Tuning the Interaction Model at MINERvA

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NNN 2018, Vancouver

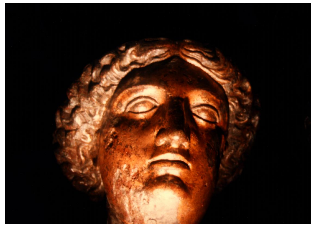
Who? What? Why?

- MINERvA is a neutrino interaction experiment in NuMI
  - Targets of CH, C, H_2O, Fe, Pb. $1.5 < E_\nu < 12$ GeV neutrinos
- MINERvA has “not awesome agreement” with GENIE out of the box within GENIE’s uncertainties.
- Neutrino has developed a model tune, based on theory models implemented in GENIE 2.12.x, D_2 bubble chamber data, and its own measurements that better describes its data than untuned generators.
- The model allows MINERvA to more realistically assess uncertainties in its own measurements.
- The tuned model is also available for use by other experiments, such as neutrino oscillation experiments.

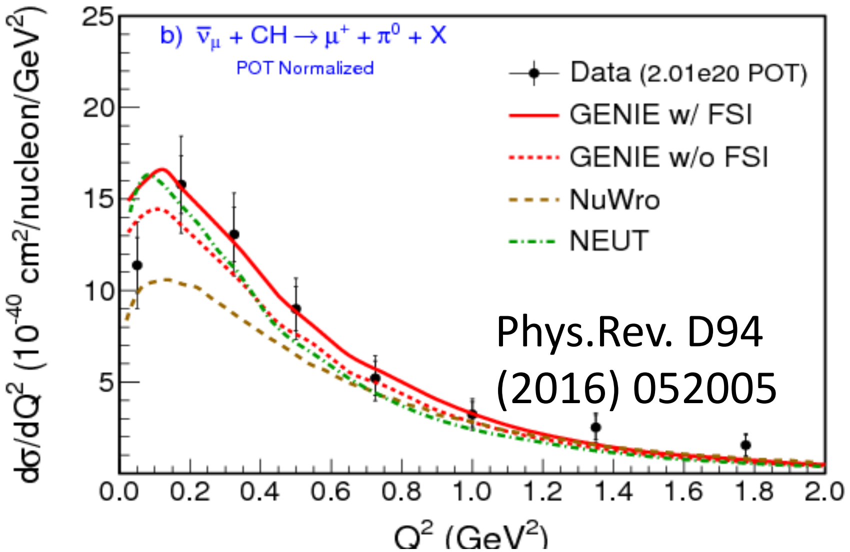
CC1π Tuning

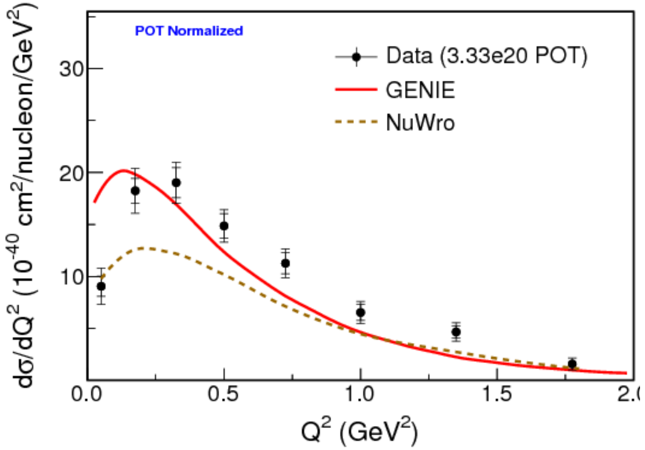
- Data used in tuning
- MINERvA data against tune

Incoherent pion production observations



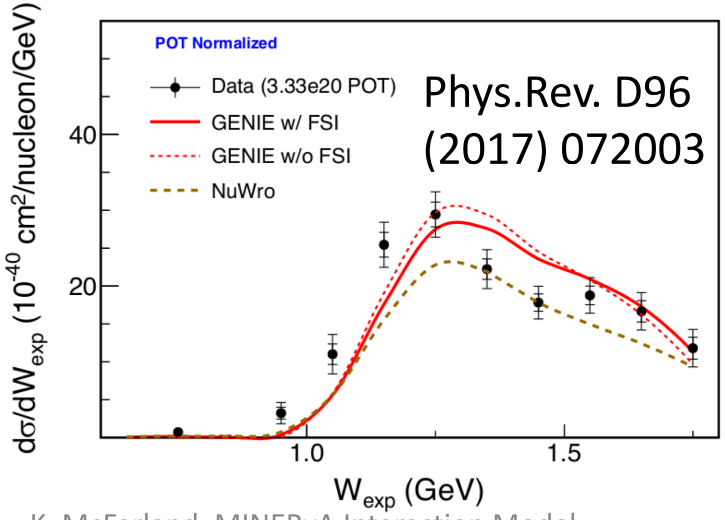
- MINERvA sees a strong deficit of pion production at low Q^2 in several channels.
  - MINOS has also seen a low Q^2 suppression in “resonance region”.
- MINERvA also sees a shift in the pion spectra to slightly lower values, which look to be consistent with a shift in the Δ(1232) peak.
  - Maybe resonant-non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

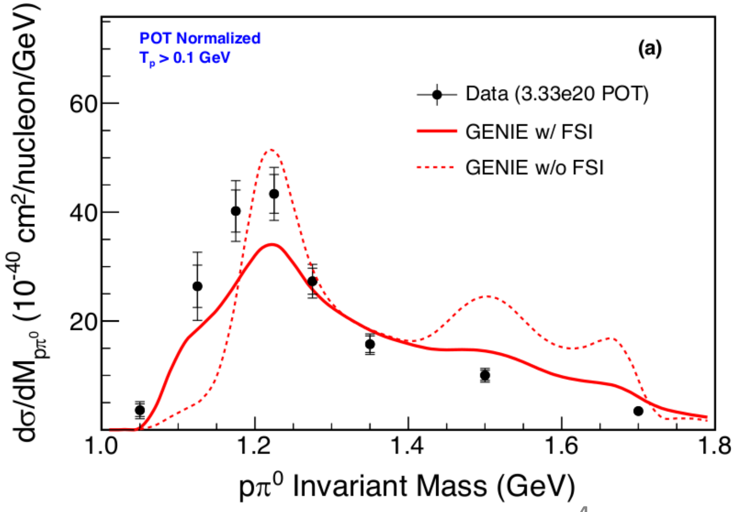




$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$

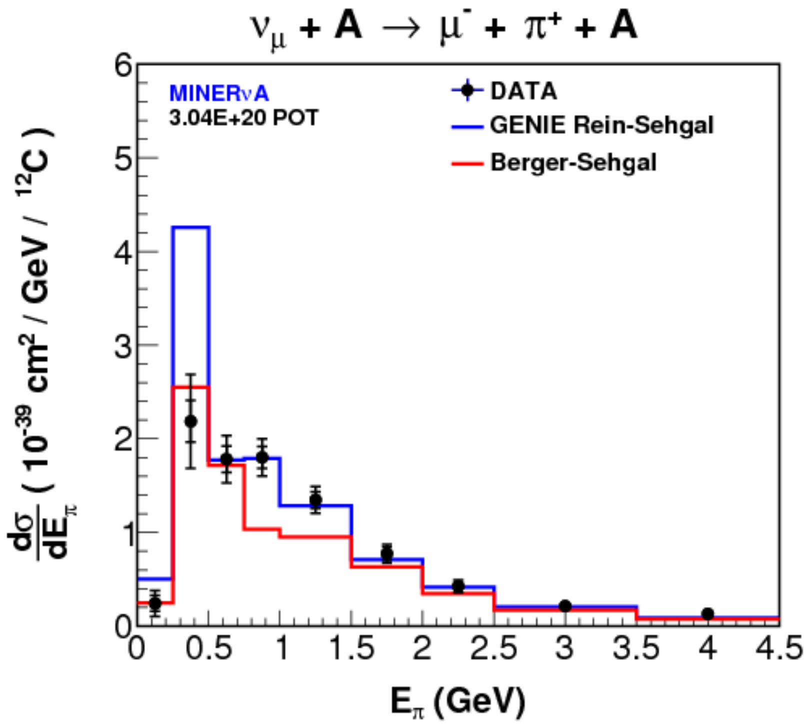
Invariant Mass calculated with proton and π^0 4-momenta



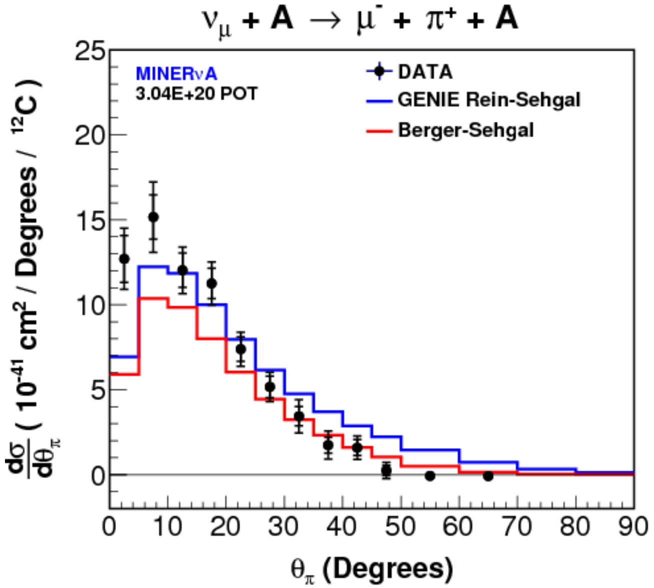


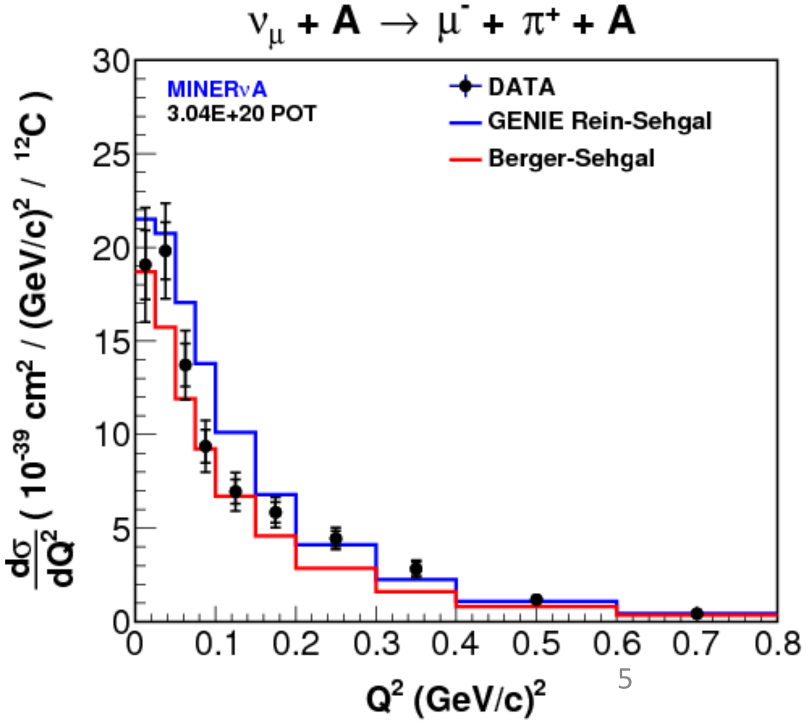
Coherent pion production

- 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.
- 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 Tune Philosophy

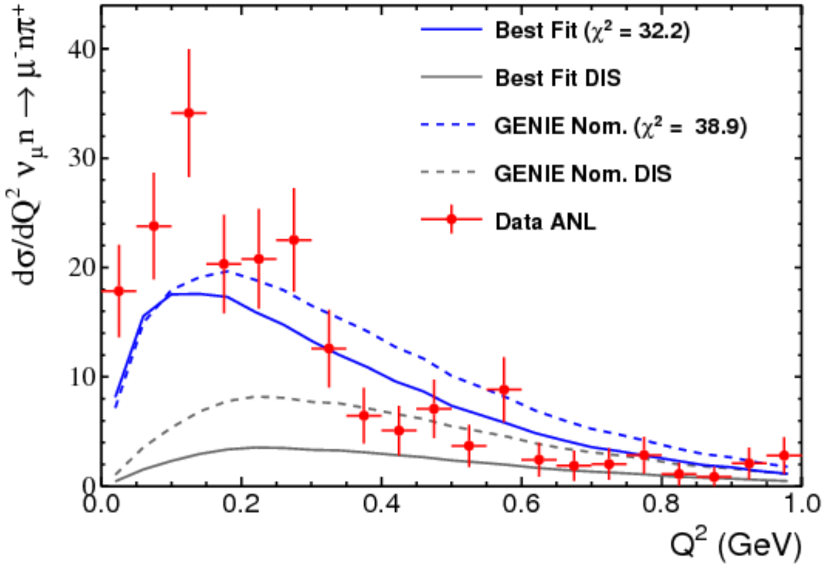
- Try to put in latest understanding from D_2 data reanalysis to give the best starting point for the incomplete Rein-Sehgal model.
- Having done that, look at varying:
  1. The pion production parameters already constrained in the deuterium analysis if needed,
  2. FSI parameters within GENIE,
  3. Angular distributions of pions in resonance decays in Rein-Sehgal,
  4. An ad hoc low Q^2 suppression.

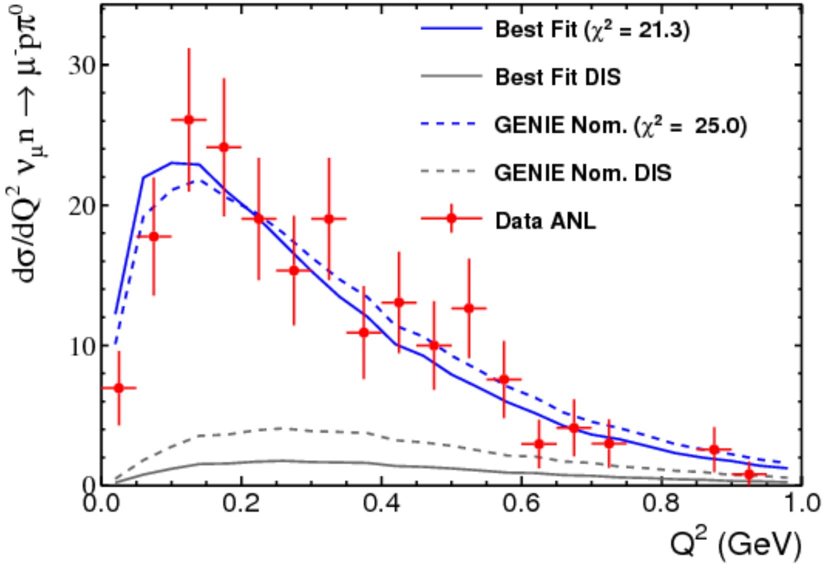
Deuterium Tune

- Results taken from analysis of ANL/BNL pion production data
- Largest change is reduction of non-resonant pion production.

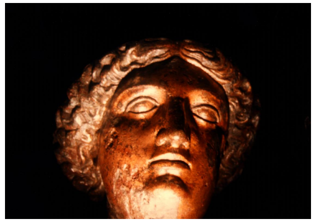
C. Wilkinson, P. Rodrigues, KSM, Eur.Phys.J. C76 (2016) 474.

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

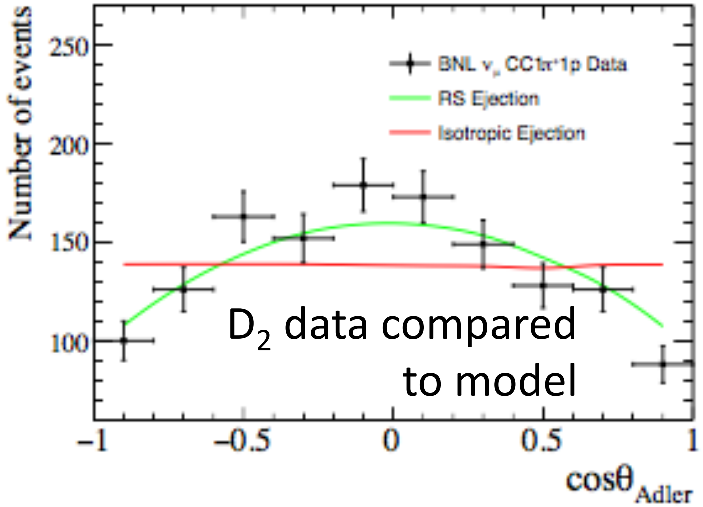


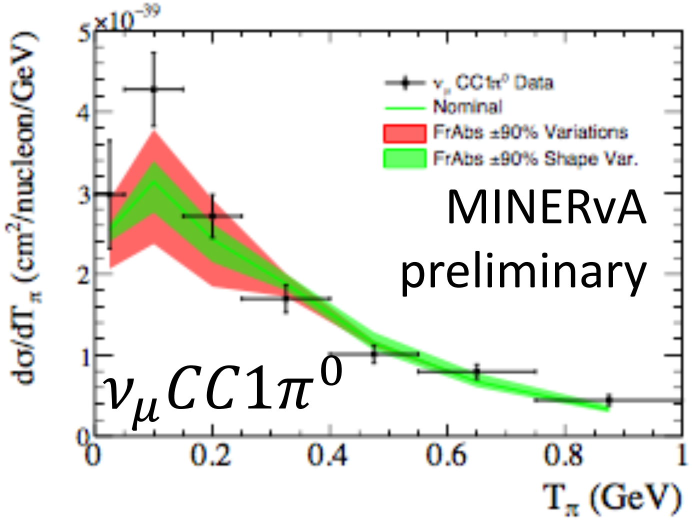


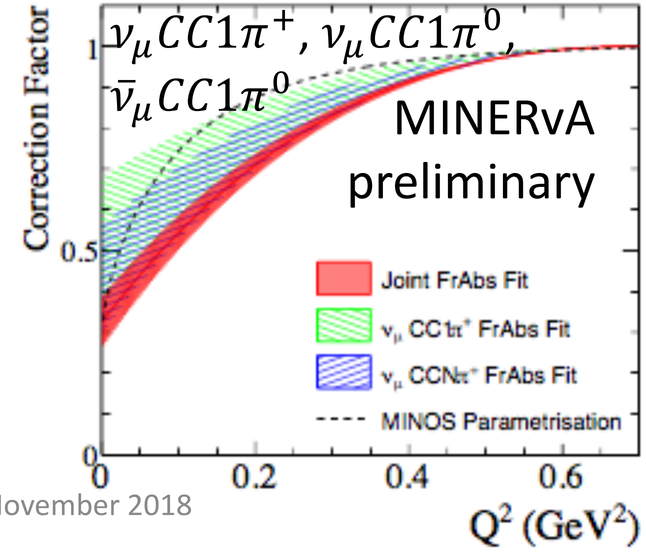
Pion tune results

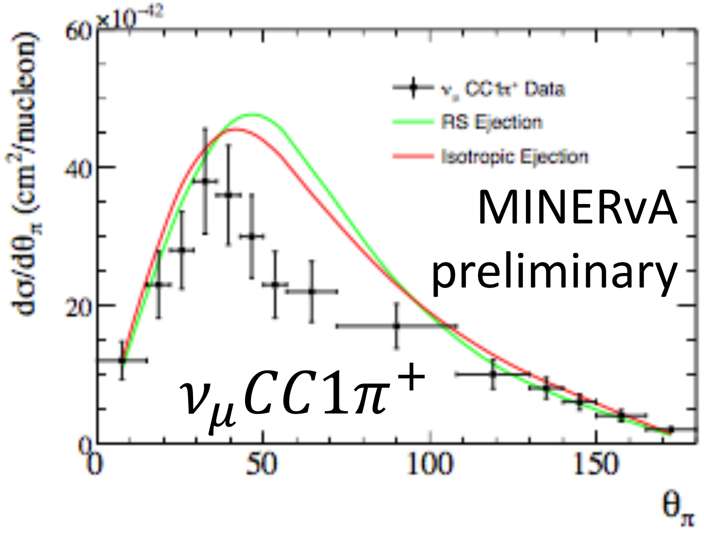


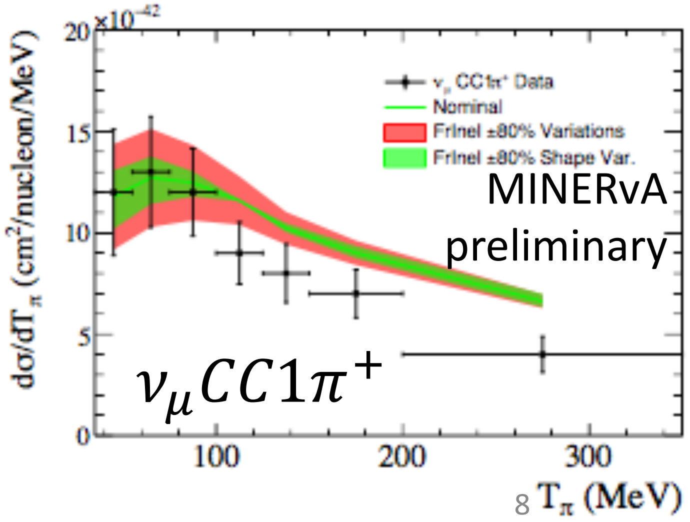
1. Form factor and non-resonant terms are not strongly pulled.
2. Strong FSI pulls are preferred, but hard to tell which.
3. Carbon data favors isotropic emission, which perhaps says more about FSI than emission.
4. Low Q^2 suppression is strongly preferred.



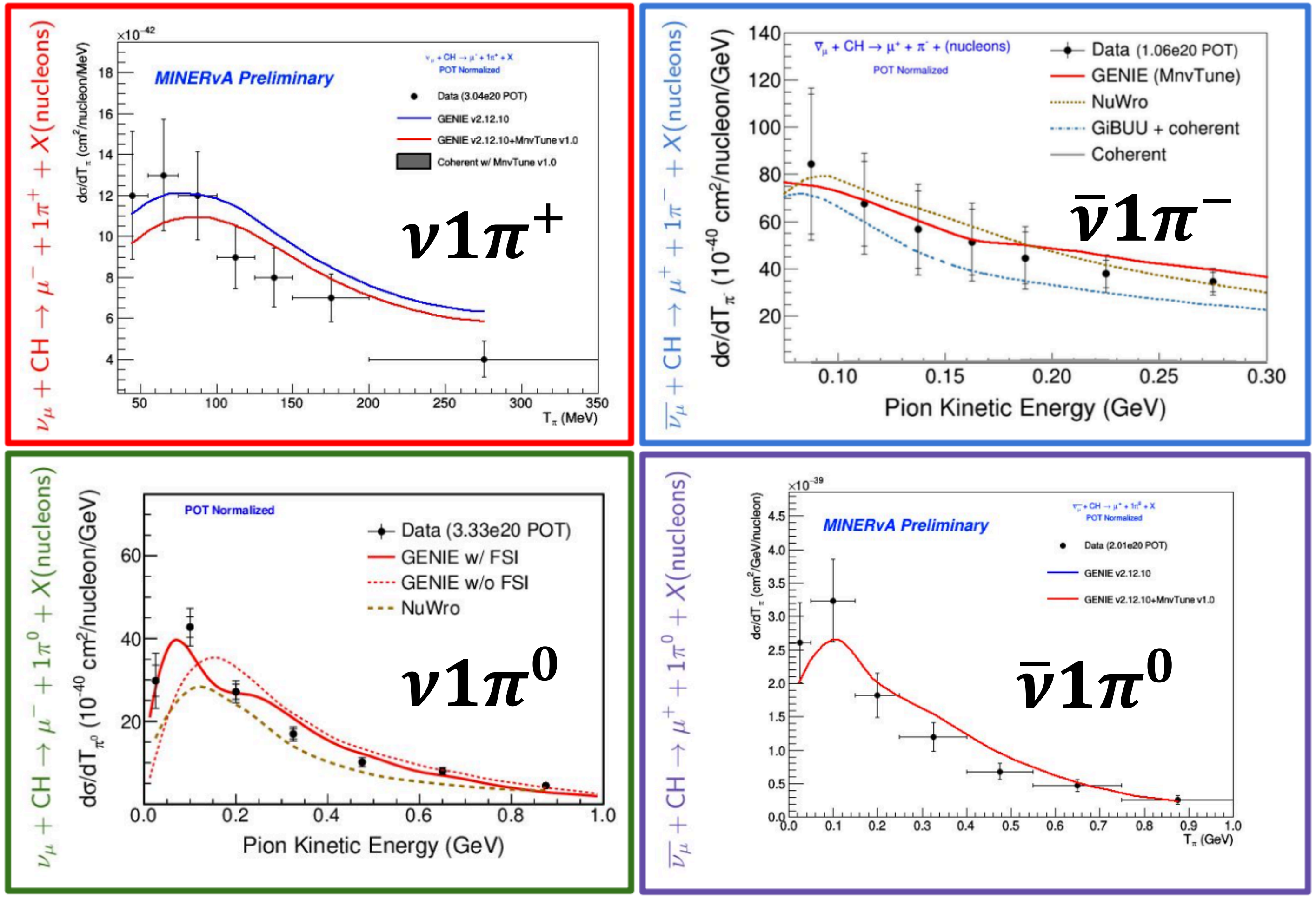








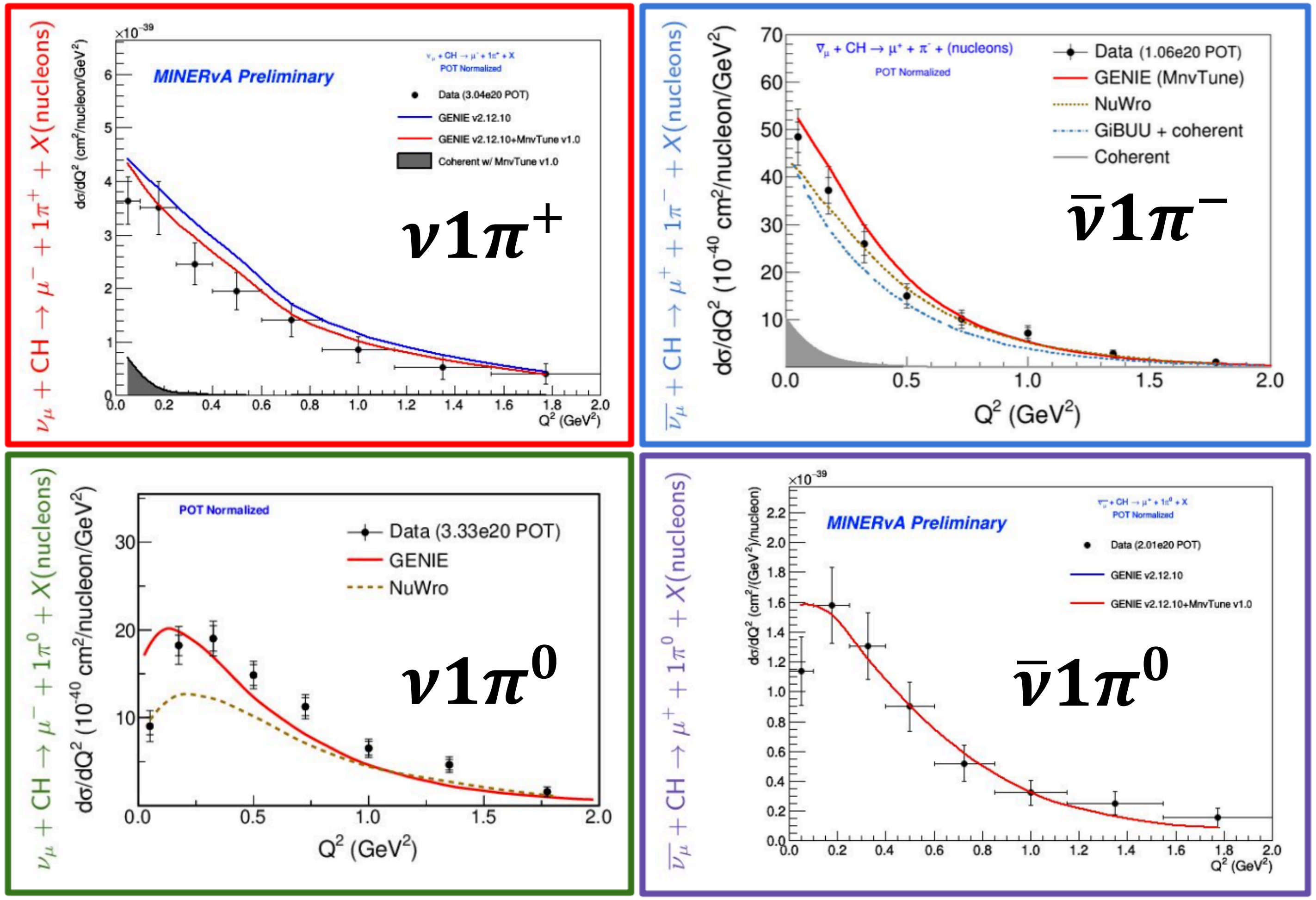
MINERvA's Four Charged-Current Single Pion Channels: T_π



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

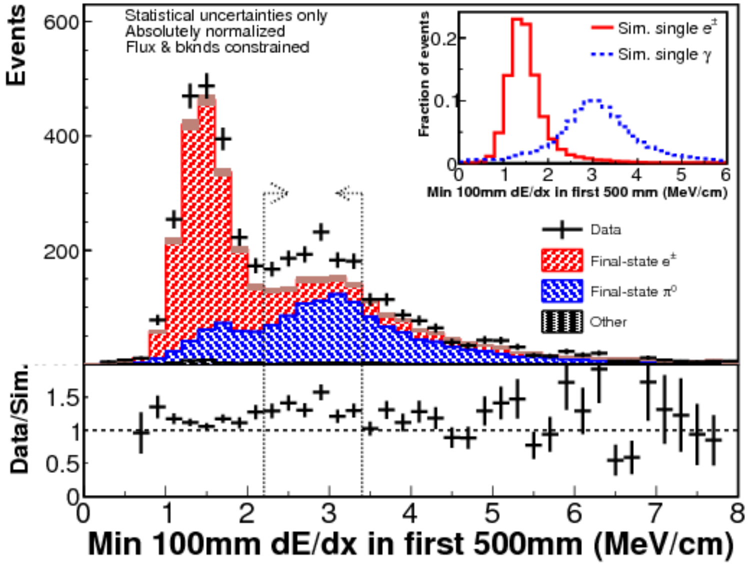


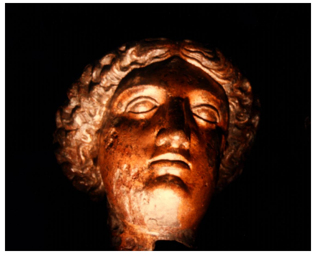
- Neutral pion production shows strong low Q^2 suppression
- Unknown nuclear effect?
- Charged pion final states have a coherent contribution included, but diffractive production from hydrogen in MINERvA unsimulated.

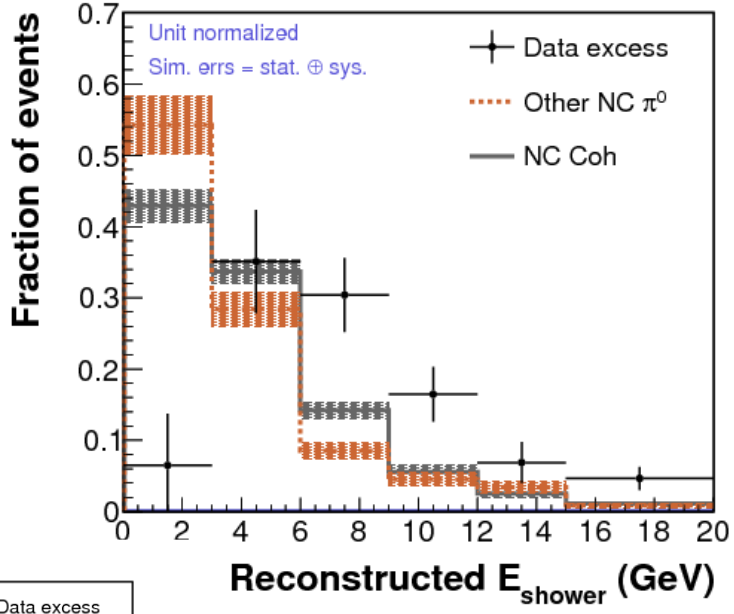
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_{\mu\nu}) - m_\mu^2 \quad (\mathrm{GeV^2/c^2})$$

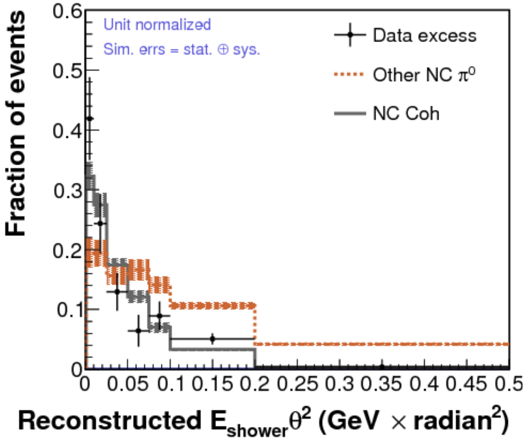
High energy diffractive (?) π^0

- 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! Sorry.

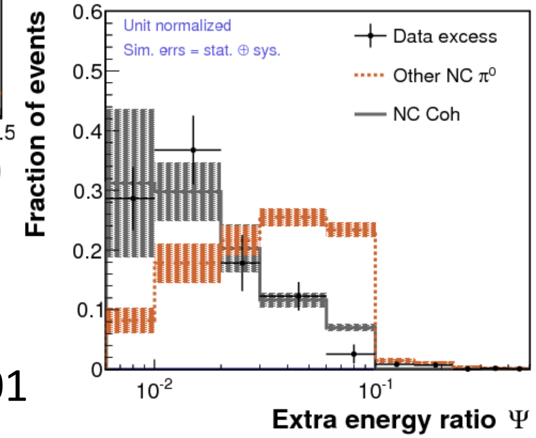


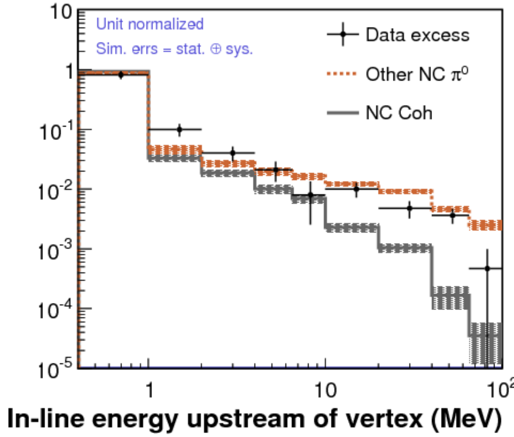






Phys.Rev.Lett. 117 (2016) 111801

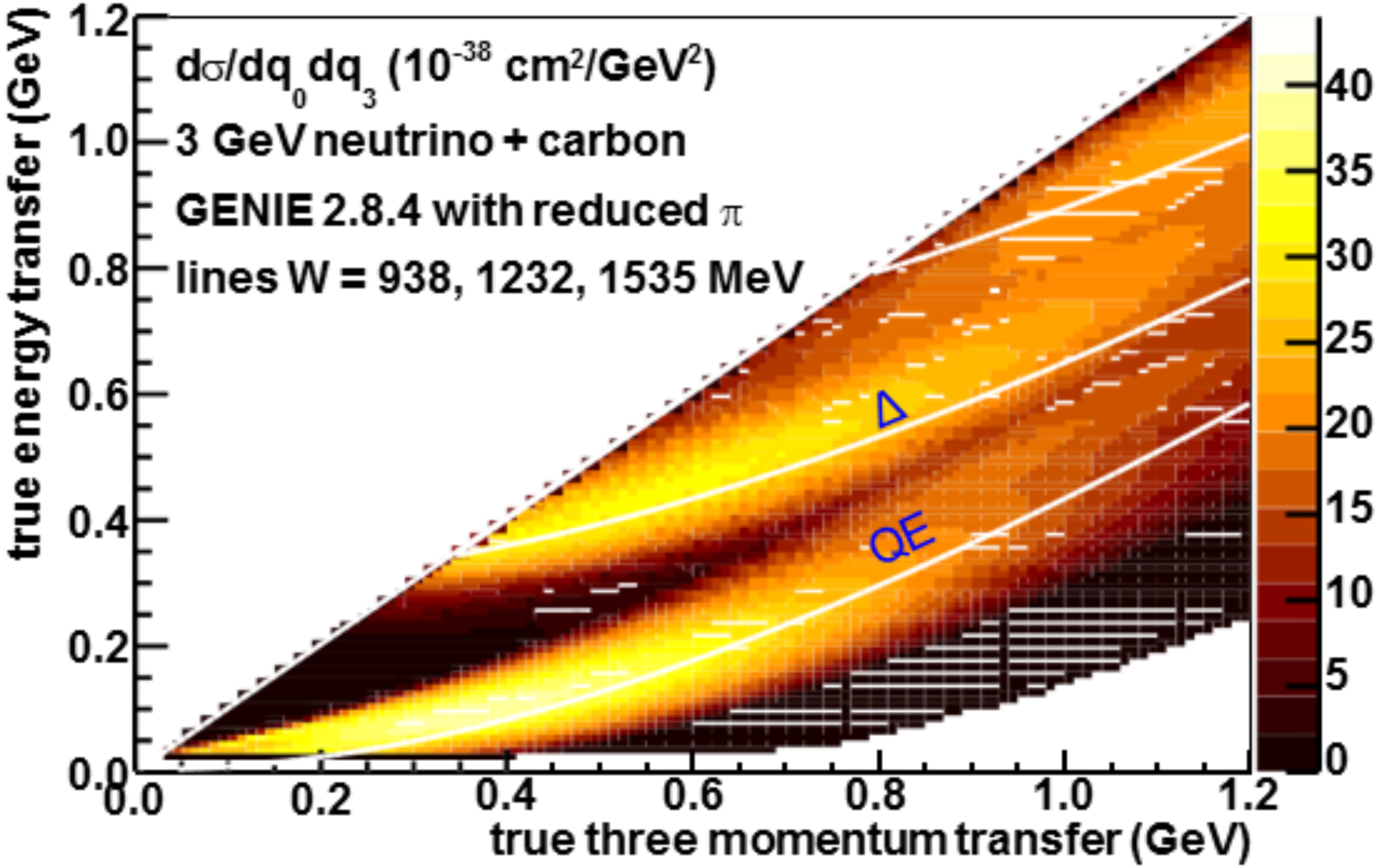




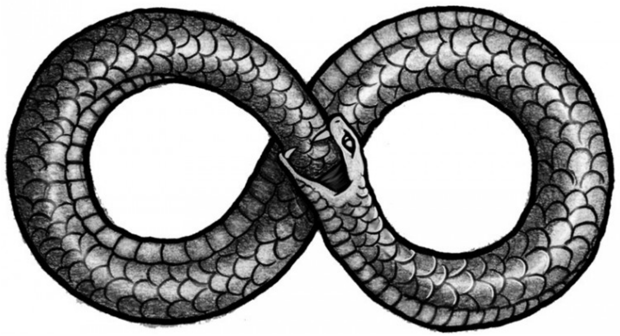
A descriptive CC0π Model

- Data that specifies the model
- Data that confirms the model
- Implications

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"*

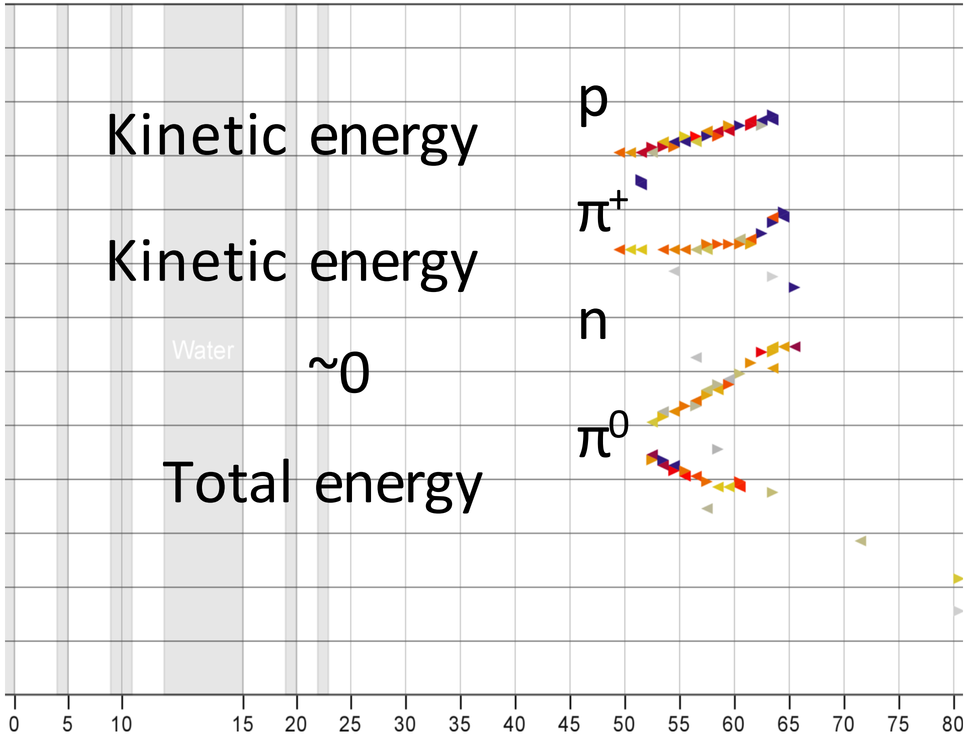
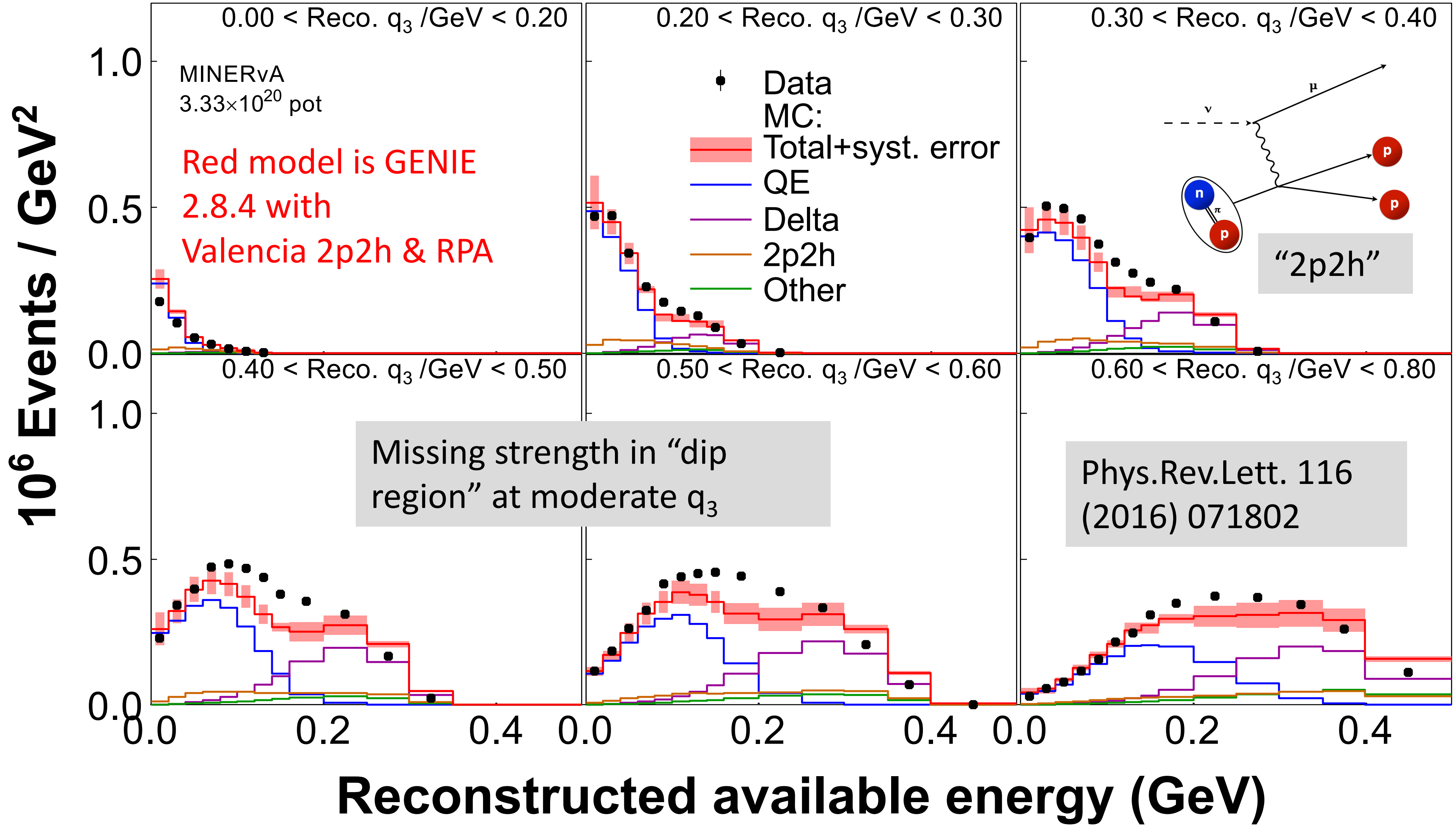


Figure courtesy P. Rodrigues

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

Moderate $|q_3|$ “Dip Region”



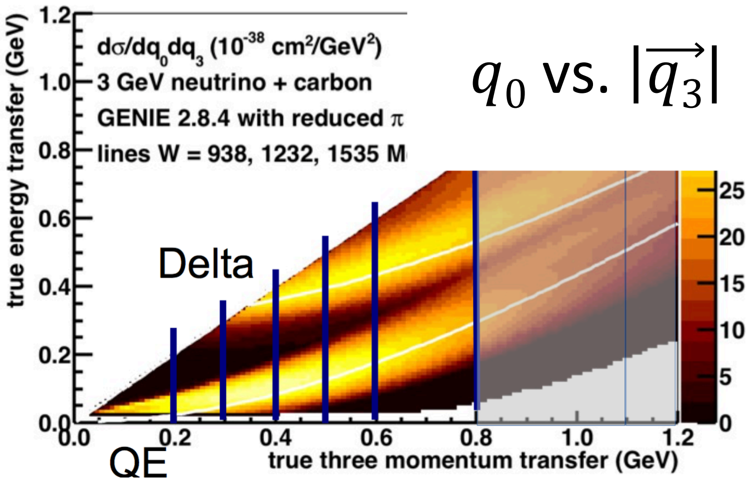
- Nieves 2p2h model added to GENIE prediction used by MINERvA.
- But it doesn’t provide enough strength at moderate $|q_3|$.

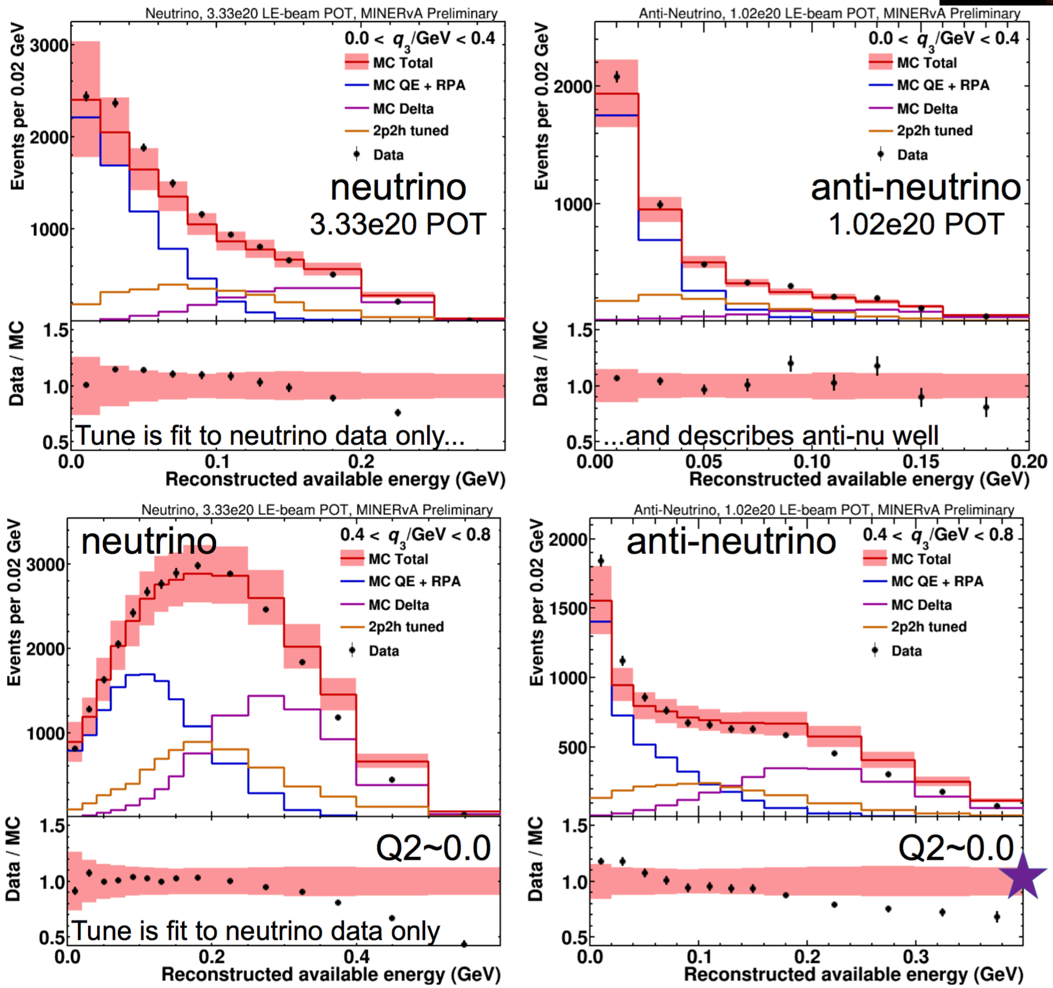
MINERvA ν_μ and anti-ν_μ "low q"

- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos

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

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

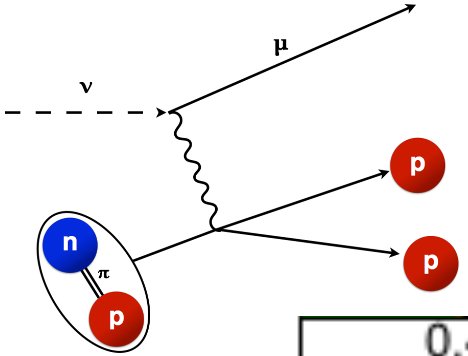


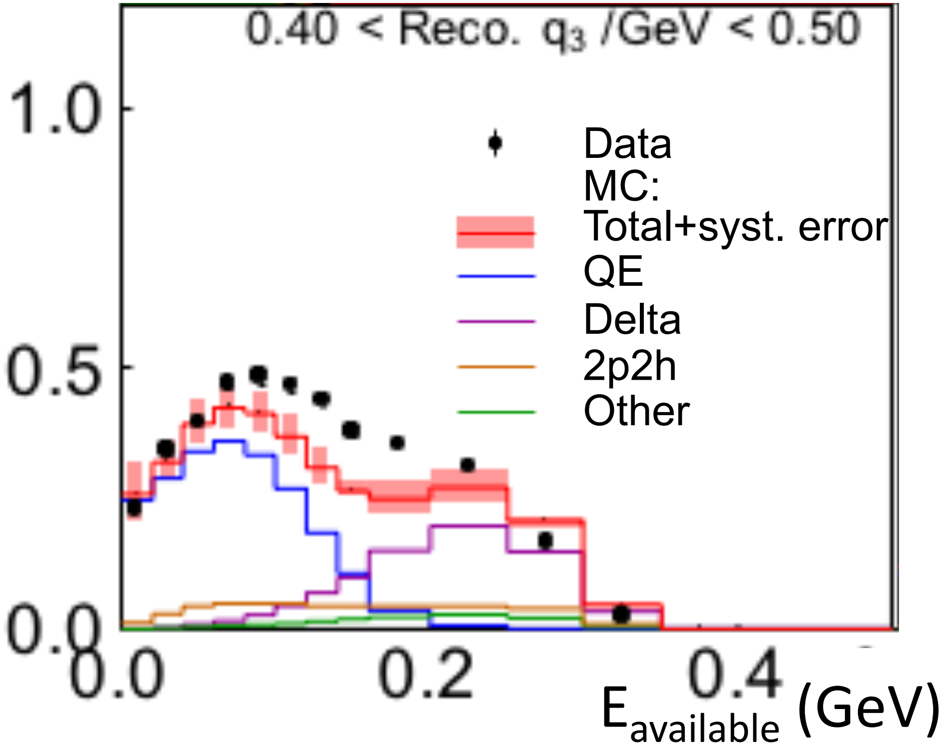


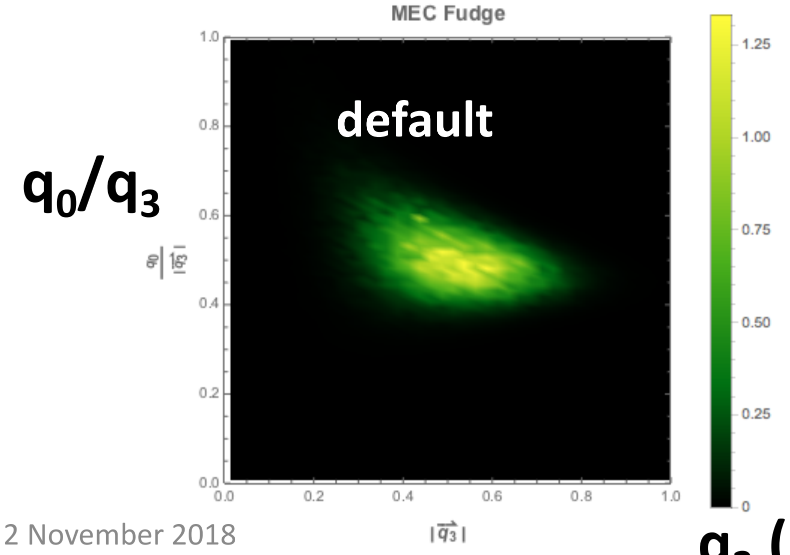
- Tune model (extra 1p1h or 2p2h) to fill in dip region between QE & Δ.
- This tune from neutrino data also agrees with antineutrino data!
- Remaining problem is low Q^2 region, consistent with pion production.

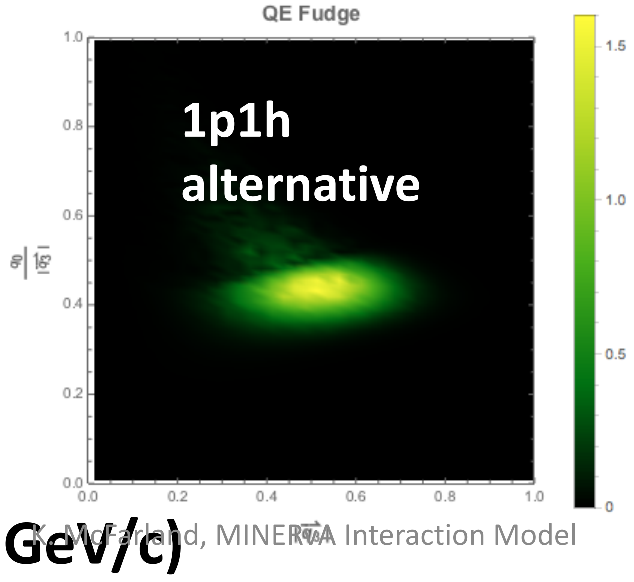
Tune Alternatives

- MINERvA low recoil identifies missing strength, but it doesn't identify $\nu_\mu A(n) \rightarrow \mu^- p A'$ from $\nu_\mu A(nn) \rightarrow \mu^- pn A'$ from $\nu_\mu A(np) \rightarrow \mu^- pp A'$
  - Different choices mean different $E_{\mathrm{avail}}(q_0)$
- Default tune augments ratio of 2p2h nn/np initial state as per Nieves model







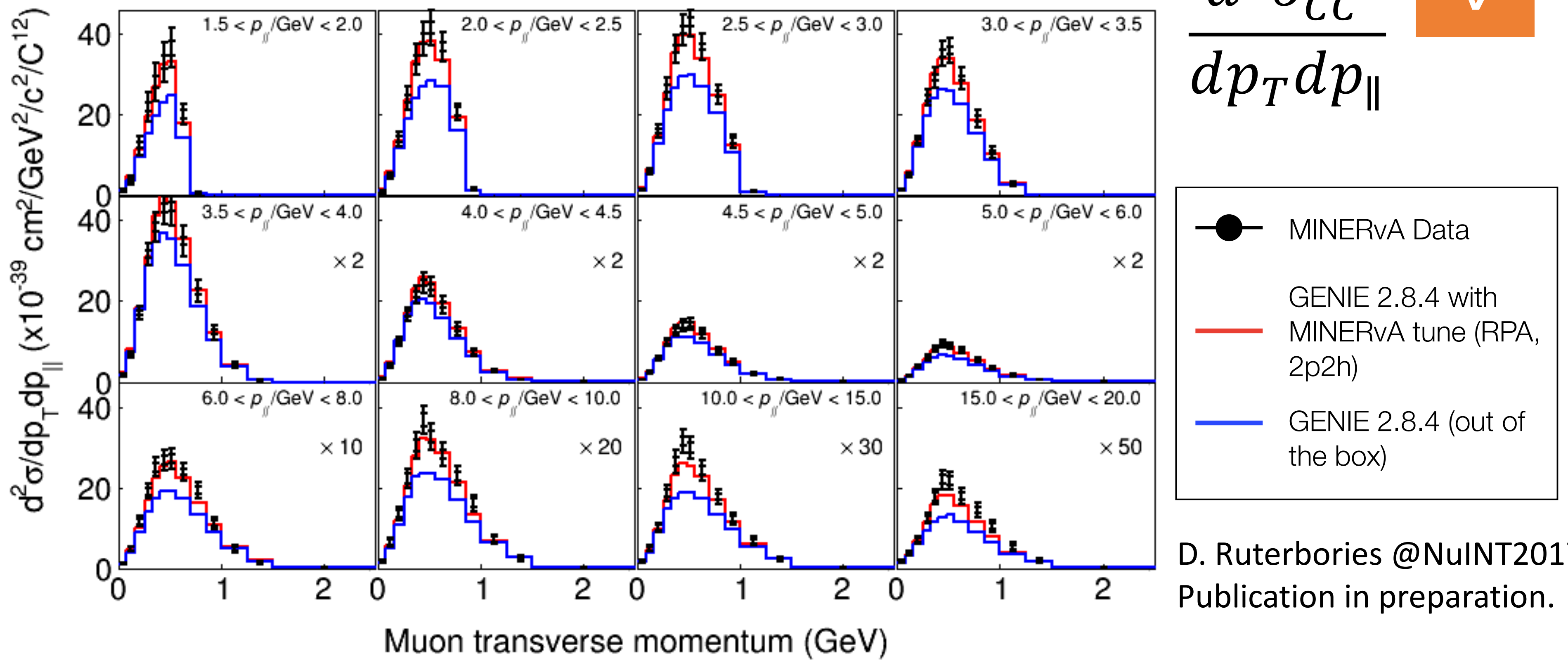


MINERvA $\boldsymbol{\nu}$ pionless events (CC0$\boldsymbol{\pi}$)

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

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

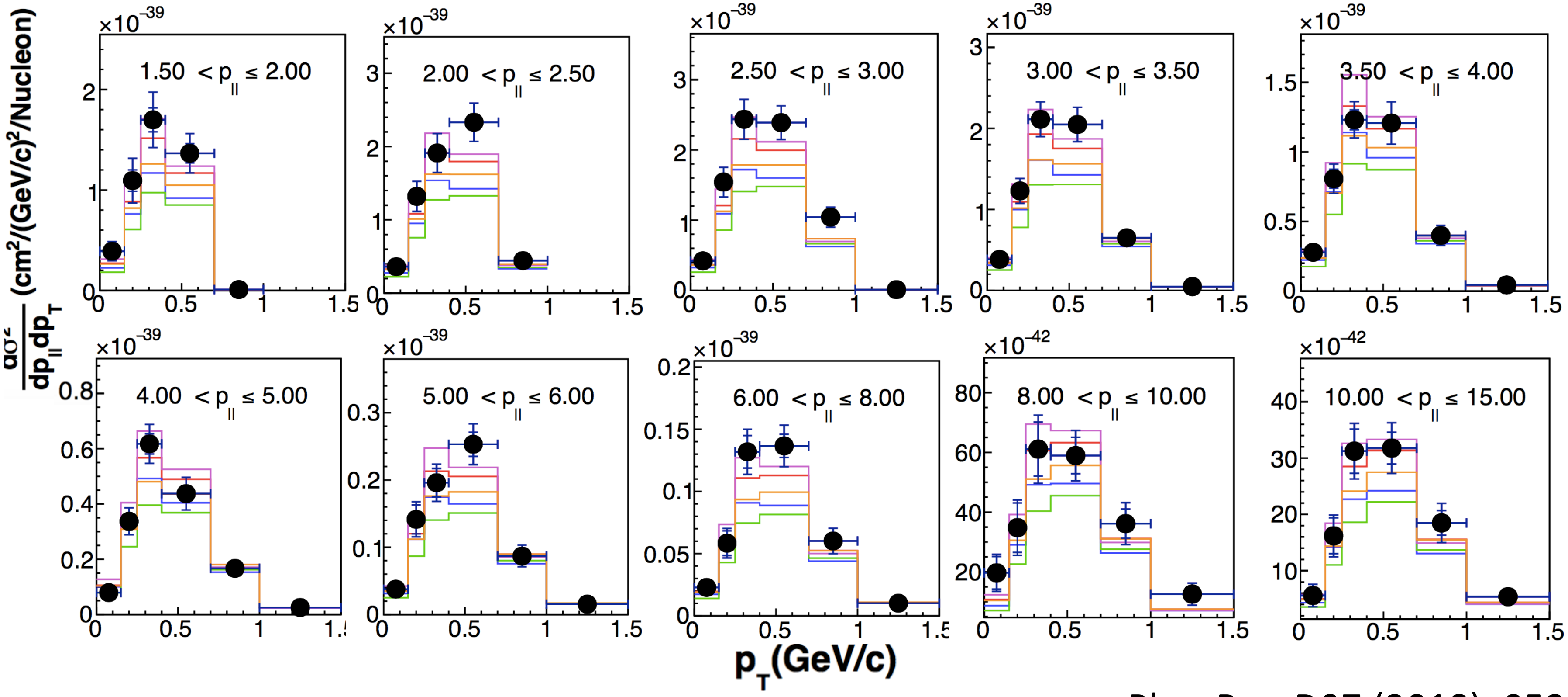
V



D. Ruterbories @NuINT2017. Publication in preparation.

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?



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

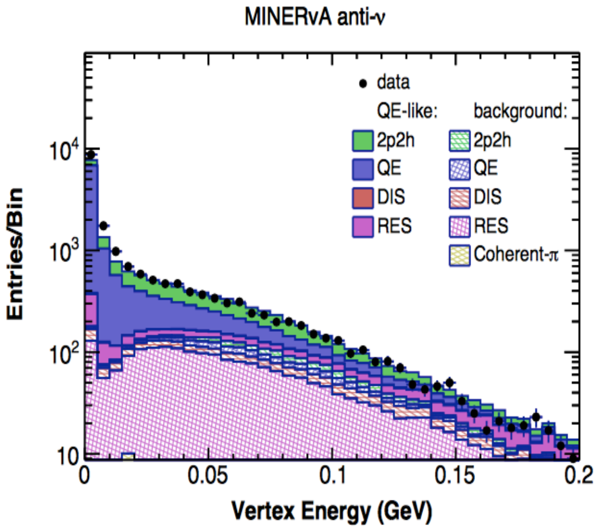
$\bar{\nu}$

Phys.Rev. D97 (2018), 052002

Low energy protons in CC0π events

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

$\bar{\nu}$



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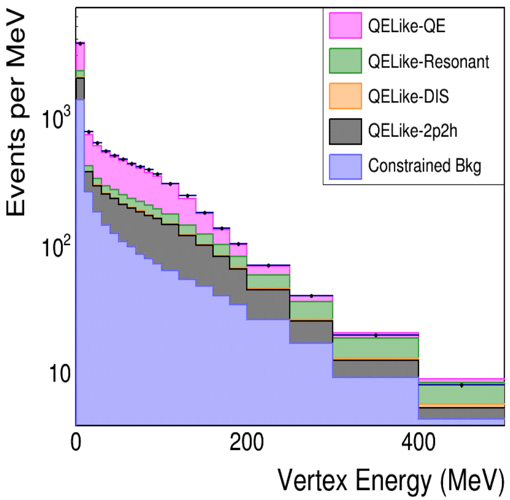
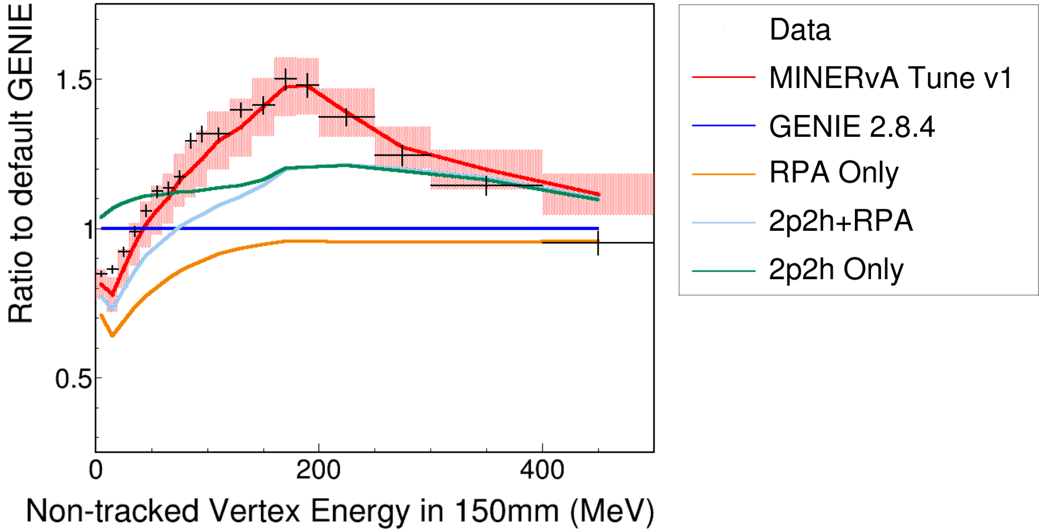
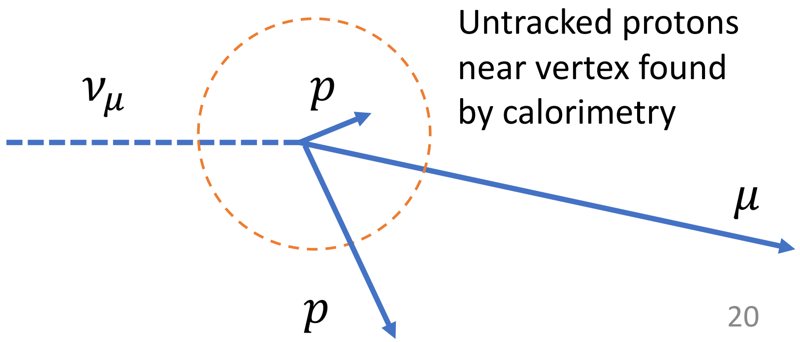
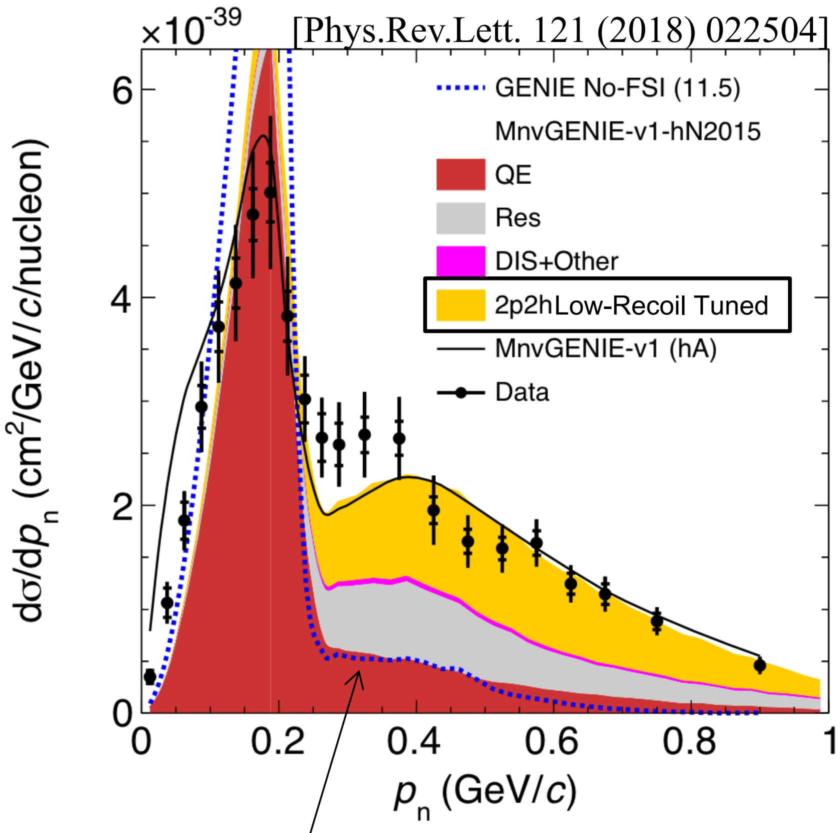


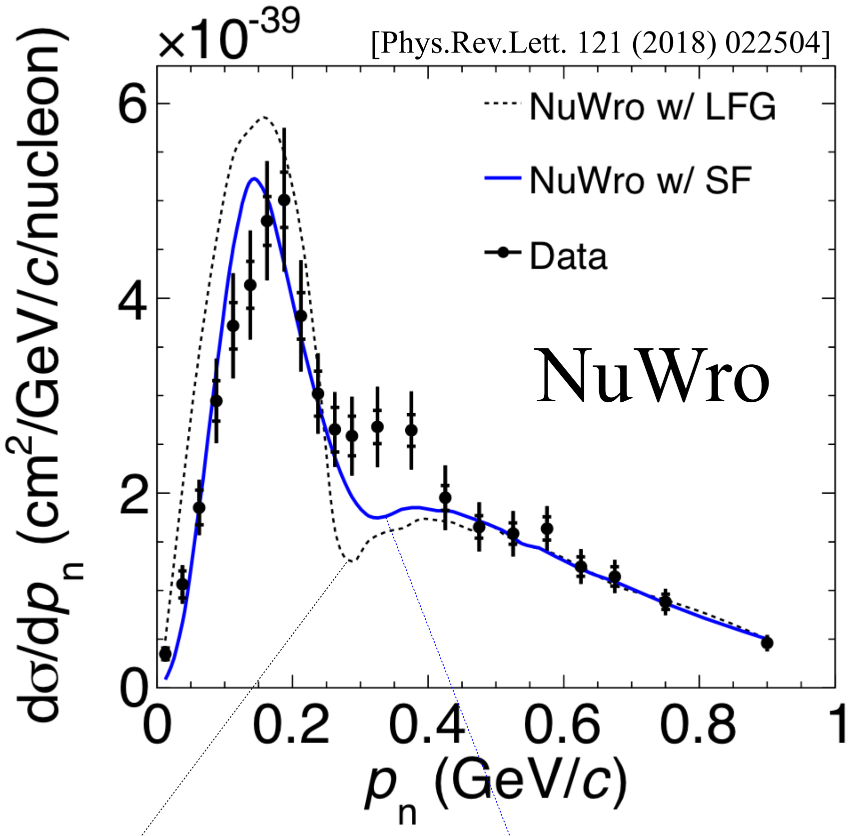


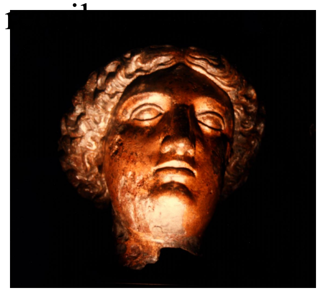


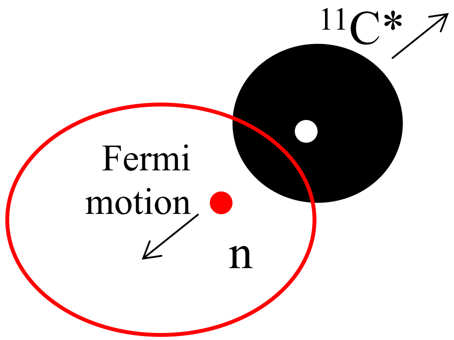
Phys.Rev. D97 (2018), 052002 and D. Ruterbories @NuINT2017

“Neutron momentum” from transverse kinematic balance









Global Fermi Gas with Bodek-Ritchie tail   Local Fermi Gas   Spectral Function

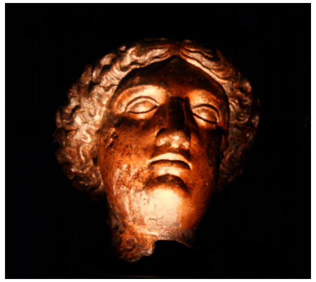
- Base Model depends on 1p1h and Short Range Correlation (SRC) modeling
- Critical to separate QE and RES to reduce Base-Model-dependence

Summary of CC0$\boldsymbol{\pi}$ Model Tune

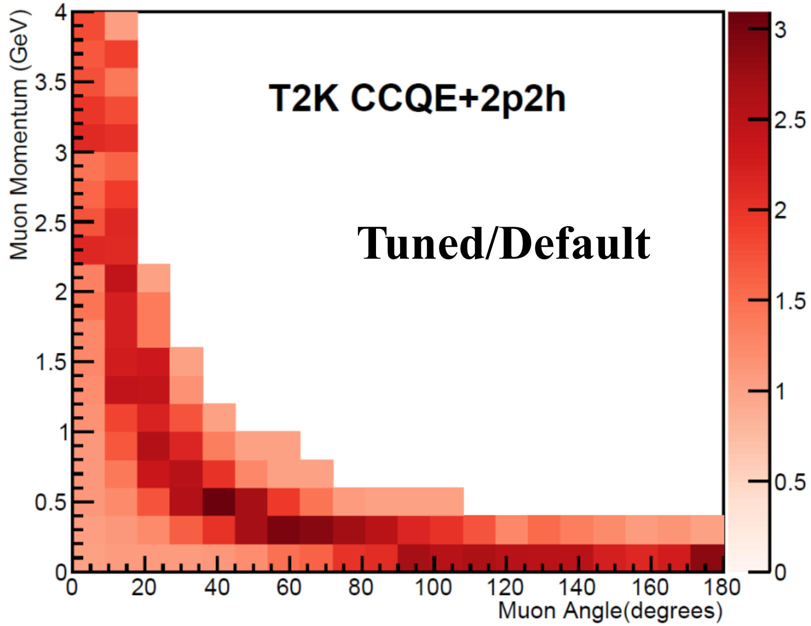
- For these "least inelastic" events, we seem to have found a model which explains:
  - Lepton energy distributions over MINERvA flux
  - Details of proton (visible) recoil
  - Neutrino and antineutrino

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

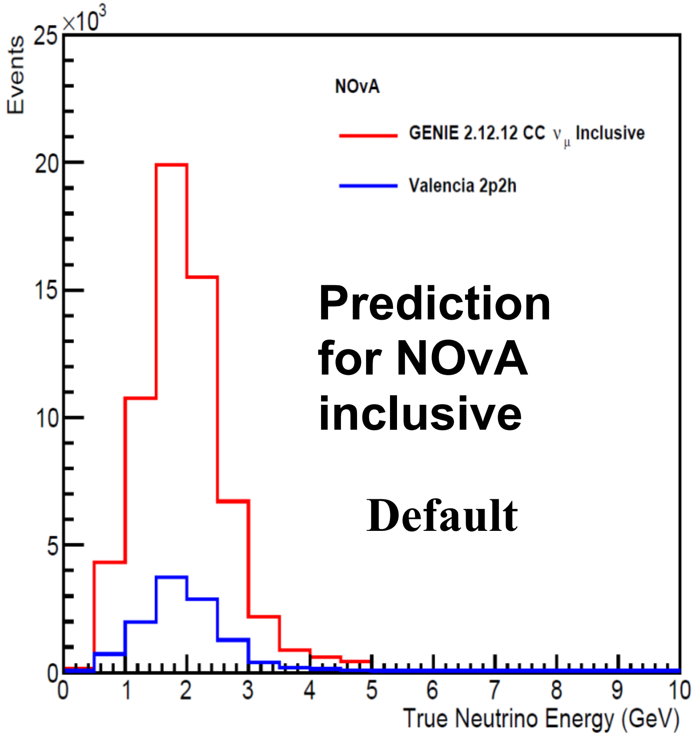
Implications for NOvA and T2K

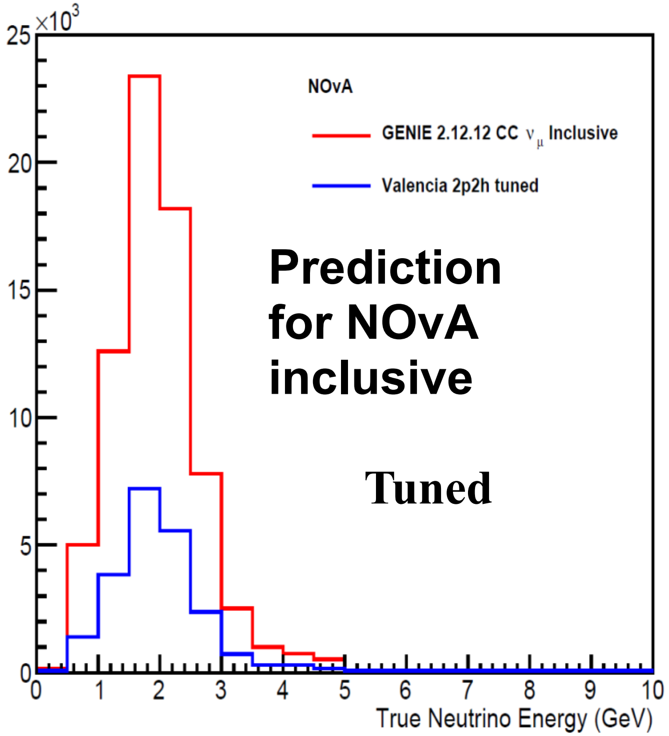


Event rate ratio: Tuned/Default



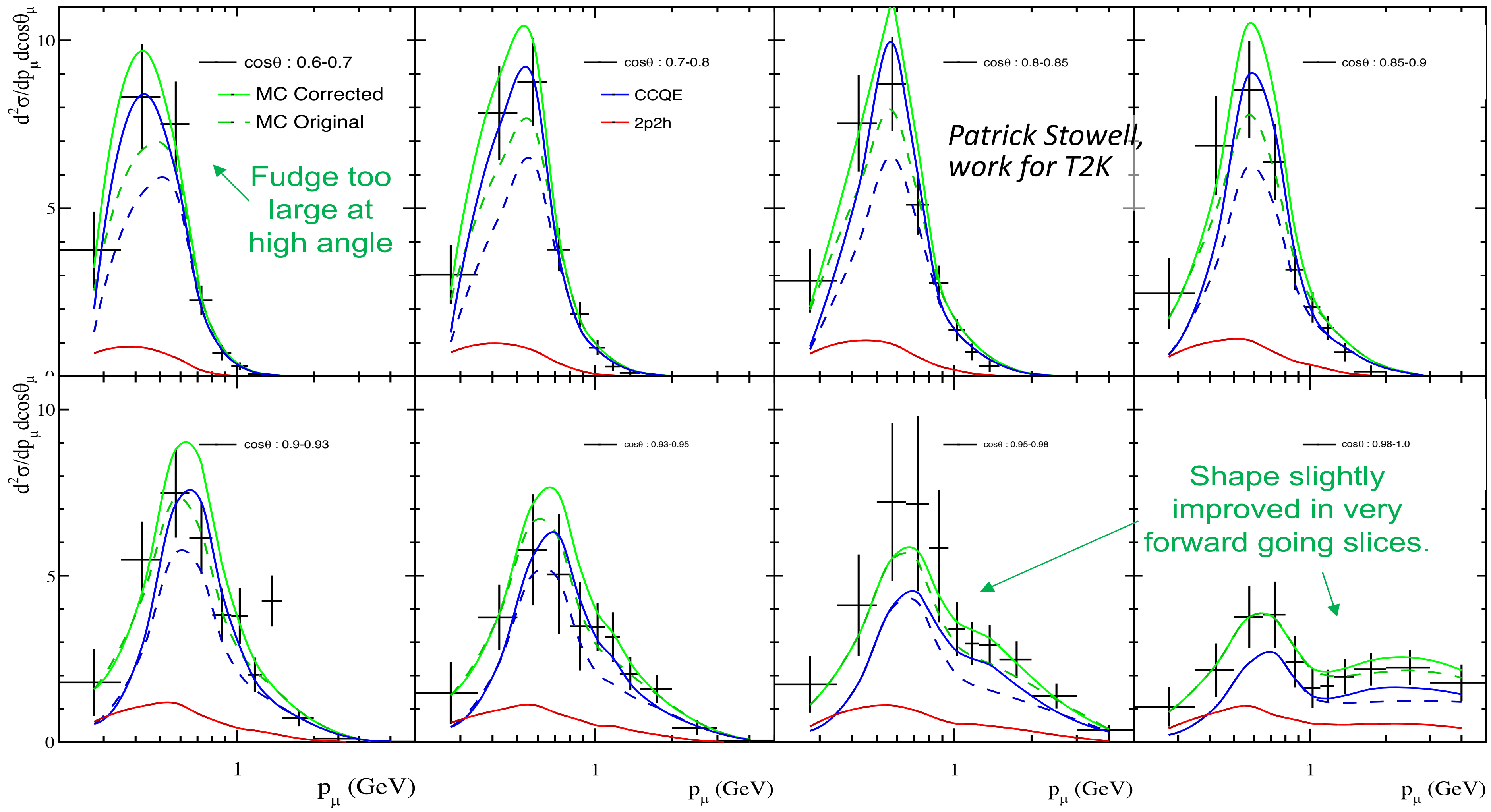
- Beam energy ~ 0.6 GeV
- Default: GENIE 2.12.12 w/ Valencia 2p2h
- Tuned: default + *2p2h-like enhancement*
- Non-negligible impact in CCQE-like full phase space at T2K energy, especially at high angle





- 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

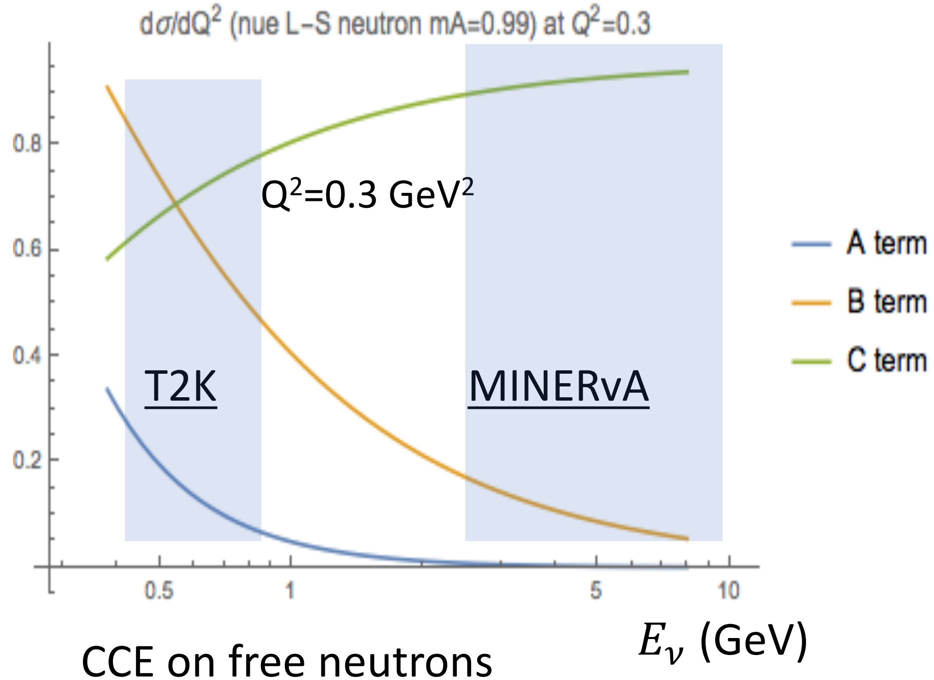
Apply to T2K CC0π… too much tune!



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.



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.

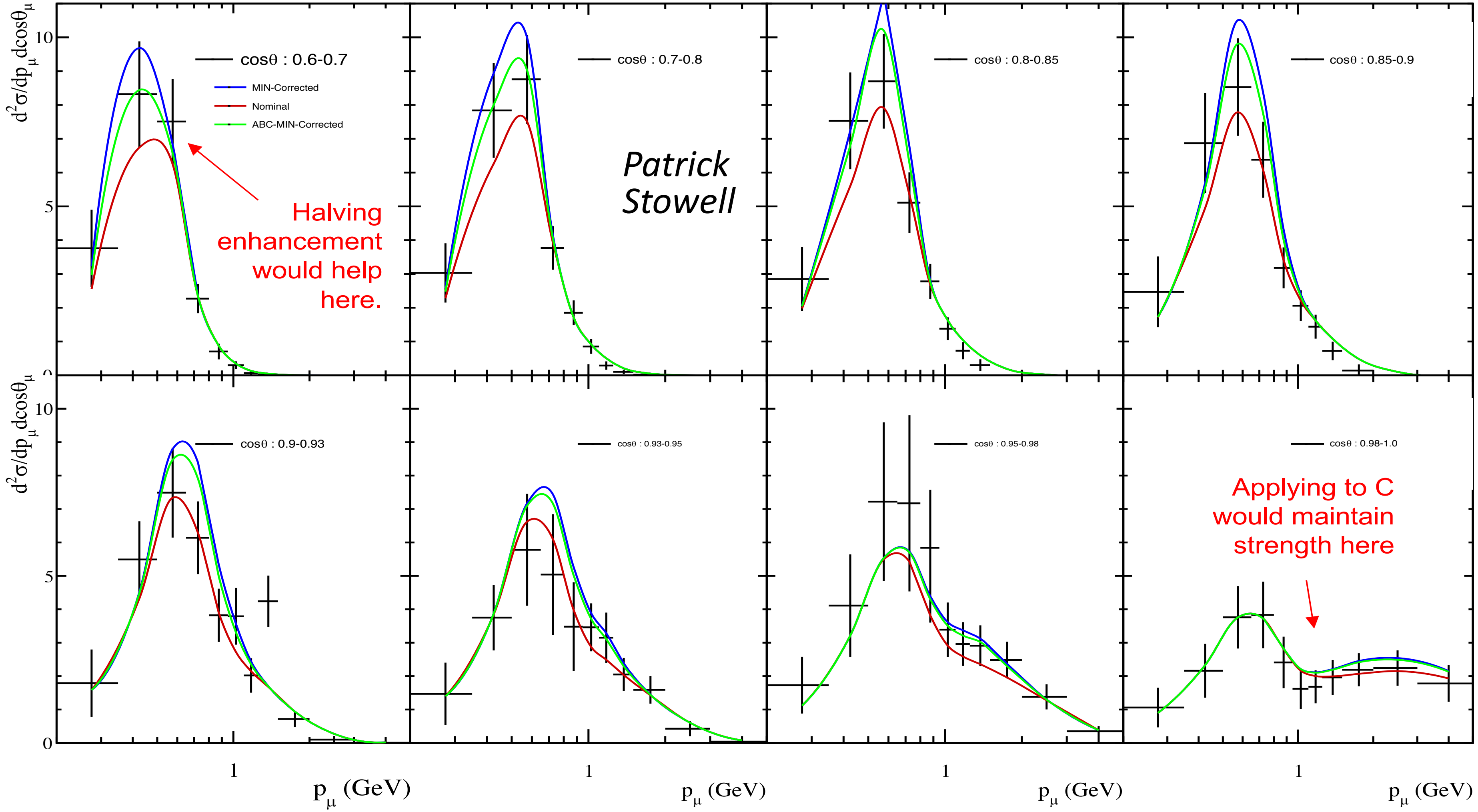
An expansion similar to eq. (2.5) holds for $\sum\sum m_{\mu\nu}$ in terms of k and q. Hence, whatever the explicit form of the lepton and hadron currents:

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

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

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

Apply to T2K C term for CC0π



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.

Conclusions

Cross Section Model at MINERvA

- MINERvA tunes pion production and pionless events relative to defaut GENIE
- Tuning generally improves model description.
- New uncertainties, such as source of extra “2p2h” strength.
- Significant impacts forecast on oscillation experiments, which already incorporate these ideas.

- Model still has deficiencies.
- Low Q^2 pion suppression and shift in Δ peak not understood.
- “2p2h” enhancement not theoretically motivated, so energy dependence unknown.
- Still see deficiencies that could be Fermi gas model of 1p1h peak in transverse variables.

Backup

Pion Selection and Kinematics

$$E_\nu = E_\mu + E_H \text{ } (E_H \text{ determined calorimetrically})$$

- Reconstructed $E_\nu \in$ [1.5, 10] GeV
- $1\pi^+$: W < 1.4 GeV
- $N\pi^+$: W < 1.8 GeV

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_H \text{ } (E_H \text{ determined calorimetrically})$$

- Reconstructed $E_\nu \in$ [1.5, 10] GeV

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_{\pi^0} + \Sigma T_p + E_{vtx} + E_{extra}$$

- Reconstructed $E_\nu \in$ [1.5, 20] GeV
- Invariant π^0 mass $\in$ [60, 200] MeV/c^2

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_H \text{ } (E_H \text{ determined calorimetrically})$$

- Reconstructed $E_\nu \in$ [1.5, 10] GeV
- Invariant π^0 mass $\in$ [75, 195] MeV/c^2
- W< 1.8 GeV

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$$

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

$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \text{ } (m_N = \text{nucleon mass})$$