Antineutrino-CH QE-Like Scattering at MINERvA: Two Views

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for the MINERvA Collaboration

NuInt 2022
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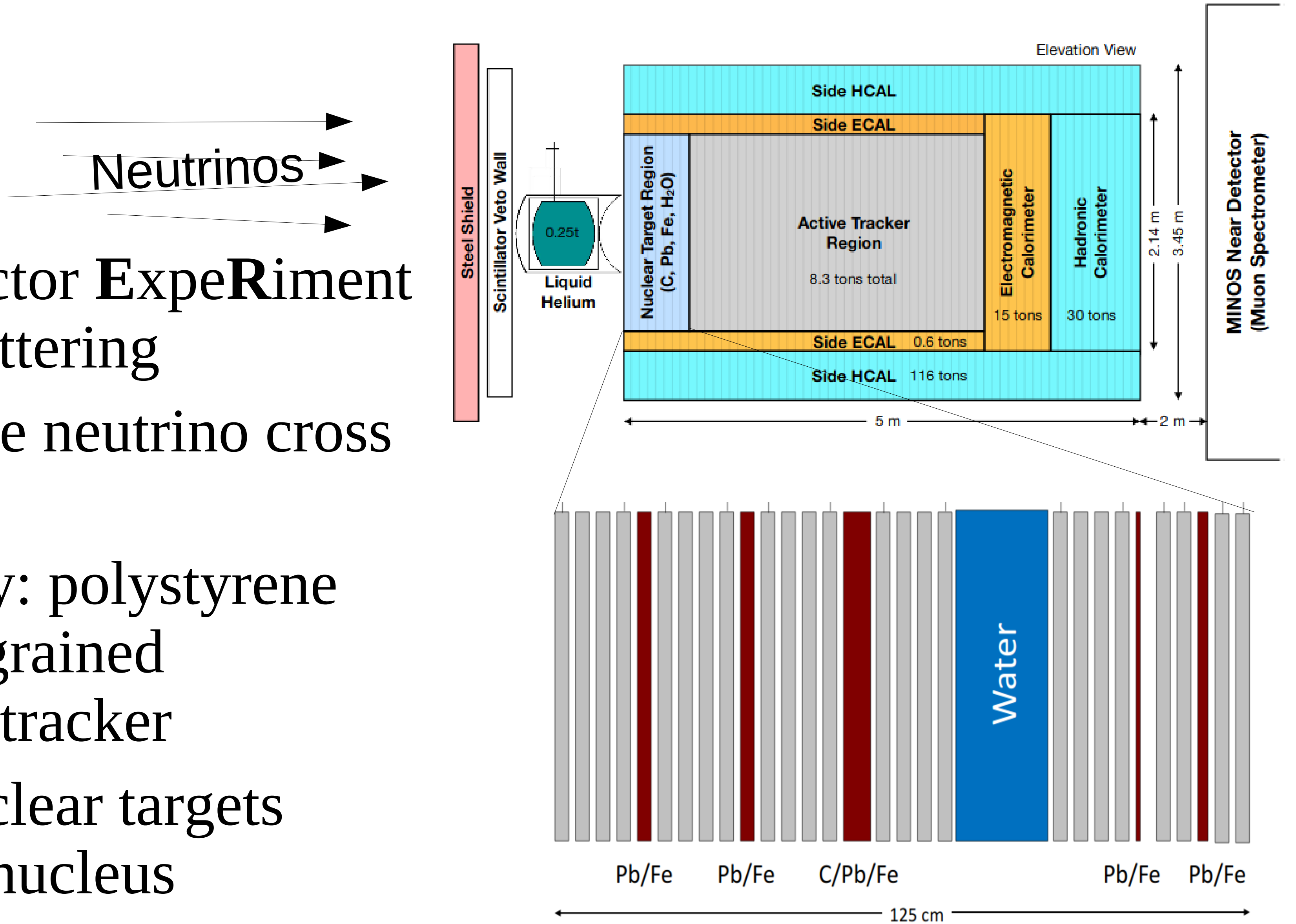
Seoul, South Korea

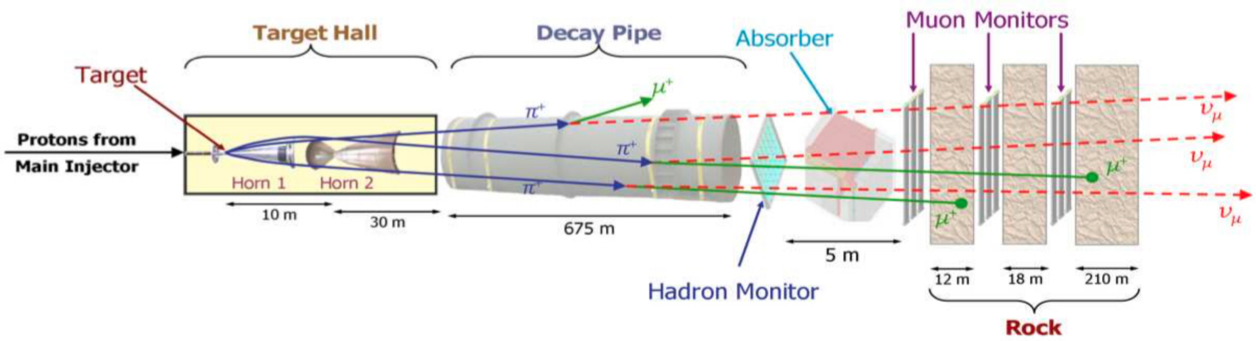
MINERvA

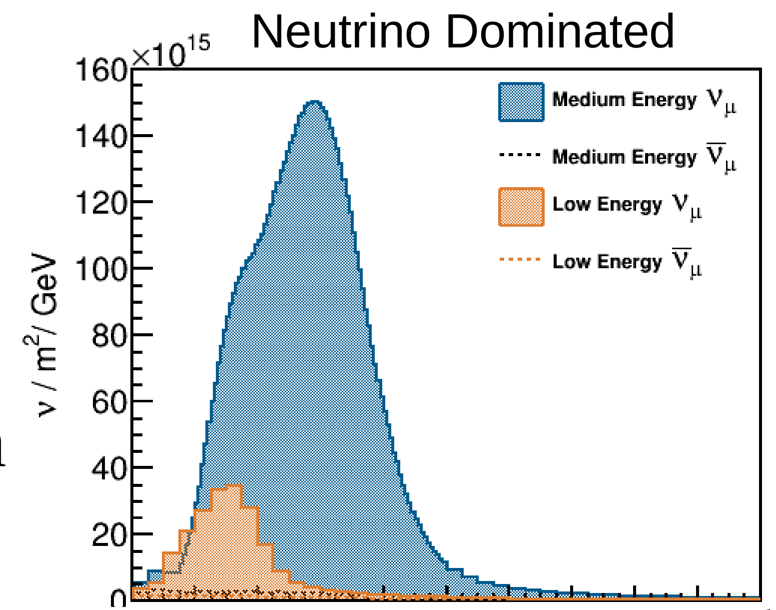
- **M**ain **IN**jector **E**xpe**R**iment for **v-A** scattering
- We measure neutrino cross sections!
- Technology: polystyrene (CH) fine-grained scintillator tracker
- Passive nuclear targets illuminate nucleus dependence

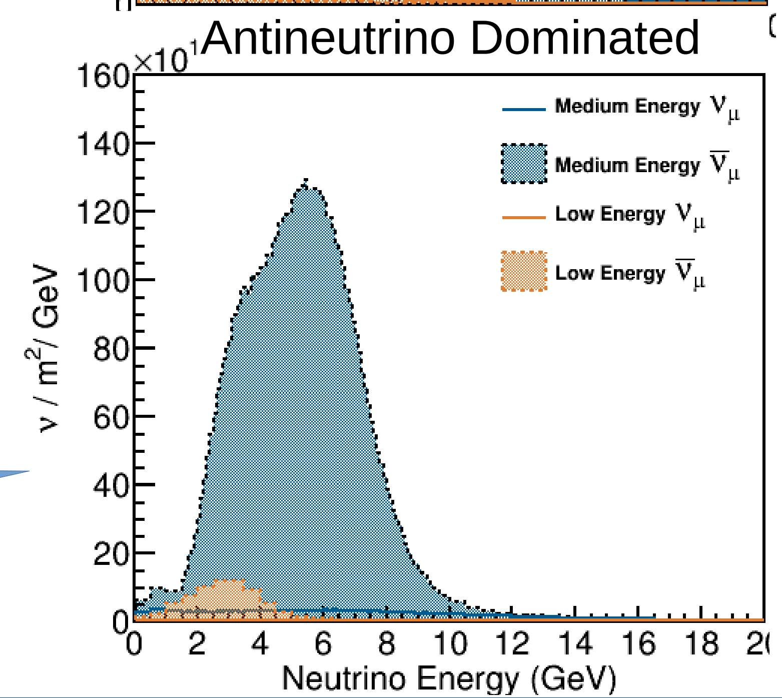


Nucl. Inst. and Meth. A743 (2014) 130

MINERvA's Data



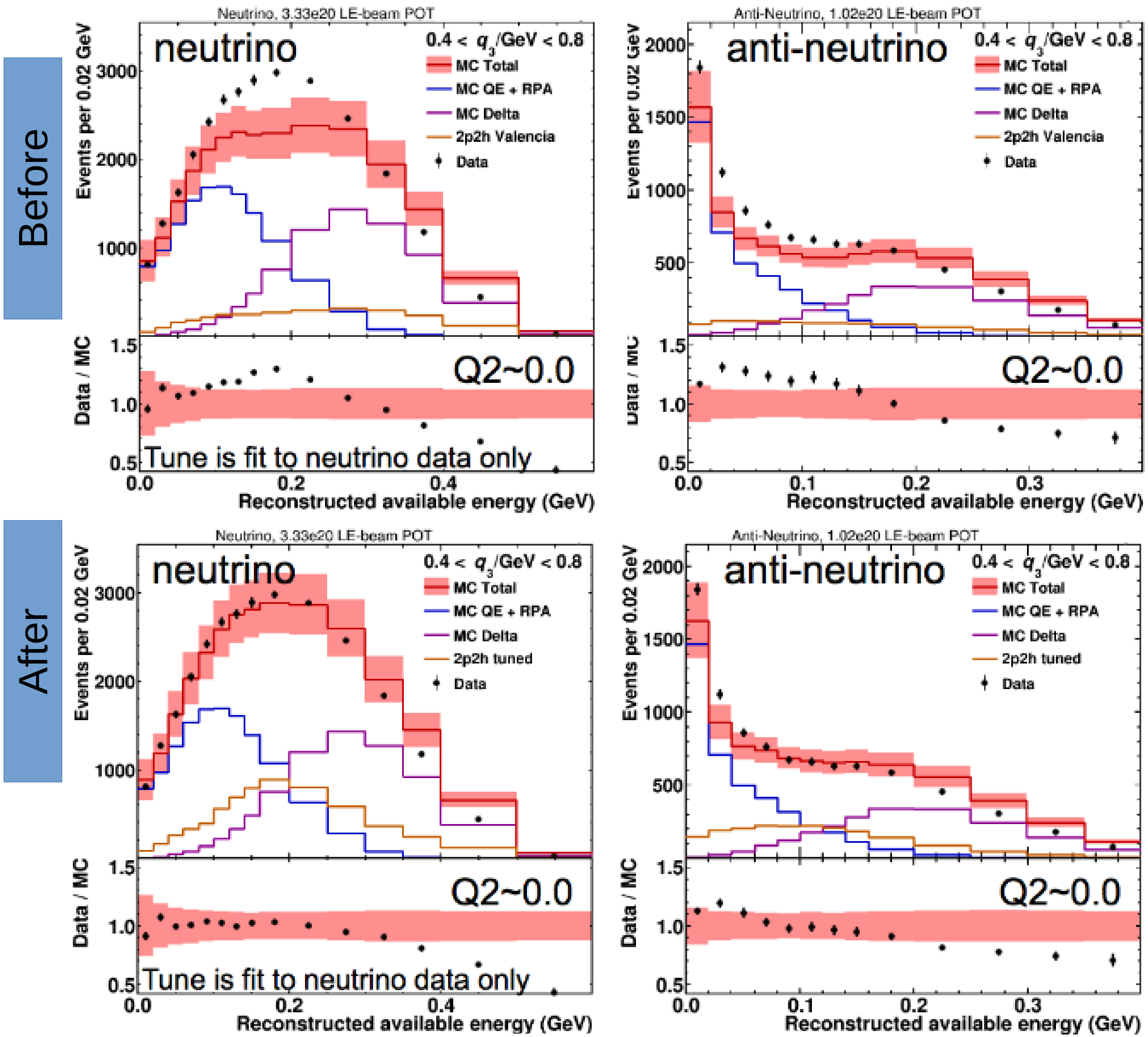




- 2 data eras: Low Energy (LE) and Medium Energy (ME)
- ME ~ NOvA era, BUT MINERvA is on axis
- $12\mathrm{x}10^{20}$ POT in each mode
- **arXiv:2209.05540**

See Talk by A. Klustova
From Tuesday

MINERvA's Physics Tune



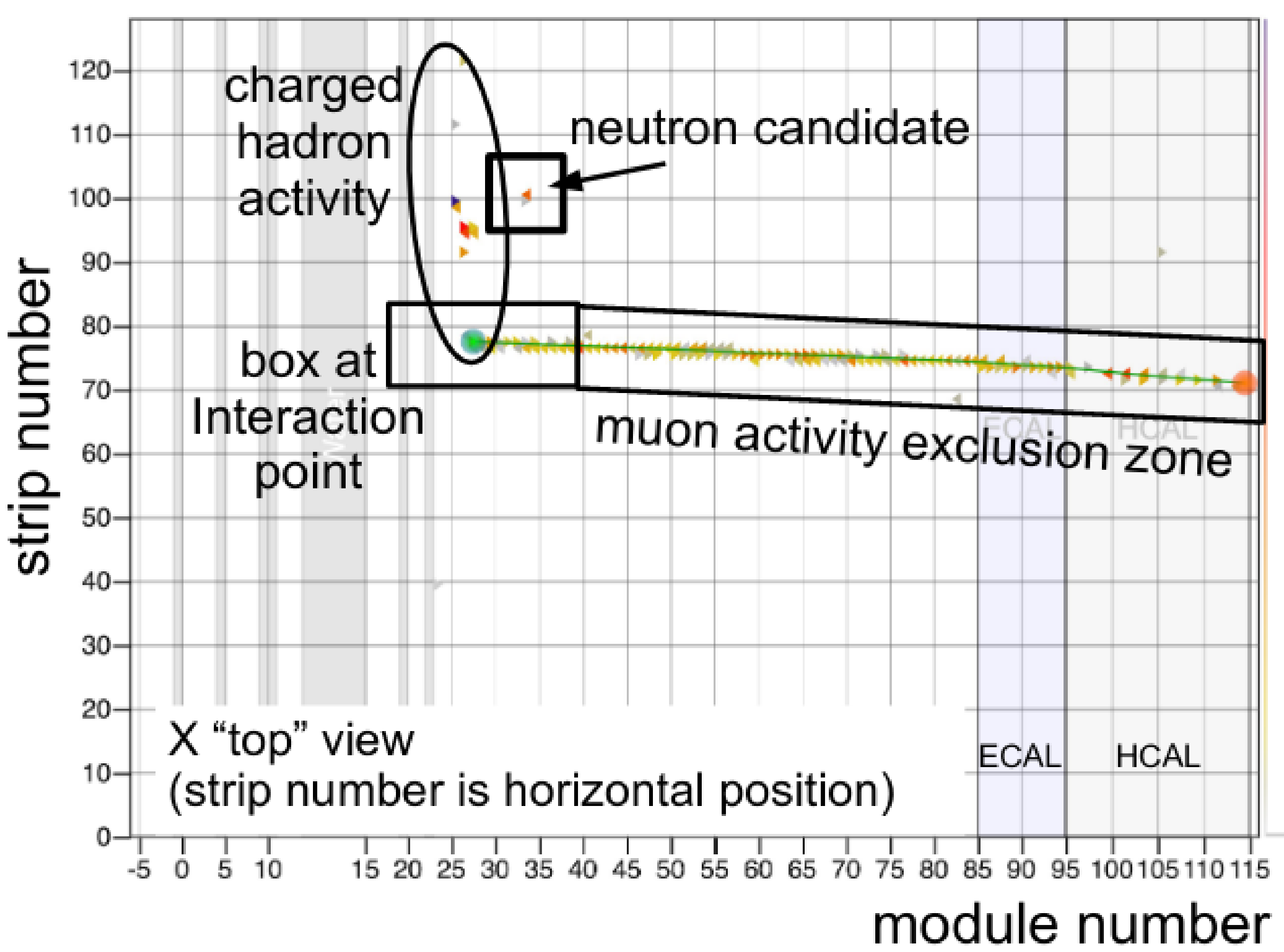
Phys. Rev. Lett. 116, 071802

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

- Original low recoil inclusive publication found data excess in "dip" region
- MnvTunev1
  - 2p2h enhancement
  - RPA modification
  - Non-resonant pion suppression
- Subsequent anti-neutrino measurement improved by tune!
- How does tune stand up to:
  - Neutrons?
  - 6 GeV antineutrinos

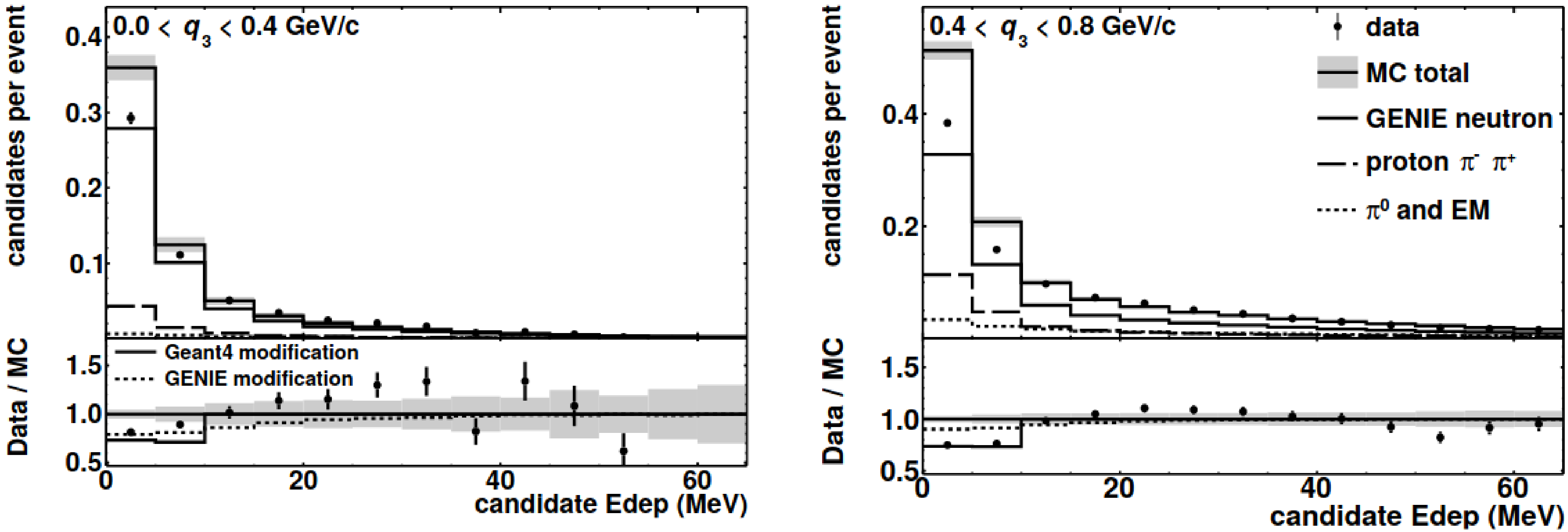
Neutron Counting at MINERvA

How MINERvA Counts Neutrons



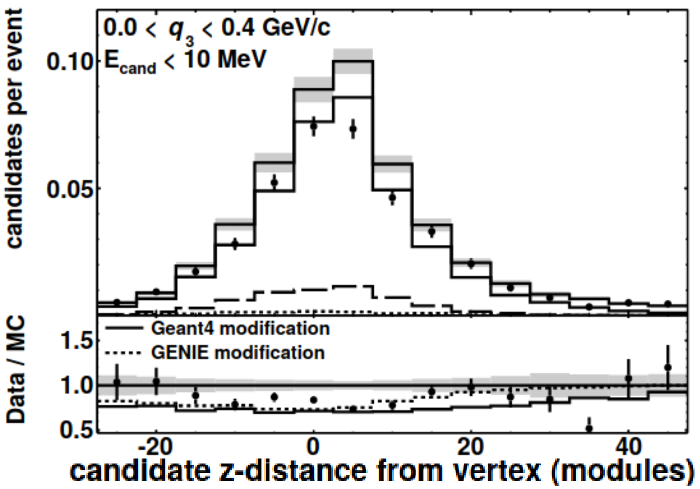
- **Phys.Rev.D 100 (2019) 5, 052002**
- Extension of LE low recoil inclusive measurement
- See mostly **inelastic scatters**
  - Direction sensitivity
  - Time sensitivity?
- At least 1.5 MeV energy deposit

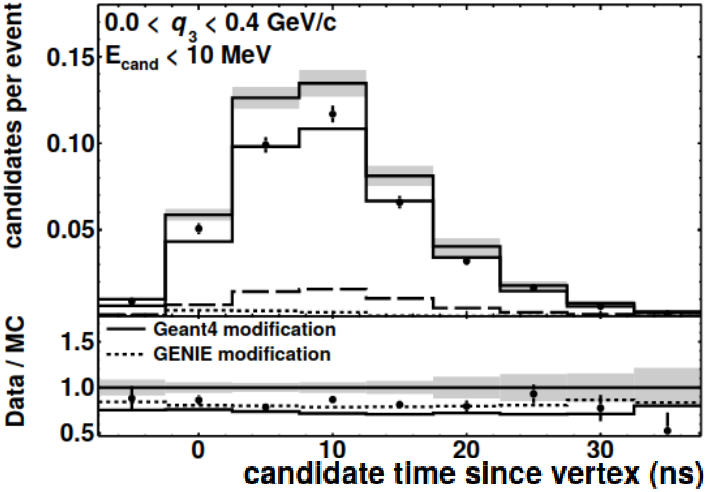
Data/MC Disagreement in Neutron Candidate Rate



- Comparing smeared energy deposits
- q_3 is 3-momentum transfer
- Follow-up on E_{avail} trends in low recoil analysis
- MC over-predicts lowest energy deposit candidates
- Neither GENIE nor GEANT is obviously source of disagreement

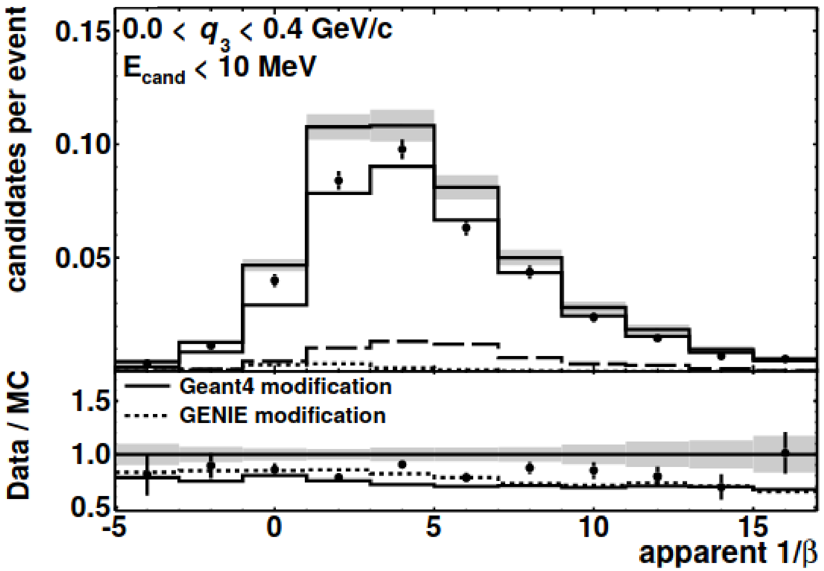
Can MINERvA Reconstruct Neutron Energy by Timing?



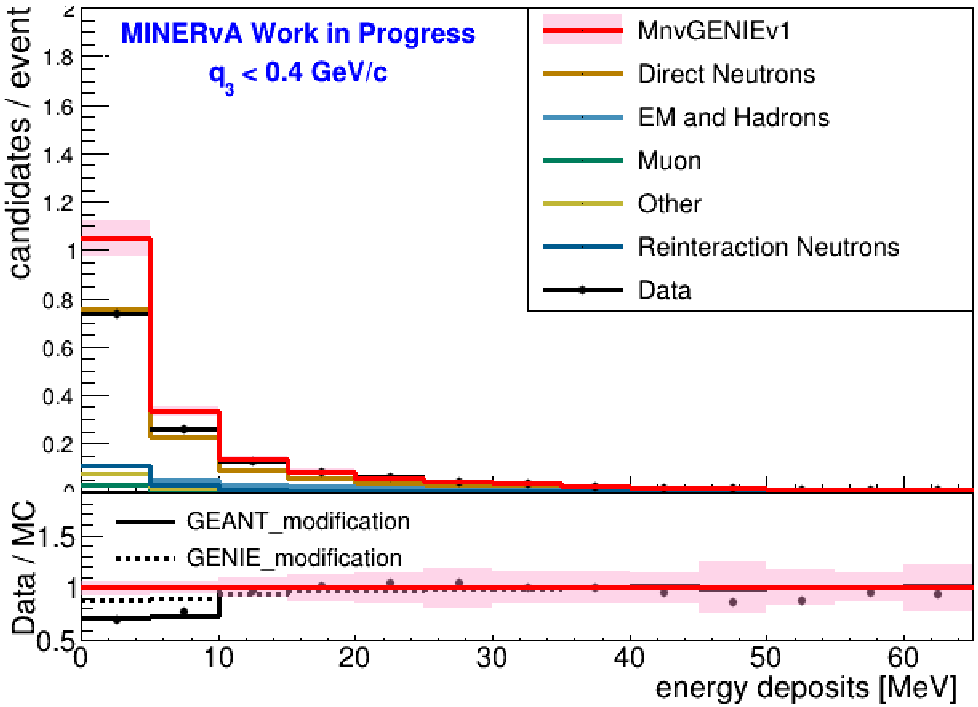


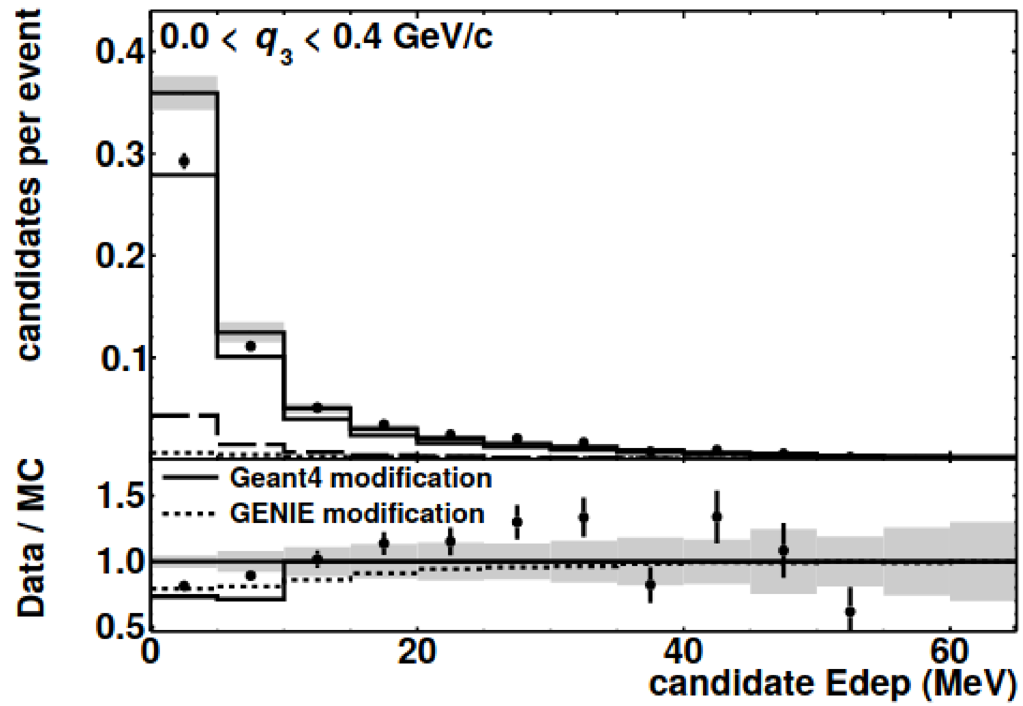
- No obvious data/MC shape in energy-sensitive observables
- Broad data/MC agreement at higher energy deposit

- Reconstruct energy by time of flight?
- Timing resolution ~4.5ns
- See some separation of candidates by timing



Neutrons in ME Data





- Comparing smeared energy deposits
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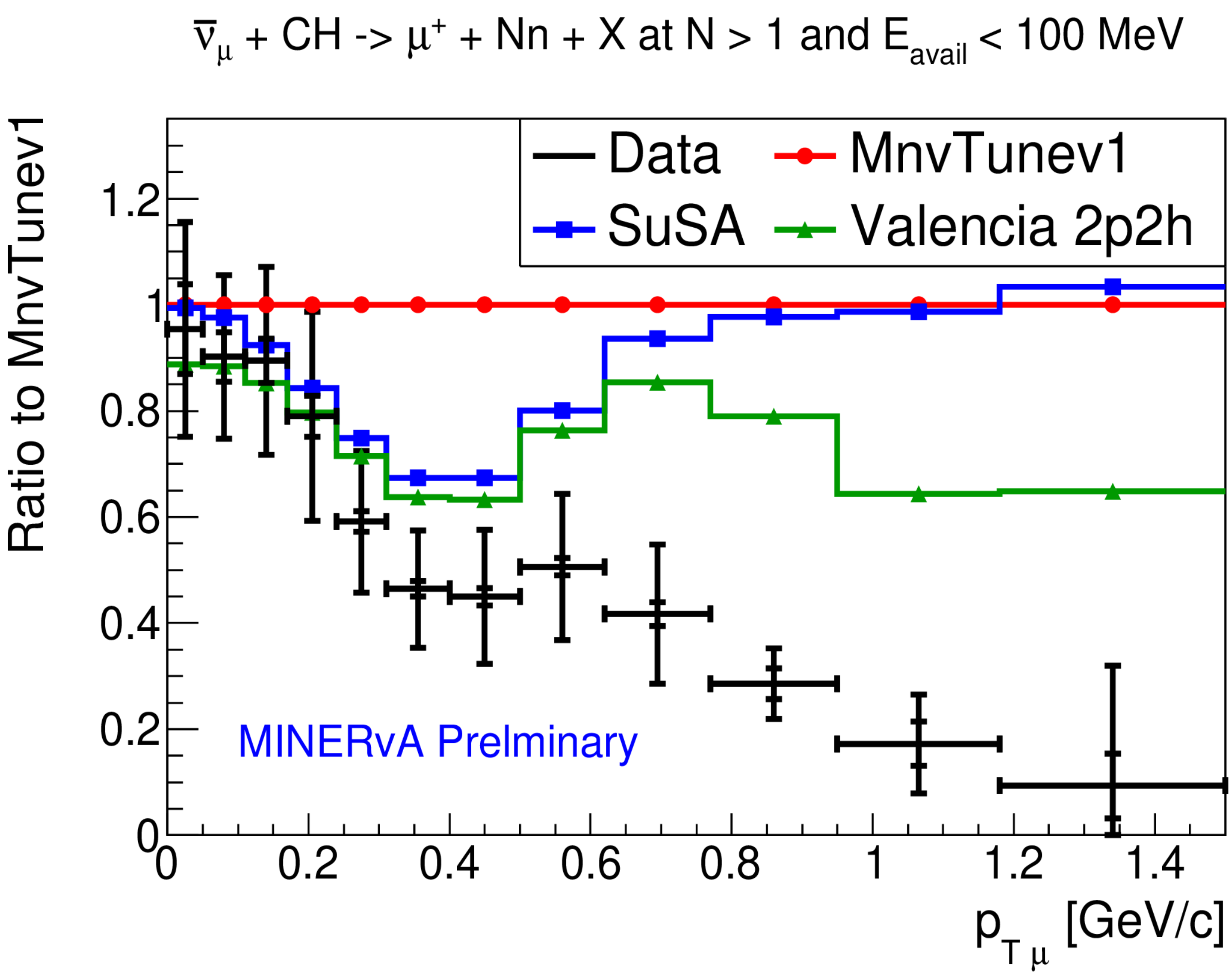
More MINERvA Neutron Results



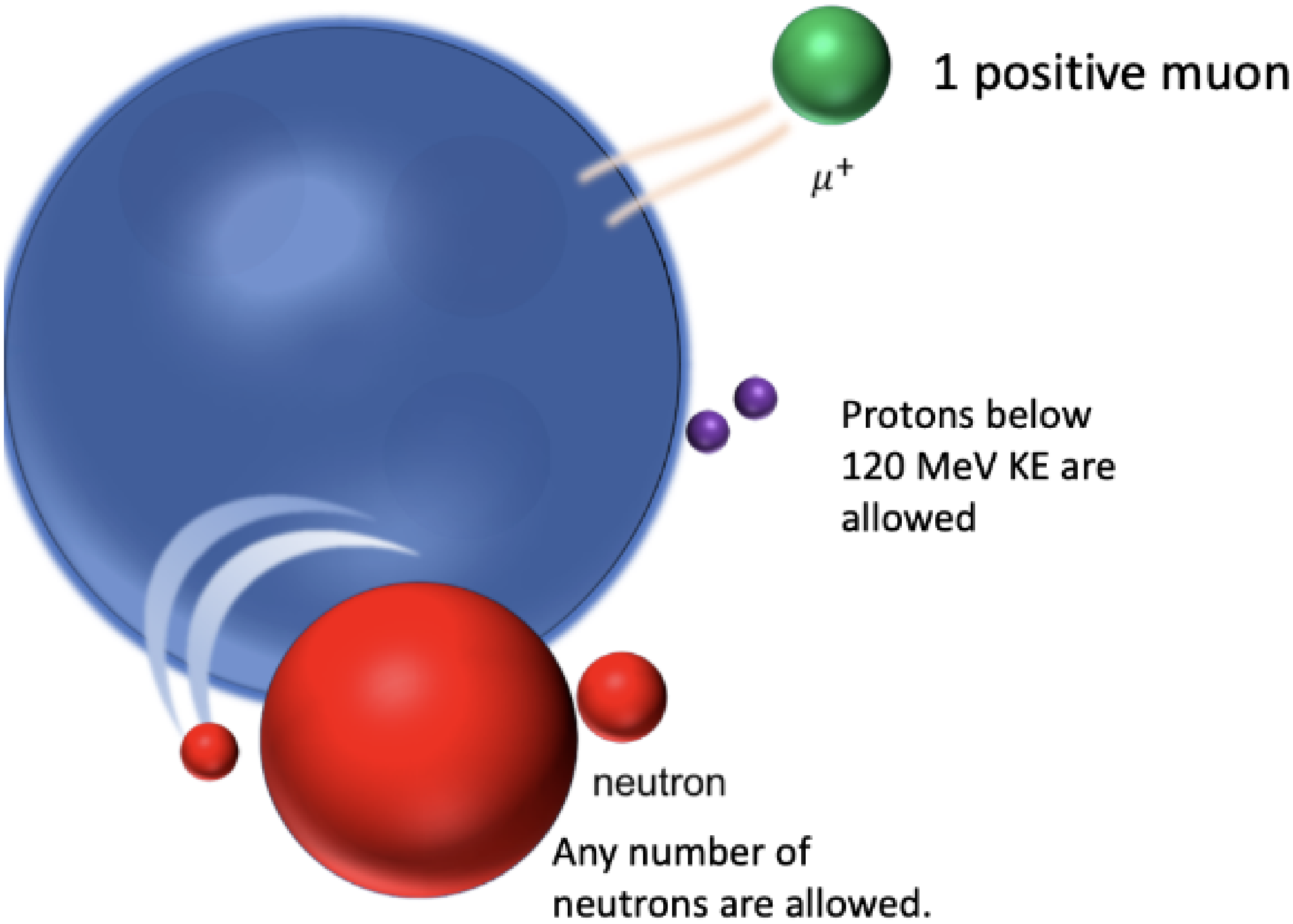
- Model- and detector-independent measure of neutrons per interaction
- Expect dominant 2p2h contribution

Poster by A. Olivier on Thursday

Talk by Tejin Cai On Monday

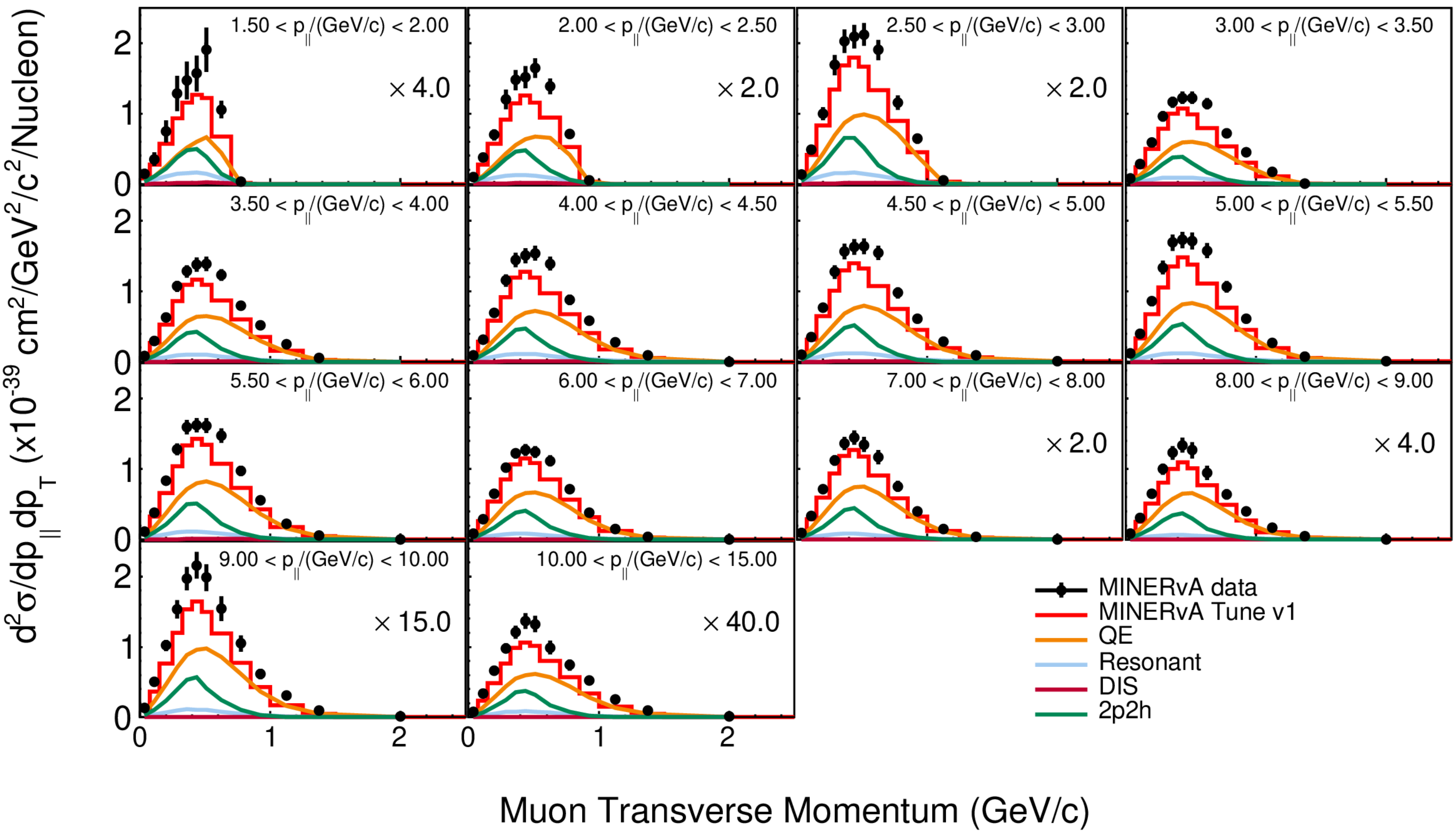
Antineutrino QE-Like in ME

Antineutrino QE-Like Selection

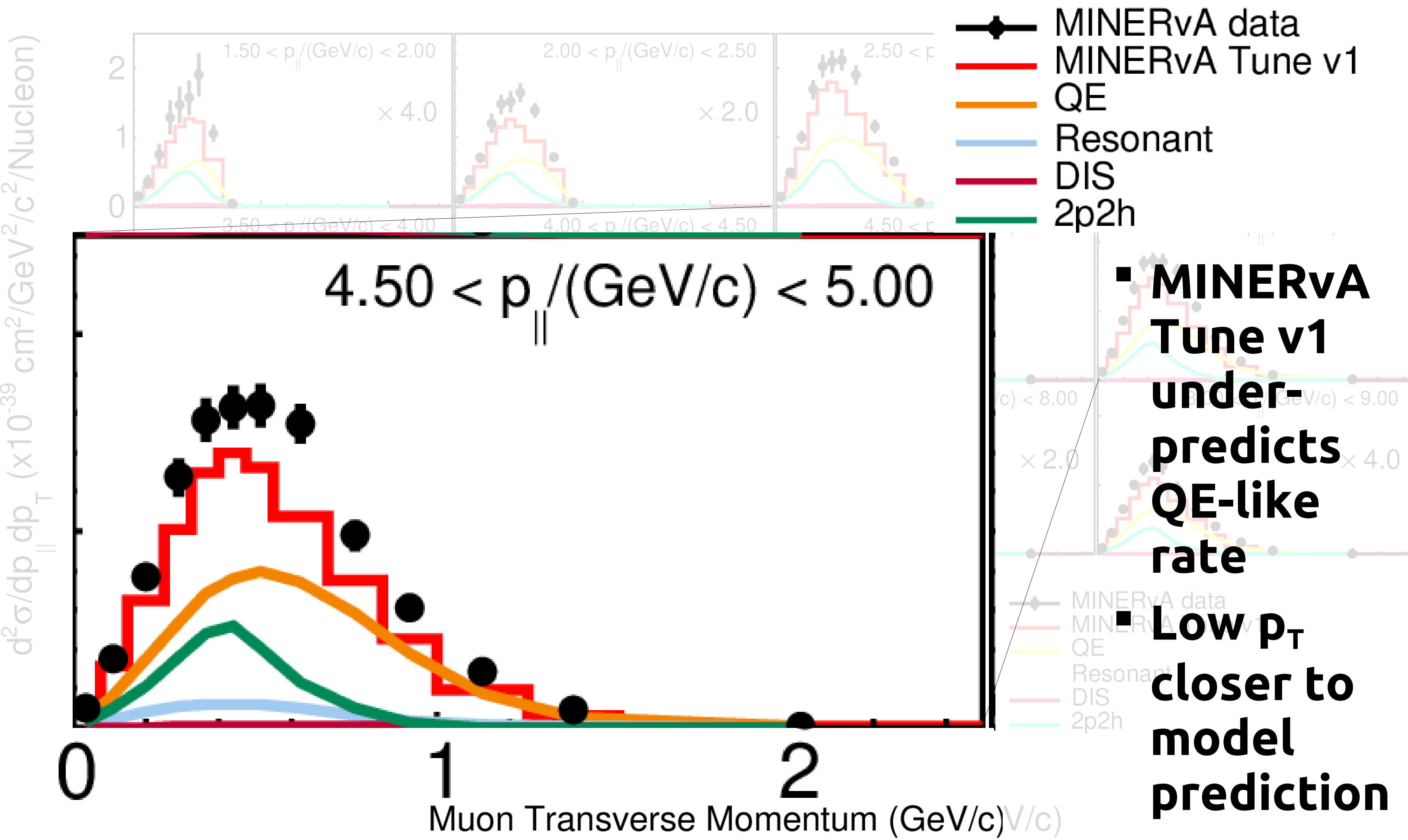


- Medium Energy analysis
- QE-like = no mesons in **final state**
- Neutrons allowed but not reconstructed
- Protons allowed below tracking threshold
- Running recoil energy cut

2D Cross Section



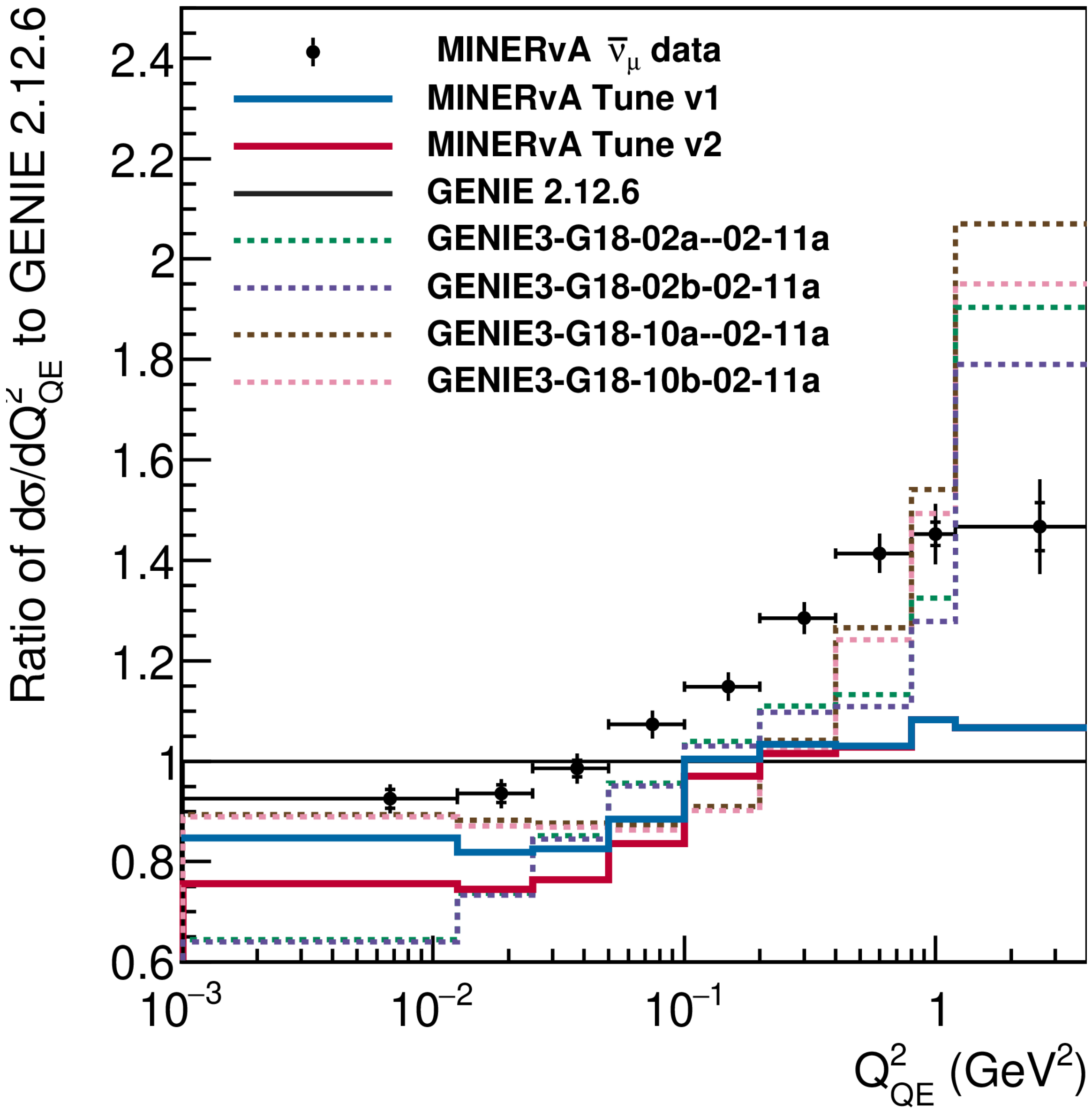
Results Zoomed



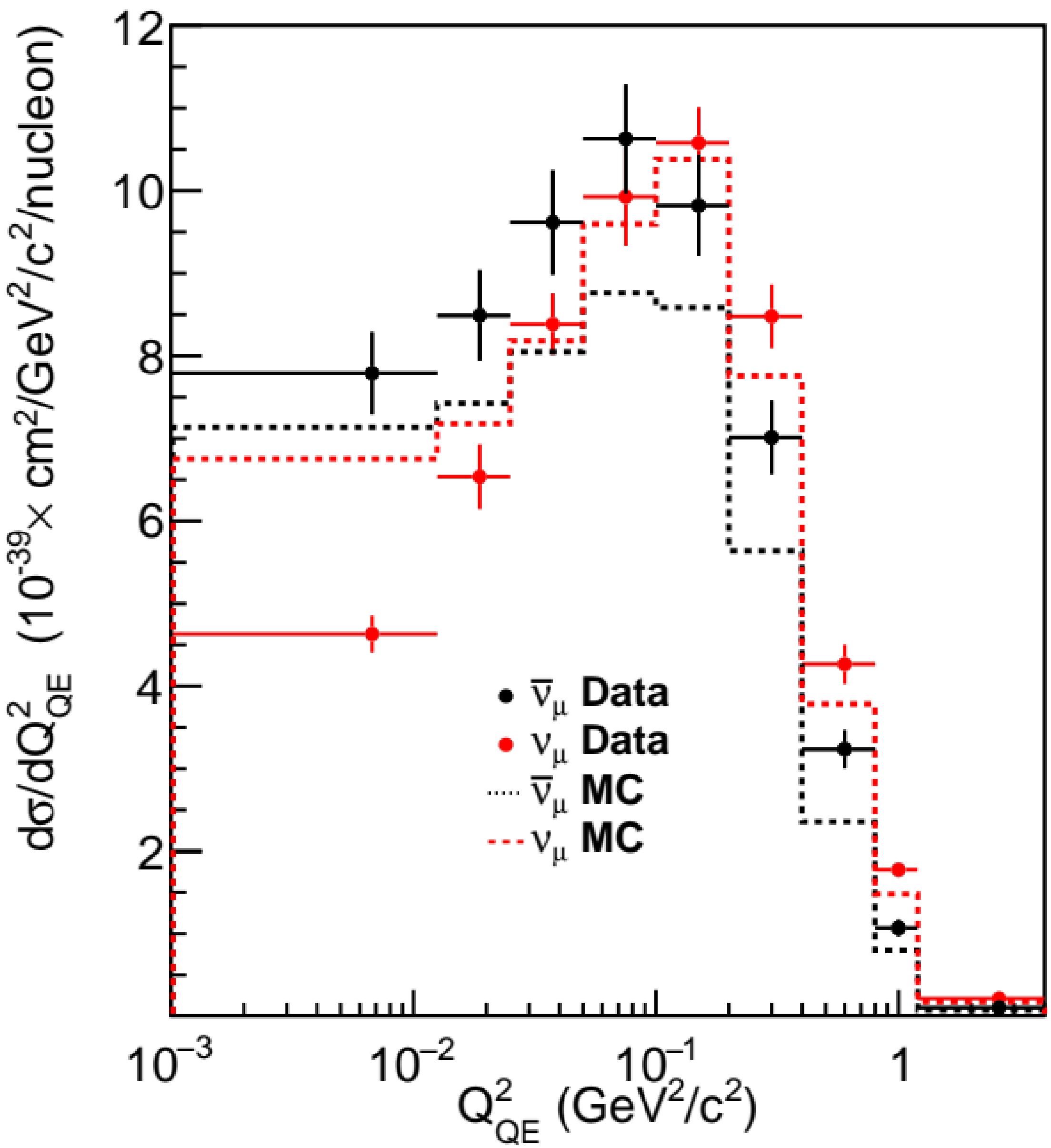
- **MINERvA Tune v1 under-predicts QE-like rate**
- **Low p_T closer to model prediction**

Model Comparison in Q^2

- GENIE3 models:
  - Rein-Seghal → Berger Seghal
  - FSI models:
    - a: hA
    - b: hN
  - 2p2h models:
    - 02: empirical
    - 10: Valencia
- GENIE3 models better match shape of data

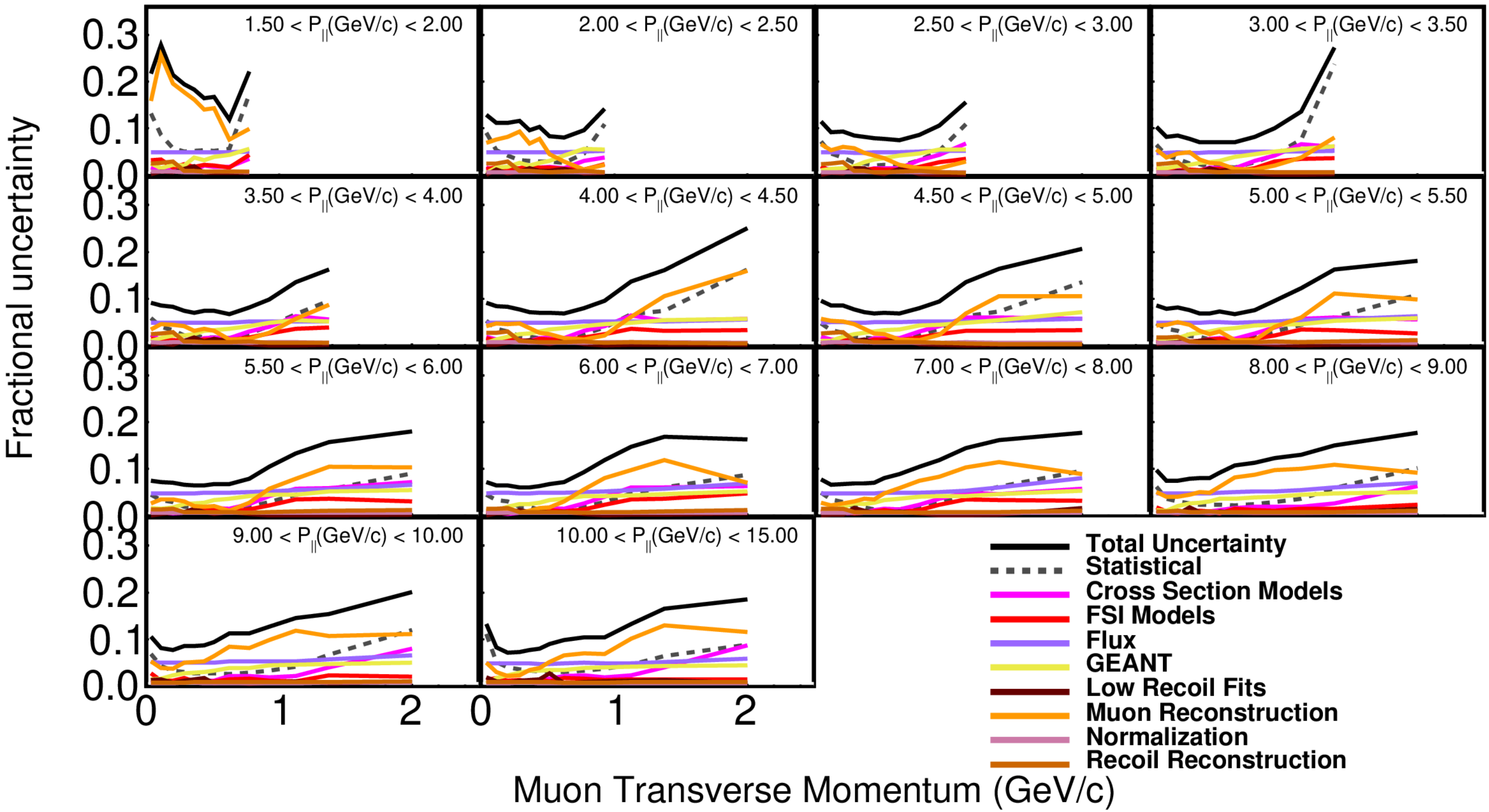


Comparison with Neutrino Data



- Different energy cut-off: was 20 GeV; is 15 GeV in $\bar{\nu}_\mu$
- ν_μ MC better matches data normalization than $\bar{\nu}_\mu$
- Compared to **Phys.Rev.Lett. 124 (2020) 12, 121801, March 2020**

Uncertainties



Conclusions

- MINERvA is sensitive to neutron production
  - Angle and coarse timing available, but not direct energy measurement
  - GENIE 2.8.4 + GEANT 4.9.3 p02 over-predicting neutron candidate rate
  - ME neutron production measurements beginning to be published
- Antineutrino QE-like measurement in ME data
  - MC needs more strength overall
  - Massive statistics enable fine binning
  - GENIE3 is a solid contender for most accurate model

63. Direct Measurement of Nuclear Effects in QE-like Neutrino Scattering at MINERvA
Dr Jeffrey Kleykamp (University of Missis... , Prof. Steven Manly (University of Roche...
26/10/2022, 09:20

Talk | Neutrino CC and NC Sca...

The MINERvA experiment at Fermilab presents results from several analyses of quasielastic-like (QE-like) ν_μ interactions on a variety of nuclear targets in the NuMI neutrino beams. In the low energy ($<E_\nu>\sim$3 GeV) beam, components of the muon-proton momentum imbalance, \tkidptx ~and \tkidpty, are used to probe Fermi motion, binding energy, and non-QE

69. Lepton-Hadron Correlations in QE-like Neutrino Scattering at MINERvA
Deborah Appel Harris (York University (CA))
26/10/2022, 14:20

Talk | Neutrino CC and NC Sca...

This talk will cover two different analyses of muon neutrino charged current interactions on a CH target, as recorded by MINERvA in the NuMI Medium Energy beam. The first analysis focuses on the 0-pion data set which has the advantage that the recoil energy in this set is dominated by the sum of the kinetic energies of the protons that are ejected from the

27. Poster: Neutrons from Antineutrino Interactions in MINERvA
Andrew Olivier
26/10/2022, 15:30

Poster | Poster

Neutron production by antineutrino interactions is an important source of uncertainty for long baseline oscillation experiments. Neutrons are a source of missing energy for calorimetry-based oscillation experiments, and an extra neutron from an antineutrino CCQE-like interaction can be evidence of a 2p2h interaction. Both problems bias oscillation

51. Poster: Measurement of Nuclear Dependence in Inclusive Antineutrino Scattering with MINERvA
Anezka Klustova
26/10/2022, 15:35

Poster | Poster

The MINERνA experiment was designed to perform precision studies of neutrino-nucleus scattering in the GeV regime on various nuclear targets using the high-intensity NuMI beam at Fermilab. This poster outlines the current progress on MINERνA's first inclusive charged-current analysis of antineutrino interactions on iron, lead, and water using antineutrino

79. Neutrino Pion Production at MINERvA
Prof. Kevin McFarland (University of Roche...
28/10/2022, 10:00

Talk | Neutrino Pion Productio...


Thank You

Backup Slides

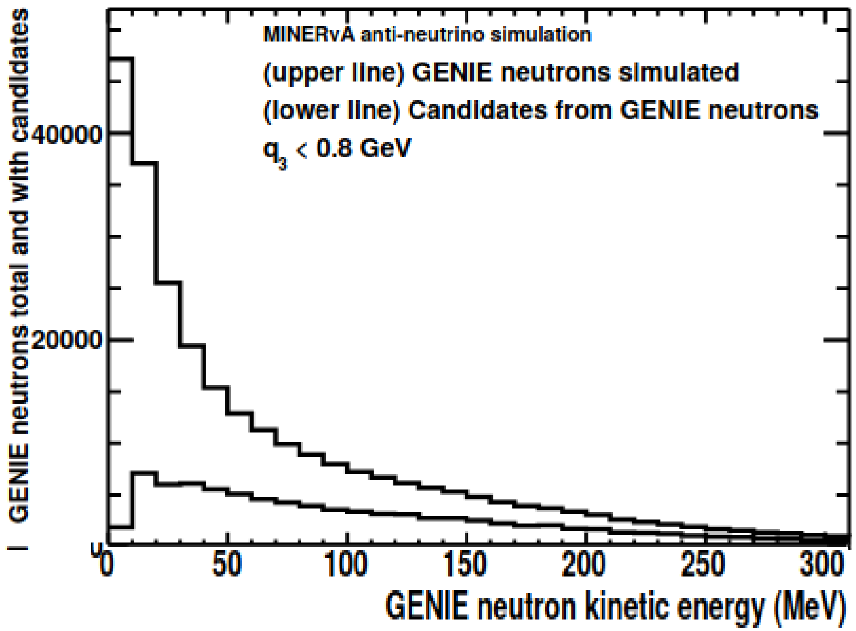
MINERvA's Model Tunes

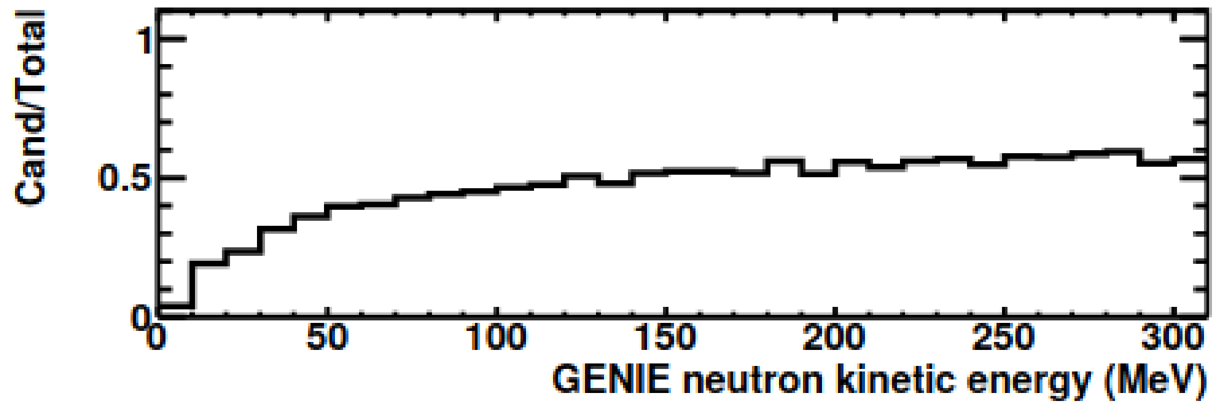
- GENIE: Generates Neutrino Interactions for Experiments
  - Simulates kinematics of initial neutrino interaction and propagation out of the nucleus
  - Low energy: 2.8.4
  - Medium energy: 2.12.6 (Valencia 2p2h added)
- MnvTunev1: GENIE 2.12.6 with the following tunes:
  - 2p2h enhancement by a Guassian 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

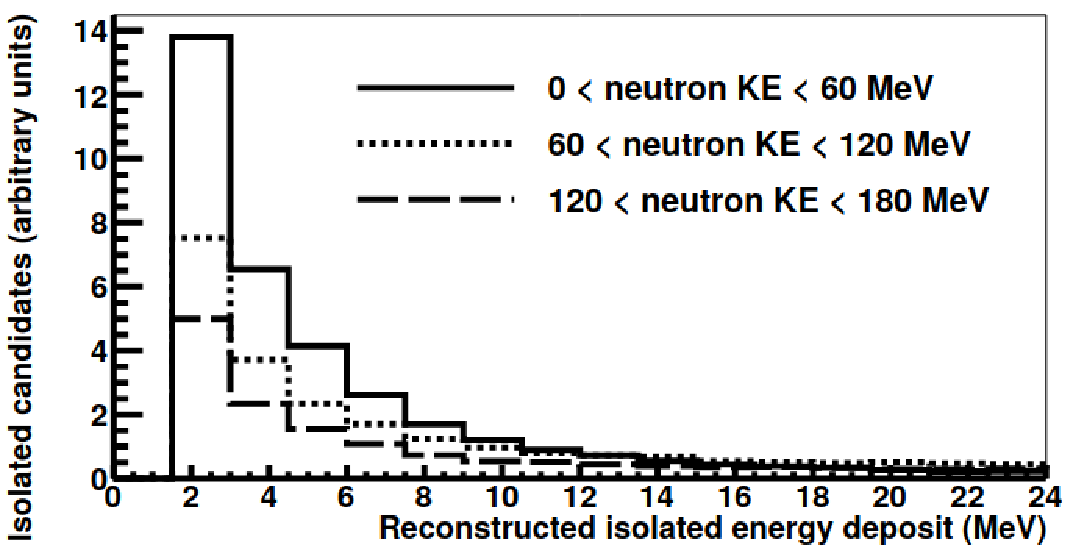
Variables of Interest

- E_{avail}: Available energy
  - Energy in non-neutron final state particles = energy we can reconstruct calorimetrically
  - Full energy of pions + KE of anything else that's not a neutron
  - Technically ignores rest mass of nucleon resonances
- TKI
  - Transverse Kinematic Imbalance
  - Use a charged hadron with the muon to look for missing momentum
  - Very sensitive to effects of FSI and interactions off of correlated nucleons (i.e. 2p2h)
  - p_N: neutron momentum under a QE hypothesis for neutrino CCQE

What Neutrons does MINERvA Detect?

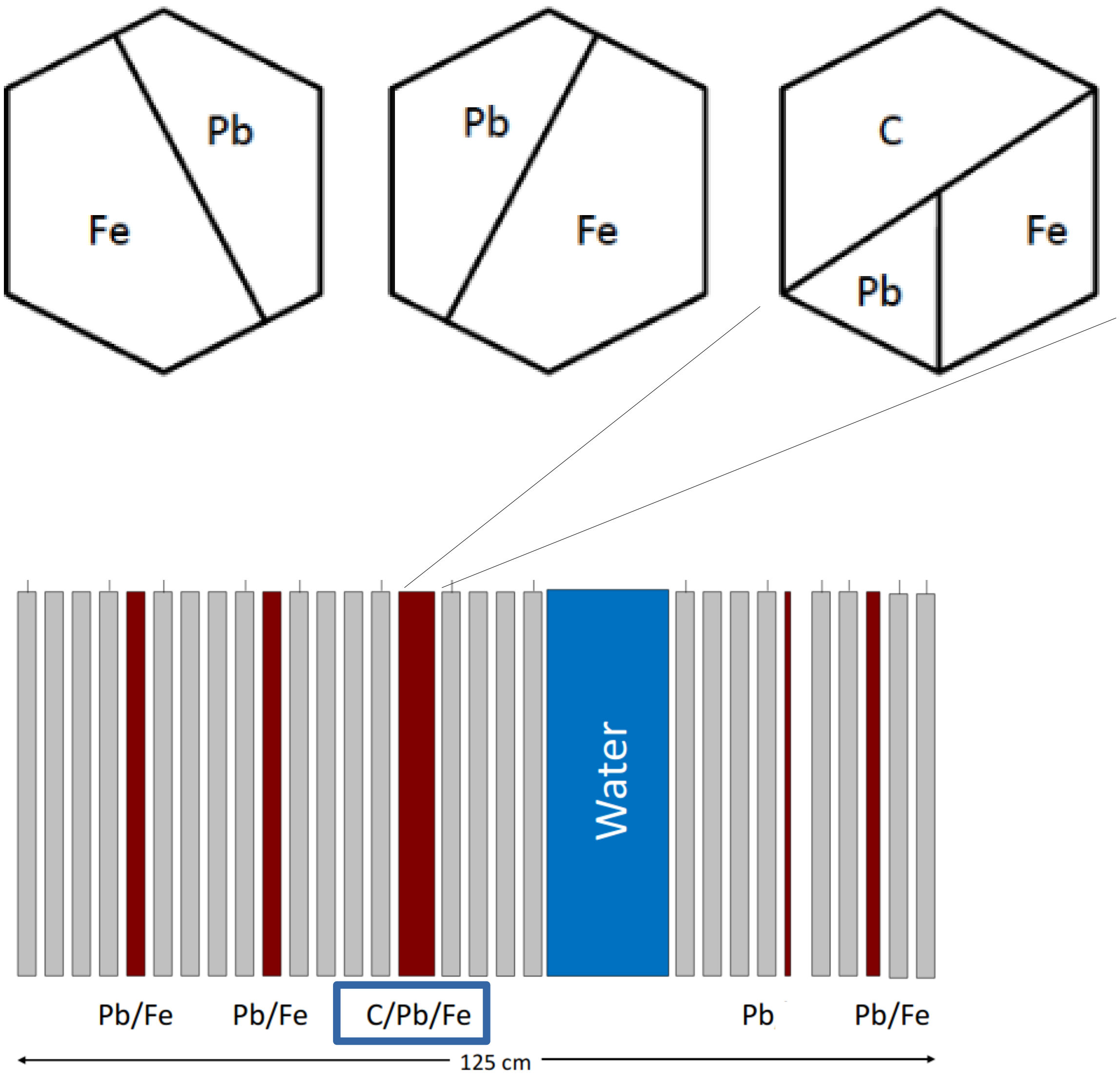






- **Prompt** neutron energy deposits
- Predicted neutrons dominated by low KE
- But detection efficiency drops off rapidly
- Bottom right: energy deposit not strongly correlated with kinetic energy

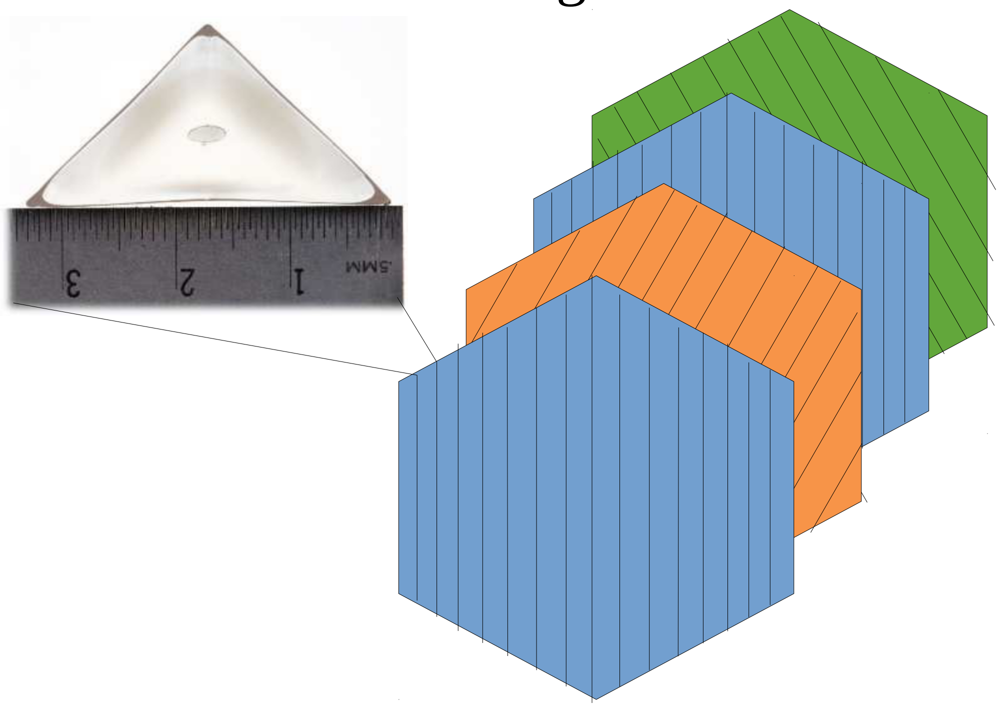
MINERvA's Nuclear Targets

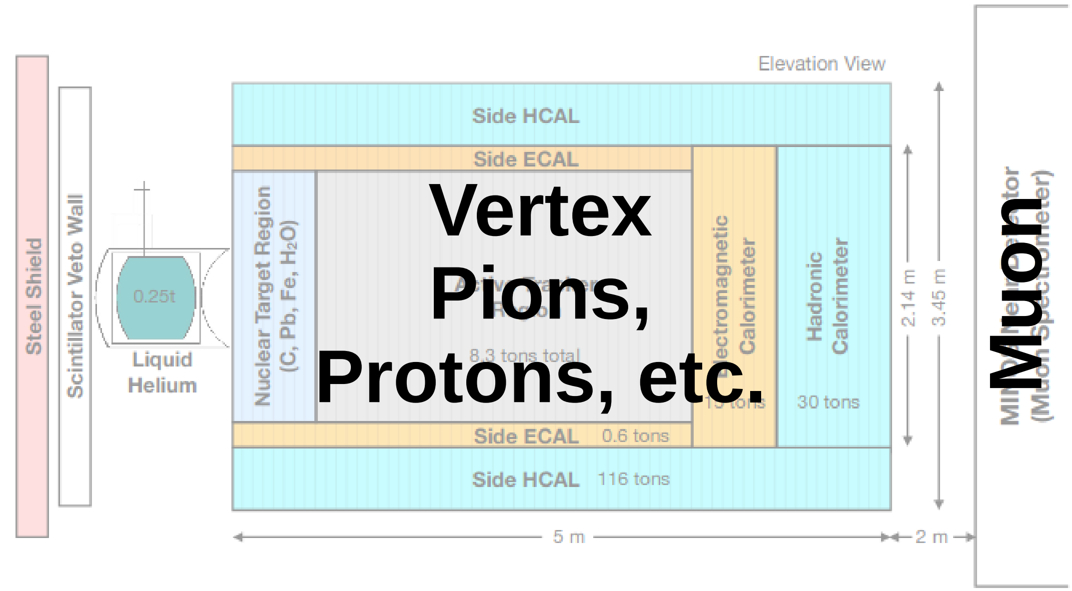


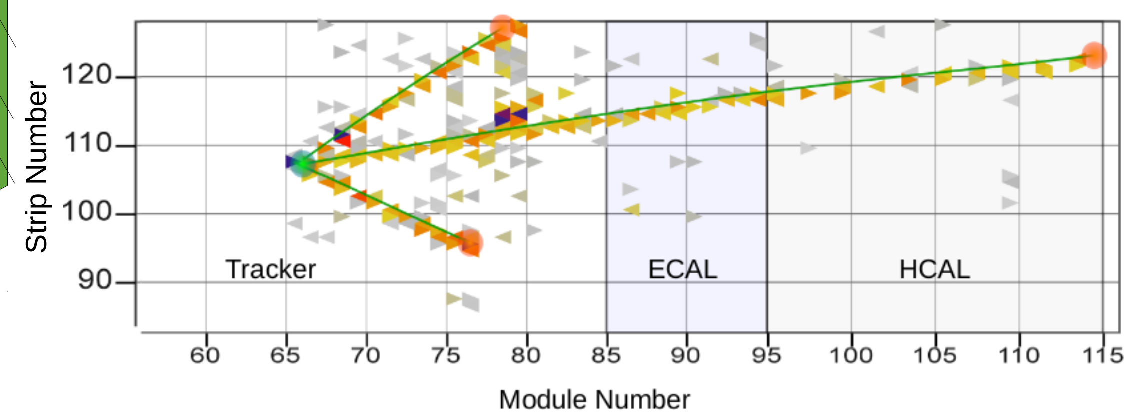
- Passive nuclear targets upstream of tracker
- Let us study A-dependence of neutrino cross sections
- Determine interaction material by x, y coordinates

How MINERvA Works

- 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



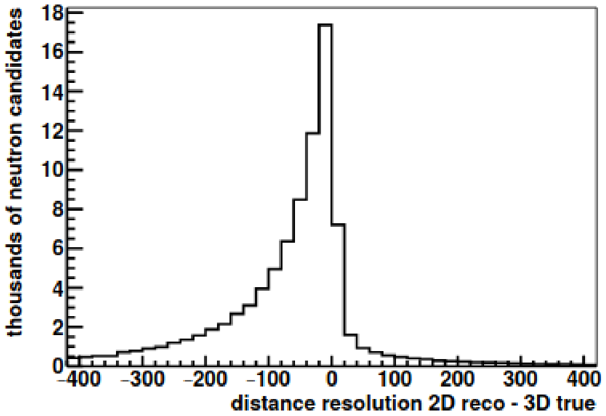




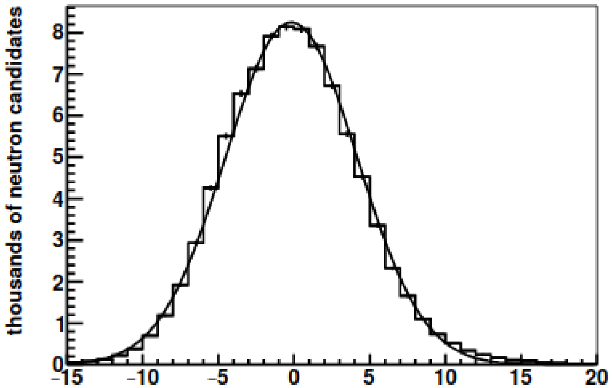
MINERvA's Tracker

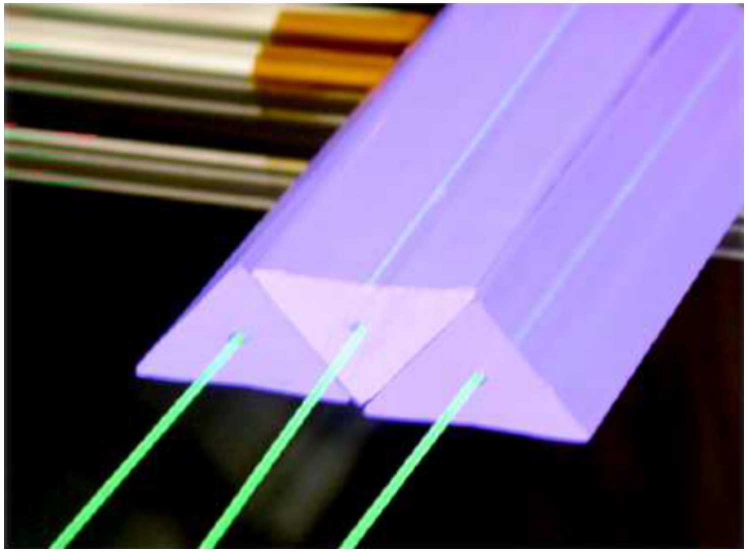
- Only read out on one end → timing resolution
- Modules have 4 planes → raises minimum proton energy for 3D reconstruction

Distance from Vertex

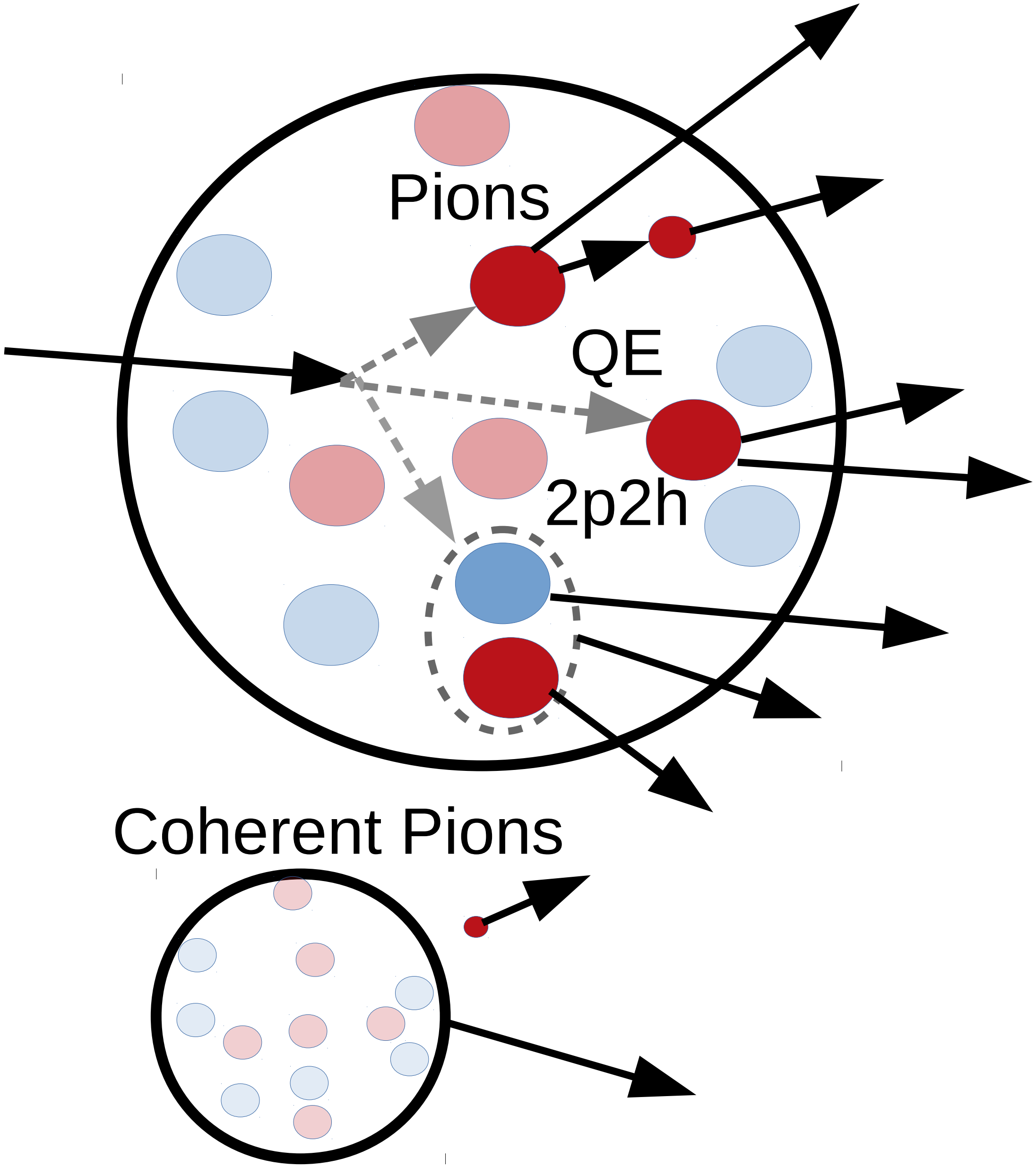


Timing



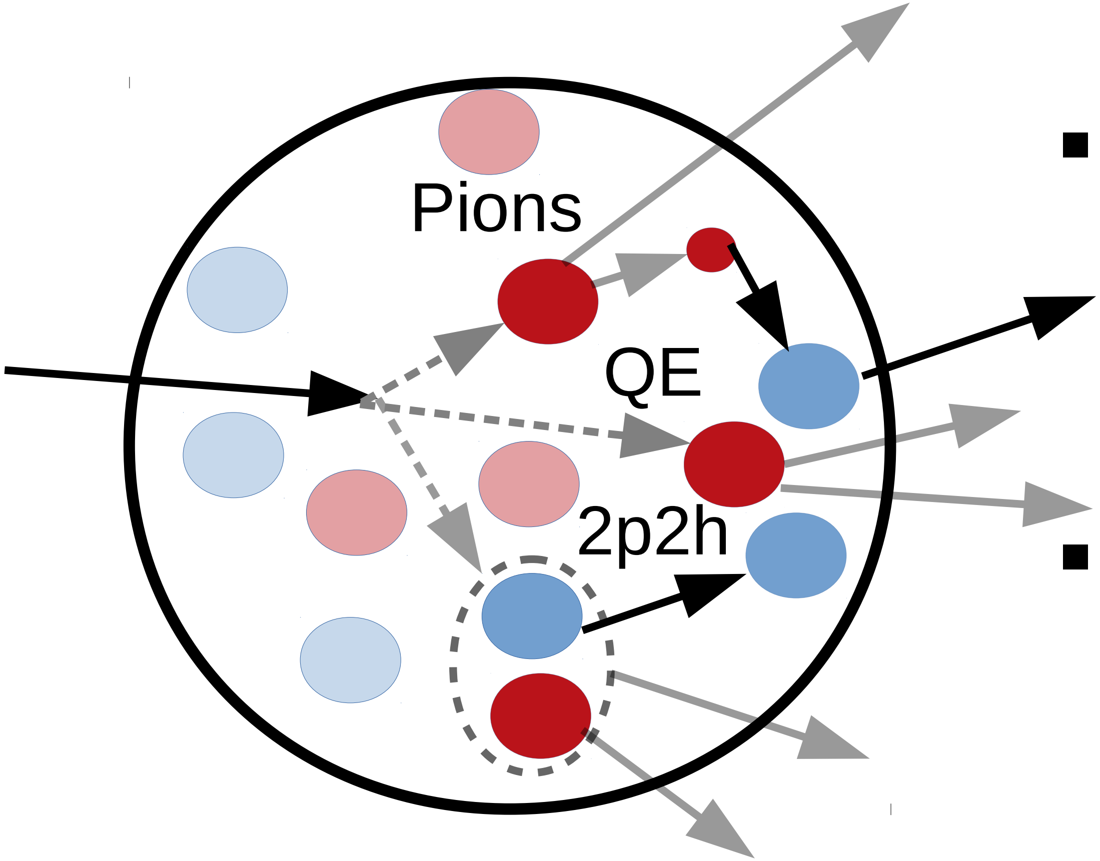


Processes We Study



- Interaction on nucleons:
  - Quasi-Elastic interaction: "billiard ball scattering". Simple kinematics → E_ν measurement
  - Pion production
  - "2p2h": interaction on multiple nucleons
- Deep Inelastic Scattering: interaction on quarks → lots of hadronic energy
- Coherent: interaction on entire nucleus

Even More Complicated: FSI



- Final State Interactions:
  - Additional nucleons
  - Pions absorbed
  - Hadron momenta changed
- Tools we can use against them:
  - QE kinematics from muon
  - Coherent pion production: interacts with whole nucleus
  - Transverse Kinematic Imbalance (TKI)

Why Measure Cross Sections?

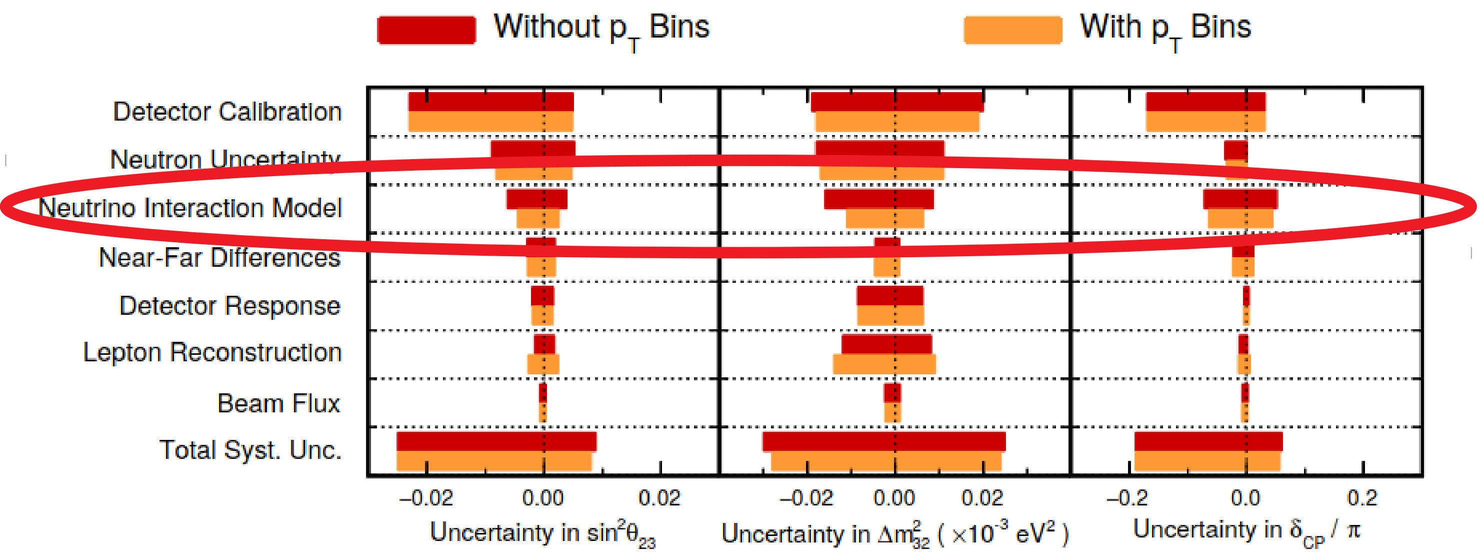
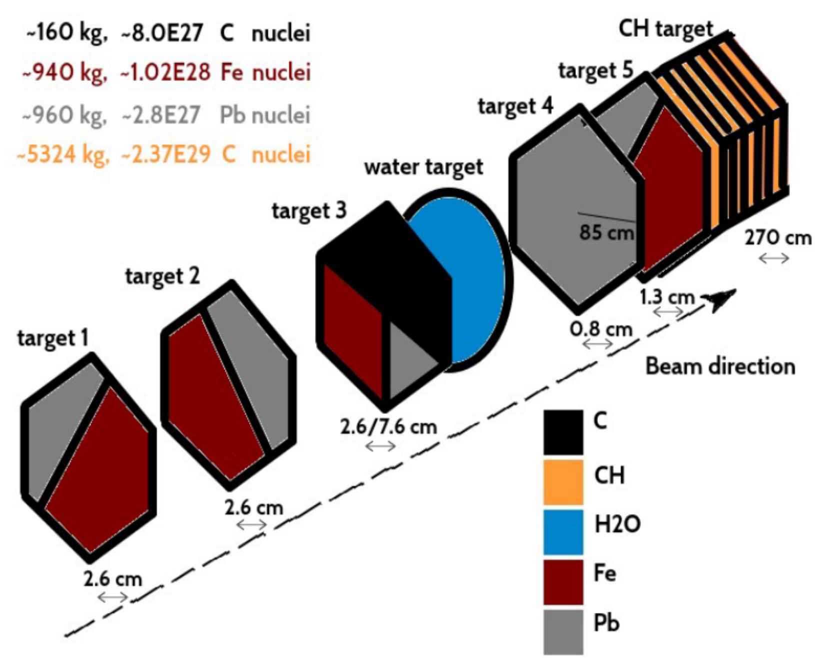


Figure by A. Ramirez Delgado

https://arxiv.org/abs/2108.08219



- Reduce interaction model uncertainty for oscillation experiments
  - Even ND fit doesn't completely cancel
  - Future oscillation experiments planning for large statistics → reduction in systematics
- First measurement of material ratios!