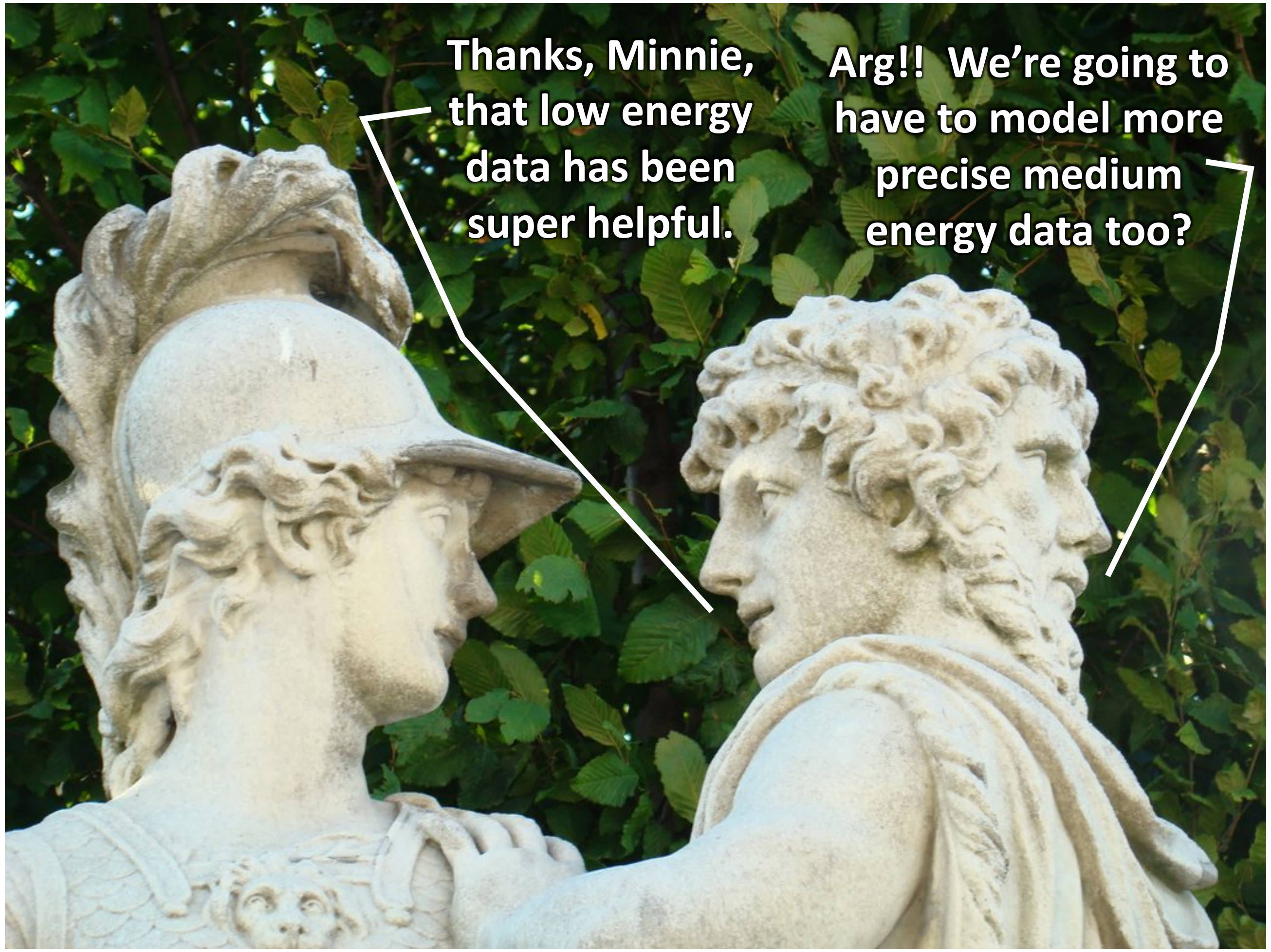
Learning about Neutrino Interactions from MINERvA: retrospect and outlook

Kevin McFarland
University of Rochester

9 November 2018

Fermilab Joint Experimental-Theoretical Seminar

Retrospect and Outlook



- MINERvA is NuMI's neutrino interaction experient
  - Targets of He, CH, C, H_2O, Fe, Pb. $1.5 < E_\nu < 12$ GeV neutrinos
- "Retrospect" discussed here is low energy run, $\langle E_\nu \rangle$~3 GeV
- "Outlook" is to higher statistics data taken concurrently with NOvA that are just beginning to appear.
  - Statistics gain of 8 (low W) to 15 (high W) for ν, and factors of 20 to 40 in $\bar{\nu}$.

History of MINERvA

2002 — **2007** — **2010** — **2012** — **today**

MINERvA EOI
Scintillator tracker and passive targets, NuMI

Construction Start
Begin fiber, scintillator production.

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

1st Interaction Papers
CCQE in neutrino and antineutrino beams.

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

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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

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Implications of the Neutrino History

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

 

Atmospheric neutrino oscillations at Super-K

 

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NOvA $\overline{\nu_e}$ Appearance

2002 — 2007 — 2010 — 2012 — today

Neutrino Oscillations at GeV Accelerator Experiments

Sub-leading effects from solar oscillations possible

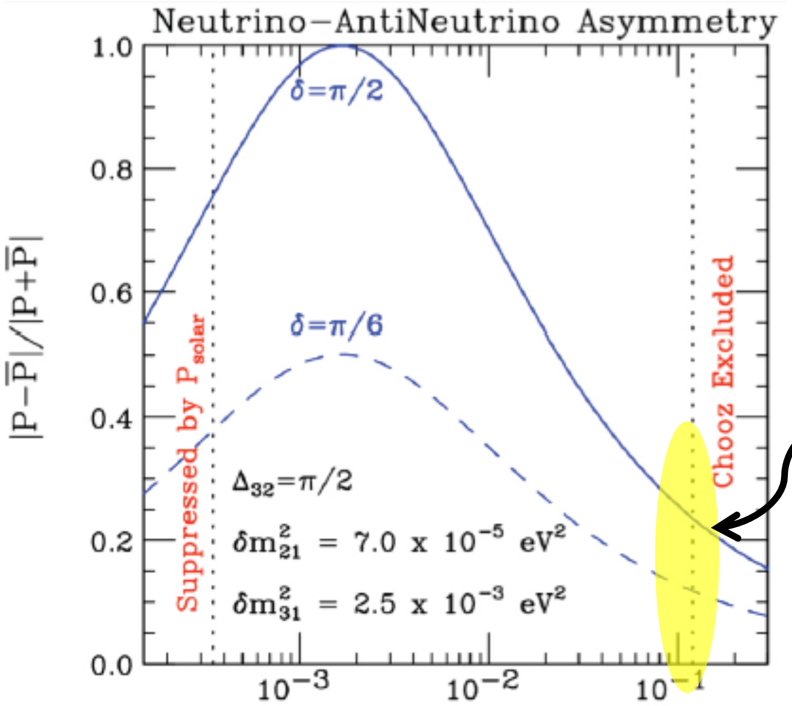
Δm^2_{23} well enough known to tune narrowband beam accelerator experiments

CP phase, δ, accessible in these experiments

Justification for DUNE and Hyper-K

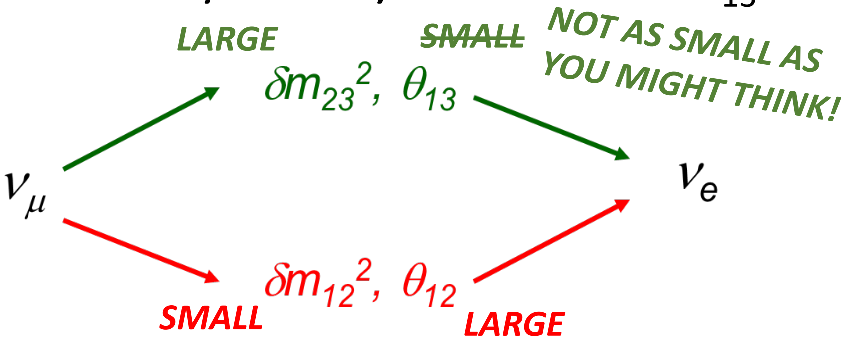
θ_{13} and Systematics

- 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)

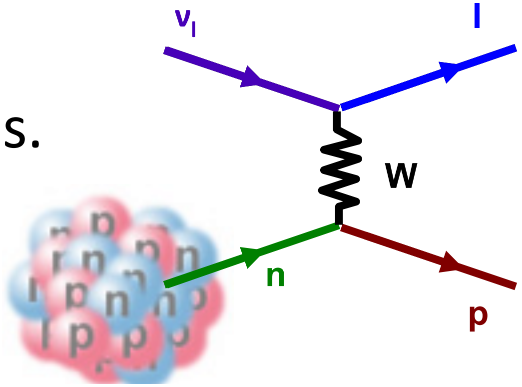
- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases



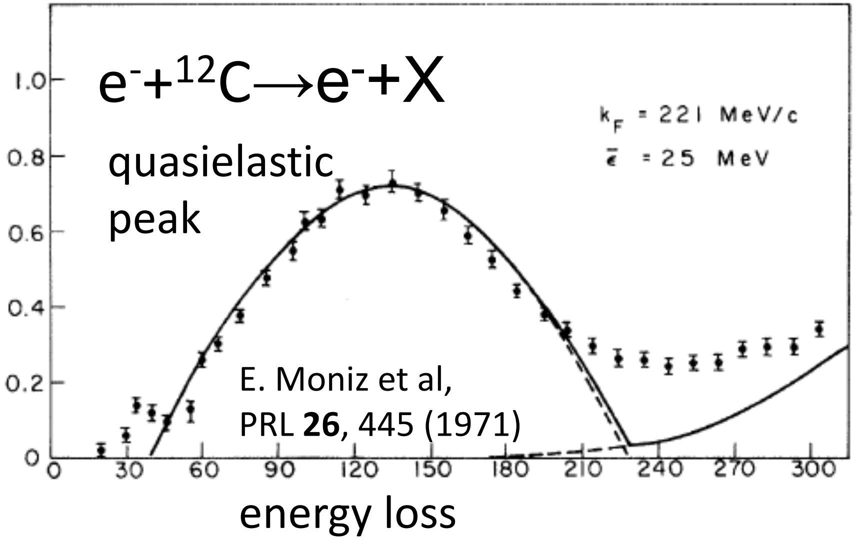
- Nature decided to put us here.
- Systematics on muon and electron neutrino signal reactions are important since we need high precision comparison of $\bar{\nu}$ and ν rates!

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)

- Oscillation experiments reconstruct neutrino energy from partial events, even in the most elastic events.
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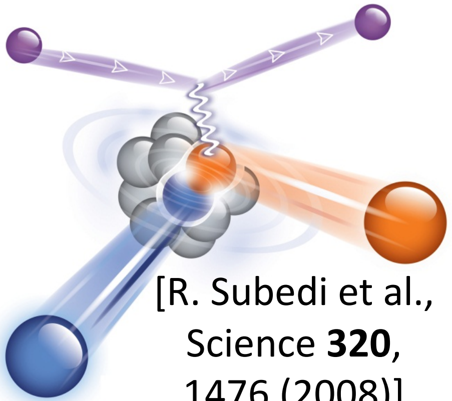
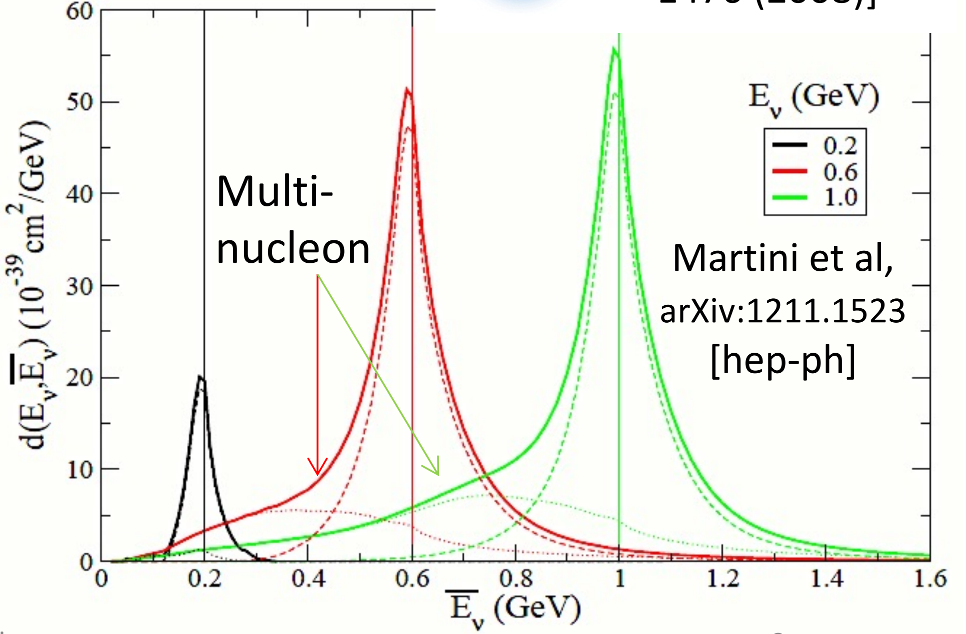


[R. Subedi et al., Science **320**, 1476 (2008)]

- 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?



MINERvA's story

- The MINERvA oeuvre✯ has found some "not awesome agreement"™ with GENIE out of the box within GENIE's uncertainties.
- MINERvA has developed a model tune in use today that better describes its own CH data than do untuned generators, based on
  - Theory and models implemented in GENIE 2.12.x → 3.0.x,
  - D_2 bubble chamber data,
  - MINERvA's own measurements.
- The tuned model allows MINERvA to more realistically assess uncertainties in its own measurements. It is also available for use by other experiments, such as neutrino oscillation experiments.
- MINERvA data also elucidates nuclear theory and model building, by agreement or disagreement with these models.

✯*say that ten times fast!*

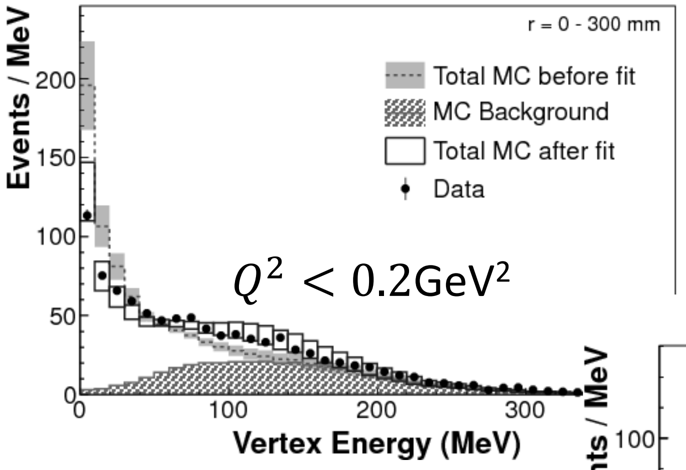
Some "not awesome agreement"™ in the most elastic events

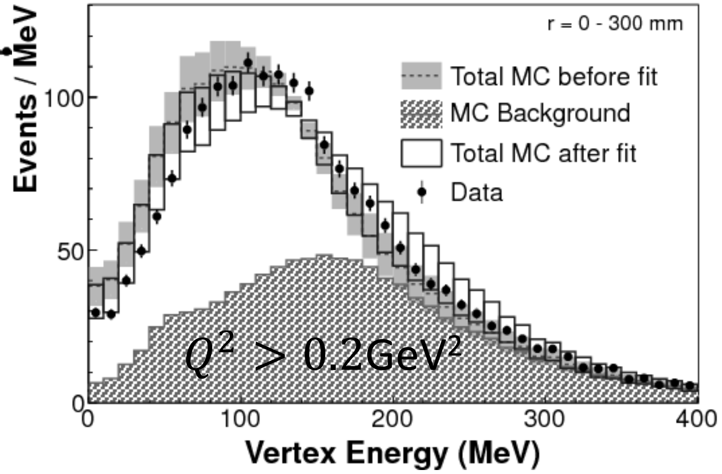
- Mostly results on scintillator
- Signs of even more trouble in heavier nuclei

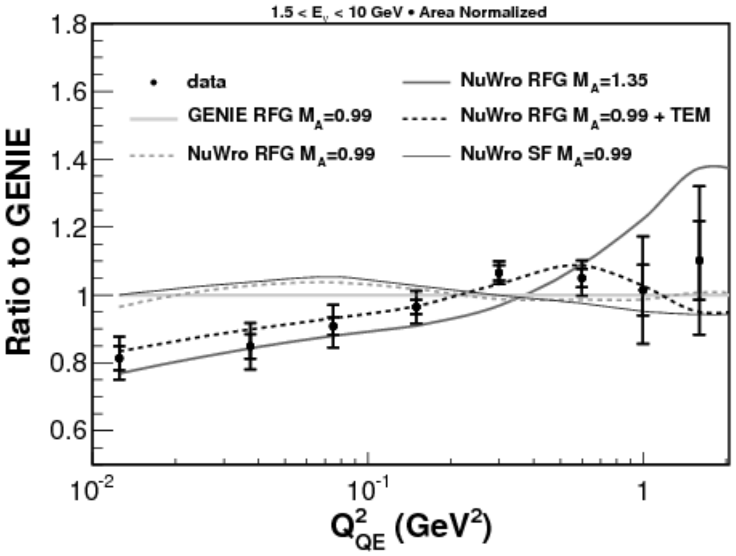
Vertex energy near the most elastic events

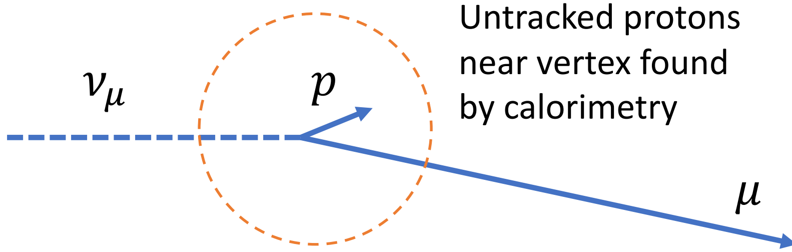
- MINERvA's first CCQE result found more vertex energy (from protons) for neutrinos, but good agreement for antineutrinos.
- ${d\sigma}/{dQ^2_{QE}}$ also showed better agreement with the "transverse enhancement" model of 2p2h.
- Suggests 2p2h processes.

Phys.Rev.Lett. 111 (2013) 022501
Phys.Rev.Lett. 111 (2013) 022502



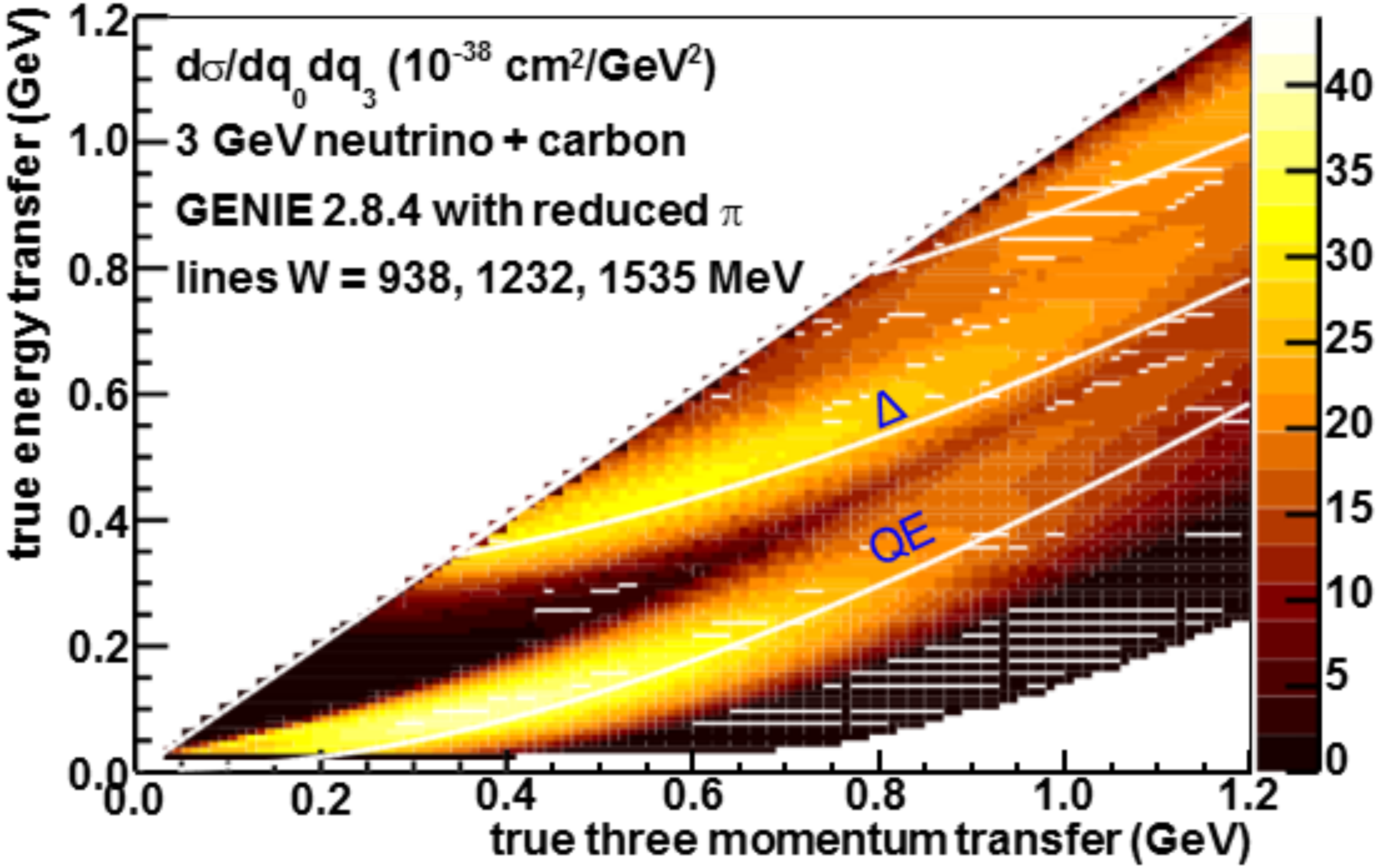




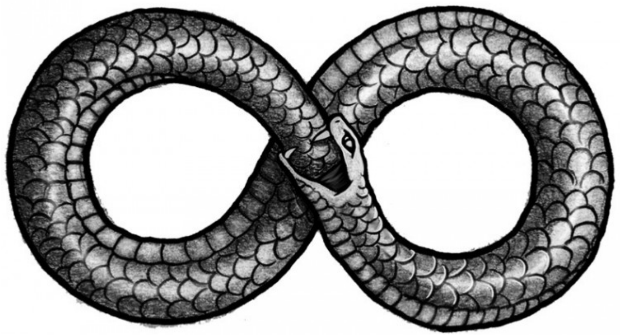


Untracked protons near vertex found by calorimetry

If we had a monochromatic neutrino beam, like electron scattering…



To do this in neutrino scattering, we have to use the final state observed energy since we don't know incoming neutrino energy.



Since we don't know neutrino energy…

- Must determine neutrino energy from the final state energy.
- If that is known,
  - Neutrino direction fixed
  - Outgoing lepton is well measured.

- *MINERvA uses calorimetry for all but the final state lepton*
  - *Don't measure energy transfer, q_0, but a related quantity dependent on the details of the final state, "available energy"*

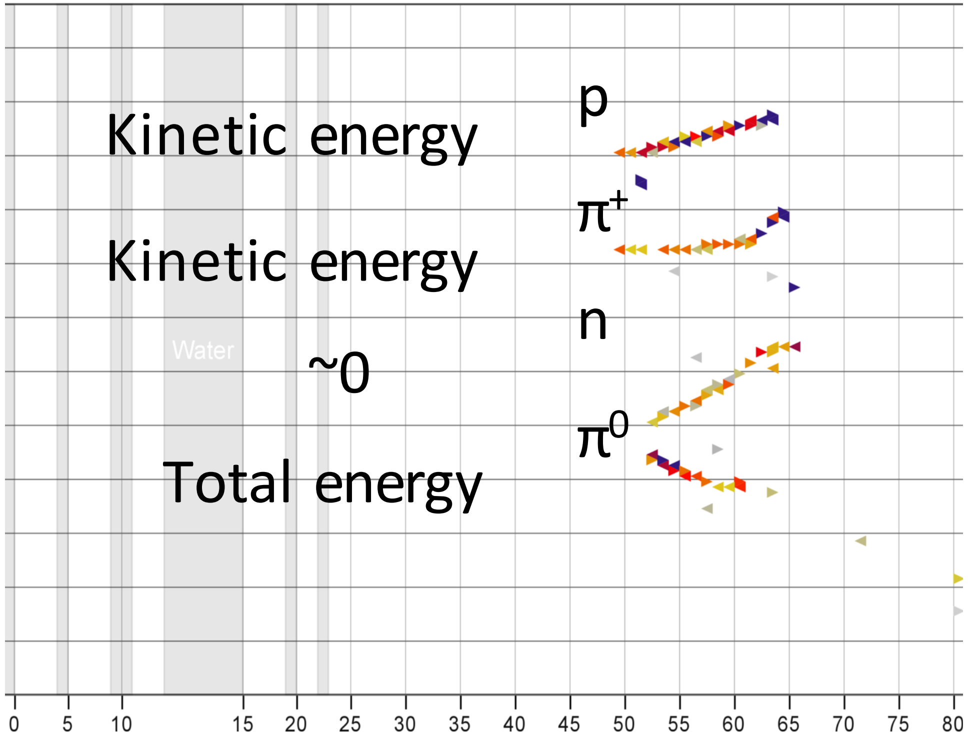
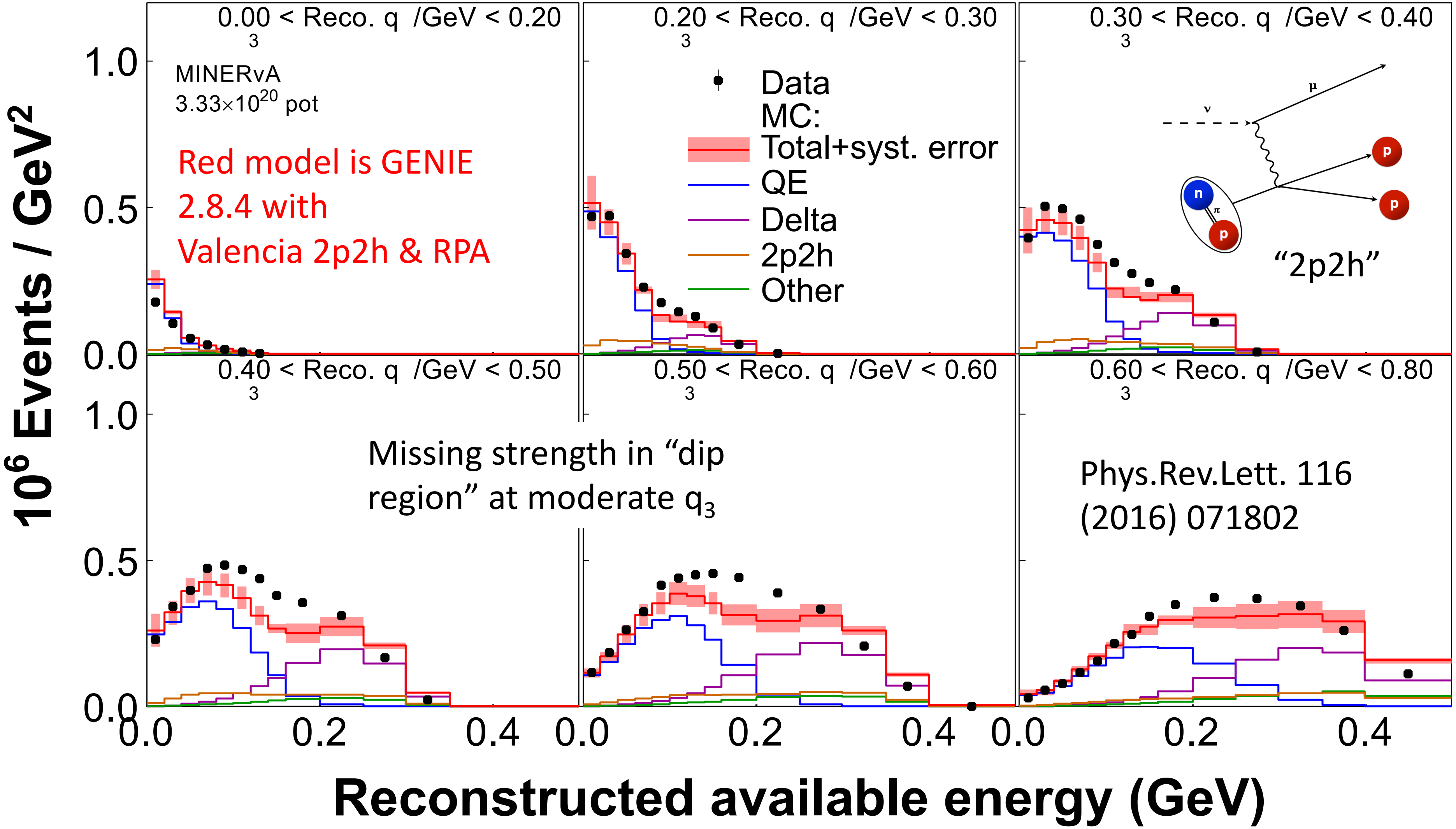


Figure courtesy P. Rodrigues

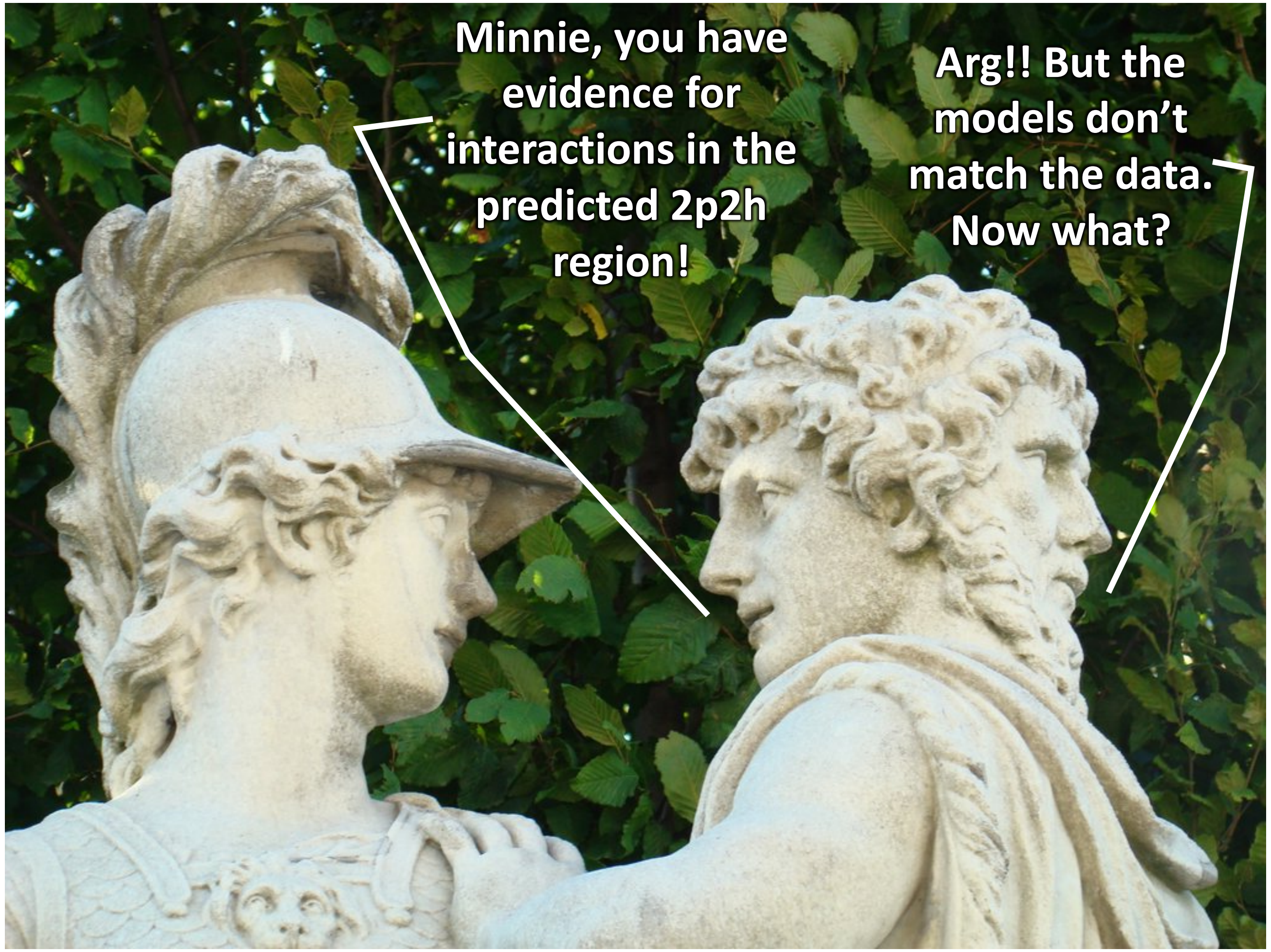
$$E_{avail} \equiv (\text{Proton and } \pi^{\pm}\ KE) + (E \text{ of other particles except neutrons})$$

Missing moderate $|q_3|$ "Dip Region"

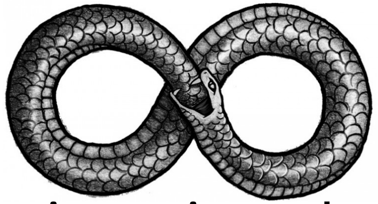


- Nieves 2p2h & RPA model added to GENIE prediction used by MINERvA.
- But it doesn't provide enough strength at moderate $|q_3|$.

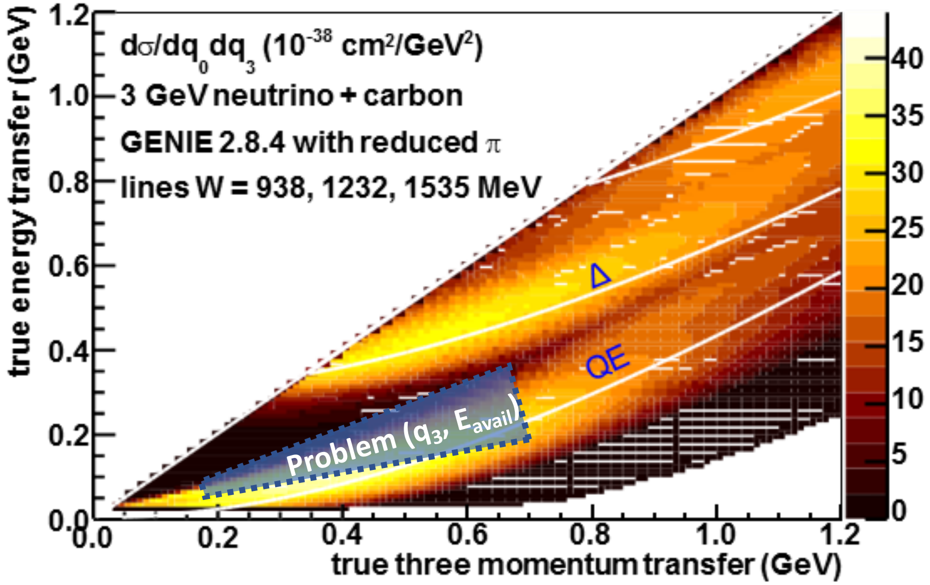
What can we do to fix it?



- Indeed, this is a problem.

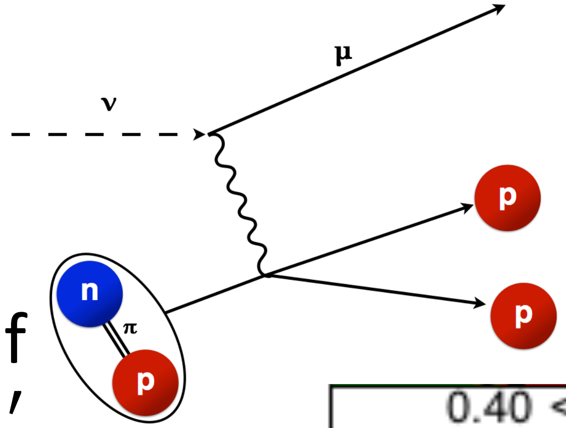


- But in this kinematic region, there are only so many possible contributing processes.

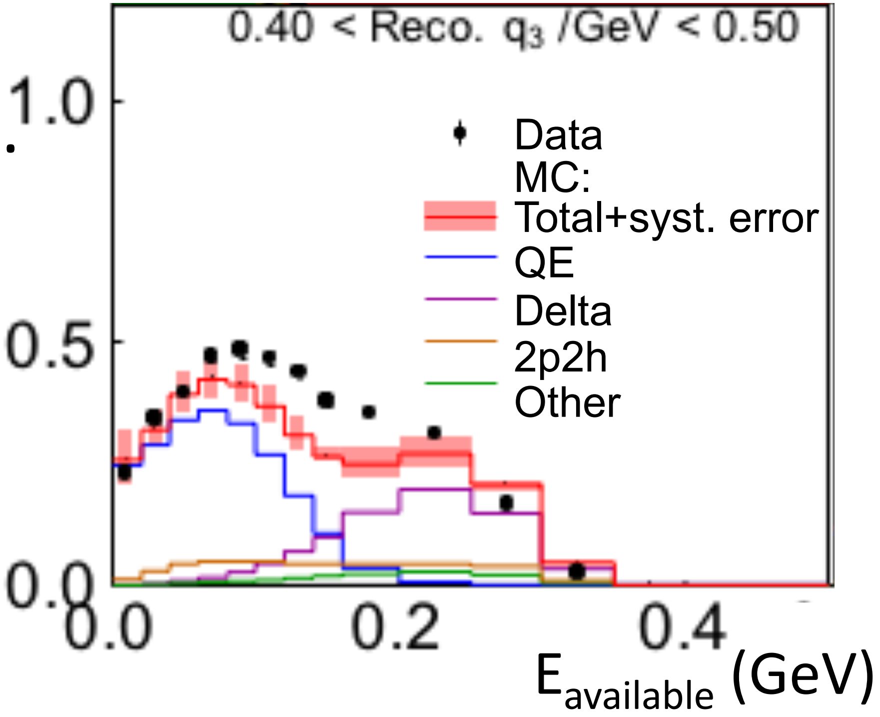


$E_{\text{avail}} \approx q_0 \underbrace{- \Sigma T_n - \Sigma m_{\pi^\pm}}_{\text{need \~200 MeV to migrate from } \Delta}.$ So, QE and 2p2h.

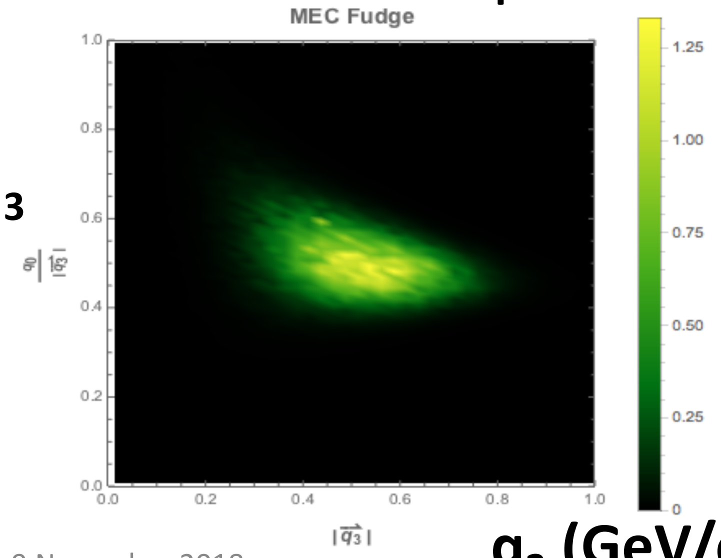
What to Fix?

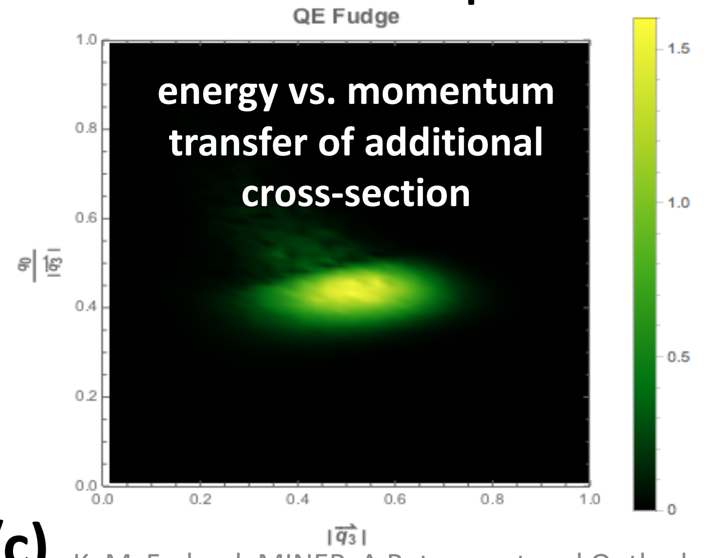


- MINERvA's low recoil data identifies missing strength, but it doesn't identify if $\nu_\mu A(n) \rightarrow \mu^- p A'$ or $\nu_\mu A(nn) \rightarrow \mu^- p n A'$ or $\nu_\mu A(np) \rightarrow \mu^- p p A'$ is the most likely source.
  - Different choices mean different $E_{\text{avail}}(q_0)$.
-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



q_0/q_3





q_3 (GeV/c)

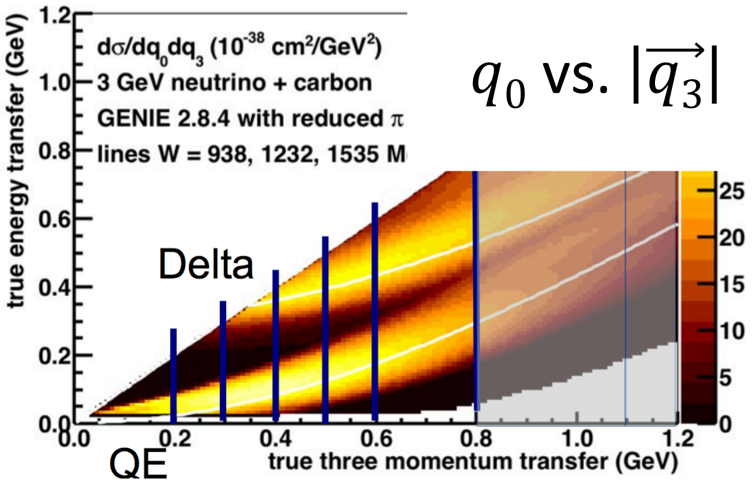
Does this lead to a descriptive $CC0\pi$ Model?

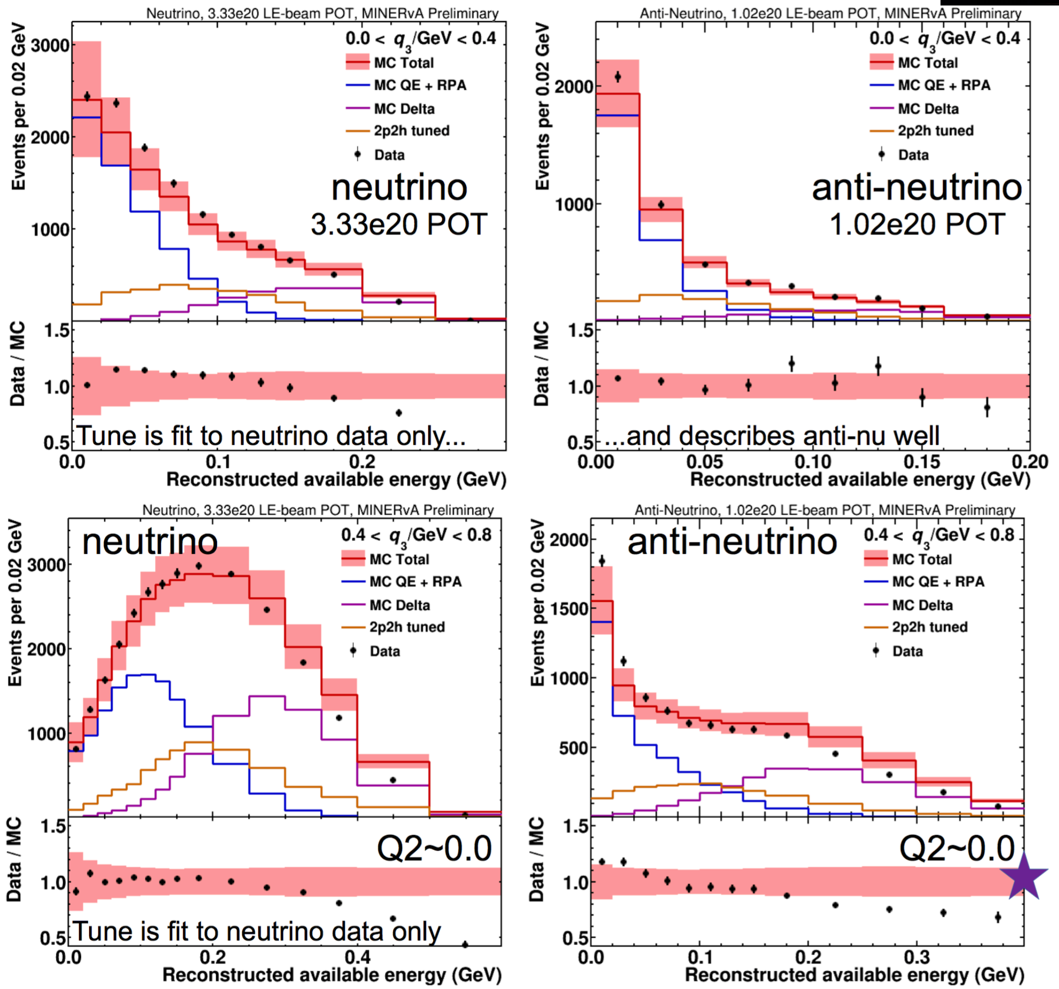
- Data that confirms or refutes the model
- Implications

MINERvA ν_μ and anti-ν_μ "low q"

- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos

Phys. Rev. Lett. 116, 071802 (2016) and
Phys. Rev. Lett. 120, 221805 (2018)



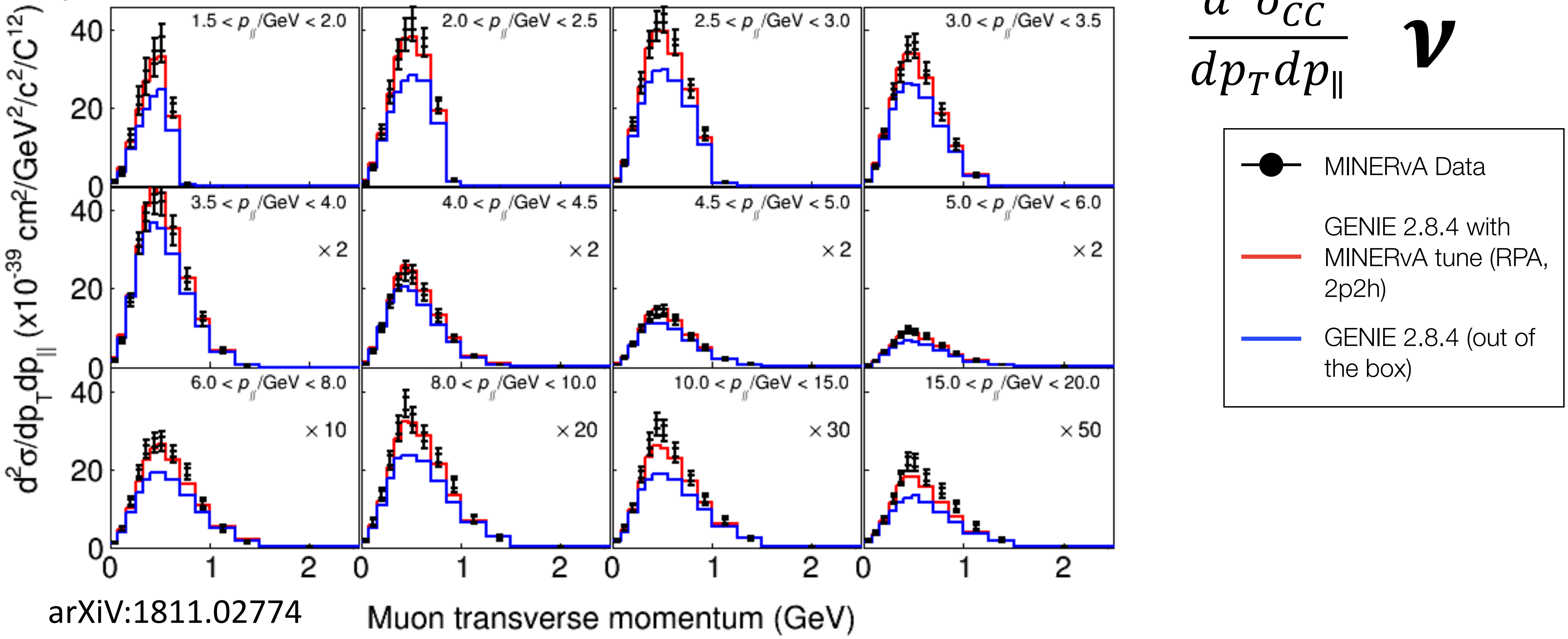


- Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.
- This tune from neutrino data also agrees with antineutrino data!
- Remaining problem is low Q^2 region, consistent with pion production.

MINERvA $\boldsymbol{\nu}$ pionless events (CC0$\boldsymbol{\pi}$)

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

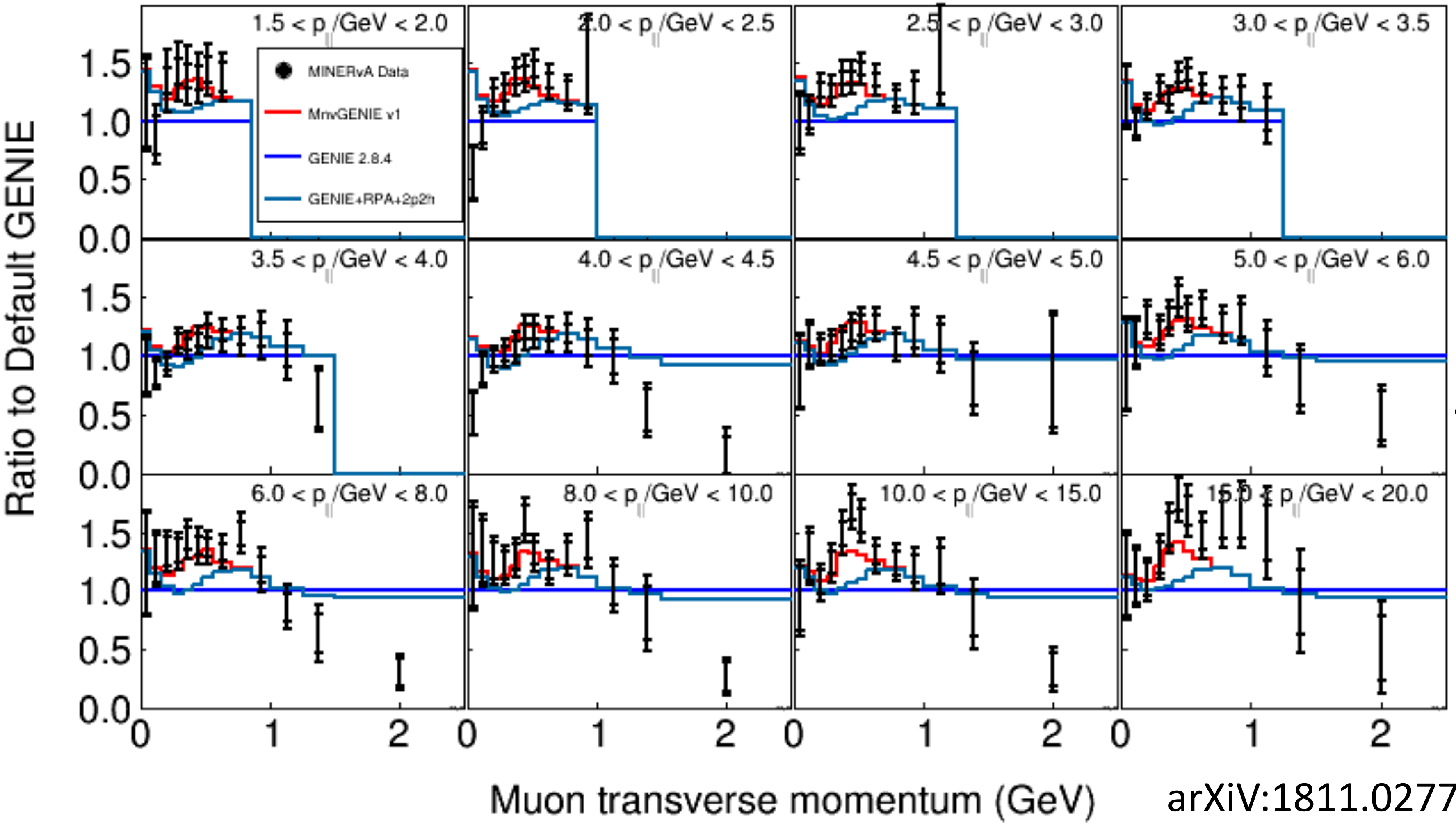
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\|}} \quad \boldsymbol{\nu}$$



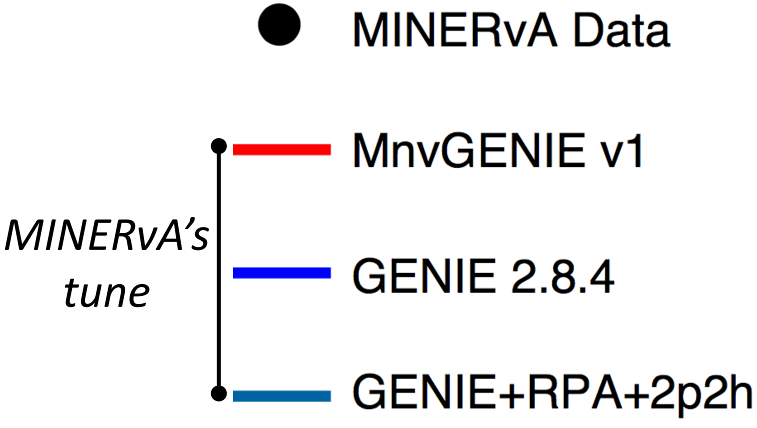
arXiV:1811.02774

MINERvA $\boldsymbol{\nu}$ pionless events (CC0$\boldsymbol{\pi}$)

- Tuned vs untuned in an exclusive channel



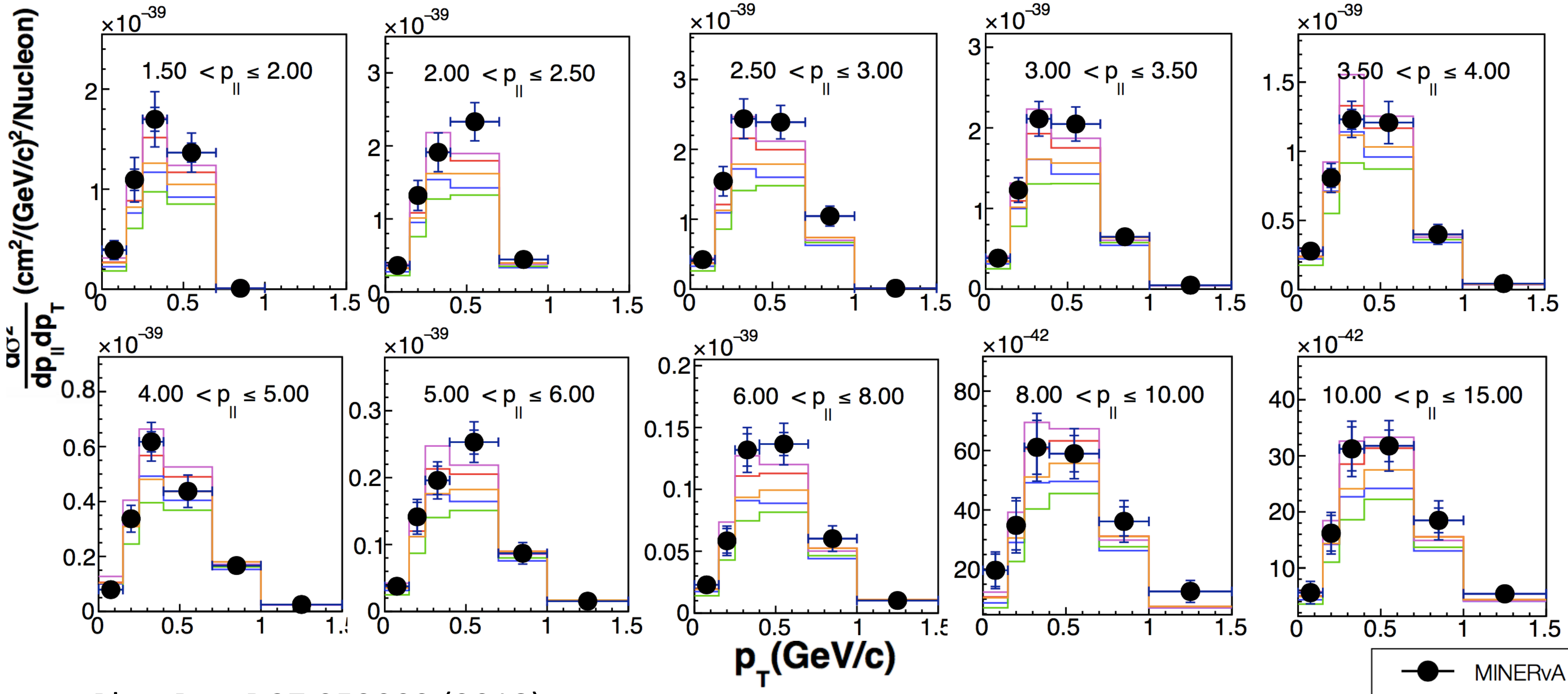
$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T dp_{\parallel}} \quad \boldsymbol{\nu}$$



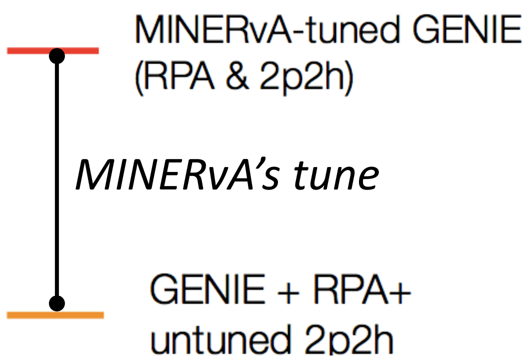
arXiV:1811.02774

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

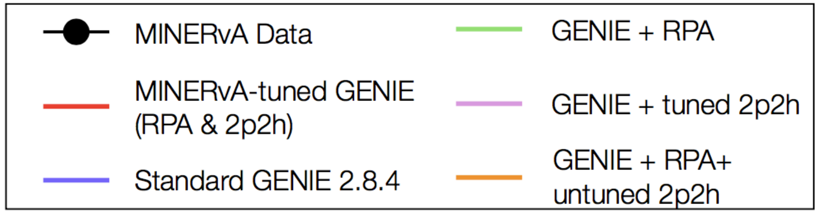
- What if we take tune to inclusive data and feed it back to predict muon distributions in a different exclusive channel?



$$\frac{d^2\sigma_{CC}^{0\pi}}{dp_T\,dp_\parallel} \qquad \bar{\nu}$$

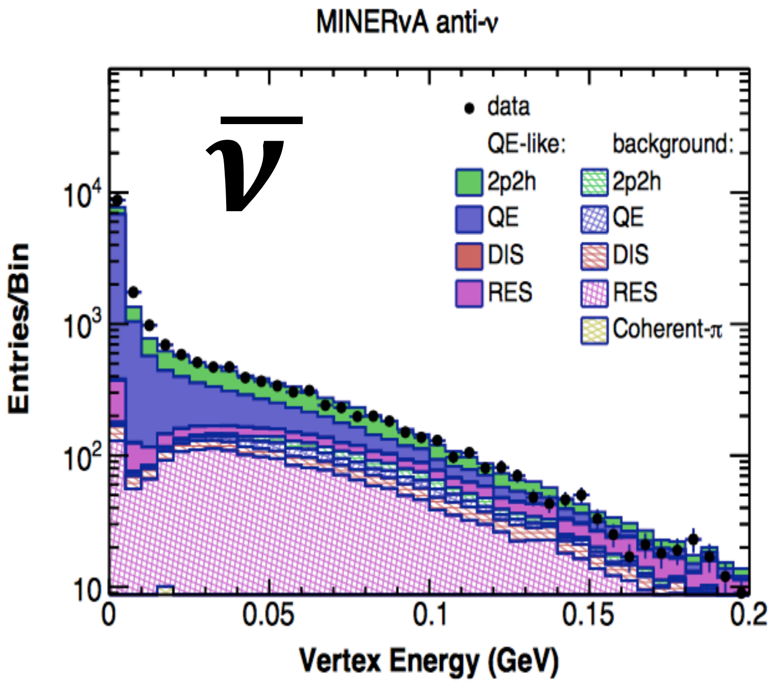


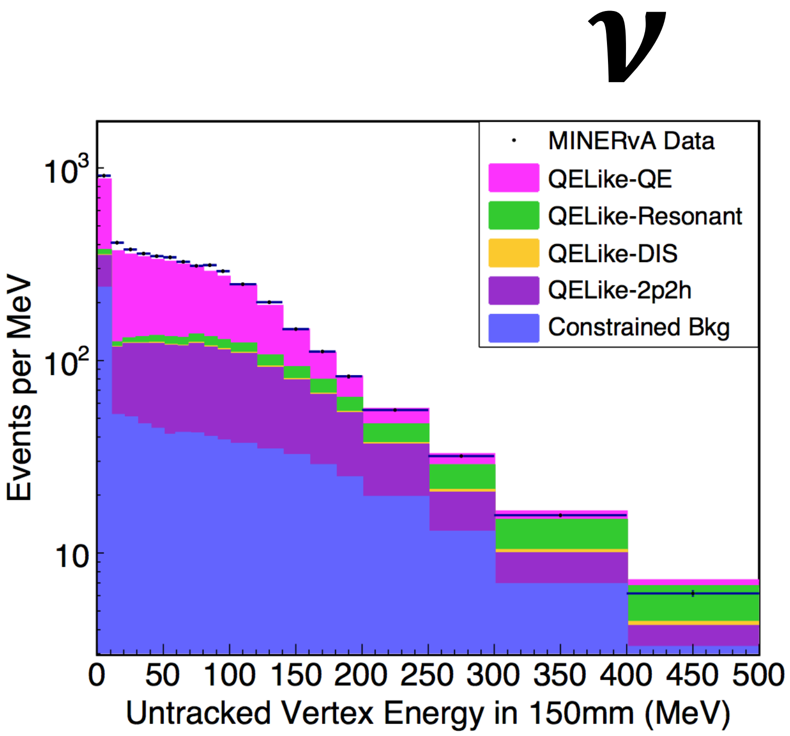
Phys.Rev. D97 052002 (2018)

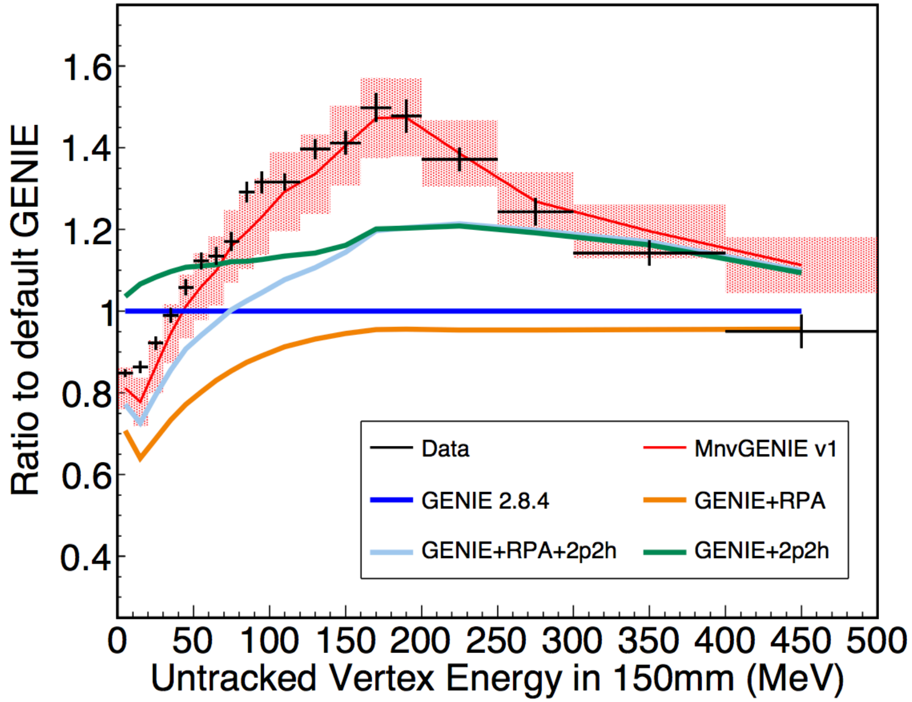


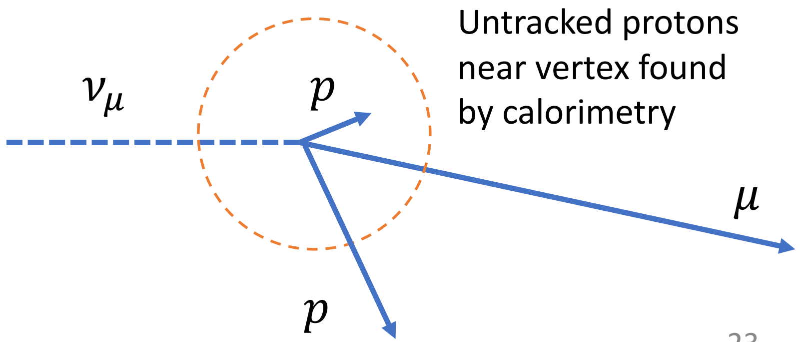
Low energy protons in CC0π events

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







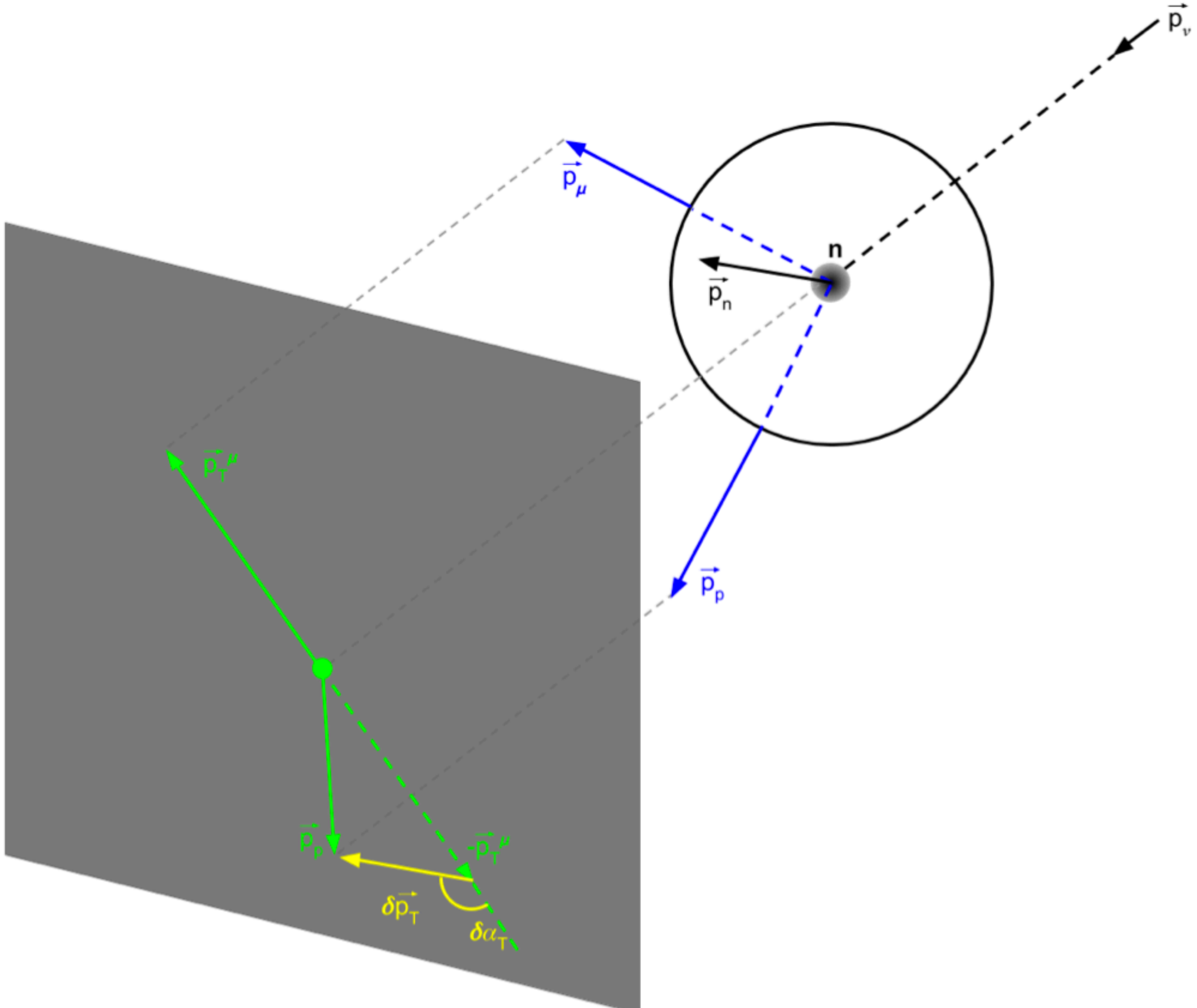


Phys.Rev. D97 (2018), 052002 and arXiV:1811.02774

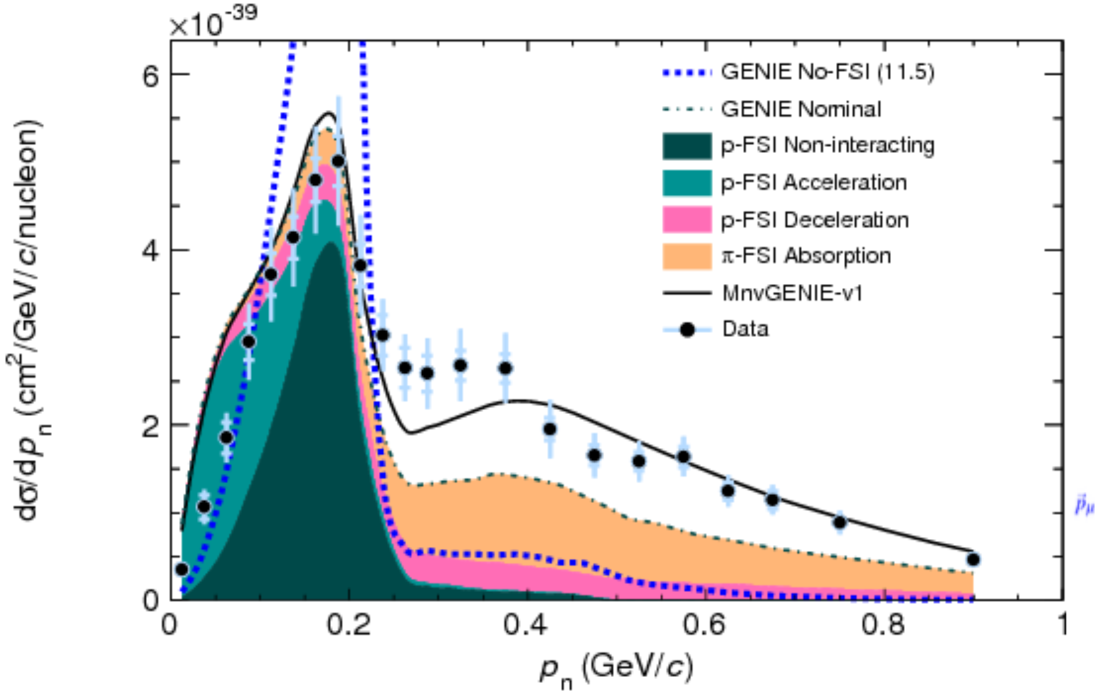
Transverse Balance in CC0π

- One very useful probe is the transverse balance of the leading proton and the lepton in CC0π events.
- In the absence of nuclear effects and extra particles in the final state, they are balanced.
- If energy of recoiling nucleus is known, can reconstruct momentum of target nucleon.

J. Sobczyjk and A. Furmanski, Phys.Rev. C95 065501 (2017)

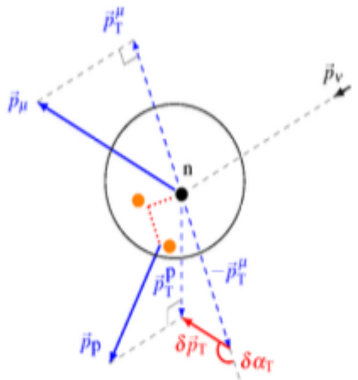


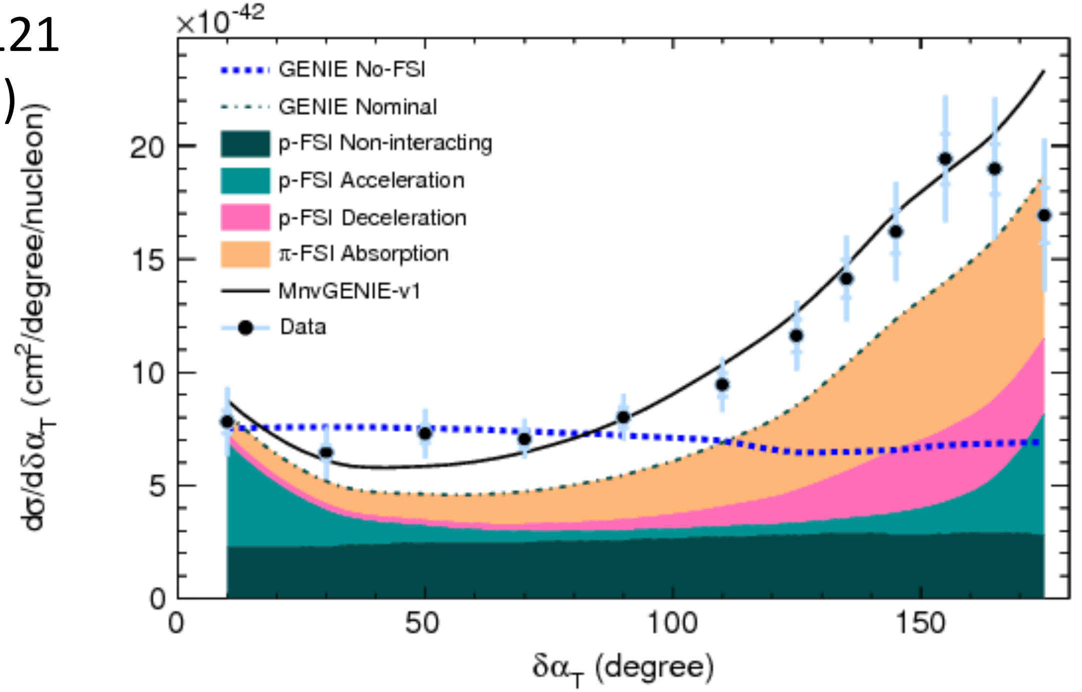
Initial State and Final State in CC0π



Neutron momentum under exclusive μp hypothesis

Phys. Rev. Lett 121 022504 (2018)





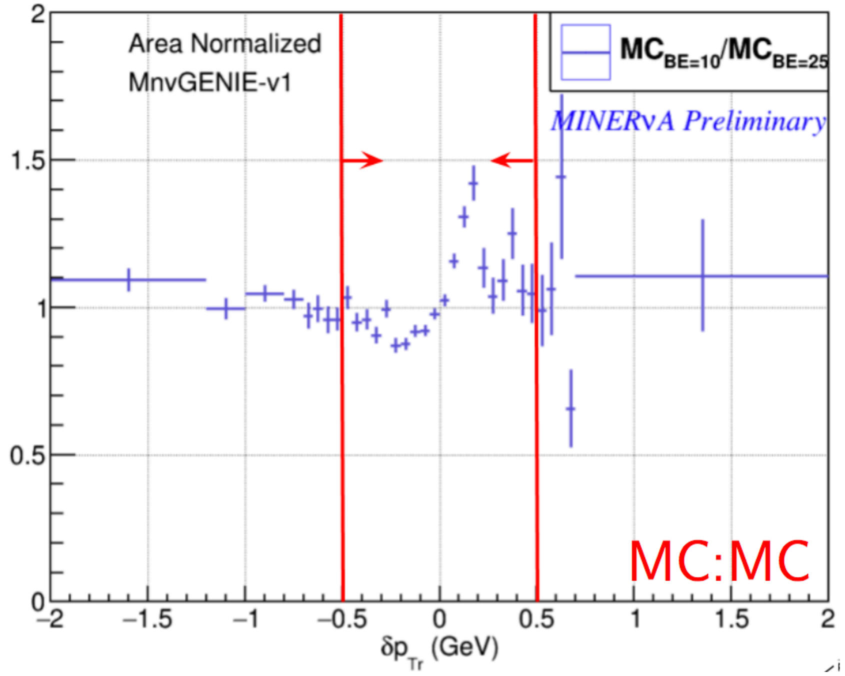
Missing p_T direction (decelerating process is 180°)

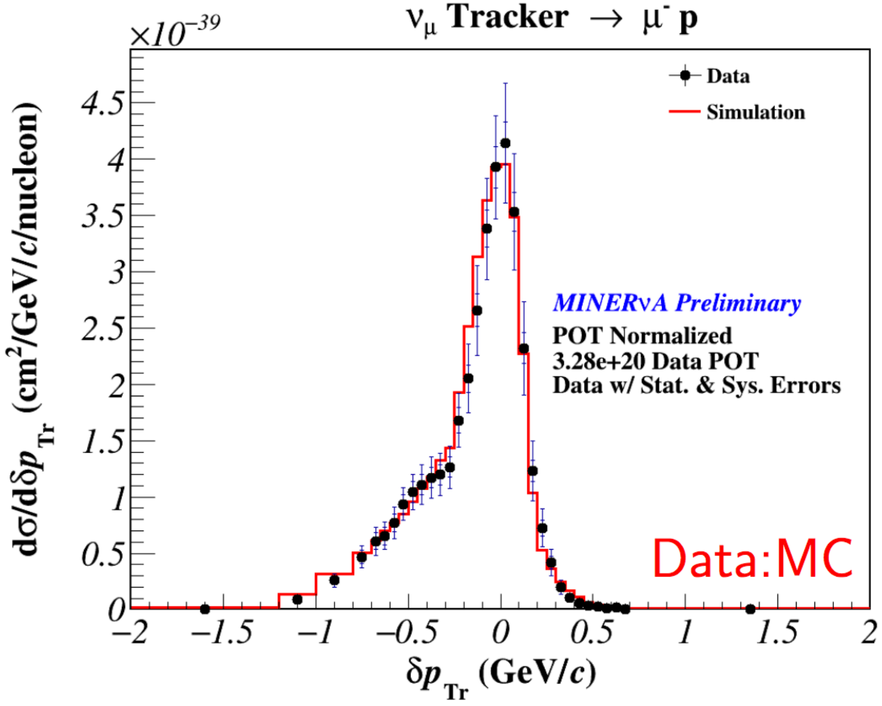
- MINERvA 2p2h tune helps! But by studying reconstructed neutron momentum and transverse variables in CC0π events, we have evidence for deficiencies in the initial and final state models (and tune?).

Transverse Variables and Binding Energy

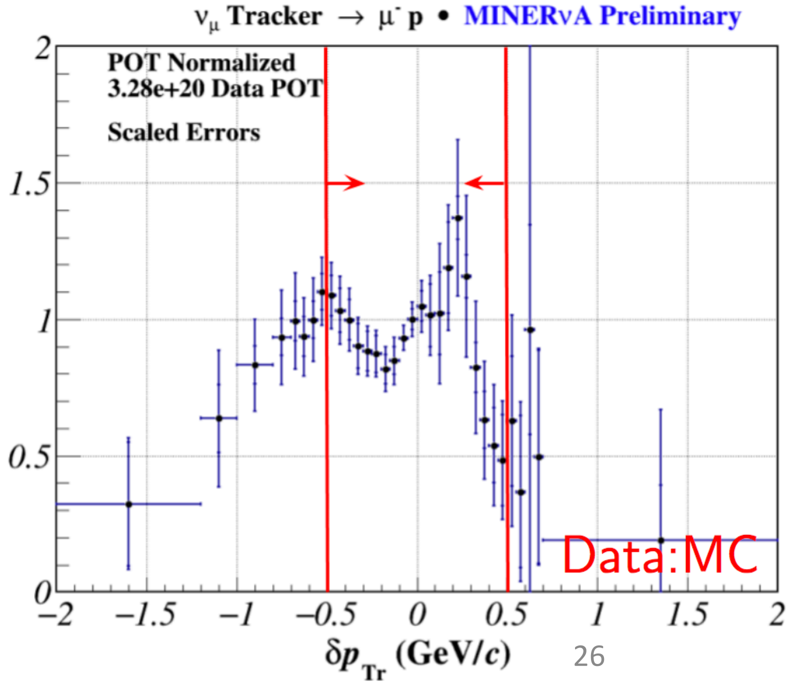
- Transverse balance projected into the reaction plane is directly biased by binding energy.

Peak shift from GENIE's default binding energy to correction proposed by Arie Bodek in arXiv:1801.07975

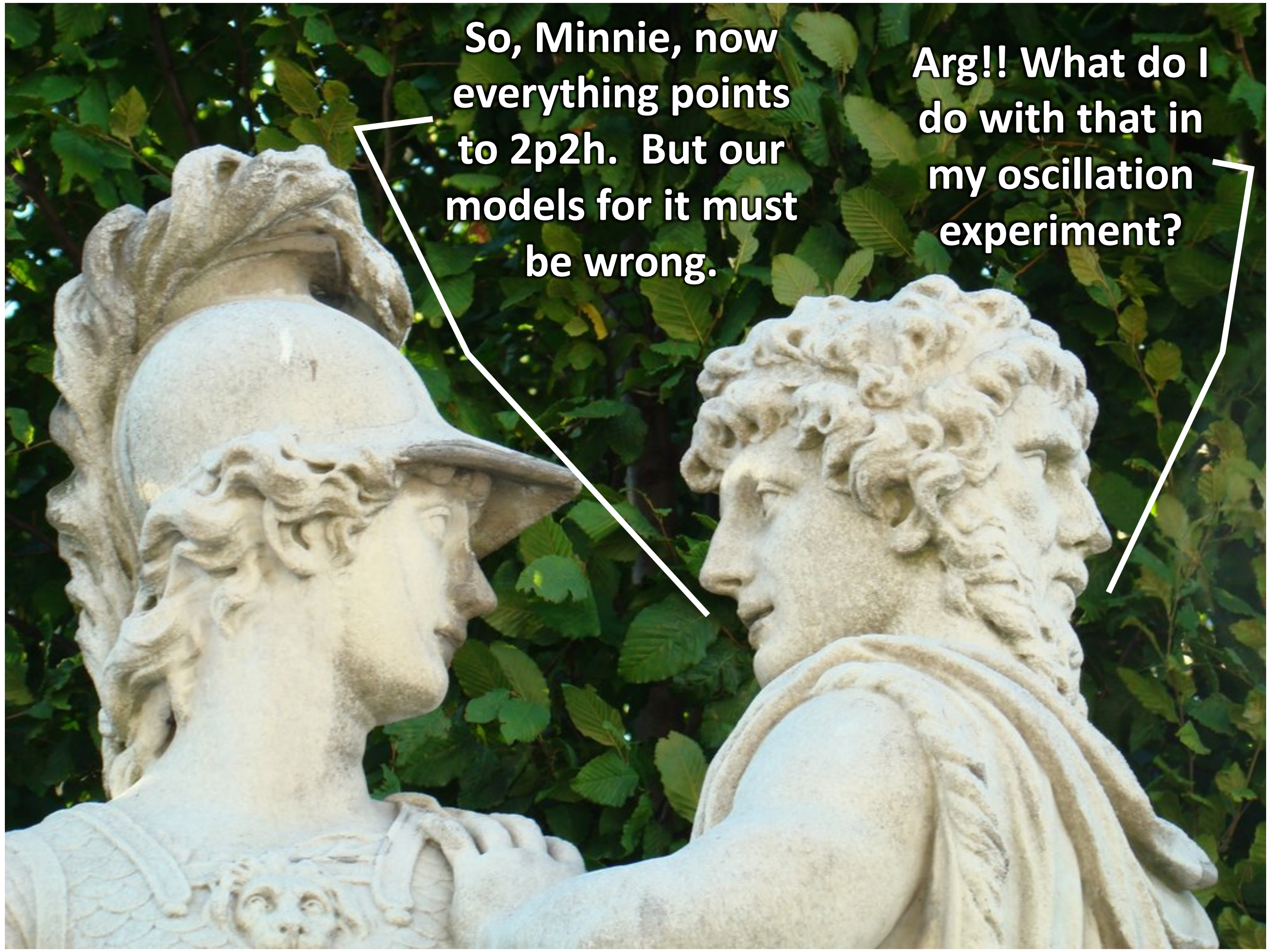




As it turns out, there is a similar shift near the peak. (Features in tail also.)



CC0$\boldsymbol{\pi}$ Model Tune

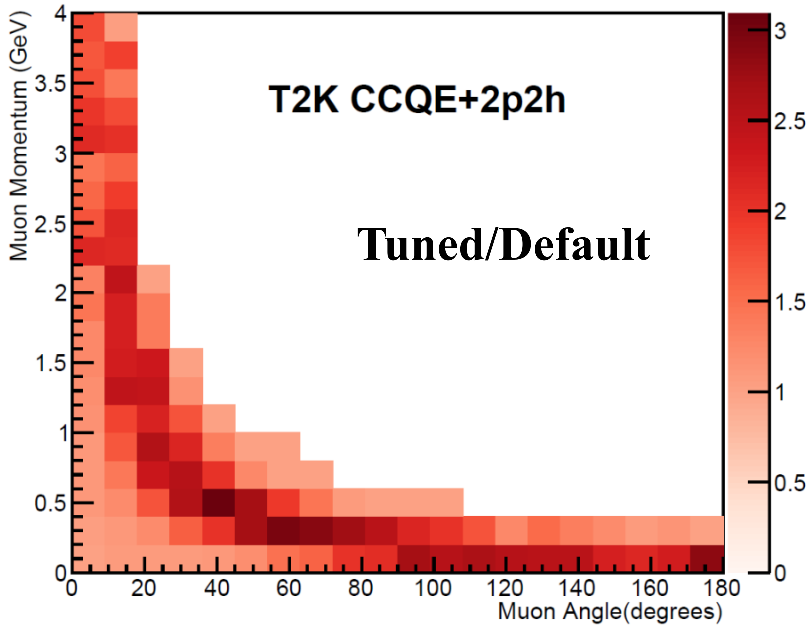


- For these "least inelastic" events, MINERvA has found a tuned model which explains:
  - Lepton energy-momentum distributions
  - Details of nucleon recoil
- Not theoretically motivated (=magic?), but identifies particular energy-momentum transfer.

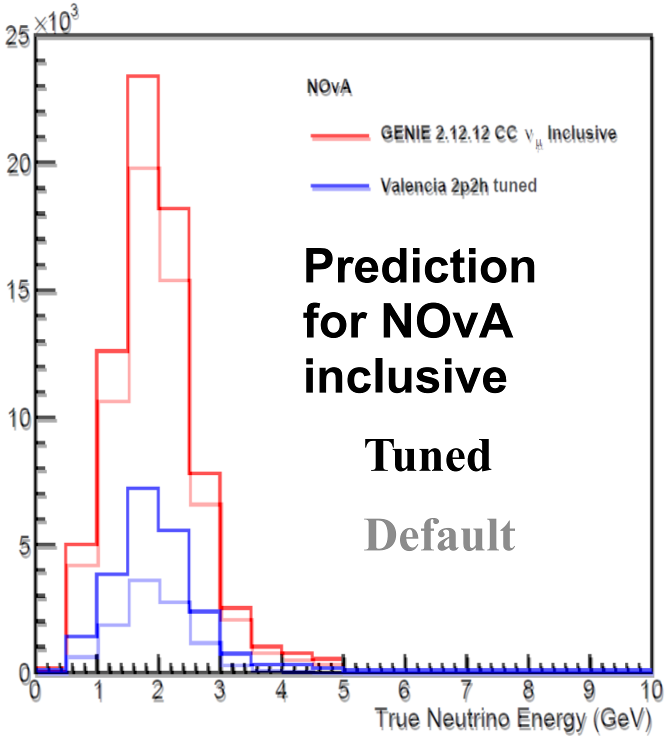
- NOvA uses this technique on its own near detector data for its oscillation analysis to tune 2p2h. ✔
- Can MINERvA's tune be applied to T2K, MicroBooNE energies?

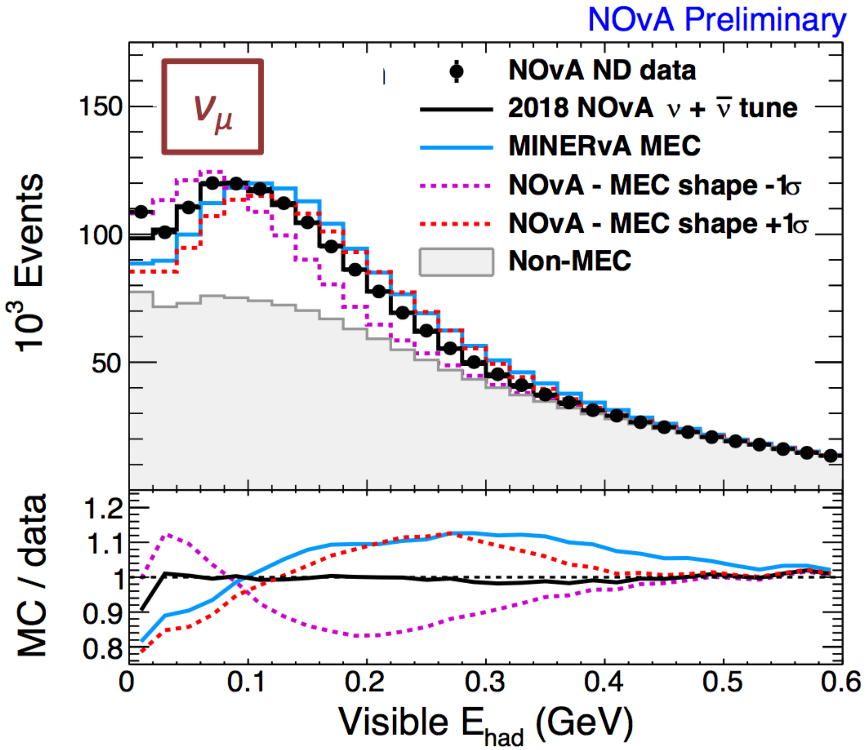
Implications for NOvA and T2K

Event rate ratio: Tuned/Default



- 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

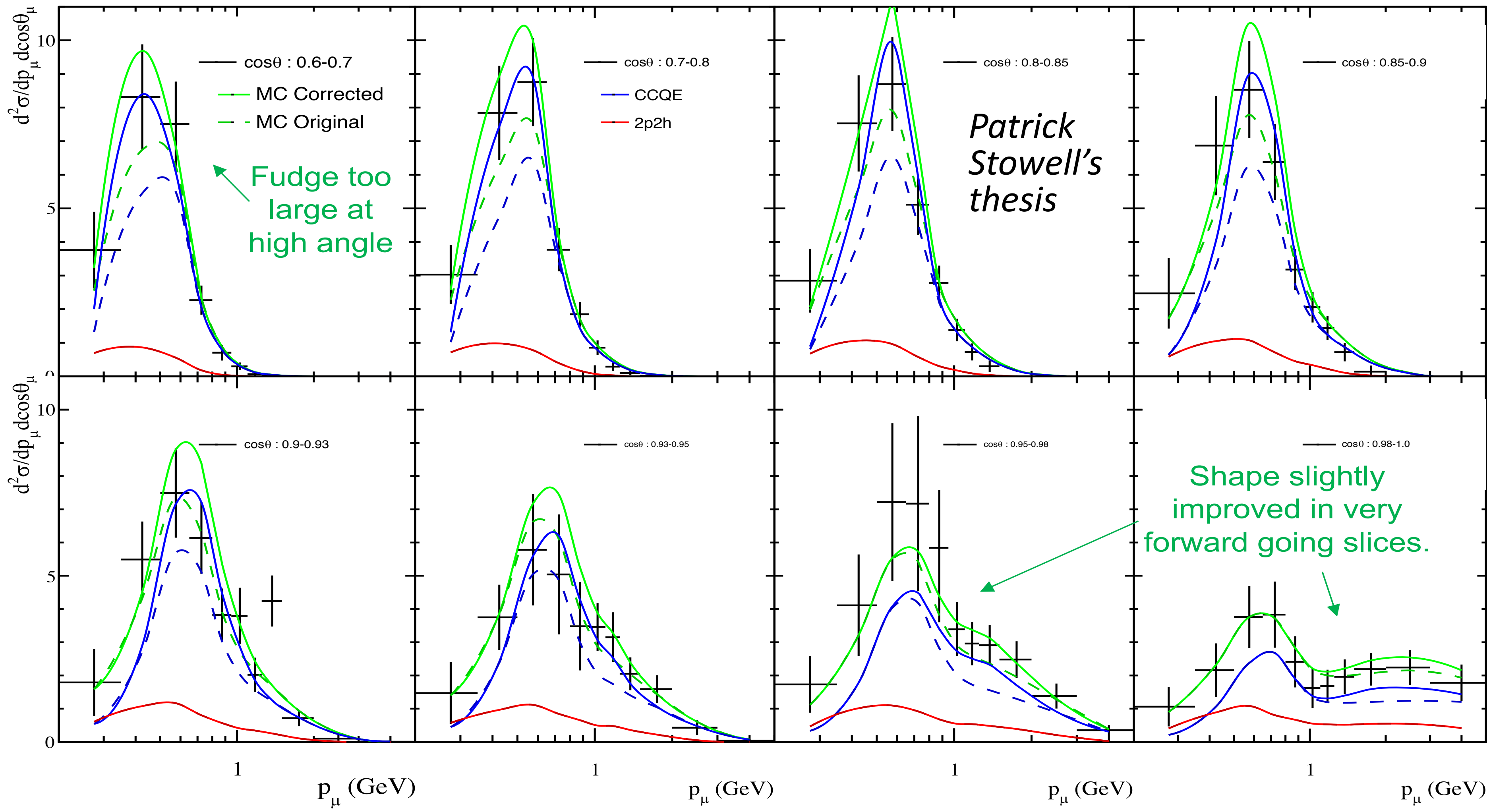




Alex Himmel, JETP Seminar, June 2018

- 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

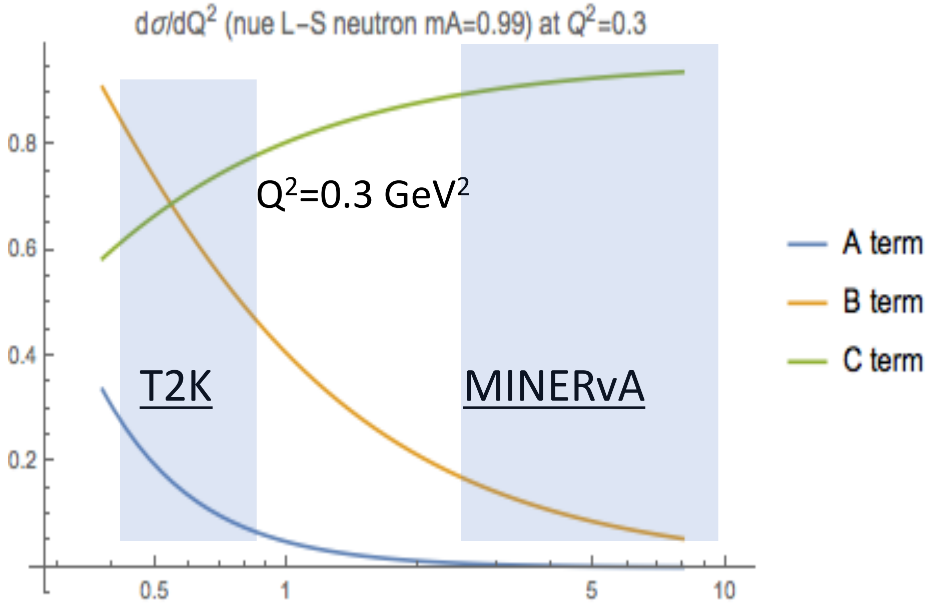
Apply to T2K CC0π… too much tune!



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.

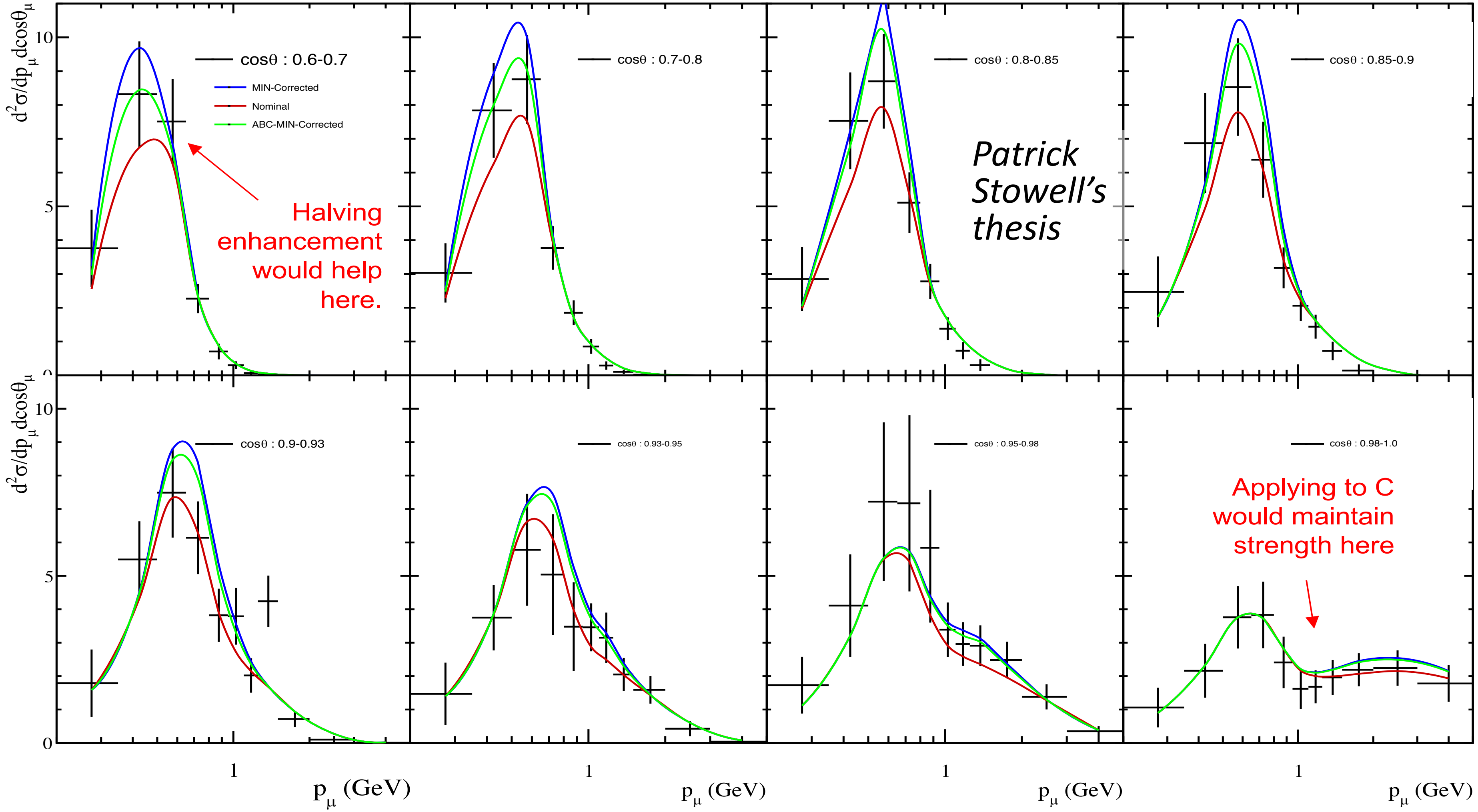
An expansion similar to eq. (2.5) holds for $\overline{\sum}\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

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

a quadratic polynomial in the laboratory energy $E_\nu = k \cdot P/M$ whose coefficients A, B and C depend on ν, q^2, and the reaction in question [L14, P2], It follows that if the interaction is of the current-current form *then* $E_\nu^2\, \mathrm{d}^2\sigma/\mathrm{d}q^2\,\mathrm{d}\nu$ *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

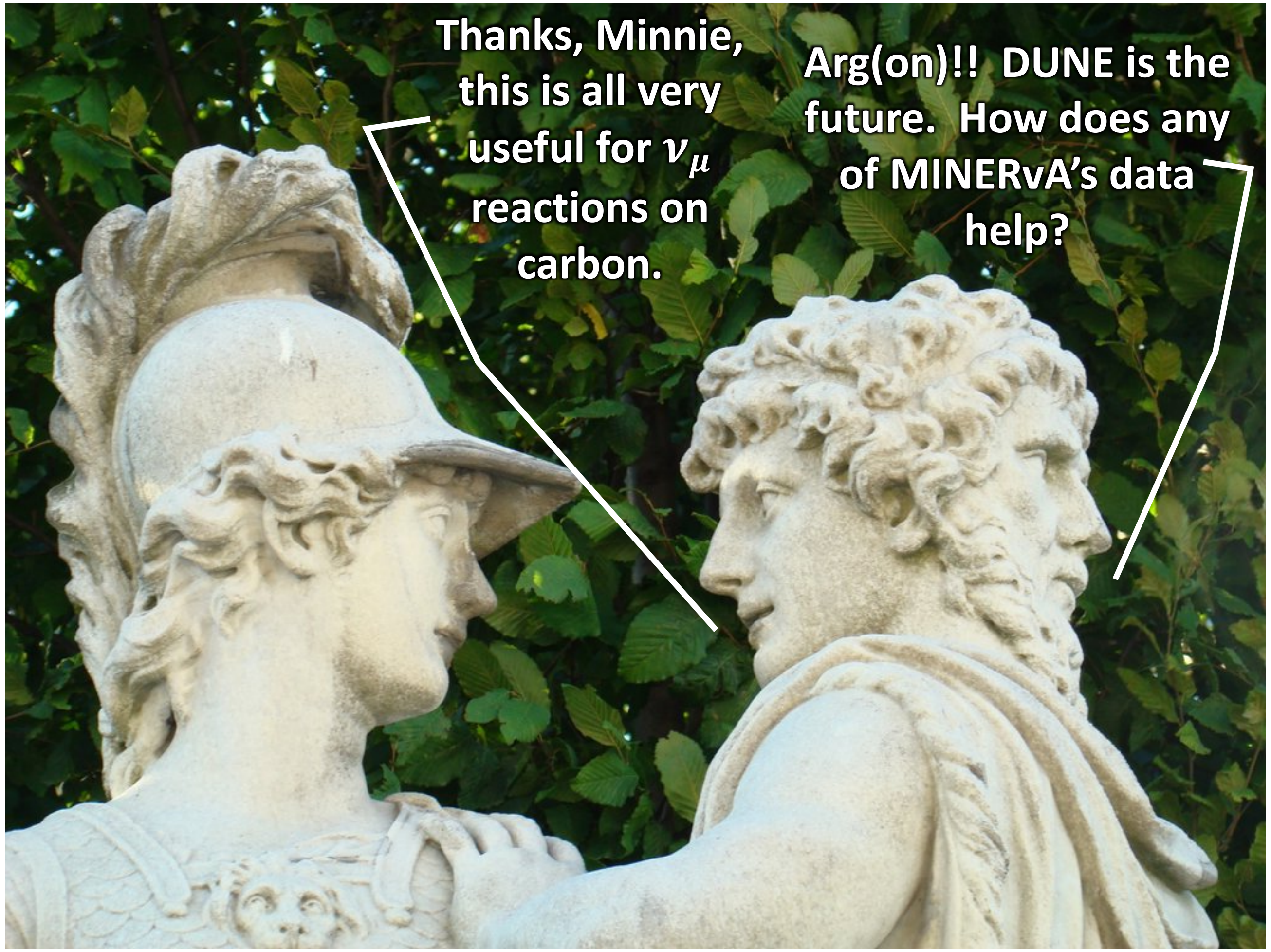
Apply to T2K C term for CC0π



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

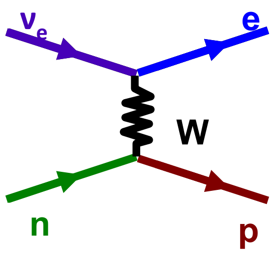
- Applying to the C term, as though this were the standard 1p1h interaction, get better agreement.
- However, without a model, we don't know energy dependence of this missing strength.

CC0$\boldsymbol{\pi}$ for the Future



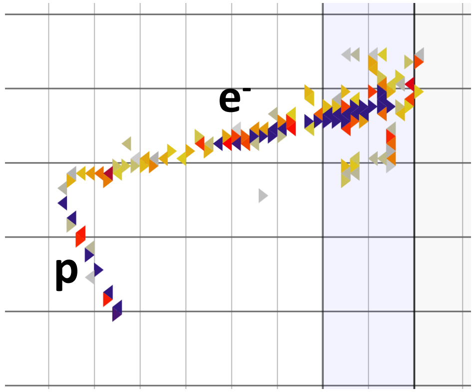
- Both neutrino flavor and nuclear dependence are largely unknown experimentally.
- However, there is theoretical guidance that tells us what to look for.
- MINERvA currently has statistics limited results, so higher statistics NOvA era data will be the final word for MINERvA.

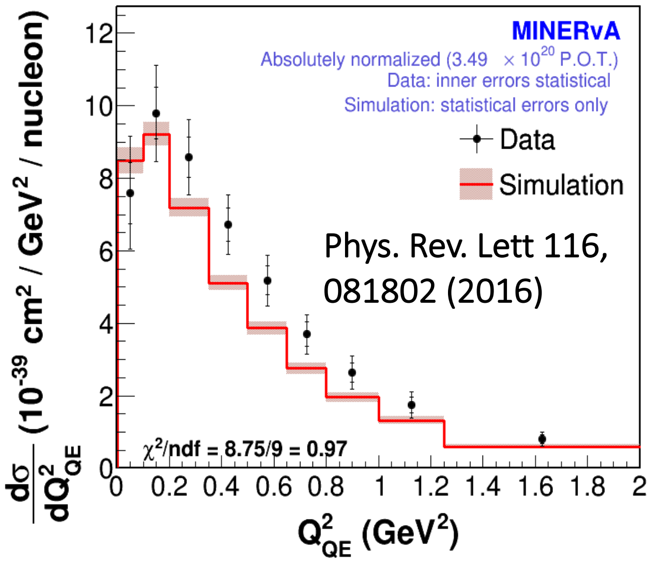
ν_e CCQE

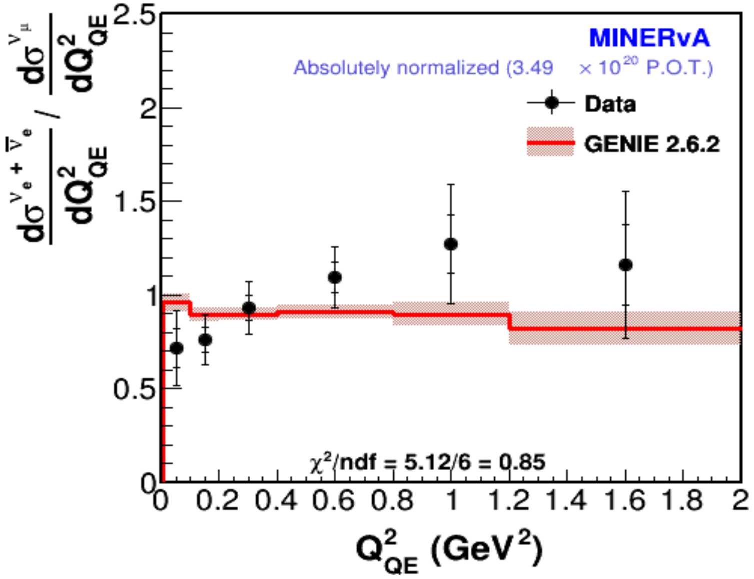


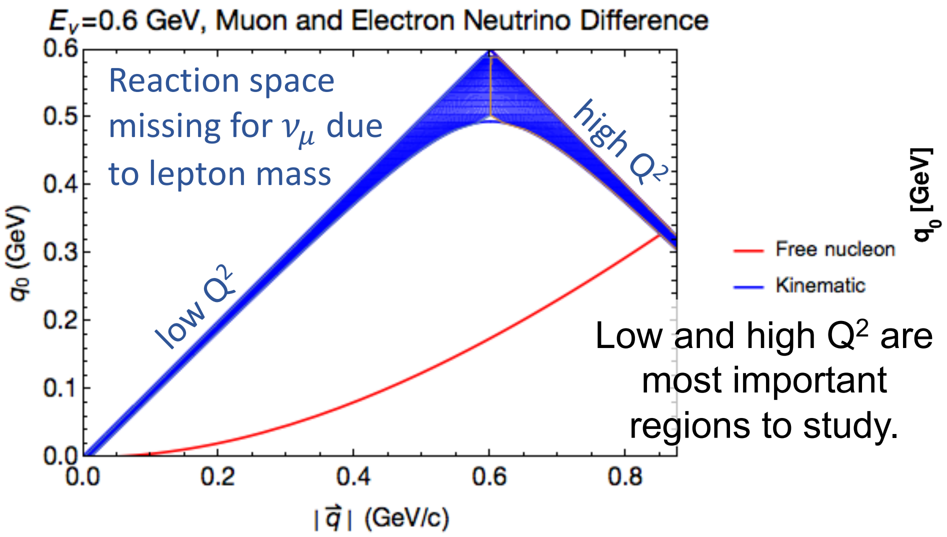
We all assume fundamental coupling is universal, but know nuclear effects are not!

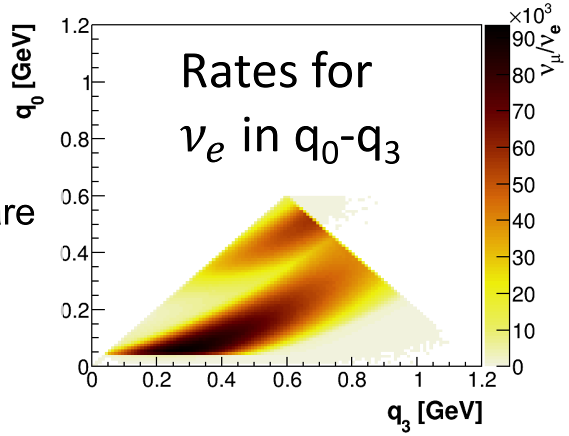
- ν_e CCQE is oscillation signal for T2K and MiniBooNE, but there is almost no data.





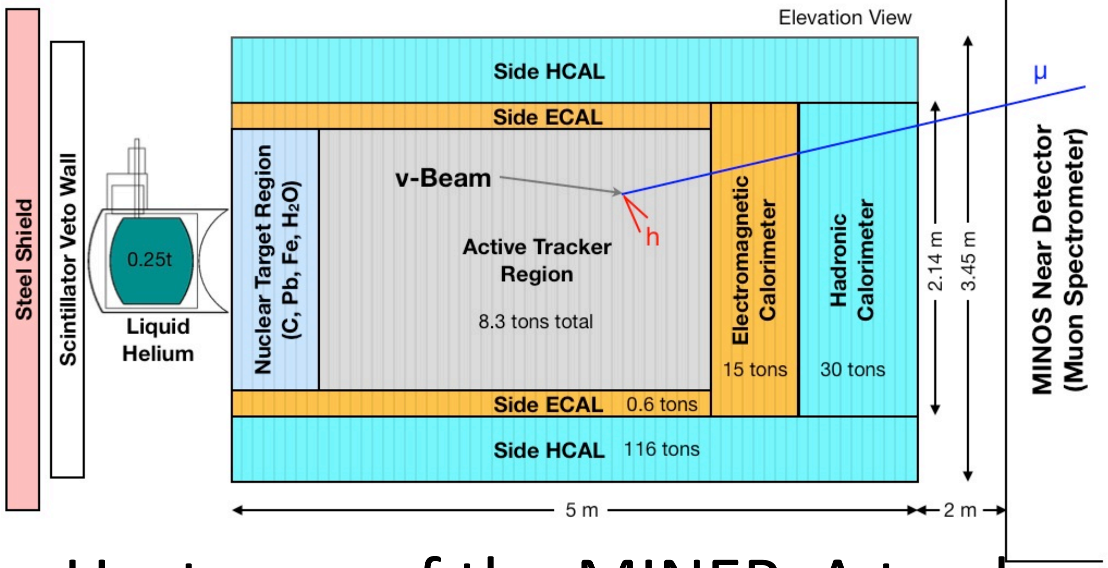


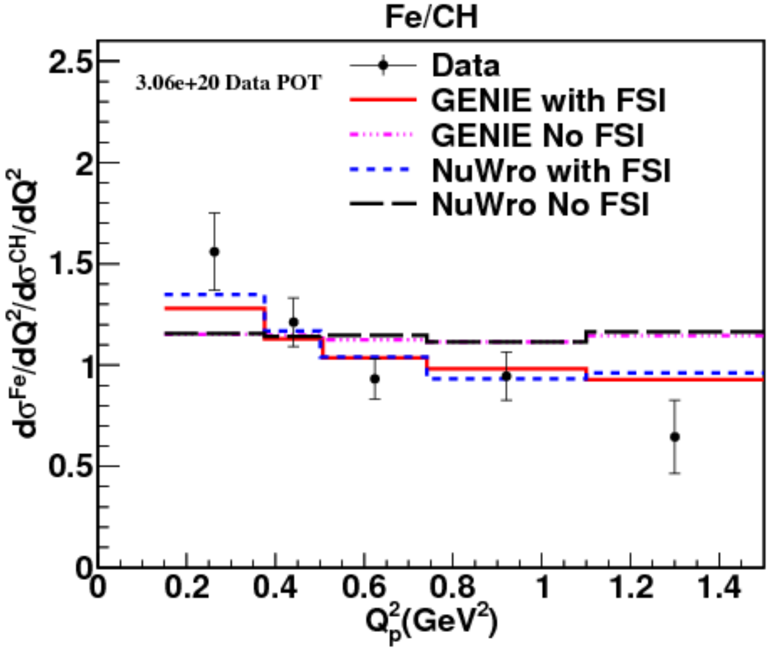




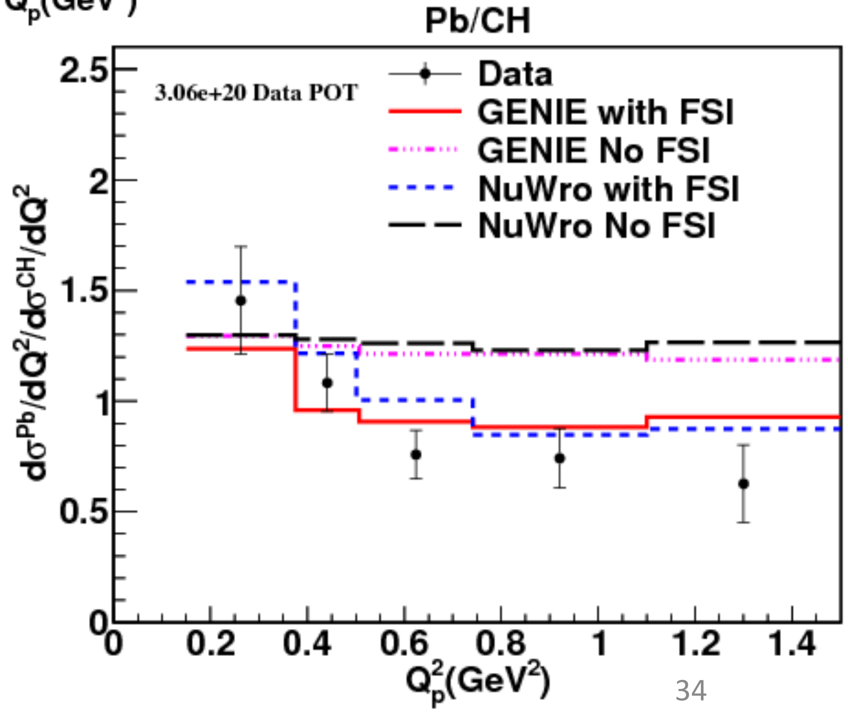
- This result probes low Q^2.
- Measured cross sections and ν_e/ν_μ ratio consistent with GENIE model @ 1σ (~10-20% uncertainties)
- Need better for DUNE.

MINERvA's Passive Targets and CC0π



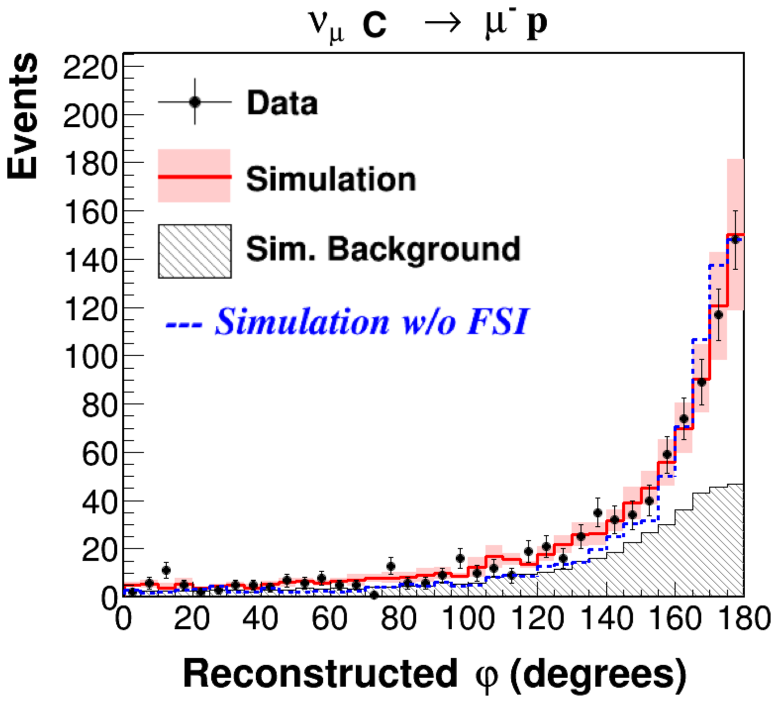


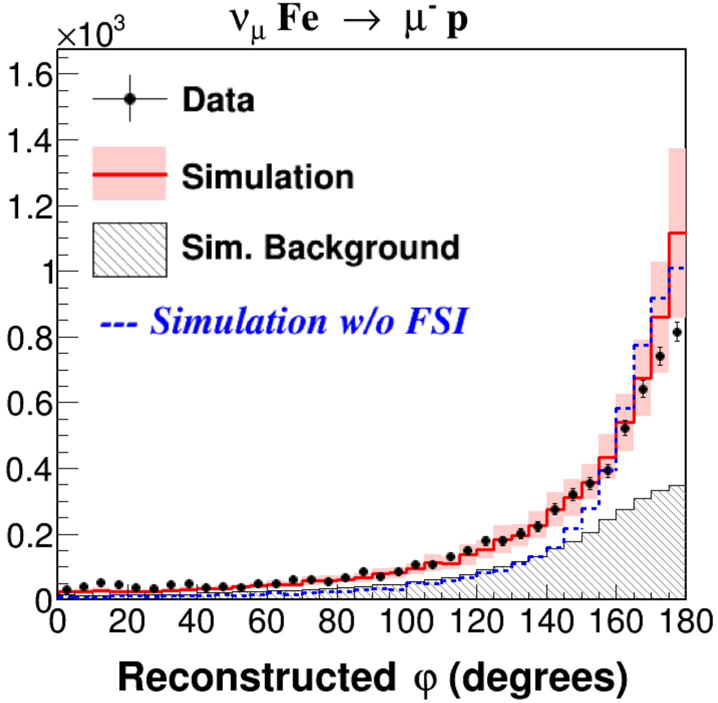
Phys.Rev.Lett. 119 (2017) 082001

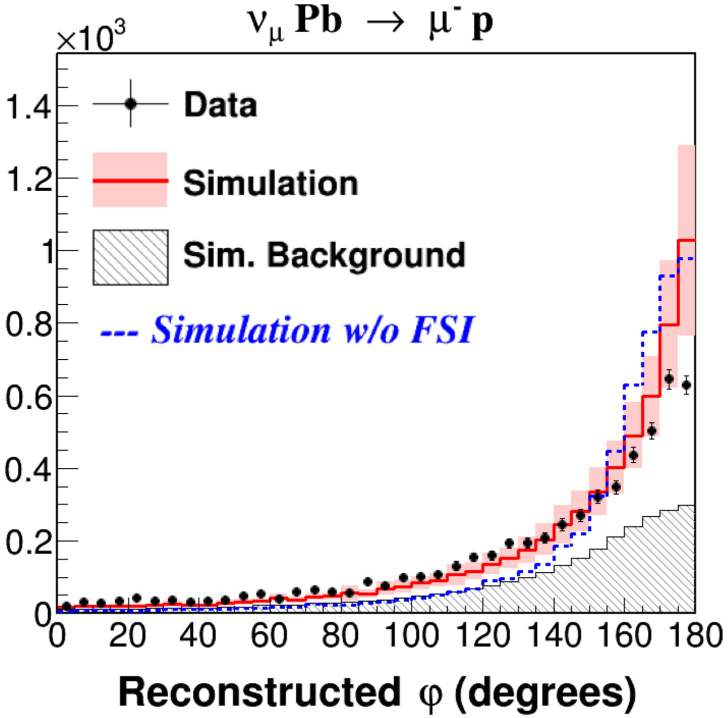


- Upstream of the MINERvA tracker is a region of He, C, H_2O, Fe, and Pb targets.
  - Masses of 0.25-0.8 ton, so statistics limited.
- First results, at right, illustrate $Q_p^2 \approx 2MT_p$.
  - Medium energy results will focus on inclusive lepton variables and lepton-hadron correlations.

MINERvA's Passive Targets and CC0$\boldsymbol{\pi}$







- Acoplanarity of C, Fe, and Pb targets in proton and muon CC0$\boldsymbol{\pi}$ events.
- Unsimulated migration away from planar peak with increasing A: C→[Arg(on)] → Fe → Pb.

Phys.Rev.Lett. 119 (2017) 082001

Pion Production: CC1π Reactions

- The “not awesome agreement” ™
- Tuning and its limitations

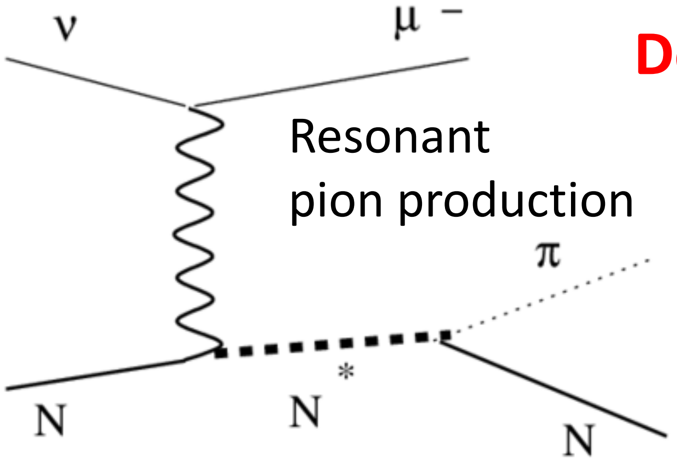
How do we produce single pions?

(Let us count the ways.)

- Many competing production mechanisms.

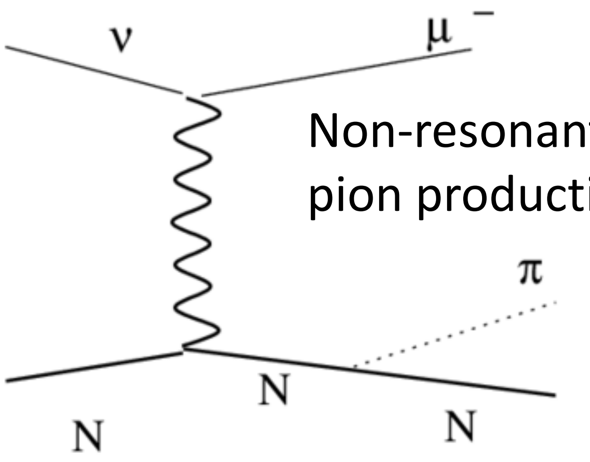
Dominant

Resonant
pion production



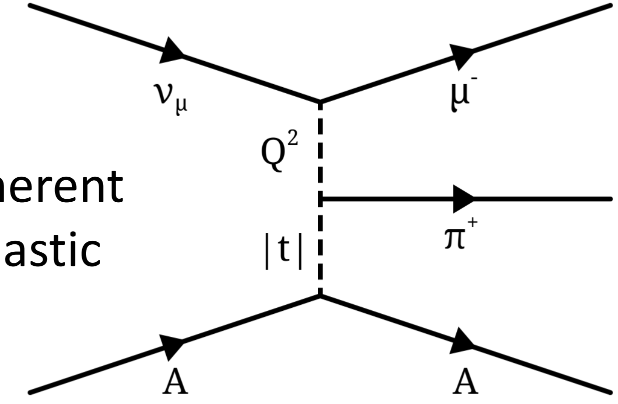
Interference may be large effect

Non-resonant
pion production



Significant

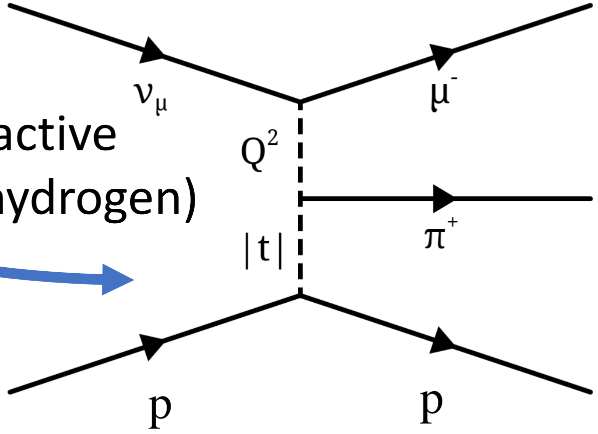
Coherent
inelastic



Sub-leading

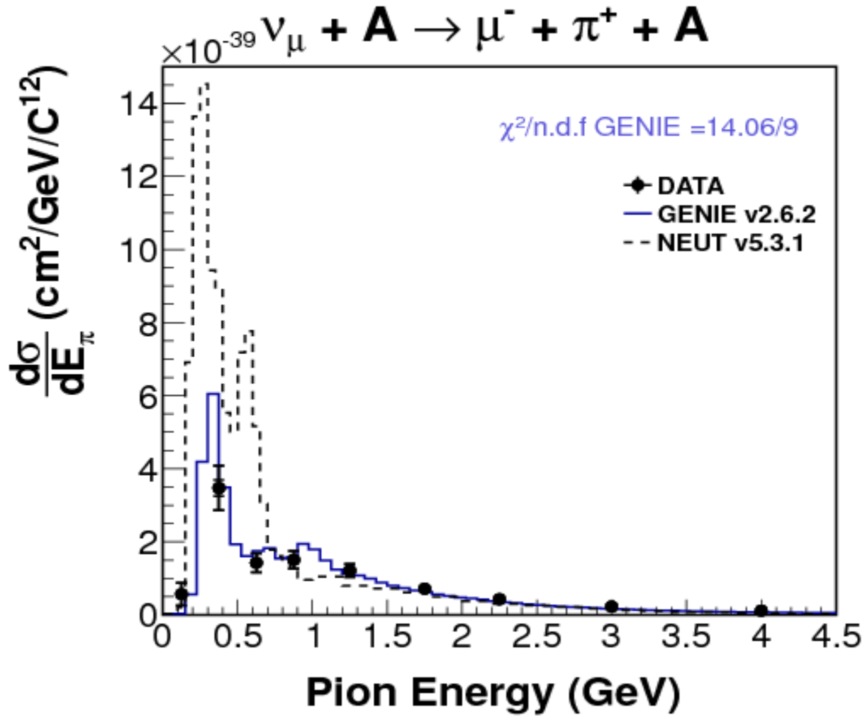
Interference at low Q^2 on hydrogen

Diffractive
(on hydrogen)

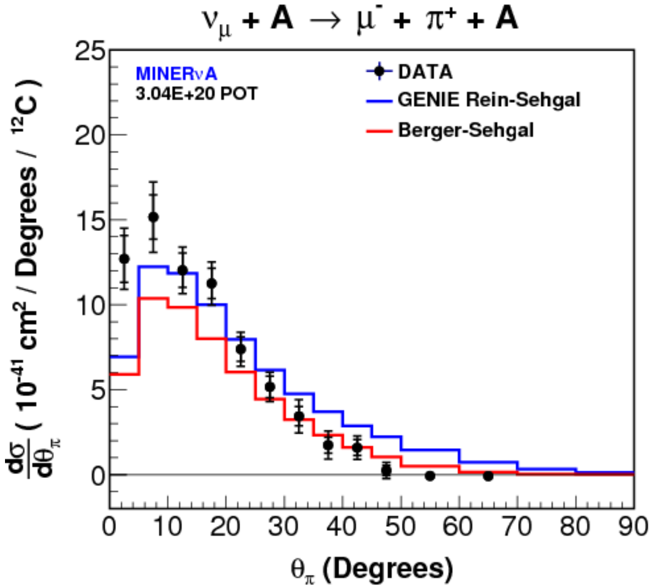


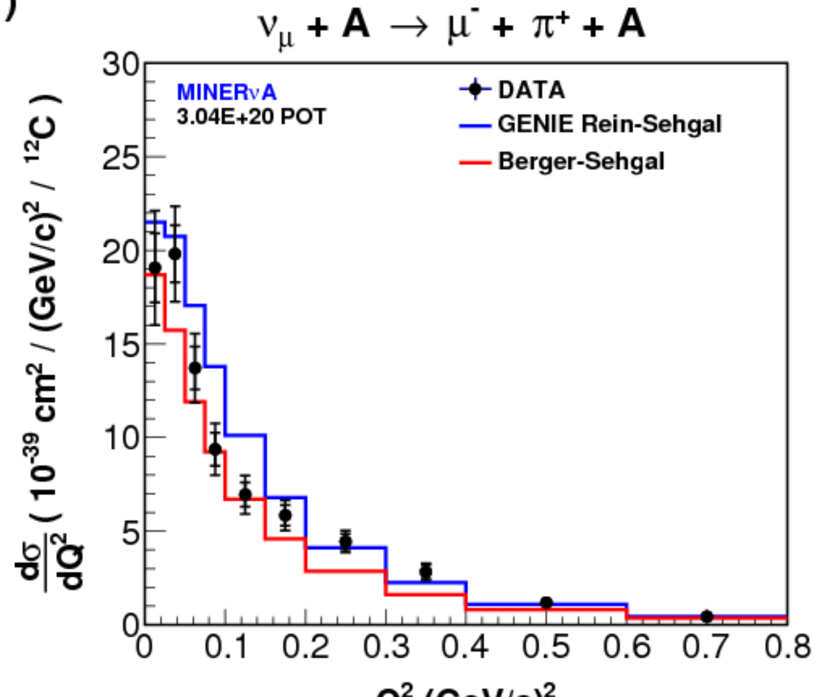
Coherent pion production

- 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.



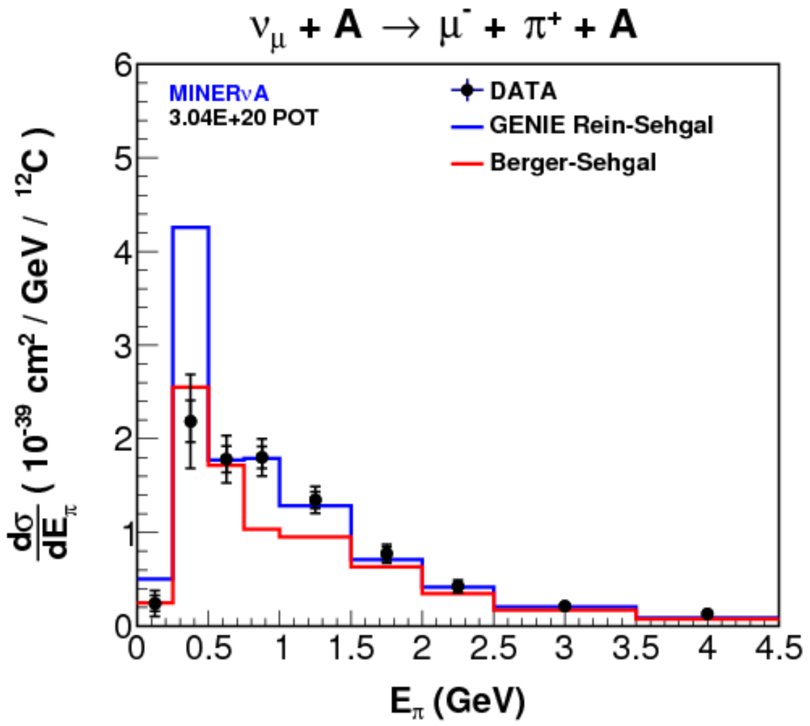
Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802



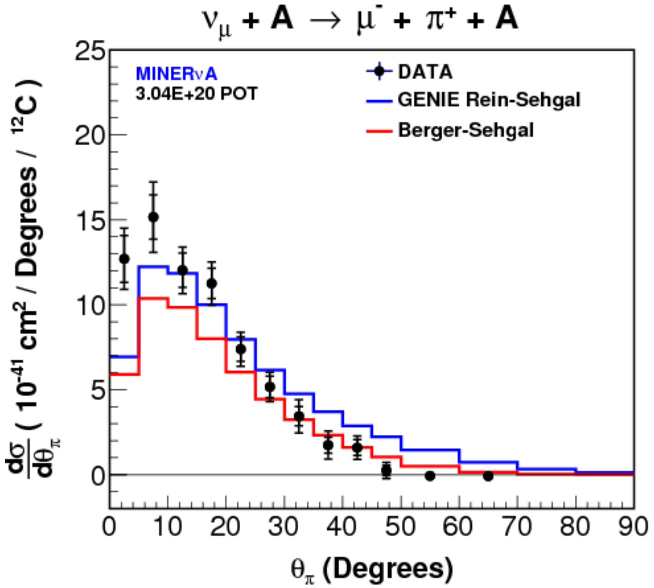


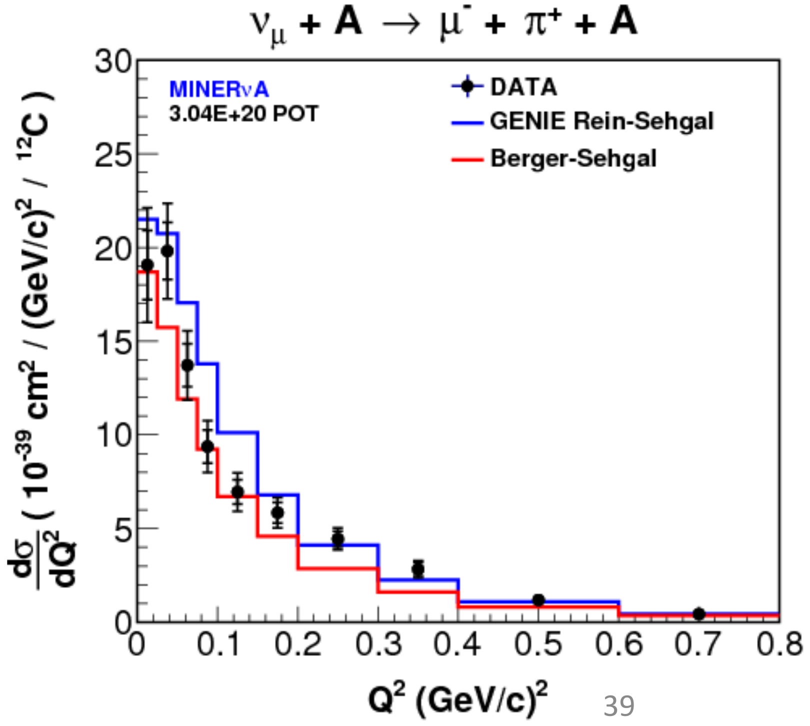
Coherent pion production

- 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.

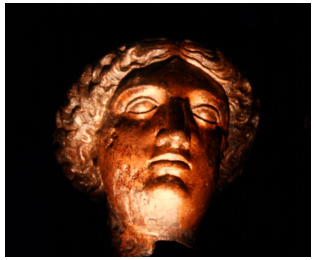


Phys.Rev. D97 (2018) 032014
Phys.Rev.Lett. 113 (2014) 261802

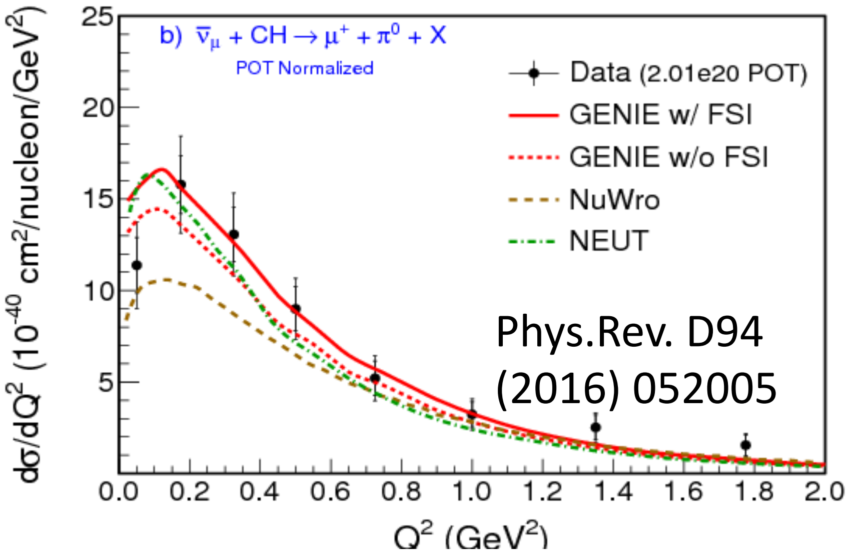


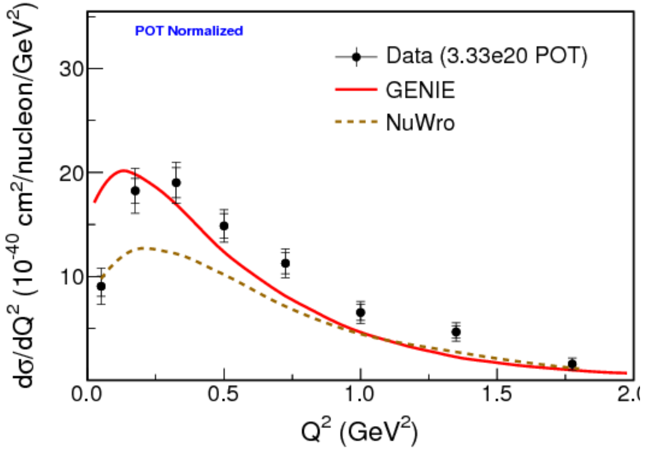


Incoherent pion production observations

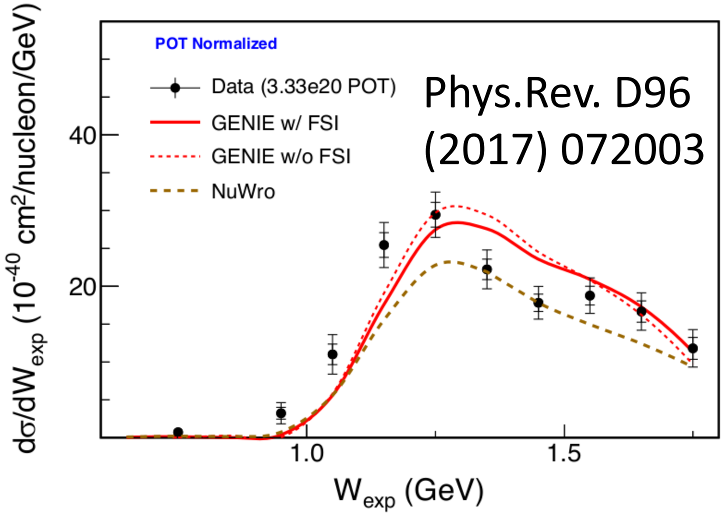


- MINERvA sees a strong deficit of pion production at low Q^2 in several channels.
  - MINOS has also seen a low Q^2 suppression in "resonance region".
- MINERvA also sees a shift in the pion spectra to slightly lower values, which look to be consistent with a shift in the Δ(1232) peak.
  - Maybe resonant-non resonant interference that is absent from model?

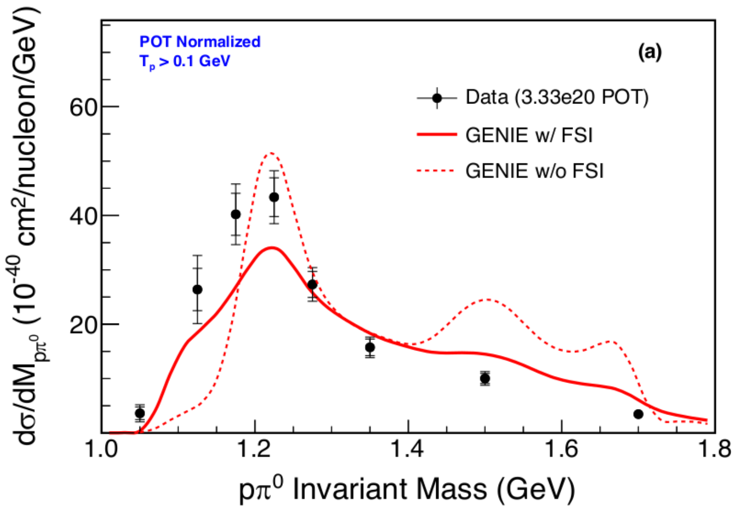




$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$



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

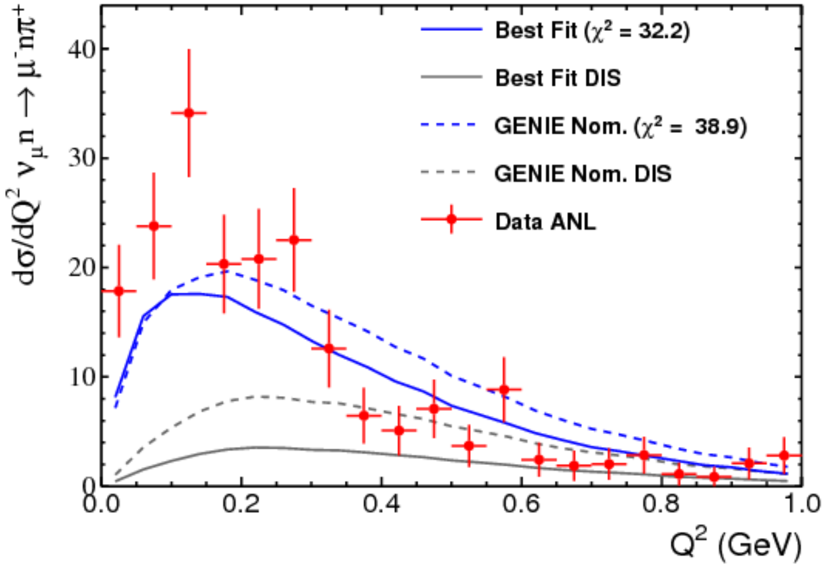


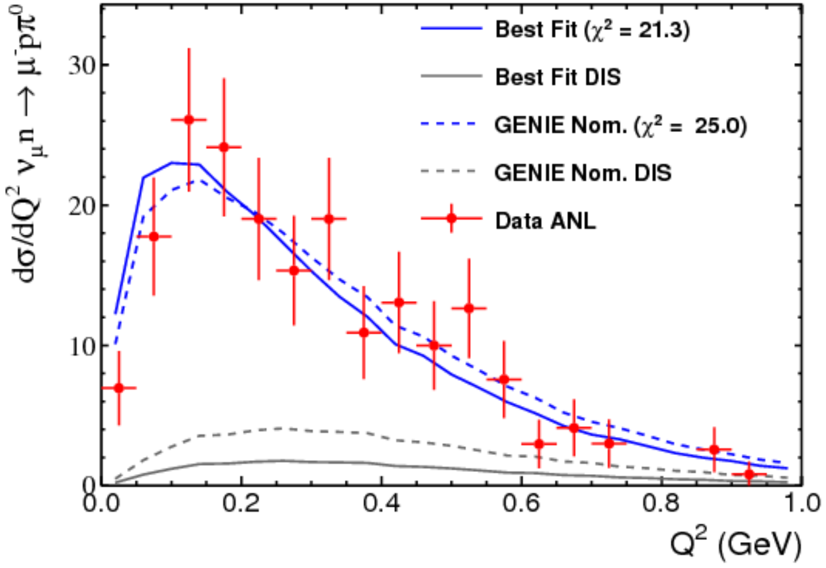
Deuterium Tune

C. Wilkinson, P. Rodrigues, KSM,
Eur.Phys.J. C76 (2016) 474.

- Results taken from analysis of ANL/BNL pion production data
- Largest change is reduction of non-resonant pion production.
- But without interference in the model, this is a bandaid.

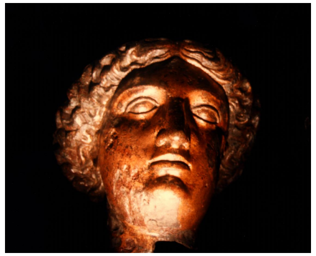
Model	GENIE default	ANL/BNL Tune
M_A^{RES} [GeV]	1.12 ± 0.22	0.94 ± 0.05
NormRES [%]	100 ± 20	115 ± 30
NonRES1π [%]	100 ± 50	43 ± 4

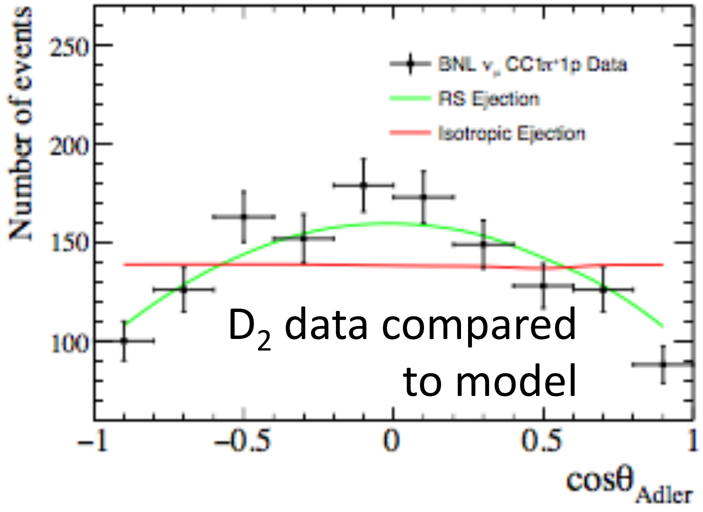


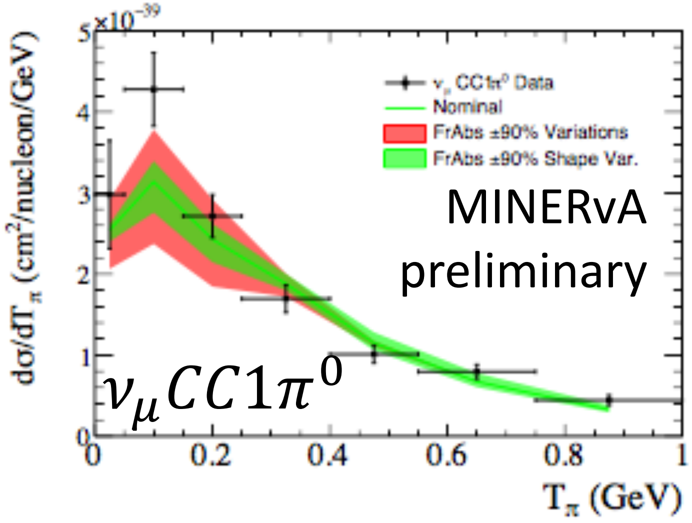


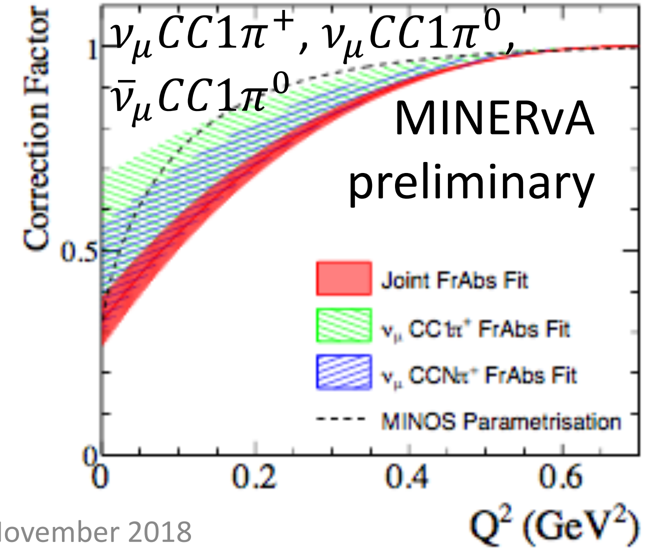
Pion tune results

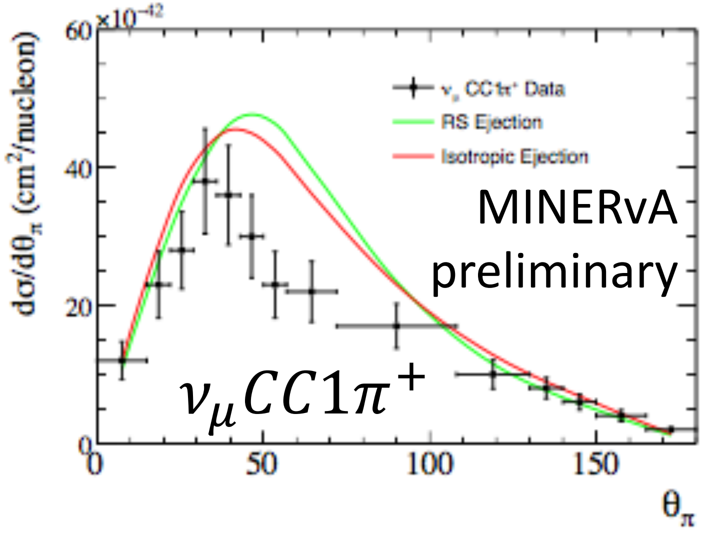
1. Form factor and non-resonant terms are not strongly pulled.
2. Strong FSI pulls are preferred, but hard to tell which.
3. Carbon data favors isotropic emission, which perhaps says more about FSI than emission.
4. Low Q^2 suppression is strongly preferred.

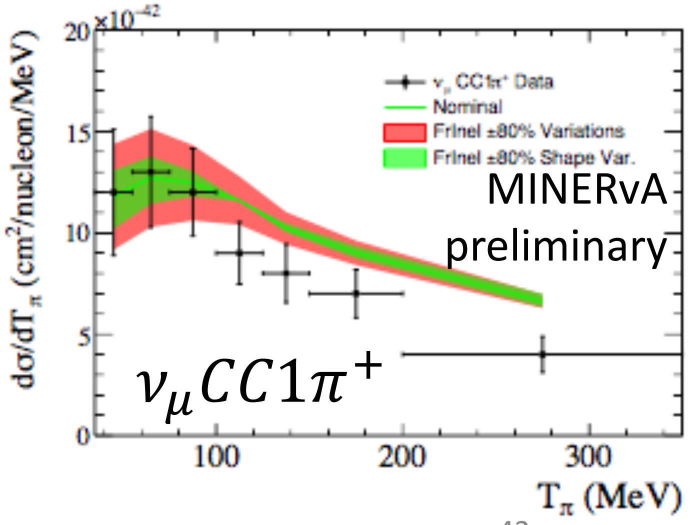




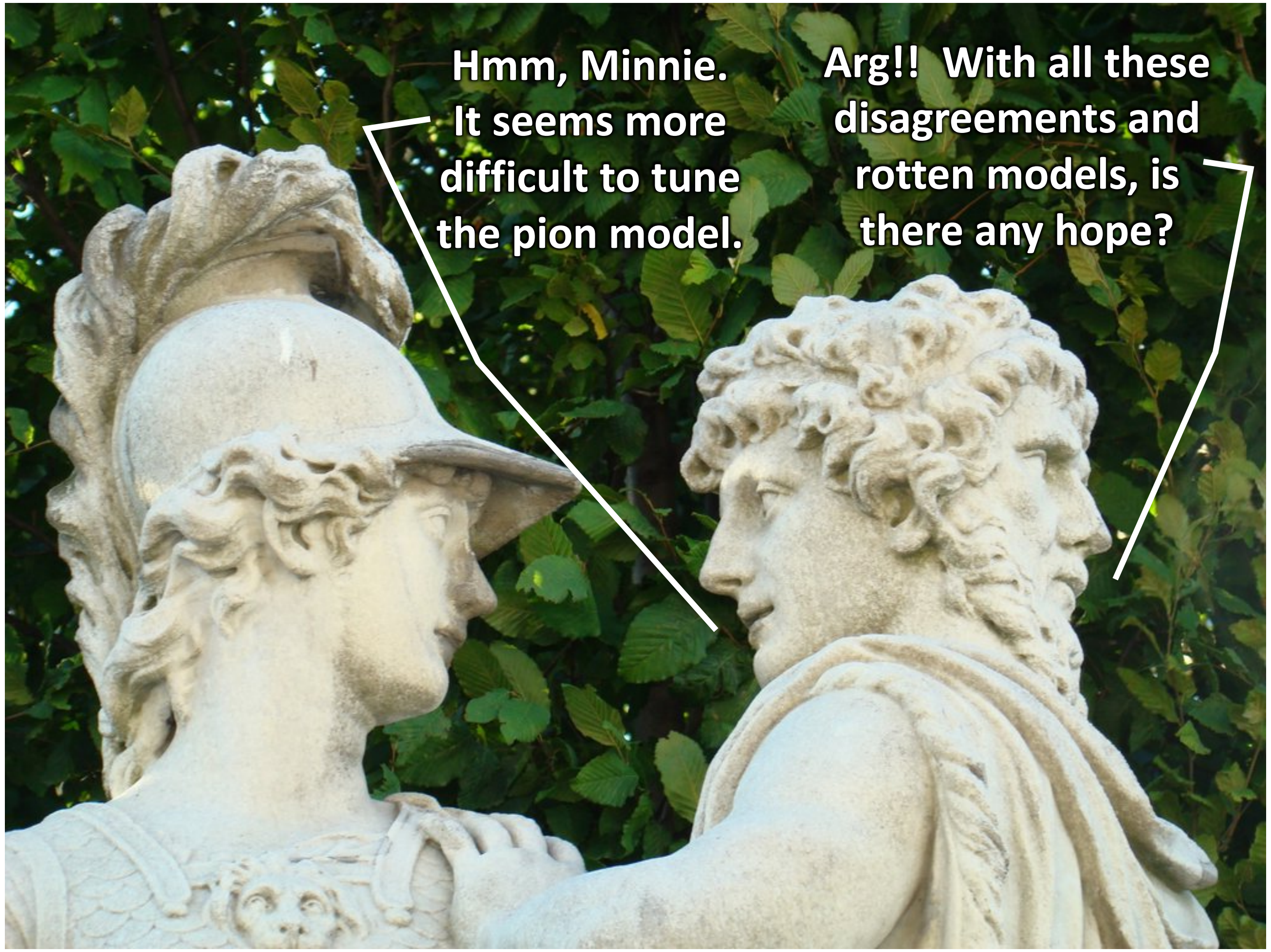






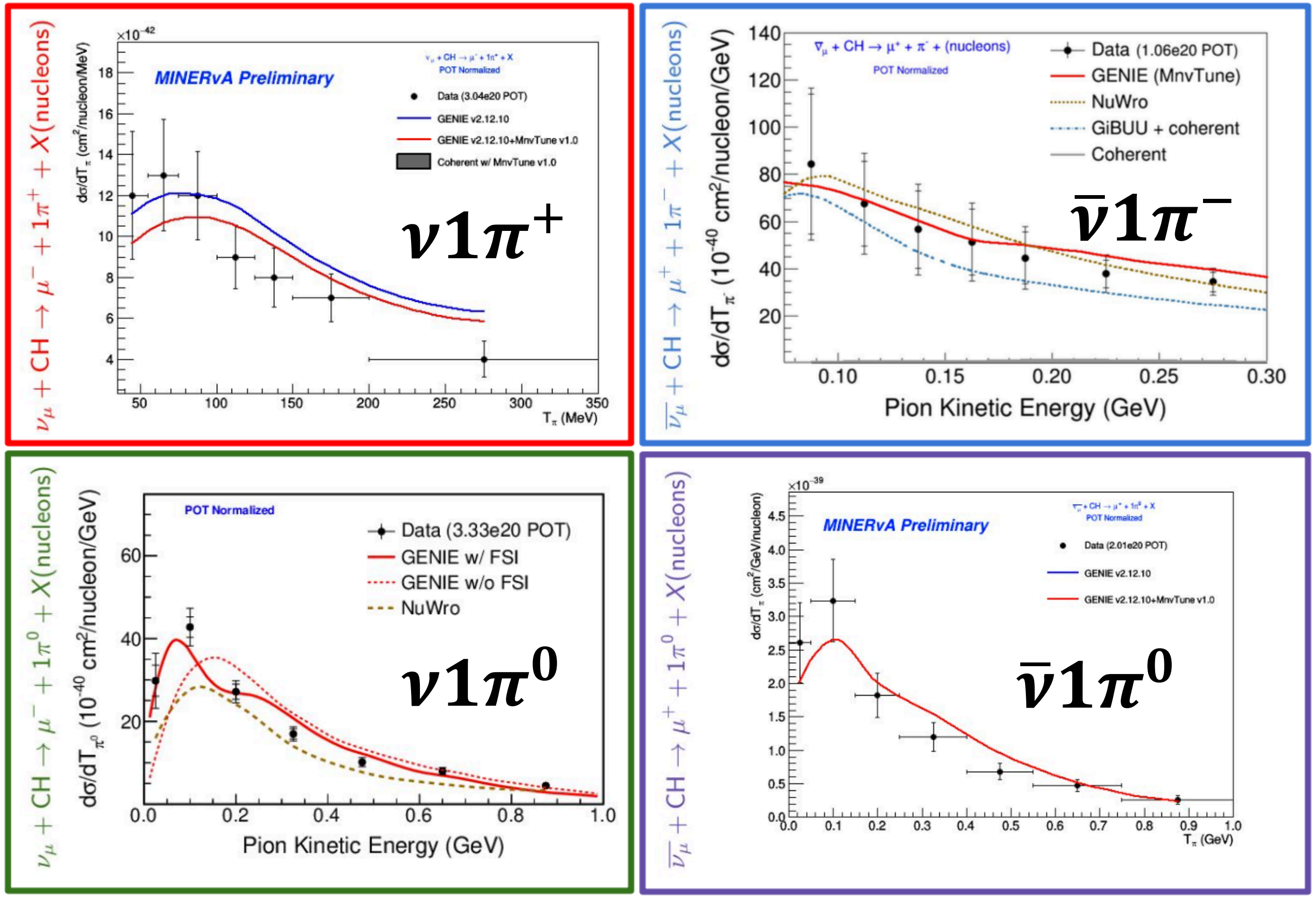


CC1$\boldsymbol{\pi}$ Tune Perspective



- With so many incomplete ingredients, it has not been as satisfying an exercise as in CC0$\boldsymbol{\pi}$.
- To make progress, additional inputs, such as improved primary production of FSI models, will probably be needed.
- Also pursuing pion tagged "low recoil" style analyses.
- Nevertheless, MINERvA's tune, with the exception of the low Q^2 puzzle, does reproduce most important variables in our single pion data well.

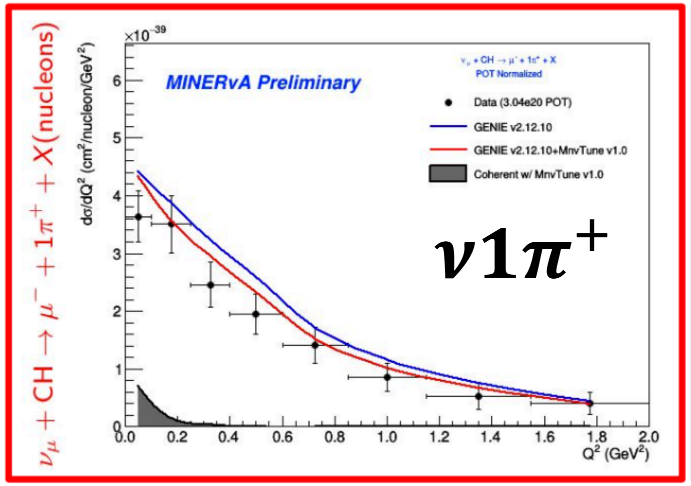
MINERvA's Four Charged-Current Single Pion Channels: T_π

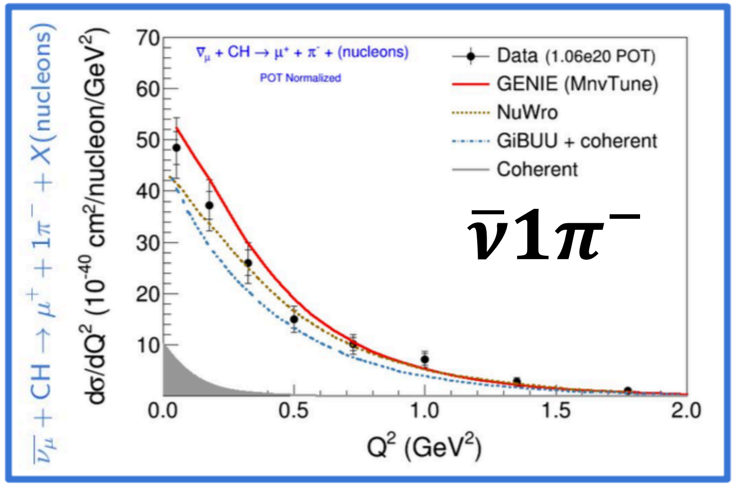


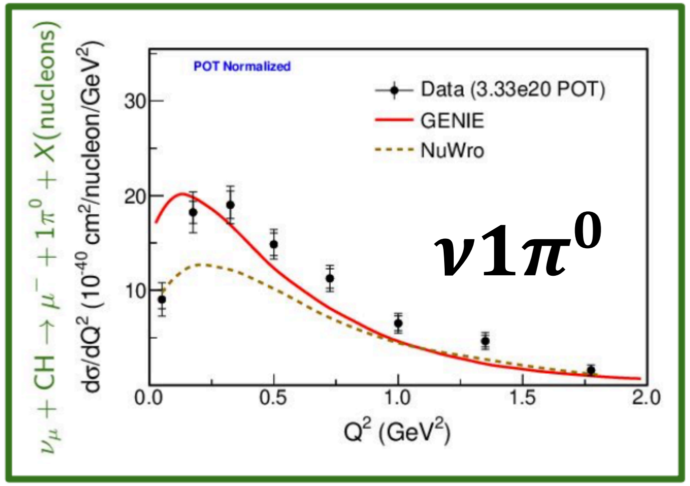
Pion Kinetic Energy (GeV)

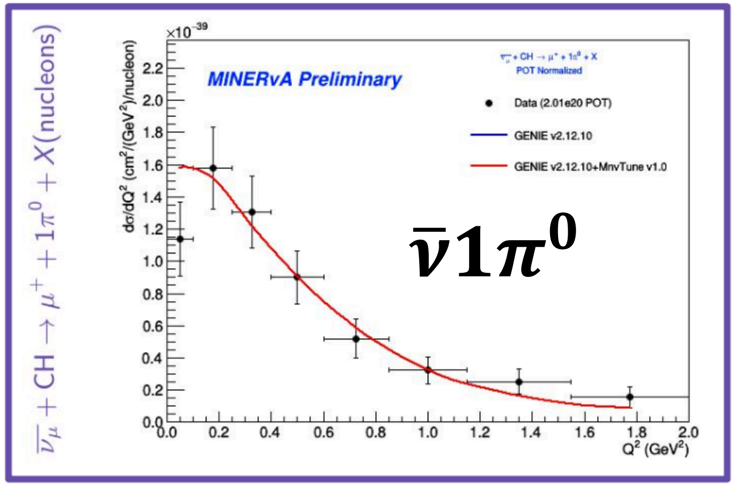
- Generally adequate description from MINERvA tuned GENIE 2.12.x
- Some tendency for more strength at lower energies
- Maybe consistent with shift of Δ? Maybe consistent with FSI alteration?

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





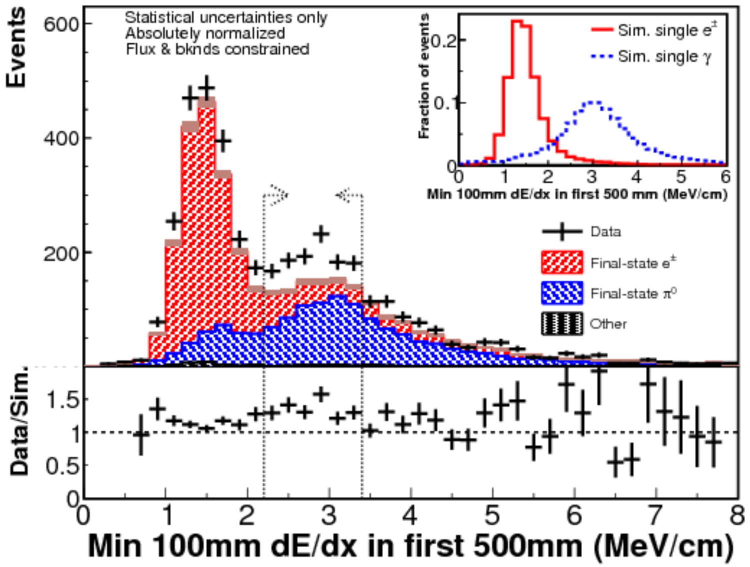


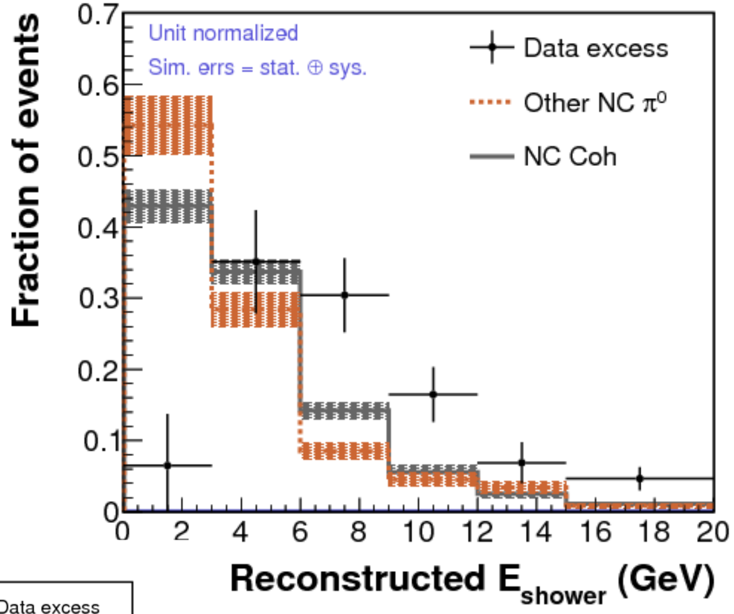


- Neutral pion production shows strong low Q^2 suppression
- Unknown nuclear effect?
- Charged pion final states have a coherent contribution included, but diffractive production from hydrogen in MINERvA unsimulated.

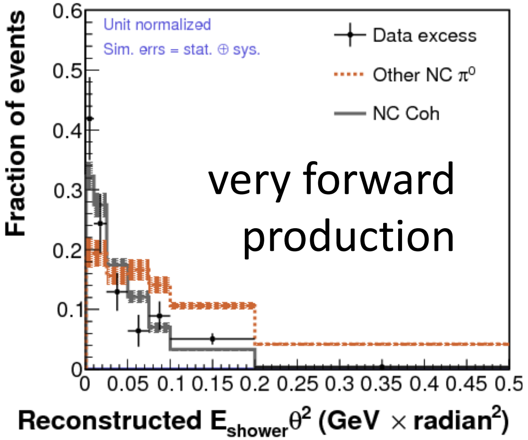
$$Q^2 = 2E_\nu\left(E_\mu - p_\mu \cos\theta_{\mu\nu}\right) - m_\mu^2 \quad (\text{GeV}^2/\text{c}^2)$$

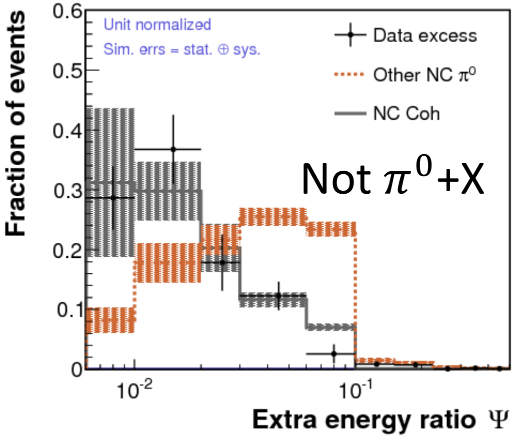
High energy diffractive (?) π^0

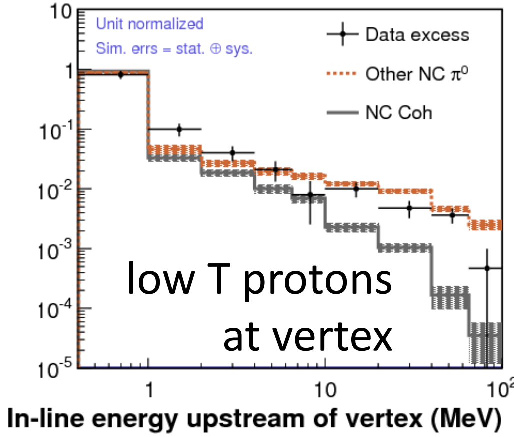




- Our electron neutrino analyses found excess events with dE/dx near the "electron" vertex consistent with photons.
- Most consistent with high energy diffractive π^0 production missing in GENIE.
- Important to add "by hand" for all electron neutrino analyses.
- No model describes this! Sorry.







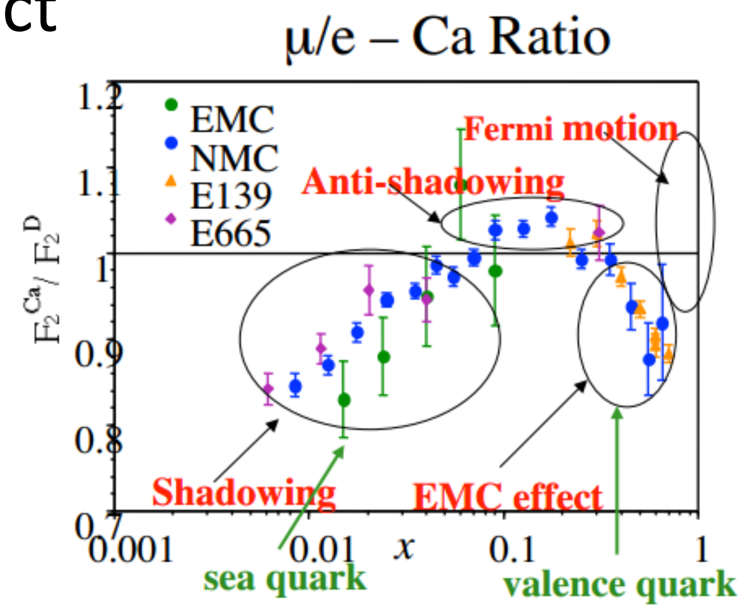
Phys.Rev.Lett. 117 (2016) 111801

More inelastic events

- Total cross-sections
- Nuclear targets
- Outlook

Another Goal: Nuclear Effects in DIS

- In Deep Inelastic kinematic regime, there are a variety of effects observed in charged lepton scattering: shadowing at low x, Fermi Motion at high x and the "EMC effect"
- Viable models exist for the former two, and related phenomena have been observed.
  - Interesting to test with neutrinos as well.



- BUT, the "EMC effect" region has one data set, charged lepton DIS, on a variety of nuclei.
- Difficult to distinguish models: the "Every Model's Cool" problem.
- No neutrino data on these ratios prior to MINERvA.

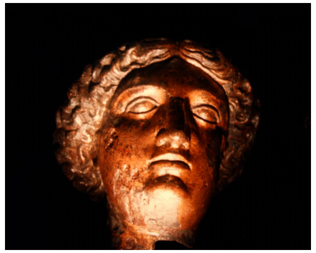
CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years

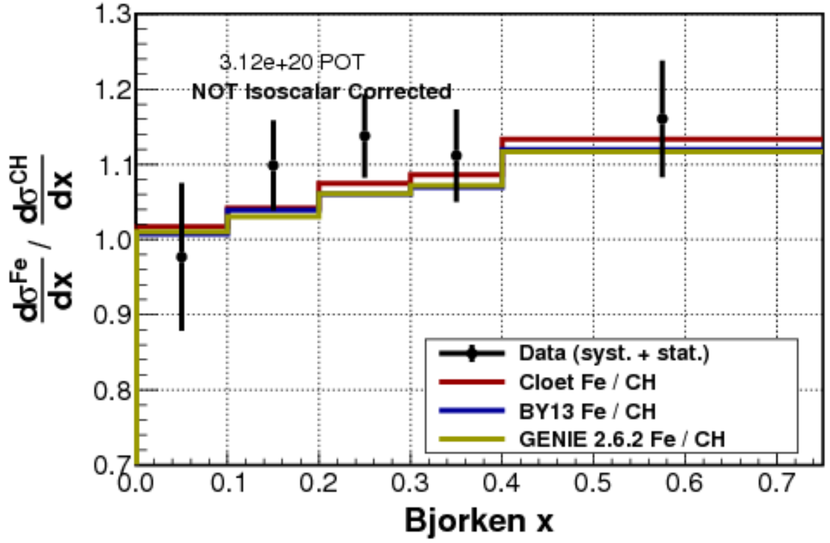
Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

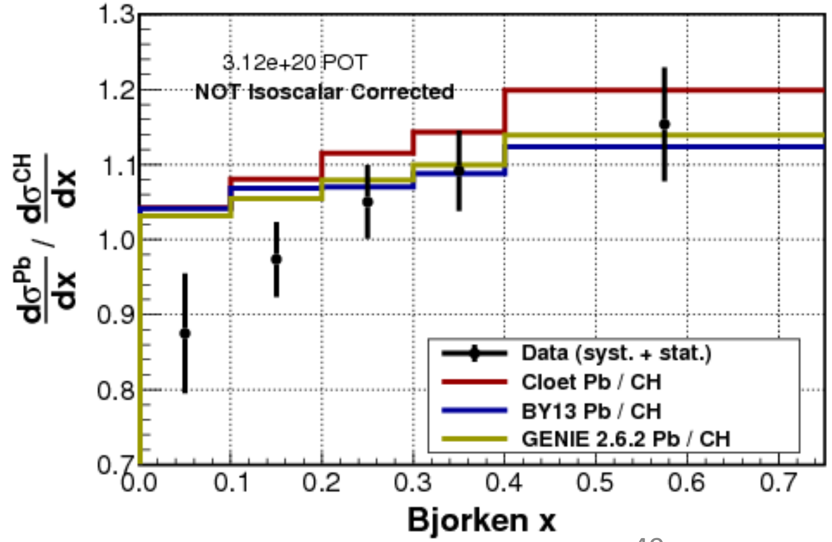
Deep Inelastic Scattering on Passive Targets



Phys.Rev. D93 (2016) 071101
Phys.Rev.Lett. 112 (2014) 231801

- Analysis with current dataset was severely statistics limited because of low energy beam.
- Insufficient statistics in antineutrinos.
- Some modest indication of shadowing beyond prediction in the lead sample.



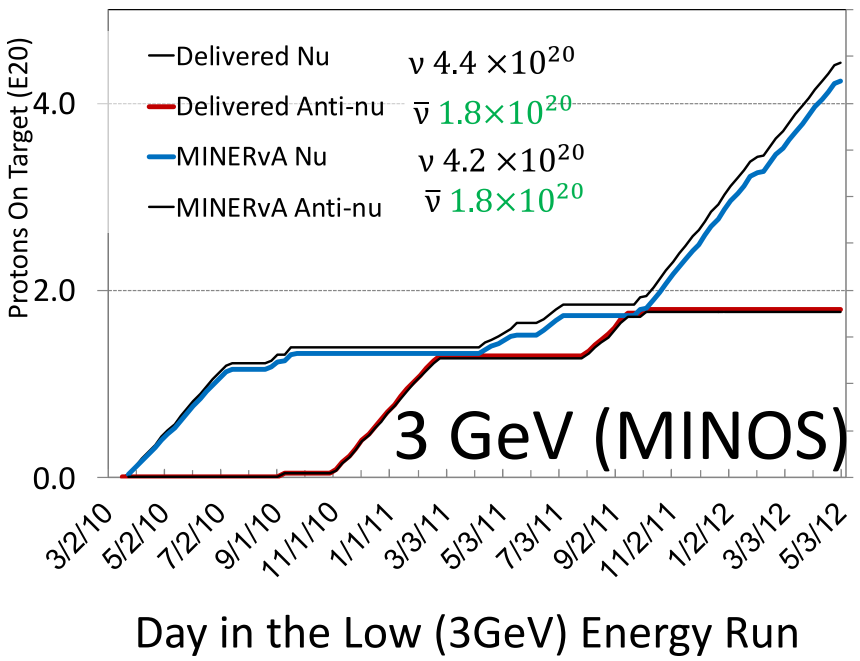


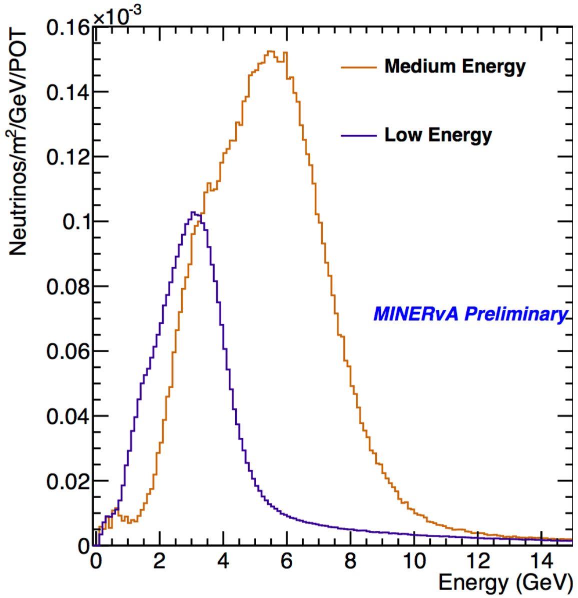
MINERvA's New Data: NOvA era

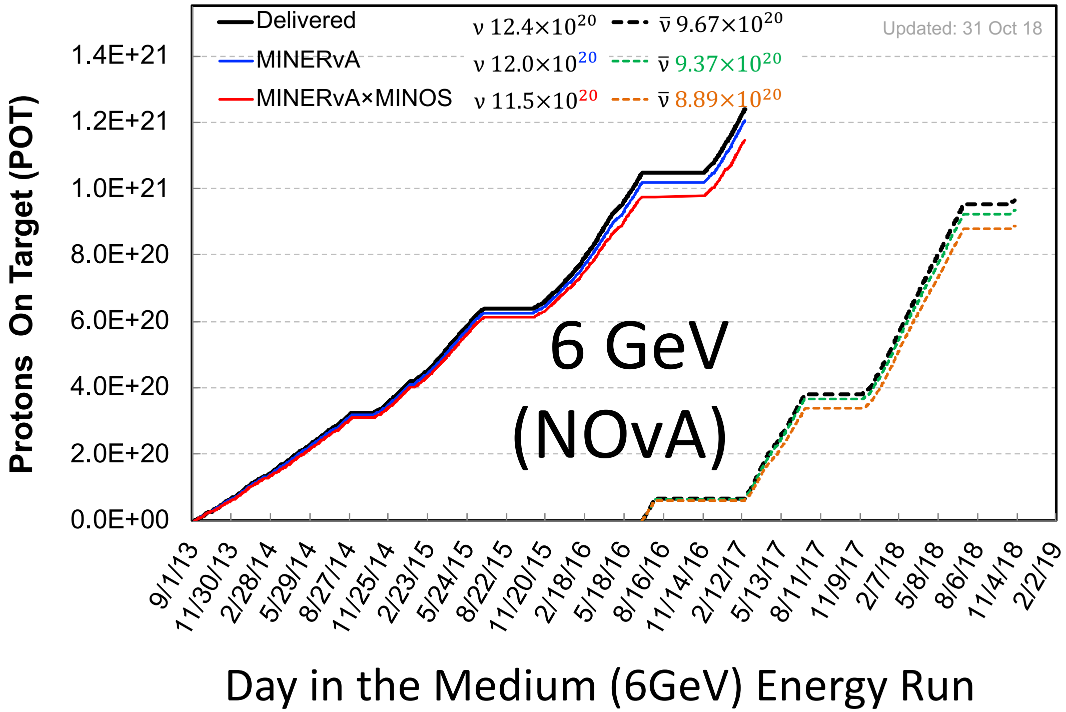
- Flux
- First look at high statistics results

MINERvA benefits from the outstanding beam delivered to MINOS and with NOvA

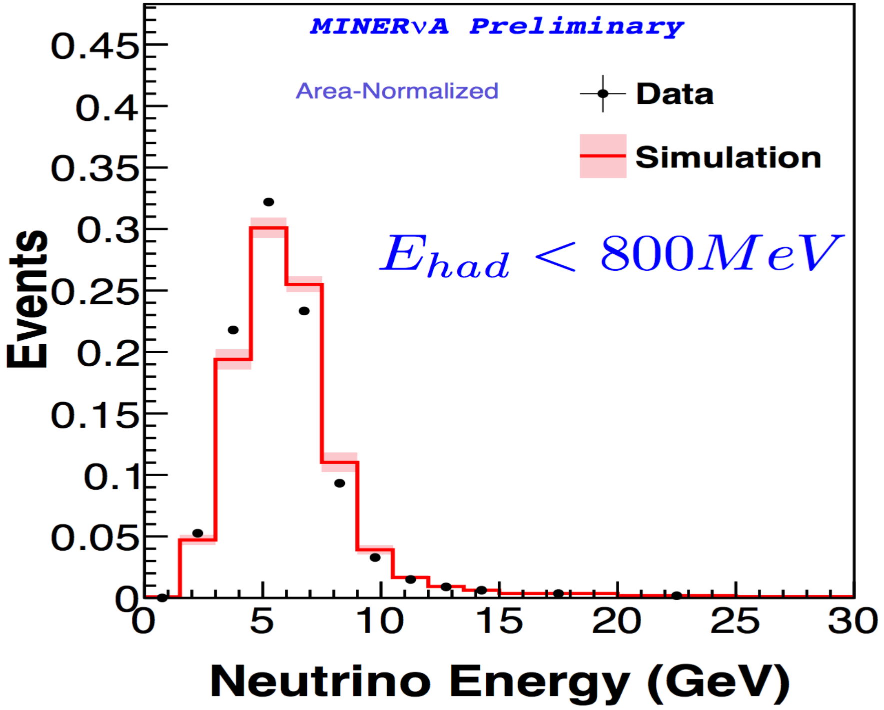
- We are grateful to the accelerator division and the NuMI beam group.

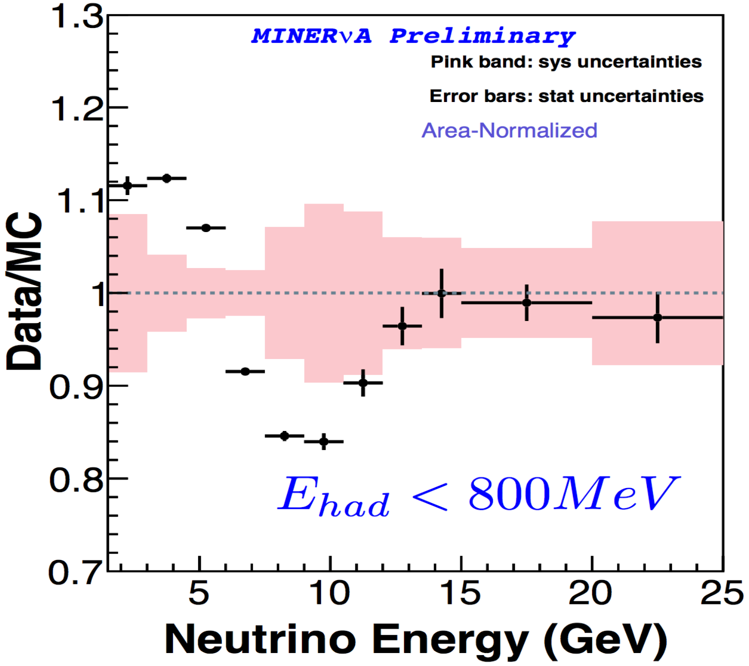






6 GeV ("Medium Energy") Flux Puzzle





low recoil events

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

normalization uncertainties not shown

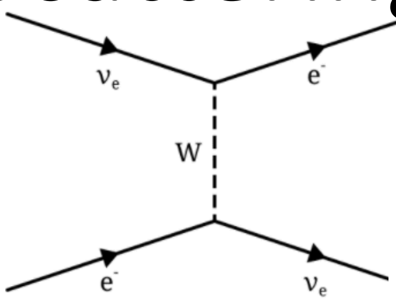
- Results of fits to low recoil flux measurement in different regions of the detector give two equally valid solutions.

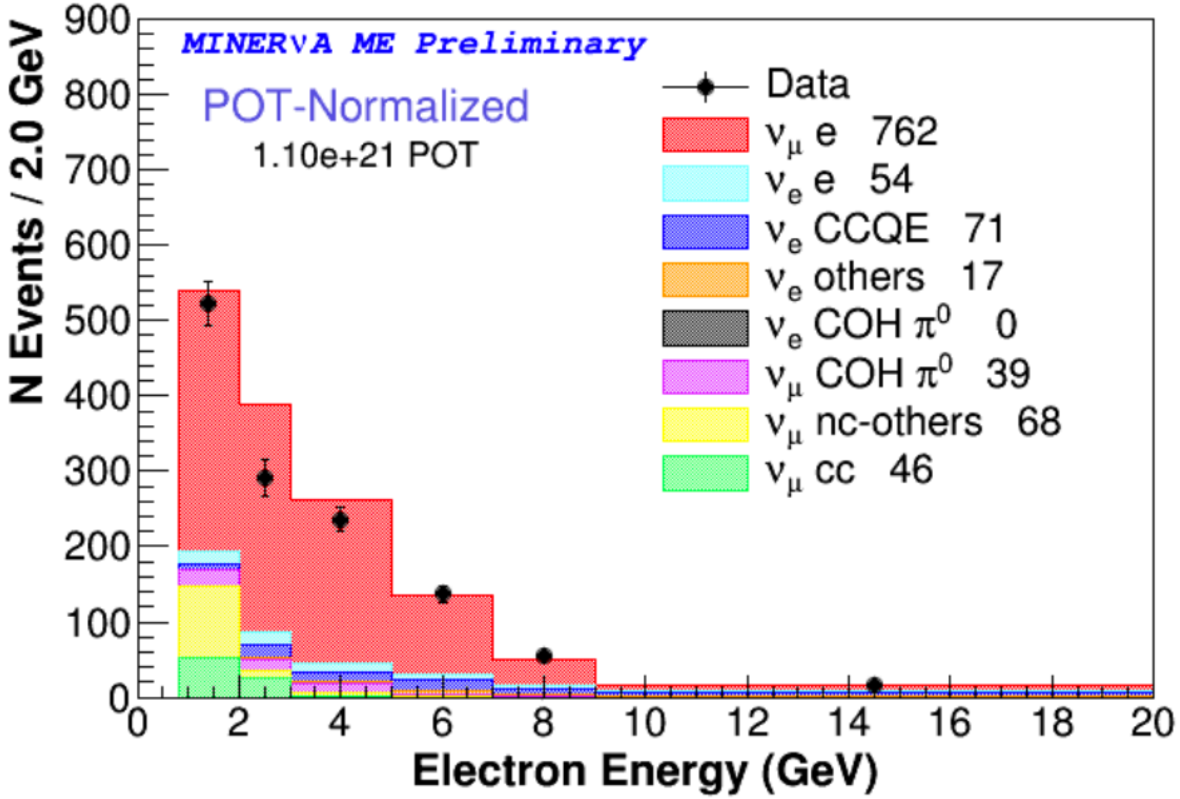
Surprisingly, this indicates NuMI's focusing peak is *a priori* more precise than our detector calibration!

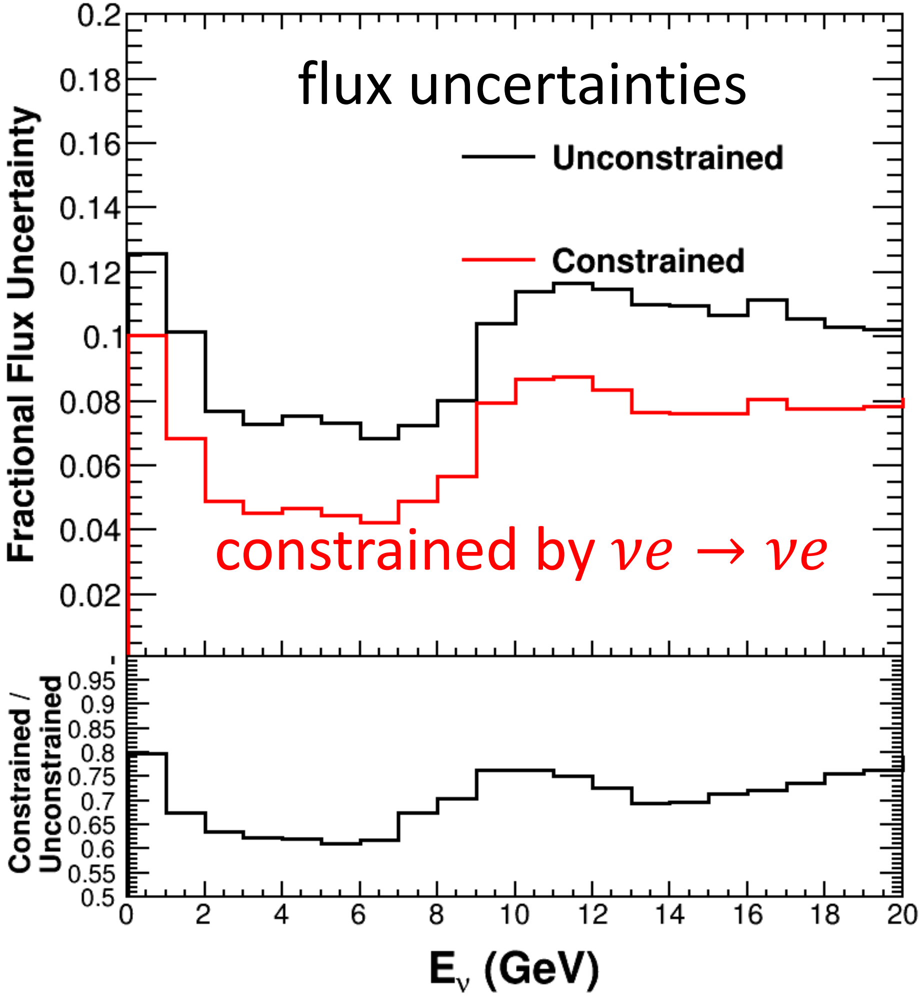
For now, we consider the full range of both solutions as uncertainties.

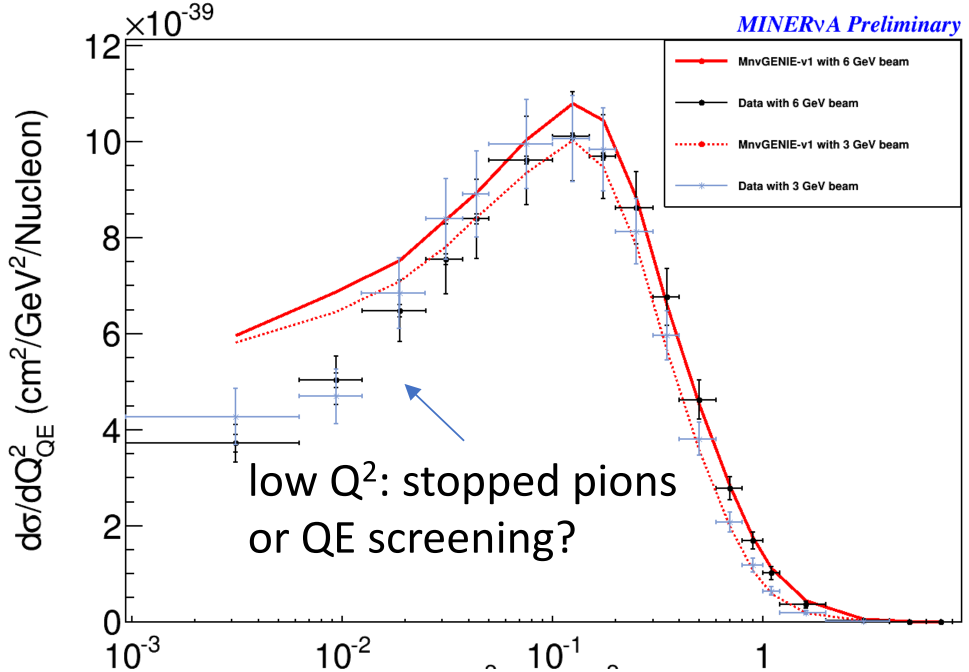
6 GeV ("Medium Energy") Flux from Neutrino-Electron Scattering

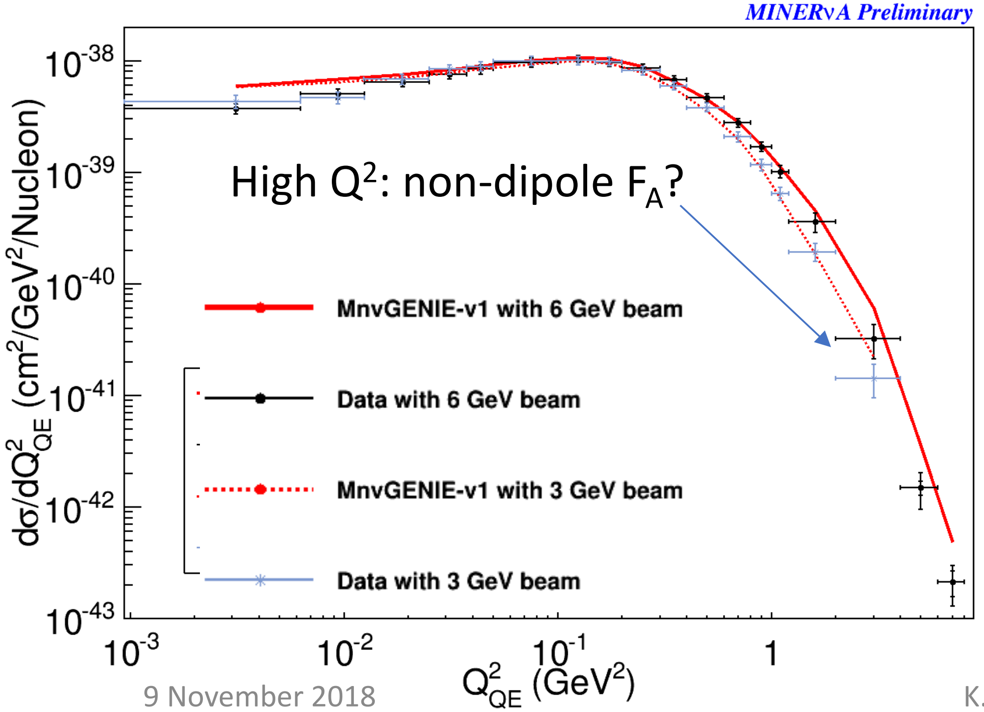
- Neutrino-electron elastic scattering is a standard candle for neutrino interactions.











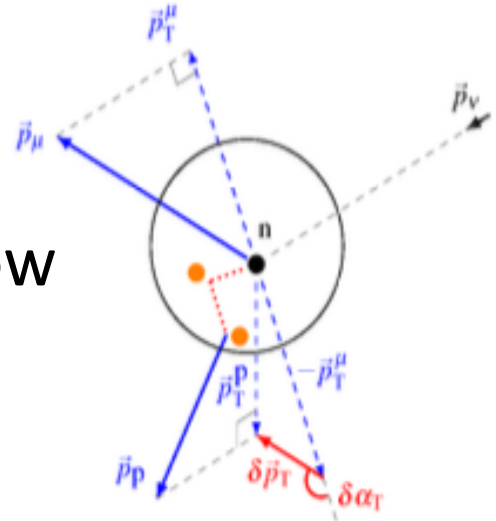
6 GeV CC0π

- 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.

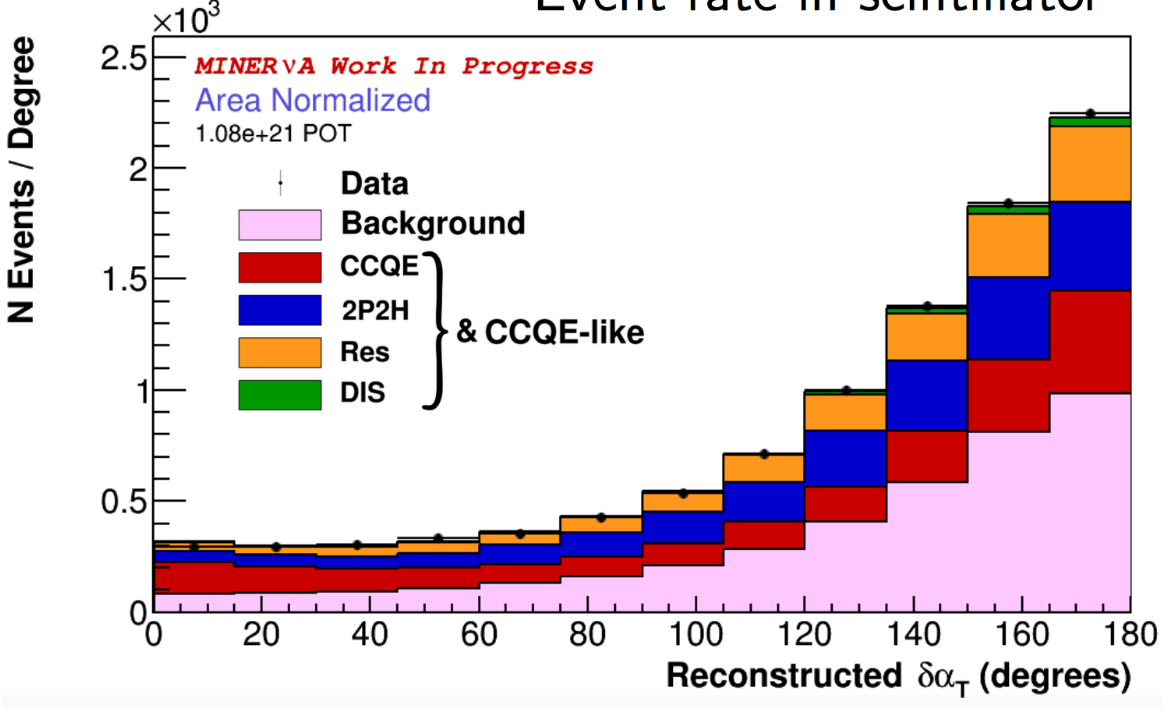
3 GeV from arXiV:1811.02774, preliminary 6 GeV results

6 GeV CC0π in Targets

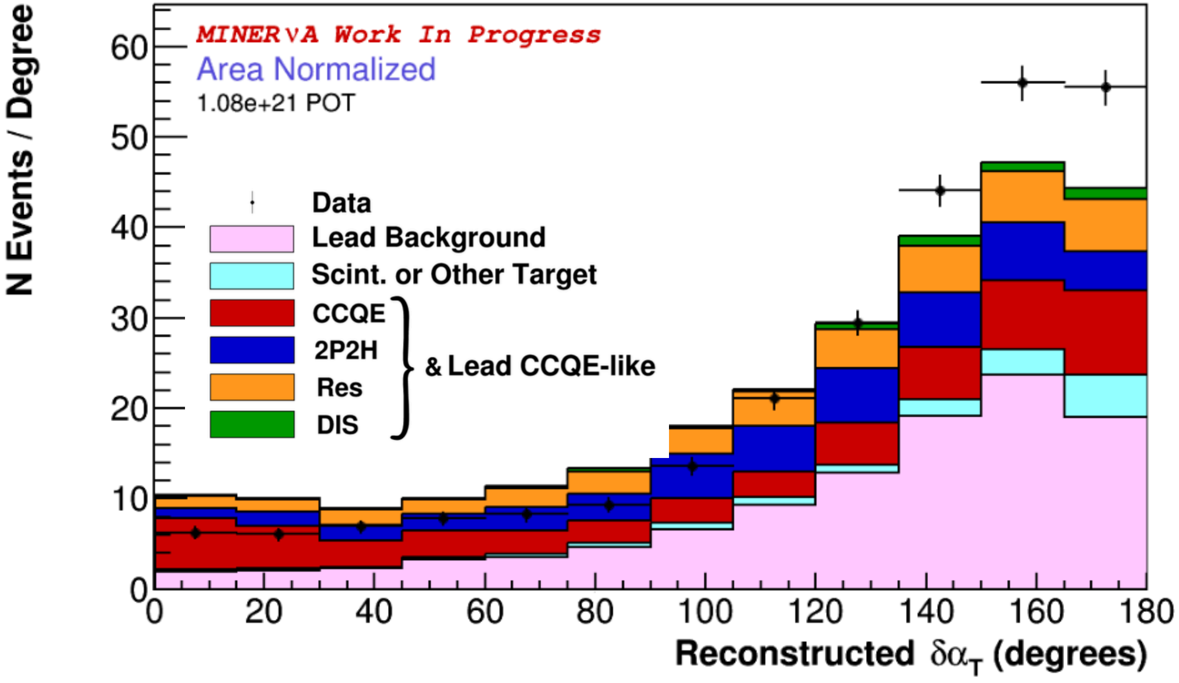
- We are studying transverse variables, but now with enough statistics to make meaningful statements in water, iron, and lead targets.



Event rate in scintillator



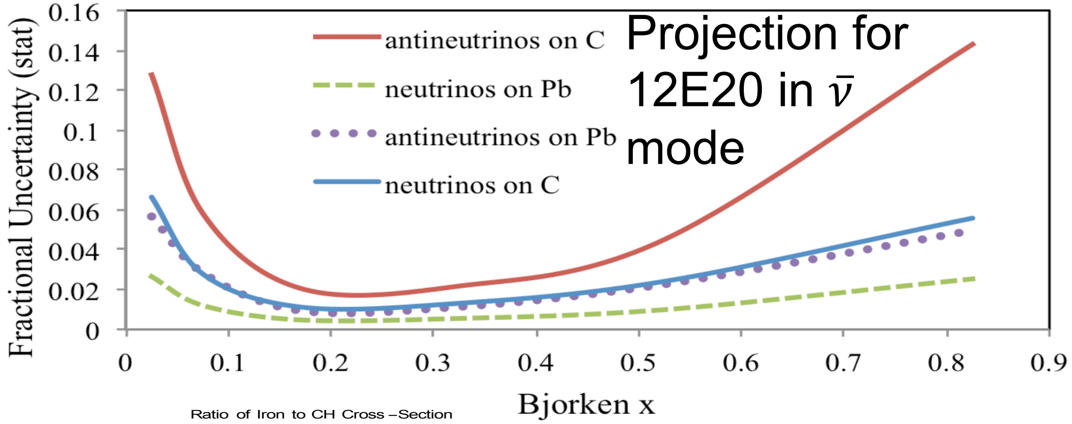
Event rate in lead

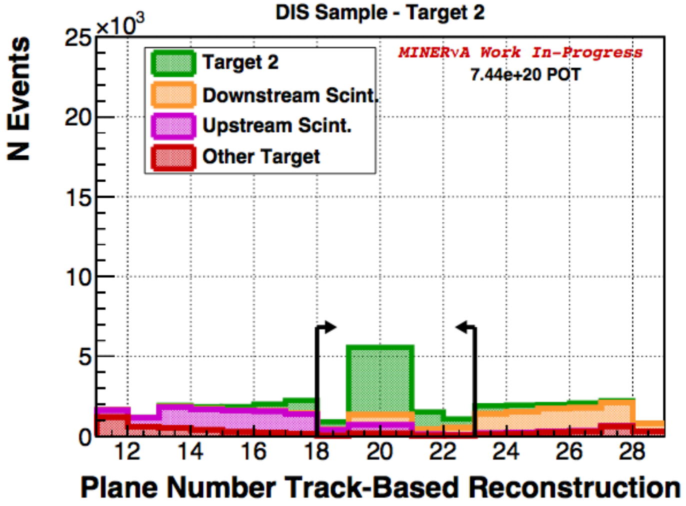


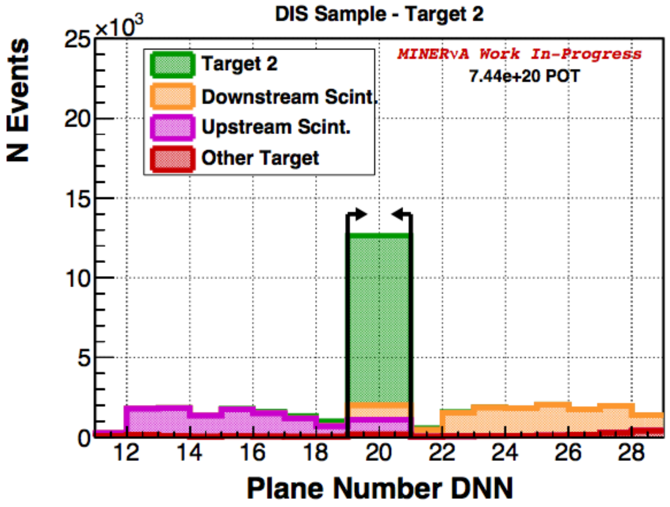
- Lead target sample, ~5000 events. Similar backgrounds to scintillator sample.

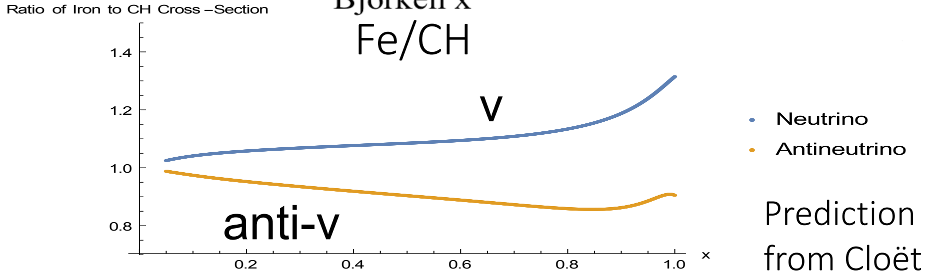
6 GeV DIS Ratios in Targets

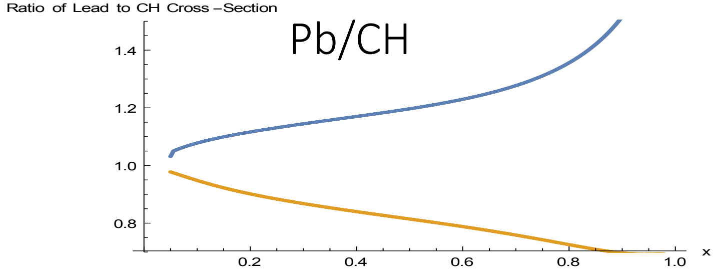
- Models for EMC effect typically predict different effects in neutrino and antineutrino scattering
- Completion of MINERvA's run allows "ν-EMC" ratio measurement vs. quark momentum fraction at ~5% precision for Fe and Pb











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. (See arXiV:1808.0883)

Conclusions

~~Lessons Learned~~
Meta-Lessons Learned

We haven't always learned about neutrino interactions in the way we thought we would. Here are a few hard won meta-lessons for other experiments to consider.

- Inclusive measurements (flux-integrated lepton kinematics for a particular final state) are crucial archival data for model comparisons.
  - But when we've learned about the underlying model, insight most often came from lepton-recoil correlations, e.g., transverse balance, low recoil.
- Sideband constraints for backgrounds are absolutely critical.
  - Tricky to do correctly, i.e., without suspicious model dependence. However, in almost every MINERvA result, the result would have been wrong or imprecise without such constraints.
- Producing results in an archival format is surprisingly easy to do poorly.
  - Some are difficult to express in a model-independent way. Statistical issues are complex. Rounding precision in covariance matrices, etc.

What we've learned about neutrino interactions at MINERvA

- MINERvA has found a number of disagreements with the default models in GENIE 2.12.x & 3.0.x
- Tunes that have been developed that improve the agreement.
- Tune from "low recoil" sample to 2p2h events event seems to have predictive power, at least on MINERvA's data.
- Significant impacts on current oscillation experiments, NOvA and T2K, which already incorporate these ideas.

- The reason that the models currently fail is currently not understood.
  - Low Q^2 pion suppression and shift in Δ peak in pion production
  - "2p2h enhancement"
- Lack of *a priori* understanding limits application of tunes at all energies and on all nuclei.
- Still see deficiencies that could be Fermi gas model of 1p1h peak in transverse variables.

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.

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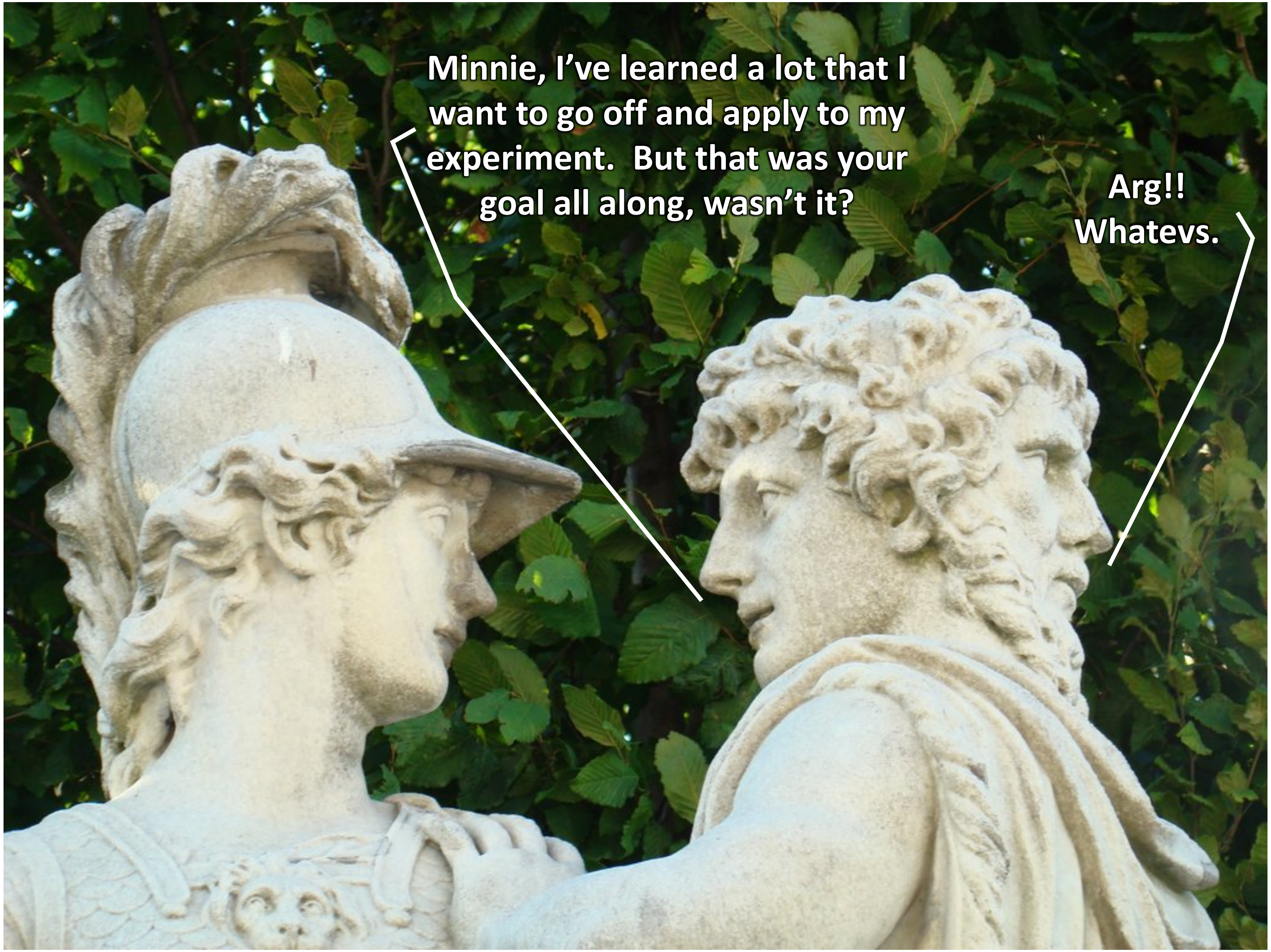
Thank you!


Minnie, I've learned a lot that I want to go off and apply to my experiment. But that was your goal all along, wasn't it?
Arg!! Whatevs.