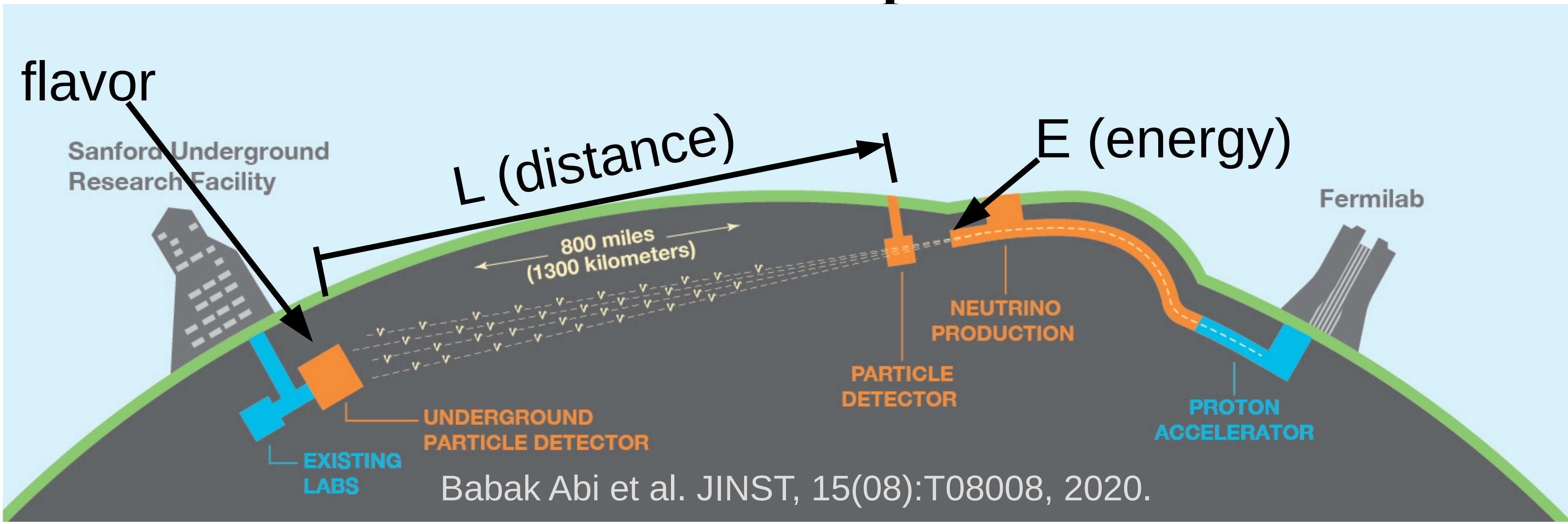
Antineutrino-Induced Neutrons at MINERvA

Andrew Olivier

October 6, 2023

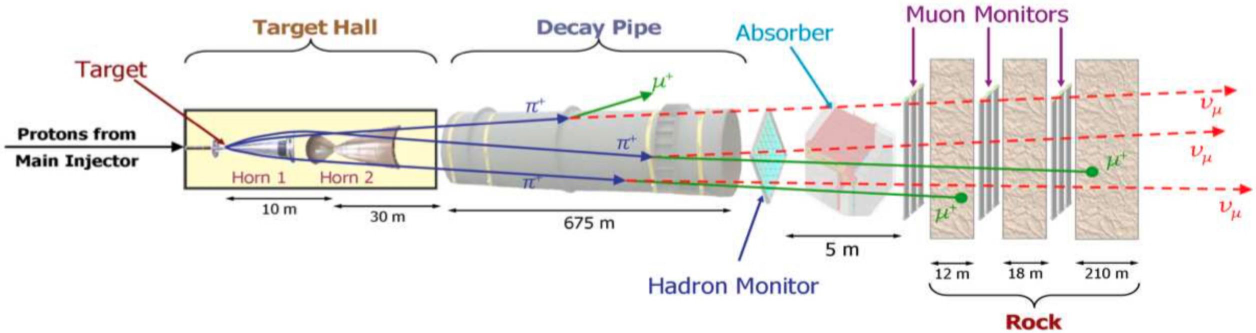
Long Baseline Neutrino Oscillation Experiments



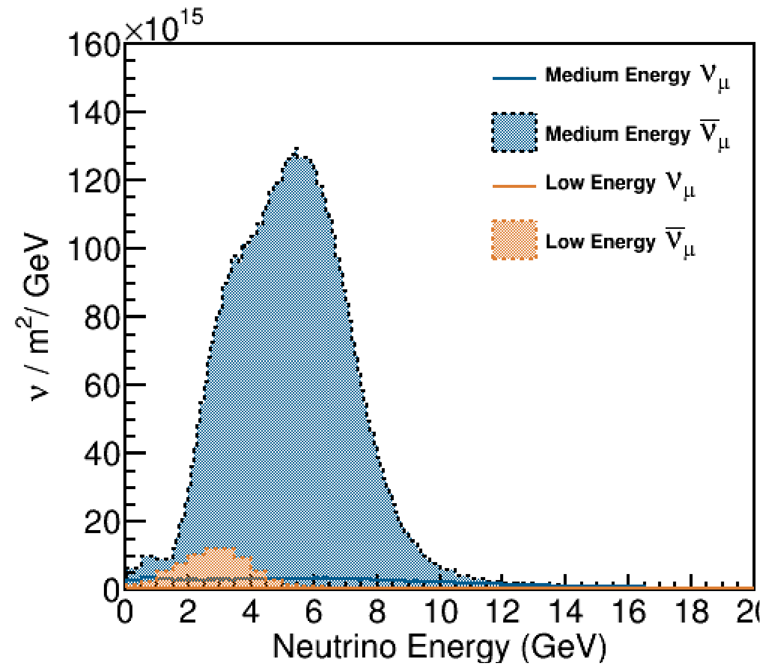
Babak Abi et al. JINST, 15(08):T08008, 2020.

- Interesting because not predicted by Standard Model. Imply neutrino mass. Potential for **CP violation**.
- Need: **L, E, flavor**
- Low interaction rate, so need **large mass, flux**

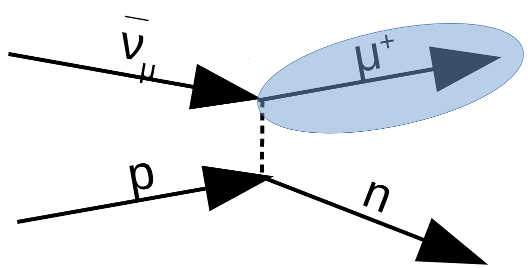
Measuring Energy isn't Easy



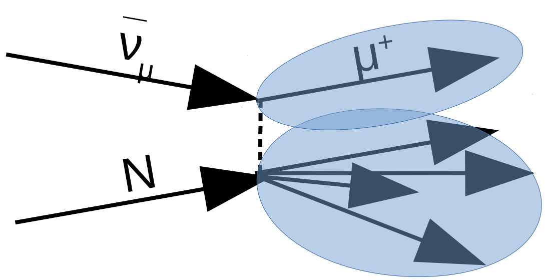
P. Adamson *et. al.* Nucl.Instrum.Meth.A 806 (2016) 279-306



Quasielastic

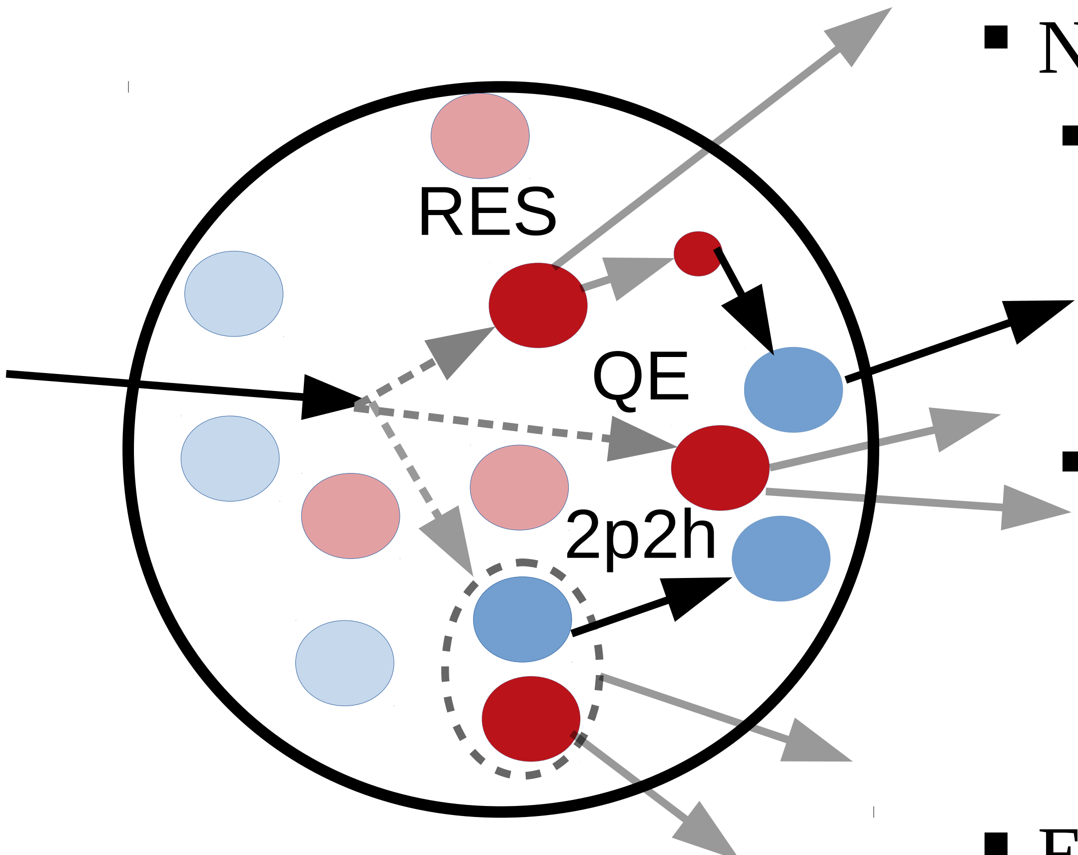


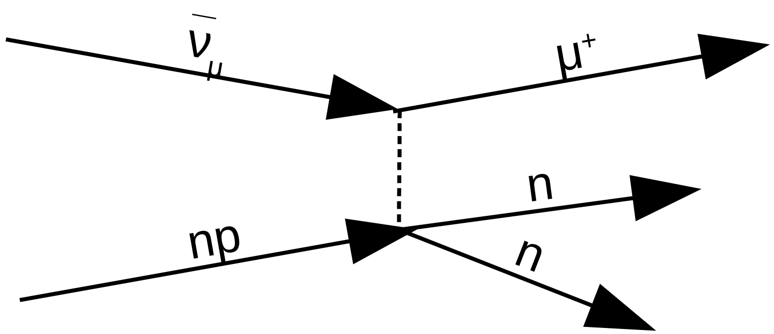
Calorimetric



- Can't focus neutrinos → must measure energy
- Can select **quasielastic** (QE) processes → reconstruct (anti)neutrino energy from lepton
- Can add all energy **calorimetrically**

Complications: Nuclear Effects

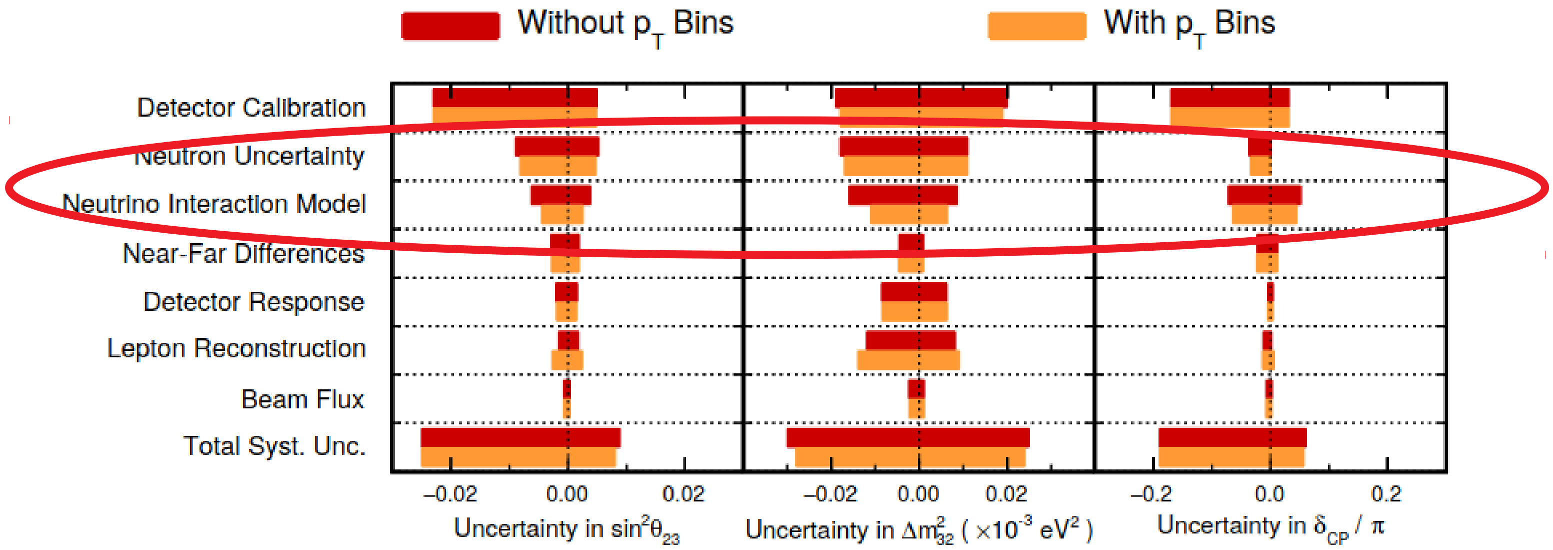




- Nuclear effects
  - Final State Interactions (FSI):
    - Additional nucleons
    - Pions absorbed
    - Hadron momenta changed
  - 2p2h
    - (Anti)neutrino interacts with pair of nucleons
    - Looks like QE, but energy reconstruction is not the same
- Effects on experiments
  - QE reconstruction: backgrounds
  - Calorimetric reconstruction: missing energy

Correct Using Simulation

- MC simulation predicts energy smearing → correction
- Price: systematic uncertainties
- Simulation uncertainties driven by cross section measurements...



Acero, M. A. et al. Improved measurement of neutrino oscillation parameters by the NOvA experiment. Phys. Rev. D 106, 032004 (2022).

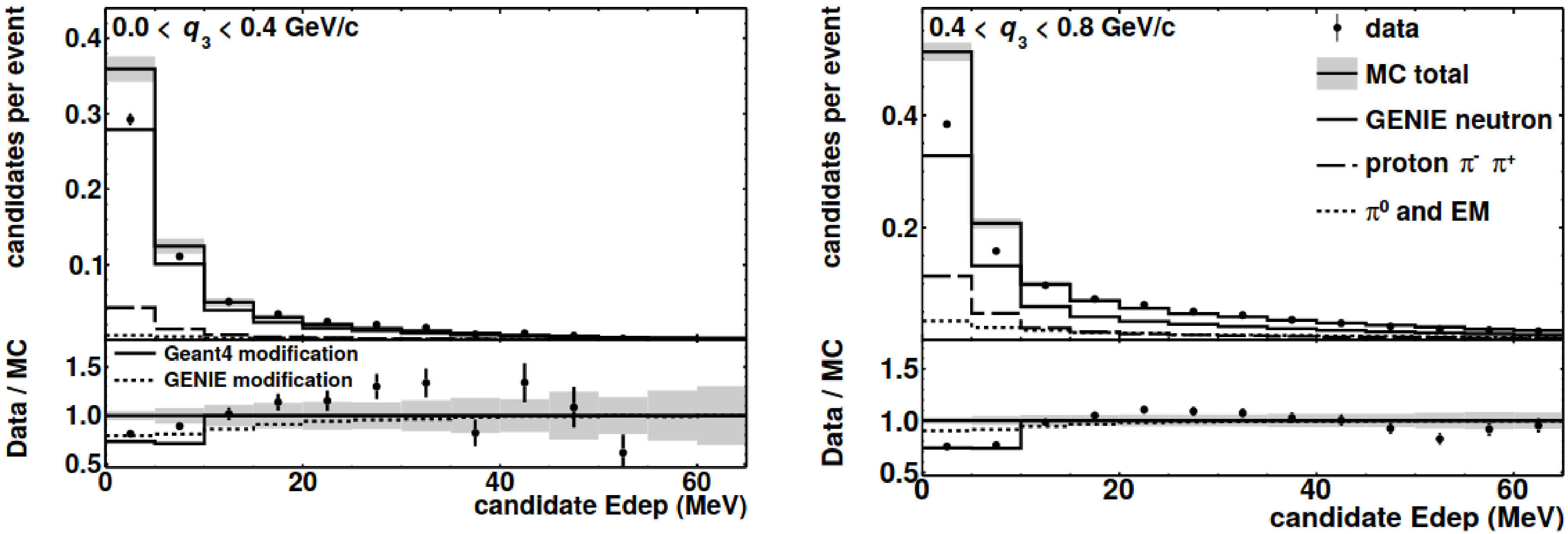
MINERvA Measures (Anti)Neutrino Cross Sections

- (Anti)neutrino cross section experiment in NuMI beam at Fermilab through Spring 2019
- CH, C, Fe, Pb, He, and water targets
- 2 energy ranges: $\langle E_\nu \rangle \sim 6$ GeV and 3 GeV
- 12×10^{20} protons on target in FHC (neutrino-dominated) and RHC (antineutrino-dominated)
- 44 publications and counting!
  - Quasielastic
  - Pions
  - Inclusive
  - DIS + SIS

Not Many O(10 MeV) Neutron Measurements

- Produced by (anti)neutrinos
  - SuperK: thermal neutron multiplicity from atmospheric antineutrinos[1]
  - SNO: Also thermal neutrons from atmospheric antineutrinos[2]
  - ANNIE plans to measure[3]
  - All rely on capture, so **little sensitivity to neutrons that obscure calorimetric reconstruction!**
- GEANT: 10-100 MeV neutron inelastic interactions from cascade tuned to O(1 GeV) neutrons?

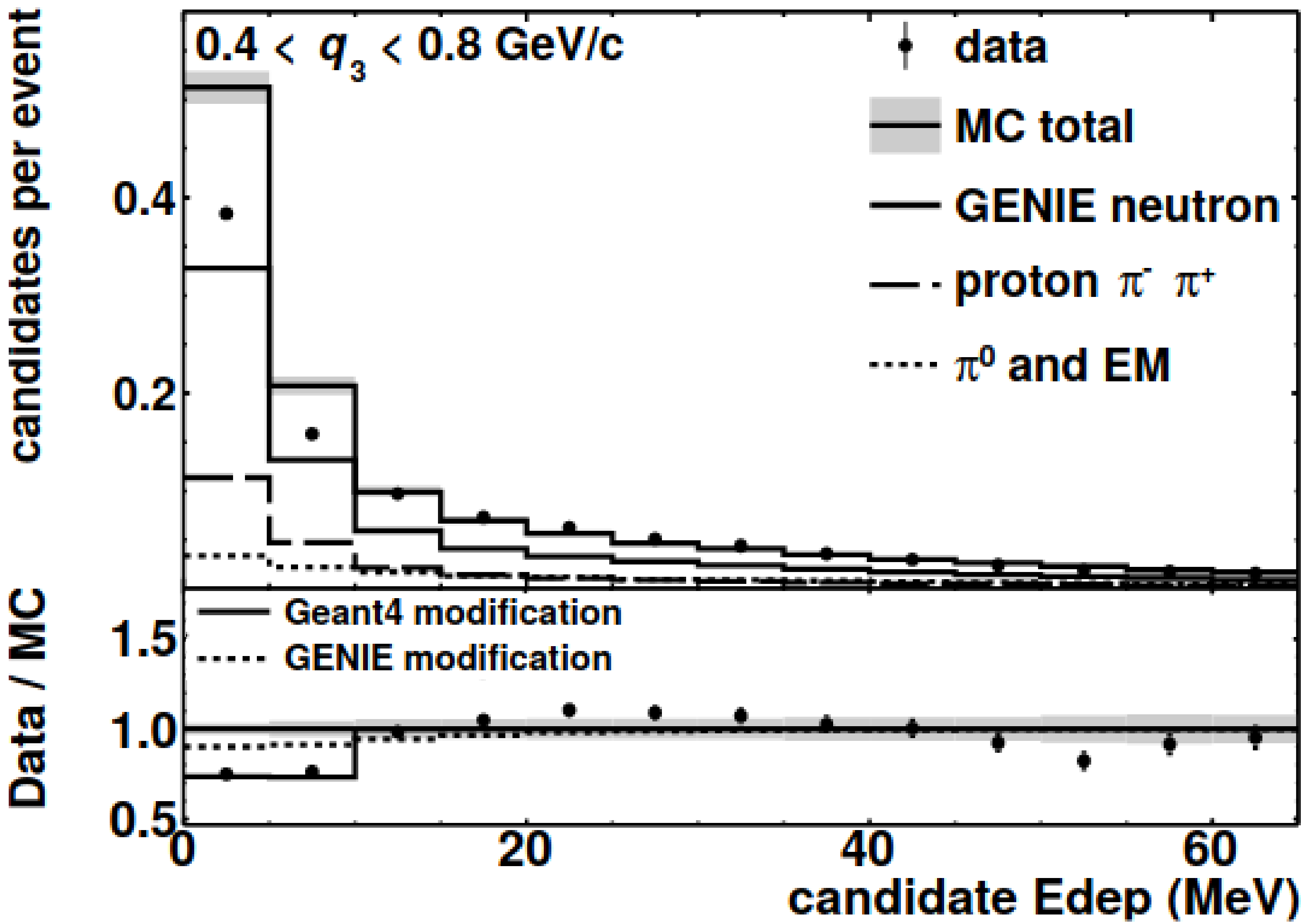
Neutrons at MINERvA



M. Elkins *et. al.* Phys. Rev. D 100, 052002 (2019)

- MINERvA sees neutrons
  - Inelastic scatters at KE >= 10 MeV
  - De-excitation photons
- Evidence that neutron production not well-modeled… but detector-dependent
- *Nature* physics with neutrons recently: measured axial vector form factor(4)

Neutrons at MINERvA



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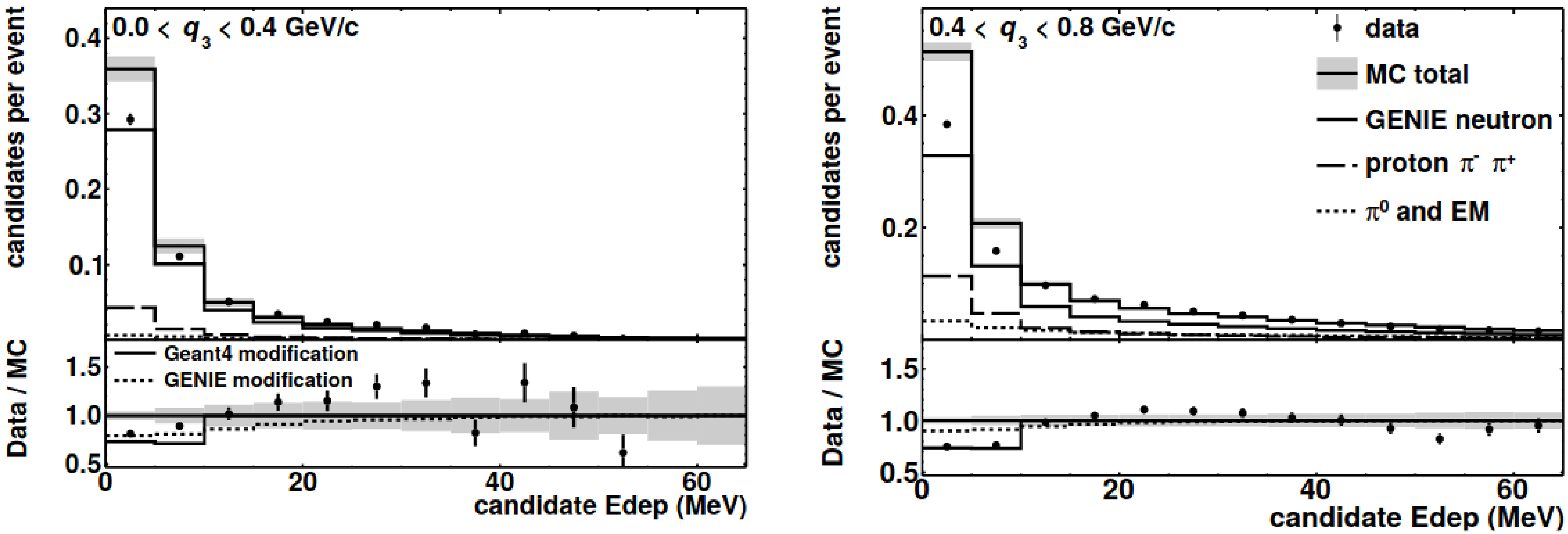
Neutrons at MINERvA



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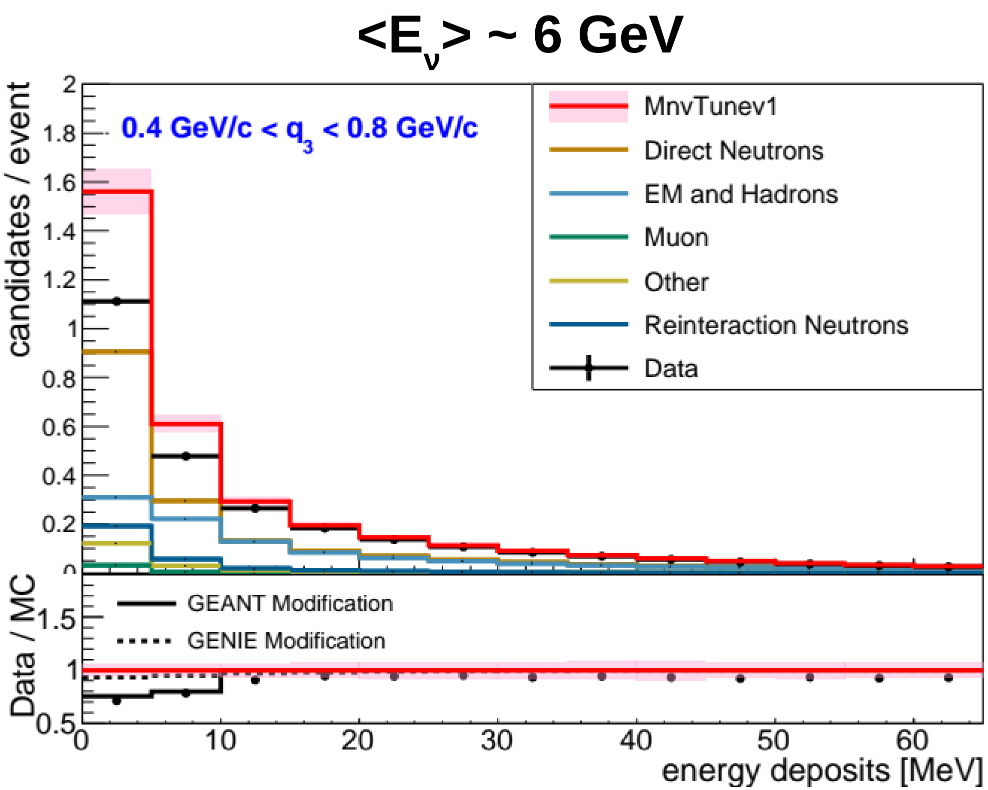
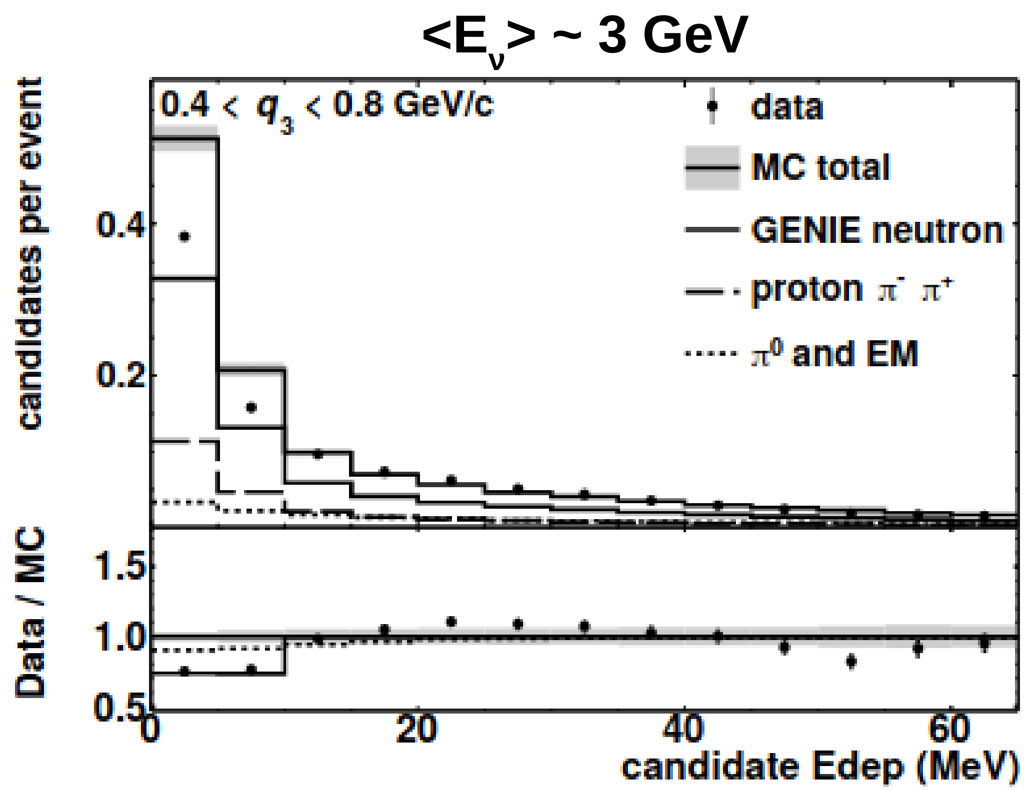
Neutrons Across Energy Ranges



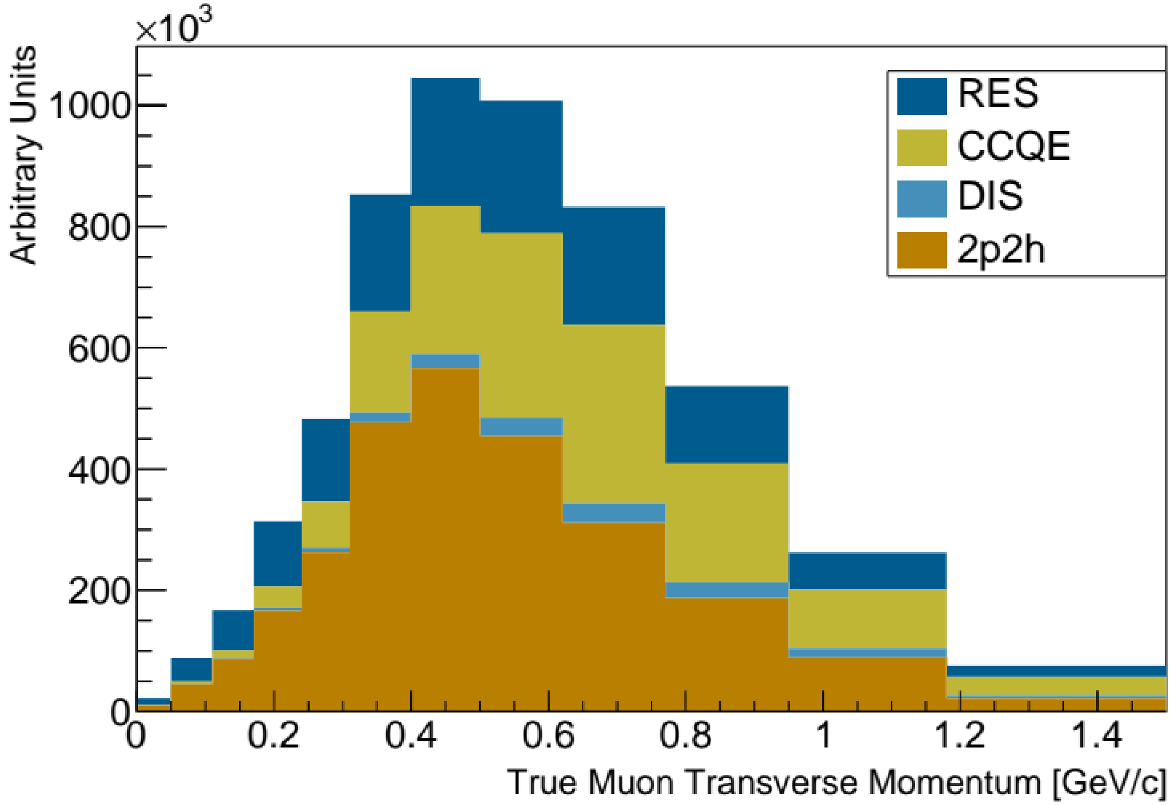


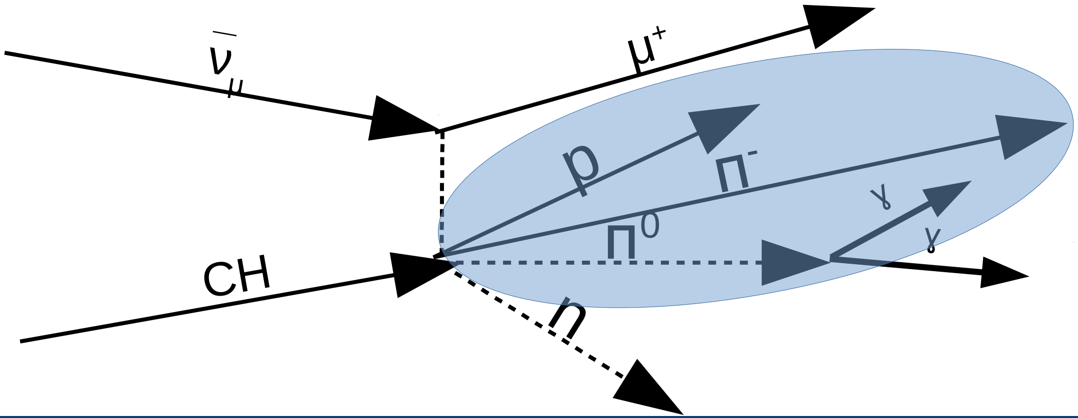
M. Elkins *et. al.* Phys. Rev. D 100, 052002 (2019)

- Same shape as low energy result but more efficient
- Same over-prediction of neutrons at low energy deposit
- Still no definitive cause

Multi-Neutron Cross Section

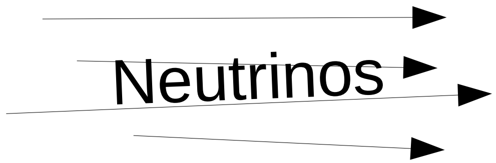
- Where we can make measurement:
  - Available energy < 100 MeV → fewer backgrounds, more QE-like
  - 2 or more neutrons with KE > 10 MeV each
- Lots of 2p2h
- FSI introduces other processes



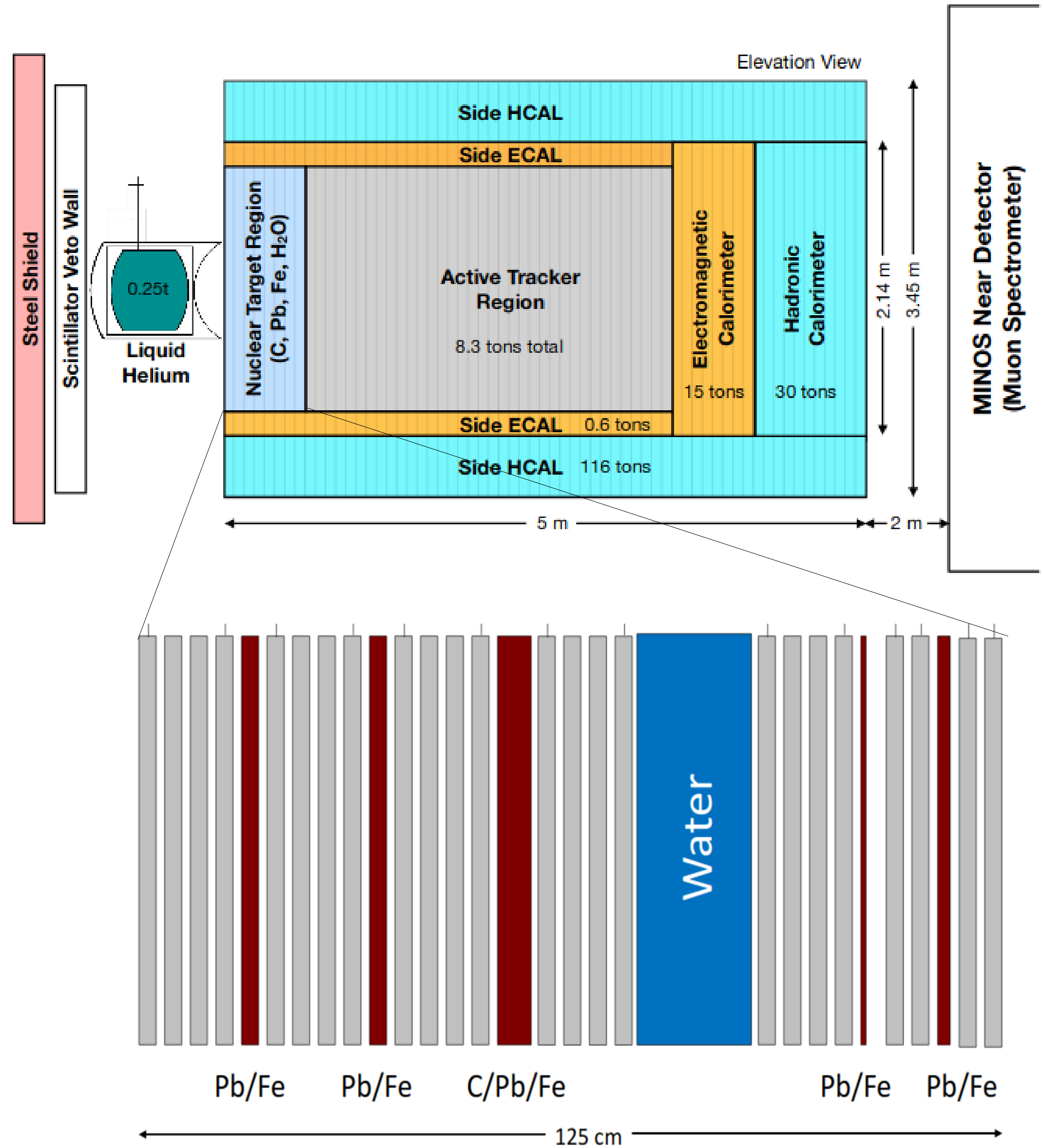


Part II: Measurement Techniques

The MINERvA Experiment



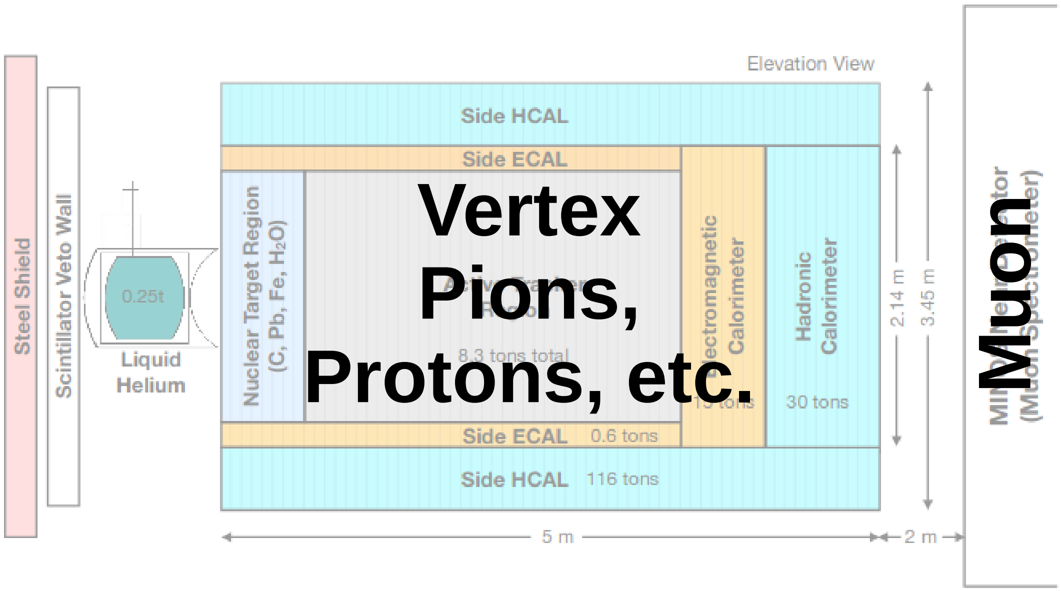
- **M**ain **IN**jector **E**xpe**R**iment for **v-A** scattering at Fermilab
- We measure (anti)neutrino cross sections!
- Technology: polystyrene (CH) fine-grained scintillator tracker
- Passive nuclear targets illuminate nucleus dependence

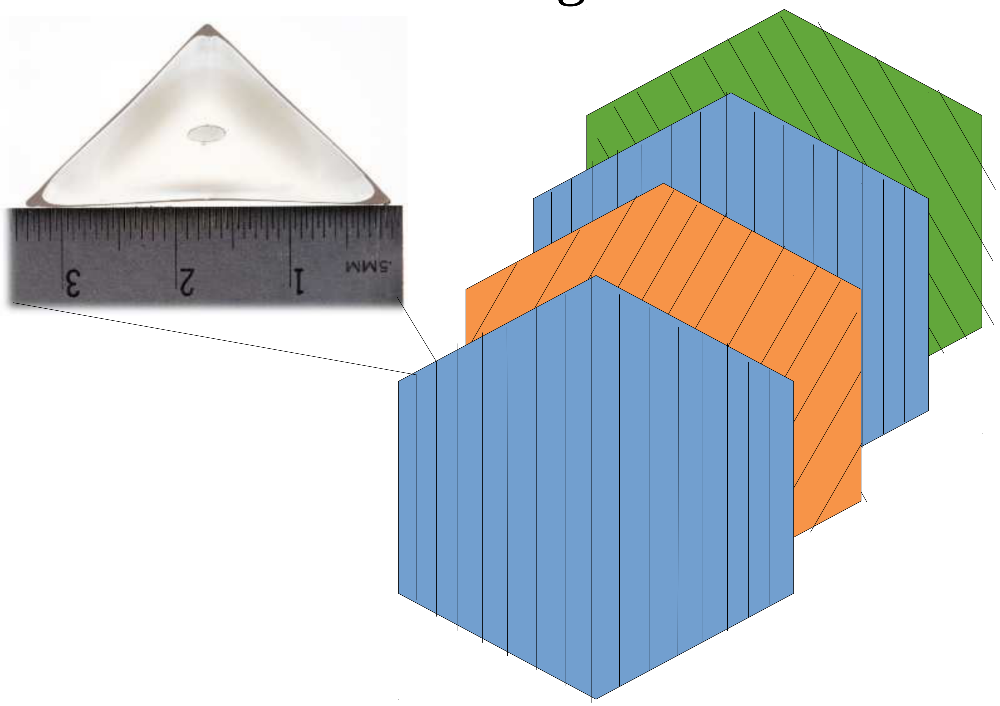


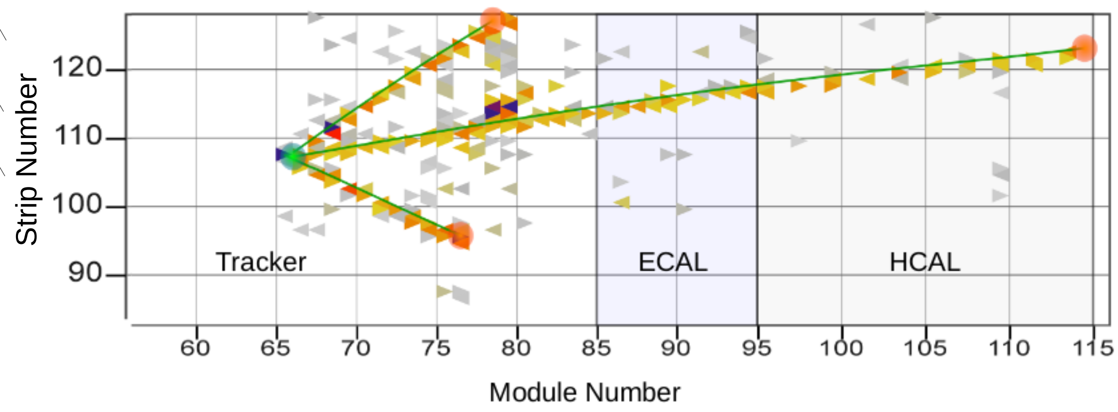
Nucl. Inst. and Meth. A743 (2014) 130

MINERvA's Tracker

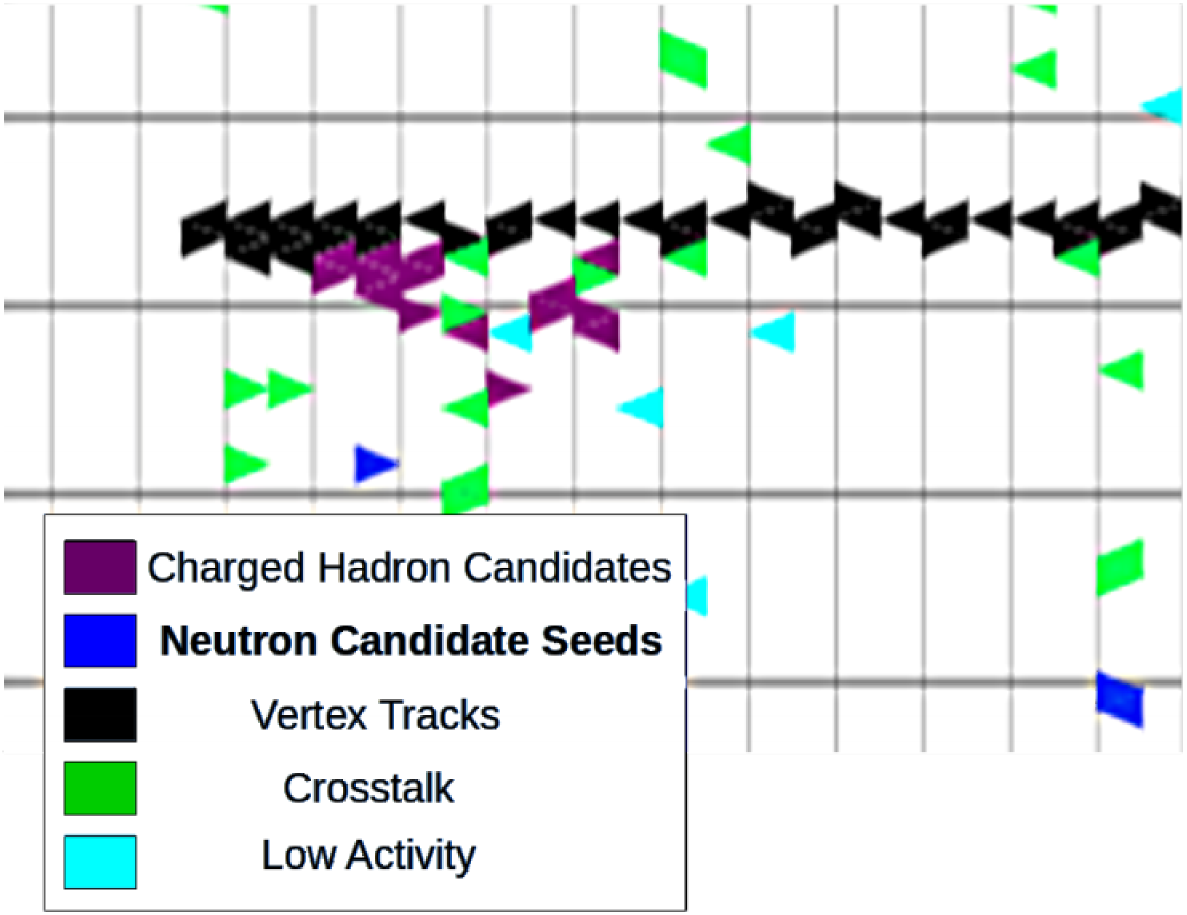
- MINOS data provides precise muon momentum
- Tracker consists of stacked planes of scintillator strips
- Each strip sees charge as light
- Put 3 views of strips together to reconstruct 3D images





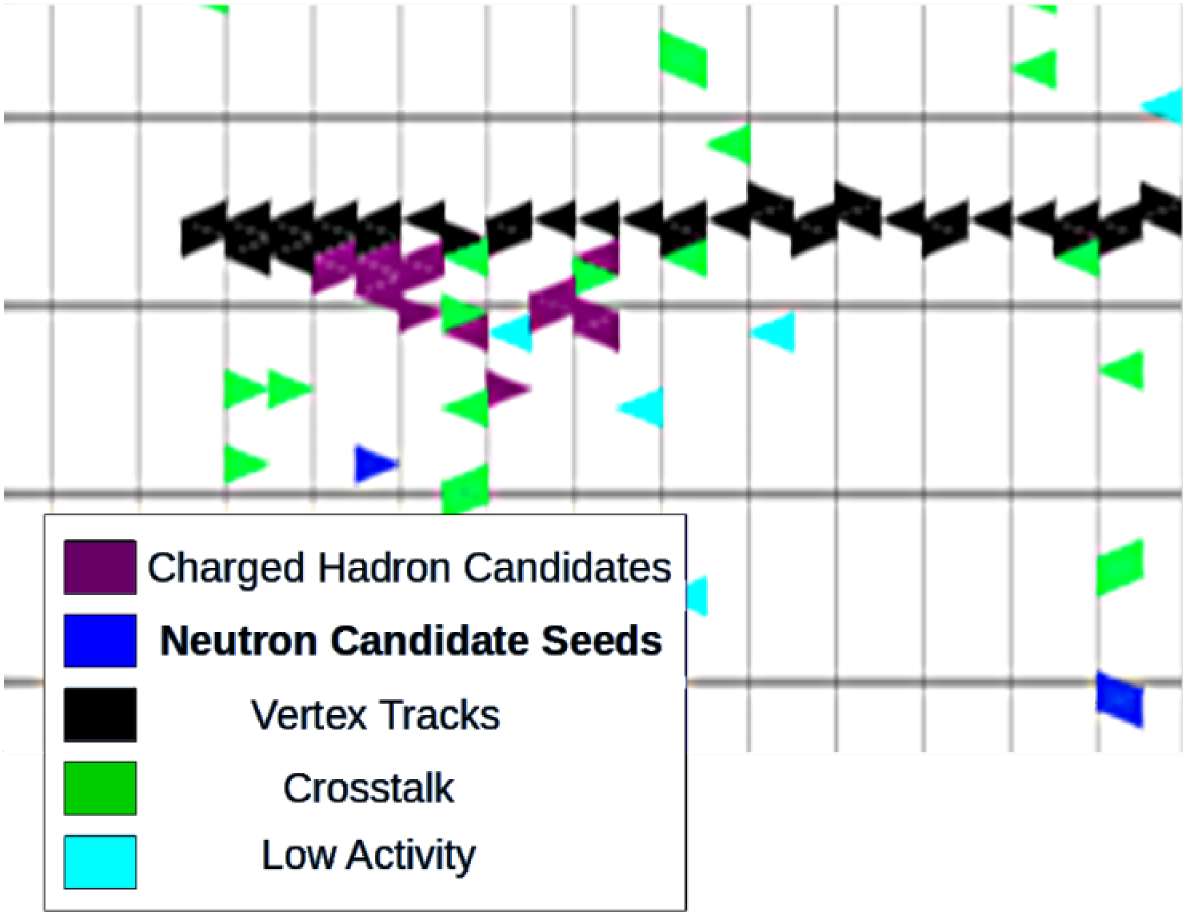


Reconstructing Available Energy



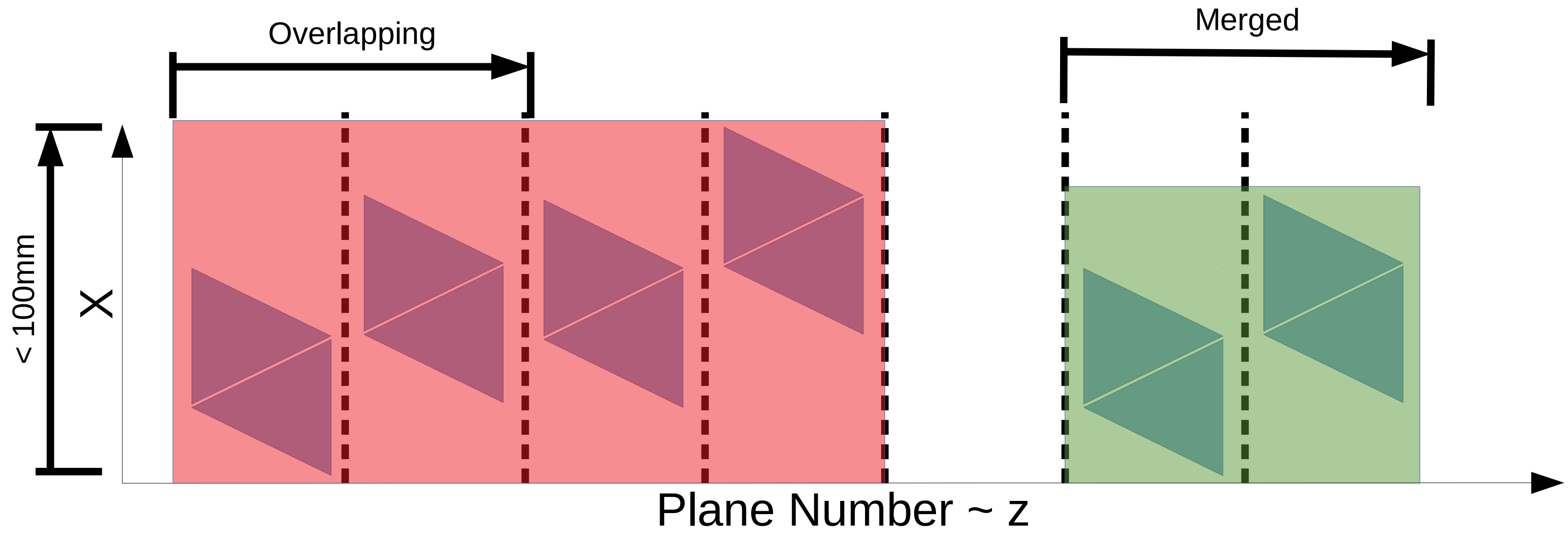
- Designed to estimated energy transfer
- Add up energy not in muon (black points)
- Subtract energy of neutron candidates (blue points)

Neutron Detection



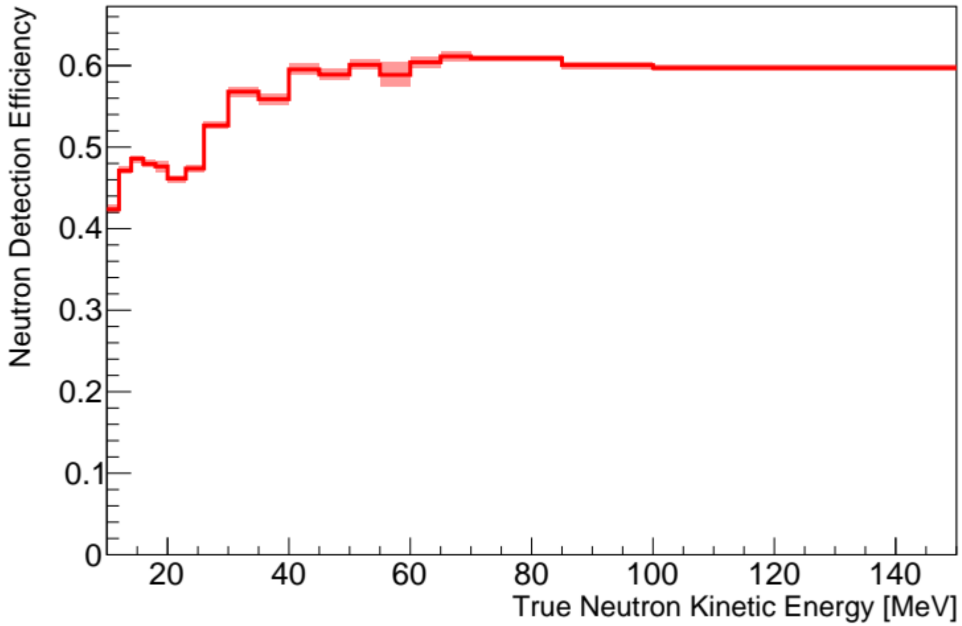
- Charge deposits far from vertex are neutron-like
- Energy deposits less than 1.5 MeV are likely backgrounds
- $E_{available} < 100$ MeV removes events with neutral pions
- Cross-talk and uncorrelated beam activity only become significant at 1.5 m from vertex

Neutron Counting



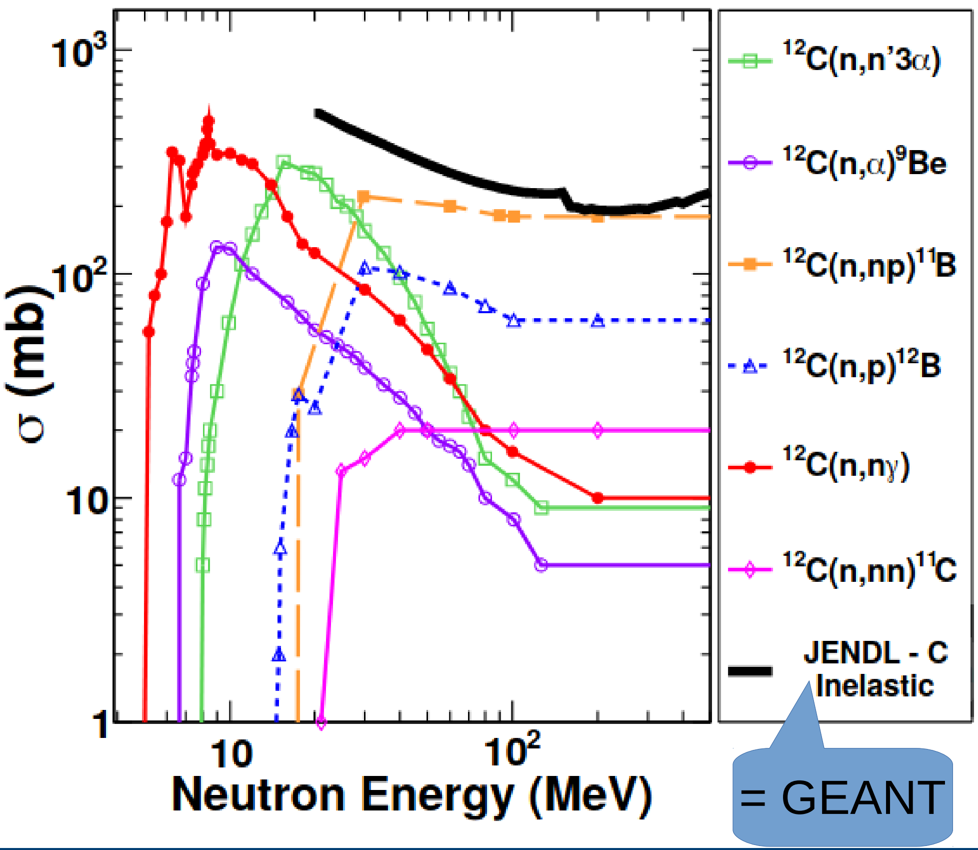
- Combine neutron "seeds", or clusters, to count neutrons
  - First combine seeds within each view, or scintillator orientation
  - Then combine candidates across views if reconstructed x positions similar enough
- Important to avoid double-counting
- Candidates from *Nature* paper plus lower energy activity

What Neutrons does MINERvA See?



- Fairly high acceptance for individual neutrons
- Acceptance dies off at < 10 MeV, and > 100 MeV not common in sample

MENATE_R: Data-Driven Neutron Transport



- MENATE_R is a neutron transport simulation driven by nuclear physics cross sections
- MoNA(7) measured neutron multiplicity and compared MENATE_R to GEANT
- MENATE_R much closer to data
- Built MINERvA uncertainty from this

Cross Section Method

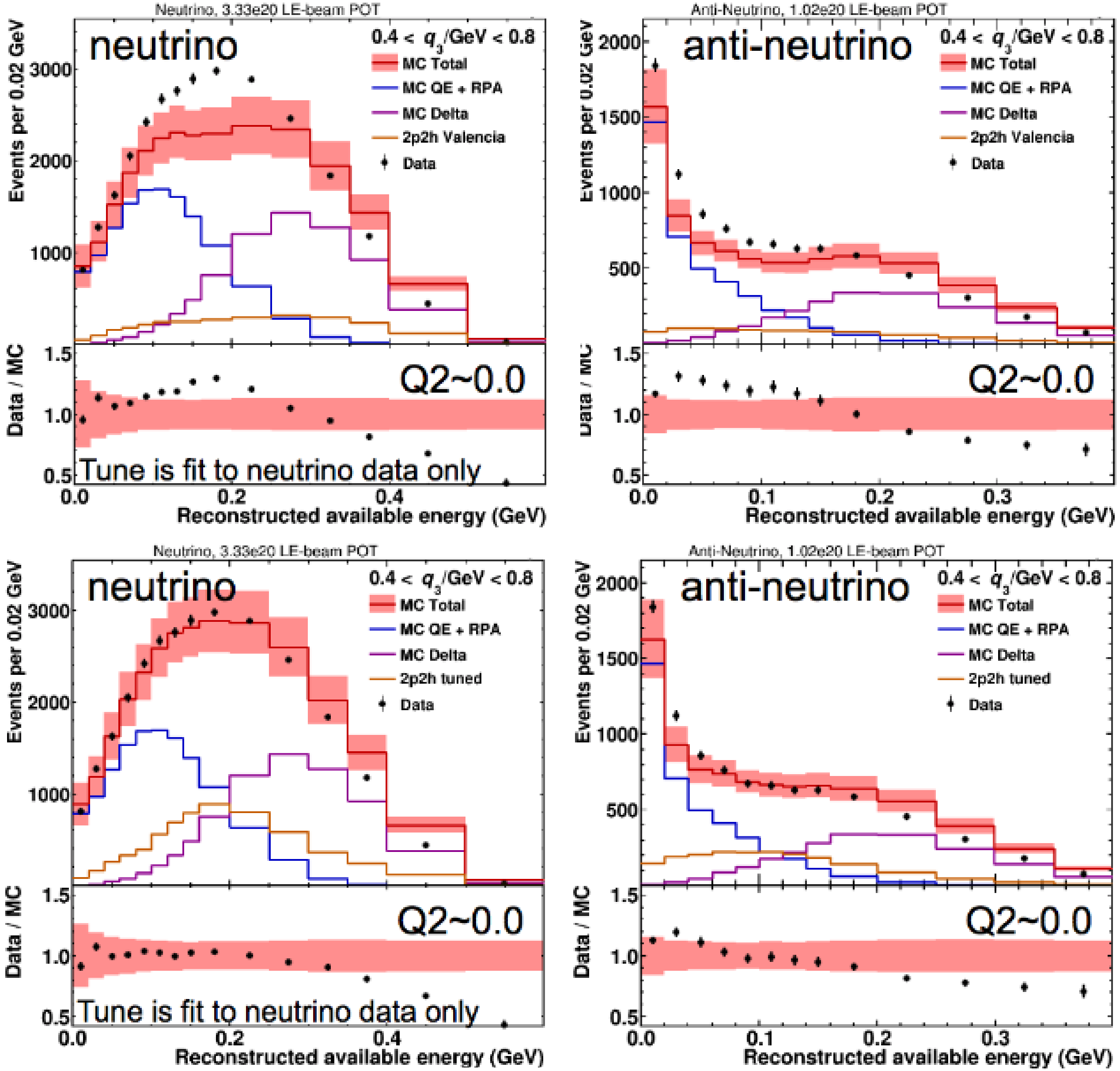
$$\frac{d\sigma_{signal}}{dp_{T\mu}}_j = \frac{\Sigma_i U_{ij}(N_i^{selected} - \Sigma_k \alpha_{ik} \times N_{background,ik}^{selected})}{\epsilon_j \Phi \Delta p_{T\mu j} N_{nucleons}}$$

- $p_{T\mu j}$: muon transverse momentum
  - Proxy for momentum transfer
  - Can be measured without dependence on hadronic model
  - Easy to compare with models and other measurements
- $N^{selected}_i$: number of reconstructed multi-neutron antineutrino interactions
- α_{ik}: background scale factors driven by data
- ε_j: efficiency and acceptance correction
- U_{ij}: unsmearing matrix estimated using simulation with d'Agostini unfolding
- Φ: integral of antineutrino flux at detector
- $N_{nucleons}$: number of antineutrino interaction targets in MINERvA's active tracker

Antineutrino Interaction Model

Before

After

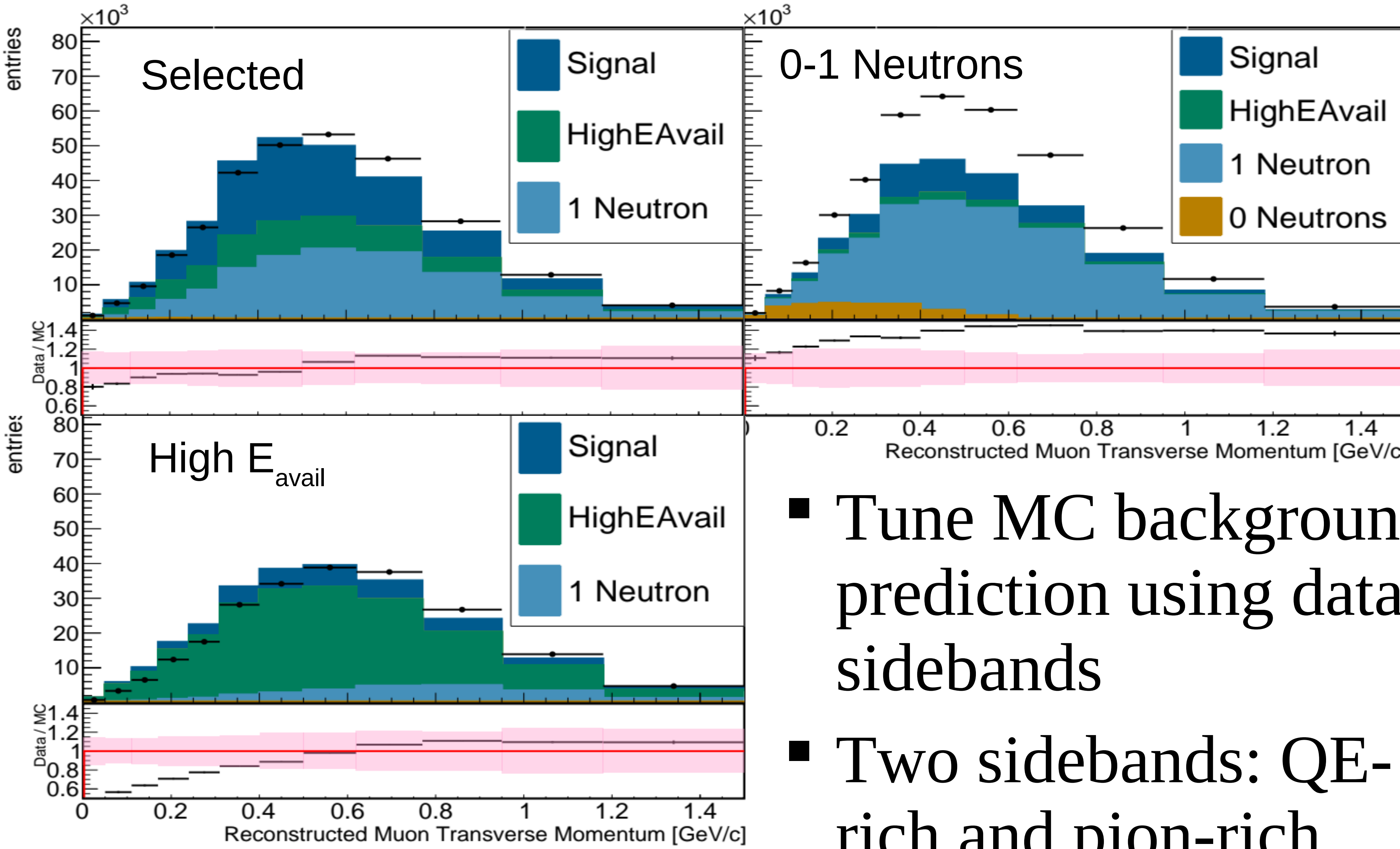


Phys. Rev. Lett. 116, 071802

Phys. Rev. Lett. 120, 221805 (2018)

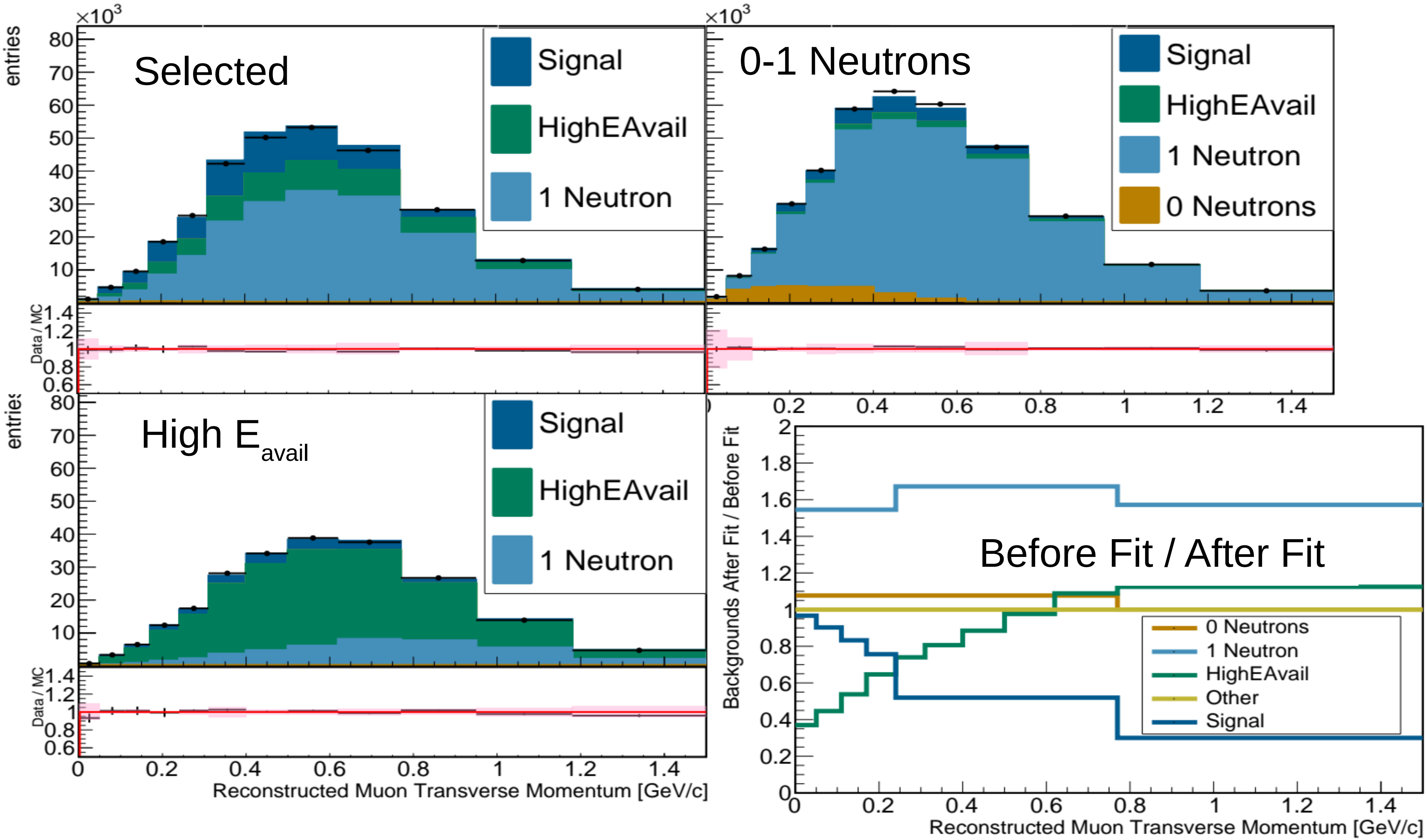
- Reweights on top of GENIE 2.12.6
- MnvTunev1
  - 2p2h enhancement
  - RPA modification
  - Non-resonant pion suppression
- 2p2h enhancement motivated by multiple LE measurements

Background Samples

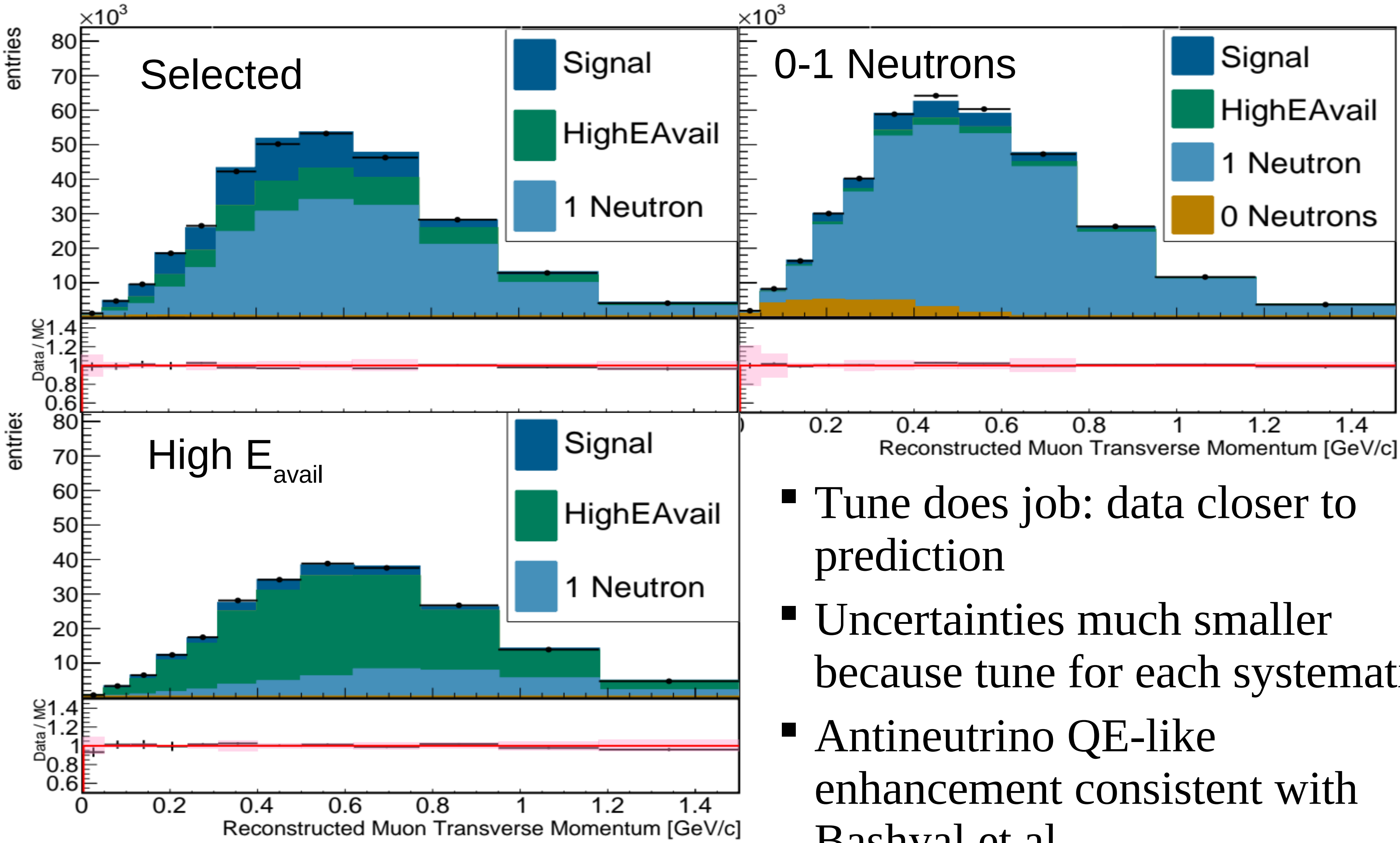


- Tune MC background prediction using data sidebands
- Two sidebands: QE-rich and pion-rich

Constraint Results



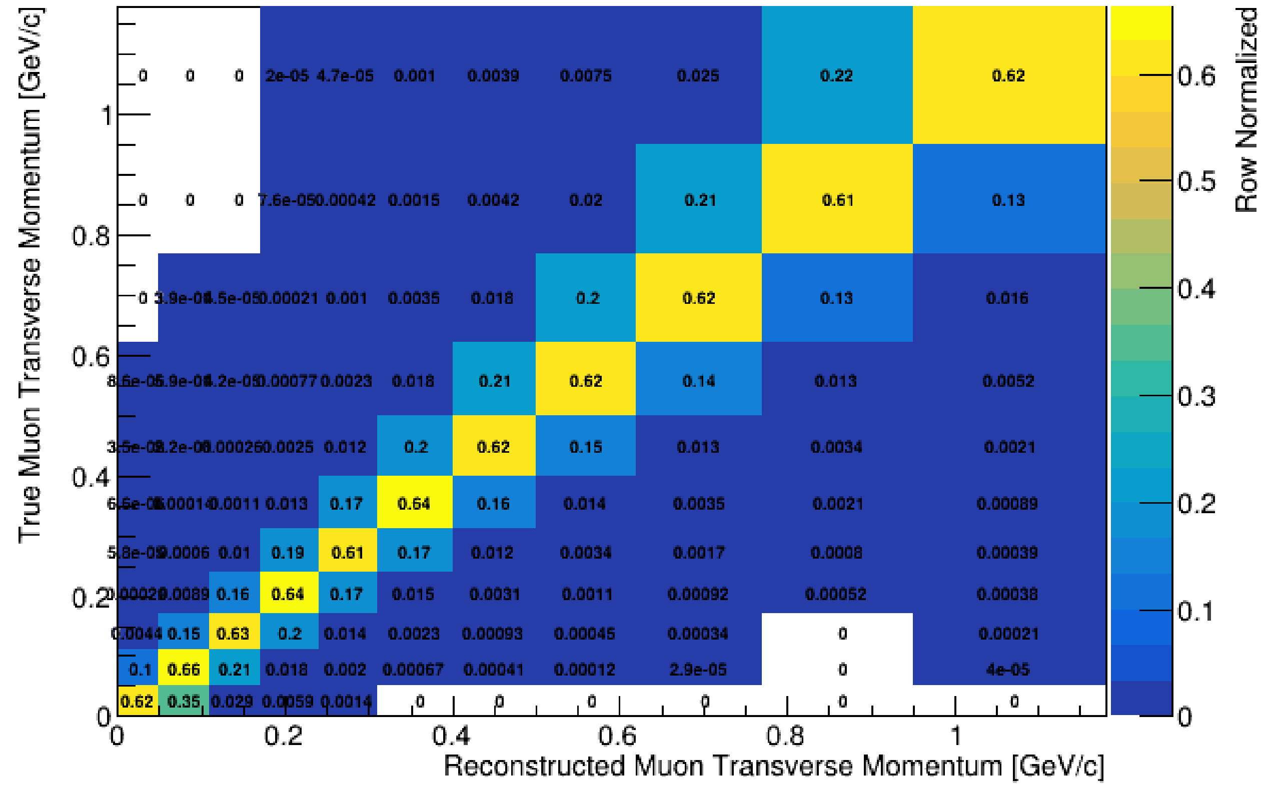
Constraint Results



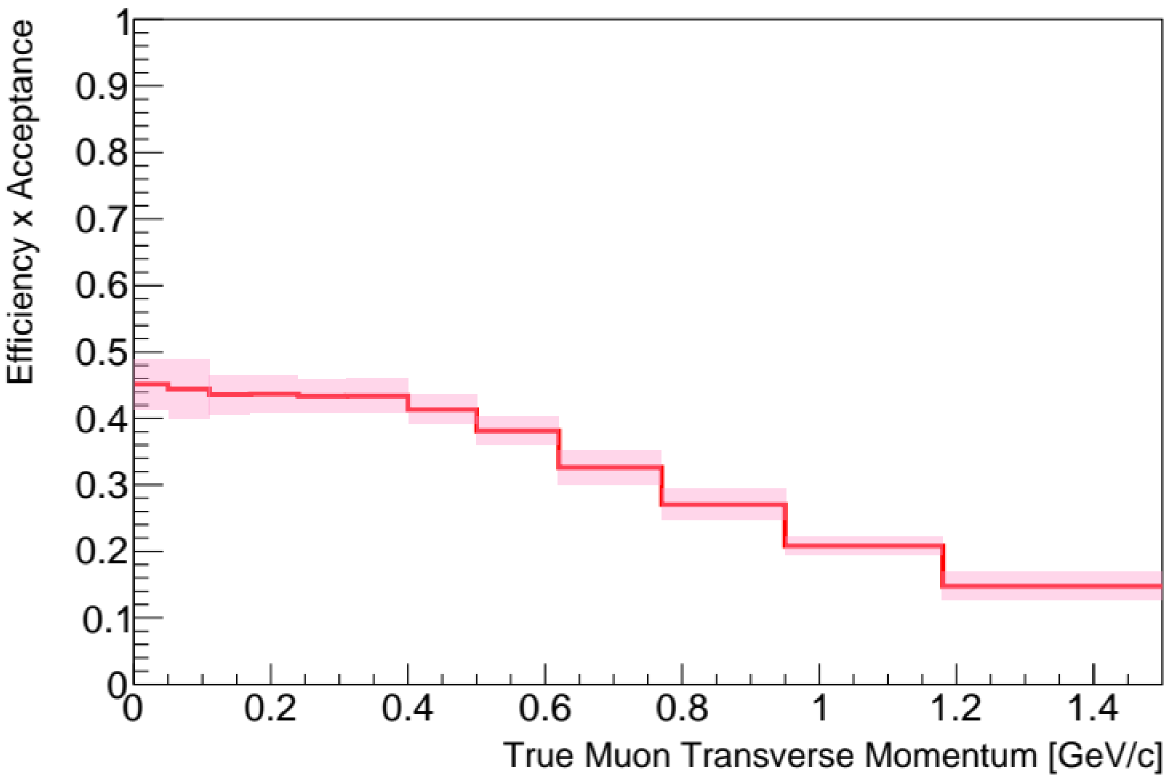
- Tune does job: data closer to prediction
- Uncertainties much smaller because tune for each systematic
- Antineutrino QE-like enhancement consistent with Bashyal et al.

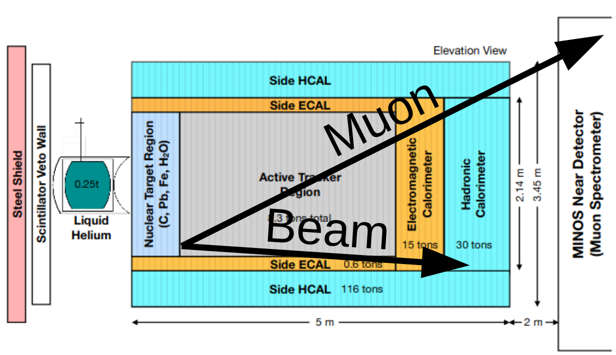
Unfolding

- MINERvA has great resolution for $p_{T\mu}$
- d’Agostini iterative unfolding
- Chose 3 iterations



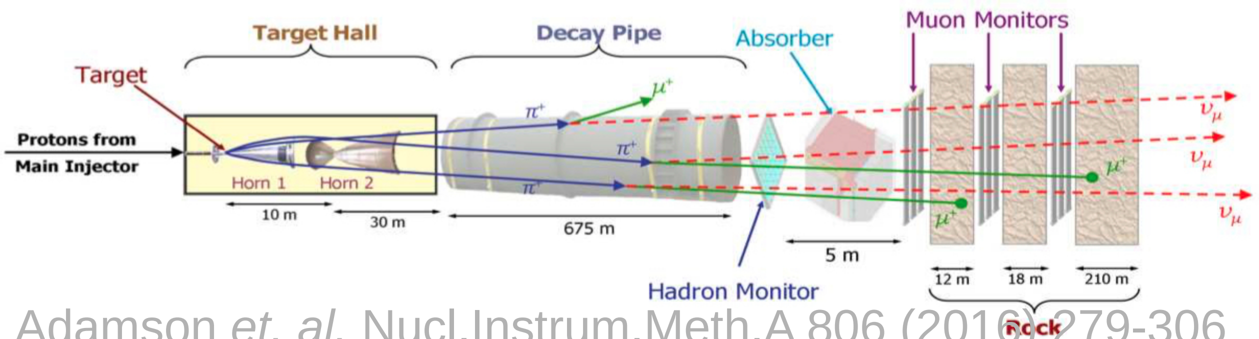
Efficiency and Acceptance



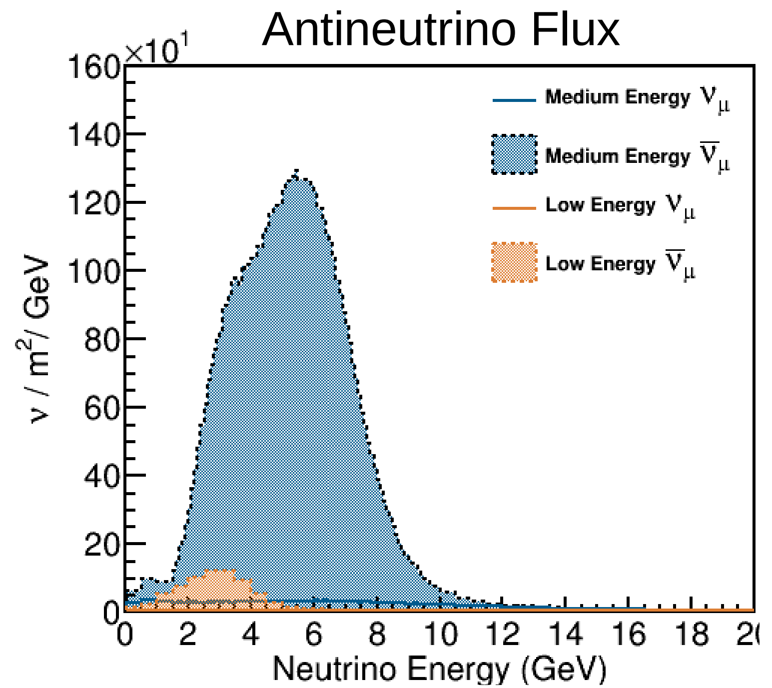


- Estimated by MC simulation
- Generally flat, especially at peak of event rate
- Gradual drop at high p_T driven by muon angular acceptance

Antineutrino Flux at MINERvA



P. Adamson *et. al.* Nucl.Instrum.Meth.A 806 (2016) 279-306

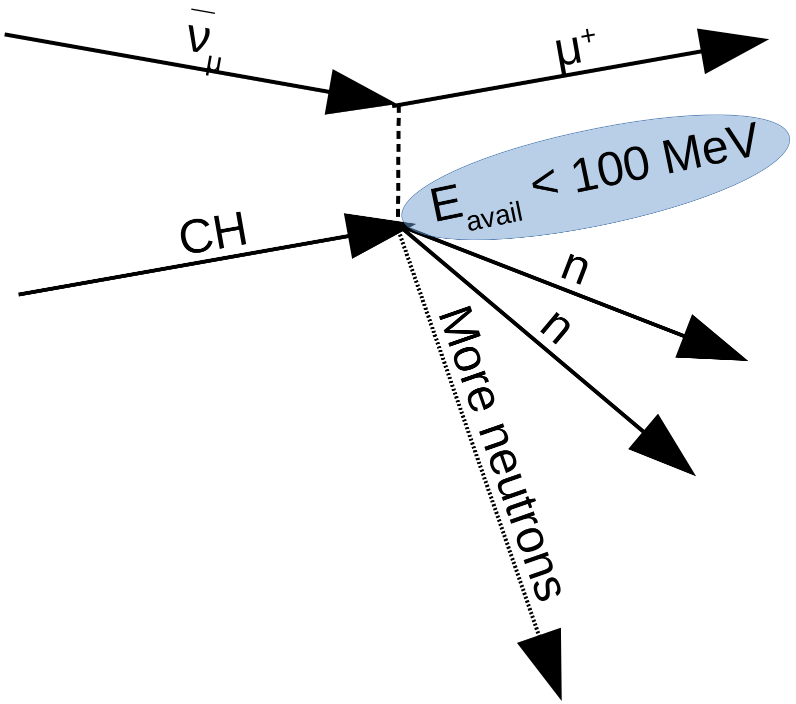


- 2 data eras: Low Energy (LE) and Medium Energy (ME)
- ME ~ NOvA era, BUT MINERvA is on axis
- ν-e scattering and inverse muon decay[8] constraint tuned flux prediction using data
- Thank you Fermilab Accelerator Division for many years of quality beam

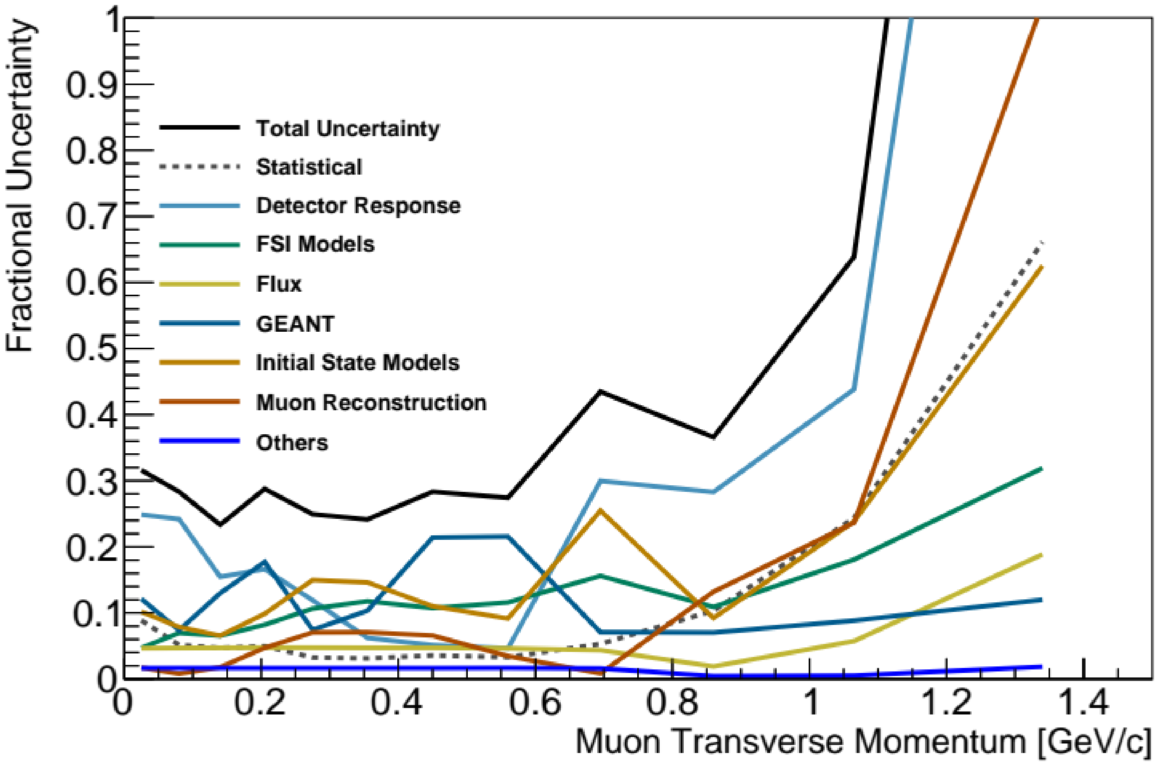
Part III: Measurements

Reminder: Signal Definition

- Antineutrino CC interaction
  - 2 GeV < p_μ < 20 GeV
  - θ_μ < 20 degrees
- 2 or more neutrons
  - KE > 10 MeV
- Available energy < 100 MeV
  - Energy from pions, protons, photons, kaons, lambdas, etc.
  - Does not include neutron energy

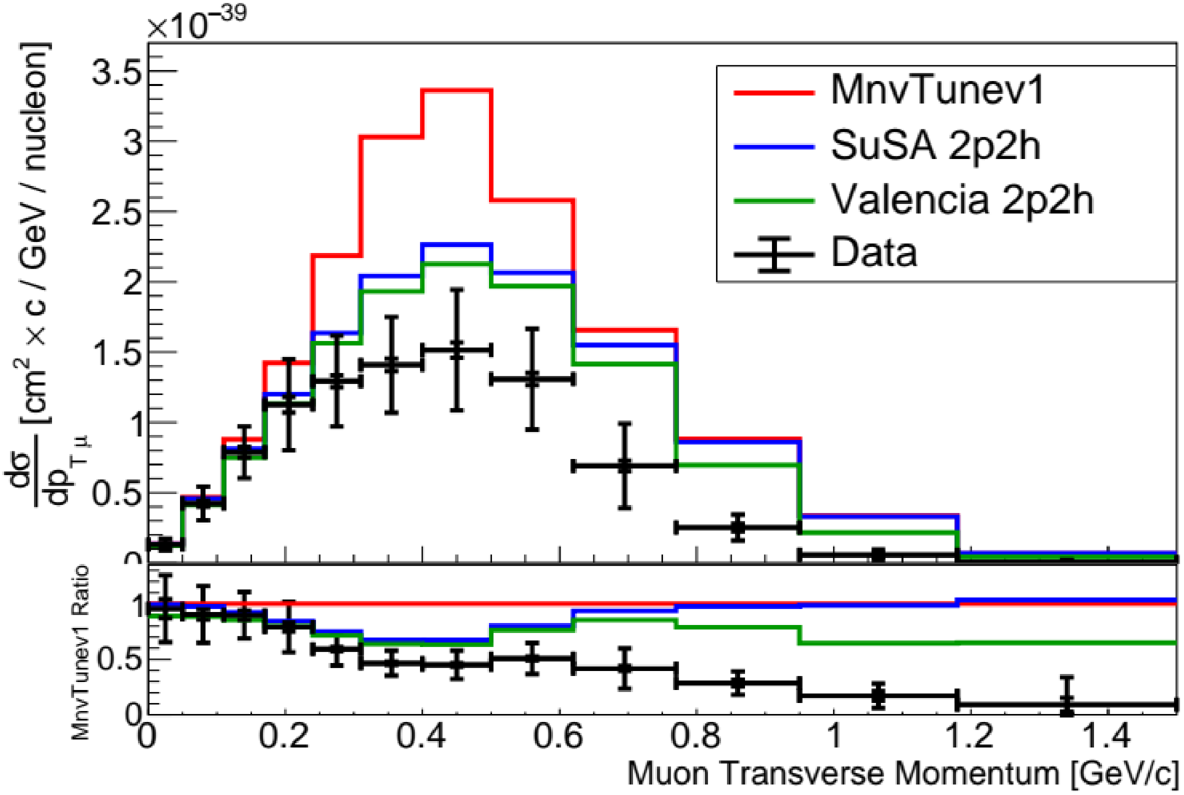


Uncertainties



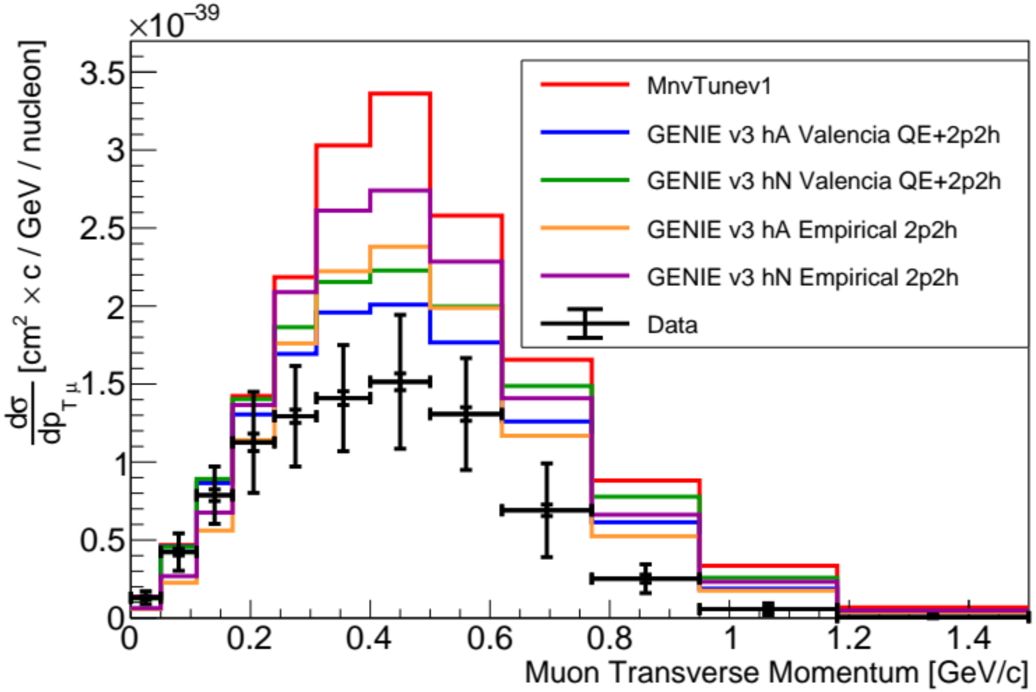
- Statistical uncertainty very small because ME era has 7x protons on target from LE era!
- “Initial state models” includes 2p2h model uncertainties
- “GEANT” dominated by MENATE_R reweight

Cross Section and MnvTunev1

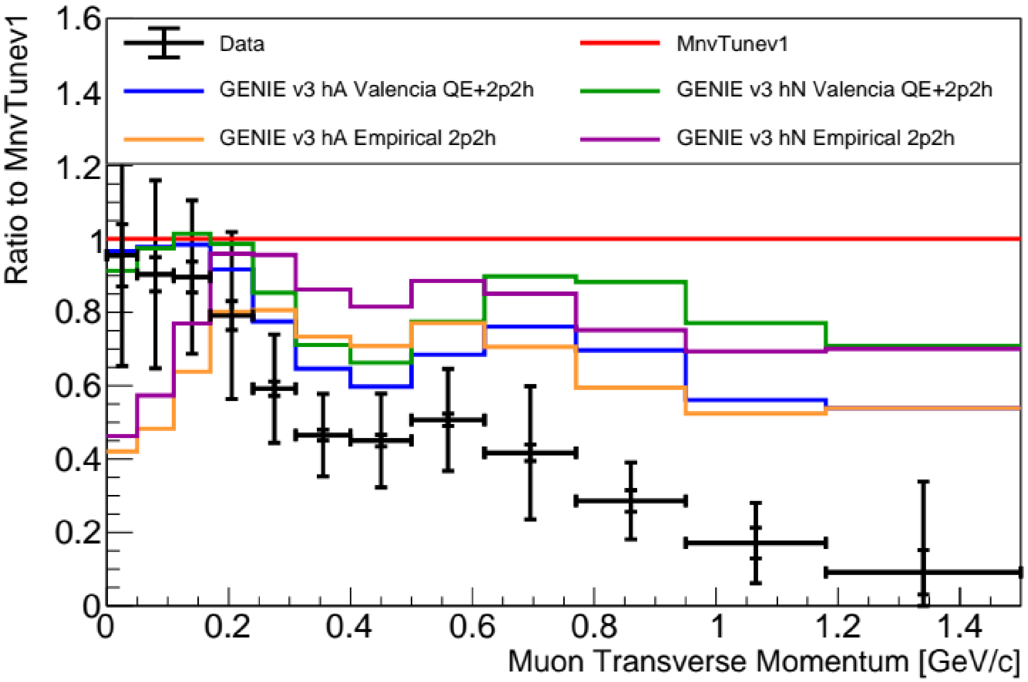


- MnvTunev1 over-predicts
- No model falls off at high transverse momentum like measurement does
- Measurement uncertainties are smaller than difference between leading models

Cross Section and GENIE v3



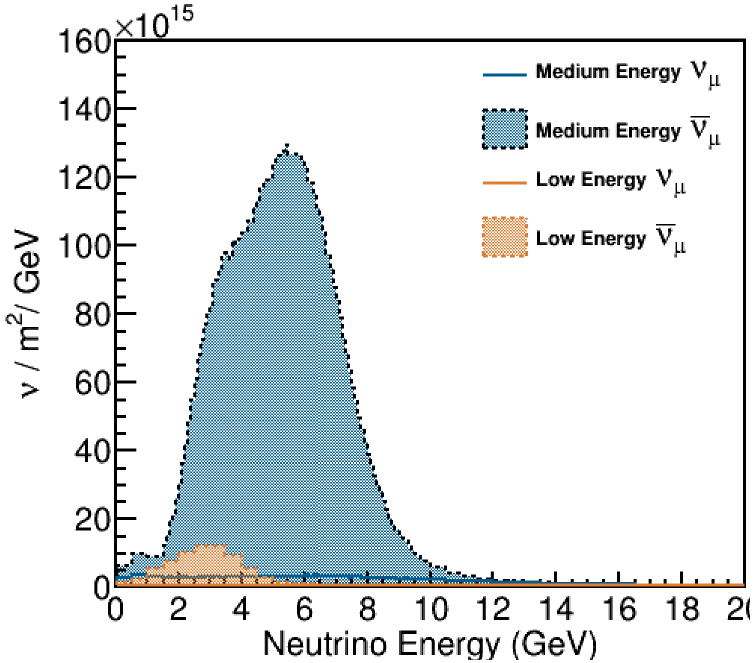
- Two 2p2h models: Valencia(5) and Dytman's(6) empirical tuning
- Two FSI models: single-step (hA) and multi-step (hN)



- All GENIE v3 models closer to measurement than MnvTunev1
- Valencia models closer than empirical 2p2h
- Most models fall off at high p_T like measurement

Future Neutron Measurements

- 7x statistics in ME data → neutrons in different nuclei
- David Last preparing QE-like cross section with neutron selection and neutron observables

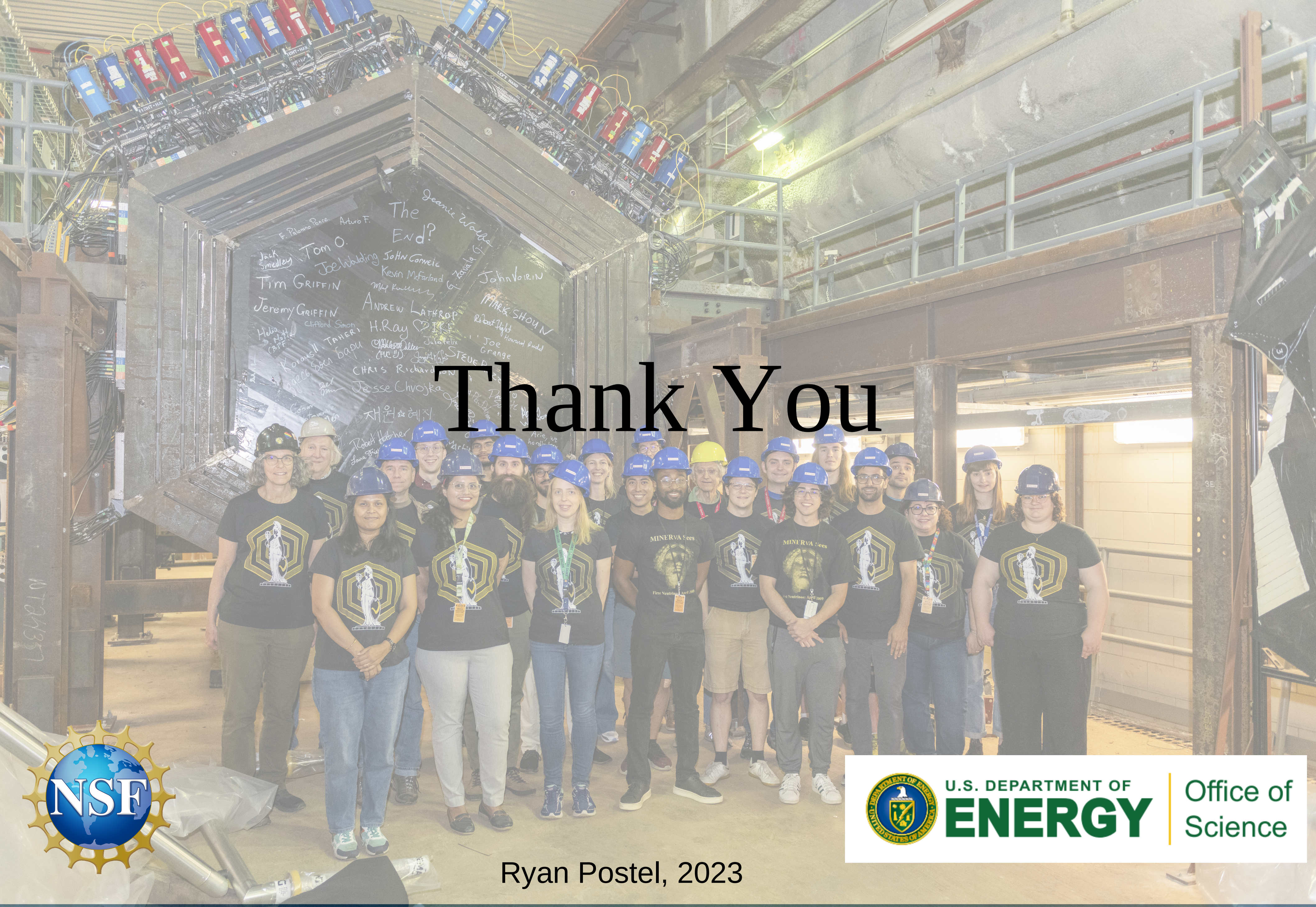


Material	# Antineutrino Interactions
Carbon	2694
Iron	11345
Lead	11926
Water	7056
CH	108100

Conclusions

- Neutron modeling is an important source of uncertainty for long baseline neutrino oscillation experiments
- MINERvA saw evidence that models were predicting too many neutrons. ME data sees same trend.
- Multi-neutron cross section enhanced too much by most models. Detector- and model-dependence reduced!
- MENATE_R neutron models important

Thank You



Ryan Postel, 2023

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(3) Anghel, I. et al. Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE). arXiv: 1504.01480 [physics.ins-det] (Apr. 2015).

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(6) J. W. Lightbody and J. S. O'Connell. Modeling single arm electron scattering and nucleon production from nuclei by GeV electrons. Comput. Phys., 2(3):57, 1988.

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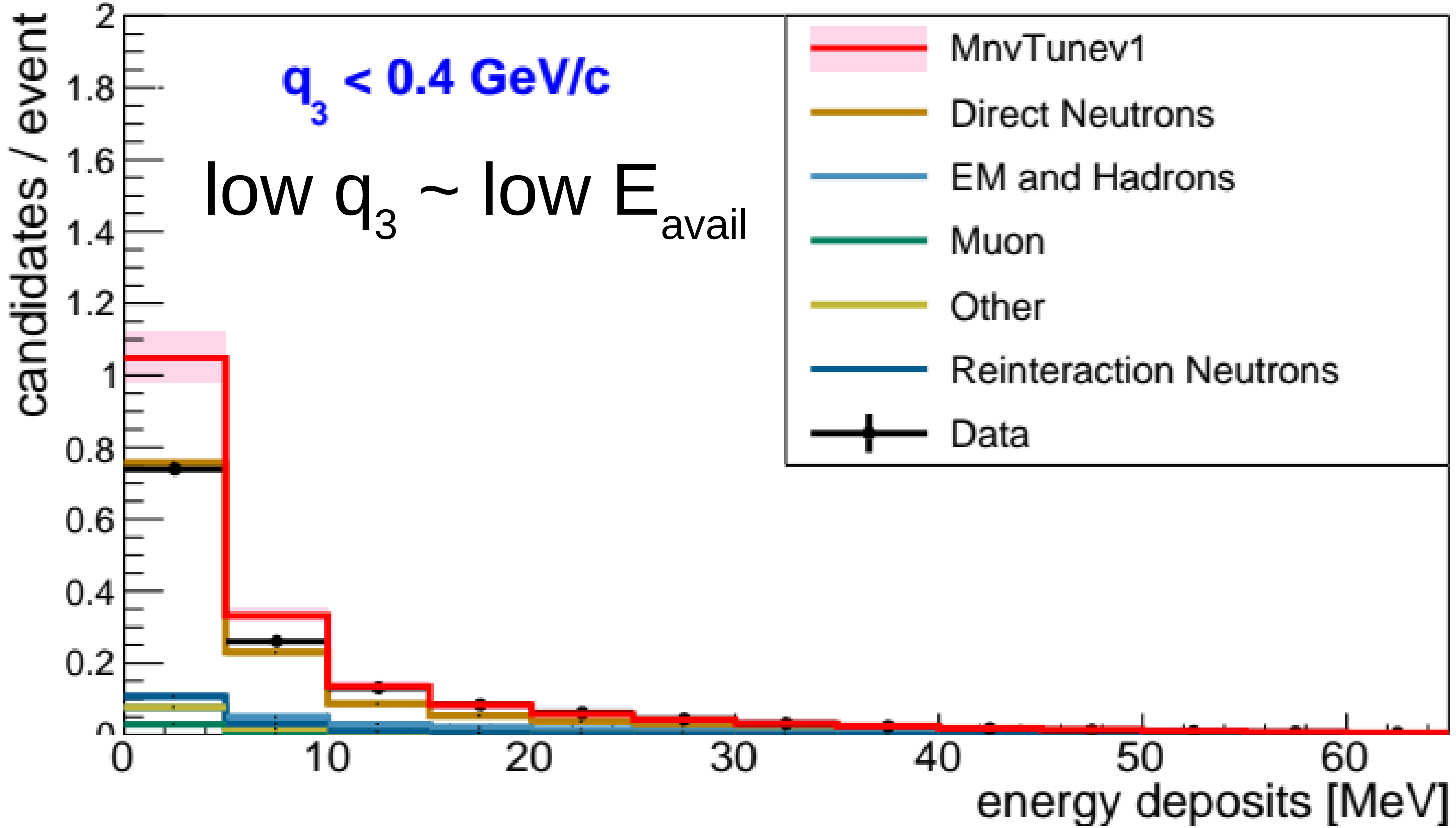
(8) Zazueta, L. et al. Improved constraint on the MINERvA medium energy neutrino flux using $\bar{e}^- \rightarrow \bar{e}^-$ data 2022. doi:10.48550/ARXIV.2209.05540. https://arxiv.org/abs/2209.05540.

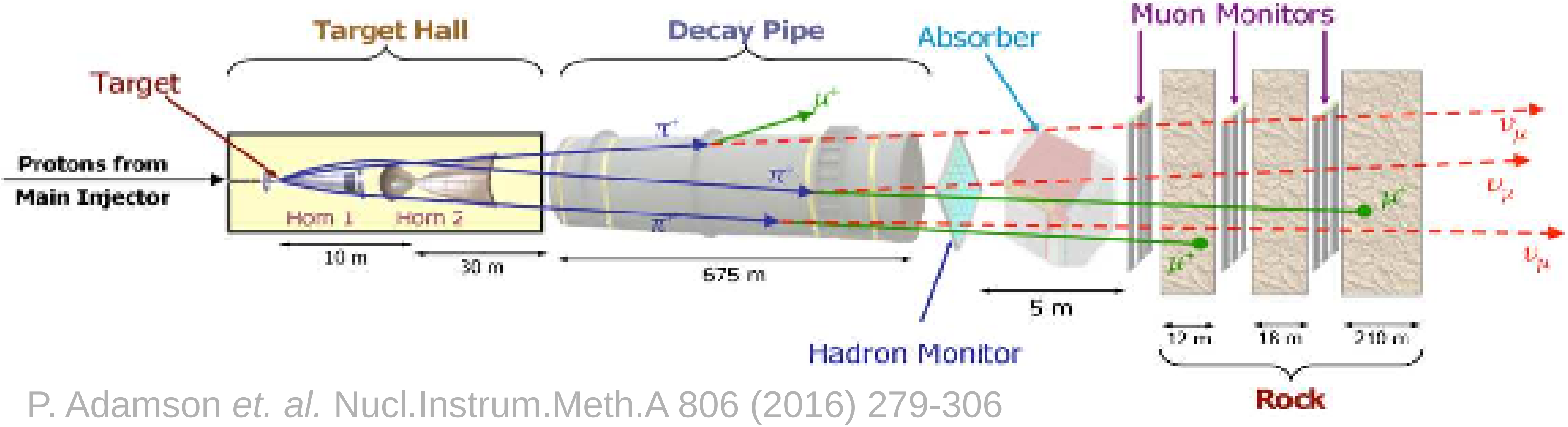
Example Neutron Backgrounds



How Neutrino Beams are Made: The NuMI Beam

http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/accel.html

- Start with proton beam
- Focus pion beam
  - Select neutrino or antineutrino by meson charge
  - Sculpt energy spectrum
- Wait for kaons, pions, and muons to decay



P. Adamson *et. al.* Nucl.Instrum.Meth.A 806 (2016) 279-306

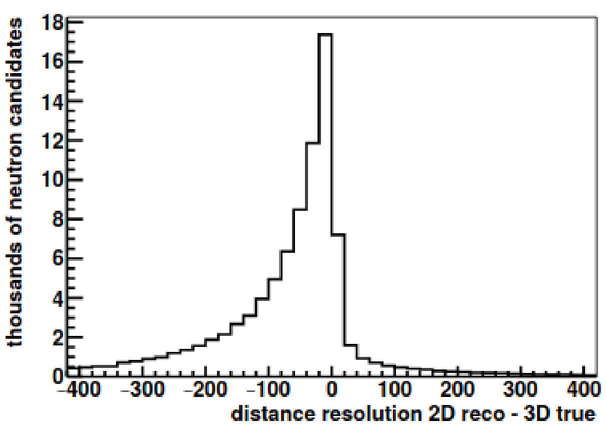
MINERvA's Model Tunes

- GENIE: Generates Neutrino Interactions for Experiments
  - Simulates kinematics of initial neutrino interaction and propagation out of the nucleus
  - Low energy: 2.8.4
  - Medium energy: 2.12.6 (Valencia 2p2h added)
- MnvTunev1: GENIE 2.12.6 with the following tunes:
  - 2p2h enhancement by a Guassian up to 50% in some regions
  - Valencia RPA suppression
  - Non-resonant pion production suppression
  - MnvTunev1.2 also includes bug fixes for relativistic kinematics of outgoing hadrons and suppression of coherent pion production
- MnvTunev3: reweights GENIE 2.12.6 to look like:
  - The 2p2h model designed to accompany SuSA
  - Bodek-Ritchie high momentum QE enhancement

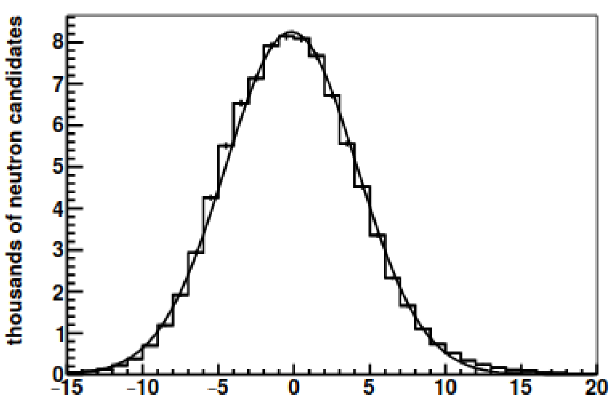
MINERvA's Tracker

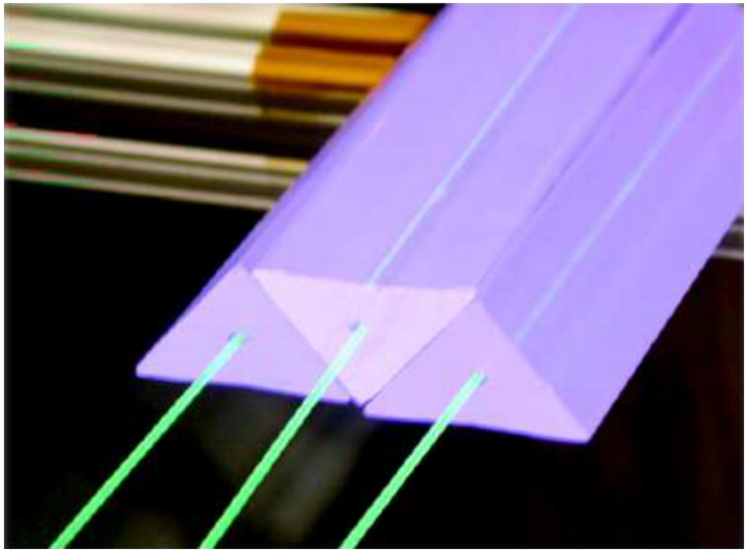
- Only read out on one end → timing resolution
- Modules have 4 planes → raises minimum proton energy for 3D reconstruction

Distance from Vertex

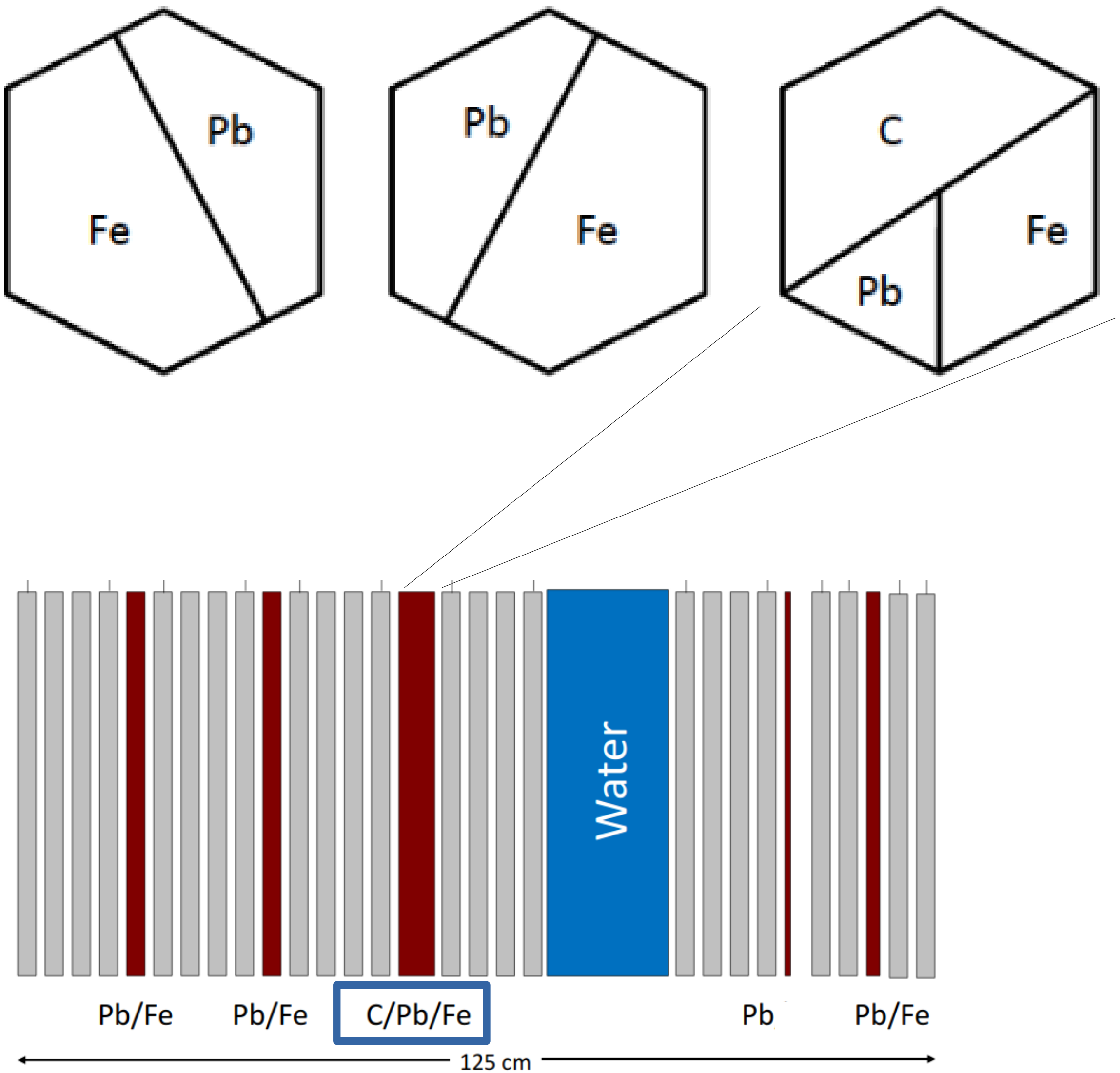


Timing



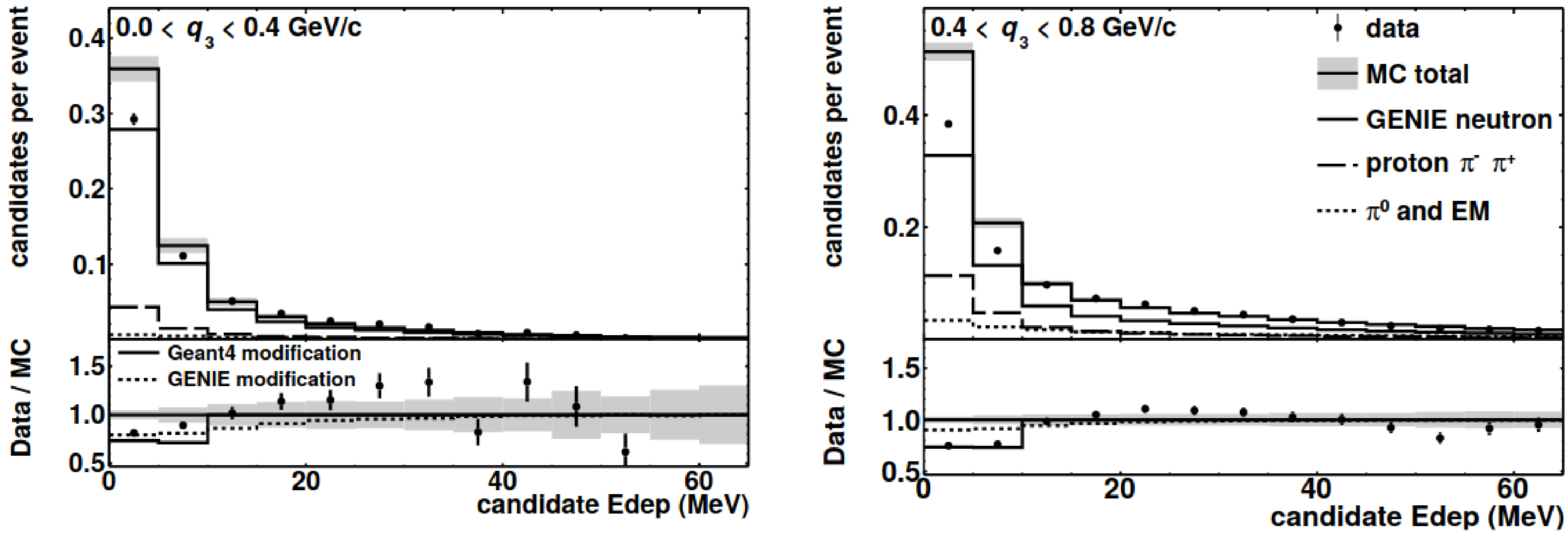


MINERvA's Nuclear Targets



- Passive nuclear targets upstream of tracker
- Let us study A-dependence of neutrino cross sections
- Determine interaction material by x, y coordinates

Neutrons at MINERvA



M. Elkins *et. al.* Phys. Rev. D 100, 052002 (2019)

- MINERvA sees neutrons
  - Inelastic scatters at KE >= 10 MeV
  - De-excitation photons
- Evidence that neutron production not well-modeled… but detector-dependent
- *Nature* physics with neutrons recently: measured axial vector form factor(4)