The Road to Precision in Neutrino Physics

Deborah Harris

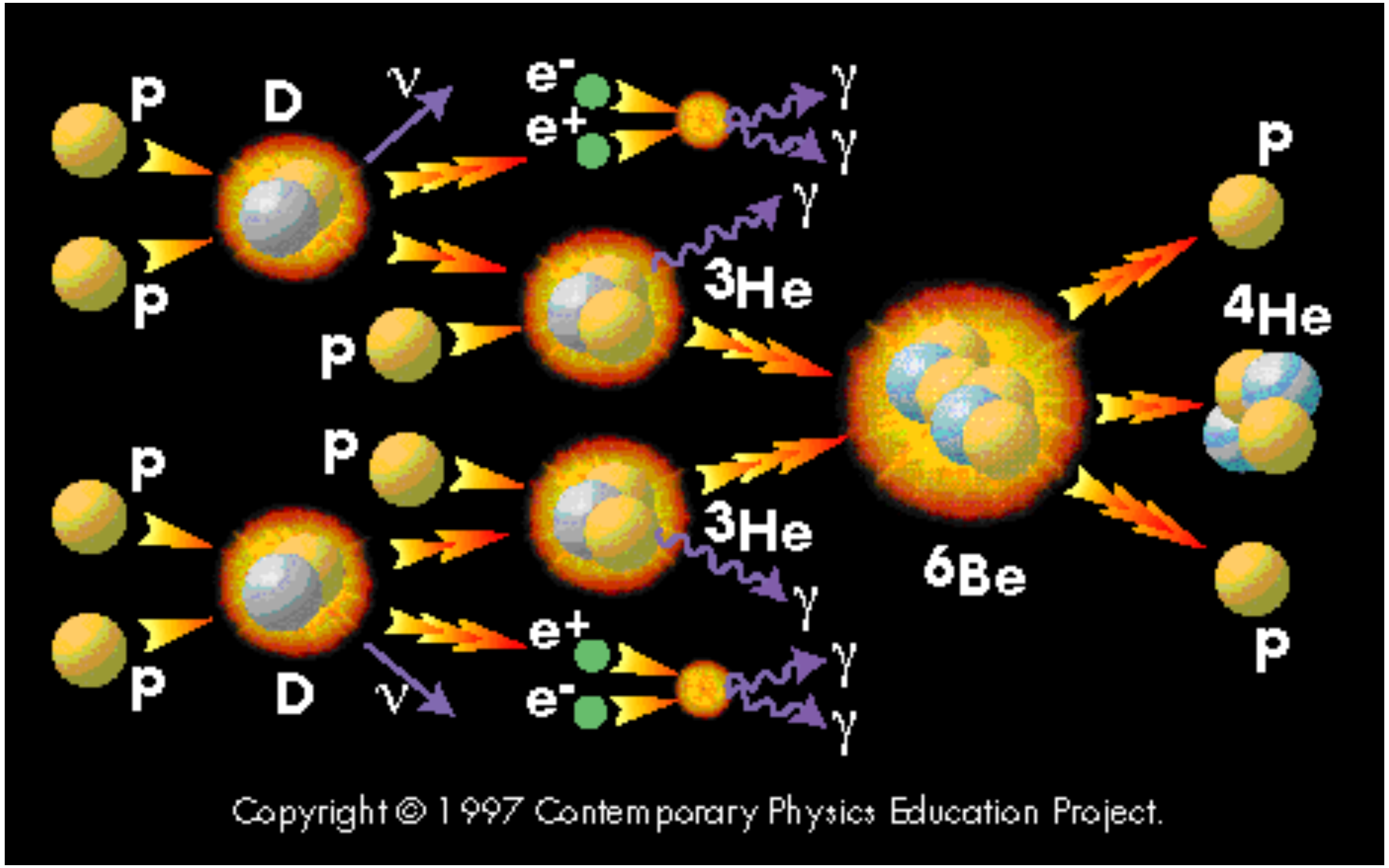
Queen Mary University London Seminar

October 13, 2025

Outline

- Why studies of neutrino flavor mixing need to understand neutrino interactions better than ever before
- Neutrino Interactions in 20 words or less
- How the nucleus affects neutrino interactions
- Introduction to MINERvA
- Quasi-elastic interactions of Neutrinos
  - On Plastic (CH), compare different ways of predicting neutrino energy
  - As function of A
    - versus transverse muon momentum (p_t)
    - versus “Missing transverse momentum” momentum (δp_t)
- Happy to talk about other channels in Q&A session afterwards

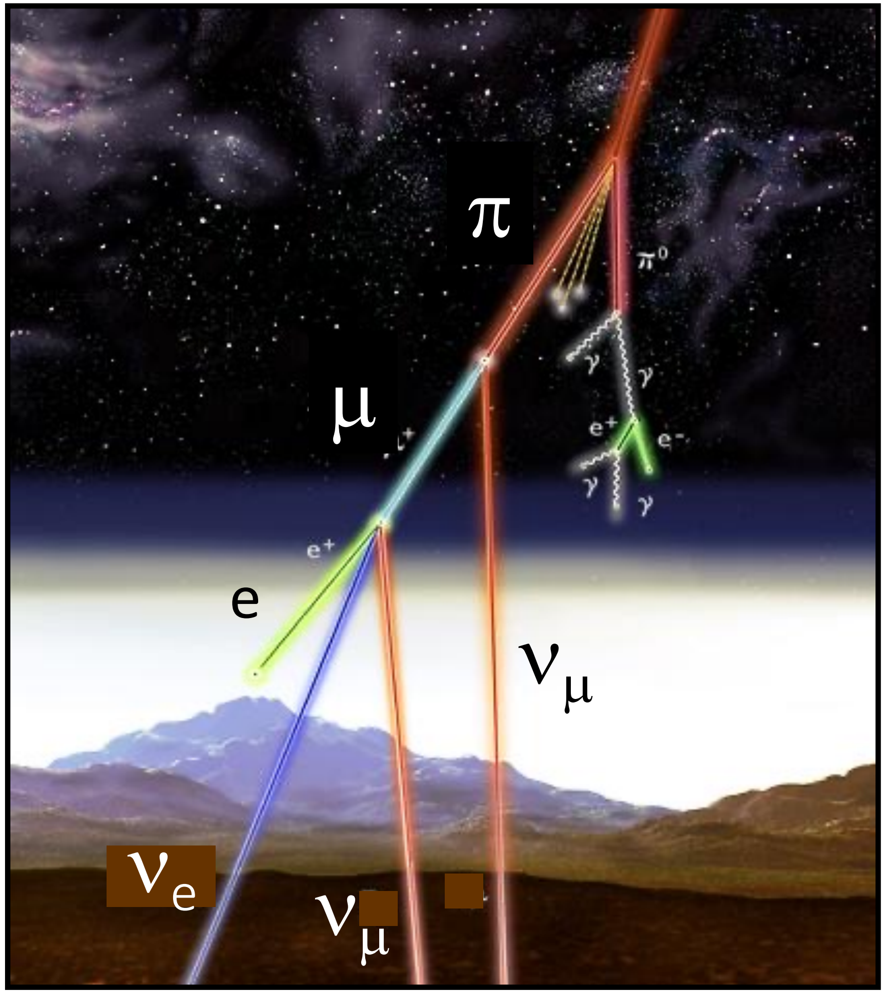
Sun: First Evidence that Neutrinos have mass: Sun



- Sun is prolific producer of neutrinos
- Test solar models of fusion: what makes the sun shine?
- Ray Davis looked for $\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Found neutrinos, but 1/3 the number expected…

Neutrinos from the Atmosphere

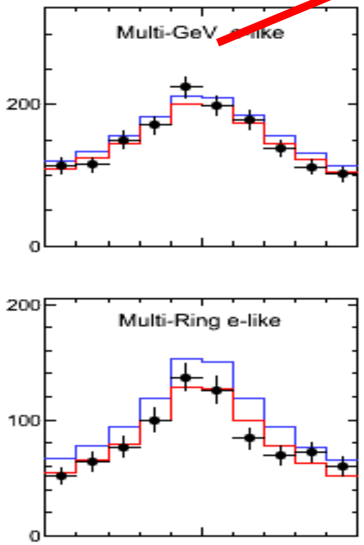
- High energy protons fly through the galaxy, when they hit the Earth's atmosphere, they make particles that decay to neutrinos
- $\pi \rightarrow \mu + \nu_\mu \quad \mu \rightarrow e + \nu_\mu + \nu_e$
- Early measurements saw fewer ν_μ than expected
- Neutrinos should reach us with ν_μ and ν_e in a 2:1 ratio
- If you can tell the direction the neutrino came from, you can determine how far it traveled, or how long it lived
- Challenge: telling ν_μ from ν_e

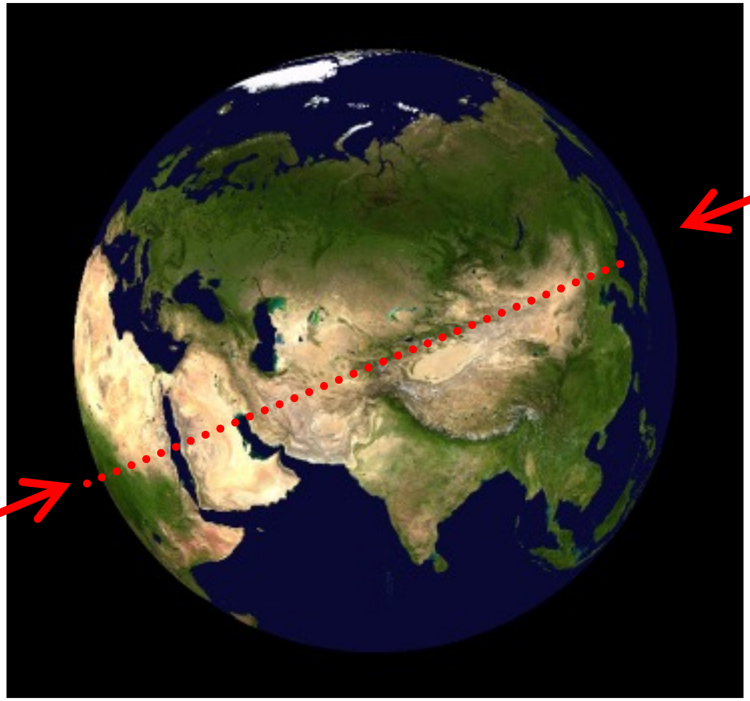


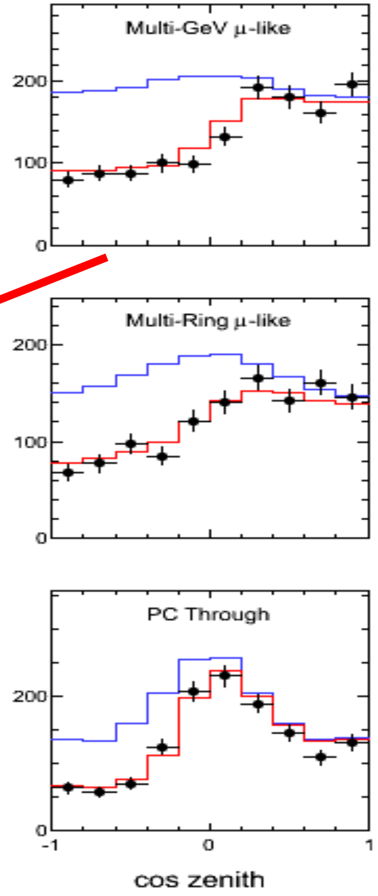
Neutrinos at many distances…

- Measure neutrinos from the atmosphere:
  - 80 to 13,000km
  - Muon Neutrinos from above don't disappear
  - Muon Neutrinos from below disappear
  - Electron neutrinos don't seem to be disappearing!

e-like







μ-like

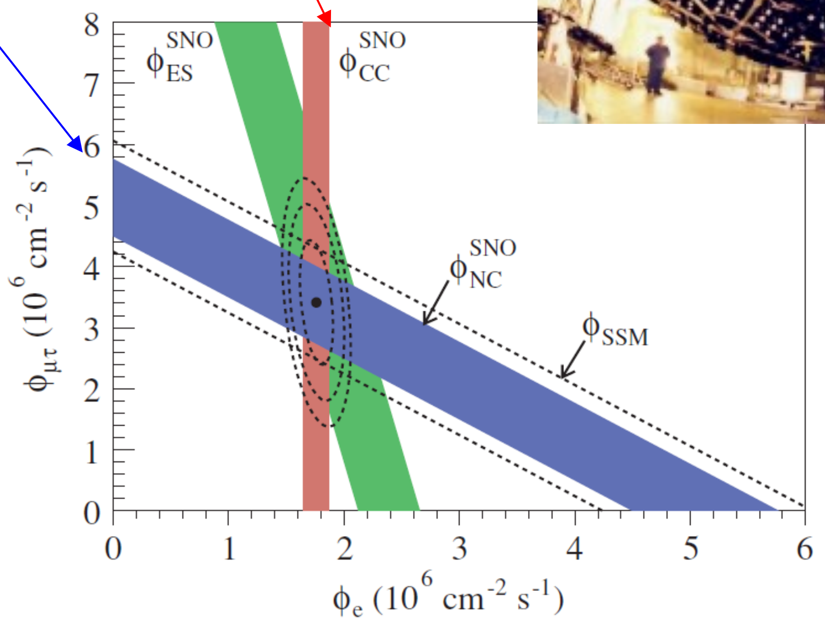
Super-Kamiokande Results
Neutrino 2010

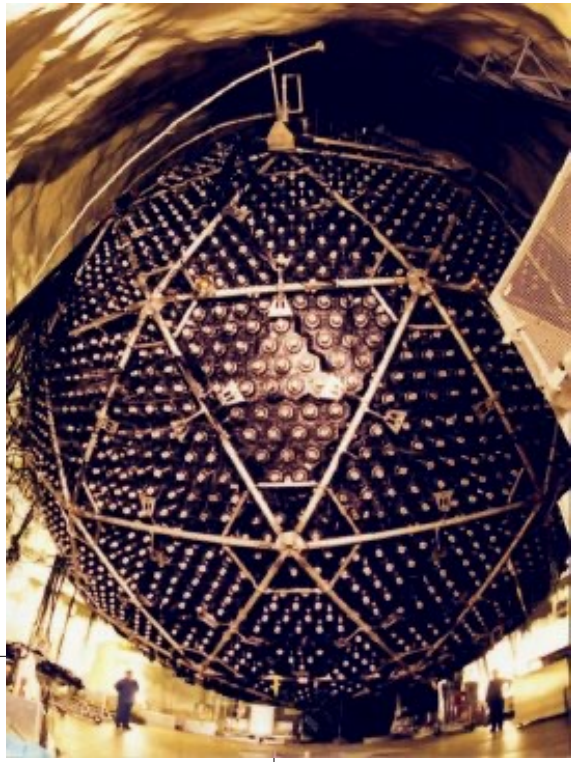
Confirmation of Solar ν's changing Flavors

- D_2O target at SNO in Sudbury, ON can uniquely tell ν_e from other neutrinos:
  - charged-current
  - neutral-current
- The former is only observed for ν_e (lepton mass)
- The latter for all types
- Solar flux is consistent with models
  - but not all ν_e at earth
- Precision interference pattern from reactor ν's at a ~180km distance

$$\nu_e d \to ppe^-$$

$$\nu_X d \to \nu_X pn$$





1000 tons of heavy water, 10,000 phototubes

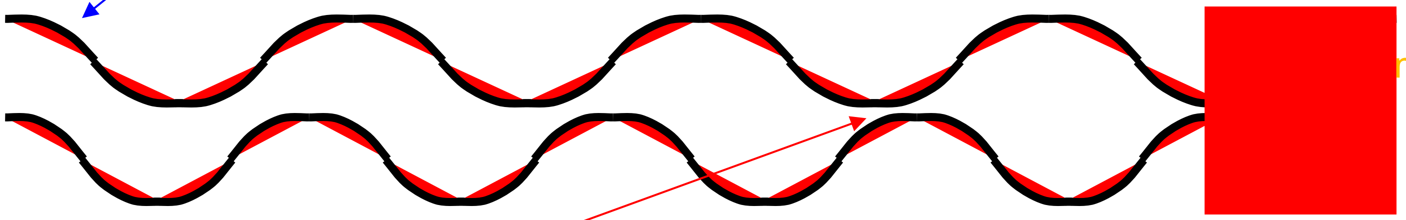
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos\pi/4\,|\nu_i\rangle + \sin\pi/4\,|\nu_j\rangle$$



different mass states alter time evolution

time

$$|\nu_\beta\rangle = -\sin\pi/4\,|\nu_i\rangle + \cos\pi/4\,|\nu_j\rangle$$

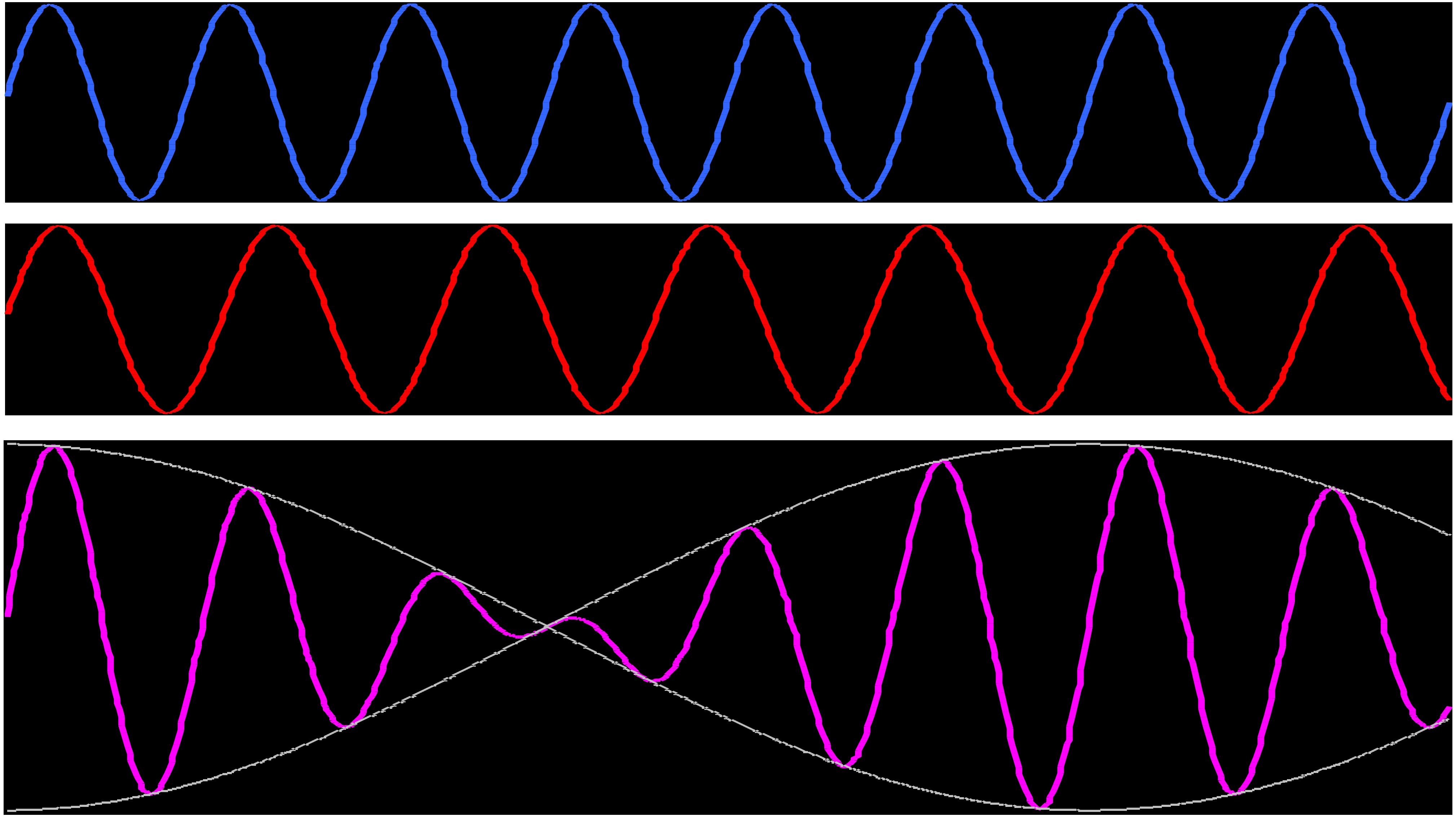
$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

Acoustic Analogy (for musicians…)

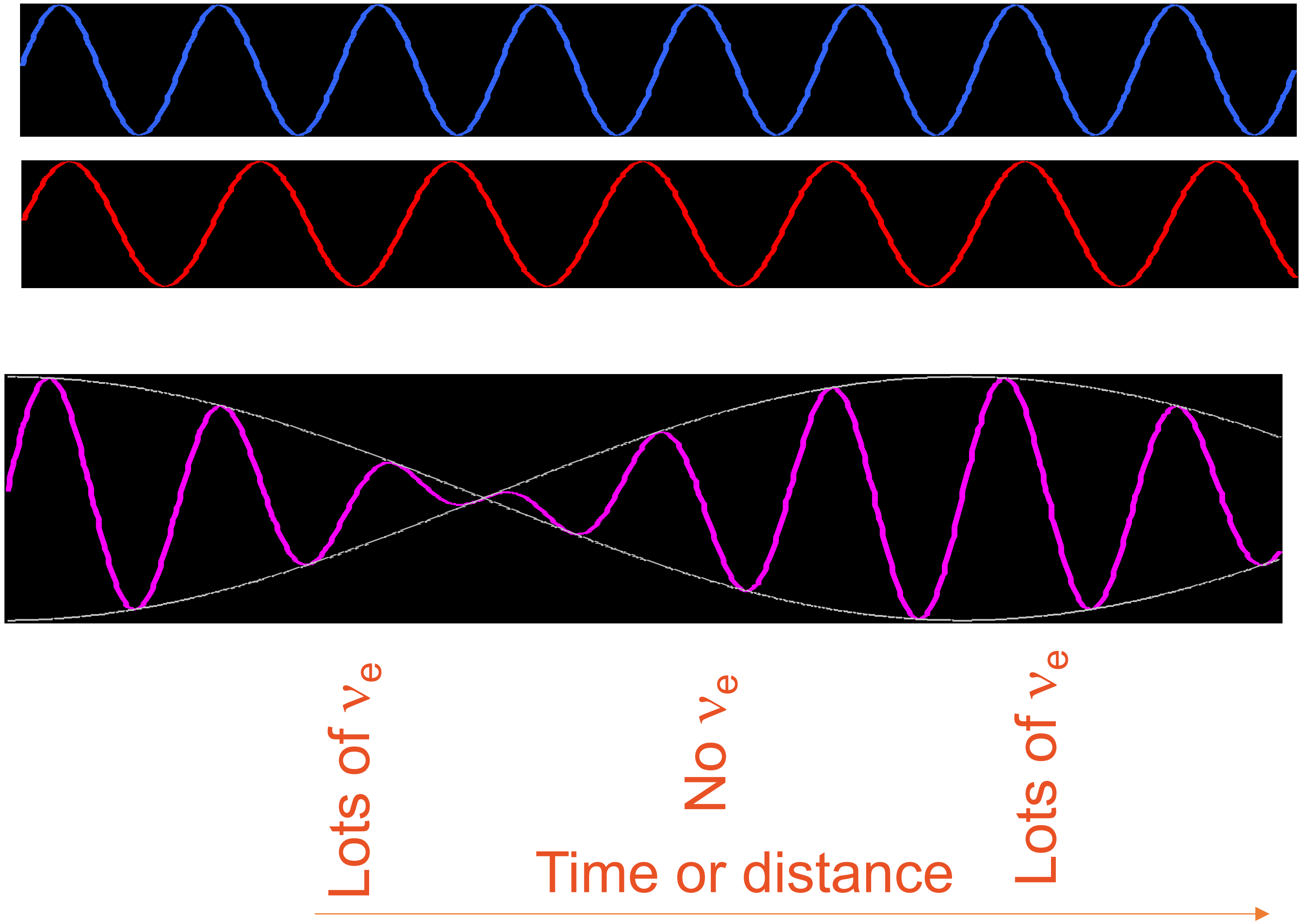
wave 1

wave 2

wave 1
+ wave 2



Neutrino Oscillations



If neutrinos are waves of slightly different frequencies:

Over time, they disappear and reappear

The bigger the frequency difference, the faster the disappearance

Particle mass difference determines the frequency

Measuring neutrinos oscillating: Measuring mass (squared) difference

If one kind of neutrino disappears, another kind must appear

Oscillation Formalism (cont'd)

Experimental Details:

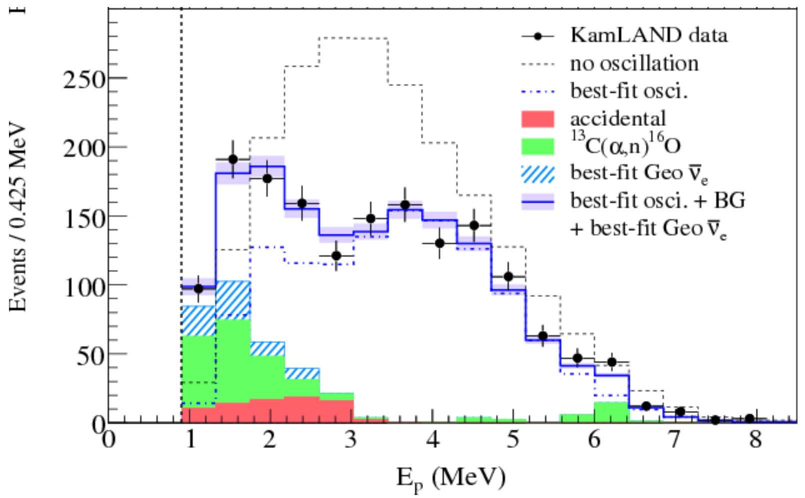
L: Baseline

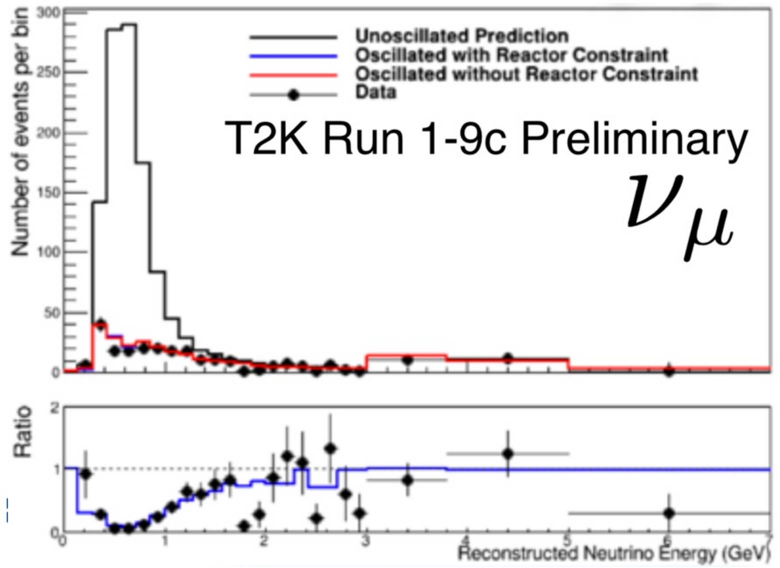
E: Neutrino Energy

- So if there were only two mass eigenstates …

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, Δm^2, and mixing angles, θ.
- But the confirmation of Solar and Atmospheric:
- Reactor ν's: 3MeV antineutrinos, 180km
- T2K: 700MeV neutrinos, 295km
- There must be more than 2 mass eigenstates





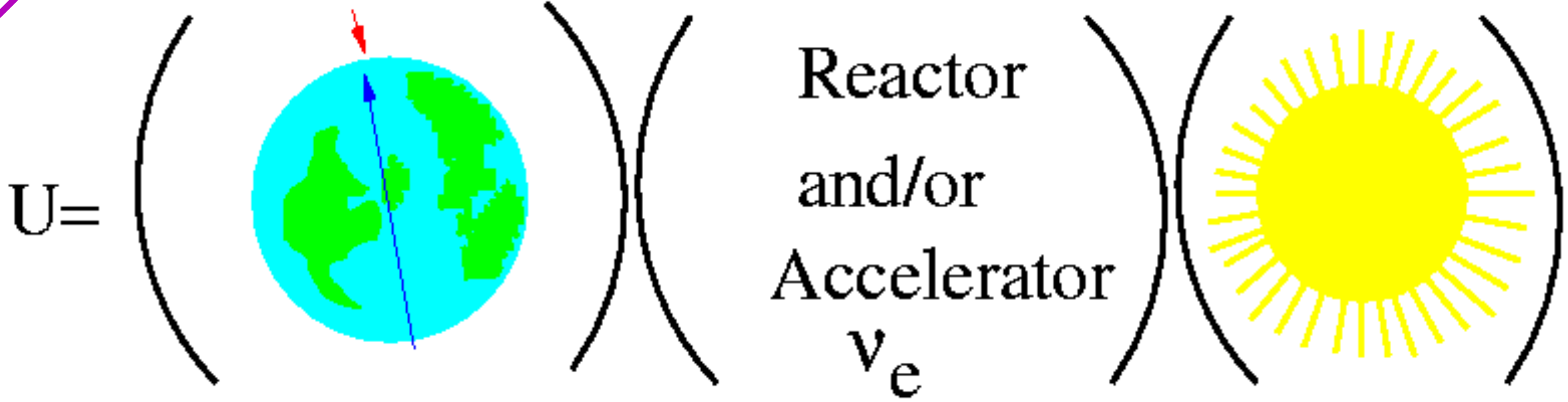
Three Generation Mixing

3x3 Unitary matrix (U): defined by 3 mixing angles (θ_{12},θ_{23},θ_{13}) and one phase (δ)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij}, \text{ and } c_{ij} = \cos\theta_{ij}$$

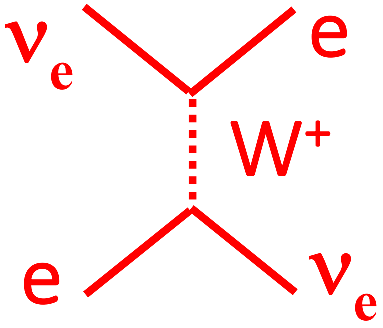


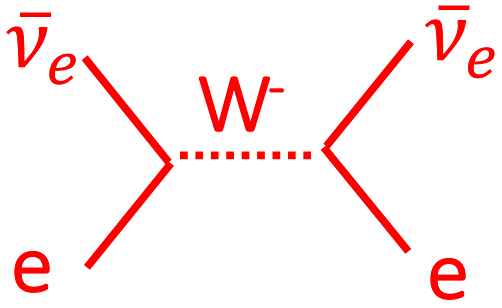
Next Goal: comparing neutrinos to antineutrinos

- The early Universe had a lot of energy to make matter and antimatter in equal amounts
- Where is the antimatter today?
  - look for annihilations.
- As far away as we can tell, today there aren't big matter and anti-matter collisions
- Maybe neutrinos oscillate differently from anti-neutrinos!

What about neutrinos passing through the Earth?

- Electrons in the earth act on ν_e and $\bar{\nu}_e$'s differently from each other, and from ν_μ or ν_τ





Wolfenstein, PRD (1978)

- For 2 generations… $$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

$$x = \frac{2\sqrt{2}G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

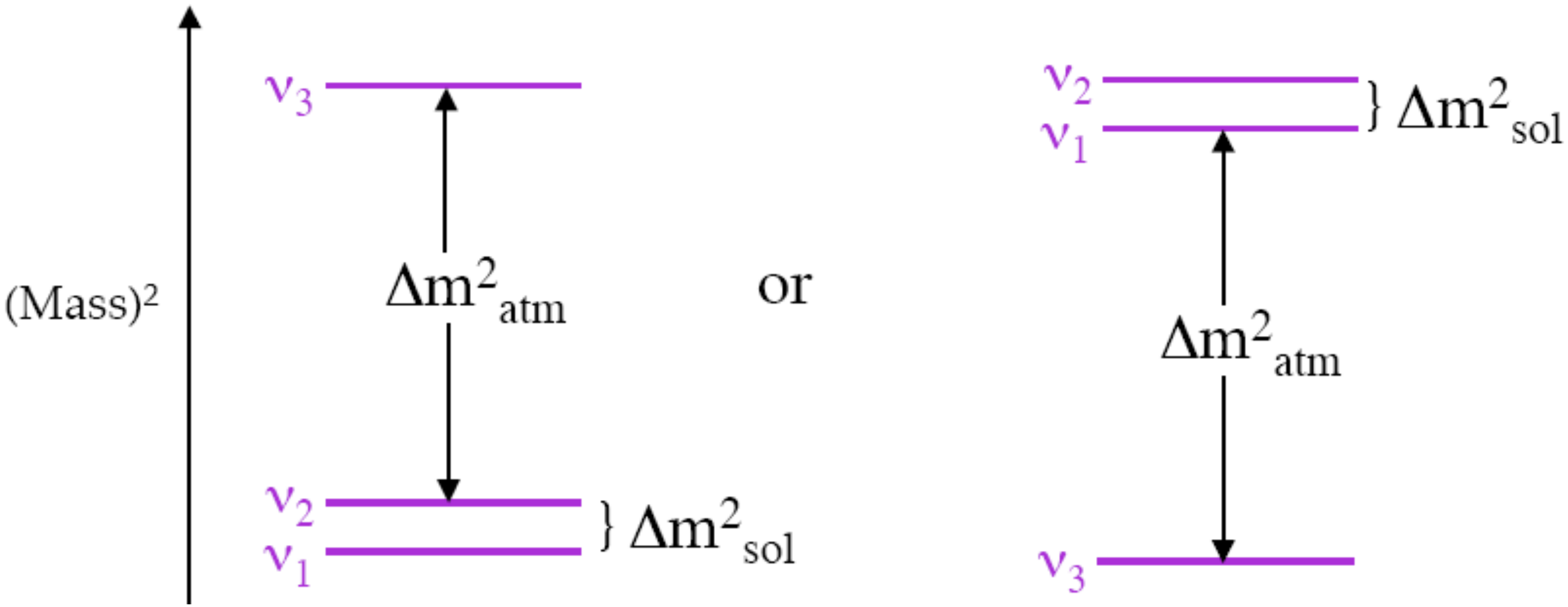
$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

This complicates search for CP violation, but it means you can measure the mass ordering
Catch: need to use a baseline that is 700km or larger to see this!

Measuring the Neutrino Mass Spectrum

- Do neutrino mass states have the same mass structure as the charged fundamental particles? Use “matter effects” to see this



figures courtesy B. Kayser

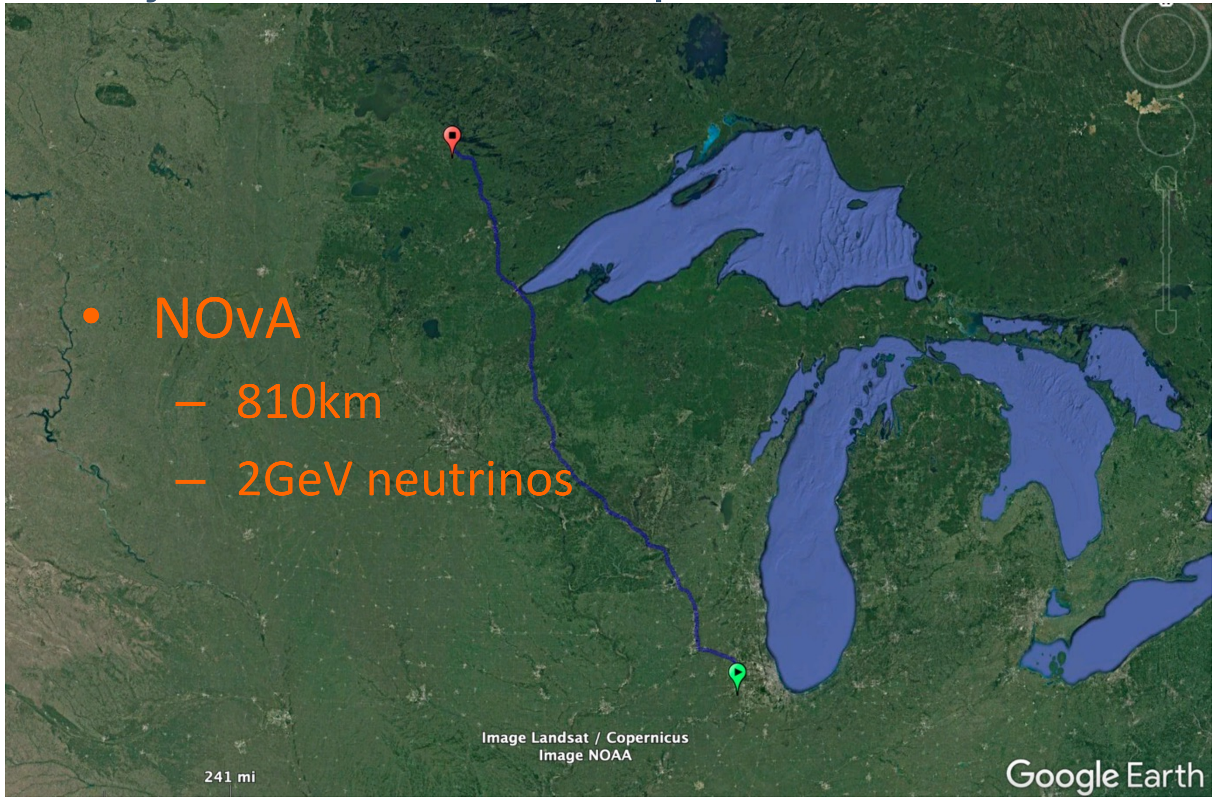
$\Delta m_{sol}^2 \rightarrow \Delta m_{12}^2 \approx 8\times10^{-5}\,eV^2$ $\Delta m_{atm}^2 \rightarrow \Delta m_{23}^2 \approx 2.5\times10^{-3}\,eV^2$

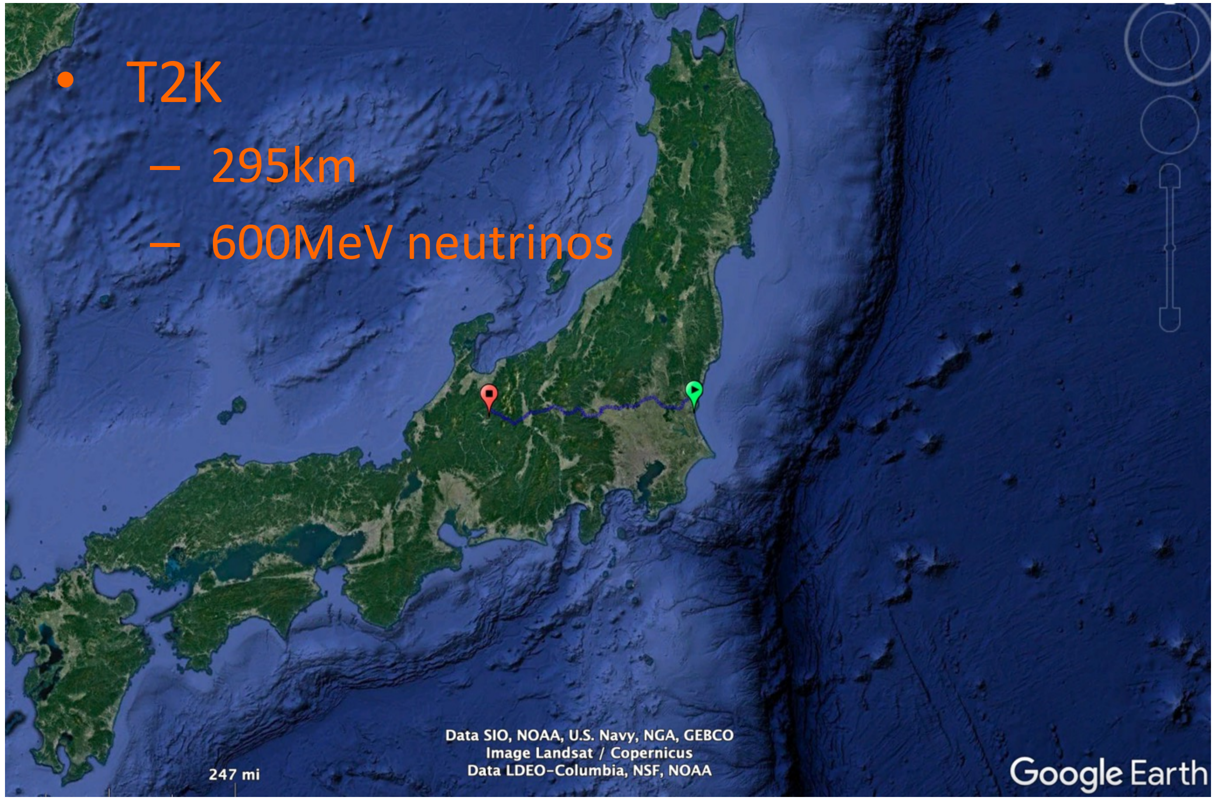
Today's Long Baseline Oscillation Experiments

- What we are trying to determine:
  - Biggest question: is this really the right formalism to describe neutrinos?
  - Do Neutrinos and Antineutrinos oscillate with the same probability? (Is there CP Violation in the Lepton Sector?)
  - Do neutrinos have a mass spectrum like the other fundamental fermions? ("normal" versus "inverted" mass ordering)
  - If ν_3 have more than 50% ν_τ in it? ("Octant" of θ_{23})
- How will we do this?
  - Measuring neutrino and antineutrino oscillation probabilities as function of neutrino energy over known distances
  - These goals depend critically on seeing $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ as a function of NEUTRINO ENERGY

State of the (Long Baseline) Art: NOvA and T2K

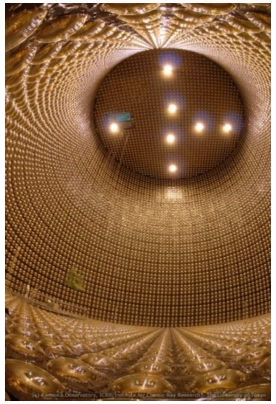
- Two accelerator experiments probing “atmospheric anomaly”
- Near and Massive Far Detectors: 14-50 kton
- Very intense beams of protons: 700-900kW

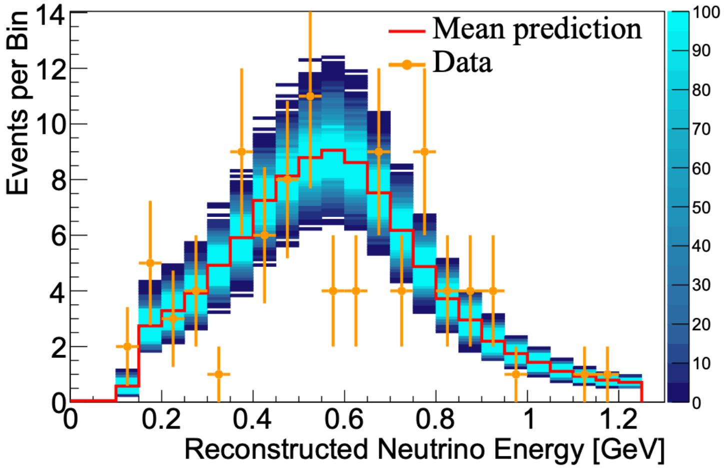




Neutrino Events at NOvA and T2K

- T2K sees an asymmetry in ν_e versus $\bar{\nu}_e$ data. NOvA does not. The two experiments are not giving a consistent picture. All eyes are on continued analysis of this data!





T2K

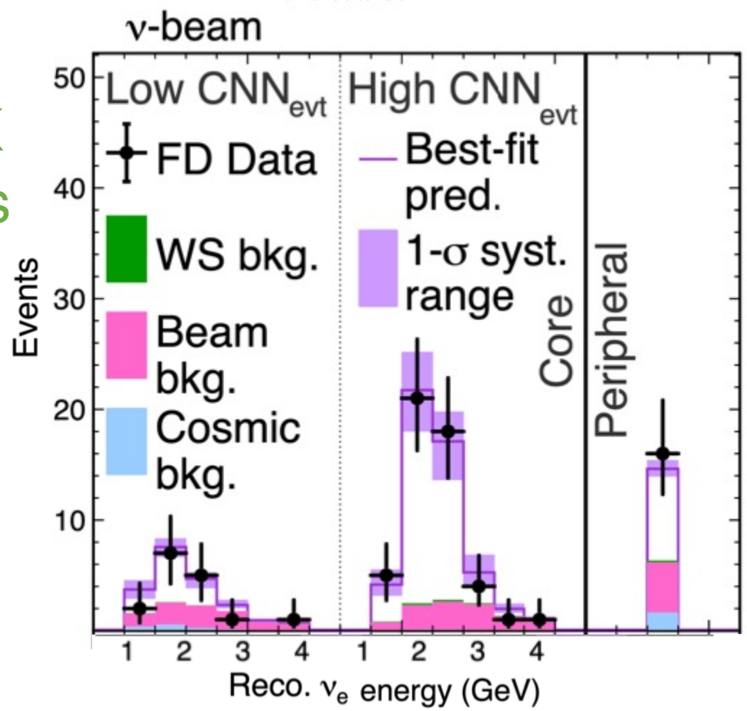
94+14 ν_e events

16 $\bar{\nu}_e$ events

T2K Collaboration, *Eur.Phys.J.C* 83 (2023) 9, 782

+ NOvA/T2K combinations in progress

DUNE will be able to resolve this



NOvA Collaboration, PRD 106, 032004 (2022)

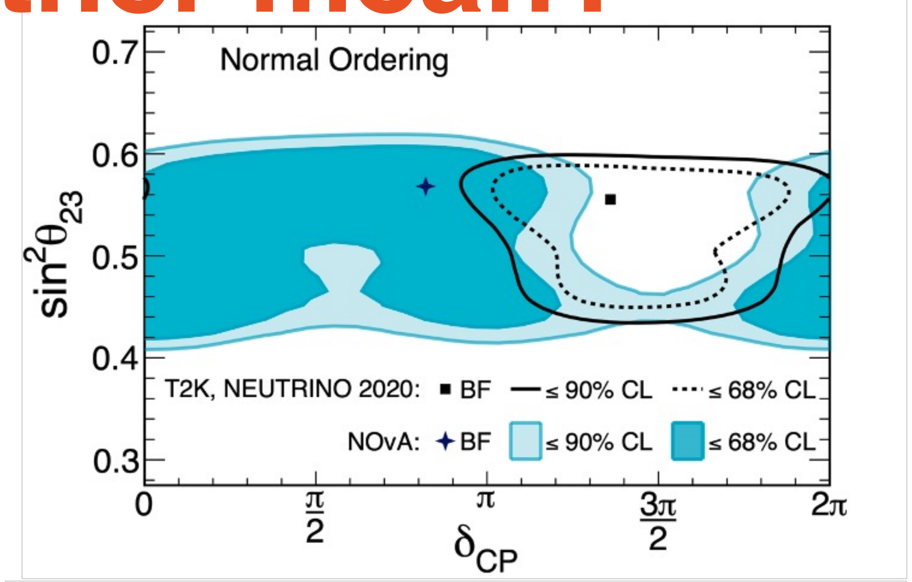
NOvA

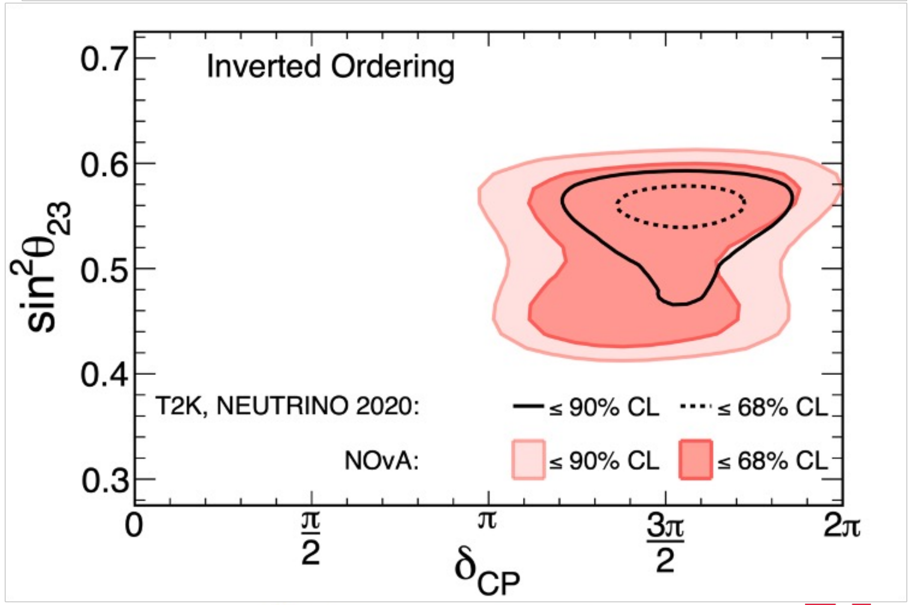
82 ν_e events

33 $\bar{\nu}_e$ events

What do both signals together mean?

- Weak preferences for normal ordering, but mutually allowed region in Inverted Ordering at <1σ
- Some regions of joint Mass Ordering-δ_{CP}-θ_{23} space are excluded at >90%
- Mass ordering and CPV are unresolved, and minimal sensitivity to physics beyond the three-flavor model
- **We need more statistics…at a minimum!**

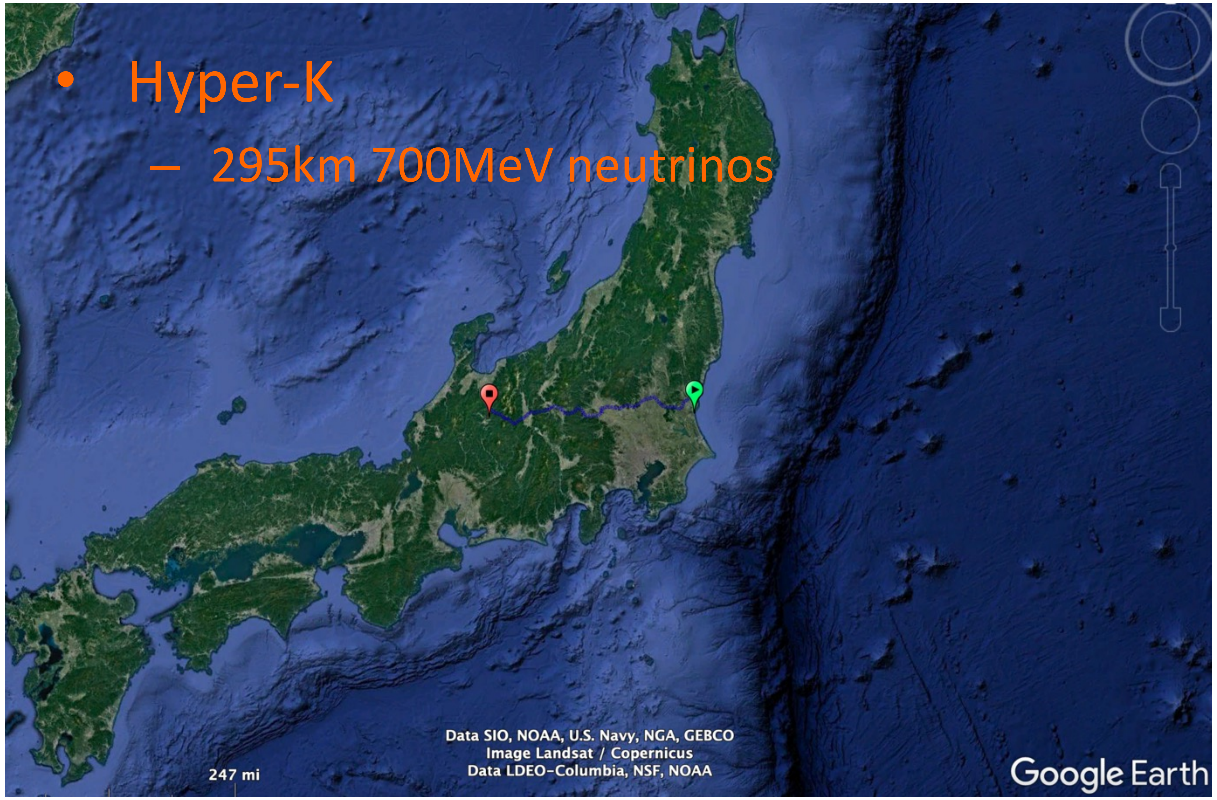


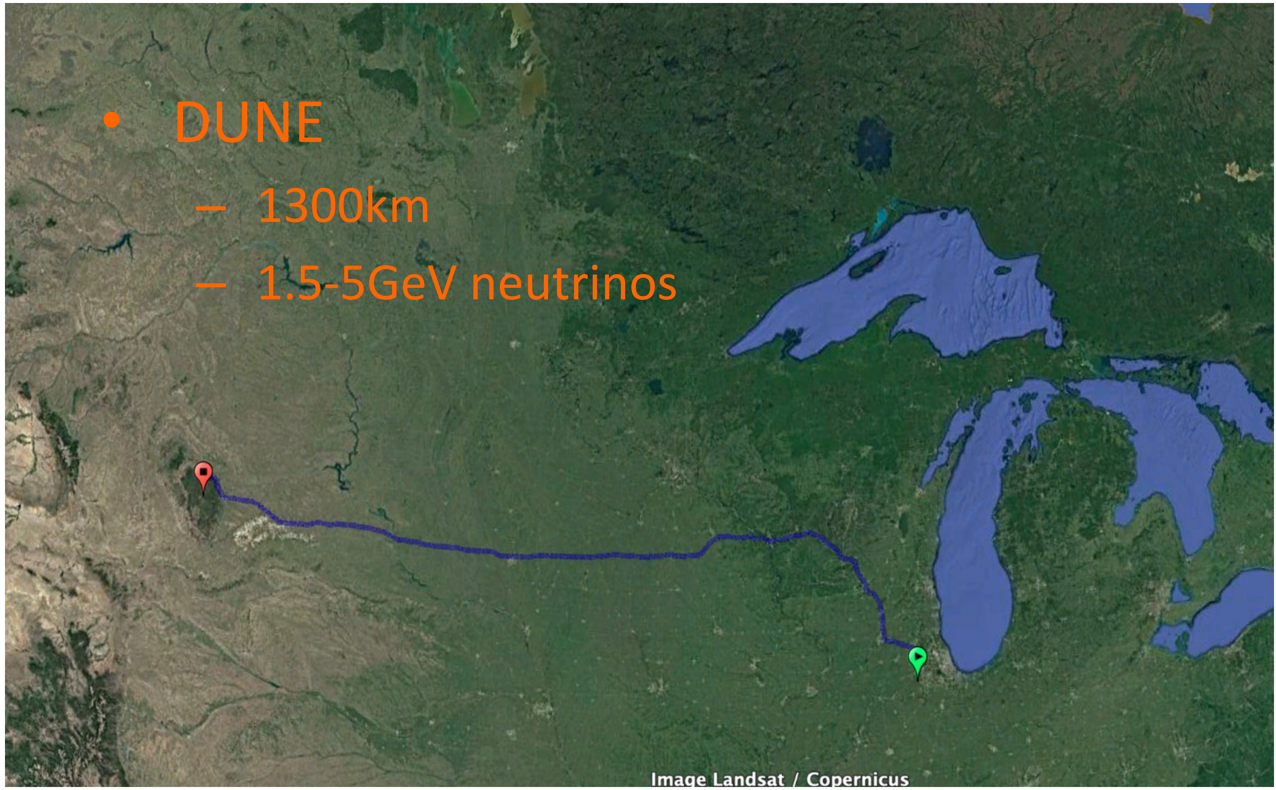


https://doi.org/10.5281/zenodo.6683827

Next Generation: Hyper-K and DUNE

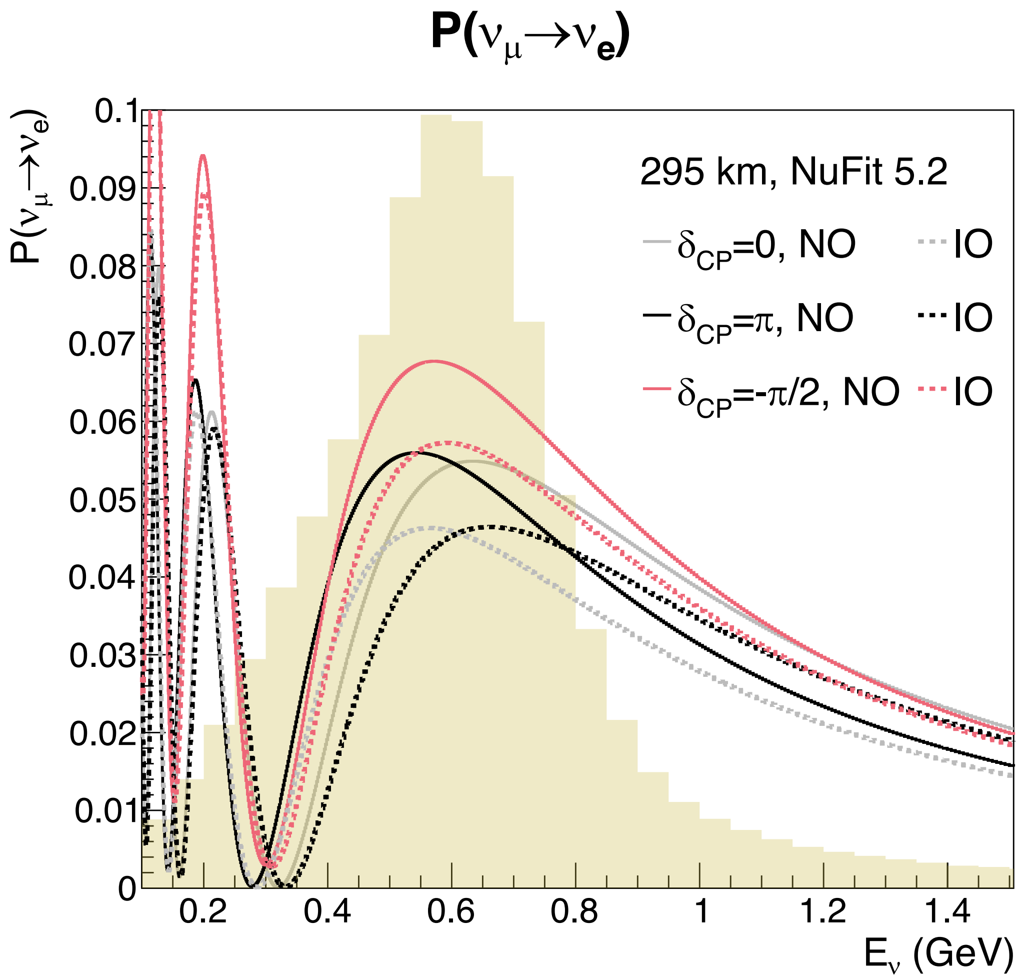
- Will collect much larger statistics than we have today to get to precision oscillation physics
- Enormous increases in neutrino beam intensities @ J-PARC and at Fermilab
- Enormous increases in Detector Mass (Hyper-K) and Granularity (DUNE)

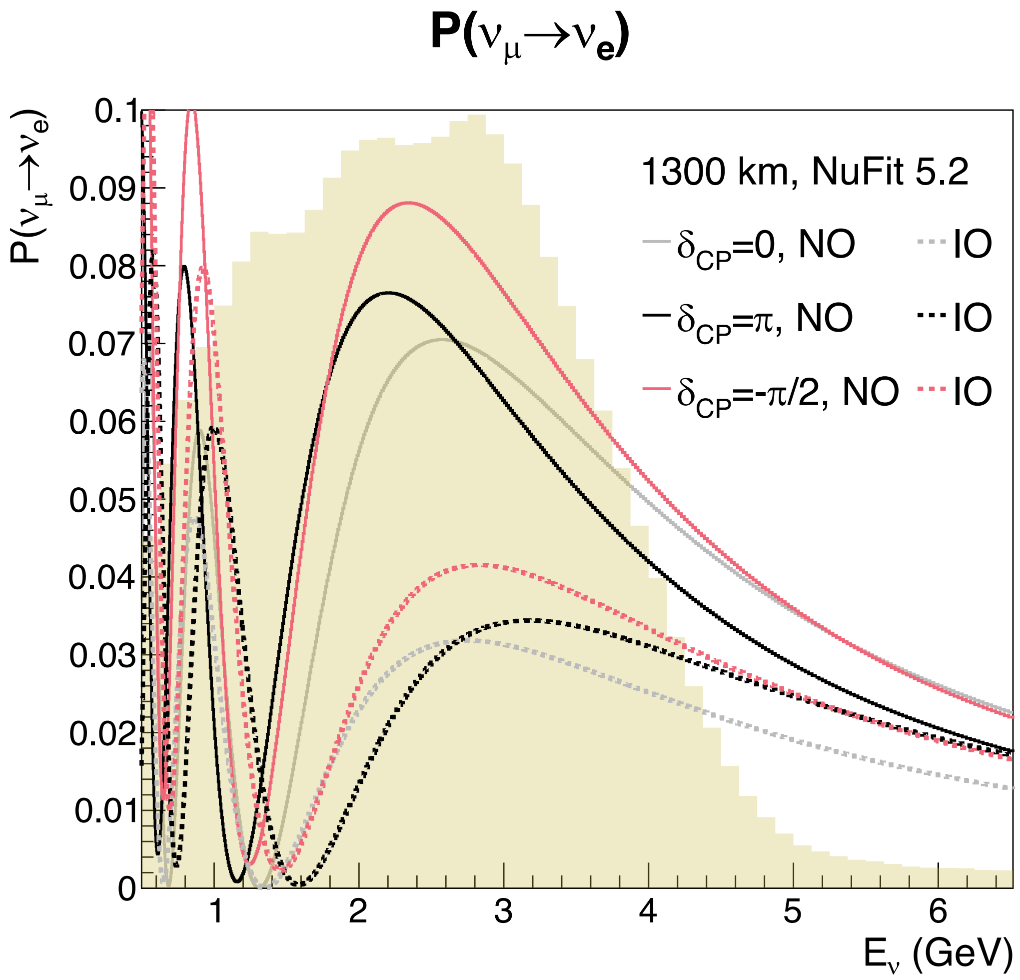




Oscillation Probabilities at Hyper-K and DUNE

Plots courtesy C. Wret



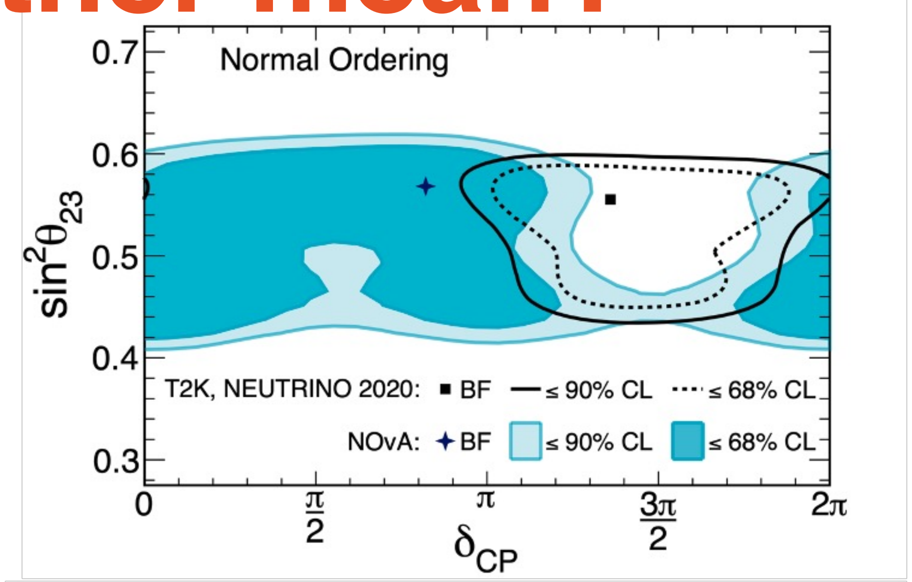


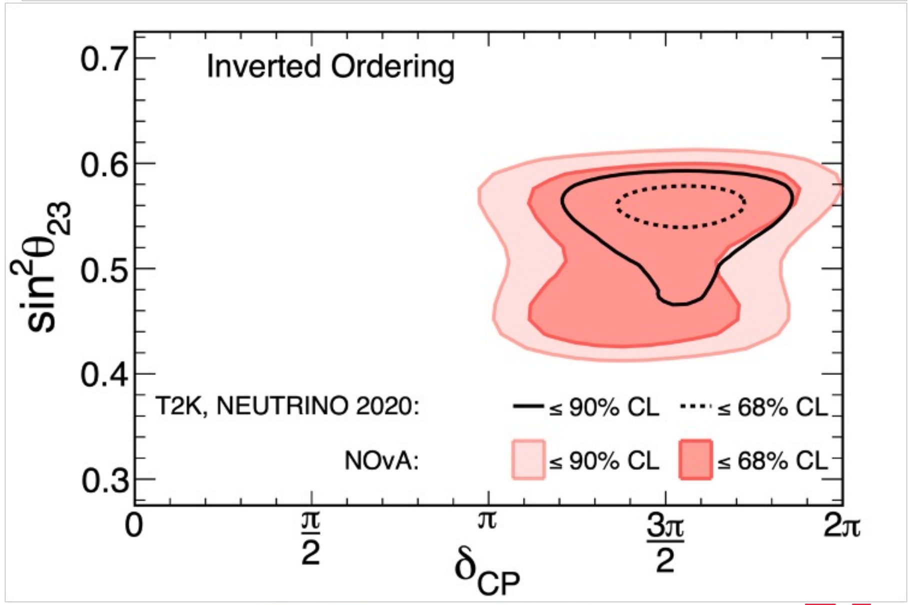
NO: Normal Mass Ordering
IO: Inverted Mass Ordering

Will need precise models to extract the most information out of the far detector statistics vs energy!

What do both signals together mean?

- We need more statistics…at a minimum!
- But…what if the DUNE and HyperK results have a similar discrepancy but at higher statistical precision?
- Could be new physics…or…could be that we need better description of how neutrinos interact





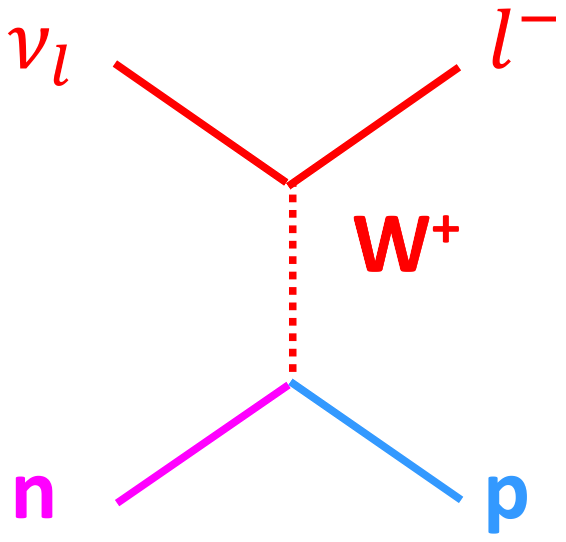
https://doi.org/10.5281/zenodo.6683827

Outline

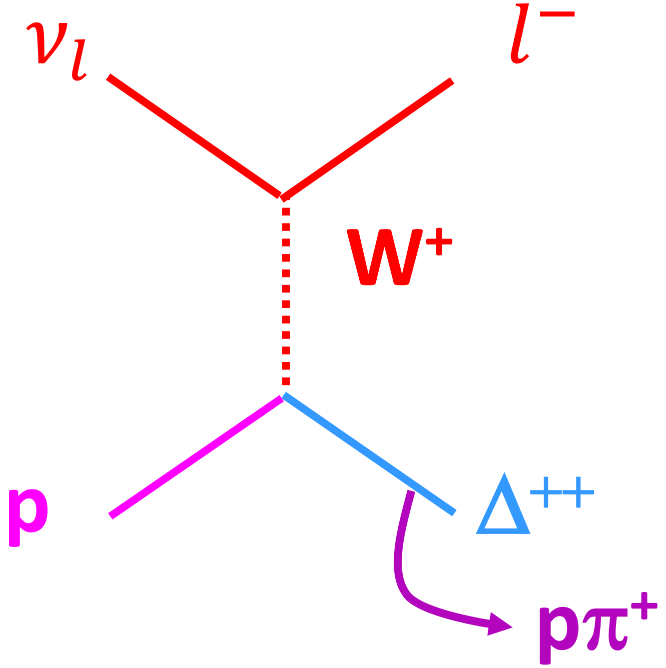
- Why studies of neutrino flavor mixing need to understand neutrino interactions better than ever before
- Neutrino Interactions in 20 words or less
- How the nucleus affects neutrino interactions
- Introduction to MINERvA
- Quasi-elastic interactions of Neutrinos
  - On Plastic (CH), compare different ways of predicting neutrino energy
  - As function of A
    - versus transverse muon momentum (p_t)
    - versus "Missing transverse momentum" momentum (δp_t)
- Happy to talk about other channels in Q&A session afterwards

Neutrino Interactions, 20 words or less

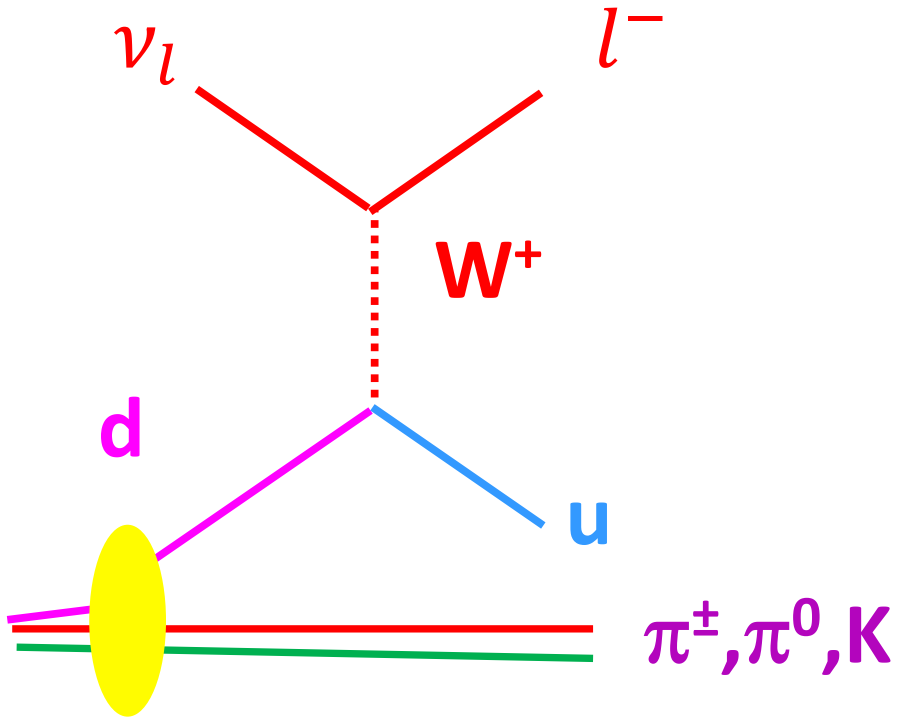
- Optics analogy: the wavelength of your probe (1/momentum transfer) determines what you can see: Introducing Q^2, or the square of the 4-momentum transferred
- High energy neutrinos can transfer more momentum, which means they can see smaller structure (quarks), and make more particles



“QuasiElastic” (QE)



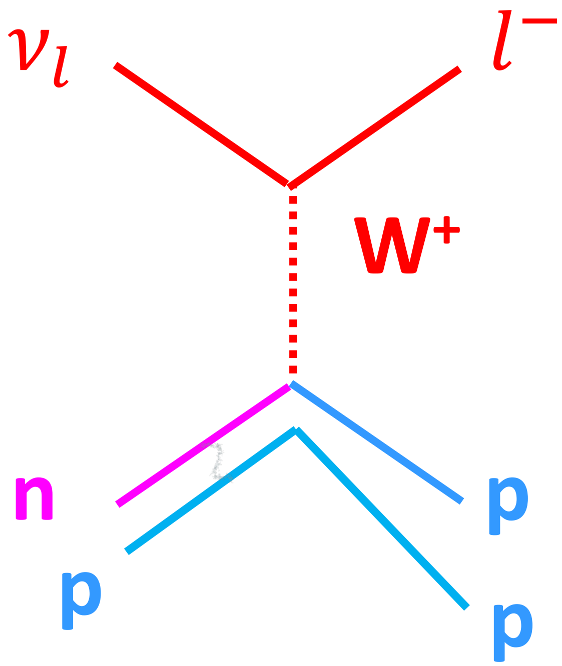
“Pion Production”



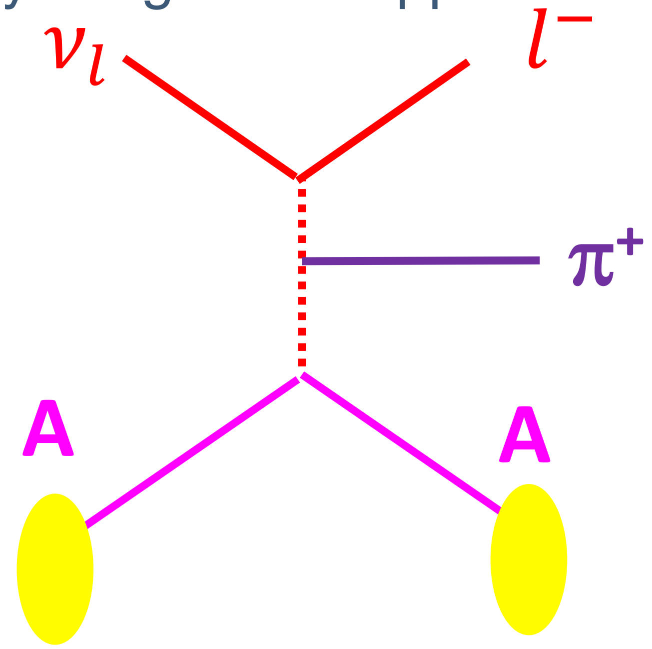
“Deep Inelastic Scattering”

Neutrino Interactions, but inside a nucleus

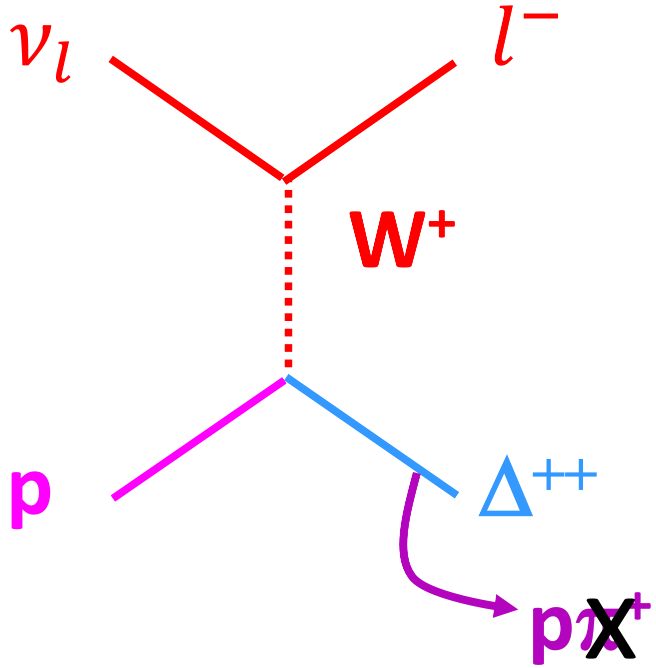
- Optics analogy: the wavelength of your probe (1/momentum transfer) determines what you can see Introducing Q^2, or the square of the 4-momentum transferred
- If the wavelength is large enough (momentum transfer is small enough) that you are seeing nearby nucleons, funny things can happen…



Meson Exchange Currents
(add “2p2h” and more “1p1h”)



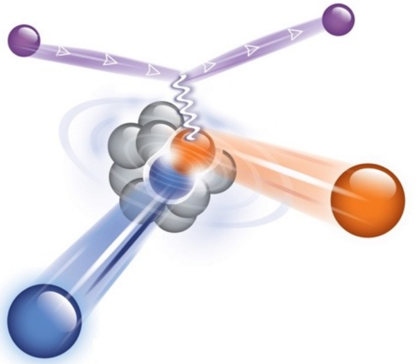
“Coherent Pion Production”



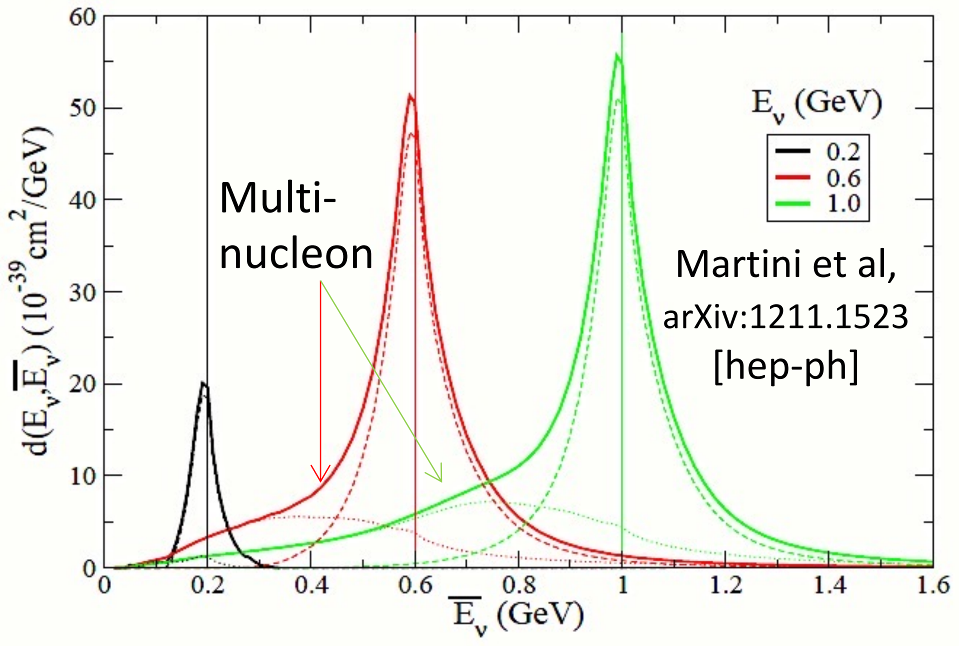
“Final State Interactions

Reconstructing Neutrino Energy

[R. Subedi et al., Science **320**, 1476 (2008)]



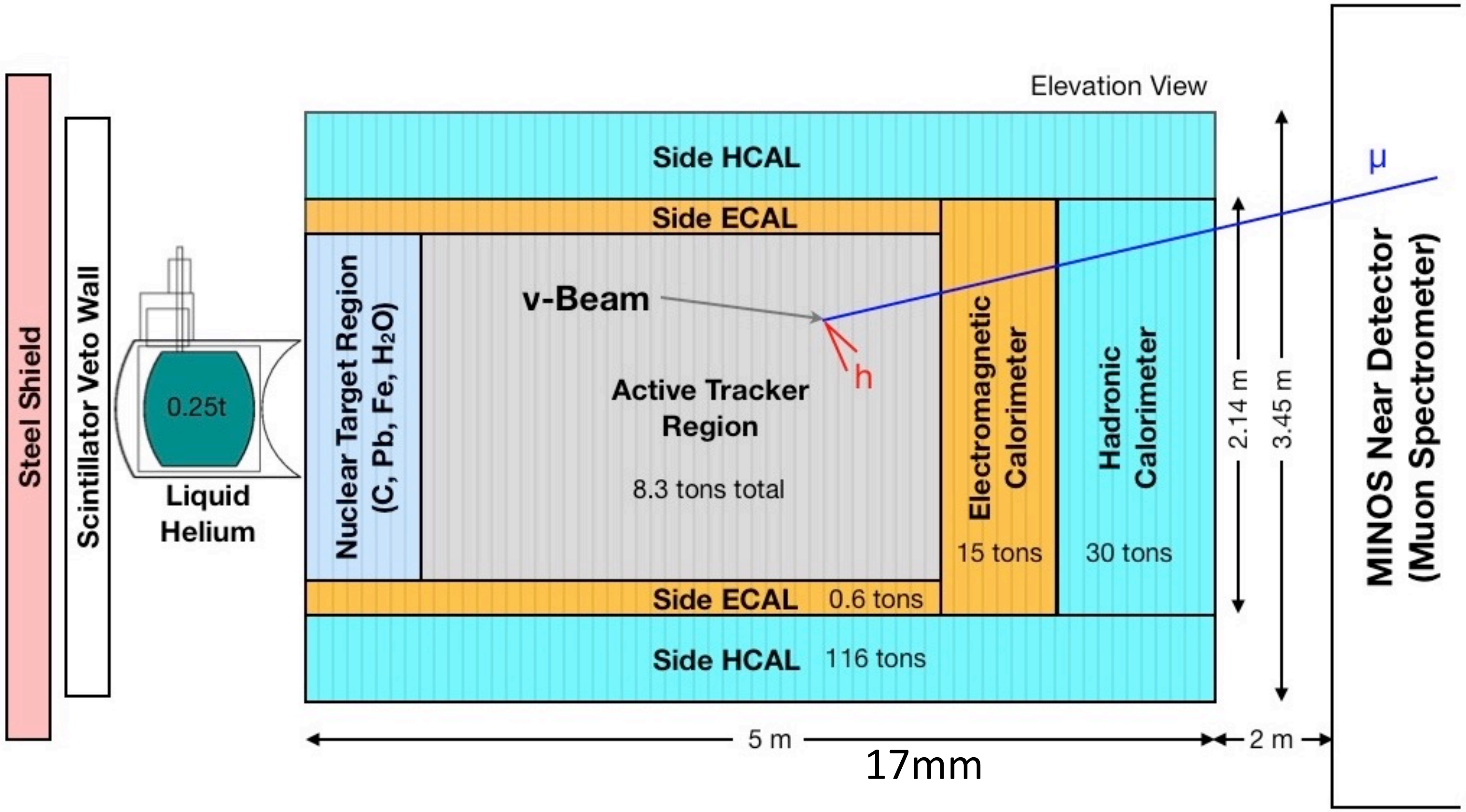
- Oscillation experiments reconstruct neutrino energy from partial events, even in the most elastic events.
  - E.g., T2K and Hyper-K from lepton energy and angle
  - E.g., NOvA and DUNE from lepton energy and kinetic energy of protons.
- Significant energy and momentum are lost to the extra outgoing nucleons in 2p2h events.
- Absorbed pions also have to be taken into account by all experiments
- Outgoing neutrons invisible to NOvA and DUNE.
- Critical corrections for T2K, Hyper-K, NOvA and DUNE. Are the models correct?



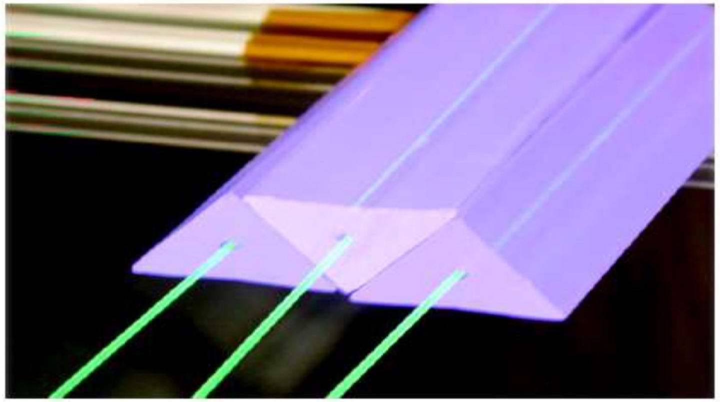
Outline

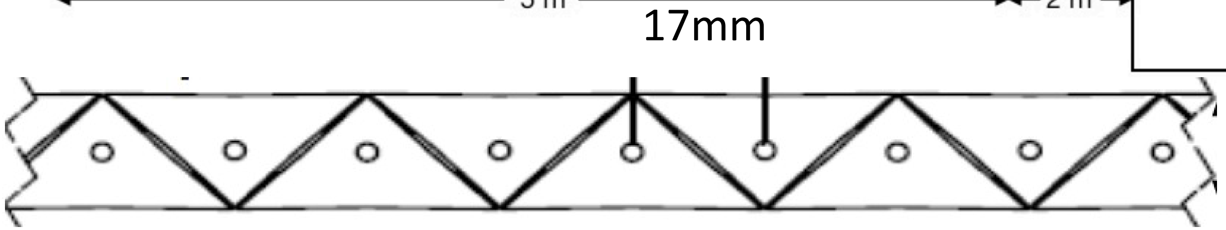
- Why studies of neutrino flavor mixing need to understand neutrino interactions better than ever before
- Neutrino Interactions in 20 words or less
- How the nucleus affects neutrino interactions
- Introduction to MINERvA
- Quasi-elastic interactions of Neutrinos
  - On Plastic (CH), compare different ways of predicting neutrino energy
  - As function of A
    - versus transverse muon momentum (p_t)
    - versus "Missing transverse momentum" momentum (δp_t)
- Happy to talk about other channels in Q&A session afterwards

Introducing MINERvA



- Solid Scintillator plus MINOS Near Detector
- Took data @Fermilab from 2009-2019



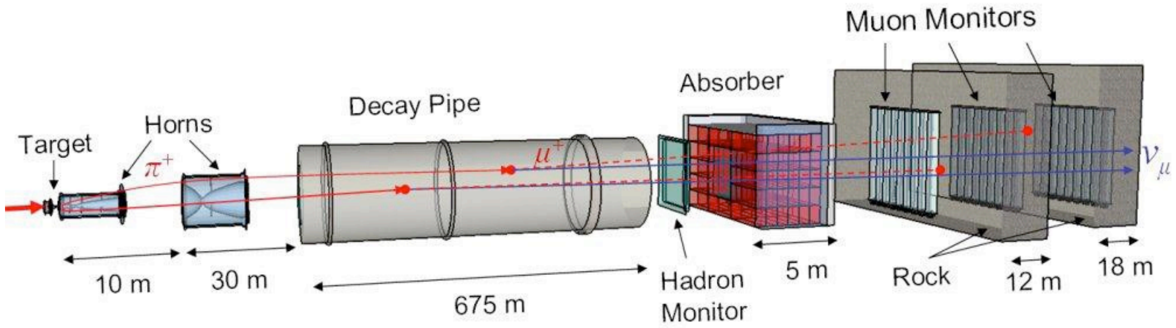


Three views:
X: Vertical
U,V: ± 60

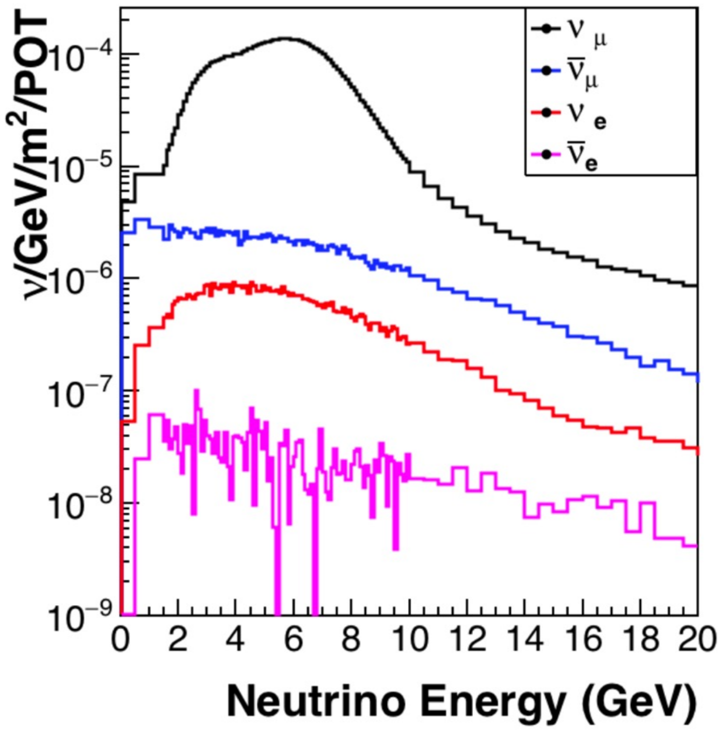
Nucl.Instrum.Meth.A 743 (2014) 130 and beam test *Nucl.Instrum.Meth.A* 789 (2015) 28

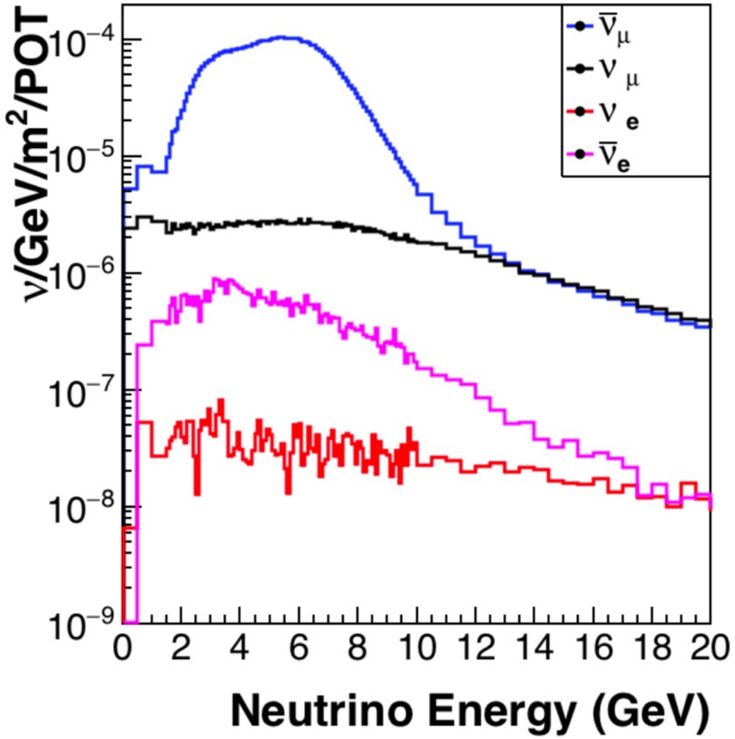
Spatial resolution ~3mm
Timing resolution ~3ns

NuMI Beamline



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



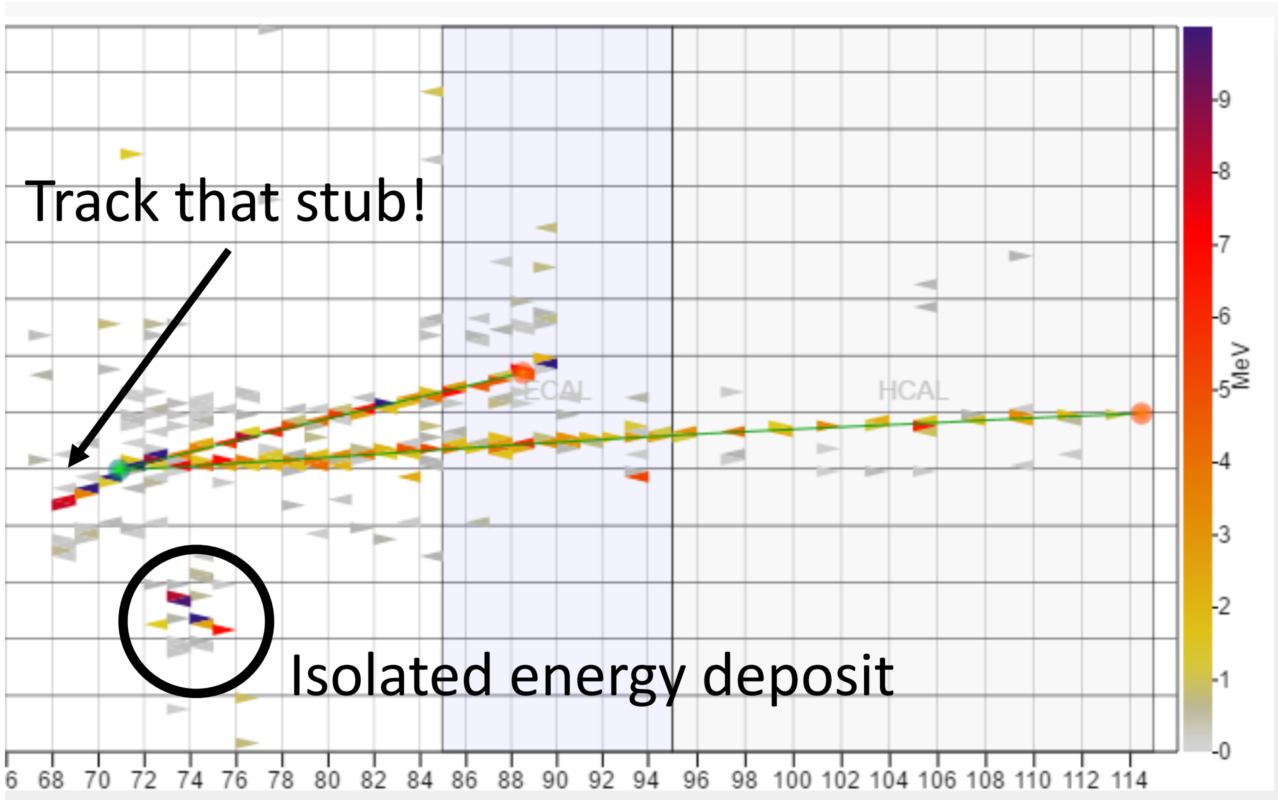


L. Zazueta et al., Phys.Rev.D 107 (2023) 1, 012001
D. Ruterbories et al., Phys.Rev.D 104 (2021) 9, 092010
A. Bashyal et al., JINST 16 (2021) P08068
E. Valencia et al., Phys. Rev. D 100, 092001 (2019).
L. Aliaga, M. Kordosky, T. Golan et al, Phys. Rev. D 94, 092005

Graphic from arXiv:2312.16631 [hep-ex]

How to find "QE-like" Events @ MINERvA

- Track muons, pions and protons
- Measure dE/dx on all non-muon tracks
  - Must be consistent with proton
  - This vetoes events w/$\pi^{\pm}$
- Count all isolated energy deposits
  - must have <2 of them
  - This vetoes events w/ π^0
- Look for $\boldsymbol{\pi} \rightarrow \boldsymbol{\mu} \rightarrow \boldsymbol{e}$ (Michel Electrons) (near all starts and ends of tracks)
  - must find 0
  - This vetoes events w/ π^+



Simplest Observables for “QE-like” events

Cross sections can be measured along 3 axes:

1) Muon longitudinal momentum: $p_{\|}$
   proxy for neutrino energy
2) Muon Transverse momentum: p_T
   proxy for momentum transfer (Q^2)
3) Total “available” Energy: ΣT_p

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

for 0π events, this is simply sum of proton Kinetic Energy

- E_{avail} is what NOvA uses to translate from muon energy to neutrino energy

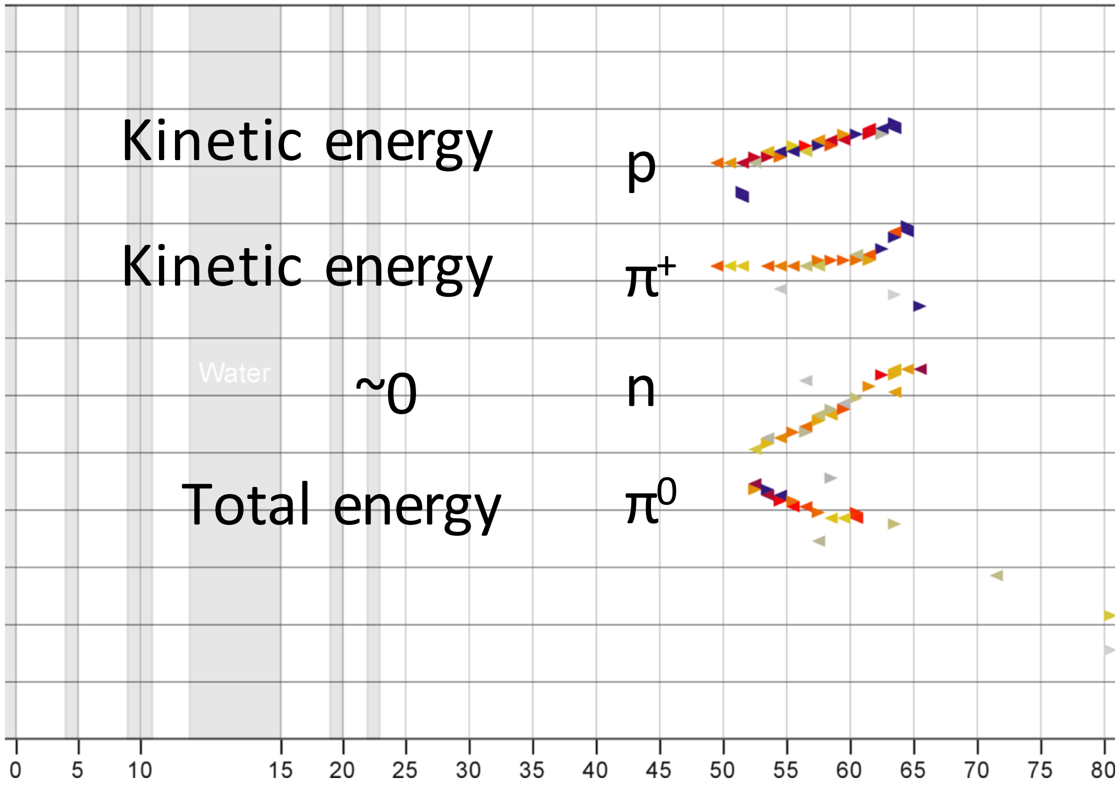
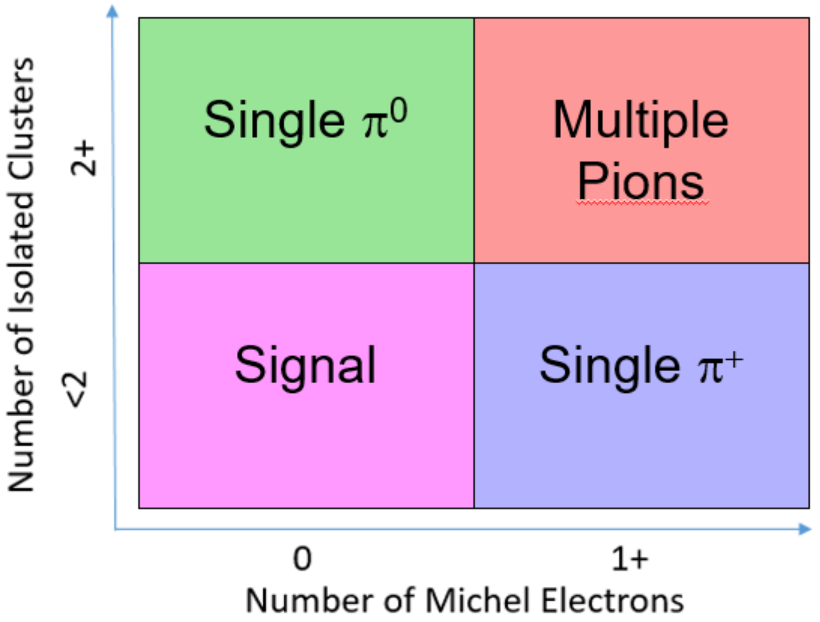
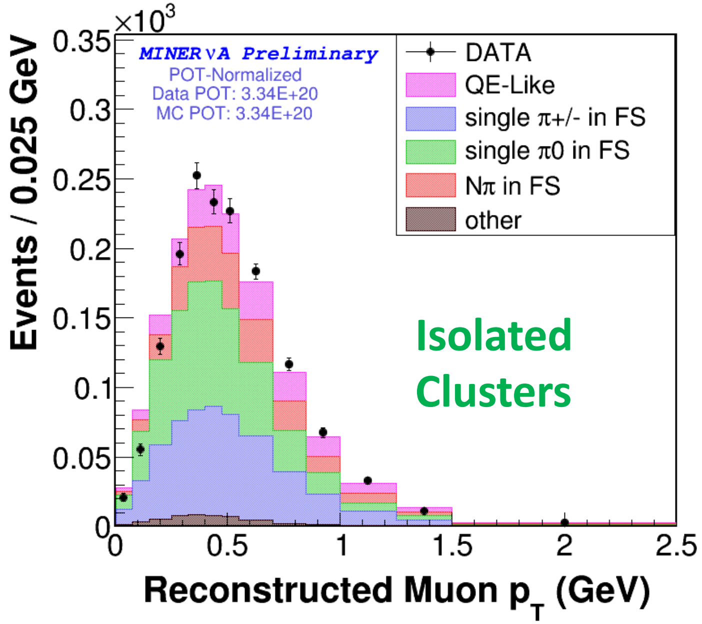


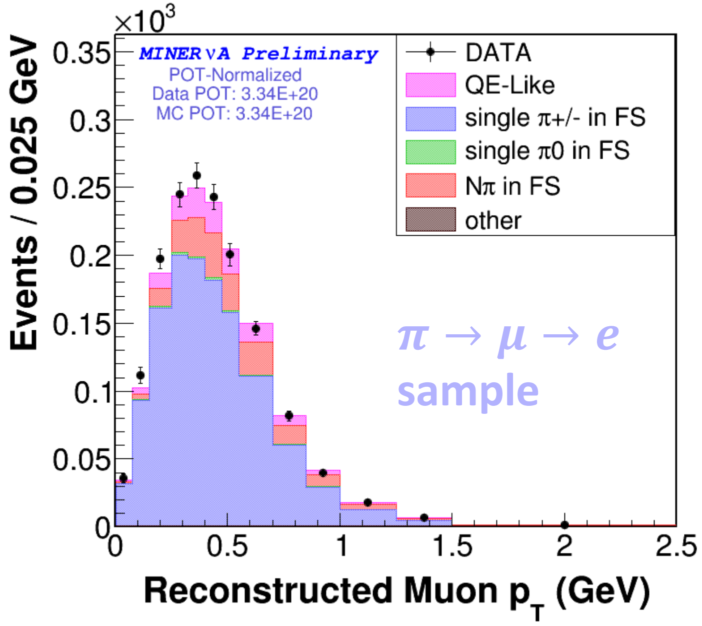
Figure courtesy P. Rodrigues

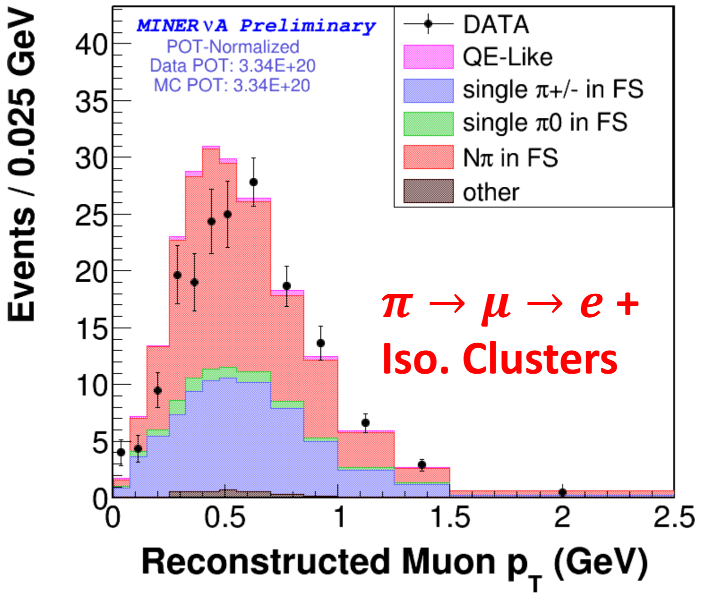
Constraining Backgrounds

- Three Backgrounds, three independent data sets
- Fit scaling factors as a function of p_t AND ΣT_p $\pi^{+/-}$,π^0,Nπ
- Statistics: single pion sidebands have 0.2M each, multi-pion one has 57k events
- Use simulation to predict $p_{\parallel}$ dependence



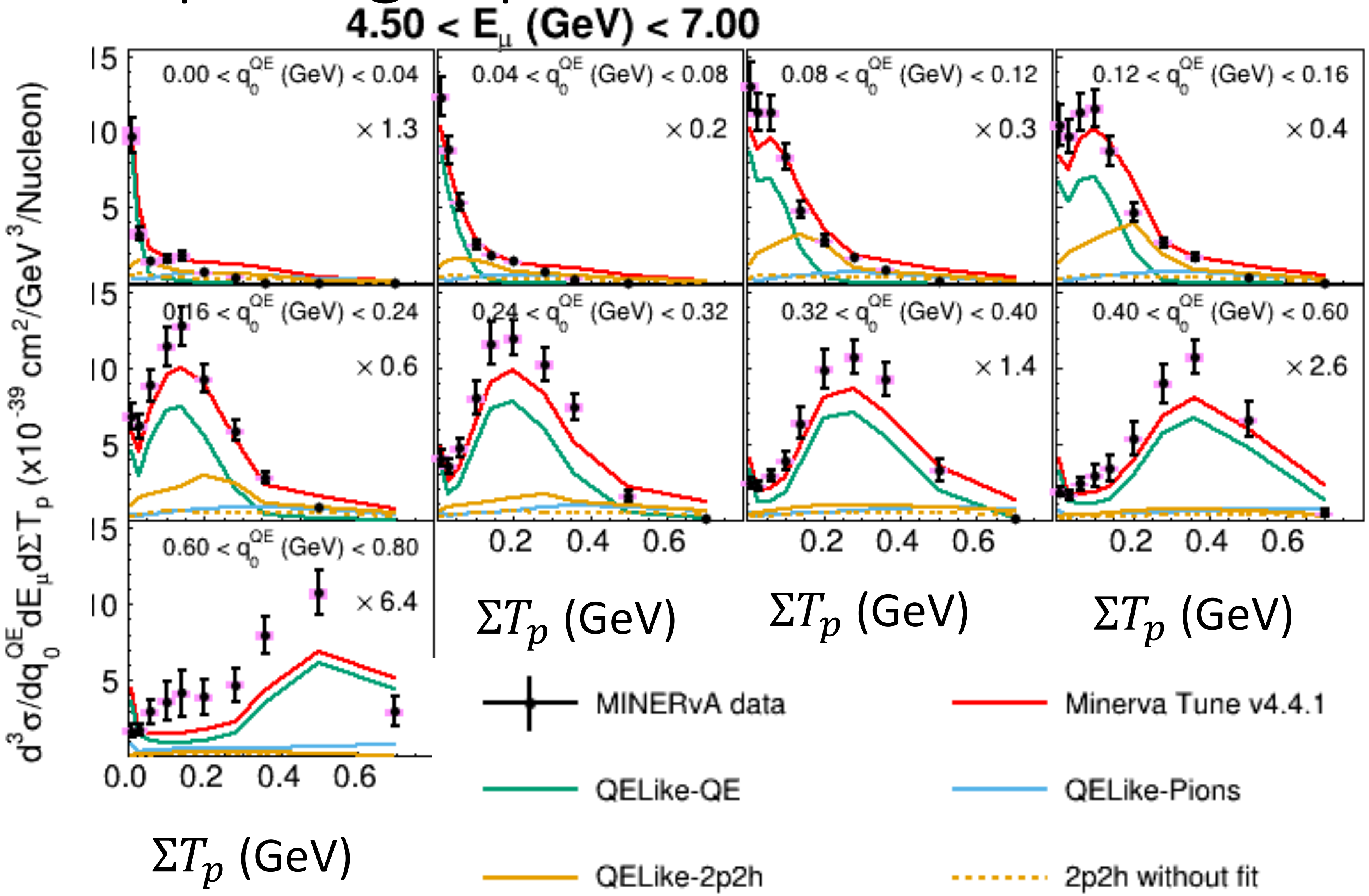






Ref: D. Ruterbories, FNAL Seminar 10/2019

Comparing 2 proxies for Neutrino Energy:



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

- T2K and HK: q_0^{QE} gets added
- NOvA, and LAr: add visible recoil energy
- The two don't agree with the model for 0π events
- Events where the QE hypothesis says there should be lots of proton energy added, MINERvA does not see that energy!

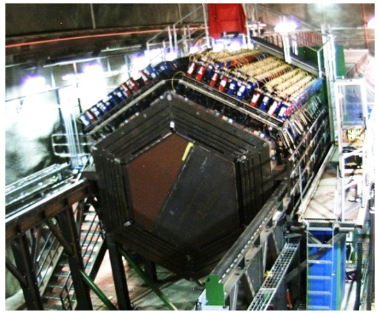
Outline

- Why studies of neutrino flavor mixing need to understand neutrino interactions better than ever before
- Neutrino Interactions in 20 words or less
- How the nucleus affects neutrino interactions
- Introduction to MINERvA
- Quasi-elastic interactions of Neutrinos
  - On Plastic (CH), compare different ways of predicting neutrino energy
  - As function of A
    - versus transverse muon momentum (p_t)
    - versus "Missing transverse momentum" momentum (δp_t)
- Happy to talk about other channels in Q&A session afterwards

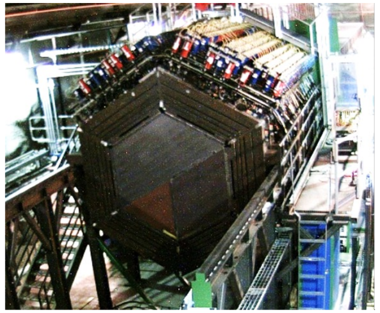
MINERvA's Nuclear Target Region

1" Fe / 1" Pb
323kg / 264kg

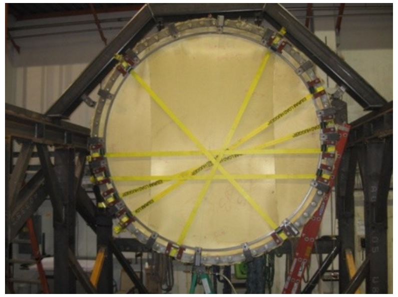
1" Pb / 1" Fe
266kg / 323kg



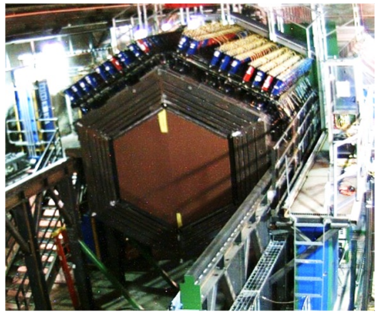
3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg



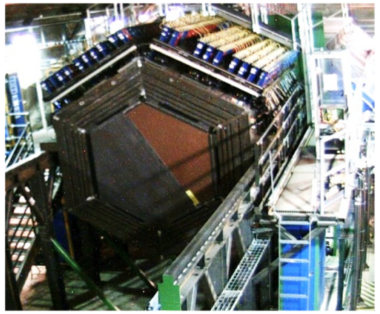
"Bag" of Water
300kg



0.3" Pb
228kg

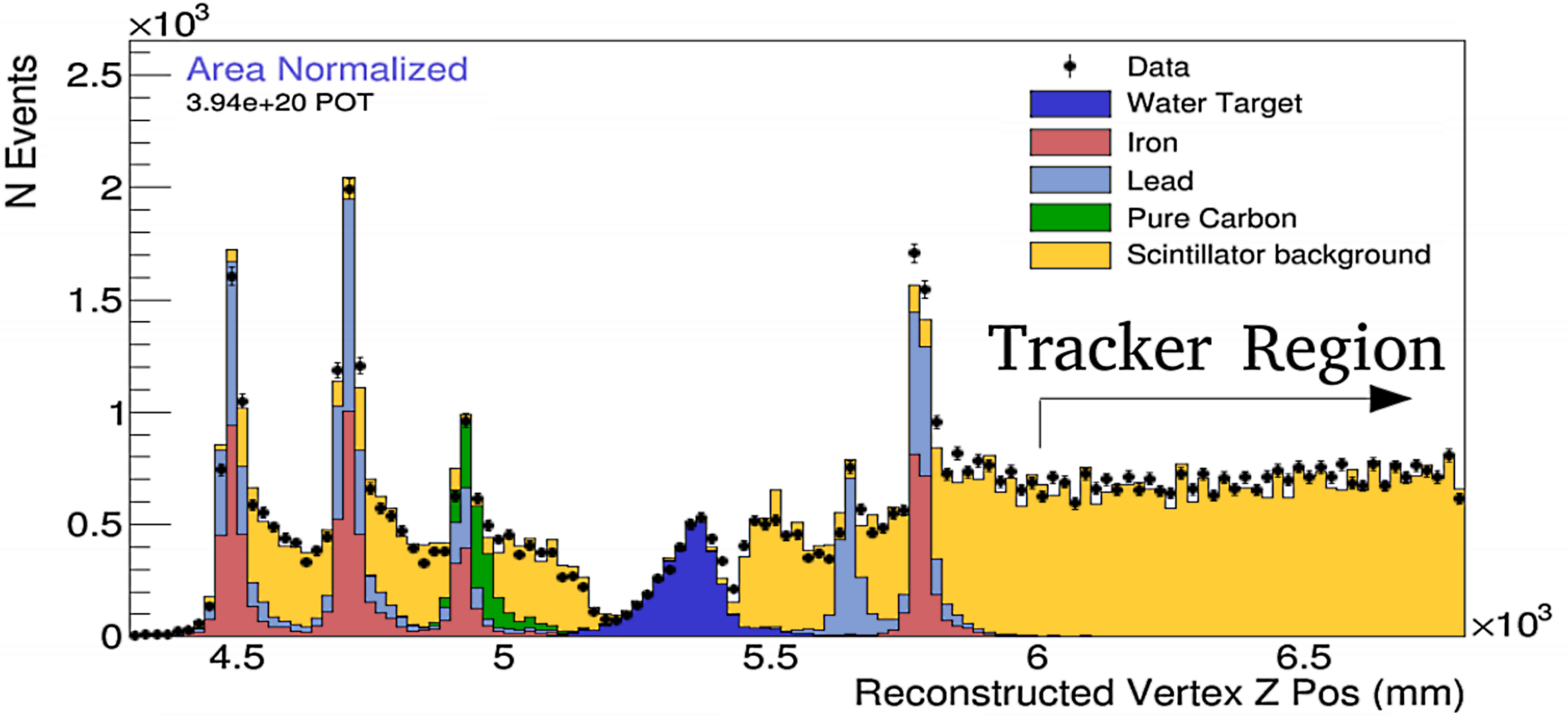


.5" Fe / .5" Pb
161kg/ 135kg



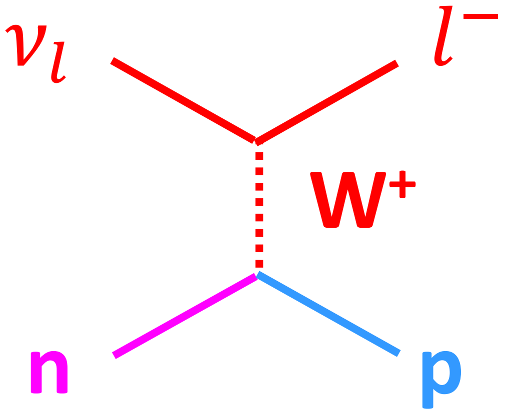
When you have lots of statistics…

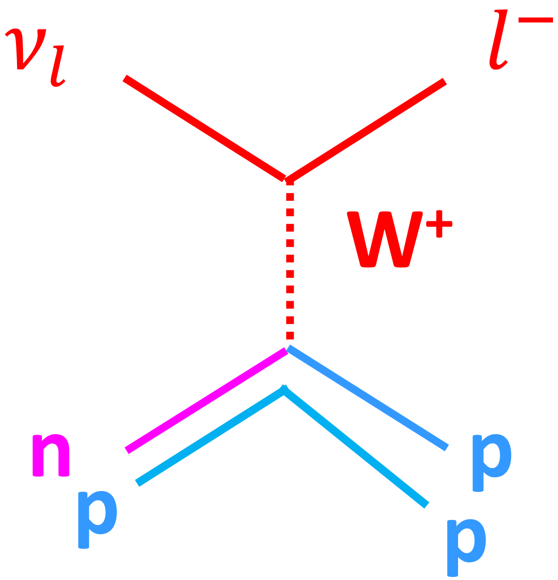
- Different density targets jump out with event rate
- Events at right are all 2-track events from data when water target was full

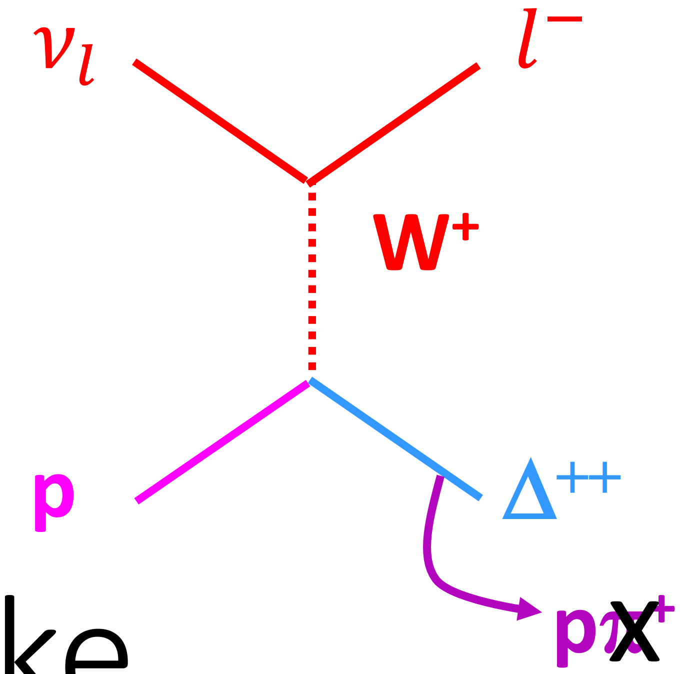


Outline

- Why studies of neutrino flavor mixing need to understand neutrino interactions better than ever before
- Neutrino Interactions in 20 words or less
- How the nucleus affects neutrino interactions
- Introduction to MINERvA
- Different channels, different nuclear dependances!
    - Quasi-elastic interactions
        - By Neutrinos
        - Seen in a new way: look in plane transverse to neutrino direction
        - If time allows…Antineutrinos
    - Happy to talk about other channels in Q&A session afterwards







Neutrino Quasielastic-Like Scattering vs A

We see how the way energy shows up in neutrino CH events doesn't match between data and prediction

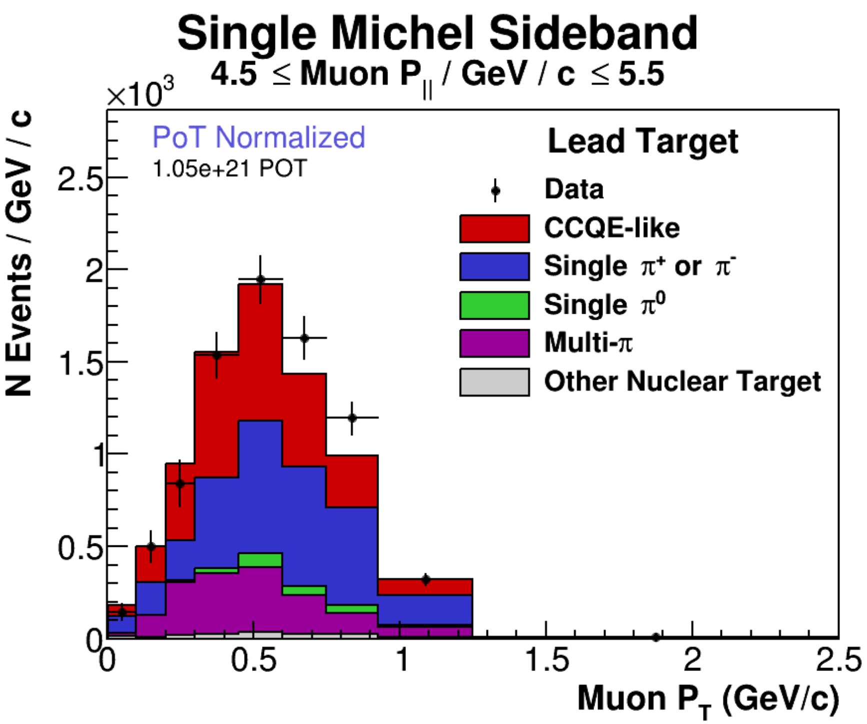
Can we look at A-dependence of this process to get a better handle on what our model is getting wrong?

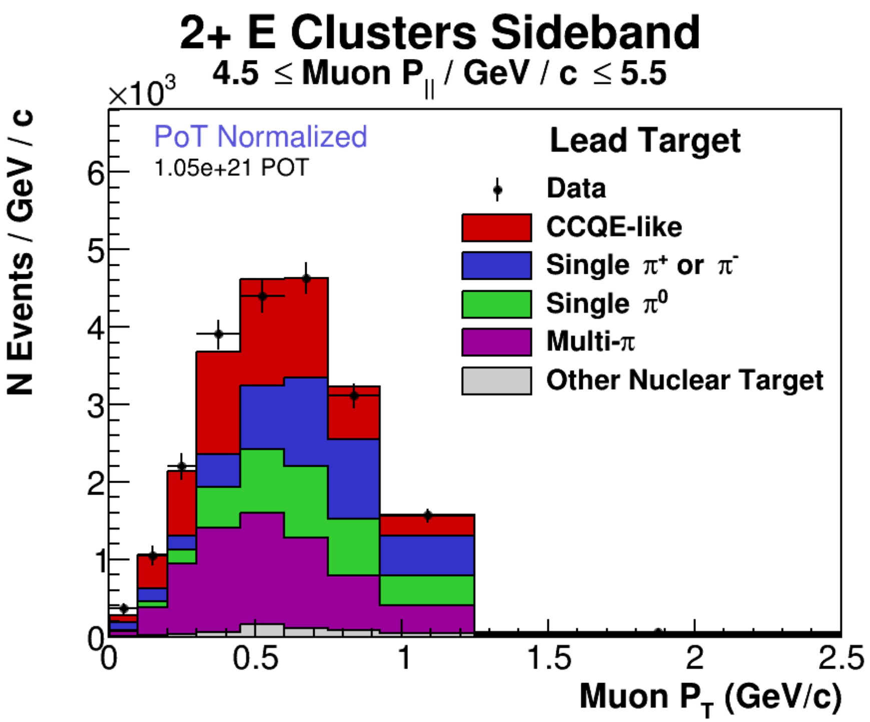
Determining Physics Backgrounds

- Make the same cuts as for the signal BUT…
- Require one Michel Electron

Or

- Require 2 or more extra clusters of energy
- Separately for each target and versus muon transverse momentum





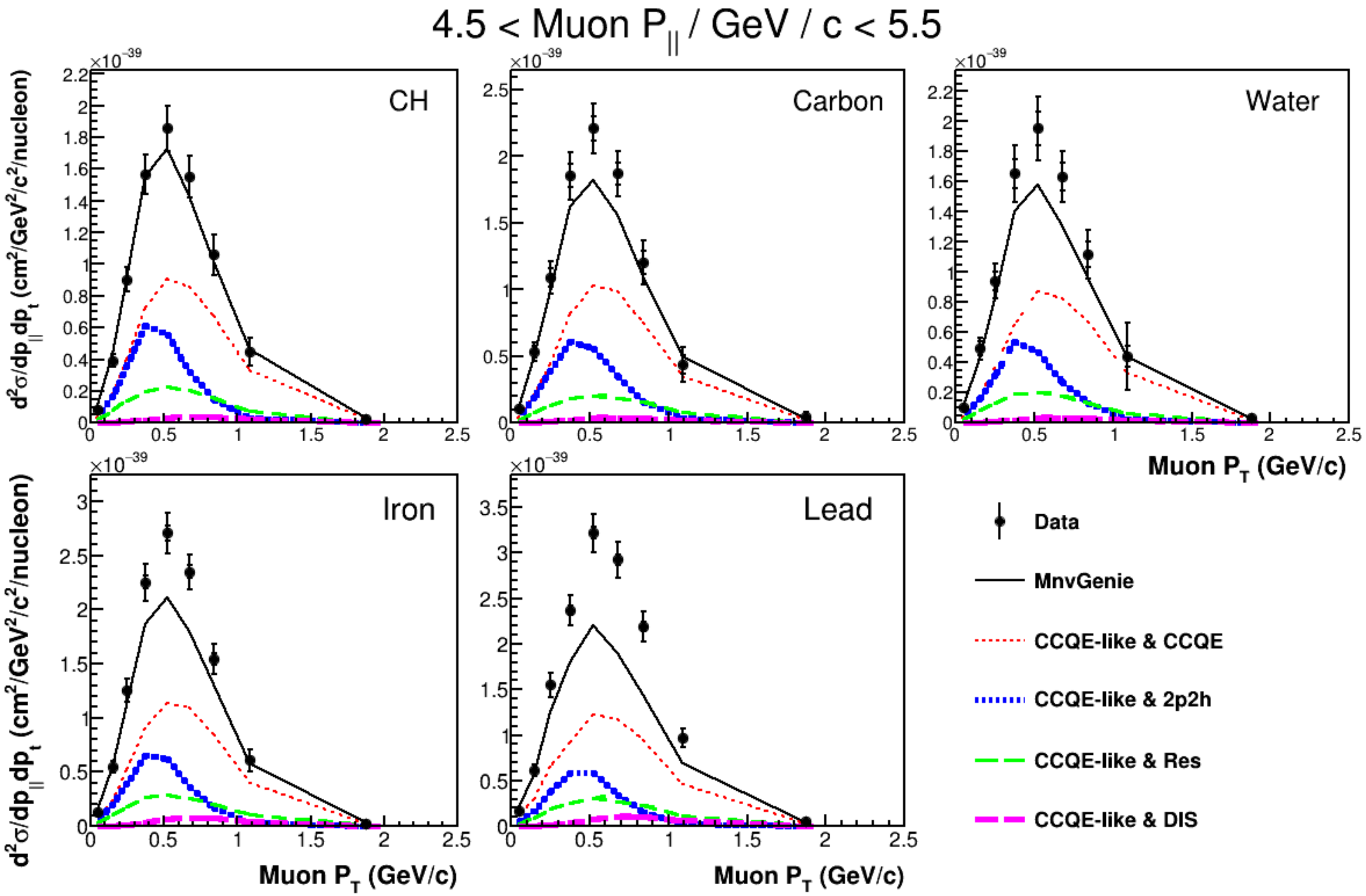
One sample has more single pion background, one has multi-pion and π^0 background

Kleykamp et al, Phys. Rev. Lett. **130**, 161801

ν_μ Quasielastic-like scattering versus A

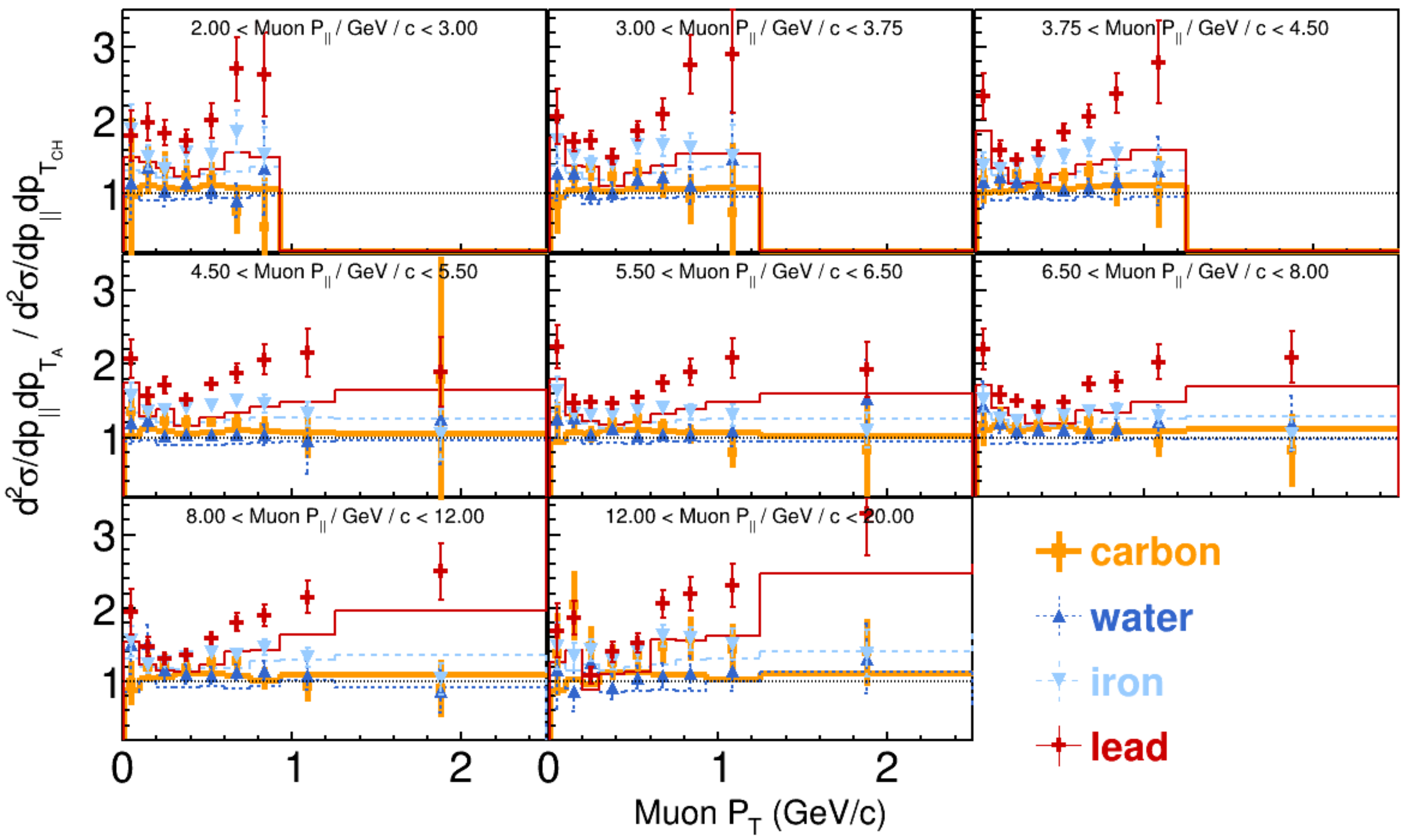
- These are results for one muon longitudinal momentum bin (sort of like one energy bin but less model-dependent)
- See discrepancy that seems to grow with A

*Kleykamp et al, Phys. Rev. Lett. **130**, 161801*



ν_μ Quasielastic-like scattering versus A

- Evidence from Pb that the data needs more contribution from pion production followed by absorption.
- MINERvA model also **overpredicts** the number that remain as pions in the Pb…see a pattern!
- Gives model builders more input to change models of how pions get absorbed



Kleykamp et al, Phys. Rev. Lett. ***130****, 161801*

NEW: Neutrino Quasielastic-Like Scattering vs A, but add a proton

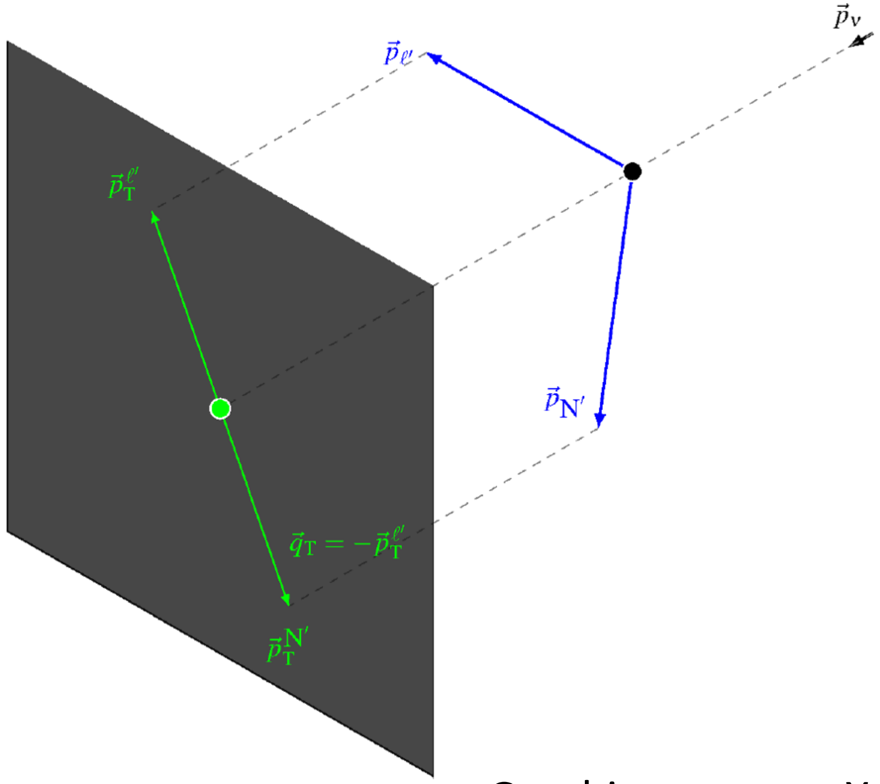
$$\nu_\mu + A \rightarrow \mu^- + p + A'$$

J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

Why add a proton? Transverse Kinematic Imbalance (TKI)

- Consider the transverse kinematic imbalance of the leading proton and the lepton in events with a single proton and no mesons
- Predictions are simple for free nucleons at rest!
- Differences can be due to:
  - Multi-nucleon correlations
  - Pion absorption
  - Fermi motion
  - Binding energy

$$\nu_\mu + n \rightarrow \mu^- + p$$

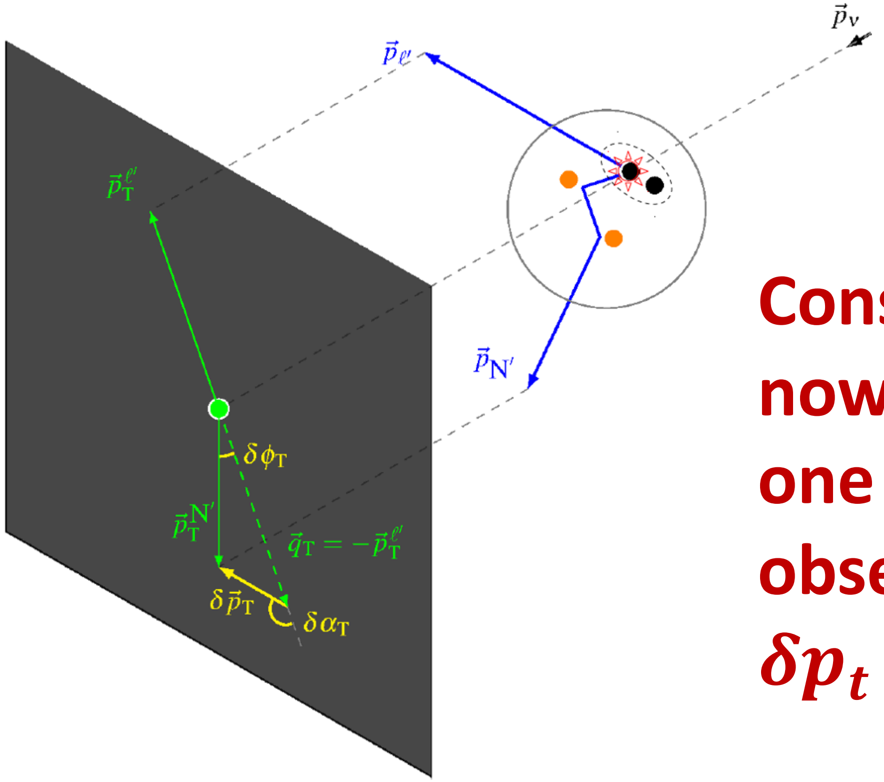


Graphics courtesy X.-G. Lu, ν2022

Why add a proton? Transverse Kinematic Imbalance (TKI)

- Consider the transverse kinematic imbalance of the leading proton and the lepton in events with a single proton and no mesons
- Predictions are simple for free nucleons at rest!
- Differences can be due to:
  - Multi-nucleon correlations
  - Pion absorption
  - Fermi motion
  - Binding energy

$$\nu_\mu + n \rightarrow \mu^- + p$$

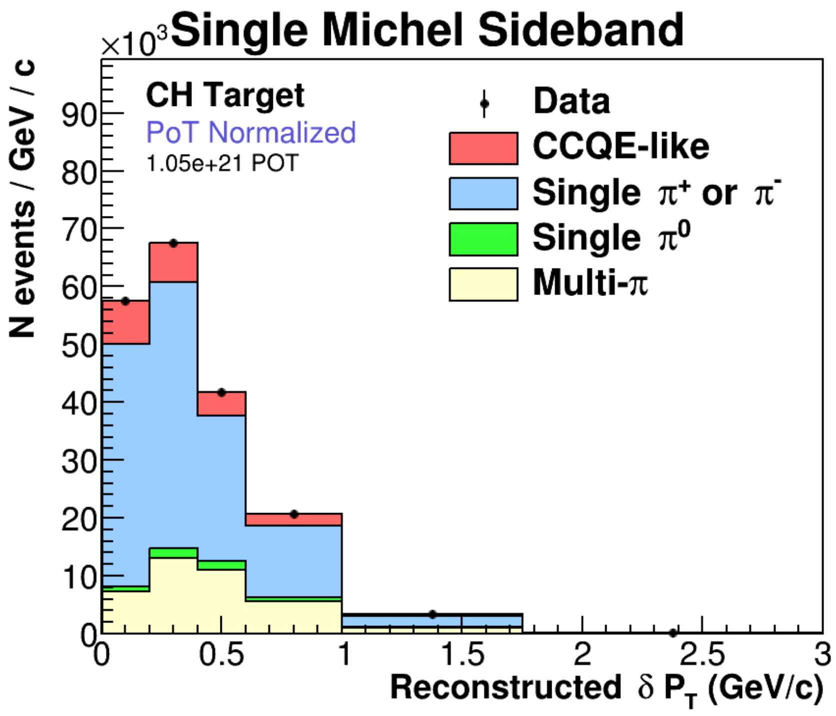


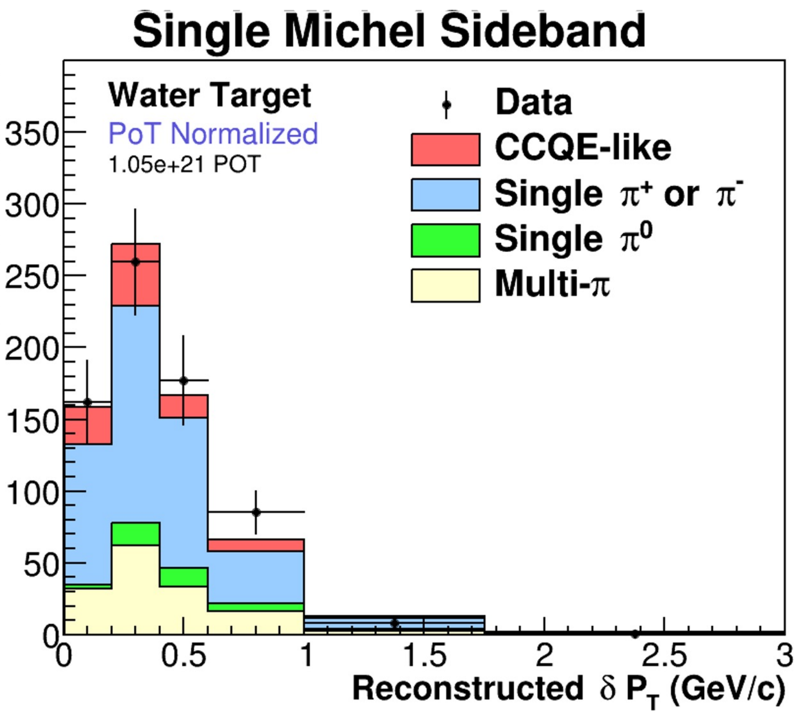
Consider for now one new observable: δp_t

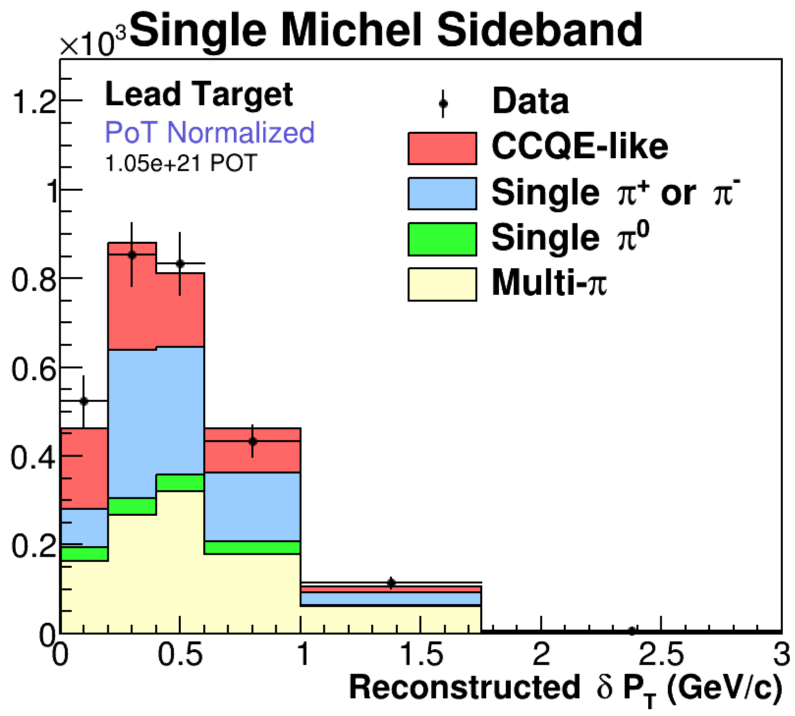
Graphics courtesy X.-G. Lu, ν2022

Predicting the right background

- Similar to analysis vs p_t,
- Now with a sample that also has a proton identified, and vs δp_t



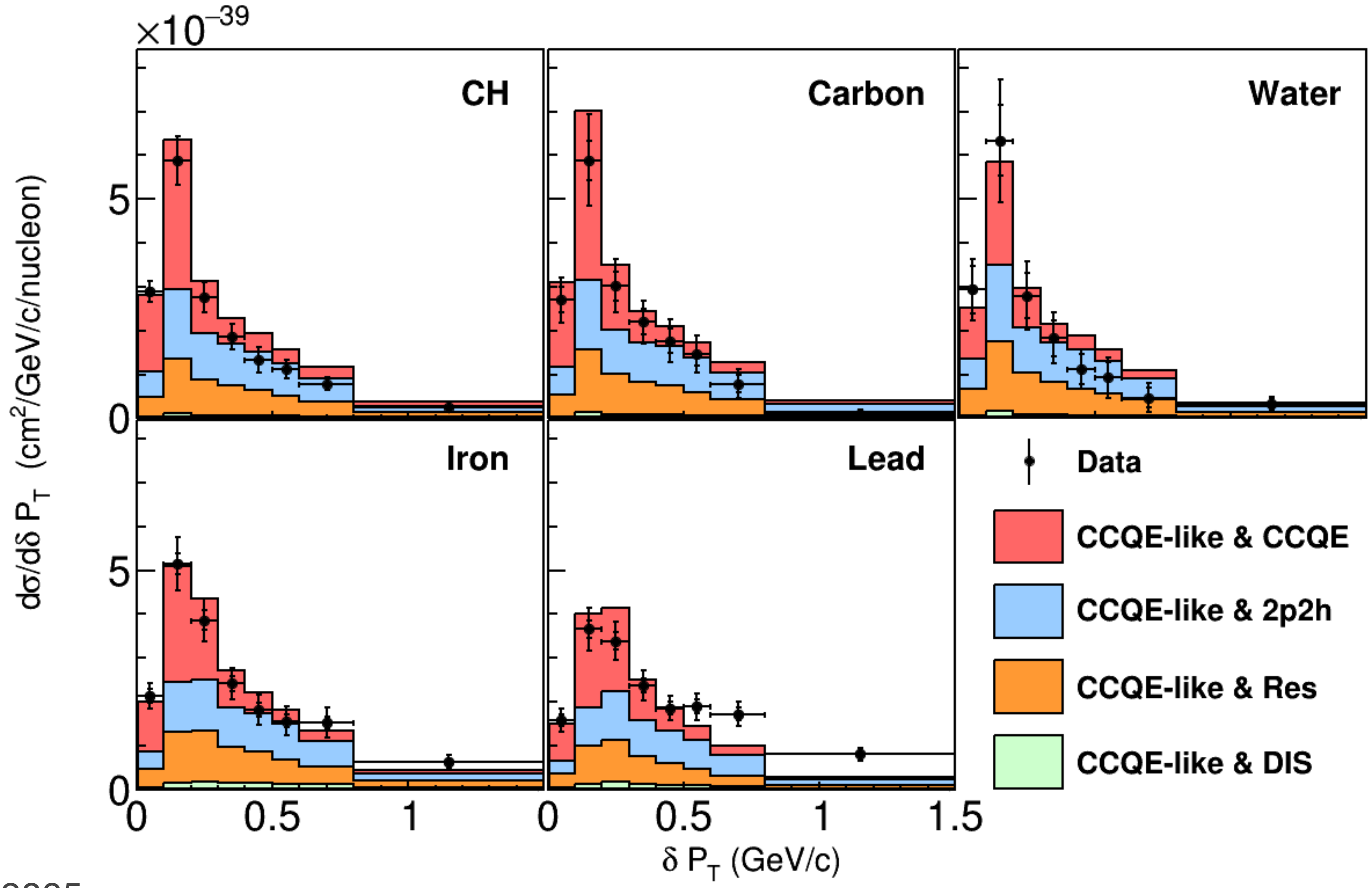




J. Kleykamp et al, arxiv.org:2503.15047

Cross Section Results vs δp_T

- Cross section scaled per nucleon
- Good agreement in bin where QE rate is largest fraction
- Successively worse agreement
  - At high δp_T
  - At high atomic number



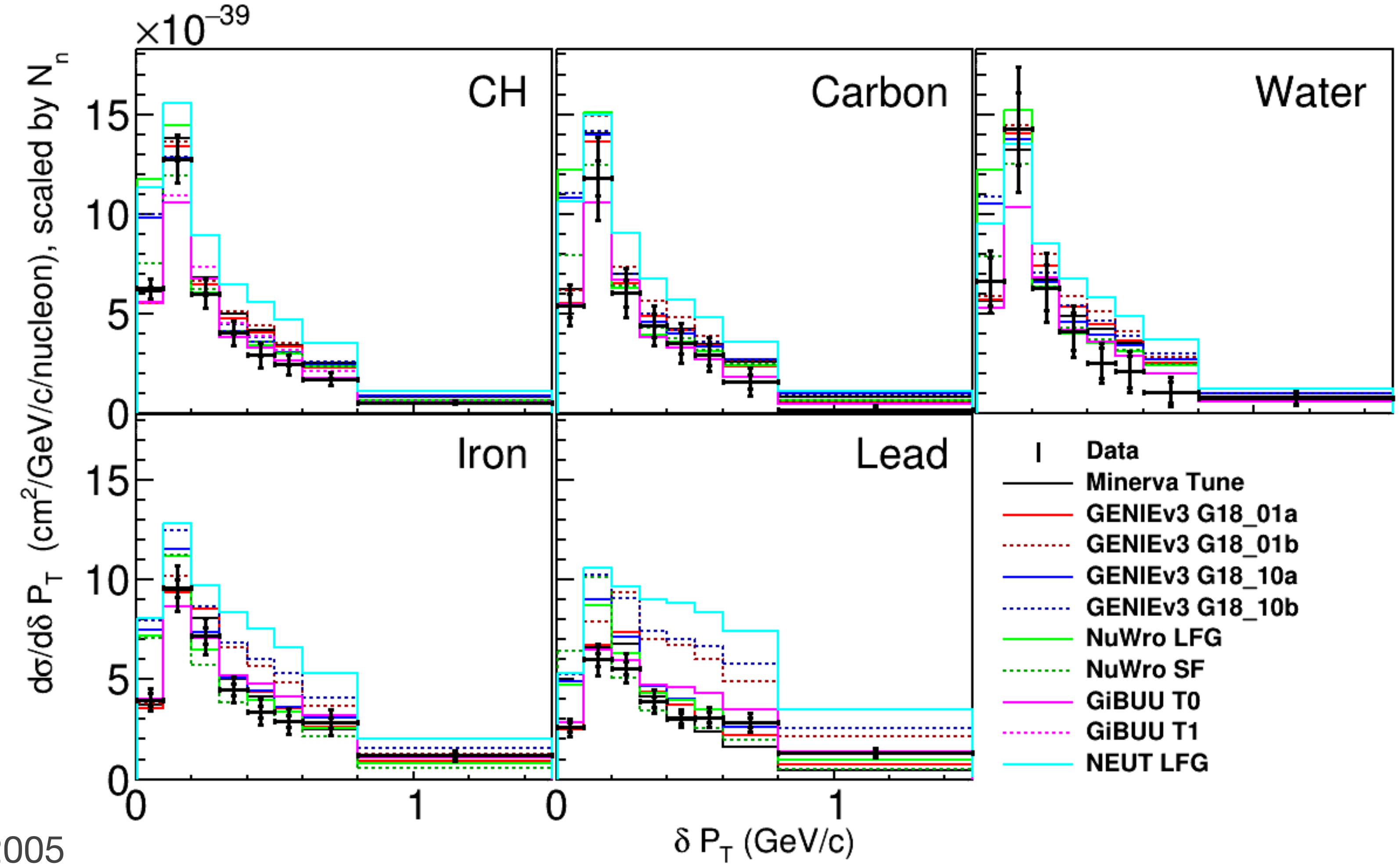
J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

What about other models?

- There are several different models, implemented in several different neutrino event generators: last week at NuINT , L. Munteanu likened them to different breeds of dogs…
- GENIE: Used by NOvA, MINERvA, Liquid Argon community
- NEUT: used by Kamiokande, T2K, HK
- NuWro: Mainly developed by theorists, newest model implementations
- GIBUU: Mainly developed by in heavy ion collision community, consistent theoretical framework for physics processes

Cross Sections vs δp_T vs Generator

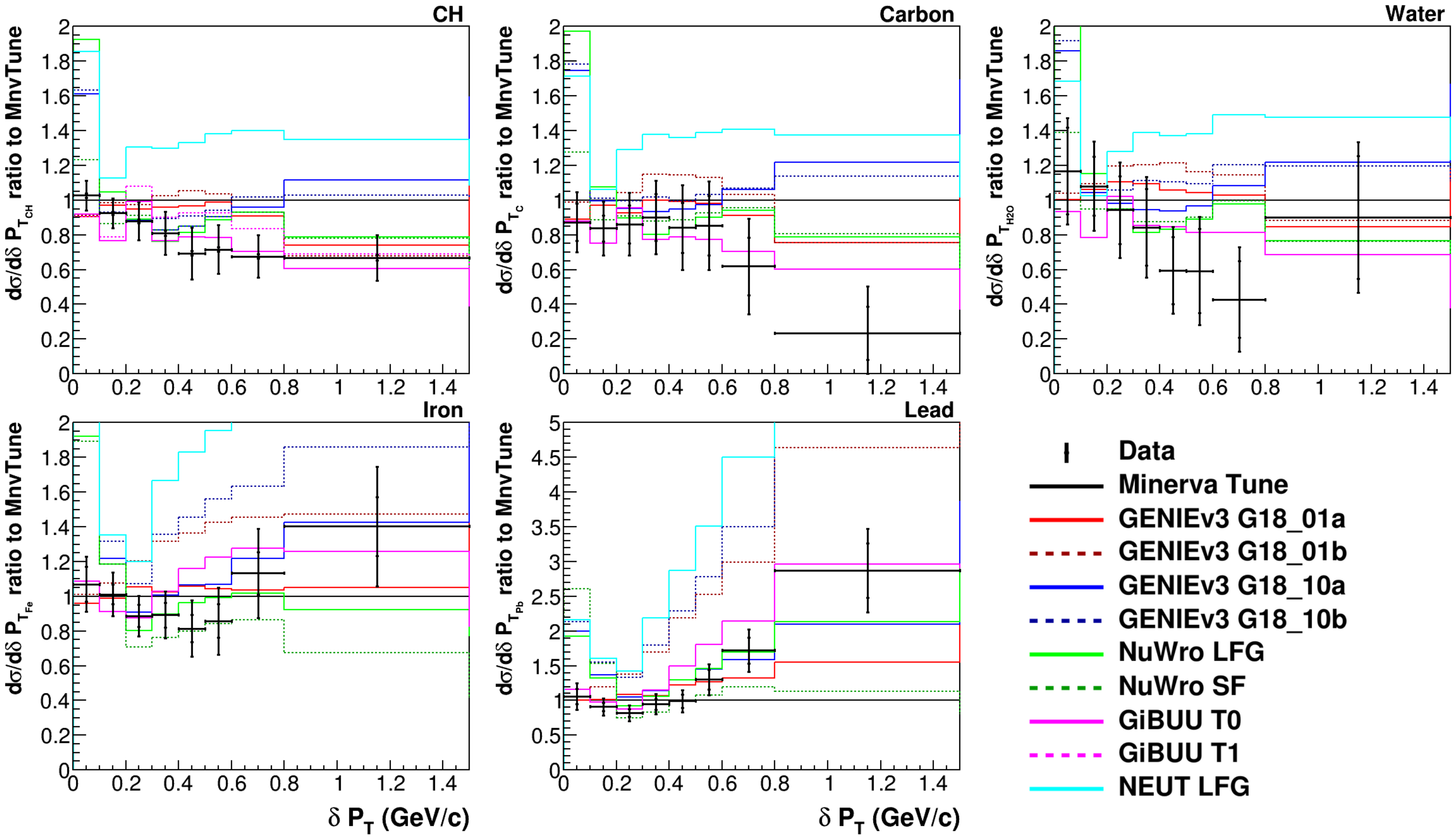
- Broad range of predictions at high δp_T for Fe, Pb
- Four GENIE3 Tunes, using empirical 2p2h model
  - Initial state nucleon: Relativistic Fermi Gas (01) or Valencia Local Fermi Gas w/RPA (10)
  - FSI: hA (a) or hN (b)
- Two NuWro Predictions, changing initial nucleon distribution
- Two GIBUU Prediction, one doubles 2p2h contribution
- NEUT (FSI model as if all non-H nuclei are isoscalar)



J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

Cross Sections vs δp_T : Ratio to Tune

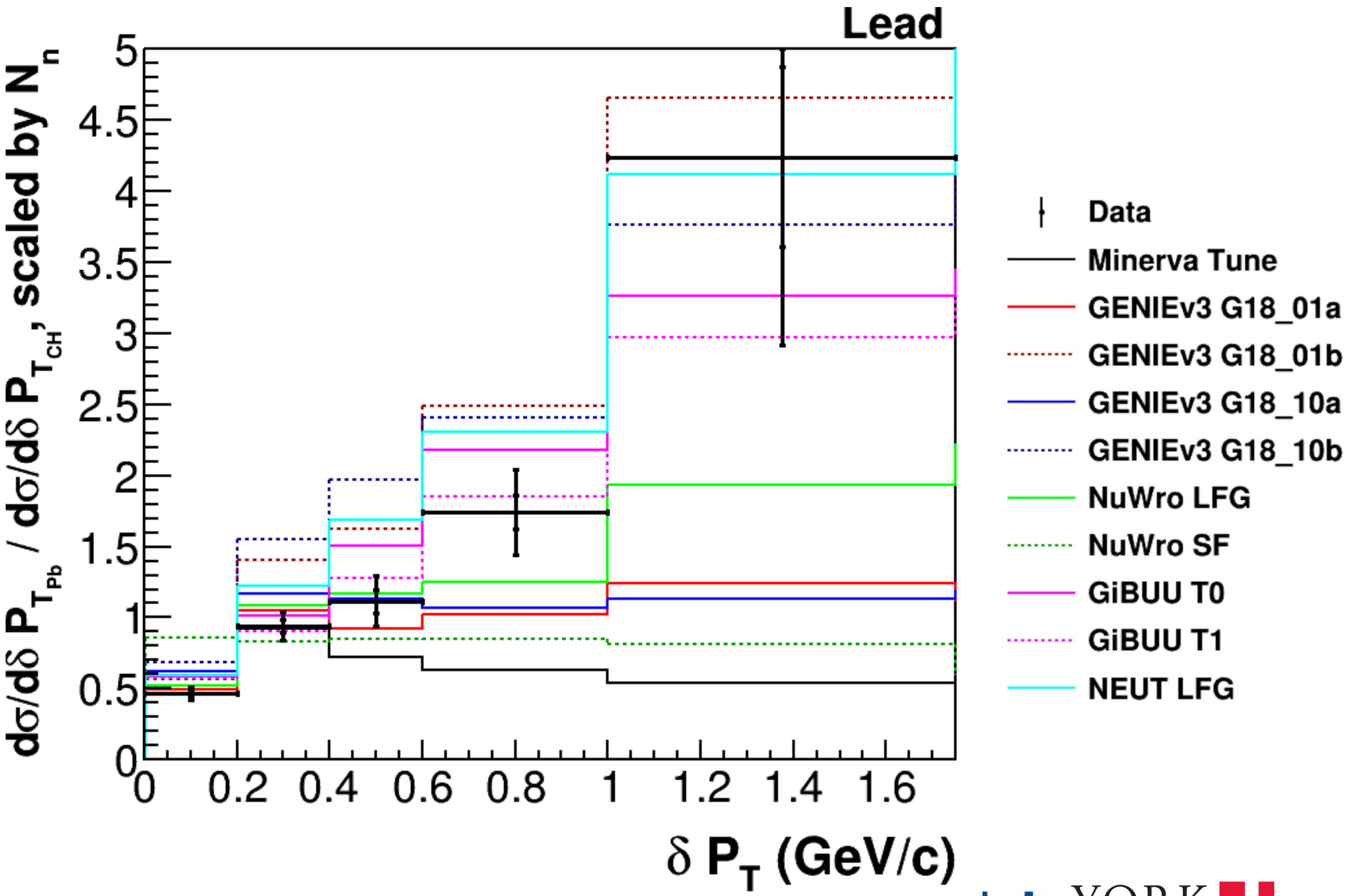
- Variations with models at high δp_T
- Changes to FSI Model matter more at high δp_T, and are bigger effect than any change to other effects
- 2p2h changes intermediate δp_T



J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

Cross Section Ratio Comparisons

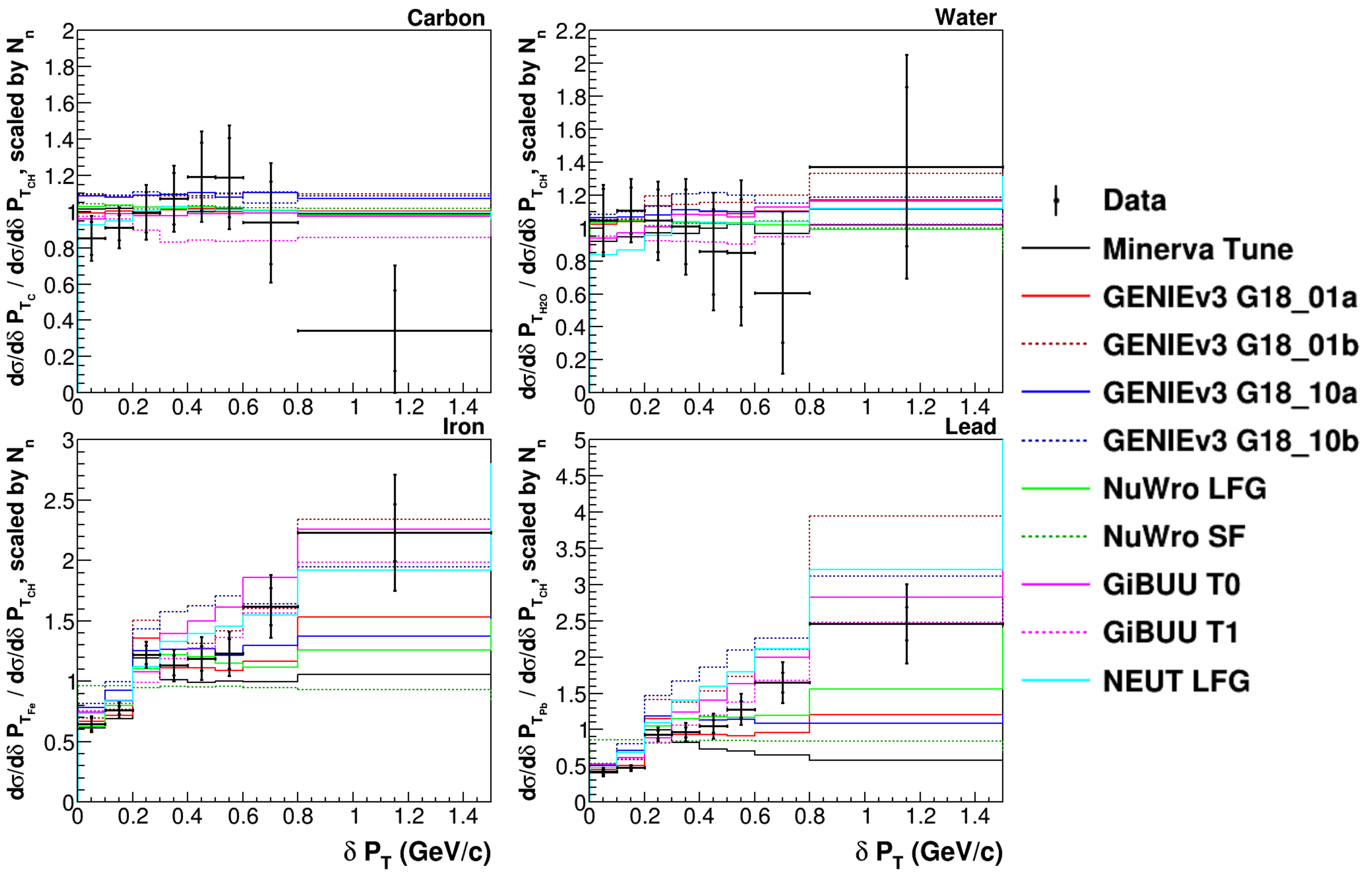
- See much better agreement in ratios at low δp_T
- Agreement diverges at high δp_T
- FSI hN treatment agrees much better in ratios than hA
- 2p2h enhancement okay for Fe, too much for Pb



J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

Cross Section Ratio Comparisons

- See much better agreement in ratios at low δp_T
- Agreement diverges at high δp_T
- FSI hN treatment agrees much better in ratios than hA at high δp_T and high A
- 2p2h enhancement okay for Fe, too much for Pb



J. Kleykamp et al, Phys.Rev.D 112 (2025) 5, 052005

Conclusions

- Understanding Nuclear Effects in Neutrino and Antineutrino Interactions are key to the next generation of Oscillation Experiments
- New results on quasielastic scattering versus A help pinpoint where models need most improvement: final state interactions inside the nucleus!
- Similar conclusions when we look at antineutrinos, and events where pions are also produced in charged current interactions (in backup)
- Just released a data preservation product so the community can continue to mine this data set for years to come!

  See https://minerva.fnal.gov/opendata

Thank you!


The End?
Tom O.
Tim GRIFFIN
Jeremy GRIFFIN
ANDREW LATHROP
JohnVoirin
MARK SHOUN
Jesse Chvojka
CHRIS Richardson
STEVE RUZZANO
Jeanie Wolfe
Kevin McFarland
David Martinez
MINERVA Sees