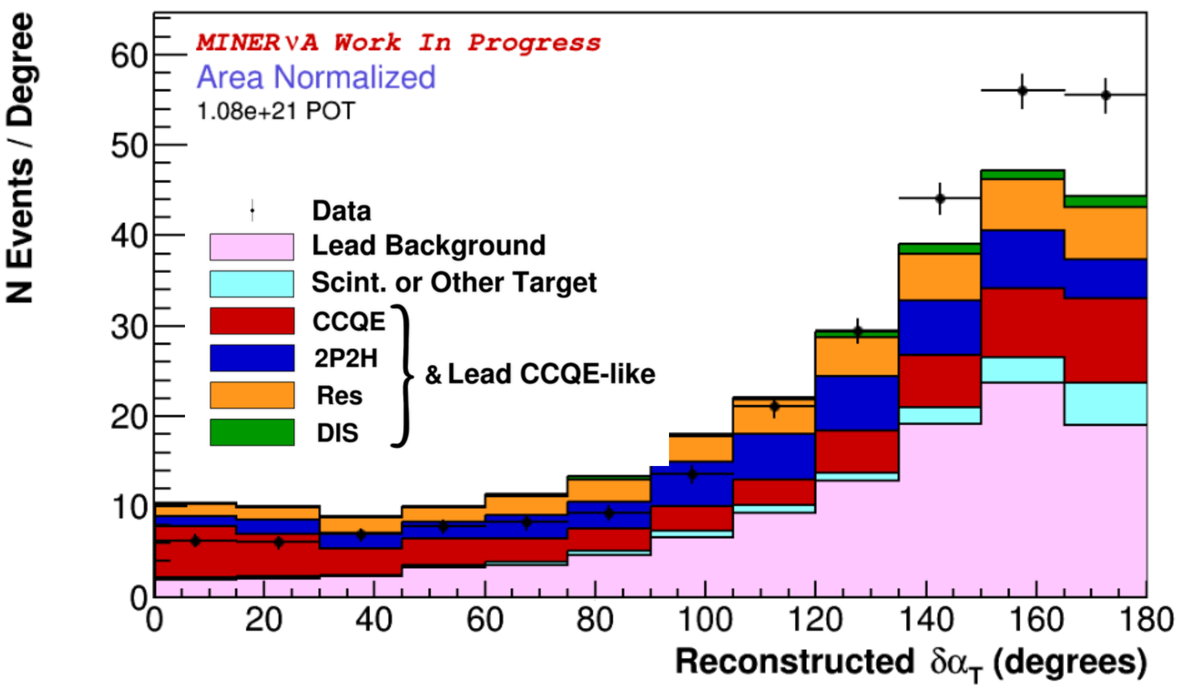
- Have enough statistics to make meaningful statements about distributions of transverse variables in water, iron, and lead targets.



Event rate in scintillator



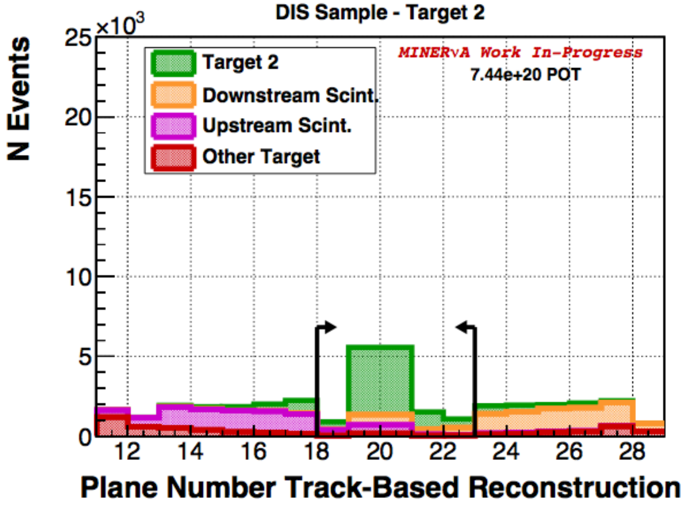
Event rate in lead

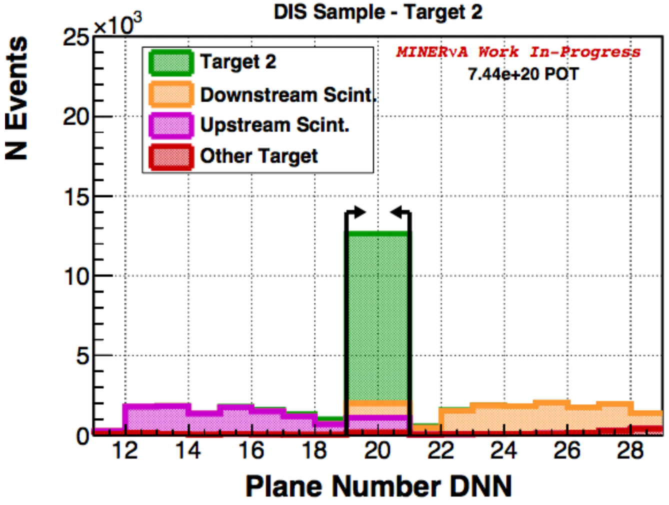


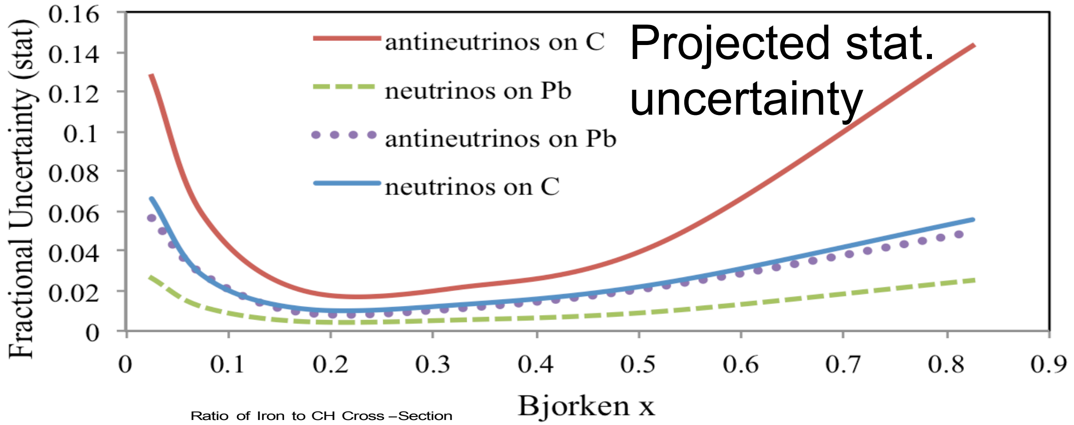
- Lead target sample, ~5000 events. Similar backgrounds to scintillator sample.

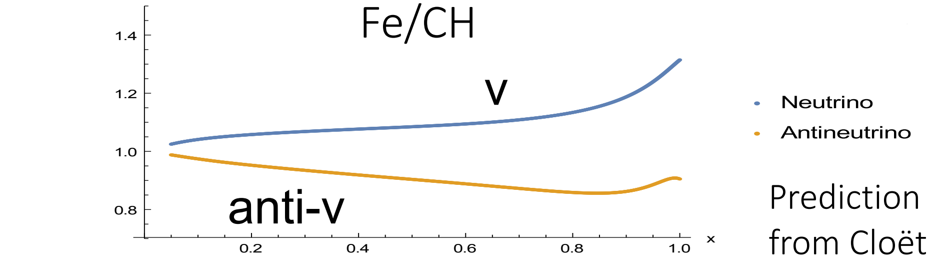
6 GeV DIS Ratios in Targets

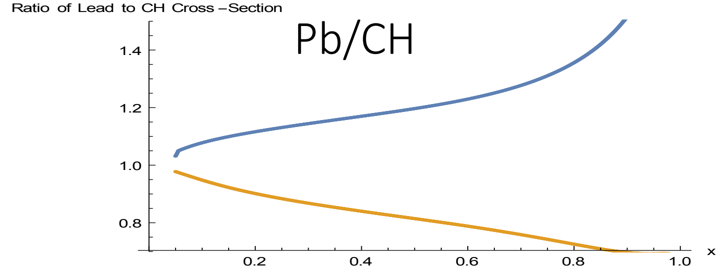
- Models for EMC effect typically predict different effects in neutrino and antineutrino scattering
- Completion of MINERvA's run allows "ν-EMC" ratio measurement vs. quark momentum fraction at ~5% precision for Fe and Pb











Prediction from Cloët model described in PRL 109, 182301

- Along the way, we've developed a deep learning method for reconstructing location of neutrino interaction.
- Uses "domain adversarial" networks that learn to ignore model dependent features (JINST 13 P11020).

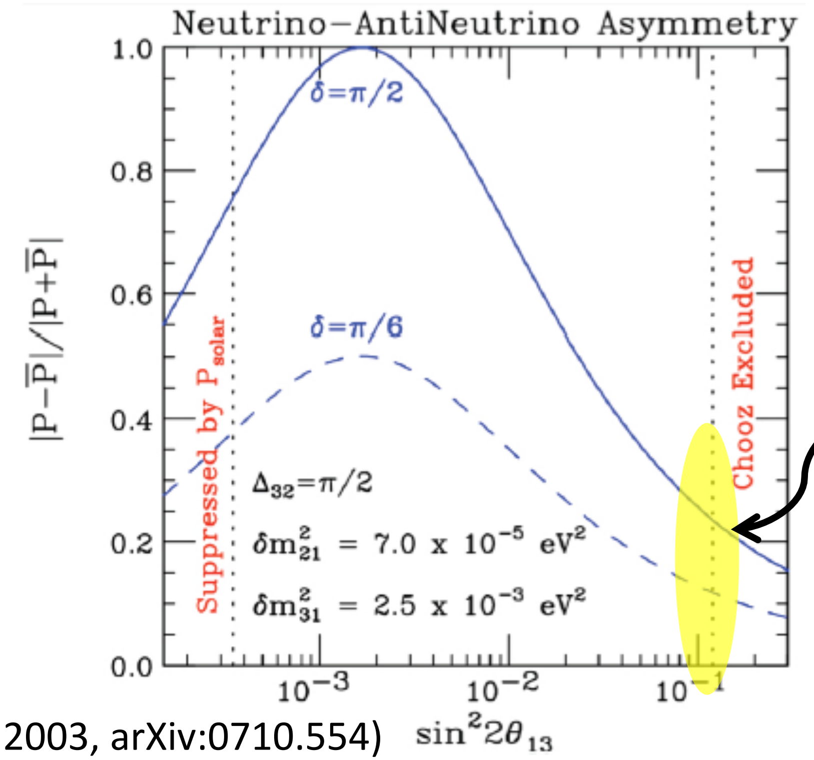
Conclusions and Outlook

- MINERvA's 3 GeV results have already transformed our knowledge of neutrino interactions, and are used by oscillation experiments.
- Extraction of 6 GeV results, with an order of magnitude more statistics, has been slowed by systematics of flux and energy scale.
- Two main thrusts of expected results:
  - Use overwhelming statistics on scintillator for lepton-hadron correlations to probe nuclear effects, both expected and unexpected in models.
  - Use nuclear targets, and ratios of events to scintillator to further probe the A-scaling of nuclear models. Important for future LAr detectors.
- MINERvA is also spending time improving models in generators and working with theorists to provide tests of their nuclear and nucleon models.
- Finally, we are also working to "preserve" this data in an analyzable format for the future as next generation experiments improve models.

Backup: Oscillation Experiments and Interactions

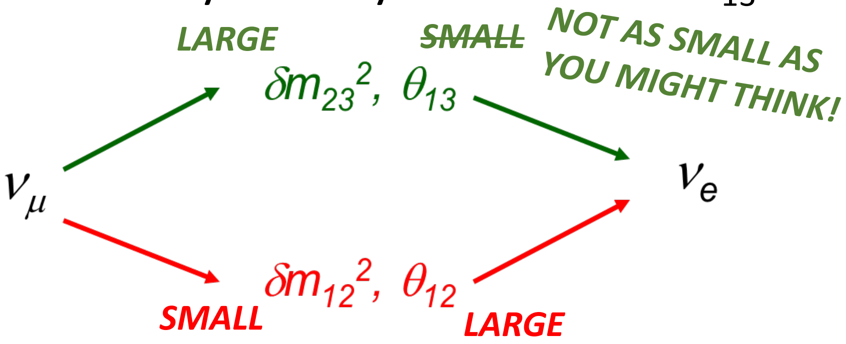
θ_{13} and Systematics

- When MINERvA was proposed, we might have thought that backgrounds to the rare electron neutrino appearance were our only problem.
- *We were very, very wrong.*



(Parke 2003, arXiv:0710.554)

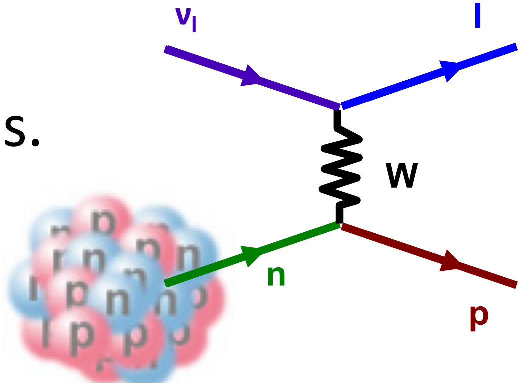
- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases



- Nature decided to put us here.
- Systematics on muon and electron neutrino signal reactions are important since we need high precision comparison of $\bar{\nu}$ and ν rates!

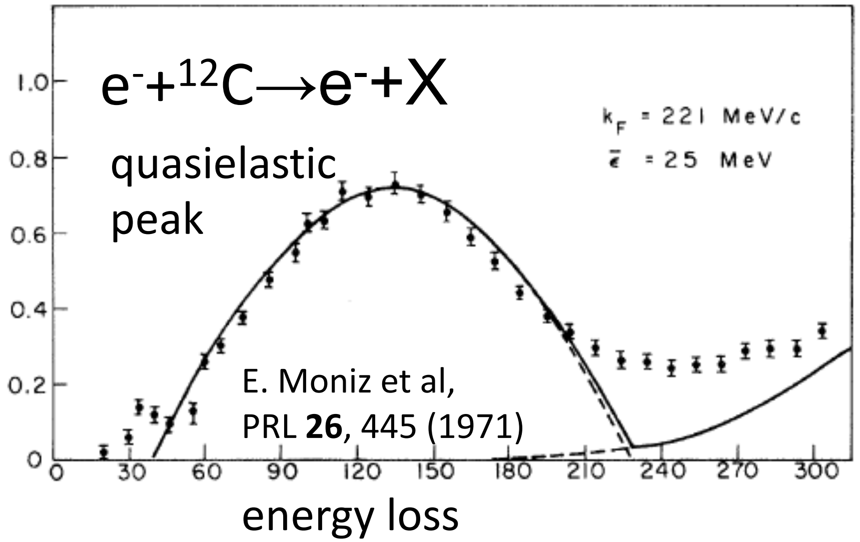
Uncertainty Example: 2p2h

- Oscillation experiments reconstruct neutrino energy from partial events, even in the most elastic events.
  - E.g., T2K and MiniBooNE from lepton energy and angle
  - E.g., NOvA from energy of lepton and kinetic energy of protons.



- For the quasielastic reaction, this can be done without significant bias, albeit with some uncertainty.

- Initial state nucleon is bound, in motion from its interaction with the rest of the nucleus.
  - Simple Fermi Gas model constrained by electron scattering was state of the art for MiniBooNE, and T2K and NOvA in their initial analyses.



Uncertainty Example, 2p2h (cont'd)

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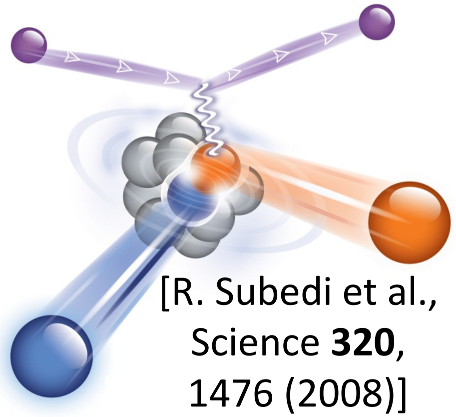
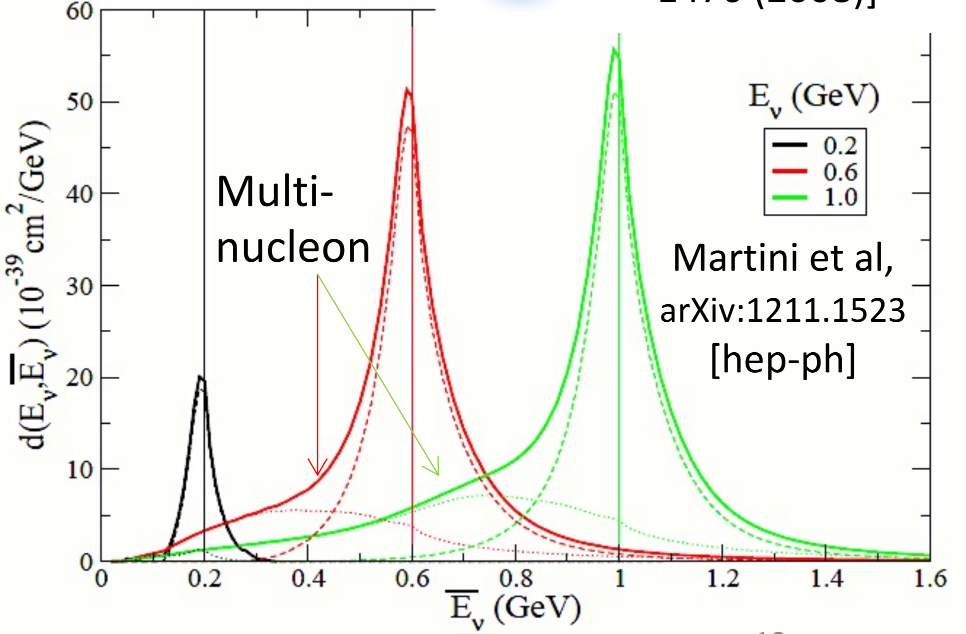


[R. Subedi et al., Science **320**, 1476 (2008)]

- We now know that in many pionless events on nuclei, multiple nucleons are involved, "2particle2hole" interactions.
  - Significant energy and momentum are lost to the extra outgoing nucleon. Invisible to T2K and MiniBooNE and neutrons invisible to NOvA.
- Critical correction for T2K and NOvA. But how do we know it's correct?



Backup: History of MINERvA

History of MINERvA

2002

MINERvA EOI
Scintillator tracker and passive targets, NuMI

2007

Construction Start
Begin fiber, scintillator production.

2010

First Data-taking
Low Energy (MINOS), March’10 – March’12

2012

1st Interaction Papers
CCQE in neutrino and antineutrino beams.

today

Results in this talk
CC0π and CC1π tunes.
Coherent π resolved.
Fe, Pb mysteries.

History of MINERvA

Elizabeth McFarland-Porter

Crane School of Music, Class of 2021

2002 — 2007 — 2010 — 2012 — today

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Scintillator tracker and passive targets, NuMI

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today — Results in this talk
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History of MINERvA in neutrinos

Atmospheric neutrino oscillations at Super-K

Precise $\Delta m^2_{\odot}$ at SNO and KAMLAND

MINOS begins; first precise Δm^2_{23}

T2K 6 ν_e Events

Reactor θ_{13}

NOvA $\overline{\nu_e}$ Appearance

2002 — 2007 — 2010 — 2012 — today

MINERvA EOI
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Implications of the Neutrino History

Atmospheric neutrino oscillations at Super-K

Precise $\Delta m^2_{\odot}$ at SNO and KAMLAND

MINOS begins; first precise Δm^2_{23}

T2K 6 ν_e Events

Reactor θ_{13}

NOvA $\overline{\nu_e}$ Appearance

2002 — 2007 — 2010 — 2012 — today

- Neutrino Oscillations at GeV Accelerator Experiments
- Sub-leading effects from solar oscillations possible
- Δm^2_{23} well enough known to tune narrowband beam accelerator experiments
- CP phase, δ, accessible in these experiments

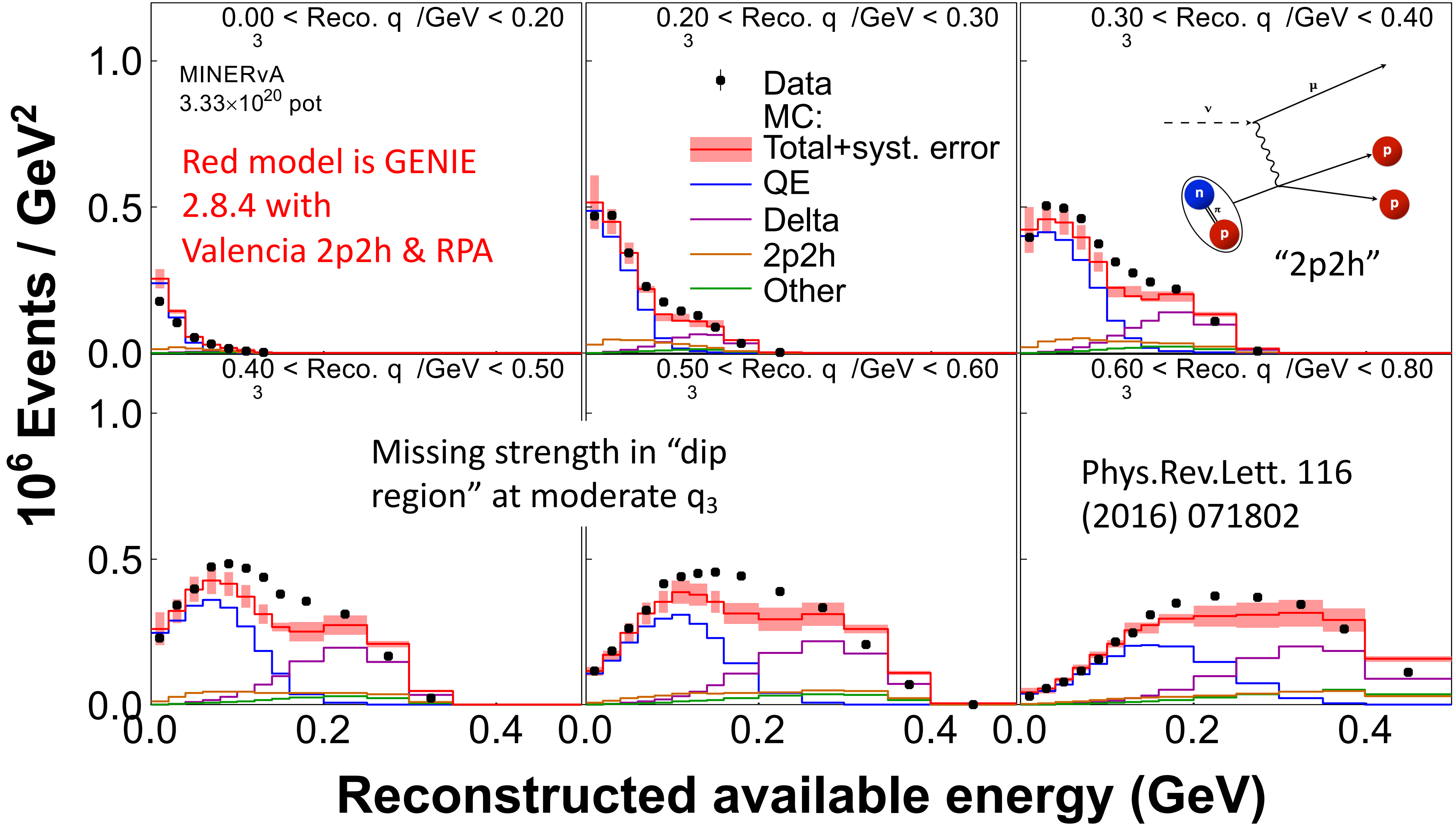
Justification for DUNE and Hyper-K

MINERvA owes a lot to Fermilab and partners at the Department of Energy

- MINERvA received a lot of encouragement and support in its formative phase.
  - Early R&D support from FNAL/PPD and DOE OHEP through the University of Rochester.
  - Fermilab's Project Support Office, particularly Ed Temple and Dean Hoffer.
  - Ted Lavine and Steve Webster, among many, at DOE for project oversight.
- Construction and Installation
  - Critical contributions from FNAL/PPD in engineering, technical, accounting, project oversight, and facilities staff.
- Operations and Analysis
  - Accelerator and beams.
  - FNAL/PPD->Neutrino Division staff for support of many construction subprojects
  - ES&H for finding ways for physicists & others to be safe working on our detector.
  - Children's center who gave us time to watch our detector.
  - Directorate support for Latin American and Indian collaborators.
  - Scientific Computing for proactive management of needed resources.
  - MINOS collaboration for operations help and analysis of muons in its near detector.

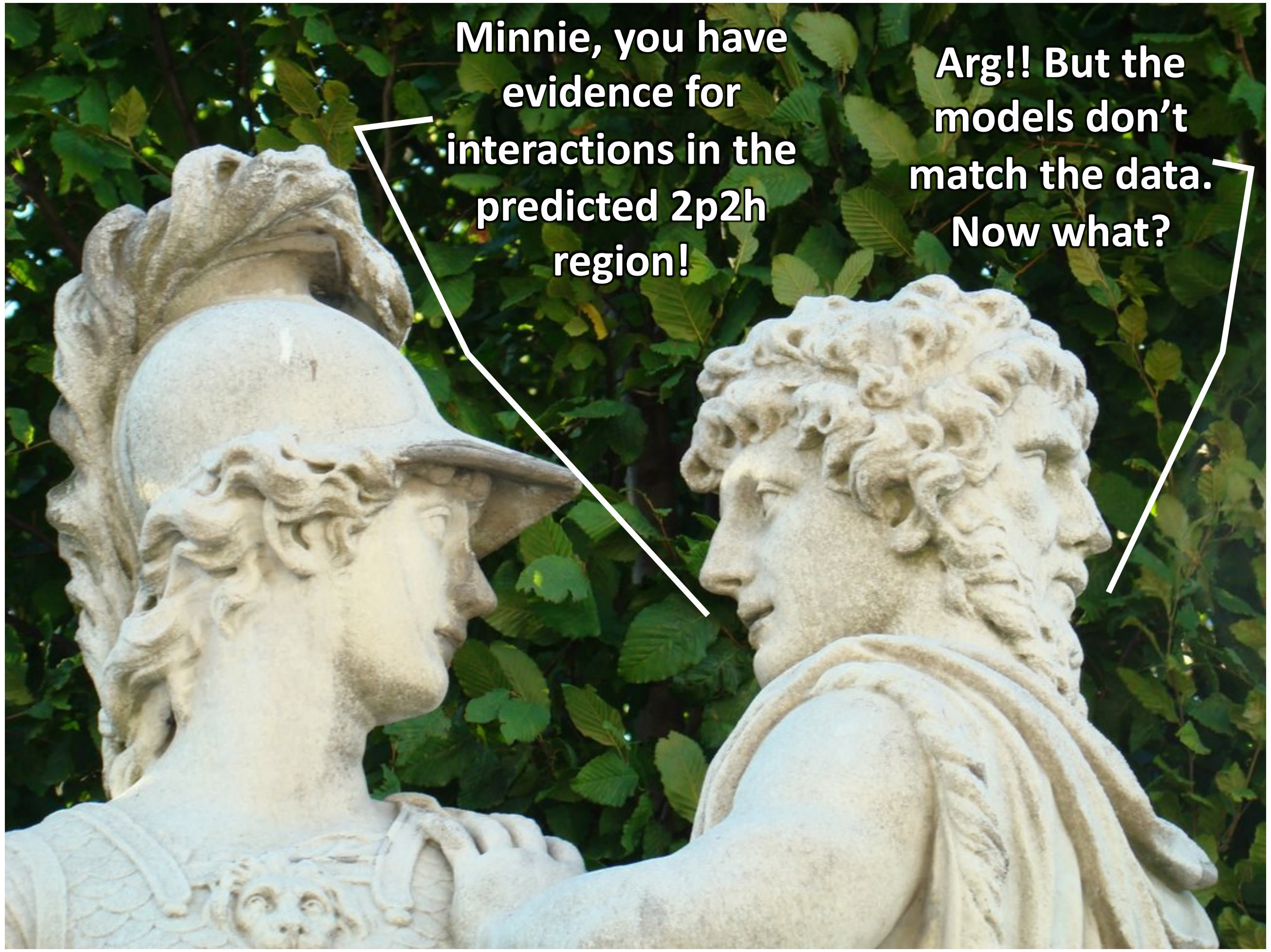
Backup: MINERvA 2p2h Tune

Missing moderate $|q_3|$ "Dip Region"

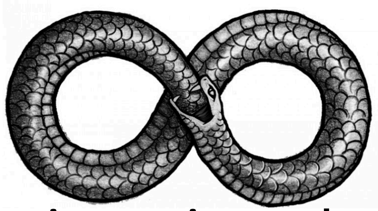


- Nieves 2p2h & RPA model added to GENIE prediction used by MINERvA.
- But it doesn't provide enough strength at moderate $|q_3|$.

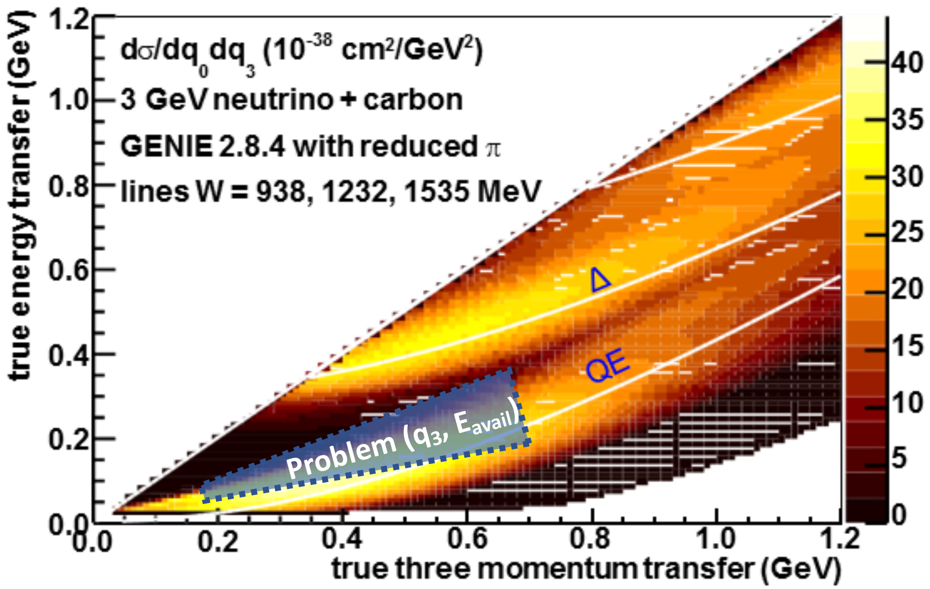
What can we do to fix it?



- Indeed, this is a problem.

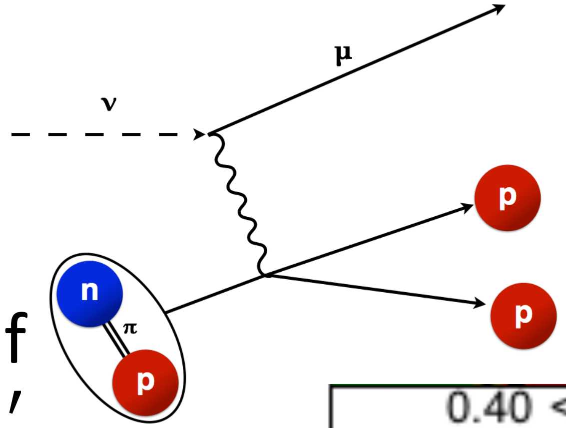


- But in this kinematic region, there are only so many possible contributing processes.

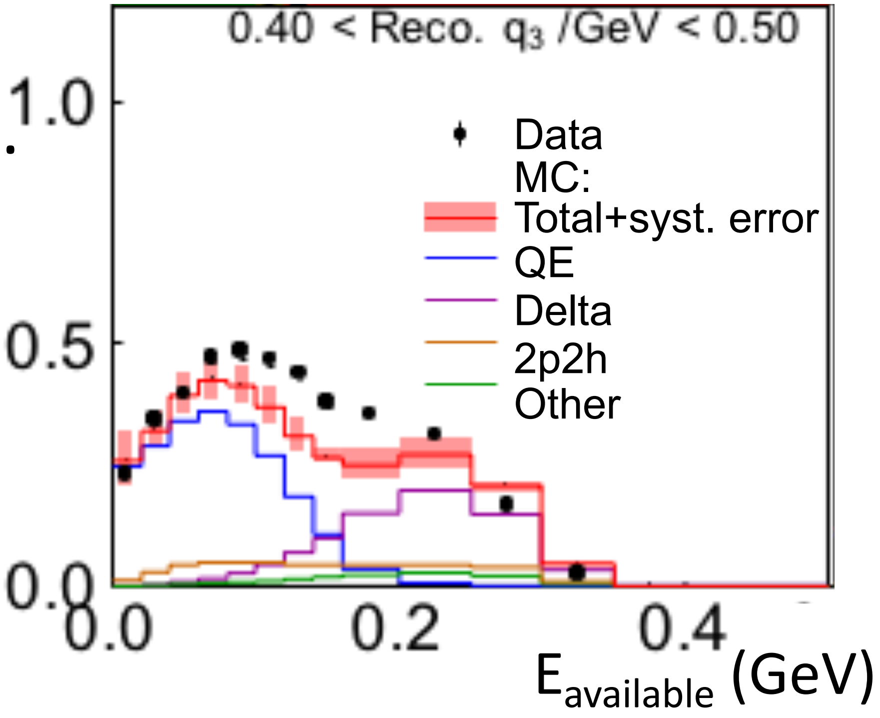


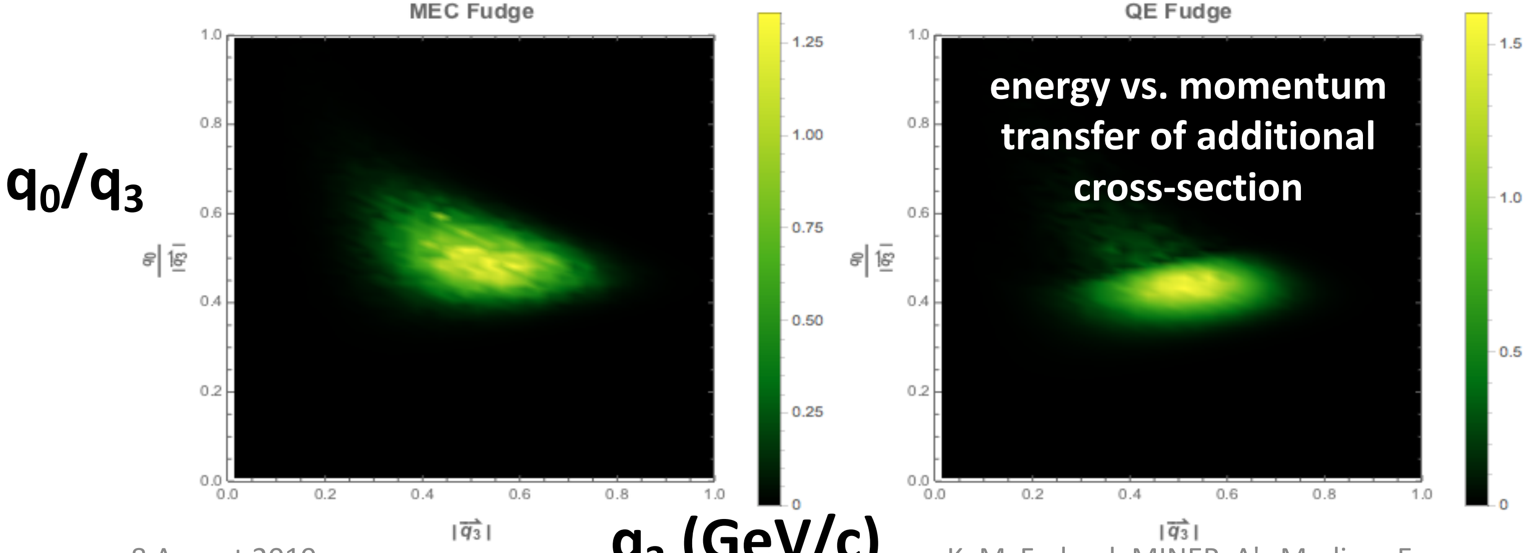
$E_{\text{avail}} \approx q_0 \underbrace{- \Sigma T_n - \Sigma m_{\pi^\pm}}_{\text{need ~200 MeV to migrate from }\Delta}.$ So, QE and 2p2h.

What to Fix?

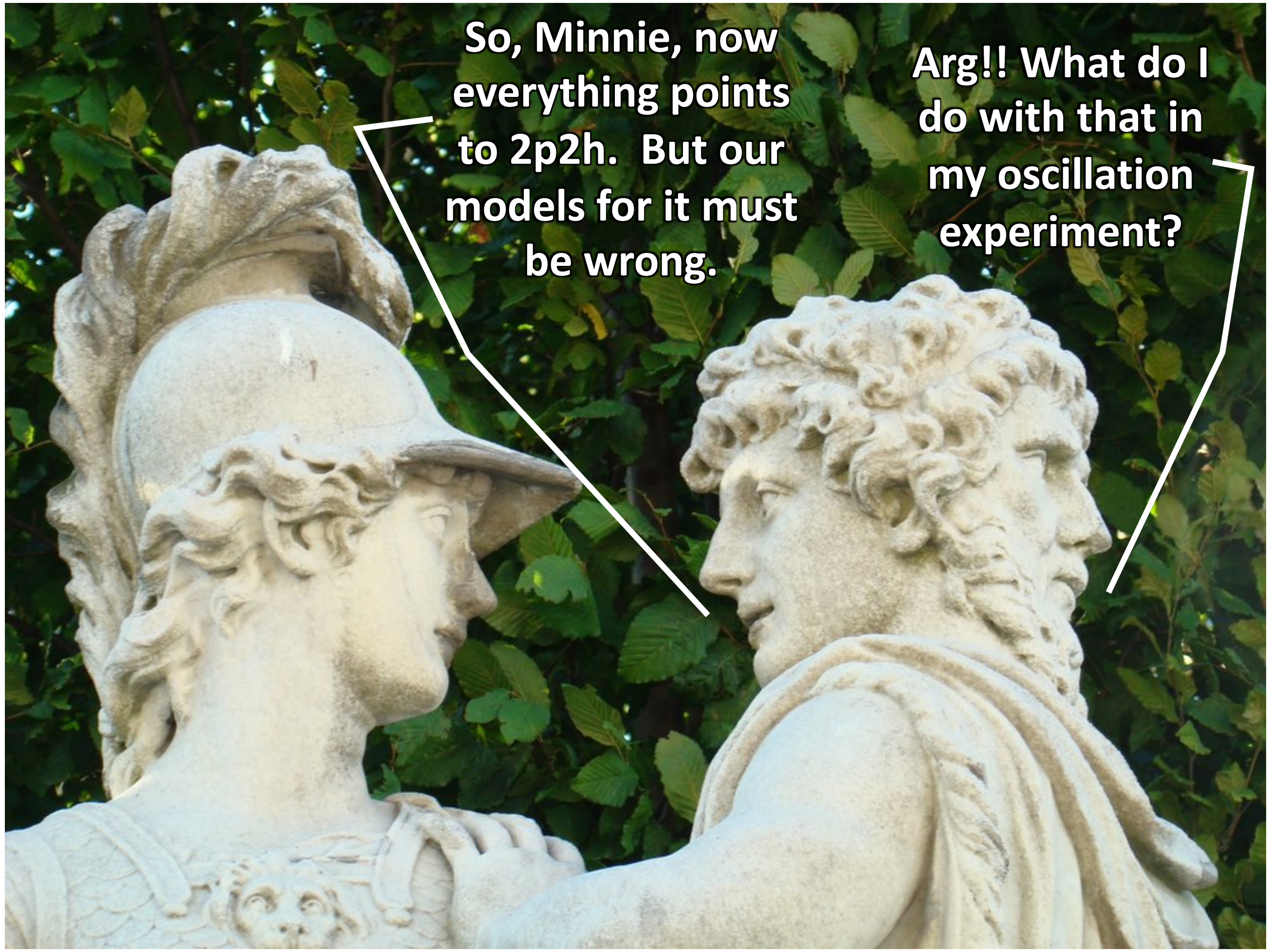


- MINERvA's low recoil data identifies missing strength, but it doesn't identify if $\nu_\mu A(n) \to \mu^- p A'$ or $\nu_\mu A(nn) \to \mu^- p n A'$ or $\nu_\mu A(np) \to \mu^- p p A'$ is the most likely source.
  - Different choices mean different $E_{\mathrm{avail}}(q_0)$.
- Default tune augments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





CC0π Model Tune

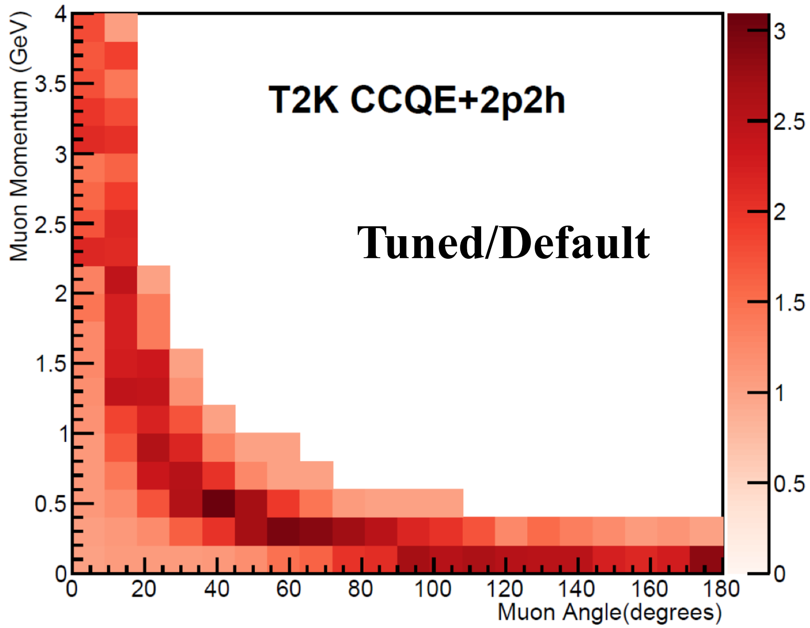


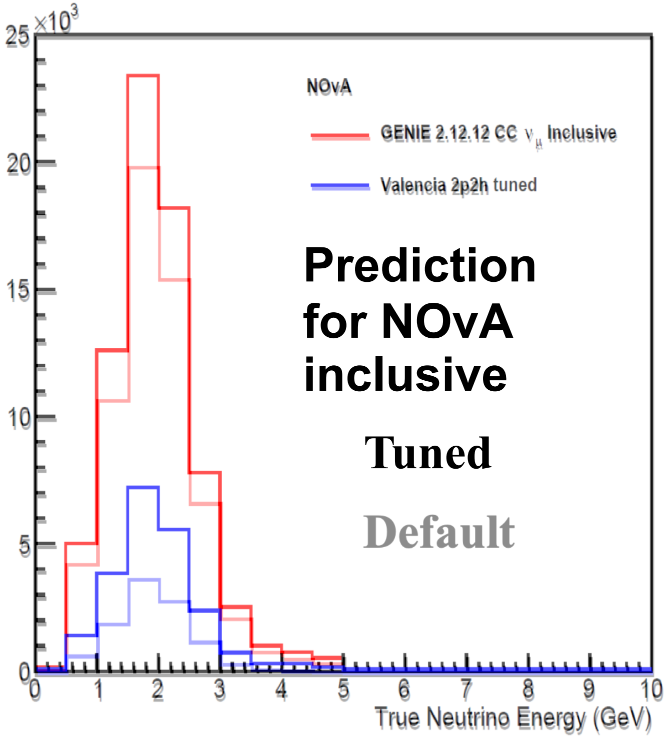
- For these "least inelastic" events, MINERvA has found a tuned model which explains:
  - Lepton energy-momentum distributions
  - Details of nucleon recoil
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.

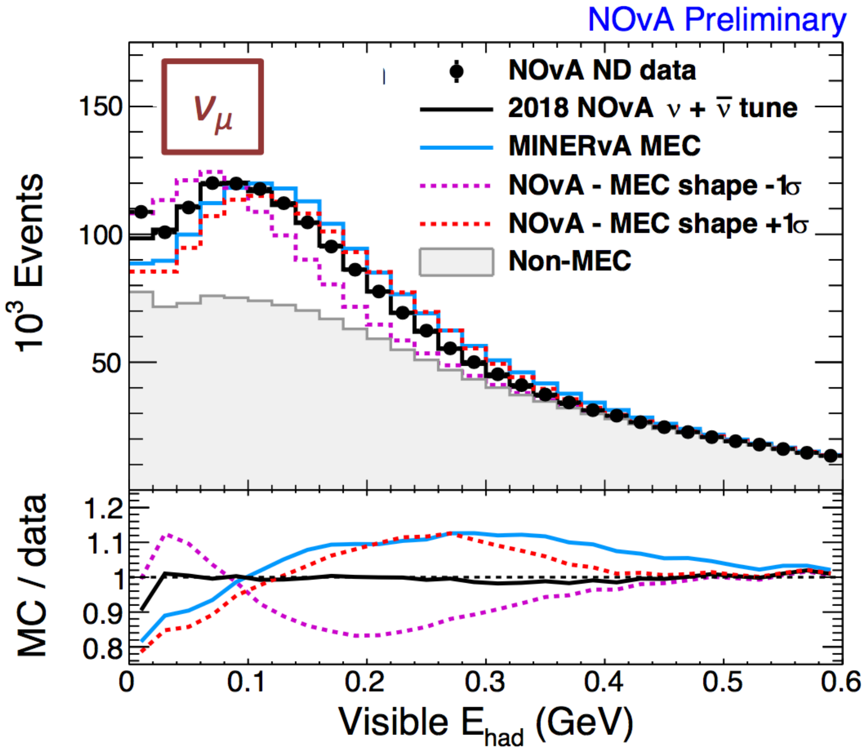
- NOvA uses this technique on its own near detector data for its oscillation analysis to tune 2p2h. ✓
- Can MINERvA's tune be applied to T2K, MicroBooNE energies?

Implications for NOvA and T2K

Event rate ratio: Tuned/Default





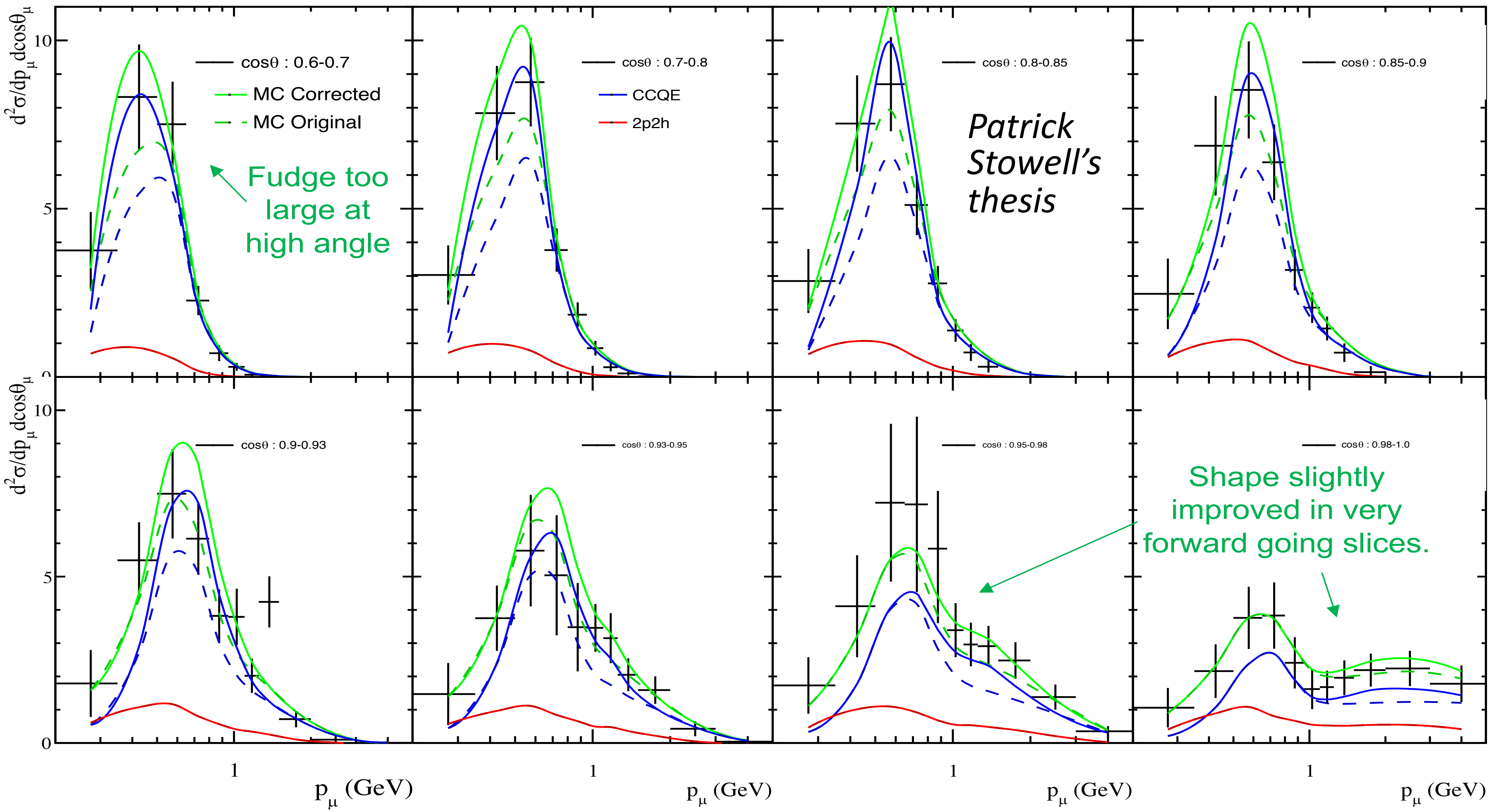


Alex Himmel, JETP Seminar, June 2018

- Beam energy ~ 0.6 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible impact in CCQE-like full phase space at T2K energy, especially at high angle

- Beam energy ~ 2 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible change in inclusive energy spectrum at NOvA energy

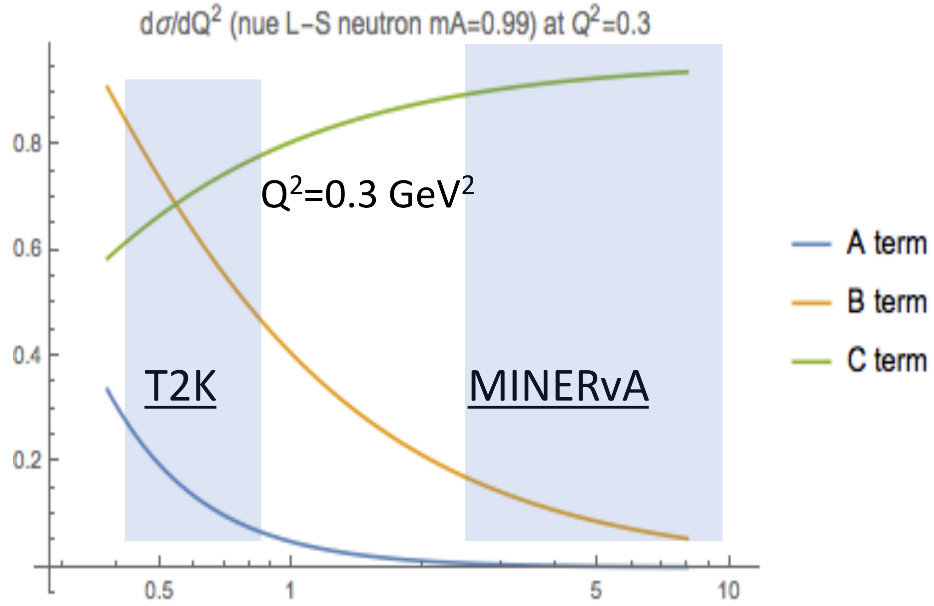
Apply to T2K CC0π… too much tune!



MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

Could the "MINERvA tune" be Energy Dependent?

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



E_ν (GeV)

CCE on free neutrons

- What are the A, B, C terms?

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

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

  - This holds for QE, 2p2h, etc.

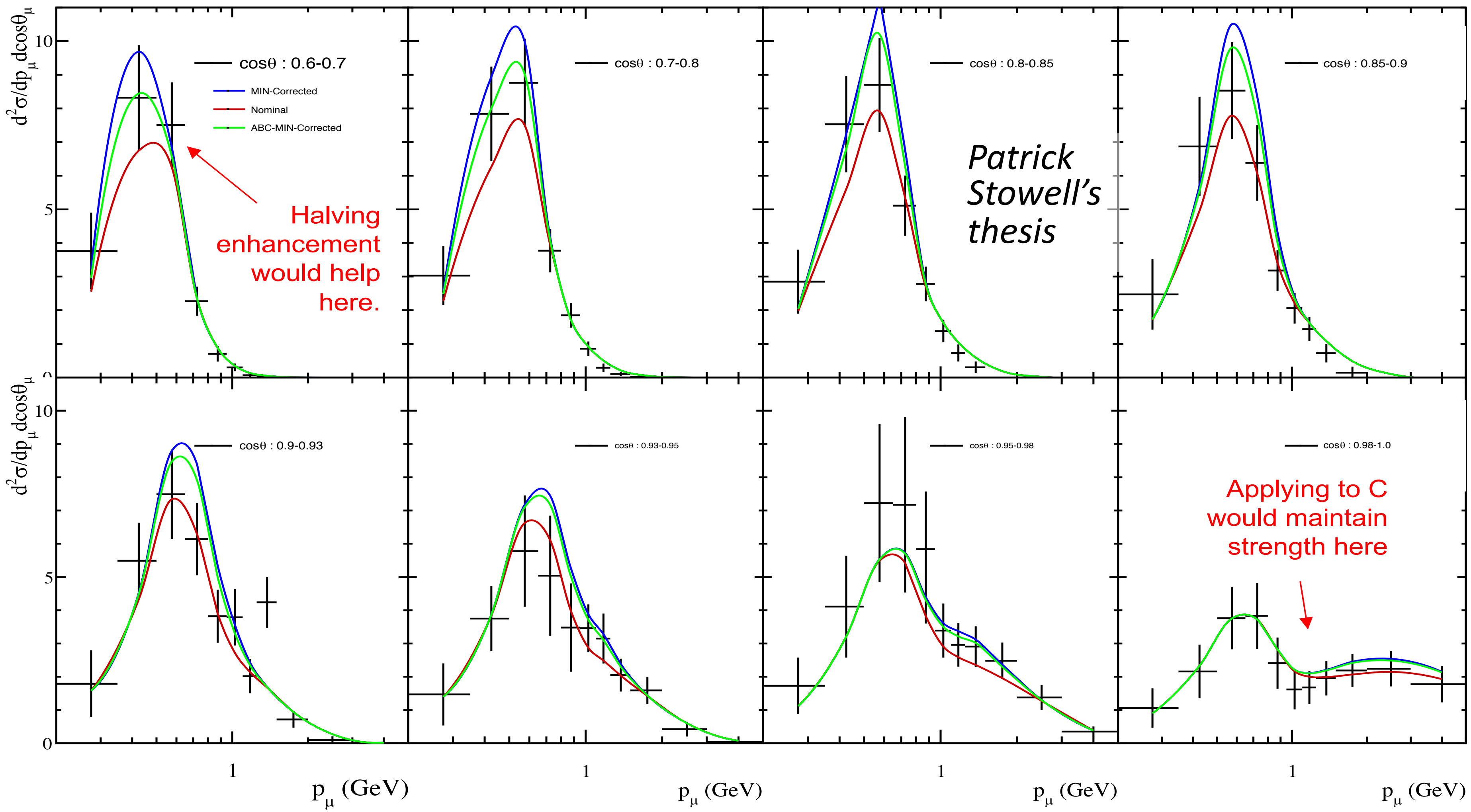
An expansion similar to eq. (2.5) holds for $\sum\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

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

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

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

Apply to T2K C term for CC0π



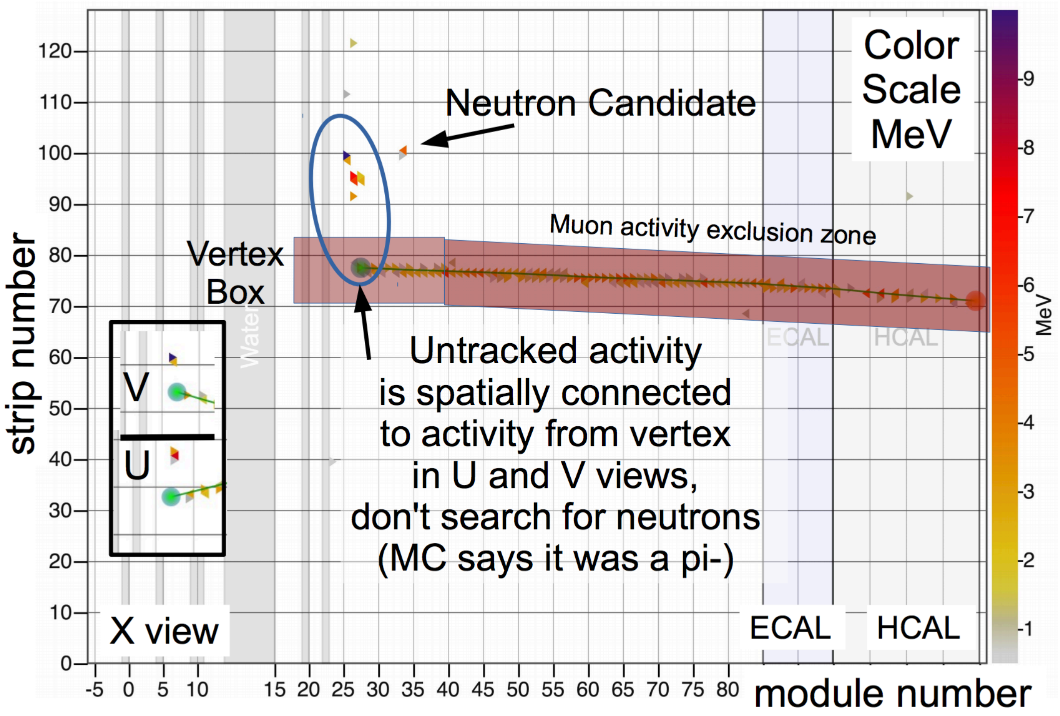
Scaled MINERvA tune, compared to data from Phys. Rev. D93, 112012 (2016)

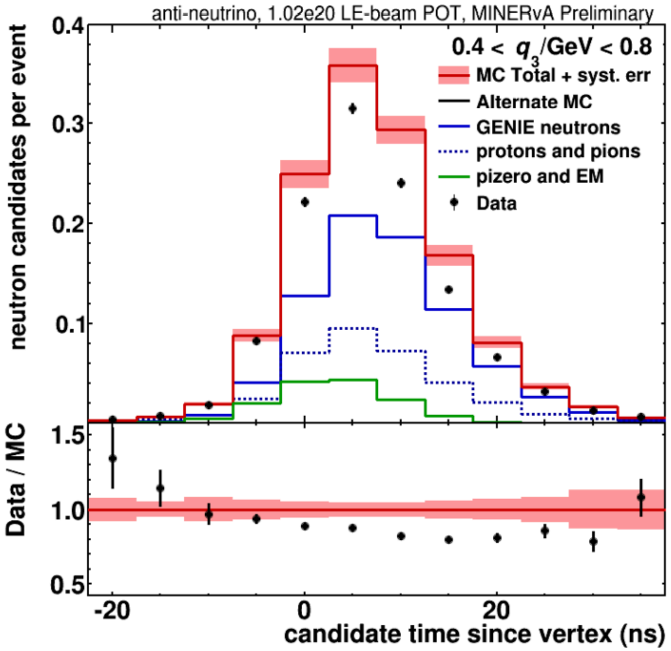
- Applying to the C term, as though this were the standard 1p1h interaction, get better agreement.
- However, without a model, we don't know energy dependence of this missing strength.

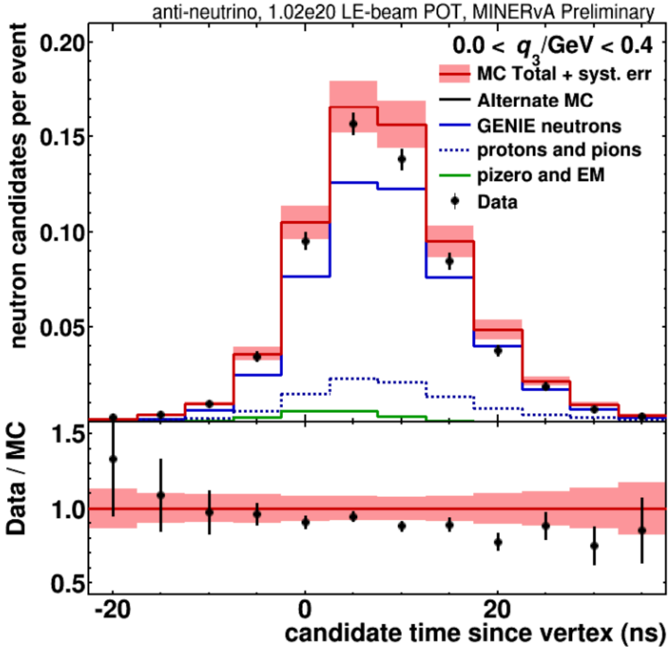
Backup: Neutrons

Neutron Production in Low Recoil $\bar{\nu}$

- Finally, we can look at the numbers of neutrons as a function of momentum transfer.







- Agreement is not as pretty. See excess of low momentum candidates at high time.
- Likely neutron interaction model or low energy neutron production.

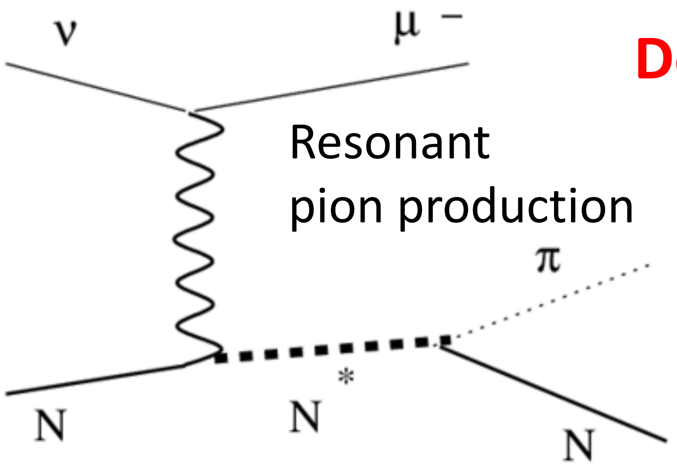
Backup: Pions

How do we produce single pions?

(Let us count the ways.)

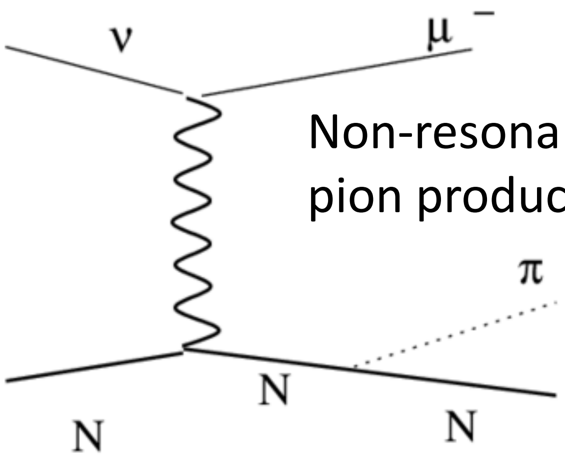
- Many competing production mechanisms.

Dominant



Resonant pion production

Interference may be large effect

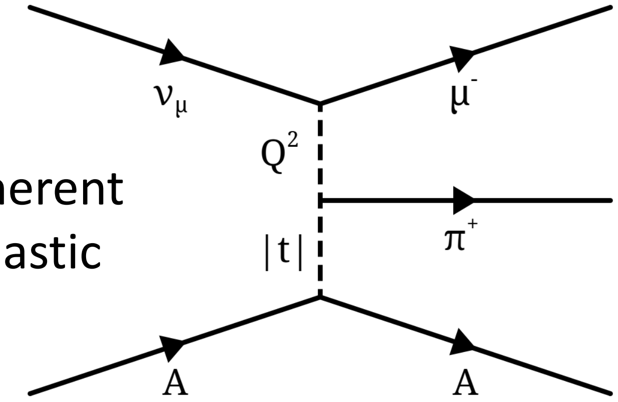


Non-resonant pion production

Significant

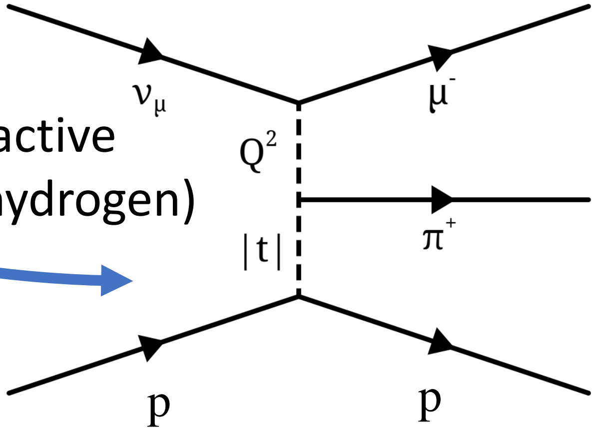
Interference at low Q^2 on hydrogen

Coherent inelastic



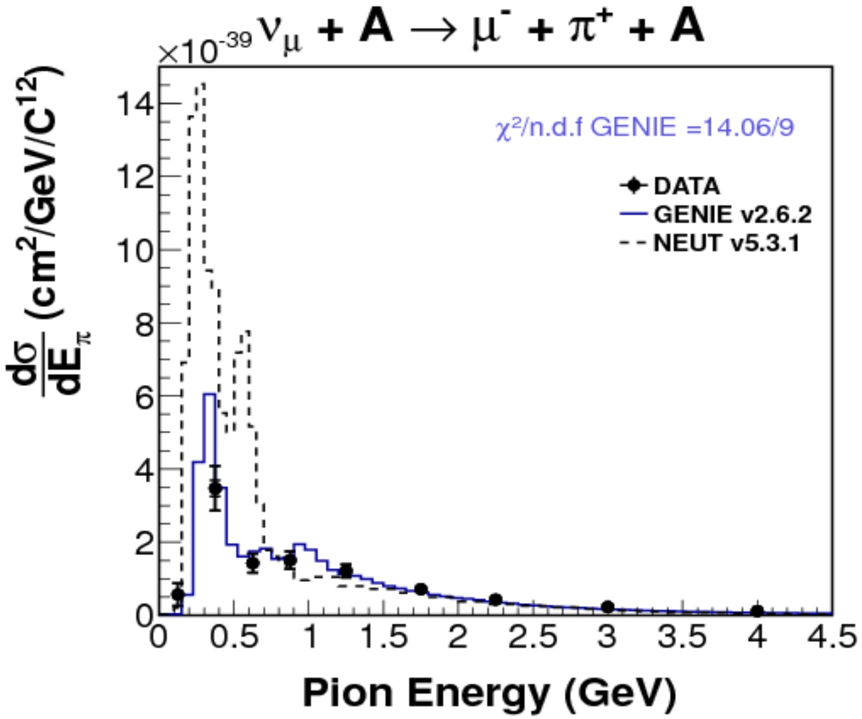
Sub-leading

Diffractive (on hydrogen)

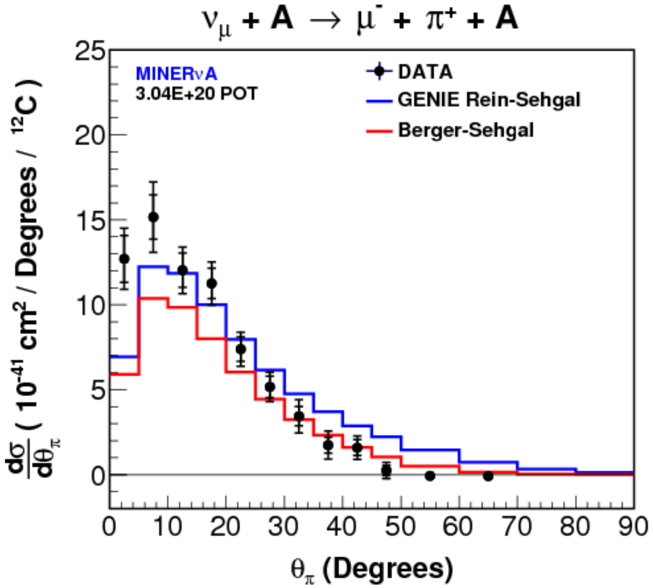


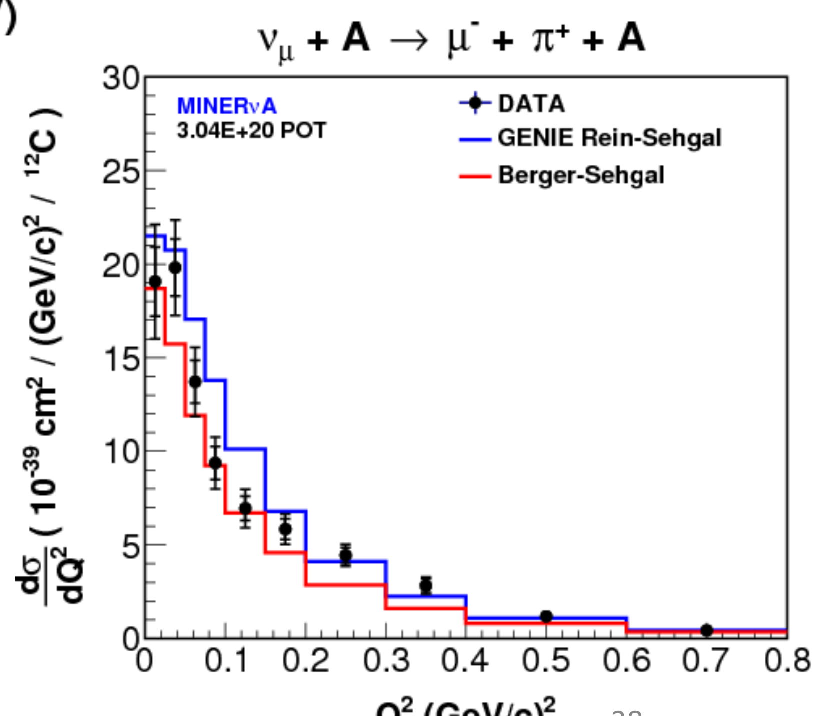
Coherent pion production

- Our coherent pion production results show some preference for Berger-Sehgal rather than GENIE's Rein-Sehgal prediction.
    - NEUT R-S prediction was poor at low pion energy.
    - T2K fixed this after MINERvA's results.



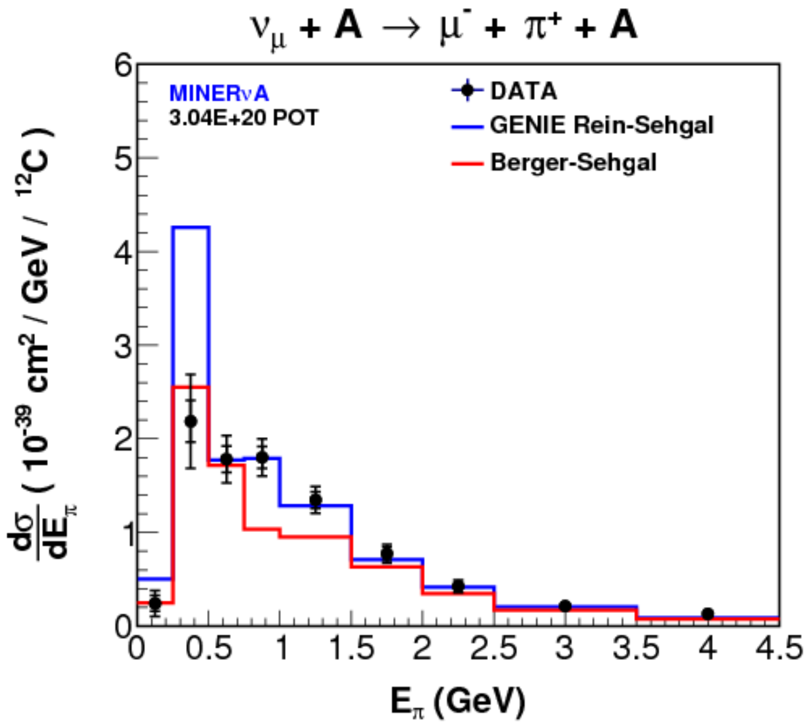
Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802



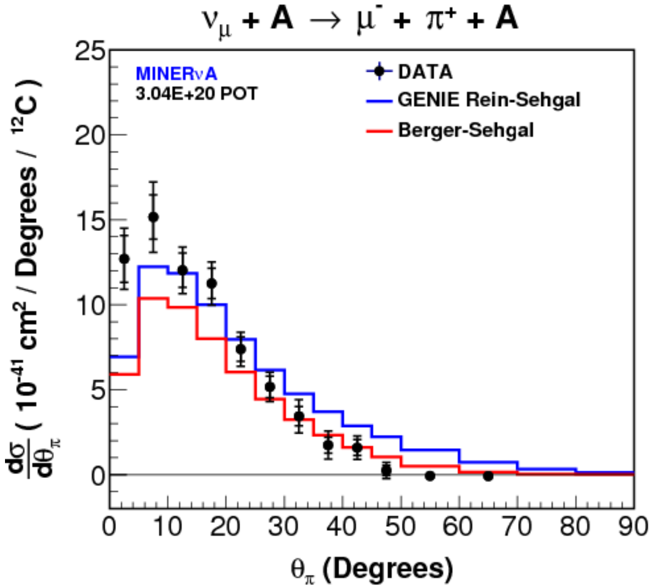


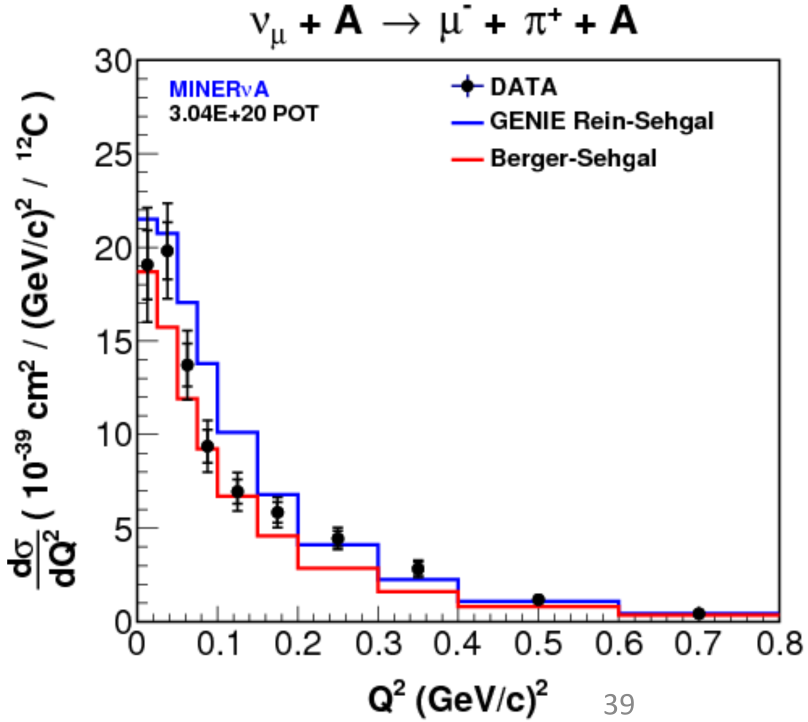
Coherent pion production

- Our coherent pion production results show some preference for Berger-Sehgal rather than GENIE's Rein-Sehgal prediction.
- Berger-Sehgal has been implemented in GENIE.
- MINERvA adds tunes in comparison to pion production with a coherent component.

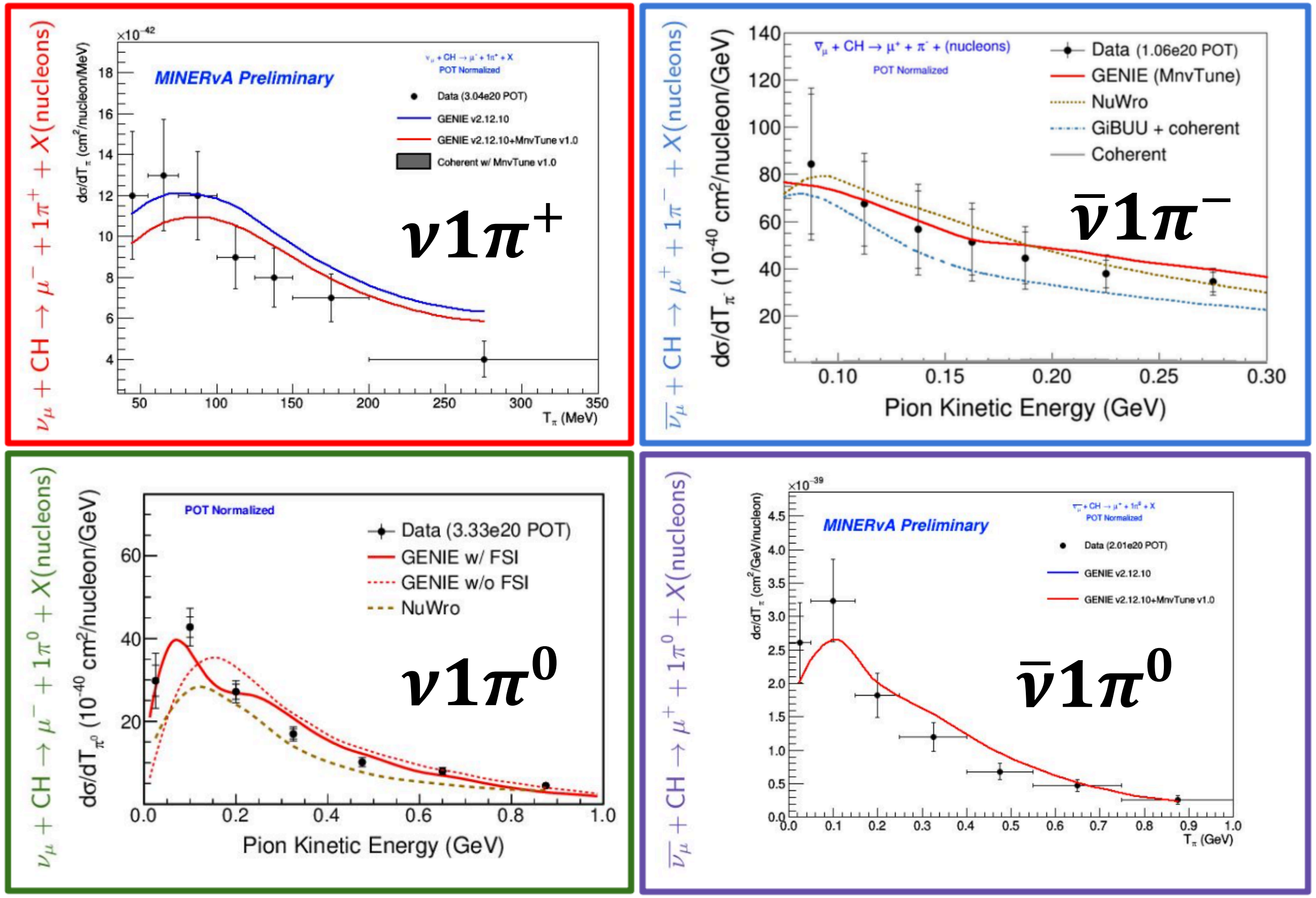


Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802





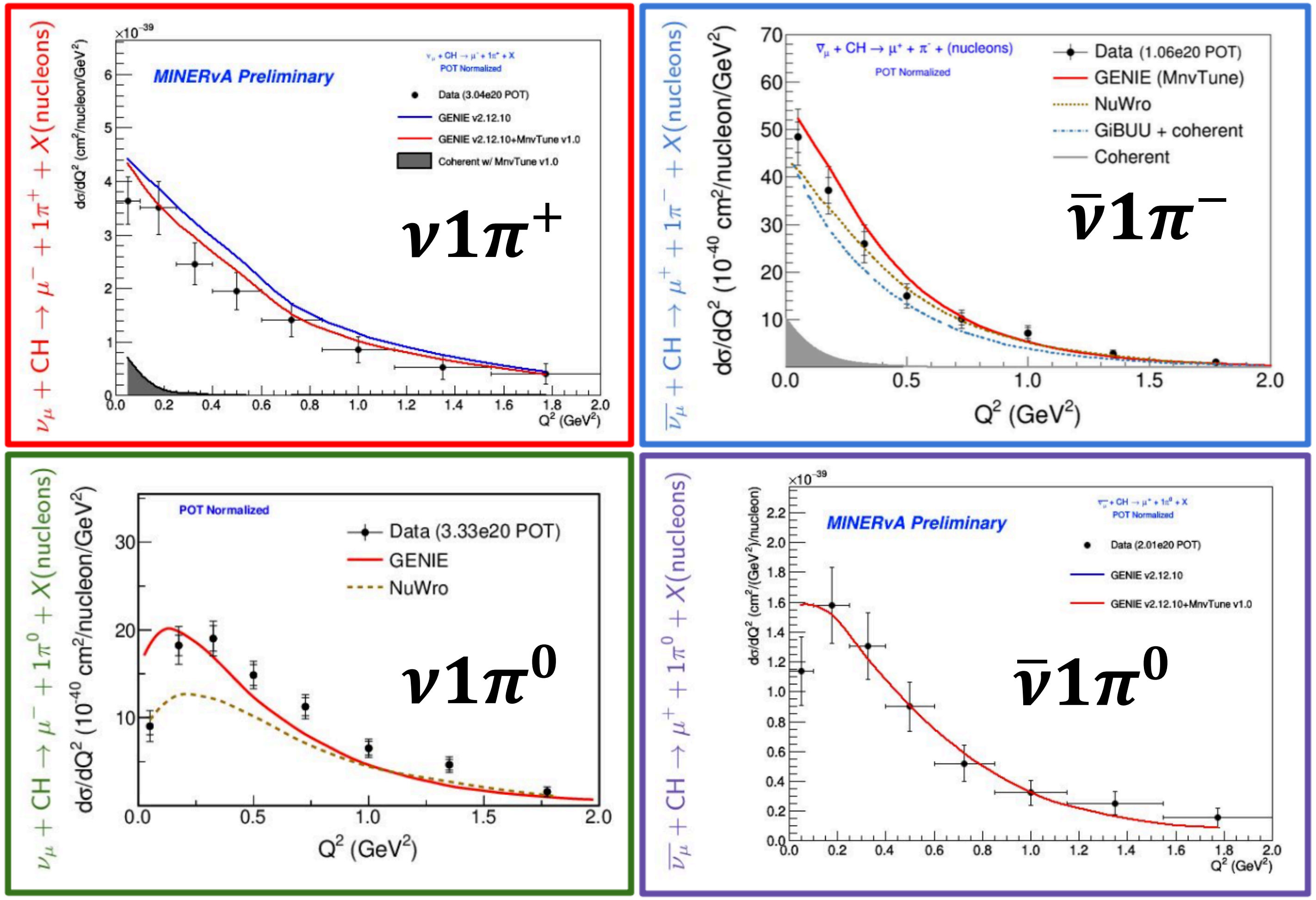
MINERvA's Four Charged-Current Single Pion Channels: T_π



Pion Kinetic Energy (GeV)

- Generally adequate description from MINERvA tuned GENIE 2.12.x
- Some tendency for more strength at lower energies
- Maybe consistent with shift of Δ? Maybe consistent with FSI alteration?

MINERvA's Four Charged-Current Single Pion Channels: Q^2

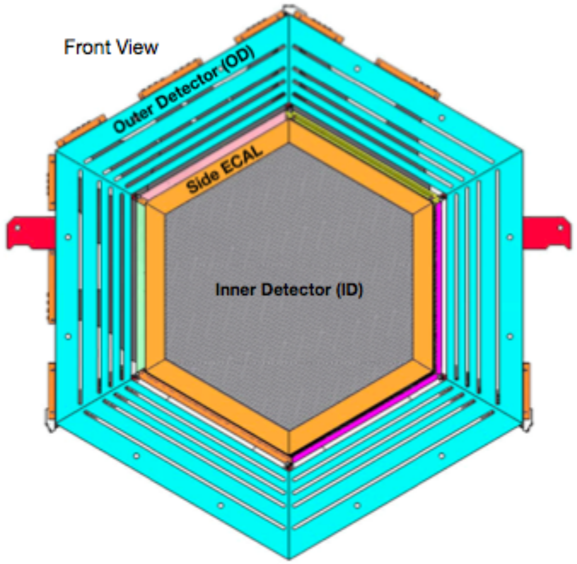


$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_{\mu\nu}\right) - m_\mu^2 \quad (\text{GeV}^2/\text{c}^2)$$

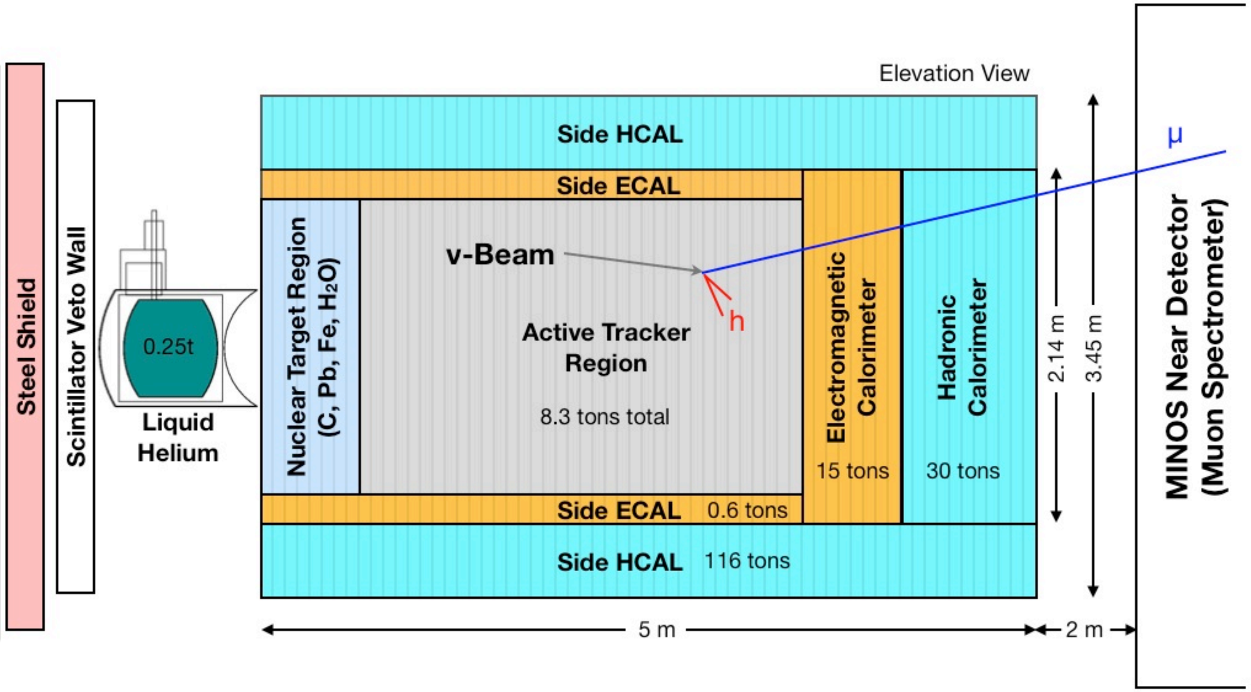
- Neutral pion production shows strong low Q^2 suppression
- Unknown nuclear effect?
- Charged pion final states have a coherent contribution included, but diffractive production from hydrogen in MINERvA unsimulated.

Backup: Detector

Detector



3 orientations
0°, +60°, −60°

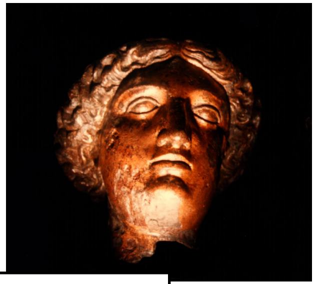


Detector comprised of **120 "modules"** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

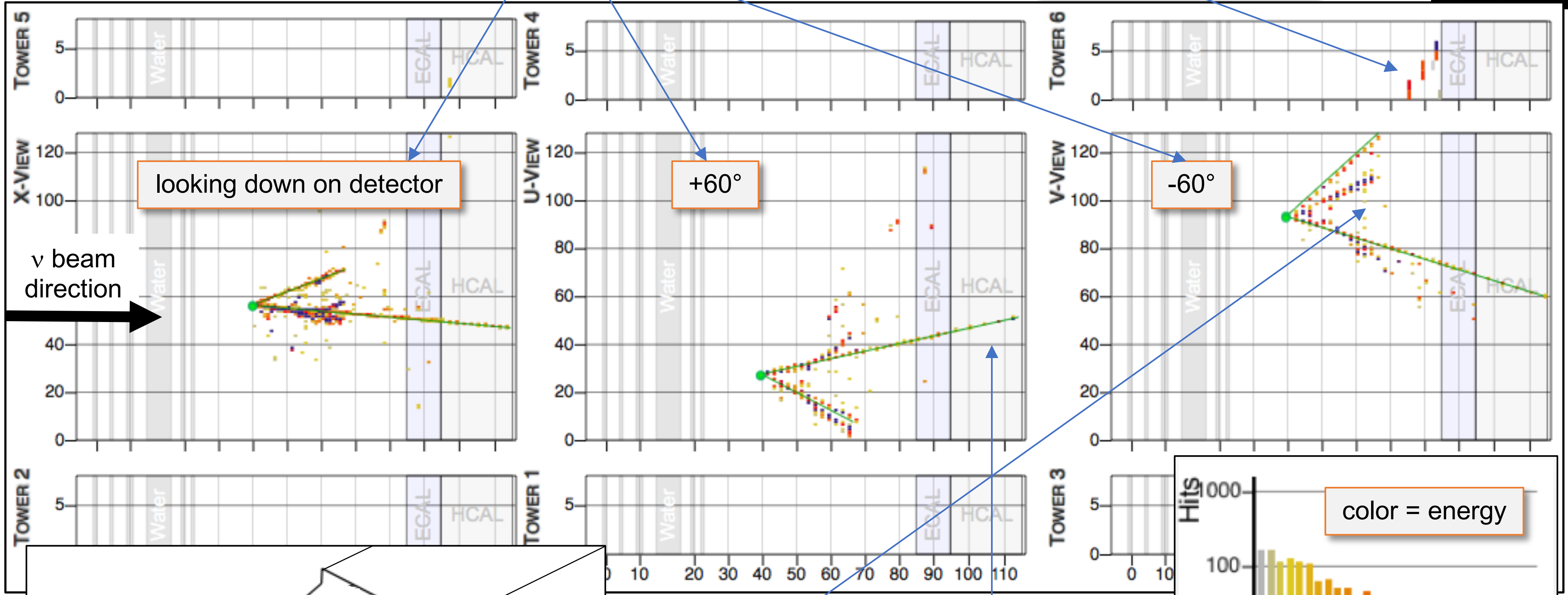
~32k plastic scintillator strip channels total

Events in MINERvA



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

Particle leaves the inner detector, stops in outer iron calorimeter

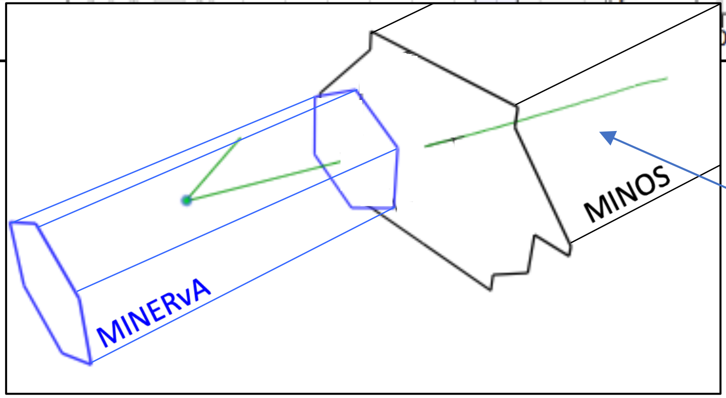


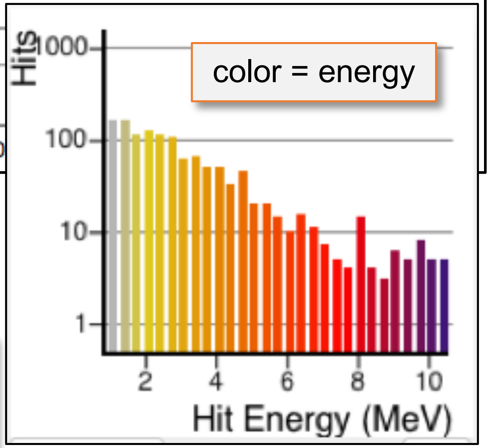
looking down on detector

+60°

-60°

ν beam direction



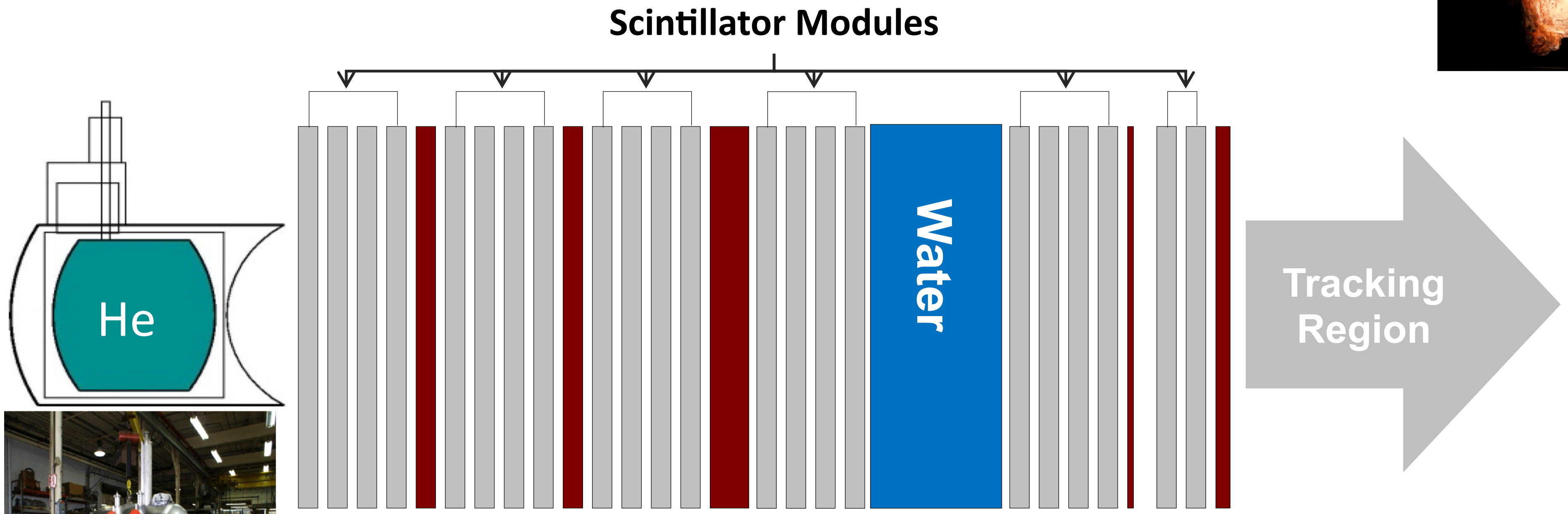


color = energy

Stops in Scintillator, best hadron particle ID

Muon leaves the back of the detector headed toward MINOS

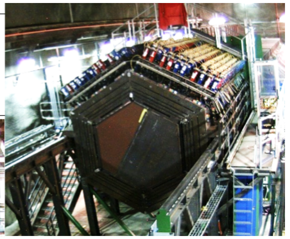
Passive Nuclear Targets



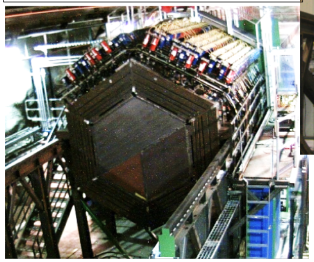
250 kg Liquid He

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

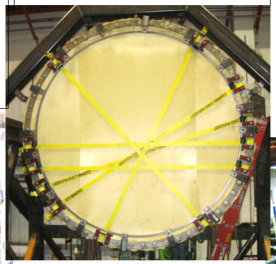
1" Pb / 1" Fe
266kg / 323kg



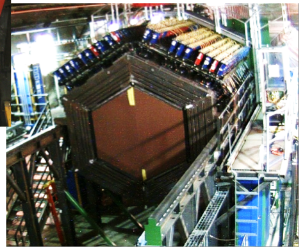
3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg



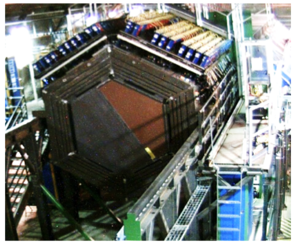
6" 500kg Water



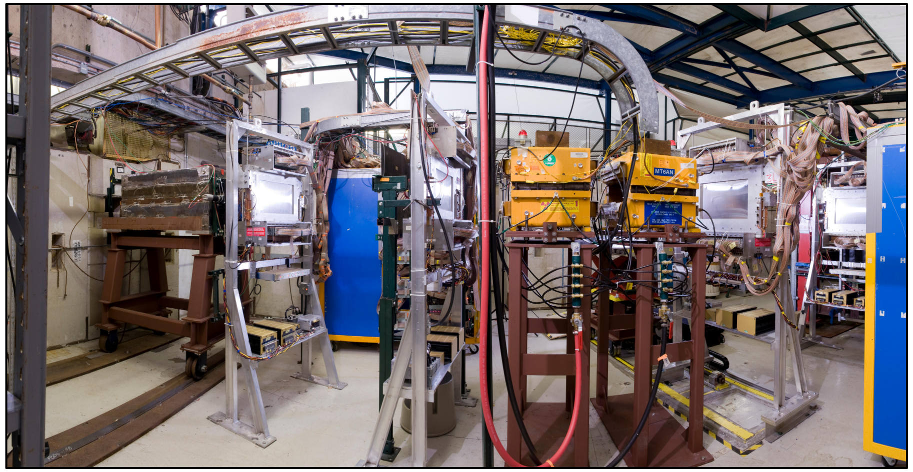
0.3" Pb
228kg

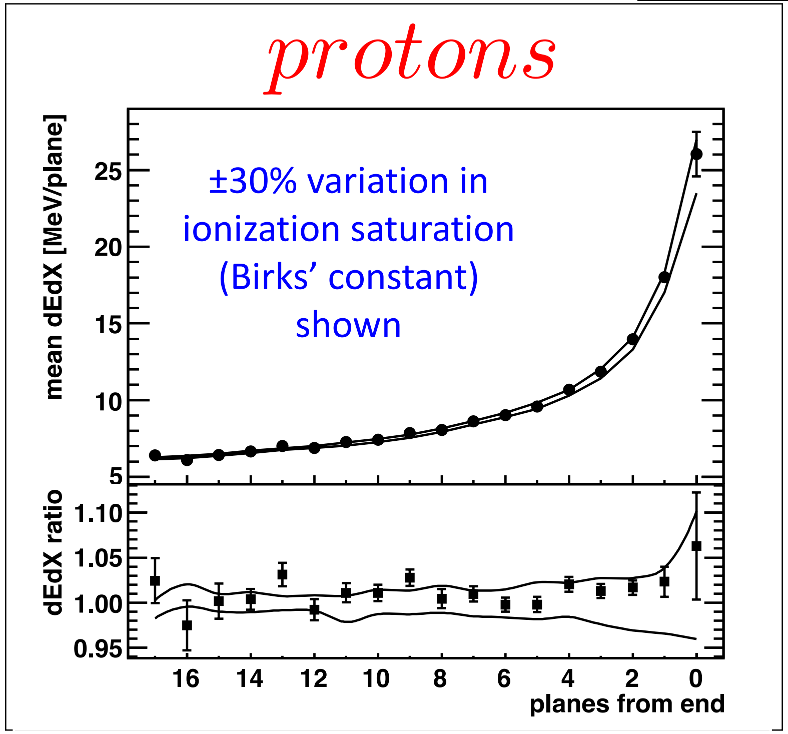


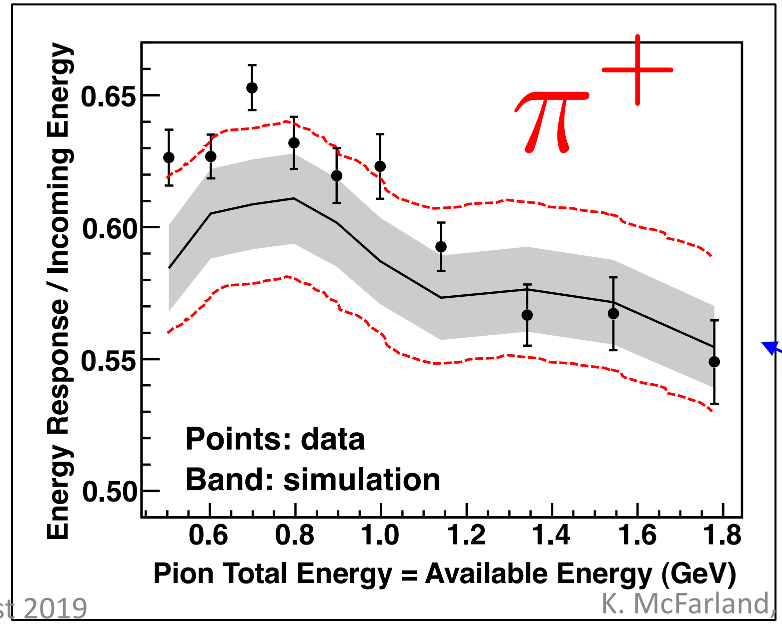
.5" Fe / .5" Pb
161kg/ 135kg



Hadron Testbeam



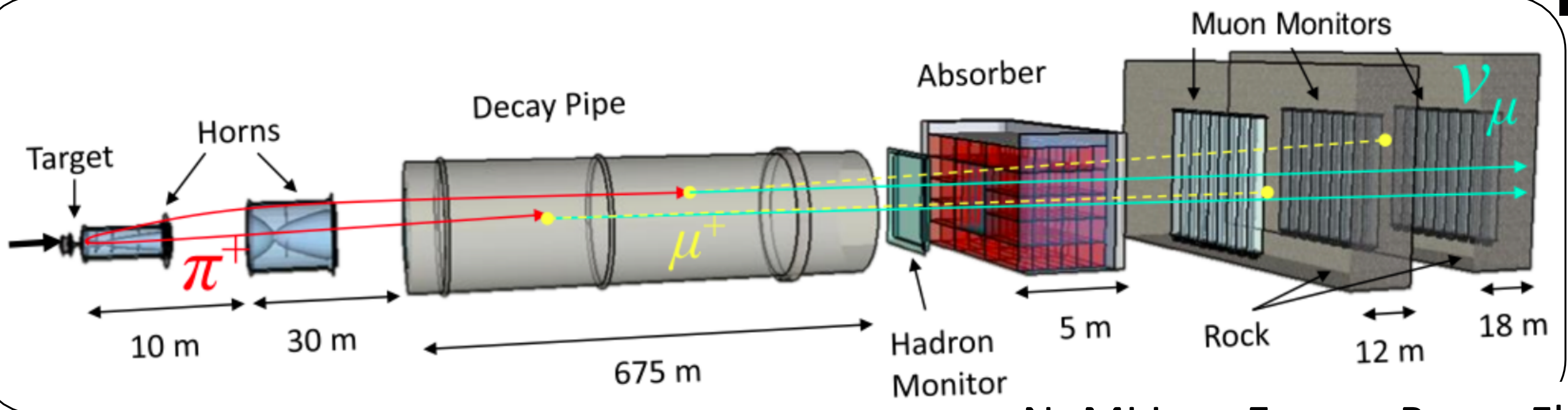




high-energy charged pion response uncertainty ≈ 5% (before tuning hadron interactions in detector)

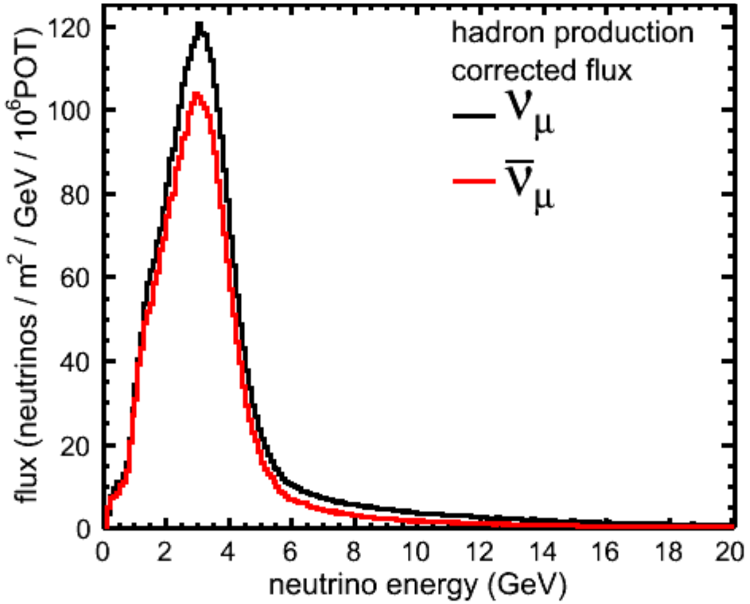
Backup: Flux and Beam

The NuMI Beam

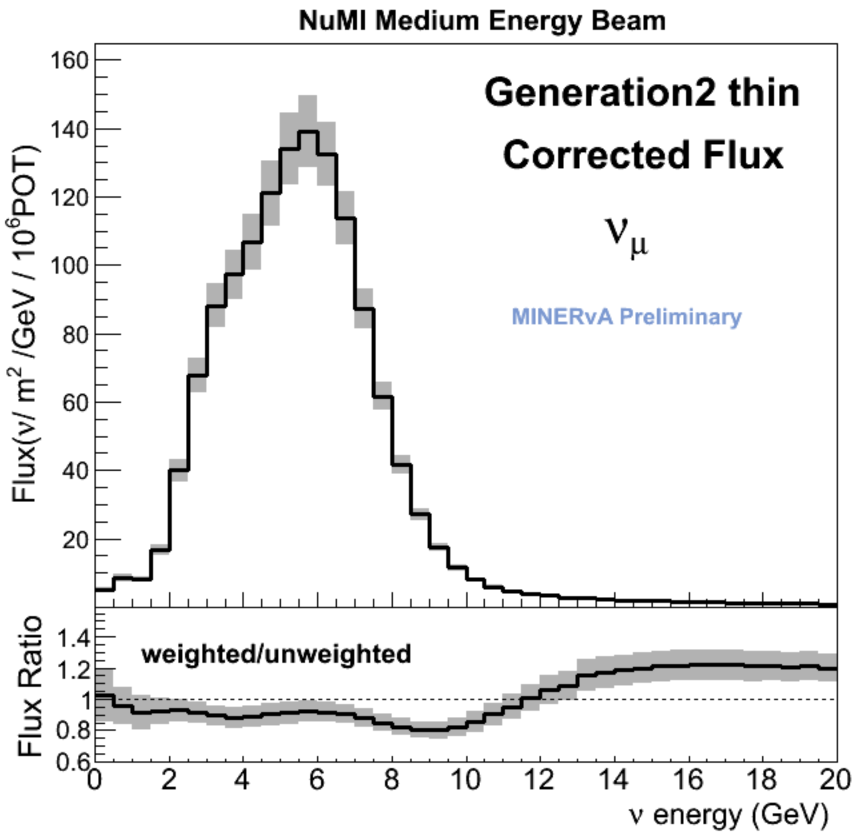


- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions
- Implies significant uncertainties in flux from hadron production and focusing
- Constrain, where possible, with hadron production data

NuMI Low Energy Beam Flux

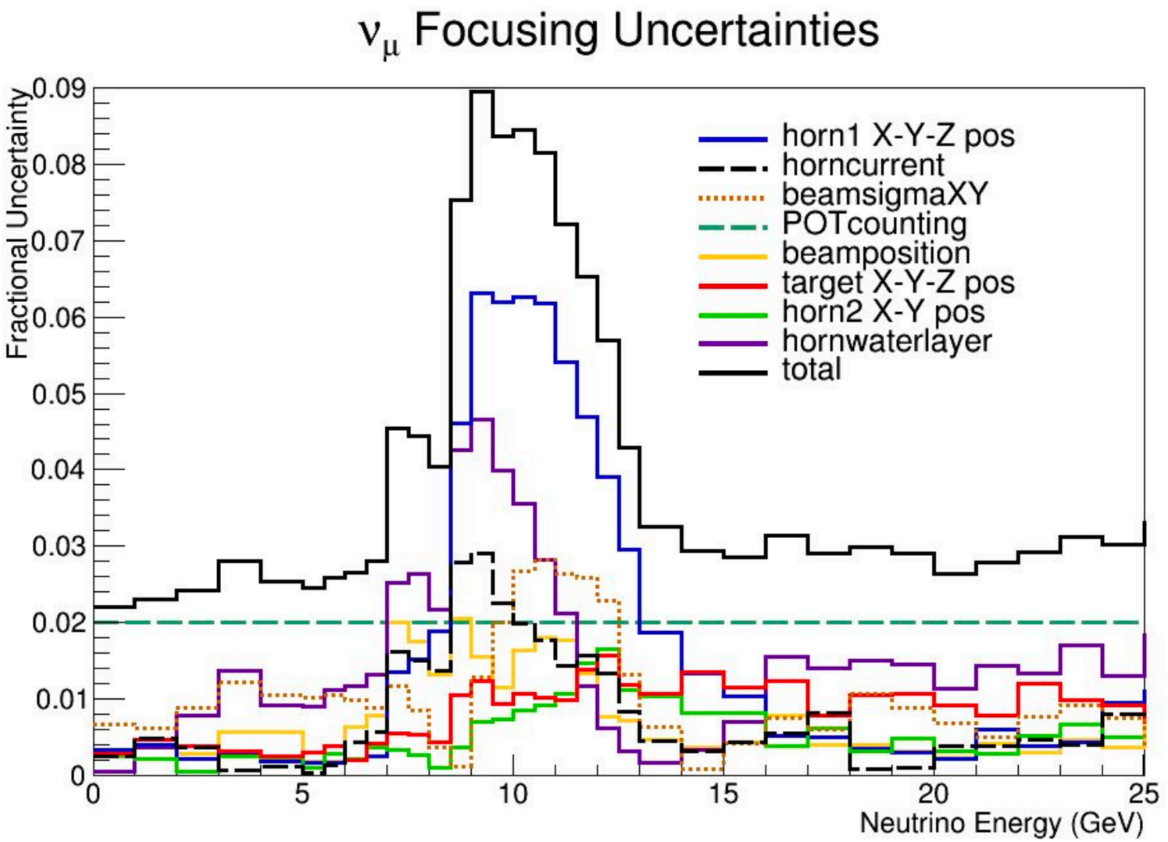


Medium Energy Flux for MINERvA:



- Hadron production and detailed beamline geometry is simulated using GEANT4
- Corrects GEANT4 predicted hadron production using world hadron production data
- Thin target (NA49) dataset used for constraining hadron production in target

Medium Energy Focusing Uncertainties:

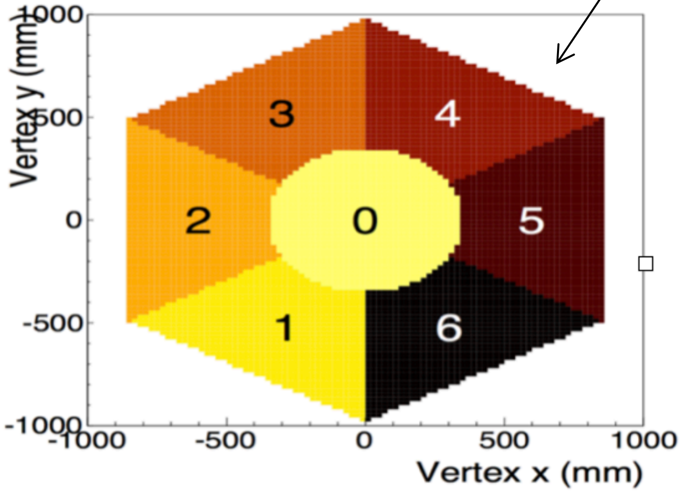


Flux Fit with focusing Parameters

Approach:

Problem in Flux Prediction: Possibly mismodeling of NuMI Focusing system

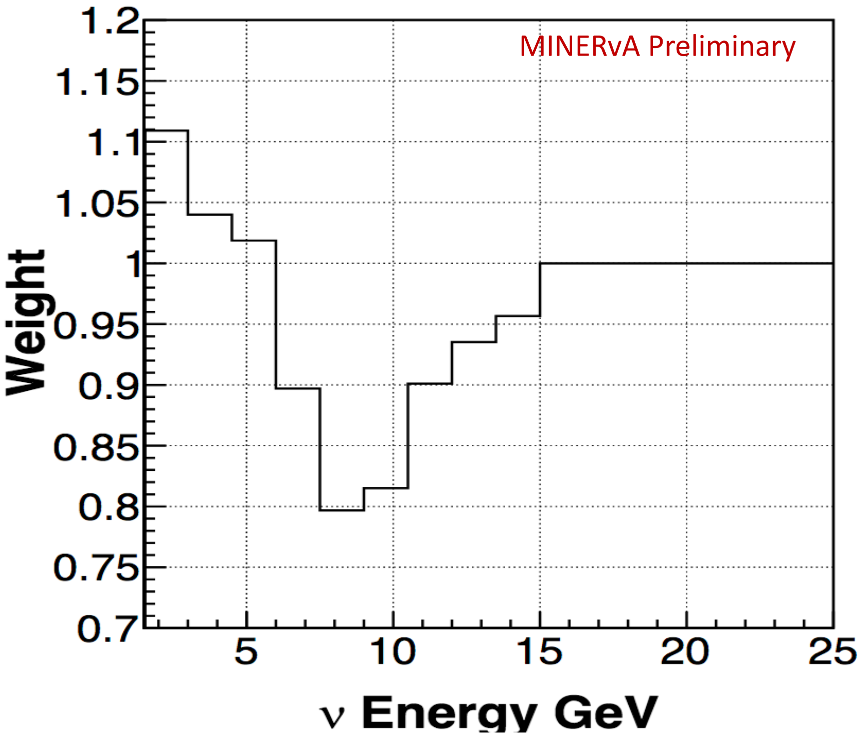
- Fit low nu MC to data by varying the focusing parameters and (look at the shifted parameters to understand the discrepancy)
- Shifting of a focusing parameter, by some amount do not produce uniform effect across the lateral face of the detector. Fit in different ***daisy bins*** of MINERvA detector and merge them later

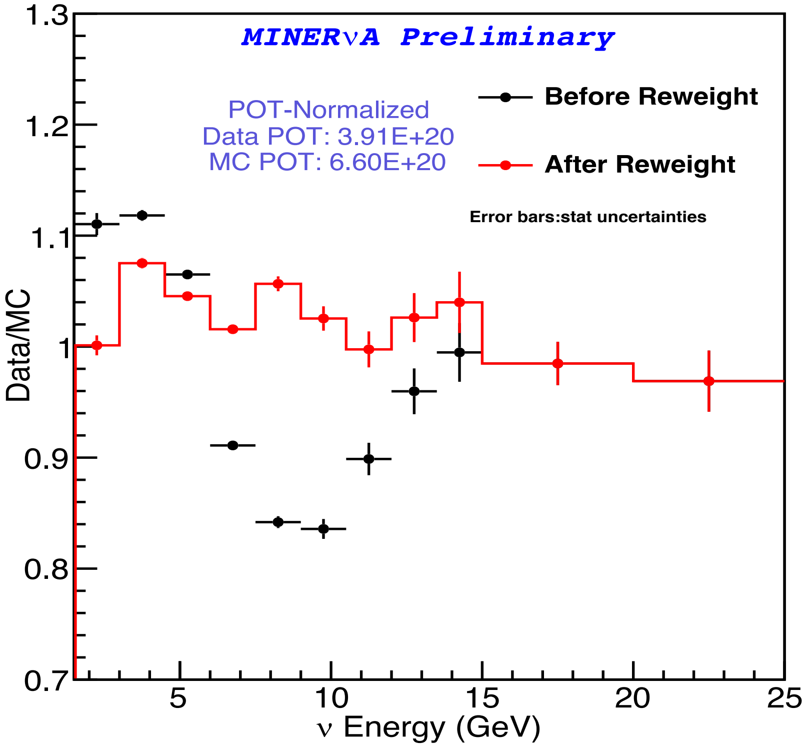


Parameter	Nominal Value	New Value	Sigma Value
Beam Position (X)	0 mm	-0.2±0.12 mm	1 mm
Beam Position (Y)	0 mm	-0.53±0.14 mm	1 mm
Beam Spot Size	1.5 mm	1.22±0.07 mm	0.3 mm
Horn Water Layer	1 mm	0.895±0.16 mm	0.5 mm
Horncurrent	200 kA	197.41±0.76 kA	1 kA
Horn1 Position (X)	0 mm	0±0.17 mm	1 mm
Horn1 Position (Y)	0 mm	-0.39±0.17 mm	1 mm
Target Position (X)	0 mm	-0.32±0.17 mm	1 mm
Target Position (Y)	0 mm	1.65±0.5 mm	1 mm
Target Position (Z)	-1433 mm	-1419.44±1.83 mm	3 mm

Flux Fit

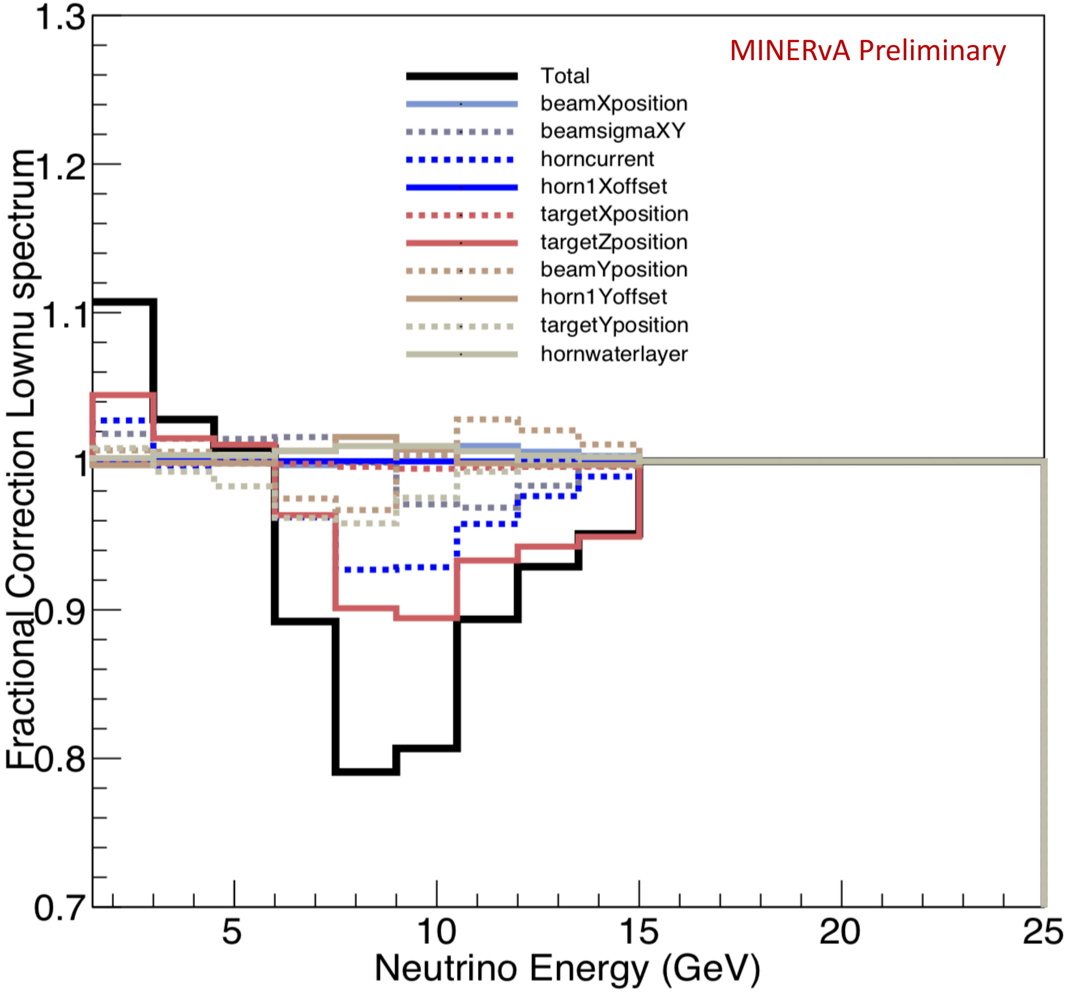
- Returns a weight function which is the function of shifted focusing parameters returned by the
- It seems to fix the wiggle problem. But this causes really large shift in target longitudinal positi
  and horn current.





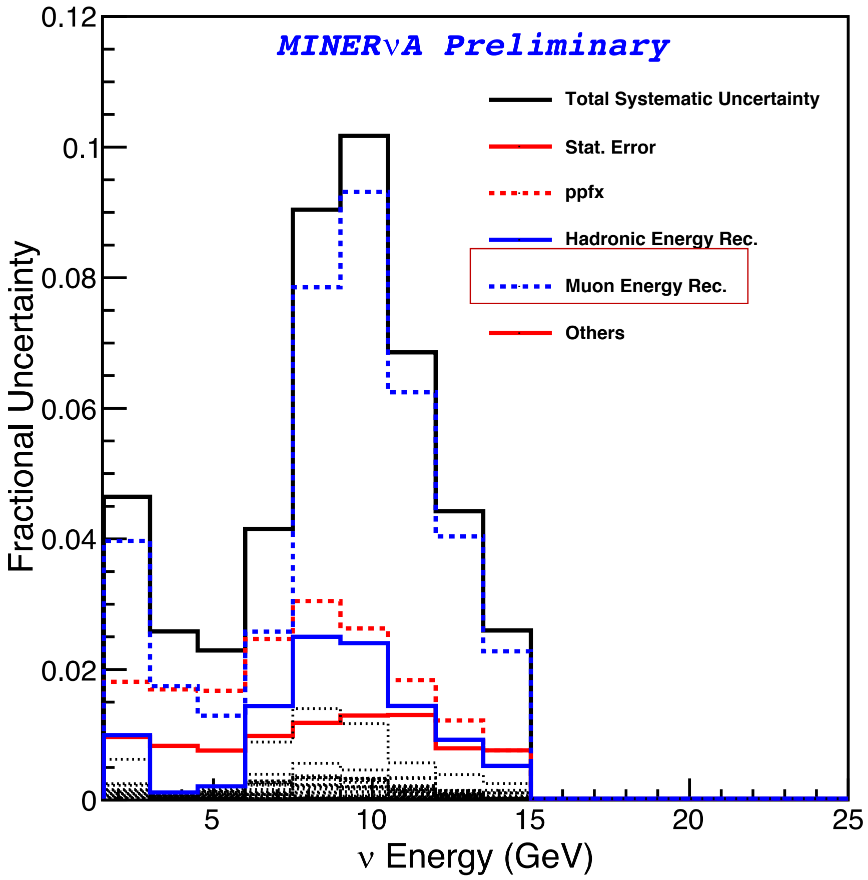
Flux Fit with Focusing Parameters

Decomposed the correction returned by the fit into various components and observe that shift in *TargetZ* and *Horn Current* are major contributors of overall correction

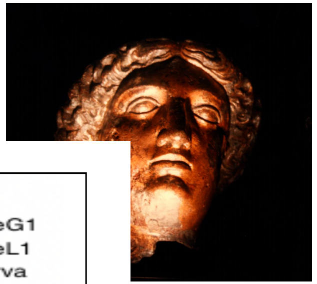


Uncertainties on Flux Fit

- Uncertainty on Flux fit as we vary MINERvA Systematics comes mainly from Muon Energy Reconstruction Systematics.
- At the falling edge of focusing peak, the change in flux is around 9%. This means 1 sigma change in muon energy means 9% change in the flux.
- Data/MC discrepancy at the peak value. Motivated us towards studying a what 2 sigma shift in Muon Energy Reconstruction would do.
- The study showed that shifting the Muon Energy Scale by -2 Sigma would almost follow the shape of the wiggle.
- Add the muon energy scale as a fitting parameter that can float and one can see the correlations among the parameters



Introducing the Muon Energy Scale as fit parameters



For the purpose of fitting:

MINOS Range

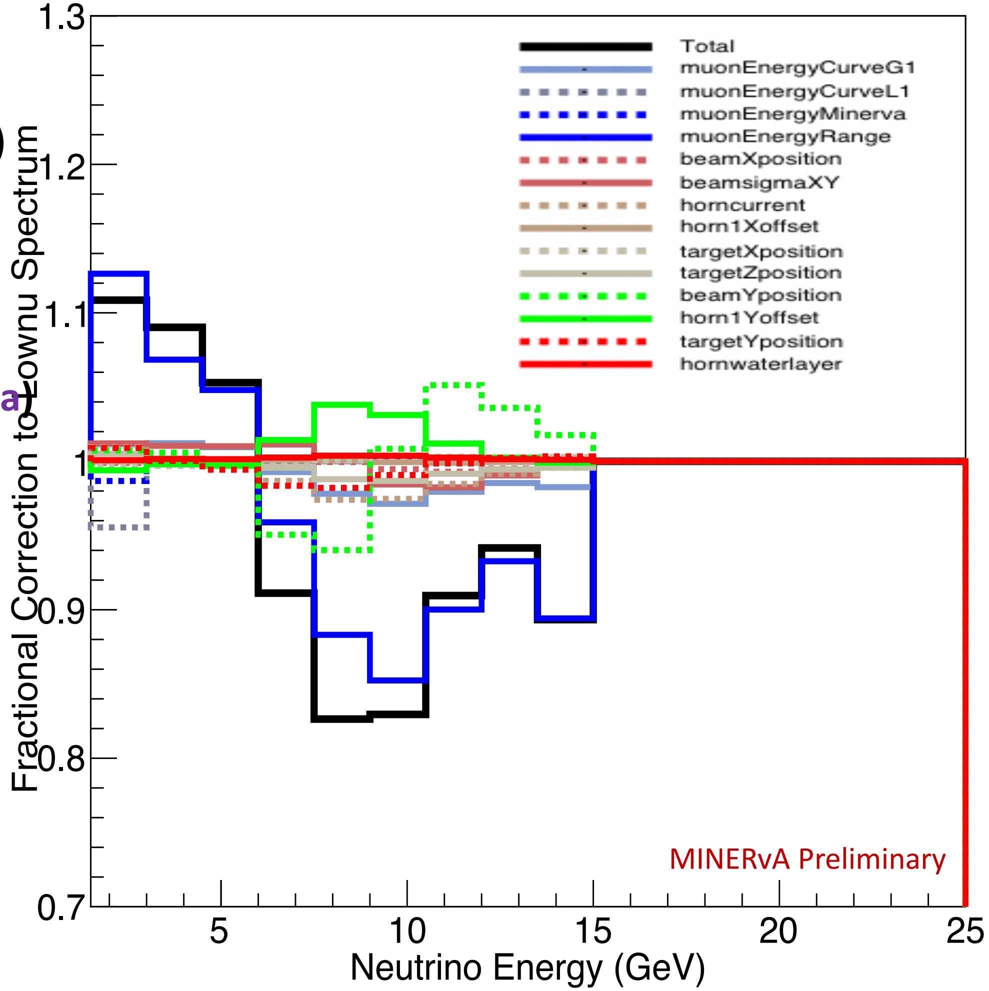
- **1 parameter (MuonEnergyRange)**

MINOS Curvature

- **MuonEnergyCurveG1**
- **MuonEnergyCurveL1**

MINERvA Systematics

- **1 Parameter(MuonEnergyMinerva)**

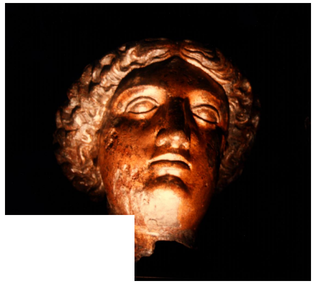


The effect of the parameter changes on the low nu prediction is shown at left.

Muon Energy Range is the biggest contributor !

This analysis uses data from the MINOS detector, but it is not endorsed by the MINOS+ collaboration.

Best Fit Values:

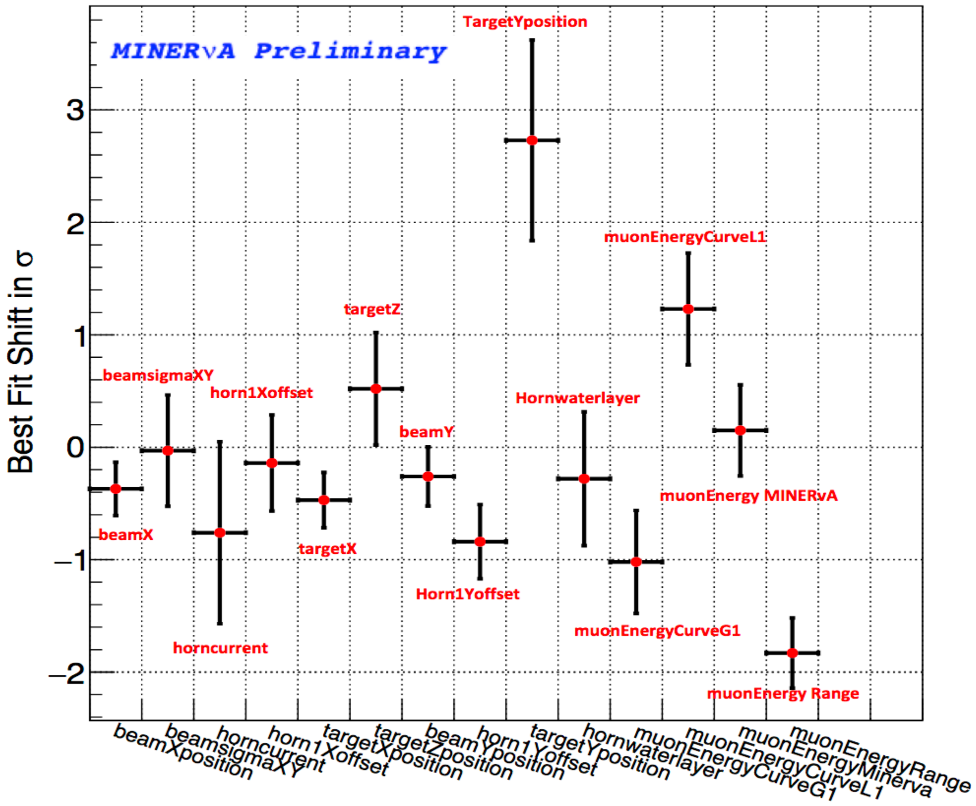


Re-do the fit by putting Muon energy scale as fit parameters along with focusing parameters.

- When we add four muon energy scale parameters to the fit, all of the focusing parameter best fit values are within their standard uncertainties, except for target y position.

- We believe the pull of the target y position is trying to fix a small up/down asymmetry in the daisy bins, and *we are investigating further.* The effect of the target y shift on the flux averaged over MINERvA is very small

- The parameter with the biggest effect on data/MC agreement is the muonEnergy Range parameter, which is pulled by 1.8 sigma



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