Probing Nuclear Effects in QE-like Neutrino Scattering at MINERvA

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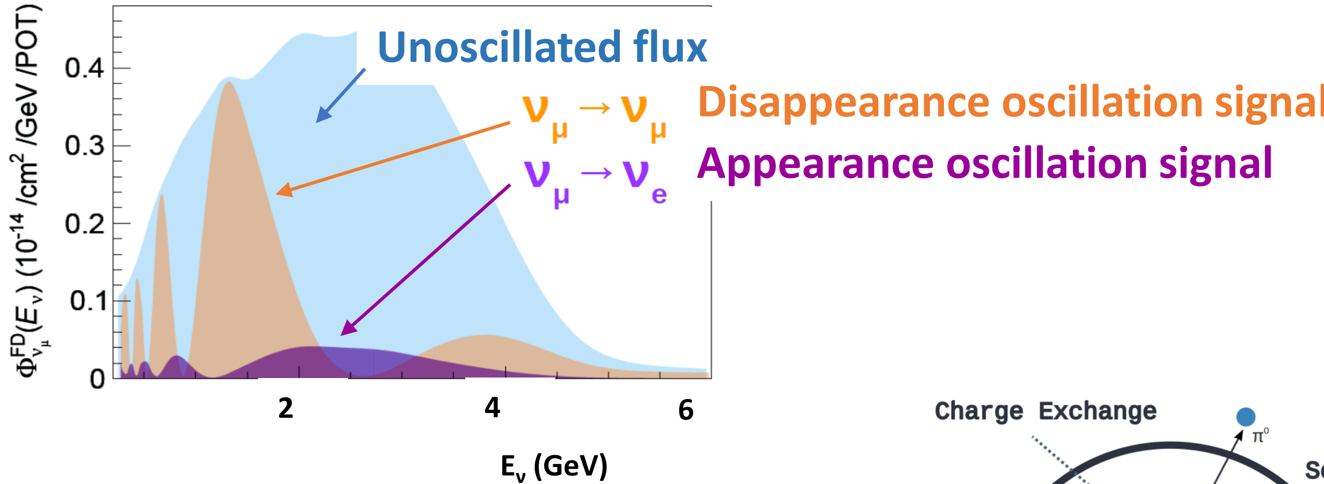
XX International Workshop on Neutrino Telescopes

Venice, October 23-27, 2023

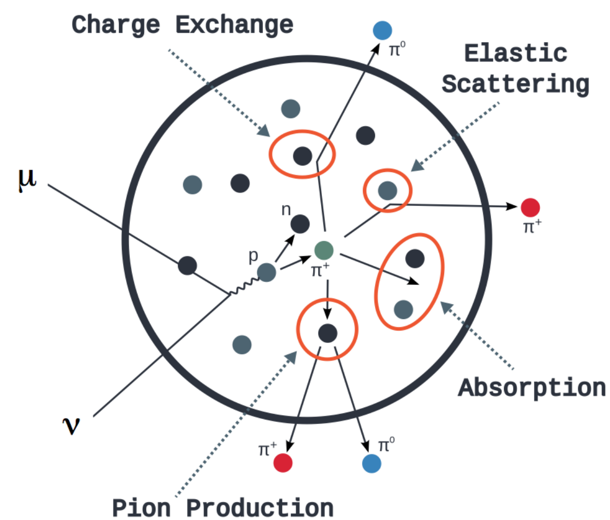
Natalie Curtis Burlin – Venice at Night - Metropolitan Museum of Art Collection – Wikimedia Commons

One motivation for this work

Estimate of flux at the DUNE far detector

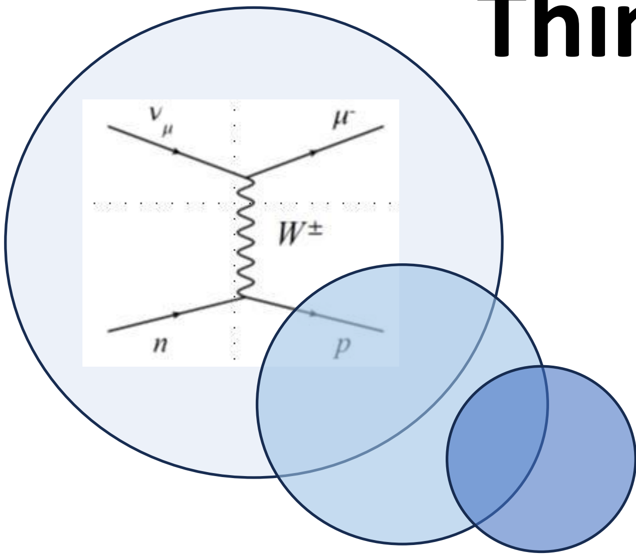


- Long baseline oscillation experiments – spectral information critical
- Reconstruct E_ν
- Things happen in nucleus
- Must model nuclear effects well
- Results here can be used to compare/develop/constrain/tune models



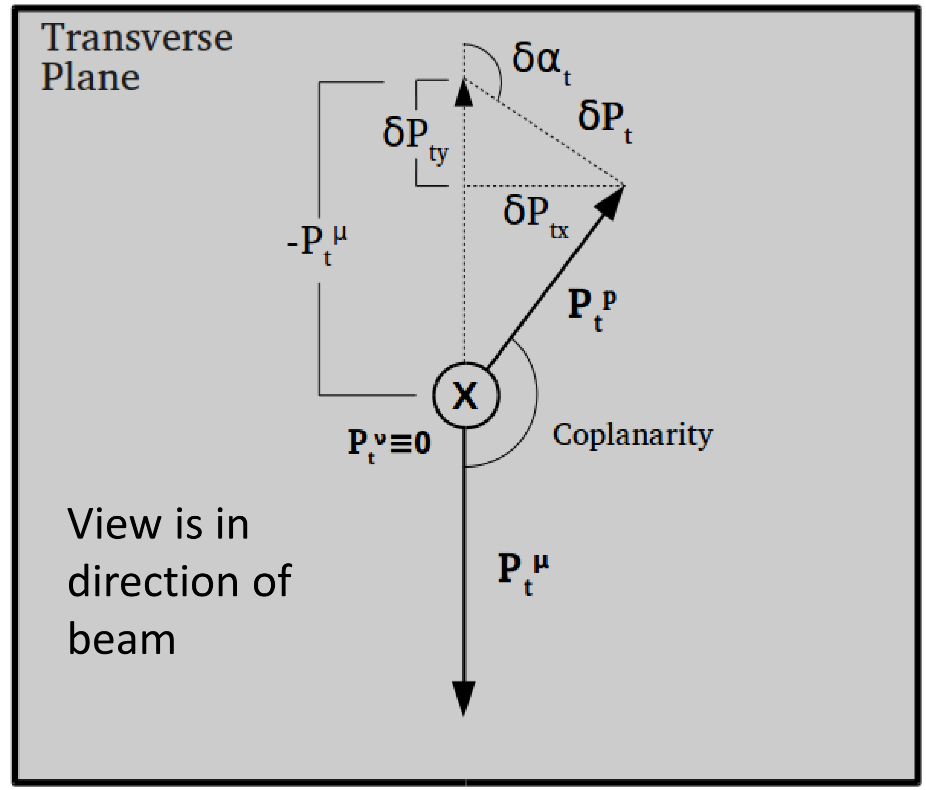
Versions of figure in common use. Internet creep. I got this from arXiv:1602.05299. I think earliest version from T. Golan.

Things to measure



Do as function of nuclear size (A)

- Transverse Kinematic Imbalance (TKI) variables: Correlate the leptonic and hadronic sides
- Derived variables also of interest



Derived variables:

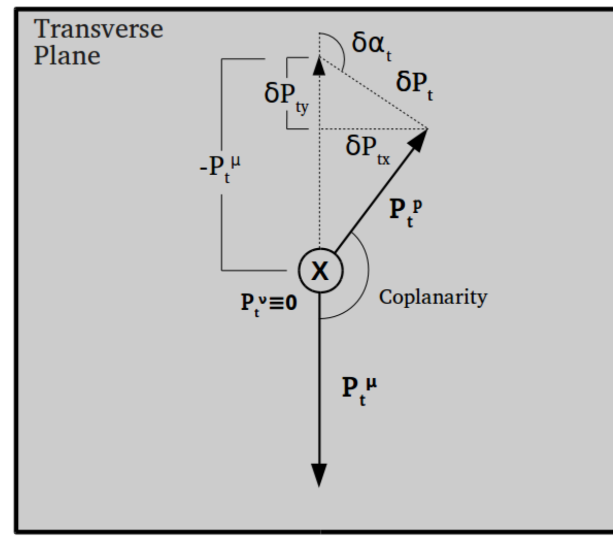
$$\delta P_L \equiv \frac{1}{2}R - \frac{m_{A'}^2 + \delta P_T^2}{2R}$$

$$P_n \equiv \sqrt{\delta {P_T}^2 + \delta {P_L}^2}$$

$$R \equiv m_A + p_L^\mu - E^\mu - E^P$$

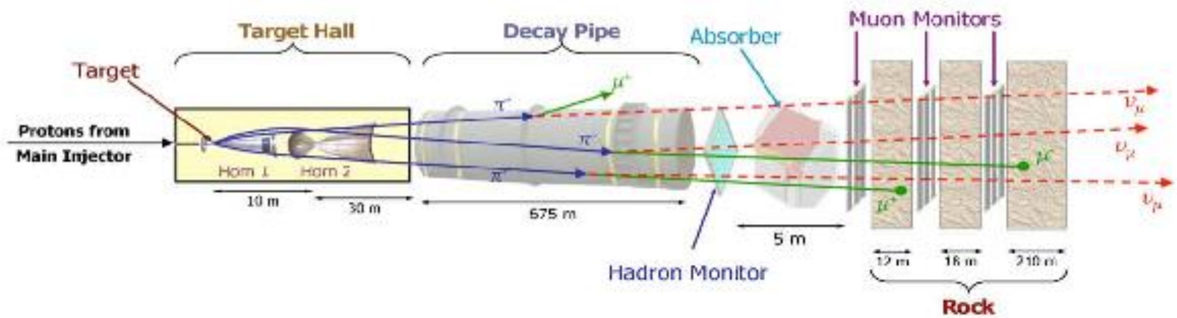
Probe initial state and final state nuclear effects

- Proton energy loss – α_T, δp_{Ty}
- Proton deflection – ϕ_T, δp_{Tx}
- Pion absorption – α_T, p_n
- Fermi momentum – δp_T, δp_{Tx}, δp_{Ty}, p_n
- Binding energy – δp_{Ty}
- Struck neutron momentum – p_n
- 2p2h (initial state nuclear correlations) – ϕ_T, p_n

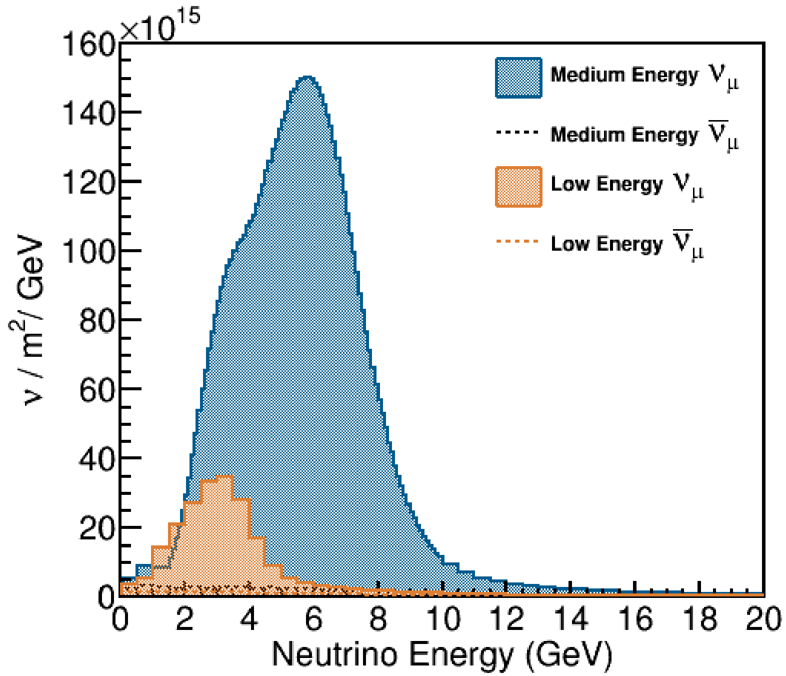


$$P_n \equiv \sqrt{\delta {P_T}^2 + \delta {P_L}^2}$$

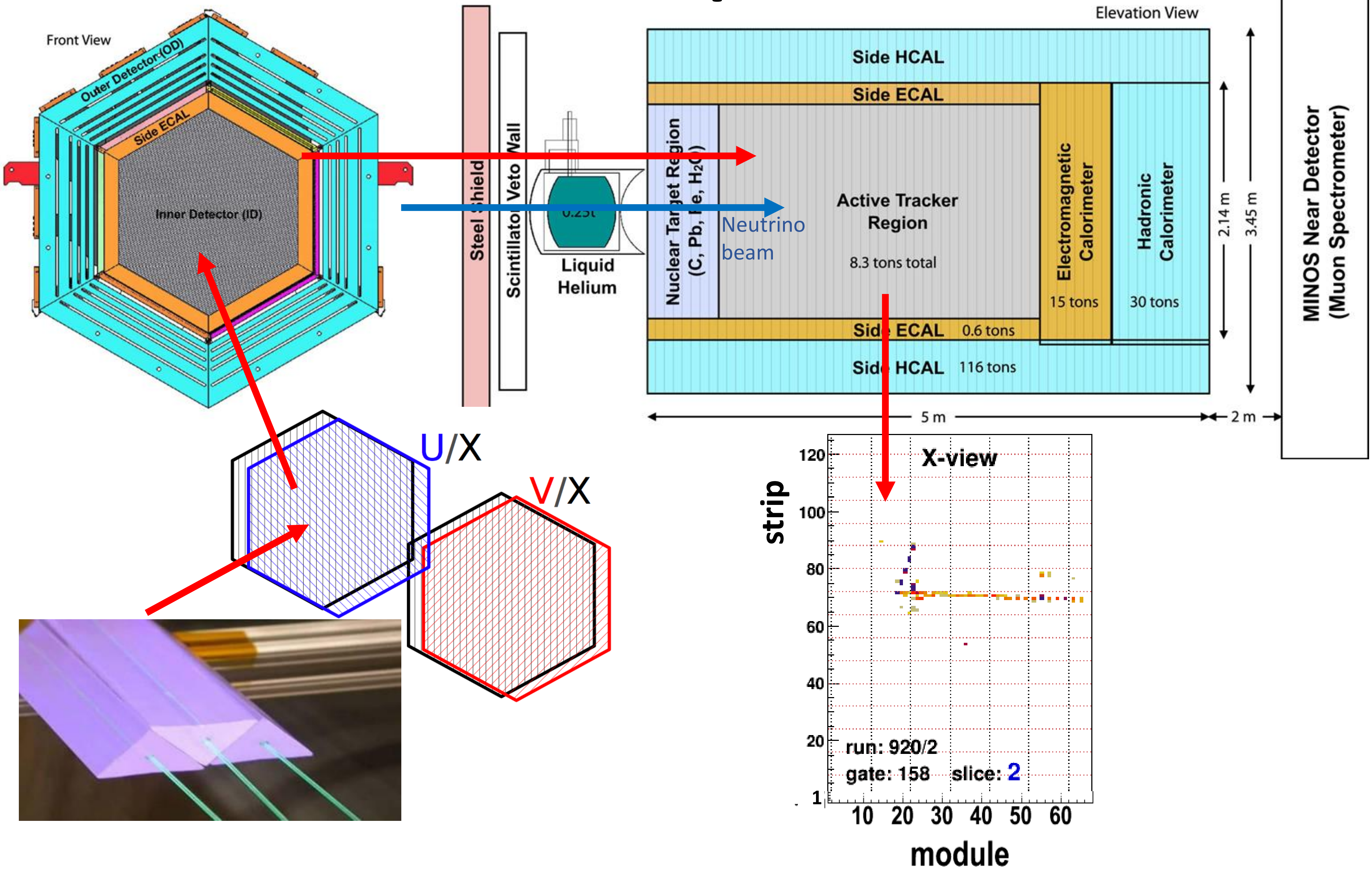
Neutrino beam: NuMI beam at Fermilab



- Data taken in neutrino enriched medium energy beam $< E_\nu > \sim 6$ GeV
- 3.8% antineutrino contamination
- High statistics:
  10.61 x 10^{20} protons-on-target



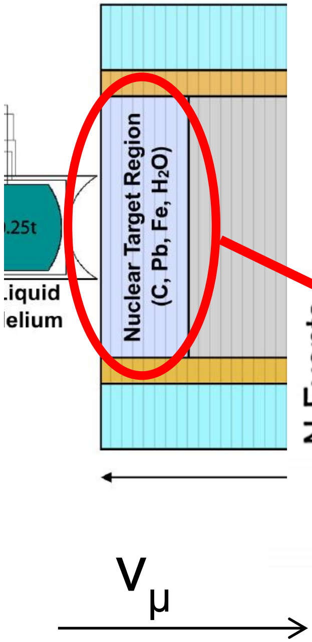
MINERvA experiment

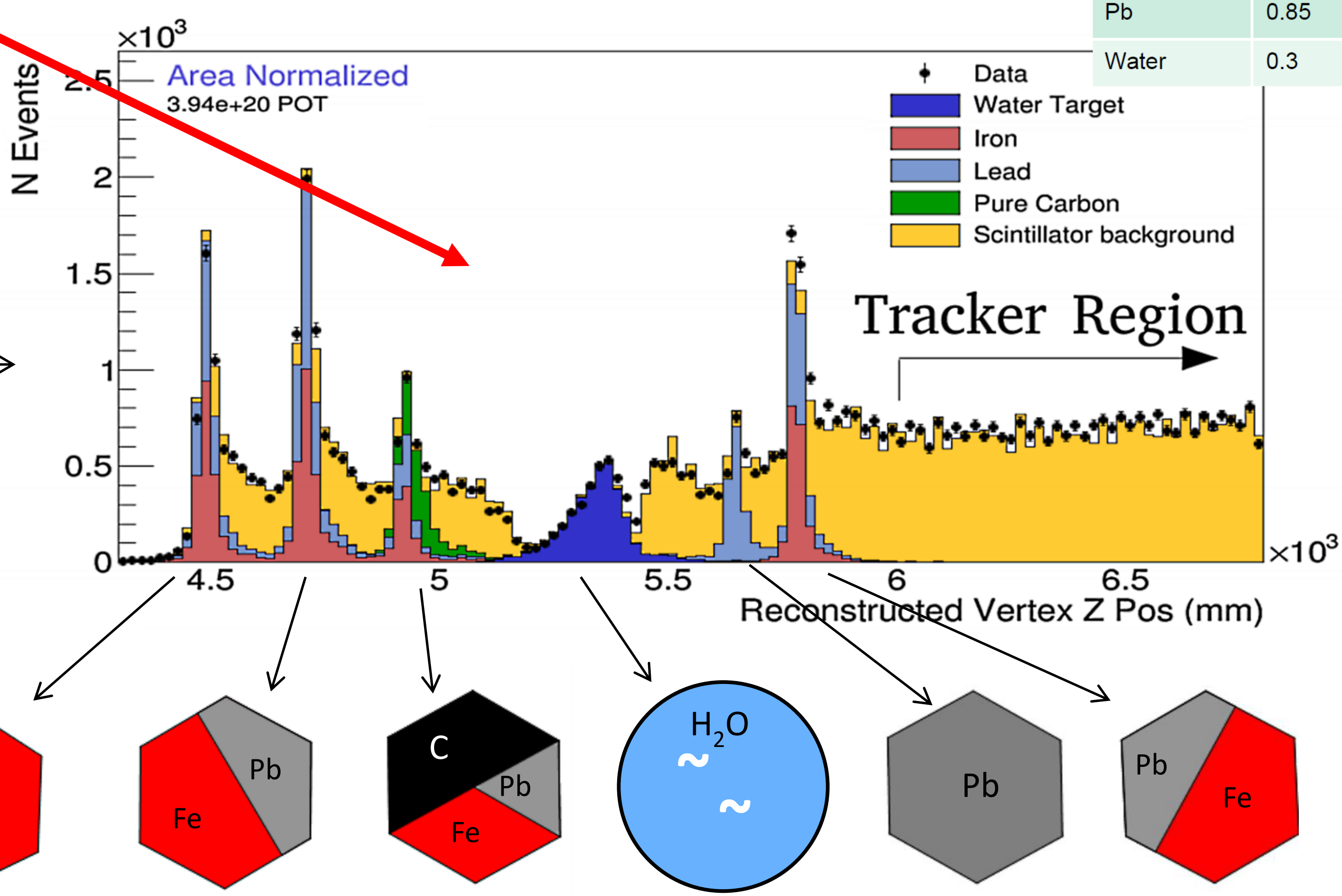


MINERvA experiment

Target	Mass in tons
Scintillator	3
He	0.2
C (graphite)	0.15
Fe	0.7
Pb	0.85
Water	0.3

Nuclear target region





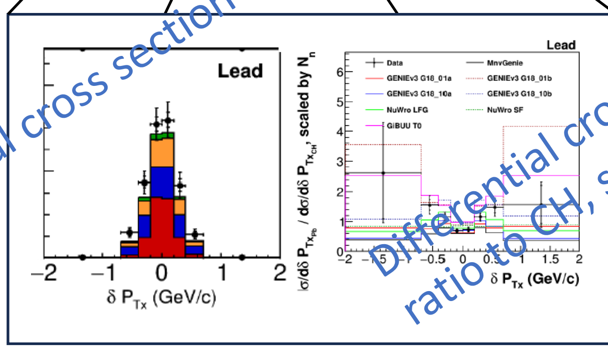
High stats – mature experiment

13 variables

5 target materials

	δp_T	ϕ_T	α_T	δp_{Tx}	δp_{Ty}	δp_L	p_n	p_p	p_{Tp}	θ_p	p_μ	$p_{T\mu}$	θ_μ
CH													
C													
H_2O													
Fe													
Pb													

Differential cross section

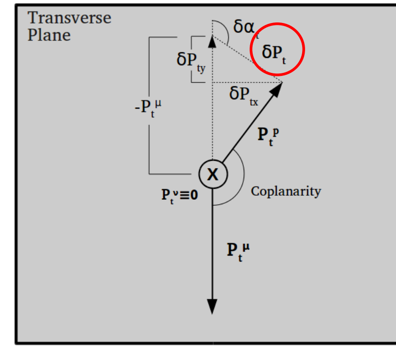


Differential cross section ratio to CH, scaled by N_n

130 plots of results
+ model comparisons
+ uncertainties

Muon (only) QE-like results on same data set (on nuclear targets) published: Phys. Rev. Lett. 130, 161801 (2023)

Analysis: using δP_T as example

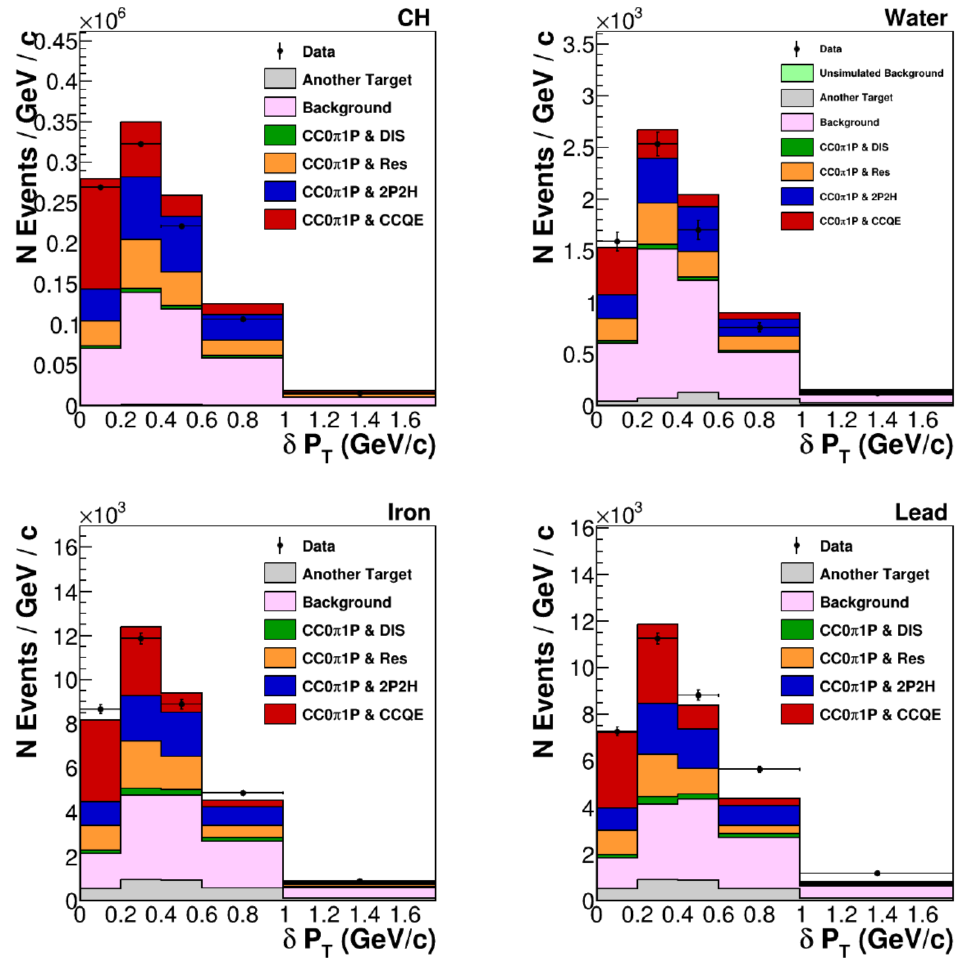


- "Two-track" sample
- 1 μ, ≥1 p, Xn, 0π, 0ϒ

Details on selection in backup

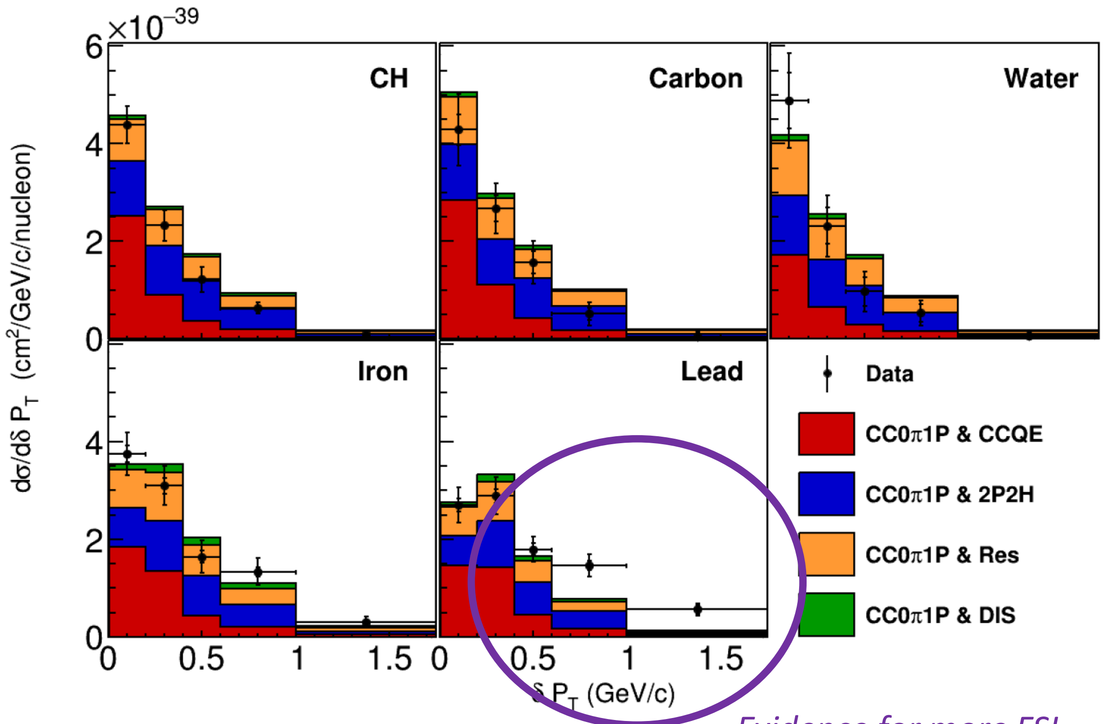
- Events used in analysis:
  - CH target – 218,000
  - C target – 2300
  - H_2O target - 1600
  - Fe target - 8600
  - Pb target - 8700

- Background in pink and smaller gray bands



Analysis: using δP_T as example

- MC background tuned using data sidebands
  - single Michel
  - two external energy clusters away from vertex
- Subtract tuned background
- Unfold
- Correct for efficiency, acceptance
- Use $N_{targets}$ and flux appropriate for each target



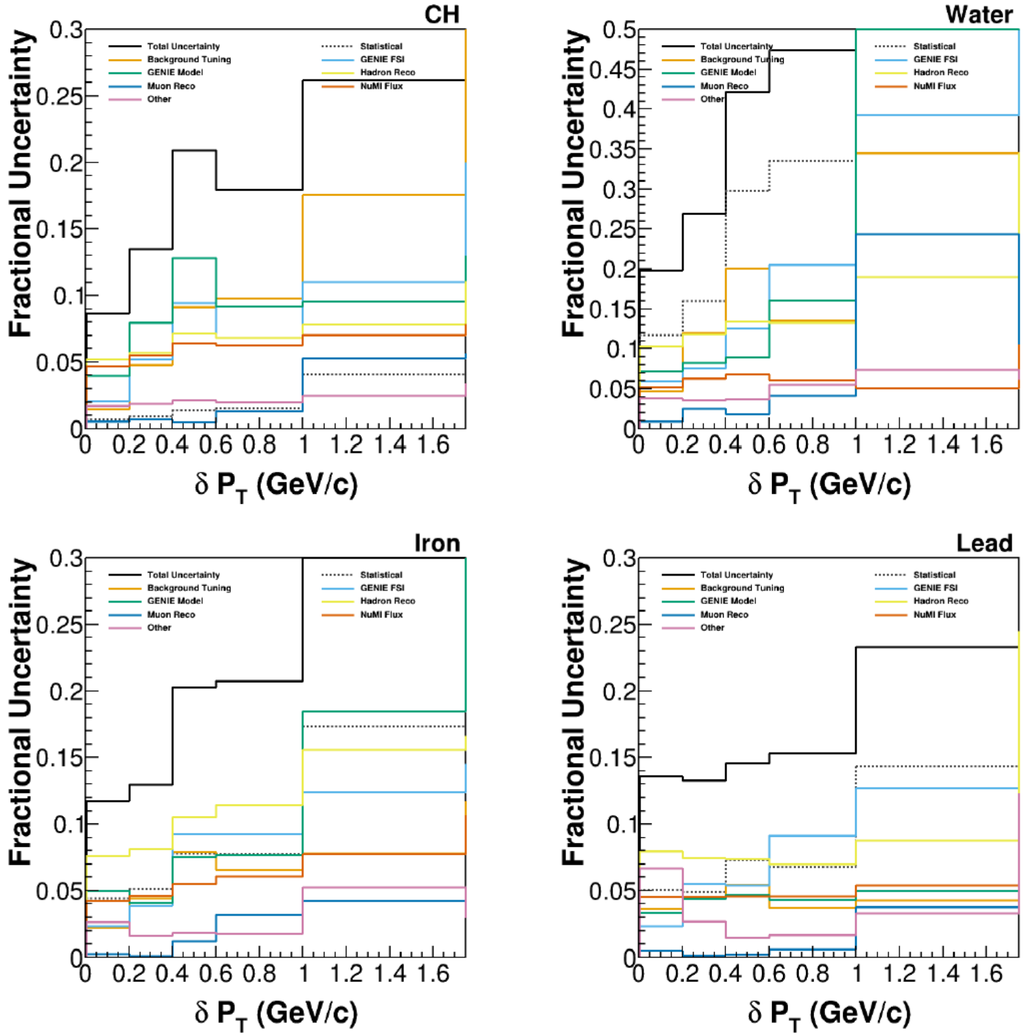
Evidence for more FSI than in model for Pb. Model ok in this respect up through Fe.

$$\frac{d\sigma}{dX}_i = \frac{\sum_j U_{ij}(N_j^{measured} - N_j^{background})}{\epsilon_i (T\Phi_i)\Delta X_i}$$

Procedure done for each target and each variable

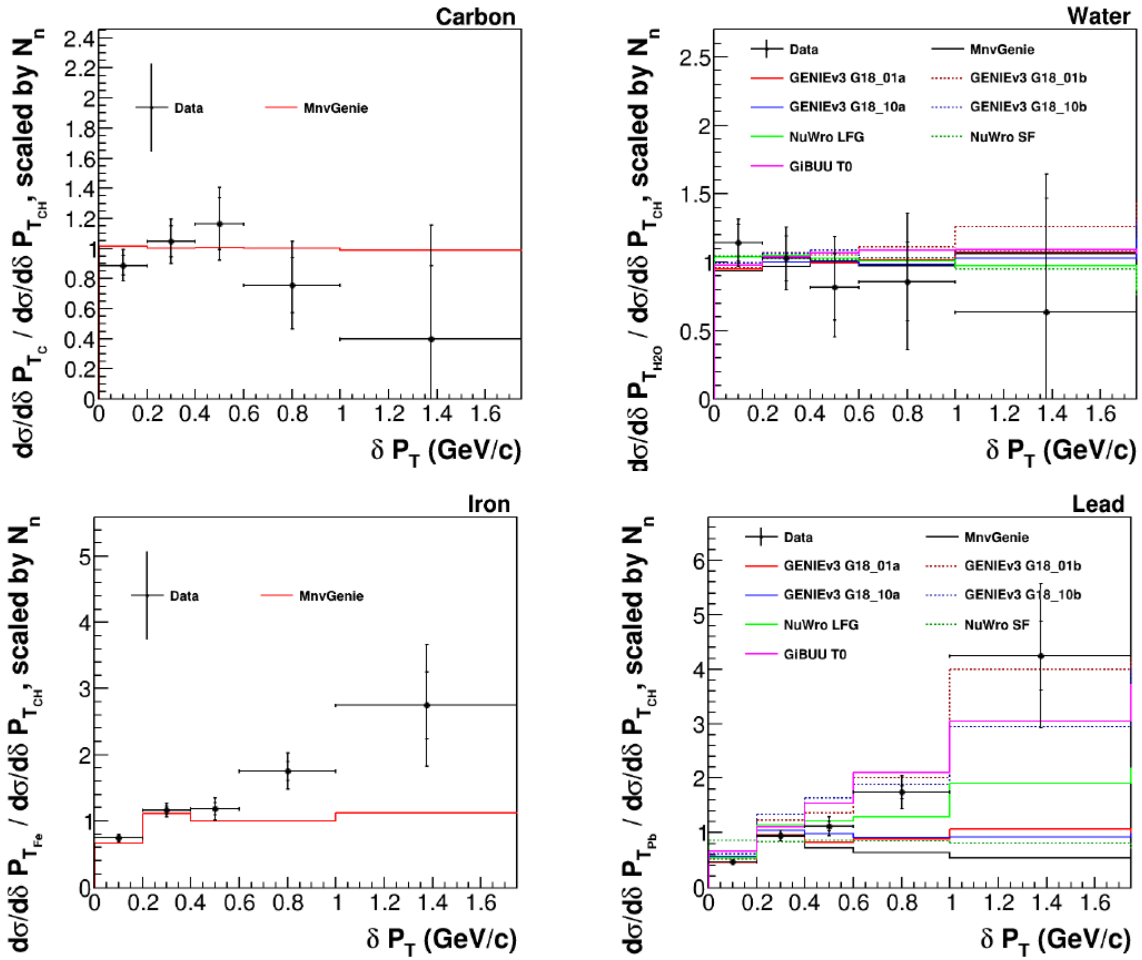
Analysis: using δP_T as example

- Use multiuniverse technique to determine most uncertainties
- Largest uncertainties
  - MC modeling (GENIE)
  - proton reconstruction
  - background tuning

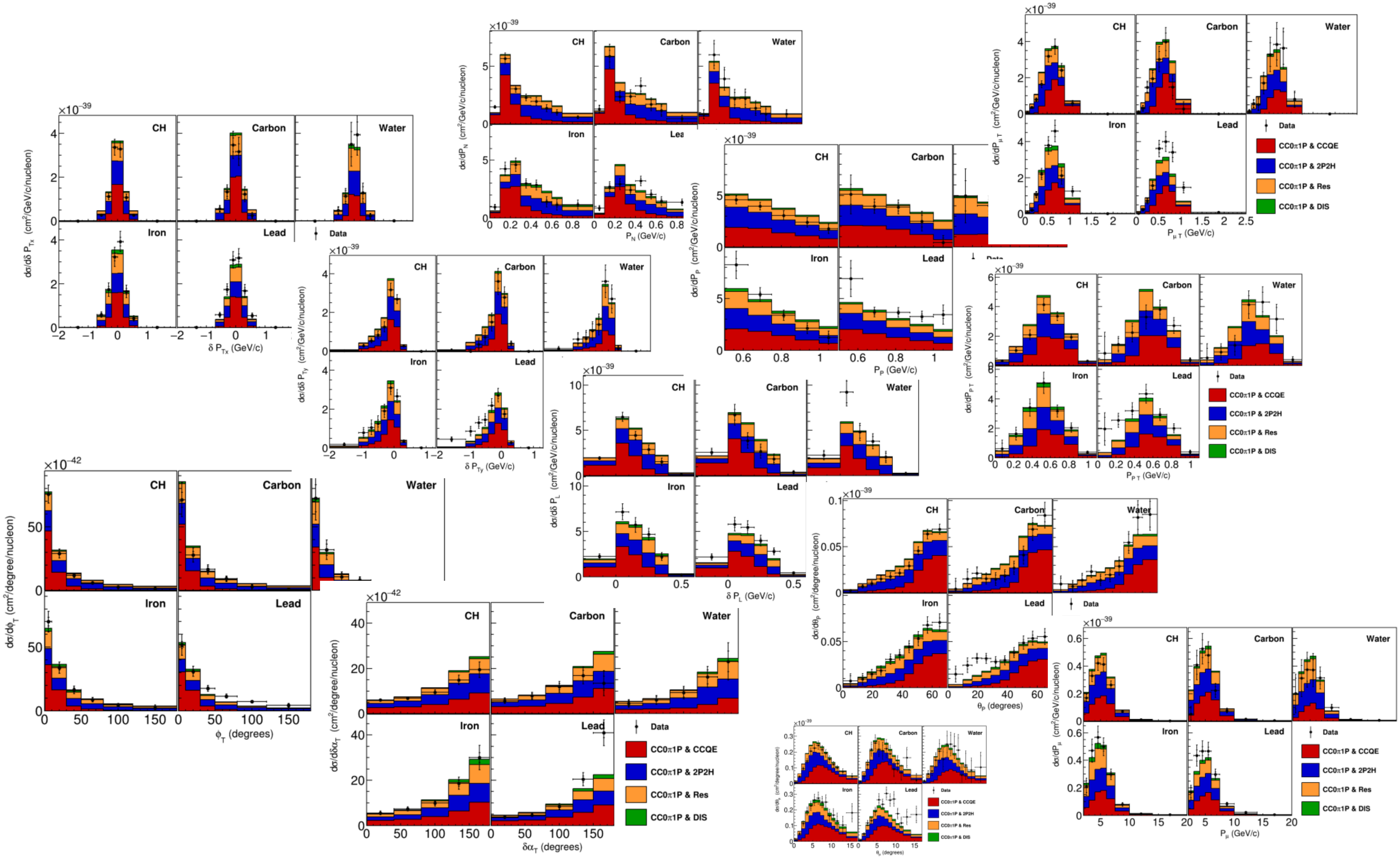


Analysis: using δP_T as example

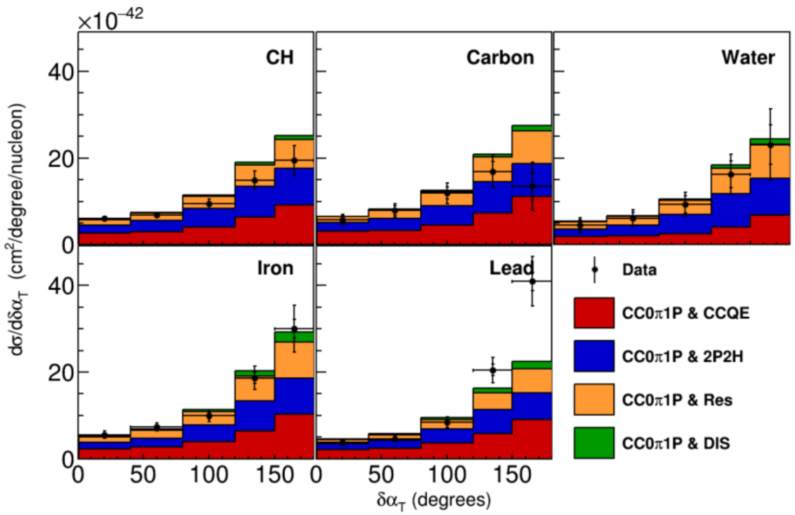
- Some uncertainties cancel in the cross-section ratio dσ/dx(target)/dσdx(CH)
- Black crosses are data
- Lines show expectation for different models (details in backup)
- Spread of models tends to cover data
- Differences tend to show up where FSI more important
- Differences increase with A
- Model comparisons with non-ratio cross sections available with data set

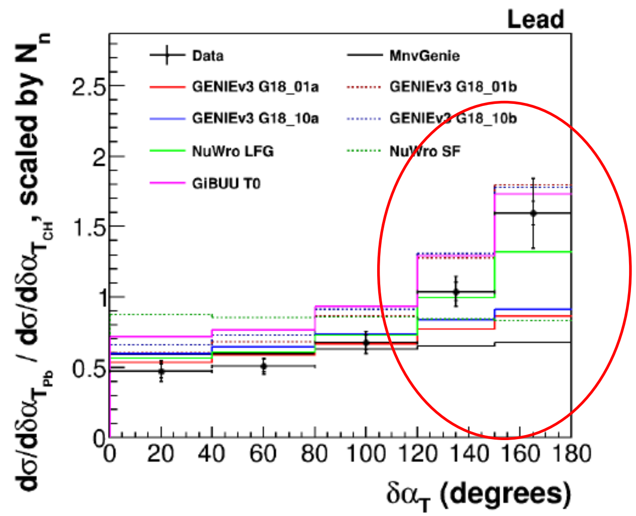


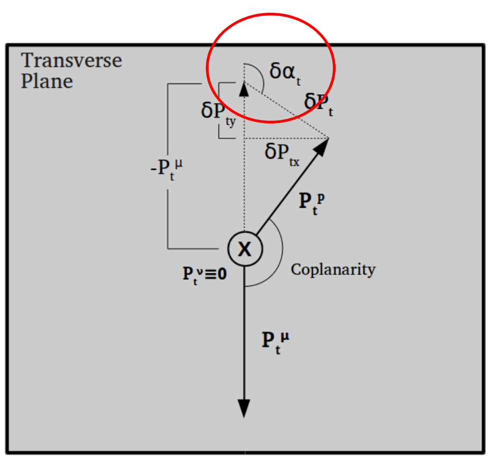
Many other variables…



Highlights

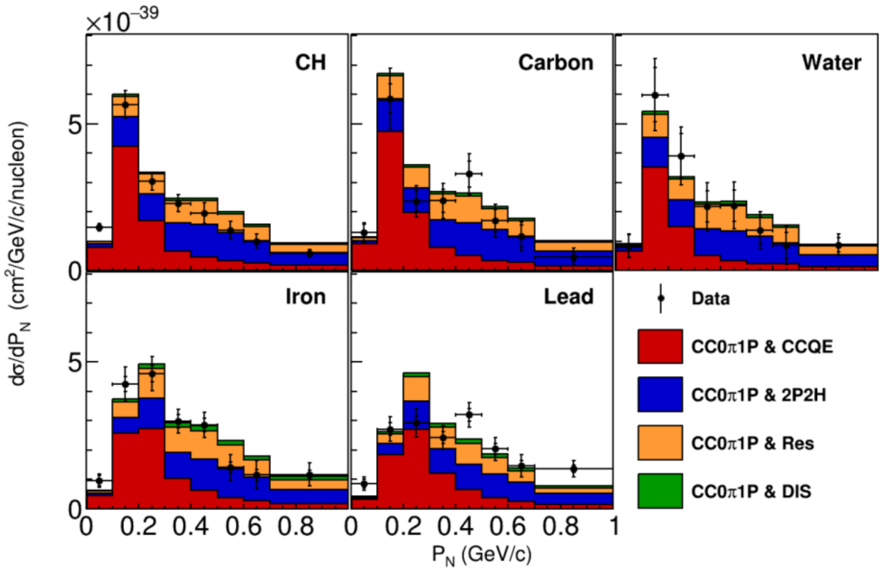


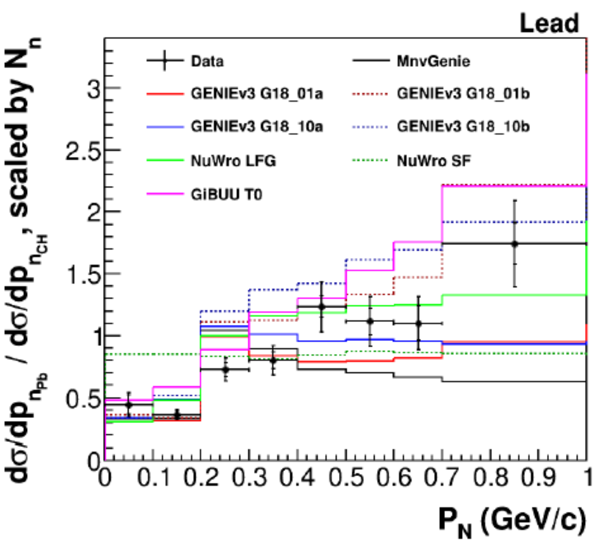




- Larger $\delta\alpha_T$ for larger FSI effects, indicates proton losing momentum
- Notice spread among models at larger $\delta\alpha_T$
- Less pronounced for Fe or smaller nuclei

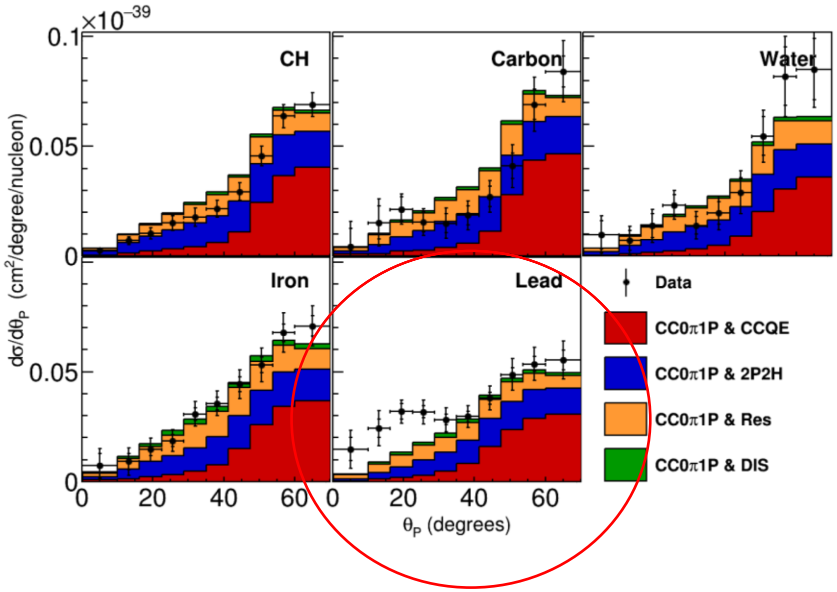
Highlights

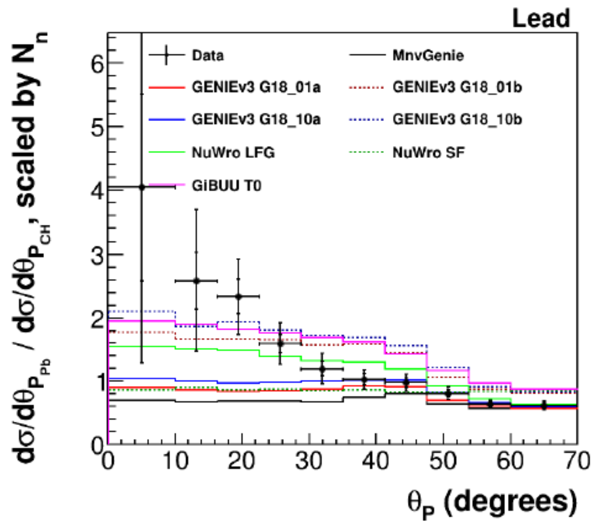




- P_n is momentum of struck neutron
- Peak at low P_n due to Fermi smearing and extended tail mostly from FSI effects
- Models do fairly well thru Fe, poorly on Pb

Highlights





- Most models miss something with the proton angle in Pb, note break at 40 degrees where CCQE kicks in
- Too little cross section in non-CCQE? Or does it mean too little π absorption in models, i.e., less π absorption puts more events in single pi sample rather than this sample

Conclusions

- MINERvA high statistics differential measurements of
  δp_T, δp_{Tx}, δp_{Ty}, α_T, p_n, ϕ_T, δp_L, p_μ, $p_{\mu T}$, Θ_μ, p_p, p_{pT}, Θ_p
- On CH, C, H_2O, Fe, Pb targets

- Explores both the leptonic and hadronic side
- Cross-section ratio of each of these to CH also measured
- Results compared to a handful of MC generators in widespread use

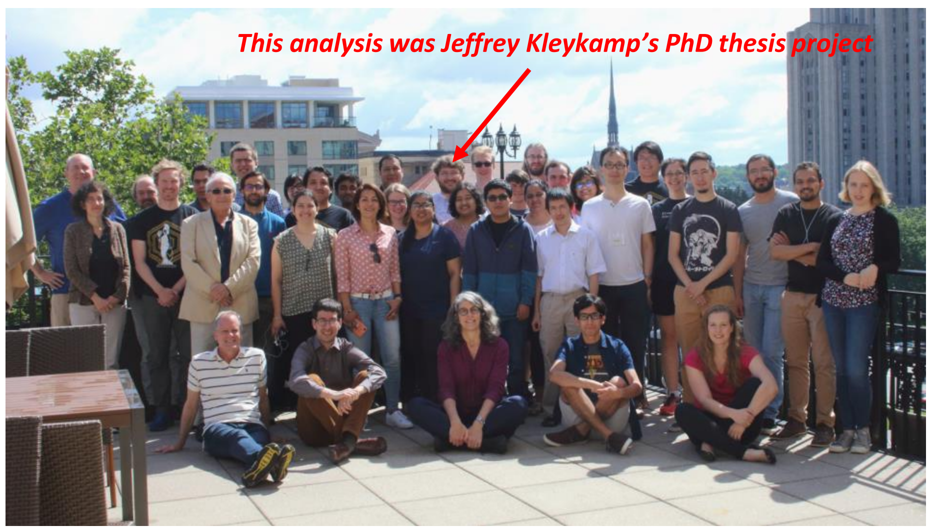
- Spread of models covers the data in most distributions
- Agreement varies with nuclear size (particularly with Pb) and in regions where FSI is more important

- Available in preliminary form now
- In process of upgrading our model comparisons
- Updating and releasing final results in publication and data release soon

More detailed presentation of these results:
J. Kleykamp, Fermilab Joint Experimental-Theoretical Physics seminar, March 24, 2023 – video can be found at
https://vms.fnal.gov/asset/detail?recid=1967704

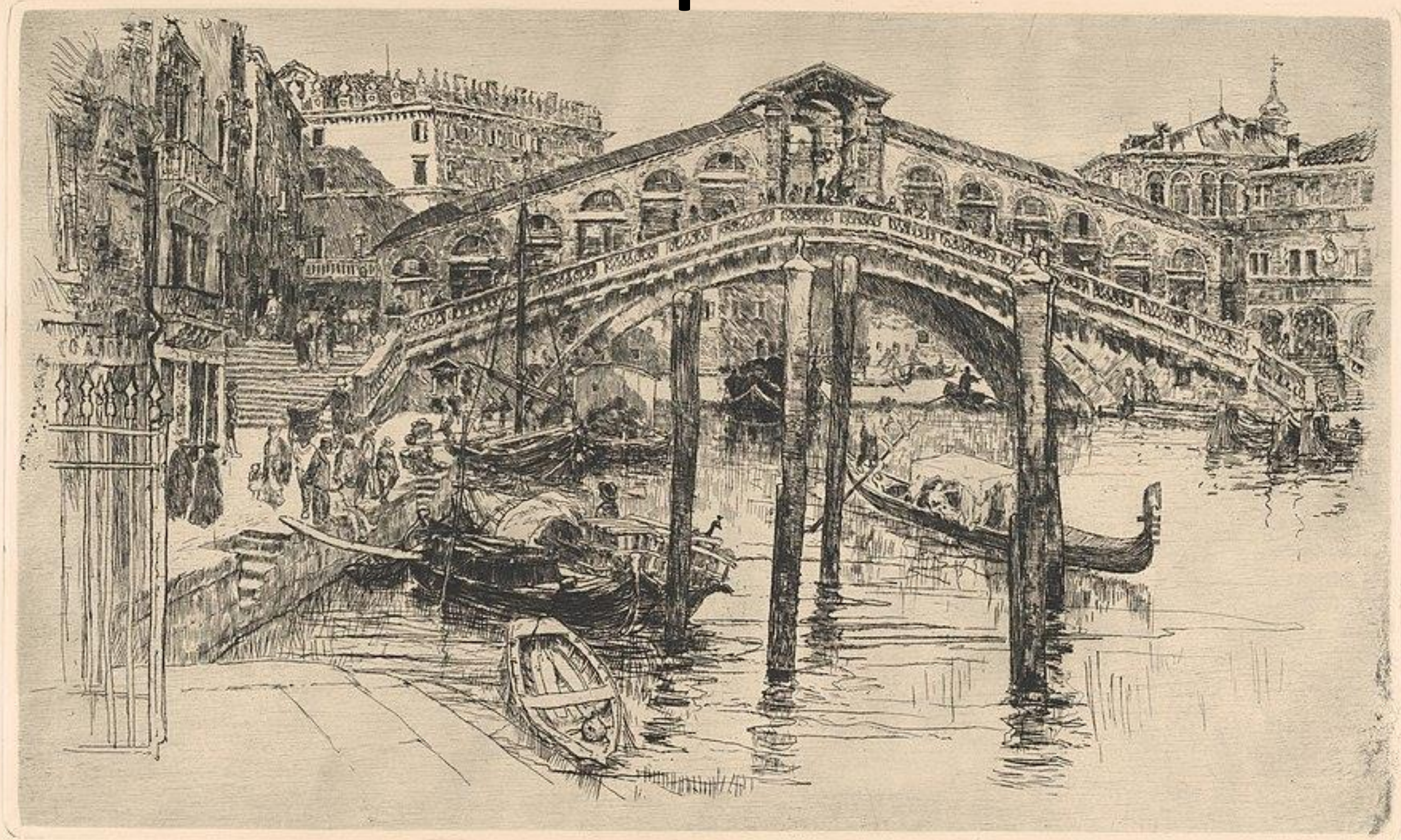
Institutions in the MINERvA Collaboration

- Aligarh Muslim University
- Centro Brasileiro de Pesquisas FÃsicas
- Fermilab
- University of Florida
- University of Geneva
- Universidad de Guanajuato
- Hampton University
- Imperial College London
- Mass. Col. Lib. Arts
- Indian Institute of Science Education and Research Mohali
- Notre Dame
- Northwestern University
- Oregon State University
- Pontificia Universidad Catolica del Peru
- University of Pittsburgh
- University of Rochester
- Rutgers University
- Tufts University
- University of Minnesota at Duluth
- Universidad Nacional Mayor de San Marcos
- Universidad TÃ©cnica Federico Santa MarÃ-a
- William and Mary
- University of Oxford
- Queen Mary University of London
- University of Mississippi
- University of Pennsylvania
- University of Warwick
- York University



Snapshot of MINERvA a few years ago

Backup slides



The Rialto, Venice – Frank Duveneck - Metropolitan Museum of Art Collection – Wikimedia Commons

Base model

- MnvGENIE – central value base model
- GENIE 2.8.4
- Tuned on MINERvA LE dataset
- Random phase approximation suppression at low Q2
- Ad hoc increase of Valencia 2p2h between QE and delta regions to fit neutrino QE-like muon cross section, also works for antineutrino data

Models used (GENIE)

- All genie v3
- G18_01 - Update of the historical default, including diffractive and lambda production interactions and updated hA FSI.
- G18_10 - A theory-driven configuration. LFG nuclear model. Nieves models for CCQE and CC 2p/2h interactions. With updated Berger-Sehgal model for RES and COH
- Version a uses hA FSI model (effective model)
  Version b uses hN FSI model (stepping model)

Models used (non-GENIE)

- NuWro
  - nuwro_19.02
  - LFG uses LFG model
  - SF uses spectra functions
- GiBUU T0 – Release 2019
  - T0 means 1x amount of 2p2h

Rough model performance conclusions

- Upgrading our model comparisons – so this is preliminary
- In regions where FSI expected to be important, GENIE models with hA FSI along with NuWro SF tend to underpredict the nuclear effects relative to what is seen in the data.
- hN versions of GENIE seem to overpredict the FSI
- GiBUU and NuWro LFG tend to model the data fairly well

Further details:
Probing nuclear effects in QE-like neutrino scattering in MINERvA

The MINERvA experiment at Fermilab presents results from quasielastic-like (QE-like) ν_μ interactions on a variety of nuclear targets in the medium energy ($<E_\nu> \sim 6$ GeV) NuMI neutrino beam. In the analysis described here, events are used where protons are cleanly reconstructed. Cross section and cross section ratio results from events produced on C, CH, H_2O, Fe, and Pb targets are presented as a function of muon, proton, and transverse kinematic imbalance variables. These variables are sensitive to nuclear effects. All of the presented observations are compared to predictions from a series of widely used neutrino event generators with different options and tunes. Qualitatively, the spread of simulated results tends to cover the data. However, none of the simulations consistently describe the data. While some of the trends and comparisons will be discussed, an important aim of this talk is to demonstrate for the neutrino community the breadth of these results and their potential utility for constraining models.

- Primary author: Steven Manly
- University of Rochester (faculty, researcher)
- Representing the MINERvA collaboration
- Neutrino cross section
- Paper still being written and to be released soon

This document was prepared by members of the MINERvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DEAC02-07CH11359. These resources included support for the MINERvA construction project, and support for construction also was granted by the United States National Science Foundation under Award No. PHY0619727 and by the University of Rochester. Support for participating scientists was provided by NSF and DOE (USA); by NSERC (Canada); by CAPES and CNPq (Brazil); by CoNaCyT (Mexico); by Proyecto Basal FB 0821, CONICYT PIA ACT1413, and Fondecyt 3170845 and 11130133 (Chile); by CONCYTEC (Consejo Nacional de Ciencia, Tecnolog´ıa e Innovaci´on Tecnol´ogica), DGI-PUCP (Direcci´on de Gesti´on de la Investigaci´on - Pontificia Universidad Cat´olica del Peru), and VRI-UNI (Vice-Rectorate for Research of National University of Engineering) (Peru); NCN Opus Grant No. 2016/21/B/ST2/01092 (Poland); by Science and Technology Facilities Council (UK); by EU Horizon 2020 Marie Sk lodowska-Curie Action. We thank the MINOS Collaboration for use of its near detector data. Finally, we thank the staff of Fermilab for support of the beam line, the detector, and computing infrastructure.