MINERvA Results

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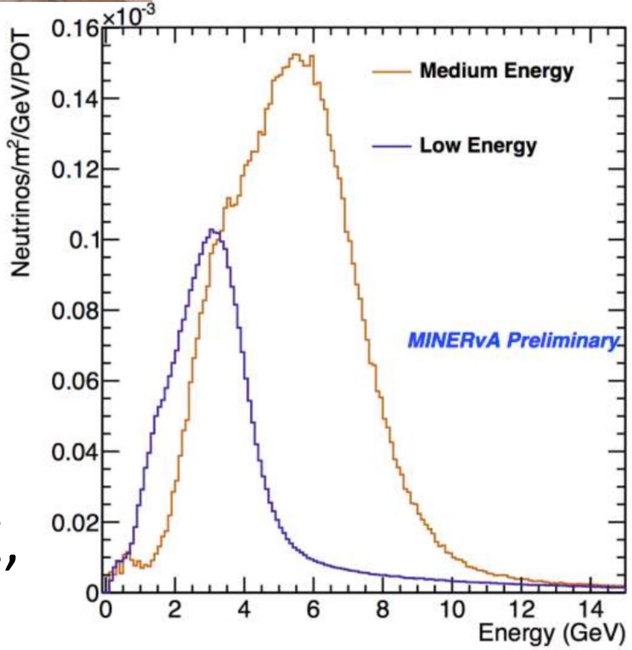
Fermilab User's Meeting

MINERvA Again?


MINERvA, 2006

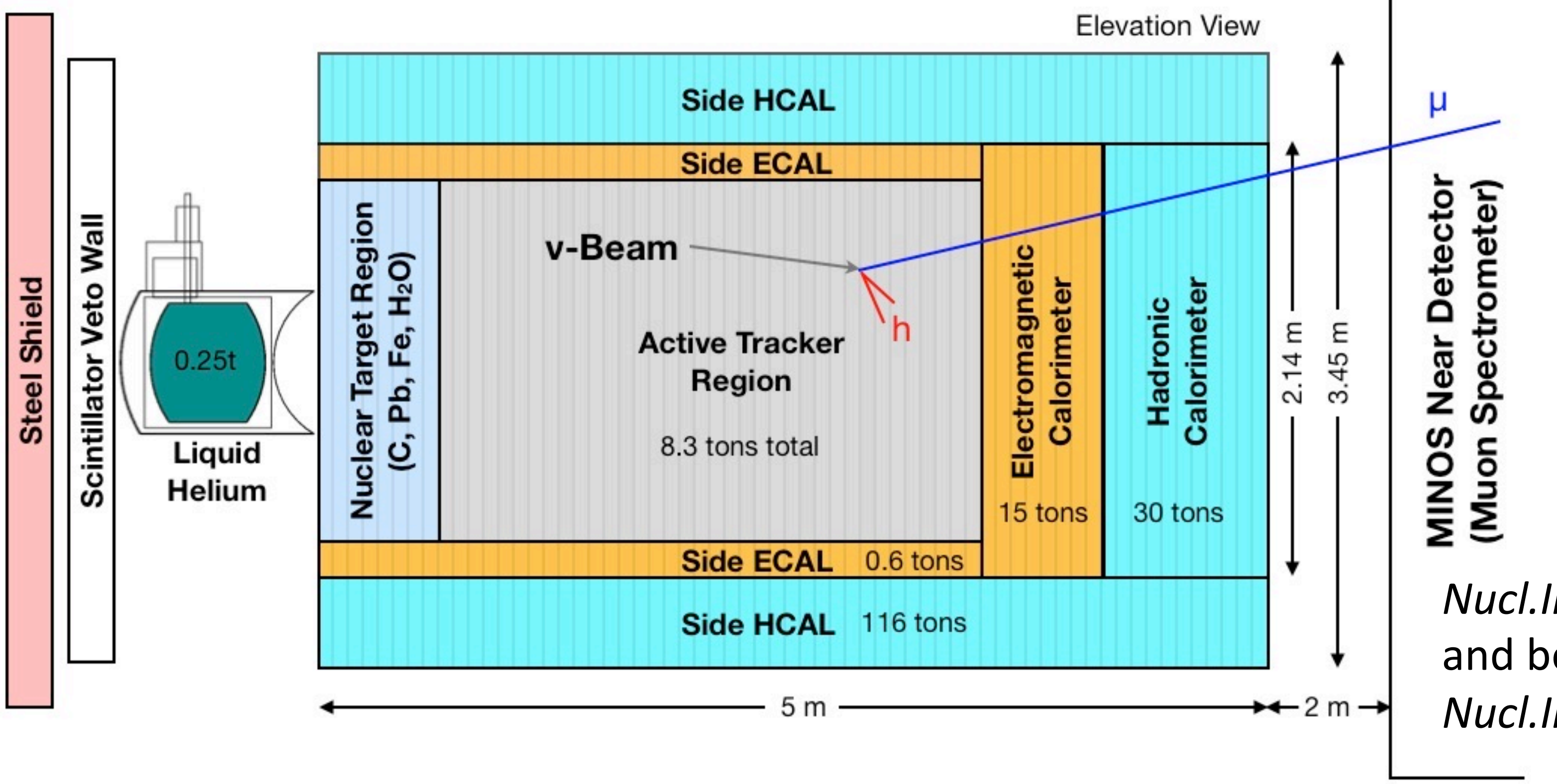
- 2009: MINERvA starts taking data with partially constructed detector
- 2010-2012: MINERvA accumulates $4x10^{20}$ POT in Low Energy Neutrino mode, $1.7x^{20}$ POT in Antineutrino mode
- 2013-2017: MINERvA takes $12x10^{20}$ POT Medium Energy Neutrino Mode Data
- 2017-2019: MINERvA takes $12x10^{20}$ POT Medium Energy Antineutrino Mode Data
- Since 2013: Publish Publish Publish! 46 physics publications in 11 years, 4 more papers currently in internal review
- This year: new measurements featuring ratios: $\nu_e/\nu_\mu$and , LE to ME, neutrino/antineutrino, and new handle on seeing pions



MINERvA Cross Section/ Flux Publications

- “Msrm't of Electron nu and Antinu Cross Sections at Low Momentum Transfer”> PRD 109, (2023) 092008
- “Msrm't of the Multi-Neutron v̄μ Charged Current DifferentialPRDon at Low Available Energy on CH” PRD 108, (2023) 112010
- “Msrm't of the axial vector form factor from antinu-proton scattering” Nature, 614, 48-53 (2023)
- “Simultaneous Msrm't of vμ QE-like xsec on CH, C, water, Fe, and Pb as a function of muon kinematics at MINERvA” PRL 130, 161801 (2023)
- “High-Statistics Msrm't of Antinu QE-like scattering at Ev~ 6~GeV on a CH Target” PRD 108, (2023) 032018 (2023)
- “nu-induced coherent π+ production in C, CH, Fe and Pb at ⟨Ev⟩~6 GeV” PRL 131, 051801 (2023)
- “Simultaneous Msrm't of vμ charged-current single π+ production in CH, C, H2O, Fe, and Pb targets in MINERvA” PRL 131, 011801 (2023)
- “Improved constraint on the MINERvA medium energy nu flux using v̄e−→v̄e− data” Phys.Rev.D 107 (2023) 1, 012001
- “Simultaneous Msrm't of proton and lepton kinematics in QE-like vμ-CH interactions from 2 to 20 GeV” PRL 129 (2022) 2, 021803
- “Msrm't of inclusive charged-current muon ν scattering on CH at ⟨Ev⟩~6 GeV with low three-momentum transfer” PRD 106 (2022) 3, 032001
- “Exploring nu-Nucleus Interactions in the GeV Regime using MINERvA” Eur.Phys.J.ST 230 (2021) 24, 4243-4257
- “Constraining the NuMI nu flux using inverse muon decay reactions in MINERvA” PRD 104 (2021) 9, 092010
- “Msrm't of inclusive charged-current vμ cross sections as a function of muon kinematics at <Ev>~6 GeV on CH” PRD 104 (2021) 9, 092007
- “Double-Differential Inclusive Charged-Current vμ Cross Sections on CH in MINERvA at ⟨Ev⟩~ 3.5 GeV” PRD 101, 11 (2020)
- “Probing Nuclear Effects with nu-induced Charged-Current Neutral Pion Production” PRD 102, 072007 (2020)
- “High-statistics Msrm't of nu QE-like scattering at =~6 GeV on a CH target” PRL 124, 121801 (2020)
- “Nuclear binding energy and transverse momentum imbalance in nu-nucleus reaction “ PRD 101, 092001 (2020)
- “Constraint of the MINERvA Medium Energy nu Flux using nu-Electron Elastic Scattering” PRD 100, 9 (2019)
- “Msrm't of v̄μ charged-current single π− production on CH in the few-GeV region using MINERvA” PRD 100, 5 (2019)
- “Tuning the GENIE Pion Production Model with MINERvA Data” PRD 100, 7 (2019)
- “Neutron Msrm'ts from anti-nu CH reactions” PRD 100, 052002 (2019)
- “Msrm't of QE-Like nu Scattering at ⟨Ev⟩~3.5 GeV on a CH Target” PRD 99, 012004 (2019)
- “Msrm't of final-state correlations in nu muon-proton mesonless production on CH at ⟨Ev⟩ = 3 GeV” PRL 121, 022504 (2018)
- “Antinu charged Current charged-current reactions on scintillator with low momentum transfer” PRL 120, 221805 (2018)
- “Msrm't of the muon anti-nu double-differential cross section for quasi-elastic scattering on CH at~Ev~3.5GeV” PRD 97, 052002 (2018)
- “Msrm't of Total and Differential Cross Sections of nu and Antinu Coherent π± Production on Carbon” PRD 97, 032014, (2018)
- “Msrm't of vμ charged-current single π0 production on CH in the few-GeV region using MINERvA” PRD 96, 072003 (2017)
- “Direct Msrm't of Nuclear Dependence of Charged Current QE-like nu Interactions using MINERvA” PRL 119, 082001 (2017)
- “Msrm't of the antinu to nu charged-current interaction cross section ratio on carbon” PRD 95, 072009 (2017)
- “Msrm't of neutral-current K+ production by nus using MINERvA” PRL 199, 011802 (2017)
- “Msrm'ts of the Inclusive nu and Antinu Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method” PRD 94, 112007 (2016)
- “nu Flux Predictions for the NuMI Beam” PRD 94, 092005 (2016)
- “First evidence of coherent K+ meson production in nu-nucleus scattering” PRL 117, 061802 (2016)
- “Msrm't of K+ production in charged-current vμ interactions” PRD 94, 012002 (2016)
- “Cross sections for nu and antinu induced pion production on CH in the few-GeV region using MINERvA” PRD 94, 052005 (2016).
- “Evidence for neutral-current diffractive neutral pion production from hydrogen in nu interactions on CH” PRL 117, 111801 (2016)
- “Msrm't of nu Flux using nu-Electron Elastic Scattering”, PRD 93, 112007 (2016)
- “Msrm't of Partonic Nuclear Effects in Deep-Inelastic nu Scattering using MINERvA”, PRD 93, 071101 (2016).
- “Identification of nuclear effects in nu-carbon interactions at low three-momentum transfer”, PRL 116, 071802 (2016).
- “Msrm't of electron nu QE and QE-like scattering on CH at average E_ν of 3.6 GeV”, PRL 116, 081802 (2016).
- “Single neutral pion production by charged-current anti-ν_μ interactions on CH at average E_ν of 3.6 GeV”, PLB 749 130-136 (2015).
- “Msrm't of muon plus proton final states in ν_μ Interactions on CH at average E_ν of 4.2 GeV” PRD 91, 071301 (2015).
- “Msrm't of Coherent Production of π± in nu and Anti-nu Beams on Carbon from E_ν of 1.5 to 20 GeV”, PRL 113, 261802 (2014).
- “Charged Pion Production in ν_μ Interactions on CH at average E_ν of 4.0 GeV” , PRD 92, 092008 (2015).
- “Msrm't of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at nu energies 2–20 GeV”, PRL 112, 231801 (2014).
- “Msrm't of Muon nu Quasi-Elastic Scattering on a CH Target at E_ν~3.5 GeV”, PRL 111, 022502 (2013).
- “Msrm't of Muon Antinu Quasi-Elastic Scattering on a CH Target at E_ν~3.5 GeV”, PRL 111, 022501 (2013).

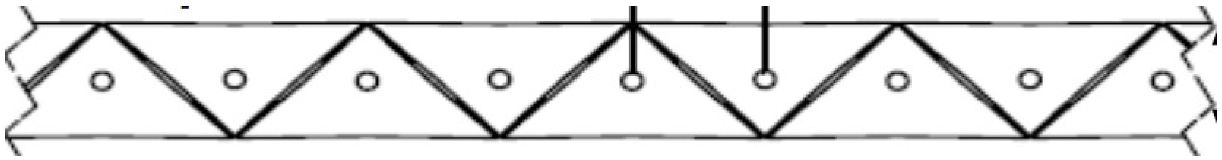
MINERvA’s Detector



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

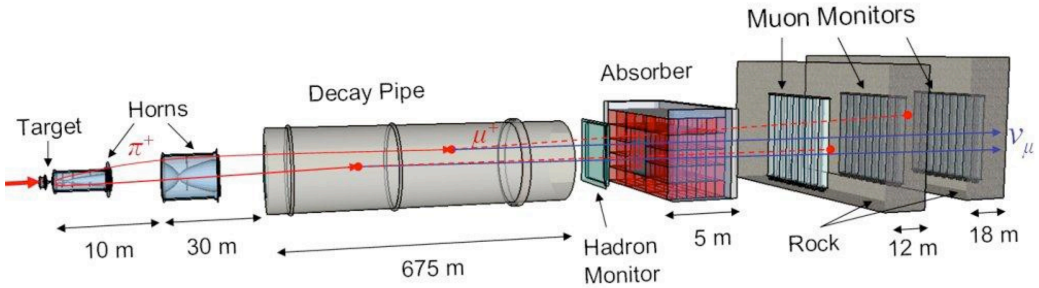
Three views:
X: Vertical
U,V: ±60

17mm

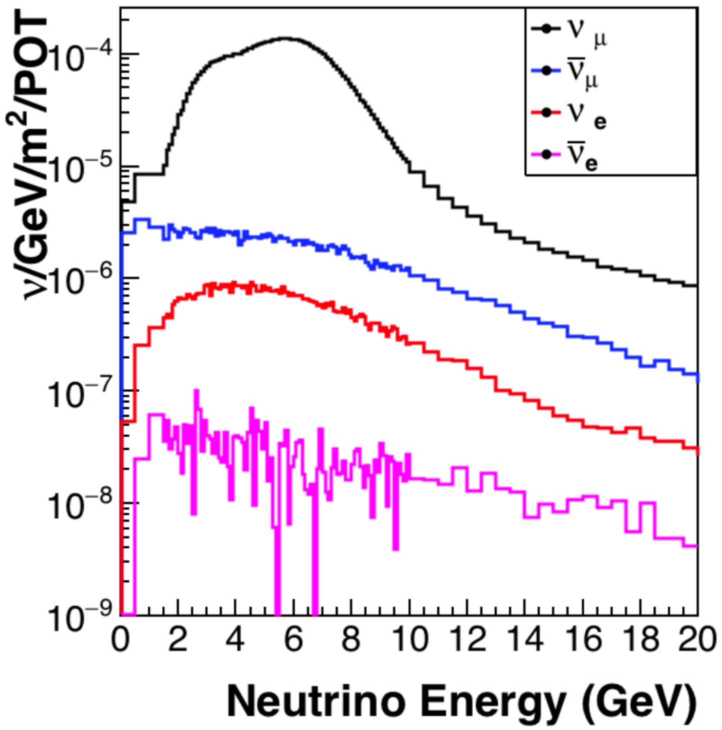


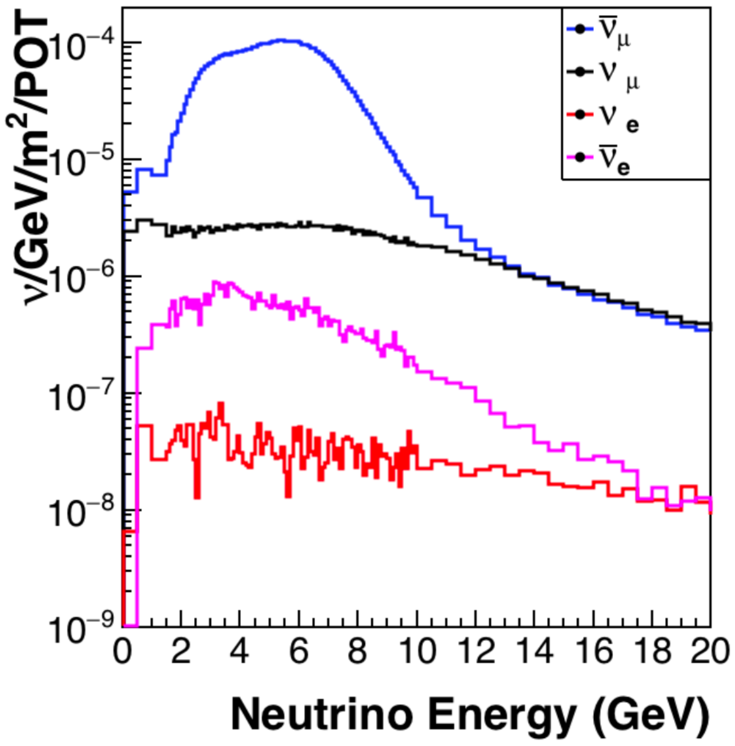
Spatial resolution ~3mm
Timing resolution ~3ns

NuMI Beamline



- Well-understood beam thanks to ν-e scattering constraints, Hadron Production Data, and low-ν shape constraint





L. Zazueta et al., Phys.Rev.D 107 (2023) 1, 012001
D. Ruterbories et al., Phys.Rev.D 104 (2021) 9, 092010
A. Bashyal et al., JINST 16 (2021) P08068
E. Valencia et al., Phys. Rev. D 100, 092001 (2019).
L. Aliaga, M. Kordosky, T. Golan et al, Phys. Rev. D 94, 092005

Graphic from arXiv:2312.16631 [hep-ex]

MINERvA's Scientific Goal

- To learn as much as we can about neutrino interactions
  - With an eye towards oscillation experiments
- Remember Oscillation formula and Current Generation goals:
  - Measure $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ as a function of neutrino energy
- Basic Requirements:
  - Flavour identification (does neutrino make a muon or an electron)
  - Energy Estimate
  - Background rejection and subtraction

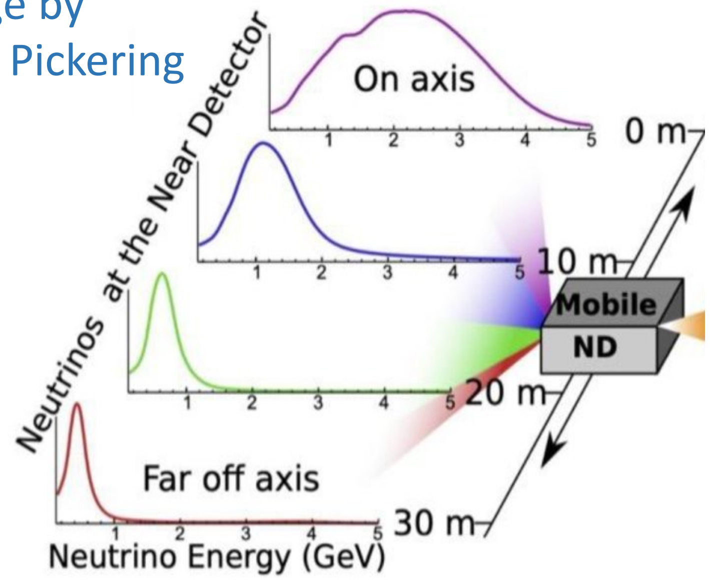
MINERvA’s Legacy for Oscillation Experiments

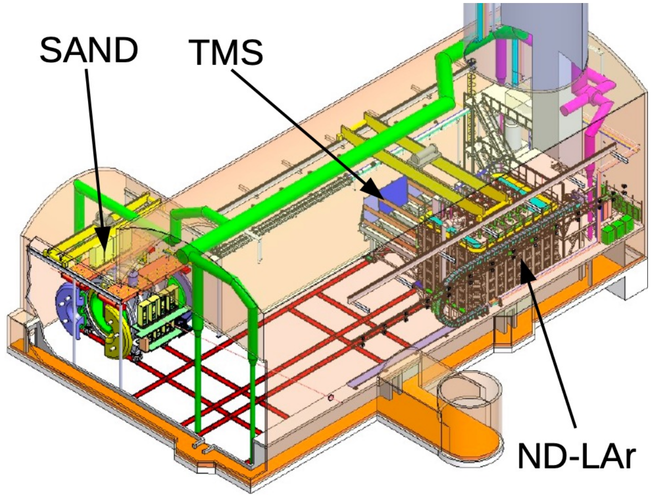
- Comparing Neutrino event rates across different energy spectra
- Measuring Neutrons in Neutrino Interactions
- Comparing Electron to Muon Neutrino Cross Sections
- Studying Pion production from many angles on many nuclei

The trouble with Neutrino Beams…

- You never know event by event what the energy is
- Need to know what the energy is to measure oscillations
- Presence of nucleus can change that visible energy compared to what you would have expected from just hitting a single nucleus
- Various coping mechanisms: look at beams at different off axis angles (PRISM) to see how visible energy changes
- MINERvA's coping mechanism: look at same cross section versus "visible neutrino energy" but two different beams: Medium and Low energy beams

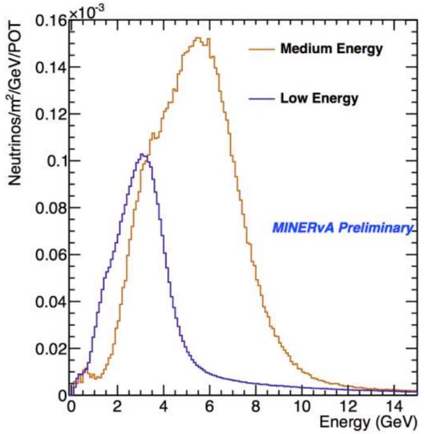
image by
Luke Pickering

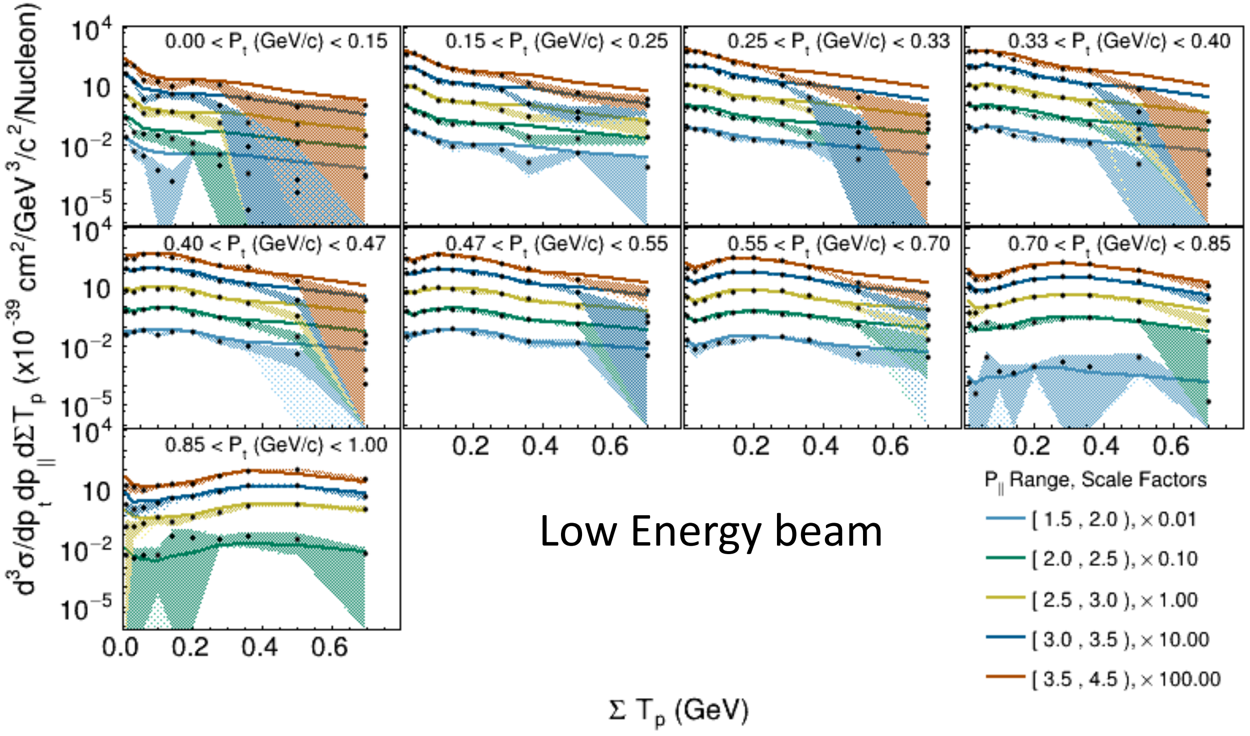




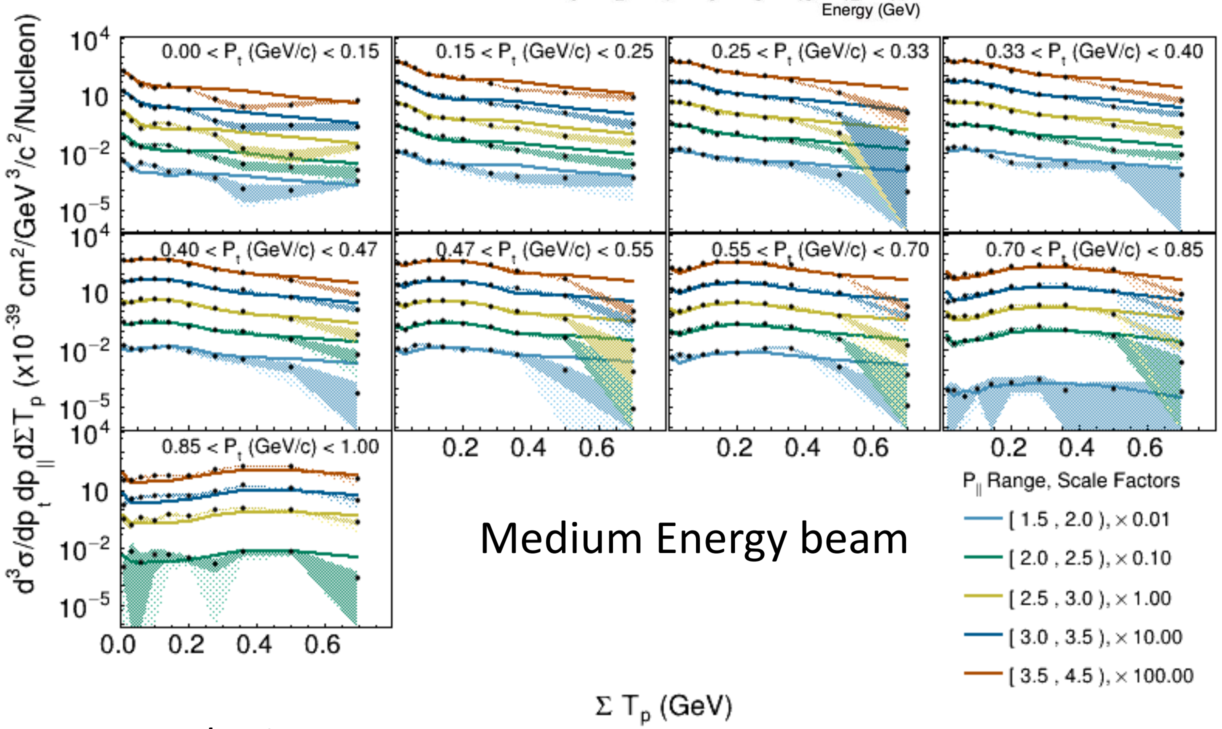
Triple-Differential Cross Sections in 2 beams

- Quasielastic-like interactions, as function of muon and hadronic energy
- Speaks to enormous capabilities of the NuMI beamline…





Low Energy beam

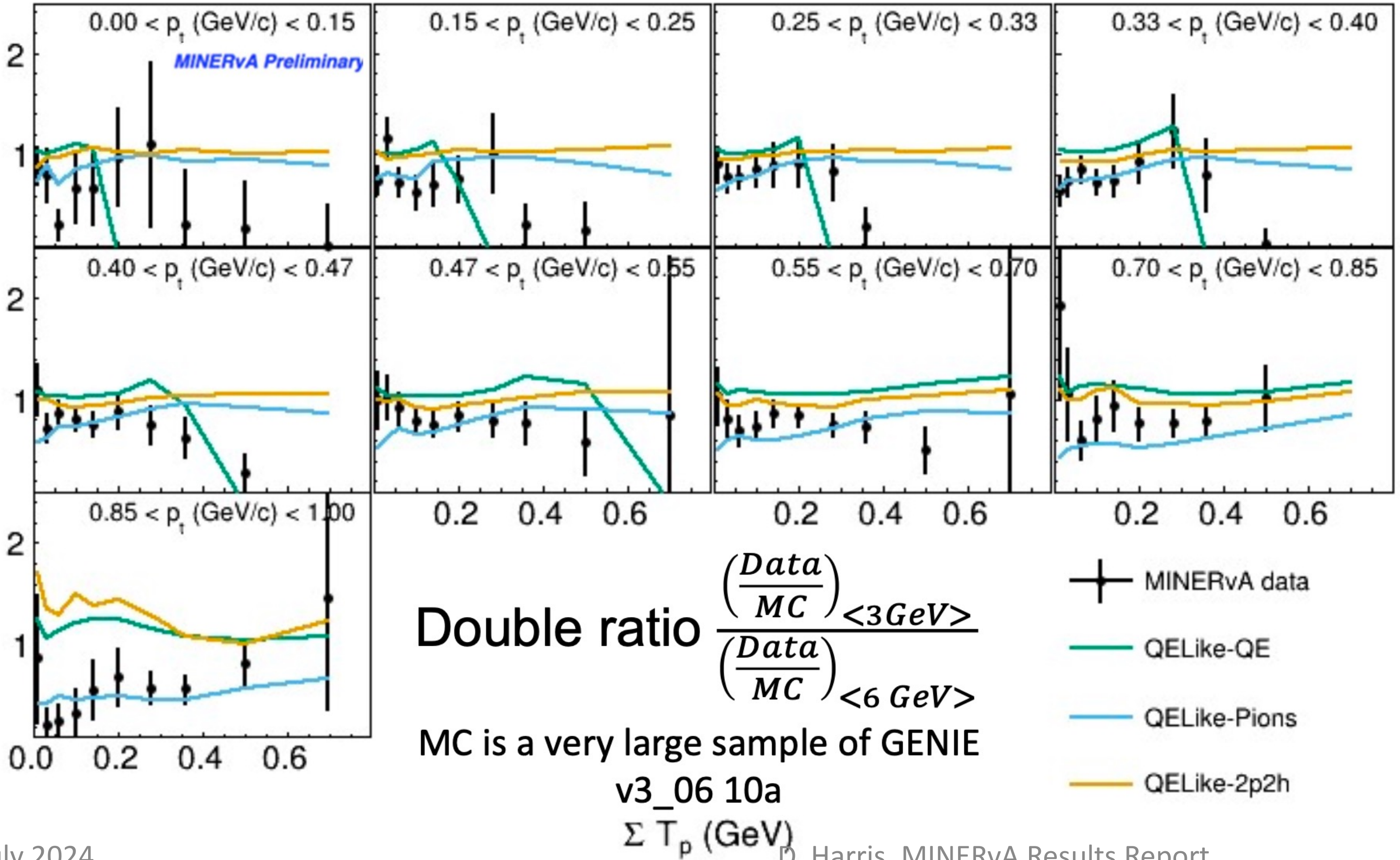


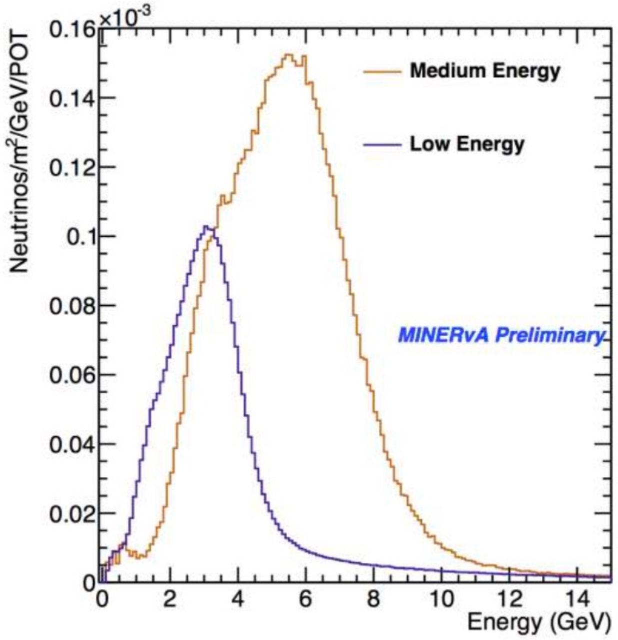
Medium Energy beam

D. Ruterbories, NuINT 2024

What can you learn from 2 beams?

- Consider three variables that SHOULD specify neutrino energy: Muon transverse and longitudinal momentum energy plus everything else for QE-like events

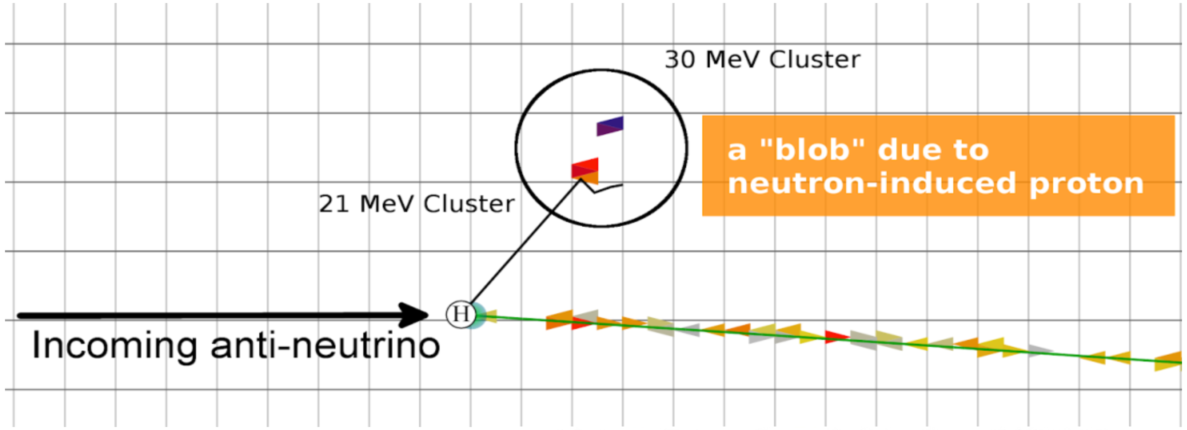


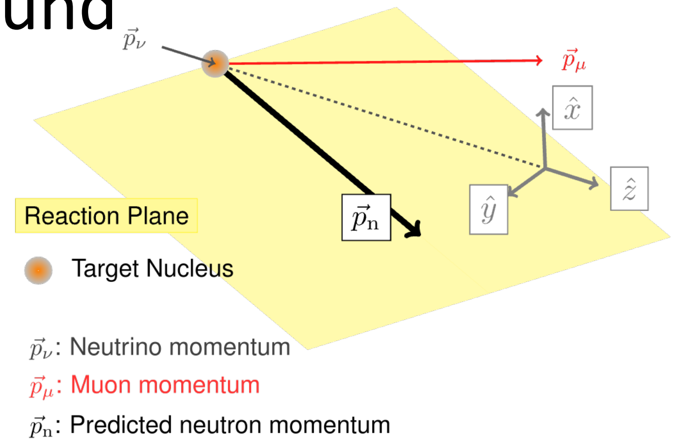


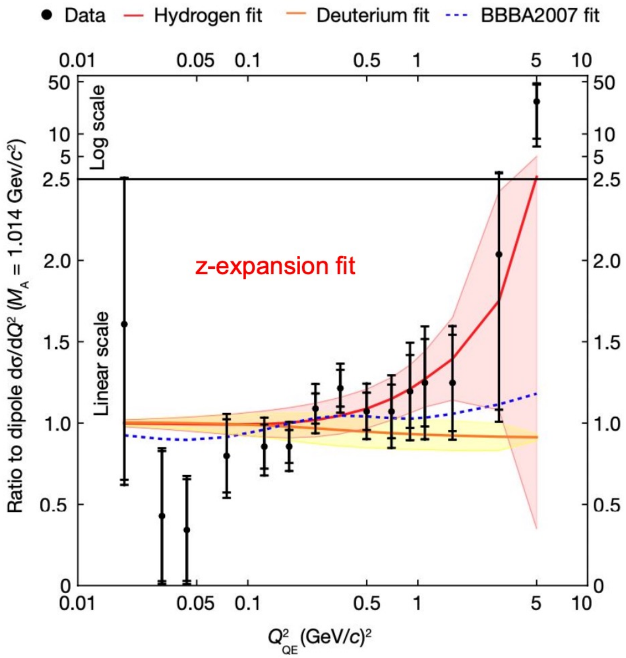
D. Ruterbories, NuINT 2024

The trouble with antineutrino interactions….

- They usually produce neutrons
- Neutrons rarely leave their kinetic energies in our detectors
- MINERvA made first measurement on free protons using CH and subtracting off C background



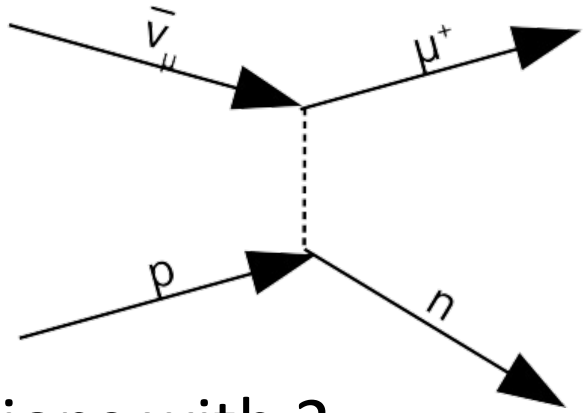




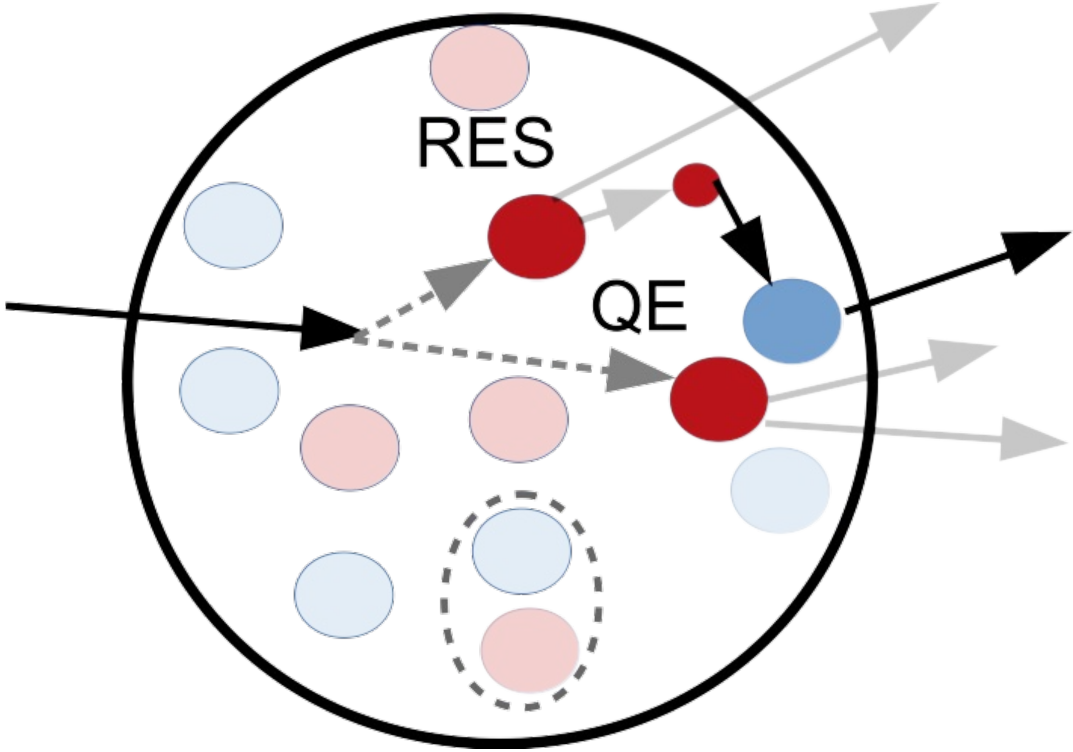
Nature, 614, 48-53

What about events with 2 neutrons?

- One neutron antineutrino event:

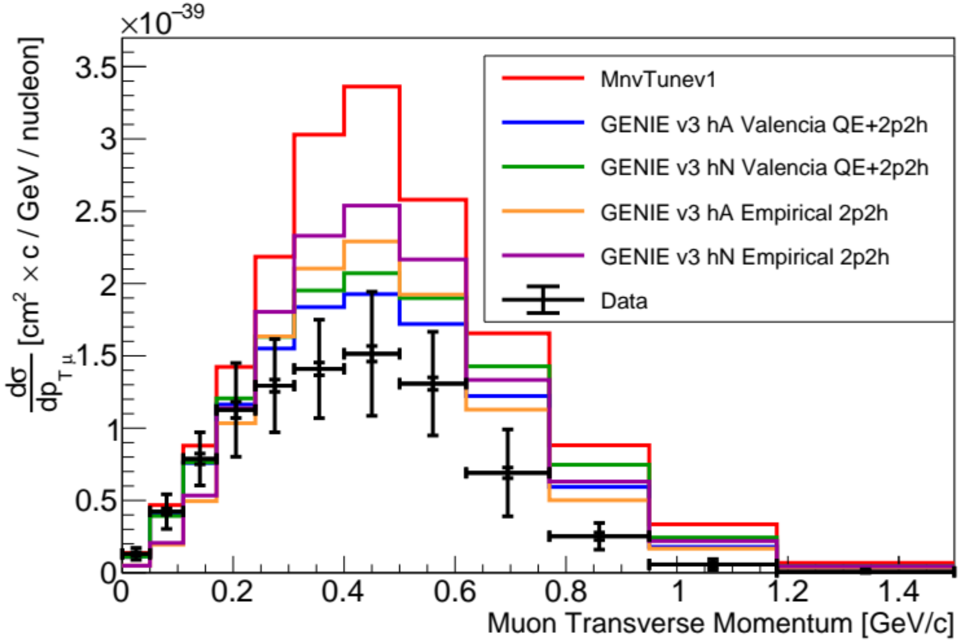


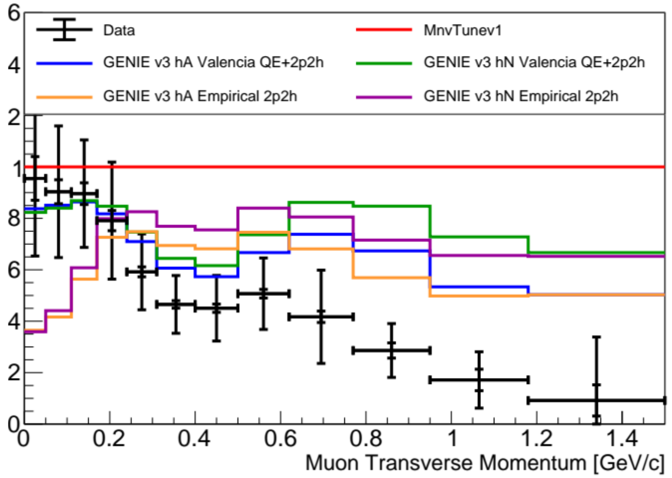
- Antineutrino interactions with 2 neutrons are particularly sensitive to correlated nucleons (2p2h) and to final state interactions
- Both of these processes will modify the “visible energy” from what you might expect from scattering off a free proton



Cross Section Result with 2 neutrons

- Show comparison of 2 2p2h models, and two Final State Interaction models: single step (hA) and multi-step (hN)
- All GENIE v3 models are closer to our new measurement than the original MINERvA tune that was based on the low energy measurements of “2p2h” process

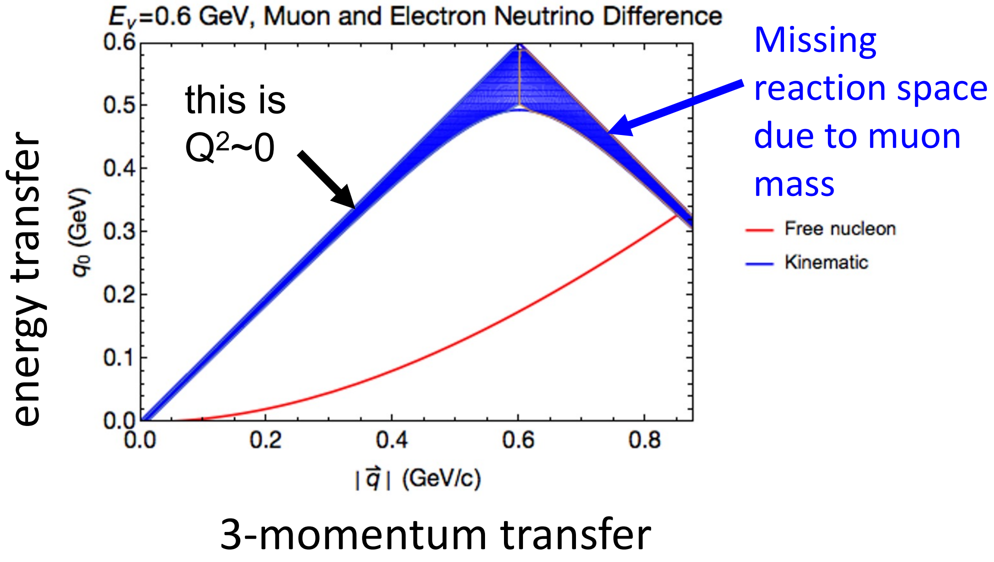


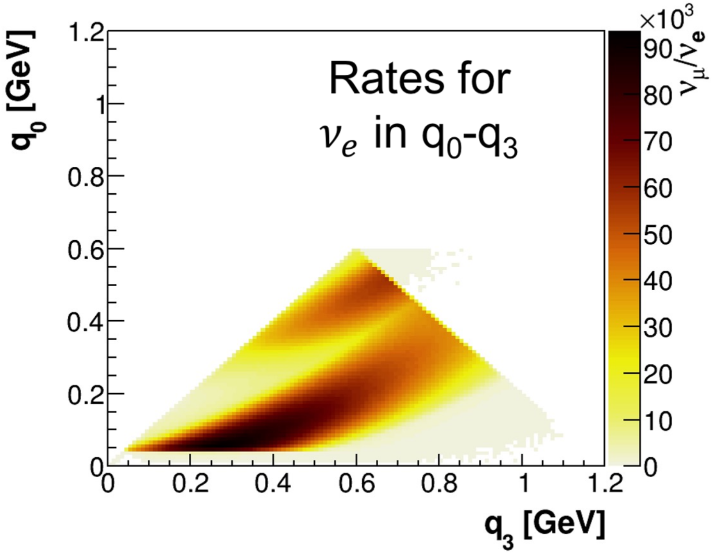


Previous Neutron measurements:
Neutron production: M. Elkins et al, Phys. Rev. D 100, 052002 (2019)
Charged-current elastic (CCE) on hydrogen: T. Cai, A. Olivier et al, Nature 614 (2023) 7946, 48-53
Multi-neutron at low $E_{available}$: A. Olivier et al, Phys. Rev. D 108 (2023) 11, 112010
One upcoming measurement: QE-like on targets with 1+ neutrons!

The trouble with ν_e 's

- By necessity, our ν_μ rich beams have few ν_e in them to allow us to study any difference between ν_μ and ν_e interactions.
- Therefore, we infer ν_e interactions from studies of ν_μ
- But what we study can't give us the whole picture.
- Phase space (below), radiative corrections, nuclear effects.





Radiative corrections:
O. Tomalak et al.,
Nature Commun. 13 (2022) 1, 5286 and
Phys.Rev.D 106 (2022) 9, 093006

Nuclear effects:
T. Dieminger et al.,
Phys.Rev.D 108 (2023) L031301

K. McFarland, Neutrino 2024

Recipe for MINERvA's Electron Neutrino Cross-Section Measurement

1. Identify electron neutrino candidates.
2. Characterize backgrounds with sidebands.
3. Remove anti-neutrinos from FHC beam, using their measurement in RHC, and vice versa.
4. Measure electron neutrino cross-sections.
5. Take ratio to muon neutrinos, accounting for different fluxes.

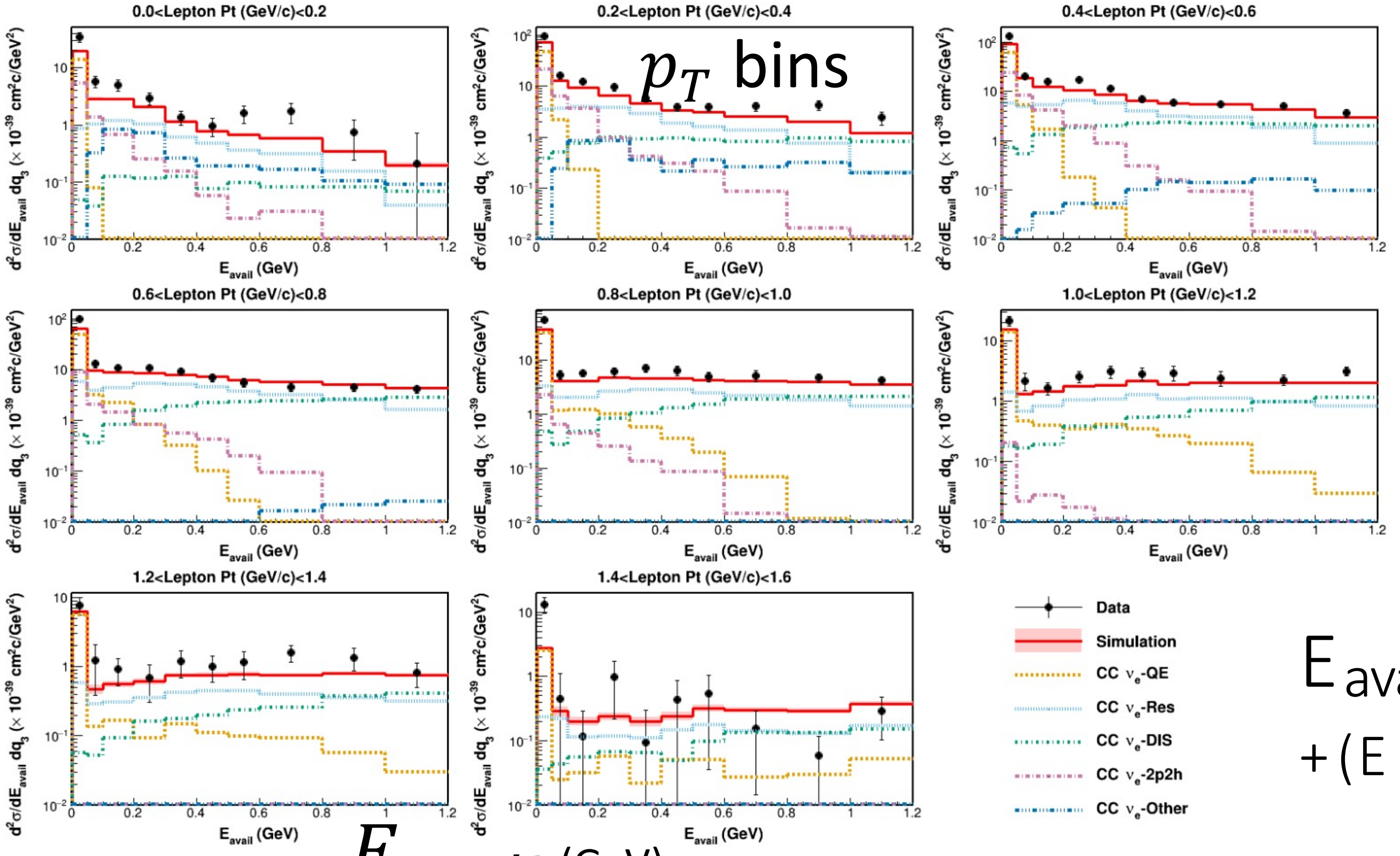
"Measurement of Electron Neutrino and Antineutrino Cross Sections at Low Momentum Transfer"
S. Henry, H. Su et al., Phys. Rev. D. 109, (2023) 092008

Ratio publication in preparation.

$\bar{\nu}_e$ Cross Section along 2 dimensions

- After background subtractions, unfolding, flux and targets calculation…

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkg})}{\epsilon_i T \Phi(\Delta x)_i}$$



E_{avail} (GeV)

S. Henry, H. Su, et al, Phys. Rev. D 109, (2023) 092008

- Measured cross-section in electron p_T bins (0.2 GeV/c width, from 0 to 1.6 GeV/c) of available calorimetric energy, E_{avail}.
  - The "usual" MINERvA prescription for this is used.
- Peaked at zero for antineutrino (quasielastic neutron knockout).

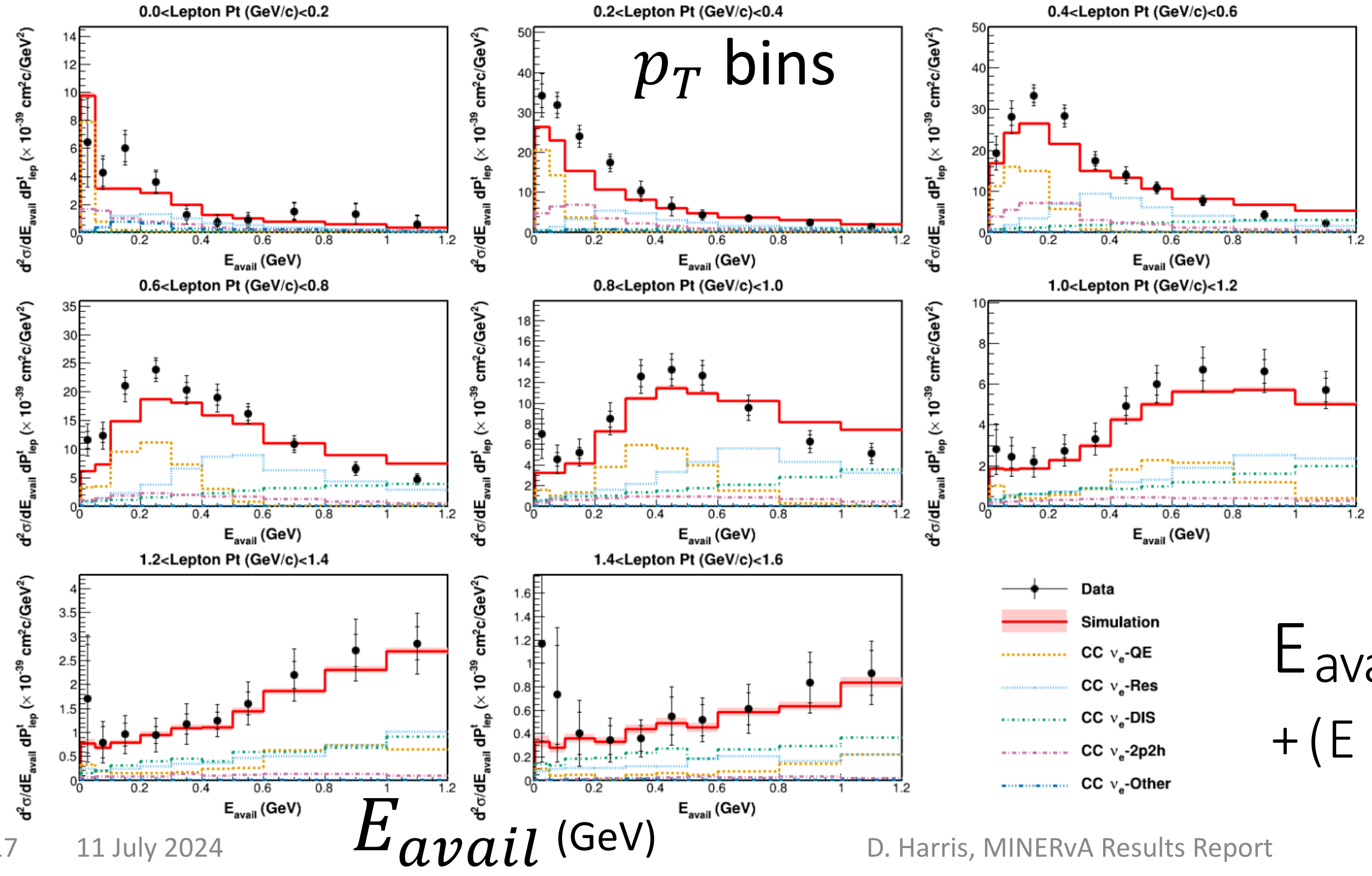
$E_{avail} \equiv$ (Proton and $\pi^{\pm}$ KE)

+ (E of other particles except neutrons)

ν_e Cross Section along 2 dimensions

- After background subtractions, unfolding, flux and targets calculation…

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkg})}{\epsilon_i T \Phi(\Delta x)_i}$$



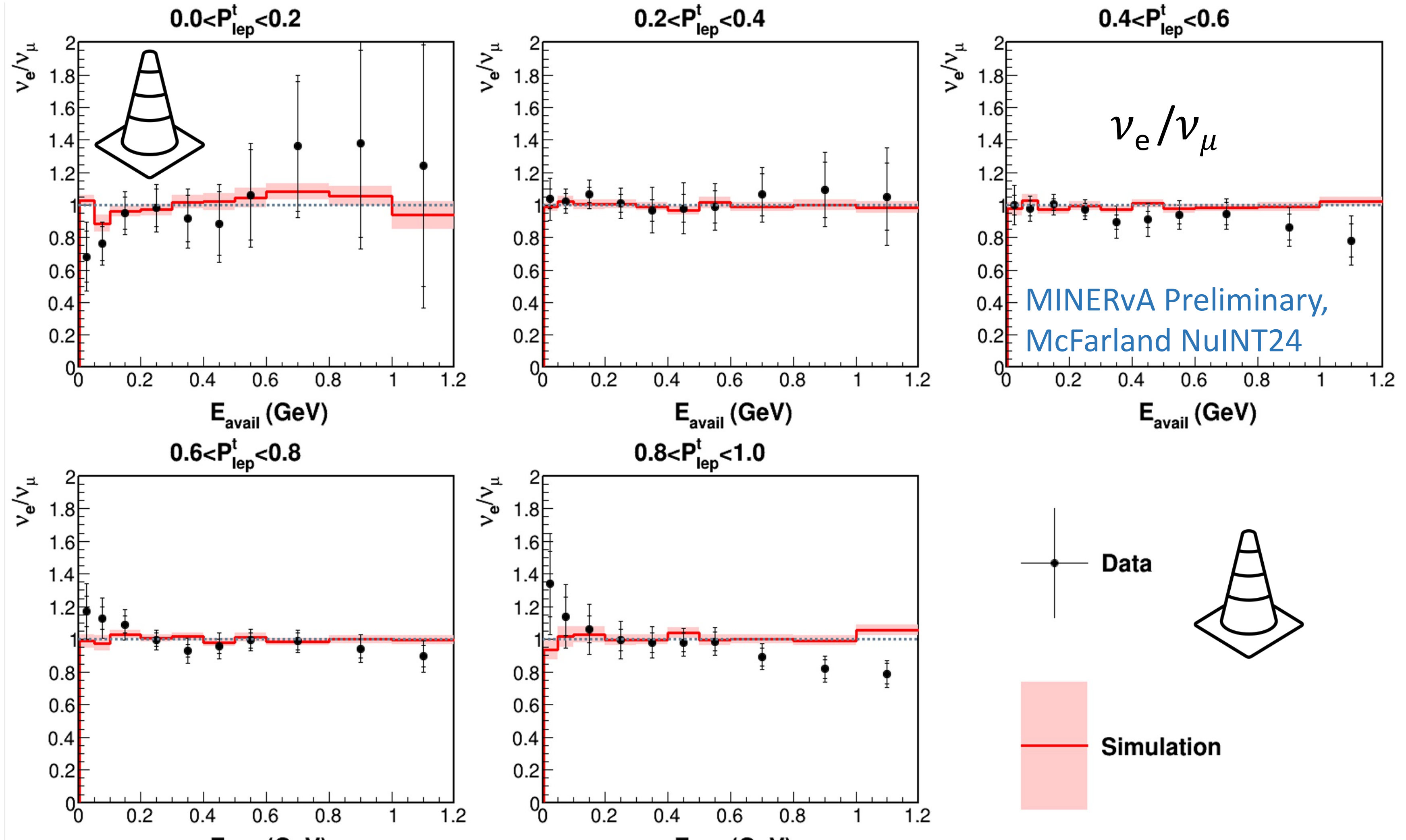
- Measured cross-section in electron p_T bins (0.2 GeV/c width, from 0 to 1.6 GeV/c) of available calorimetric energy, E_{avail}.
  - The "usual" MINERvA prescription for this is used.
- Quasielastic peak shifts with p_T. As with antineutrino, inelastic is high E_{avail}.

$E_{avail} \equiv$ (Proton and $\pi^{\pm}$ KE)

+(E of other particles except neutrons)

S. Henry, H. Su, et al, Phys. Rev. D 109, (2023) 092008

MINERvA ν_e/ν_μ Ratios

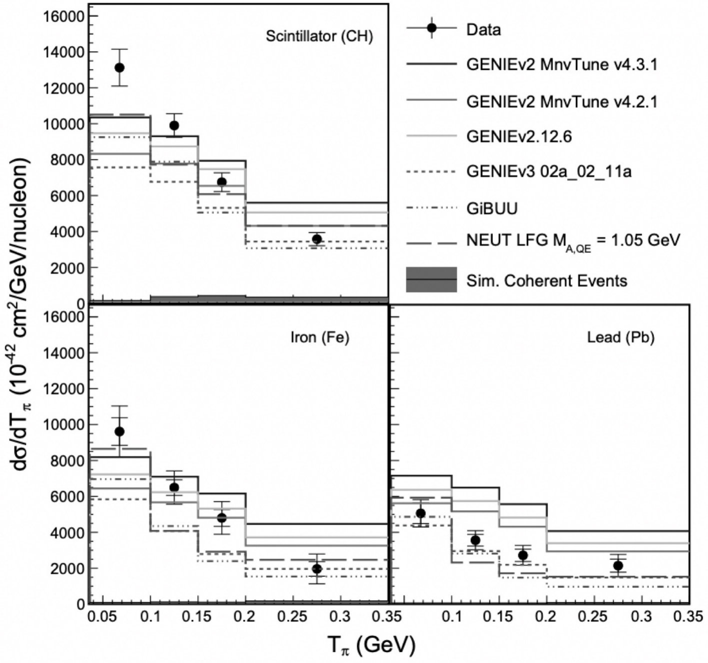


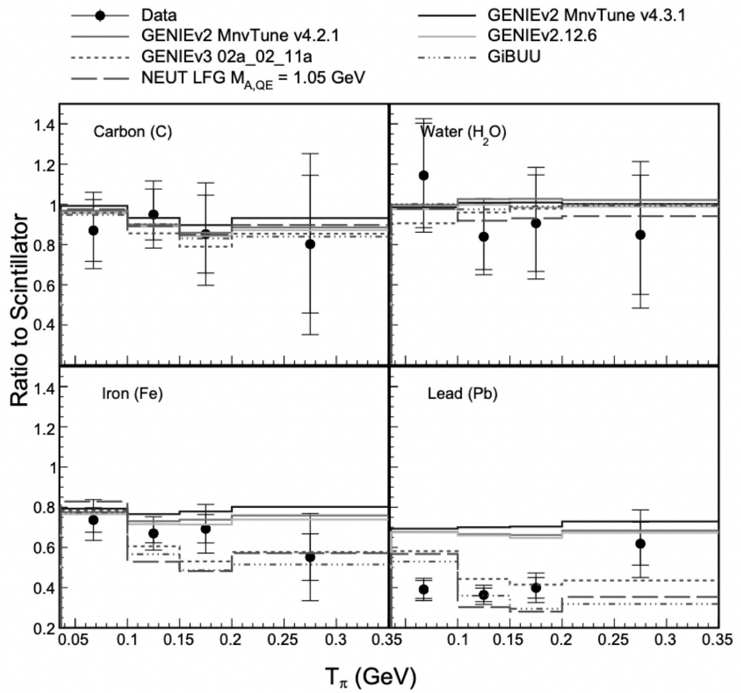
K. McFarland, NuINT 2024

- Preliminary.
- Cross-sections in panels of p_T^ℓ as a function of "available energy", energy in calorimetrically visible particles, e.g., not neutrons.
- Simulation confidently predicts a ratio very close to one dominated by statistical uncertainties.
- Testing the confidence of generators ☺.

The trouble with pions

- A huge effort has gone into understanding quasielastic interactions because T2K and NOvA are both using low energy beams where that process is dominant
- DUNE will need to understand pion production at least as well as we now understand quasielastic interactions
- Reminder from last year: for single pion production see much bigger discrepancies with model across all nuclei, in addition to an overall level change

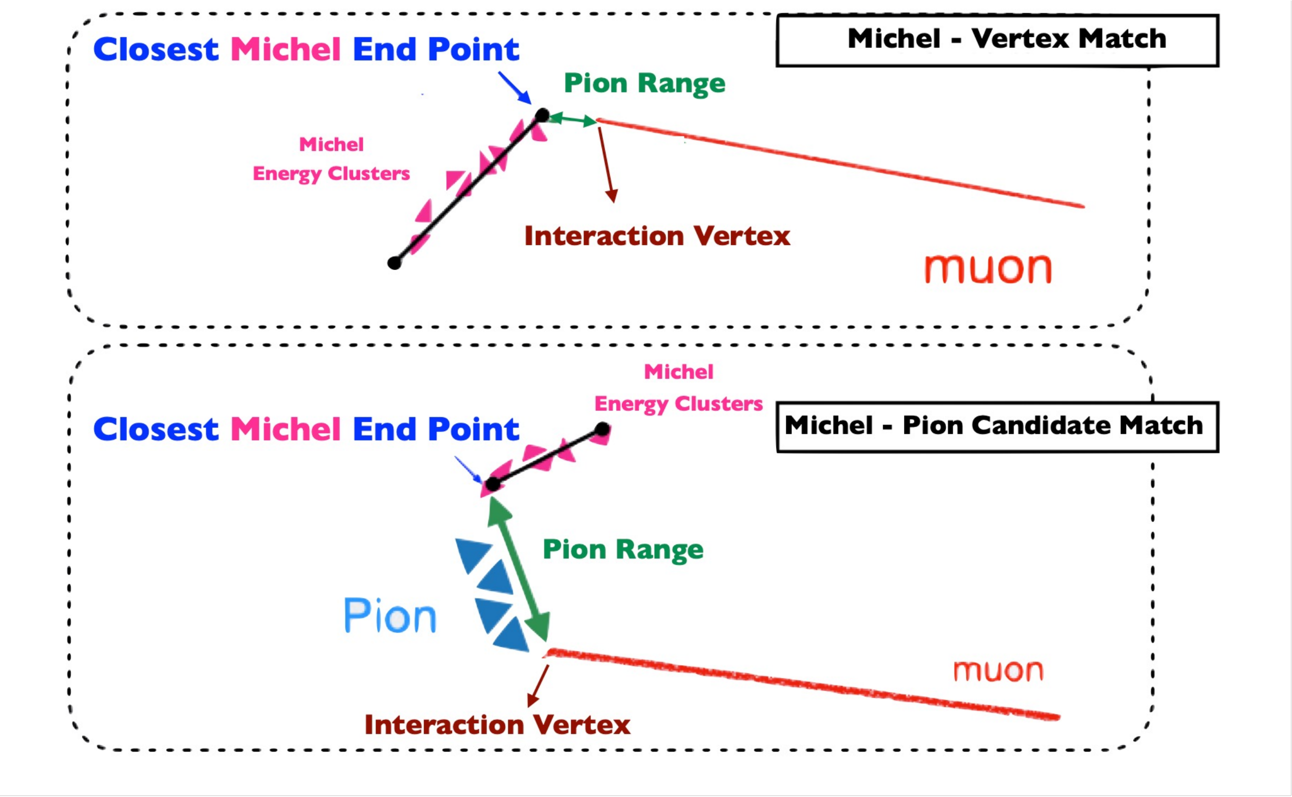




A. Bercellie et al, Phys. Rev. Lett. 131, 011801 (2023)

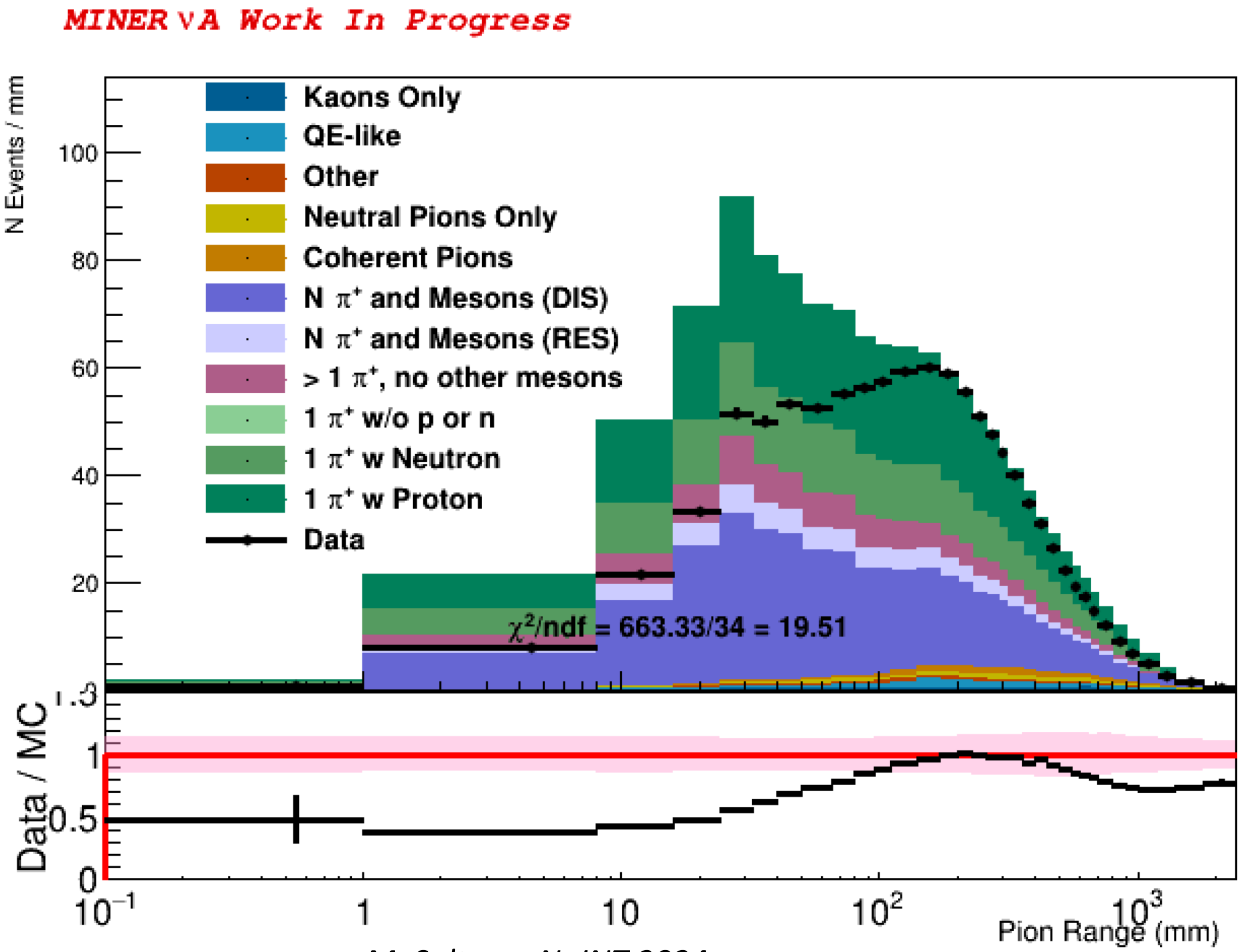
The trouble with pions

- A huge effort has gone into understanding quasielastic interactions because T2K and NOvA are both using low energy beams where that process is dominant
- DUNE will need to understand pion production at least as well as we now understand quasielastic interactions
- New for this year: extending reach to lower energy pions by using distance between pions and electron coming from from $\pi \rightarrow \mu \rightarrow e$ decay chain



What do we se at lower pion energies?

- Agreement is poor: previous models unconstrained in this kinematic region!
- This sample only has requirement of
  - negatively charged muon,
  - Muon $p_{t\mu}$<1.8GeV and 1.5GeV<p_{μ}<20GeV
  - Available energy<1.5GeV
- Have to develop a reweight of simulation to correctly predict smearing



M. Sultana, NuINT 2024

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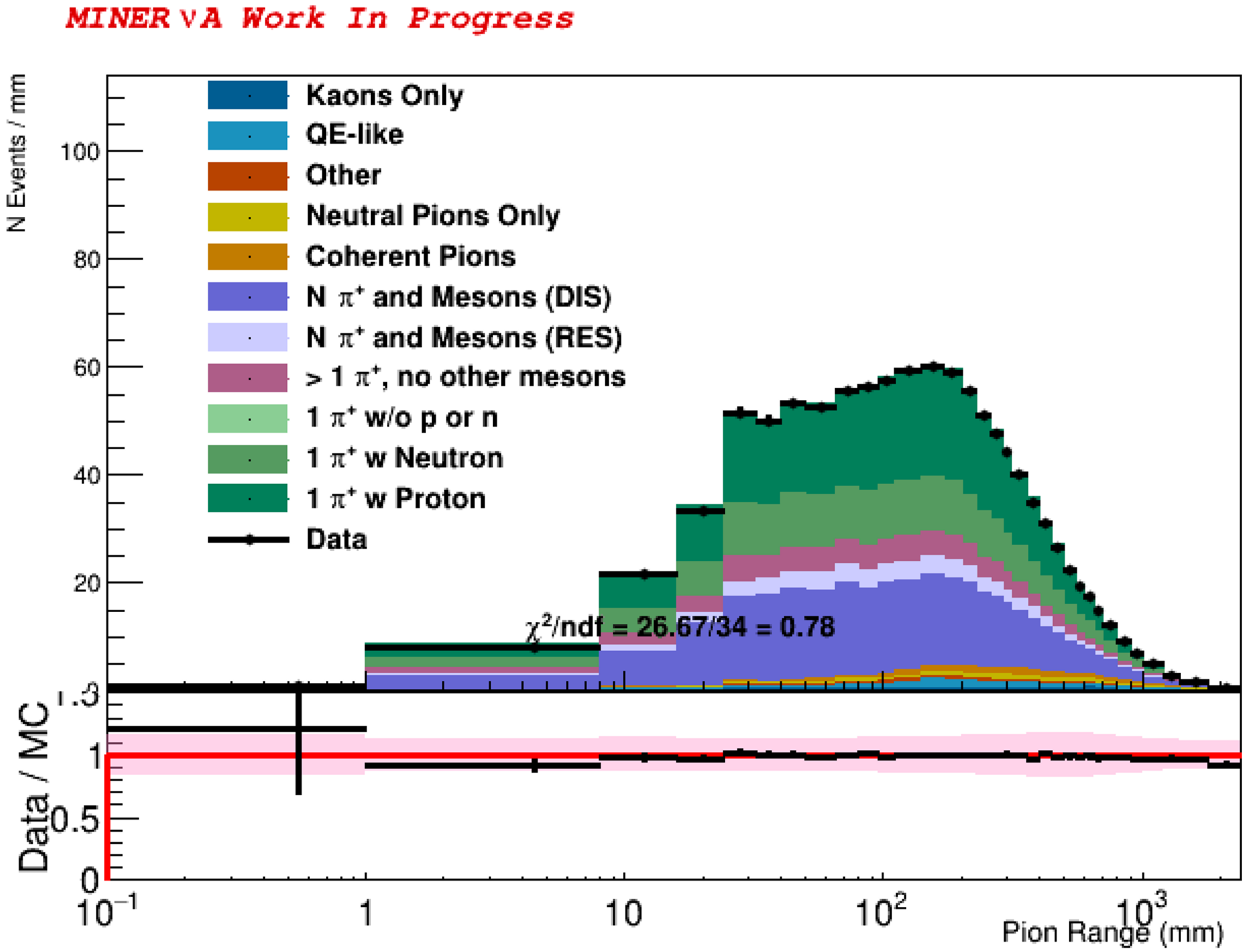
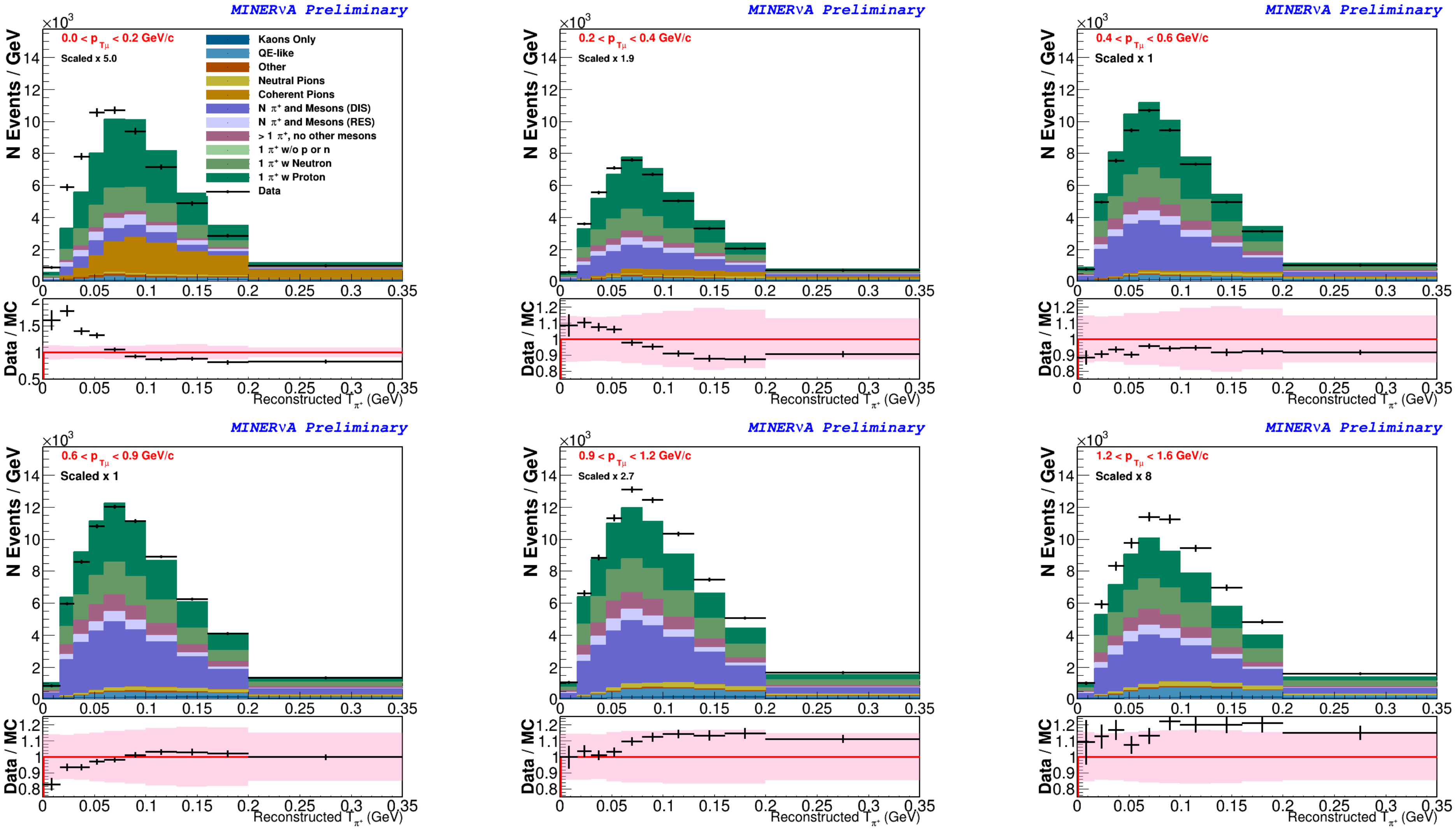


M. Sultana, NuINT 2024

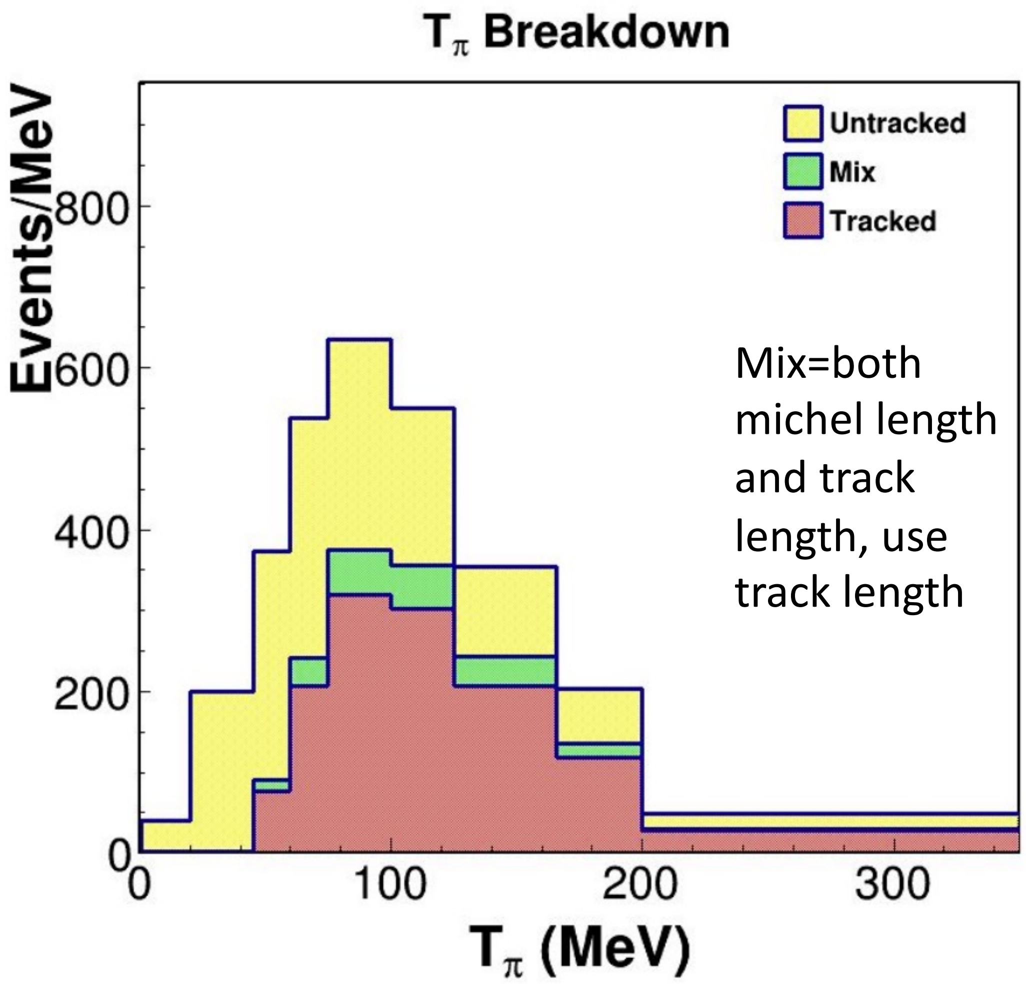
CC≥1π^+ Events versus T_π and p^t_μ with tune



- Notice many contributing processes at each pion momentum
- Statistical error only on data points

Getting back to Single Pion production

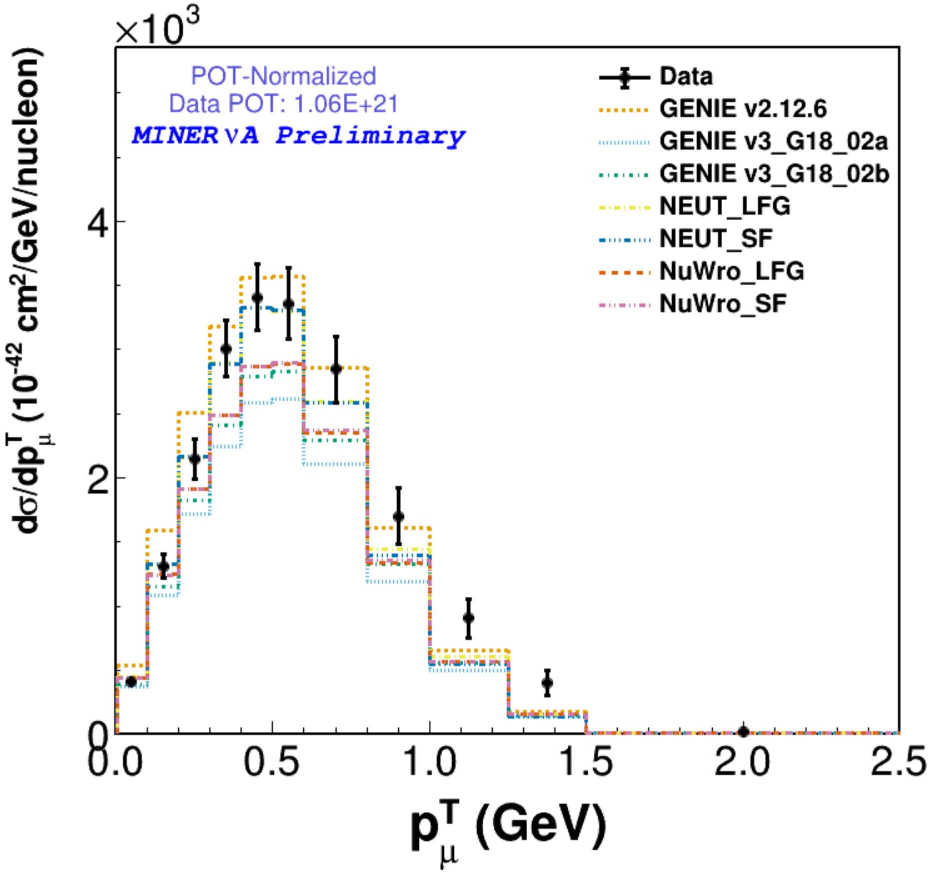
- Can add this new technique for measuring pion Kinetic Energy (T_π) for single pion analysis:
- MINERvA measured this before but with 35MeV minimum cut in the definition.
- New Signal Definition
  - Exactly one π^+ any number of baryons
  - Pion Kinetic Energy (T_π) between 0 and 350MeV (between 35 and 350MeV for θ_π result)
  - Muon Angle w/rt beam: <20º
  - Muon momentum between 1.5 and 20GeV
  - New Tune: MnvTunev4.3.1 (backup)
  - New weight to get efficiency right vs T_π

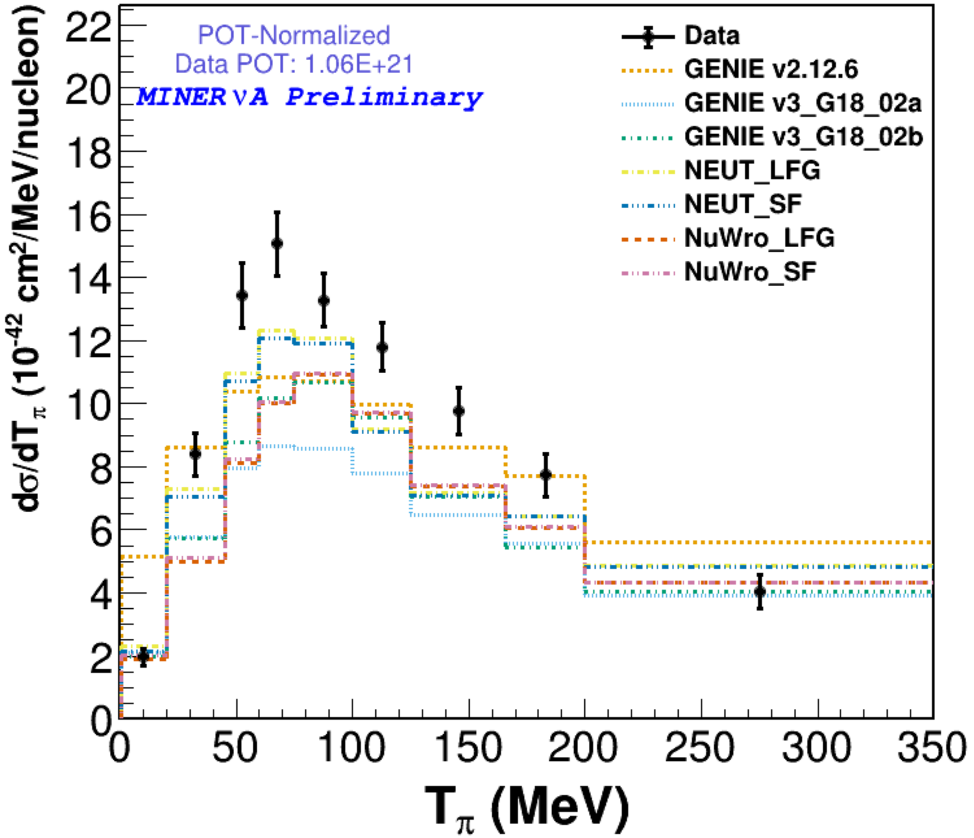


M. Sultana for E. Granados and B. Messerly, NuINT 2024

New $1\pi^+$ Results in Scintillator

- Models get muon dependence but miss pion kinetic energy dependence

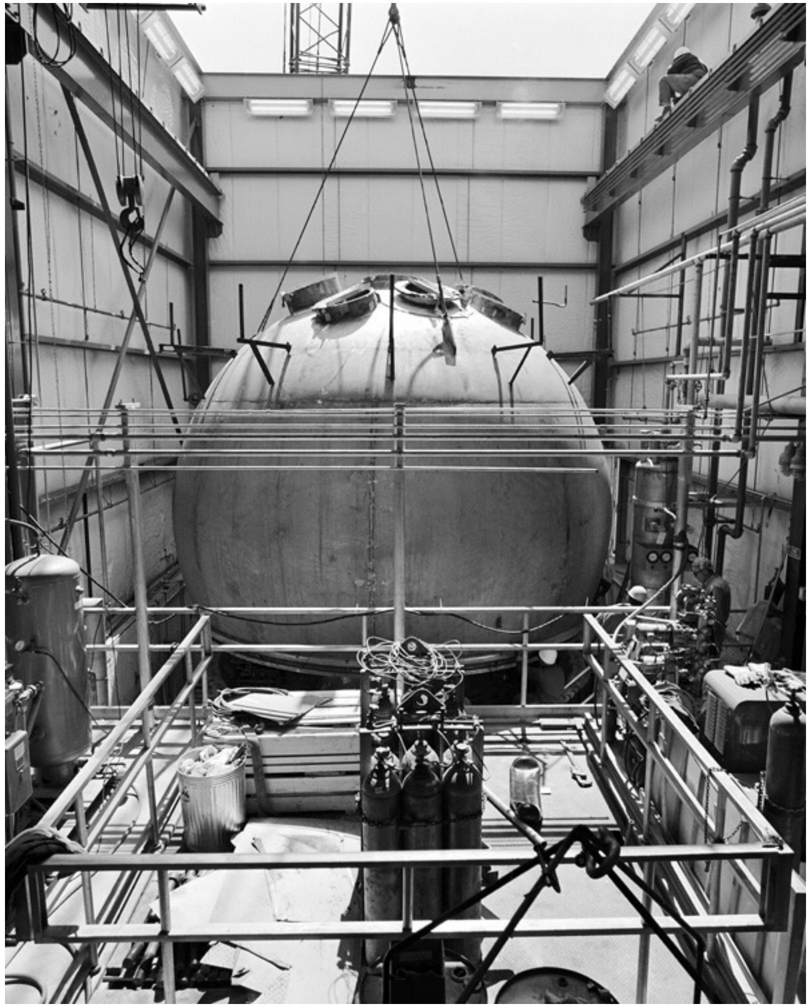




M. Sultana for E. Granados and B. Messerly, NuINT 2024

The trouble with neutrino experiments

- The questions you think you want to answer when you write the proposal are not the same questions you have ~~20~~ 50 years later
- If only we could look at those bubble chamber images again and analyze them the way we do now
- If only we could use a modern flux prediction to re-extract the results



Fermilab photo archive, 1972-05-09

Keeping MINERvA data available

- MINERvA has embarked on a project to preserve its data to give the ability to address “late breaking” questions from its own results or driven by outside work. For example…
  - Would any of MINERvA’s precision quasielastic-like cross-sections be altered if measured with an alternate reference model?
  - There are many $A(\nu_\mu, \mu^- p \ldots)A'$ kinematic imbalance results. Is it the same in a $A(\nu_e, e^- p \ldots)A'$ sample?
  - Are there more fruitful comparisons of MINERvA’s two (LE and ME, 3 and 6 GeV, respectively) beams to get at energy dependence?
  - Are there hints of non-standard interactions that would be revealed if we looked at other variables, like time relative to beam RF structure or energy, in some of our rare event topologies?

K. McFarland, Neutrino 2024

Data Preservation (cont'd)

- In brief, it is a set of tuples of the results of our standard reconstructions for every event, and a set of macros to allow an analyzer to efficiently interpret that data, focused on the measurement of a cross-section, but not limited to that goal.

Tuples with reconstructed objects
- Data, ME and LE
- Simulation, ~4x data in ME beam and ~10x or LE beam

→

Event Loop Macros

→

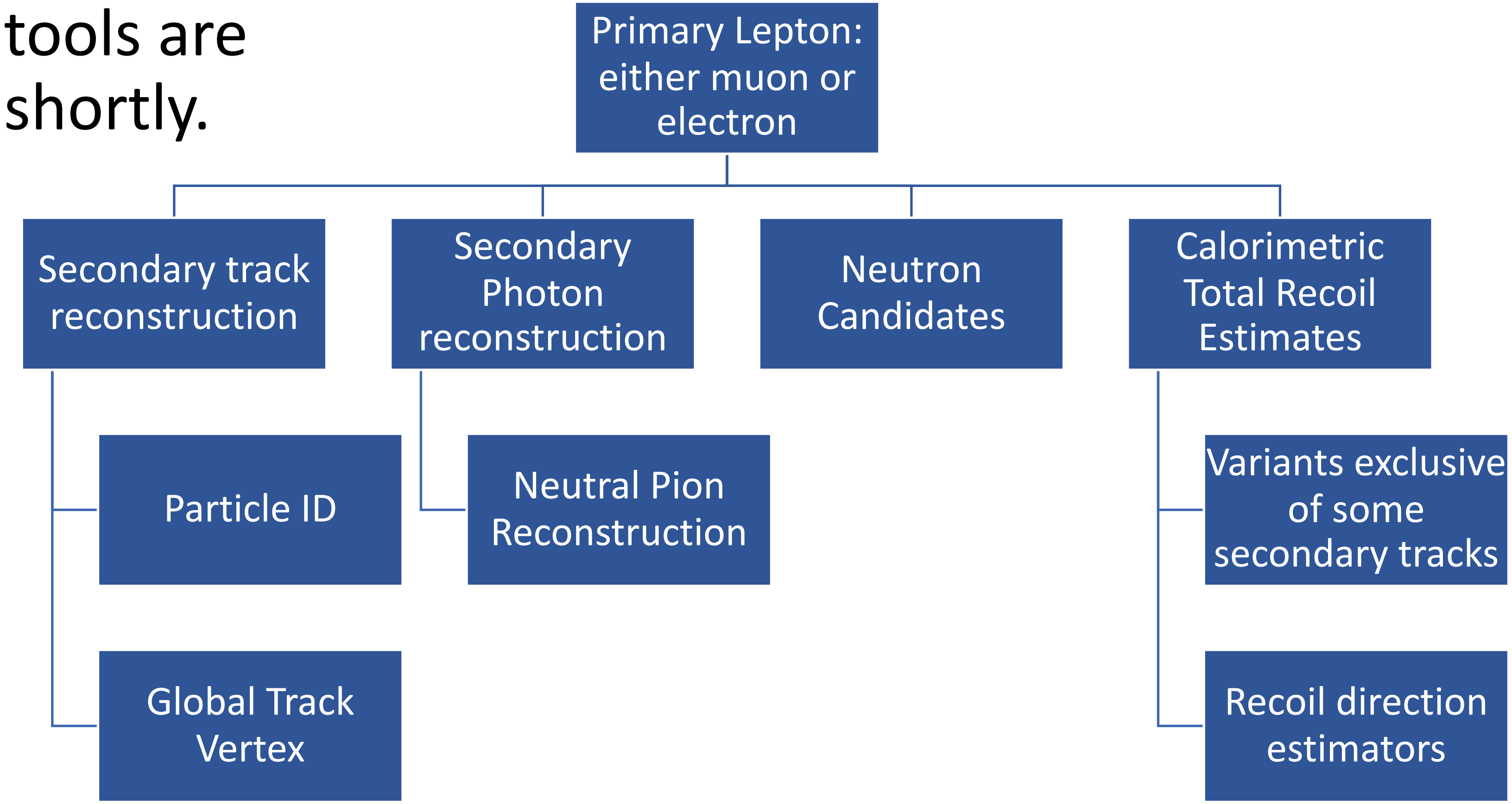
Interpretation Macros:
- background subtraction from sidebands
- unfolding and efficiency correction
- flux and target counting

"An Error Analysis Toolkit for Binned Counting Experiments" B. Messerly, R. Fine, A. Olivier et al, EPJ Web Conf. 251 (2021) 03046

K. McFarland, Neutrino 2024

Data Preservation (cont'd)

- What is in the reconstruction?
- All macros and analysis tools are public, and data will be shortly.
- Documentation with analysis examples.
- May serve as a useful starting point for more experiments to do something similar.



K. McFarland, Neutrino 2024

MINERvA's Legacy for Oscillation Experiments

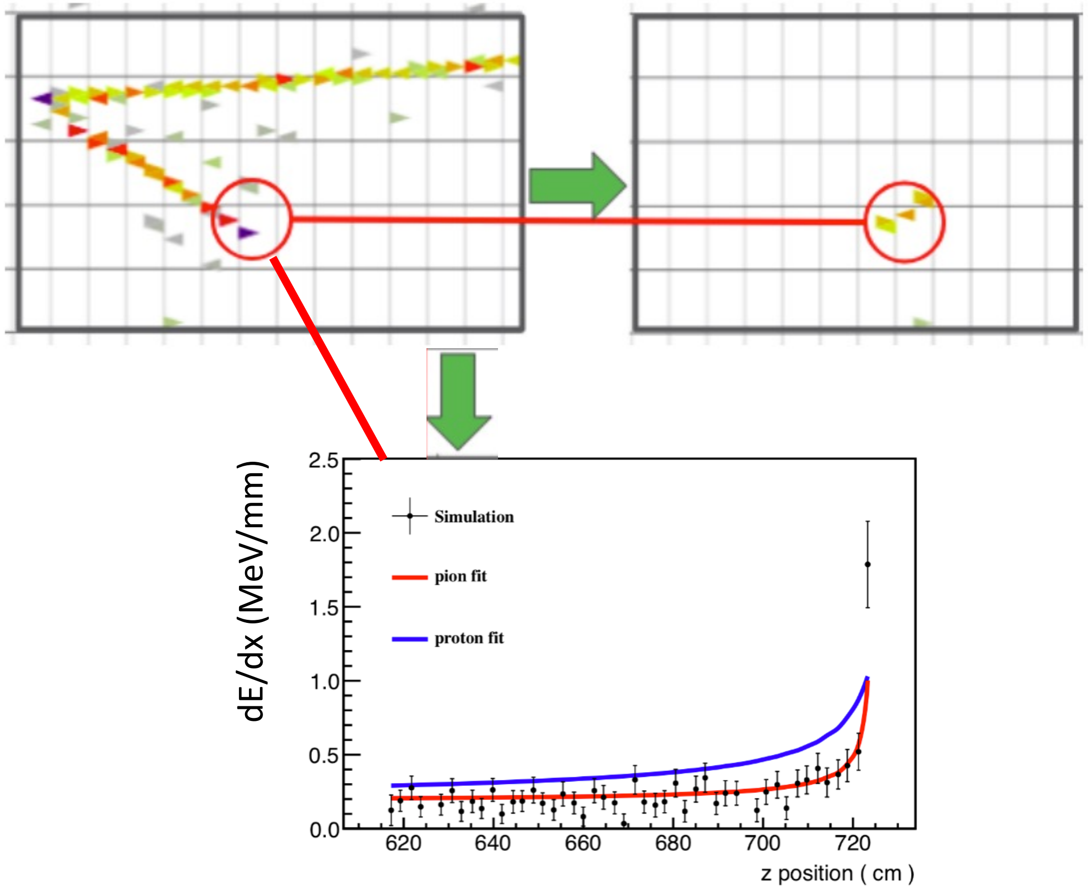
- Comparing Neutrino event rates across different energy spectra
  - Looking at Low and Medium Energy neutrino event rates
  - Future efforts: PRISM technique at T2K, DUNE, SBND
- Measuring Neutrons in Neutrino Interactions
  - From last year: cross sections on H, by subtracting off C
  - This year: antineutrino interactions with 2 neutrons
  - Future efforts: T2K's Near Detector Upgrade, DUNE's near detector
- Comparing Electron to Muon Neutrino Cross Sections
  - Since oscillations depend on making predictions for nu_e events based on muon neutrino events at a near detector
- Getting a better look at pion production
  - From last year's pion production in nuclear targets, we need to focus more on the cross section for pion production itself, less on the nuclear dependence of that cross section.
- Saving our data for you to use

Thank you

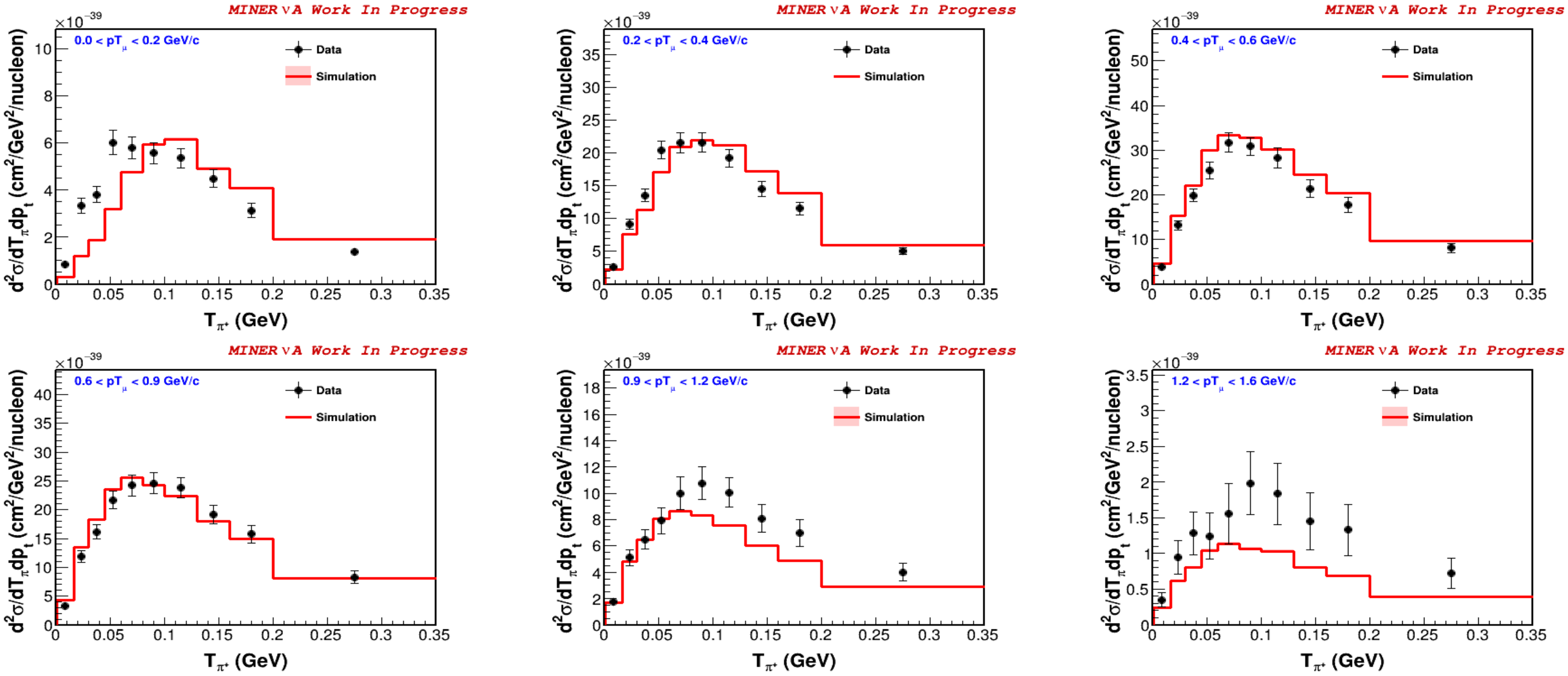

The
End?
Tom O.
Tim GRIFFIN
Jeremy GRIFFIN
Kevin McFarland
ANDREW LATHROP
H.Ray
STEVE RUZZANO
CHRIS Richardson
Jesse Chvojka
David Martinez
John Voirin
MARK SHOUN
MINERVA Sees

Charged Pion Identification

- MINERvA can…
  - use dE/dx, tag $\pi^+ \rightarrow \mu^+ \rightarrow e^+$.
- Michel technique is far more pure but less efficient.
- Tracking survives limited inelastic interactions in the detector, with some loss of energy resolution.
  - π^- are problematic because inelastic interactions produce neutrons.
- None of this works for high energy
- Focus today on low energy part of the pion spectrum



CC≥1π^+ Cross Section vs. T_π and $p_{t\mu}$



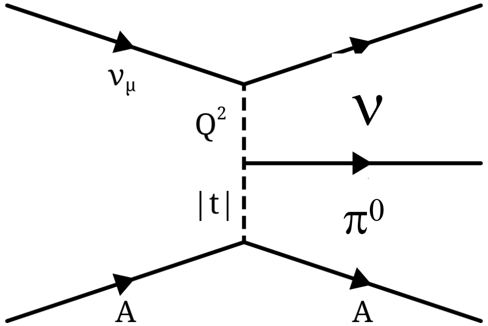
- Can look at transition from resonance to SIS to DIS

Notice excess at low p_t and high p_t, intermediate p_t shows better agreement with base model (MnvTunev4.3.1)

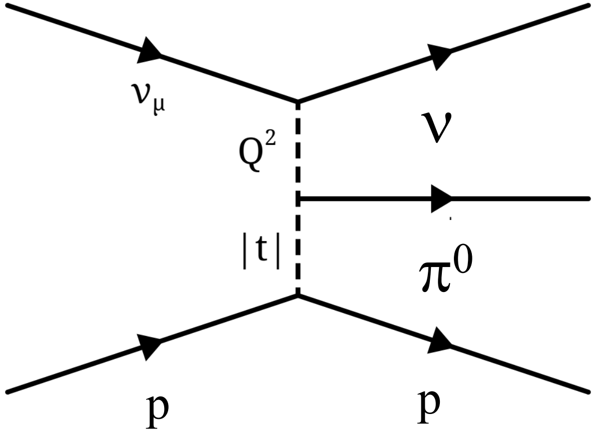
Pion Production: NCπ^0 Reactions

- What reactions are we talking about?
- How MINERvA detects neutral pions

Coherent inelastic

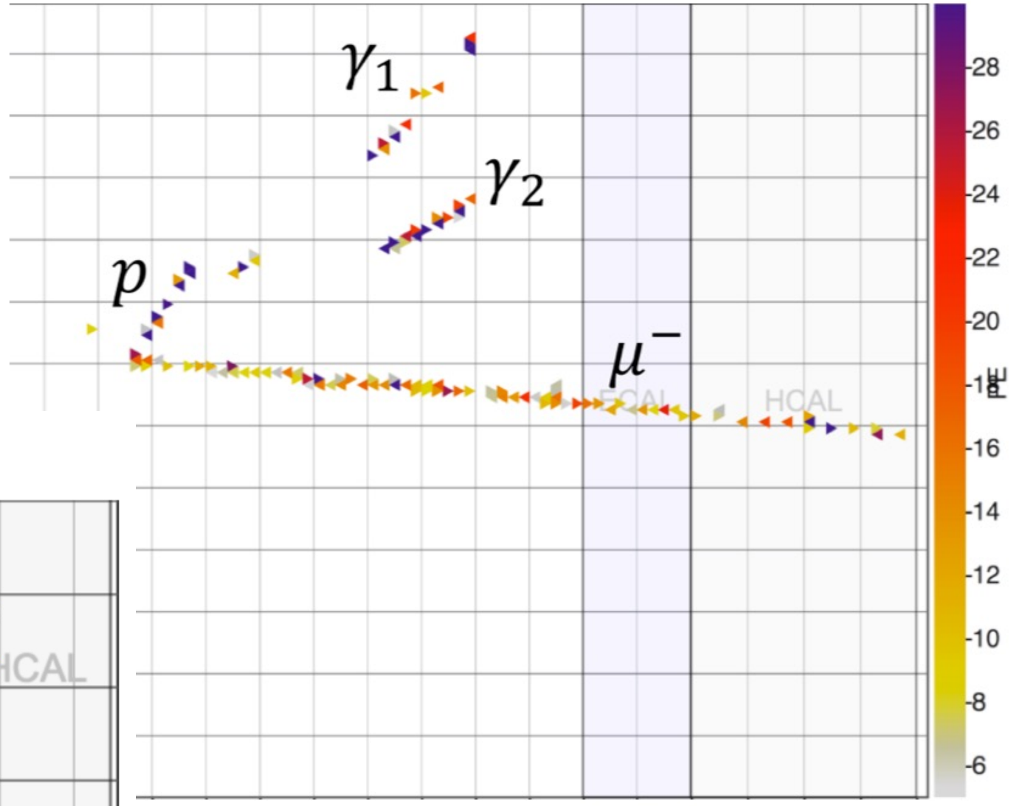


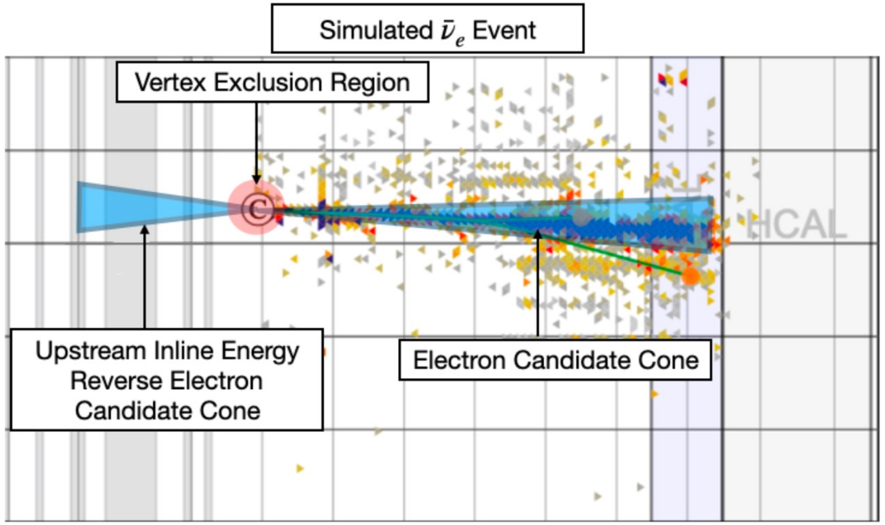
Diffractive (on hydrogen)



New High Energy Neutral Pion Identification

- Identify detached photons from π^0 decay.
  - Many space points between neutrino vertex and photons.
  - Photons convert at high efficiency due to lead layers at edges of scintillator volume.
  - But what about when the π^0 is high energy?
  - 2 showers overlap and it's a background to ν_e cross section measurement if there's no μ!

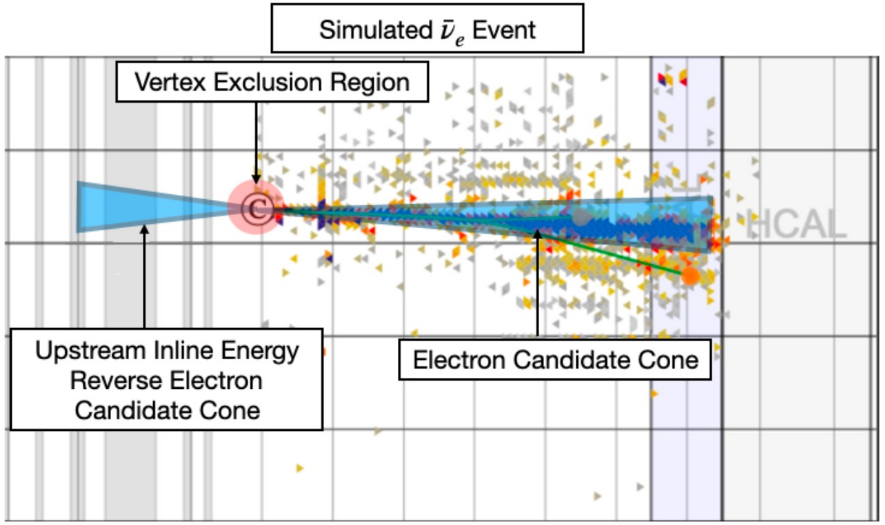


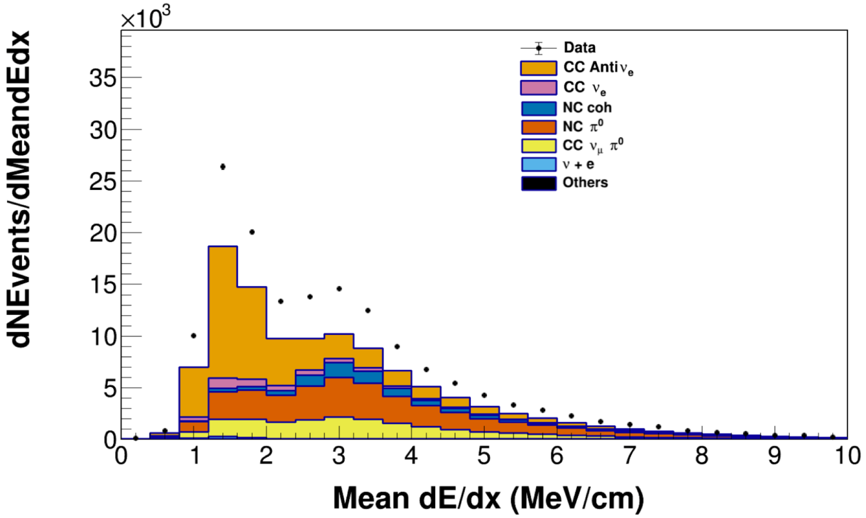


K. McFarland, NuINT 2022

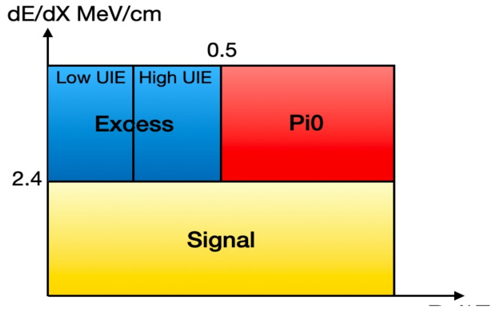
Identification of Electrons

- These are high energy electrons in the analysis, $E_e > 2.5$ GeV, and which are mostly forward by kinematics. (Require $\theta_e < 30°$.)
- Primary background is photons from high energy π^0 decay. At these energies, two photons from $\pi^0 \to \gamma\gamma$ are likely to be coalesced into a visible single shower.
- Discriminant is dE/dx at start of the shower.
  - Look for minimum region of dE/dx near the start to avoid contamination from other particles produced at the vertex.



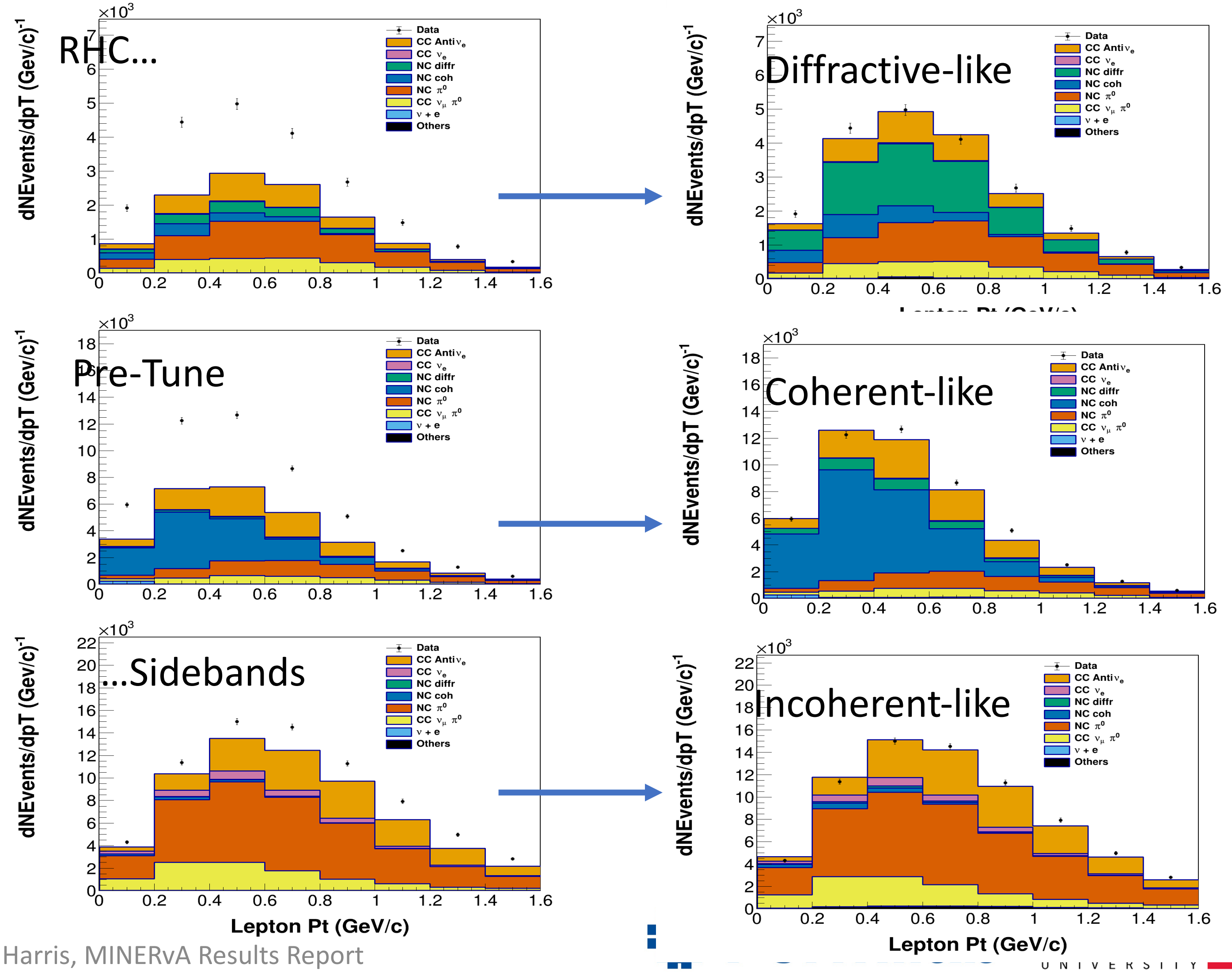


Characterization of Backgrounds



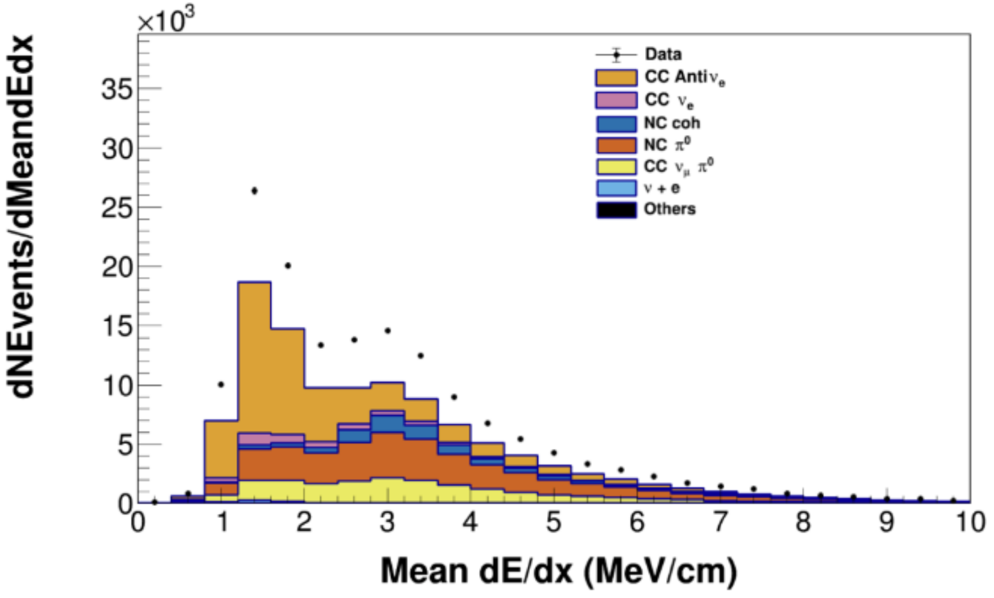
- Tune primarily in electron p_T for each process separately.
- RHC (antineutrino dominant) has much less incoherent π^0 production, so use the RHC results in FHC (neutrino dominant) beam for coherent and π^0 production from carbon is the dark blue.)

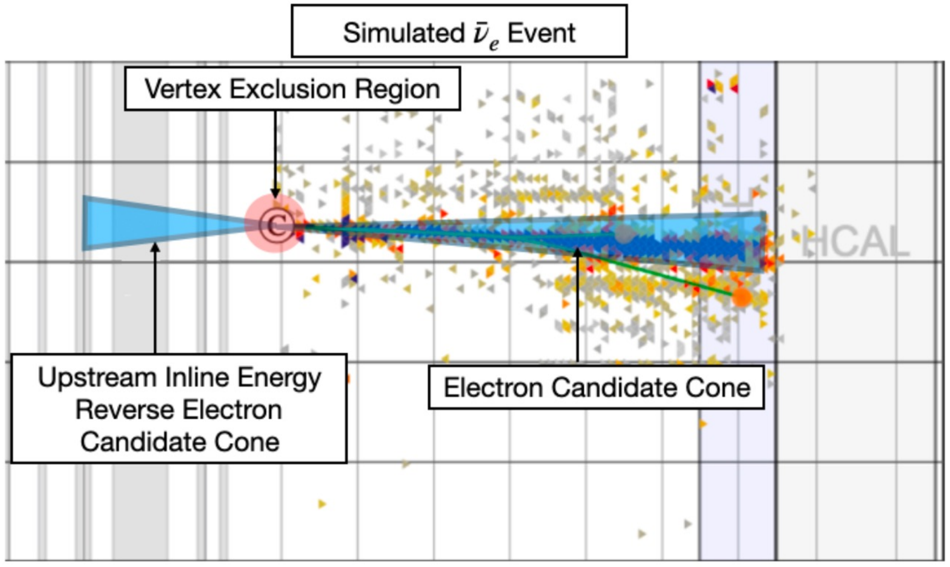
- (Sideband tune has tensions in FHC beam not observed in RHC. Add an extra systematic uncertainty to cover this in FHC.)



NC Neutral Pion Production @ MINERvA

- Turn lemons into lemonade by taking sideband events in electron neutrino analysis as signal, and see if we can pull out coherent NC and Diffractive π^0 events



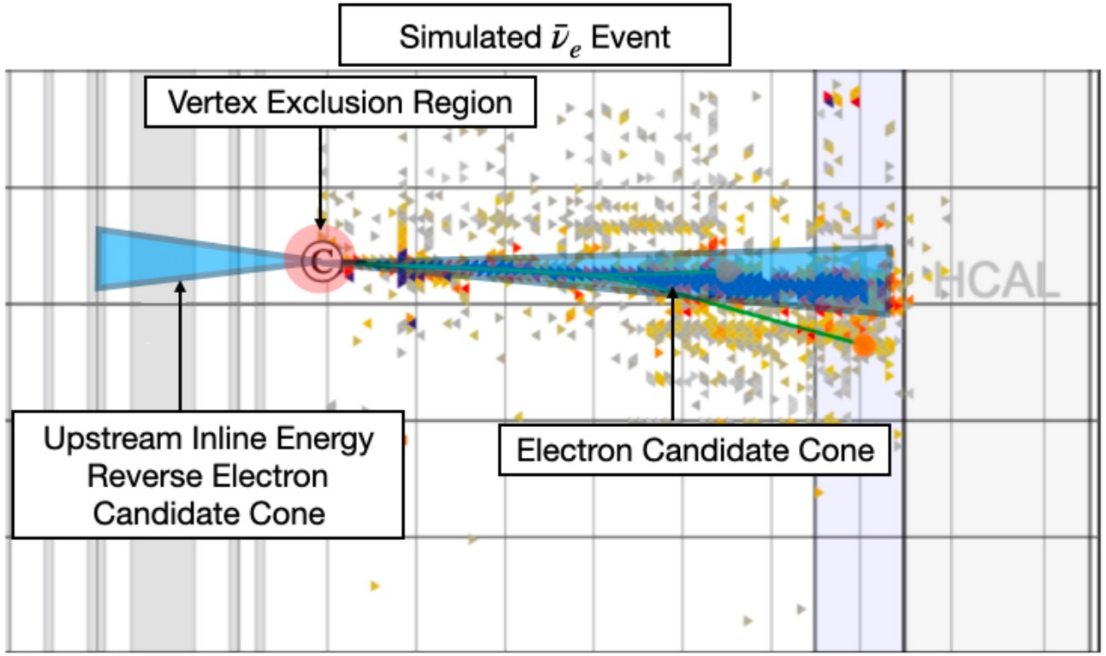


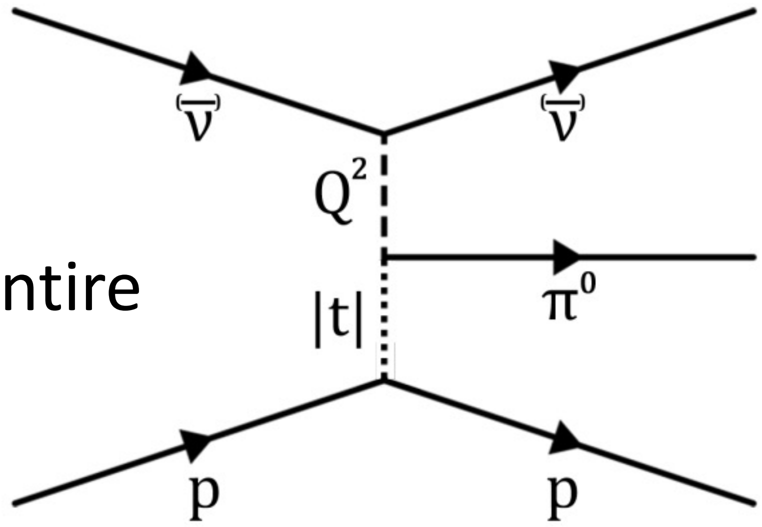
How to predict Non-Coherent And electron neutrino background

ArXiv: 2312.16631, accepted for publication @PRD

What would coherent and diffractive events look like?

- Consider the difference between scattering off single proton or off entire nucleus:





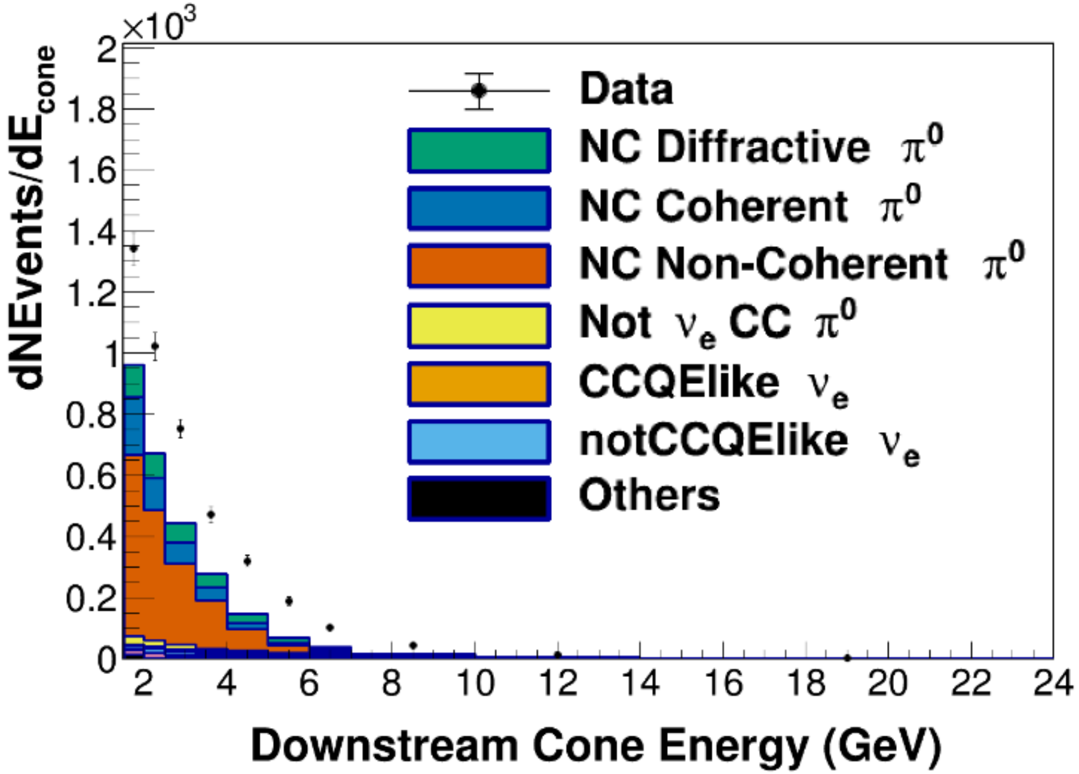
Signal Definition:
π^0 produced in a neutral current diffractive reaction
$|t| > 0.03\ (GeV/c)^2$
Pion Energy > 1.5 GeV

Cuts to find Signal:

- Downstream Cone Energy > 1.5 GeV
- Inline Upstream Energy > 10 MeV
- Inline upstream energy separated by 2 scintillator planes
- Front dE/dx > 2.4 MeV/cm
- Total Upstream Energy < 120 MeV Eavail < 500 MeV

NC Diffractive π^0 analysis

- After all cuts, what is the energy in the cone? Determine backgrounds by sideband analyses



3 backgrounds, 3 sidebands:

Coherent pi0 Events:

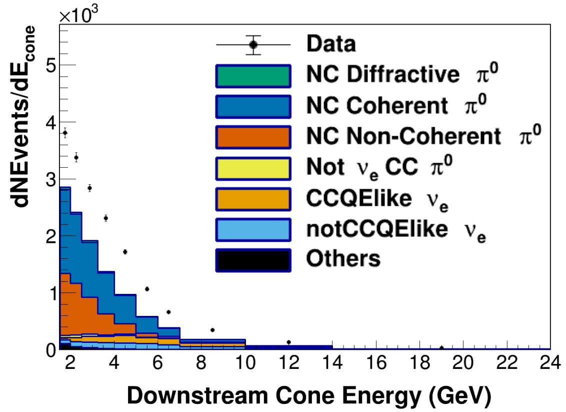
Inline Upstream Energy < 10 MeV

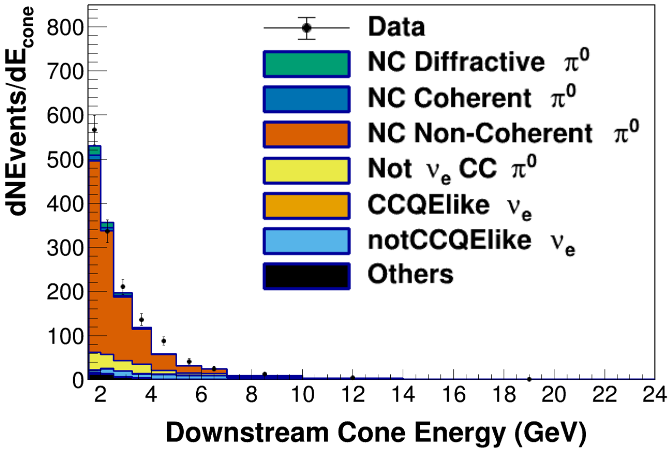
Non-Coherent pi0 events:

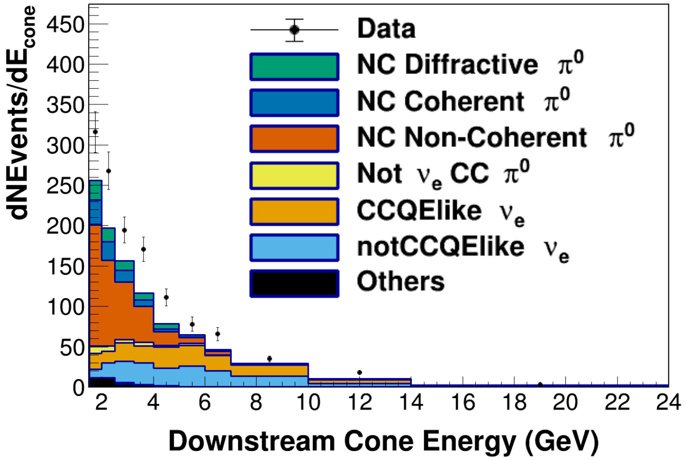
500 MeV < Eavail < 800 MeV

Electron Neutrino Sideband:

Front dE/dx < 2.4 MeV/cm



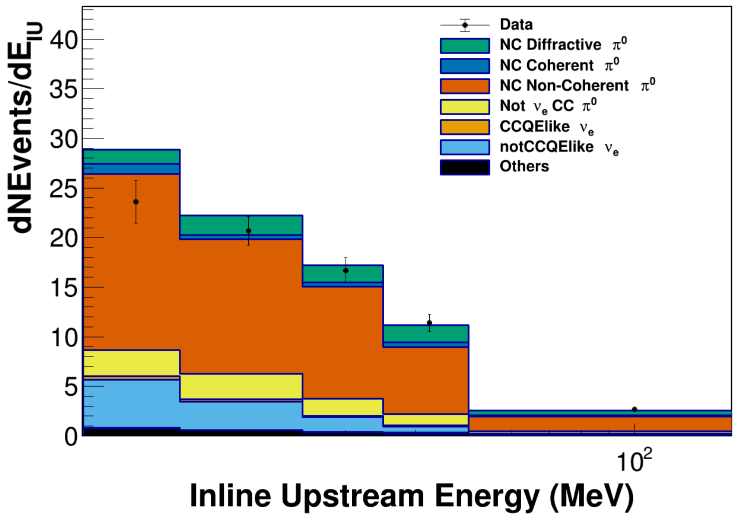




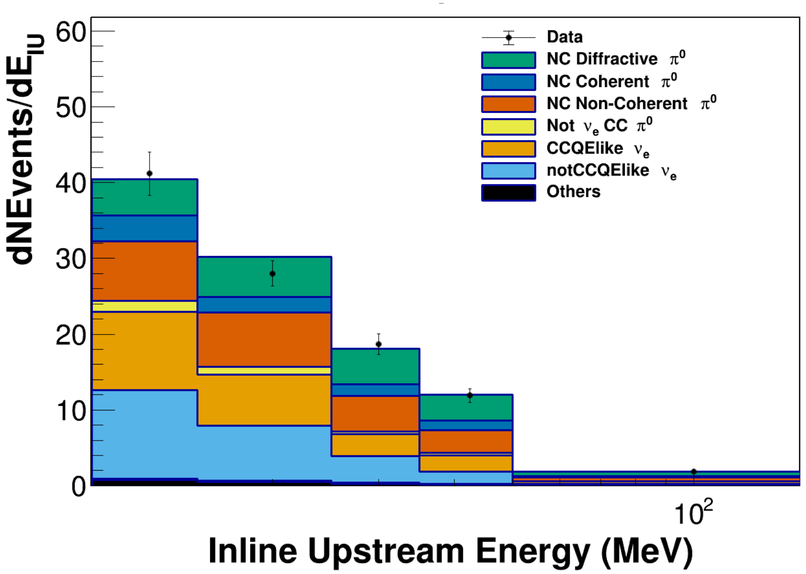
NC Diffractive π^0 Background Fit

- Do simultaneous background fit to all three sidebands together, for each bin of Cone energy
- $N_{ij}\, w_j = x_i$, i is the 3 sidebands + signal region,
  j is the process category (3 backgrounds, 1 signal),
  w is the weight for that process
- Resulting inline upstream energy distributions after fit:

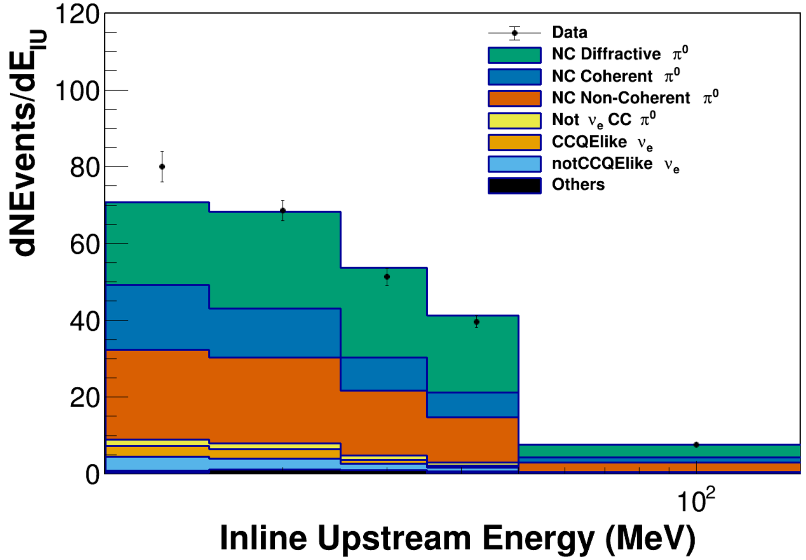
NC non-Coherent PI0 sideband



Electron Neutrino Sideband

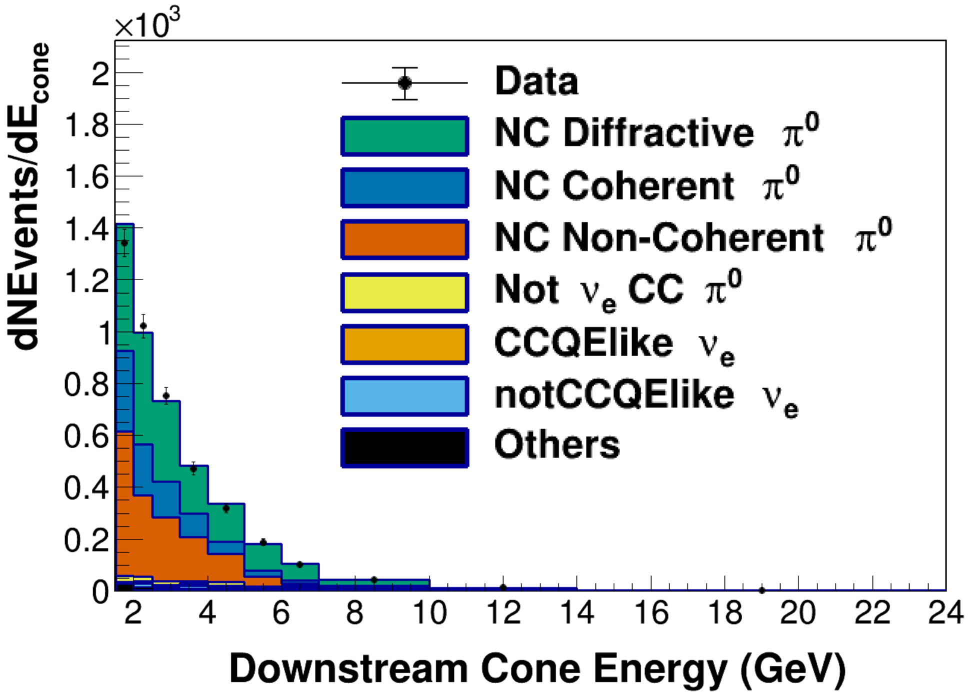


Signal Region

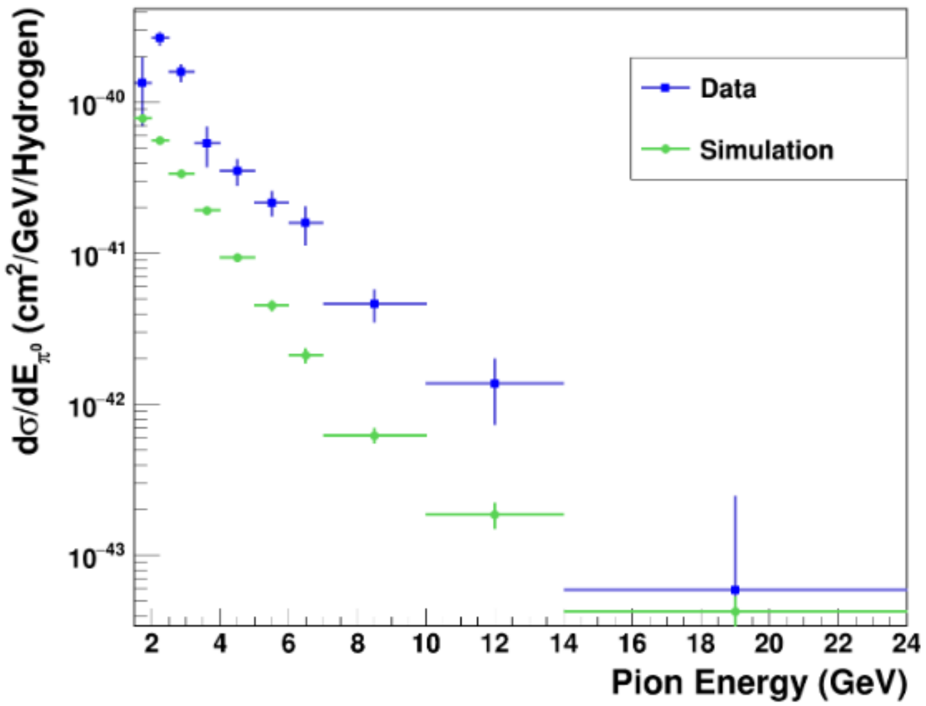


NC Diffractive π^0 Signal Result

- After fitting for the signal+backgrounds, subtract backgrounds, unfold, correct for efficiency… find that GENIE underestimates Diffractive π^0 production by factor of 4 but gets kinematics right



See Expected ratio between Diffractive and Coherent π^0 processes in data



MnvTunev4.3.1 , starts with GENIE 2.12.6

- Non-Resonant pion reduction
- Full Deuterium Pion constraint
- LowRecoil 2p2h Reweight from MINERvA's Low Energy result
- Valencia RPA Reweight
- FSI Reweight
- Coherent Pion Reweight https://inspirehep.net/literature/2159830 (previous NuINT 2022 coherent pion result in nuclear targets)
- Diffractive Reweight
- Low Q2 Pion Reweight https://inspirehep.net/literature/2070948 (previous NuINT 2022 pion result in nuclear targets)