MINERνA: Latest Results and Data Preservation Efforts

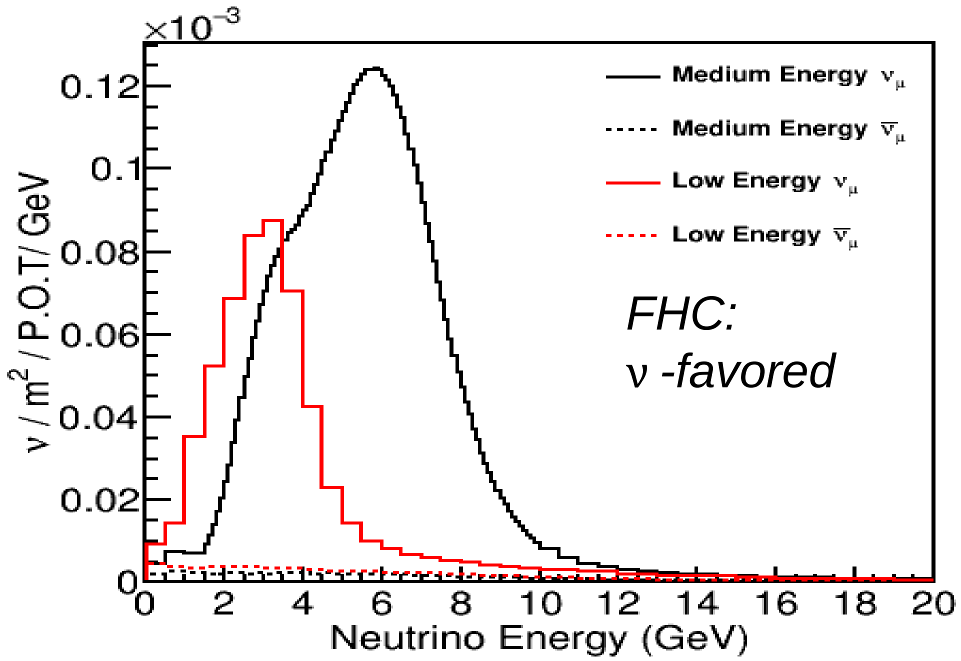
David Last (dlast@sas.upenn.edu)
University of Pennsylvania
On behalf of the MINERνA Collaboration
Our Website

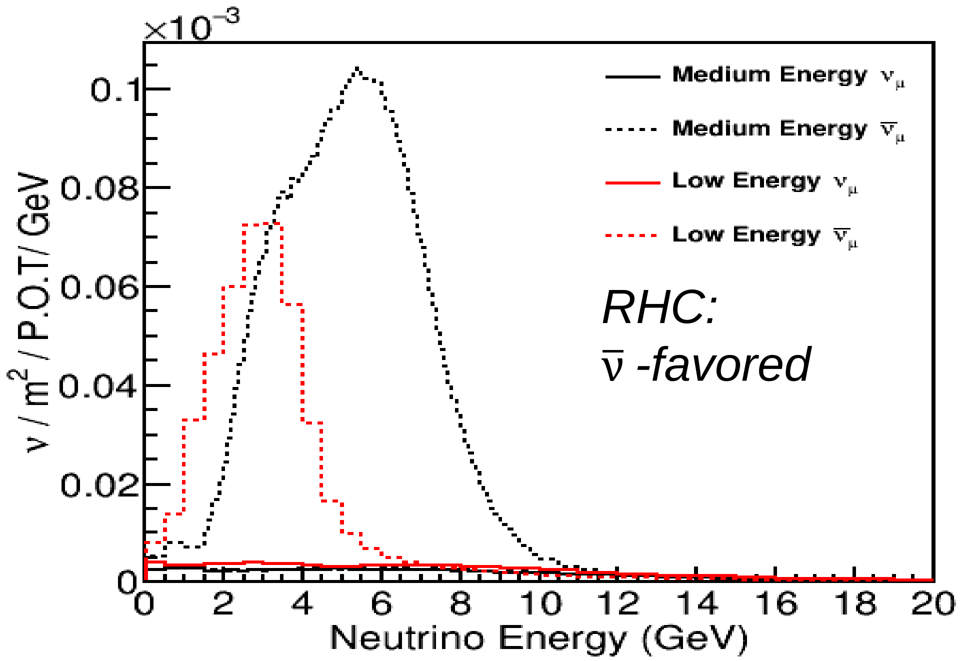
NNN23 Procida

October 13, 2023

MINERνA History, Datasets, and Fluxes

- Expression of interest: 2002, Construction Start: 2007, First Full Detector Data: 2009
- Data-taking has been completed (in 2019) for both energy configurations → **<u>MINERvA has been decommissioned</u>**
- Design and physics efforts focused on (anti)neutrino-nucleus interaction cross-sections



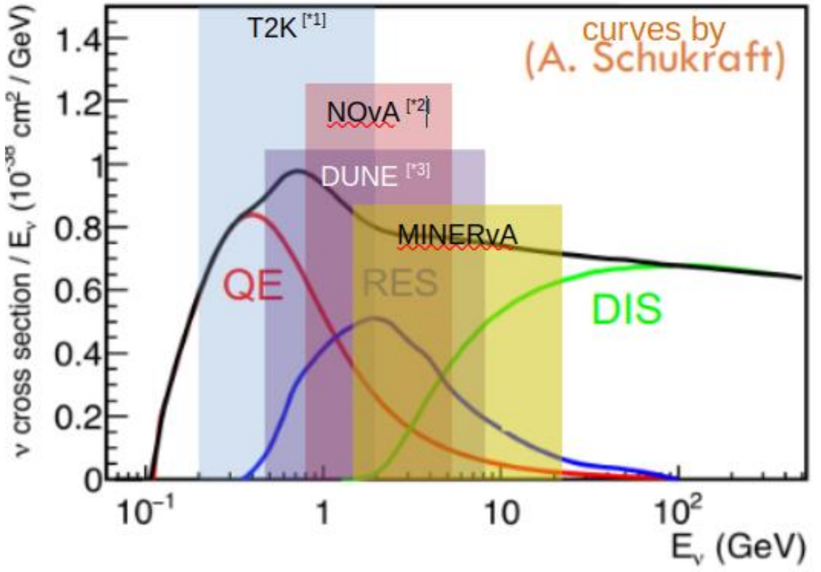


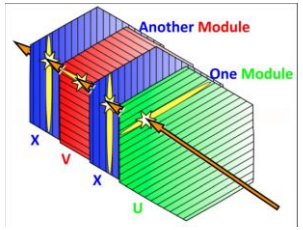
Energy	ν- P.O.T.	ν̄ - P.O.T.
Low Energy: ~3.5 GeV peak (2010-2012)	4.0×10^{20}	1.7×10^{20}
Medium Energy: ~6 GeV peak (2013-2019)	12.1×10^{20}	12.4×10^{20}

“P.O.T.”: Protons on Target, a proxy for number of neutrinos produced

MINERνA Detector and Sensitivity

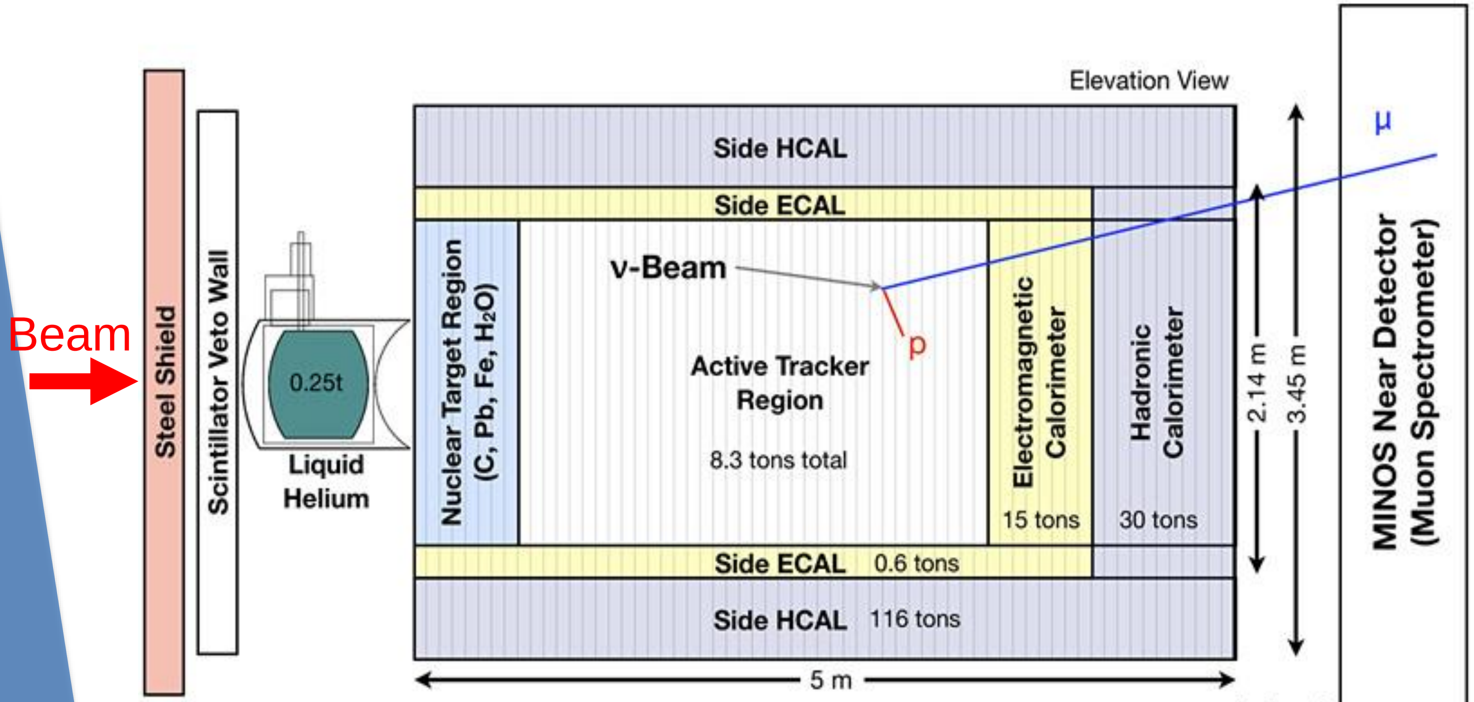
- MINERvA, with NuMI beam's energy range, well-positioned to constrain models for broad set of experiments, final states
- Primary tracker region allows for precision tracking with well-understood and well-simulated technology of plastic scintillator
- Exposure of broad range of nuclear targets to same beam allows for critical study of nuclear size effects
- Downstream magnetized MINOS near detector acted as muon spectrometer

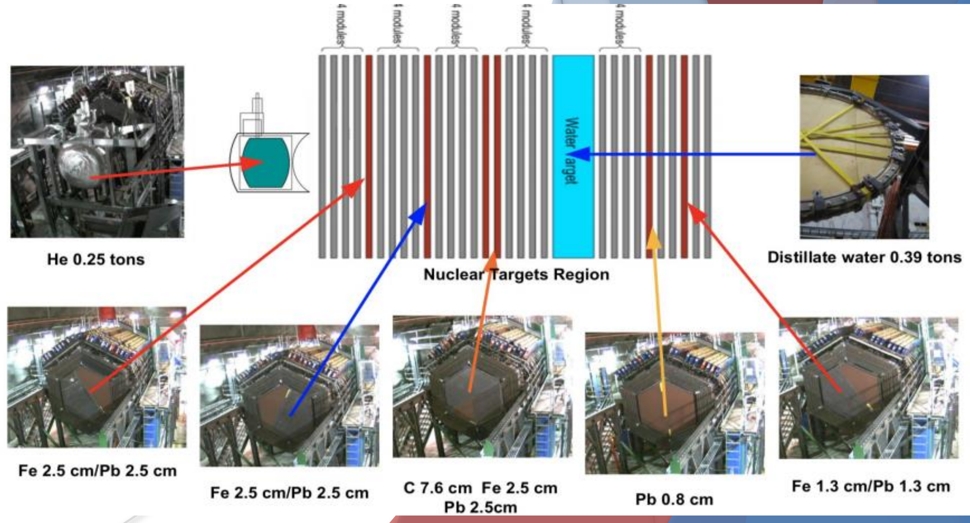




Plane rotation of scintillator allows for tracking

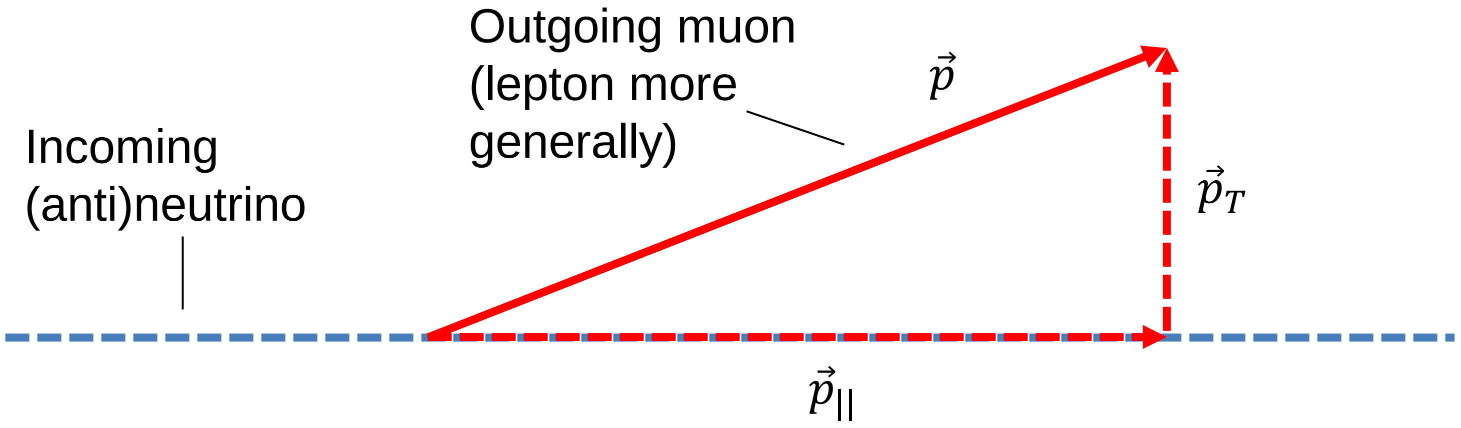
*: References in backup





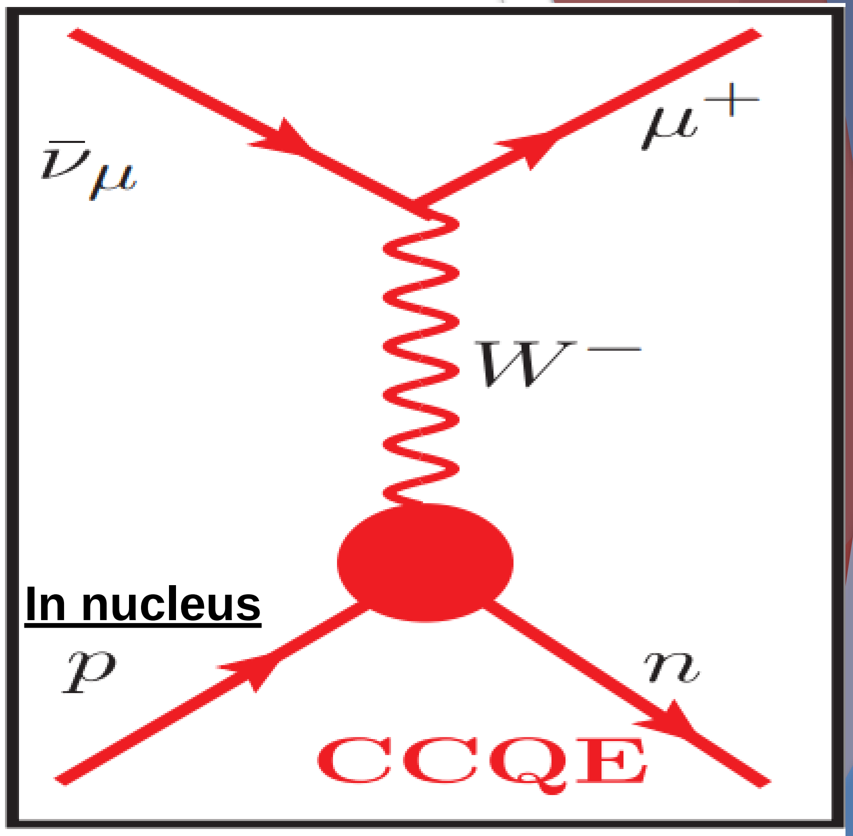
High Statistics Measurements:

Two-Dimensional $\bar{\nu}_\mu$ CCQE-like Cross Section on CH



Transverse muon momentum ($\vec{p}_T$): Muon momentum transverse to incoming (anti)neutrino direction. **Proxy to $\boldsymbol{Q^2}$**, the additive inverse of the squared 4-momentum transfer to the target, without needing to measure hadronic system.

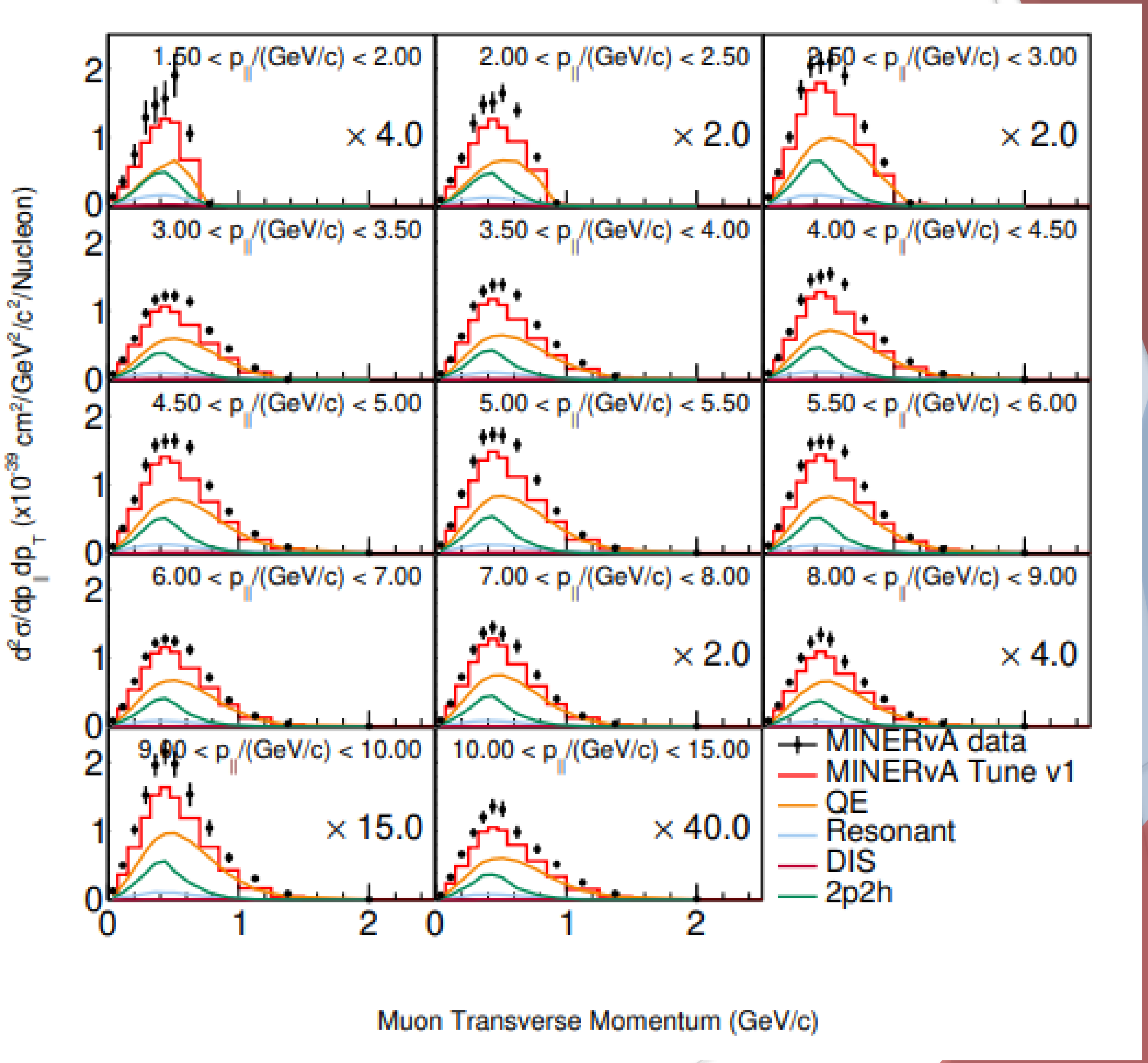
Parallel/longitudinal muon momentum ($\vec{p}_{||}$): Muon momentum along incoming (anti)neutrino direction. **Proxy to (anti)neutrino energy**, also without needing to measure hadronic system.



CCQE-like: hadronic system consists solely of nucleons

$\bar{\nu}_\mu$ CCQE-like on CH: Muon p_T vs. $p_{||}$ Cross-Section

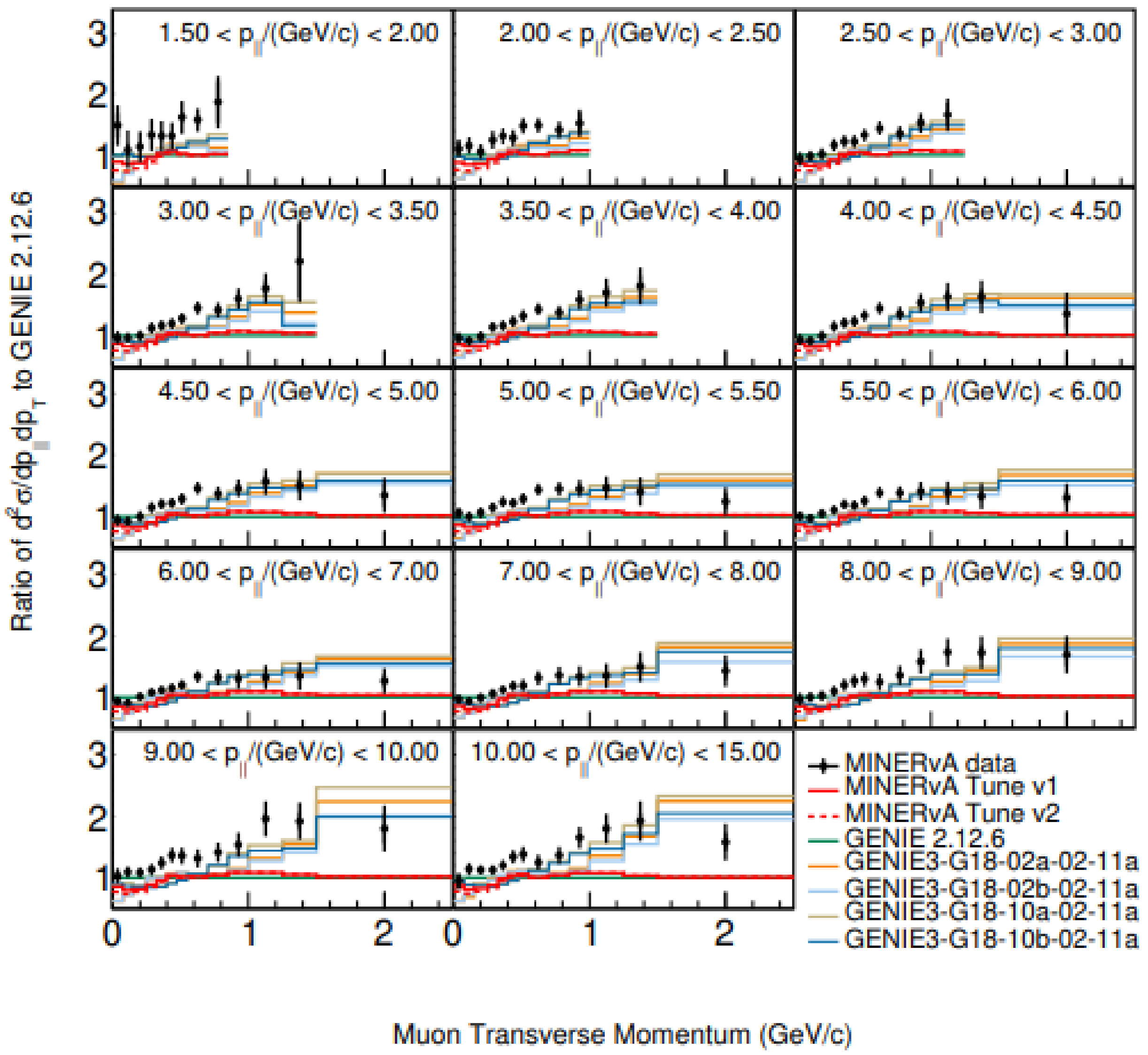
- MINERνA's **vast dataset** allows for sufficient statistics for measurement across a broad phase space
  - **635k events** after background subtraction!
- Measurement indicates **underprediction** of the model in all ranges of $p_{||}$
- **Complementary measurement** to high-statistics three-dimensional ν_μ CCQE-like on CH measurement and measurements across MINERνA's nuclear targets (see backup)
- The fractional components of the signal by interaction type can be seen in the backup



[A. Bashyal et al., Phys. Rev. D 108, 032018 (2023)]

$\bar{\nu}_\mu$ CCQE-like on CH: Muon p_T vs. $p_{||}$ Cross-Section Model Comparison Ratios

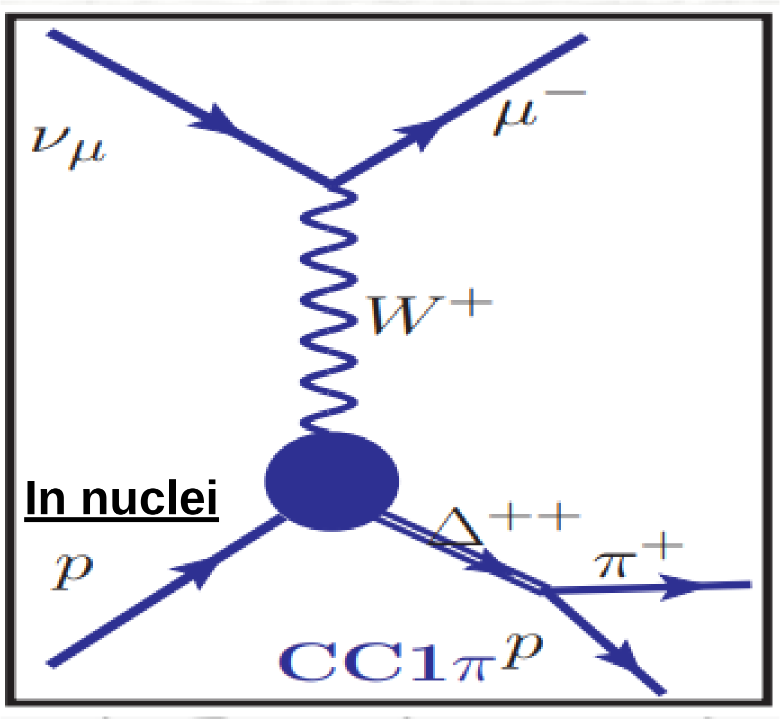
- Model comparisons show that GENIE 3-based models appear to predict the higher transverse momenta regions' behavior more closely
- **<u>None of the models</u>** appear to capture the phase space in its entirety
- Comparisons in Q^2 (in backup) bring forth a consistent conclusion of **<u>GENIE 3 more accurately predicting</u>** the behavior at higher Q^2, which is correlated with higher transverse momentum



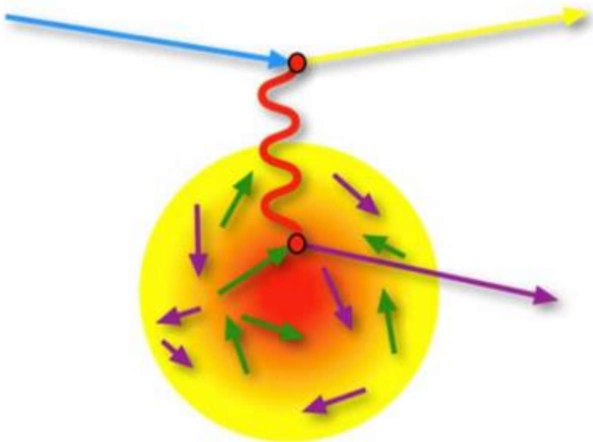
A. Bashyal et al., Phys. Rev. D 108, 032018 (2023)

Measurements of Nuclear Dependence:

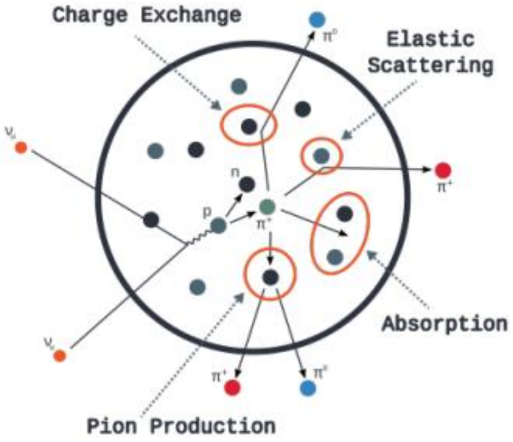
One-dimensional ν_μ CC1π^+ Cross Sections and Ratios



Example of dominant CC1π^+ process of resonant production



Probe the behavior of nucleons in nuclei: correlations of nuclei, distribution of nuclear momentum



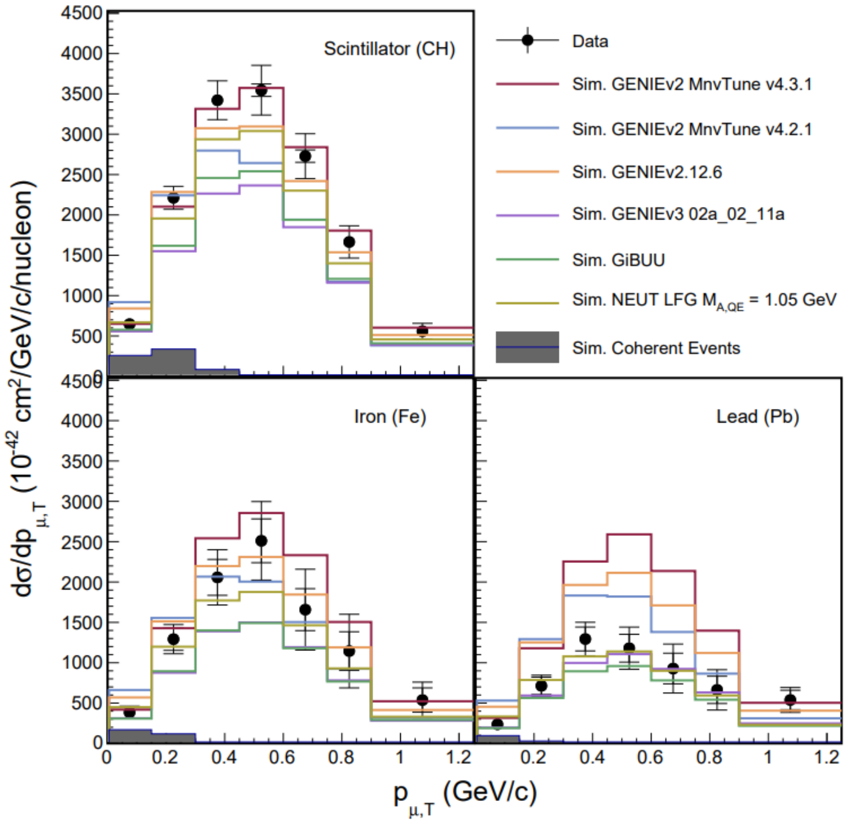
Final State Interactions “FSI”: Interactions of neutrino final state particles exiting the nucleus.

Investigating across MINERνA’s range of nuclei allows for understanding how these effects scale with size.

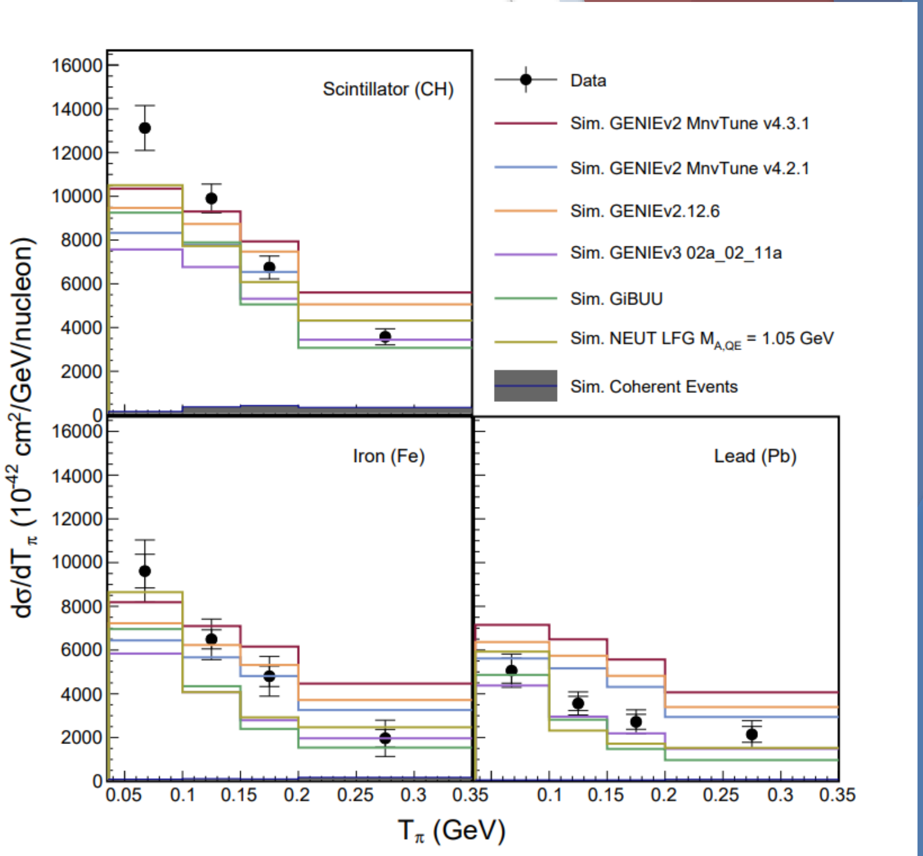
ν_μ CC1π^+ Cross Sections

- **Discrepancy** with tuned MC from previous MINERνA /external data, MnvTune v4.2.1
- **Derived tune** from this scintillator data, MnvTune v4.3.1 agrees broadly across targets
- **No model** agrees with these absolute cross sections in each target
- Carbon and Water cross-sections also measured, but statistics-limited:
  - Ratios shown on next slide

Muon p_T



Pion Kinetic Energy (T_π)



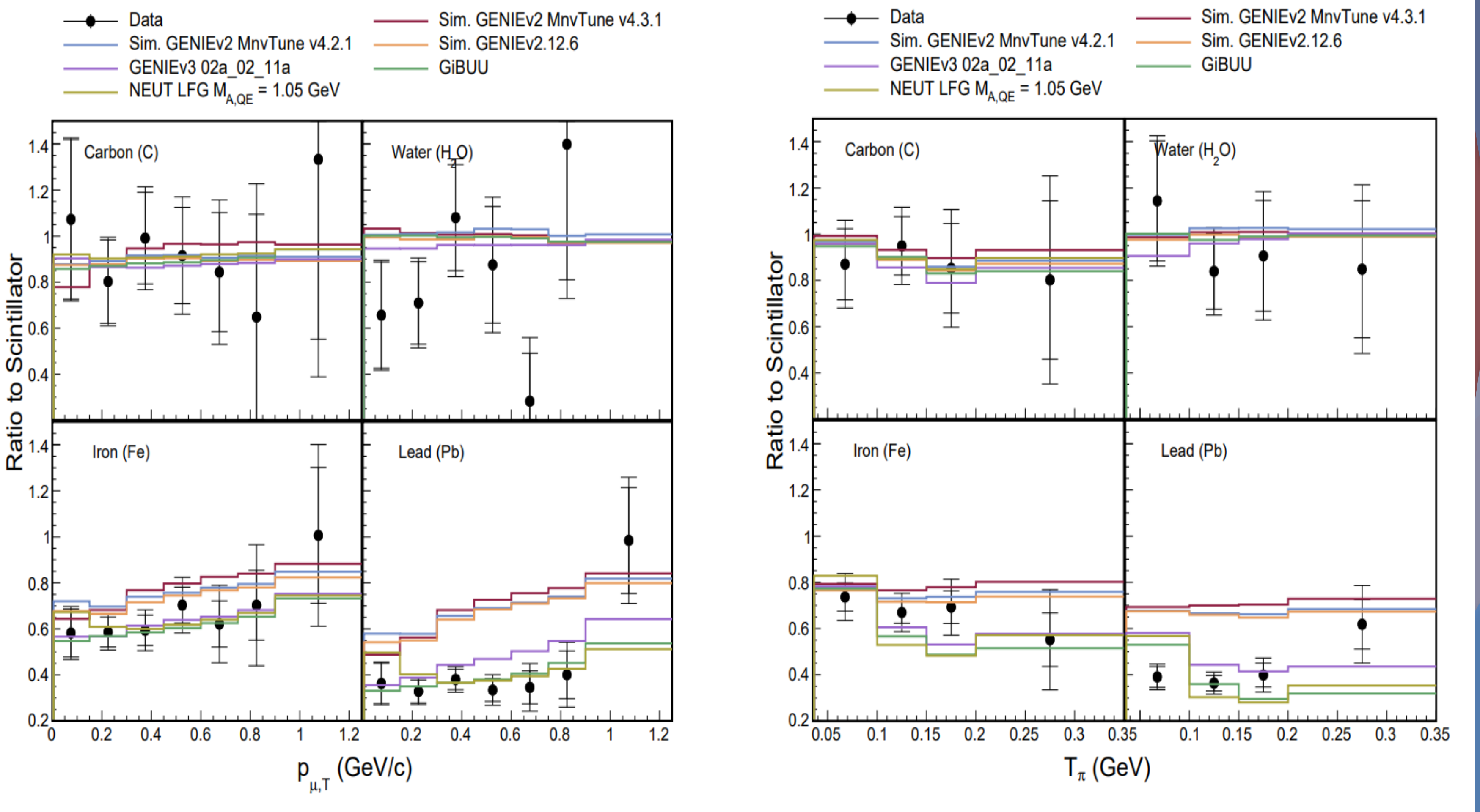
A. Bercellie et al., Phys. Rev. Lett.131, 011801 (2023)

ν_μ CC1π^+ Cross Section Ratios

- Simultaneous exposure of the targets allows for **systematics cancellation** in division of higher-stats tracker measurement:
  - **33k events** in tracker sample
- Models largely **overpredict A scaling**:
  - Possible **underprediction** of A scaling of **pion absorption**
  - **Opposite sign** of CCQE-like discrepancy in A-scaling (see backup)
- Carbon and Water ratios consistent with unity

Muon p_T

Pion Kinetic Energy (T_π)



[A. Bercellie et al., Phys. Rev. Lett.131, 011801 (2023)]

Highly Exclusive Channels:
$\bar{\nu}_\mu$ "Charged-Current Elastic (CCE) Scattering" on Hydrogen

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

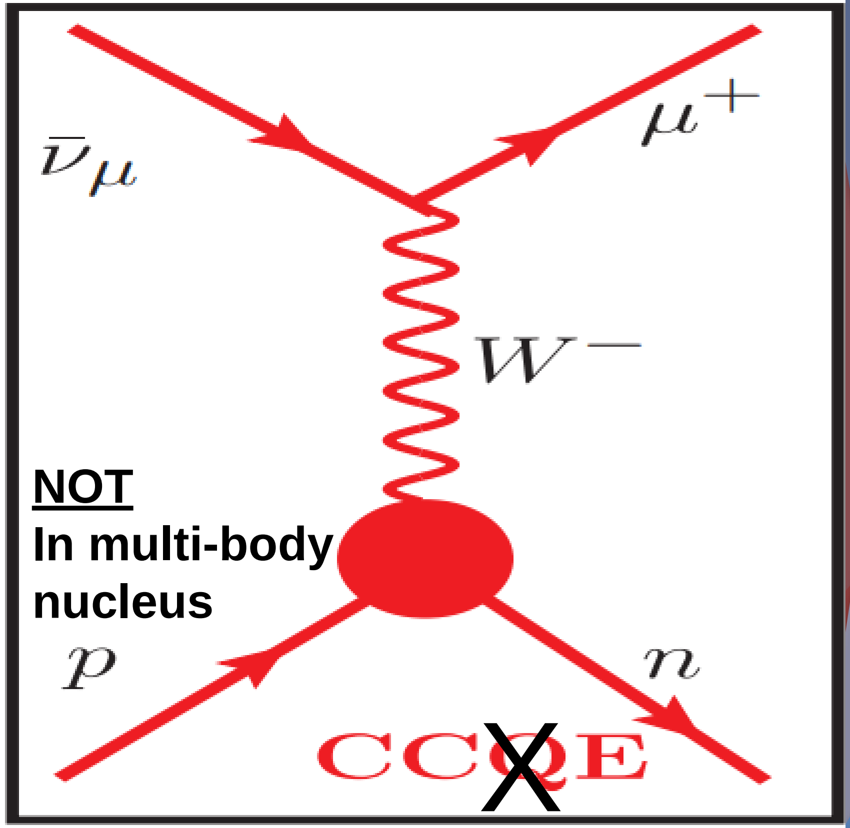
$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\left(1-\frac{Q^2}{4M^2}\right)|\xi F_V^2|^2 + \frac{4Q^2}{M^2}\mathrm{Re}F_V^{1*}\xi F_V^2 + \mathcal{O}\left(\frac{m^2}{M^2}\right)\right],$$

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

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

F_A: **Axial form factor**, accessible in **weak interactions**. Accessible through **neutrino scattering experiments**, though historical data limited and relied on nuclear assumptions. Other (blue) form factors well-constrained by charged lepton scattering data. Previous measurements assumed to be of **dipole form**:

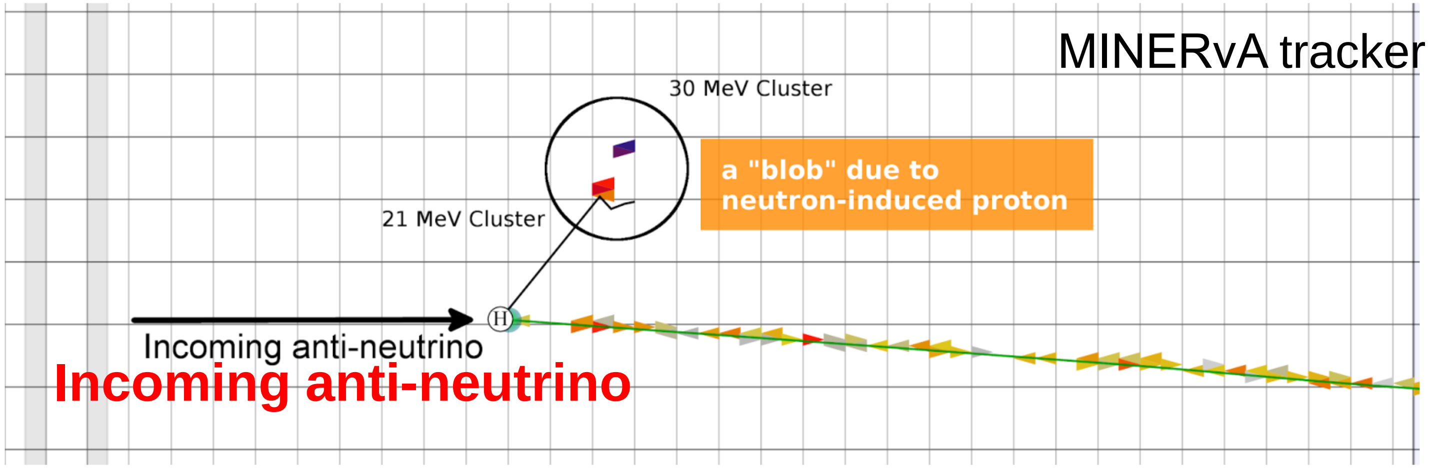
$$F_A(Q^2) = F_A(0)(1+Q^2/M_A^2)^{-2}$$



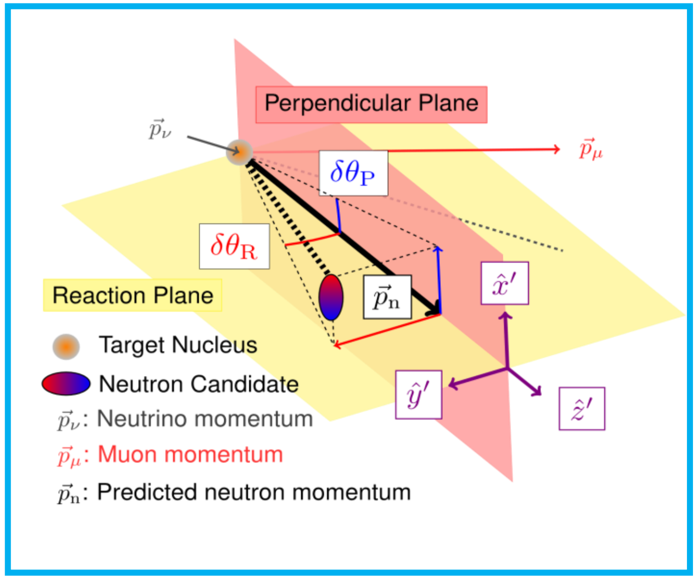
CCE: Explicitly one positive muon, one neutron

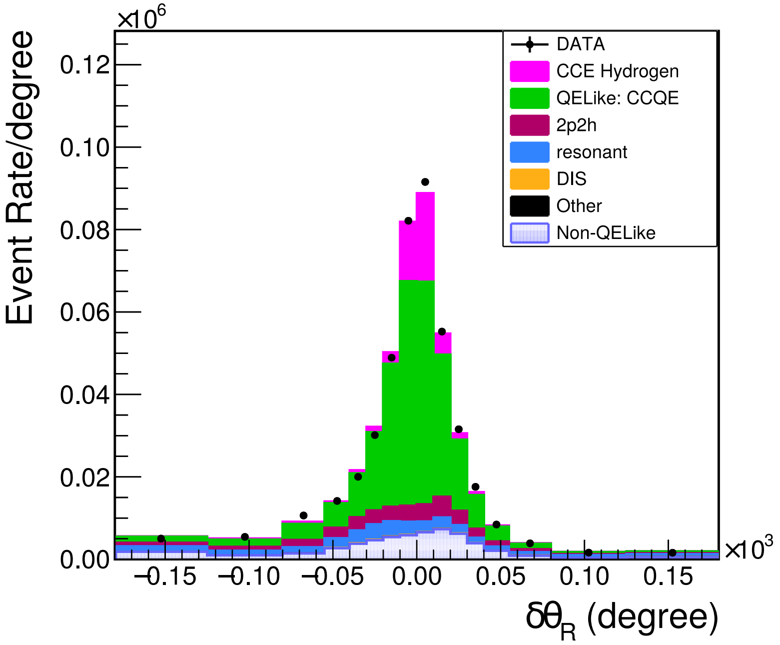
$\bar{\nu}_\mu$ CCE Approach

- Nuclear effects smear out neutron correlation in analogous CCQE-like measurement:
  - Neutrons observed in expected direction from two-body kinematics enhance CCE signal!
- High statistics available allow for ~**<u>5000 signal events in this sample</u>**! Previous world's best sample had 13 candidates.



[T. Cai et al, Nature 614, 48–53 (2023)](#)

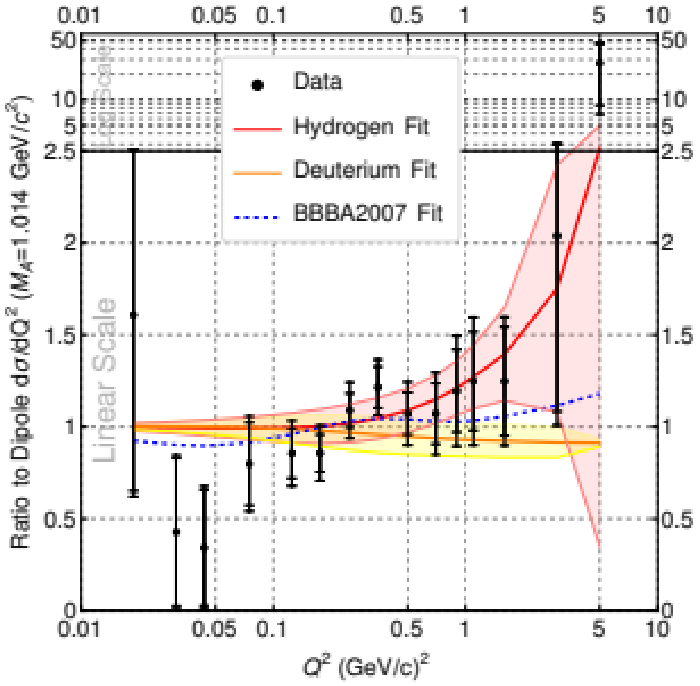




Note the CCE signal peaking near low difference in the difference from the expected reaction plane angle. See backup for more on the signal separation by angular variable

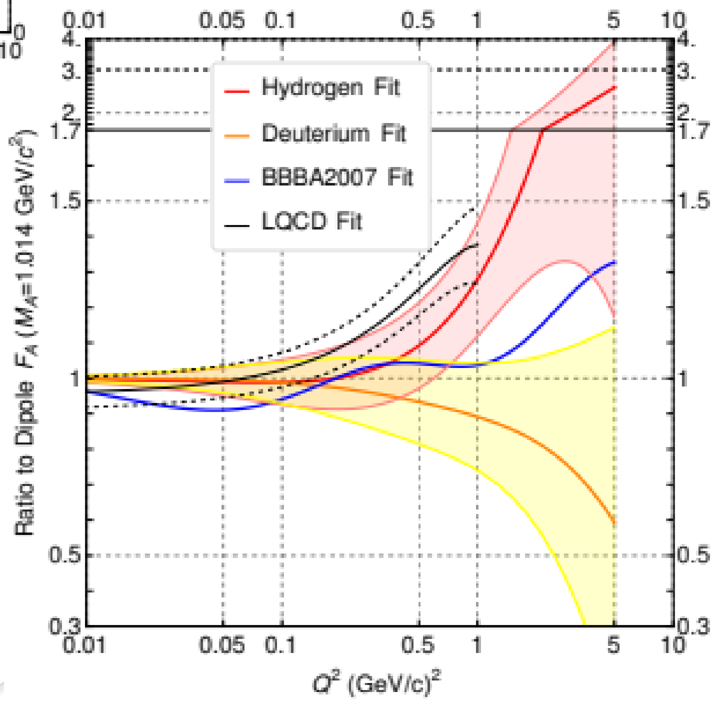
$\bar{\nu}_\mu$ CCE Results

- Weak-only interaction allows for more direct access to axial vector form factor:
  - Results provide insight into fundamental scattering properties separated from nuclear effects
- Another example of the breadth of physics accessible through MINERνA data:
  - Potential for other more exclusive measurements
  - **Complimentary analysis** to the study of nuclear effects in related interactions
  - Notable use of **neutron detection**



Left: Cross-section results with ratio to dipole form factor

Right: Comparison of different fit results. Recent Lattice QCD result, [H.-W. Lin, Phys. Lett. B 824, 136821 (2021)] appears to more closely follow this results fit at high Q^2



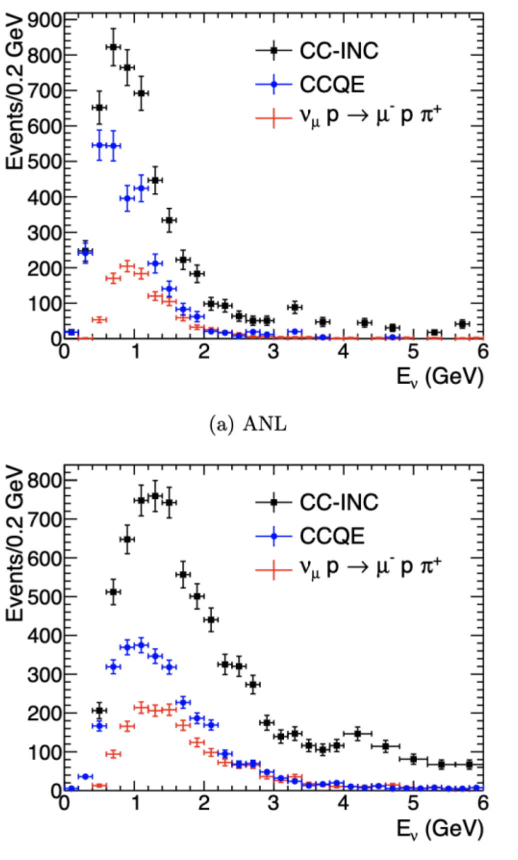
Plots from [T. Cai et al, Nature 614, 48–53 (2023)]

Data Preservation at MINERνA

Why Preserve MINERνA Data?

- The Realities:
  - Data-taking ended in 2019
  - Active MINERνA person-power dwindling
  - MINERνA Expertise is dispersing
  - Support for decade-old software ending
  - MINERνA dataset has access to more physics than analyzers to study said physics
- The Value:
  - MINERνA dataset has access to more physics than analyzers to study said physics: **There's much still novel to dig into!:**
    - **For dataset scale reference: >4M selected events in medium-energy inclusive CC muon neutrino tracker sample*****
  - **<u>Unique dataset</u>** of intermediate-to-high energy transfer (anti)neutrino interactions on multiple nuclear targets in the same beam leading up to DUNE near detector
  - Re-analysis proves useful, some examples:
    - New approaches/observables with particular physics sensitivity e.g. Transverse Kinematic Imbalance (TKI)
    - Comparisons to new models
  - Beam energy range broadly covers final state topologies pertinent to **current and future oscillation experiments**

*** Reference: D. Ruterbories et al., Phys. Rev. D104, 092007 (2021)



(a) ANL

(b) BNL

Re-analyzed ANL/BNL bubble chamber data: C. Wilkinson et al., Phys. Rev. D 90, 112017 (2014)

MINERνA Data Preservation Approach

- Overarching goal: Provide the necessary framework to maximize the usefulness of MINERνA data to the broader community

- This has led to three data preservation products in development:

1. **Tuples**: Processed MINERνA data to provide reconstruction quantities/variables from which current and future analyses can be performed
2. **Toolkit**: Provide robust, standardized tools for performing MINERνA analyses
3. **Training**: Tutorials, examples, and robust documentation for general neutrino experts to follow and build from

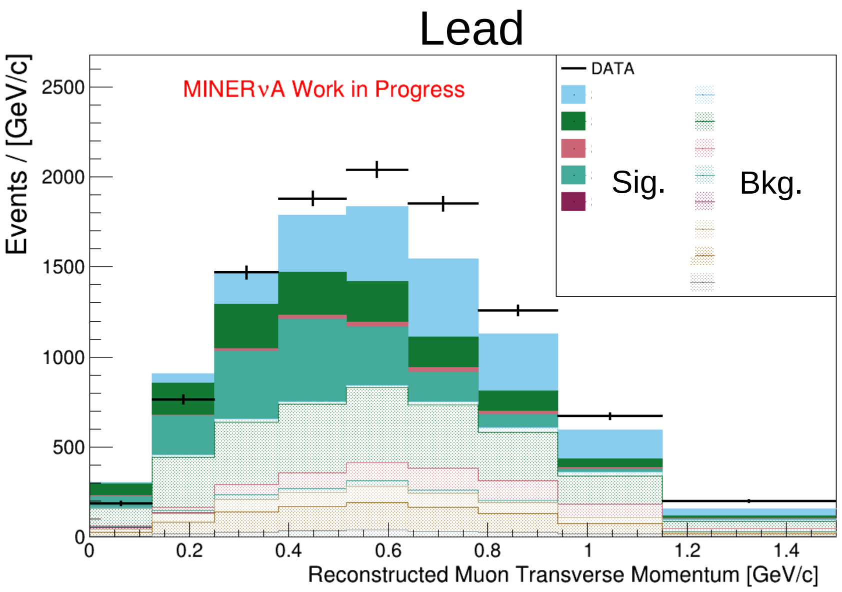
The Tuples: The Last MINERνA Production

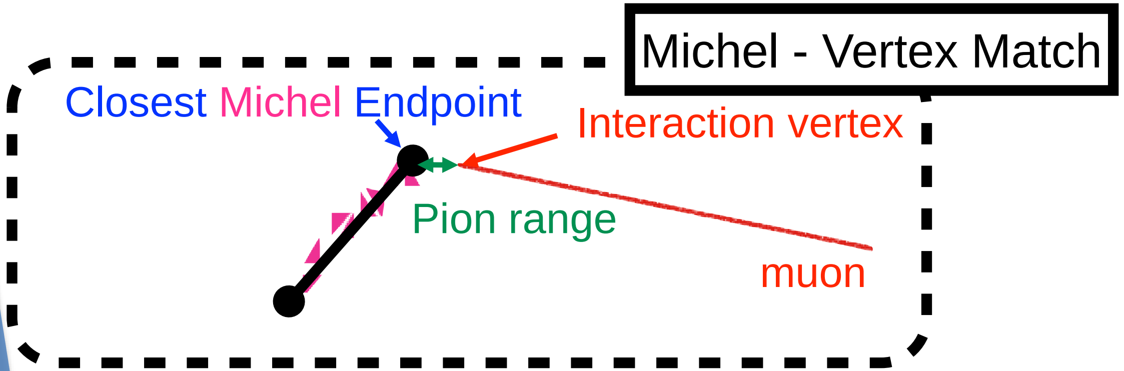
Tuples: Input to Analyzer Code

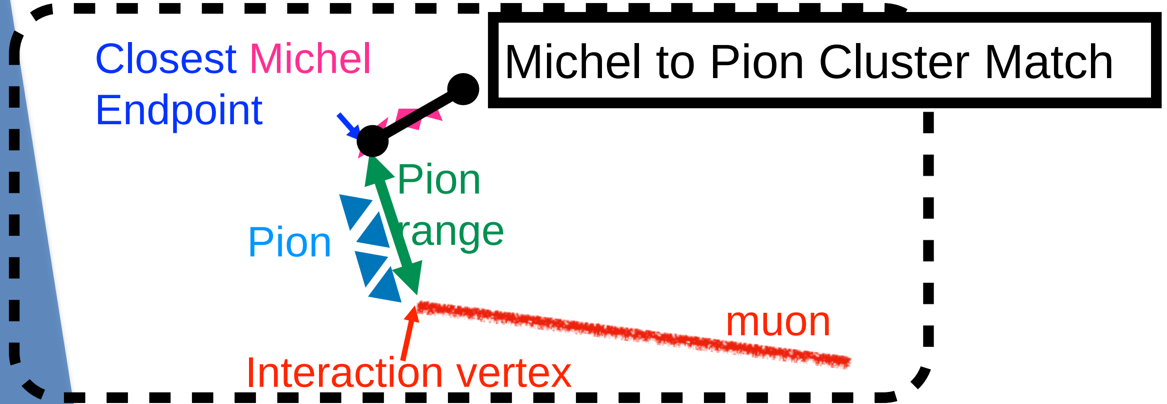
- MINERνA historically produced "AnaTuples" on an analysis-by-analysis basis using Gaudi framework which were then processed by analysis macros to analyze the data
- Approach:
  - **Merge the tools** developed from various analyses into a singular code base which provides the outputs in a singular product, **standardizing reconstruction and systematics**
  - Perform regular code **review** and **validation**
  - Produce **data and Monte Carlo (MC)** "AnaTuples" for MINERνA **low** energy and **medium** energy datasets, as well as **special samples:**
    - Standard MC samples have 4 times the data statistics
- Limitations:
  - Changing computing infrastructure at Fermilab means MINERνA **framework retired sometime in 2024**
  - Personpower limited in the merging of analysis tools, so **not all** historic or possible MINERνA analyses will be supported by the data preservation tuples (e.g. no dedicated neutral-current reconstruction)

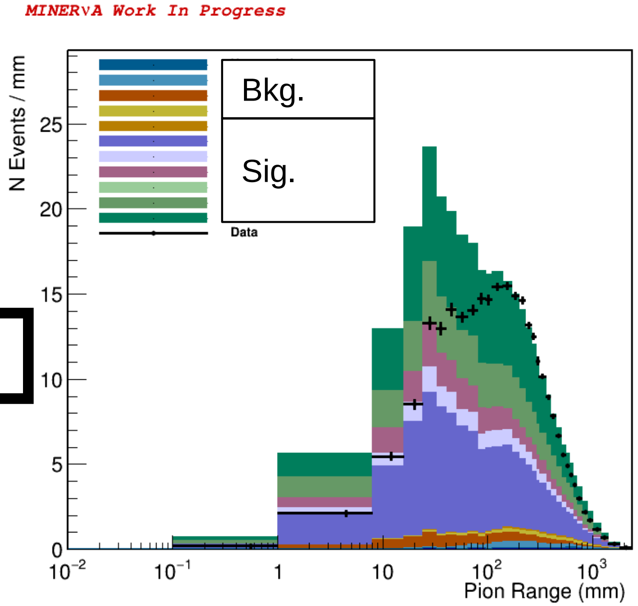
Tuple Content: Some Examples

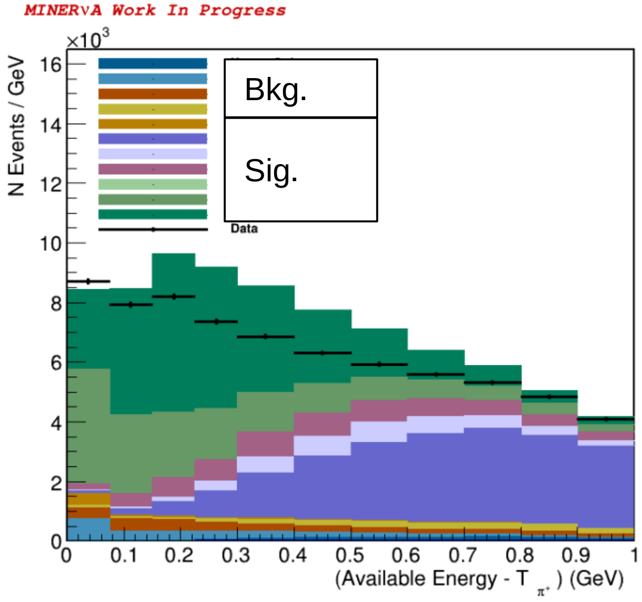
- Right: Standard Muon Transverse Momentum for **antineutrino** interactions on **lead** with a **neutron tagging** selection
- Bottom: Simultaneously calculated variables for a **neutrino, michel-reconstructed pion** analysis
- **These were produced from the same set of data preservation tuples! Broad set of low-/high-level analysis quantities accessible to and calculable by analyzers in neutrino and antineutrino data for all targets, allowing us to continue explore more of the data's sensitivity to physics.**











Tuple Content Overview

- Physics Events:
  - Events which have a well-matched muon to downstream ($\nu_\mu/\bar{\nu}_\mu$ CC)
  - Events which have a primary shower consistent with an electron ($\nu_e/\bar{\nu}_e$ CC)
  - Events in Nuclear Target Region, Tracker, and Downstream electromagnetic calorimeter and hadronic calorimeter
  - Special Signal Samples (e.g. coherent/diffractive, heavy neutral lepton, high statistics electron neutrino)
- Reconstruction:
  - Primary tracking (lepton, and long- and short- tracks)
  - Untracked energy calorimetry and systematics
  - Neutron Tagging
  - Trackless Pion Identification by Michels
  - Track-based and ML vertex identification

    ... and so on
- Thorough **documentation** explaining the contents of the tuples is also a **planned** data preservation product

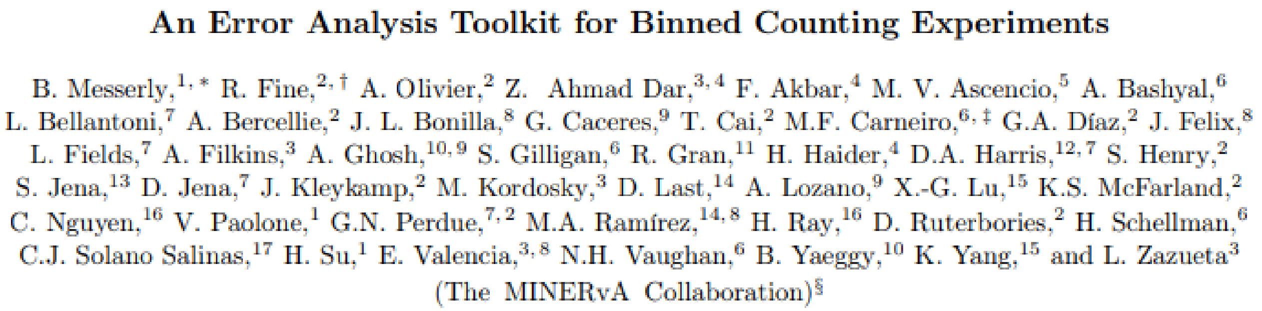
Tuple Production and Access

- Production Status:
  - Currently processing a standard production which correctly addresses issues from previous productions and standardizes calorimetric systematic information→ Highly varied **physics results** capable from this production
  - Plan in place to finalize data preservation code base and special MC samples ahead of the retiring of MINERνA software framework
  - Low energy data and MC able to be processed with equivalent software and reconstruction
- Tuple Access:
  - Final dataset expected to be roughly ~10TB
  - Confirmed Fermilab storage location with **public access**, no Fermilab credentials required

The Tools: The MINERνA Analysis Toolkit and More!

MINERνA Analysis Toolkit (MAT)

- **MINERνA-independent tools** developed primarily to handle many universe systematic approach, but with many other useful tools for analysis standardization
- Central object, the **MnvHnD**:
  - Simultaneously **carries** the values in the **systematically-shifted universes** in individual THnDs
  - **Covariance matrices** available on demand
- Adoption:
  - **All** current analyses on MINERνA utilize the core tools of the MAT
  - Will only need significant changes when they occur in ROOT
  - Designed to be usable in any ROOT-based counting analysis
  - Utilized in MicroBooNE analysis, P. Abratenko et al. (MicroBooNE Collaboration), Phys. Rev. D 107, 012004 (2023)



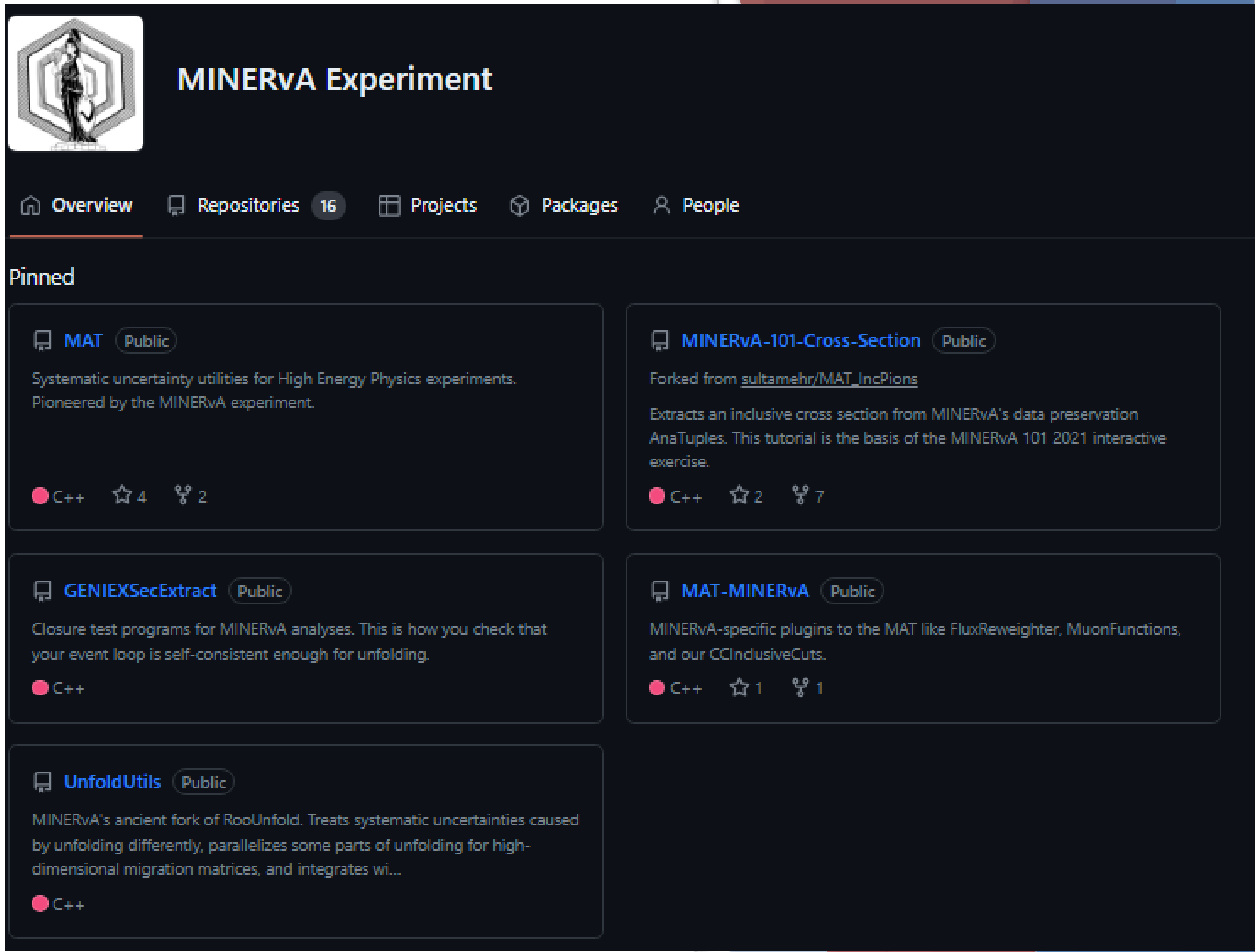
An Error Analysis Toolkit for Binned Counting Experiments

B. Messerly,[1,*] R. Fine,[2,†] A. Olivier,[2] Z. Ahmad Dar,[3,4] F. Akbar,[4] M. V. Ascencio,[5] A. Bashyal,[6] L. Bellantoni,[7] A. Bercellie,[2] J. L. Bonilla,[8] G. Caceres,[9] T. Cai,[2] M.F. Carneiro,[6,‡] G.A. Díaz,[2] J. Felix,[8] L. Fields,[7] A. Filkins,[3] A. Ghosh,[10,9] S. Gilligan,[6] R. Gran,[11] H. Haider,[4] D.A. Harris,[12,7] S. Henry,[2] S. Jena,[13] D. Jena,[7] J. Kleykamp,[2] M. Kordosky,[3] D. Last,[14] A. Lozano,[9] X.-G. Lu,[15] K.S. McFarland,[2] C. Nguyen,[16] V. Paolone,[1] G.N. Perdue,[7,2] M.A. Ramírez,[14,8] H. Ray,[16] D. Ruterbories,[2] H. Schellman,[6] C.J. Solano Salinas,[17] H. Su,[1] E. Valencia,[3,8] N.H. Vaughan,[6] B. Yaeggy,[10] K. Yang,[15] and L. Zazueta[3]
(The MINERvA Collaboration)[§]

For a detailed description of the implementation of the many universe method of systematics in the MAT, as well as discussions on when the MAT is appropriate for use, please refer to the above-pictured reference: B. Messerly et al., EPJ Web of Conferences 251, 03046 (2021)

Full Data Preservation Macro Tools

- Separated from the more broadly applicable MAT, the **MINERνA-specific** analyses packages are also provided:
  - MAT-MINERνA: Standardized cuts, systematic universes, reconstruction quantities, reweighters
  - GENIEXSecExtract: Tools to extract the predicted cross-section for a signal definition from the truth information in the processed tuples
  - UnfoldUtils: Utilizes “RooUnfold” to perform unfolding in each systematic universe in the MnvHnD objects
  - MParamFiles/MATFluxAndReweightFiles: CVS and CVMFS-hosted files containing necessary information for model reweights, flux, etc.
- These tools are also adopted by <u>all</u> current MINERνA analyses, and are also <u>publicly available</u>

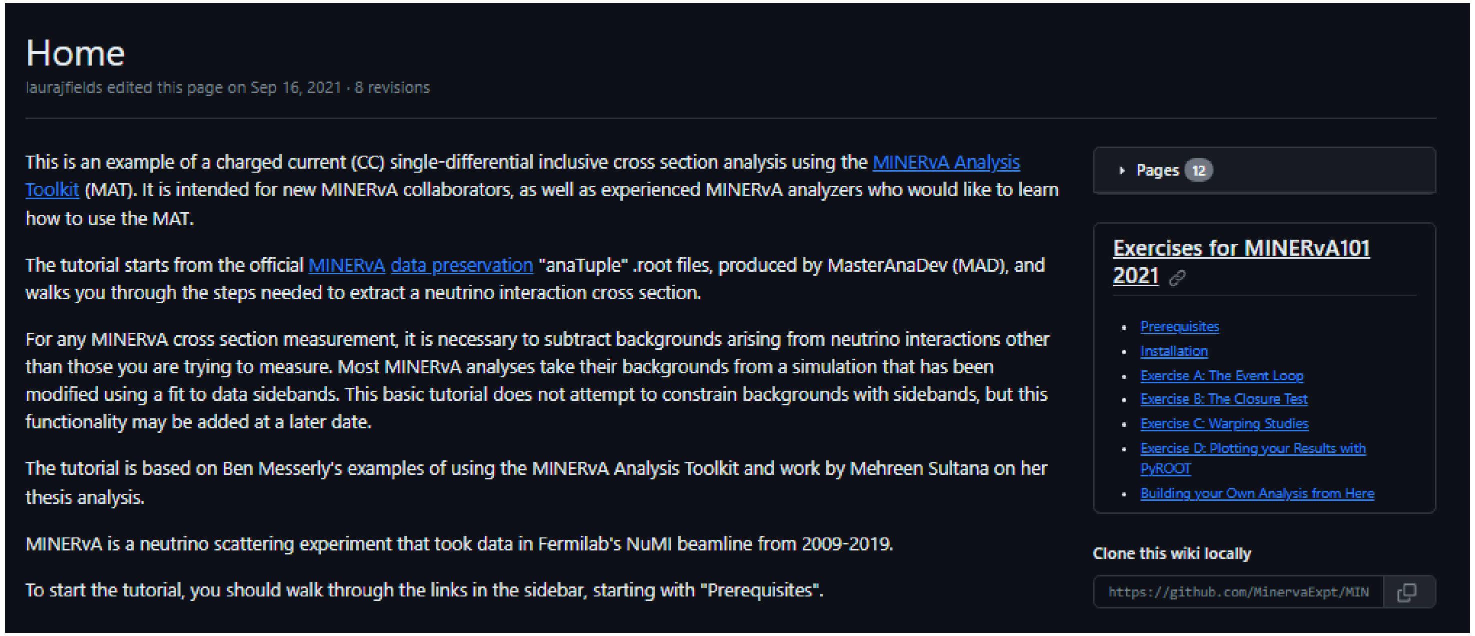


Screenshot of <u>MinervaExpt</u> Github organization which houses the MAT and its corresponding tools

The Training: How will one learn to perform MINERνA analyses?

Tutorial!

- Tutorial developed which utilizes many of the useful tools in the MAT
- Verifiably produces a result consistent with a published MINERνA result
- Provides careful instruction in how to approach the analysis questions
- Many current analyzers developed from this tutorial as a base



Home

laurajfields edited this page on Sep 16, 2021 · 8 revisions

This is an example of a charged current (CC) single-differential inclusive cross section analysis using the MINERvA Analysis Toolkit (MAT). It is intended for new MINERvA collaborators, as well as experienced MINERvA analyzers who would like to learn how to use the MAT.

The tutorial starts from the official MINERvA data preservation "anaTuple" .root files, produced by MasterAnaDev (MAD), and walks you through the steps needed to extract a neutrino interaction cross section.

For any MINERvA cross section measurement, it is necessary to subtract backgrounds arising from neutrino interactions other than those you are trying to measure. Most MINERvA analyses take their backgrounds from a simulation that has been modified using a fit to data sidebands. This basic tutorial does not attempt to constrain backgrounds with sidebands, but this functionality may be added at a later date.

The tutorial is based on Ben Messerly's examples of using the MINERvA Analysis Toolkit and work by Mehreen Sultana on her thesis analysis.

MINERvA is a neutrino scattering experiment that took data in Fermilab's NuMI beamline from 2009-2019.

To start the tutorial, you should walk through the links in the sidebar, starting with "Prerequisites".

Pages 12

Exercises for MINERvA101 2021

- Prerequisites
- Installation
- Exercise A: The Event Loop
- Exercise B: The Closure Test
- Exercise C: Warping Studies
- Exercise D: Plotting your Results with PyROOT
- Building your Own Analysis from Here

Clone this wiki locally

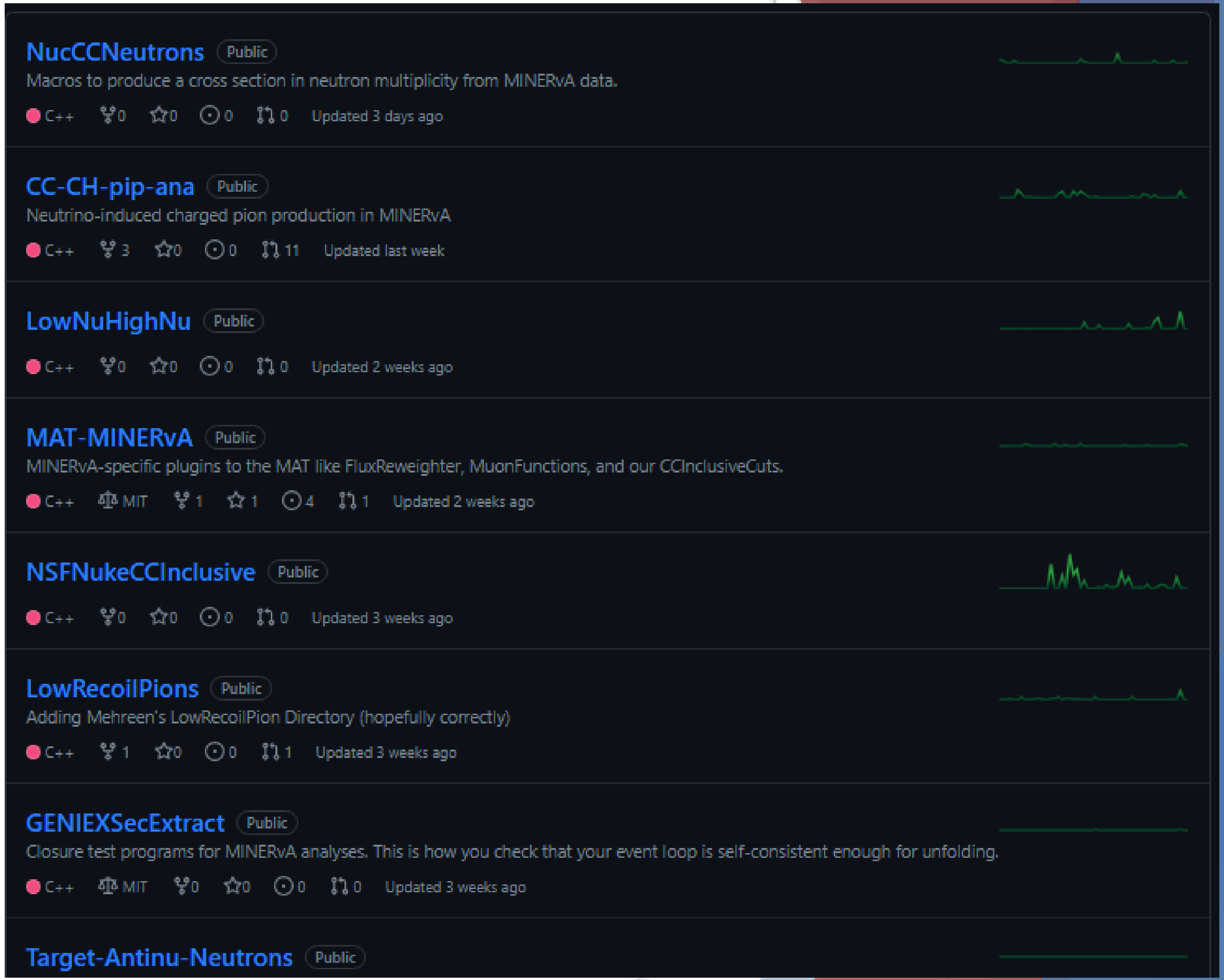
https://github.com/MinervaExpt/MIN

Github repository for the tutorial. Find the above at the “wiki” tab which has the instructions for the tutorial and insights how to utilize the tools for a novel analysis.

Learn by Example!

- Current and past analyzers are heavily encouraged to utilize the code history and documentation tools in Github

- Previously-mentioned Github organization houses many analyses already which can be utilized as examples of MINERνA analyses which utilize the MAT to process MINERνA tuples



Screenshot of the MinervaExpt Github organization list of reops, including multiple analyses repos

Summary

Summary

- MINERνA's **rich and unique** dataset has successfully provided much insight into neutrino-nucleus interactions:
  - See backup for more on our recent measurements and in-development analyses
- MINERνA as a collaboration has undertaken an extensive and robust data preservation effort:
  - Comprehensive tuples which allow support current MINERνA analyses and the flexibility to approach novel ideas are in production with a final production coming at the latest in the next year
  - Standardized tools to support these analyses efforts are already available
  - Tutorials, examples and documentation available to aid in the analysis of the data preservation product
- MINERνA data looks to be useful for years to come for understanding neutrino interactions at energies critical to GeV-scale oscillation programs
- Feel free to reach out to me if you're interested in the current or future use of these tools! You can also get in touch with our co-spokespersons.

Backup

Fluxes from slide 3 references

1. K. Abe et al. Nature 580 (2020) 7803, 339-344 3.

2. M.A. Acero(U. Atlantico, Barranquilla) et al. Phys.Rev.Lett. 123 (2019) 15, 151803 4.

3. Babak Abiet et al. (DUNE), “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics,” (2020),arXiv:2002.03005 [physics.ins-det].

MINERνA Works in Development

- CCQE-like:
  - Three-dimensional ν_μ with TKI variables
  - Three-dimensional $\bar{\nu}_\mu$
  - ν_μ/ $\bar{\nu}_\mu$ ratios
  - Neutron-tagged
- Low Recoil Energy of Hadronic System:
  - Multi-neutron tagged
  - Electron neutrino and antineutrino
  - Charged pion interactions
- Inelastic:
  - Many Deep and Shallow Inelastic Scattering Results (DIS/SIS)
  - Interactions with helium
- Many CC Inclusive Results
- And many more

MINERνA MC Tunes

All applied to MINERνA base GENIE v2.12.6

Naming MnvTune vX.Y.Z

These are NOT cumulative, e.g. v4.4 doesn't apply Y=1,2,3 to get to 4

X	Description
1	the original tune. Valencia RPA applied to QE (RFG), non-resonant pion production reduction, low recoil fit (LE) applied to Valencia 2p2h
2	Same as 1 but includes the Stowell et. al (MINERvA) GENIE pion tune low Q2 suppression
3	Replace Valencia 2p2h with SuSA 2p2h, non-resonant pion production reduction, QE is still RFG with RPA correction from Valencia but has enhanced Bodek-Ritchie tail, removal of 25 MeV from Eavail in pion events with protons in the final state
4	Same as 1 but includes the full pion bubble chamber fit, CCNormRes increased to 1.15 (from 1) and MaRES set to 0.94. Also includes full treatment of the correlations between MaRES and CCNormRes in the fit

Y	Description
1	Normalization change of coherent pion production Epi
2	Normalization change of coherent pion production using the angle and E pi distributions (ME)
3	A. Bercellie low Q2 pion production suppression (see docDB 30137) and normalization of coherent pion production using the angle and E pi distributions (ME)
4	Replace dipole form of the axial form factor of QE with the Meyer et. al. z-expansion
5	Replace QE RFG nuclear model with NuWro SF

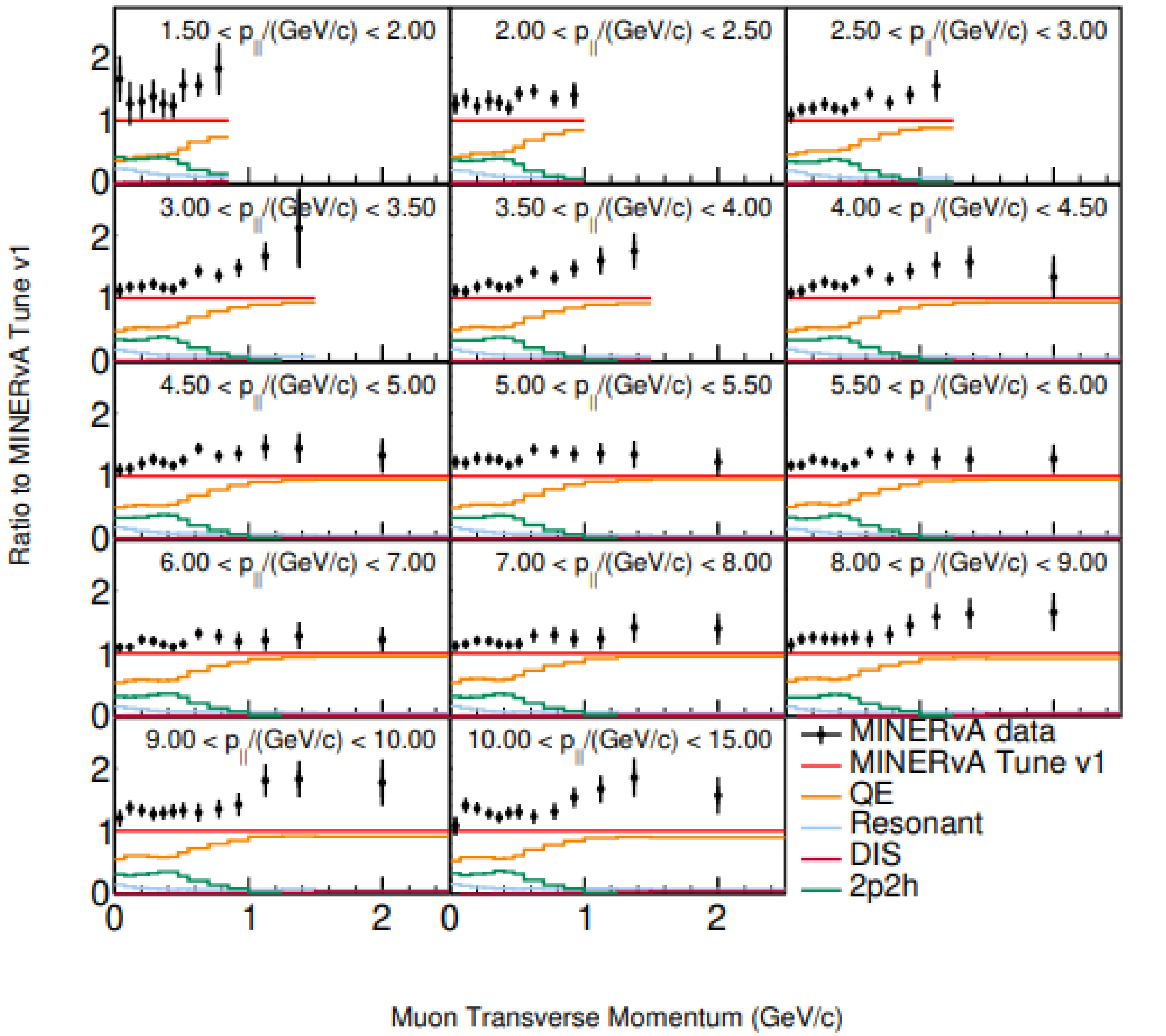
Z	Description
1	Bug fix of elastic FSI in pions and protons

High Statistics Measurements:

Two-Dimensional $\bar{\nu}_\mu$ CCQE-like Cross Section on CH Further Details

$\bar{\nu}_\mu$ CCQE-like on CH: Muon p_T vs. $p_{||}$ Cross-Section Fractional Components

- MINERvA's vast dataset allows for sufficient statistics for measurement across a broad phase space
- Measurement indicates underprediction of the model in all ranges of $p_{||}$
- Complementary measurement to high-statistics 3D ν_μ CC0π on CH measurement and measurements across MINERvA's nuclear targets

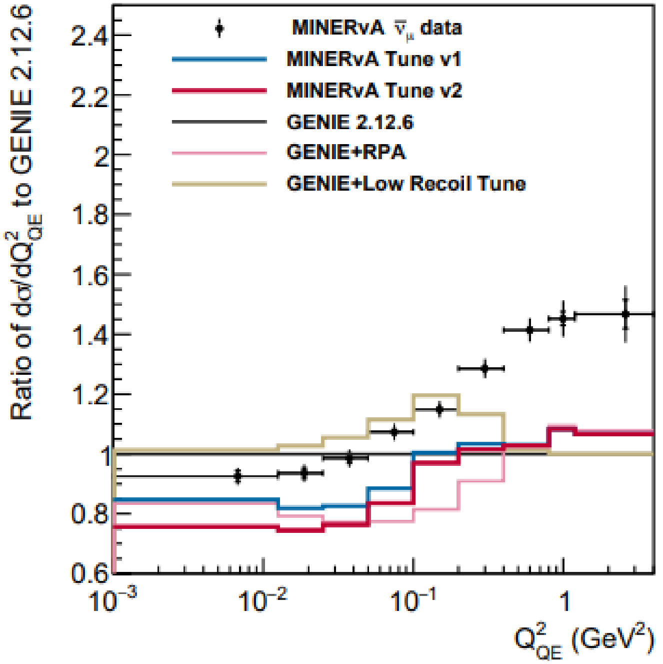


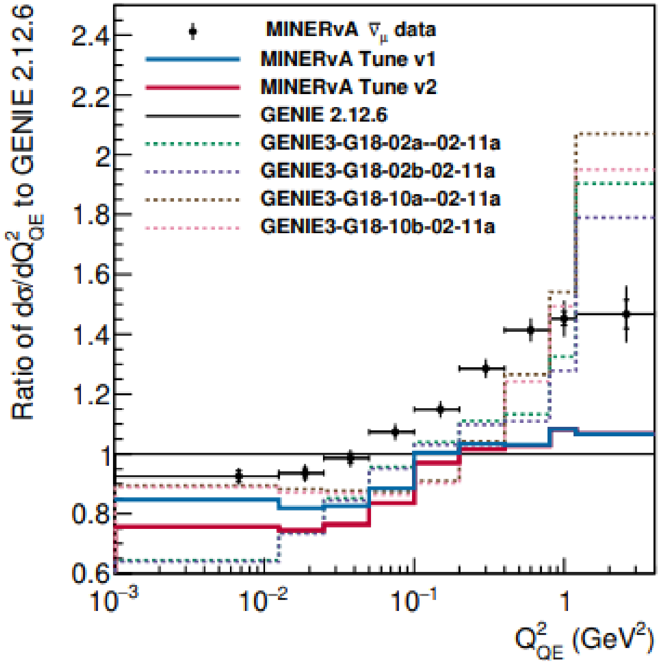
A. Bashyal et al., Phys. Rev. D 108, 032018 (2023)

$\bar{\nu}_\mu$ CCQE-like on CH: Muon p_T vs. $p_{||}$ Cross-Section Model Comparisons

Model	χ^2 - linear	χ^2 - log
GENIE 2.12.6 Tunes		
MINERvA Tune v1	362.6	580.4
MINERvA Tune v2	364.4	601.4
GENIE w/o 2p2h	226.5	473.2
GENIE (Default)	346.4	550.6
GENIE+πtune	354.3	568.5
GENIE+RPA	230.0	406.7
GENIE+RPA+πtune	231.7	414.6
GENIE+Low Recoil Tune	755.4	1059.4
GENIE+Low Recoil Tune+RPA	361.2	570.0
GENIE+Low Recoil Tune+πtune	760.6	1081.8
GENIE 3.0.6 Tunes		
GENIE 3.0.6 G18_02a_02_11a	602.9	865.0
GENIE 3.0.6 G18_02b_02_11a	586.9	878.3
GENIE 3.0.6 G18_10a_02_11a	353.1	447.5
GENIE 3.0.6 G18_10b_02_11a	312.8	421.7

TABLE II. $p_{||} - p_\perp$ χ^2 between data and model variants derived from GENIE. The number of degrees of freedom is 171. Both the χ^2 between the values and between the logs of the values are listed.





Higher Q^2 (where QE dominates) behavior appears to be a better match for GENIE 3-based models.

Note: result extracted using GENIE 2-based model (MnvTune v1)

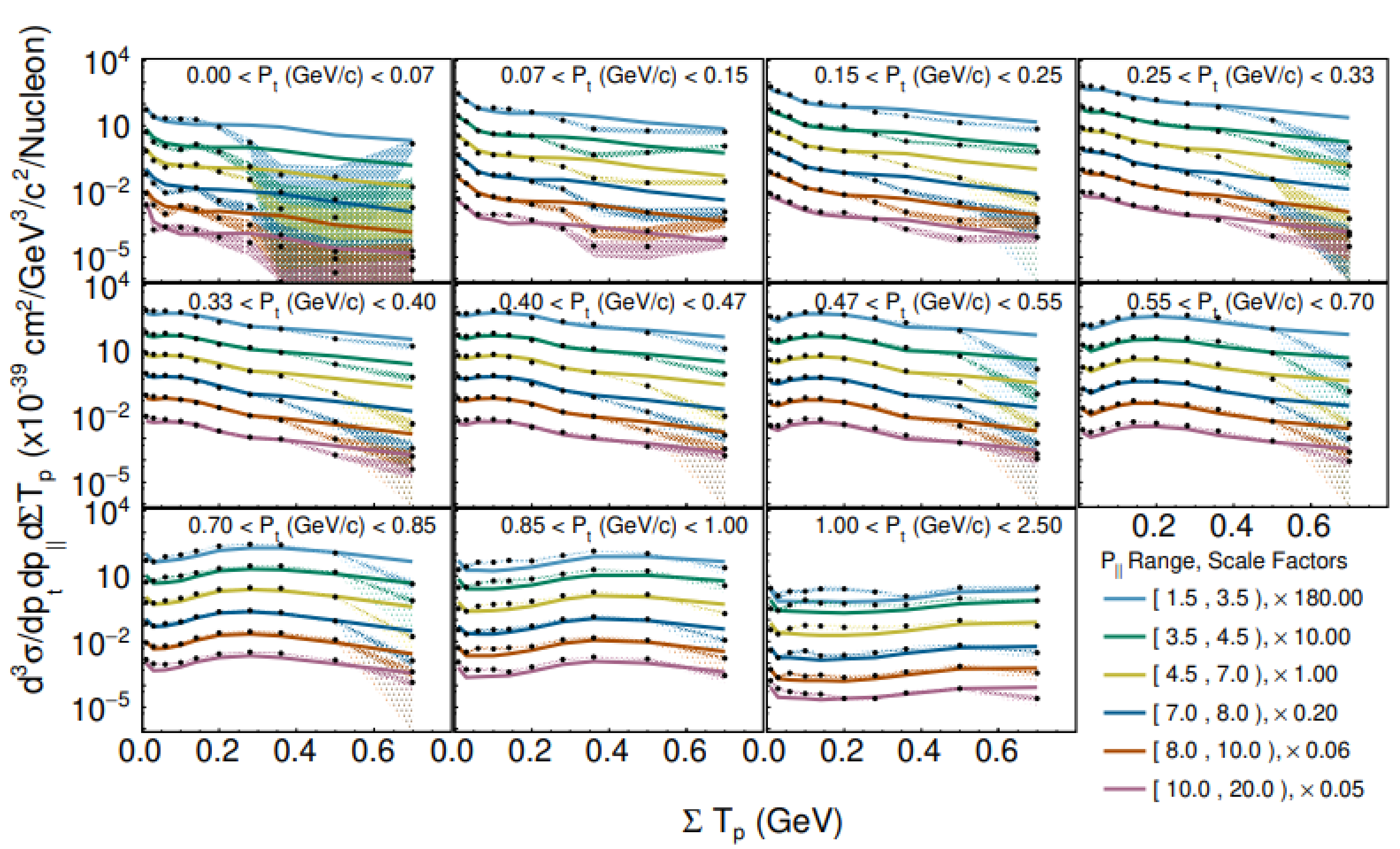
A. Bashyal et al., Phys. Rev. D 108, 032018 (2023)

High Statistic Measurements:

Three-Dimensional ν_μ CCQE-like Cross Section on CH

ν_μ CCQE-like in CH: Muon p_T vs. $p_{||}$ vs. total proton KE ($\sum T_p$) Cross-Section

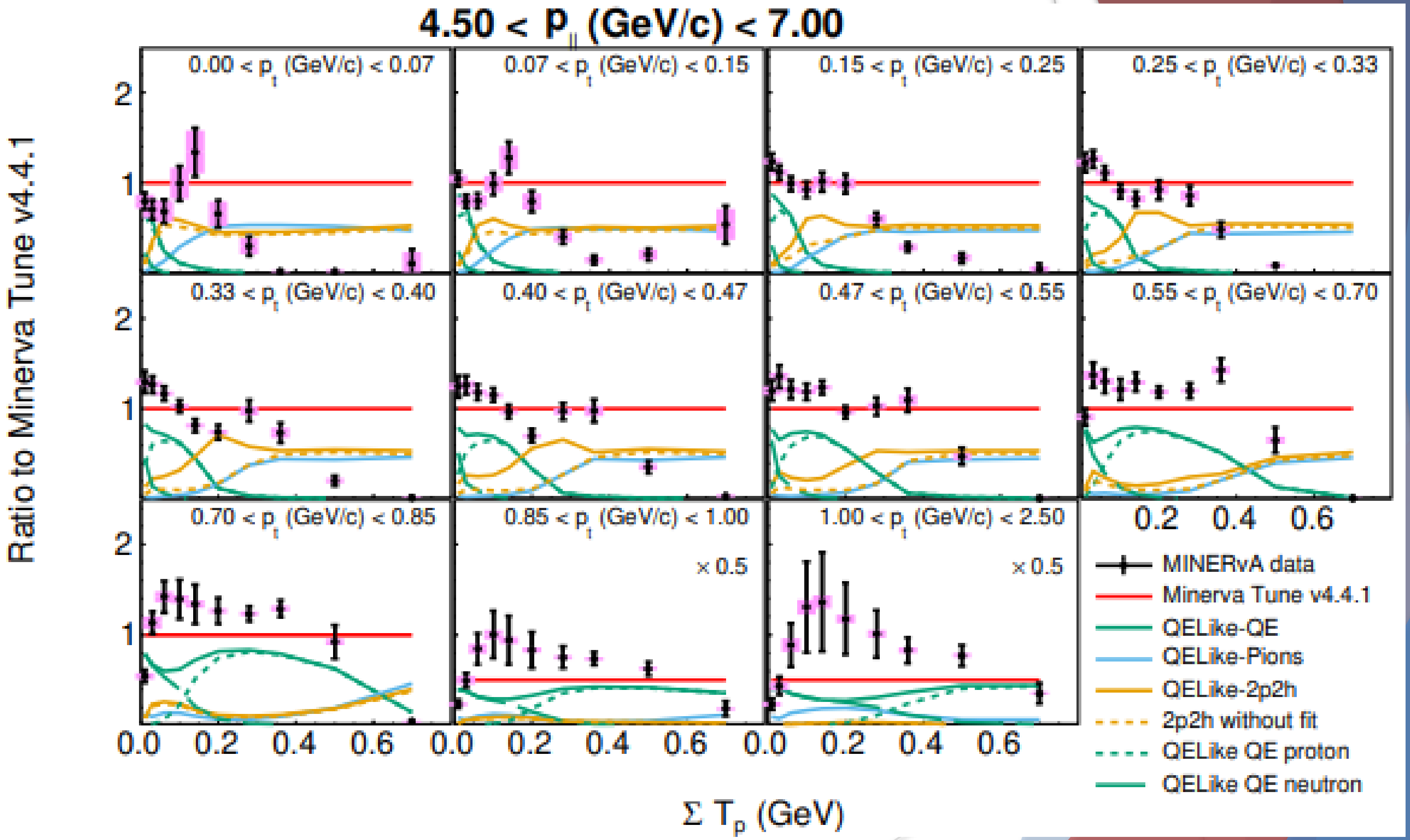
- First high statistics triple differential measurement
- Inclusion of proton kinematics allows for exploration of nuclear effects
- Significant discrepancies in many regions of phase space



[D. Ruterbories et al., Phys. Rev. Lett.129, 021803 (2022)]

ν_μ CCQE-like in CH: Muon p_T vs. $p_{||}$ vs. total proton KE ($\sum T_p$) Cross-Section

- Underlying processes can be traced to the discrepancies
- Non-QE, QE-like tails in summed proton KE at lower muon transverse momentum are particularly notable as discrepant

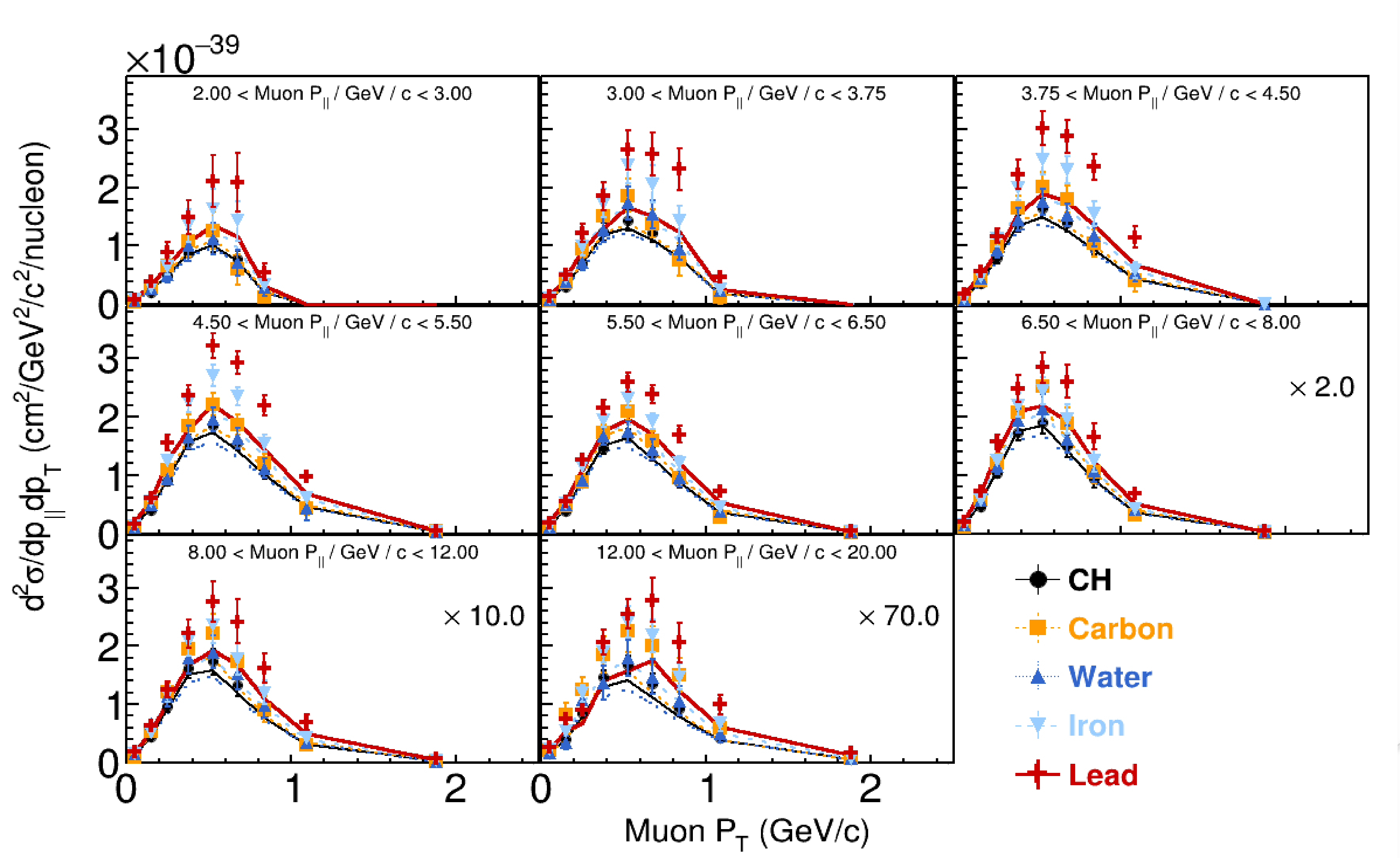


[D. Ruterbories et al., Phys. Rev. Lett.129, 021803 (2022)]

High Statistic Measurement of Nuclear Dependence:

Two-Dimensional ν_μ CCQE-like Cross Section and Ratios

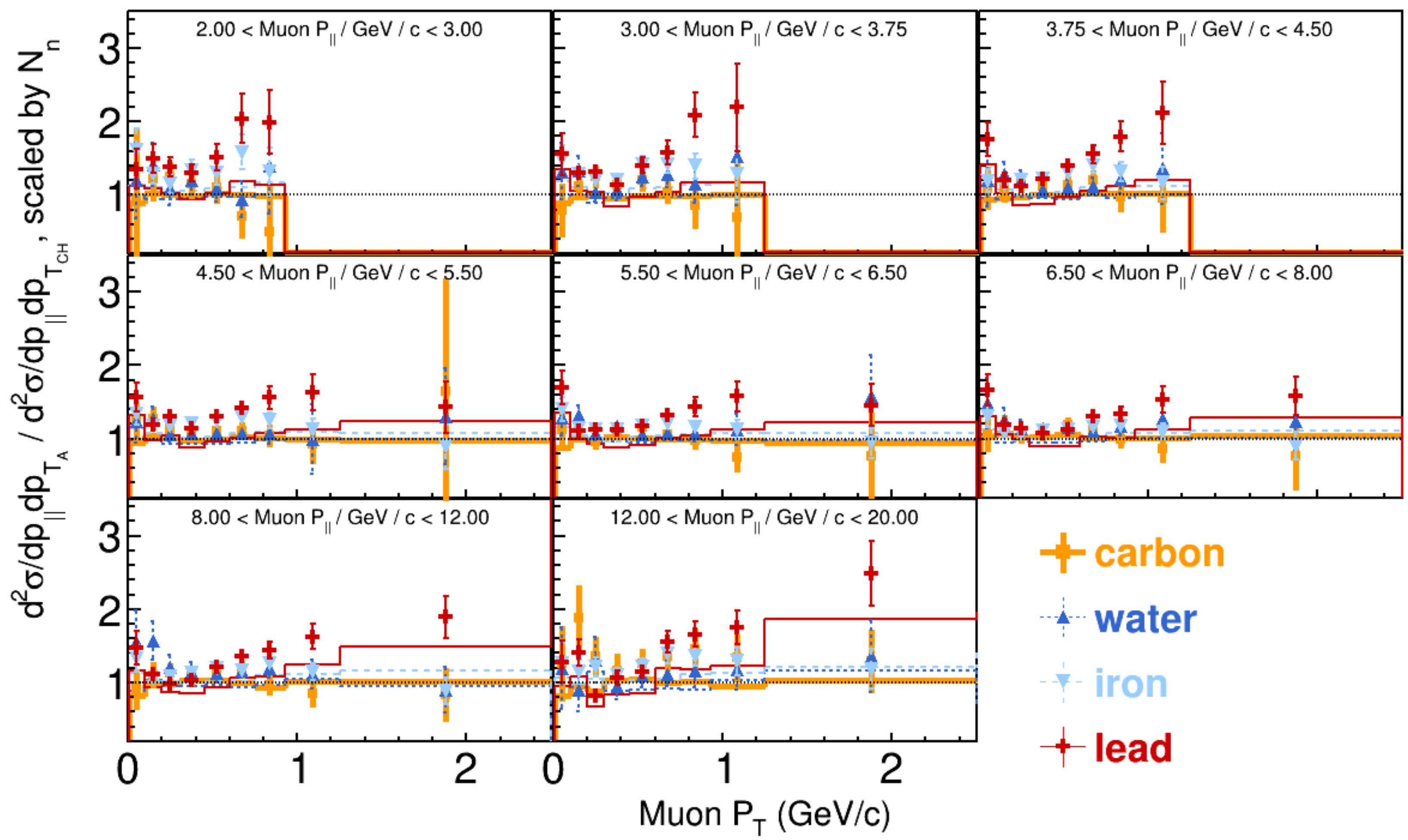
ν_μ CCQE-like in Nuclear Targets: Muon p_T vs. $p_{||}$ Cross-Sections



J. Kleyklamp et al., Phys. Rev. Lett.130, 161801 (2023)

ν_μ CCQE-like in Nuclear Targets: Muon p_T vs. $p_{||}$ Cross-Section Ratios

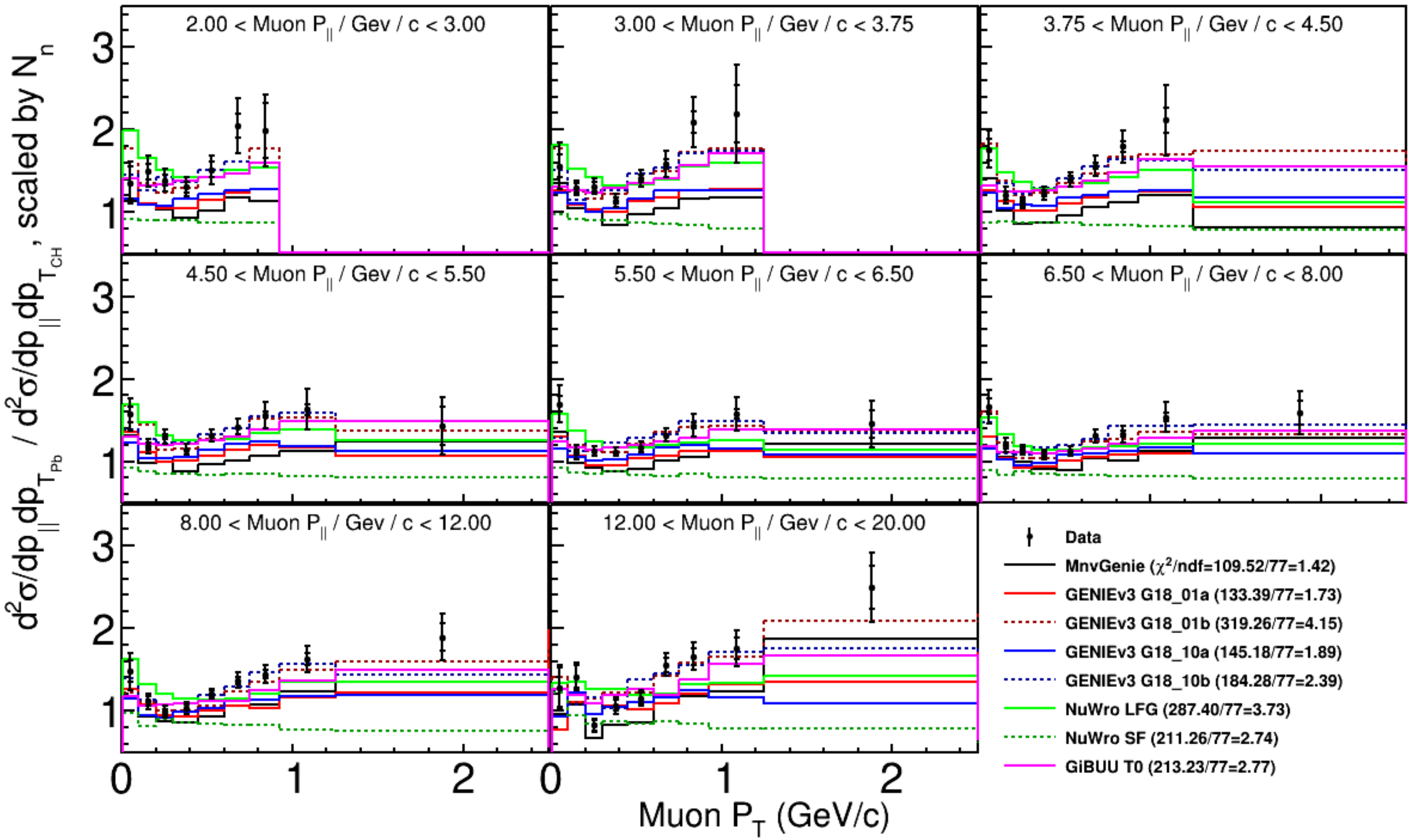
- Ratio to high-statistics tracker sample provides systematics cancellations
- Data/Model discrepancy grows with A:
  - At higher muon p_T suggests overall QELike A-scaling **underpredicted**
  - At lowest muon p_T suggests non-QE, QELike scaling underpredicted



J. Kleyklamp et al., Phys. Rev. Lett.130, 161801 (2023)

Two-Dimensional Neutrino CCQE-like: Lead Ratio Model Comparison

- Comparison shows no generator captures all features across the phase space



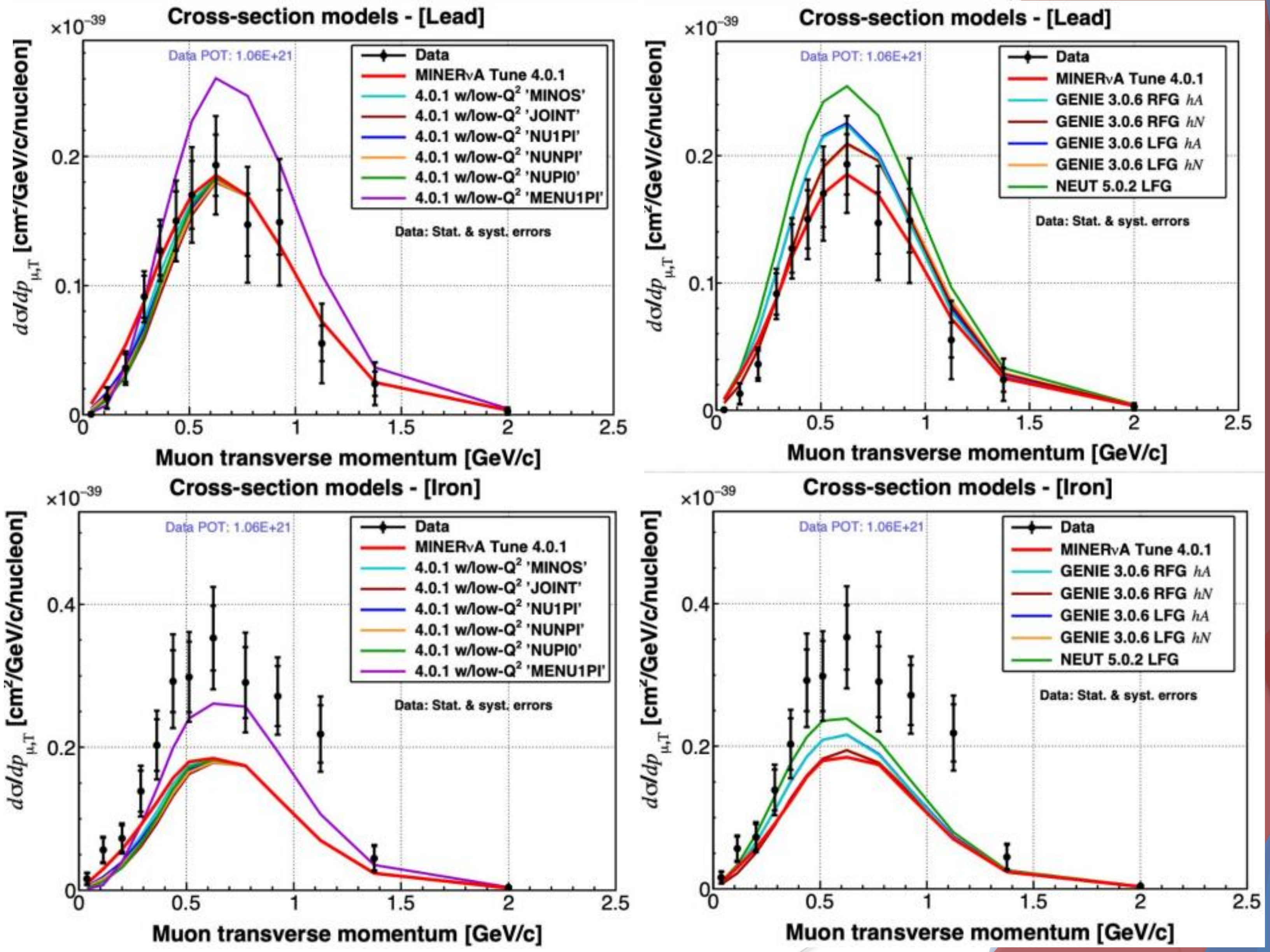
J. Kleyklamp et al., Phys. Rev. Lett.130, 161801 (2023)

Measurements of Nuclear Dependence:

ν_μ $CC1\pi^0$ Cross Sections on Fe and Pb

ν_μ CC1π^0 Cross Sections

- Strong suppression on low p_T on lead
- Model predictions in iron are more significantly suppressed
- Can combine this measurement with other CC1π measurements to help improve modeling!

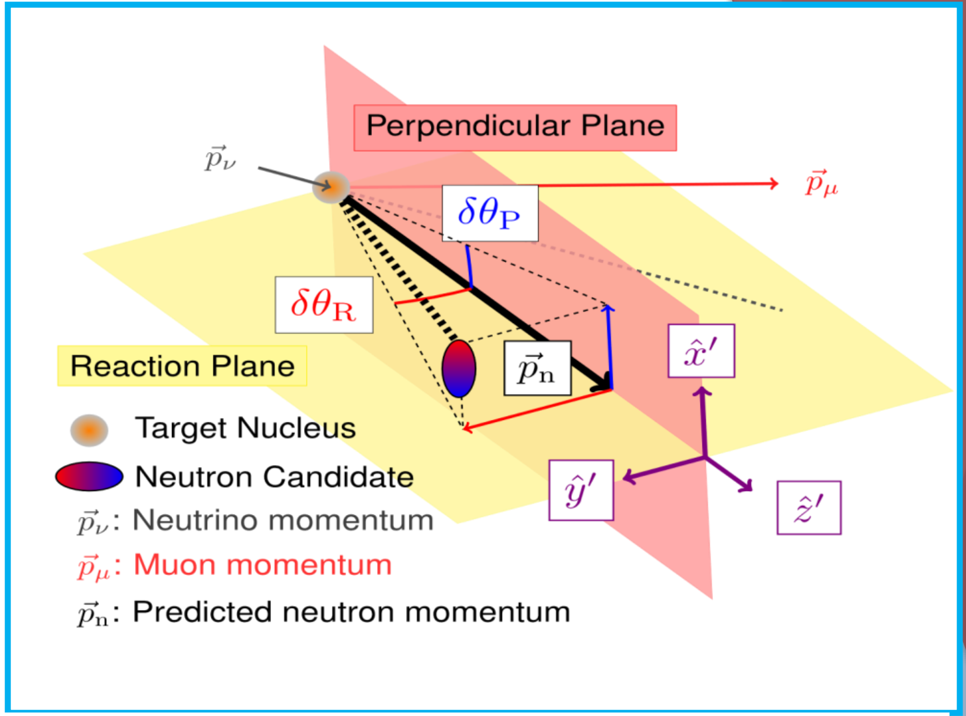


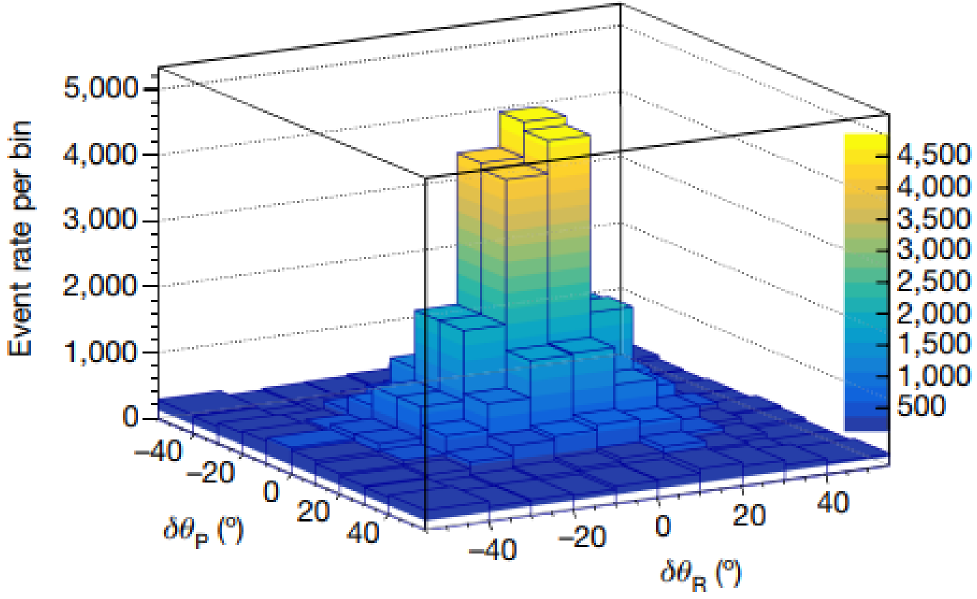
Paper in Preparation, G. Diaz and A Bercellie, Fermilab Joint Experimental-Theoretical Physics Seminar Dec. 2, 2022

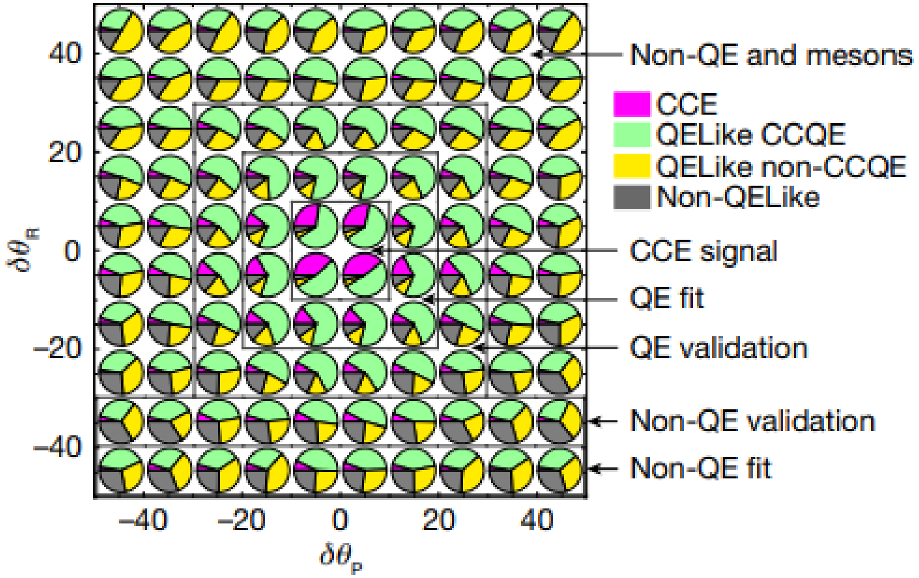
Highly Exclusive Channels:
$\bar{\nu}_\mu$ "Charged-Current Elastic (CCE) Scattering" on Hydrogen
Further Angular Separation Details

$\bar{\nu}_\mu$ CCE Angular Separation

- Nuclear effects smear out neutron correlation in analogous CCQE-like measurement
- The various regions in the two-dimensional plane of the comparison of these two angular deviations allow for control of the non-CCE backgrounds near the signal-rich origin





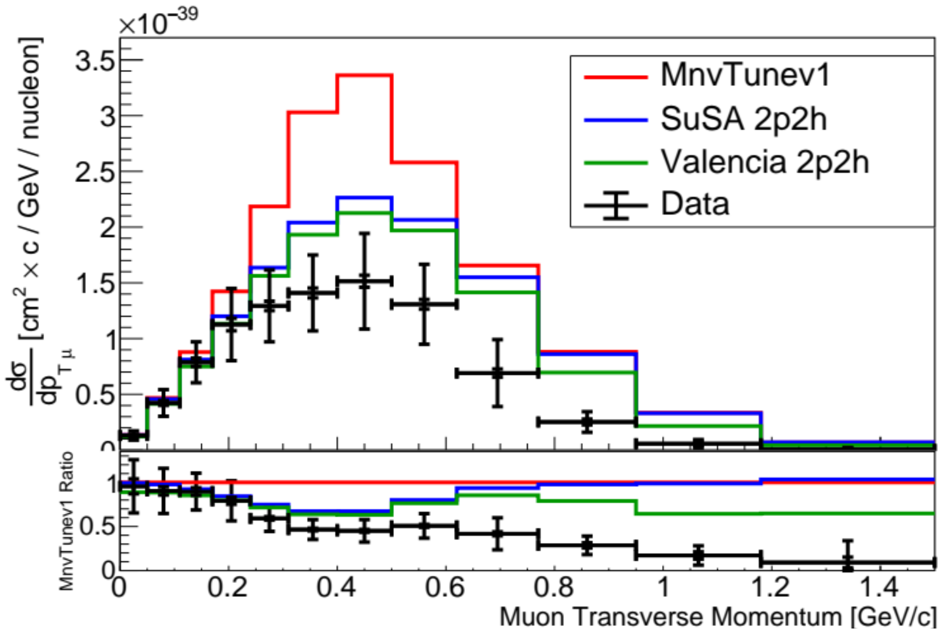


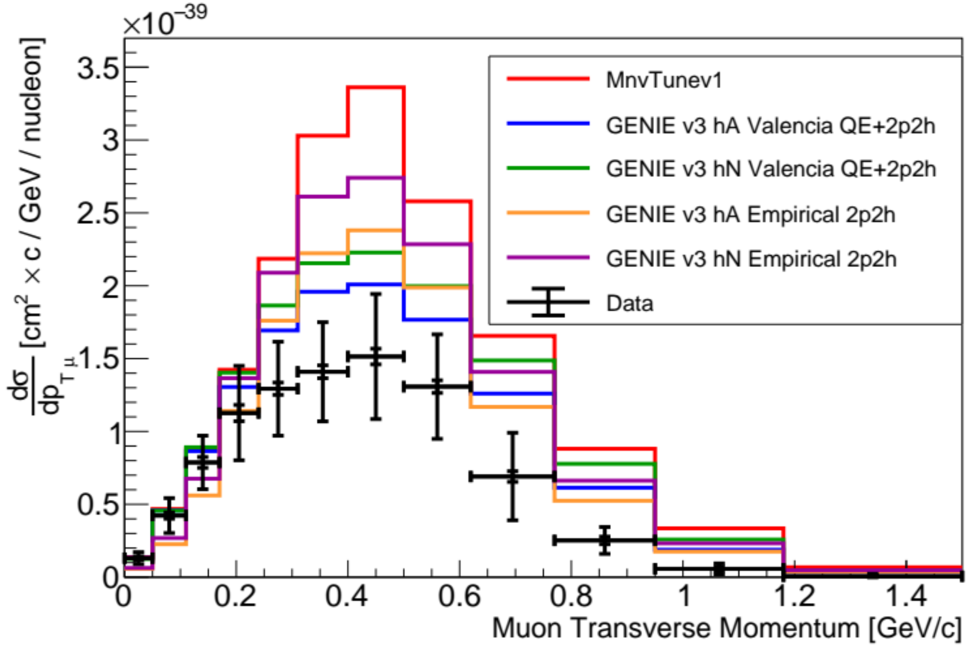
T. Cai et al, Nature 614, 48–53 (2023)

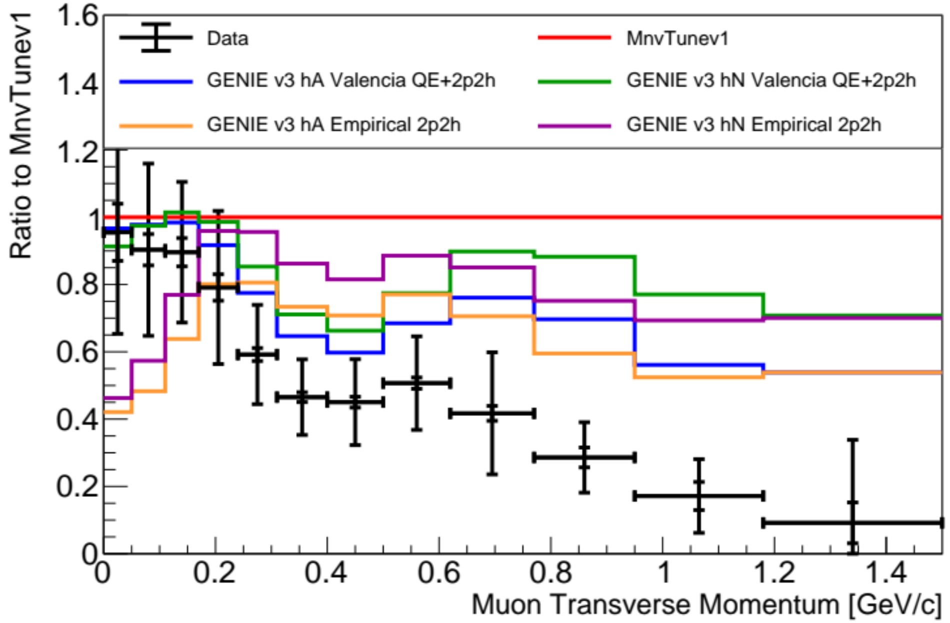
Highly Exclusive Channels:
$\bar{\nu}_\mu$ CC Multi-Neutron (2 or more) Production Cross Section at Low Available Energy

$\bar{\nu}_\mu$ CC Multi-Neutron Production Cross Section

- MnvTuneV1 scales Valencia two-particle, two-hole (2p2h) up according to data in “low energy” flux configuration, and overpredicts as a result in the 2p2h-dominant peak of this distribution
- Both SuSA and Valencia 2p2h are closer matches for the data, but don’t fall off at the same rate
- Comparisons with various handlings of 2p2h and Final-State Interactions in GENIE v3 have none which account for the full shape in muon p_T







Paper in Preparation, A. Olivier, Fermilab Joint Experimental-Theoretical Physics Seminar Oct. 6, 2023