New MINERνA Results Across Various Nuclear Targets

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

Lake Louise Winter Institute
Feb. 22, 2023

Borrowed from Tejin Cai's talk preceding this one

Neutrino flavors change

Neutrinos are produced in one of the three flavor eigenstates: e, μ, τ, but travels as a mixture of mass eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_\mathbf{i}\rangle$$

$$|\nu_j(t)\rangle = e^{-i(E_j t - \vec{p}\vec{x})}|\nu_j(0)\rangle$$

$$\approx e^{-i\left(\frac{m_j^2 L}{2E}\right)}|\nu_j(0)\rangle$$

$$P_{\alpha\to\beta} = \langle\nu_\beta|\nu_\alpha\rangle$$

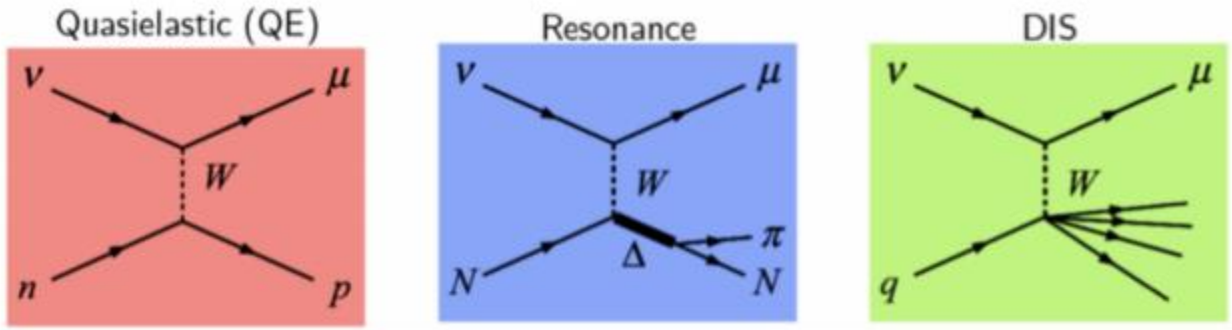
$$= \delta_{\alpha\beta} - 4\sum \mathcal{R}(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + \dots$$

Recall Neutrino Energy Dependence of oscillation phenomenon.

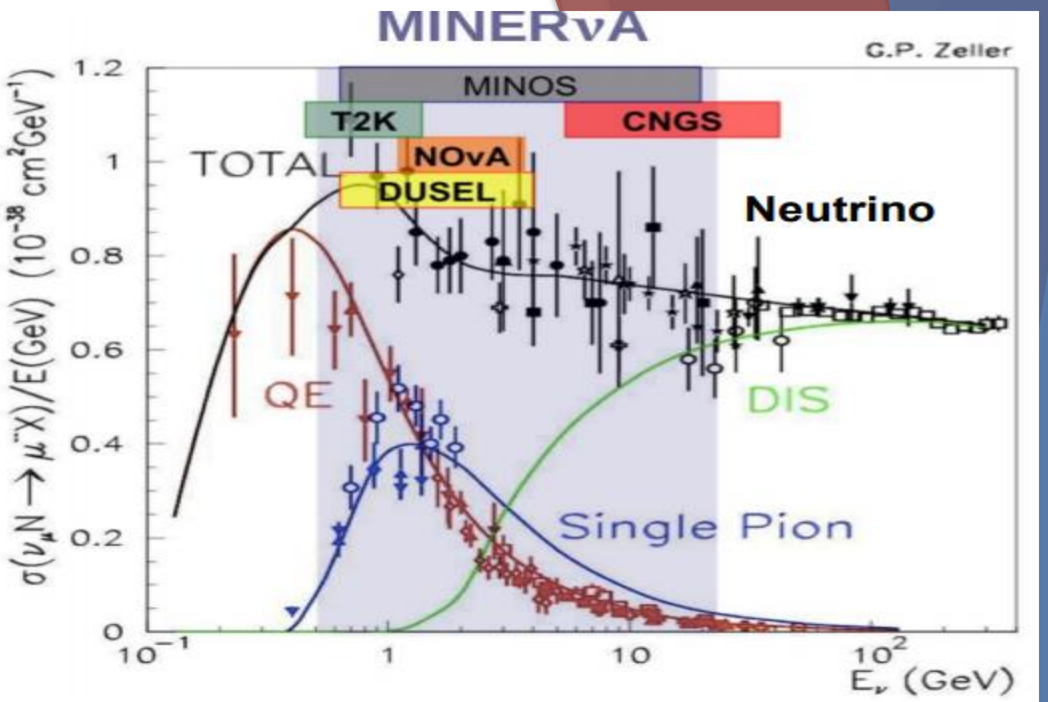
L: Distance
E: Energy
$\Delta m^2_{ij} = m^2_i - m^2_j$

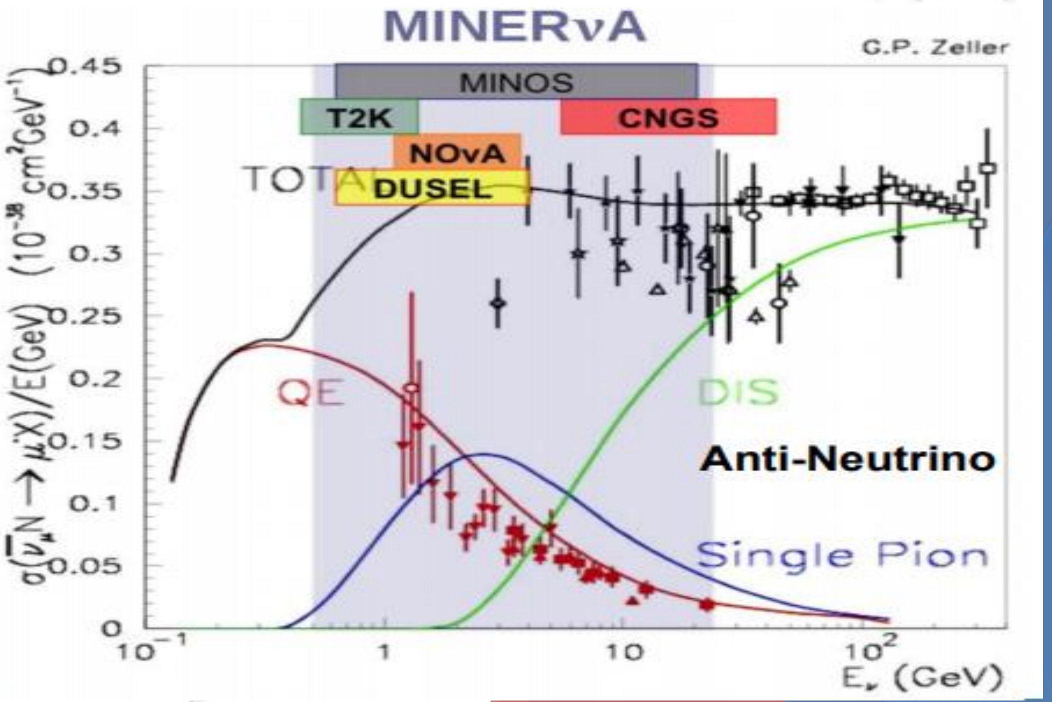
Neutrino Measurement Complications

- “Neutrino Energy needs to be reconstructed using observed reaction” - Tejin Cai (previous talk)
- Neutrino event generators (e.g. GENIE) rely on neutrino-nucleus interaction models: improved by high precision measurements
- MINERvA, with NuMI beam’s energy range, well-positioned to constrain models for broad set of experiments, final states



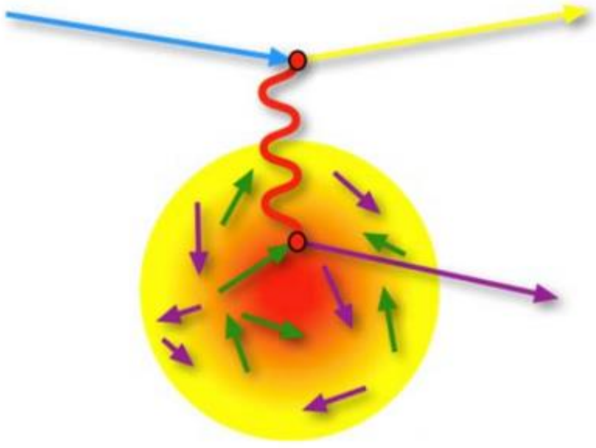
Different charged-current (CC) neutrino interaction modes



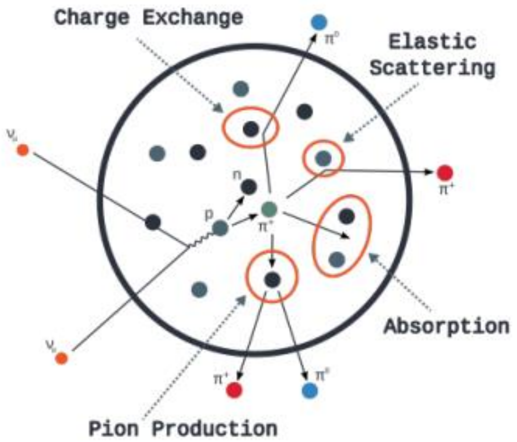


Probing Nuclear Structure and Effects

- These effects are expected to depend on nuclear size
- Complimentary ways to study these effects:
  - Study interactions across various nuclei of different sizes (this talk)
  - Study interactions on singular nucleons to study nucleon structure (Hydrogen result presented previous talk)



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

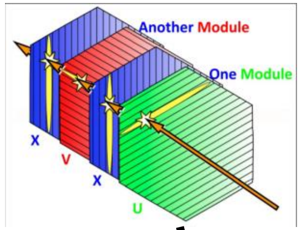


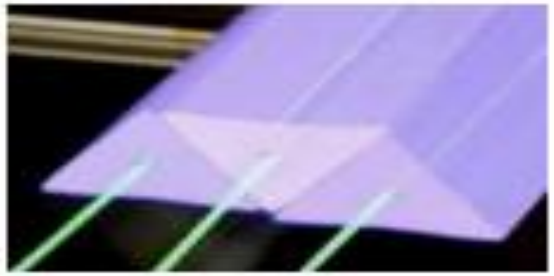
Final State Interactions “FSI”: Interactions of neutrino final state particles exiting the nucleus.

Both categories affect neutrino energy reconstruction through modified final states in both particle content and kinematics.

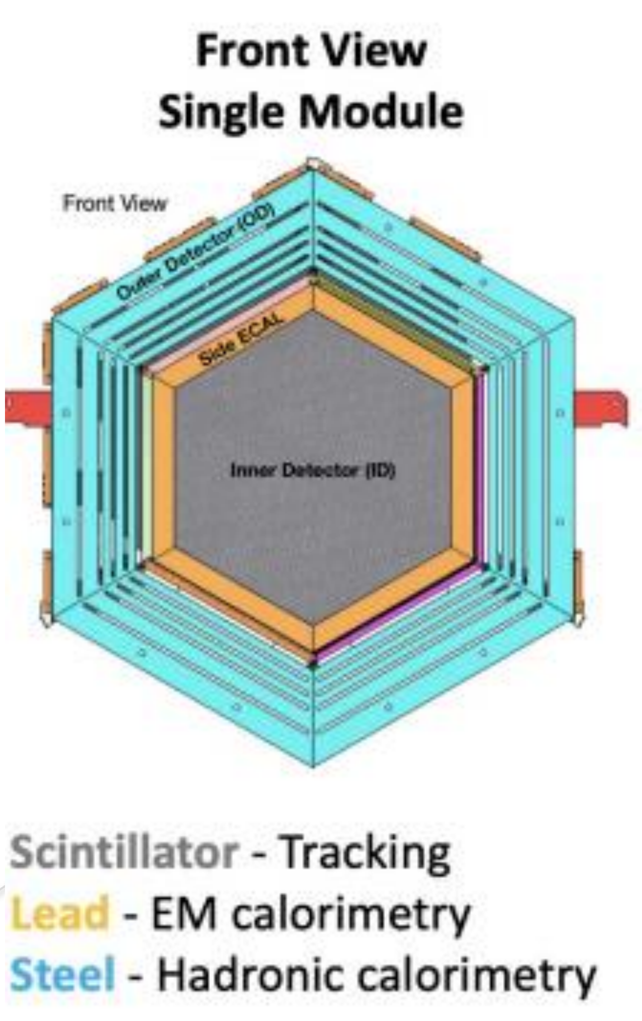
MINERνA Detector

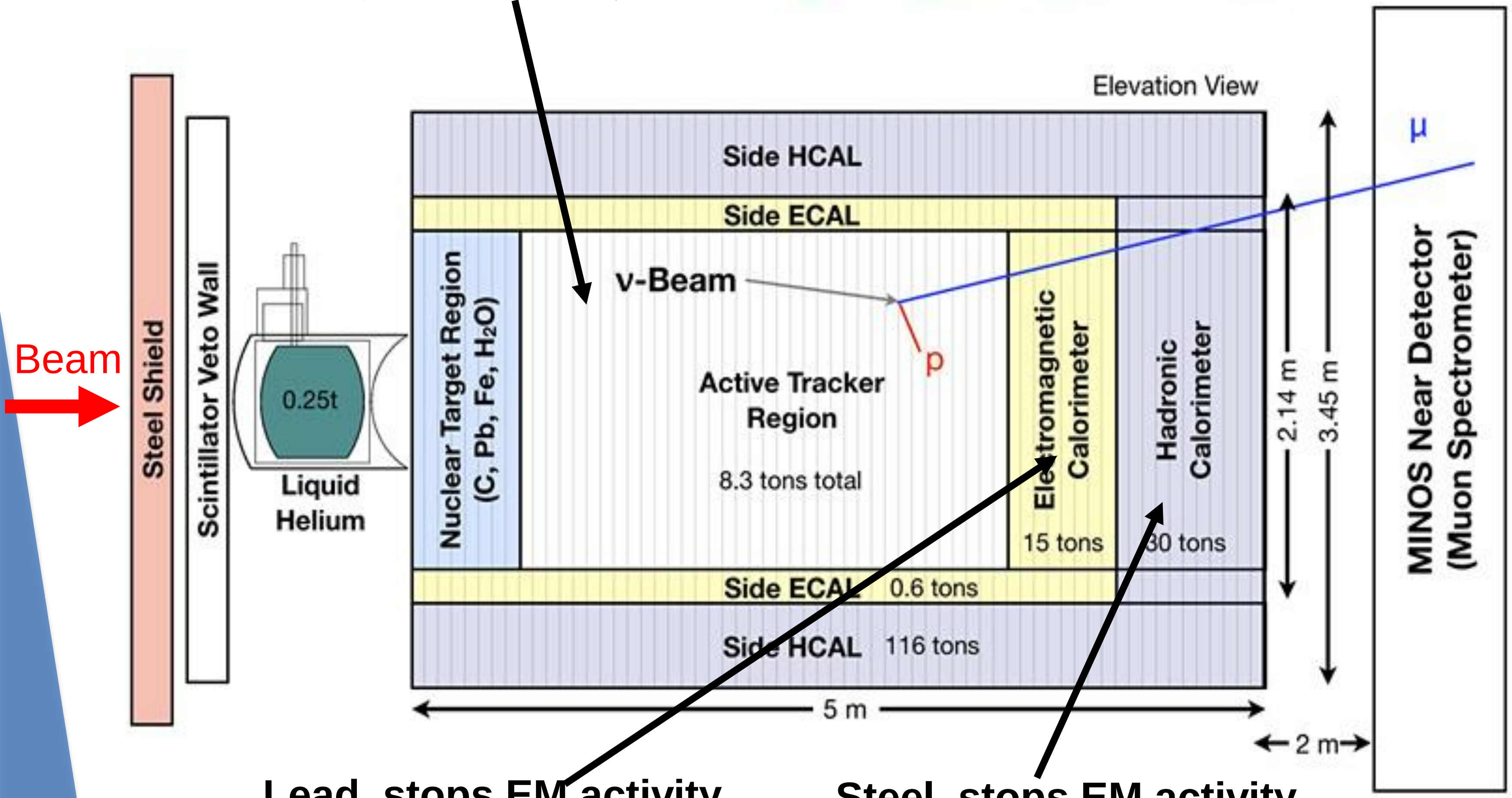
Plane rotation of scintillator allows for tracking





Charged particles pass through strips of scintillator. Light collected by fibers, measured by photomultiplier tubes.



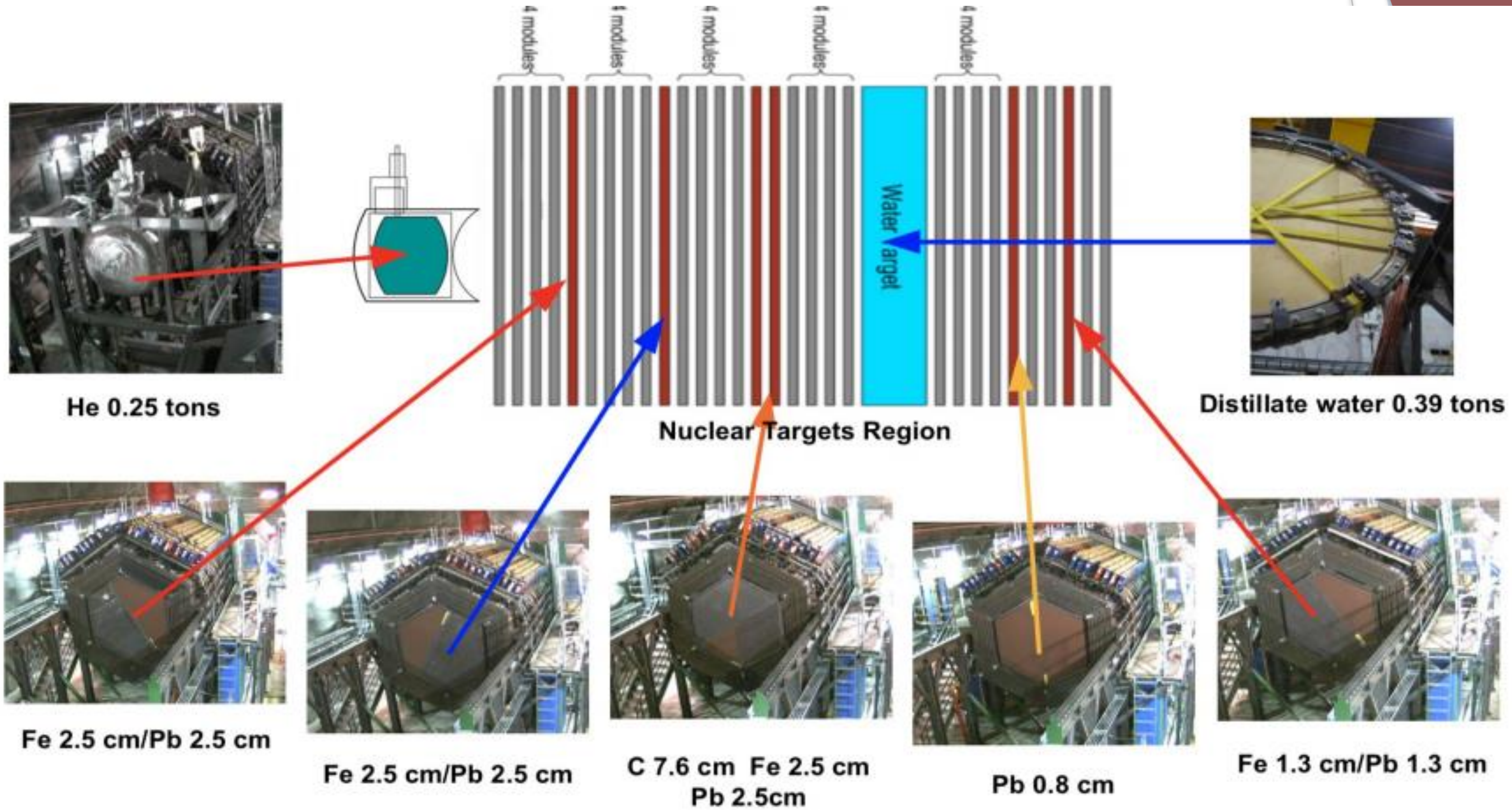


Lead, stops EM activity

Steel, stops EM activity

MINERνA Detector: Target Region

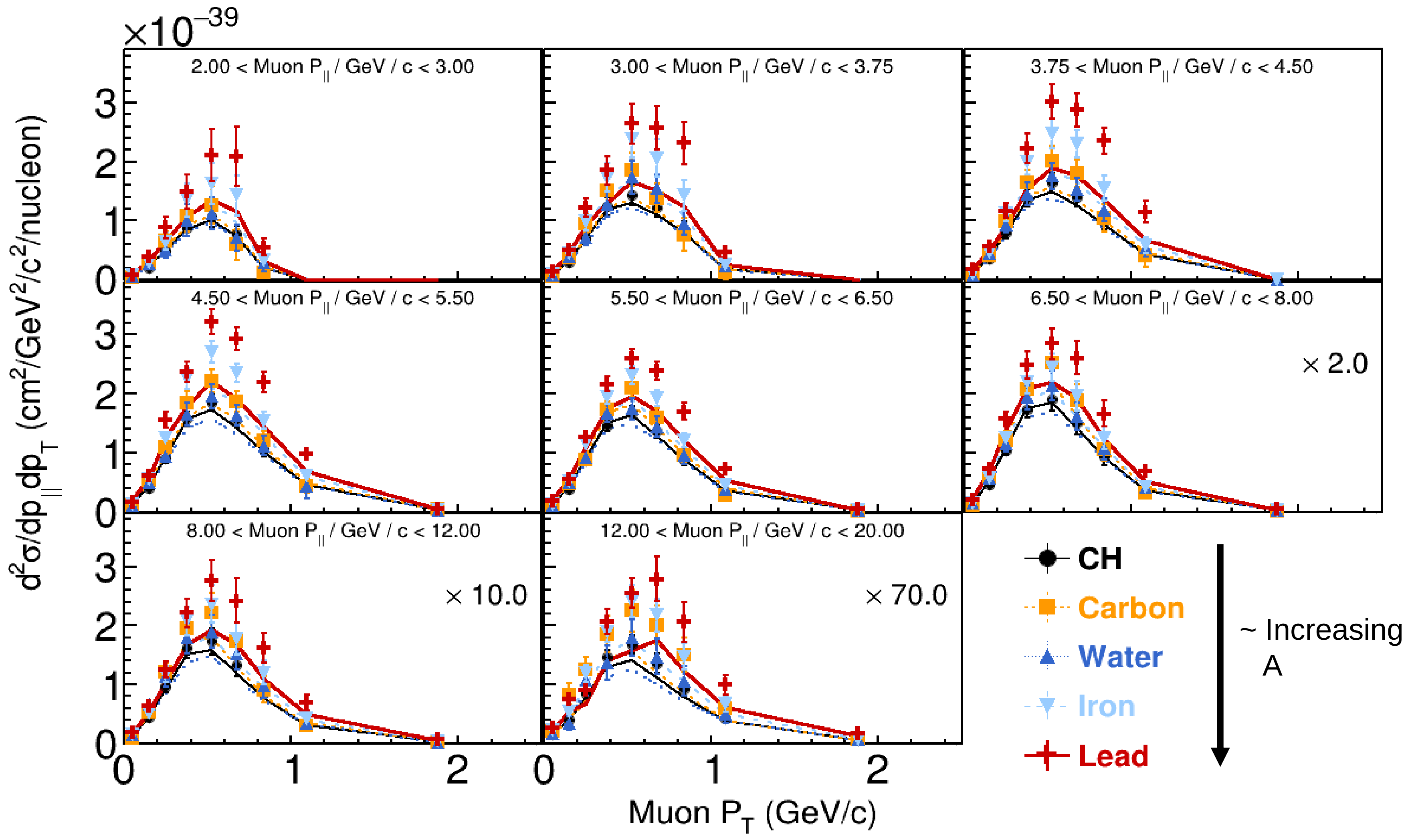
Range of nuclear sizes allows for probe of nuclear effects' dependence on said size



Results in Nuclear Targets:

2D ν_μ CCQELike Cross Sections and Ratios

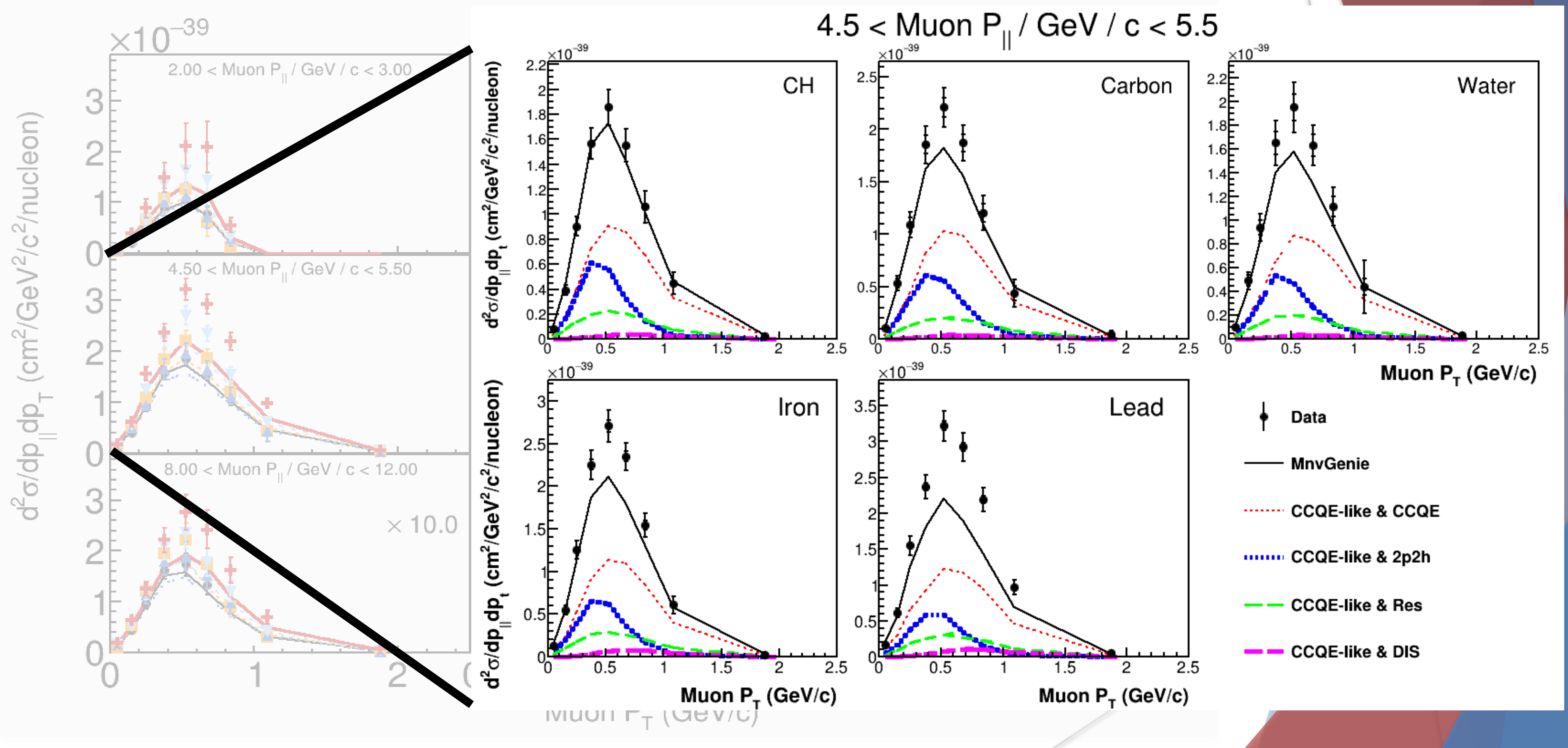
ν_μ CCQELike: Muon P_T vs. $P_{||}$ Cross-Sections



J. Kleyklamp et al.: [arxiv: 2301.02272]

ν_μ CCQELike: Muon P_T vs. $P_{||}$ Cross-Sections

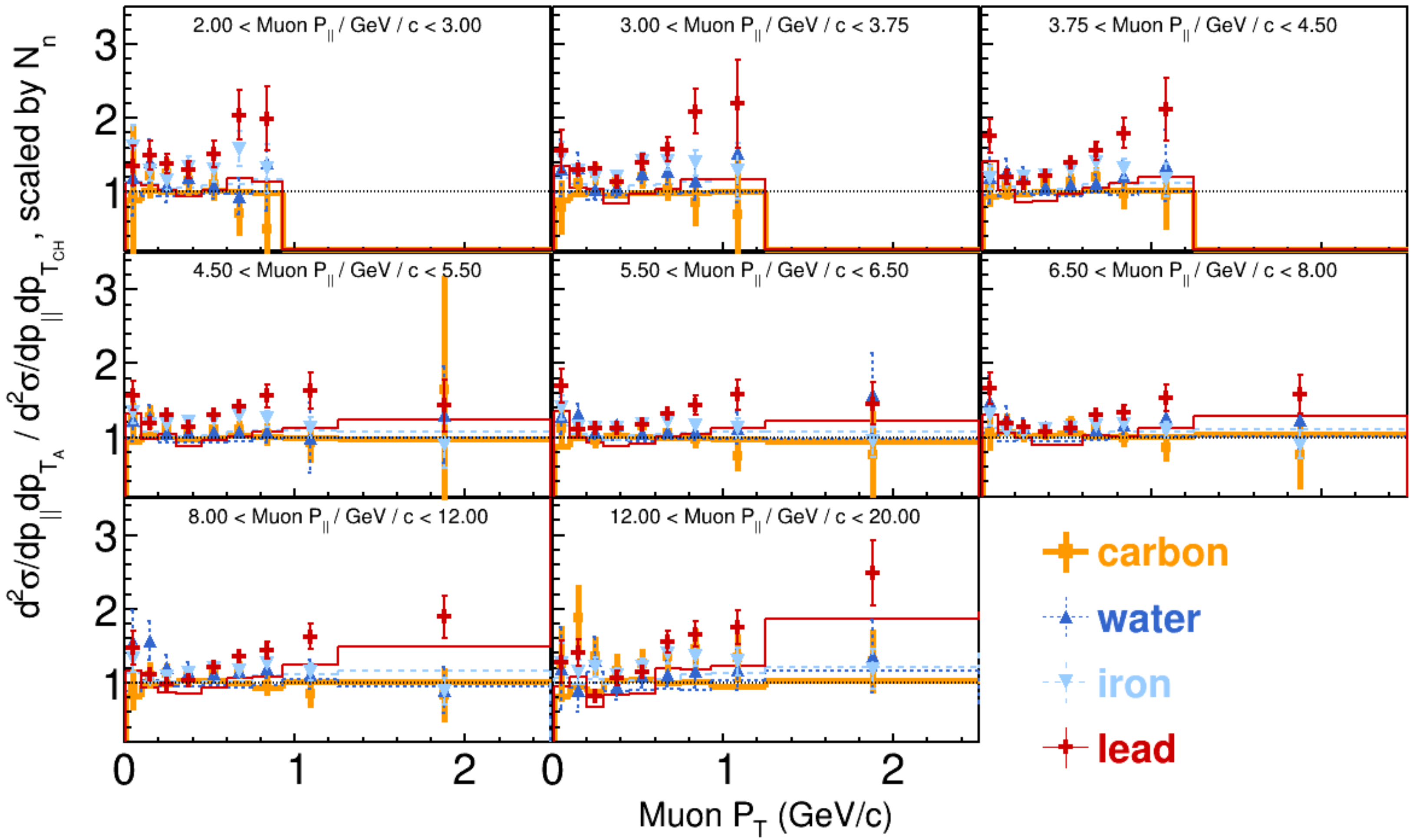
Zooming in on one $p_{||}$ bin shows power to probe different initial state contributions.



J. Kleyklamp et al.: [arxiv: 2301.02272](https://arxiv.org/abs/2301.02272)

ν_μ CCQELike: 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



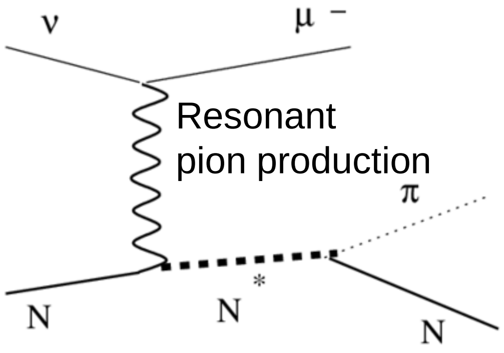
J. Kleyklamp et al.: arxiv: 2301.02272

Single Pions (CC1π)

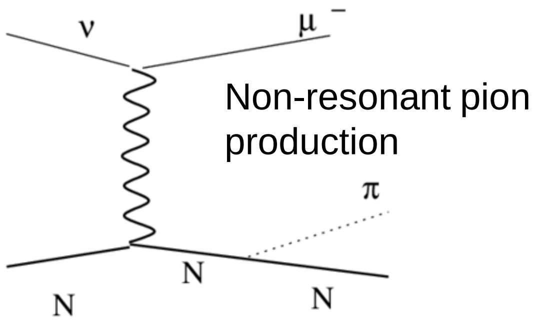
CC1π Interactions and Importance

- MINERvA's high resolution scintillator allows for pion identification
- Single pion production significant in many experimental energy ranges
- Multiple, interfering initial state processes contribute to single pion production
- Coherent production can mimic oscillation signals if particles not fully and accurately reconstructed in the final state

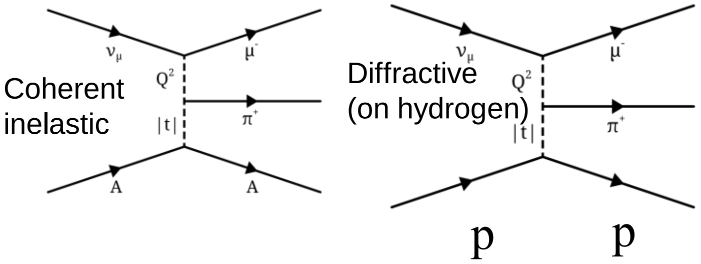
Dominant



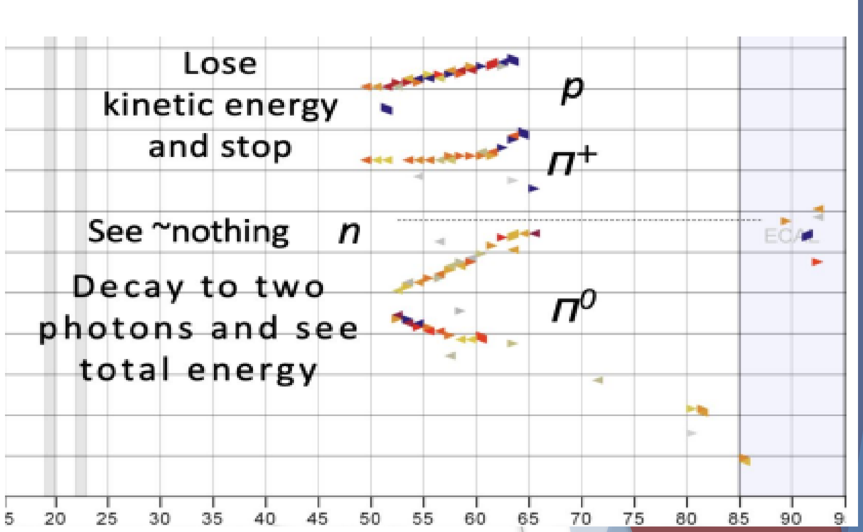
Significant

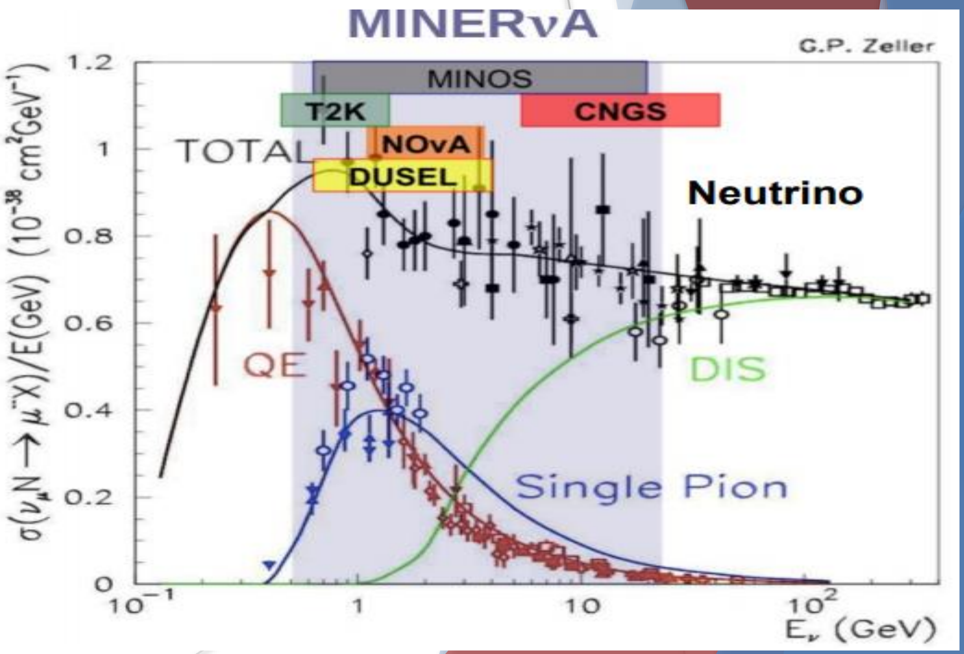


Sub-leading



From Kevin McFarland





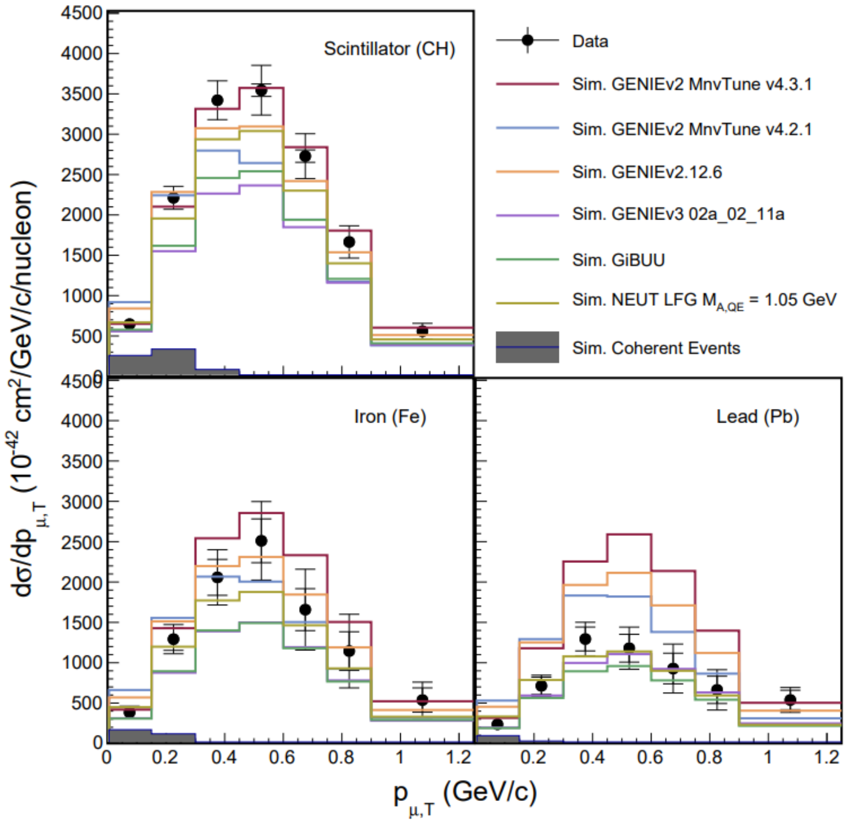
Results in Nuclear Targets:

1D ν_μ CC1π^+ Cross Sections and Ratios

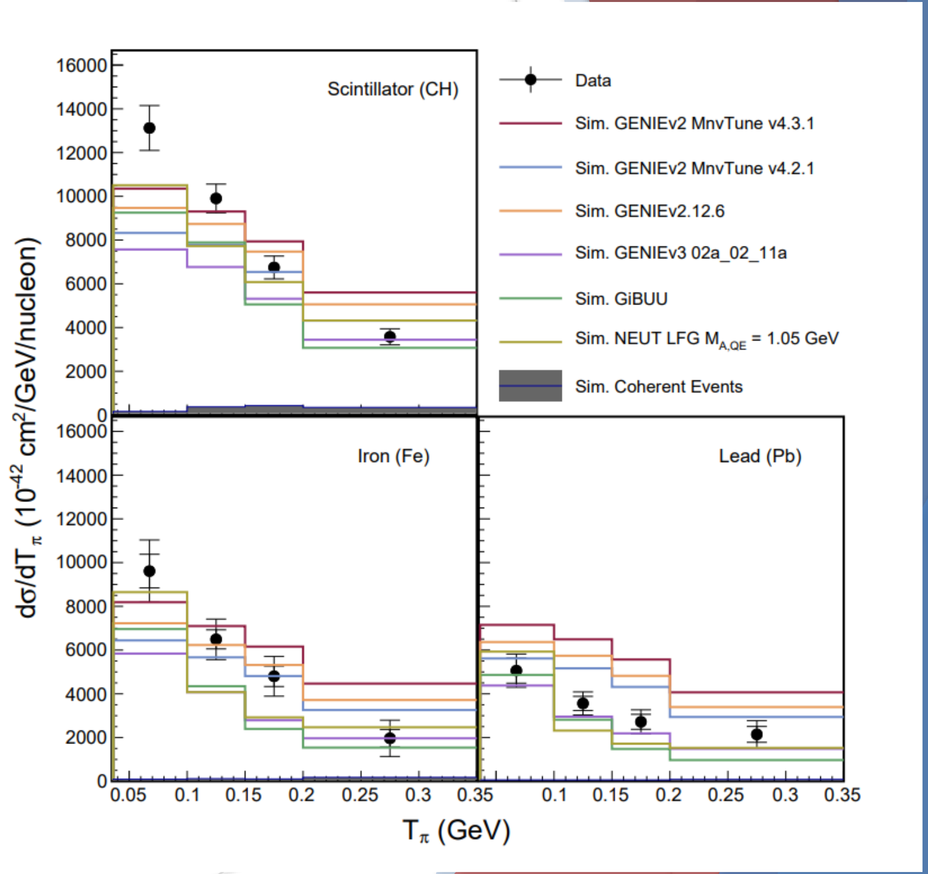
ν_μ CC1π^+ Cross Sections

- Discrepancy with tuned MC from previous MINERvA/external data, MnvTune v4.2.1
- Derived tune from this scintillator data, MnvTune v4.3.1 does better across each target
- 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)

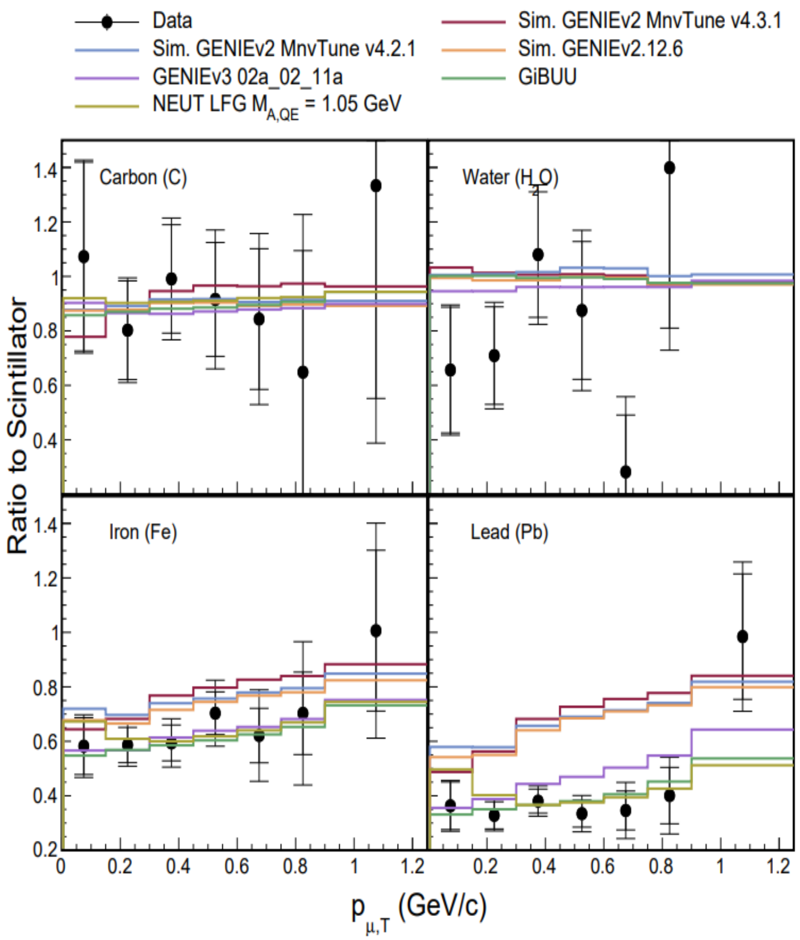


A. Bercellie et al.: arXiv: 2209.07852

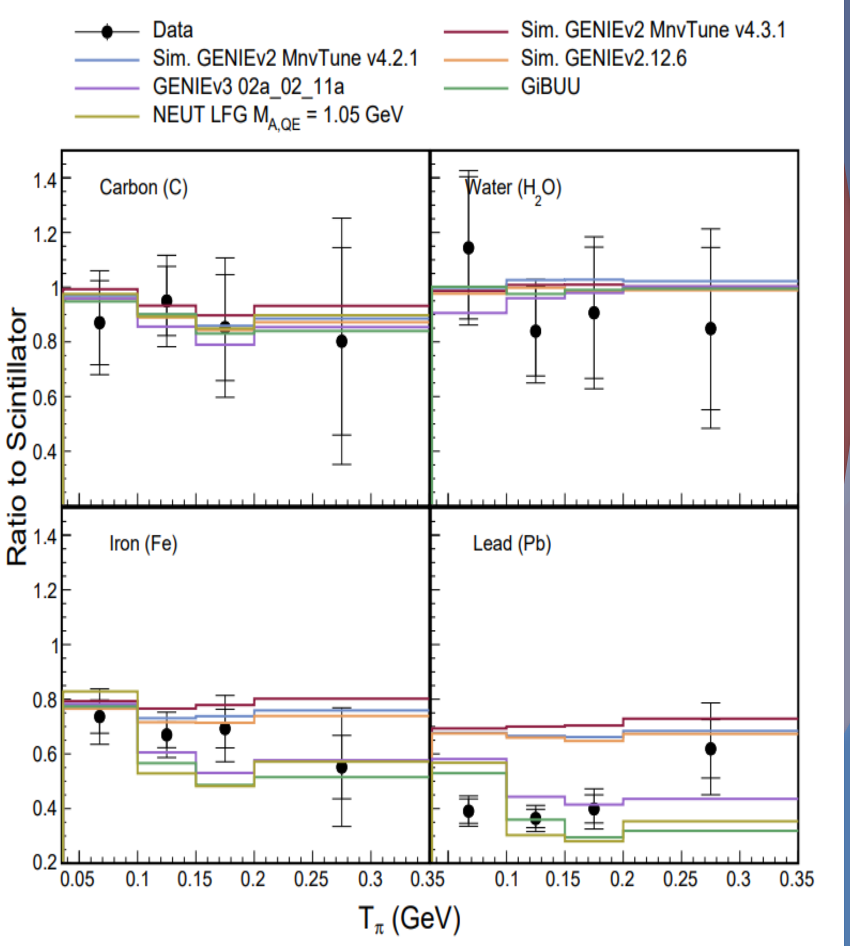
ν_μ CC1π^+ Cross Section Ratios

- Models largely overpredict A scaling:
  - Possible underprediction of A scaling of pion absorption
  - Opposite sign of CCQELike discrepancy
- Carbon and Water ratios consistent with unity

Muon P_T



Pion Kinetic Energy (T_π)



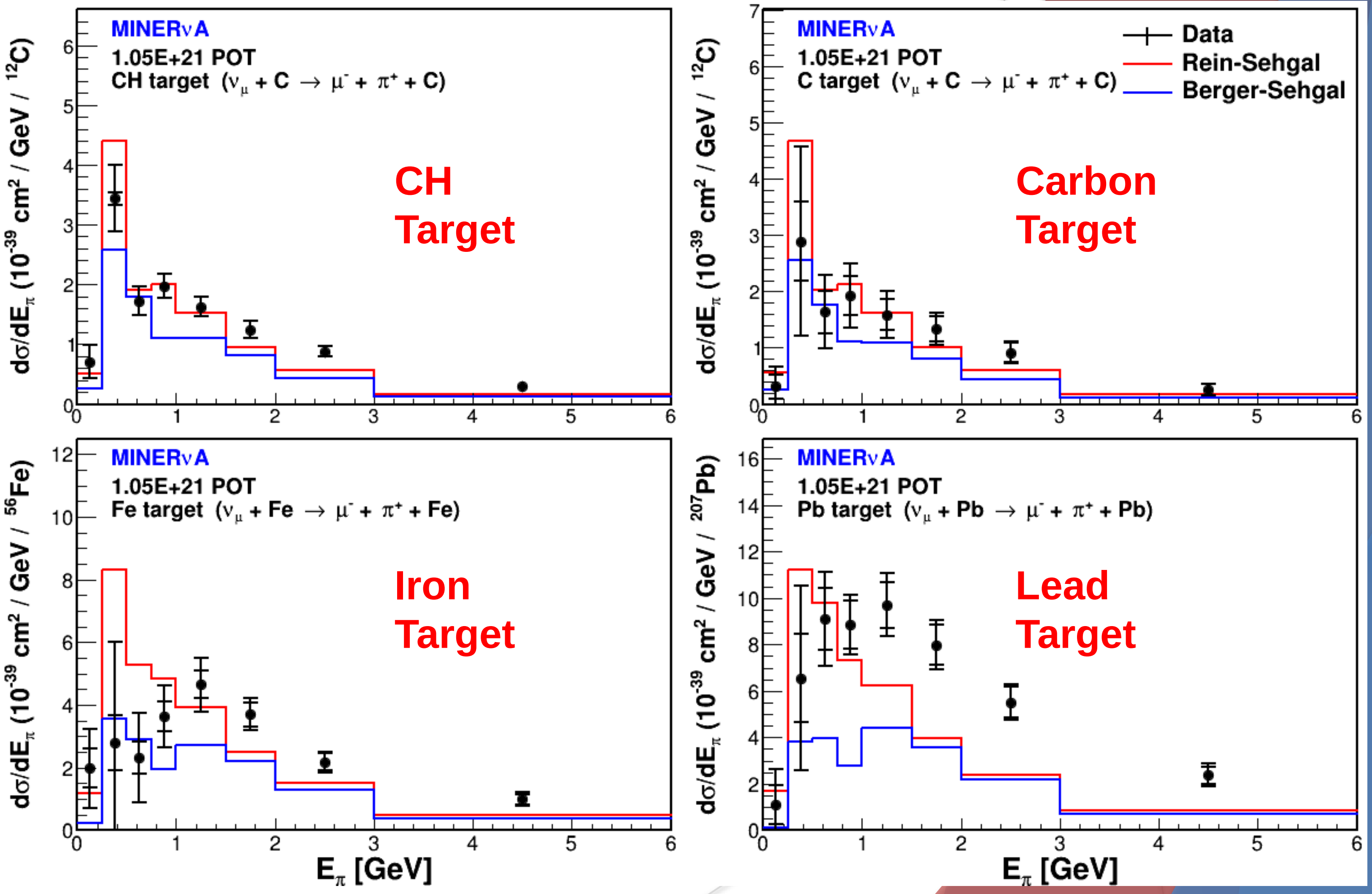
Results in Nuclear Targets:

1D ν_μ Coherent CC1π^+ Cross Sections and A Scaling

ν_μ Coherent CC1π^+ Cross Sections

- First measurement of the CC process in A > 40
- Neither model predicts well the pion energy distribution, especially for iron and lead
- Pion angle in backup
- Two models being compared:
  - GENIE v2.12.6 (Rein-Seghal)
  - GENIE v3.0.6 (Berger-Seghal)

Pion Energy (E_π)

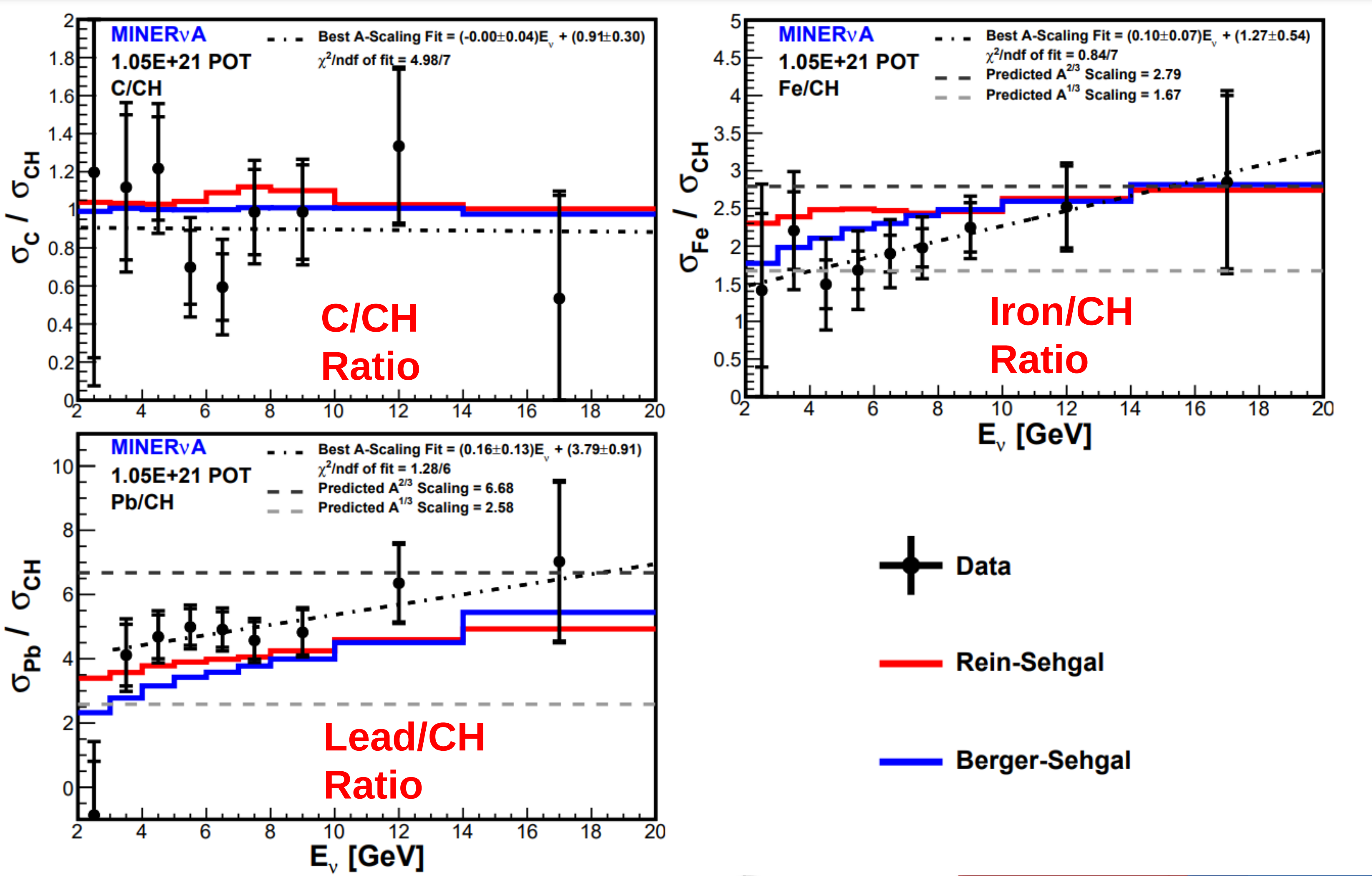


M. A. Ramírez et al.: arXiv: 2210.01285

ν_μ Coherent CC1π^+ Cross Section Scaling

- A-dependence of scaling predicted to be:
  - $A^{1/3}$ (Rein-Seghal)
  - $A^{2/3}$ (Berger-Seghal)
- Absolute measurements in backup
- Energy dependence of Fe scaling appears to follow prediction of Belkov-Kopeliovich model ($A^{1/3}$ transition to $A^{2/3}$ with increasing energy)
- Two models being compared:
  - GENIE v2.12.6 (Rein-Seghal)
  - GENIE v3.0.6 (Berger-Seghal)

Neutrino Energy Ratio to CH



M. A. Ramírez et al.: arXiv: 2210.01285

Summary

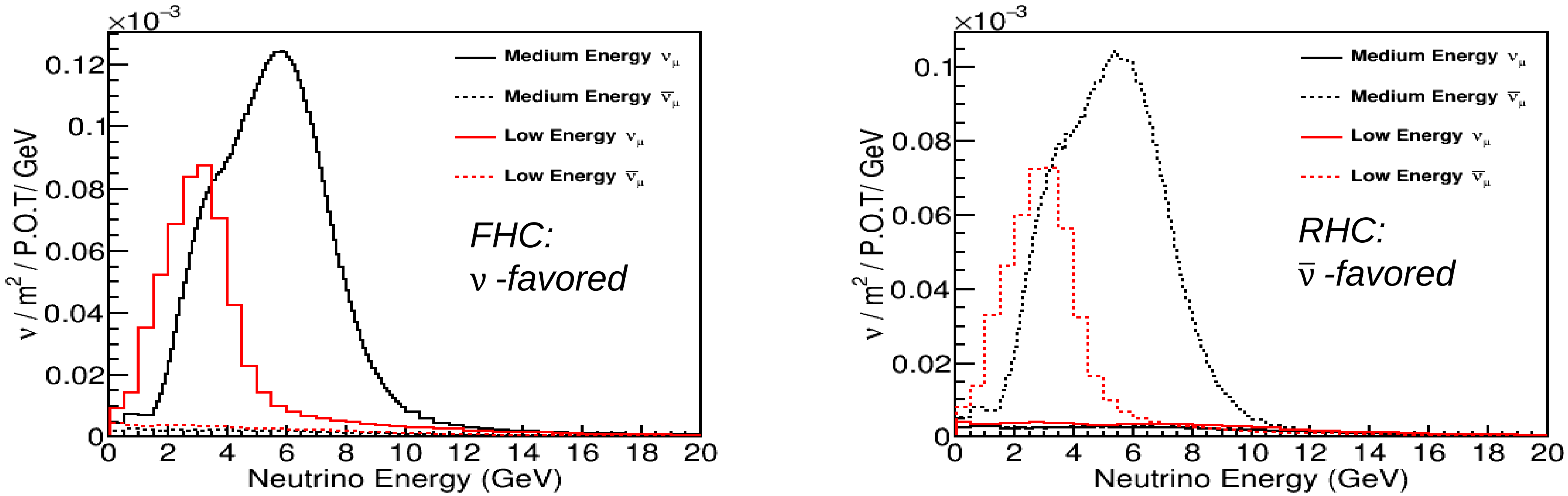
MINERνA and its Nuclear Targets

- MINERνA's recent results from its nuclear targets have provided great insight into neutrino interactions with a range of nuclei
- Measurements across different final states have provided complimentary insight into the model predictions for neutrino scattering
- MINERνA's large statistics dataset allowed for the first simultaneous measurement of neutrino-induced coherent pion production in multiple materials to allow for ratio measurement
- More nuclear target measurements to come!

Backup

MINERνA History, Datasets, and Fluxes

- EOI: 2002, Construction Start: 2007, First Full Detector Data: 2009
- Data-taking has been completed for both energy configurations → **MINERvA has been decommissioned**



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

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

MINERνA 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

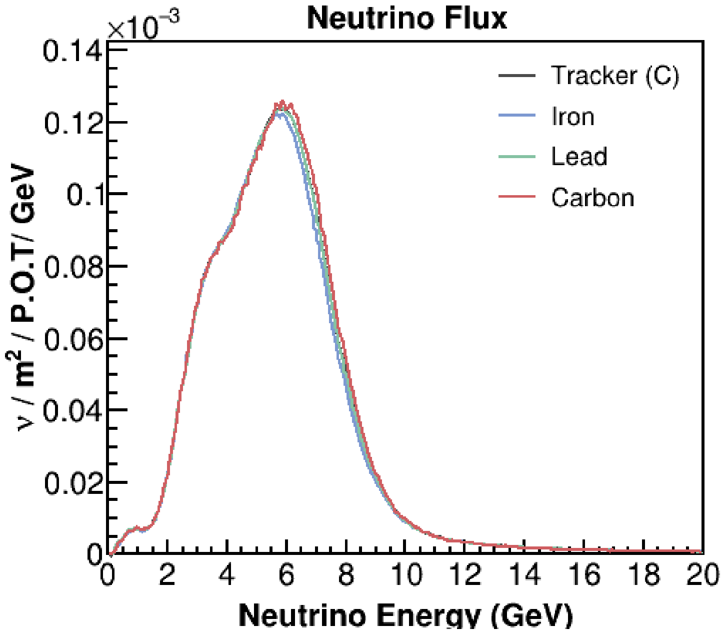
X	Description
1	the original tune. Valencia RPA applied to QE (RFG), non-resonant pion production reduction, low recoil fit (LE) applied to Valencia 2p2h
2	Same as 1 but includes the Stowell et. al (MINERvA) GENIE pion tune low Q2 suppression
3	Replace Valencia 2p2h with SuSA 2p2h, non-resonant pion 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

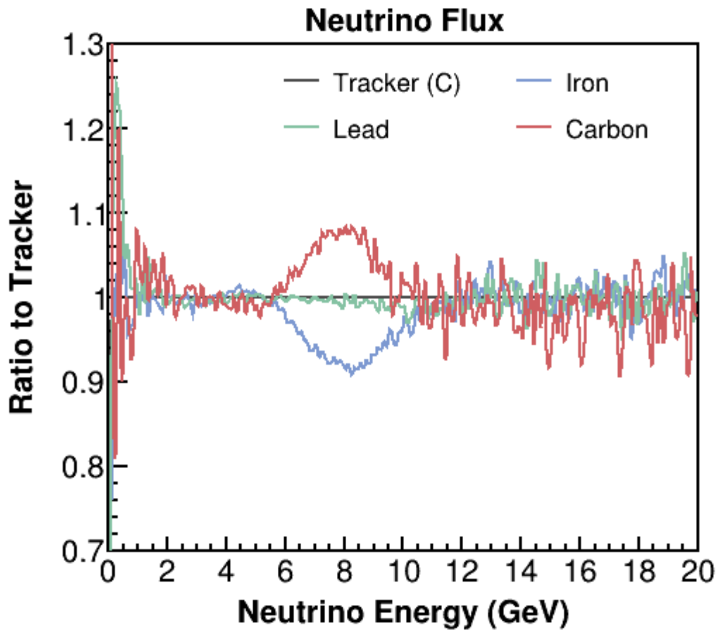
Y	Description
1	Normalization change of coherent pion production Epi
2	Normalization change of coherent pion production using the angle and E pi distributions (ME)
3	A. Bercellie low Q2 pion production suppression (see docDB 30137) and normalization of coherent pion production using the angle and E pi 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

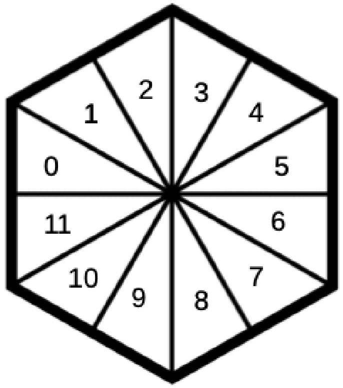
Z	Description
1	Bug fix of elastic FSI in pions and protons

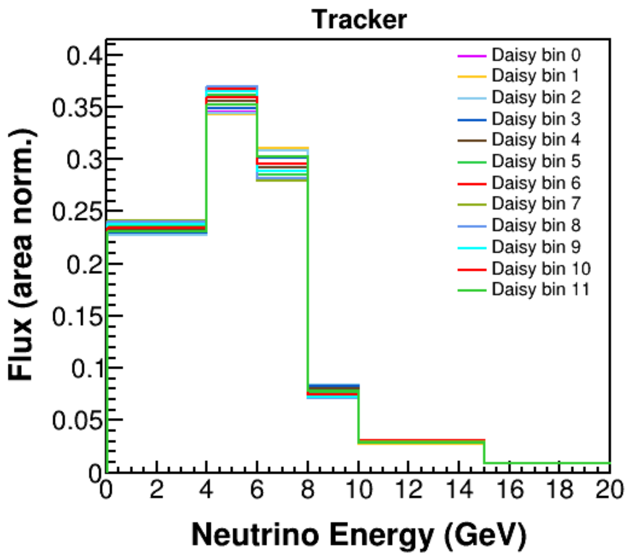
Flux for Cross-Section Ratios

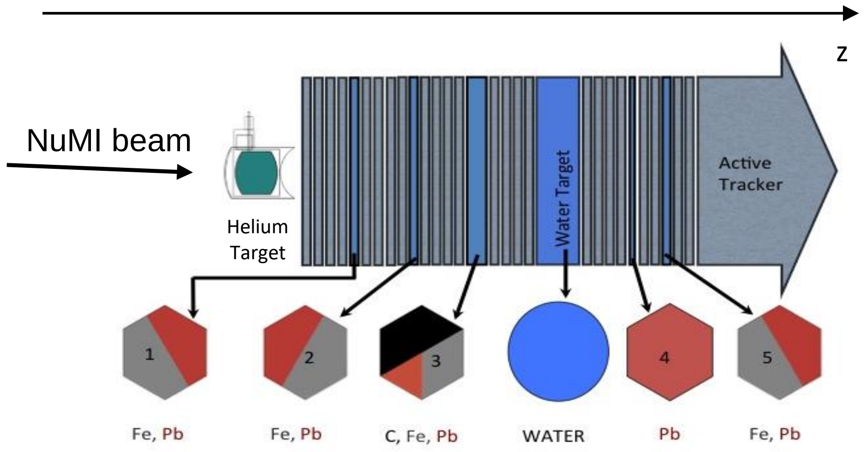
- NuMI beam pointed downwards → transverse center of the beam changes as a function of the longitudinal position
- Difference in the flux shape + normalization in the nuclear targets compared to the tracker (problem for cross-section ratios)
- **“Daisy technique”** – take linear combination of tracker fluxes in 12 bins to match the target







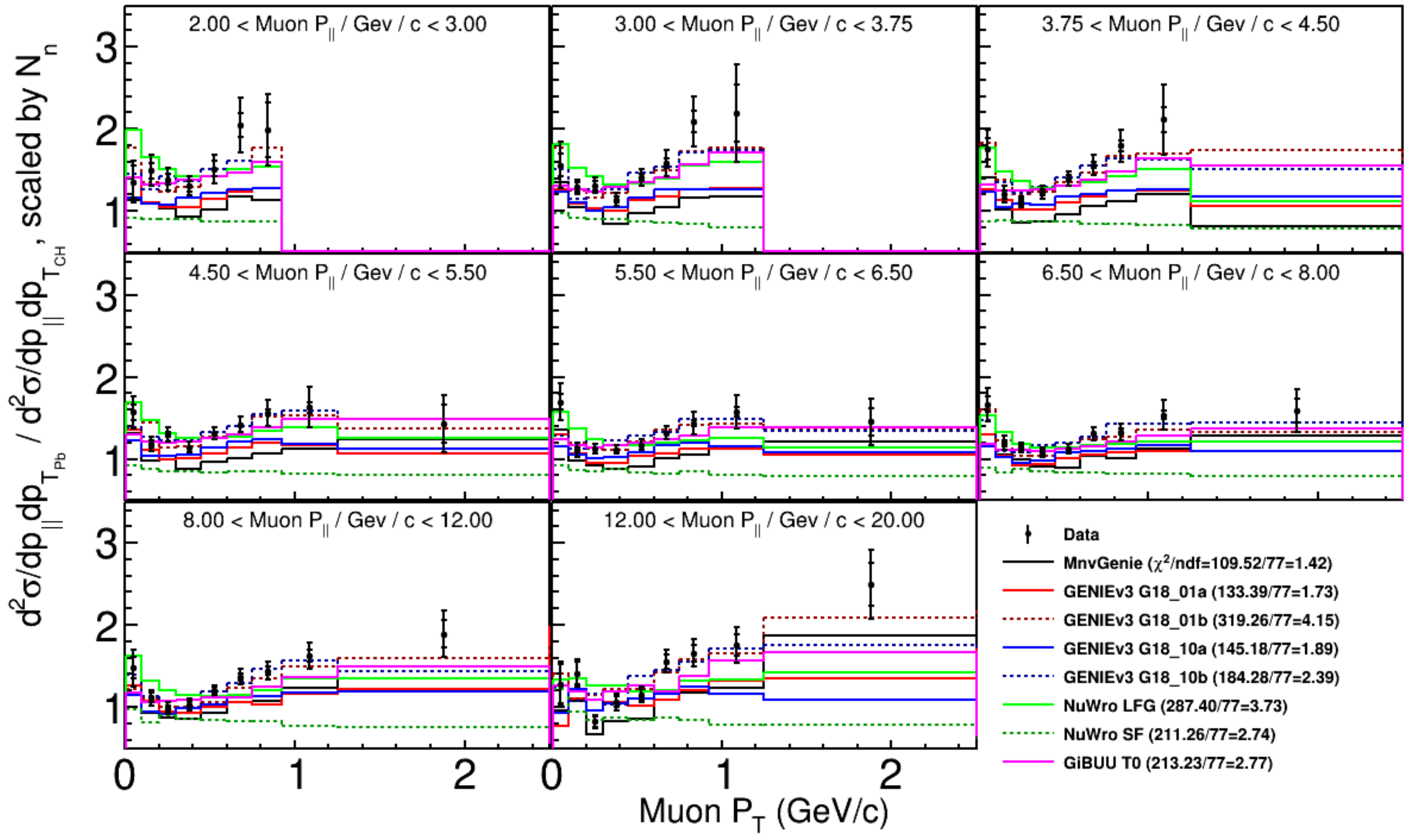




Slide borrowed from collaborator, Anežka Klustová

2D Neutrino CCQELike/CC0π: Lead Ratio Model Comparison

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

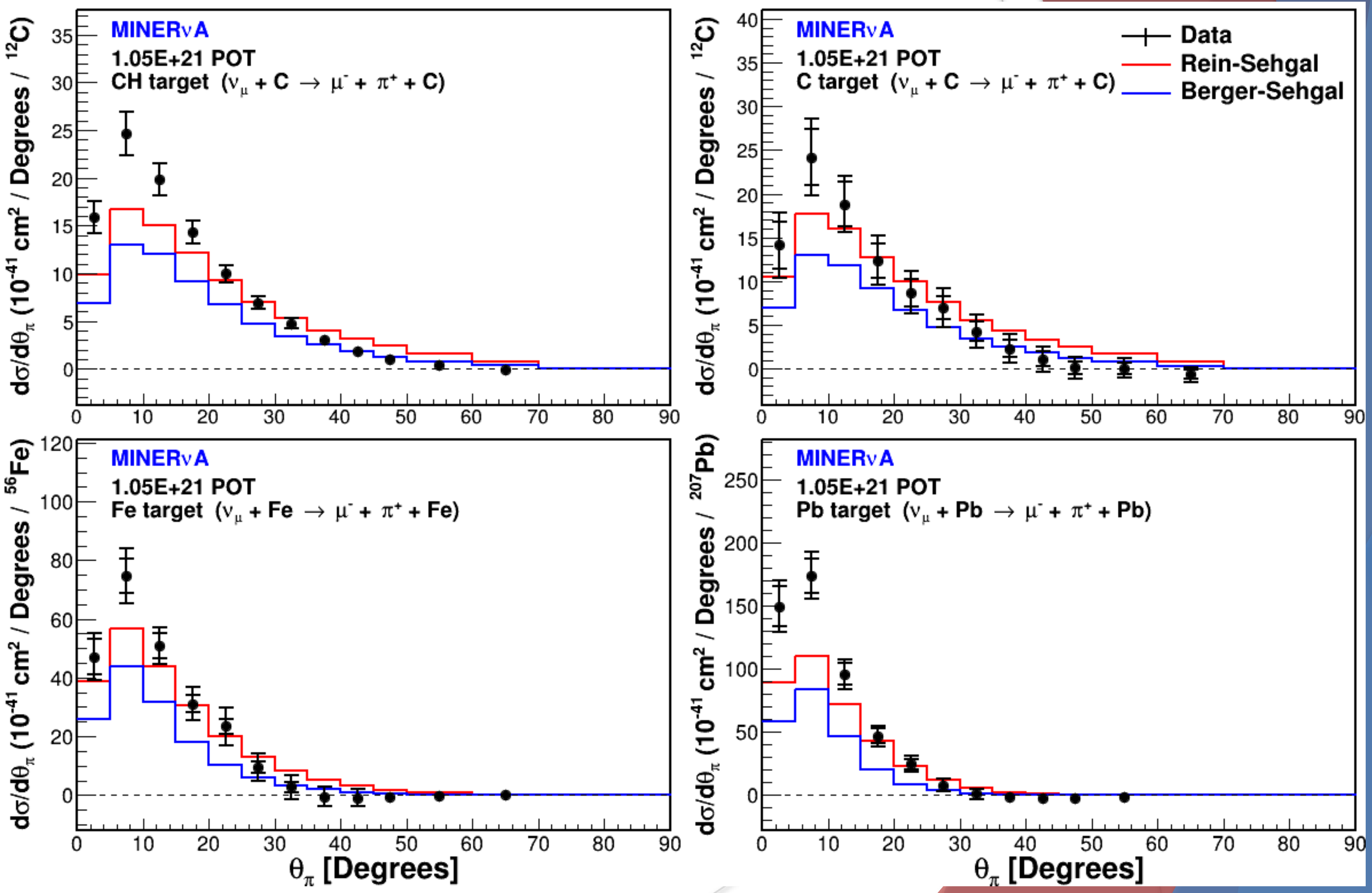


J. Kleyklamp et al.: arxiv: 2301.02272

ν_μ Coherent CC1π^+ Cross Sections

- Models underpredict forward pions, more so for lead
- Two models being compared:
  - GENIE v2.12.6 (Rein-Seghal)
  - GENIE v3.0.6 (Berger-Seghal)

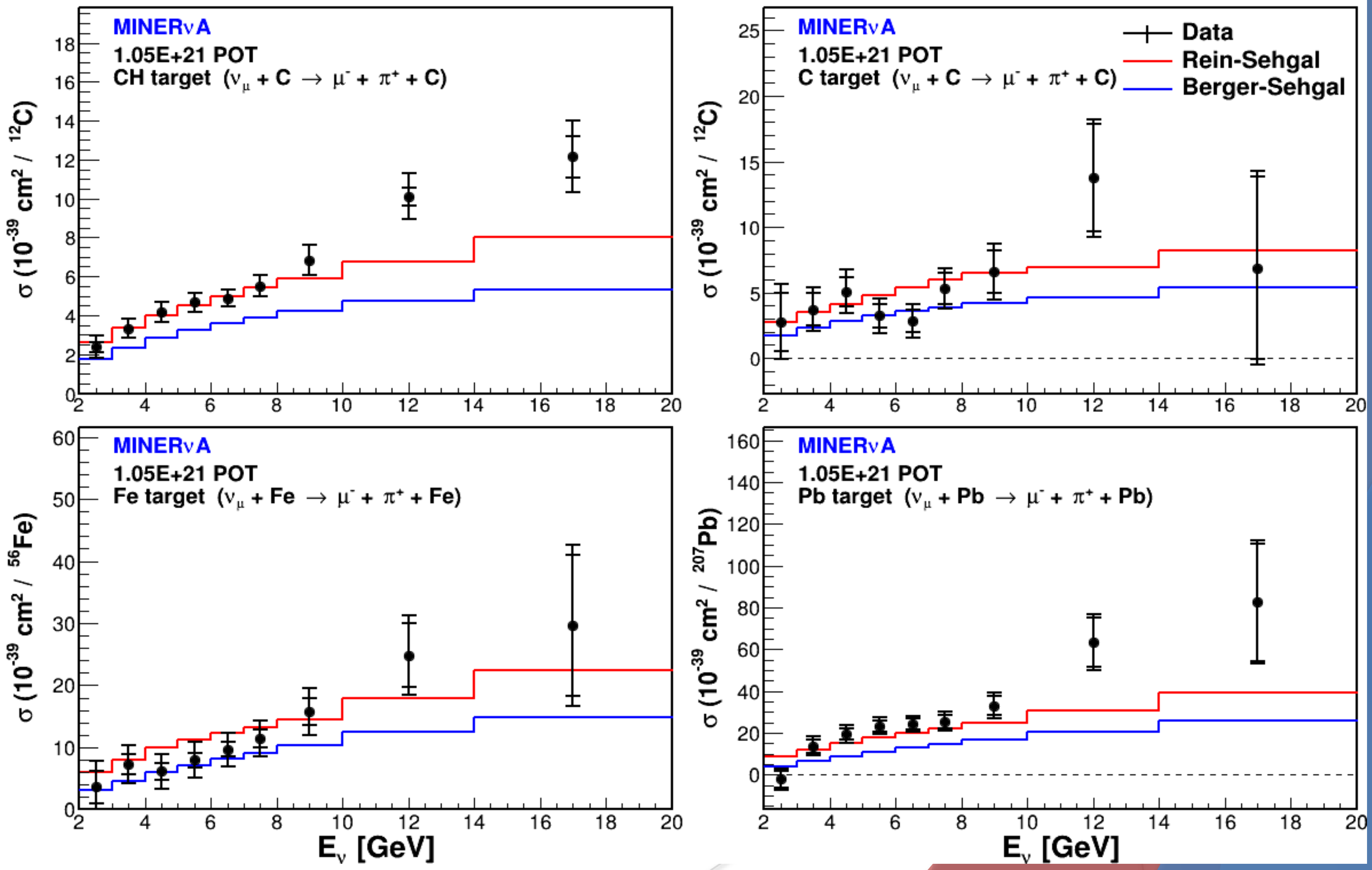
Pion Angle (θ_π)



M. A. Ramírez et al.: arXiv: 2210.01285

ν_μ Coherent CC1π^+ Cross Sections

Neutrino Energy (E_ν)



- Disagreement with both models at high E_ν
- Two models being compared:
  - GENIE v2.12.6 (Rein-Seghal)
  - GENIE v3.0.6 (Berger-Seghal)

M. A. Ramírez et al.: arXiv: 2210.01285