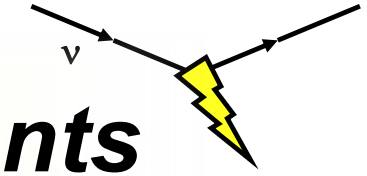
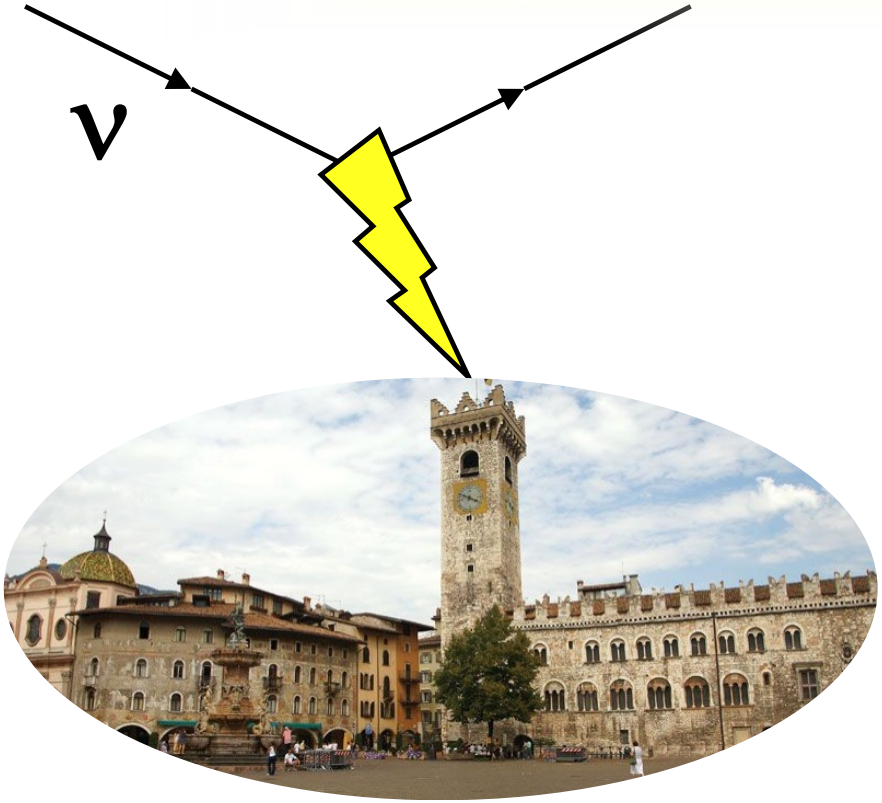


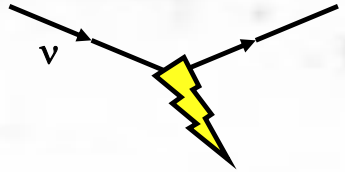
Neutrino Interaction Measurements with Hydrocarbon-Based Detectors



Kevin McFarland
University of Rochester

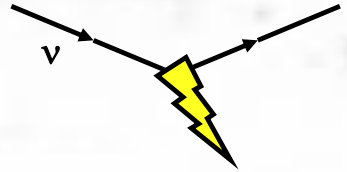
FBK ECT*, Trento
21 October 2024

"Help from CH-land"?



- I love amusing and broad titles as much as anyone.
- This one is particularly so.

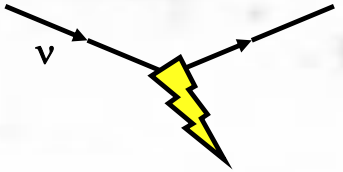
"Help from CH-land"?



- I love amusing and broad titles as much as anyone.
- This one is particularly so.
  - Is the Swiss army invading?

Jeremy regrets joining The Swiss Army.

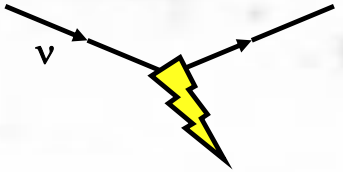
"Help from CH-land"?



- I love amusing and broad titles as much as anyone.
- This one is particularly so.
  - Is the Swiss army invading?
  - Did I take a wrong turn over the Atlantic and end up in CHicagoland?

(yes, foodie me is aware this is a fictional sign, but it reminds me so much of real Chicago…)

"Help from CH-land"?



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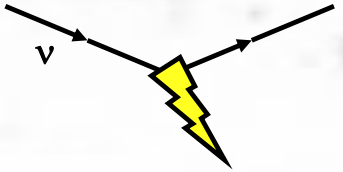
  - Is the chemical industry of the 1960s coming to save us?

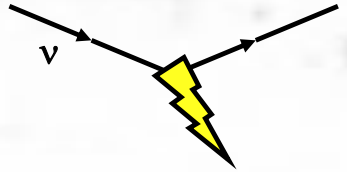
"Help from CH-land"?



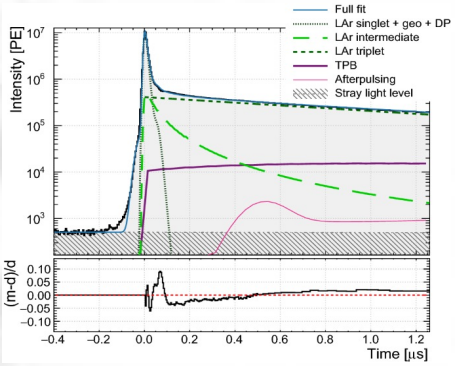
- I love amusing and broad titles as much as anyone.
- This one is particularly so.
  - Is the Swiss army invading?
  - Did I take a wrong turn over the Atlantic and end up in CHicagoland?
  - Is the chemical industry of the 1960s coming to save us?
  - Long-last Beatles album subtitle?

♫ *Help! We need some plastic. Help! Not just any plastic.* ♫♪

Thoughts about What The Title Might Mean



- Experiments arguably have bifurcated between two different detector technologies for neutrino interactions.
- Why liquid argon (not my remit)?
  - Though slow to read out (even for a large portion of the scintillation light!), liquid argon charge imaging resolution is better than a ton-scale scintillator detector.

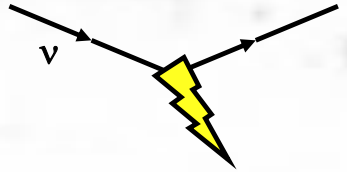


e.g., DEAP-360 light model, Eur. Phys. J. C 80, 303 (2020)

- It follows that there must be some other advantage(s) for plastic scintillator detectors since we keep building them.

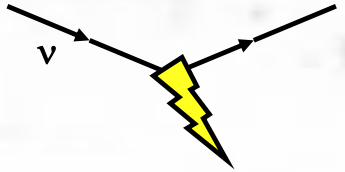
(I assume the organizers will now rush me off the stage if I have it wrong, but if not, you'll see the rest of my slides.)

Signature Advantages of CH-Scintillator

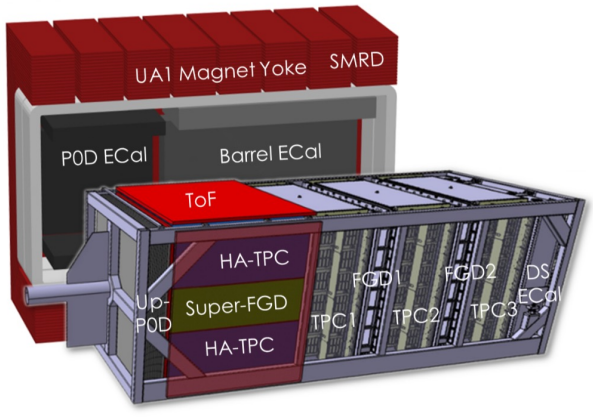


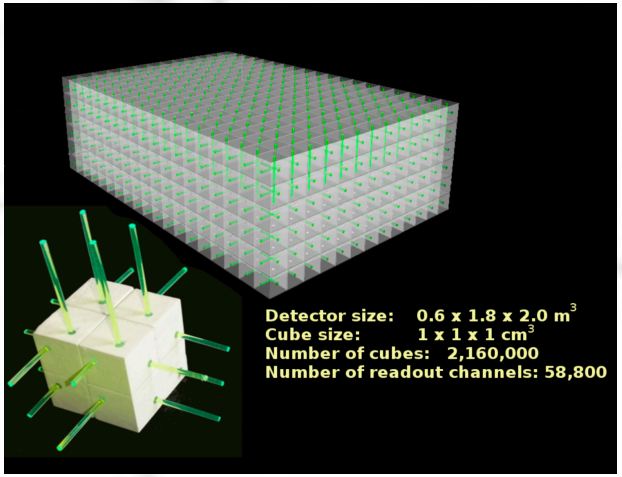
- Inherently low-background fast readout, which leads to…
  - High-rate capability.
  - Easy separation and correct association of sub-events with $\mathcal{O}$(ns) resolution for neutrons, stopped K^+, and of course stopped $\mu^\pm$
- Malleable and configurable (what's the word I'm looking for? oh, right, "plastic")
  - Easily segmented, up to channel count considerations.
  - Other materials can be incorporated to study how neutrino interactions compare on different nuclei.
  - Can be paired with other detectors (without cryogenic containment in the way) for purposes such as tracking in a magnetic field.

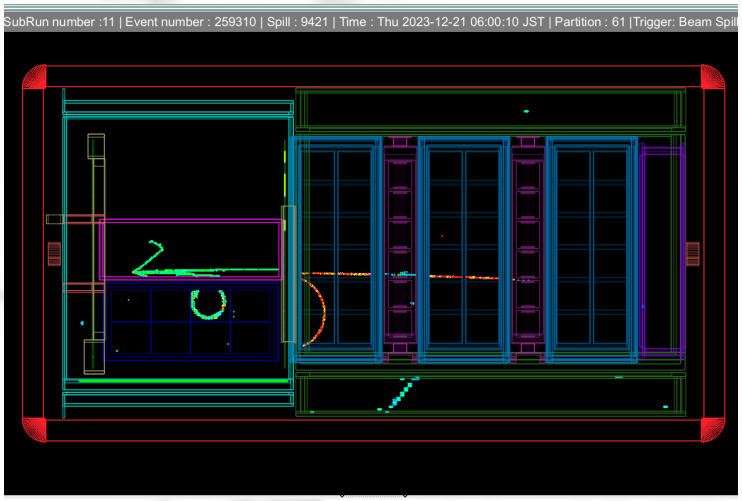
An Illustration of Both Principles



- T2K ND280 (upgraded) detector for T2K/HK configurable, fast CH scintillator.
- The SuperFGD 3D pixelated scintillator is interspersed with gaseous tracking in a magnetic field for charge ID and high resolution dE/dx PID.
- The SuperFGD also has excellent neutron capability, including time-of-flight momentum reconstruction (more later).

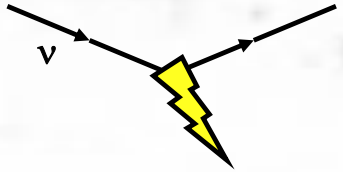


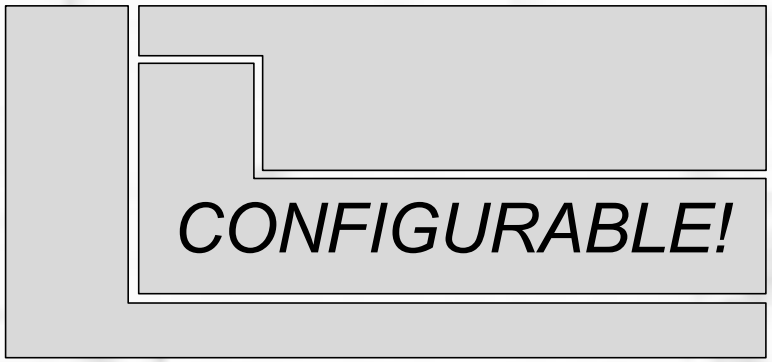


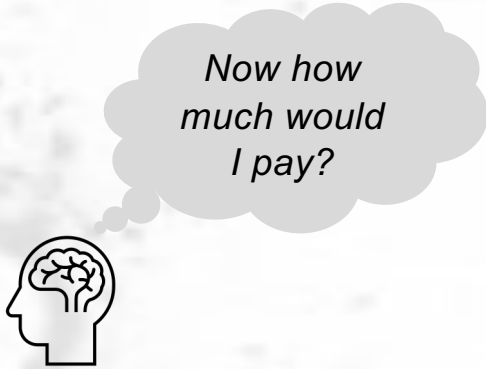


(Pictures assembled by C. Giganti.)

Topics for this CH review



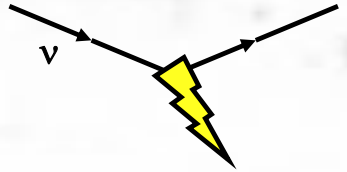




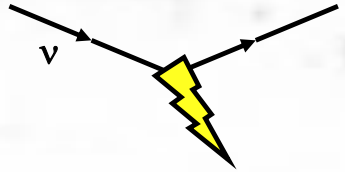
- Tagged π^+ reconstruction.
- Electron and muon neutrino comparisons.
- Multiply differential reaction measurements.
- Neutron reconstruction
- Comparisons among nuclei.
  - and free protons too!

Maybe the organizers also expected this, but most of my examples will be related to work I know best from MINERvA or T2K. Sorry if this unintentionally leaves your work out..

And why those matter for DUNE and HK



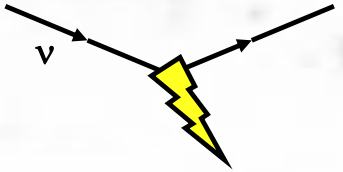
- Neutron reconstruction and tagged π^+ reconstruction…
  - Because oscillation experiment far detectors may not respond uniformly to all particles, leading to energy misestimation from the final state.
- Electron to muon neutrino comparisons…
  - Because both DUNE and HK will extrapolate their observed muon neutrino reactions to predict electron neutrinos.
- Massively differential measurements…
  - Because they test correlation of probe (lepton) and target (hadron) sides of the interaction, which is also important for energy reconstruction.
- Comparison of nuclei (and hydrogen too!)…
  - Because they help us build a more predictive nuclear model.



π^+ Tagging and Production Cross-Sections

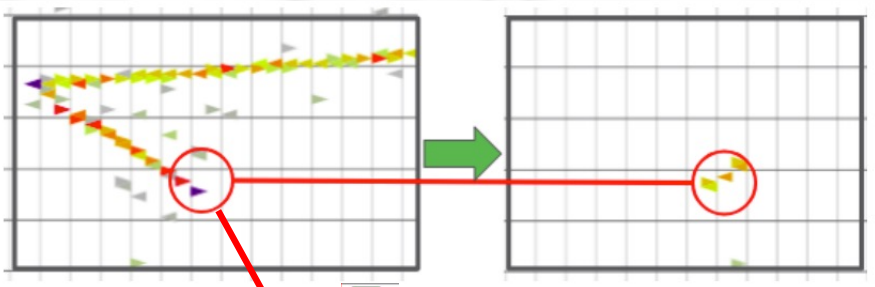
(important for calorimetry and event selection in oscillation experiments)

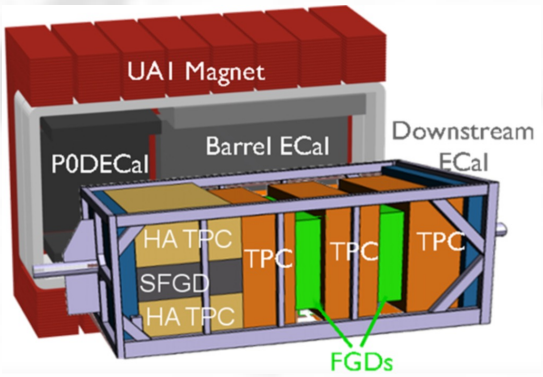
How do we identify π^+ in CH?

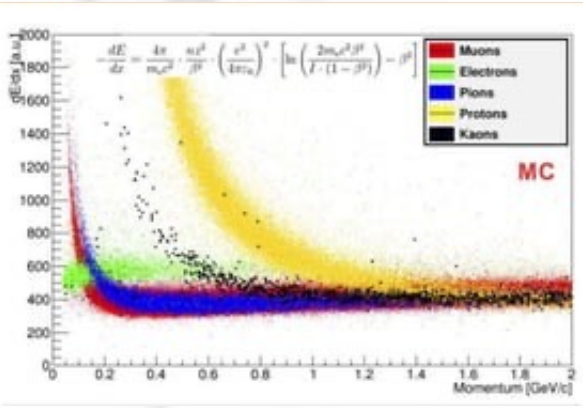


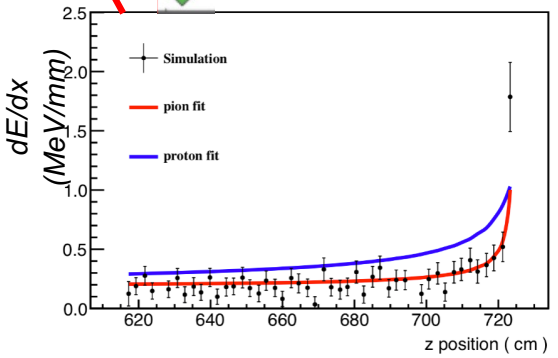
- Broadly speaking, we can identify the Michel electrons from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$, or from energy loss *dE/dx* along a track.
- T2K's *dE/dx* is particularly outstanding…gaseous TPC tracking!

MINERvA's techniques

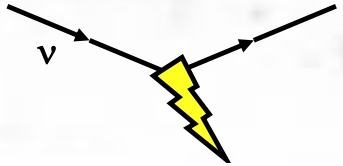




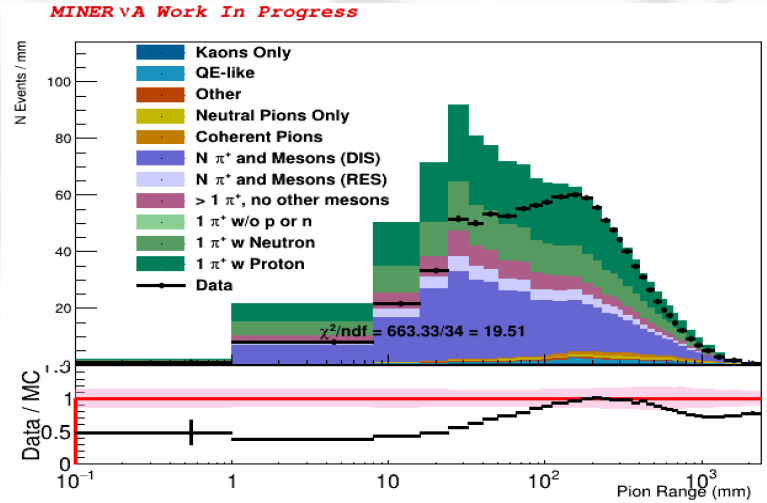




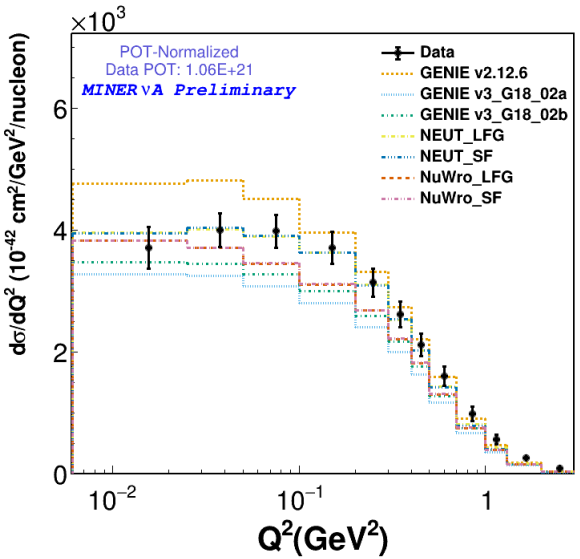
A few π^+ Results...



- Generator predictions don't do a fantastic job in giving a clear and accurate prediction for the T_π and Q^2 distributions for these events.
- Examples in progress from MINERvA…

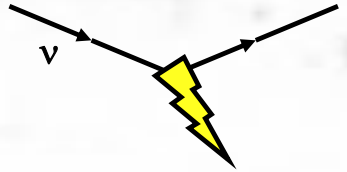


MINERvA Preliminary, Harris NuINT24



- At low Q^2, data is helpful for model selection, but see a wide variation.
- T_π below tracking threshold seems very poorly modeled.

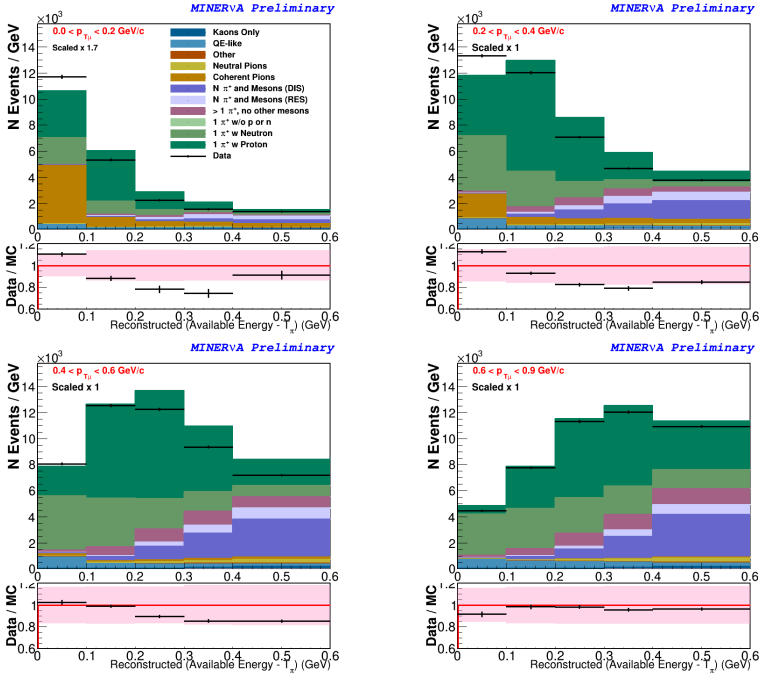
One last MINERvA π^+ result in progress…



- Look at visible energy associated with the π^+.
- Over prediction of this energy at low p_T?

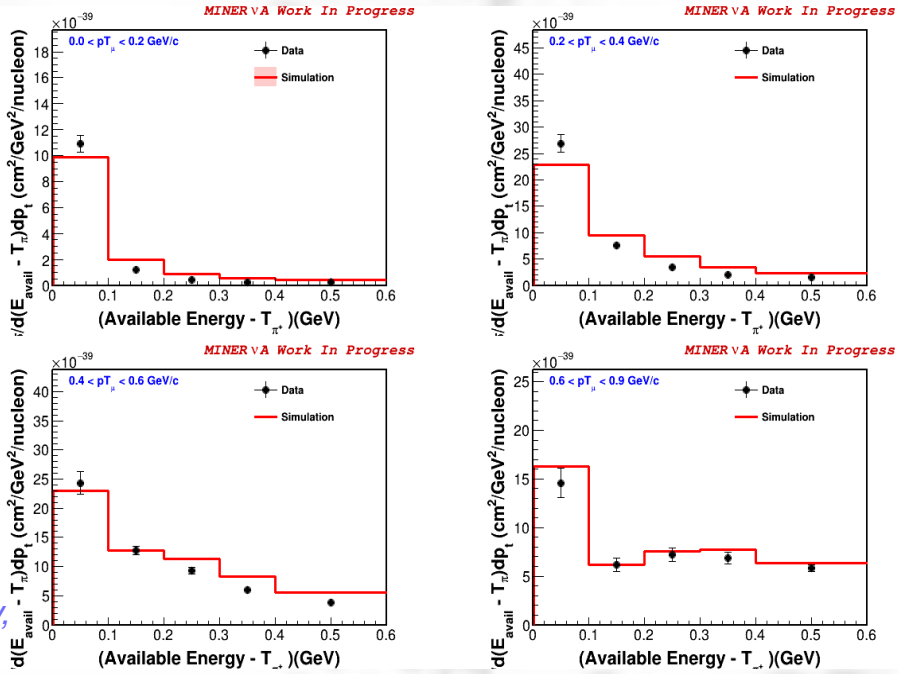
$$E_{avail} = \sum T_p + \sum T_{\pi^{+/-}} + \sum E_{particles}$$

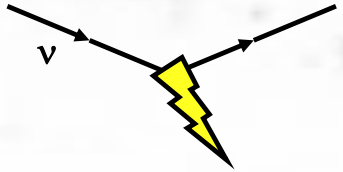
(Excluding neutrons)



events, to cross-section

MINERvA Preliminary, Harris NuINT24

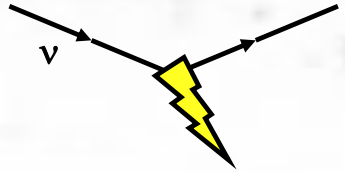




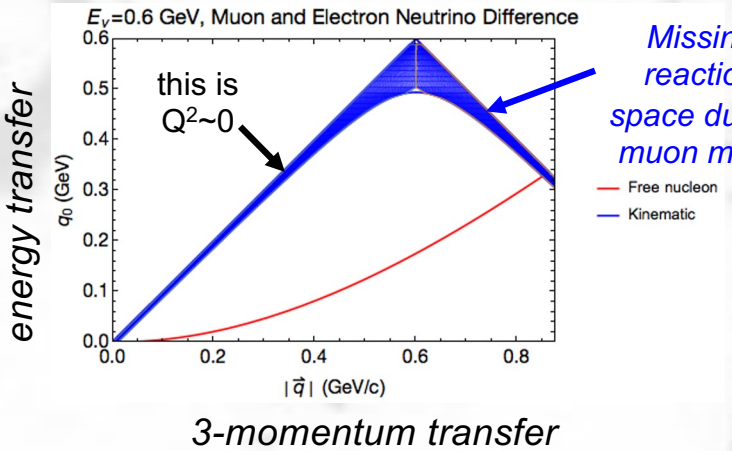
Electron and Muon Flavors

(in American English, it's not only irony
to note that there is no "u" in "flavor")

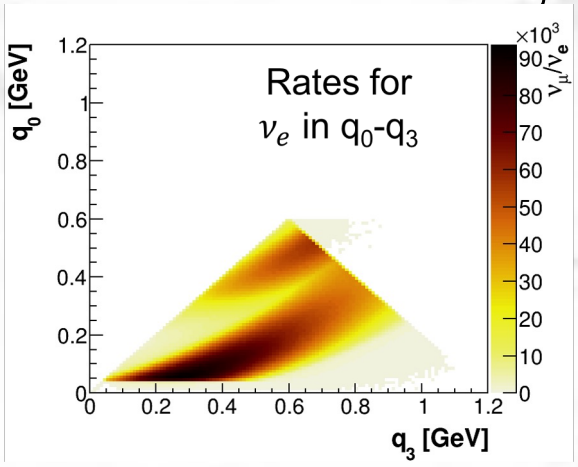
The ν_e Problem



- 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.



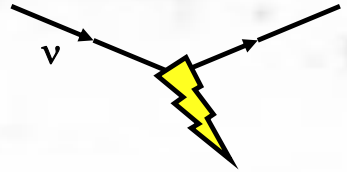
Missing reaction space due to muon mass

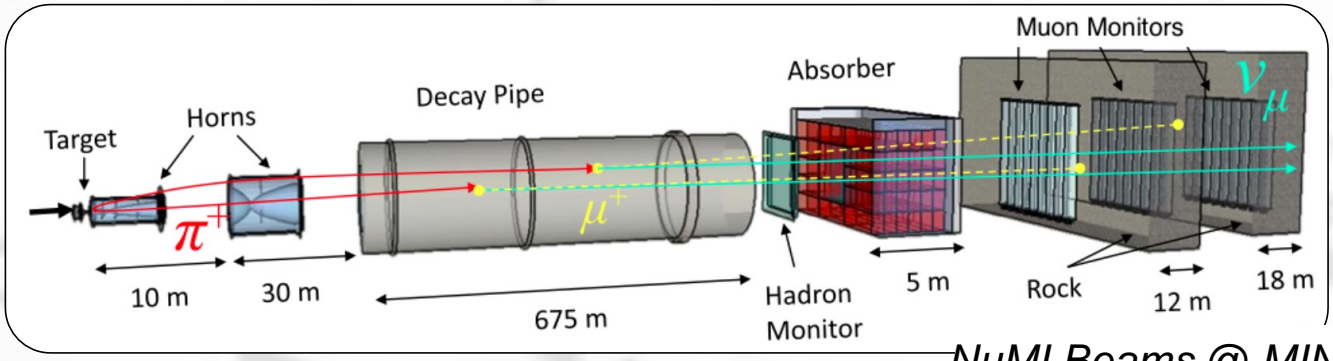


Radiative corrections:
O. Tomalak et al.,
Nature Commun. 13 (2022) 1, 5286
and Phys.Rev.D 106 (2022) 9, 093006

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

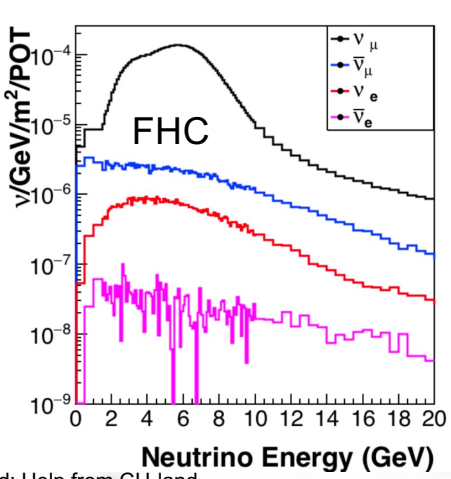
MINERvA: Electron Neutrino Flux

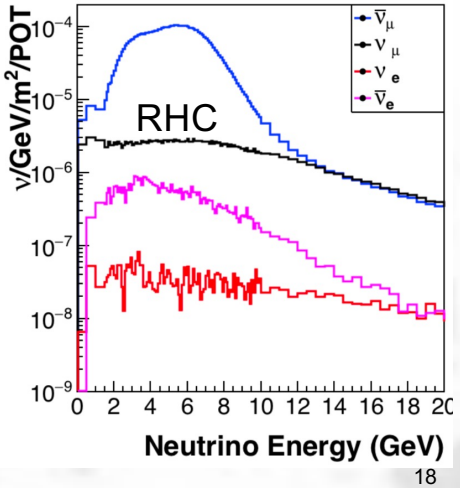




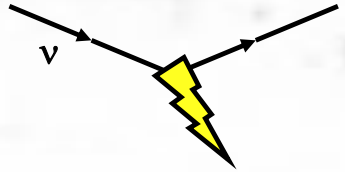
NuMI Beams @ MINERvA

- NuMI is a "conventional" neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons or kaons.
- ~1% contribution of the beam.

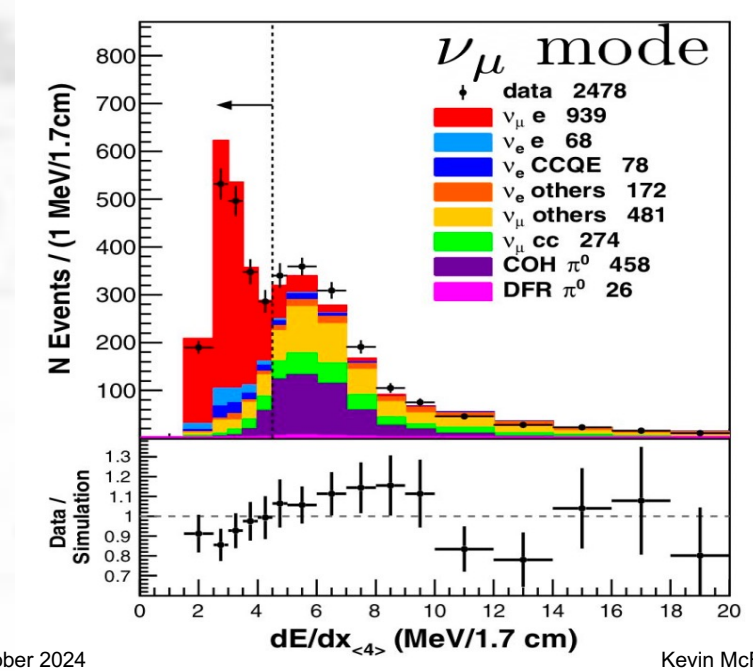


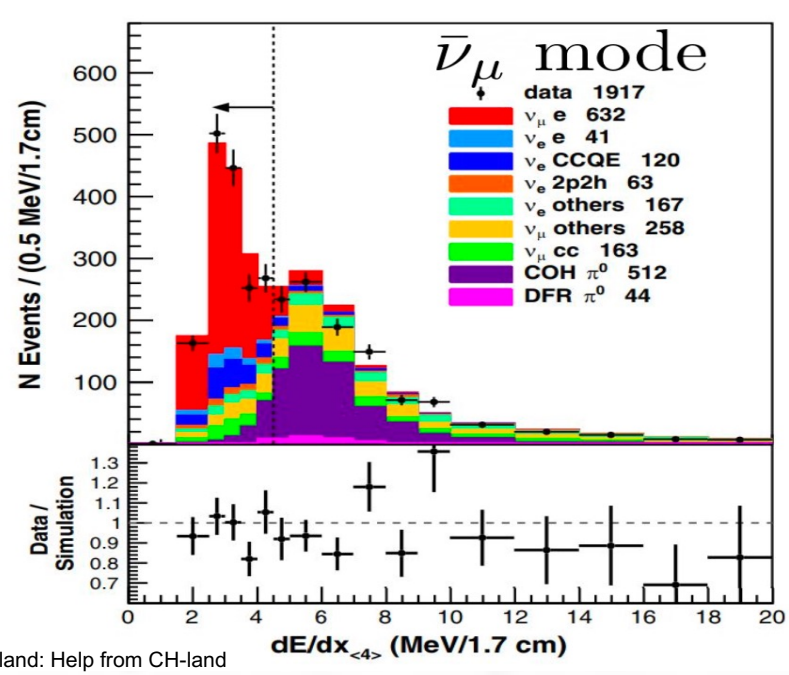


Electron/Photon Separation in $\nu e^- \rightarrow \nu e^-$



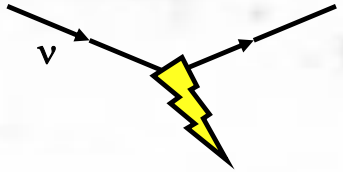
- Background from production neutral pions is manageable with *dE/dx* in scintillator, even with an electron energy threshold of 800 MeV.
- In Liquid argon TPCs, separation by *dE/dx* is surprisingly(?) similar.





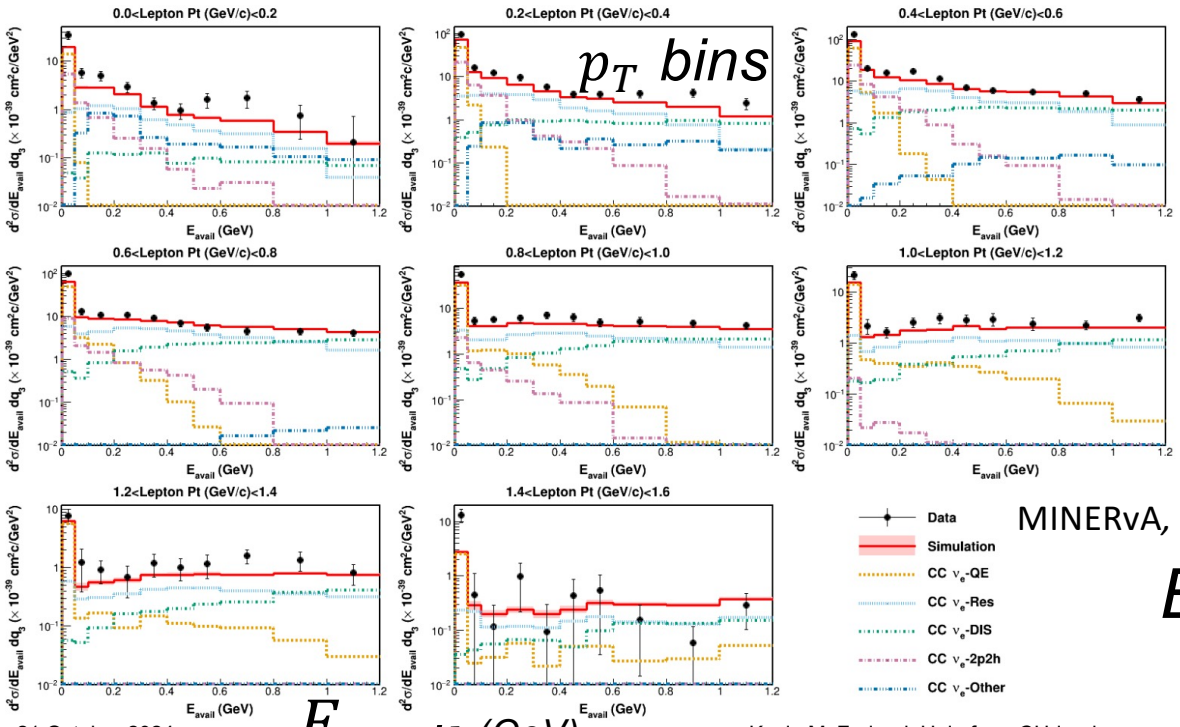
MINERvA, Phys.Rev.D 107 (2023) 1, 012001

Antineutrino Cross Section



- After background subtractions, unfolding flux and targets calculation…

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



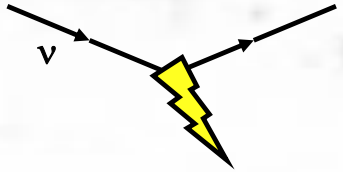
E_{avail} (GeV)

- 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).

MINERvA, *Phys.Rev.D* 109 (2024) 9, 092008

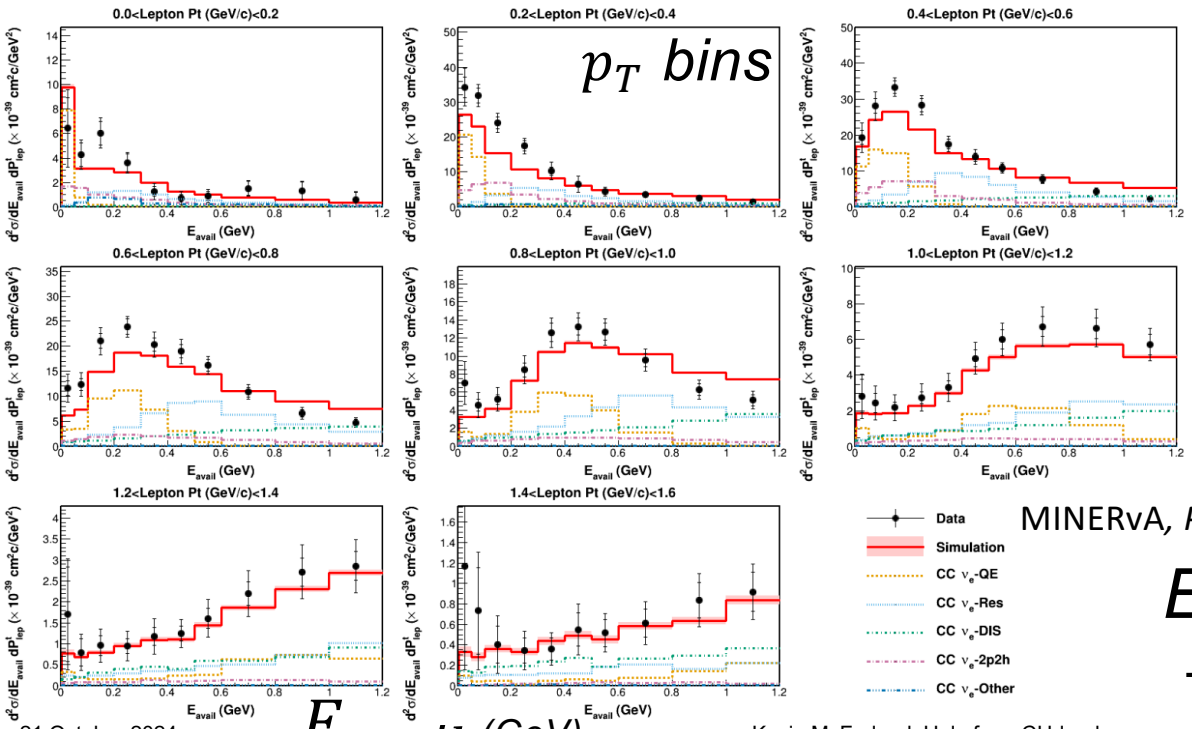
E_{avail} ≡ *(Proton and* $\pi^{\pm}$ *KE) + (E of other particles except neutrons)*

Neutrino Cross Section



- After background subtractions, unfolding flux and targets calculation…

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



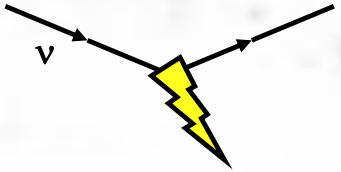
E_{avail} (GeV)

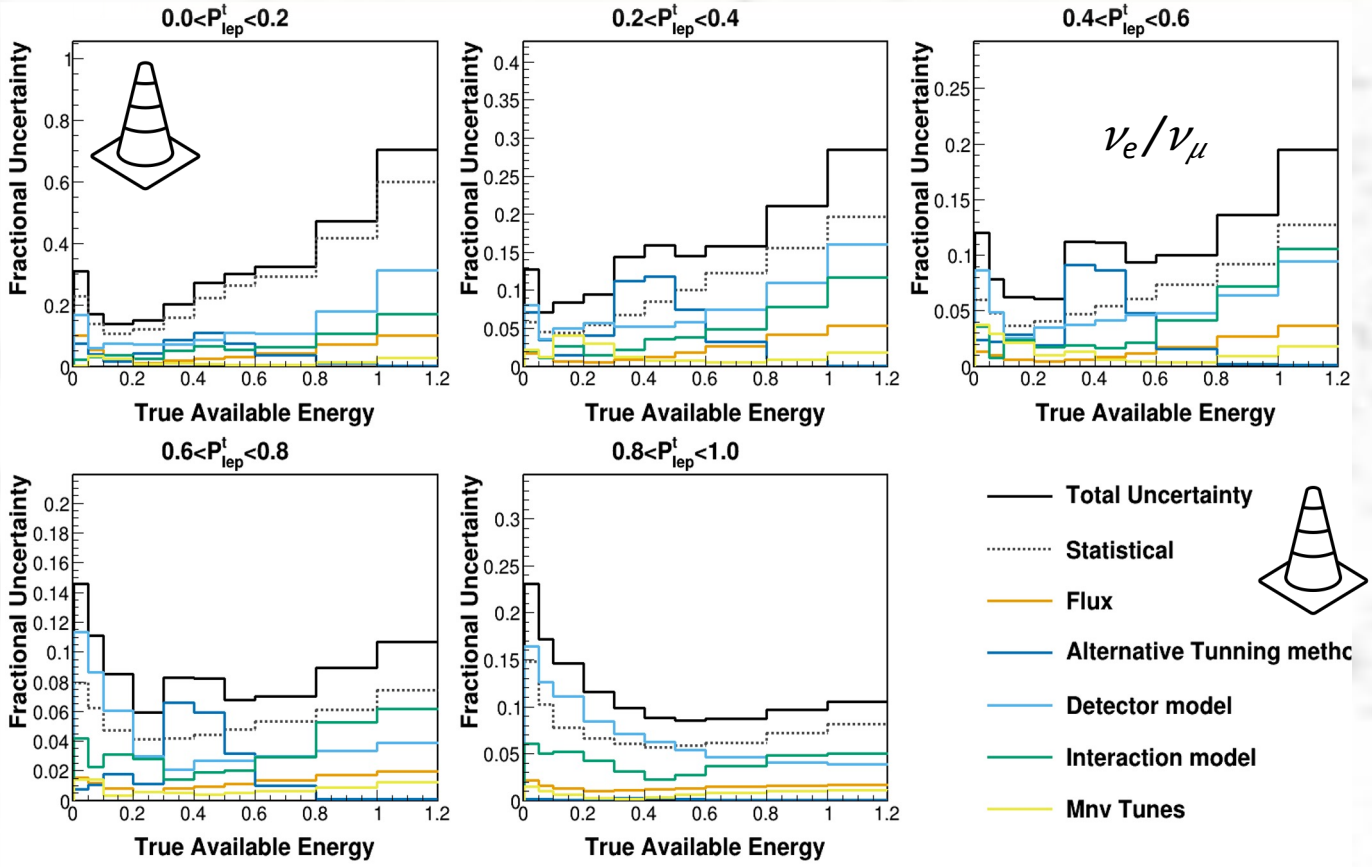
- Measured cross-section in electron p_T bins (0.2 GeV/c width, from 0 to 1.6 GeV/c) of available calorimetric energy, E_{avail}.
- Quasielastic peak shifts with p_T. As with antineutrino, inelastic is high E_{avail}.

MINERvA, *Phys.Rev.D* 109 (2024) 9, 092008

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

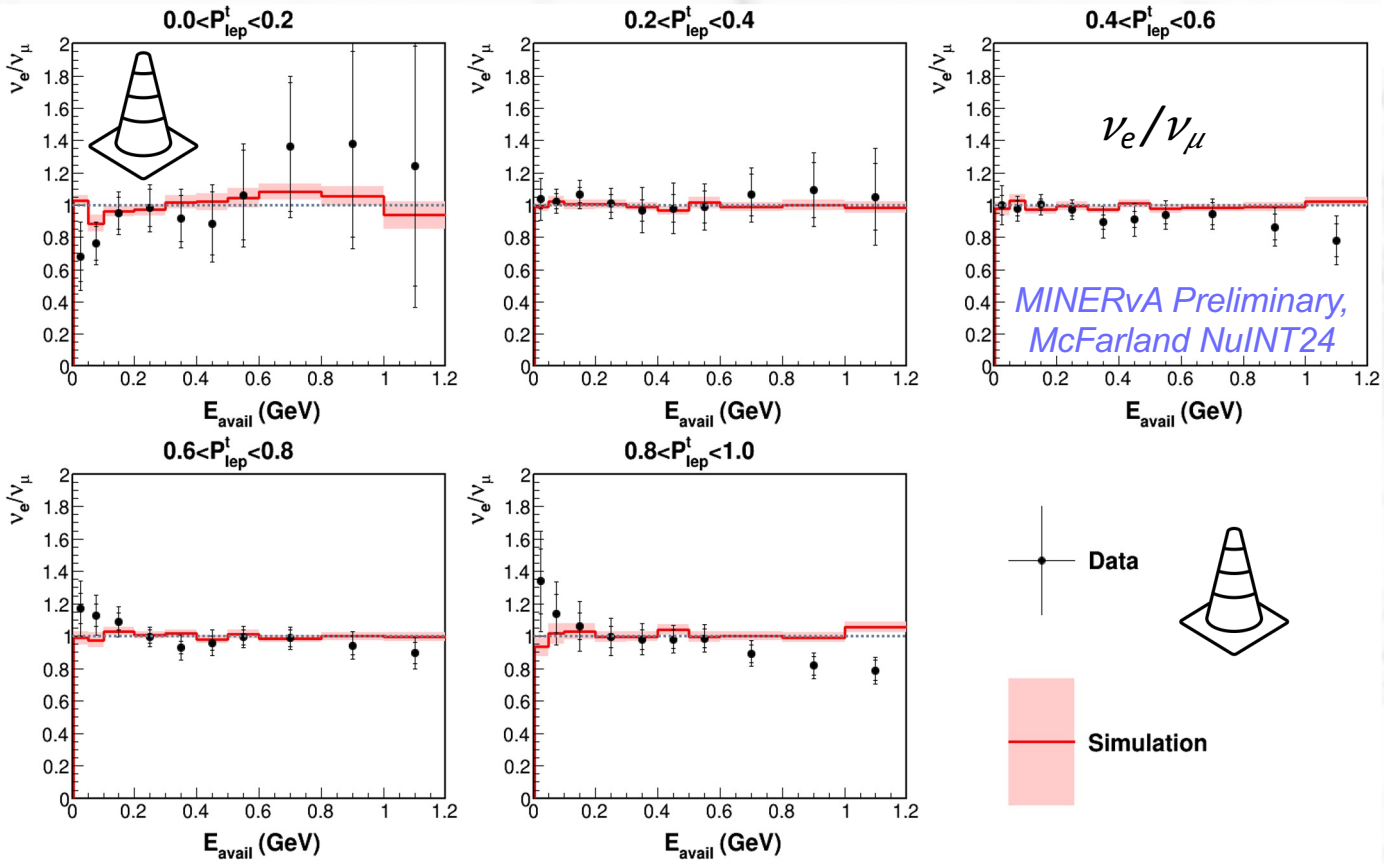
MINERvA: Uncertainties on ν_e/ν_μ

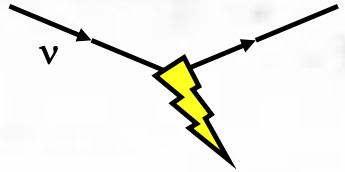




- These are preliminary, and so far only for neutrinos.
- Systematic uncertainties are ~subdominant, at least in any given bin.
- Detector model (muon energy scale) becomes significant. But flux and interaction models are small uncertainties.

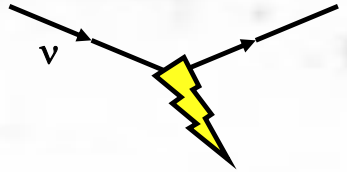
MINERvA ν_e/ν_μ Ratios



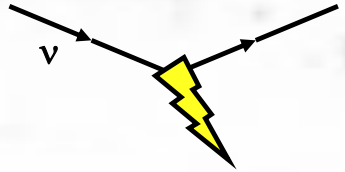


- Preliminary.
- Cross-sections in panels of p_T^ℓ as a function of "available energy", energy in calorimetrically visible particles, e.g., not neutrons.
- Simulation predicts a ratio very close to one dominated by statistical uncertainties.
- Testing the confidence of generators ☺.

Flavor (or color?) commentary



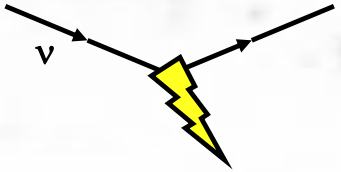
- I've given one (MINERvA) example, but T2K, MicroBooNE, and NOvA (in order of increasing statistics) are active early explorers.
- The MINERvA inclusive measurement has ~10% uncertainties in many bins across a wide range of recoil and transverse momenta, with systematic uncertainties ~few% in the high statistics bins.
  - We need to do better than that by factors of two or three in order to interpret oscillation experiments with experimental confirmation of flavor dependence of cross-sections.
- With very high statistics from future beams, supplemented by far off-axis samples (enriched in ν_e) from SBN (ICARUS) and MicroBooNE, we can make a go at this. Still very difficult.

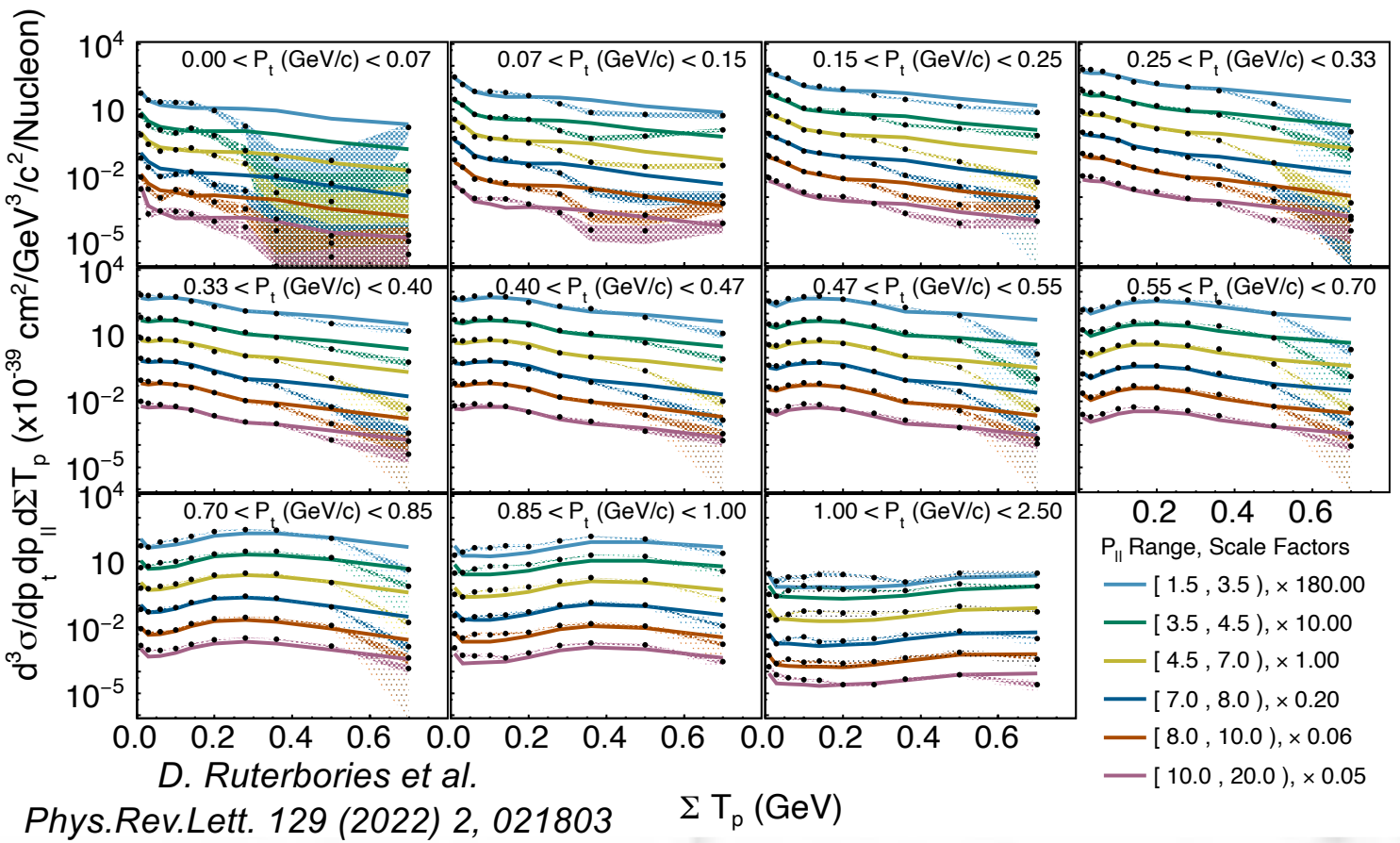


Multiply Differential Measurements

(if need to use both the lepton and recoil to learn about neutrino energy, don't we need to know how they are correlated?)

MINERvA "3D" CC0π ΣT_p, p_T, $p_\parallel$





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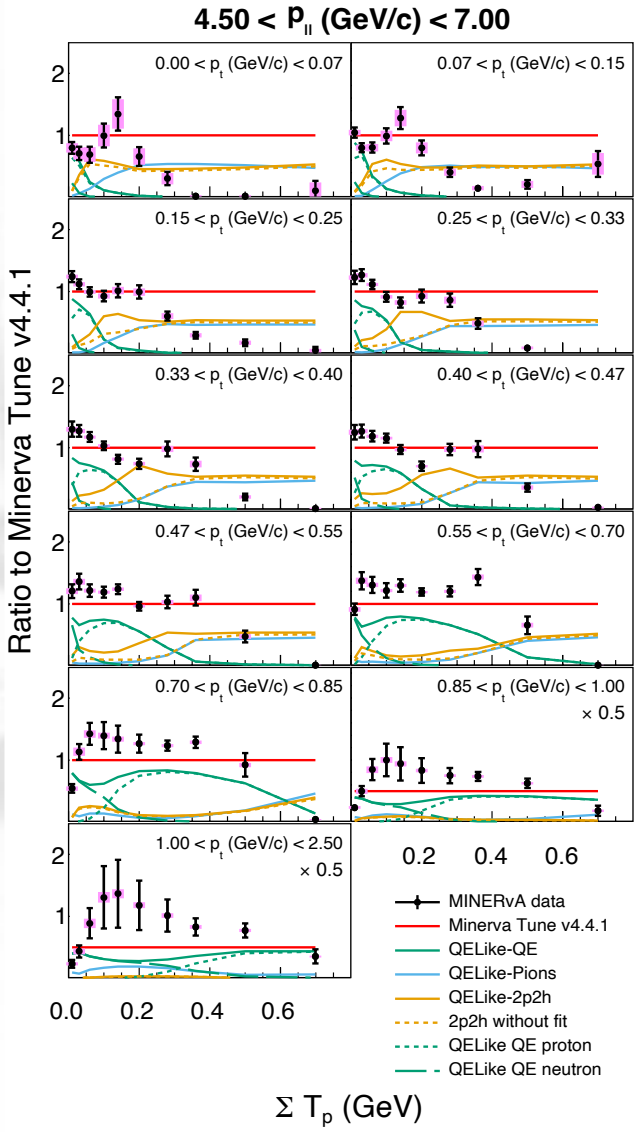
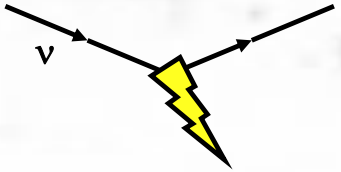
- *Transverse and longitudinal lepton momenta, and visible (proton) energy.*
- *The trends we see are independent of $p_\parallel$, suggesting they are not strongly energy dependent.*
- *Easier see in a single bin of $p_\parallel$*





Results: CC0π ΣT_p, p_T, $p_\parallel$

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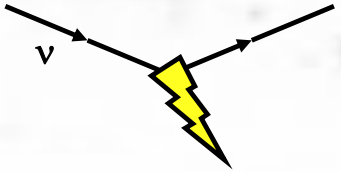
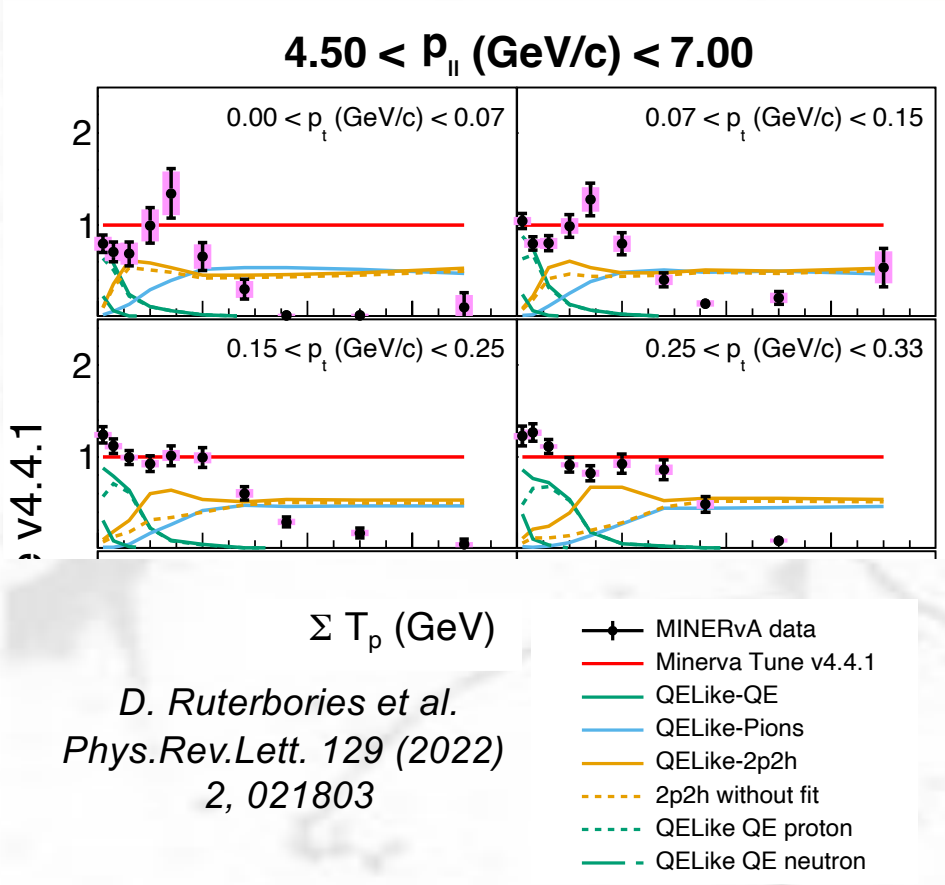
- The biggest change in cross-section, though not in the ratio, are the small deviations just above the QE peak. Maybe MINERvA's tune was affected by non- CC0π events? Or…?
- Low p_T high ΣT_p events predicted by the model as 2p2h and stopped pions are almost completely absent in the data.
- Highest 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.

Results: CC0π ΣT_p, p_T, $p_\parallel$





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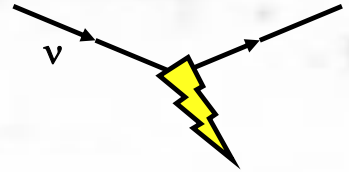

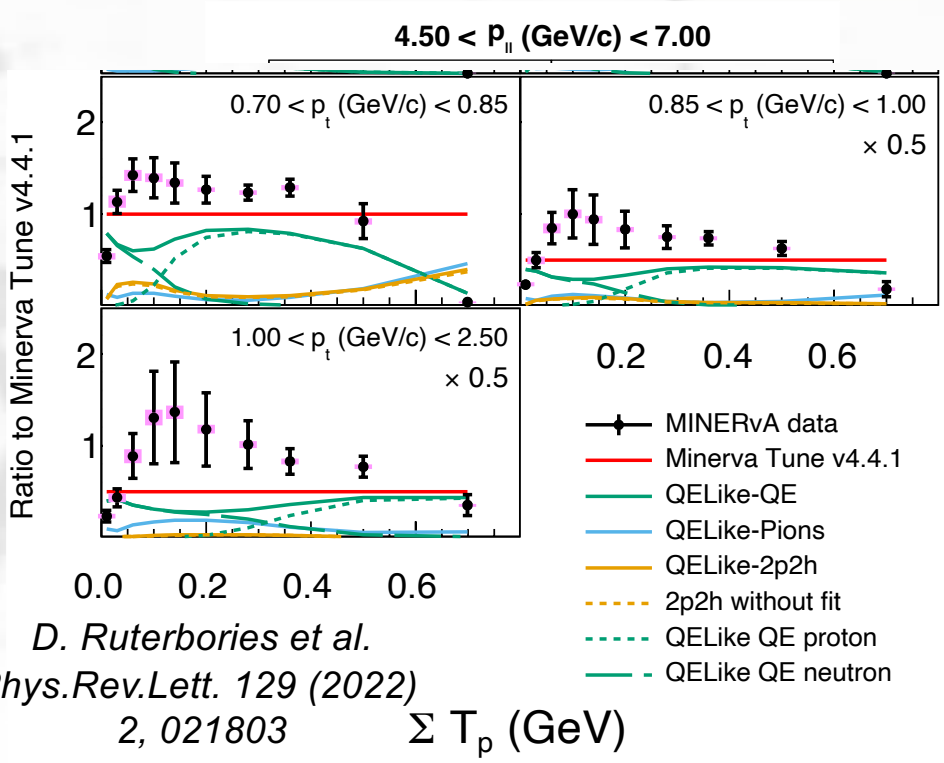

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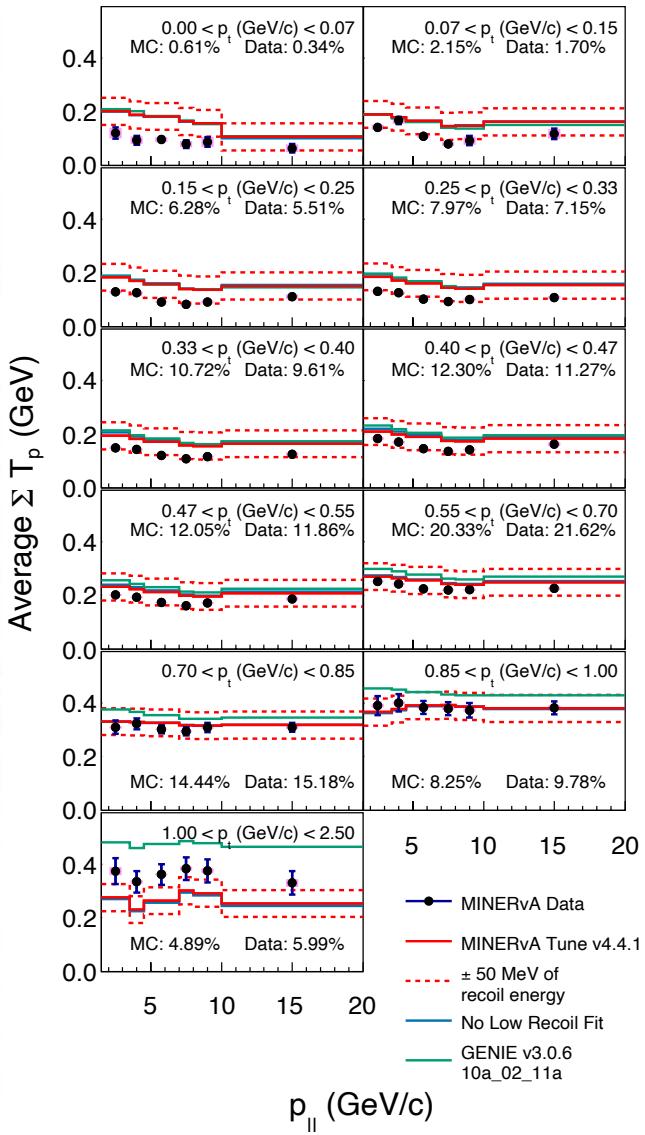
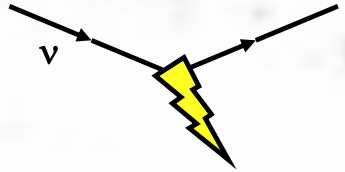


Another visualization of CC0π ΣT_p, p_T, $p_\parallel$



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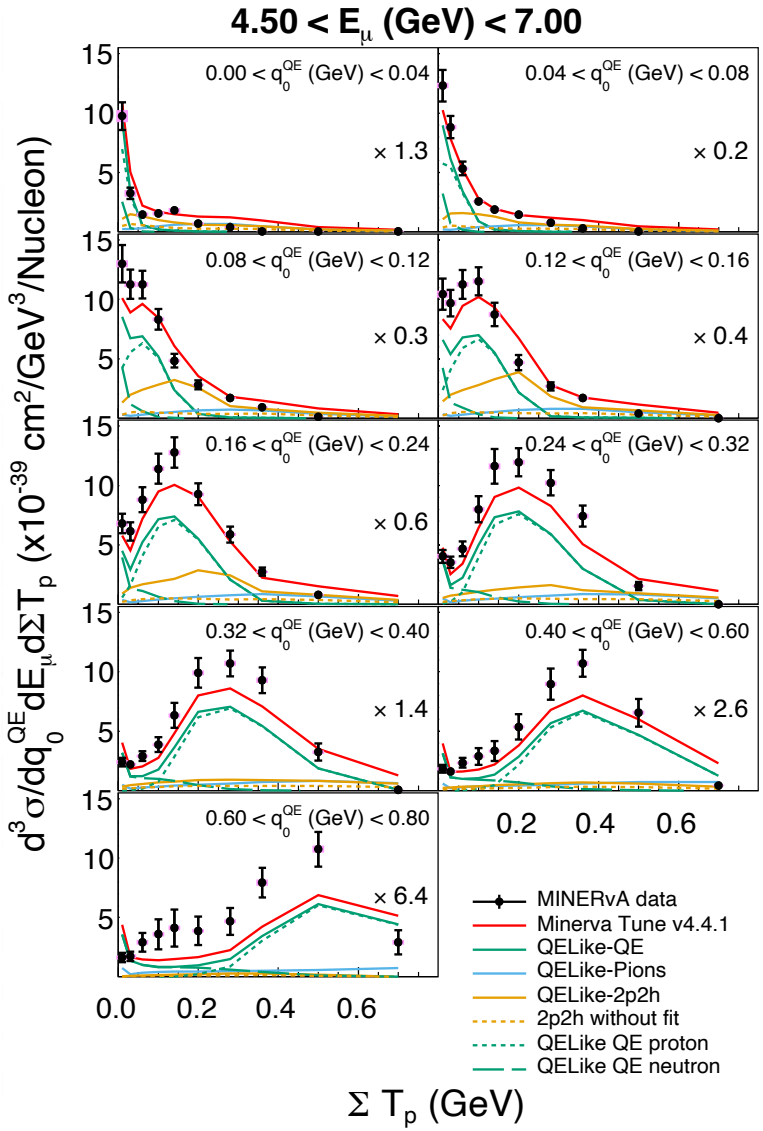
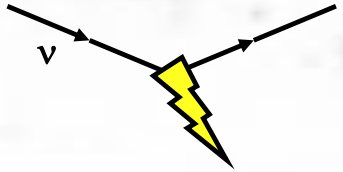
- The first and second discrepancies are the biggest and potentially most important effects in cross-sections: large parts of the rate shows up at a given p_T with a different recoil than expected.
- Problem for interferometry experiments?
  - In T2K (and future Hyper-K) p_T is used to measure the recoiling energy by two body quasielastic kinematics.
  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won't agree.
- Recoil is 50 MeV too high, until high Q^2. No model we checked sees anything like this discrepancy.



Another visualization of CC0π ΣT_p, p_T, $p_\parallel$



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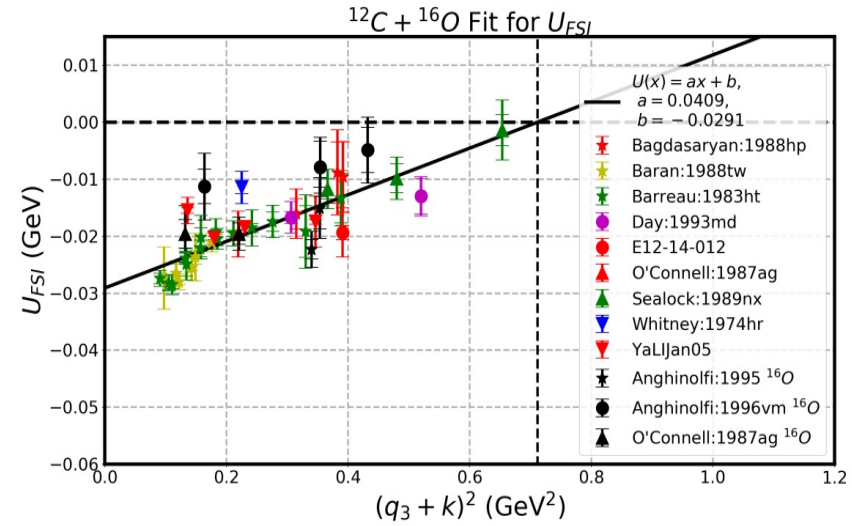
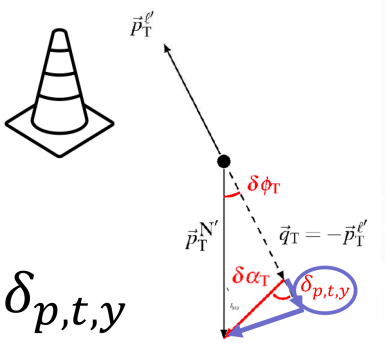
  - In NOvA and DUNE, the visible recoil is measured. And SBN can do both.
  - Apparently, these two won't agree.
- We can actually directly compare the two types of energy measures: recoil in bins of q_0^{QE}.
- Agreement with the model is, as expected, poor.
  - Peaks are missed at low p_T.
  - High side tail is overestimated and low side is underestimated.

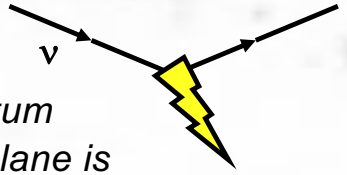
Transverse variables, full MINERvA CC0π statistics



Summary of optical potential from electron scattering
A. Bodek and T. Cai, Eur. Phys. J. C. (2019) 79: 293

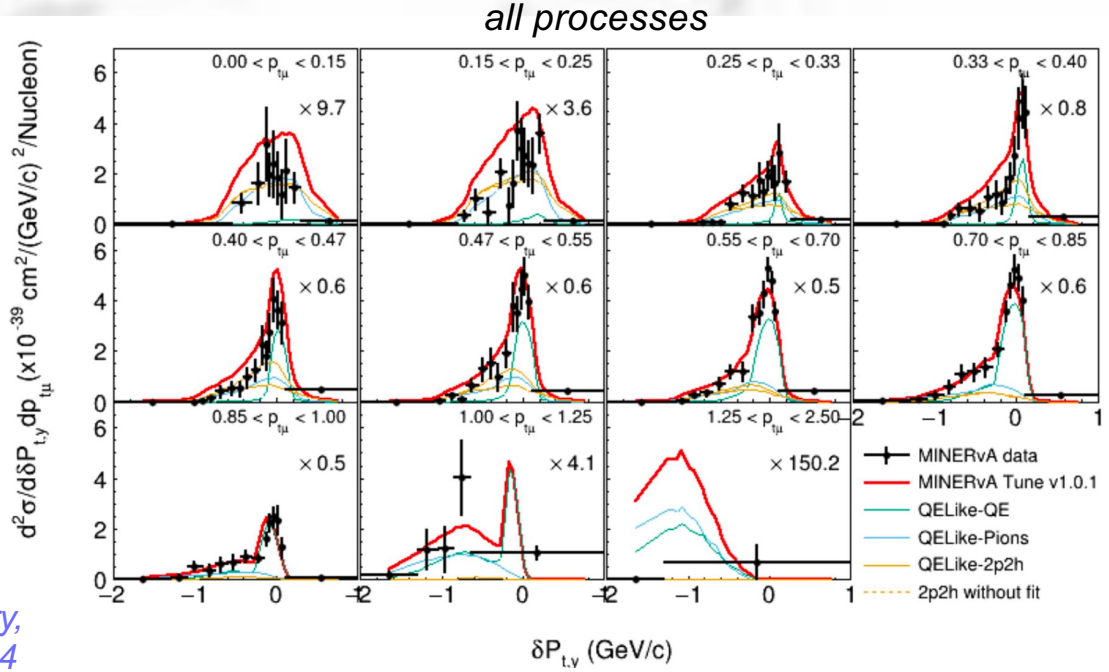


$\delta_{p,t,y}$



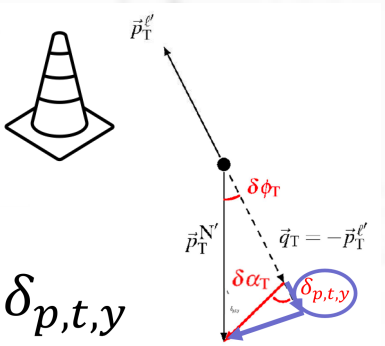
Transverse momentum imbalance in reaction plane is sensitive to Fermi motion and (bias) from removal energy. Expect momentum dependence.

all processes

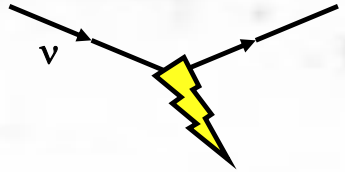


MINERvA Preliminary,
Ruterbories NuINT24

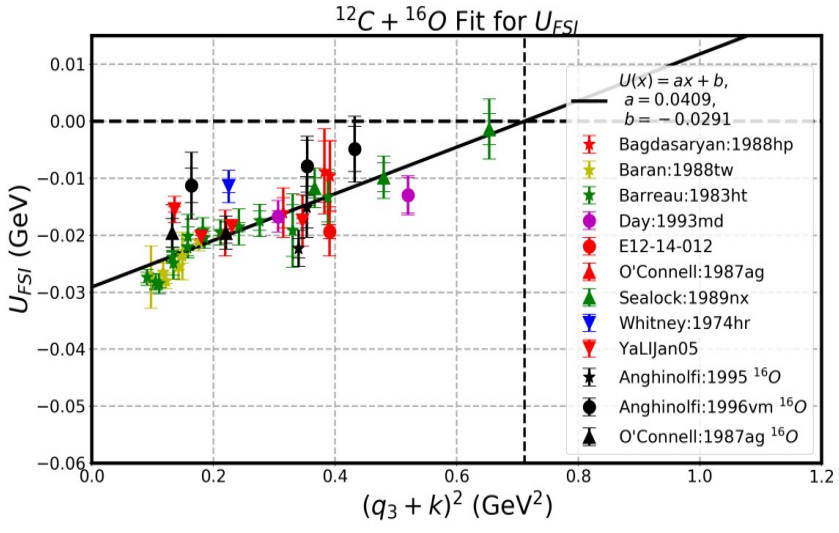
Transverse variables, full MINERvA CC0π statistics



$\delta_{p,t,y}$

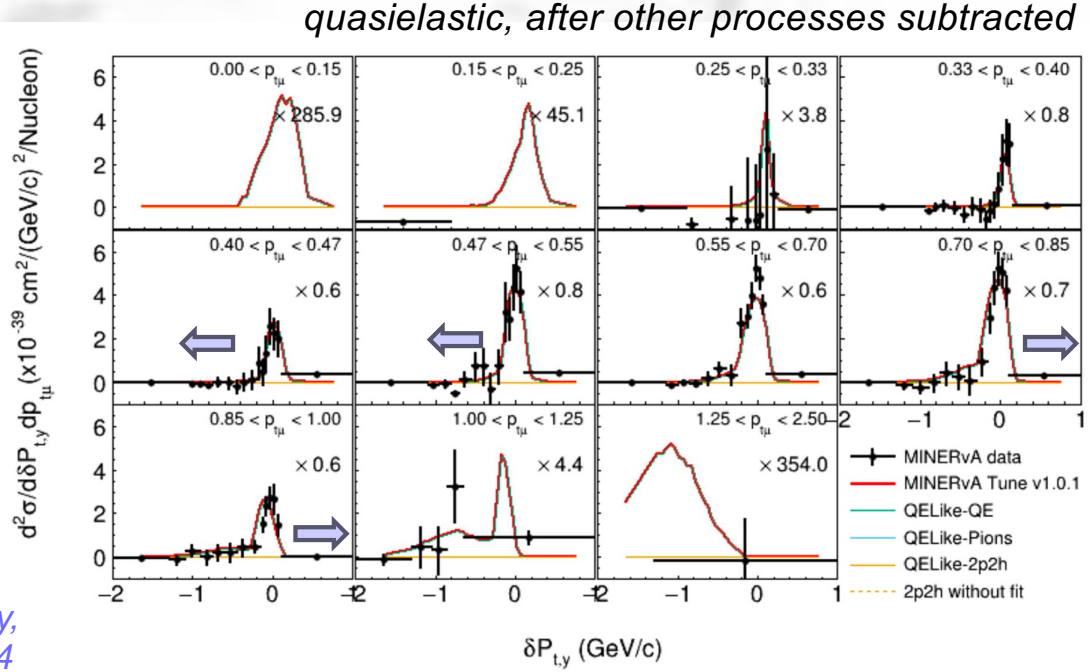


in reaction plane, sensitive to Fermi motion and (bias) from removal energy

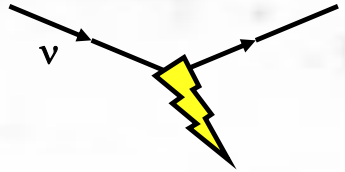


Summary of optical potential from electron scattering
A. Bodek and T. Cai, Eur. Phys. J. C. (2019) 79: 293

quasielastic, after other processes subtracted



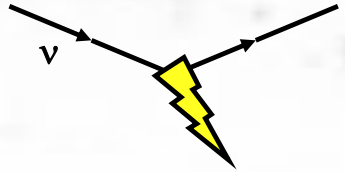
MINERvA Preliminary,
Ruterbories NuINT24



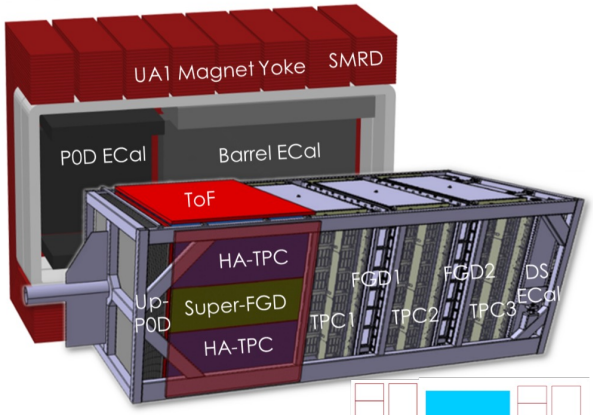
Different Nuclei

(and how different are they for our purposes?)

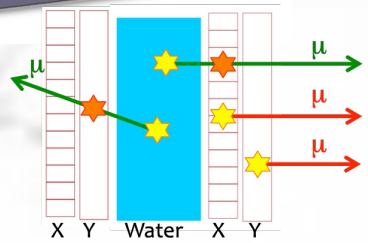
Is a nucleus a nucleus a nucleus?



- Details of nuclei, such as energies and momenta of individual nucleons within the nucleus, vary.
- But we are beginning to see some consistencies in how models describe different nuclei equally well (or equally poorly).



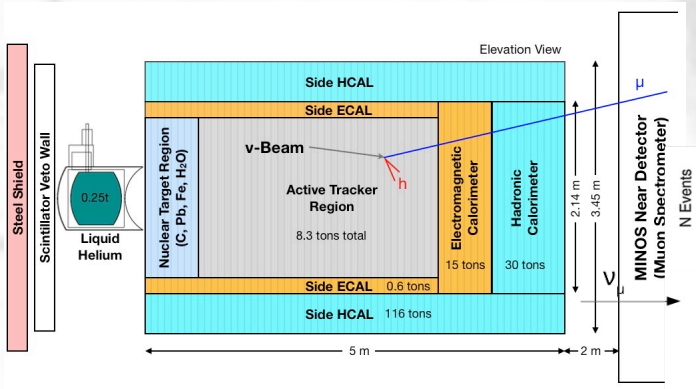
T2K
CH/H_2O



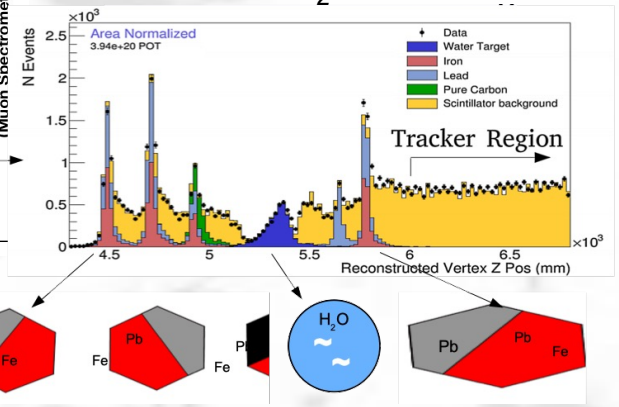
CCoπ in water: first muon hit in X layer

CCoπ in X layer

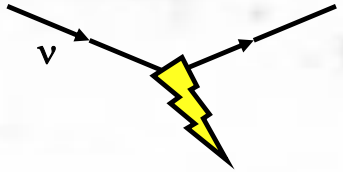
CCoπ in Y layer



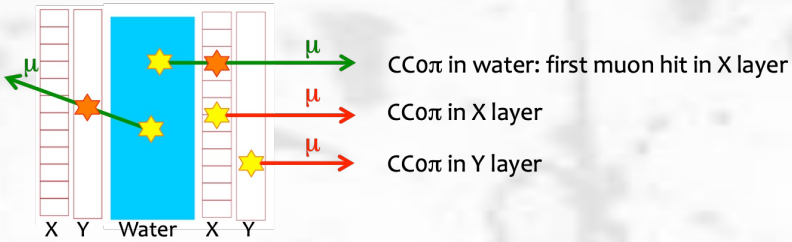
MINERvA
$CH/C/H_2O/Fe/Pb$

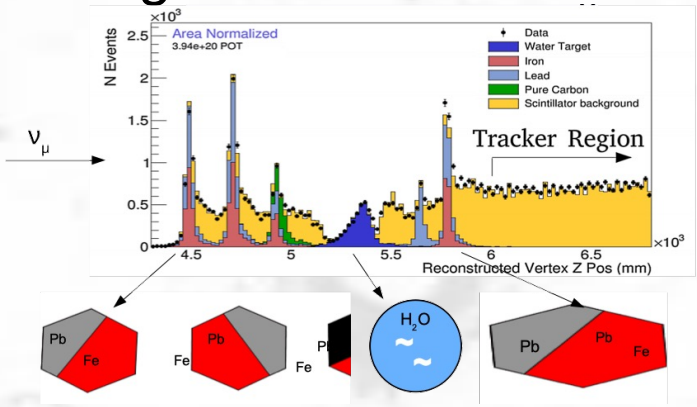


CH Detector and Passive Targets



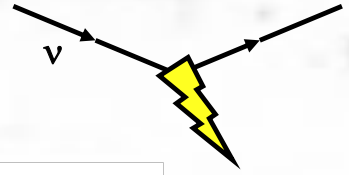
- Experiments with passive interspersed targets use a vertex and background subtraction technique.



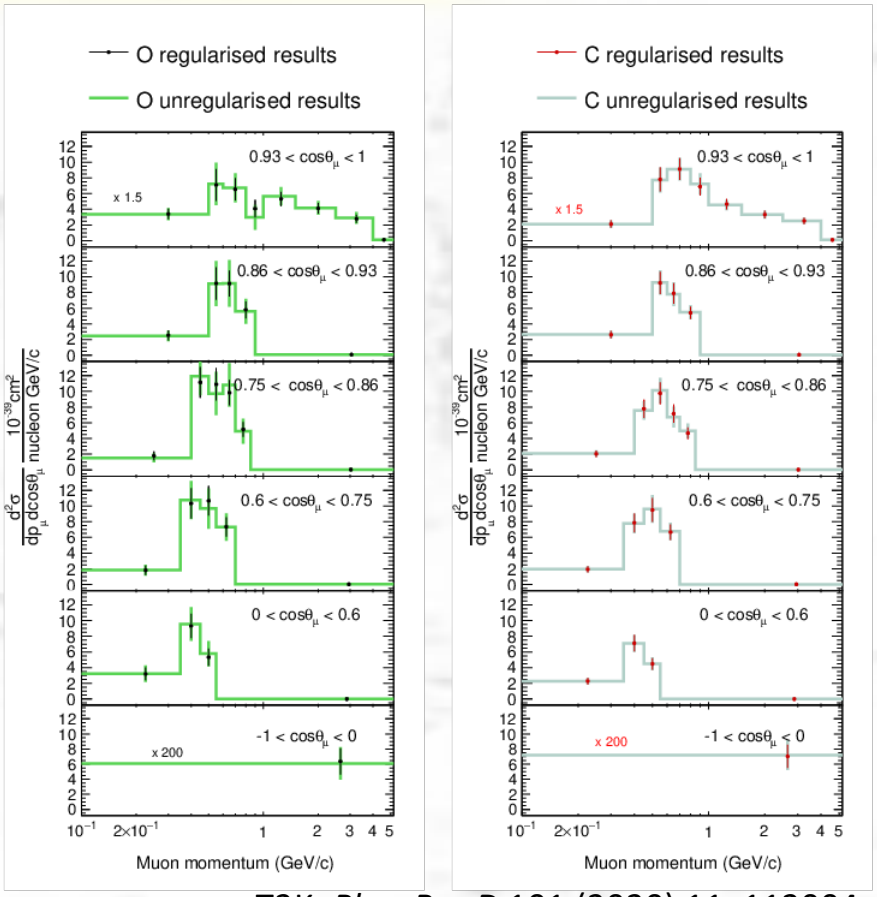


- Can control the backgrounds, at least in part, by reconstructing scintillator events adjacent in detector to the passive target.

T2K CC0π CH vs H_2O

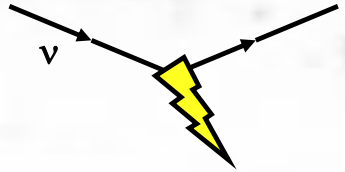


- T2K compares CC0π cross-sections on its CH vs H_2O.
  - Labeled “O” and “C” since there is no neutrino CC0π cross-section on hydrogen.
- Measurements directly check lepton kinematic differences since in the same beam.
  - Consistent with model within uncertainties.
  - Same beam is very important for reducing uncertainties!

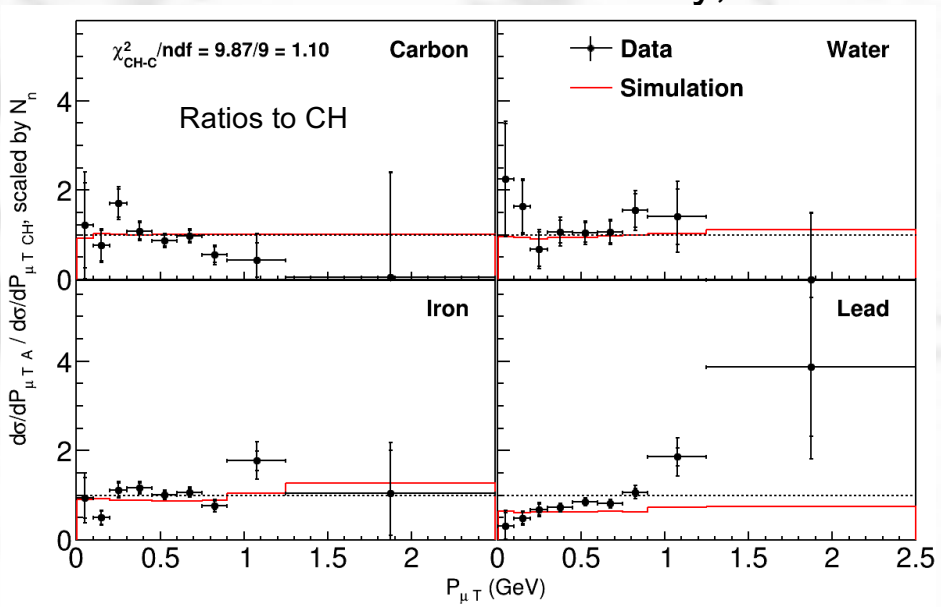


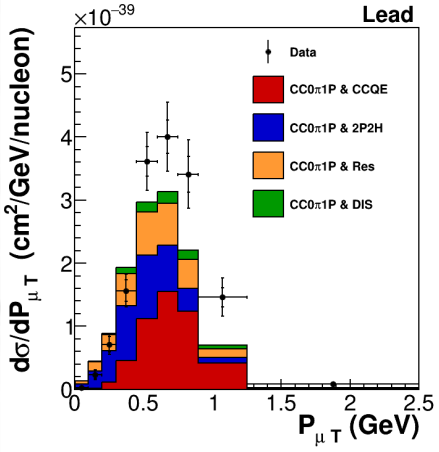
T2K, *Phys.Rev.D* 101 (2020) 11, 112004

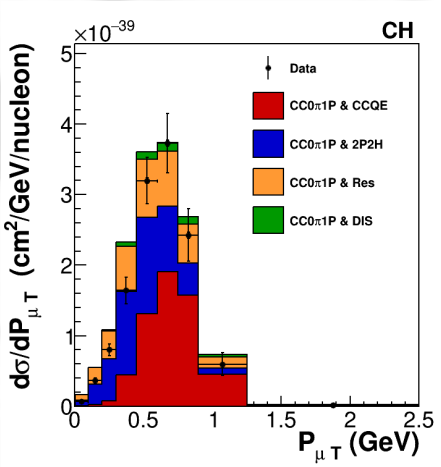
MINERvA CC0π {C, H_2O, Fe, Pb}/CH



- MINERvA's targets allow for comparison across a wide range of *A*.
  - Not particularly high statistics for most C and H_2O results (so not enough to subtract out CH-H to get hydrogen, for example), but good statistics for Fe and Pb.
  - Reasonable consistency, if varied the fraction of non-quasielastic events?



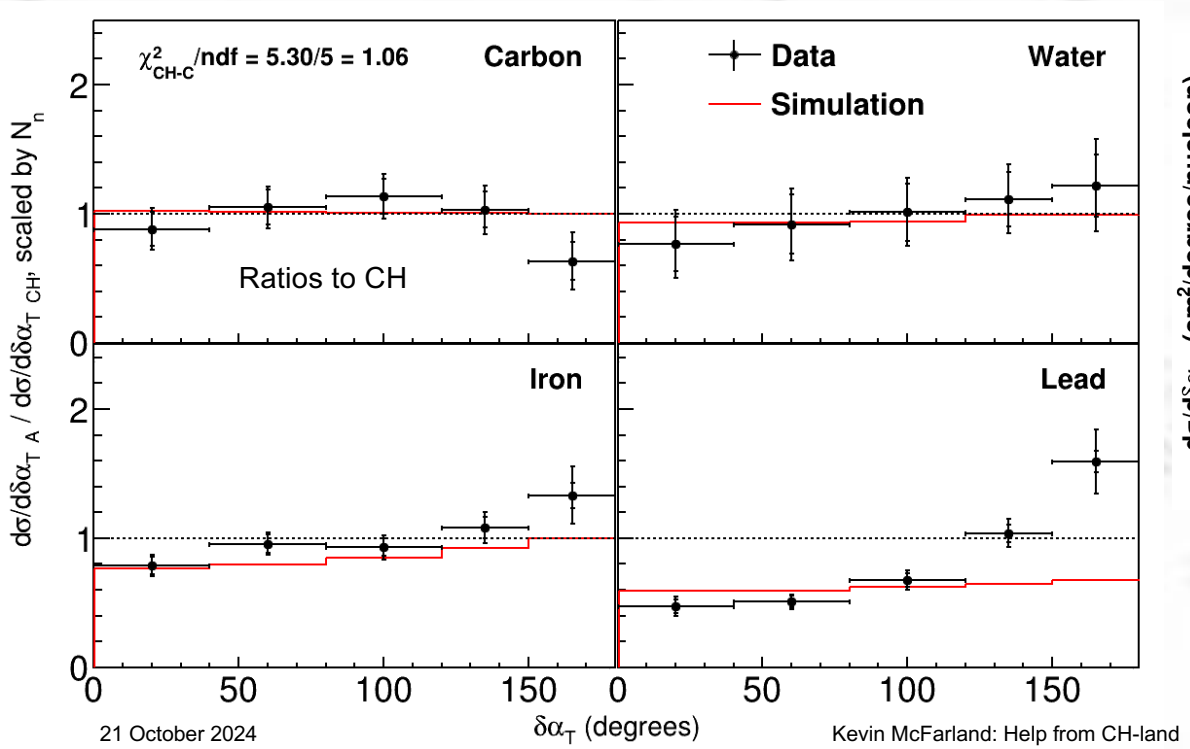


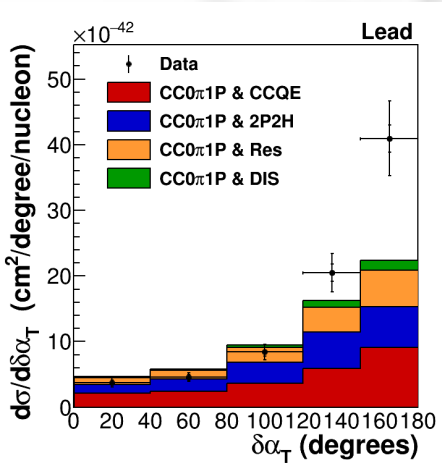


MINERvA, *Phys.Rev.Lett.* 130 (2023) 16, 161801

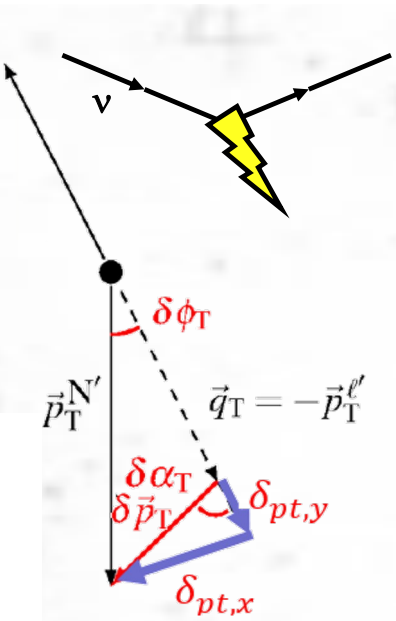
MINERvA CC0π {C, H_2O, Fe, Pb}/CH

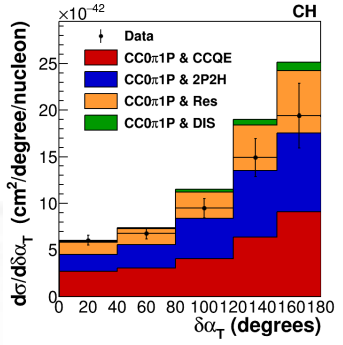
- Also ratios for transverse kinematic imbalances.
- Perhaps same issue with non-quasielastic contribution differing?





$\delta\alpha_T$





MINERvA, *publication in process,*
J. Kleykamp FNAL W&C

MINERvA CC0π {C, H_2O, Fe, Pb}/CH

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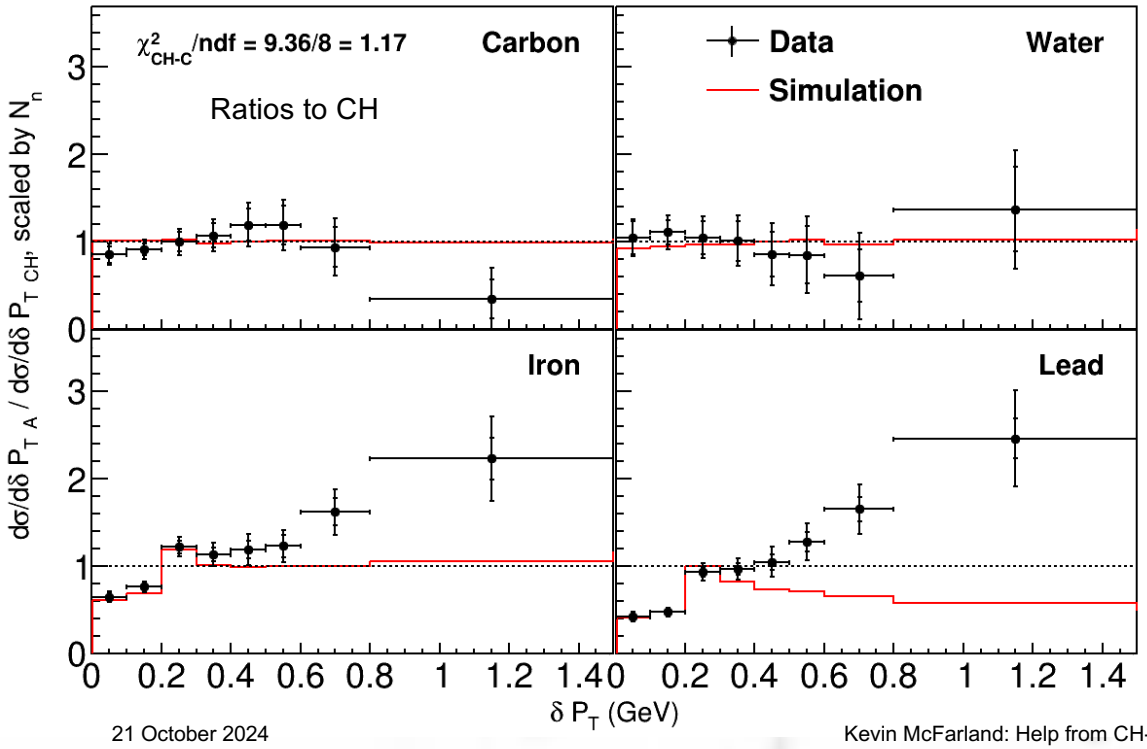
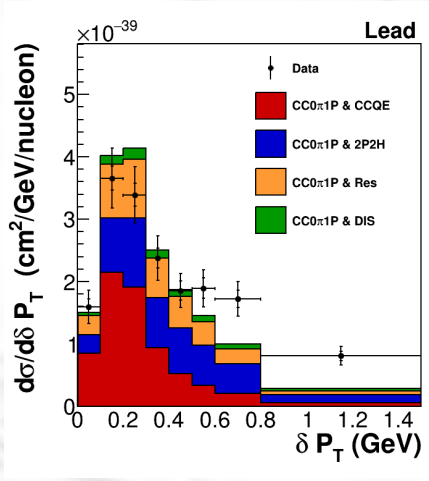
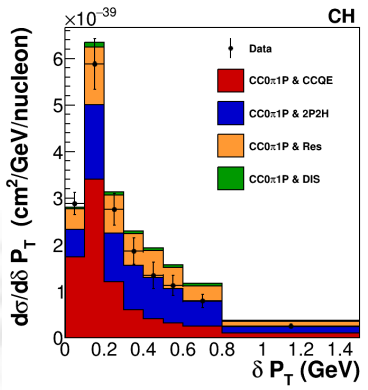
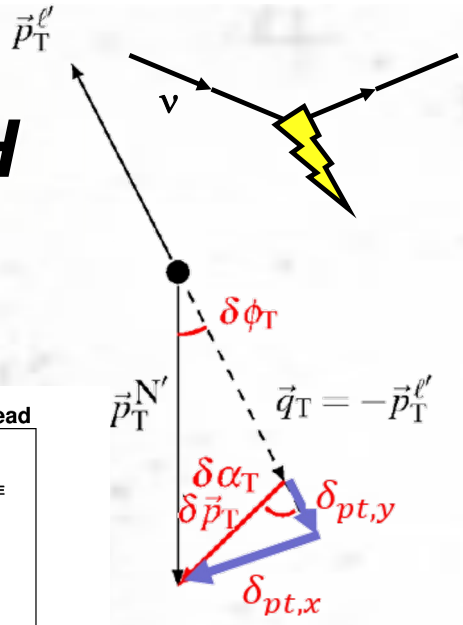
- Perhaps same issue with non-quasielastic contribution differing?





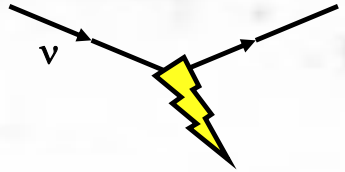
δp_T



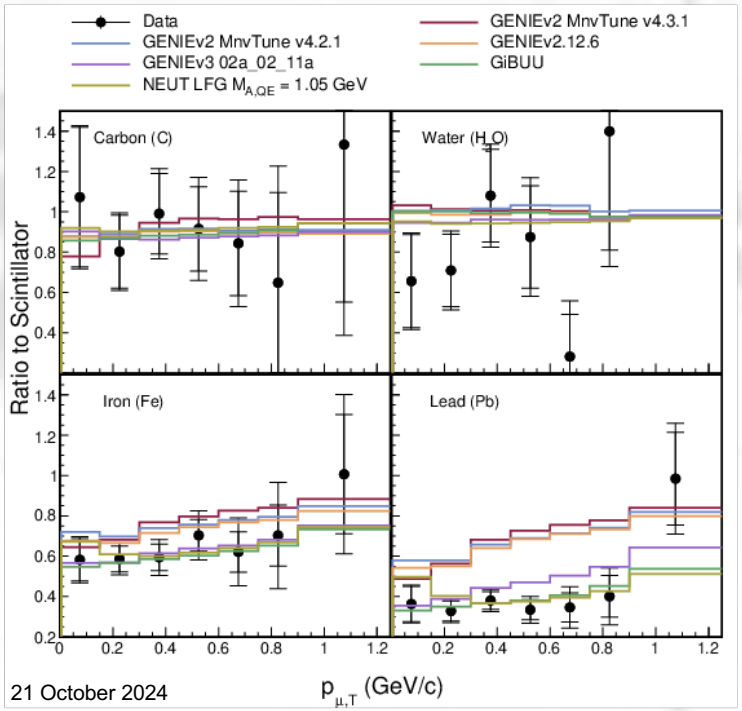


MINERvA, *publication in process*,
J. Kleykamp FNAL W&C

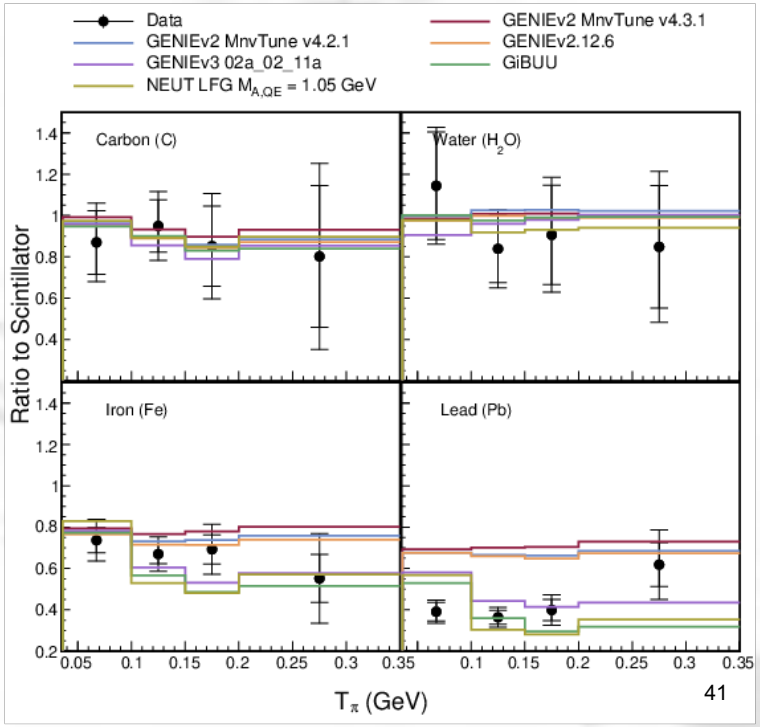
MINERvA CCπ⁺ {C, H_2O, Fe, Pb}/CH

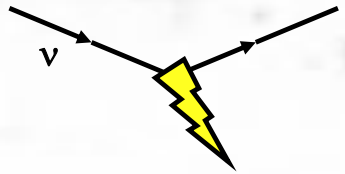


- Result is generally that we see similar shapes in T_π and p_T^μ ($Q^2 \approx \left(p_T^\mu\right)^2 \left(1 + \frac{\nu}{E_\mu}\right)$).
- However the overall result rate is different, for some models of π⁺ FSI.



MINERvA, *Phys.Rev.Lett.* 131 (2023) 1, 1

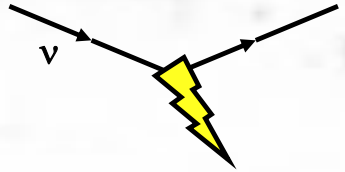




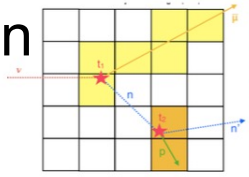
Neutrons, Nucleons and Nuclei

(rapid recent development)

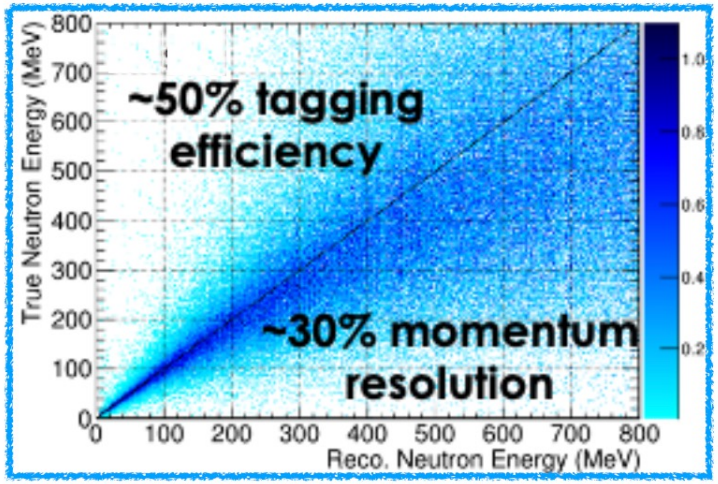
Neutron reconstruction

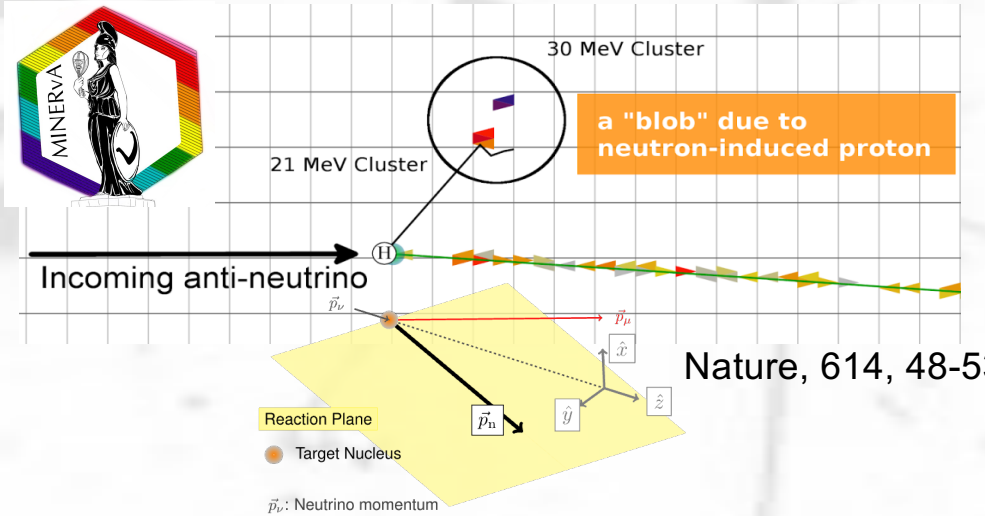


- MINERvA has, and SuperFGD will reconstruct neutrons through their quasielastic knockout of protons from nuclei, e.g., $^{12}C(n,np)^{11}B$
  - SuperFGD has lower threshold three-dimensional reconstruction AND time-of-flight momentum.

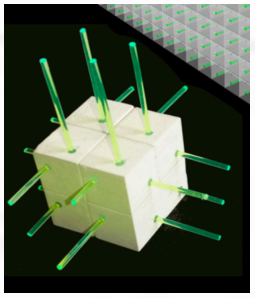


$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$





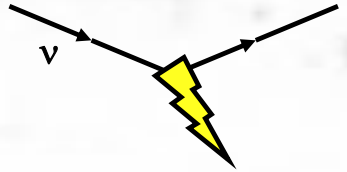
Nature, 614, 48-53



Phys. Rev. D101 (2020) 9, 092003

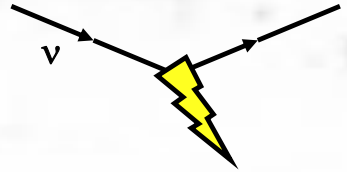
Giganti, T2K

Why Neutron Reconstruction Matters

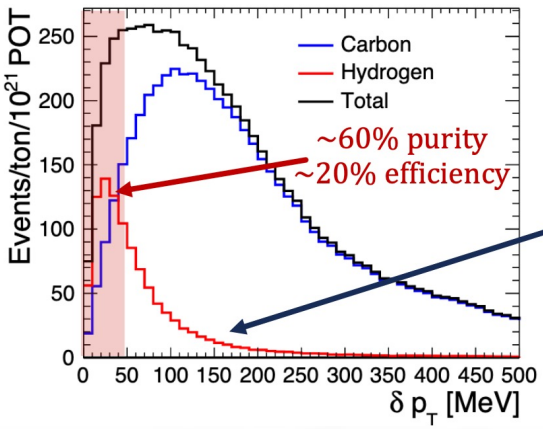


- Neutron measurement techniques developed in recent years, through detector and analysis technologies, are having its time.
  - I will emphasize isolation of hydrogen on $\bar{\nu}_\mu p \rightarrow \mu^+ n$.
  - But this also has applications for understanding of energy lost to nuclei in interactions because of very low detection thresholds, neutrino and antineutrino separation, etc.
- Efficiency of reconstruction is significantly less than unity, requires capable (often smaller) detectors, so the highest intensity neutrino beams will also be important for this work.

Neutron and Axial Form Factor



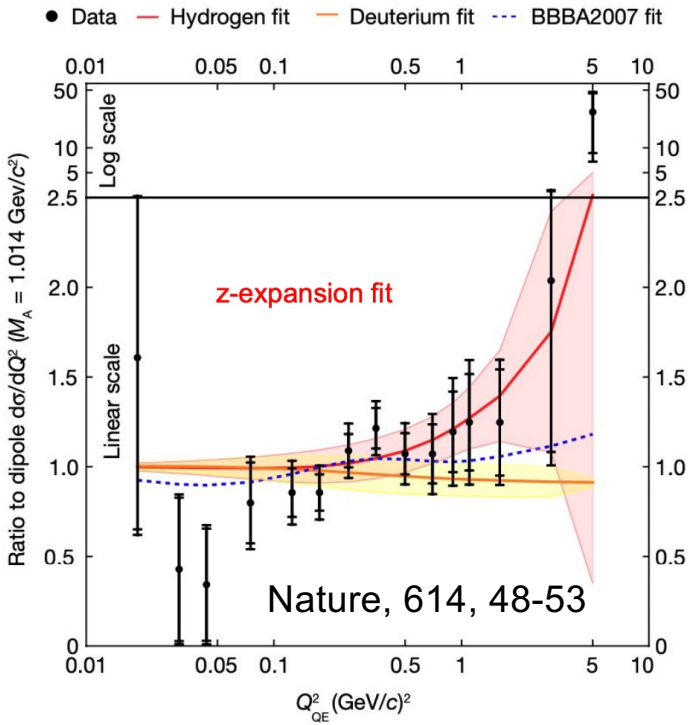
- MINERvA used neutron reconstruction and ability to isolate events on hydrogen (only with direction!) to measure $F_A(Q^2)$ with useful precision $0.06 < Q^2 \lesssim 2$ GeV².
- SuperFGD will have two handles, direction and energy, to isolate hydrogen scattering.



Antineutrinos:
Peak from interactions on hydrogen

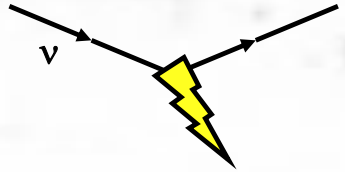
No nuclear effects

Possible thanks to **neutron detection**!

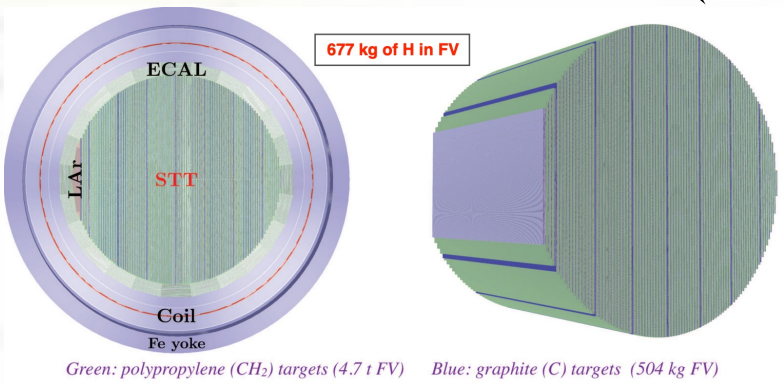


Phys. Rev. D 101, 092003 (2020),
(figure assembled by L. Munteanu)

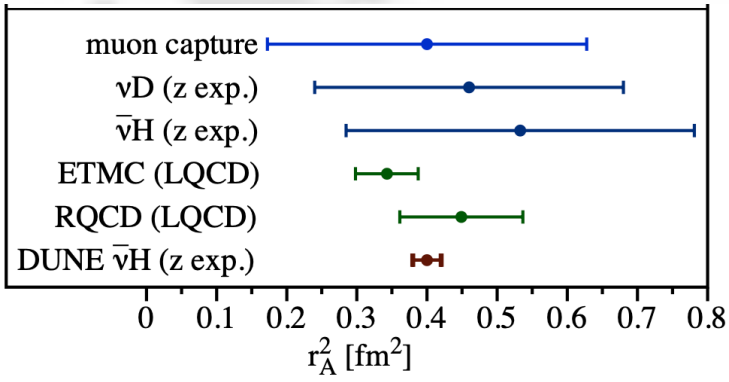
DUNE-ND "Solid Hydrogen" from CH_n



- The DUNE SAND near detector plans CH_2 and C foils interspersed with low density tracker.
- This adds a third handle to direction and energy constraints, for separating hydrogen interactions by subtraction.
- Significant potential to dramatically reduce backgrounds and systematics in a high statistics measurement.
  - *Caveat: the estimate at right isn't a projection from DUNE (third-party authors), and IMHO it uses a deeply flawed metric. (But "it's got a beat, and you can dance to it.")*

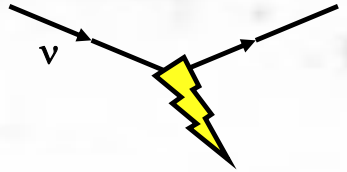


one realization of the SAND low-density tracker

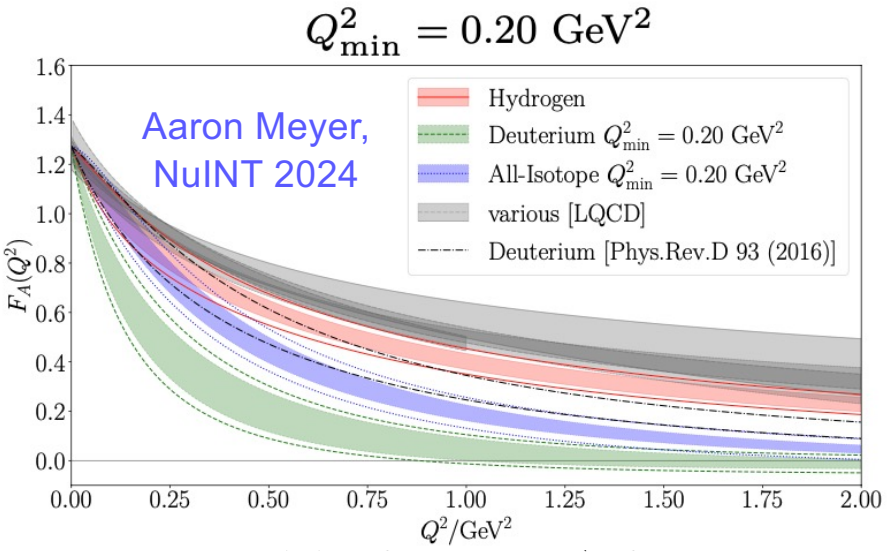


Phys.Rev.D 109 (2024) 5, L051301

Nucleons vs Nuclei



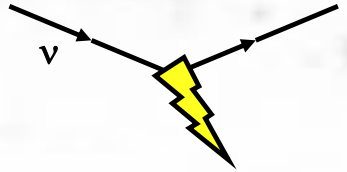
- By contrast, we are struggling to understand cross-sections on free nucleons as a base for calculating cross-sections on nucleons.
- In $F_A(Q^2)$, there are significant tensions between the deuterium bubble chamber legacy data, and either the MINERvA hydrogen or lattice QCD calculations.
- Why? It's possible that nuclear model assumptions in the analysis of the deuterium data played a role.
- *More from Aaron and Minoo on Thursday*.



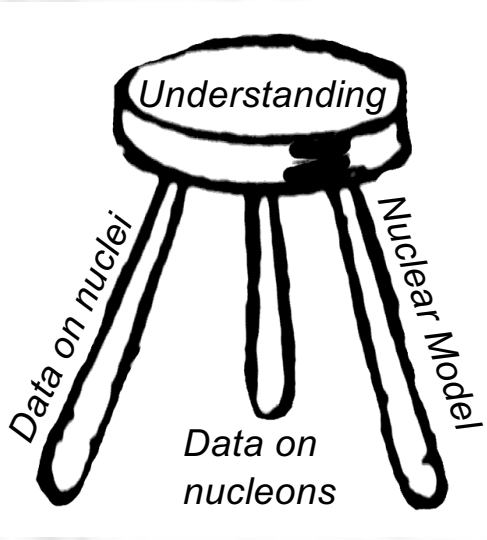
	$\{a_k\}_{\text{D}}$	p_{D}	$\{a_k\}_{\text{H}}$	p_{H}
$\chi^2_{\text{D}}/\text{DoF}_{\text{D}}$	94.9/94	0.45	167.7/96	8.3×10^{-6}
$\chi^2_{\text{H}}/\text{DoF}_{\text{H}}$	23.3/15	0.08	10.0/13	0.69

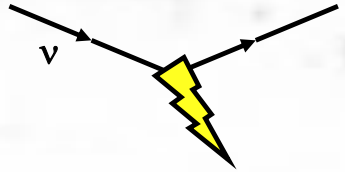
Deuterium is incompatible with hydrogen, LQCD

Nucleon and Nuclei commentary



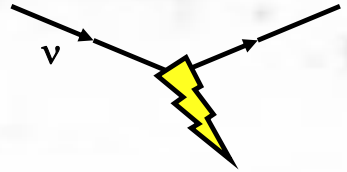
- We've made progress in our nuclear models, informed by electron scattering, theory, and data from neutrinos and hadron scattering.
- While there is growing evidence that these models may be helping us to understand nuclear effects, there is also growing evidence that the input of free nucleon predictions is not serving us well.
- Experiments that can measure or theory that can calculate free-nucleon interactions, will become increasingly important.
  - This suggests a continuing role for scintillator, but maybe also a future need for free nucleon (hydrogen) detectors.



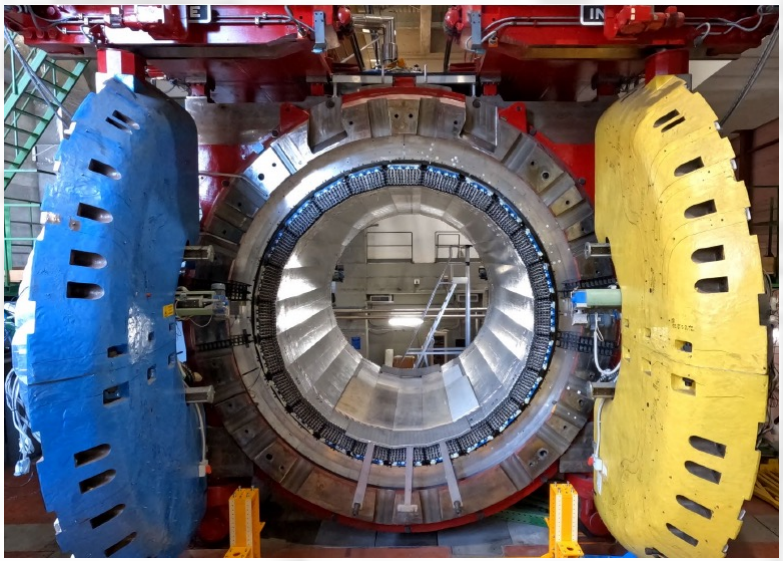


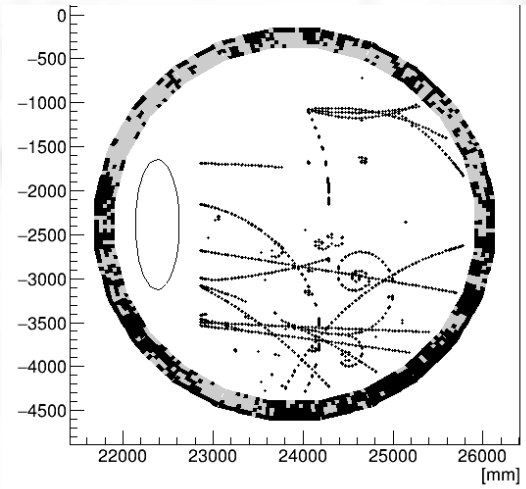
Closing Thoughts

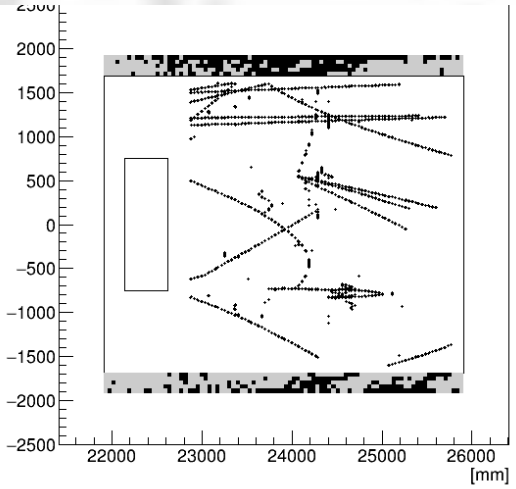
H and C and Ar… Can't we just all be friends?



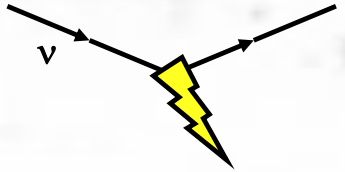
- As Callum mentioned in passing, SAND (DUNE Phase One on-axis Near Detector) plans to include CH_2 and C, for separation of H and C, ***and*** Ar targets to compare interactions on different nuclei.







Brave Brew World?



- Ar targets inside a CH detector reminded me of the enthusiasm of true believers.

the ONION

New Starbucks Opens In Rest Room Of Existing Starbucks

CAMBRIDGE, MA—Starbucks, the nation's largest coffee-shop chain, continued its rapid expansion Tuesday, opening its newest location in the men's room of an existing Starbucks.

"Coffee lovers just can't stand being far from their favorite Starbucks gourmet blends," said Chris Tuttle, Starbucks vice-president of franchising. "Now, people can enjoy a delicious Frappuccino or espresso just about any time they please, even while defecating."

The new men's-room-based Starbucks, the coffee giant's 1,531st U.S. location, will be open to both men and women when not "in use." In addition to offering specialty coffees from around the world, it will serve freshly baked pastries, Italian pannini sandwiches and soups, as well as the rest room's usual selection of toilet paper and soap…

According to Starbucks CEO Howard Schultz, the new location represents the beginning of a long-term expansion plan… At some point a 'Starbucks Express' window will eventually open in the walk-in closet of the men's room Starbucks."

"Drink our coffee," Schultz said. "Drink it."

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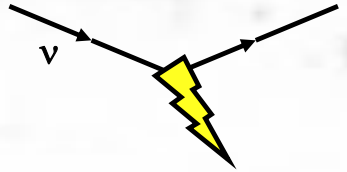

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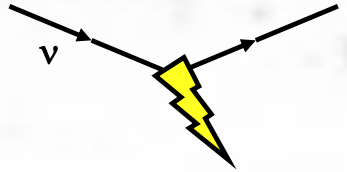

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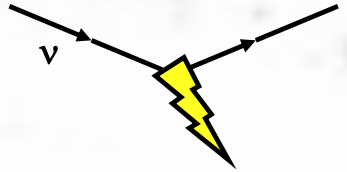
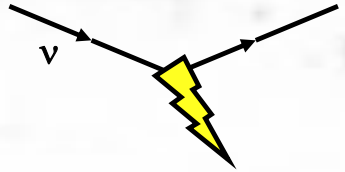
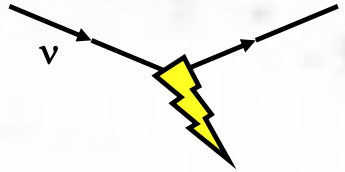
"Measure Neutrino Interactions", Schultz said. "Measure Them."



- Although Starbucks CEO Howard Schultz and I may not agree about the importance and function of labor unions, we both agree that measuring neutrino interactions in CH is very important.
- There are key capabilities of CH detectors that are hard to duplicate in LAr TPCs, even if resolution is generally worse.
  - Configurability of plastic detectors to add alternate targets.
  - Fast timing enables high rates and aggressive use of sub-event relative timing for neutrons and weakly decaying mesons.
  - Cases where improved ionization resolution isn't necessarily a big advantage, such as electron identification.
- Expect CH to continue to have impact on models, even for DUNE.

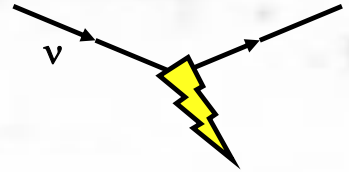


Backup

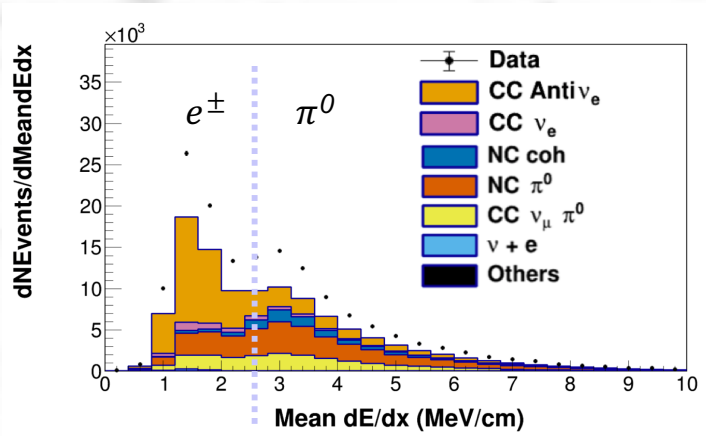


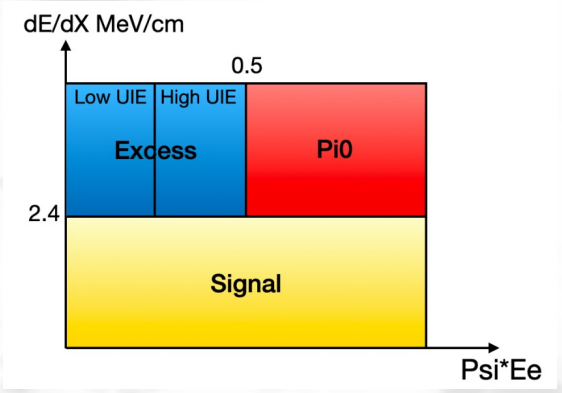
More on MINERvA's Electron Neutrinos

Characterization of Backgrounds

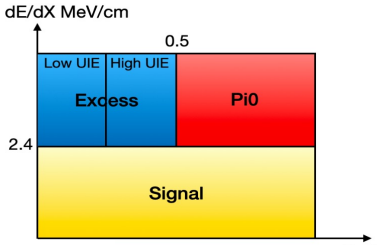


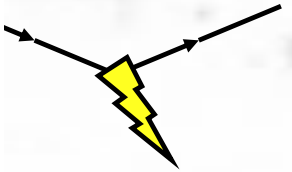
- Discriminant is dE/dx at start of the shower.
- Missing diffractive π^0 production on scattering from hydrogen! (Coherent π^0 production from carbon is the dark blue.)
  - Also, both diffractive and coherent π^0 production are badly underestimated by the Rein model and Rein-Sehgal and Berger-Sehgal models at high energies, respectively.
- There is also significant contamination of electrons to high dE/dx (early showering) and photons to low dE/dx (very asymmetric pair production).
- Divide high dE/dx region into diffractive-like (recoiling proton at vertex), coherent-like, and incoherent-like to characterize backgrounds.



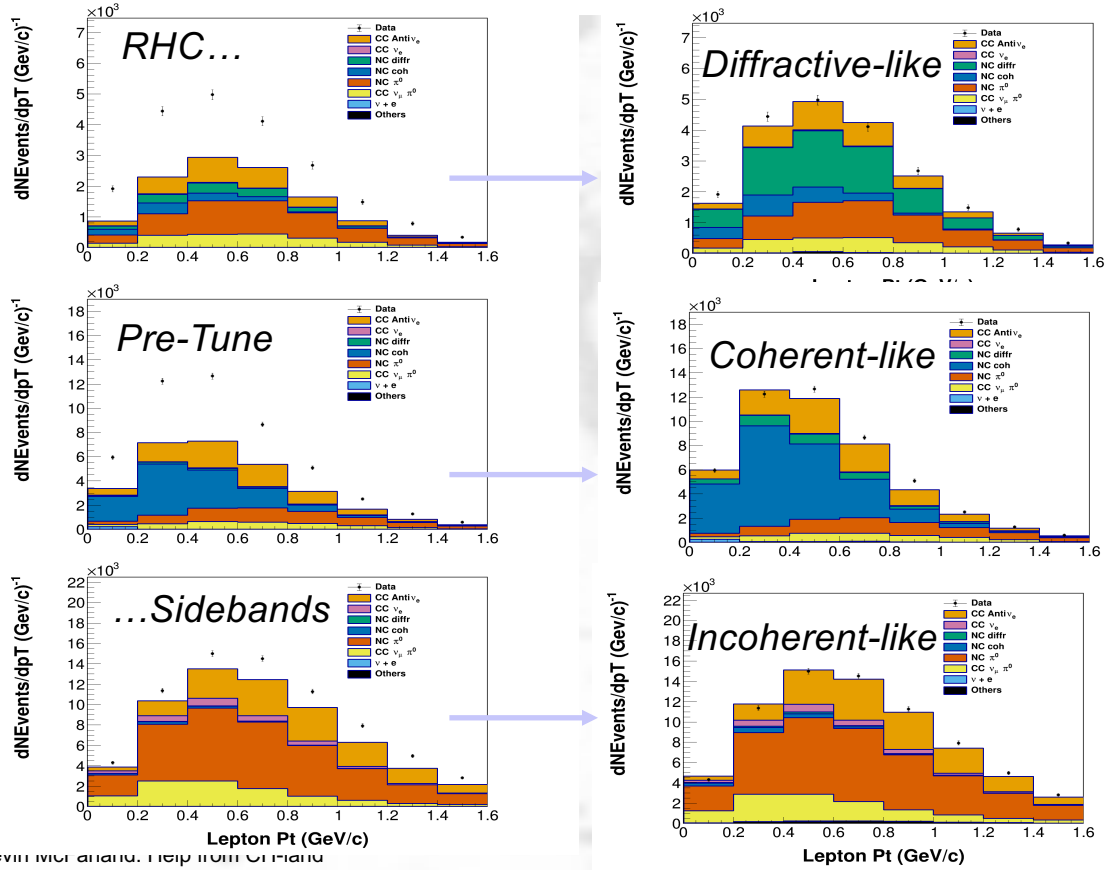


Characterization of Backgrounds

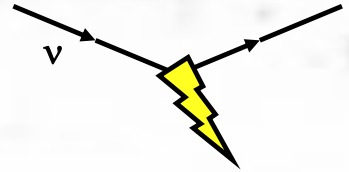




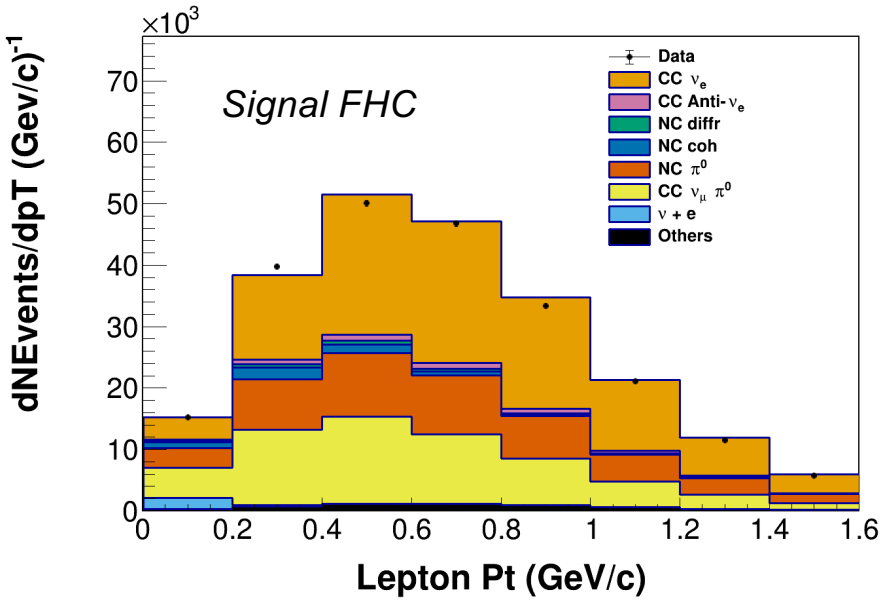
- Tune primarily in electron p_T for each process separately.
- RHC (antineutrino dominant) has much less incoherent π^0 production, so use the RHC results in FHC (neutrino dominant) beam for coherent and π^0 production from carbon is the dark blue.)
- (Sideband tune has tensions in FHC beam not observed in RHC. Add an extra systematic uncertainty to cover this in FHC.)

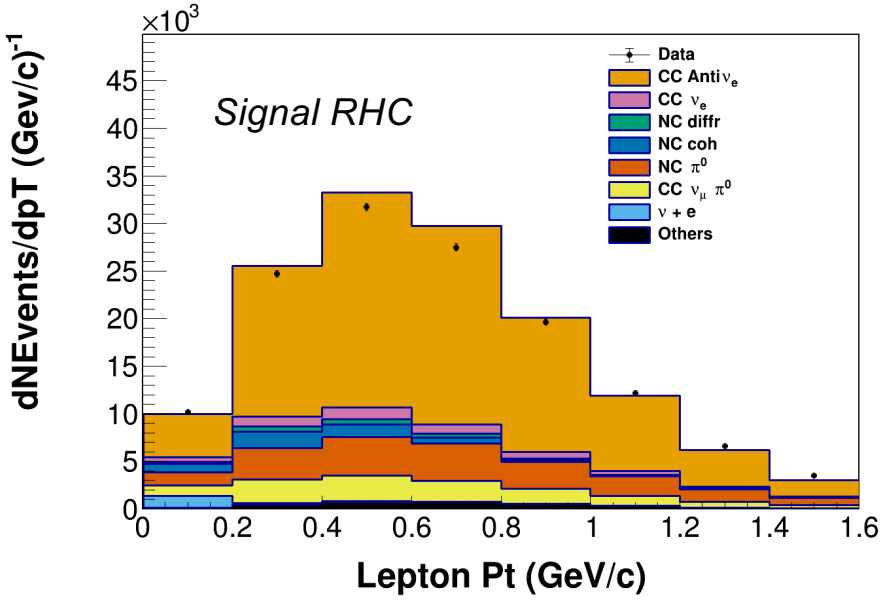


Signal Region after Background Tunes

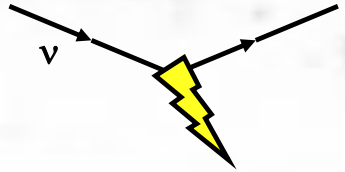


- After tuning the backgrounds, compare signal region.
- As expected, backgrounds much larger in FHC (incoherent processes).

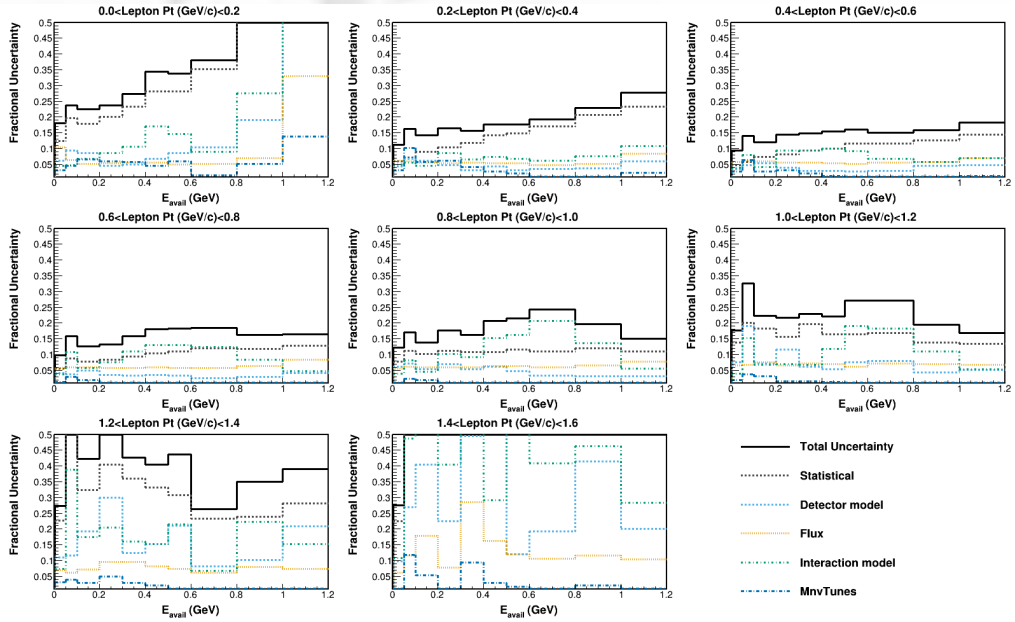




Discussion and Uncertainties

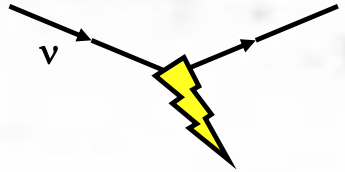


- Reference model is GENIE 2.12.6 with MINERvA tunes. (And yes, Andy Furmanski, a correction for the FSI bug…)
- Most useful in comparison to muon neutrinos, *BUT* this tune largely predicts the MINERvA muon neutrino measurements.
- Statistics dominated, mostly, with significant interaction model uncertainties at mid-p_T.
- Flux uncertainties ~5%.

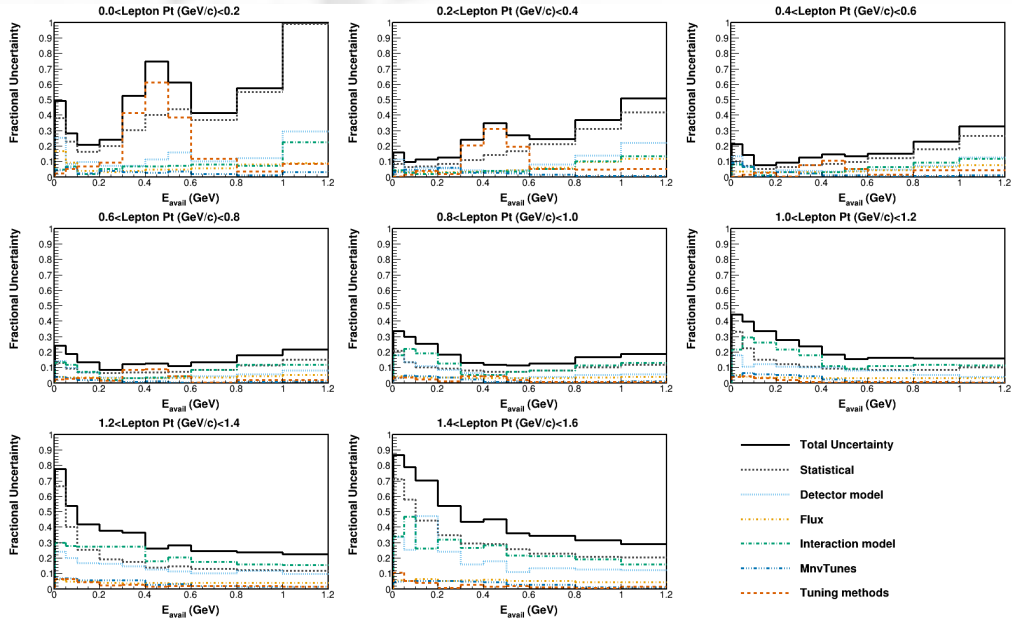


Anti-neutrino uncertainties

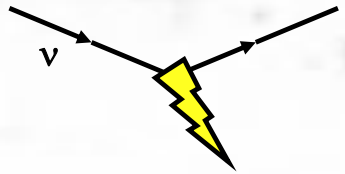
Uncertainties in FHC



- Statistics dominated, mostly, with significant interaction model uncertainties at mid-p_T.
- FHC has the background tuning uncertainty, due to imperfect sidebands agreement very visible at low p_T.
- Flux uncertainties ~4%.

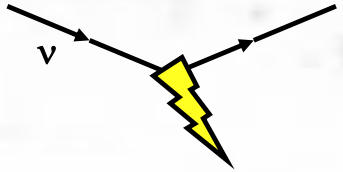


Neutrino uncertainties

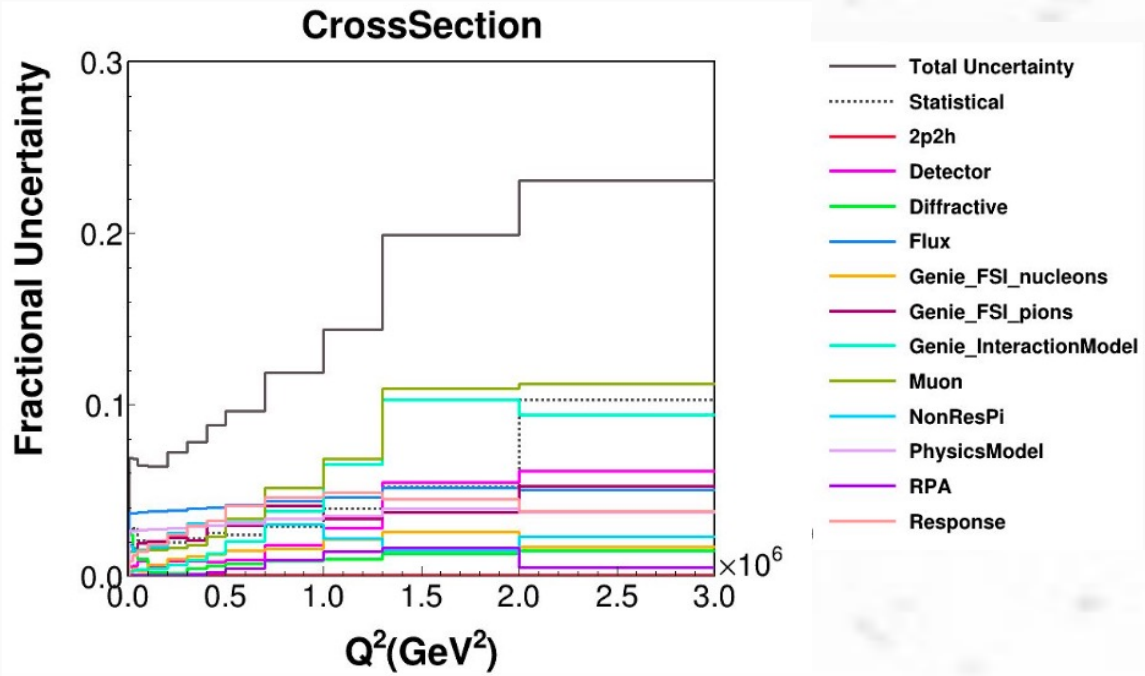


More on MINERvA's π^+ Results

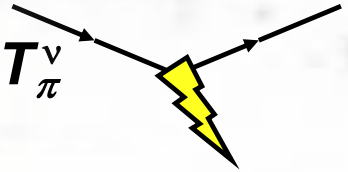
New $1\pi^+$ Result Uncertainties



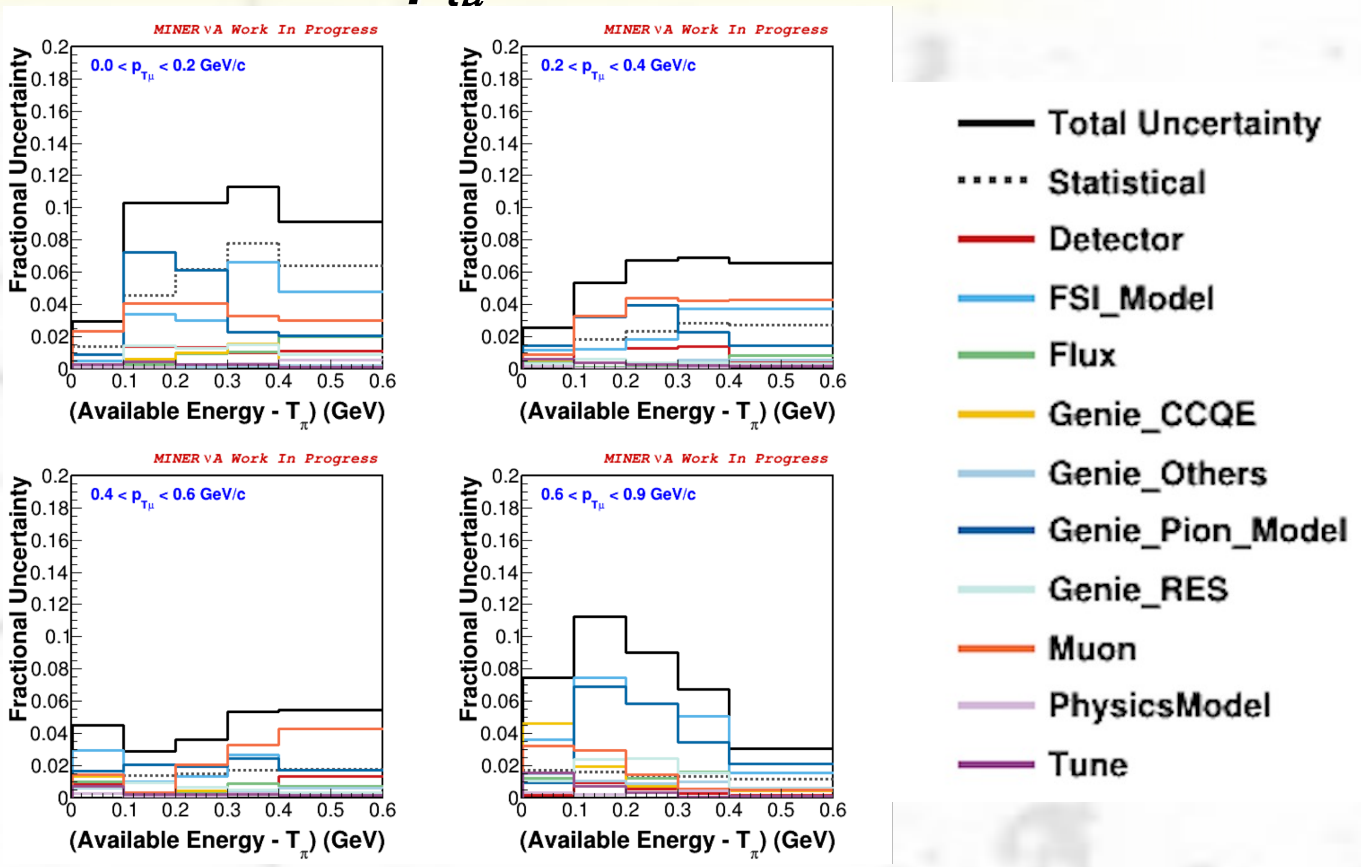
- Cross Sections versus Q^2



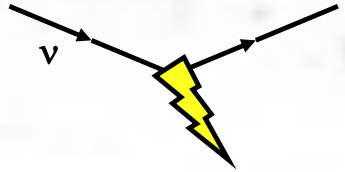
CC≥1π Cross Section Uncertainties vs. Available Energy-T_π^ν and $p_{t\mu}$



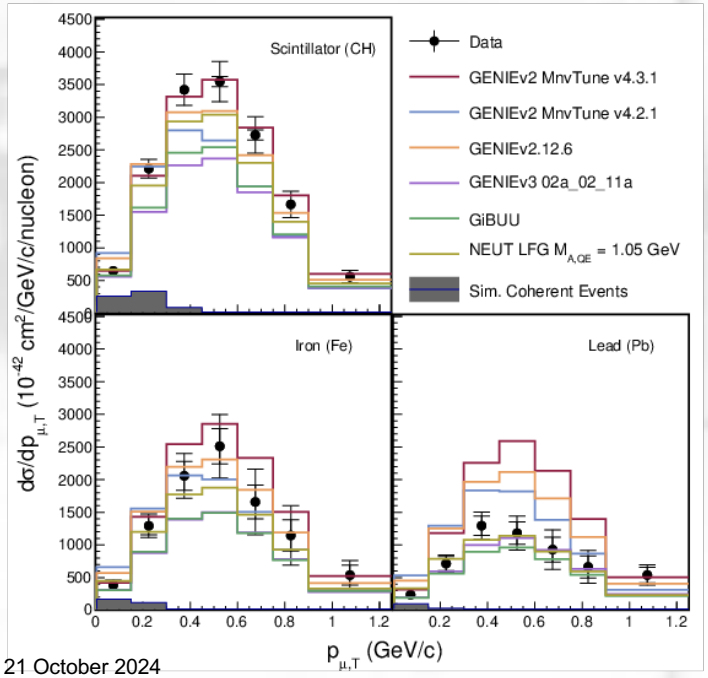
- Fractional Uncertainties larger for this quantity
- Still there are contributions from several sources, no clear source dominates



MINERvA CCπ⁺ {CH, Fe, Pb}



- Result is generally that we see similar shapes in T_π and p_T^μ ($Q^2 \approx \left(p_T^\mu\right)^2 \left(1 + \frac{\nu}{E_\mu}\right)$).
- However the overall result rate is different, for some models of π^+ FSI.



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