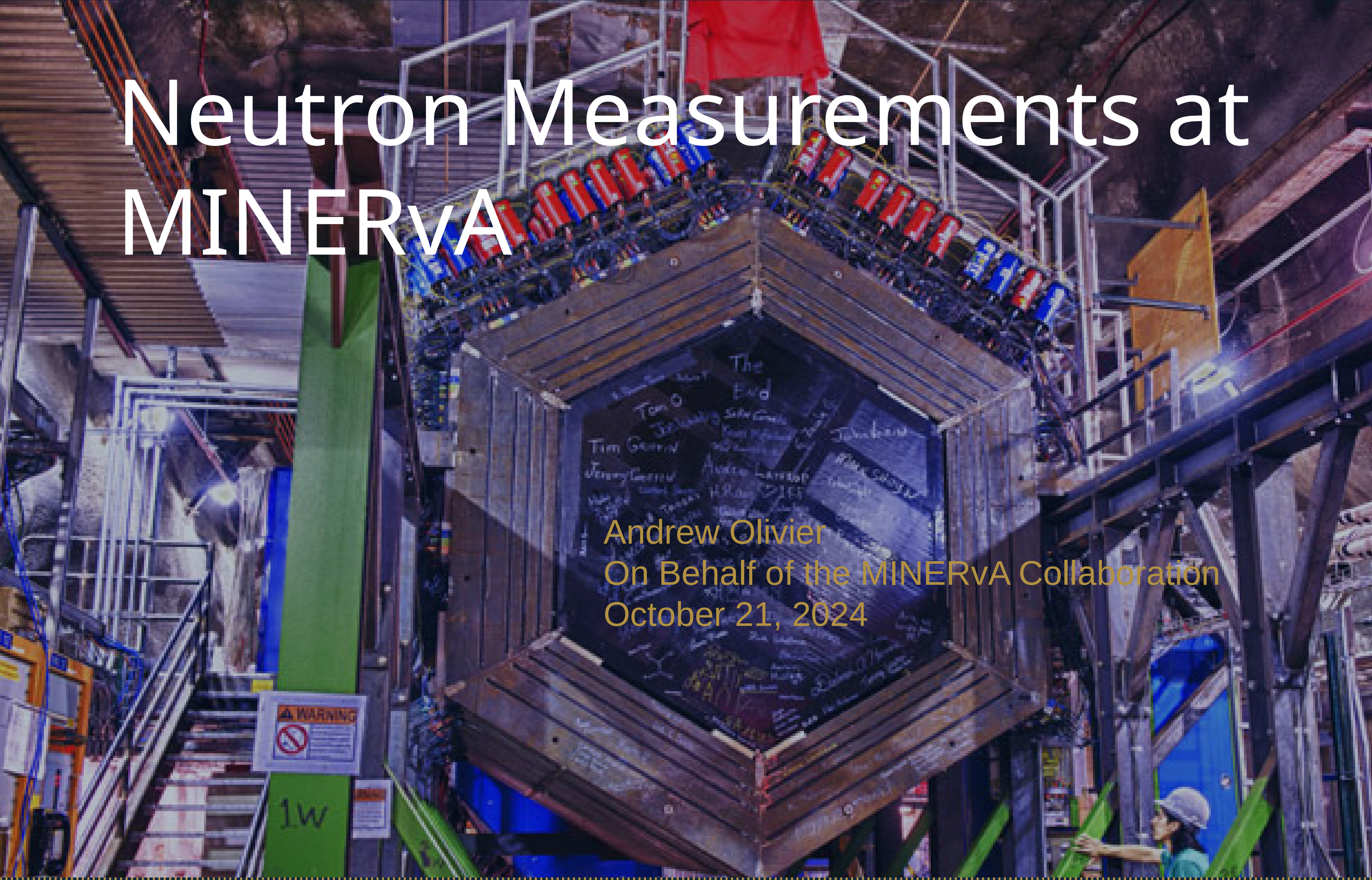
Neutron Measurements at MINERvA



Andrew Olivier
On Behalf of the MINERvA Collaboration

October 21, 2024

Bringing **Neutrons** Into Sharp Focus

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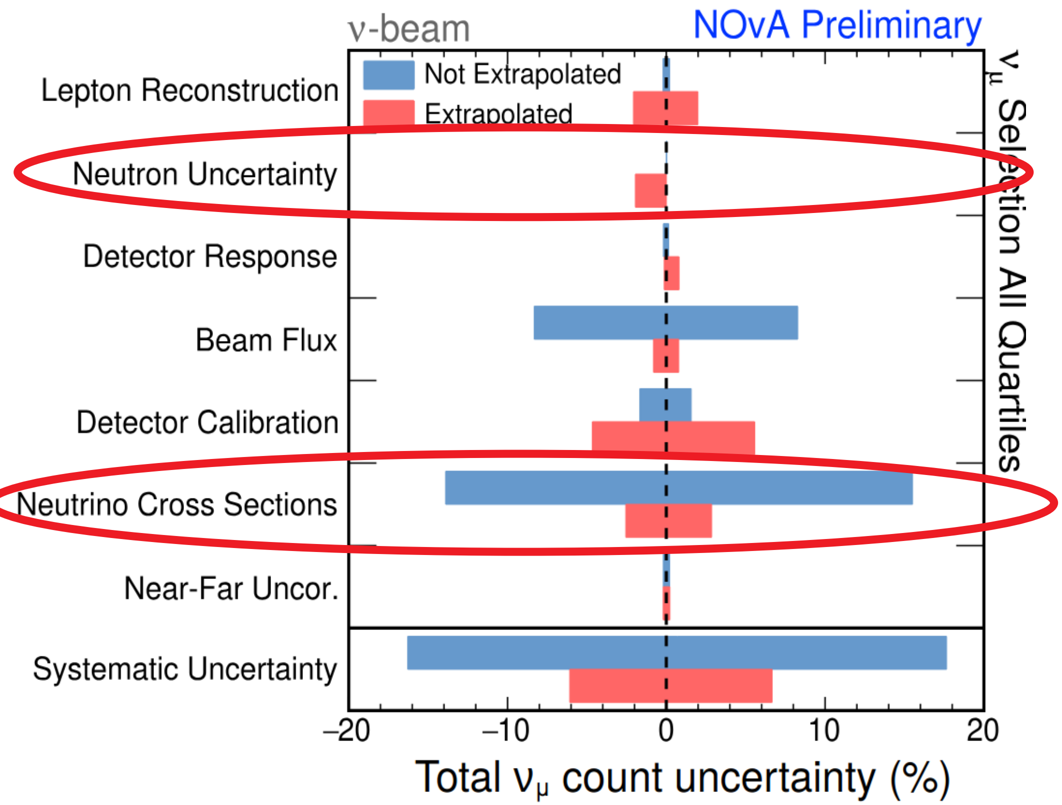
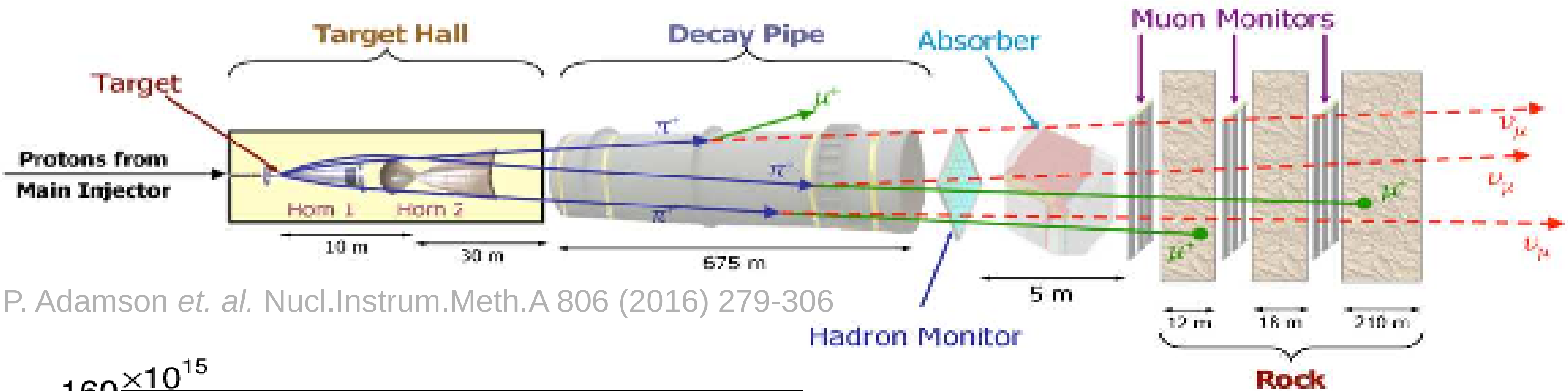
- MINERvA measures primarily **cross sections** to **reduce uncertainties** for **oscillation** and **scattering** experiments
  - Free nucleon cross section
  - Neutron production
  - Nuclear effects
  - Scaling across nuclear targets
- To do this, we need:
  - Percent-level beam predictions
  - Centimeter position resolution
  - Nanosecond timing resolution
  - Neutron detection

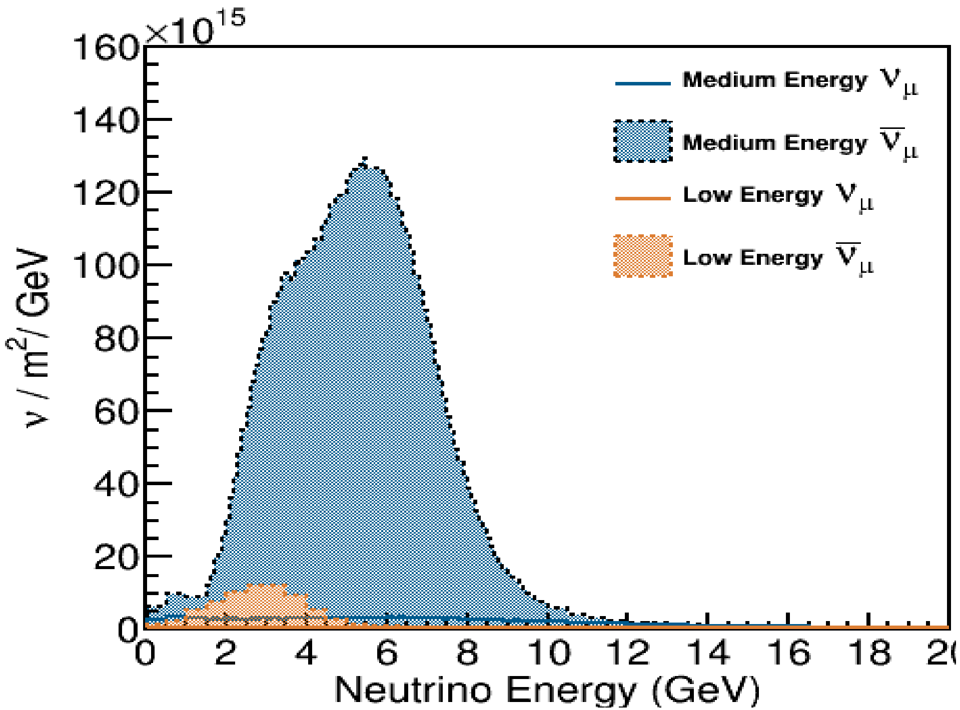


J. Wolcott, Neutrino 2024

Neutrino Beam at MINERvA

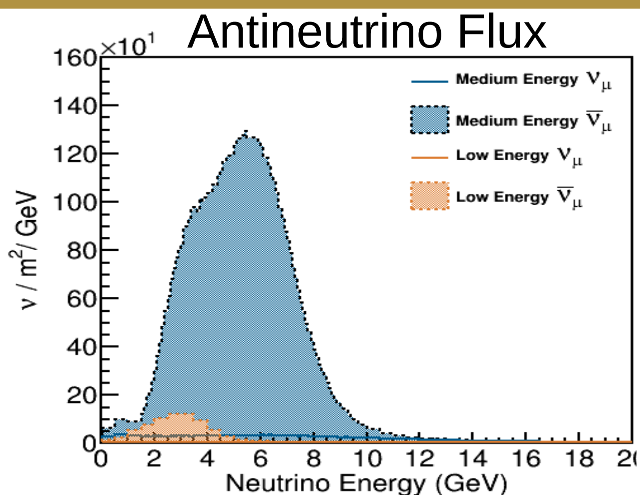


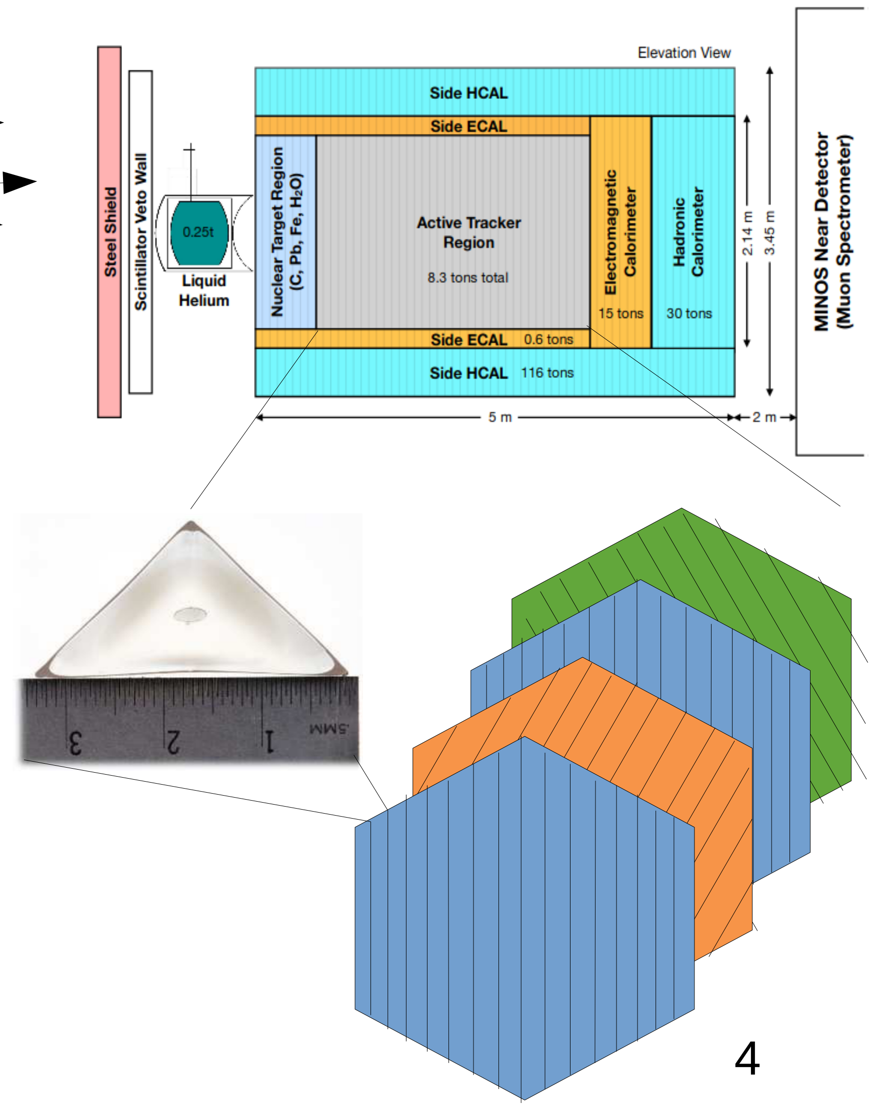
P. Adamson *et. al.* Nucl.Instrum.Meth.A 806 (2016) 279-306



- NuMI beam at Fermilab
- **6 GeV** neutrino energy peak
- Using exclusively **Medium Energy** (ME) results today
- Flux constrained by neutrino-electron elastic scattering and inverse muon decay

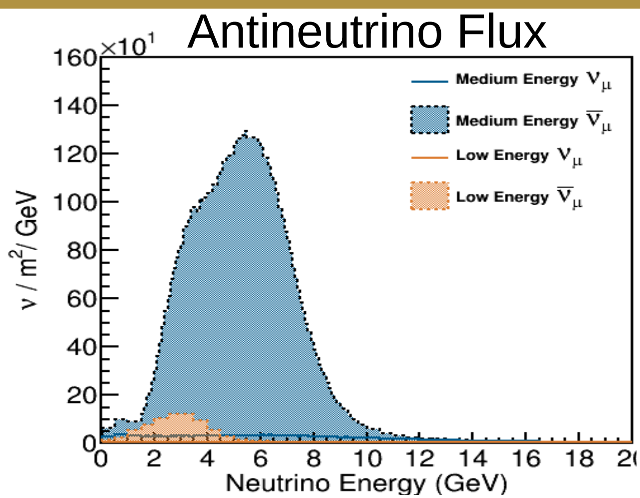
MINERvA's Tracker

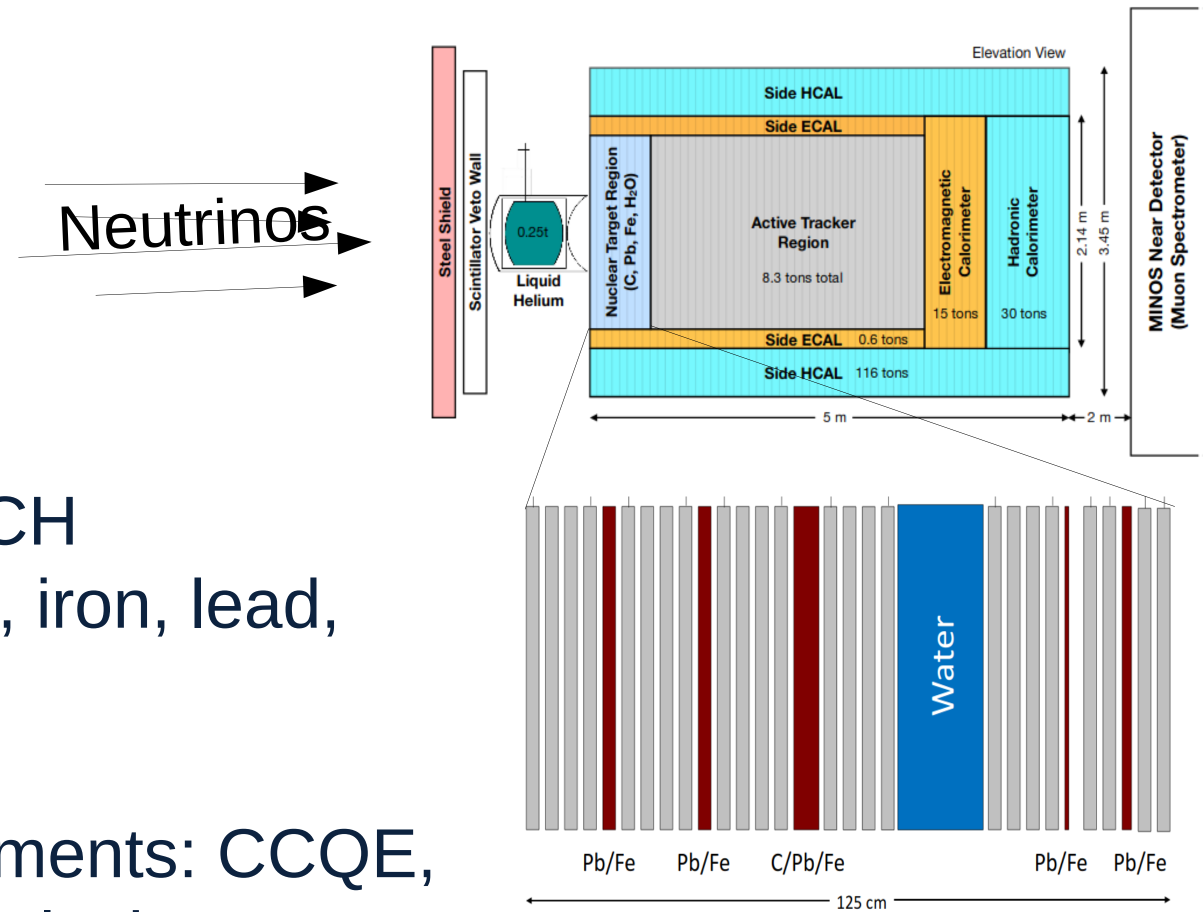




- Segmented scintillator tracker
- 3cm x 1.7cm triangular strips
- 3 orientations → 3D track reconstruction
- Good position resolution; great timing

Nuclear Targets



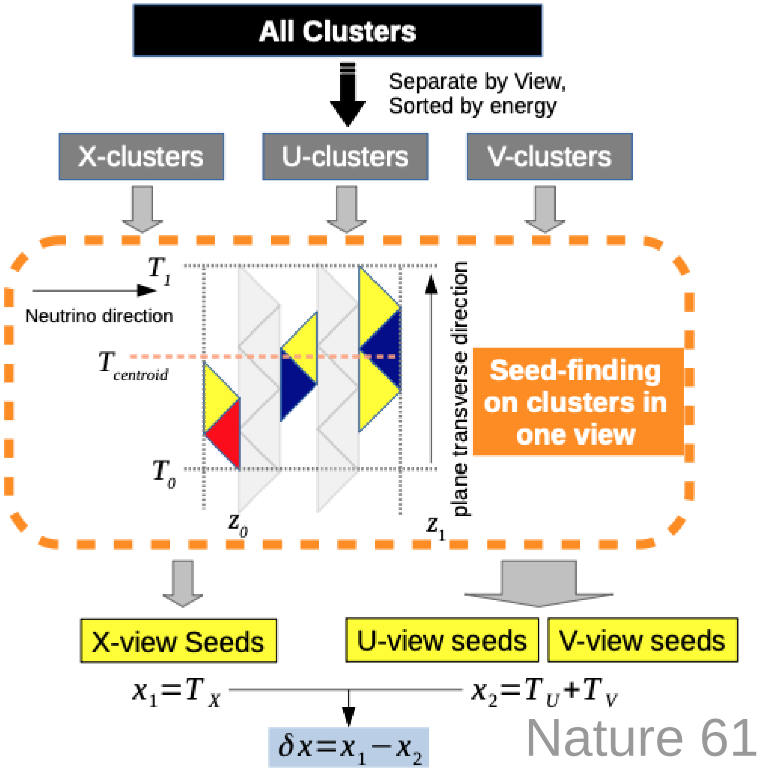


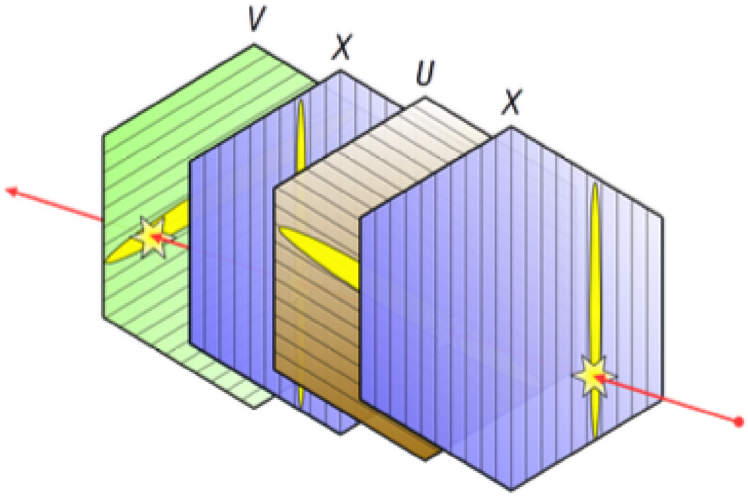
Nucl. Inst. and Meth. A743 (2014) 130

- Bulk of detector: CH
- In tracker: carbon, iron, lead, water
- Upstream: helium
- Existing measurements: CCQE, coherent pions, inclusive

Neutron Detection at MINERvA

- Look for charged particle activity isolated from the (anti)muon
- Stitch one-view pockets of charge (clusters) into 2D seeds
- Combine 2D seeds that match seeds from other views





Nature 614 (2023) 7946, 48-53

What Neutrons Look Like in MINERvA

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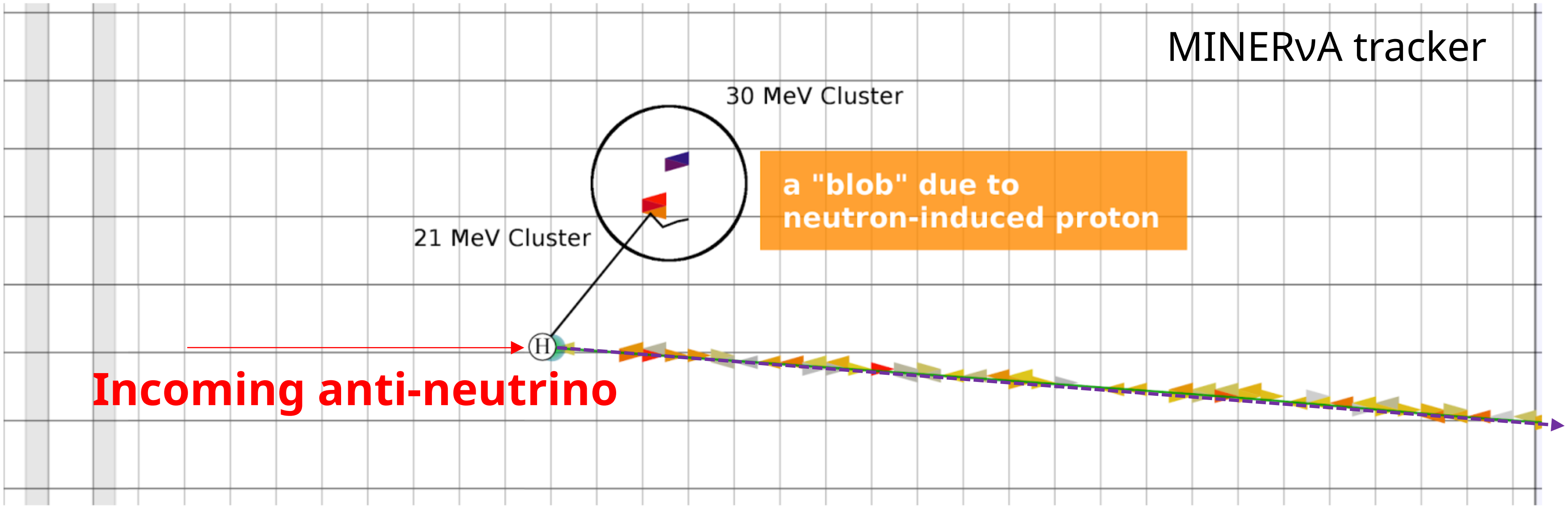
- Muon
- Neutron
- **Prompt** scattering → relative directions



Nature 614 (2023) 7946, 48-53

Free Nucleon Measurement: Charged Current Elastic Scattering

- "Form factors": parameters in cross section expression
  - F_V^1, F_V^2: "vector" form factors from E&M. Can be probed by electron scattering
  - F_A: "axial" form factor for weak force. Only dominant for e.g. neutrino scattering

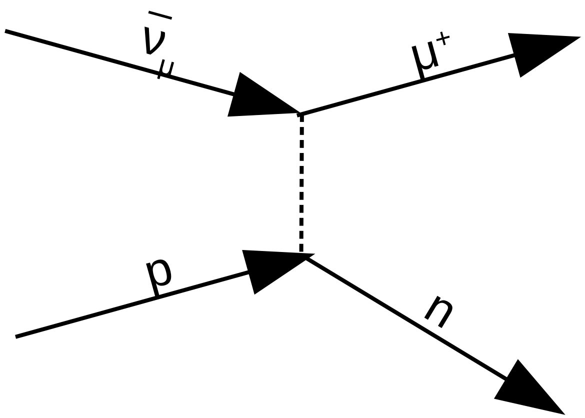
$$\frac{d\sigma}{dQ^2}\begin{pmatrix}\nu n \to l^- p \\ \bar{\nu} p \to l^+ n\end{pmatrix} = \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \mp B(Q^2)\frac{(s-u)}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right]$$

$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_V^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}\,F_V^{1*}\xi F_V^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],$$

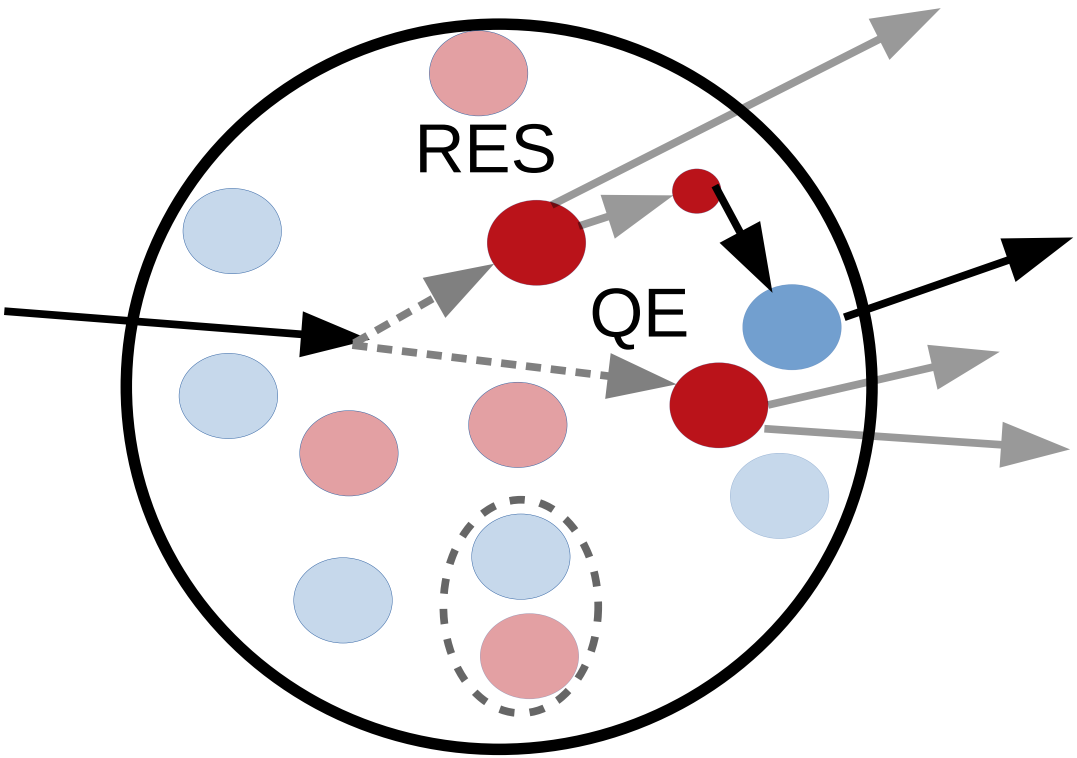
$$B(Q^2) = \frac{Q^2}{M^2}\mathrm{Re}\,F_A^*(F_V^1 + \xi F_V^2),$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{4M^2}|\xi F_V^2|^2\right)$$

- Electron experiments can measure some parts…
- Axial-vector form factor only affects weak force. **Neutrinos** isolate it



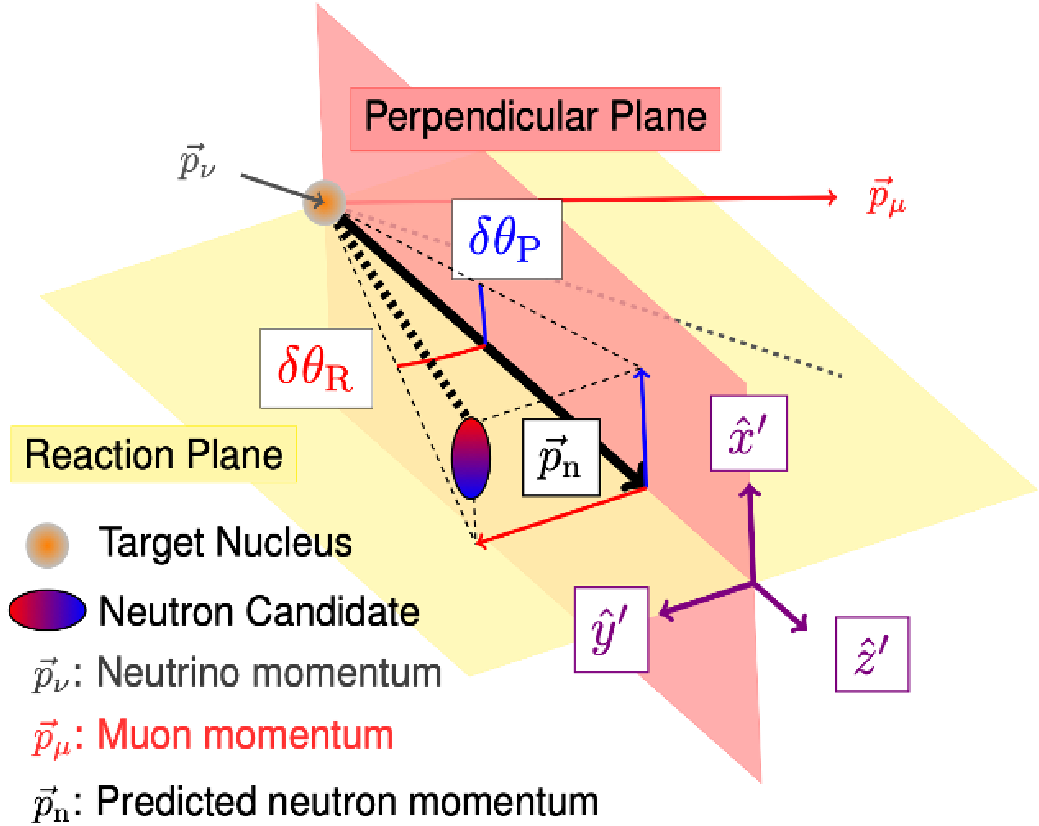
Different from CCQE Because of FSI



- Pions, protons, etc. scatter in nuclear medium!
  - Could gain/lose momentum
  - Could produce more hadrons
  - Could be absorbed
- None of this visible to detector!
- Cascade simulation state of the art for neutrinos

Transverse Kinematic Imbalance

- Conservation of momentum
- Assume antineutrino direction is beam direction
- If striking ***stationary free*** nucleon, sum of muon and neutron momenta is in beam direction
- Assumption NOT true for carbon:
  - "Fermi momentum": nucleons moving inside nucleus
  - Many-body physics
- If neutron and muon "line up", very likely to be hydrogen



Background Constraint

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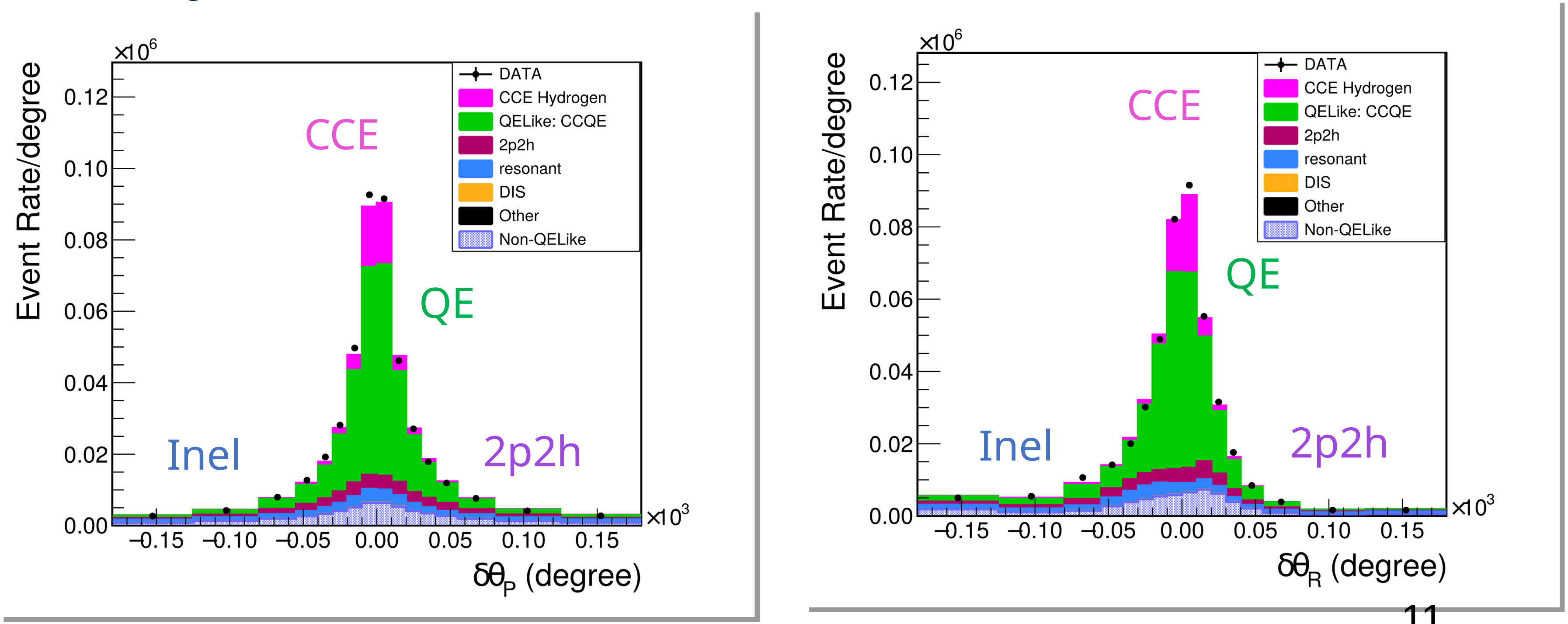
- Nuclear many-body physics of carbon not necessarily well modeled
- Cross-check: plot deviation from momentum-conserving angles
- Also separates background-rich regions from signal-rich regions → background constraint



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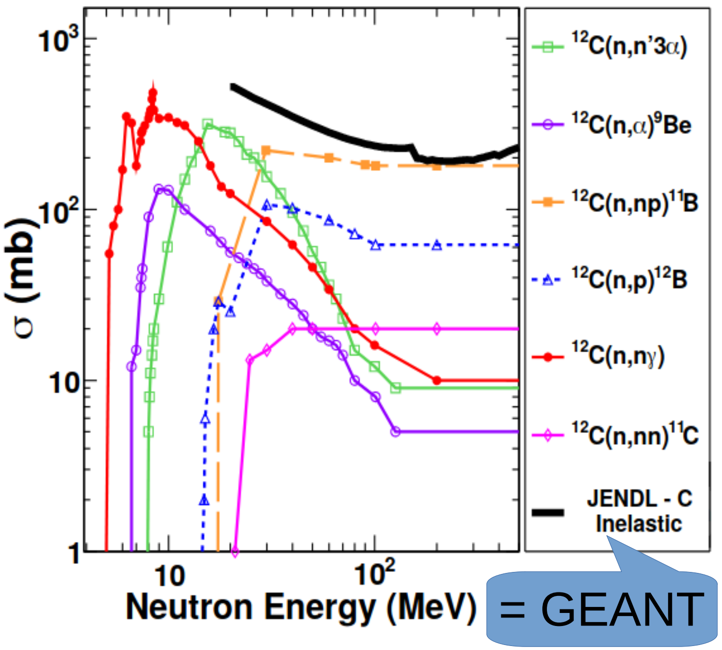
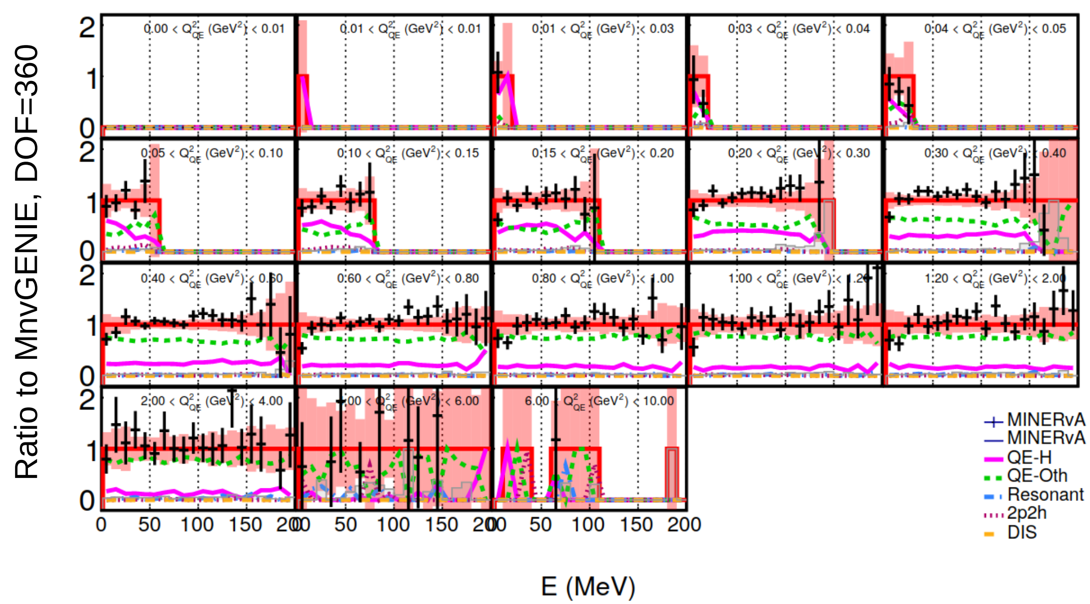
Nuclear Physics Constraint

MENATE_R: Data-Driven Neutron Transport



- MoNA nuclear physics collaboration also wanted to model neutrons on CH
- Compared to MENATE_R model
- Test beam data favors MENATE_R over GEANT 4.9.2

- Study nuisance variables like candidate energy deposit
- Reweight MINERvA MC to look like MENATE_R simulation
- X^2 goes from ~288 to ~254



Nature 614, 48–53 (2023).

Result: Hydrogen CCE Cross Section

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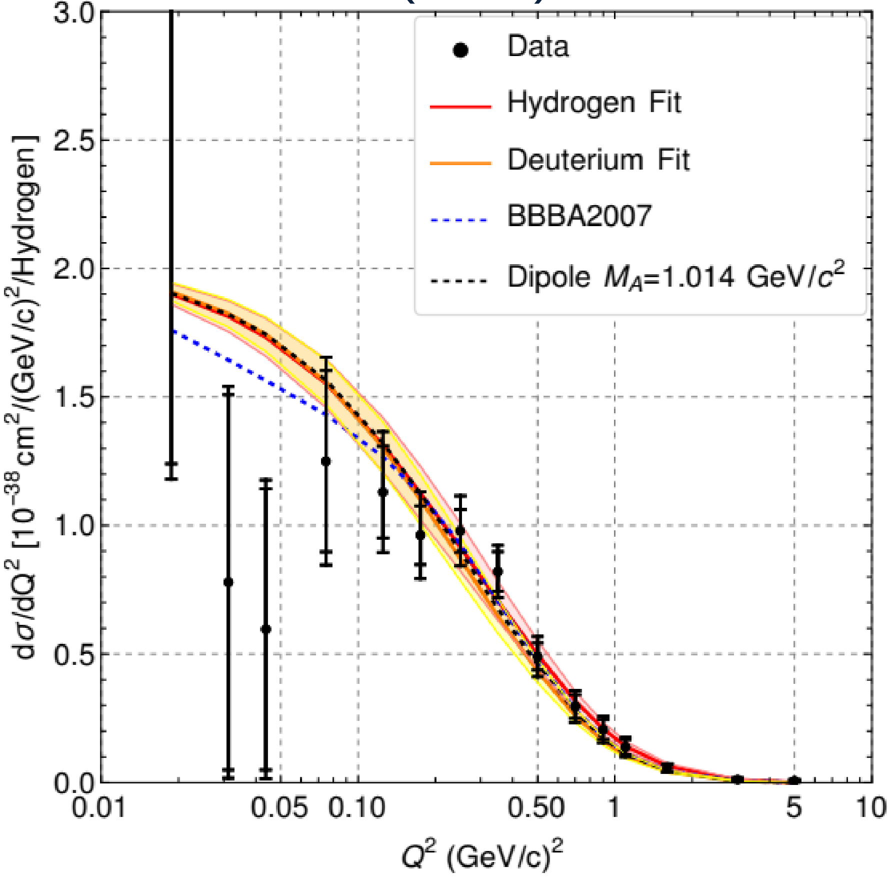
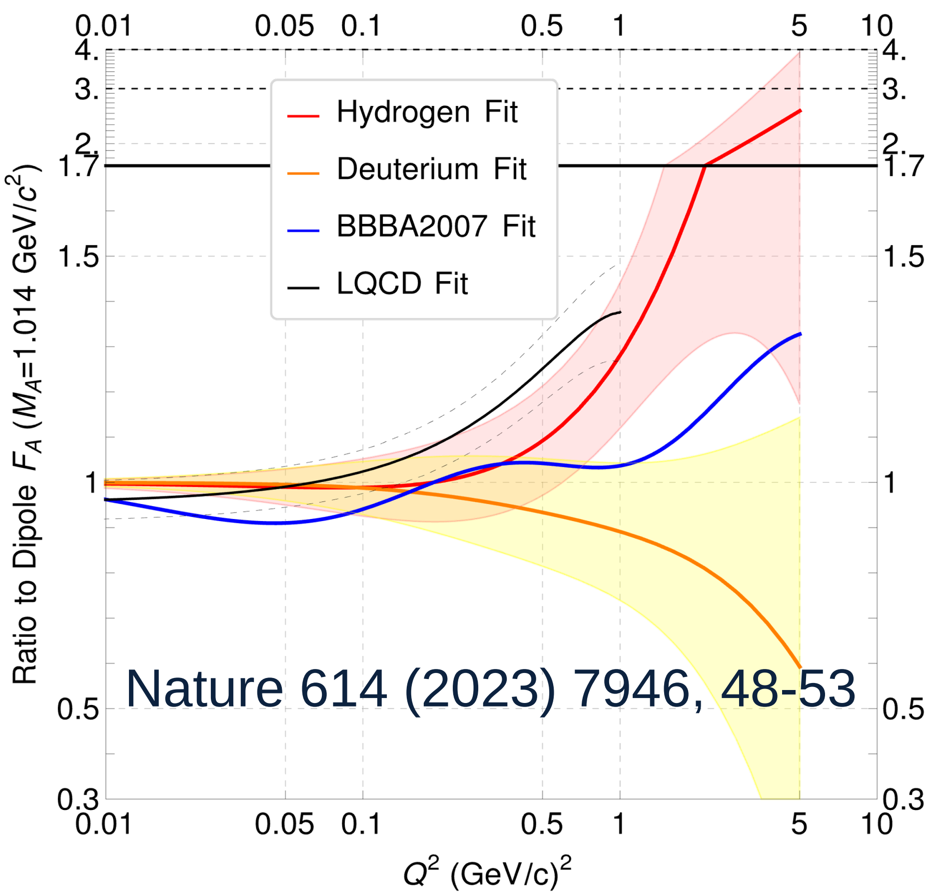
- Prediction for cross section that depends on form factors
- Binned in Q^2: four-momentum transfer
- Corrected for:
  - Constrained backgrounds
  - Smearing
  - Detector efficiency
  - Flux
  - Number of hydrogen atoms in detector

Nature 614 (2023) 7946, 48-53



Result: Axial Form Factor

- Large uncertainty: ~5800 events on a background of ~12500
- Deuterium fit is based on decades-old measurements
  - Low statistics
  - Nuclear effects interfere
- BBBA2007 is global fit including electron scattering
- LQCD fit gets close at high Q^2: *Phys. Lett. B* 824, 136821 (2022).



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Compatibility with Deuterium Data?

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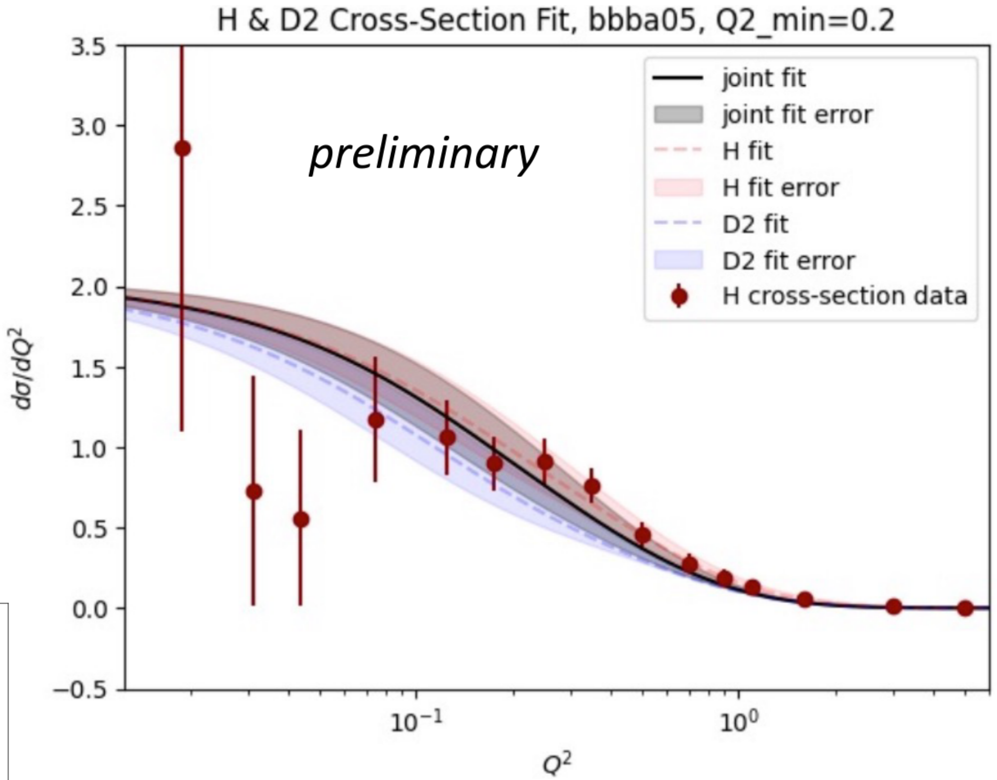
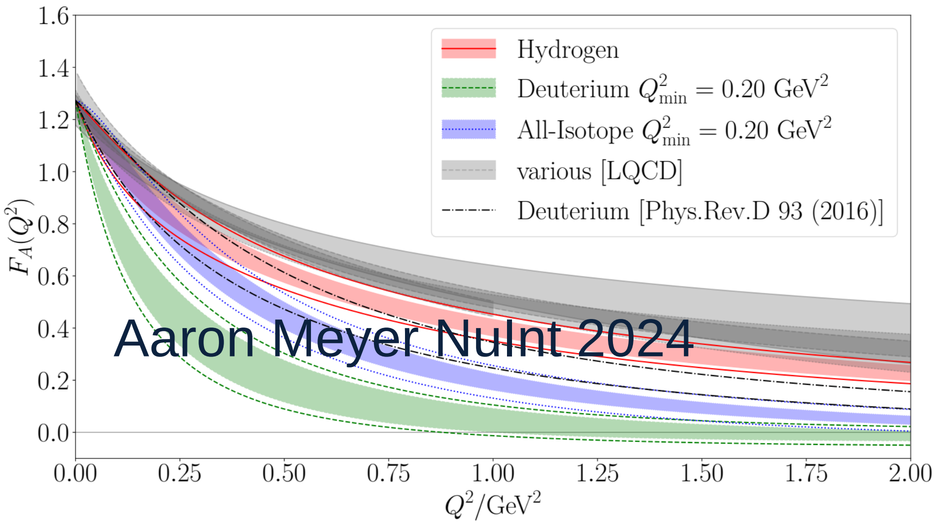
- Joint fit of MINERvA FA results with *Phys. Rev. D* 93 (2016) 11, 113015
- With BBBA05 vector form factors and $Q^2 > 0.2$ GeV^2, $\delta X^2 \sim 5.5$ or p-value of 2%

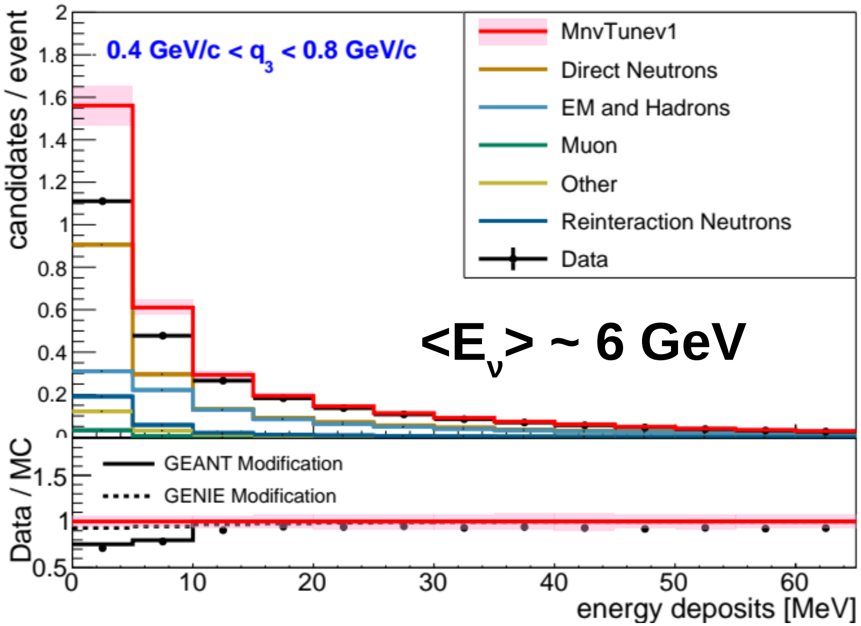




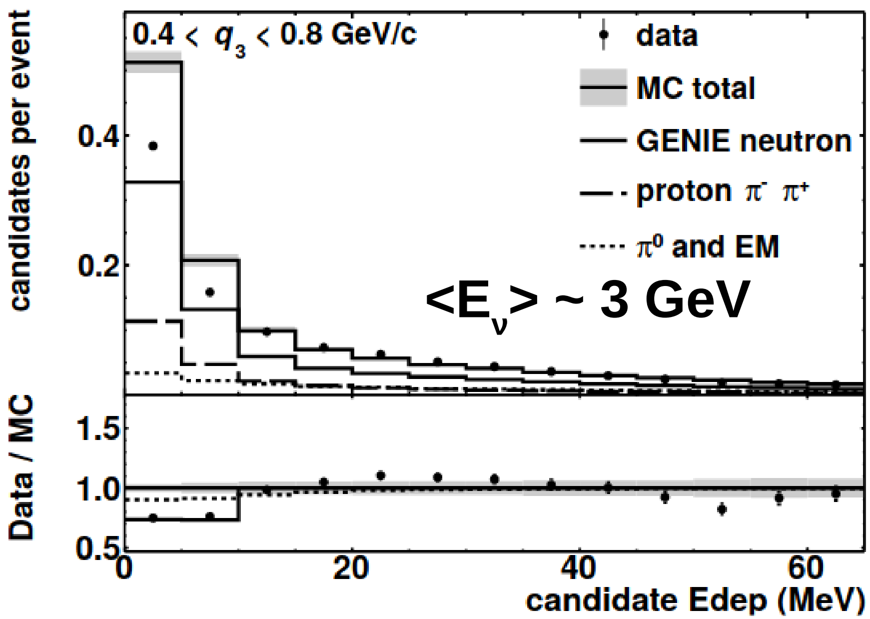
Aaron Meyer NuInt 2024

- Deuterium dipole and joint fit not compatible with hydrogen data

Neutron Detection at MINERvA



Phys. Rev. D 108 (2023) 11, 112010



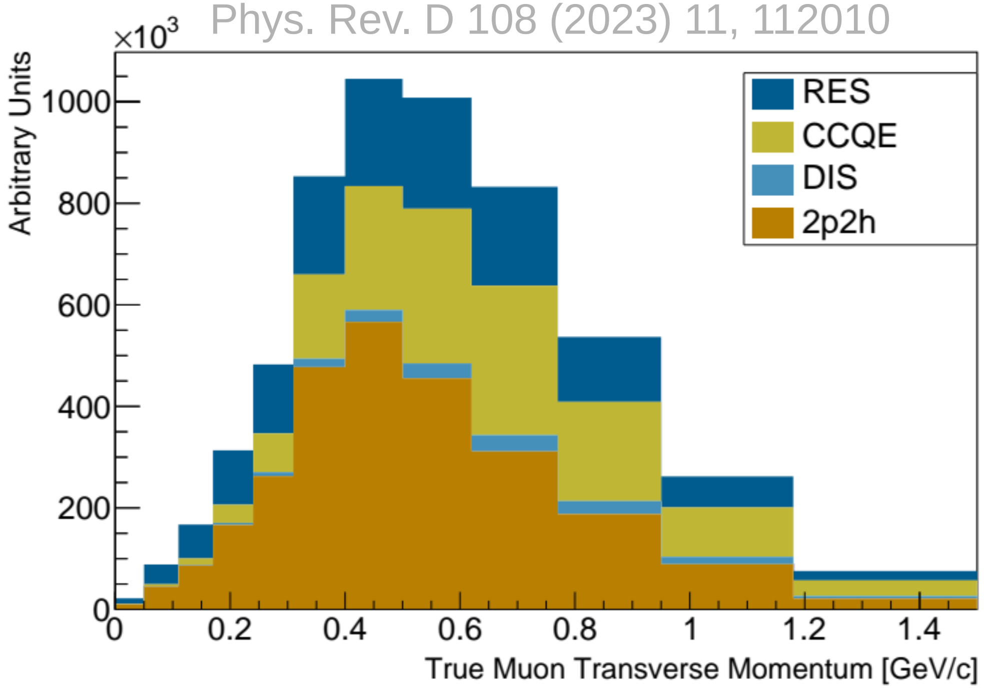
Phys. Rev. D 100, 052002 (2019)

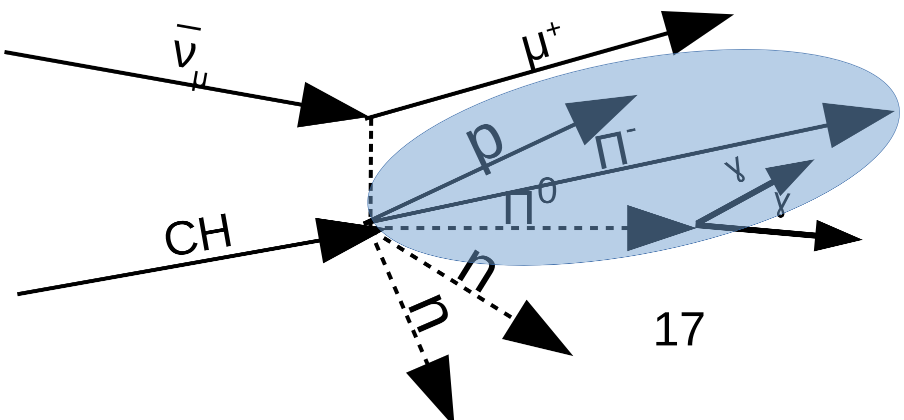
- Showed that neutrino experiment tracker can see neutrons!
- Neutron modeling close, but not quite right
- No conclusive evidence whether problem is at GEANT- or GENIE-level

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

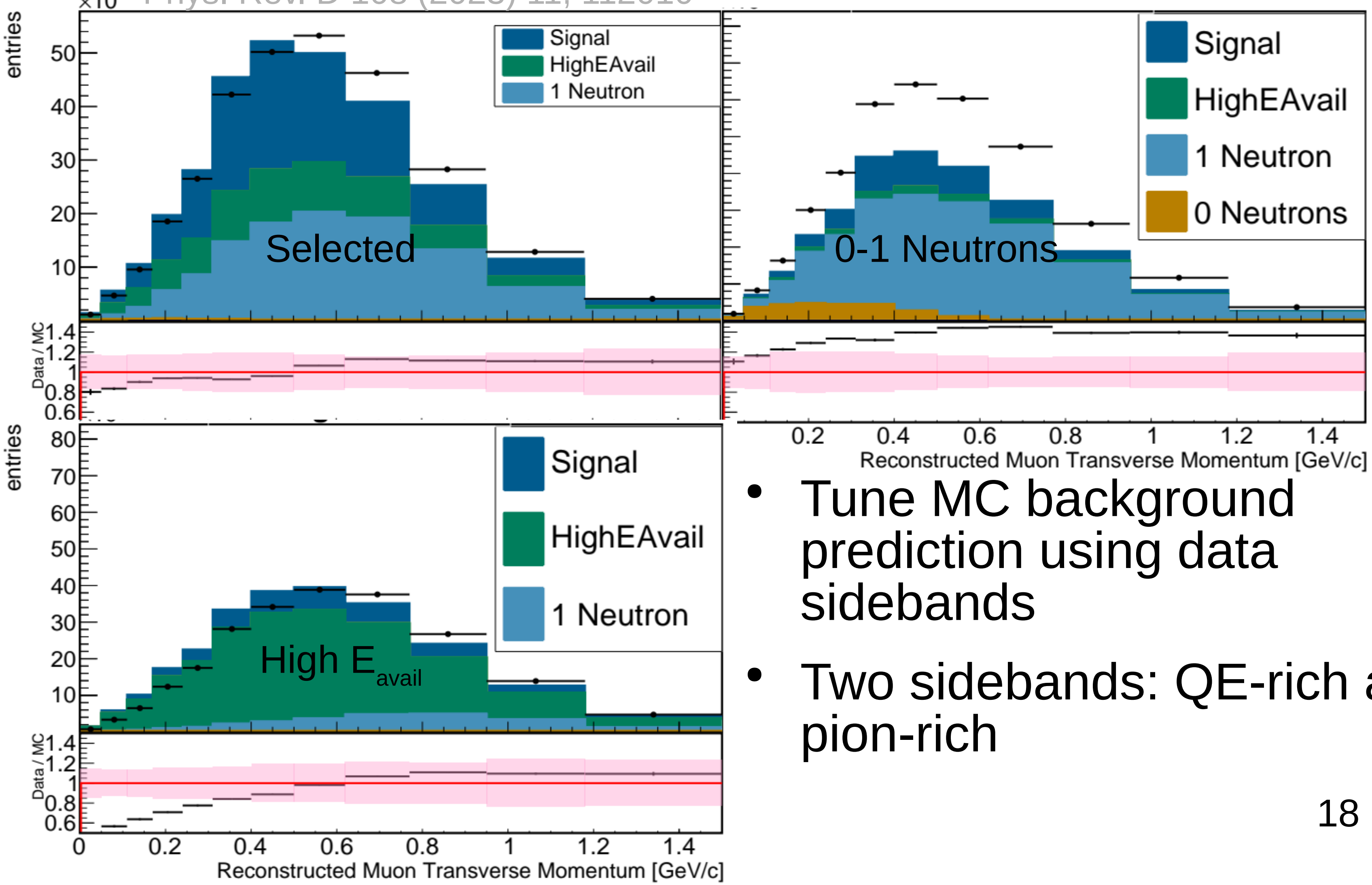
Phys. Rev. D 108 (2023) 11, 112010





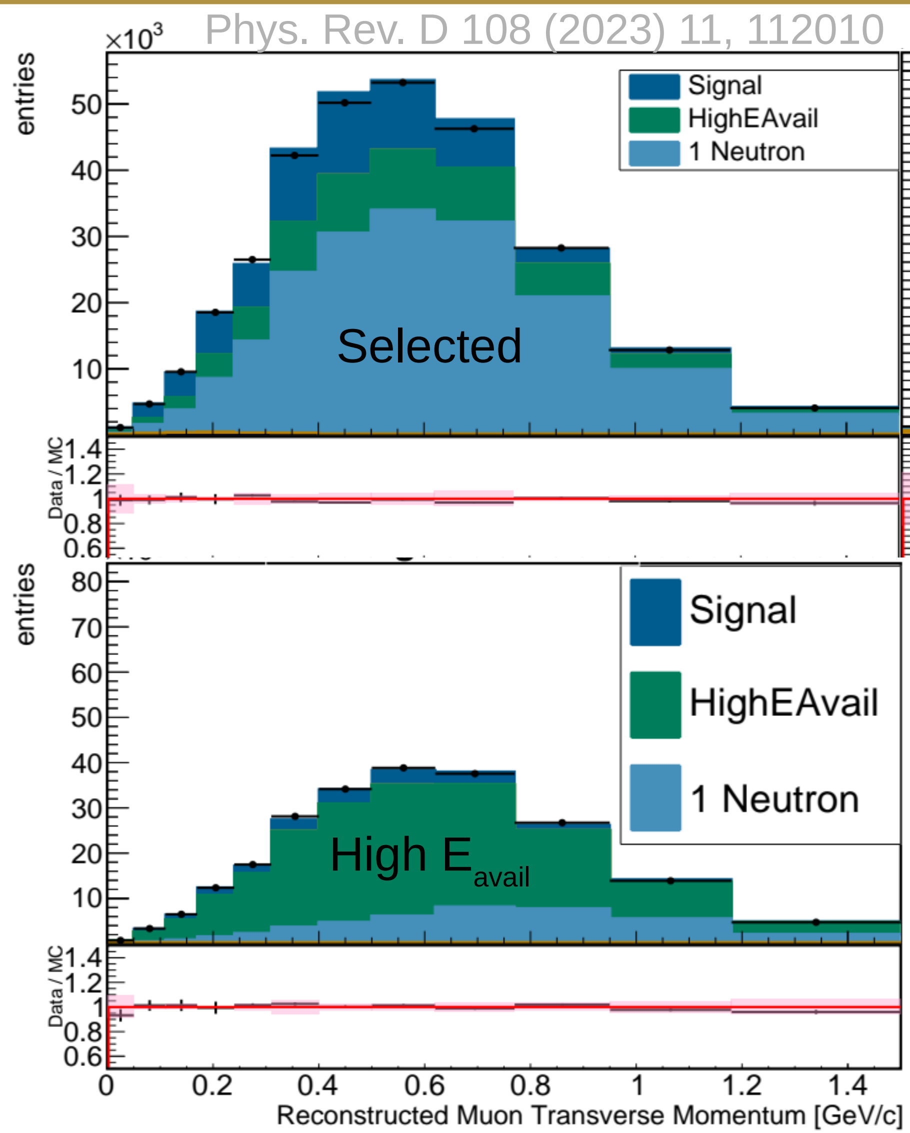
Backgrounds

Phys. Rev. D 108 (2023) 11, 112010



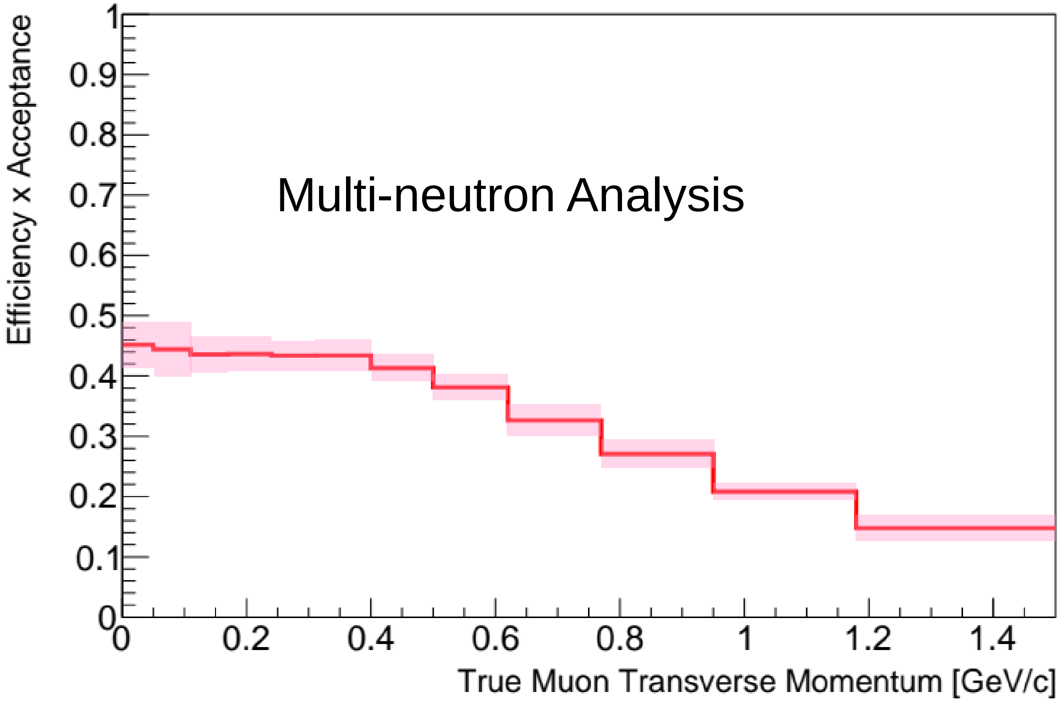
- Tune MC background prediction using data sidebands
- Two sidebands: QE-rich and pion-rich

Constraint Results

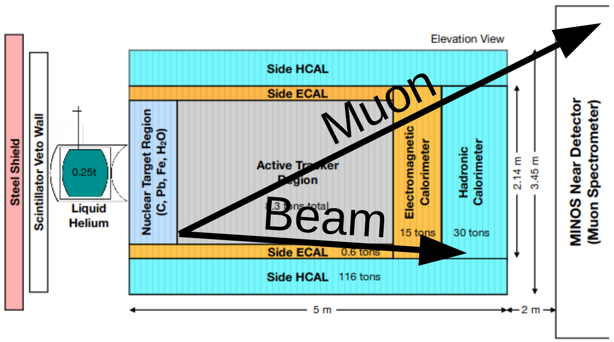


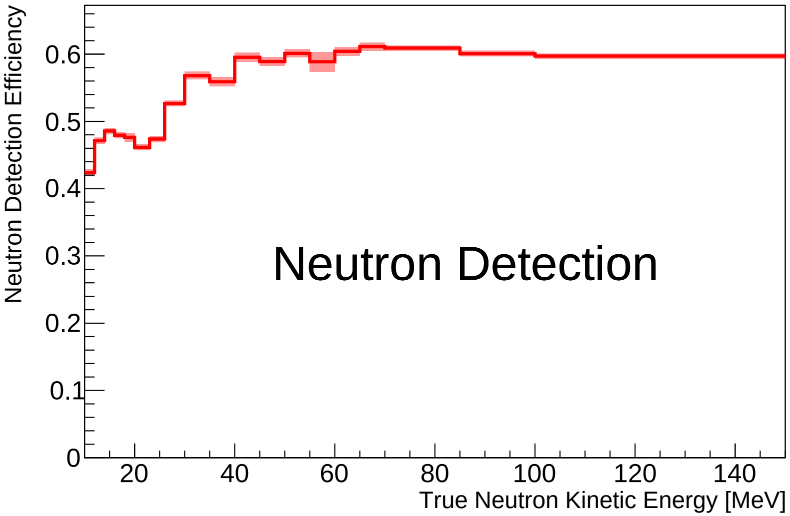
- Tuned up QE-like 1 neutron sample
- Linear scale to pion-rich high E_{avail}
- Similar to other MINERvA results

Multi-Neutron Efficiency

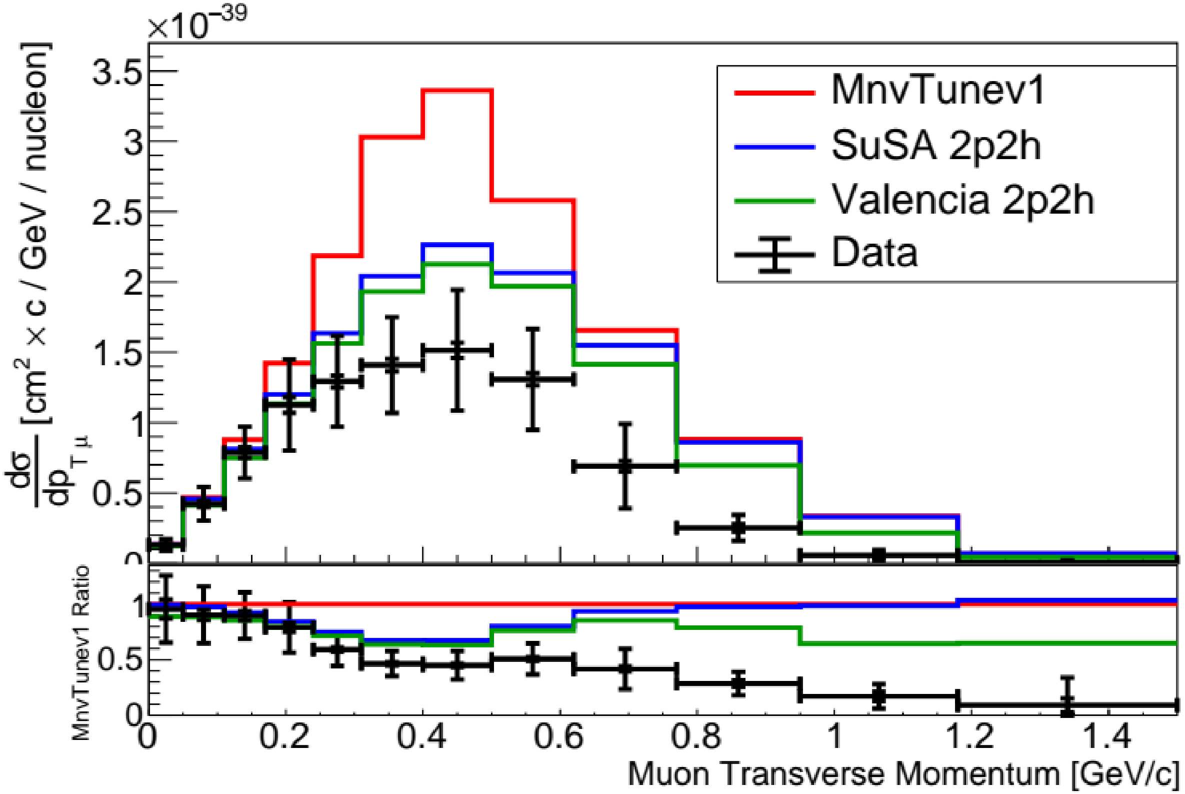


- Estimated by MC simulation
- Generally flat, especially at peak of event rate
- Gradual drop at high p_T driven by muon angular acceptance





Comparison with Tuned GENIE



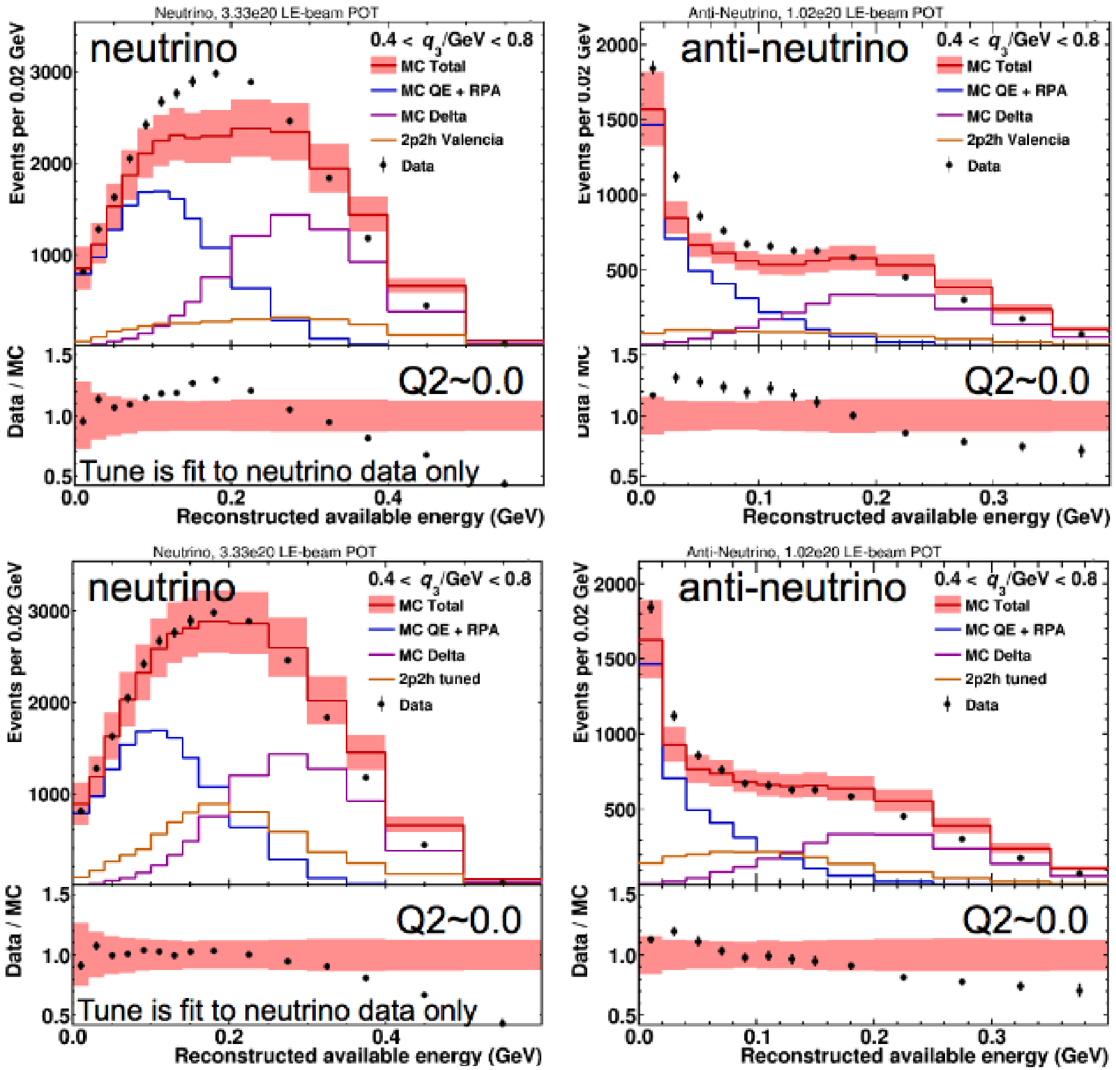
Phys. Rev. D 108 (2023) 11, 112010

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

MnvTunev1

Before

After

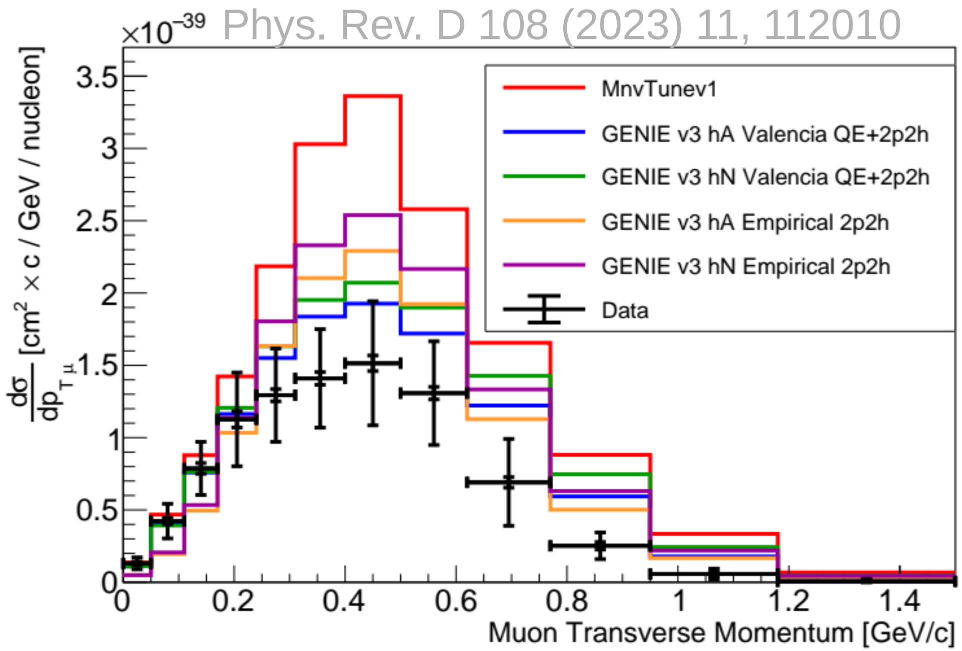


Phys. Rev. Lett. 116, 071802

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

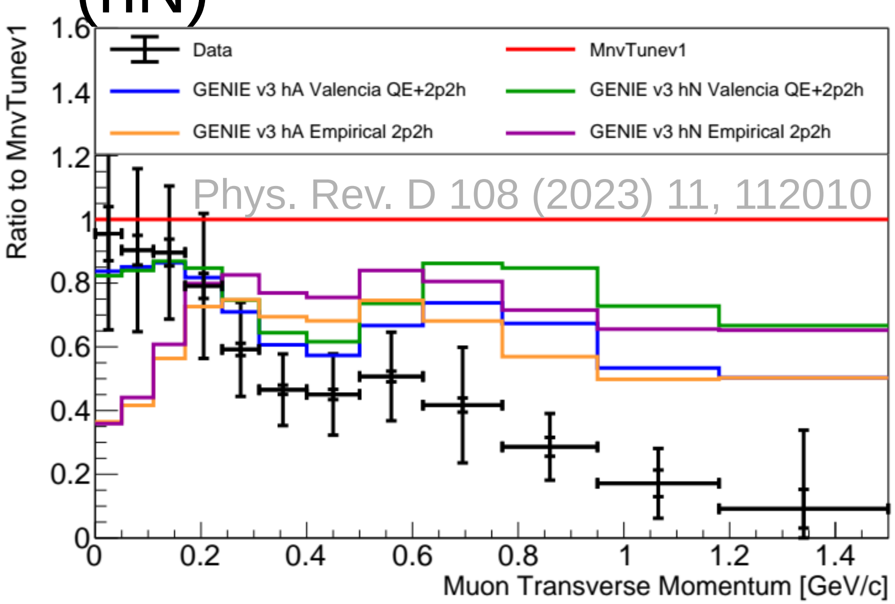
- Reweights on top of GENIE 2.12.6
- MnvTunev1
  - 2p2h enhancement
  - RPA modification
  - Non-resonant pion suppression
- 2p2h enhancement motivated by multiple LE measurements

Comparison with GENIE v3



- 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

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



Neutrons in Nuclear Targets

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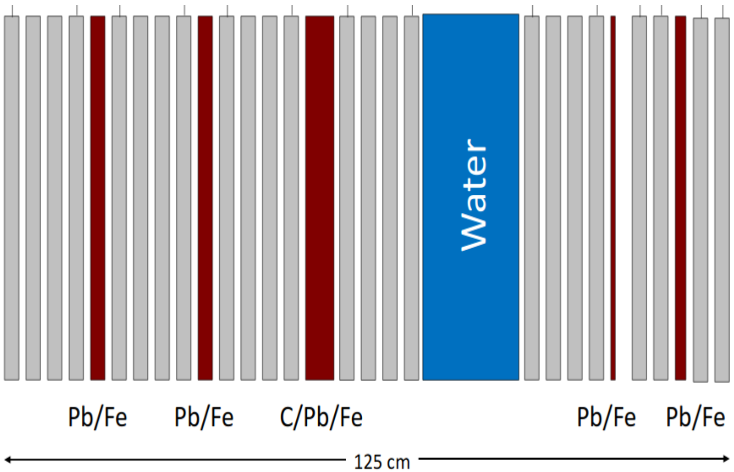
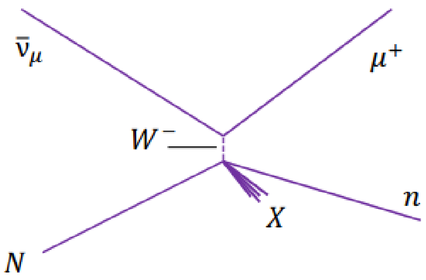
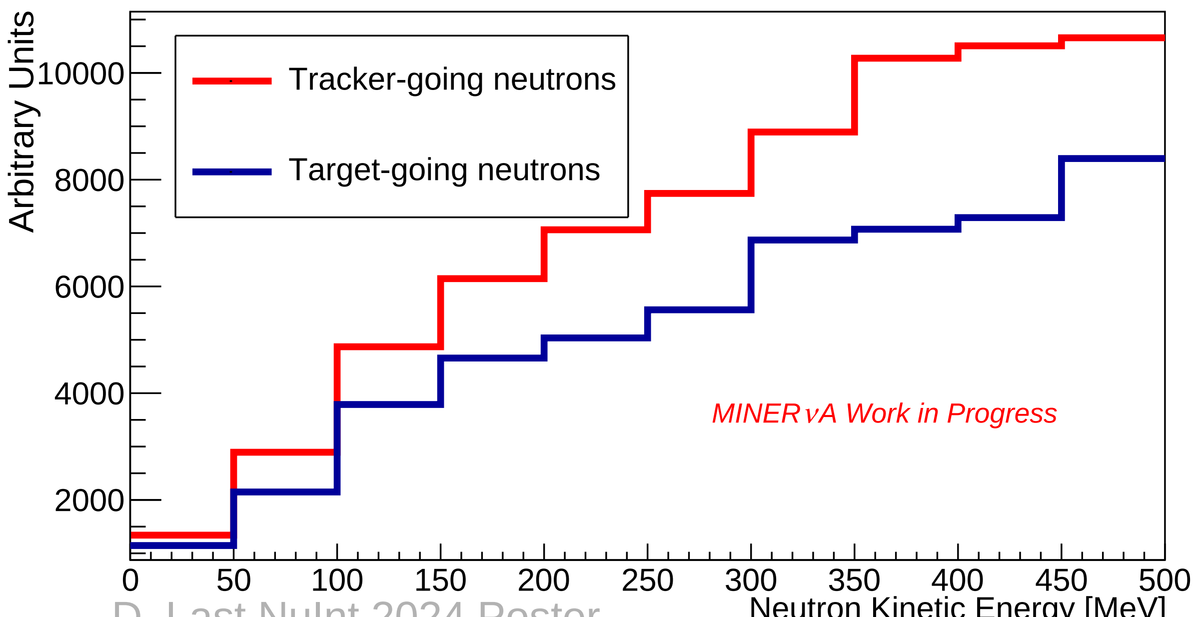




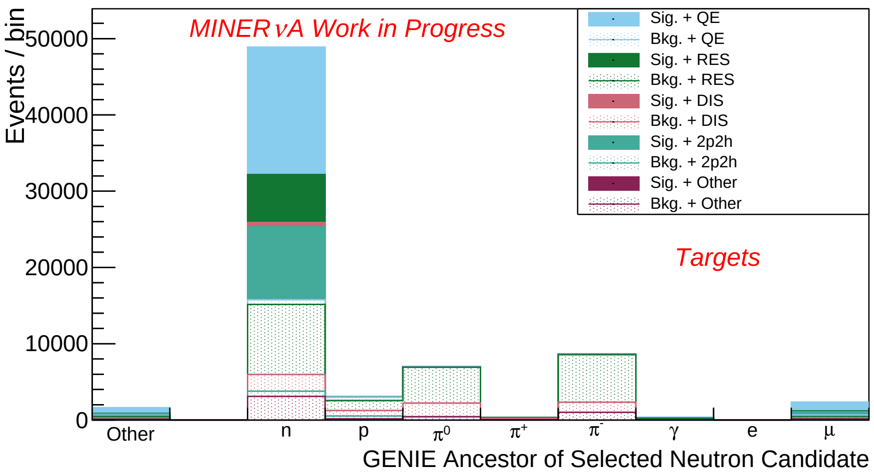


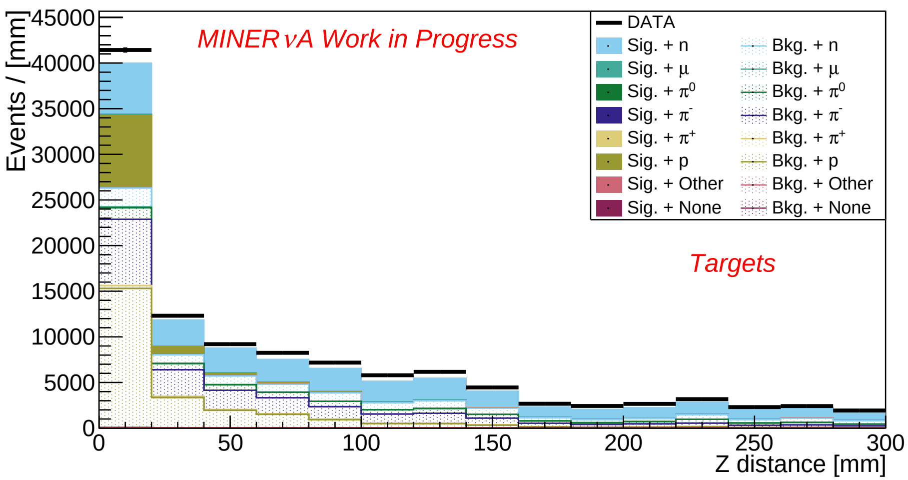
- Can MINERvA make neutron measurement in targets?
- How well do neutron results extend to other nuclei?

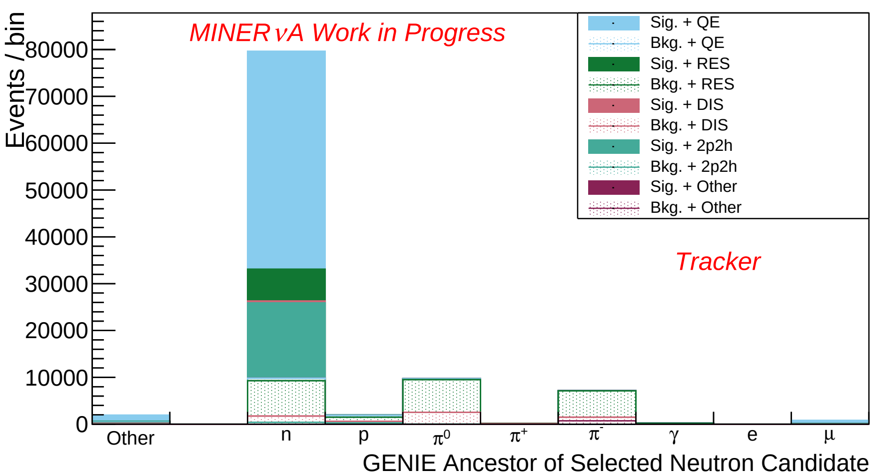
Neutron detection efficiency is very close in targets

D. Last NuInt 2024 Poster

Can Distinguish Neutrons from Others







- Neutron detection works well in targets
- Distance cut helps distinguish neutrons from protons and others

Future: Neutrons in Nuclear Targets

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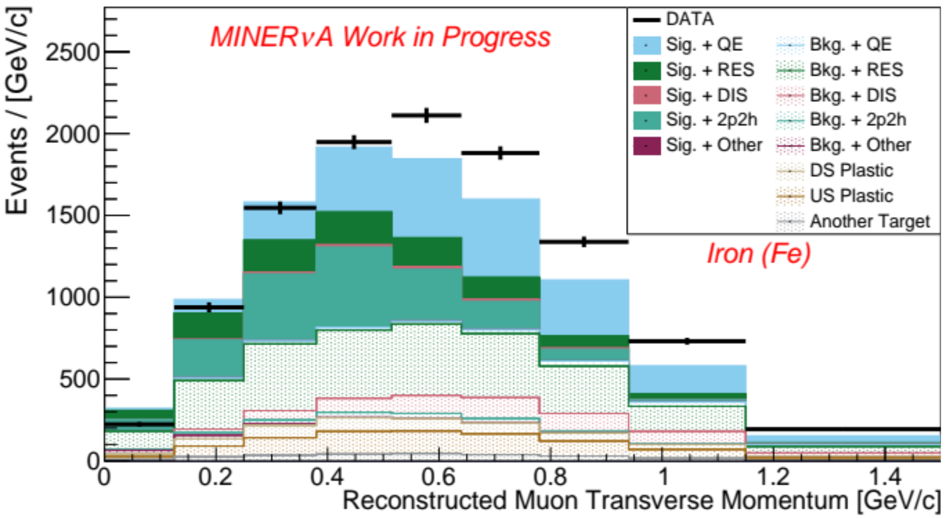
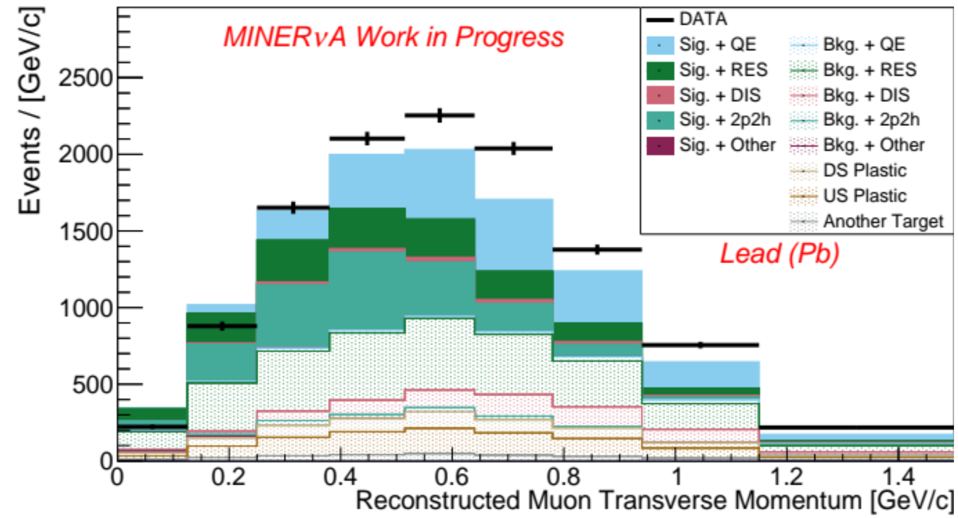
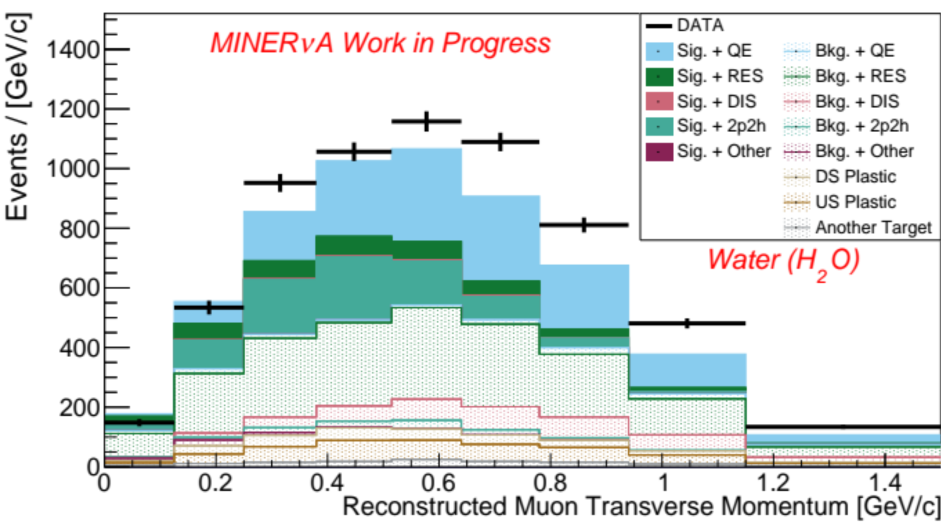


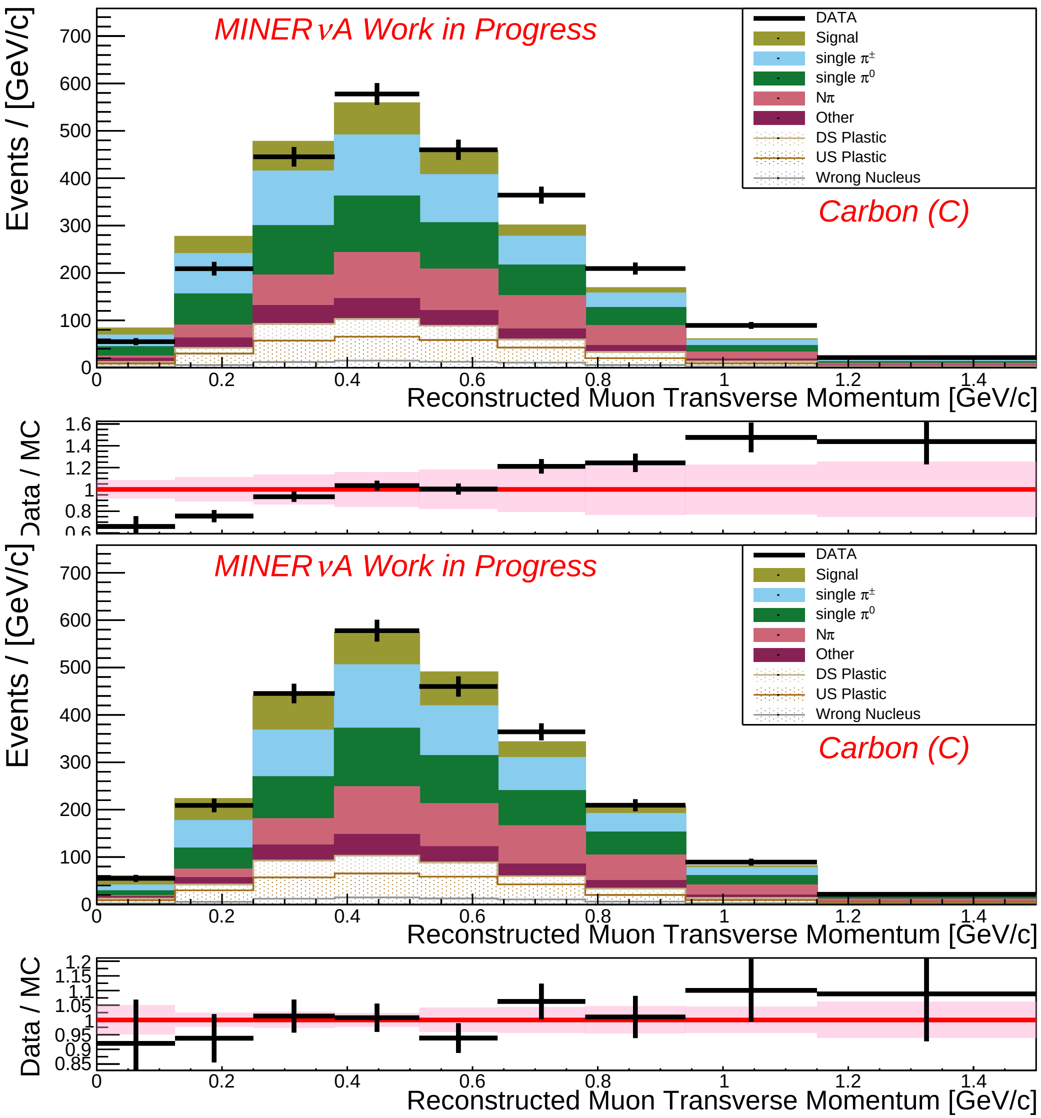




- Neutron production by QE-like in nuclear targets
- With tagged neutron
- CH and water in same detector

D. Last NuInt 2024 Poster

Status: Sideband Fits



- Currently developing sideband fits
- Fit in two pieces:
  - Physics in tracker
  - CH and target backgrounds
- Also weighing alternative CV models

Conclusions

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- MINERvA has made measurements sensitive to neutrons through many different channels
  - Charged-current elastic scattering: leading constraint on axial-vector form factor
  - Neutron candidate rate: low recoil inclusive
  - Multi-neutron: neutrons produced by 2p2h and FSI
- No single model describes our neutron measurements well
  - FSI discrepancies are not simple
  - 2p2h models hint that empirical tune is not the whole picture
- Will extend neutron measurements to multiple nuclei

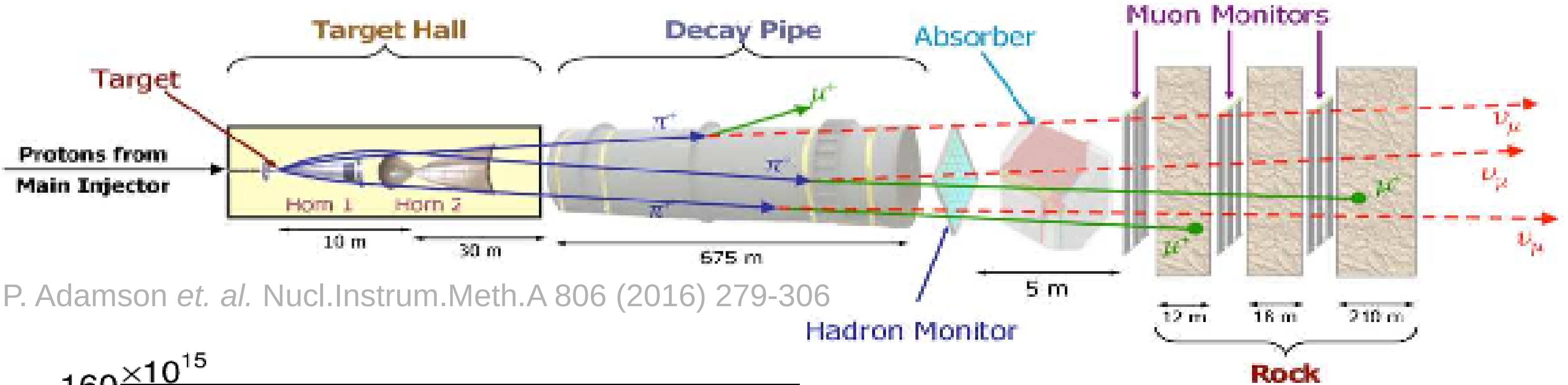
Thank You

Ryan Postel, 2023

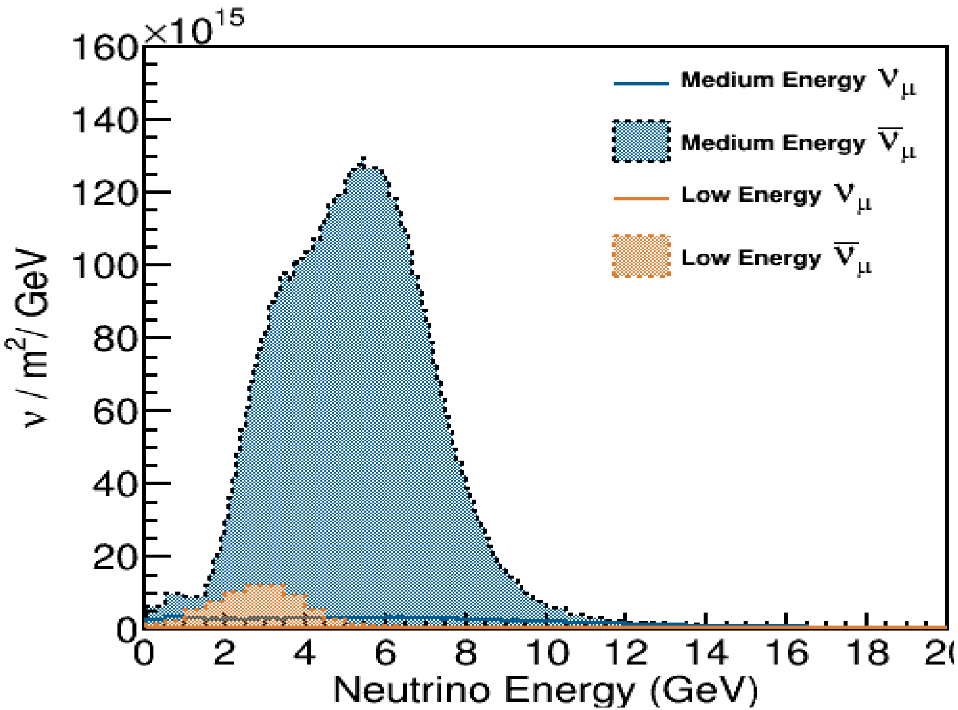
U.S. DEPARTMENT OF ENERGY | Office of Science

Backup Slides

Neutrino Beam at MINERvA



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



- NuMI beam at Fermilab
- **6 GeV** neutrino energy peak
- Using exclusively **Medium Energy** (ME) results today
- Flux constrained by neutrino-electron elastic scattering and inverse muon decay

MINERvA's Tracker

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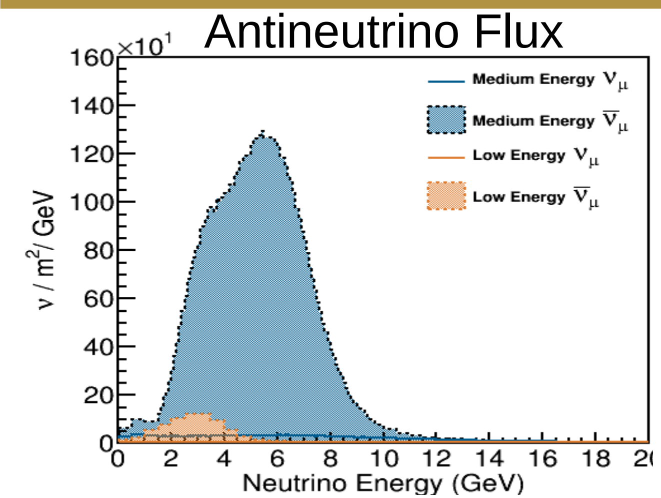
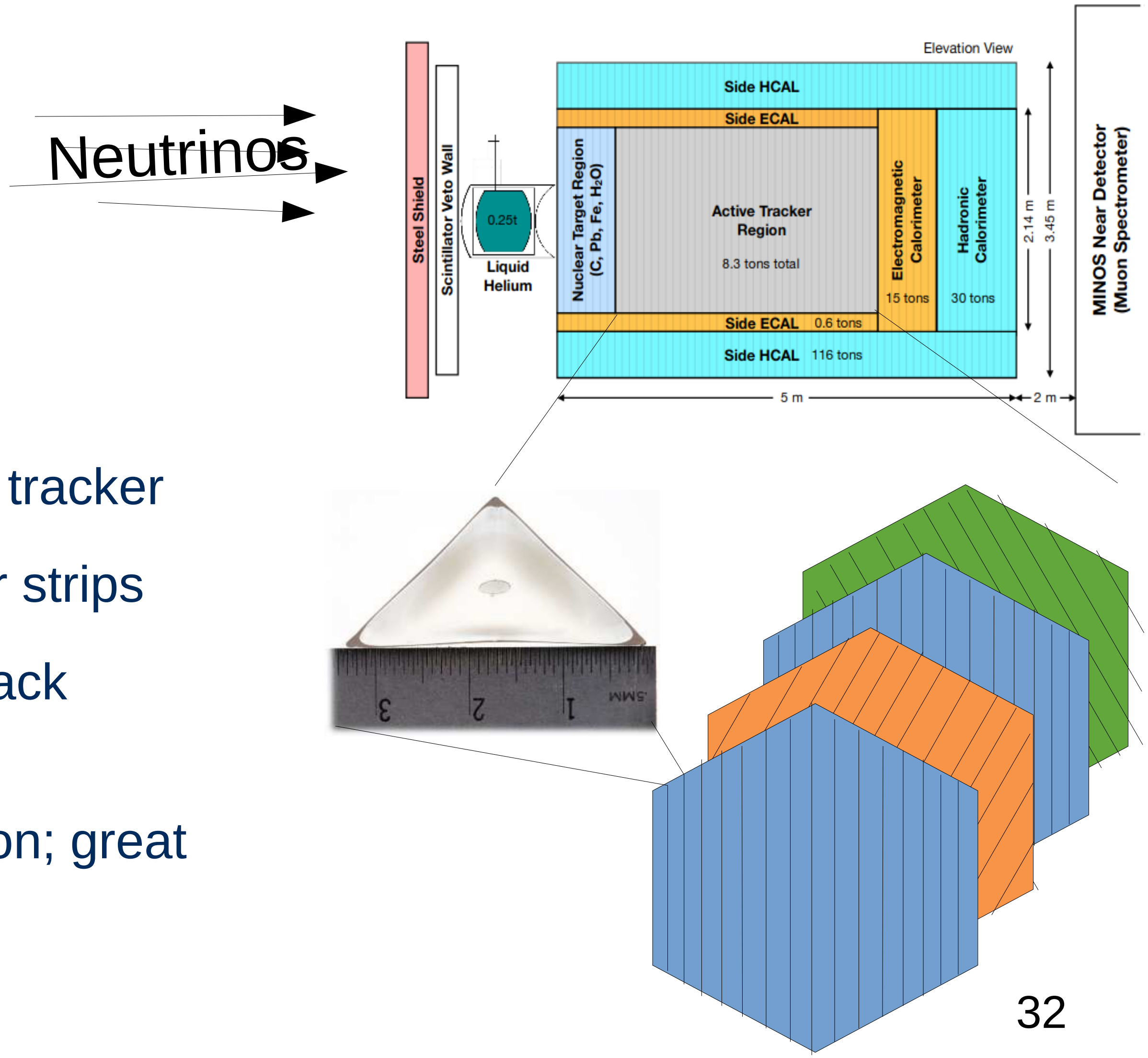
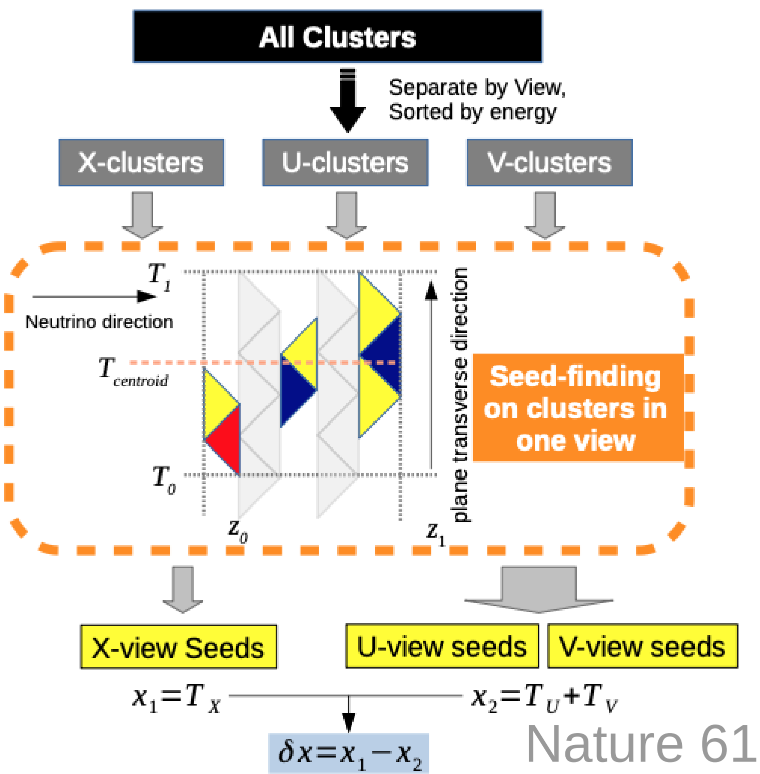


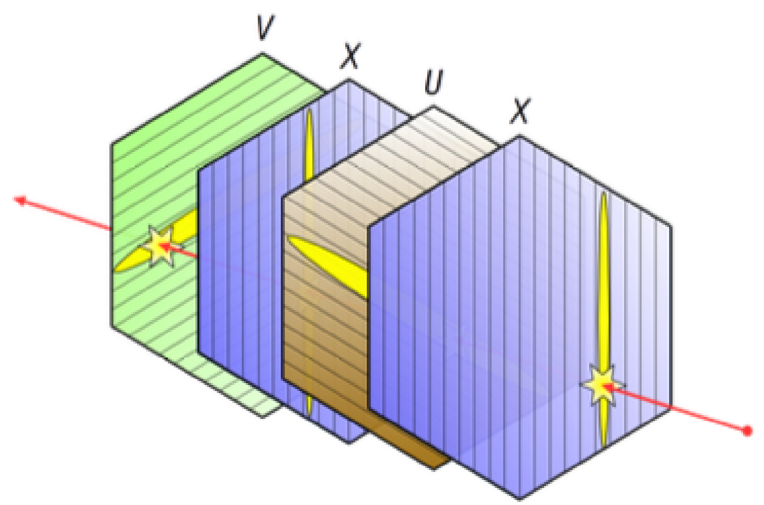


- Segmented scintillator tracker
- 3cm x 1.7cm triangular strips
- 3 orientations → 3D track reconstruction
- Good position resolution; great timing

Neutron Detection at MINERvA

- Look for charged particle activity isolated from the (anti)muon
- Stitch one-view pockets of charge (clusters) into 2D seeds
- Combine 2D seeds that match seeds from other views





Nature 614 (2023) 7946, 48-53

Fit for Form Factor

- Fit across all bins because cross section not linear in F_A
- Fit z-expansion formalism for form factor as in Phys.Rev.D 93 (2016) 11, 113015
- Regularized by L-curve

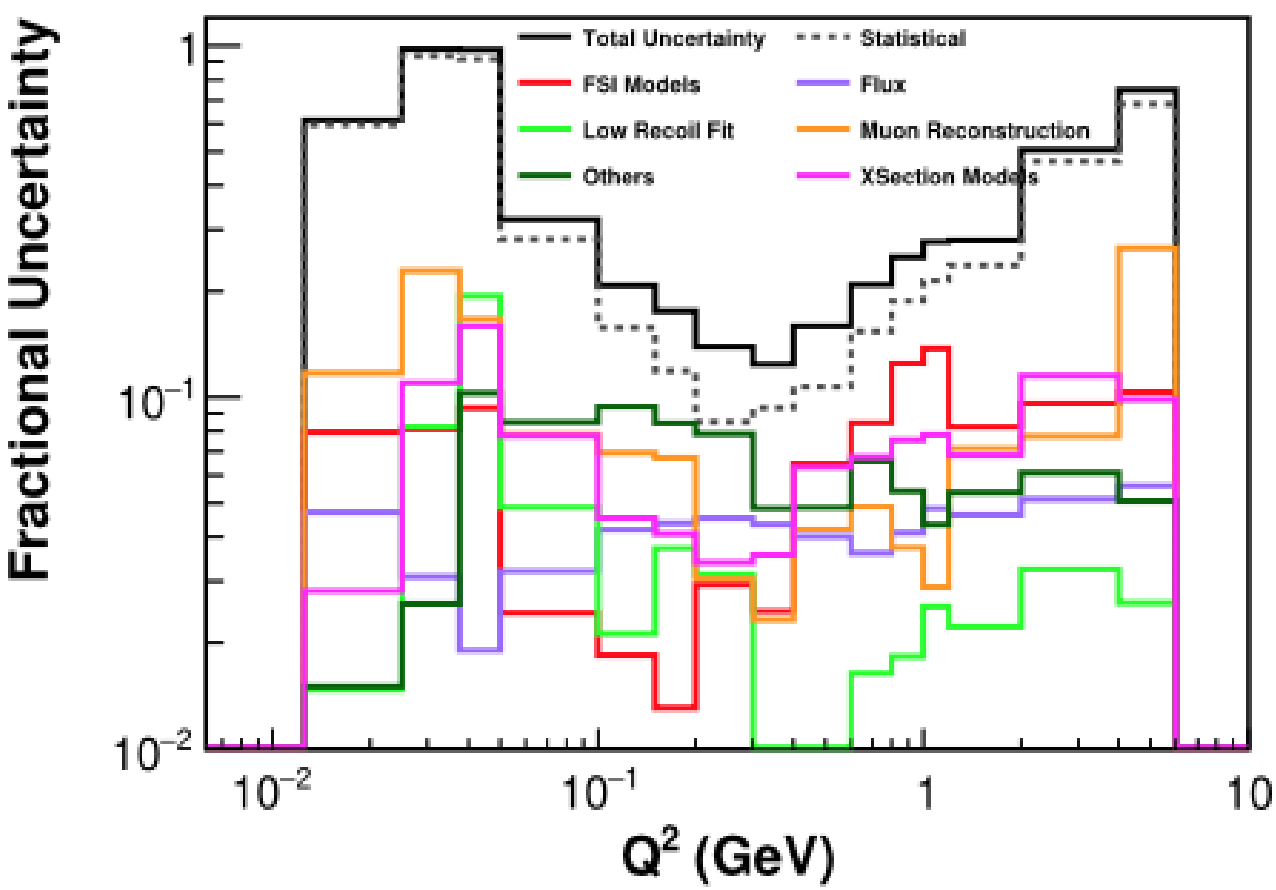
$$F_A(Q^2) = \sum_{k=0}^{k_{max}} a_k z^k$$

$$z = \frac{\sqrt{t_{cut} + Q^2} - \sqrt{t_{cut} - t_0}}{\sqrt{t_{cut} + Q^2} + \sqrt{t_{cut} - t_0}}$$

$$\sum_{k=n}^{\infty} k(k-1)\ldots(k-n+1)a_k = 0, n \in (0,1,2,3)$$

$$\chi^2 = \Delta X \cdot \mathrm{cov}^{-1} \cdot \Delta X + \lambda \left[\sum_{k=1}^{5} \left(\frac{a_k}{5a_0} \right)^2 + \sum_{k=5}^{k_{max}} \left(\frac{k a_k}{25 a_0} \right)^2 \right]$$

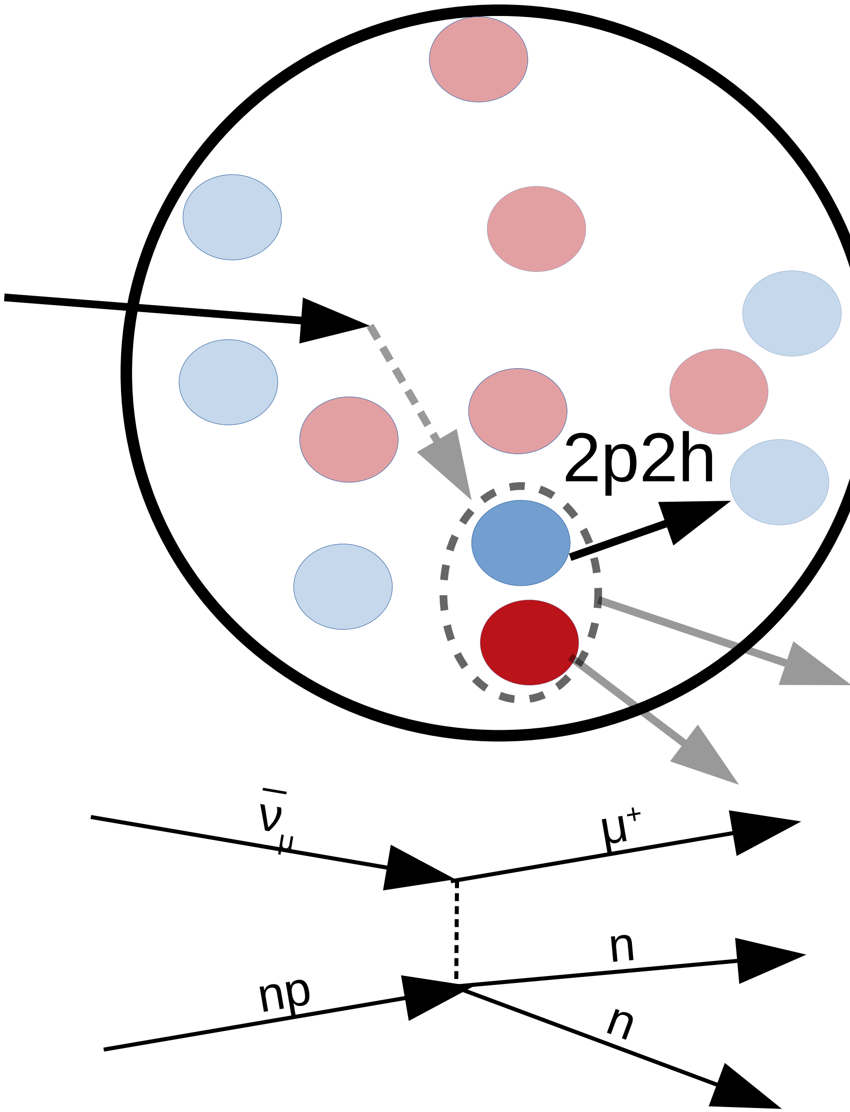
Cross Section Uncertainties



- Dominated by statistical uncertainty
- Model uncertainties controlled by background constraint
- “Others” driven by neutron uncertainty

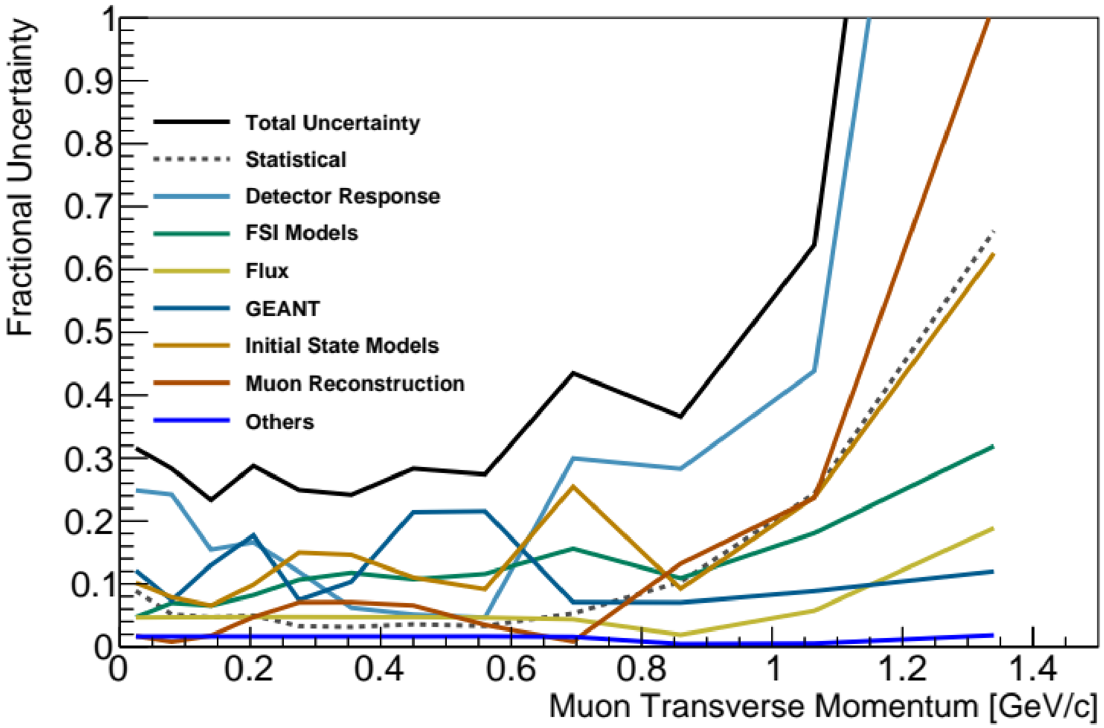
Nature 614 (2023) 7946, 48-53

Two-Particles Two-Holes



- Electron scattering experiments saw another interaction mode
- Nucleons pair up in nucleus: short range correlations
- Most common pair is neutron-proton: 2p2h interaction
  - Often looks like "CCQE"
  - But target mass different
  - → biased energy reconstruction
- Overlaps with CCQE and resonance production phase space → hard to measure

Multi-Neutron Uncertainties

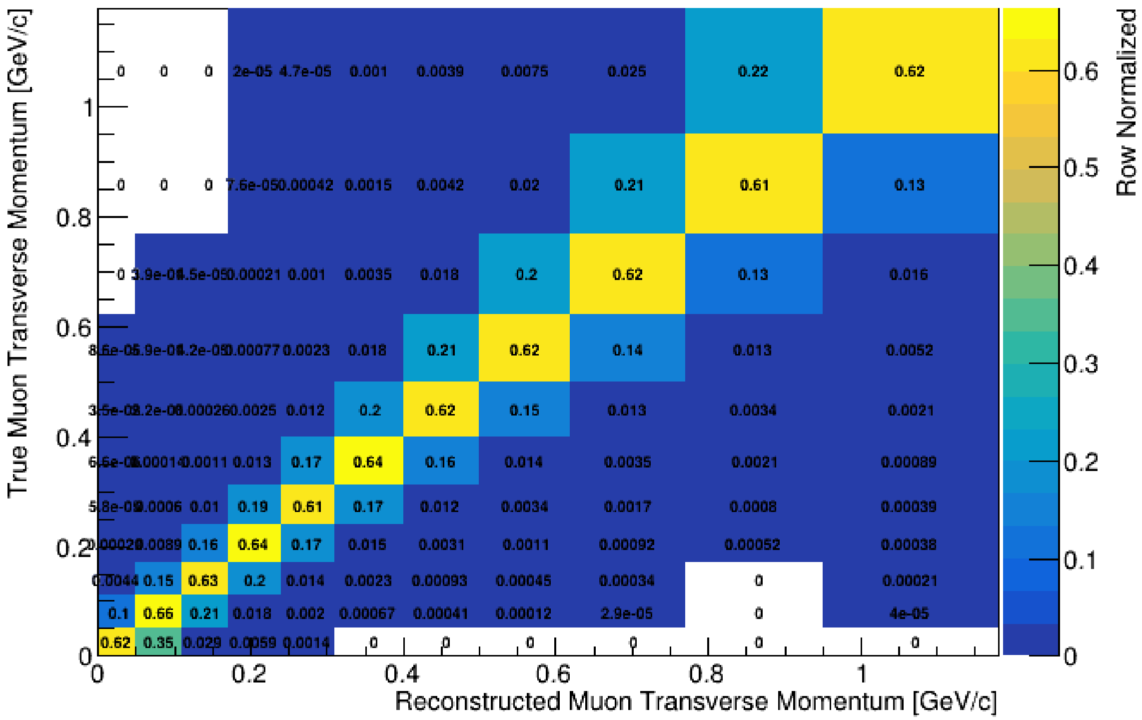


Phys. Rev. D 108 (2023) 11, 112010

- 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

Multi-Neutron Unfolding

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



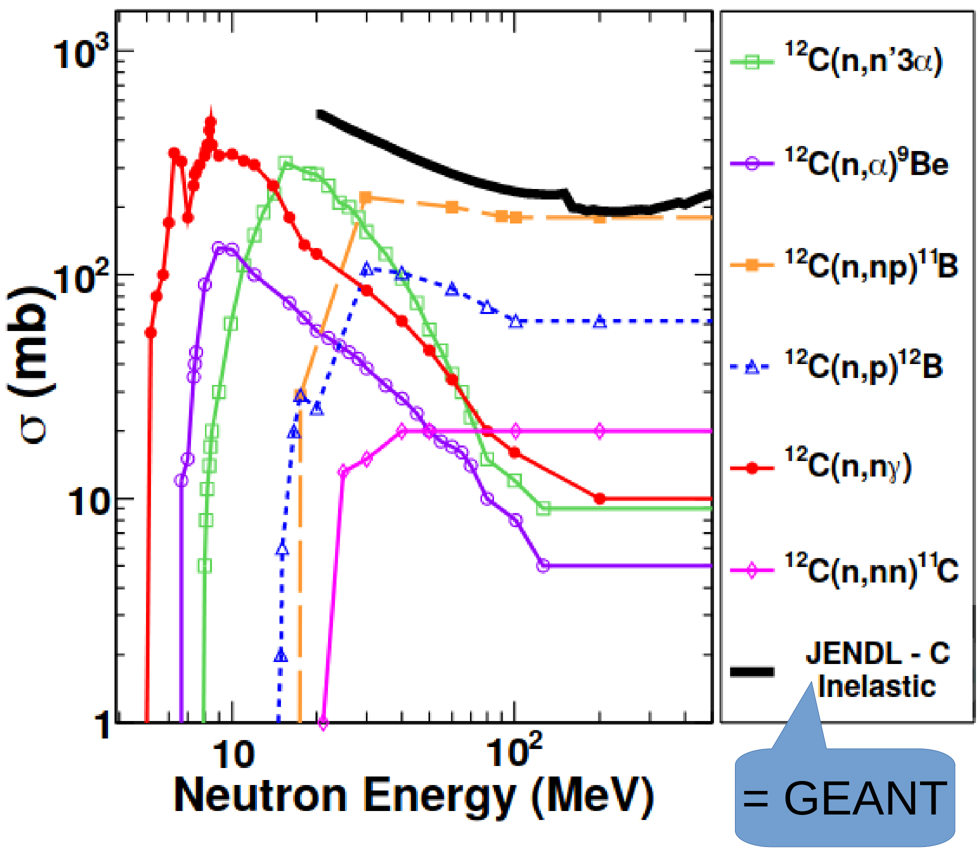
MINERvA's Neutron Measurements

UNIVERSITY OF NOTRE DAME

- One past measurement:
  - Neutron production: Phys. Rev. D 100, 052002 (2019)
- Two recent measurements:
  - Charged-current elastic (CCE) on hydrogen: Nature 614 (2023) 7946, 48-53
  - Multi-neutron at low $E_{available}$: Phys. Rev. D 108 (2023) 11, 112010
- One upcoming measurement: QE-like on targets with 1+ neutrons: poster session

Neutron Cross Sections from Nuclear Physics

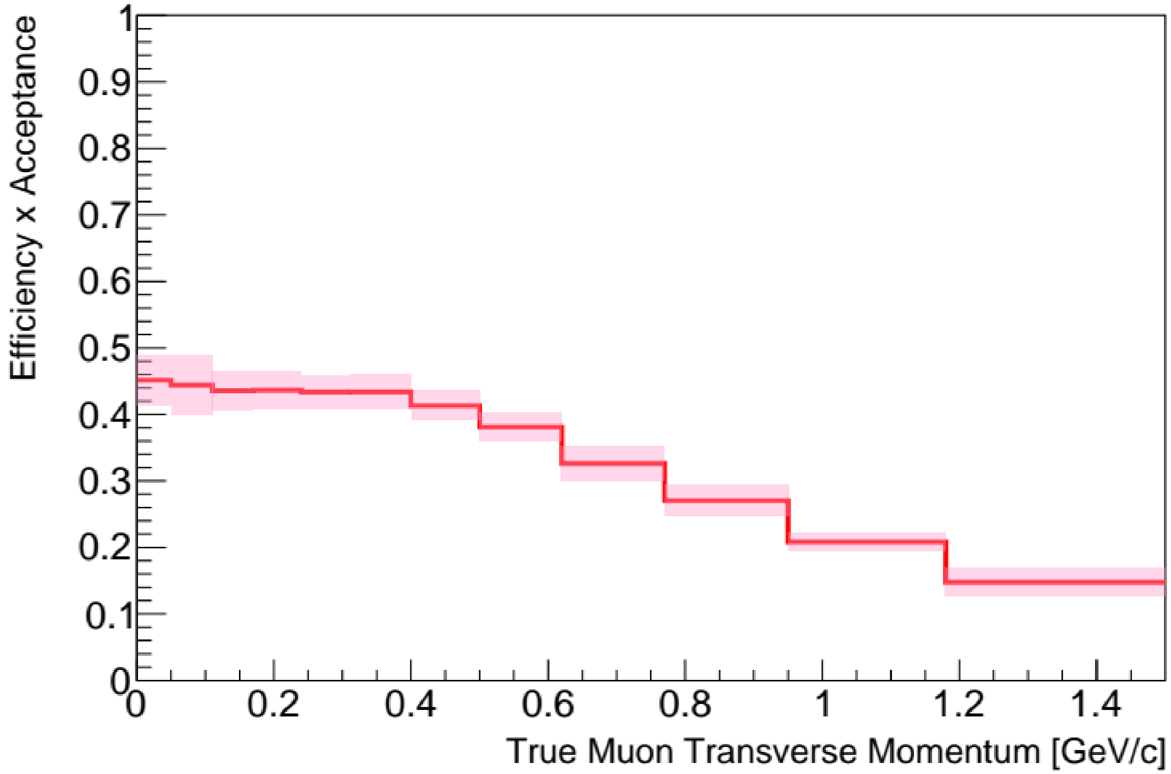
MENATE_R: Data-Driven Neutron Transport



NIM-A. 682 (2012), 59-65

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

Multi-Neutron Efficiency



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