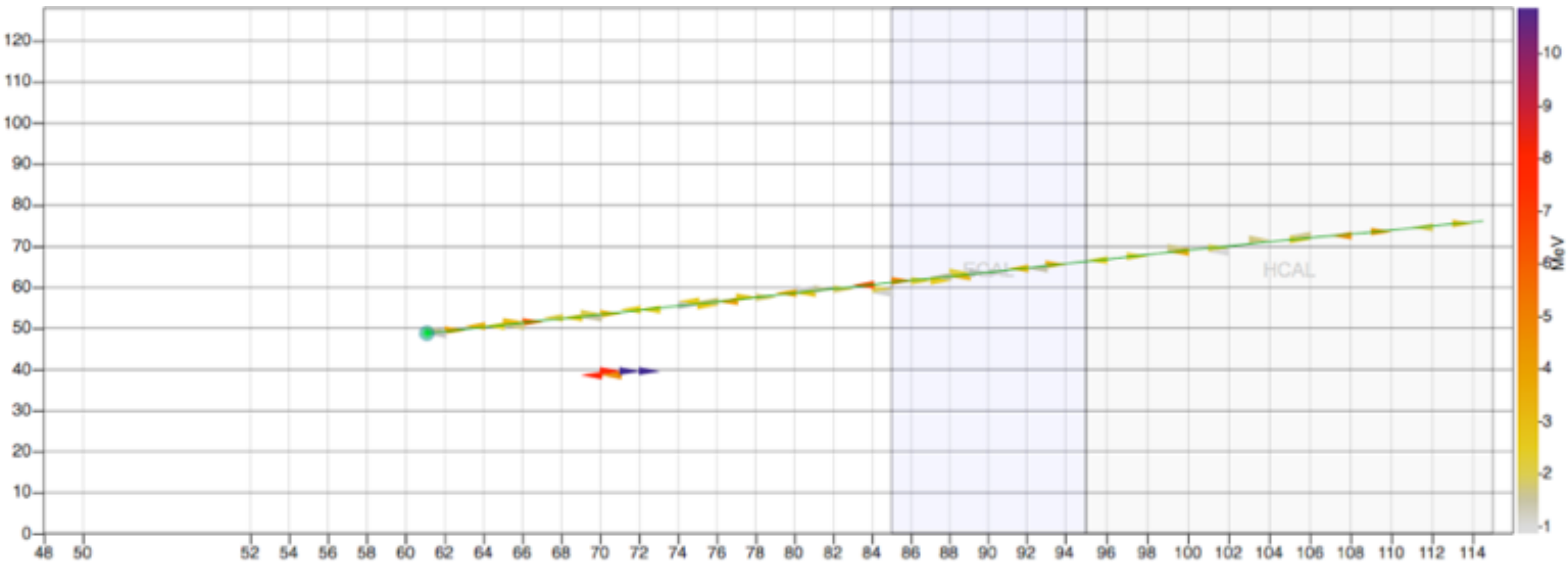


Results for quasi-elastic anti-neutrino scattering on scintillator from the MINERvA experiment

7/5/18

Heidi Schellman for the MINERvA Collaboration

Big question

- Why is almost everything matter instead of anti-matter?

- Answer may be CP-violating processes
- Make particle/anti-particle and compare behavior
  - Quarks → B, K decays
  - Neutrinos → oscillations

Neutrino CP violation

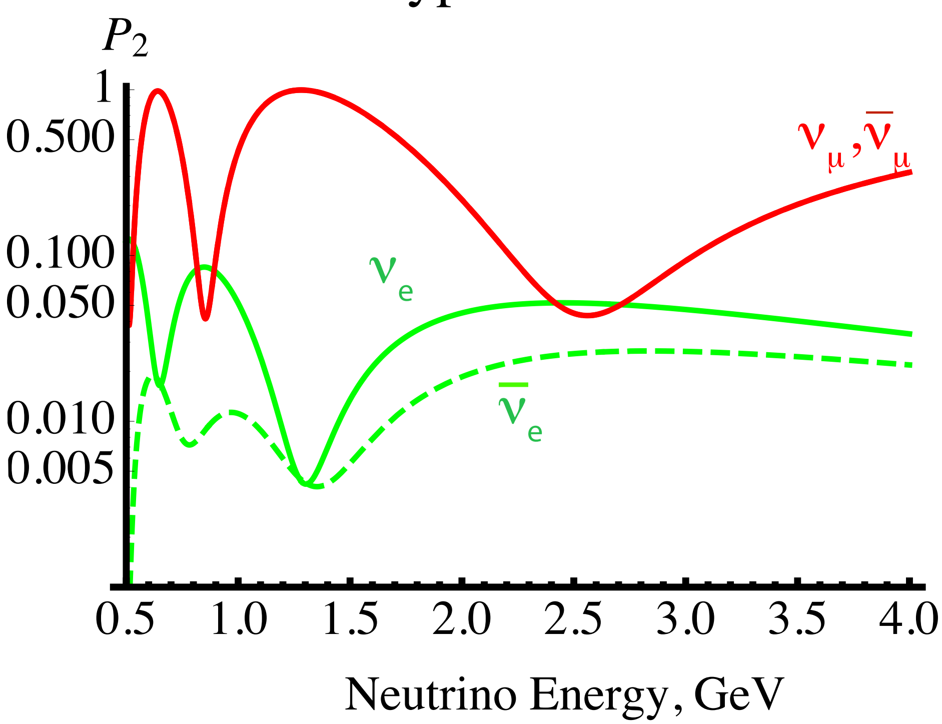
Neutrinos oscillate between flavors!

Do neutrinos and anti-neutrinos behave the same?

Not necessarily! Study $\nu_\mu \to \nu_e$

$\overline{\nu}_\mu \to \overline{\nu}_e$

probability of finding each type of neutrino



Oscillations for

ν_μ @ 1300 km

CP phase $\delta = -\pi/2$

Flips for $\delta = \pi/2$

Need to understand anti-neutrino interactions!

- What do interactions look like?
- What is the neutrino energy?
- This is especially important for anti-neutrinos as processes like

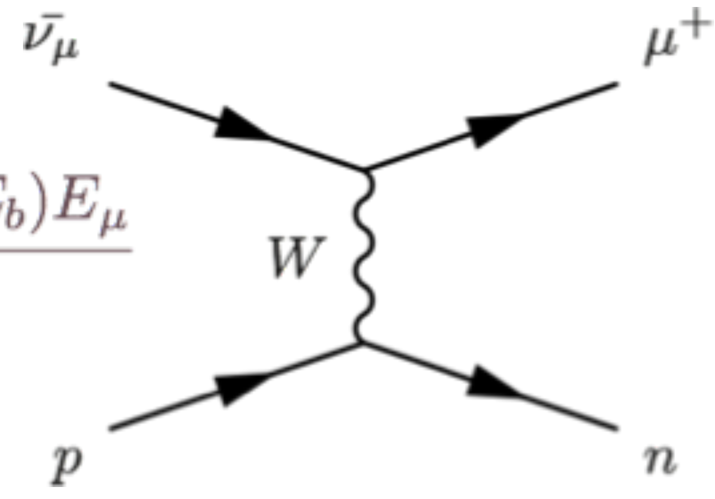
$$\overline{\nu} + p \to \ell^+ + n$$

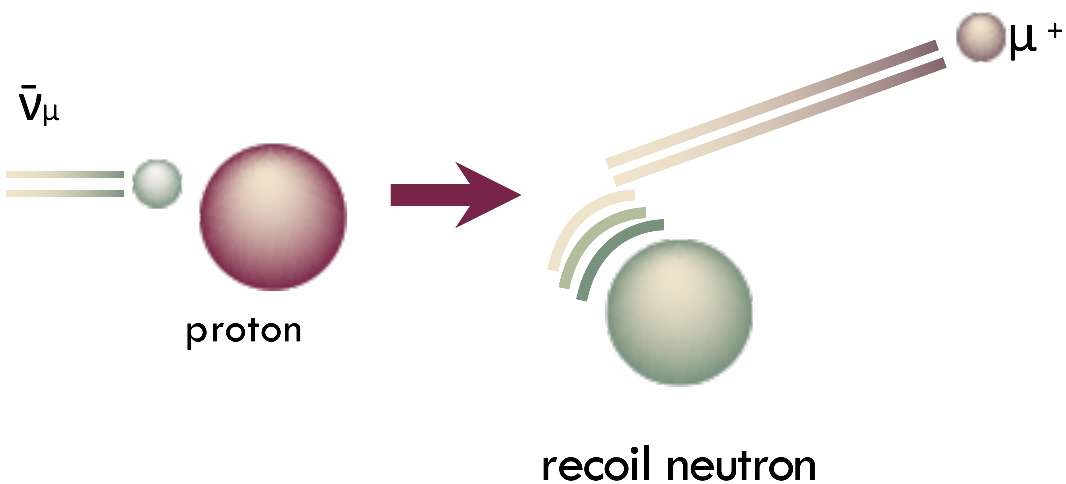
have hard-to-reconstruct final states

Quasi-elastic scattering on nucleons (CCQE)

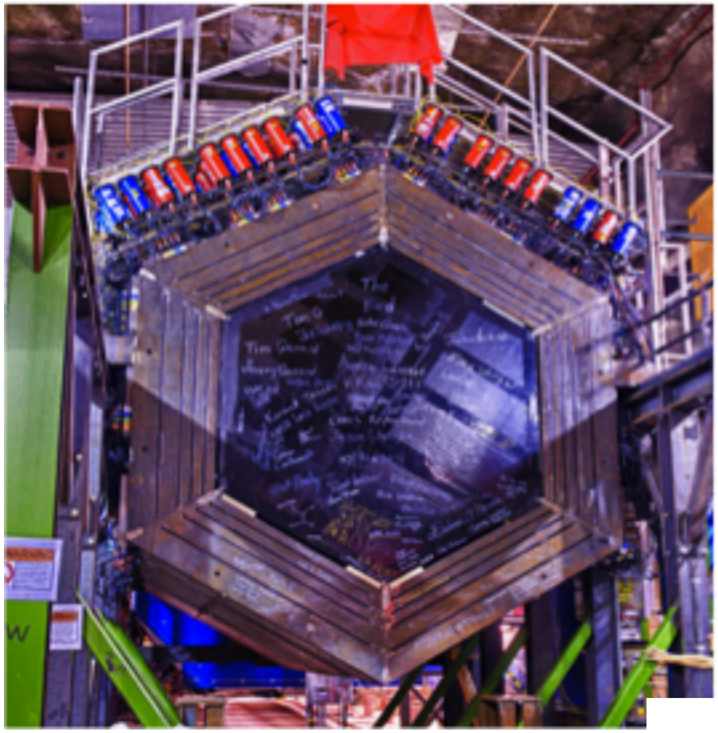
$$E_\nu^{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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



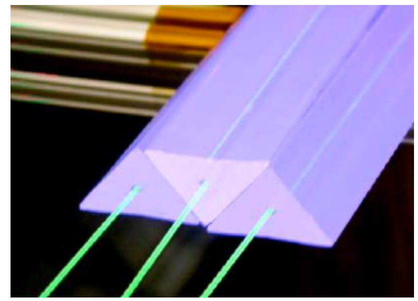


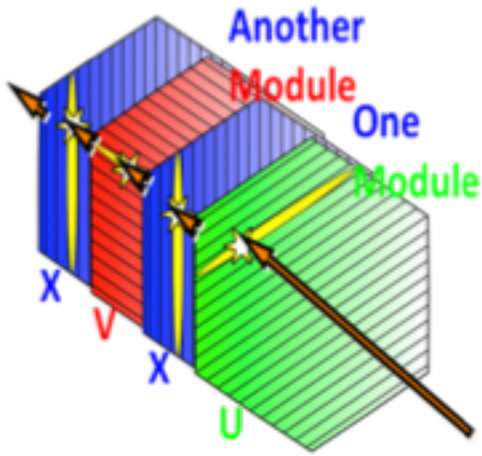
In principle 2-body scatter from a nucleon at rest allows full reconstruction of the kinematics from the muon alone.

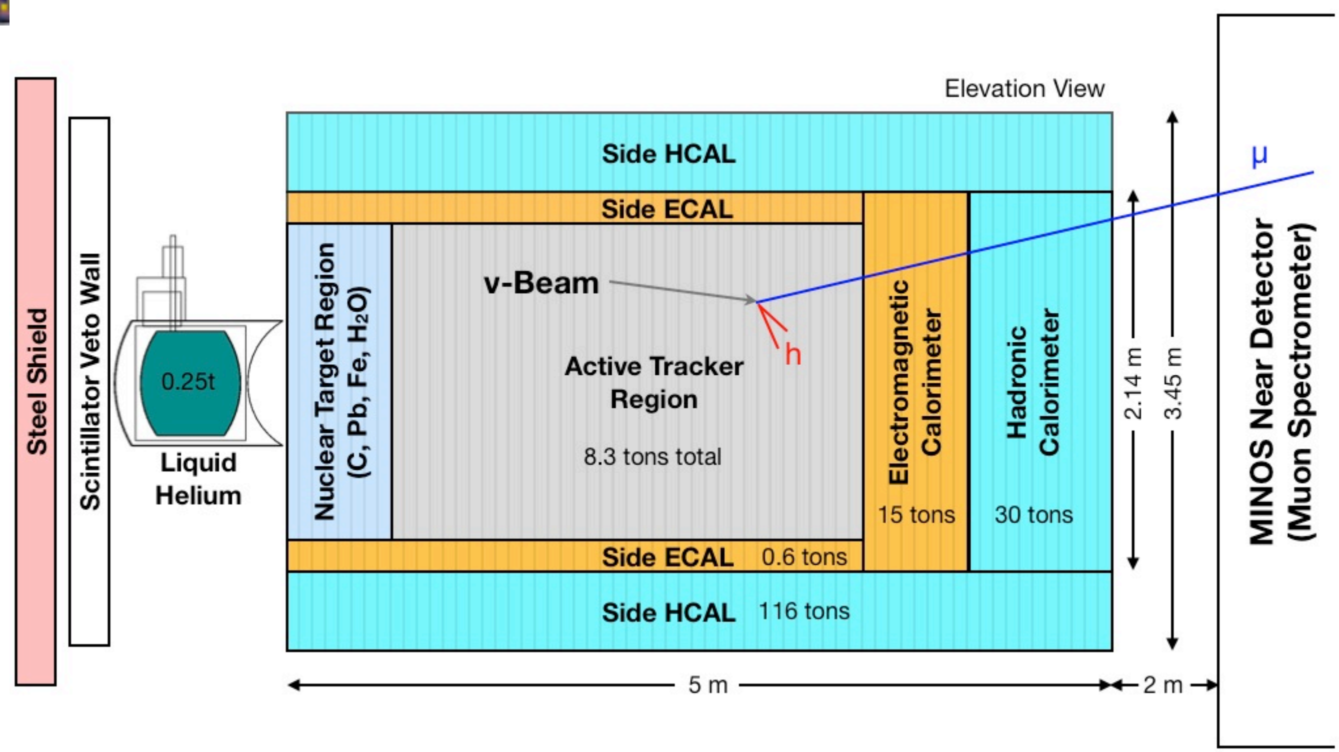


MINERvA Experiment @Fermilab

5.4 Ton Active Scintillator Fiducial Volume







7

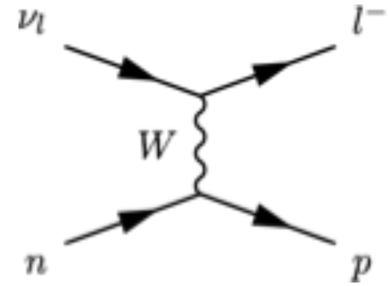
MINERvA

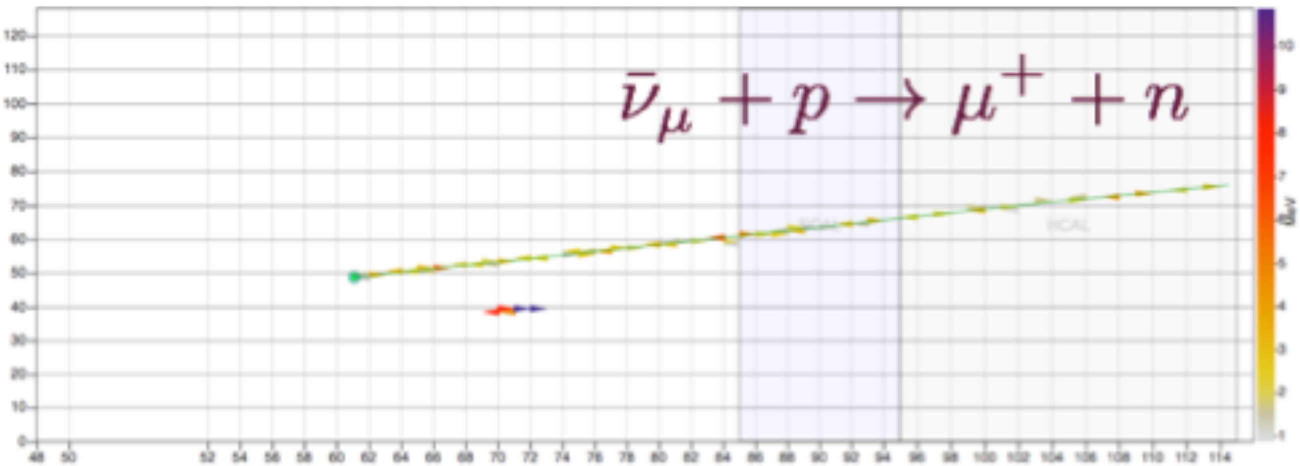
Quasi-elastic scattering on CH (scintillator)

Muons tracked and momentum analyzed

Protons > 120 MeV can be detected

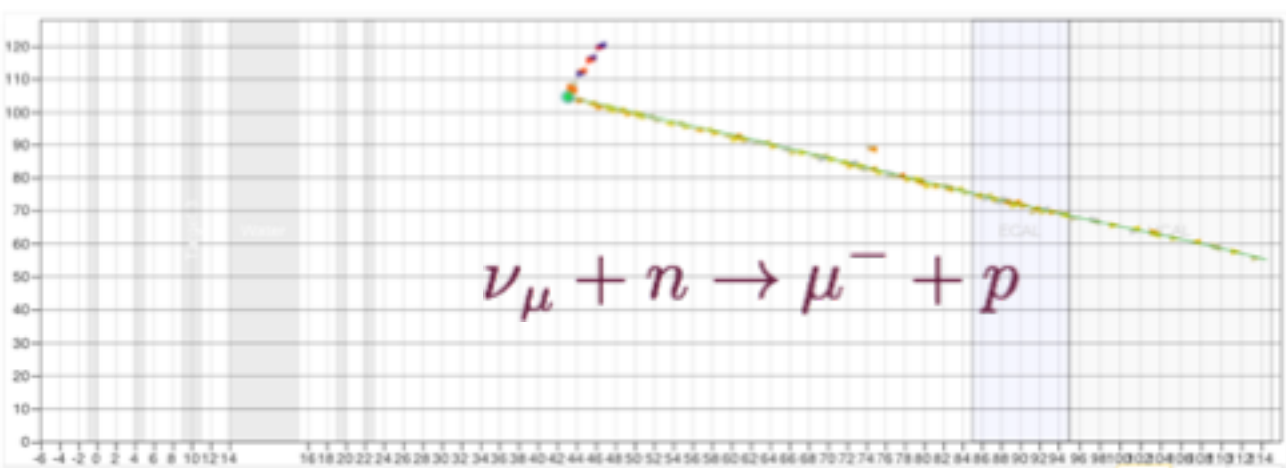
Neutrons ~50% of the time





Classic signature:

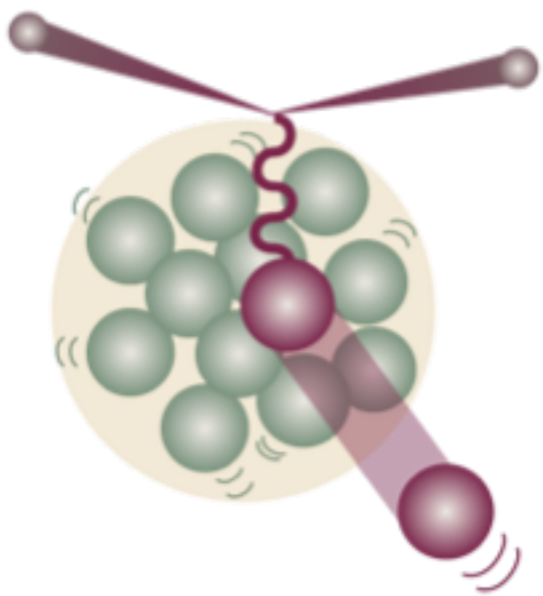
- Final state muon analyzed in MINOS
- No extra recoil energy!!



Around 14,000 anti-neutrino candidates in this sample

X10 more coming soon!

Complications



Nuclei are complex

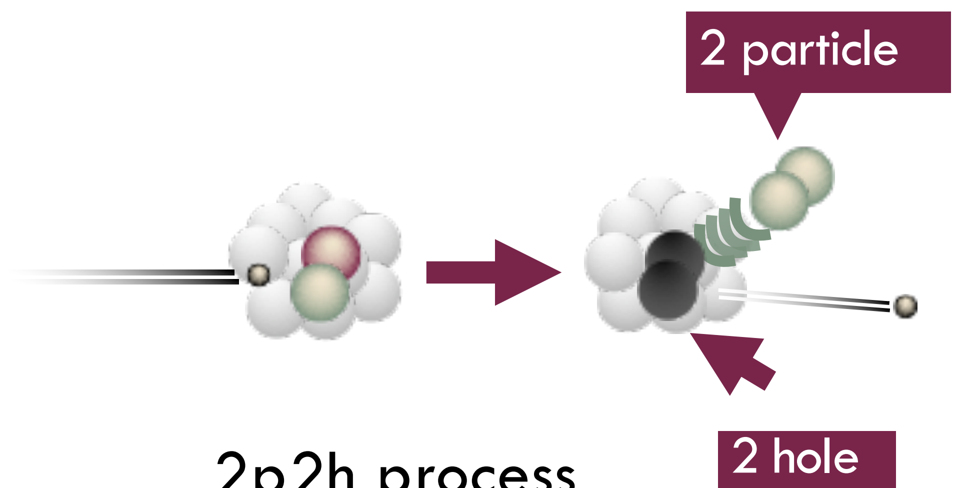
Fermi motion ..

Screening …

No longer a scatter at rest!

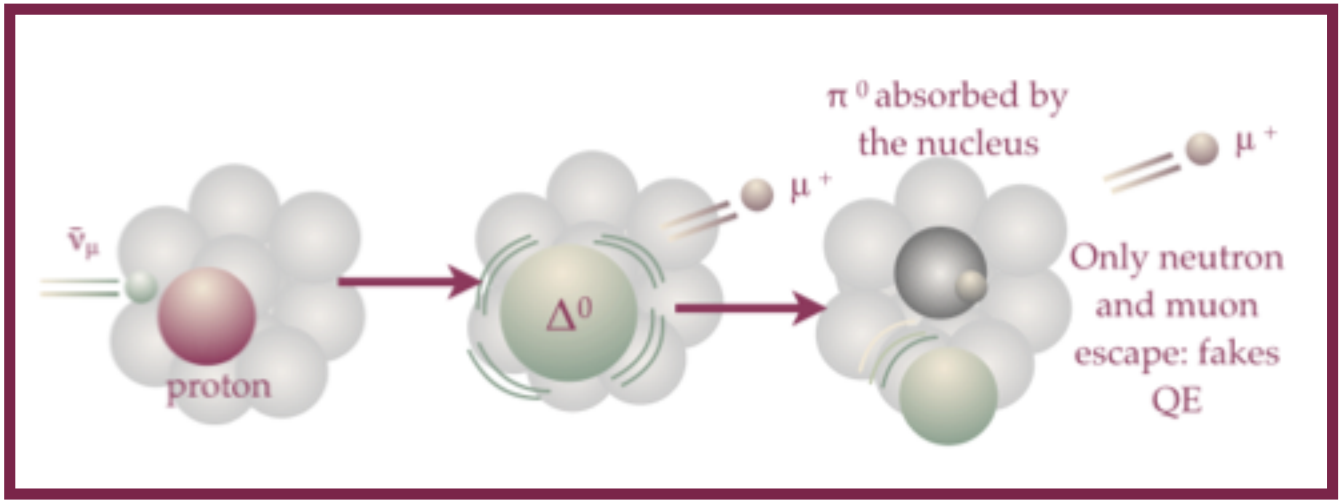
Electron-scattering experiments have found that, approximately 20% of the time, electrons scattered from **correlated pairs** of nucleons instead of single nucleons.

~90% of these pairs consist of a proton and a neutron.

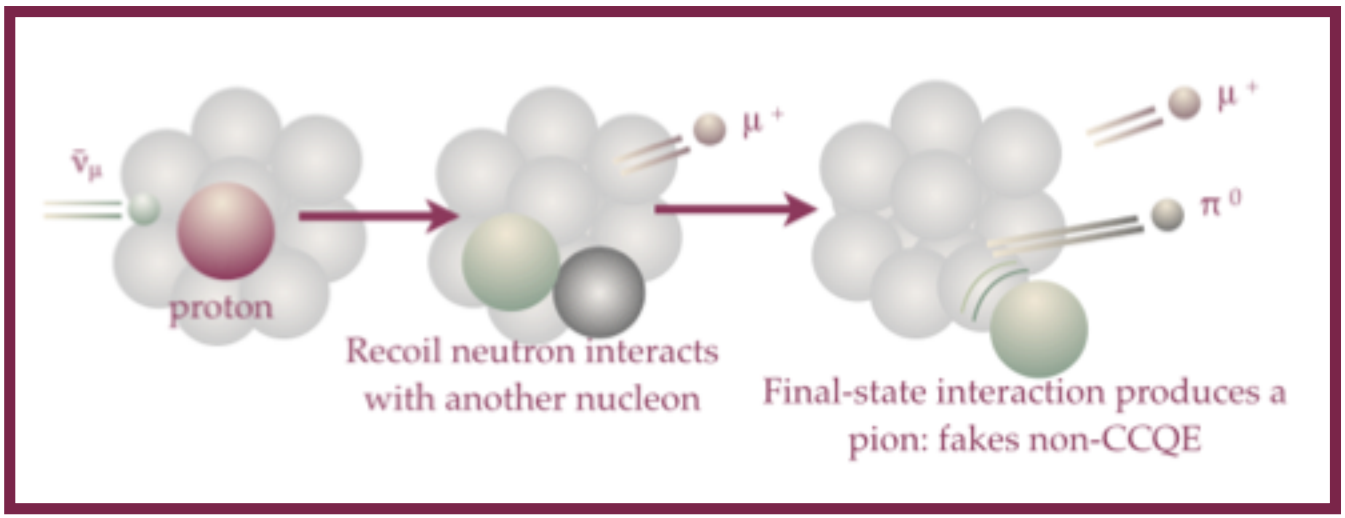


2p2h process

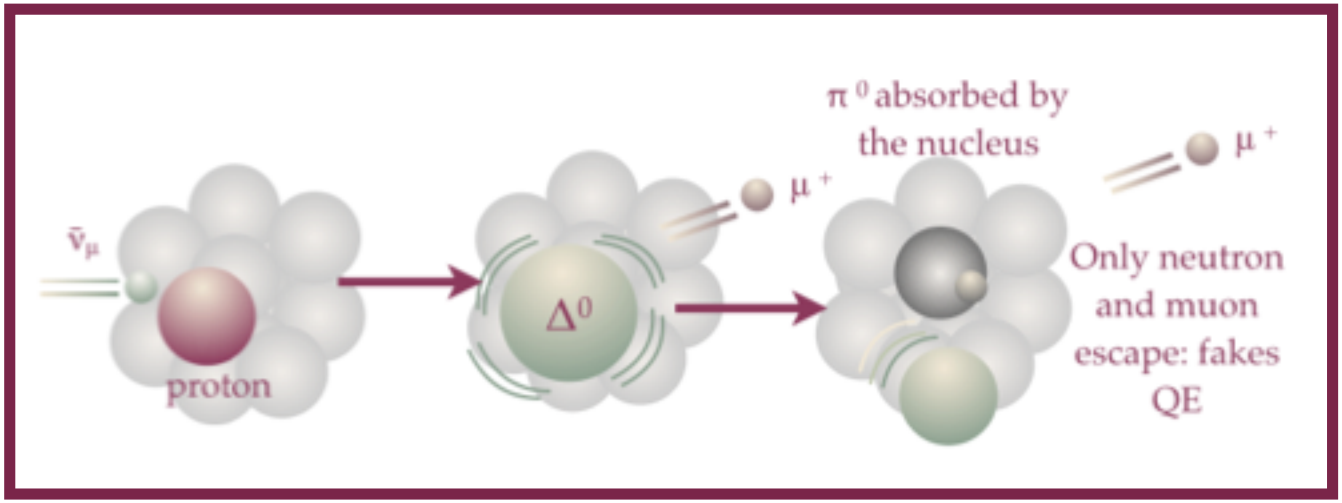
R. Subedi et al. Science, 320(5882):1476–1478, 2008



Initial interaction is not CCQE
But the observed event looks like it

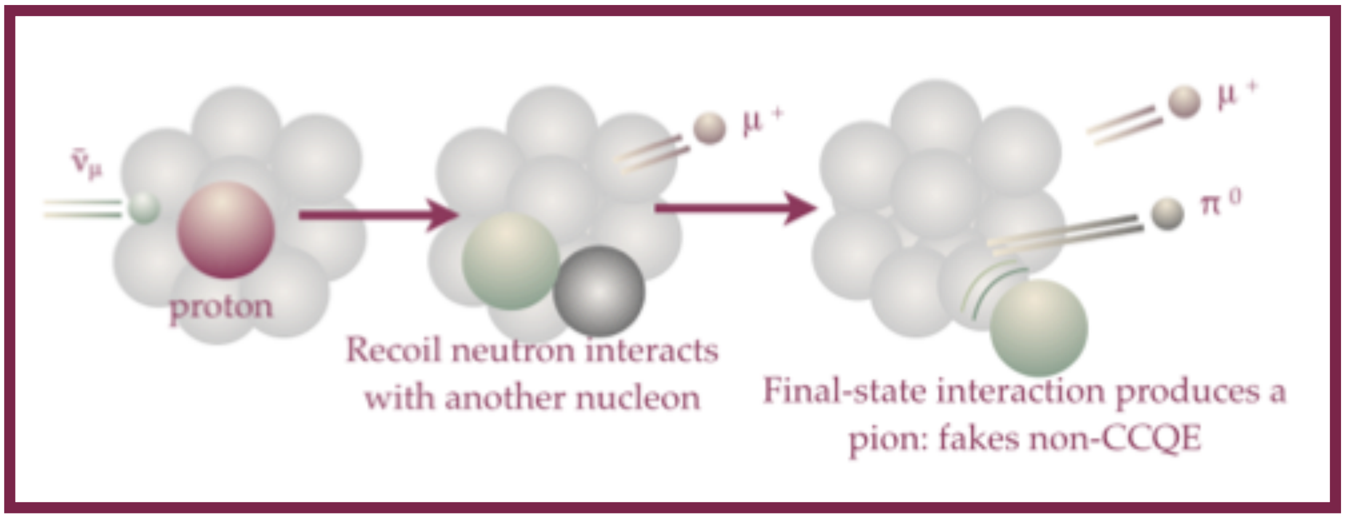


Initial interaction is CCQE but the observed event is not!

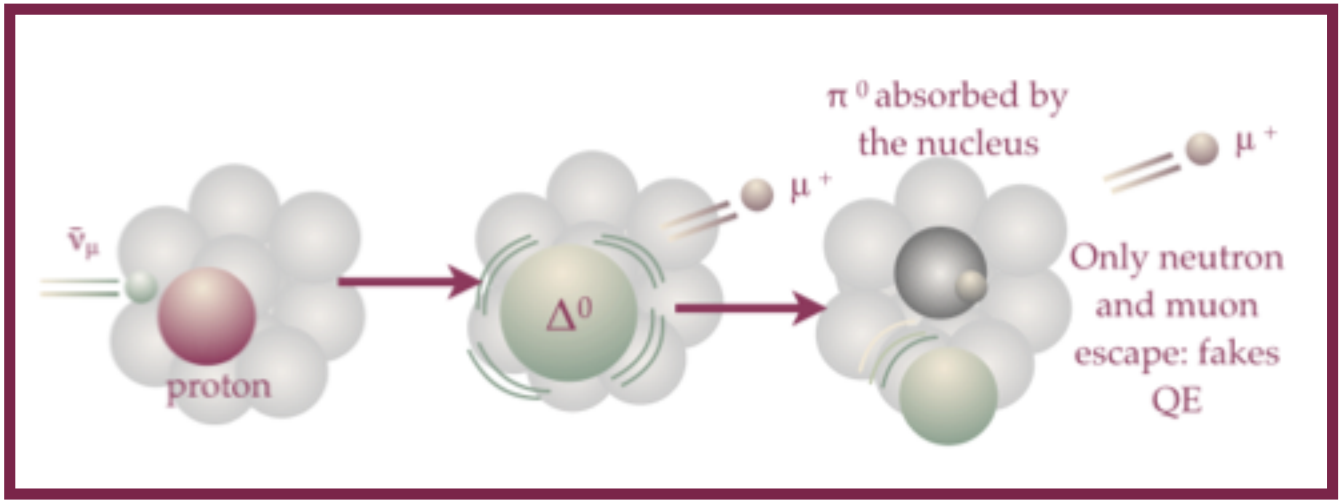


Two strategies:

QE-like: define a signal that is corresponds to what we see in the final state.

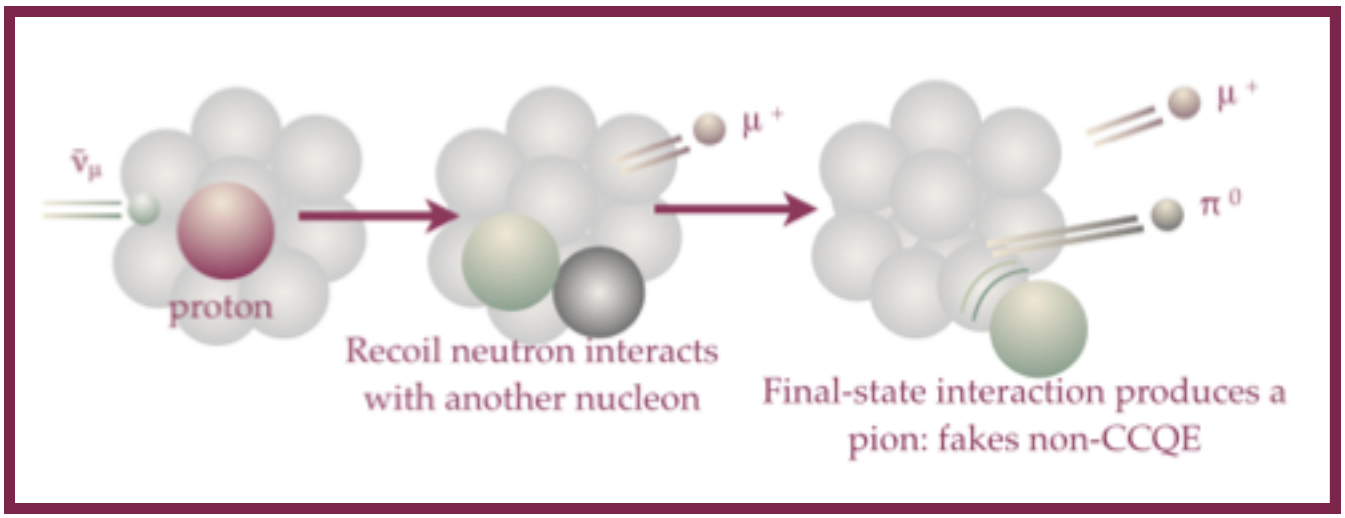


CCQE: correct your signal back to what the initial interaction was.



Two strategies:

QE-like (0π) : define a signal that is corresponds to what we see in the final state. More accurate, harder to interpret.



CCQE: correct your signal back to what the initial interaction was. Less accurate, easier to interpret.

Practical signal definitions

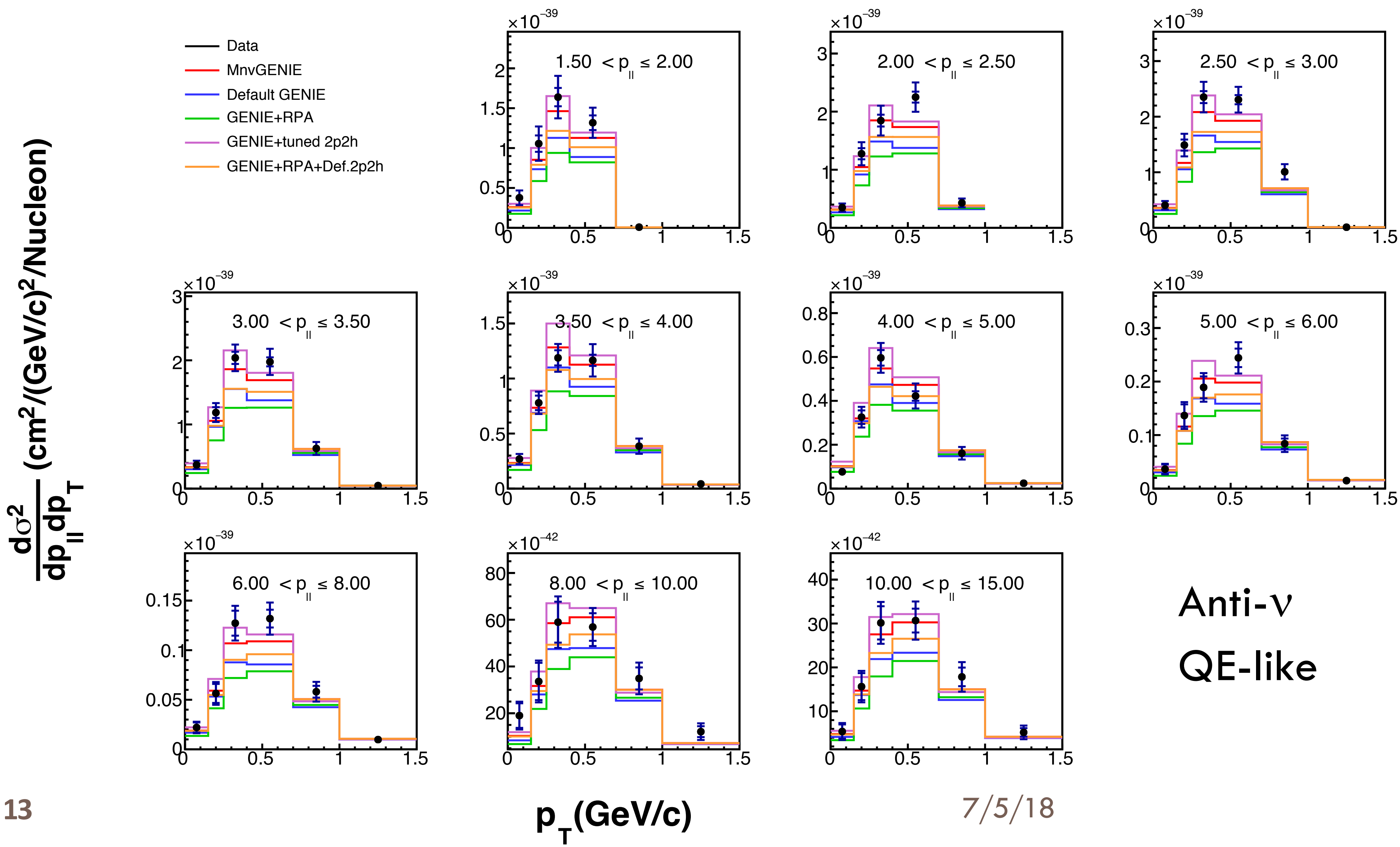
Ideal CCQE

- One charged muon
- One neutron
- No protons
- No pions
- Low recoil activity

CCQE-Like = 0π

- One charged muon
- May not see the neutron
- No protons > 120 MeV
- No pions
- Low recoil activity
- We allow any number of neutrons to include 2p2h contributions

Lots of data – 2D measurement

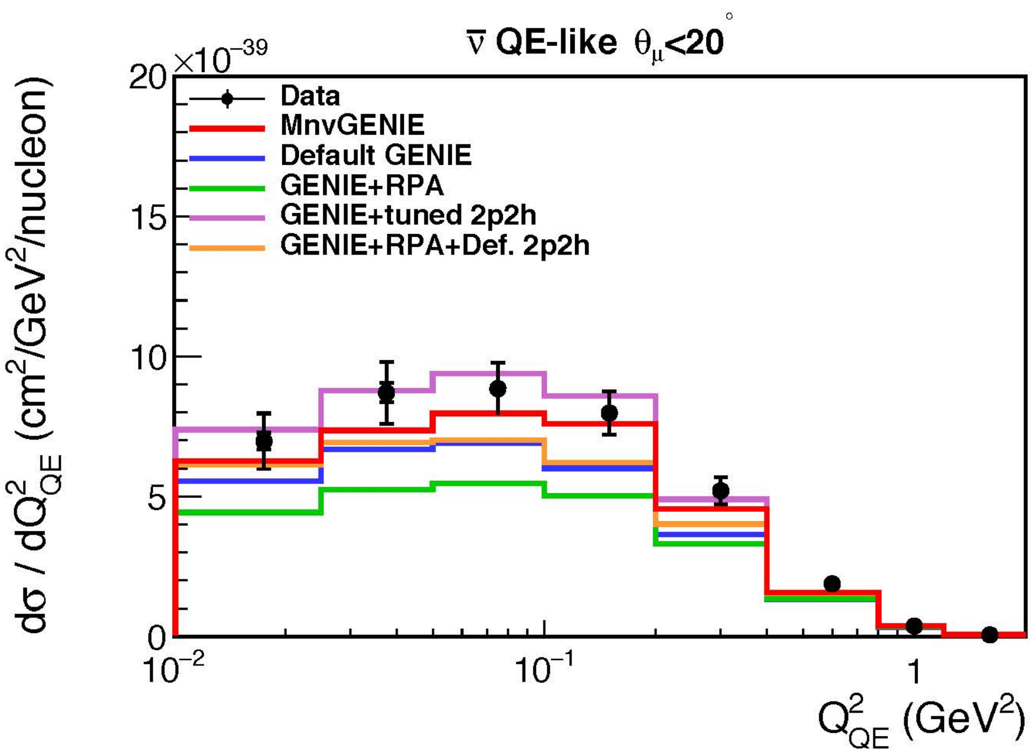


Anti-ν

QE-like

Can we model this?

- Default GENIE 2.8.4
  - (Relativistic Fermi Gas)
- Add in Random Phase Approximation (RPA) to account for screening at low Q^2
- Add ~20% 2p2h effects guided by Jlab results w/o RPA
- Add RPA and tune 2p2h to our neutrino data to get MnvGENIE



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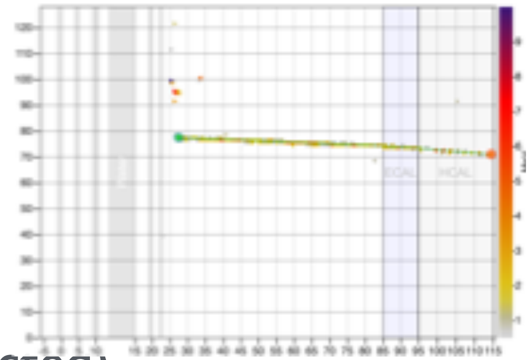
How MINERvA tunes the simulation

- Read lots of papers
- Listen to our eN→eN colleagues
- Look at the neutrino data where the process is
  - $\nu_\mu + n \to \mu^- + p$
- Look for the final state neutrons in
  - $\bar{\nu}_\mu + p \to \mu^+ + n$
- All of these indicate both a need for screening (RPA) at low Q2 and 2p2h effects.
- MINERvA tunes the 2p2h model on neutrino data

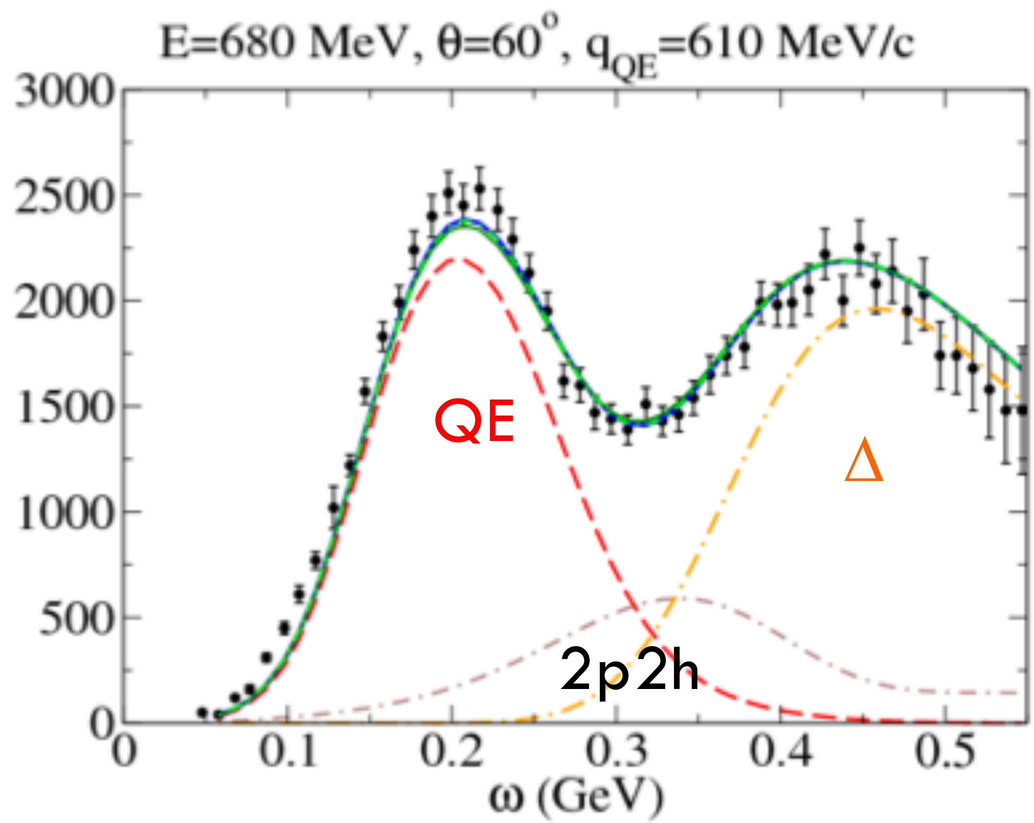
Multinucleon Effects



- Look at CC double differential cross section in q_0 and q_3
  - q_0: calorimetric hadronic energy (would be ω if n could be detected)
  - q_3: is the three momentum transfer $$q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$$

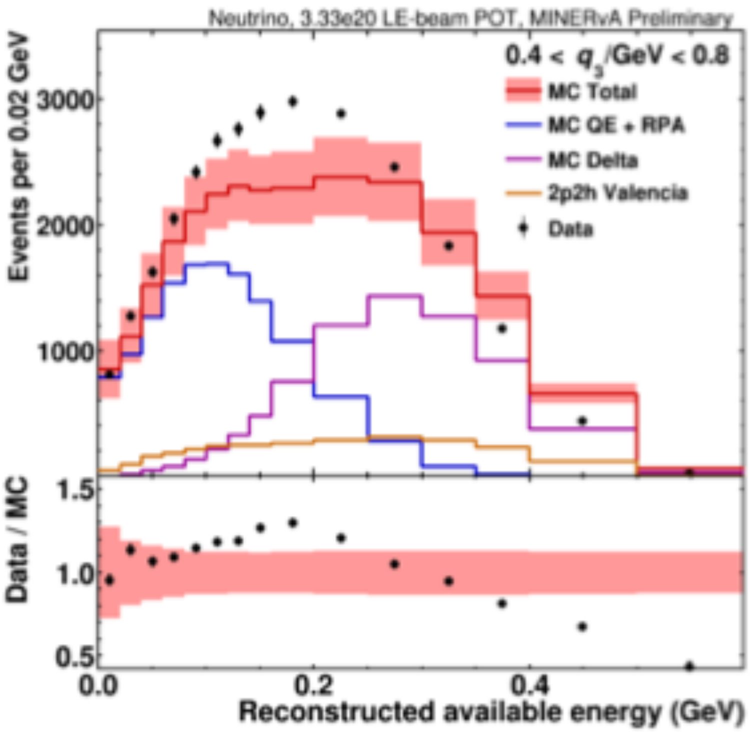
Motivated by electron scattering data on C.

Megias et al., Phys.Rev. D94 (2016) 013012

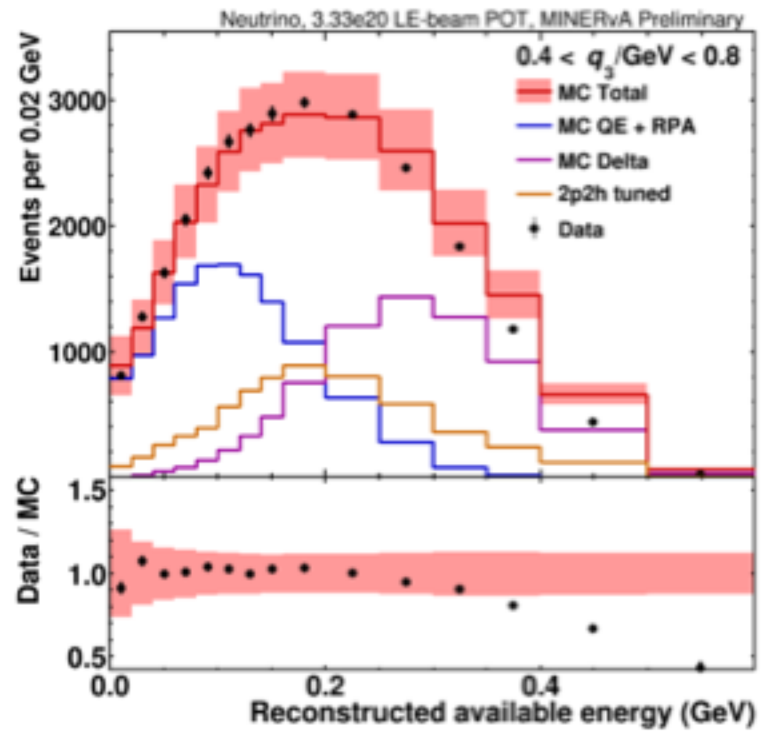


From Inclusive Neutrino Low Recoil Measurements

Phys.Rev.Lett. 116 (2016) 071802



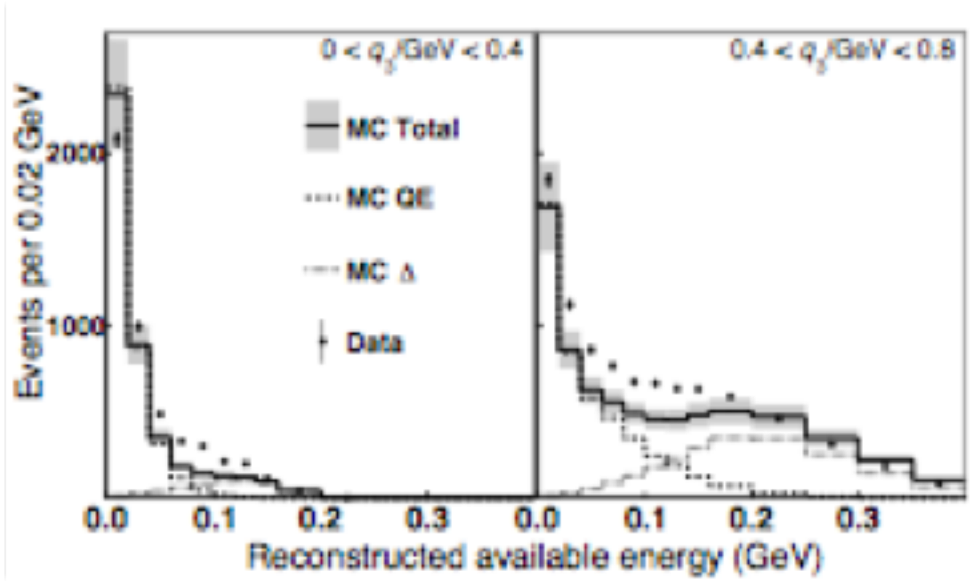
Tuning the 2p2h



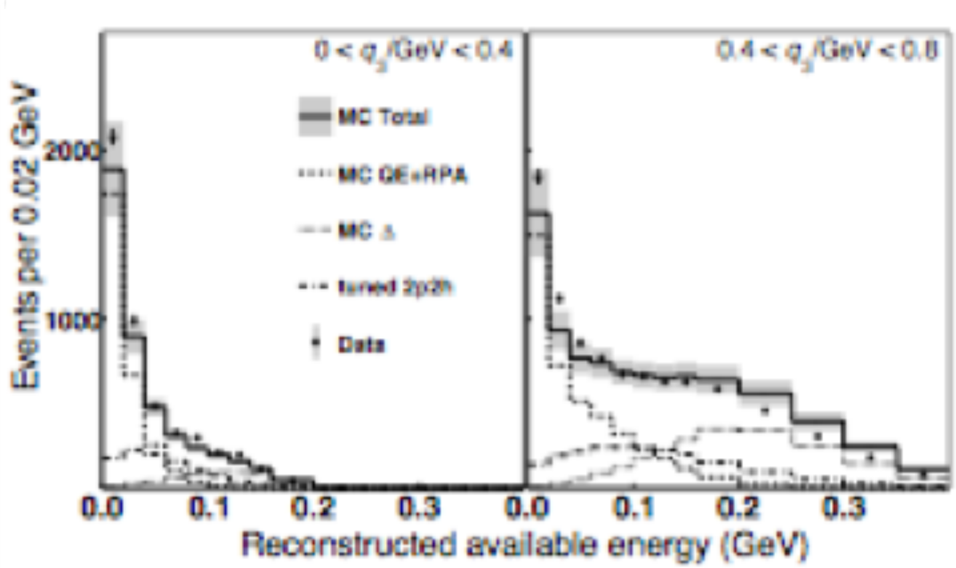
- Fitting a 2D Gaussian in true (q0, q3) as a reweighting function to the 2p2h contribution to get the best agreement between data and MC
- The QE and RES interactions are unchanged

Nuclear Effects at low Three Momentum Transfer (Antineutrino)

- Applying the extracted 2p2h weights from the neutrino sample to antineutrino



Before



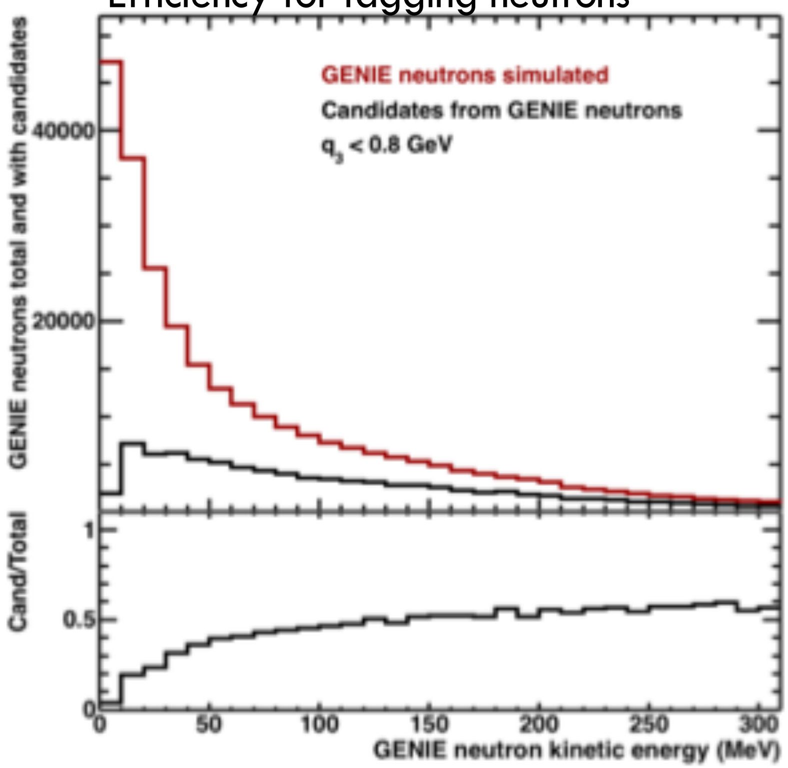
After

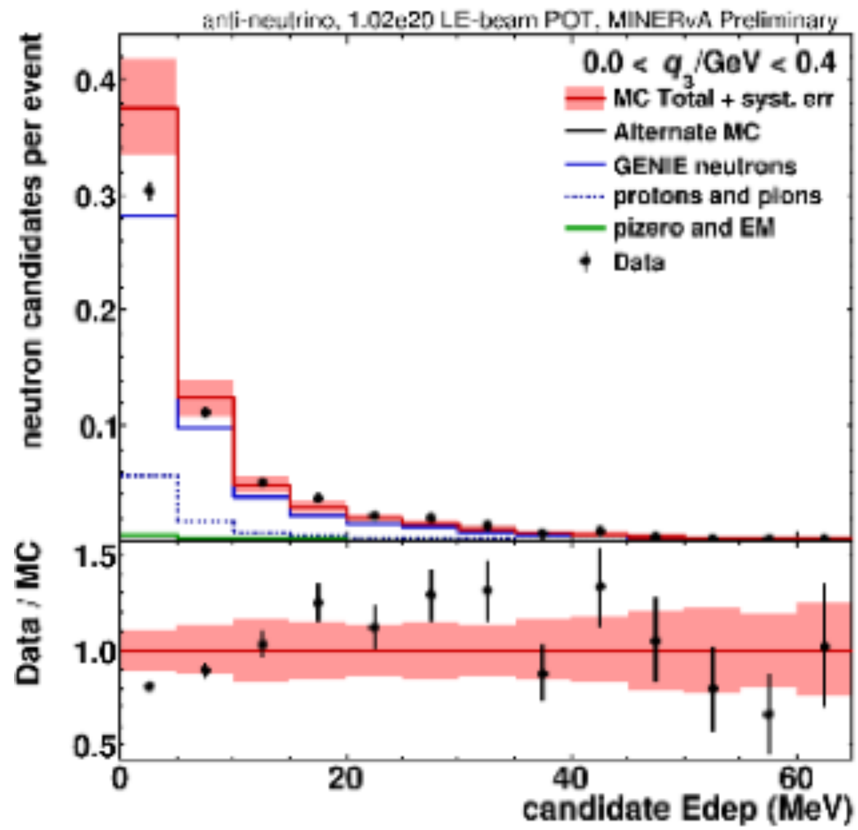
Phys.Rev.Lett. 120 (2018) no.22, 221805

Neutron detection update

- MINERvA has a new neutron detection algorithm in scintillator

Efficiency for tagging neutrons





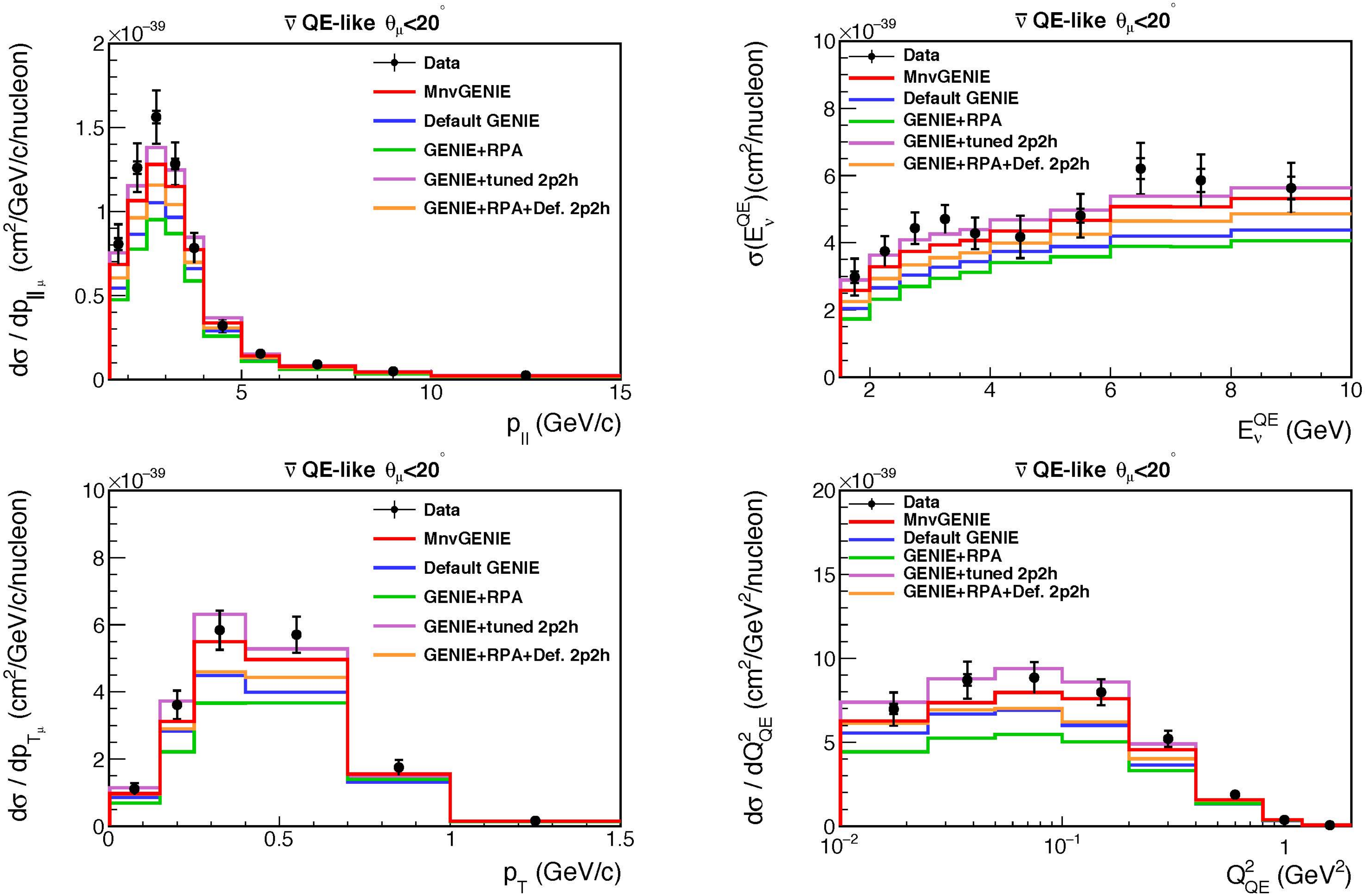
- Excess in the MC in the first bin small energy deposition

 Paper in preparation

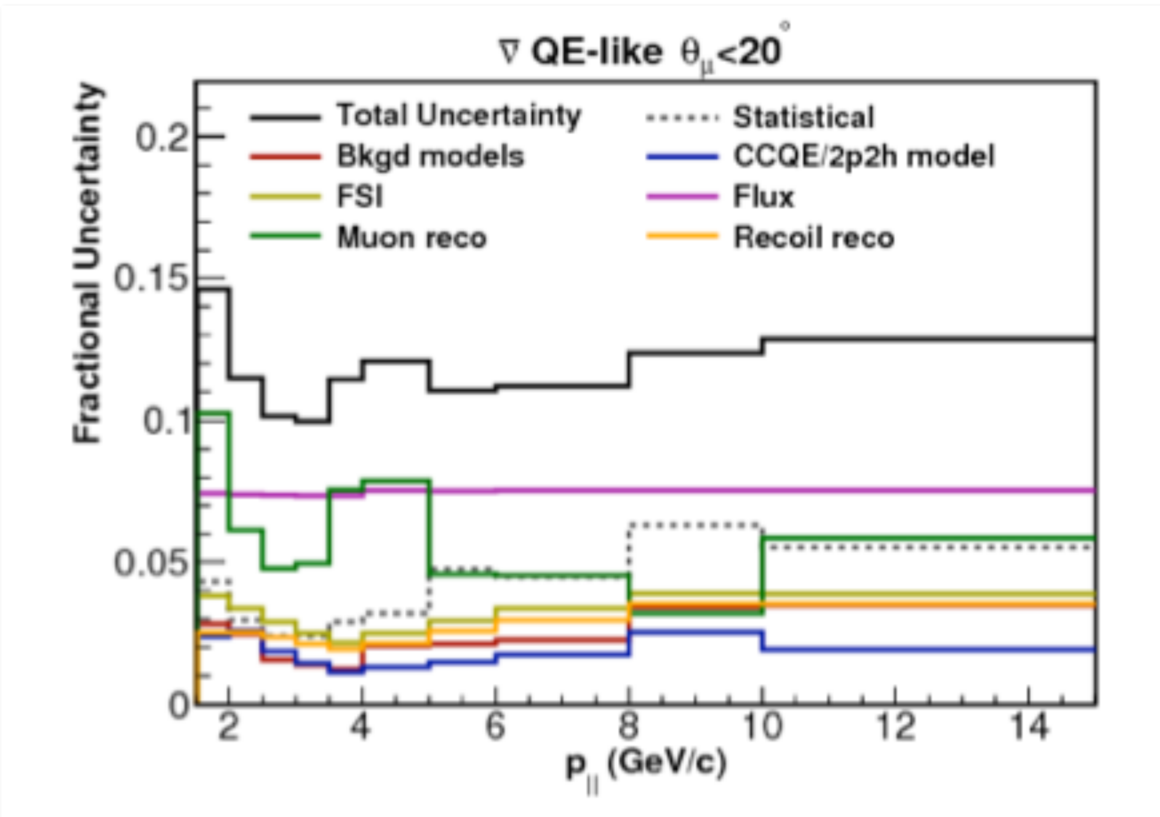
Bottom line

- Take Relativistic Fermi Gas model with final state interactions (GENIE 2.8.4)
- Add in screening (RPA) and multiparticle (2p2h) effects
- Use neutrino data to tune the 2p2h model.
- Get MnVGENIE model which agrees with our inclusive anti-neutrino data.

Back to inclusives now that we understand our simulation:
1-D distributions for QE-like



Systematic uncertainty sources



Statistical uncertainty

Background models

resonances

CCQE / 2p2h model

Final-state interactions

pion absorption dominates

Flux

beam focusing

tertiary hadron production

reweight to other experiments

Muon reconstruction

muon energy scale dominates

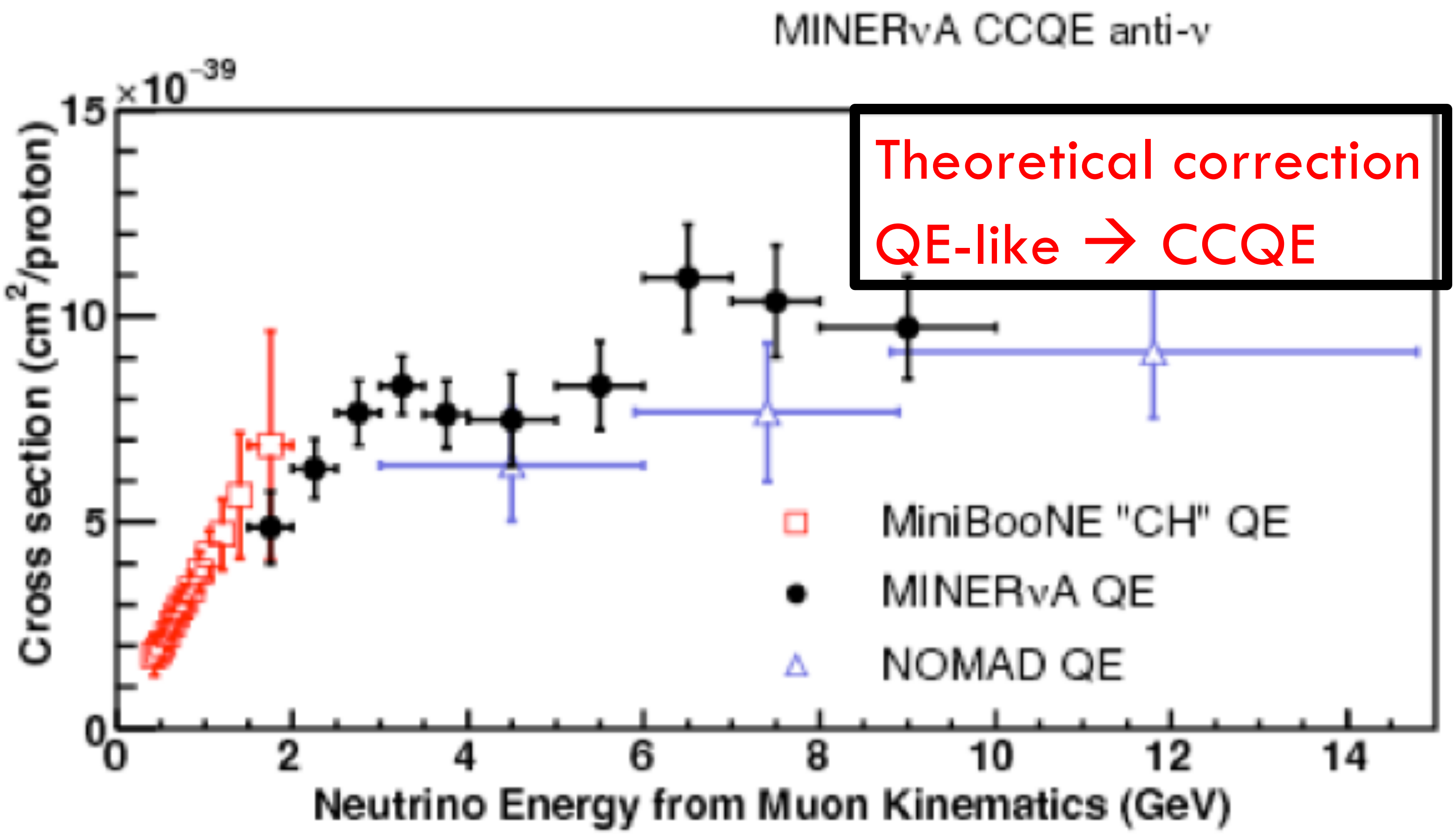
tracking efficiency

muon angle and vertex position

Recoil reconstruction

detector response to different particles - neutron dominates

Switch to CCQE to compare to other experiments
Bridge the gap!



MINERvA result includes an angle cut which lowers rate for E<4 GeV

Conclusions

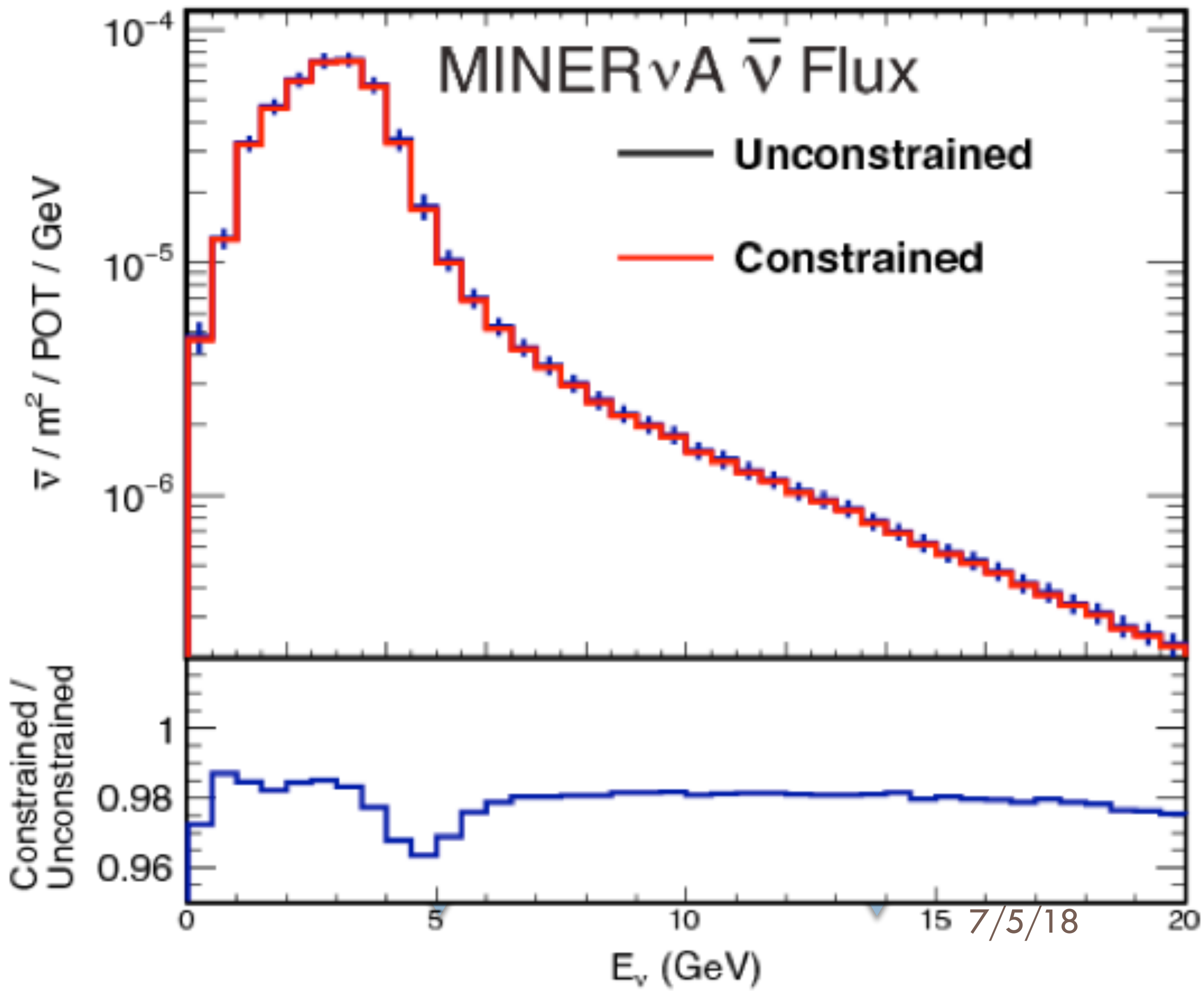
- We have measured anti-neutrino quasi-elastic scattering on scintillator with uncertainties dominated by the 7-8% flux normalization uncertainty.
- Bridges the gap between MiniBooNE and NOMAD
- Able to differentiate nuclear models – we favor a 2p2h component
- More details in Cheryl Patrick's June 17 seminar and her thesis (FNAL THESIS-2016-04)
- Published as 10.1103/PhysRevD.97.052002
- Data tables at: https://arxiv.org/abs/1801.01197
- Data from Medium Energy Run at higher energy coming soon.

The anti-neutrino team:

Heidi Schellman, Cheryl Patrick, Laura Fields

Backup slides

NuMI low energy anti-neutrino flux



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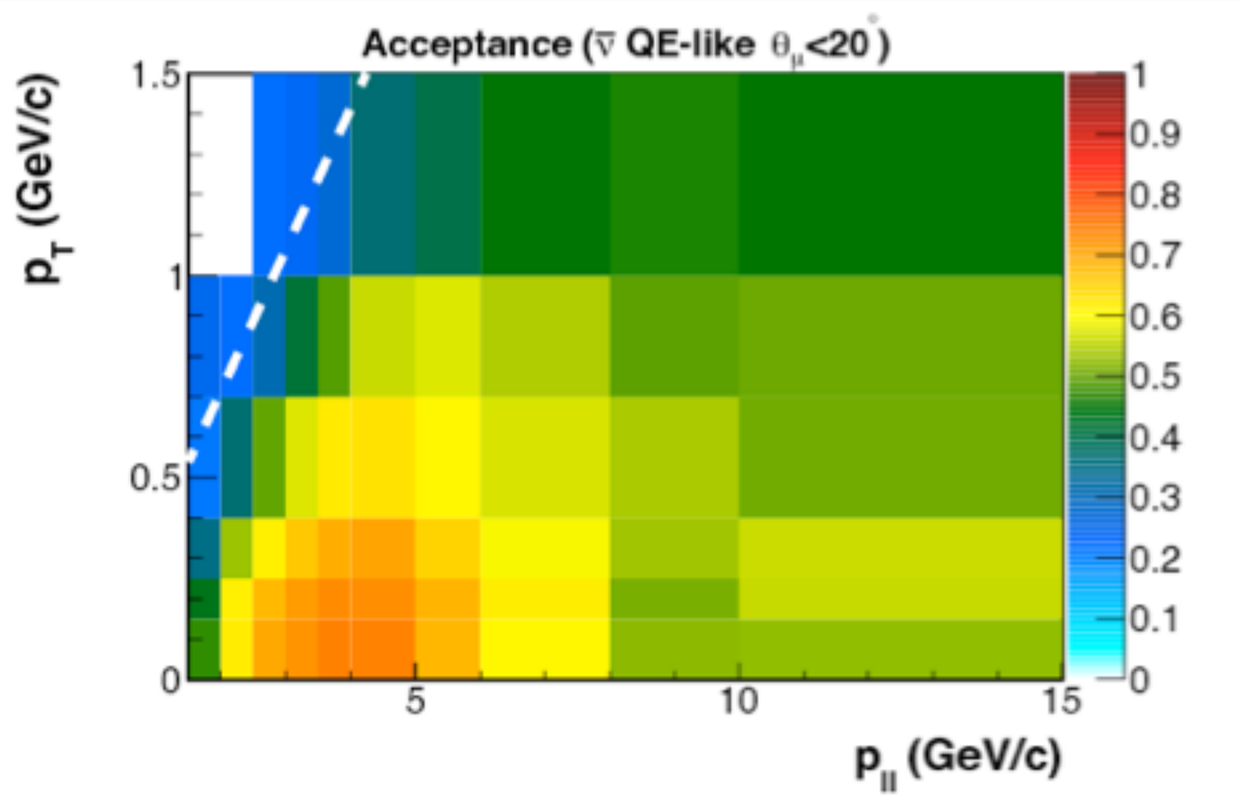
Muon kinematics acceptance



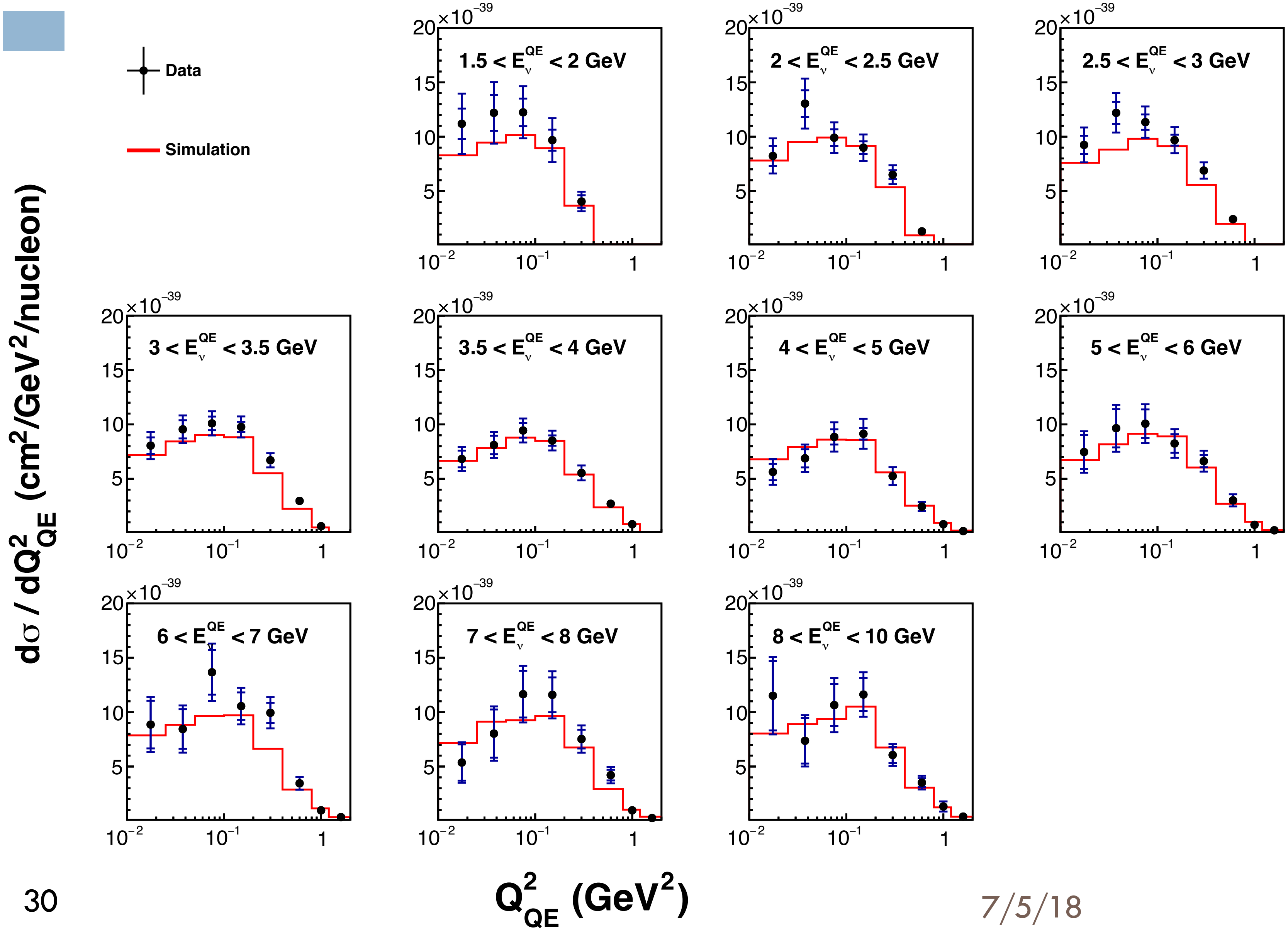
We measure the cross section in ~60 muon p_Z, p_T bins

2-D cross sections are normalized to integrated neutrino flux per nucleon

Model details

- We use GENIE 2.8.4 as our baseline Monte Carlo generator
- Nuclear effects
  - Relativistic Fermi Gas model with Bodek-Ritchie tail
  - Fermi momentum k_F=221 MeV
  - non-resonant pion production scaled by 57% to match fits to bubble chamber data as detailed in arXiv:1601.01888
  - RPA and 2p2h are added for the MnvGENIE model we use to correct our data.
- Nucleon effects
  - Proton form factor Axial mass M_A=0.99 GeV
  - BBBA05 model for vector form factors

Cross section vs Q^2



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Model references

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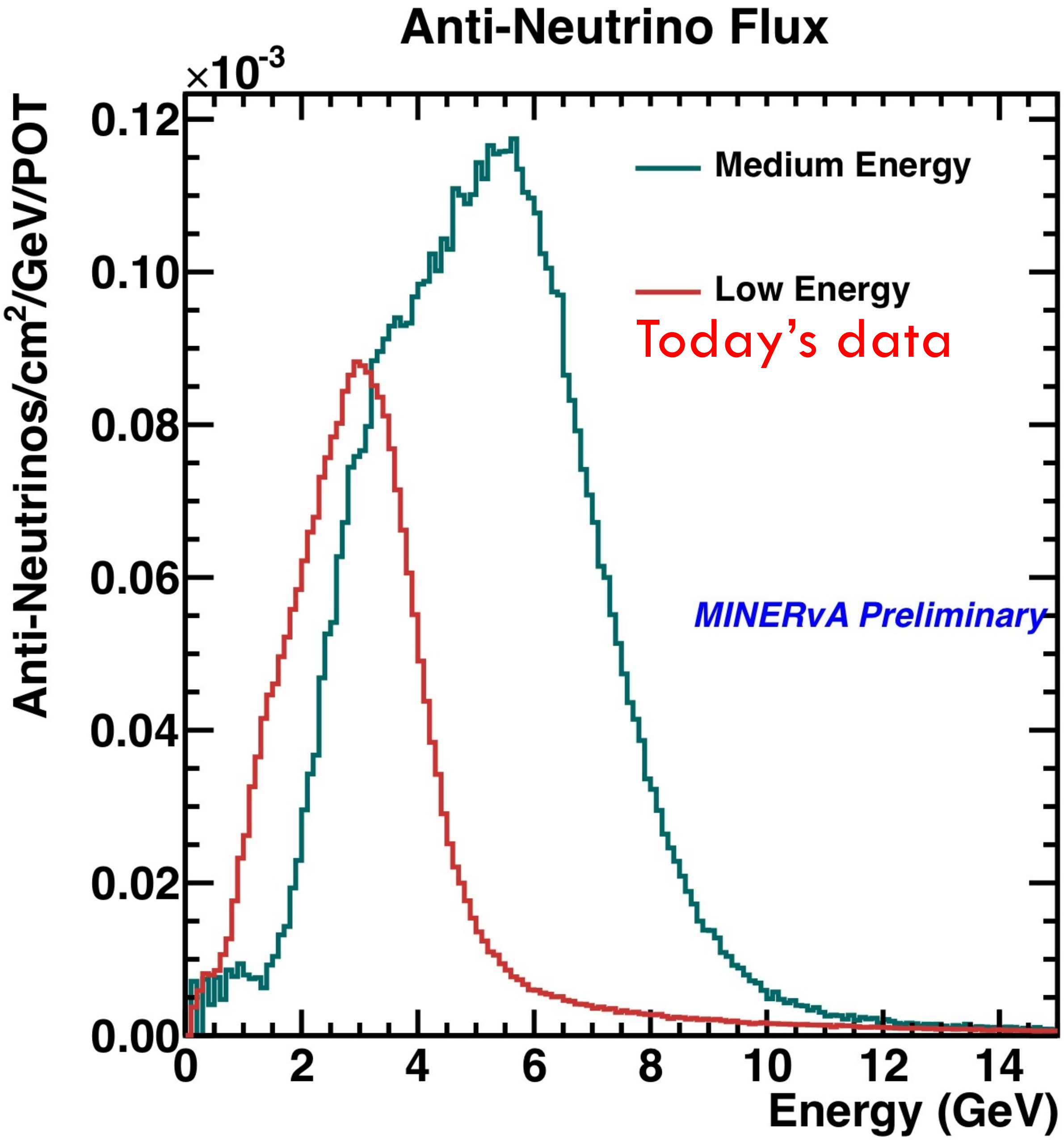
- *Spectral Functions: O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)*
- *Meson Exchange Currents: J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501*
- *Local Fermi Gas: AK. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)*
- *Relativistic Fermi Gas: R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972)*
- *NuWro: T.Golan, C. Juszczak and J.T.Sobczyk, Phys.Rev. C86, 015505 (2012)*
- *GENIE: C. Andreopoulos et al., arXiv:1510.05494*
- *Random Phase Approximation: J. Morfin, J. Nieves, J. Sobsczyk, Adv.High Energy Phys. 2012 (2012) 934597*


Anti-Neutrino Flux
×10^-3
Anti-Neutrinos/cm²/GeV/POT
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
2
4
6
8
10
12
14
Energy (GeV)
Medium Energy
Low Energy
Today's data
MINERvA Preliminary