MINERvA:
Results and Prospects

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NOW 2022

September 6, 2022

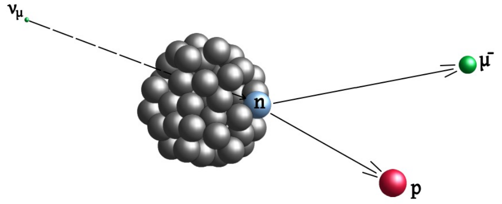
Why is this talk in a "Future Neutrino Oscillation Experiment" session?

- MINERvA is a dedicated cross section experiment
- Ran in the NuMI beamline from 2009 – 2019
- As we heard yesterday, lessons learned from MINERvA are already being incorporated in today's oscillation experiments

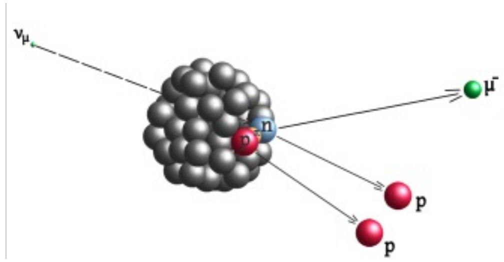
- Focus of this talk:

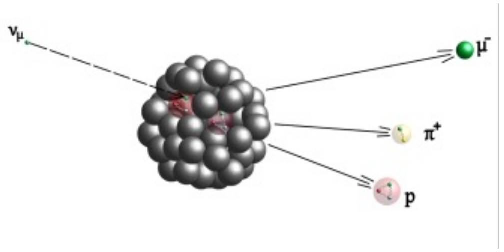
  Recent & upcoming measurements and how they will inform future oscillation experiments

Why Oscillation Experiments need Cross Section Experiments



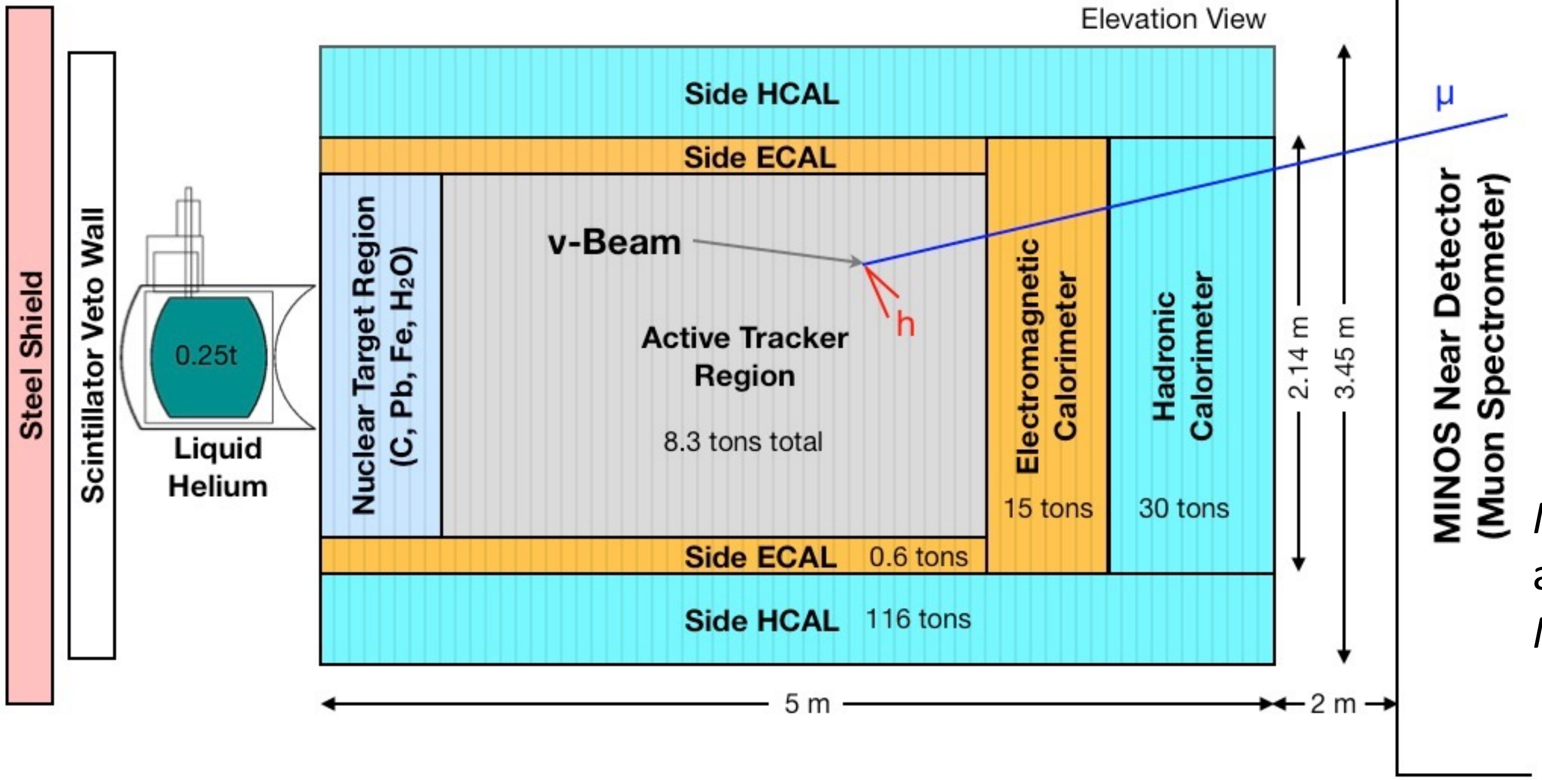
- Oscillation experiments want to measure $P(E_\nu)$ but are stuck with imperfect measures of E_ν
  - Cerenkov Detectors: have to reconstruct using lepton kinematics, and an assumption about what kind of process produced the lepton
    - This works great on free nucleons at rest but…
      - Can't afford hydrogen bubble chambers for far detectors
      - Nucleons have fermi motion, long/short range correlations
      - Other processes can mimic the process you are assuming
  - Calorimetric/Tracking Detectors: not all final particles' energies can be measured
    - Neutrons barely leave any energy
    - Neutral pions leave total energy, but charged pions only leave their kinetic energy
- Backgrounds still need to be predicted well

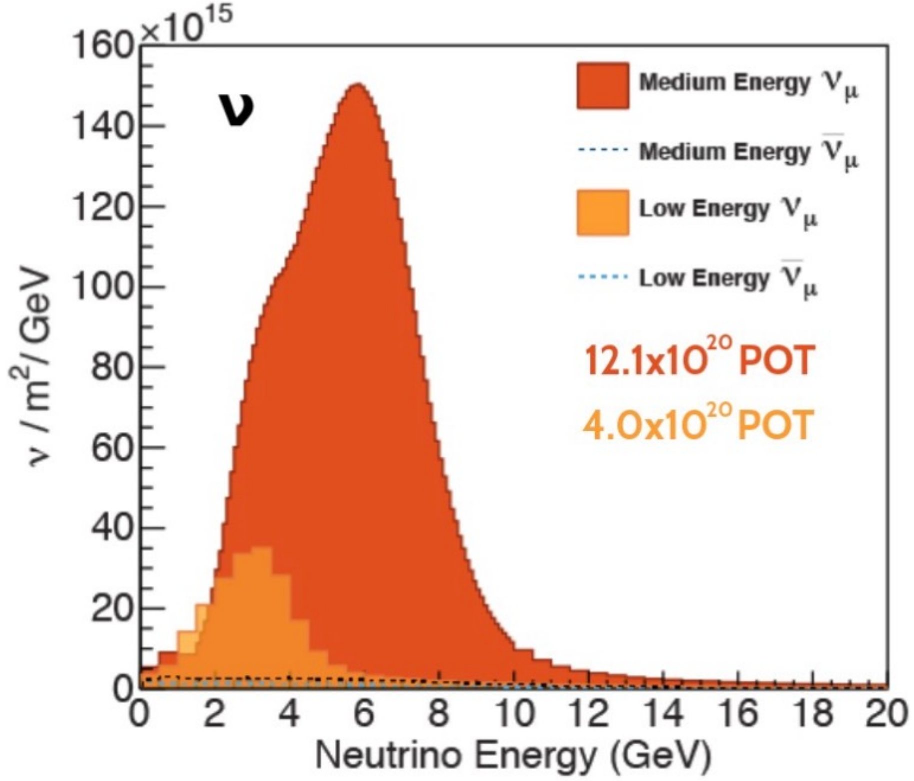




Enter MINERvA

- Data with neutrinos and antineutrinos
- Ran with two different energy beams
- Targets of He, C, H2O, Fe, Pb and CH



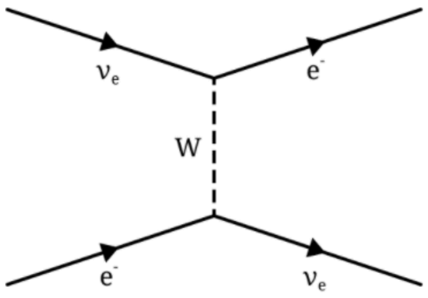


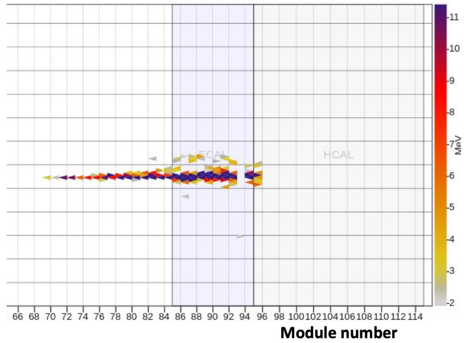
Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

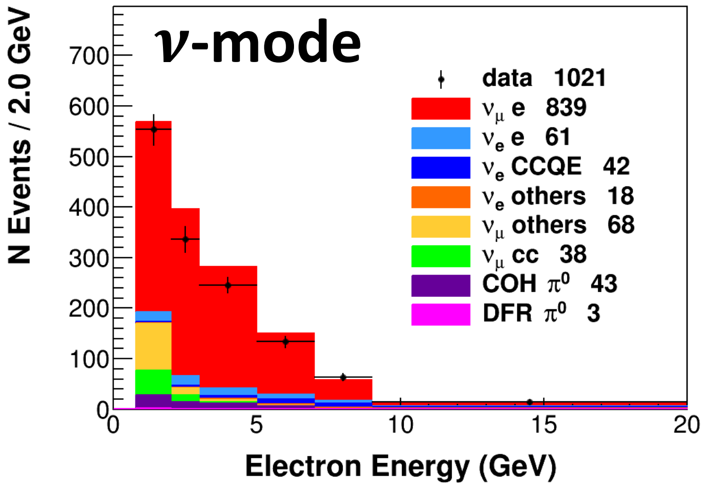
New Flux from Neutrino-Electron Scattering

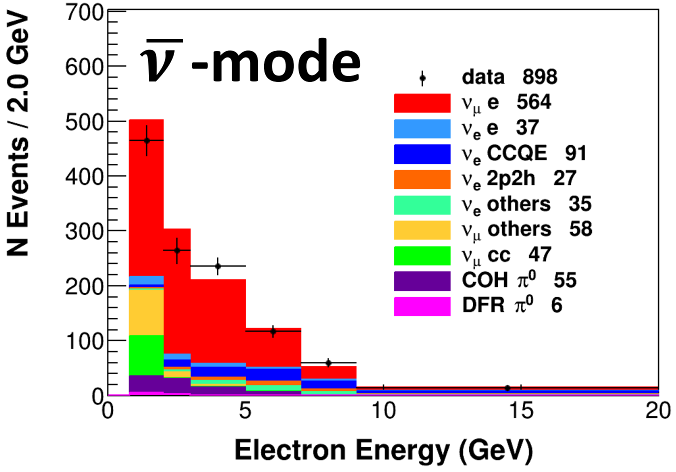
Phys.Rev.D 100 (2019) 9, 092001; *Phys.Rev.D* 104 (2021) 9, 092010, + 1 more soon to appear on the arXiv

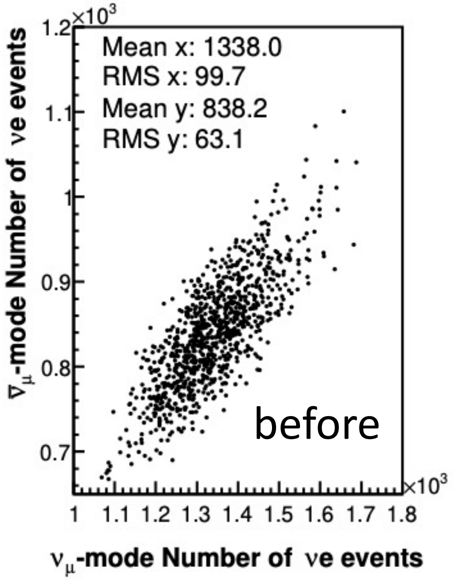
- Neutrino-electron elastic scattering is a standard candle for neutrino interactions.
- Using this reaction 6 GeV neutrino and anti-neutrino beams, and using inverse muon decay, flux uncertainties are ~3.3% and 4.7%!
- Combined fit paper in preparation (L. Zazueta et al…)

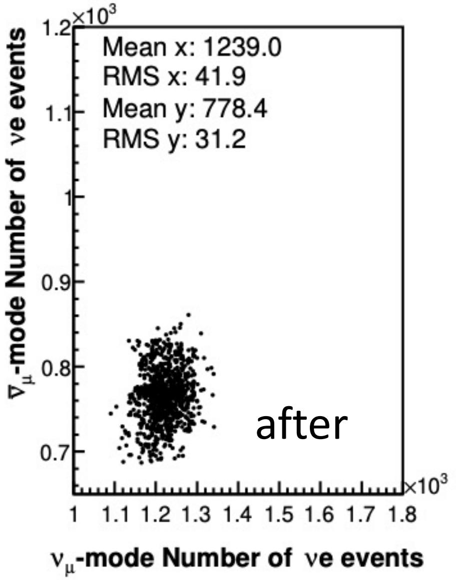












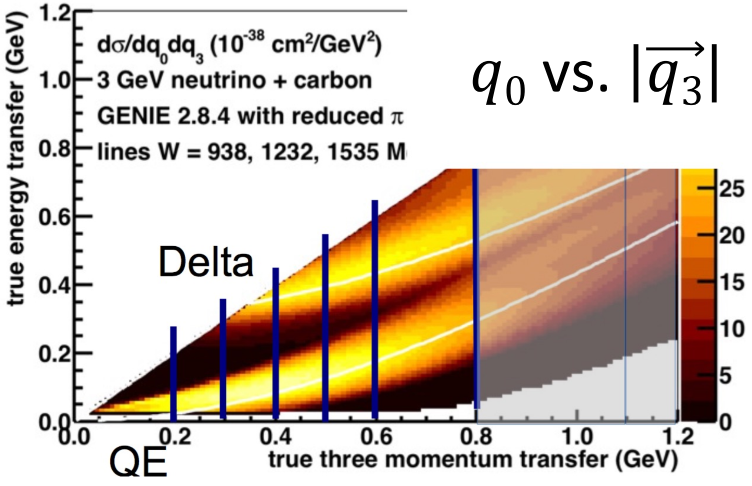
The "MINERvA Tune"

- In our 3GeV data, we found discrepancies compared to generators (GENIE) out of the box that surpass the standard "GENIE" uncertainties.
- MINERvA has developed a model tune in use today that better describes its own CH data than do untuned generators, based on
  - Theory and models implemented in GENIE 2.12.x → 3.0.x,
  - D_2 bubble chamber data (in particular for non-resonant pion production),
  - and MINERvA's own measurements
- The tuned model allows MINERvA to more realistically assess uncertainties in its own measurements. It is also available for use by other experiments, such as neutrino oscillation experiments.

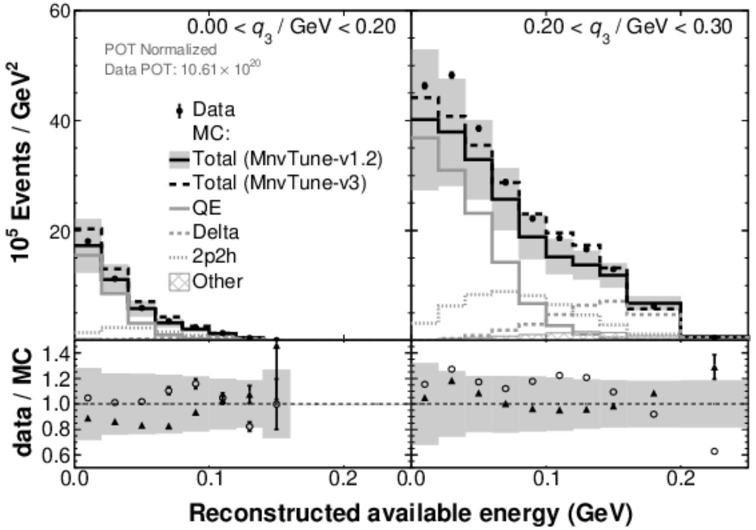
New “low q” Results from Medium Energy Data

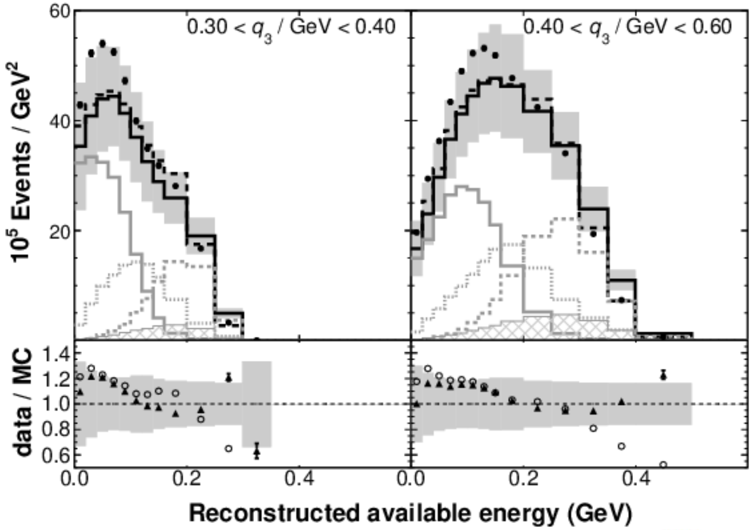
- Look at inclusive sample of events as function of energy AND momentum transferred
- New data sample still sees need for 2p2h
- Use broader range of “q”
- Several new models of 2p2h process are now available for comparison (NuWRO, SUSAv2)

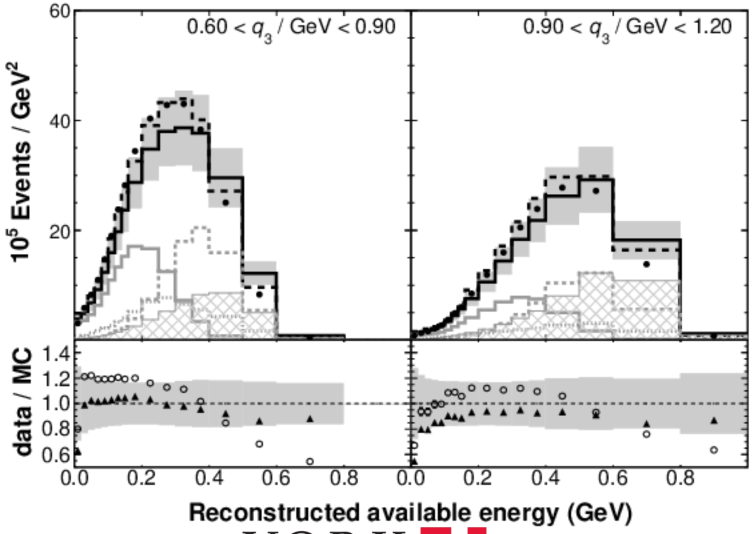
M. Ascencio et al,
Phys.Rev.D 106 (2022) 3, 032001



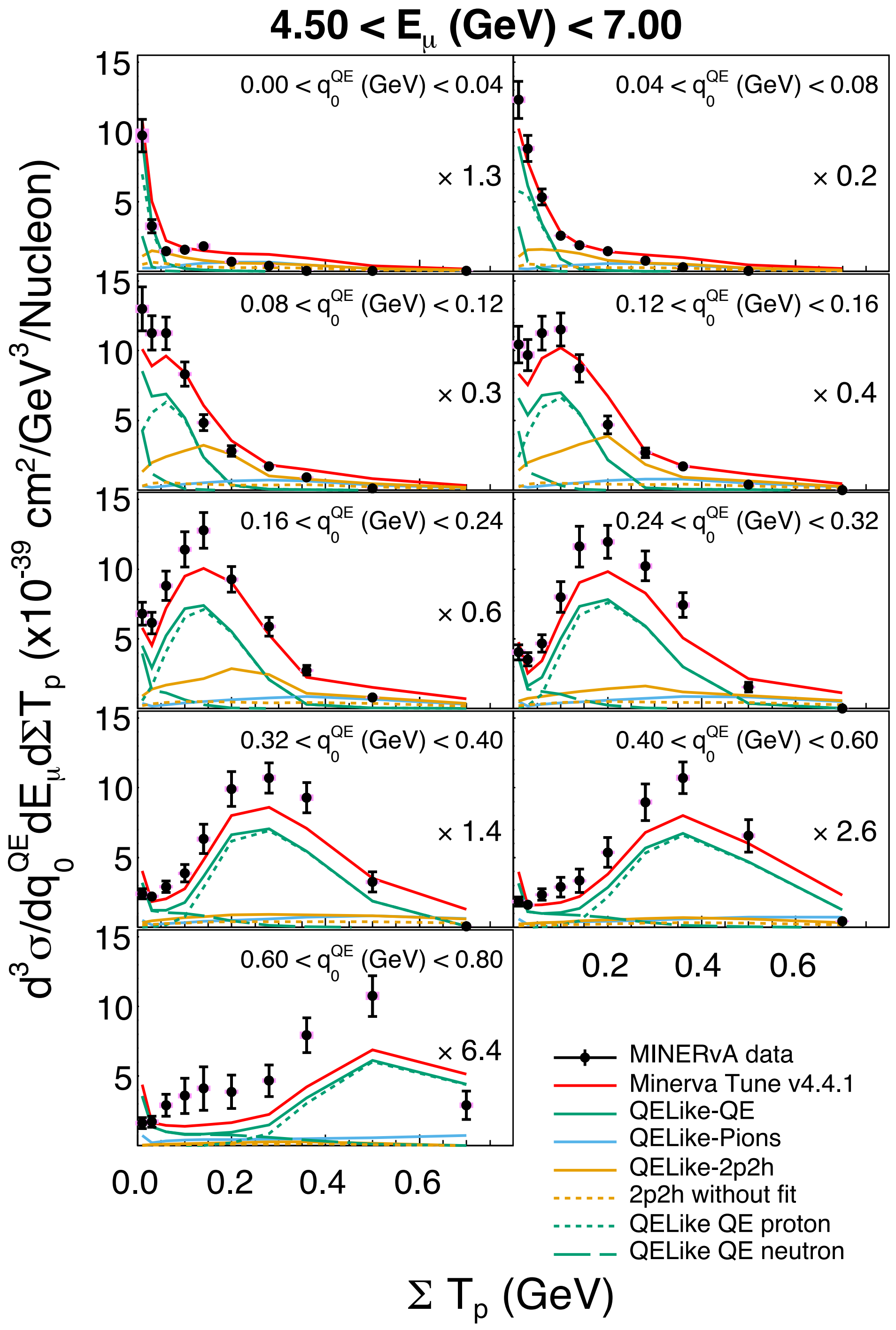
q_0 vs. $|\overrightarrow{q_3}|$





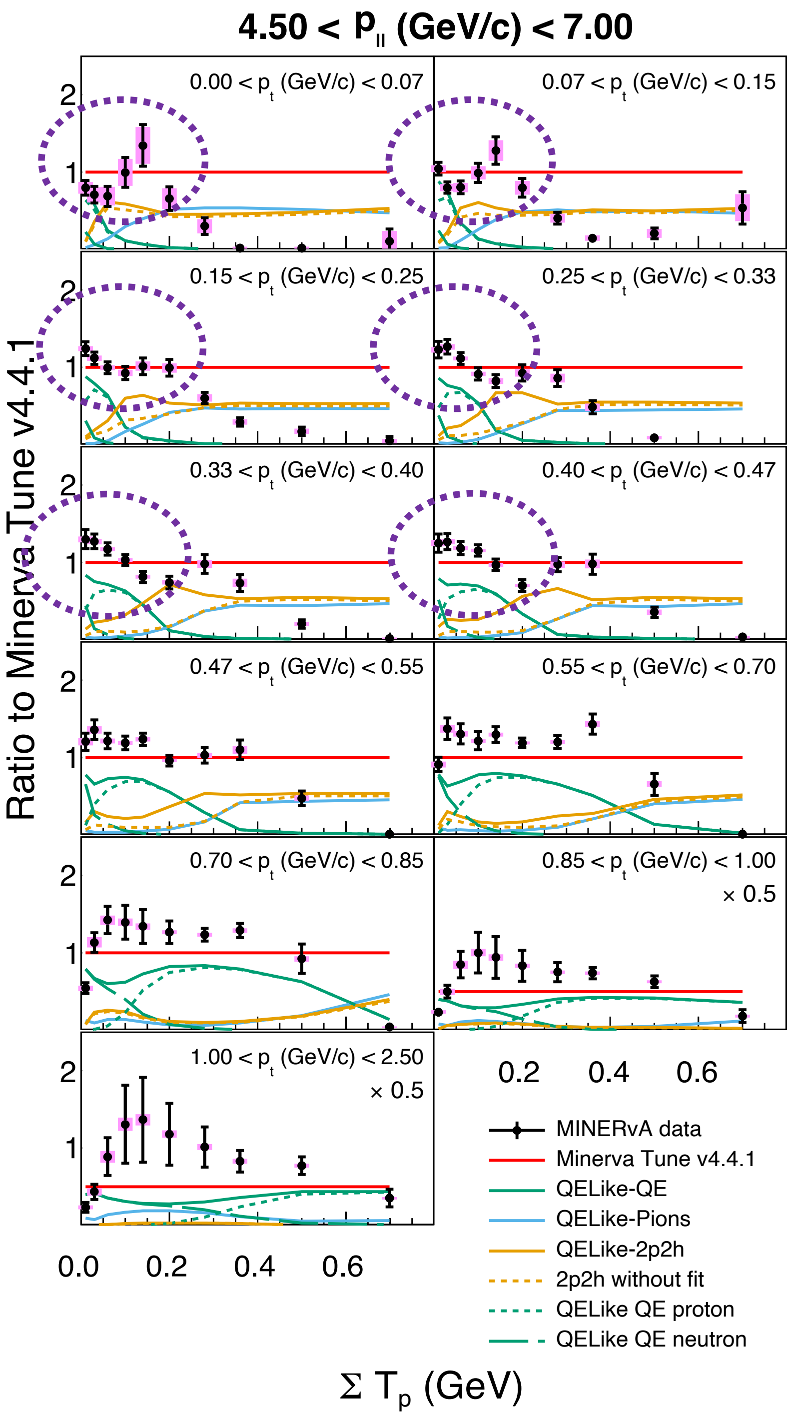


CC0$\boldsymbol{\pi}$ $E_{\nu,\text{reconstructed}}$-$E_{\text{lepton}}$ in T2K vs NOvA



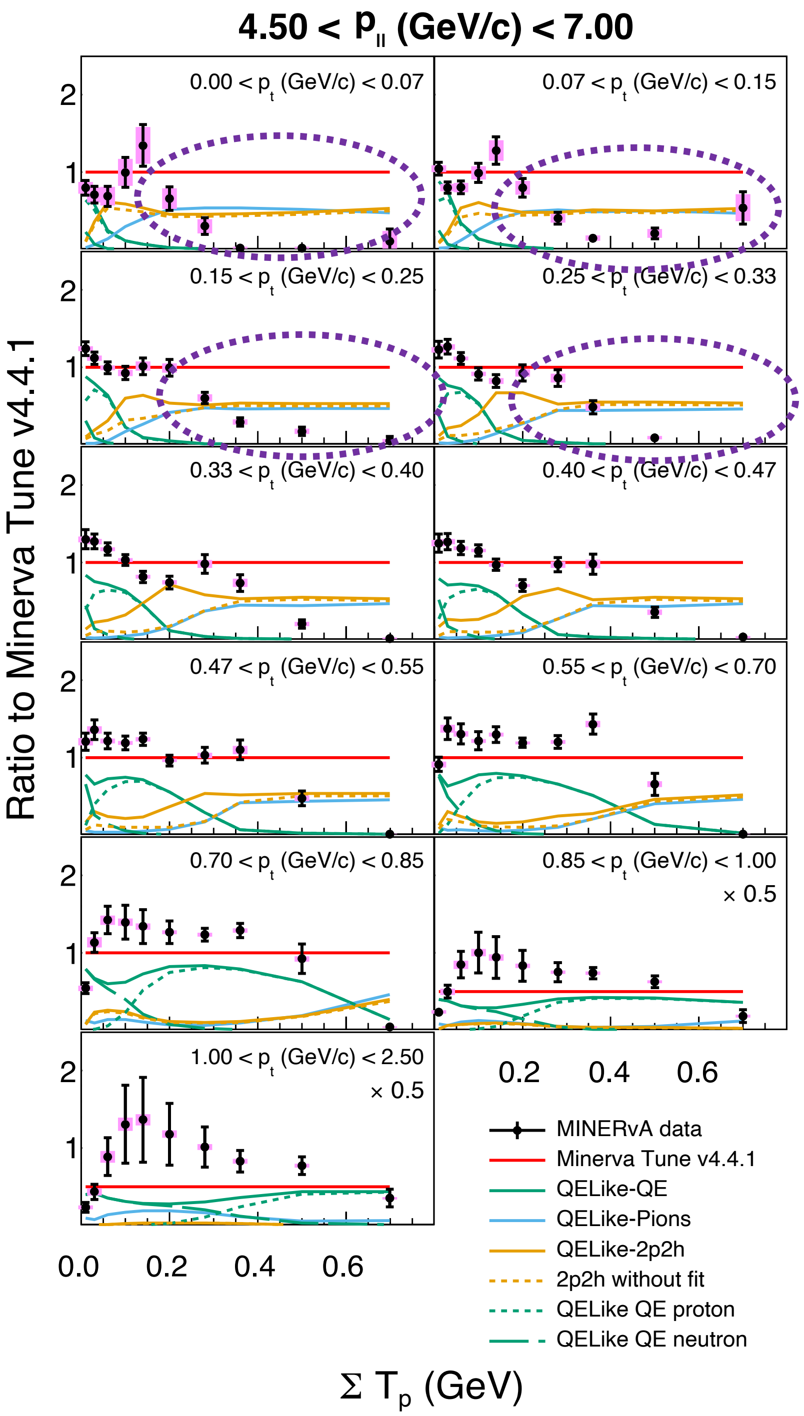
D. Ruterbories *et al, Phys.Rev.Lett.* 129 (2022) 2, 021803

- Reminder from K. McFarland's talk yesterday: In T2K (and future Hyper-K) p_T of lepton is used to measure the recoiling energy by two body quasielastic kinematics.
- In NOvA and DUNE, the visible recoil is measured. Liquid Argon TPC's do both.
- We compare the two types of energy measures: recoil in bins of q_0^{QE}
- Agreement with the model is poor
  - Events where the QE hypothesis says there should be lots of proton energy added, but MINERvA does not see that energy!



Looking at the same data but as CC0$\boldsymbol{\pi}$ $\Sigma T_p, p_T, p_{\parallel}$

- The biggest change in cross-section, though not in the ratio, are the small deviations just above the QE peak. Maybe MINERvA's tune was affected by non- CC0$\boldsymbol{\pi}$ events?
- Low p_T high ΣT_p events predicted by the model as 2p2h and stopped pions are almost completely absent in the data.
- Highest p_T low ΣT_p events, events where the leading proton's energy ends up as neutrons through final state interactions, are also very overpredicted.



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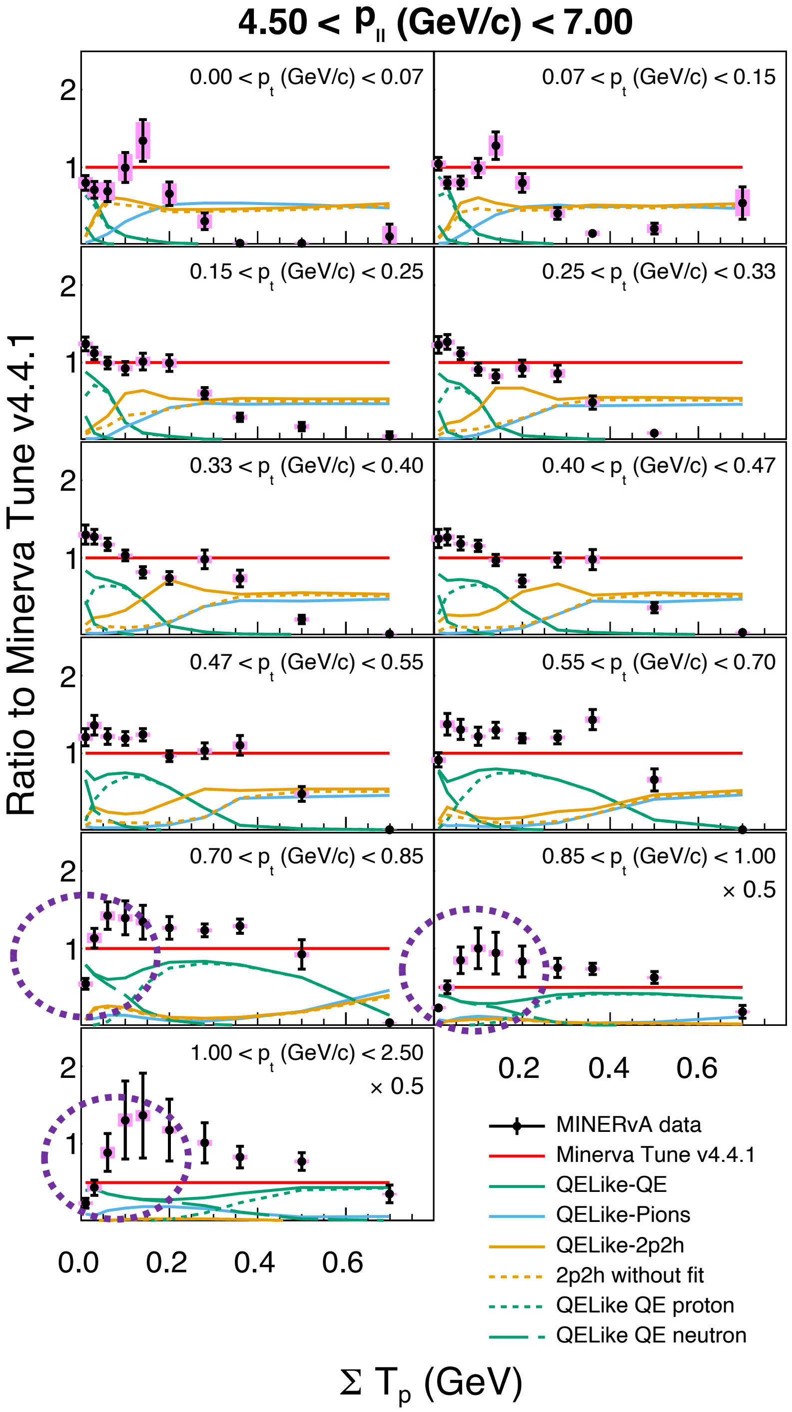

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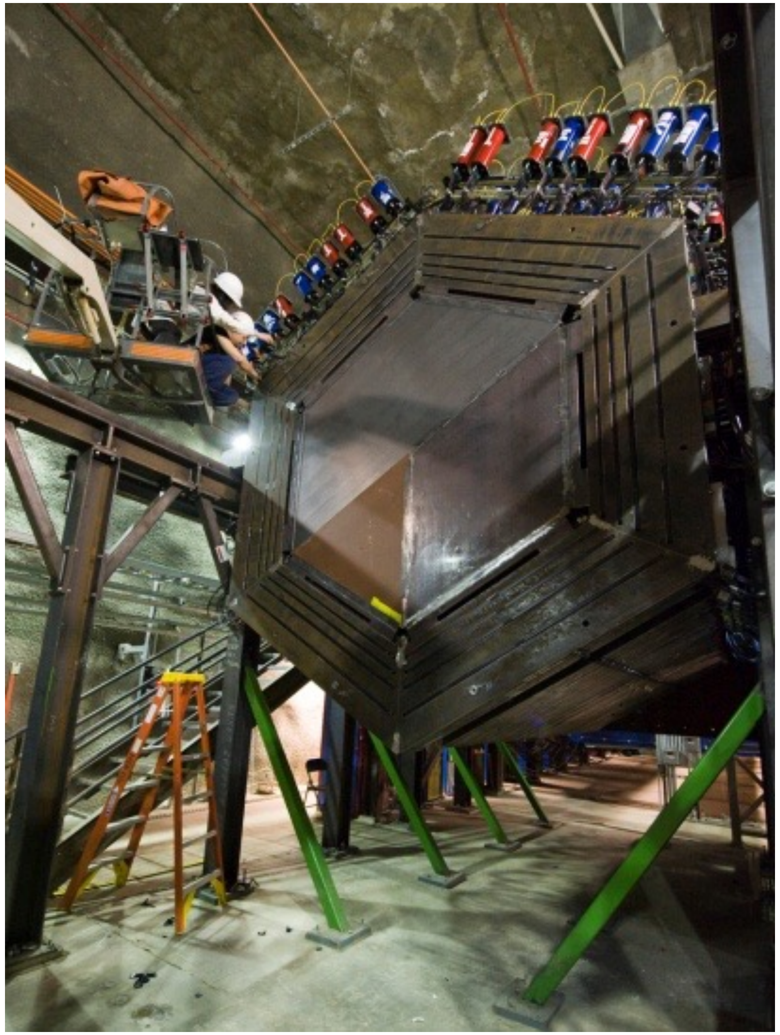
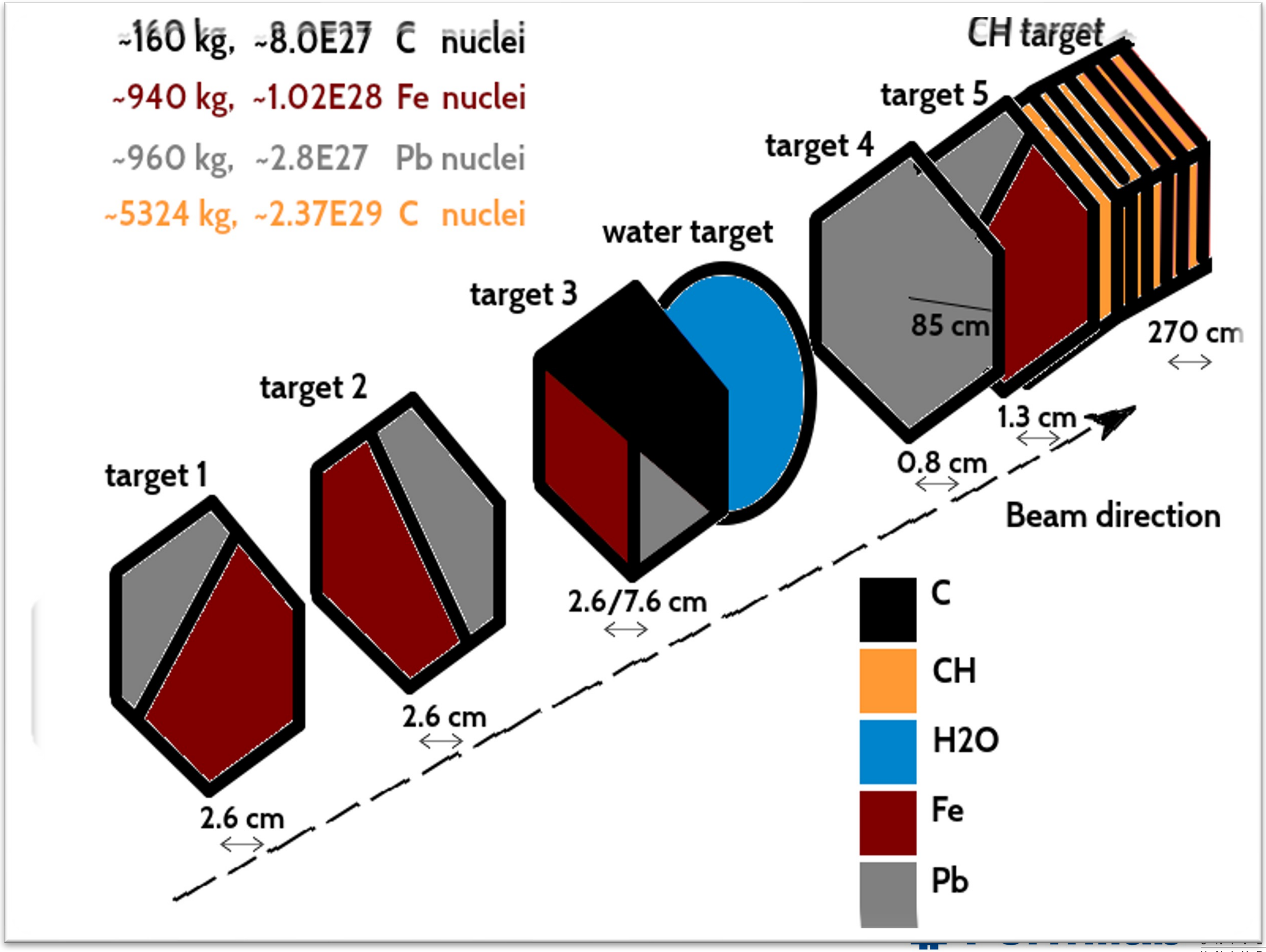
What else can you do with MINERvA's Medium Energy Data set?

- Huge statistics also means ability to measure exclusive processes off nuclear targets
    - "Scintillator target" is 8.3 tons total
    - Lead and Iron are about 1 ton each
    - Water target is 0.4 tons, but had to run ½ the time with
      water target empty for subtraction
    - C is 0.16 tons, used as cross-check



MINERvA's Nuclear Targets



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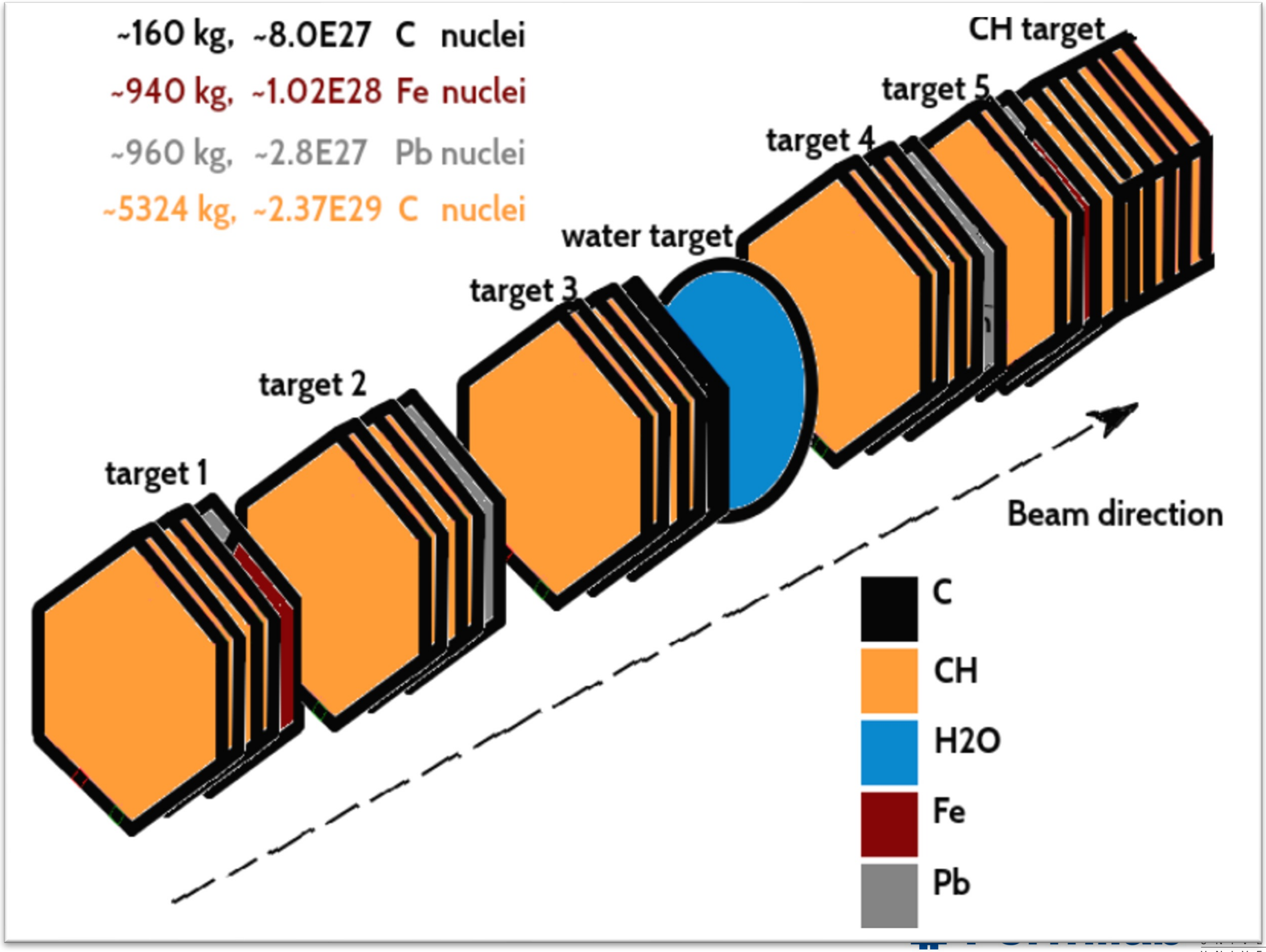
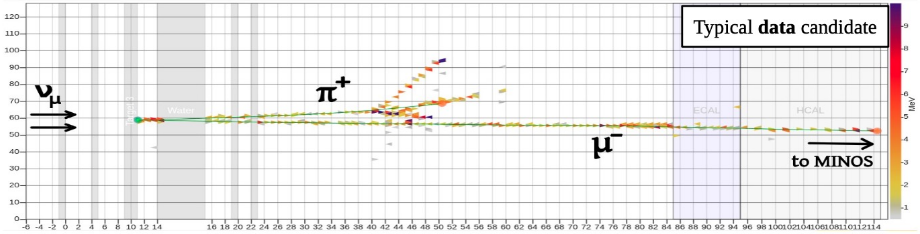
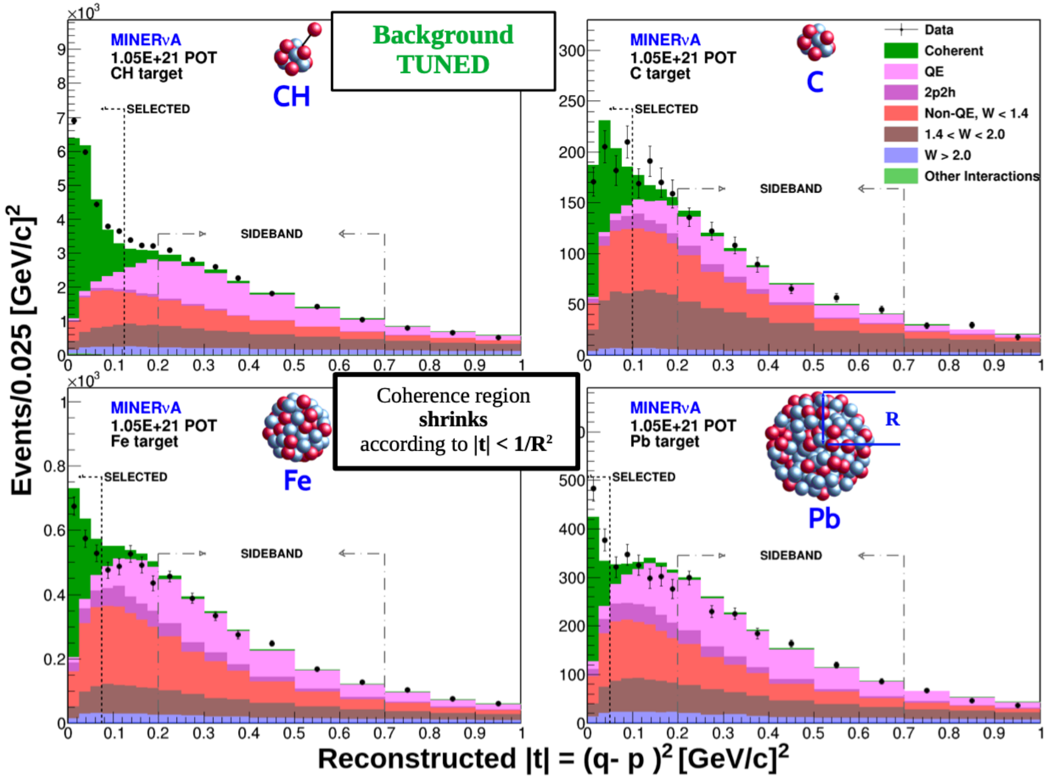


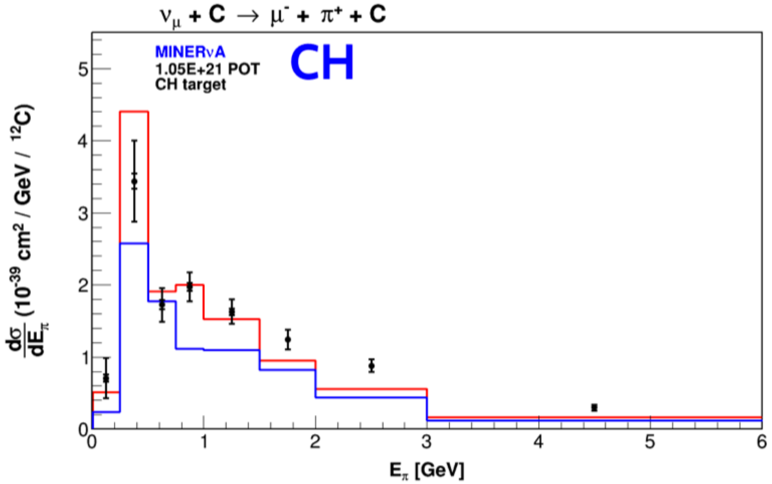
Coherent Pion Production vs A!

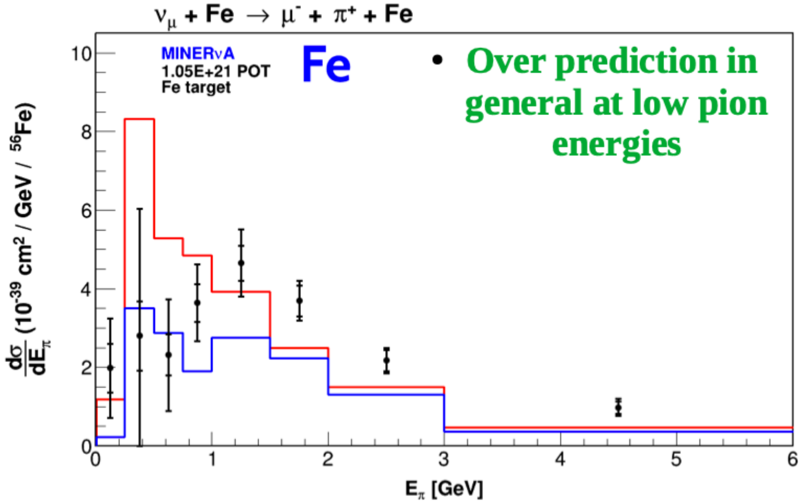
- NC channel is background to ν_e appearance

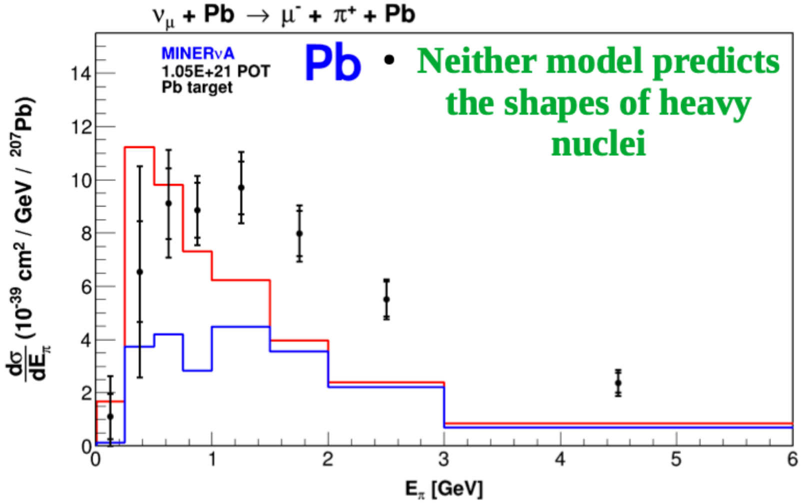


- Paper almost ready to submit, but see for yourself: (A. Ramirez, FNAL seminar) https://vms.fnal.gov/asset/detail?recid=1965797



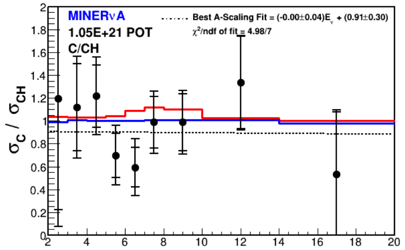




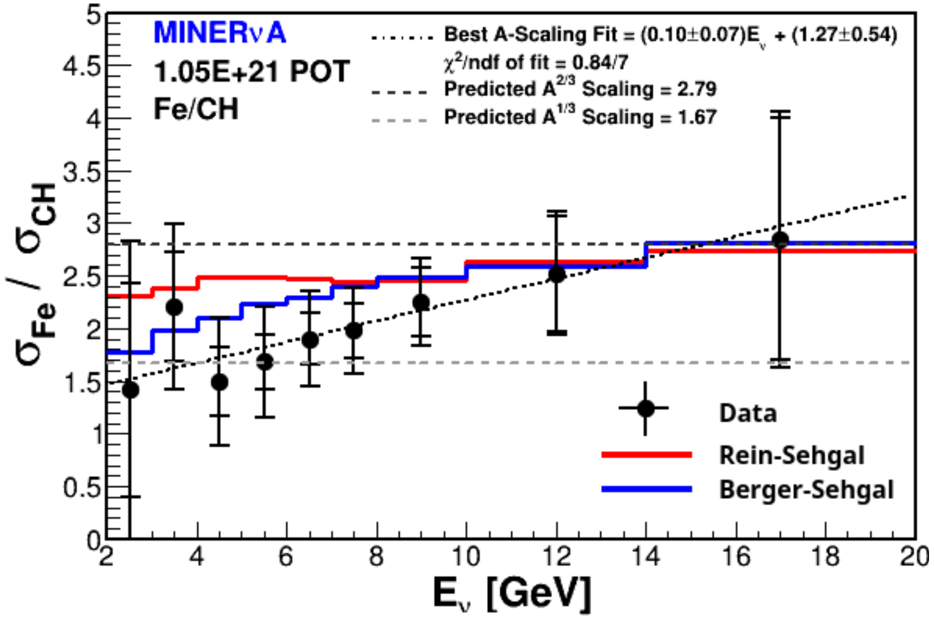


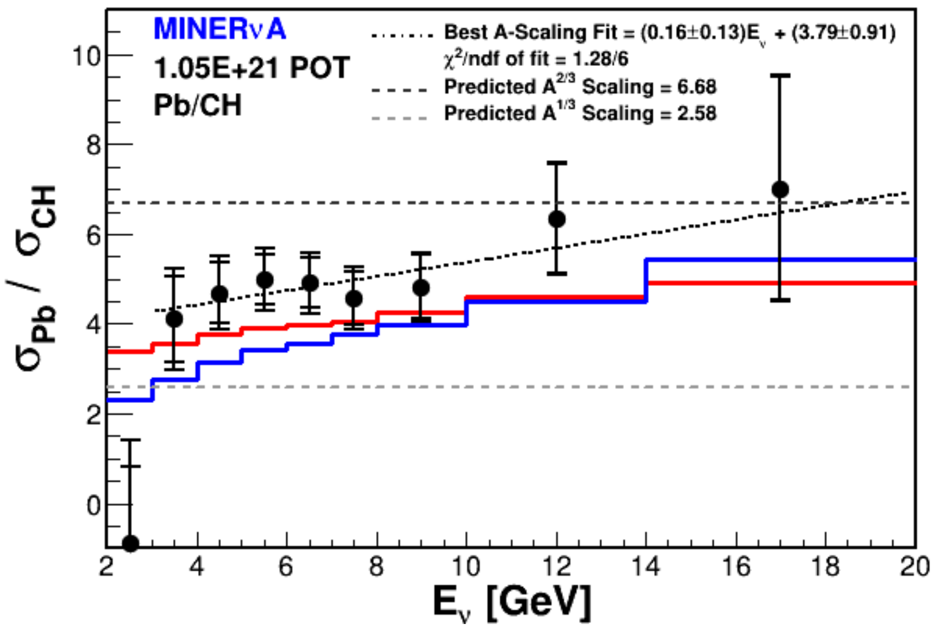
Coherent π: Cross Section Ratios vs A *and* E_ν

- C/CH
  - consistent with 1.0



- Fe/CH
  - Neither model does a good description.
  - Closer to $A^{1/3}$ scaling for E_ν < 8 GeV.
  - Closer to $A^{2/3}$ scaling for E_ν > 10 GeV.
- Pb/CH
  - Neither model does a good description.
  - Closer to $A^{2/3}$ scaling for E_ν > 10 GeV.
  - Low E_ν A-scaling in between predictions.

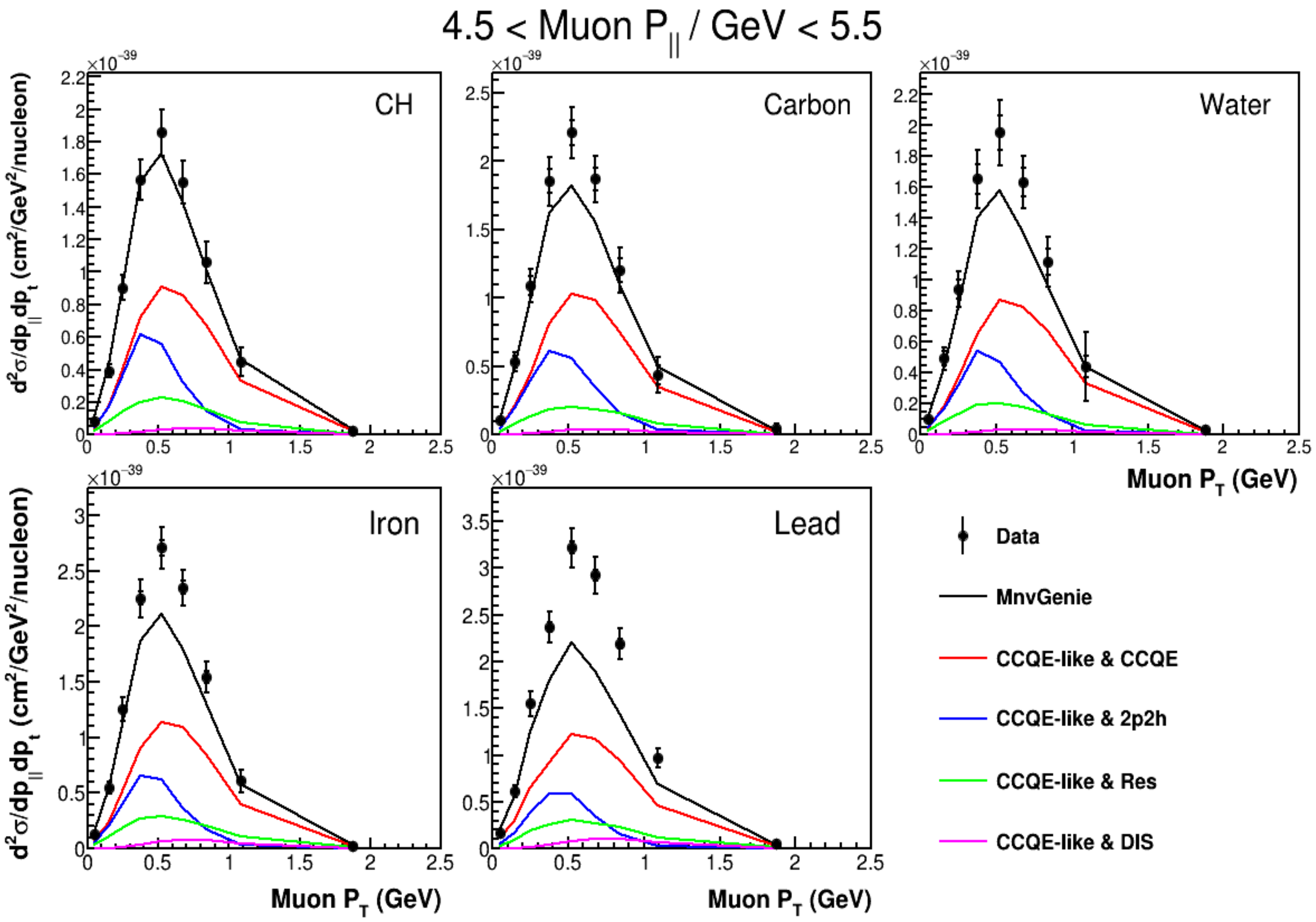




(Paper in preparation, A. Ramirez et al…)

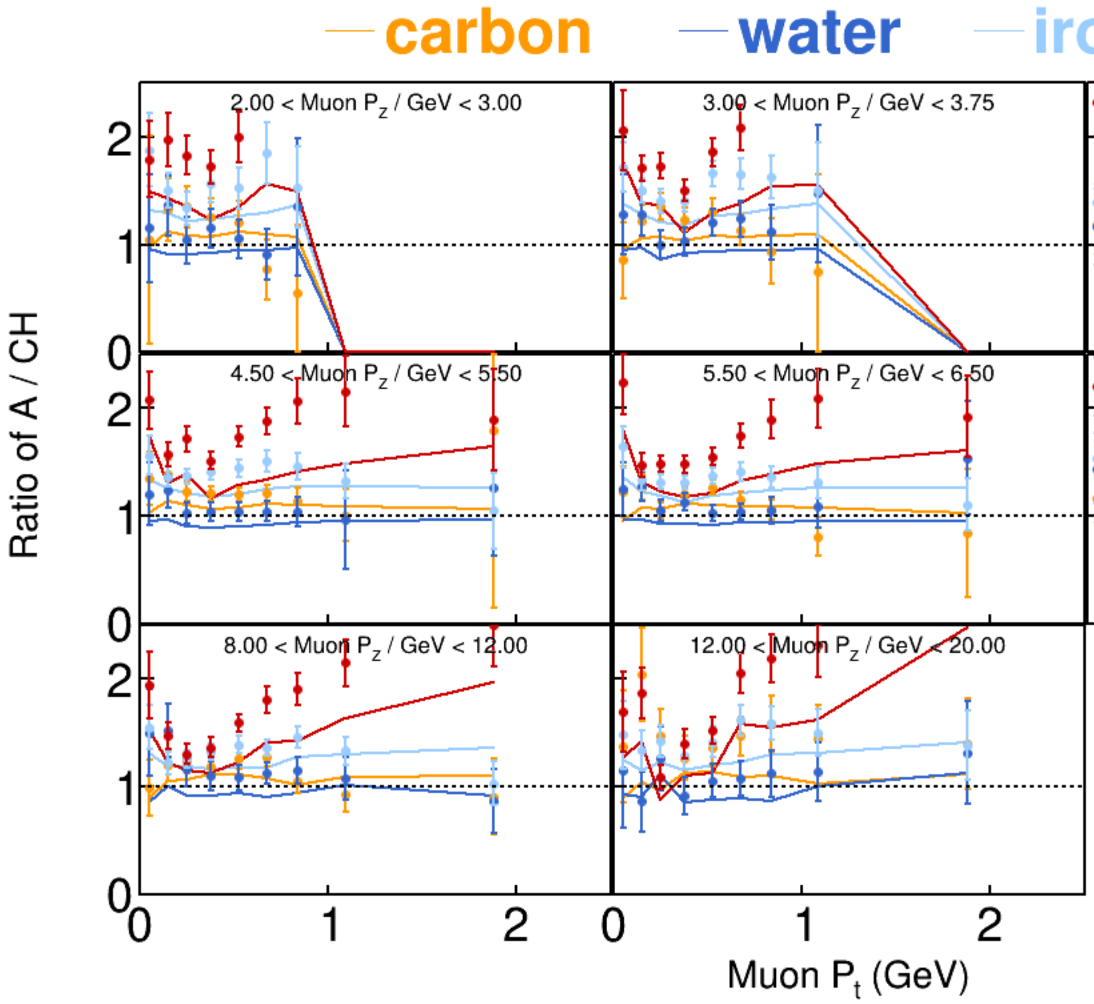
A preview of 6 GeV CC0π Lepton Kinematics on targets

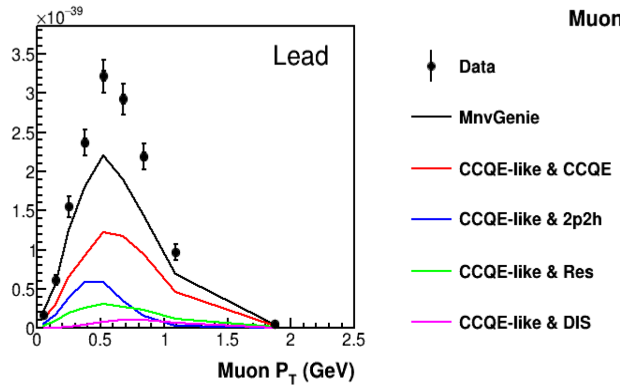
- Agreement with CH helped by MINERvA's 3GeV "tune"
- There is a large predicted cross-section in the more neutron rich targets; but within this model that prediction doesn't explain the changes.
- Overpredicted processes (stopped pions) on proton? 2p2h scaling?
- Take ratios to cancel flux and muon energy uncertainties…



6 GeV CC0π Ratios A/CH

- Direct measurement of A-dependence in CC0π scattering!
- Plot shows per nucleon cross section in data (points) and MINERvA's "tune" in GENIE
- There's work to be done
- What about per neutron cross section, then do Pb and Fe agree?
- Paper in preparation (J. Kleykamp et al…)





6 GeV CC0π Ratios A/CH **per neutron**

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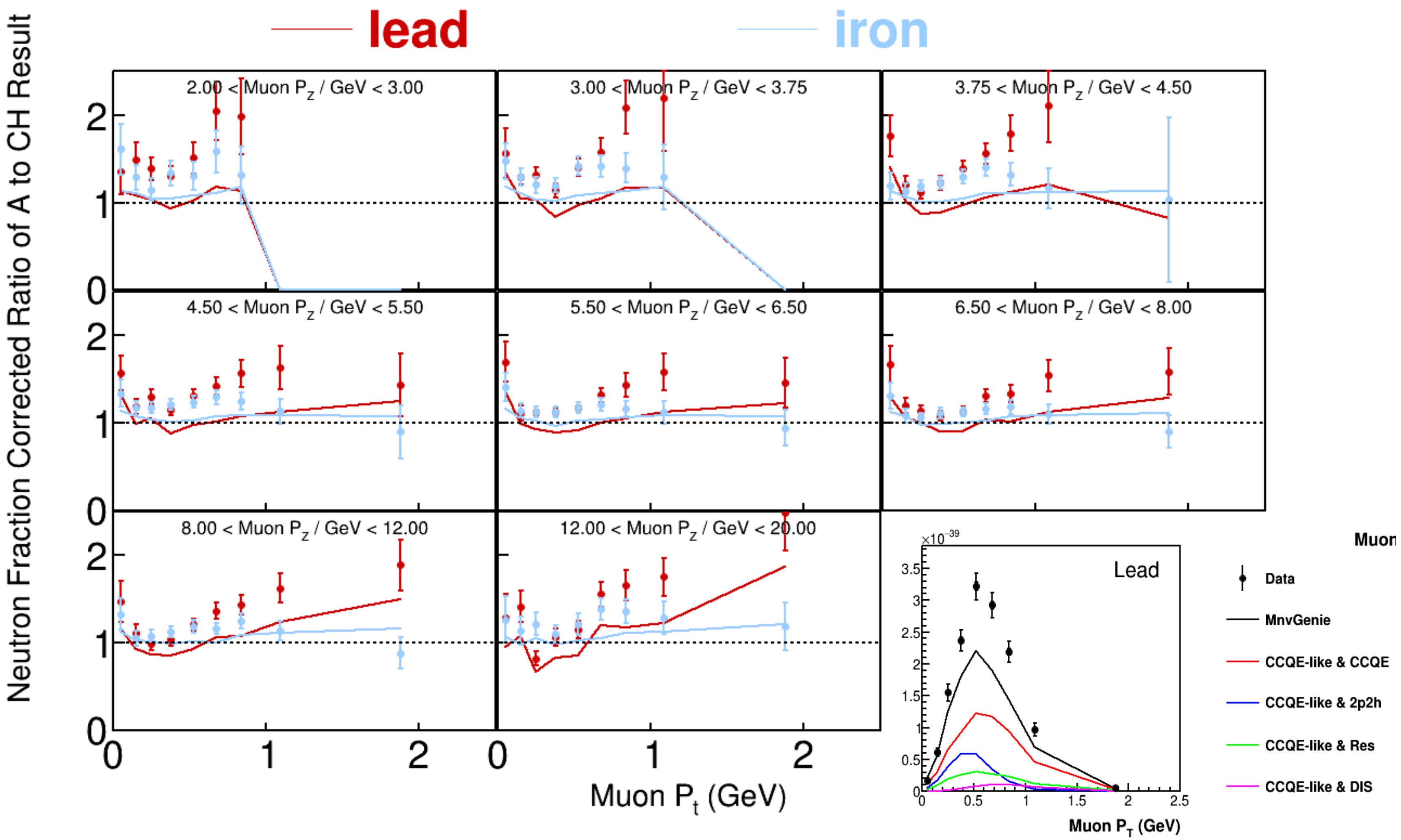
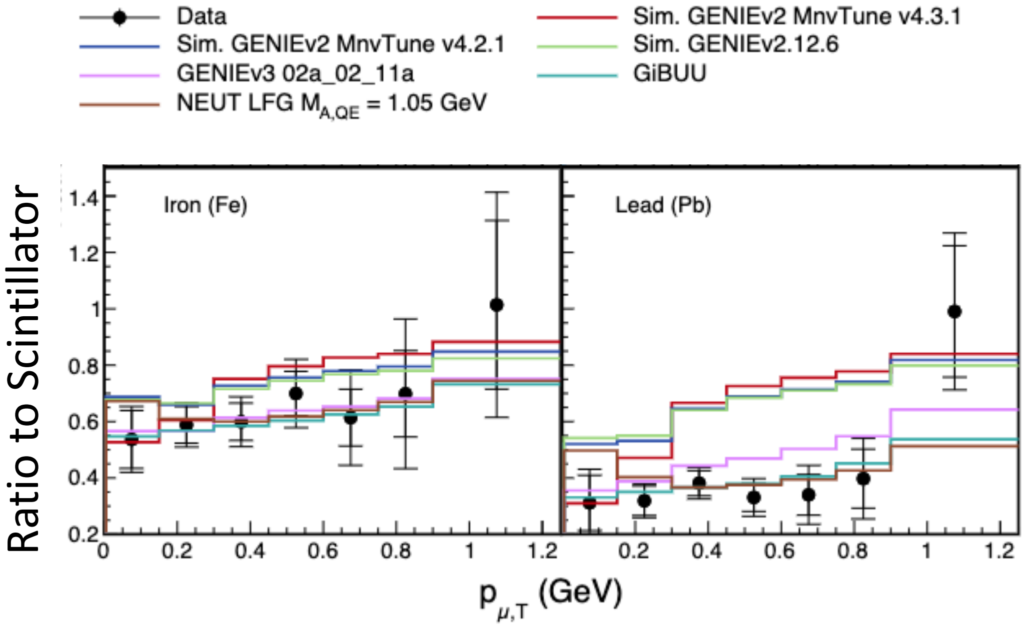
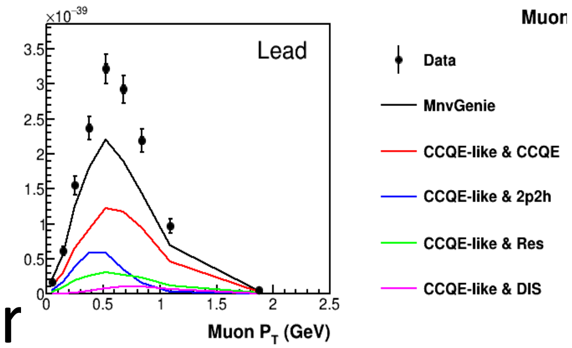
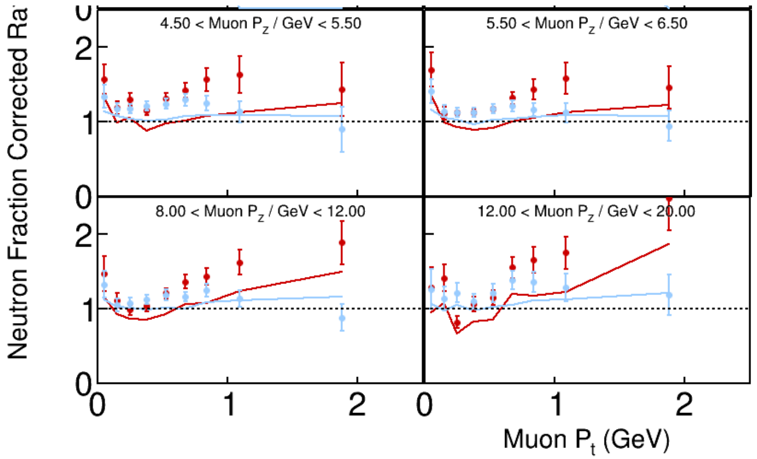


Interpretation

- Reminder from K.McFarland's plenary talk:
  - The charged current incoherent pion versus A data see a deficit that is ~flat vs μ transverse momentum; changes from 0.8 for Fe to 0.5 for Pb relative to the CH Pion production rates
- MINERvA also sees an excess of CC0π-like events in the regions you expect pion absorption!
- Message to NOW2022: more energy may be missing from your final state than your generators are predicting…

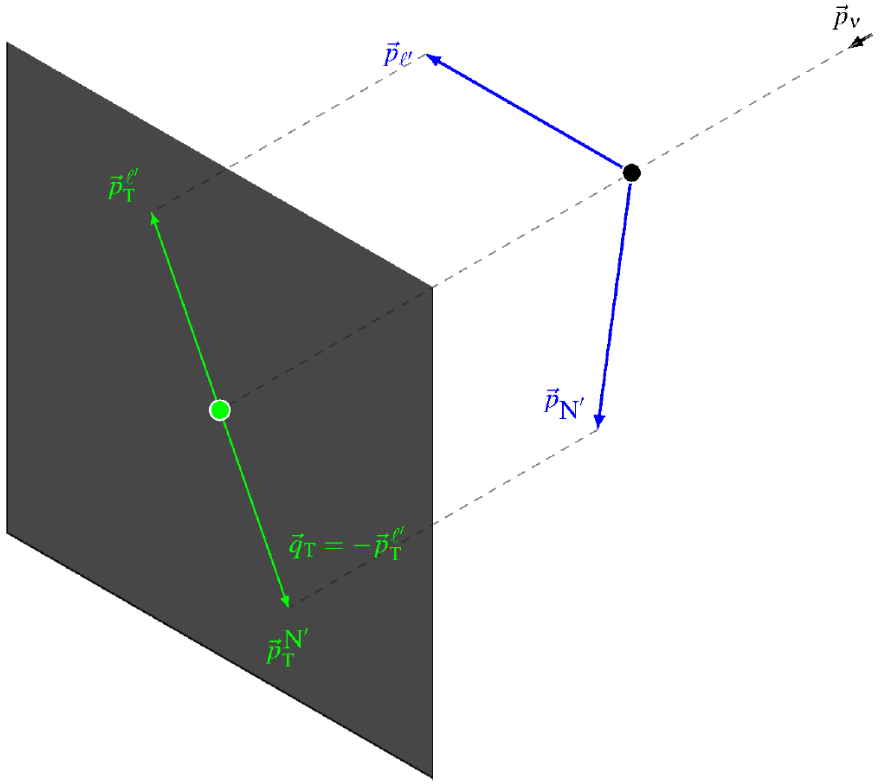






Transverse Kinematic Imbalance (TKI) in CC0π

- Consider the transverse kinematic imbalance of the leading proton and the lepton in CC0π events.
- Predictions are simple for free nucleons at rest!
- Differences can be due to:
    - Multi-nucleon correlations
    - Pion absorption
    - Fermi motion
    - Binding energy



Graphics courtesy X.-G. Lu, ν2022

https://inspirehep.net/literature/1410087

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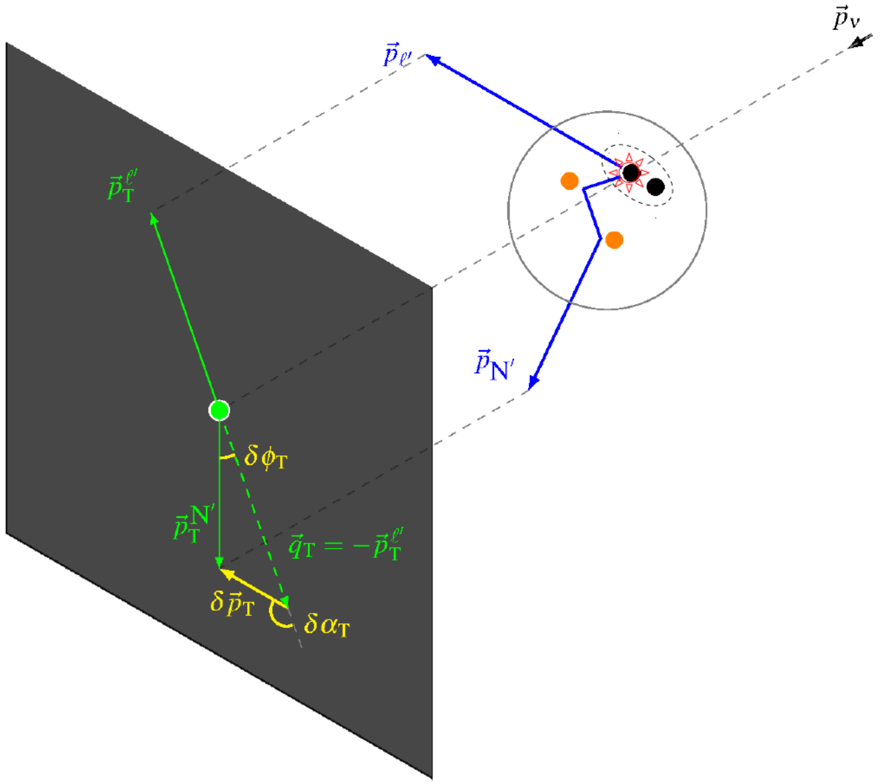
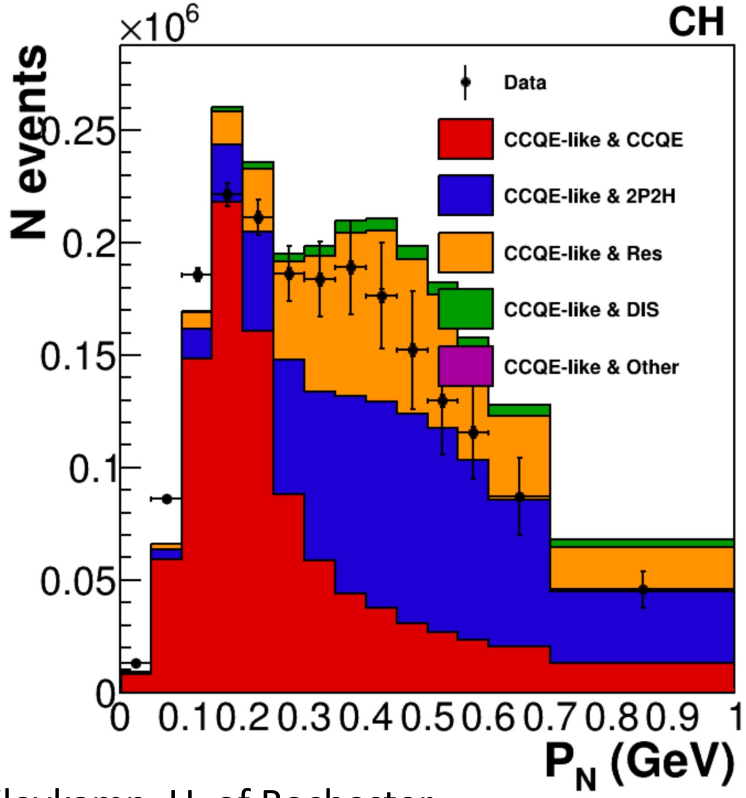


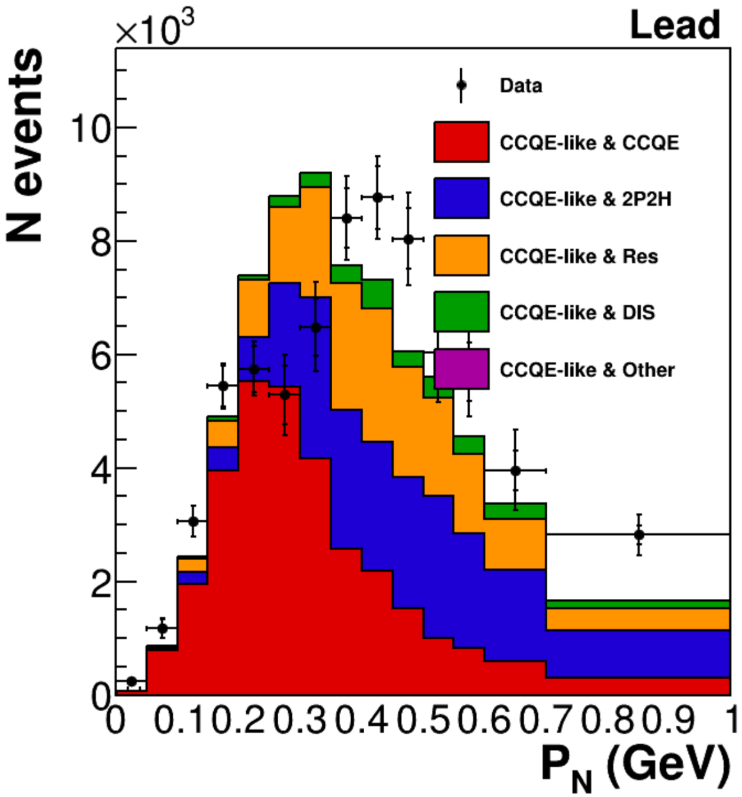
Graphics courtesy X.-G. Lu, ν2022

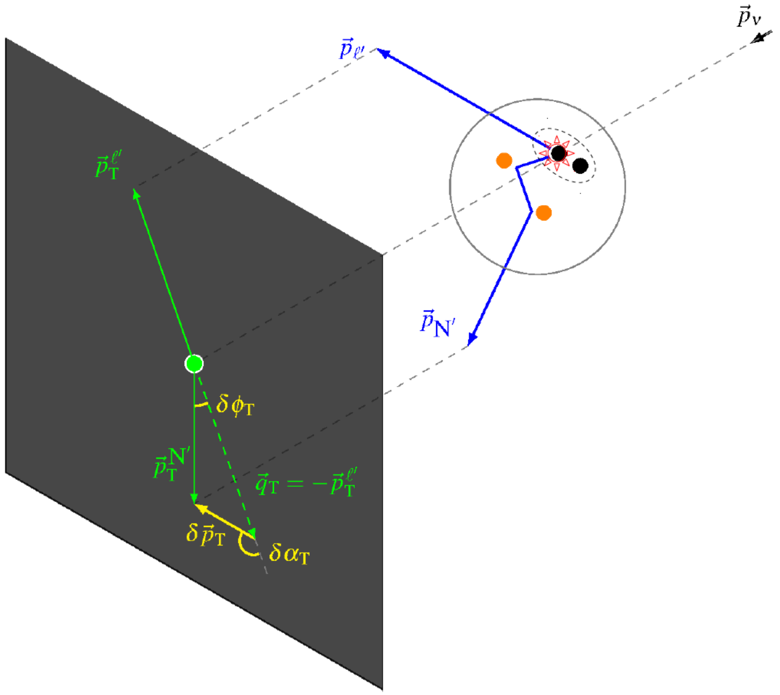
https://inspirehep.net/literature/1410087

Preview: Transverse Kinematic Imbalance vs A

- We can now look at the TKI variables for C, H_2O, Fe, Pb & CH!
- Spoiler alert: GENIE gets Carbon and CH distributions more right than it gets the heavier nuclei, more π absorption as A increases





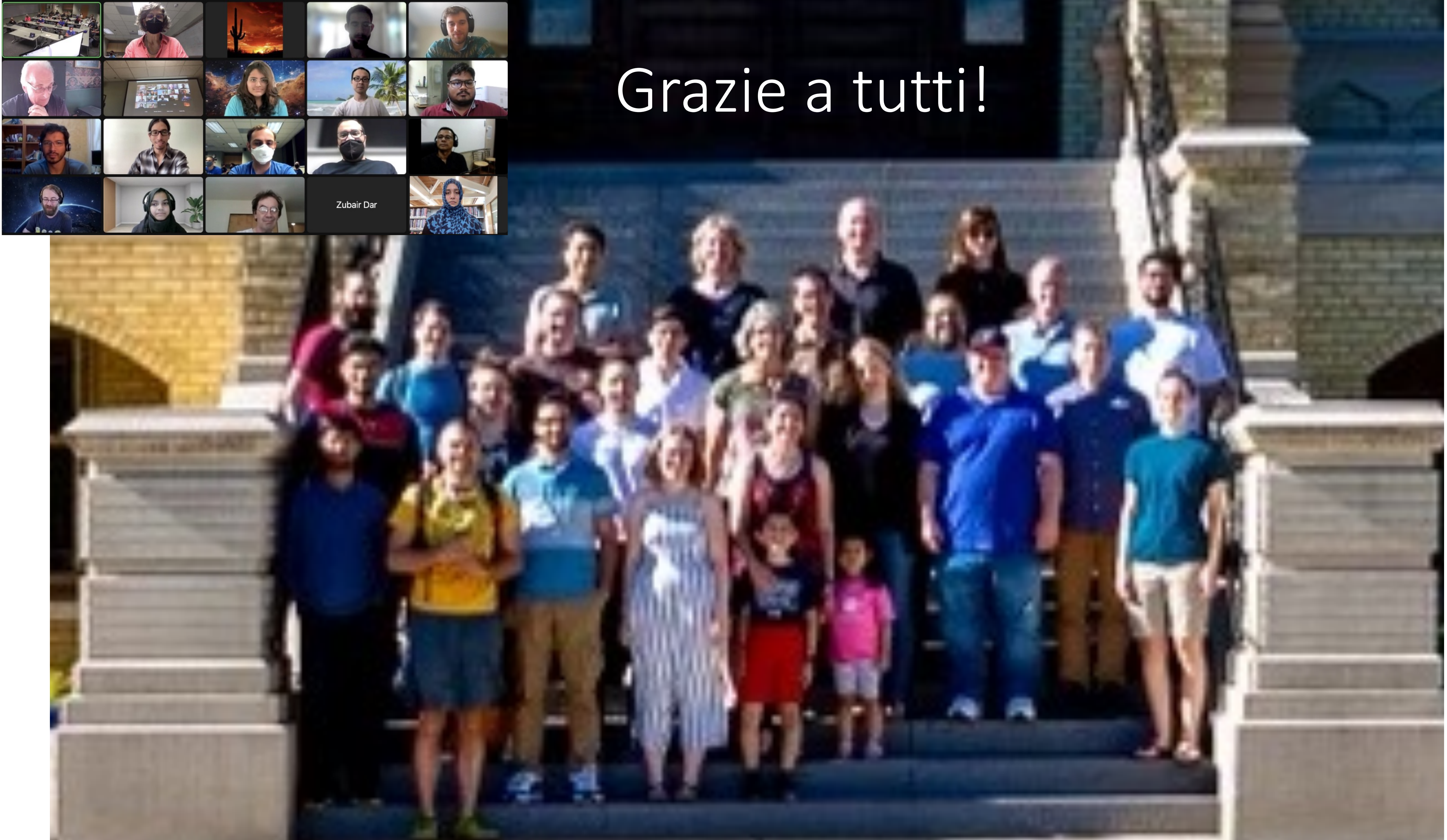


J. Kleykamp, U. of Rochester
Thesis, publication in preparation

Conclusions

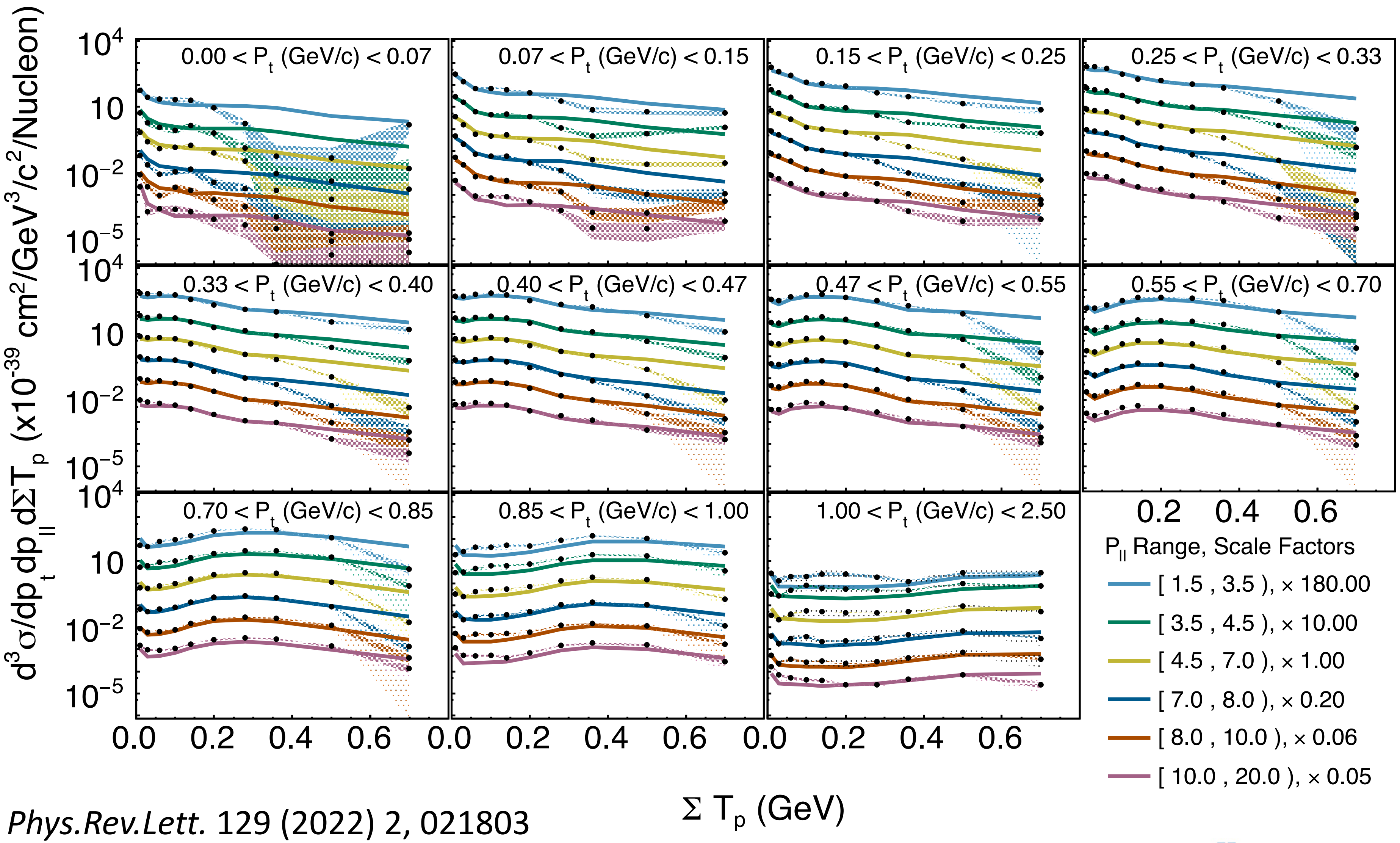
- MINERvA continues to have a lot to say to current and future oscillation experiments
- Have established a "tune" that gets most of the details of our ~3GeV data right, testing it now on ~6GeV data now
- Have the statistics to pick out exclusive state cross sections vs A
  - Seeing where our improved model falls short
- Many results *a presto*
  - **Comparisons vs A**: CC0π , CC1π, CC coherent π
  - Electron Neutrino and Anti-Neutrino "low q" measurements
- Working on a data preservation product so the community can continue to mine this data set for years to come!

Grazie a tutti!



Backup Slides

Looking at CC0$\boldsymbol{\pi}$ in 3 dimensions $\Sigma T_p, p_T, p_\parallel$



Phys.Rev.Lett. 129 (2022) 2, 021803

- Lots to see!
- The trends are independent of $p_\parallel$, so not strongly energy dependent.
- Many processes contribute to "CC0$\boldsymbol{\pi}$"
  - CCQE
  - 2p2h
  - Resonance+π absorption
  - DIS

Energy deposits in MINERvA

- This is not so different from other tracking/calorimetric ν detectors

$$E_{avail} \equiv (\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{E of other particles except neutrons})$$

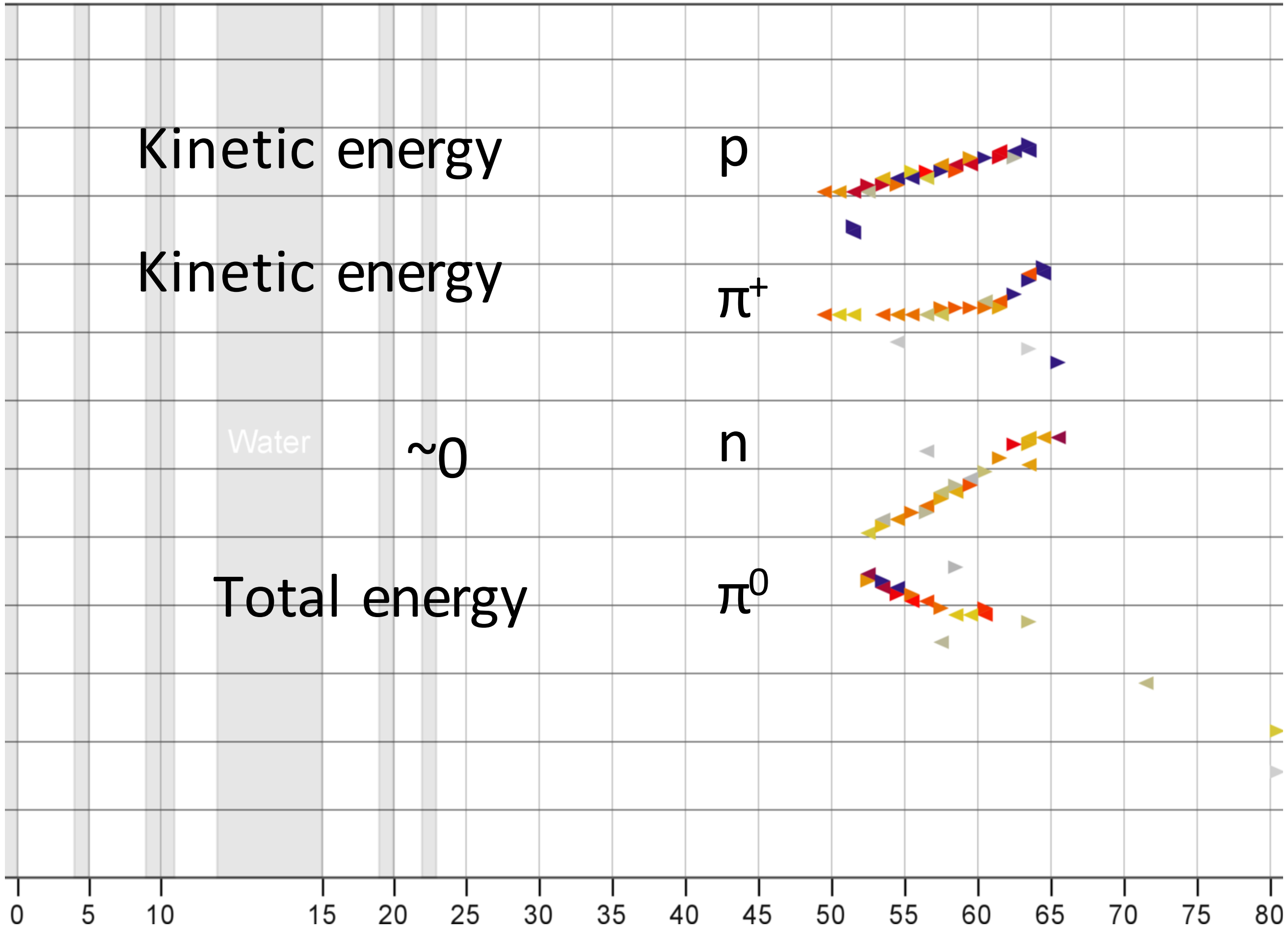


Figure courtesy P. Rodrigues