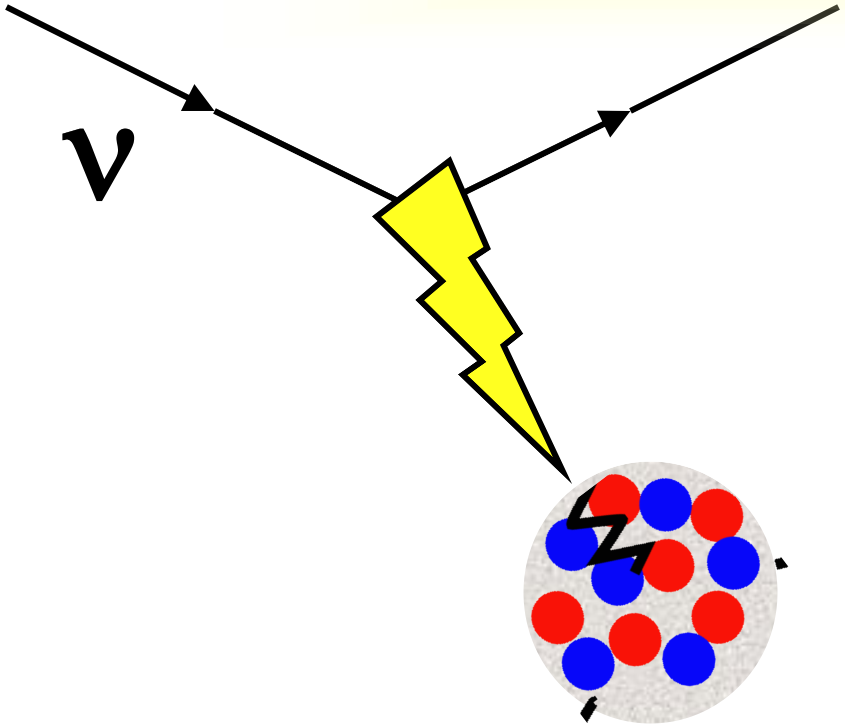
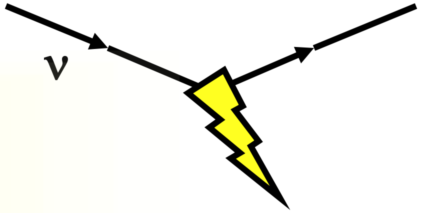
Inelastic Interactions on Nuclei





Kevin McFarland
University of Rochester

NNN 2025, Sudbury

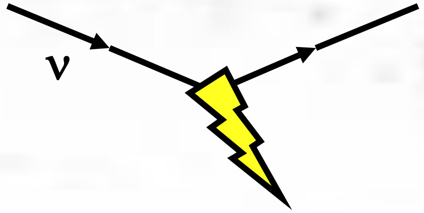
2 October 2025

Plan for This Lecture

- Why?
- Experiments
- A selection of Results and Trends
- Lunch

Plan for This Lecture

- Why would anyone willingly study this?
- Experiments
- A selection of Results and Trends
- Lunch

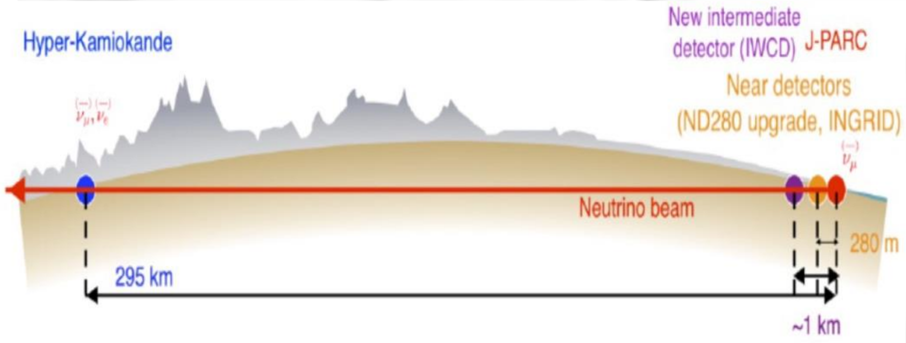


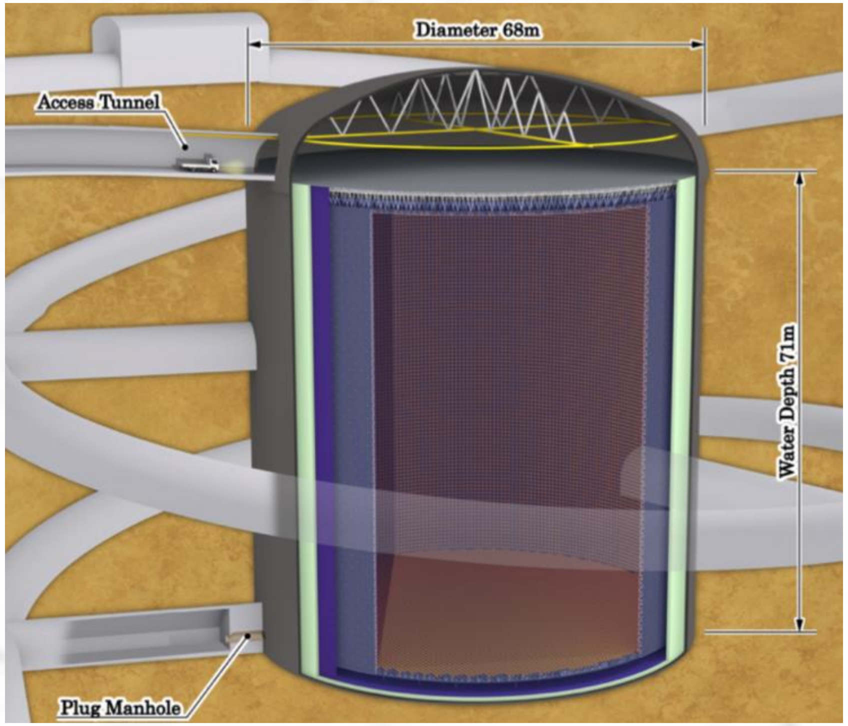
Why?

("because it's there" is always the wrong answer)

Future Neutrino Experiments: T2HyperK

- Major upgrade of the T2K beam and a larger far detector, HyperKamiokande, in approximately the same location.

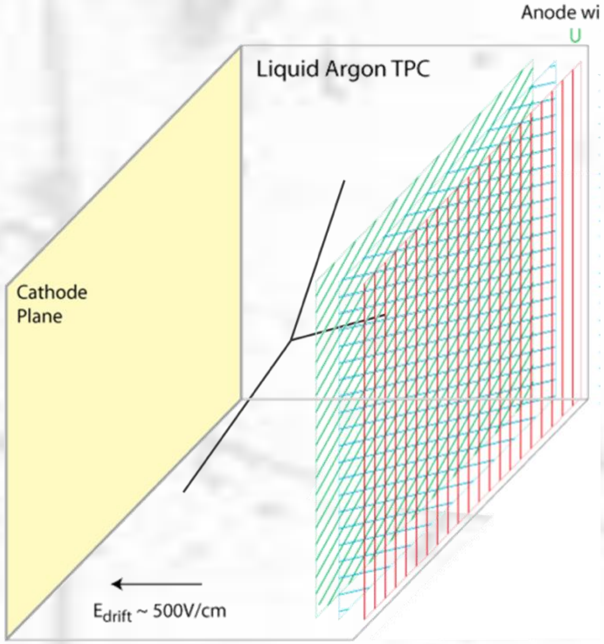




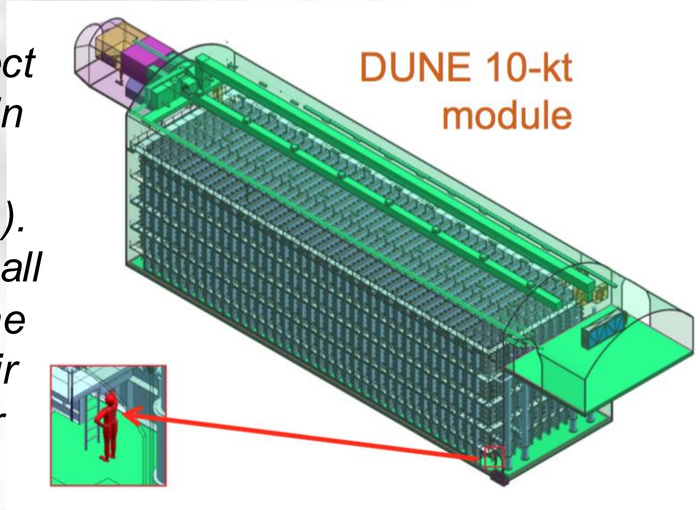
- *Designed to be a high statistics test of the observed (with low statistics) CP asymmetry in the T2K oscillation result.*

Future Neutrino Experiments: DUNE

- Happy coincidence of location of Sanford lab (the former Homestake mine where neutrino emission from the sun was discovered!) and locations of high-power multi-GeV proton sources at an optimal distance.

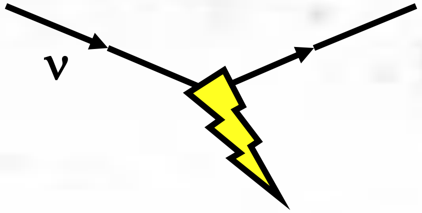


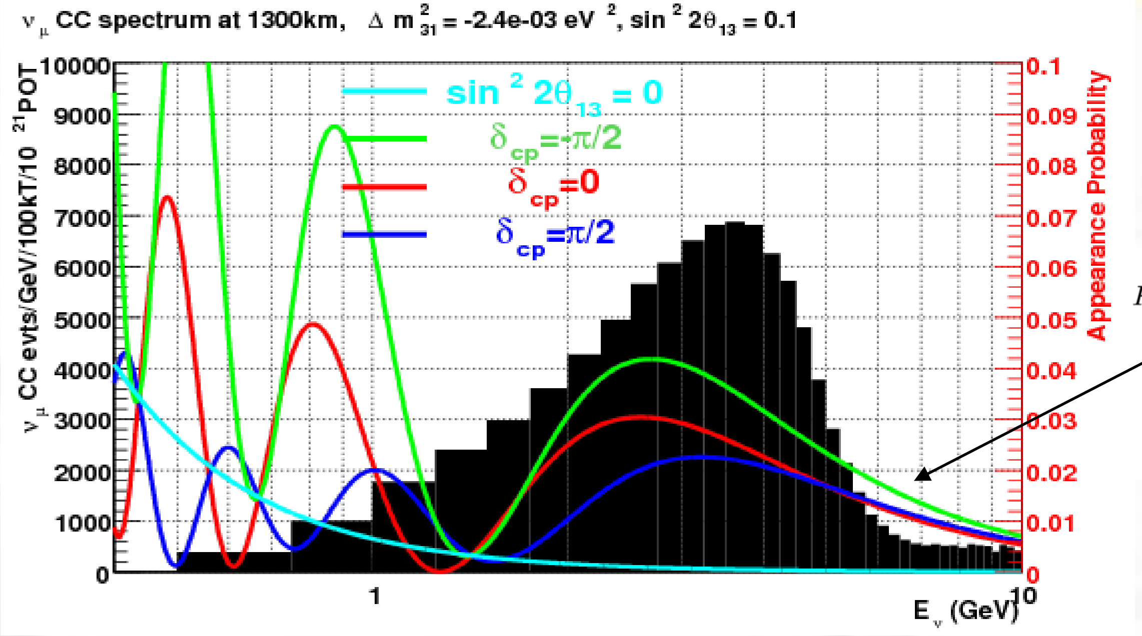
Drift and collect ionization e⁻ in liquid argon (~2 e⁻ per μm). Try to identify all particles in the event by their ionization or interactions.



- *Detector mass of ~40kTon (or 40Gg if you prefer) of material capable of measuring ionization from neutrino interaction products anywhere in that mass.*

What must the detectors measure?





Rate and spectral differences as a function of CP phase

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\left(1+\frac{4\sqrt{2}G_F n_e E}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

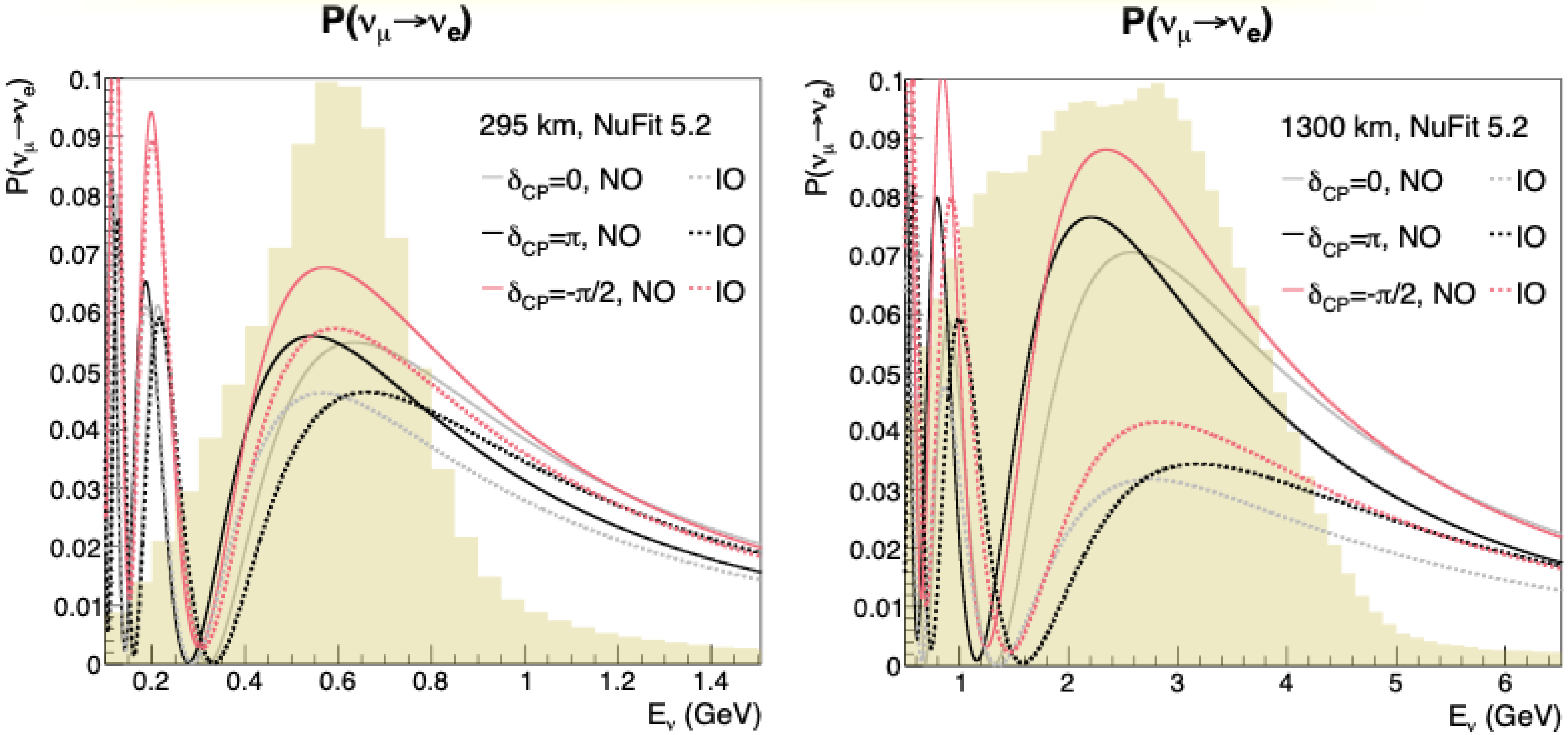
← Leading term

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)$$

↖CP violating term

- In flavor interferometry, neutrinos are characterized by <u>flavor</u> and <u>energy</u>.
- But the beam has a broad spectrum. And events are rare, so need to observe flavor and energy from all the possible final states.
  - *Requires a detailed understanding of a large number of neutrino interaction mechanisms, and how they may obscure energy and flavor.*

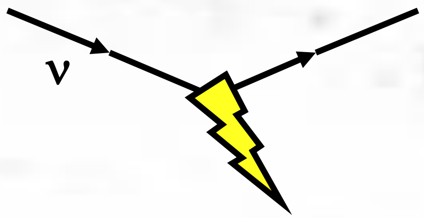
Oscillation at Hyper-K and DUNE



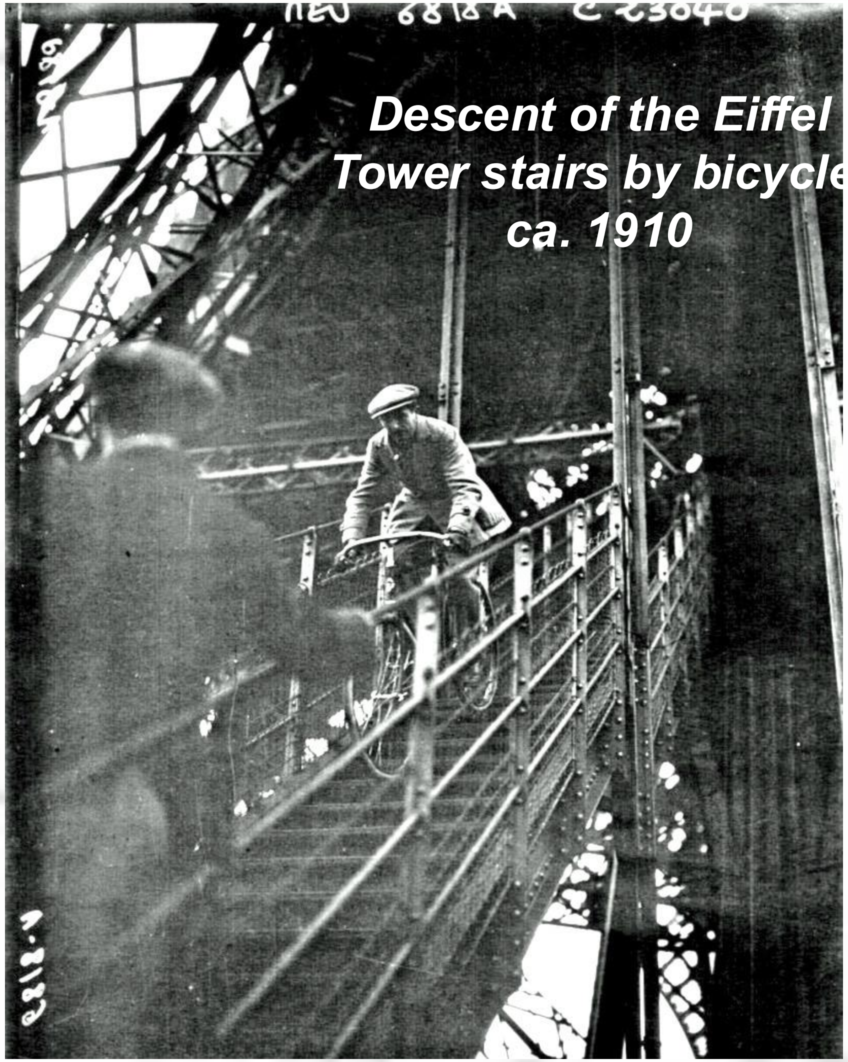
NO: Normal Mass Ordering
IO: Inverted Mass Ordering

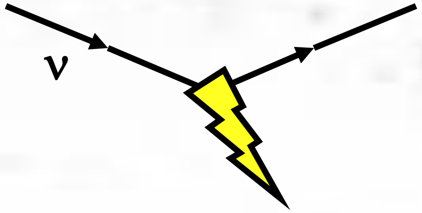
- *Note the very different probabilities for HyperK and DUNE!*

Failed Multi-Scale Problems



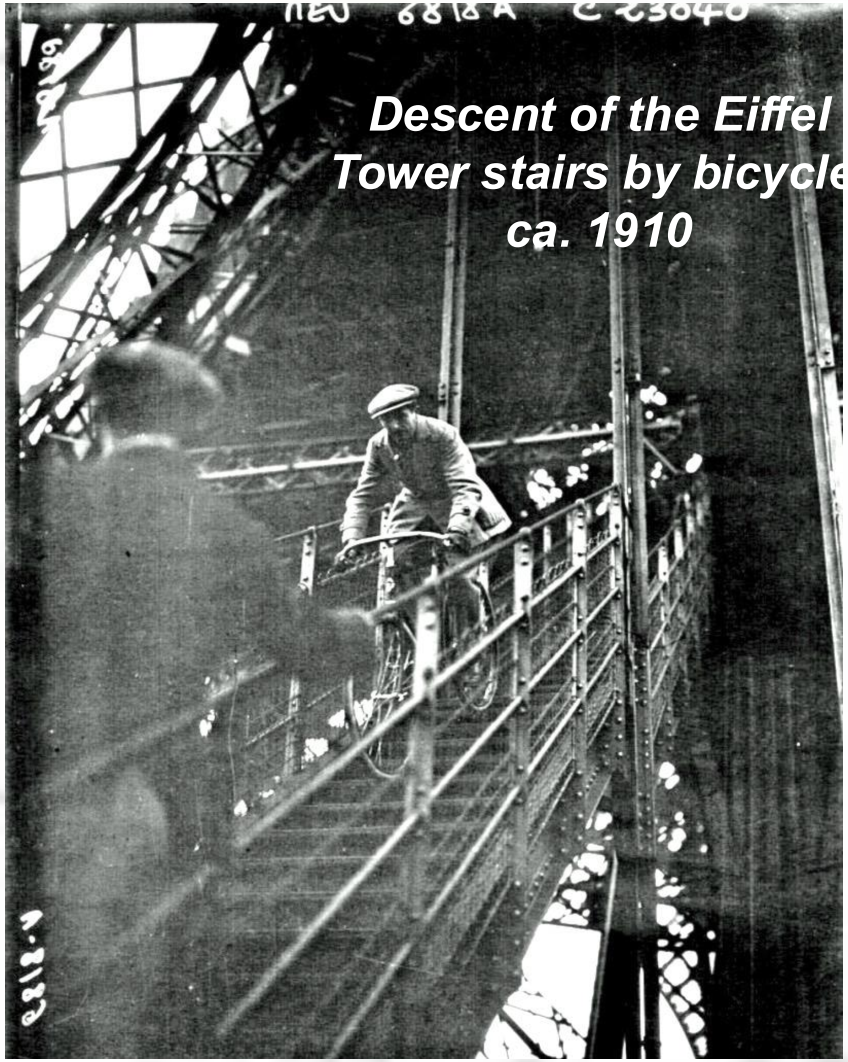
- Consider a bicycle rider at right, descending the stairs of the Eiffel Tower
  - A bicycle wheel is ~1m in diameter.
  - If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist's trajectory.

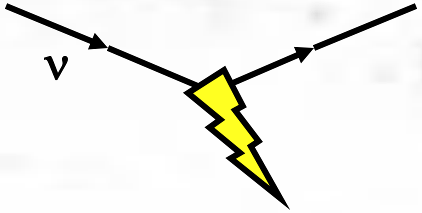




Failed Multi-Scale Problems

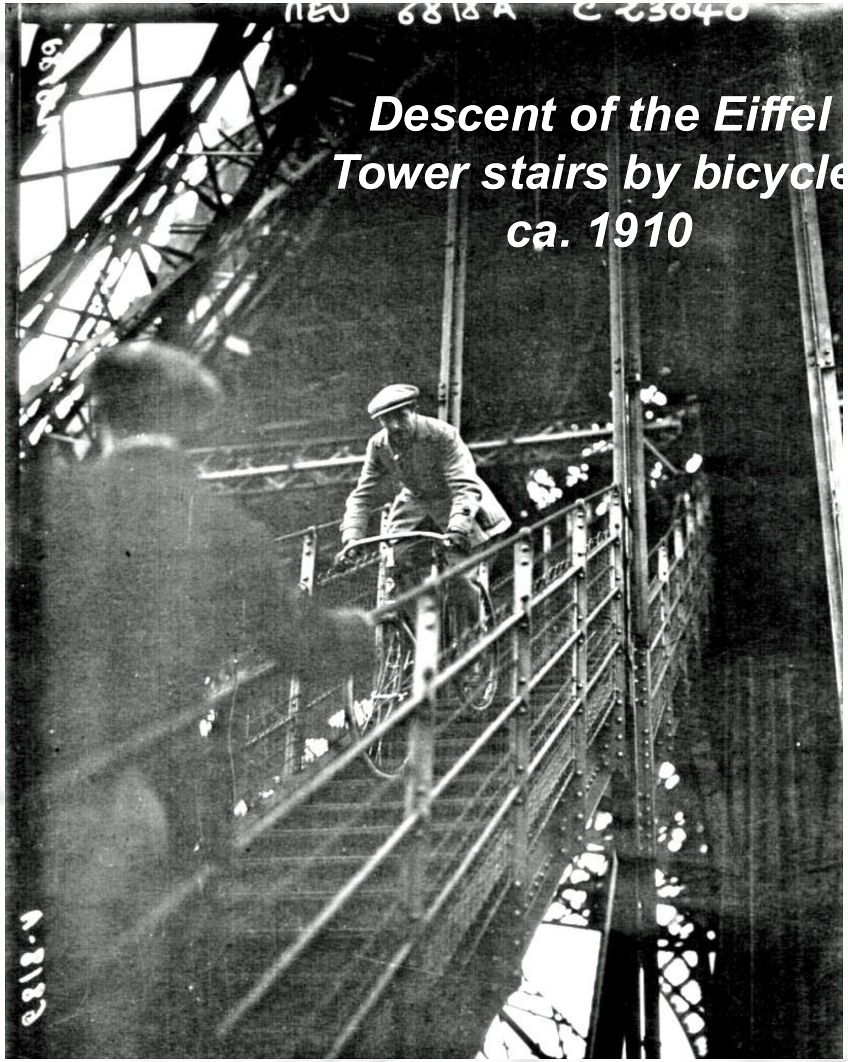
- Consider a bicycle rider at right, descending the stairs of the Eiffel Tower
  - A bicycle wheel is ~1m in diameter.
  - If steps were ~1cm height or the steps were ramps of ~100m, we could predict the cyclist's trajectory.
- *But since the wheel size is too close to the step size, the only reliable prediction is that it is going to be painful.*





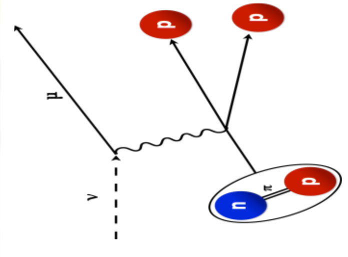
Our Failed Multi-Scale Problem

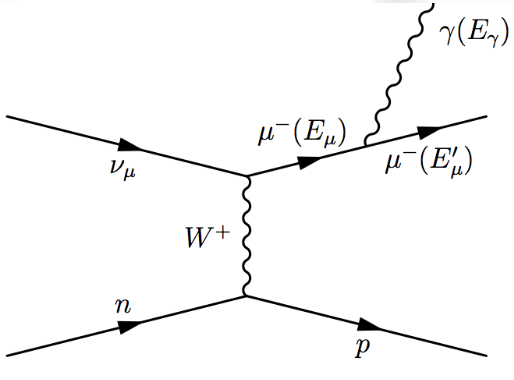
- We have $E_\nu \sim 500 - 5000$ MeV, and therefore energy transfers from nearly zero to $\mathcal{O}(1000)$ MeV.
- Nuclear response at these neutrino energies spans elastic, metastable excitations, quasielastic (knockout), and inelastic (production of new particles).
- But single nucleon separation energy in ^{40}Ar is ~ 30 MeV, and the inelastic threshold, $m_\Delta - m_N \sim 250$ MeV.
- Processes cannot be cleanly separated, and models can't approximate away nuclear structure, nor final state degrees of freedom.
- *Sacre bleu! Hang onto your handlebars!*

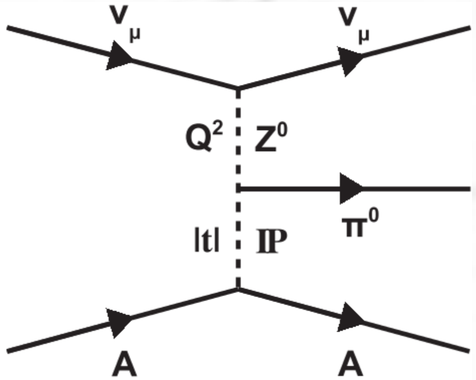

Descent of the Eiffel Tower stairs by bicycle ca. 1910

More Problems in ν Interactions

- There are other, subleading processes that are also difficult to model, but potentially important.
- Knocking out multiple nucleons ("2p2h", two-particle-two-hole, or more) is surprisingly common and difficult to model.
- Radiative corrections to neutrino interactions will be different for muon and electron neutrinos.
- Coherent π^0 production on nuclei produces very energetic photons with little else in the event to warn it wasn't a ν_e with an energetic electron.
- And so forth…

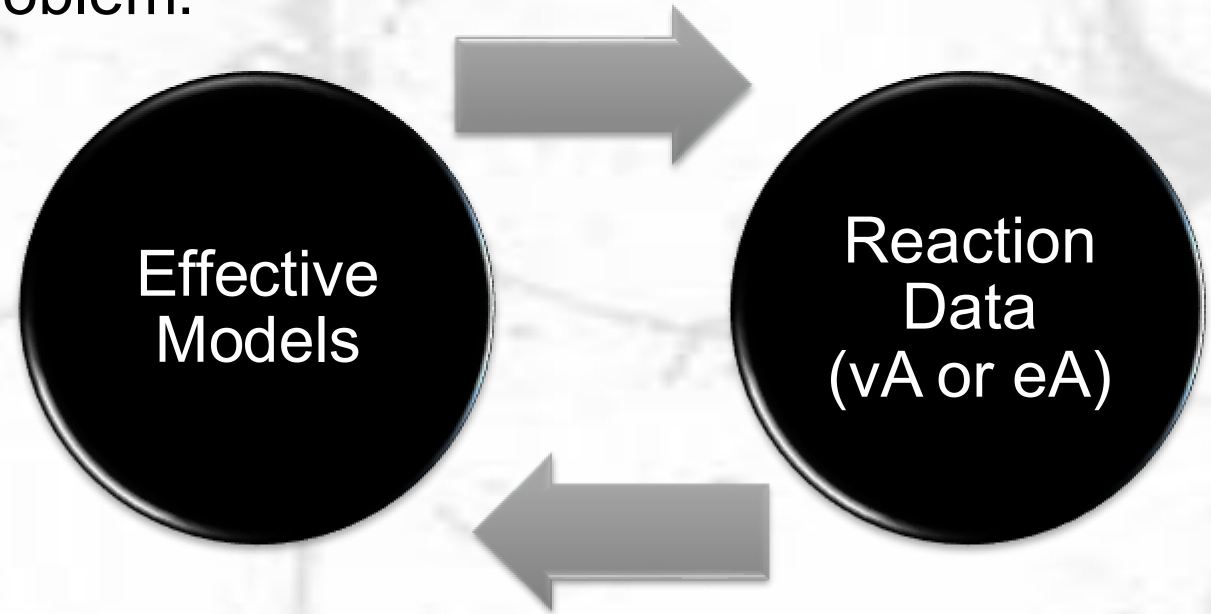






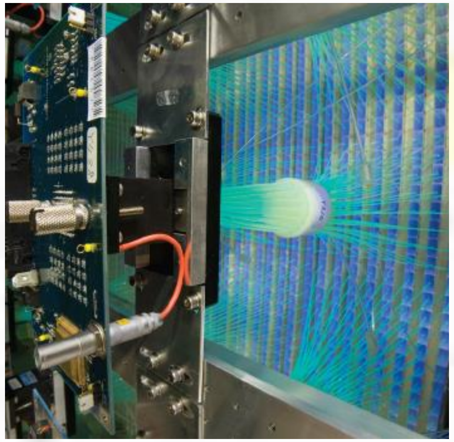
Theory and Experiment

- Both are critical, but both are limited in what they can offer.
- Theory, as noted, uses necessary approximations, is limited in phase space, or calculates overly inclusive reactions ill-suited to describing the full final state.
- Data are good at pointing out modeling deficiencies, but often poor at pinpointing the problem.

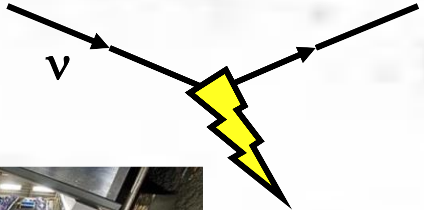


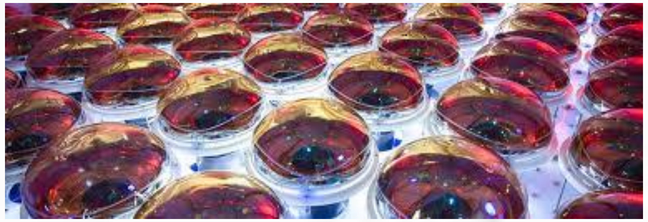
Experiments: Detectors

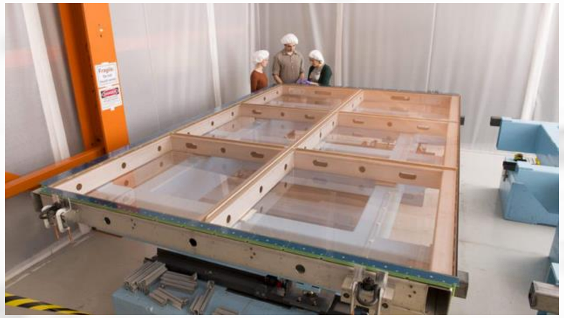
(who studies this, and how?)

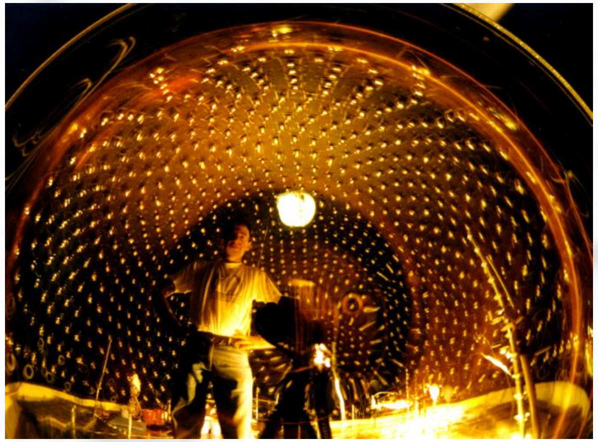


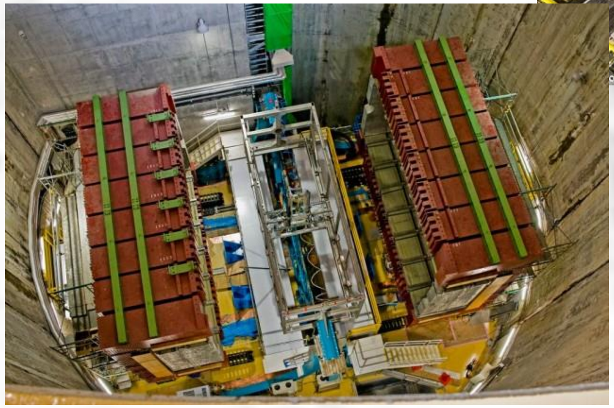
Lots of Experiments









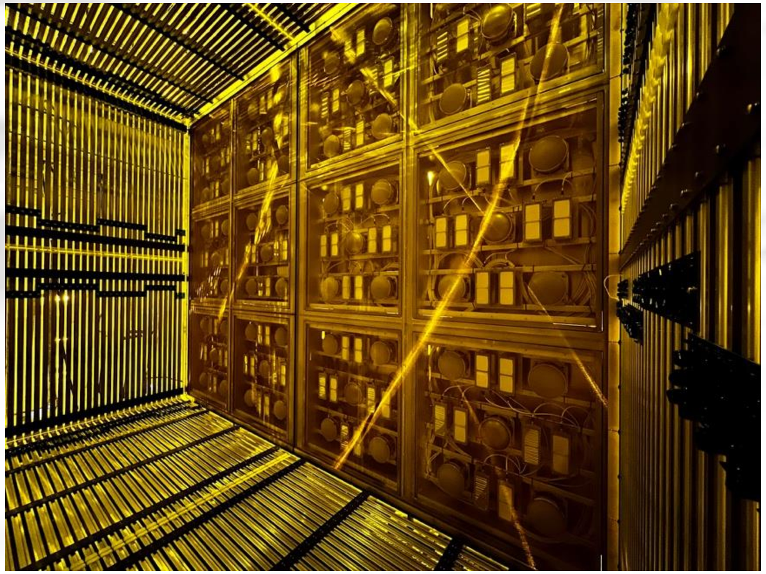


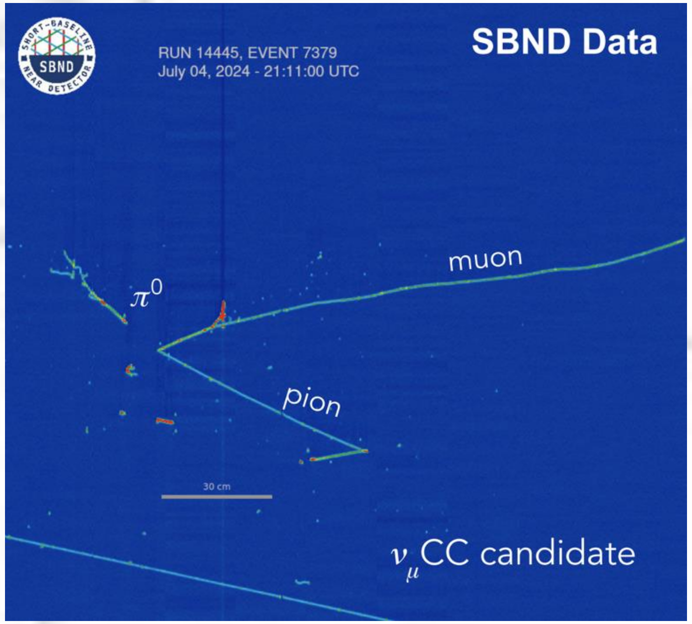
- Short baseline oscillation experiments have enough rate to also measure neutrino interactions: LSND, MiniBooNE, MicroBooNE.
- Oscillation experiments have near detectors which measure interactions with varying degrees of effort: K2K, MINOS, T2K, NOvA, SBN.
- A few dedicated experiments: SciBooNE, MINERvA, ANNIE.

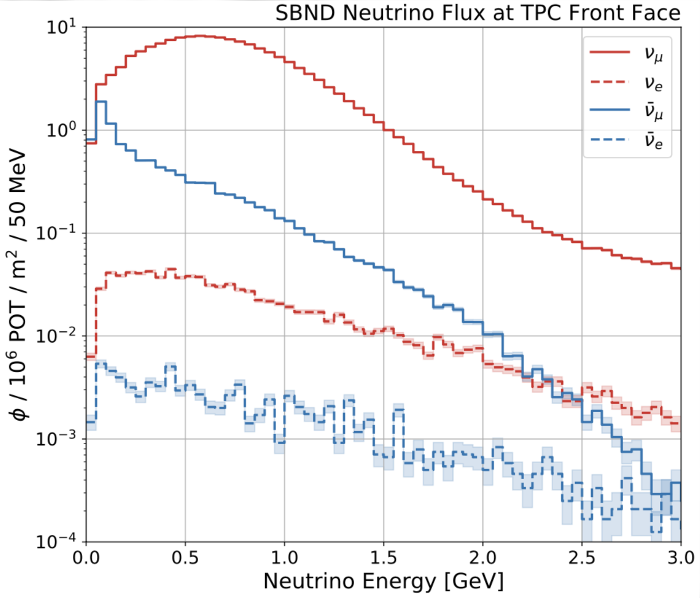
DONE, PUBLISHING, ALMOST…

SBN Program Near Detector (SBND)

- SBND utilizes liquid argon TPC (LArTPC) technology because of its low particle thresholds and good particle identification.
- Close to the beam source and massive, it will accumulate nearly NOvA near detector or MINERvA sized statistics on argon.

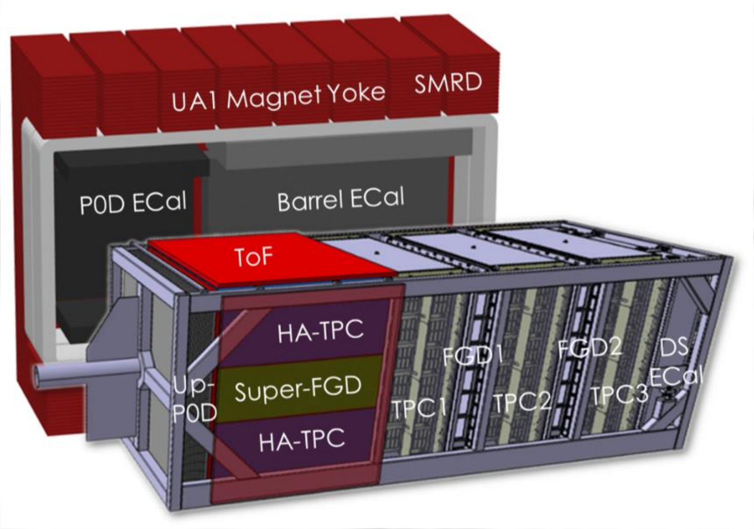


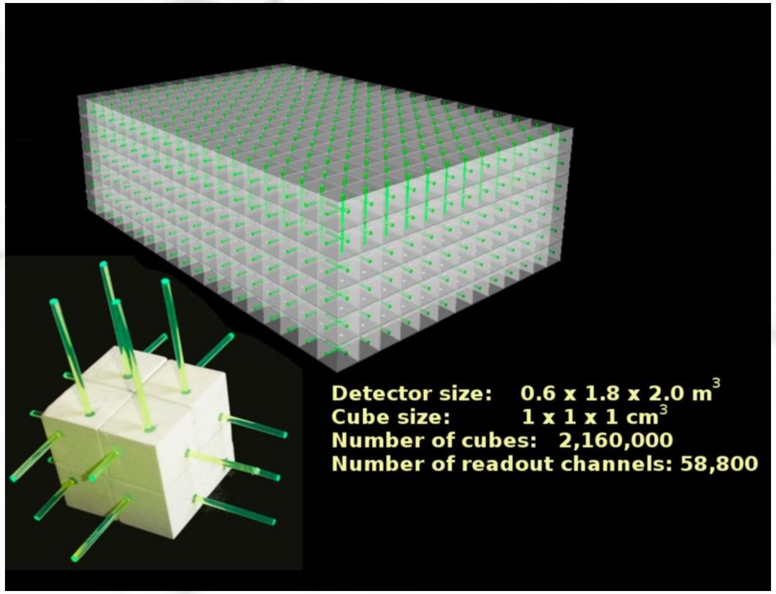


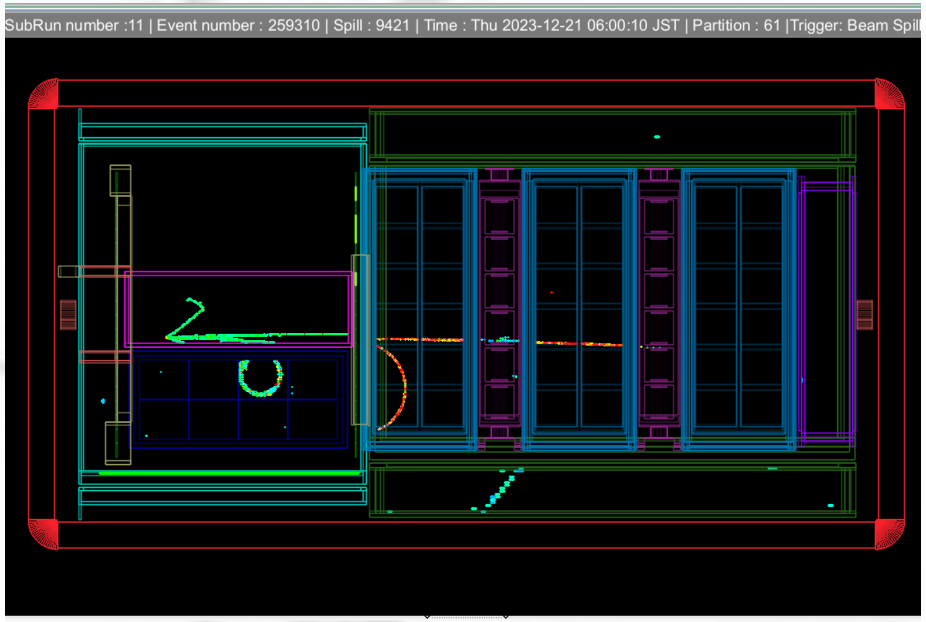


T2K/HyperKamiokande SuperFGD

- The SuperFGD 3D pixelated scintillator also provides increased granularity for high multiplicity and low thresholds.
- Also has excellent neutron capability, including time-of-flight momentum reconstruction.

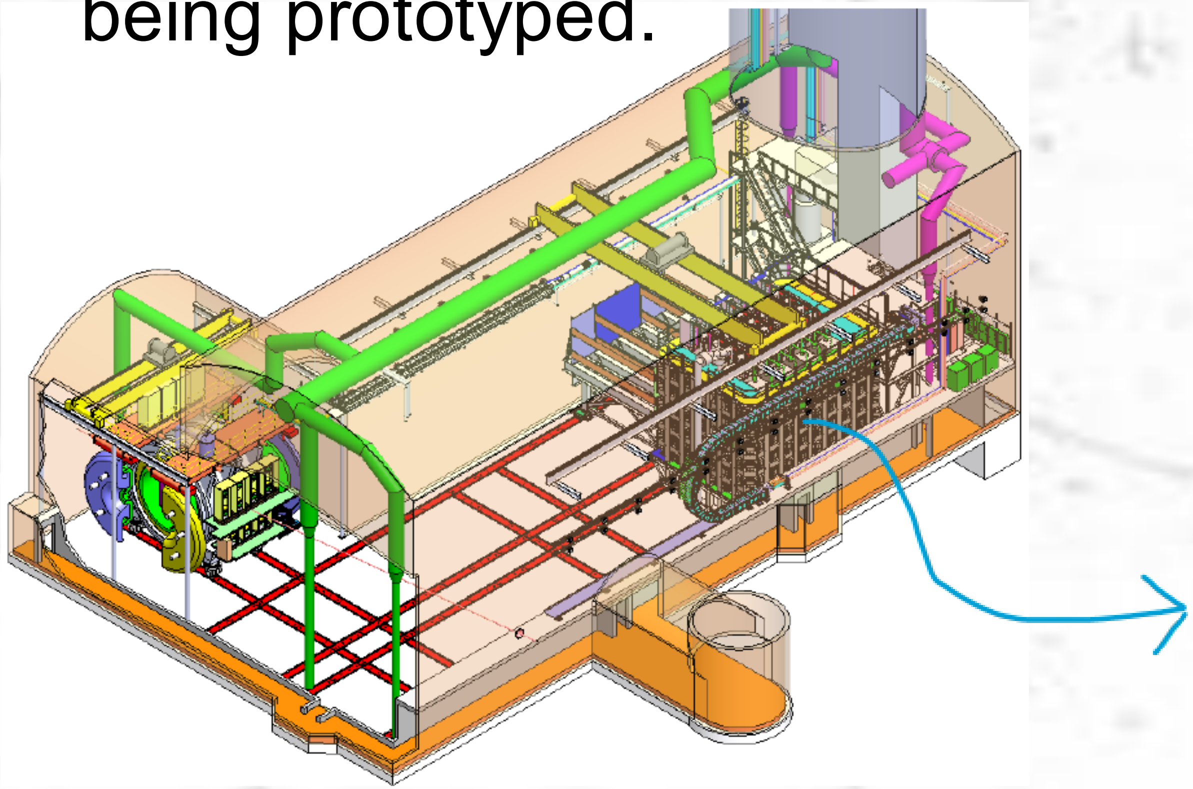


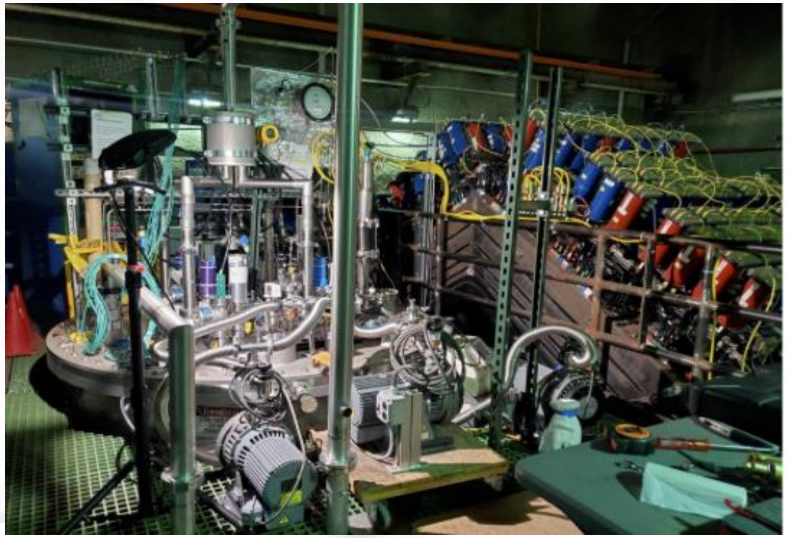


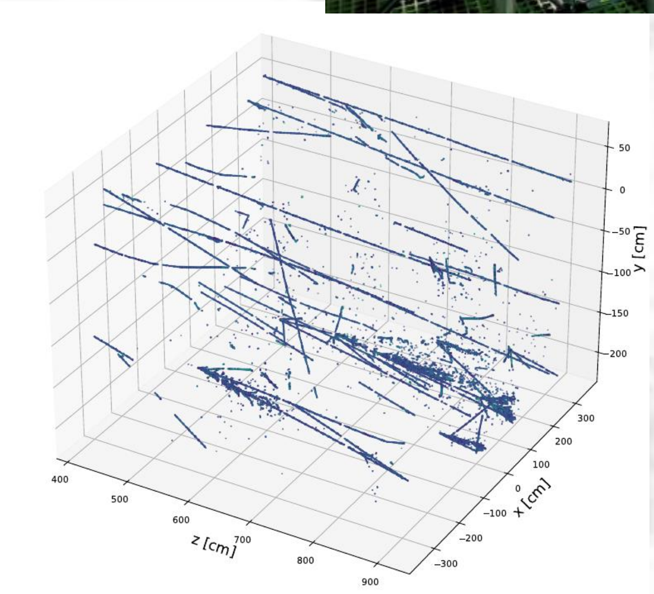


Future: DUNE Phase One Near Detector

- Includes PRISM concept in novel segmented LArTPC, which is currently being prototyped.

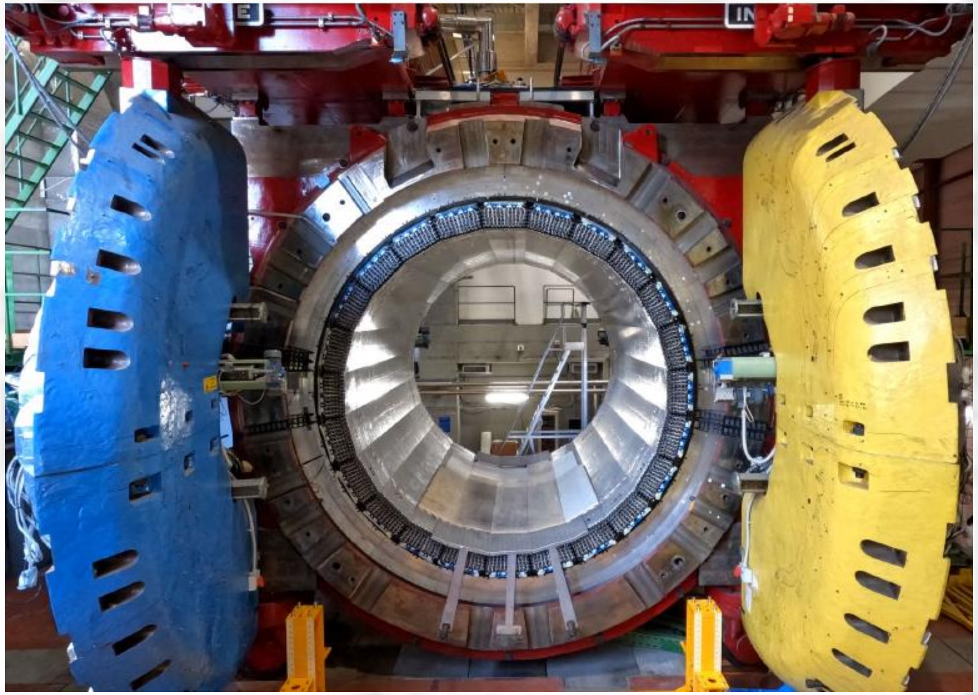


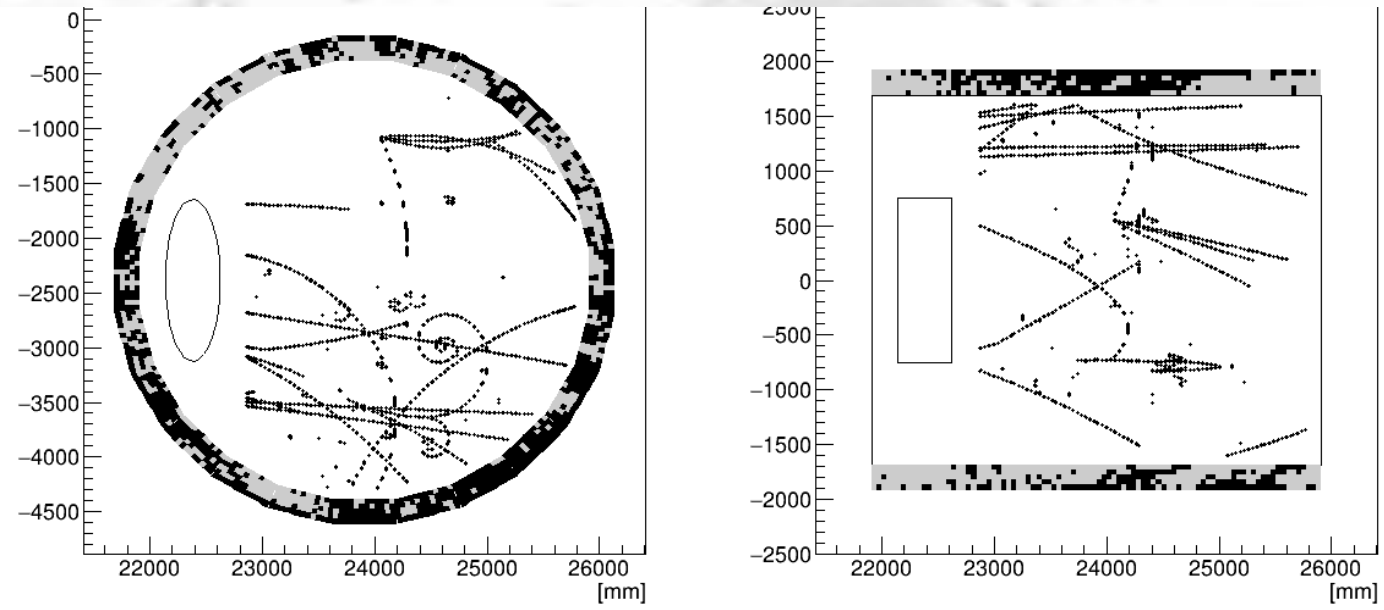




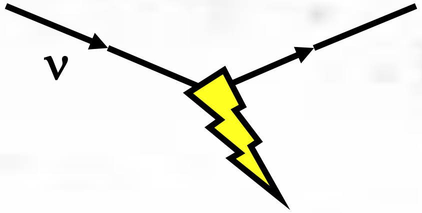
DUNE Phase One Near Detector

- SAND includes CH_2 and C (for separation of H and C) and Ar targets to compare interactions on different nuclei.

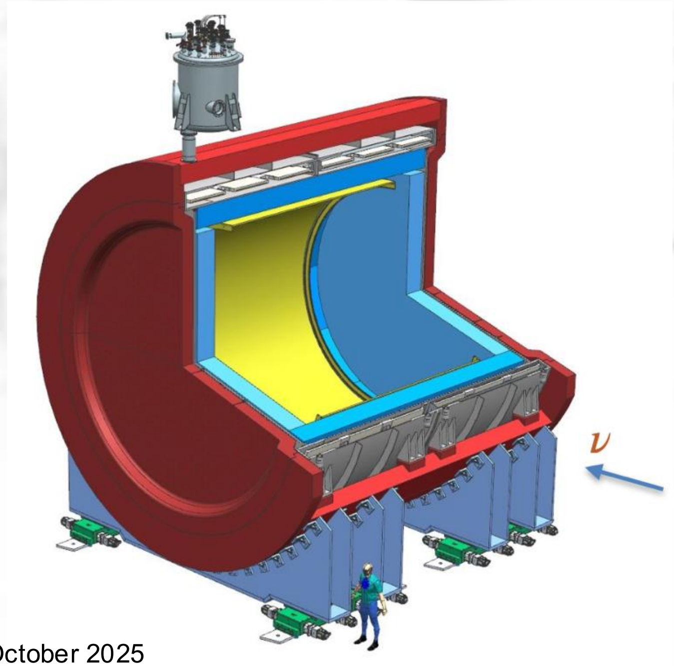


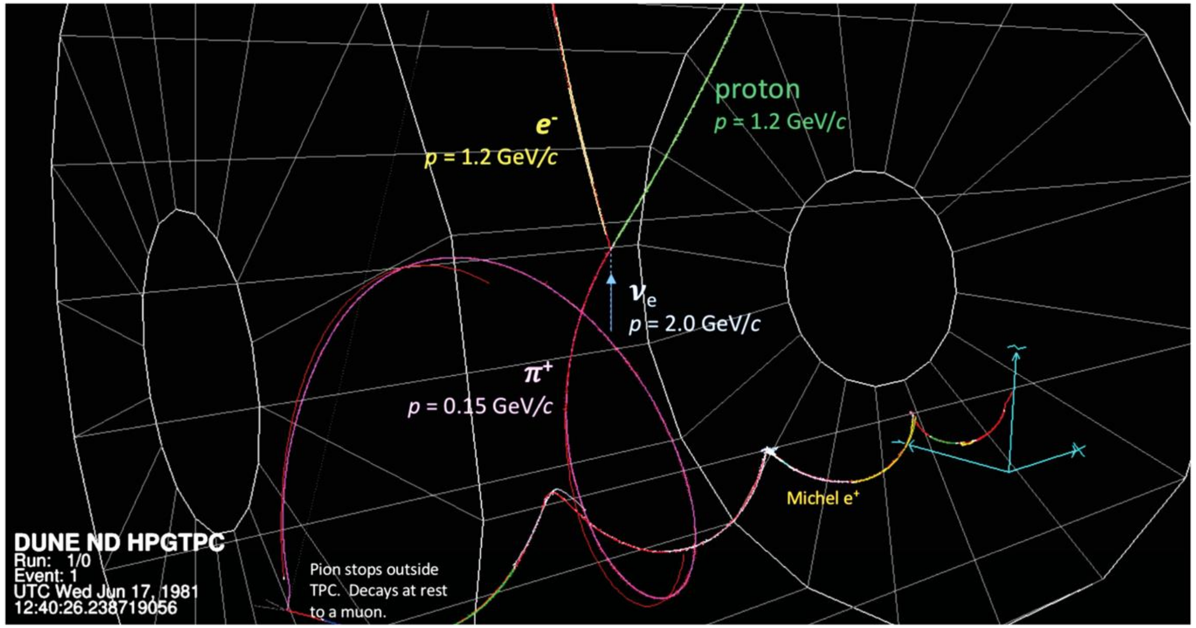


DUNE Phase Two Gaseous *“more capable”* ND

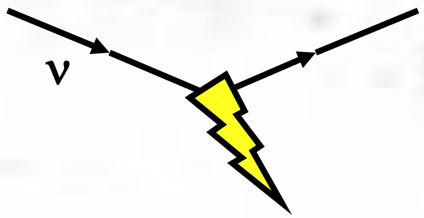


- A future gaseous argon detector would provide bubble-chamber like low thresholds for reconstruction of charged particles.
- Valuable information about energy lost to nuclear final states.



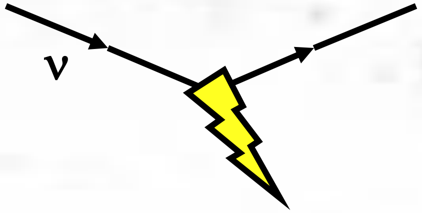


P5 Town Hall March 2023



Experiments: Neutrino Beams

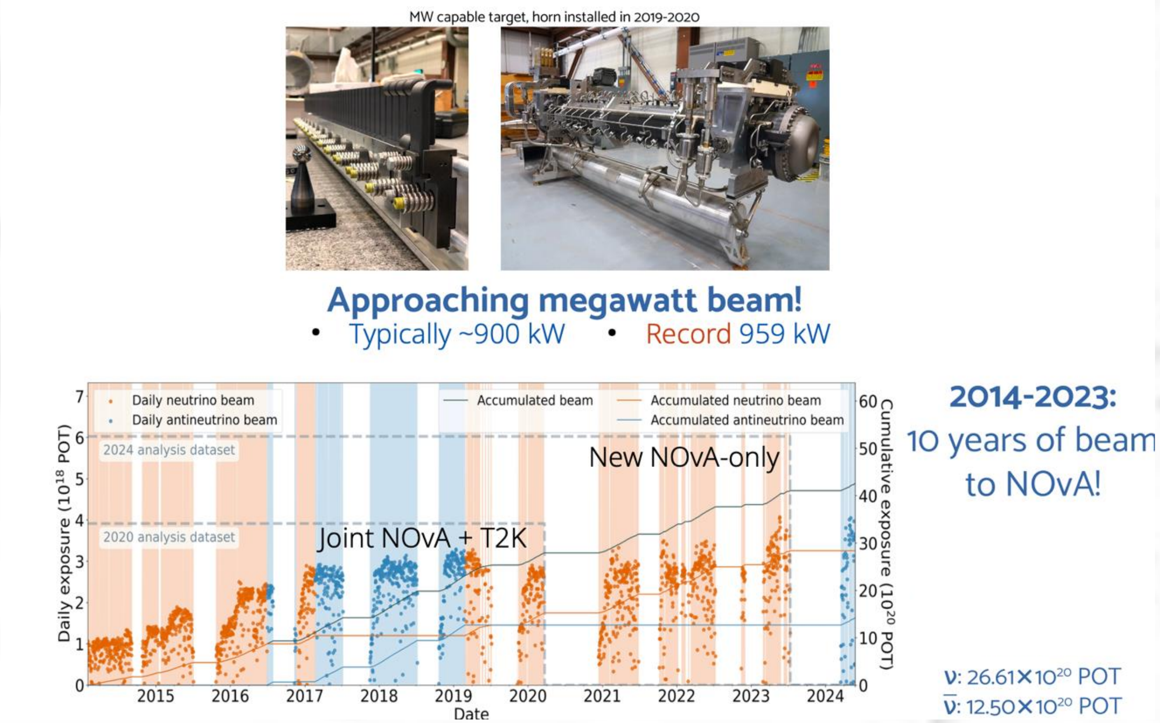
what do we have to work with?



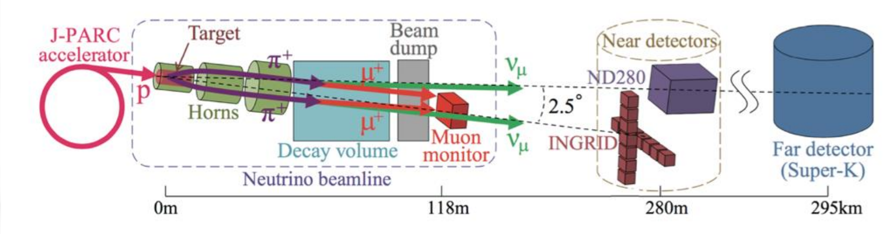
Neutrino Beams: Intensity

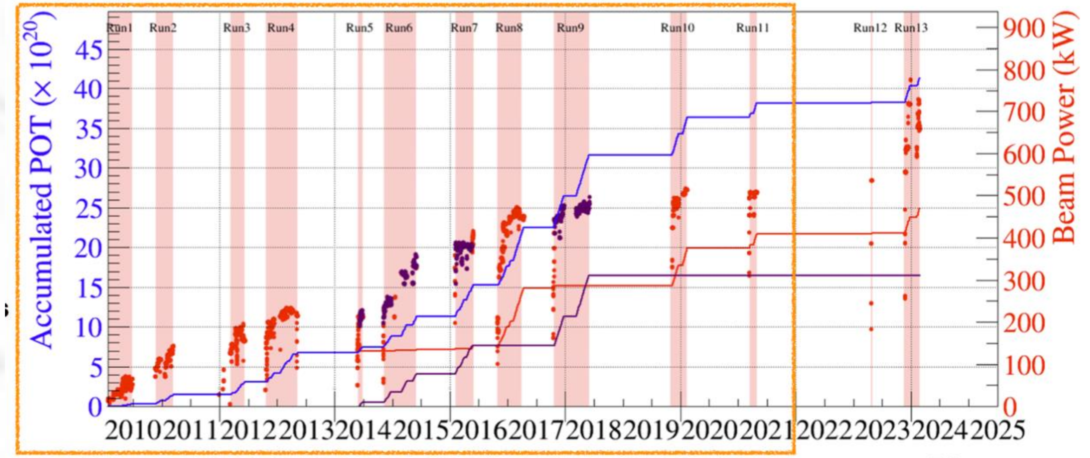
- We have two ~GeV neutrino beams approaching 1MW beam power, both with incremental paths to slowly increasing power.

NOvA beam (NuMI)

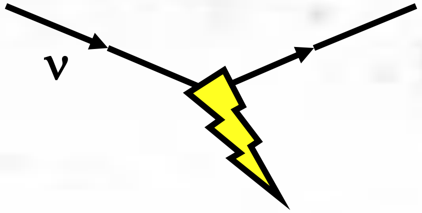


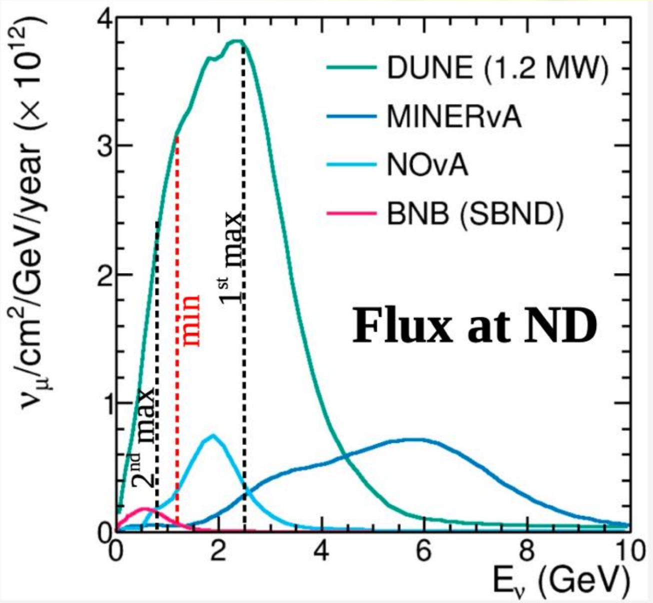
T2K beam





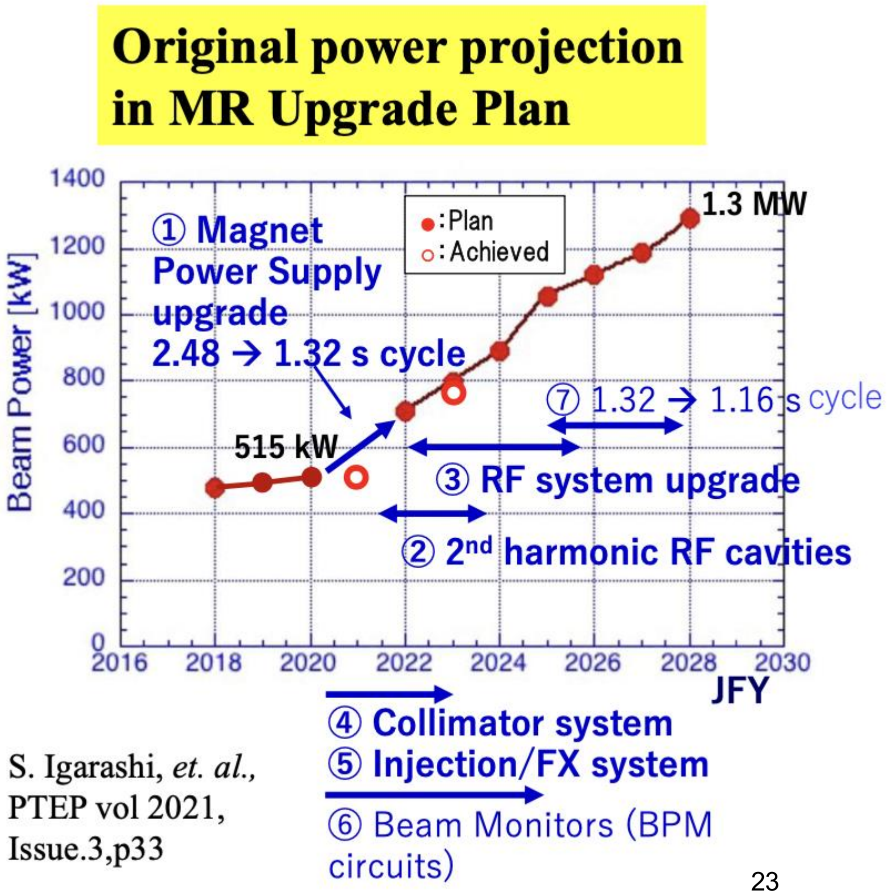
Neutrino Beams: Intensity



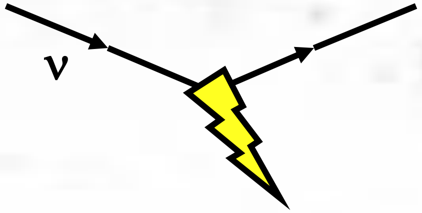


- Both FNAL and J-PARC have paths to significant increases in what is now the visible future.

- ACE-MIRT upgrade enables >2MW beam by ~doubling frequency of spills, and can be achieved before operations begin

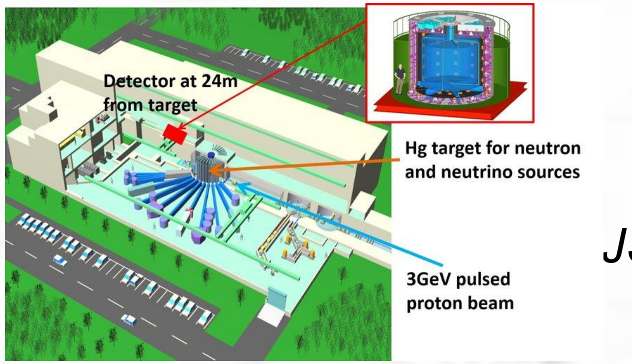


S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

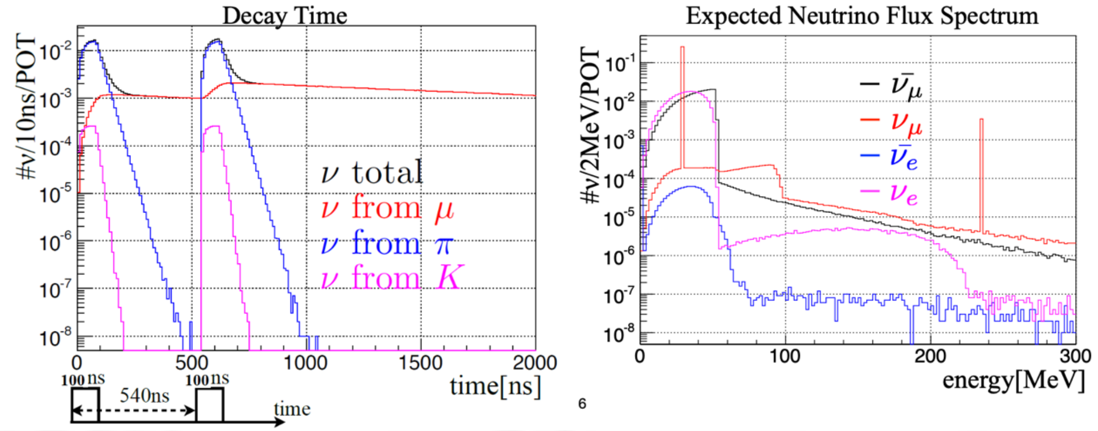


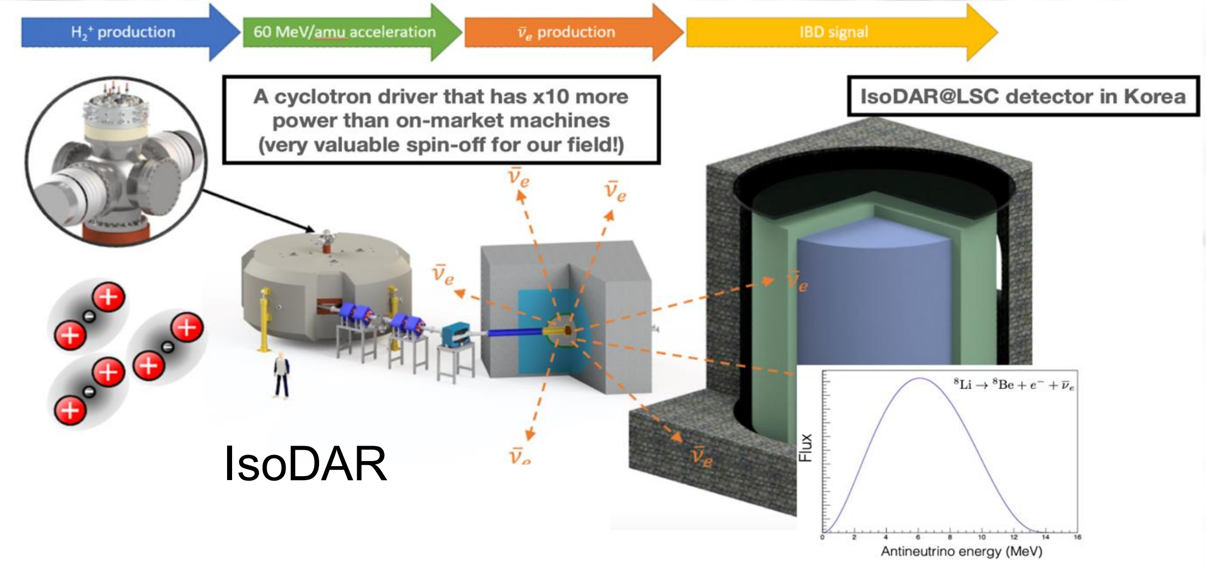
Neutrino Beams: Flavor

- Our conventional beams are muon neutrinos. But…
- …can produce *electron neutrinos* through decay-at-rest of leptons or ions, and even tackle the challenging task of capturing and accelerating them (nuSTORM).

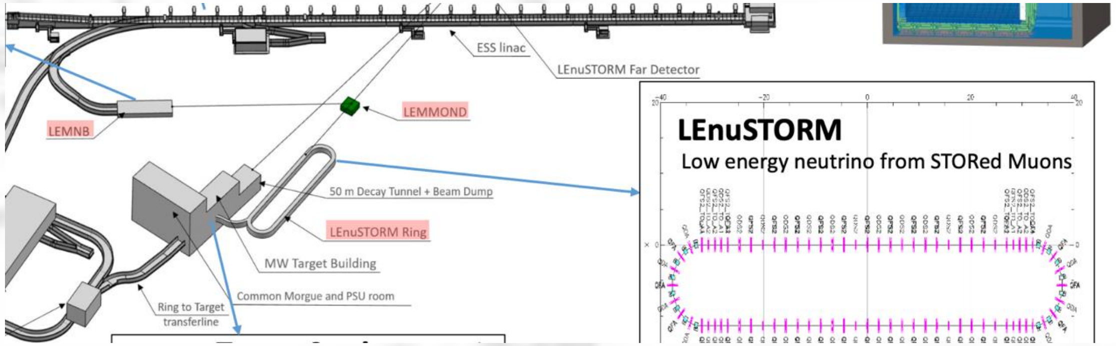


JSNS





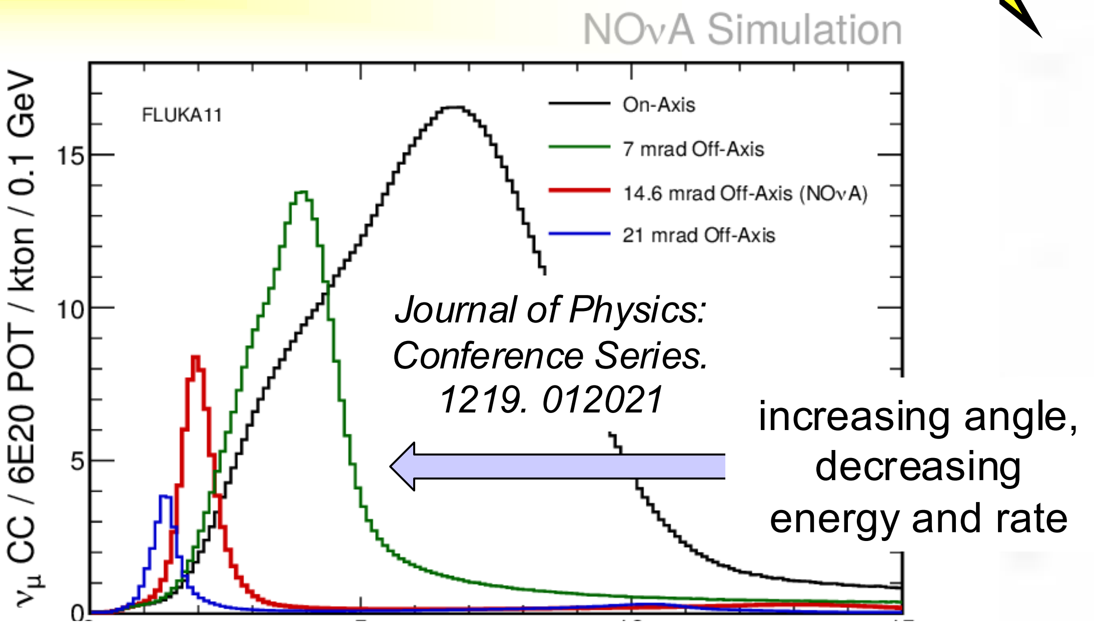
IsoDAR

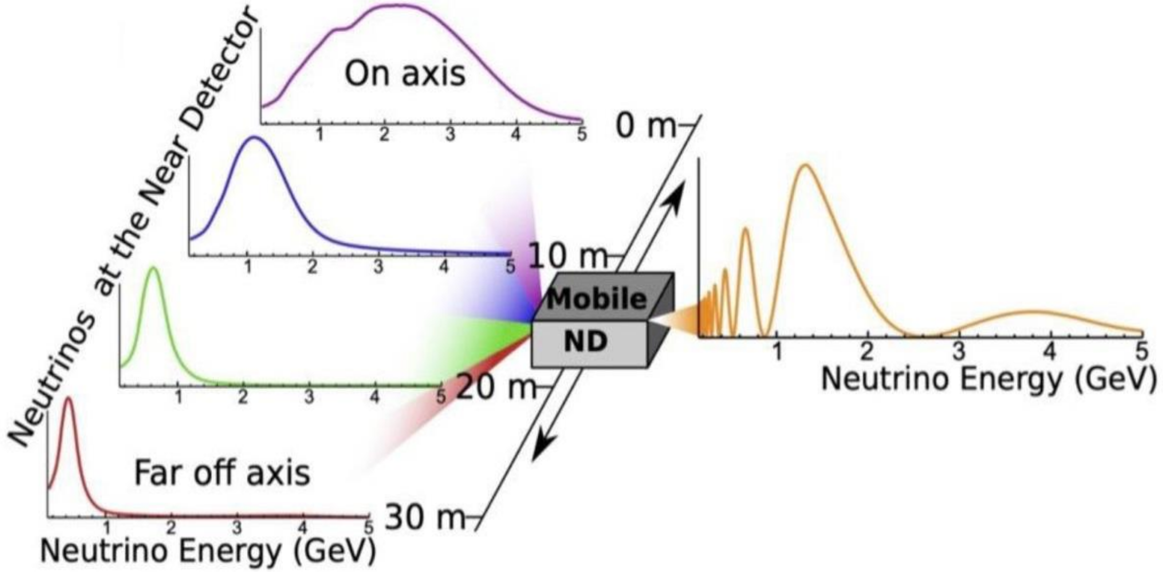


ESSnuSB

Energy by Location

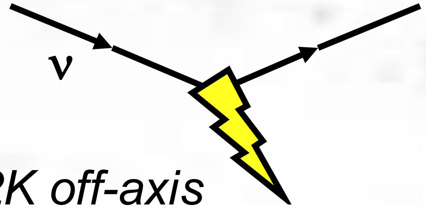
- Beams (like NuMI) can be tuned to produce different energies.
- But also, NOvA and T2K use the “off-axis” technique, pointing the beam away from the detector to select neutrino energy.
- PRISM: measure many off-axis angles in the same near detector to study beams of different energies.



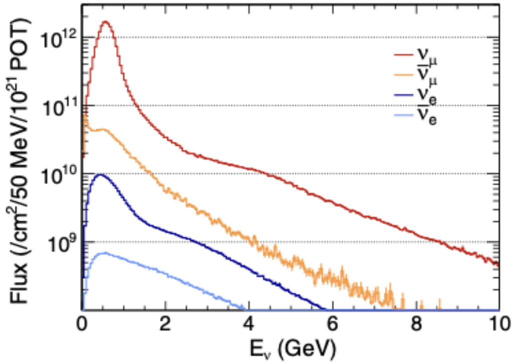


Energy by Location

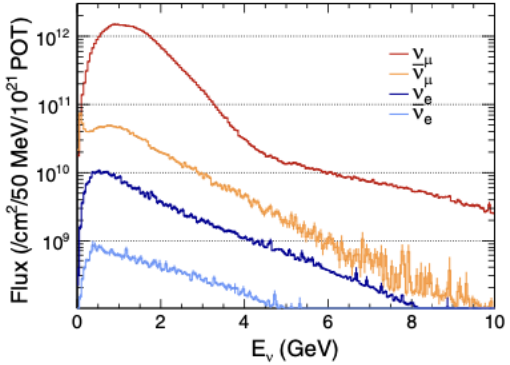
- T2K and MINERvA have both produced first results exploiting this to measure energy dependence.
  - T2K by using different detectors in different locations.

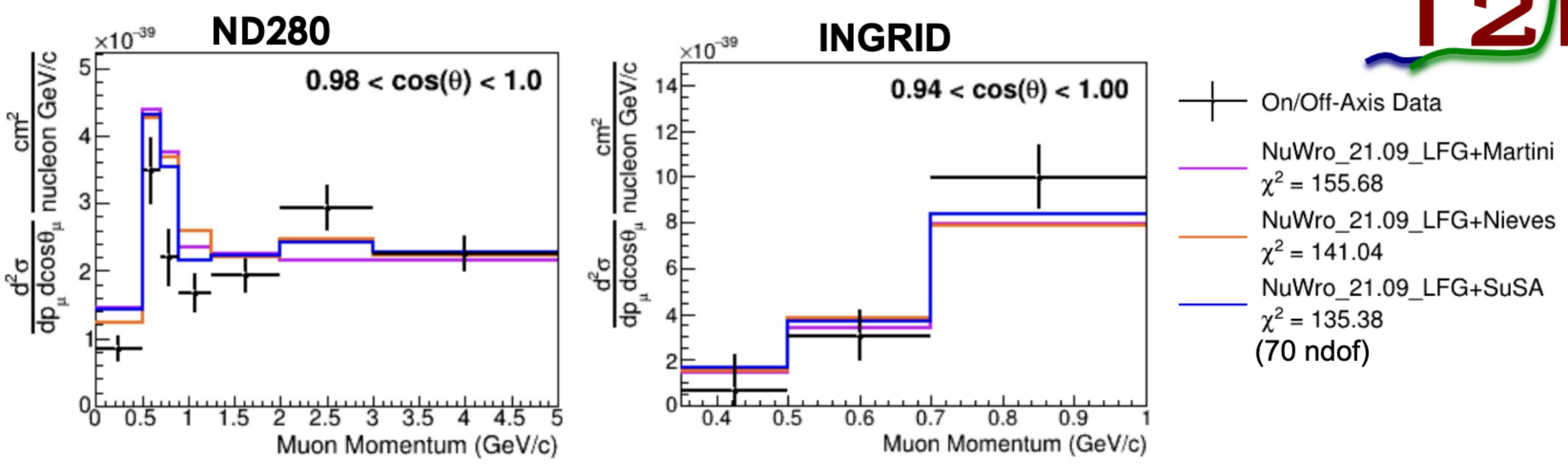


T2K off-axis



T2K on-axis

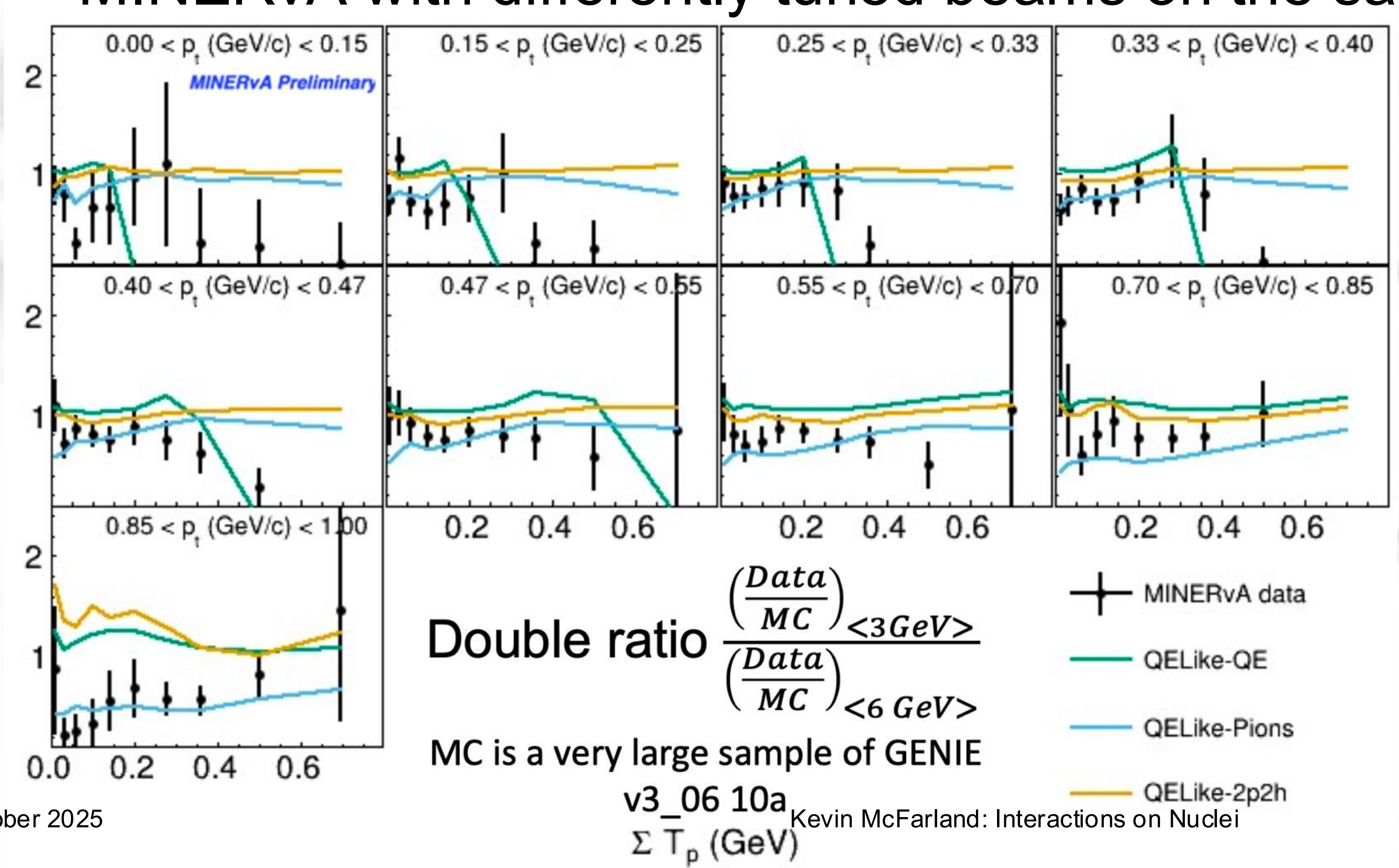


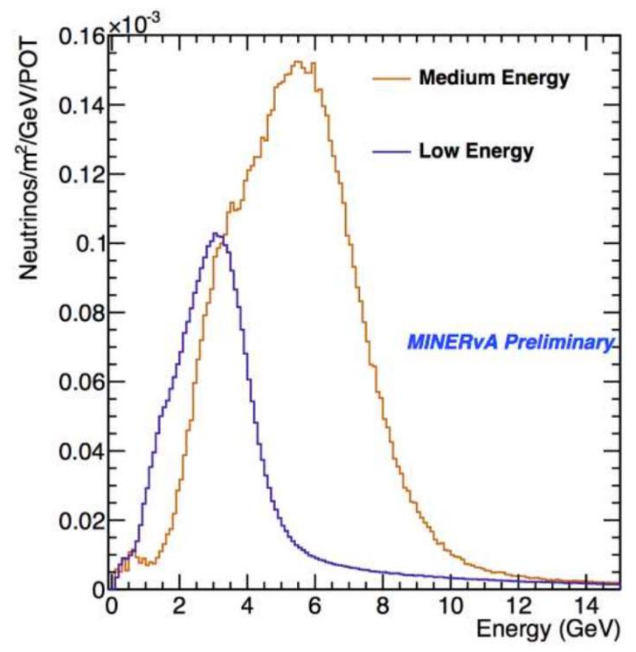


Phys Rev D108, 112009 (2023)

Location… for energy

- T2K and MINERvA have both produced first results exploiting this to measure energy dependence.
  - MINERvA with differently tuned beams on the same detector!

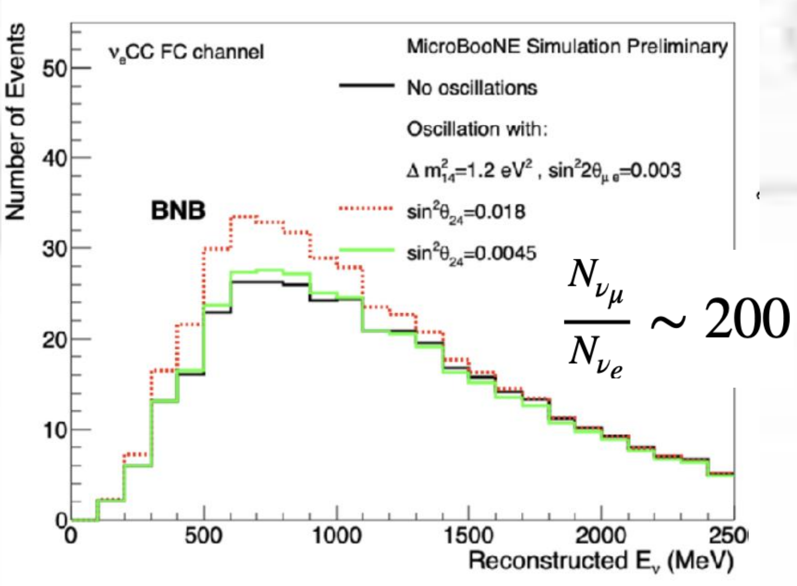


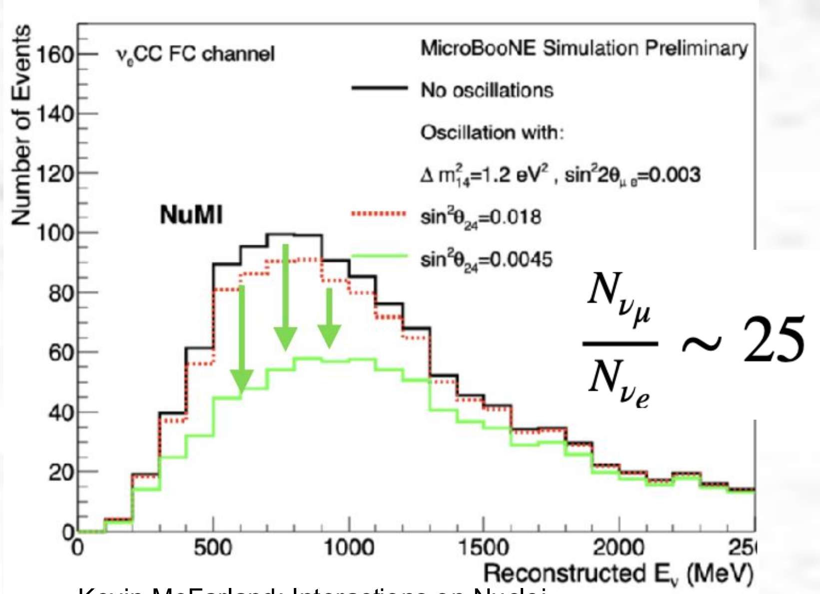


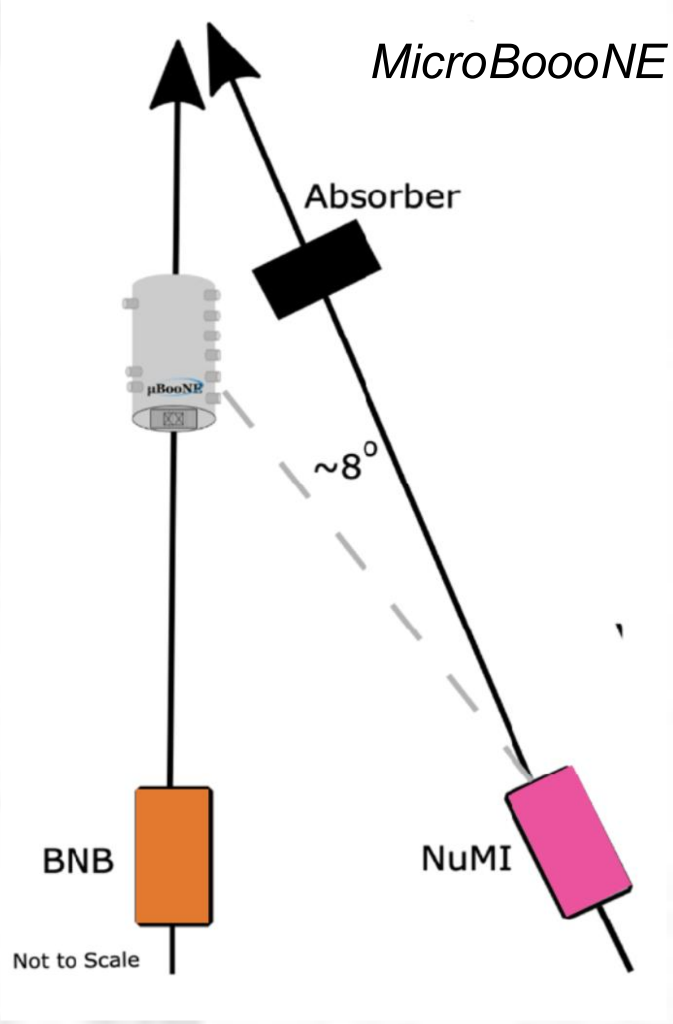
Dan Ruterbories, NuINT 2024

Flavor! By Location

- MicroBooNE uses the NuMI beam **far** off-axis, where there are enhanced contributions from kaon decays, and therefore a larger ν_e fraction.
- MicroBooNE and SBN (ICARUS) plan to exploit this for oscillation and interaction studies.

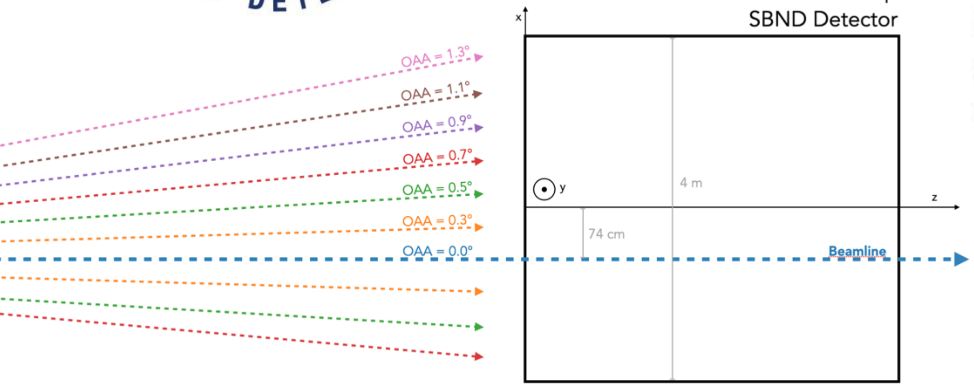


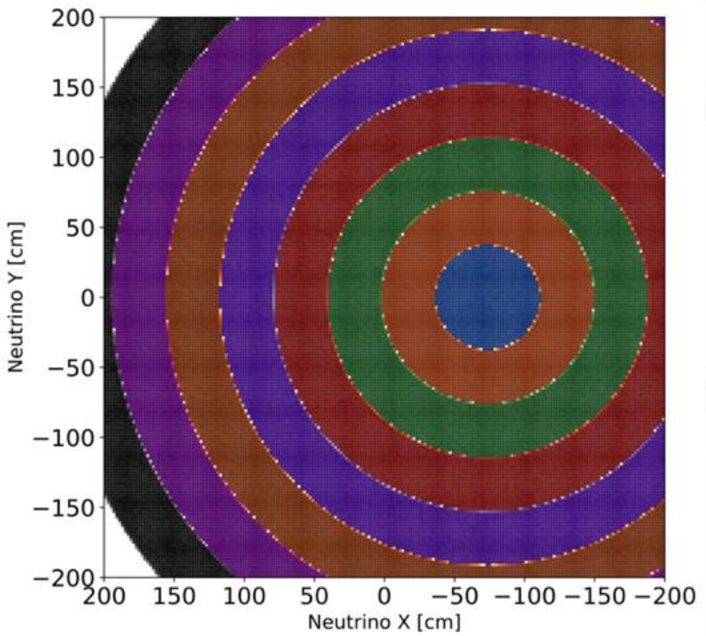


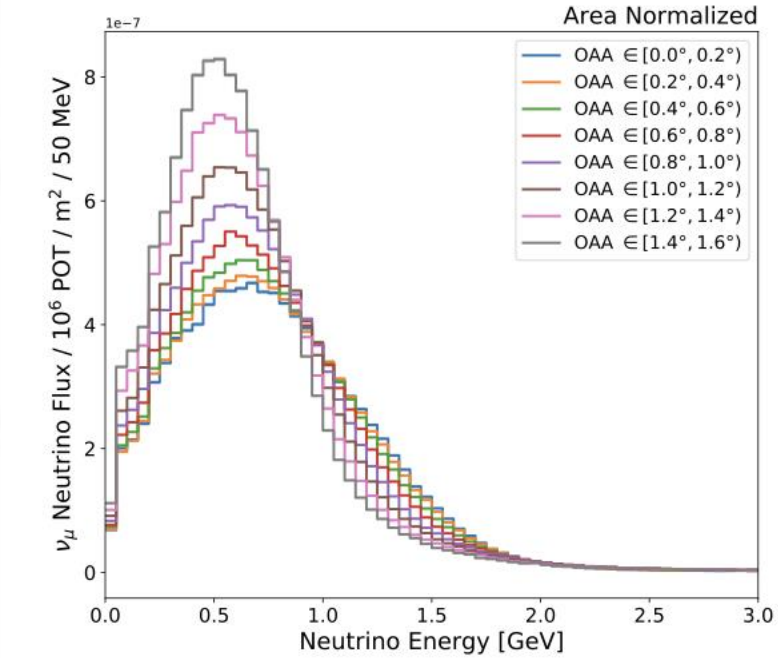


SBND "Mini" *(my word)* PRISM

- In the near future, SBND will be able to do this *within their* detector.
  - Enabled by high statistics, and proximity to a low energy beam.
  - Will be limited by access to low energies far off axis, but it should work well from 0.7 to 1.5 GeV in neutrino energy.

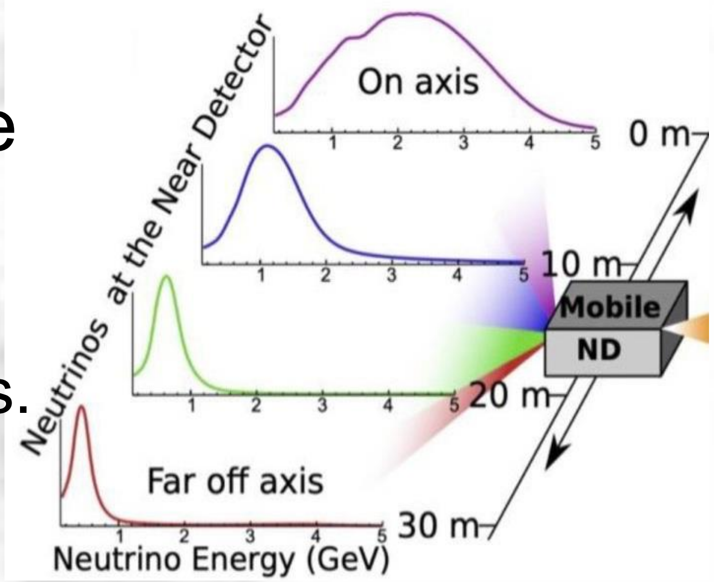




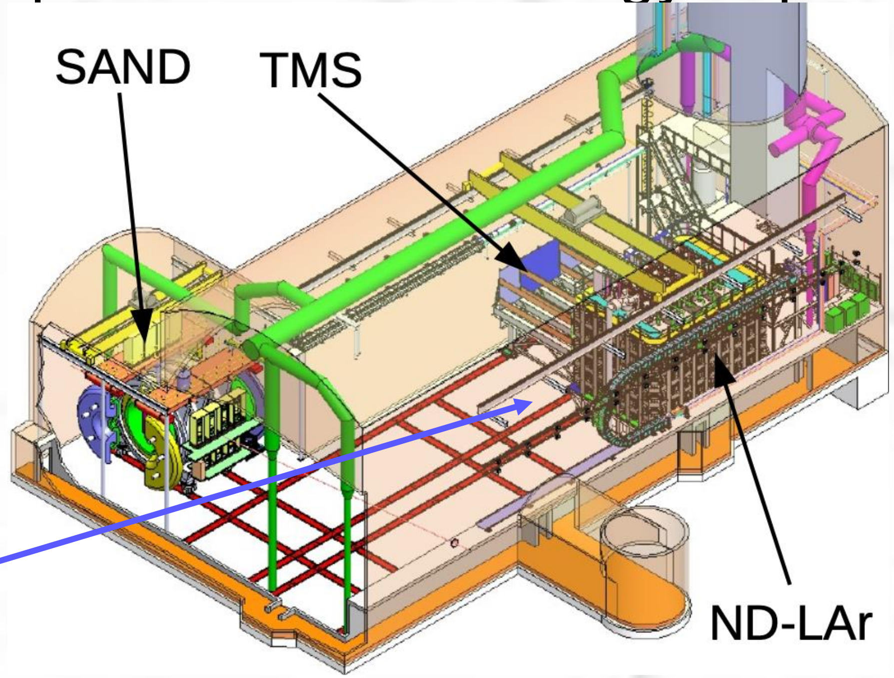


DUNE and HyperKamiokande PRISM

- DUNE and HyperKamiokande both intend to have movable detectors for the PRISM technique.
  - While framed as a tool directly applied to oscillations, this probes neutrino energy dependence of interactions.

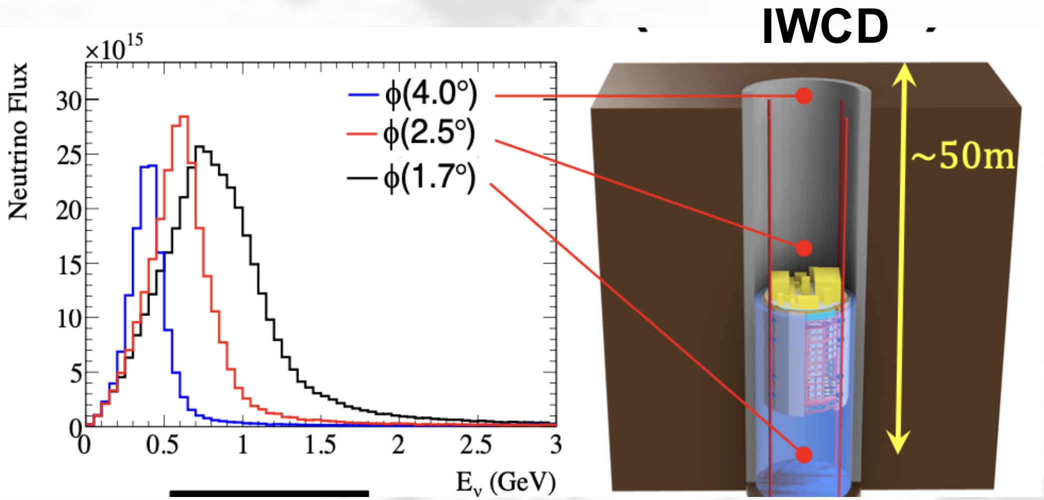


DUNE



movable, for PRISM

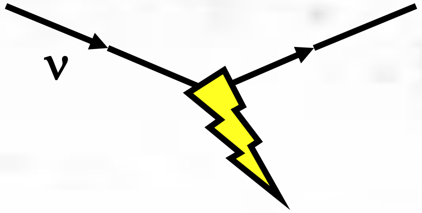
HyperKamiokande



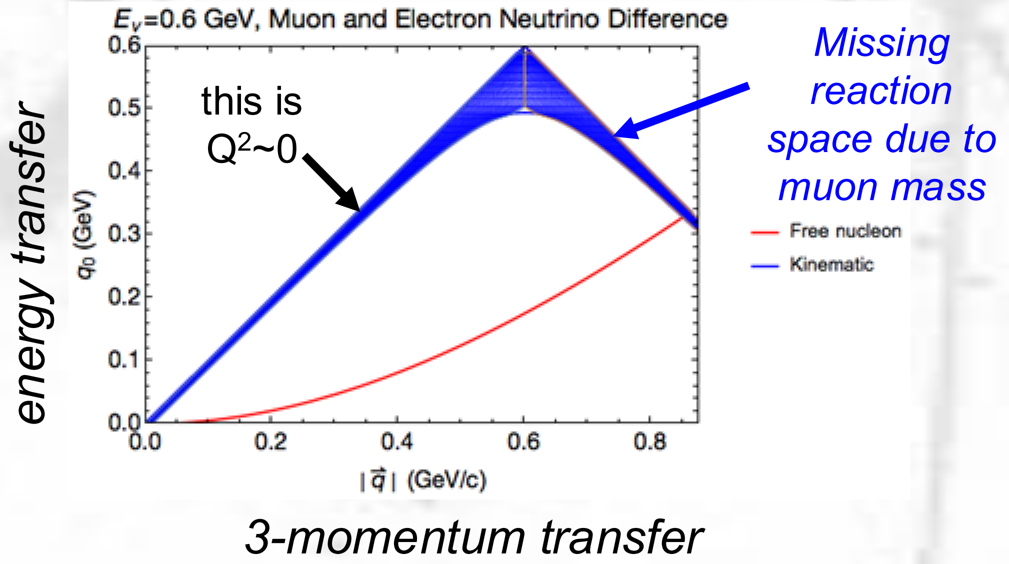
Results and Trends: Interactions by Neutrino Flavor

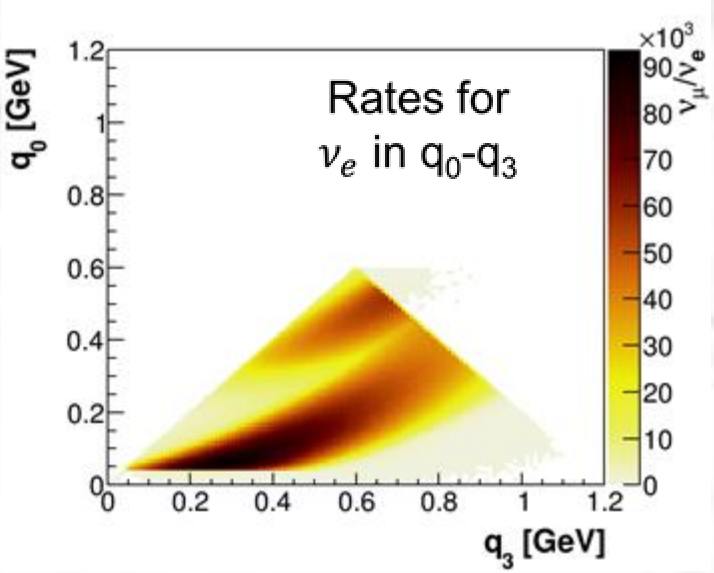
(in American English,
there is no “u” in “flavor”)

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.

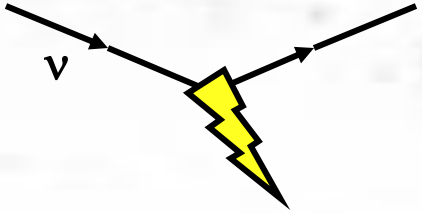


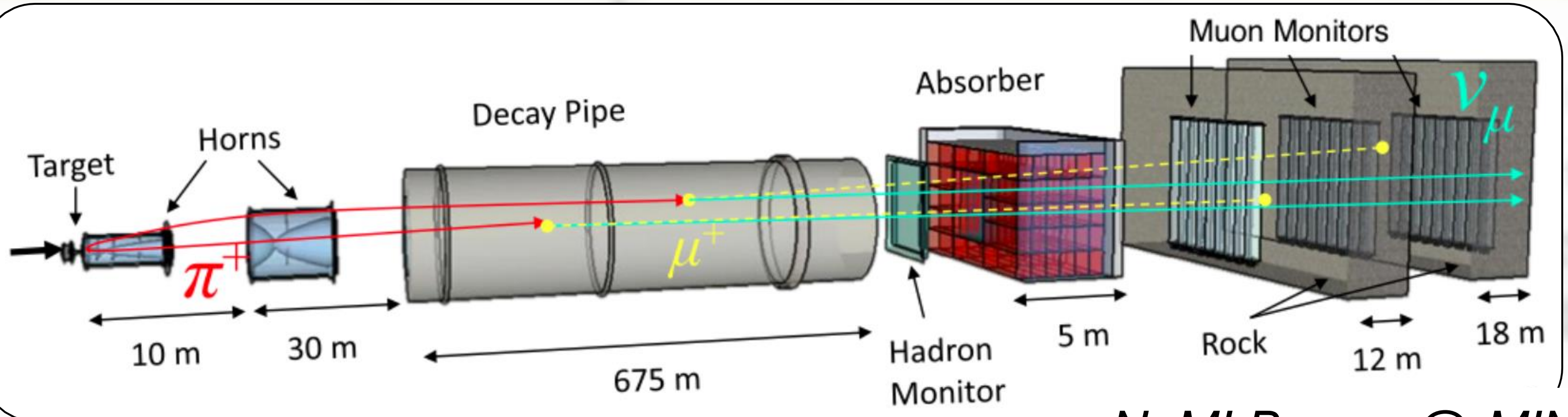


Radiative corrections:
O. Tomalak et al.,
Nature Commun. 13 (2022) 1, 5286
and Phys.Rev.D 106 (2022) 9, 093006

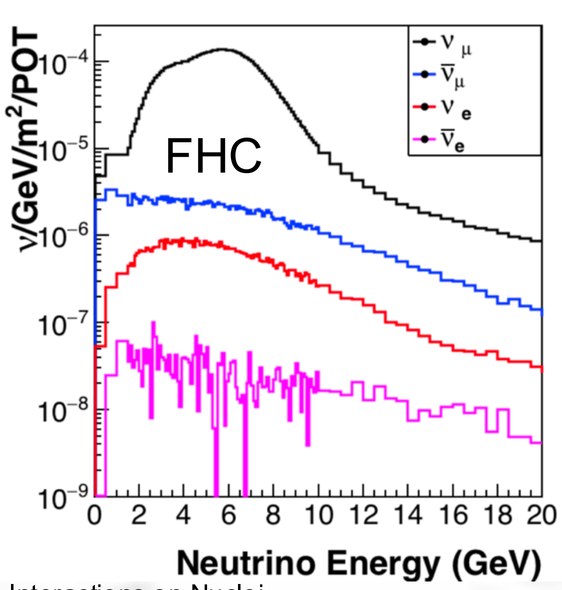
Nuclear effects:
T. Dieminger et al.,
Phys.Rev.D 108 (2023) L031301

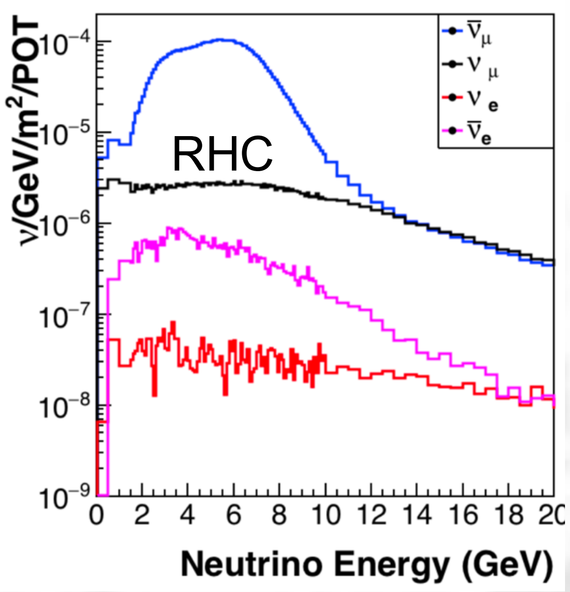
MINERvA: Electron Neutrino Flux





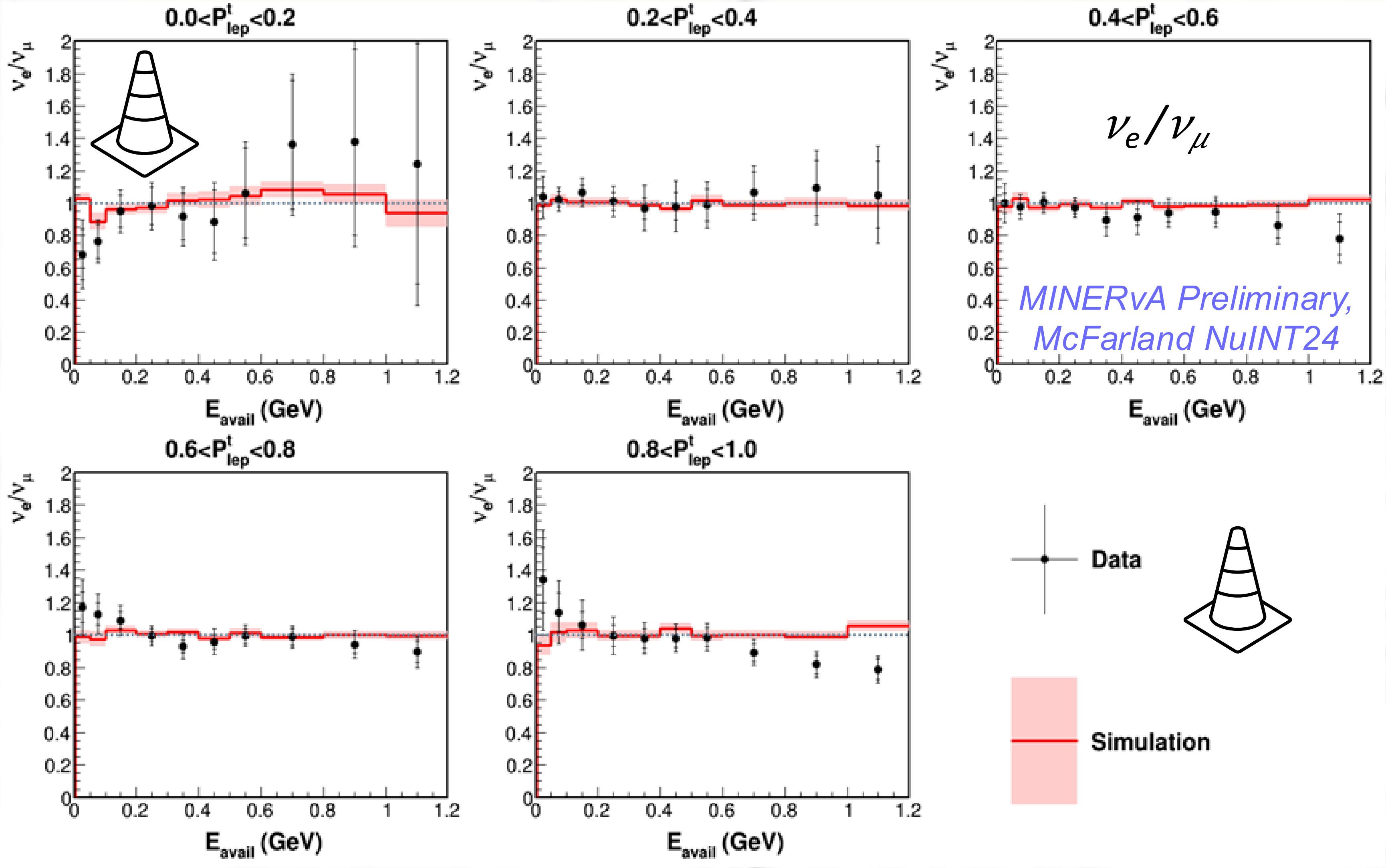
NuMI Beams @ MINERvA

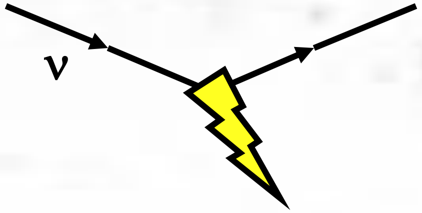




- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons or kaons.
- ~1% contribution of the beam.

MINERvA ν_e/ν_μ Ratios

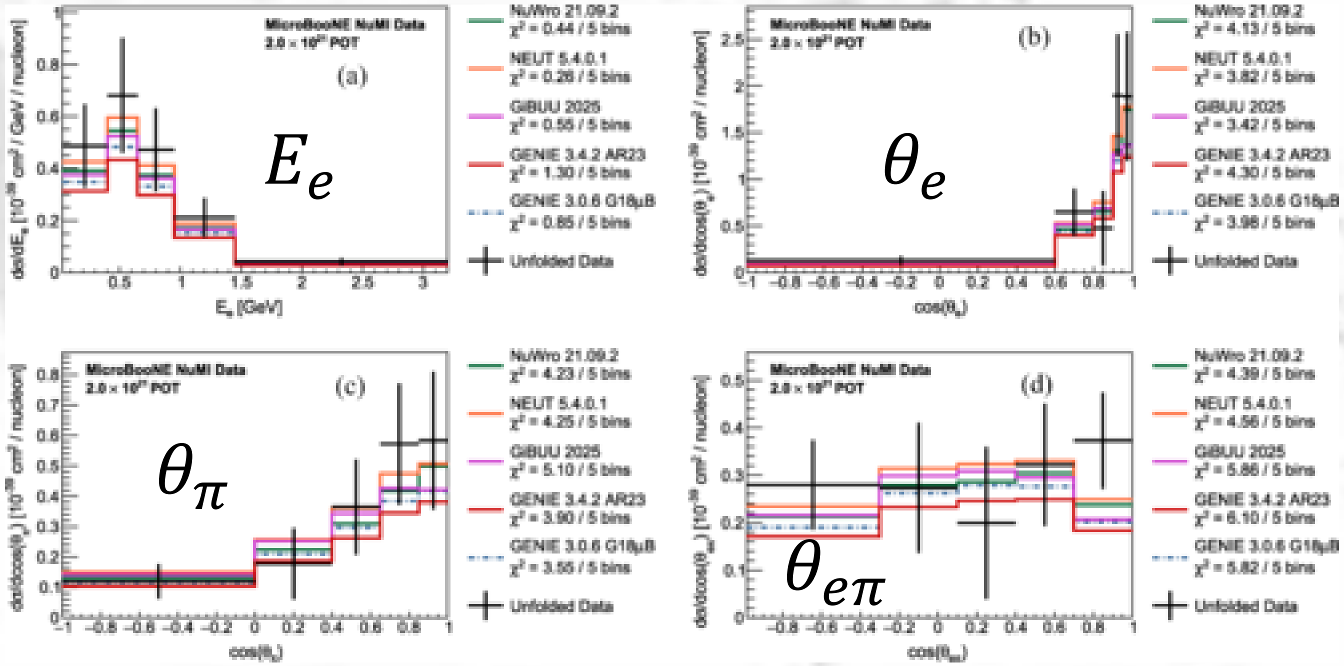


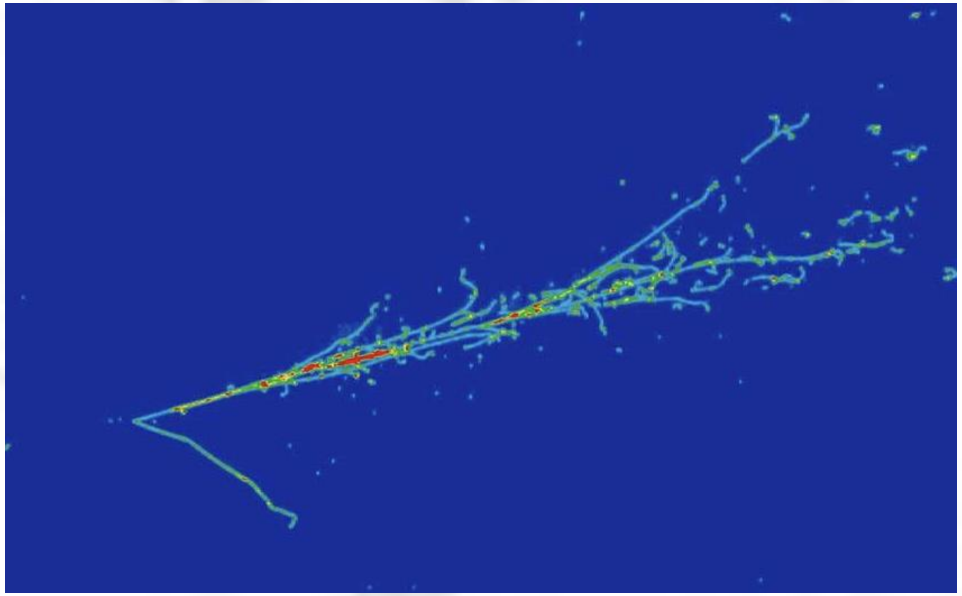


- *Preliminary*.
- Cross-sections in panels of p_T^ℓ as a function of “available energy”, energy in calorimetrically visible particles, e.g., not neutrons.
- Simulation predicts a ratio very close to one dominated by statistical uncertainties.
- Testing the confidence of generators that ratio should be ≈1.

MicroBooNE ν_e Pion Production

- MicroBooNE has begun to probe exclusive electron neutrino interactions, exploiting capabitilies of liquid Ar TPCs.
- Results are relatively low statistics today, but they point to the ability to do this in SBND at high statistics. Will be particularly interesting when this can be done near threshold for the process and compared to muon neutrinos.



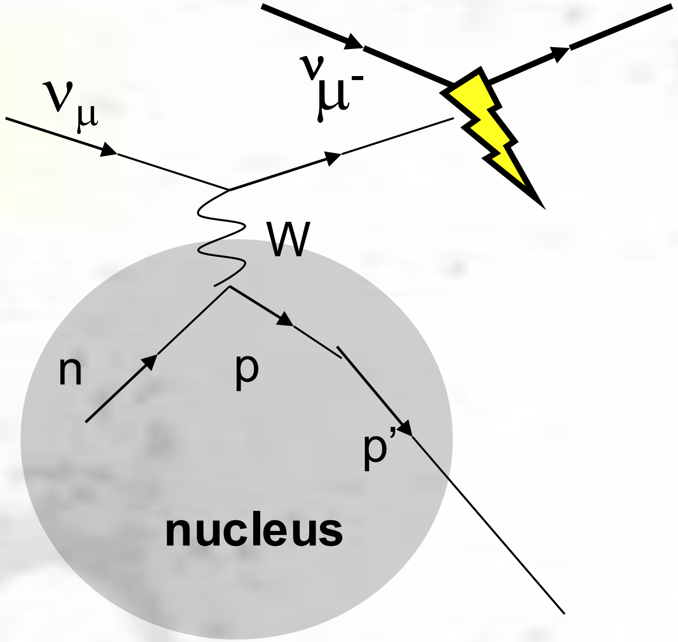


MicroBooNE collaboration,
Phys. Rev. Lett. 135, 061802

Results and Trends: Lepton-Hadron Correlations

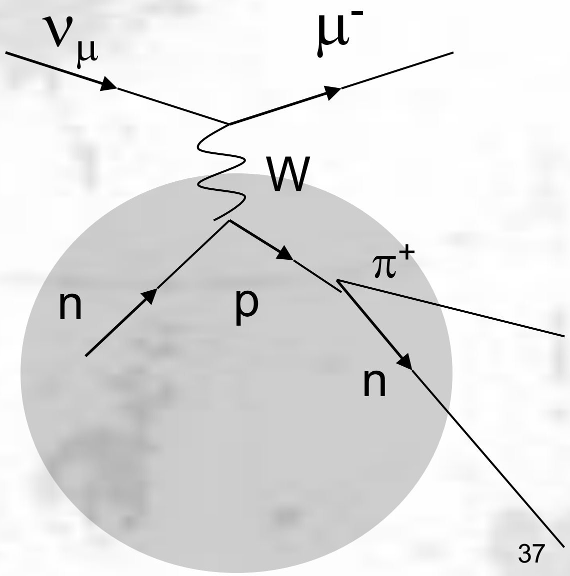
(high dimensionality enabled by high statistics)

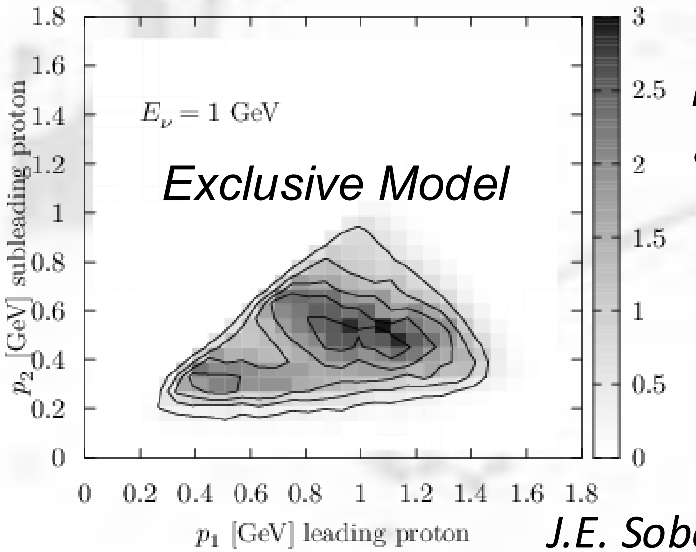
Theory and Correlations



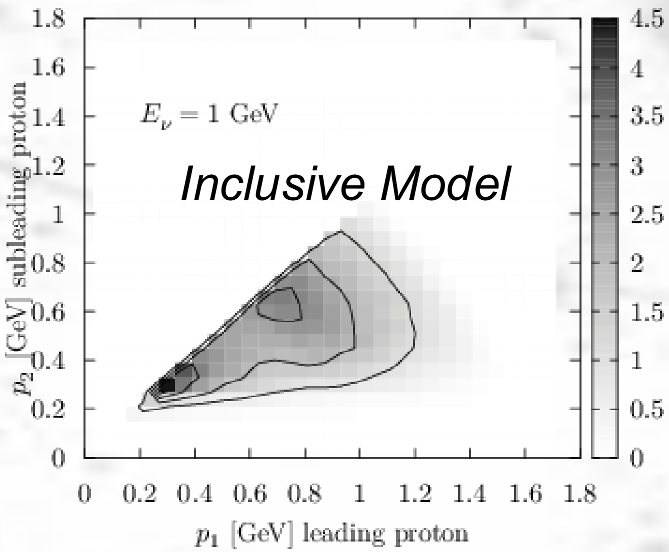
- This is a many-layered problem:
  - prediction is high-dimensional, growing rapidly multiplicity
  - interaction with nucleus can modify kinematics of outgoing hadrons, or change an event with one collection of final state particles to another.
- But effects can be large, and important. Example from a calculation of multinucleon knockout kinematics.

final state interactions

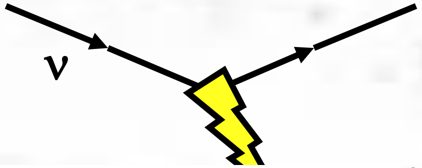




in this example, see a large difference in momentum sharing among leading and sub-leading nucleons

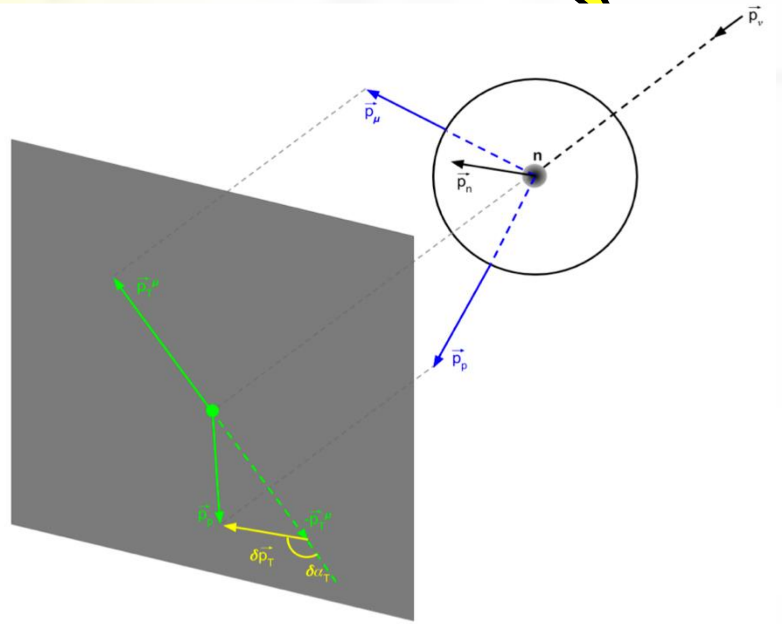


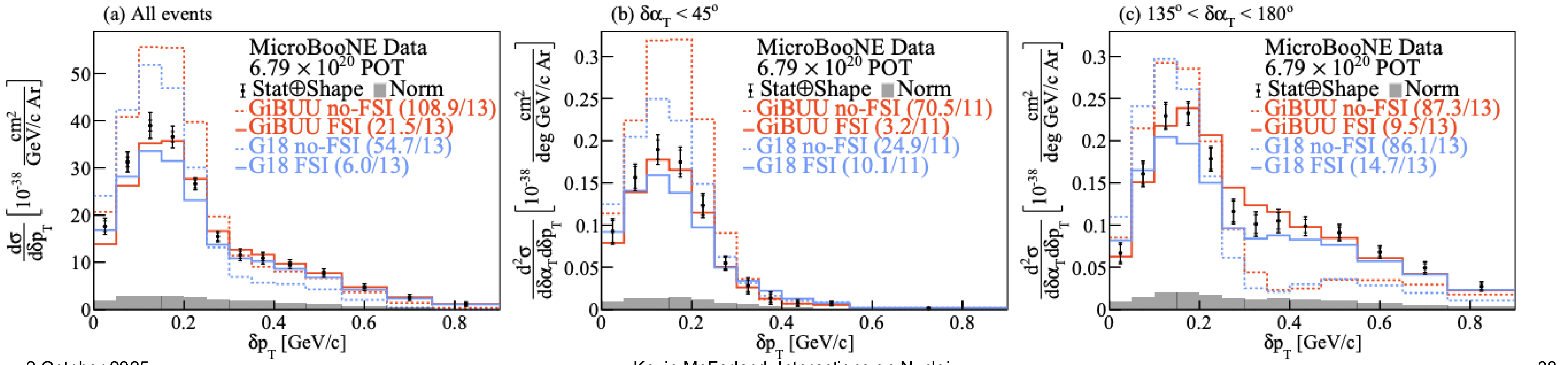
J.E. Sobczyk et al, Phys.Rev.C 102 (2020) 2, 024601



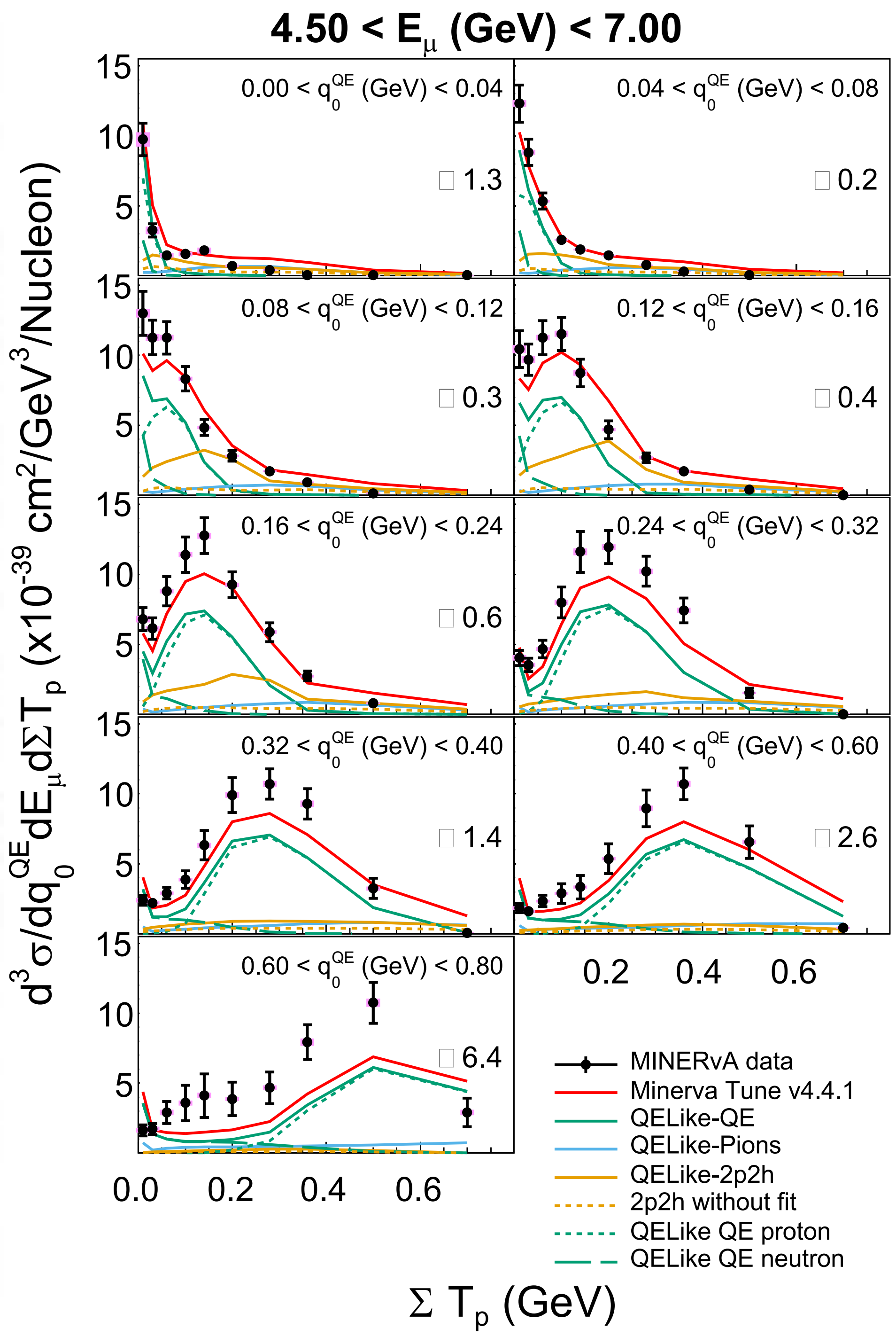
Correlations in Experiment

- MicroBooNE measured multi-dimensional kinematic imbalance in $\mu^- + p$ events due to nuclear effects.
- Here, momentum imbalance in slices of imbalance angle, $\delta\alpha_T$, where high $\delta\alpha_T$ is the location of almost all reactions with inelastic interactions in the nucleus or with multi-nucleon production.
- Note the dramatic range of model predictions.

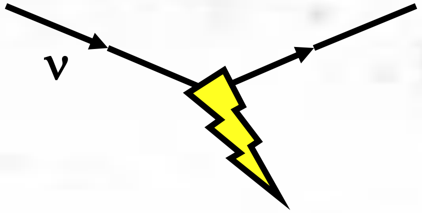




Phys.Rev.Lett. 131 (2023) 10, 101802

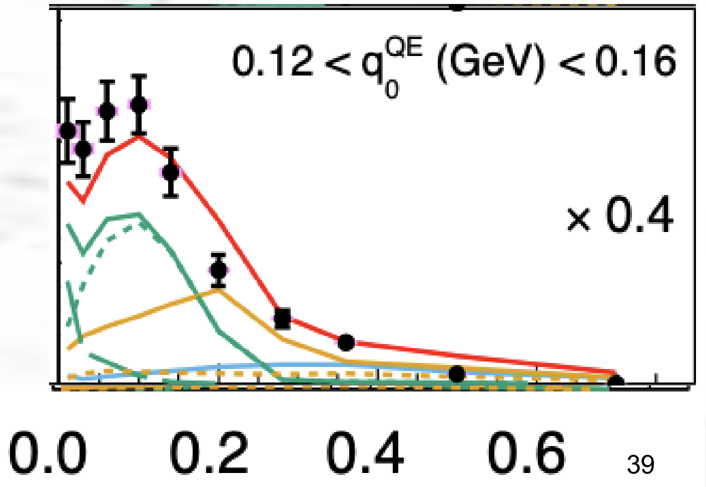


Correlations in Experiment



- Can directly look at neutrino energy determination from $\mu^- + p + \cdots$ events by calorimetry (NOvA or DUNE) and by lepton kinematics (T2K or HK).
- Disagreements with simple nuclear models in generators are evident.
- Must fix this to combine experiments at high statistics in the future.

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

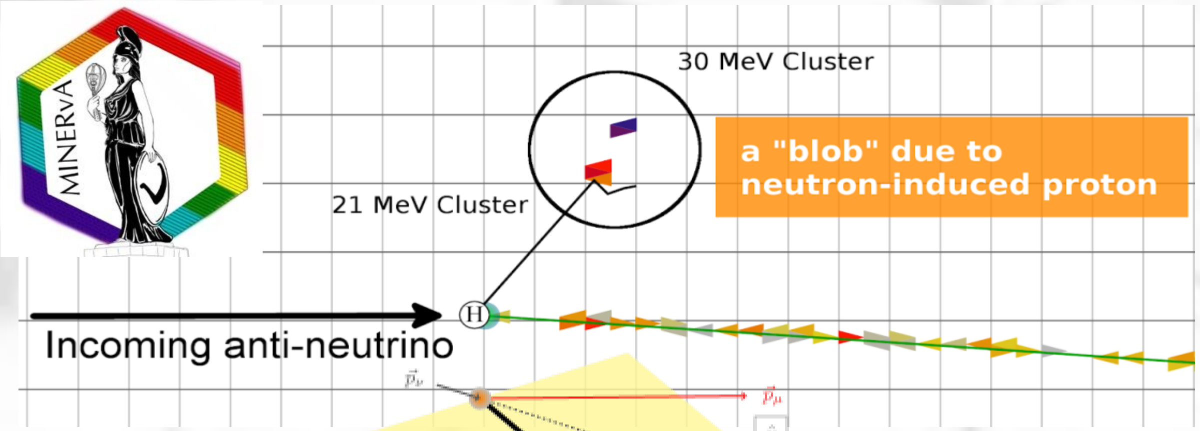


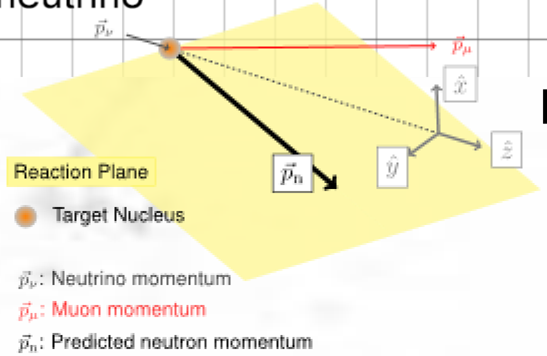
Results and Trends: Neutrons

(we're acquainted with light neutral long-lived particles, so maybe we should meet heavy ones?)

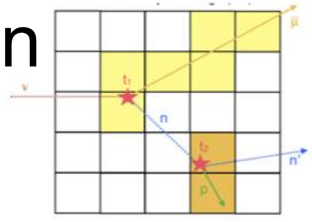
Neutron reconstruction

- 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.

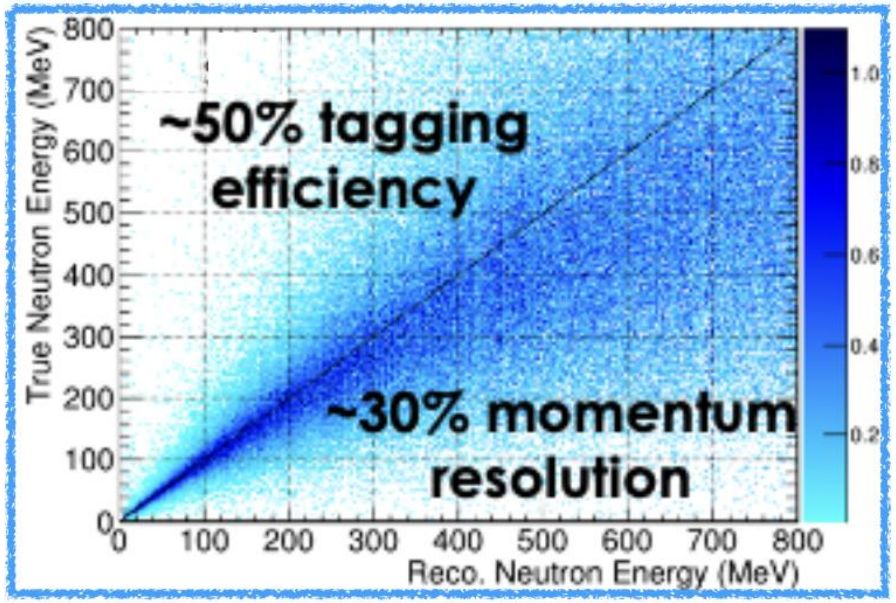


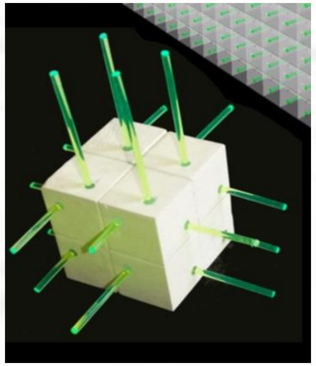


Nature, 614, 48-53



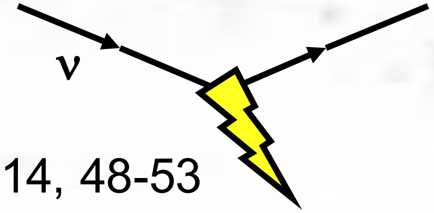
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$





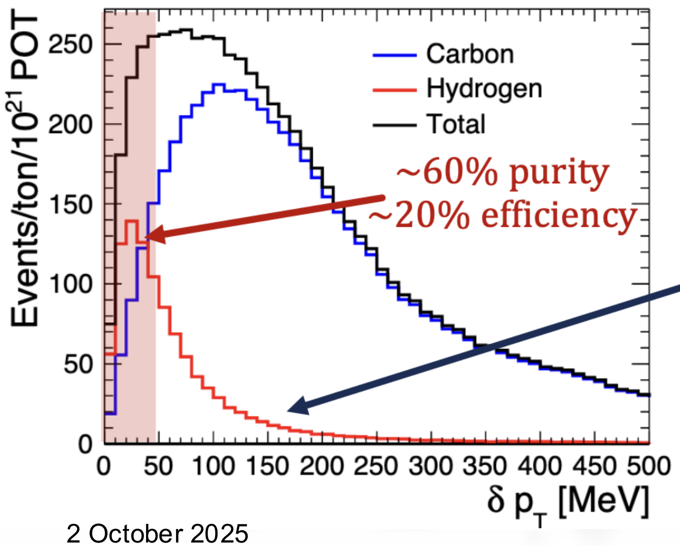
Phys. Rev. D101 (2020) 9, 092003

Neutron and Axial Form Factor



Nature, 614, 48-53

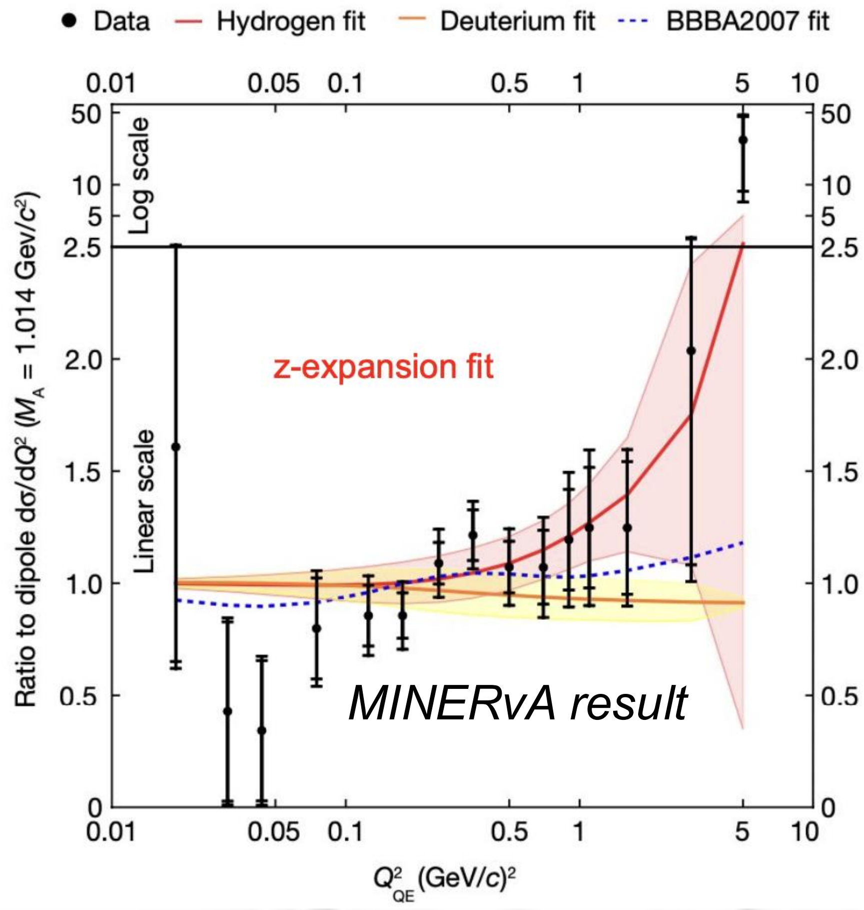
- MINERvA used neutron reconstruction and ability to isolate events on hydrogen (only with direction!) to measure $F_A(Q^2)$ with useful precision $0.06 < Q^2 < 2$ GeV².
- SuperFGD will have two handles, direction and energy, to isolate hydrogen scattering.



Antineutrinos:
Peak from interactions on hydrogen

No nuclear effects

Possible thanks to **neutron detection**!

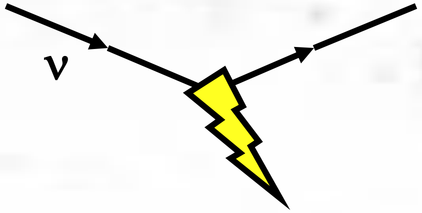


Phys. Rev. D 101, 092003 (2020)

Trend: Nucleons and Nuclei

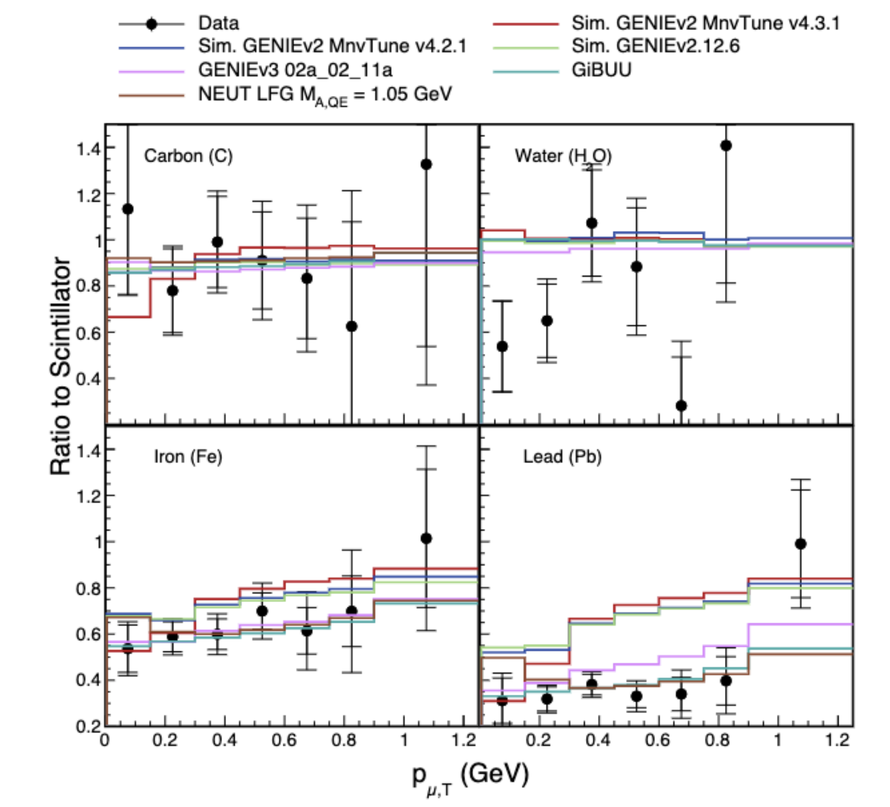
(can we use scattering on one to understand scattering on the other?)

Is a nucleus a nucleus a nucleus?



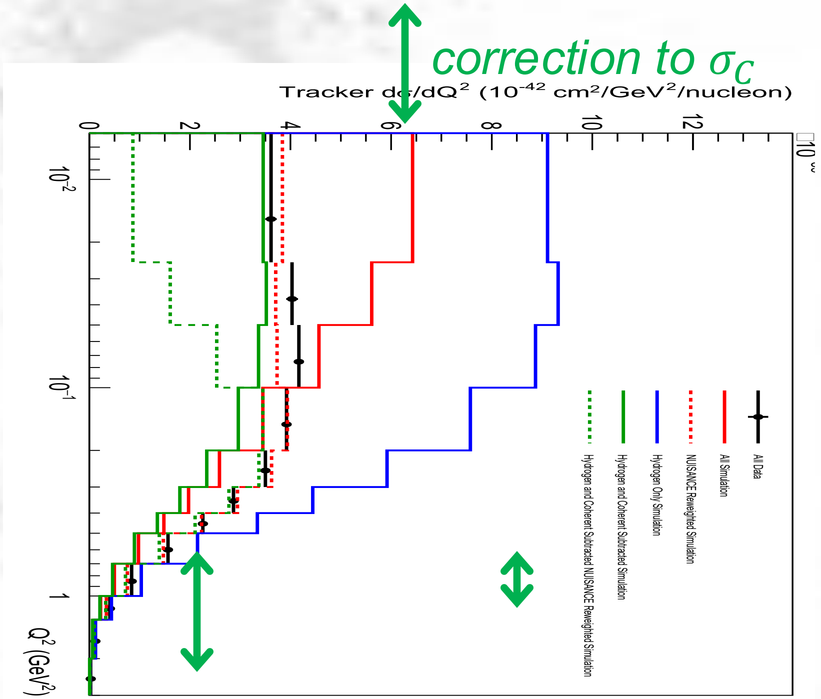
- In energies and momenta of individual nucleons within the nucleus, nuclei vary.
- But we are beginning to see some consistencies in how models describe different nuclei equally well (or equally poorly).

MINERvA, A. Bercellie et al, Phys.Rev.Lett. 131 (2023) 1, 1



This result, transverse momentum dependence of pion production on different nuclei, shows how different final state interaction models give different overall rates.

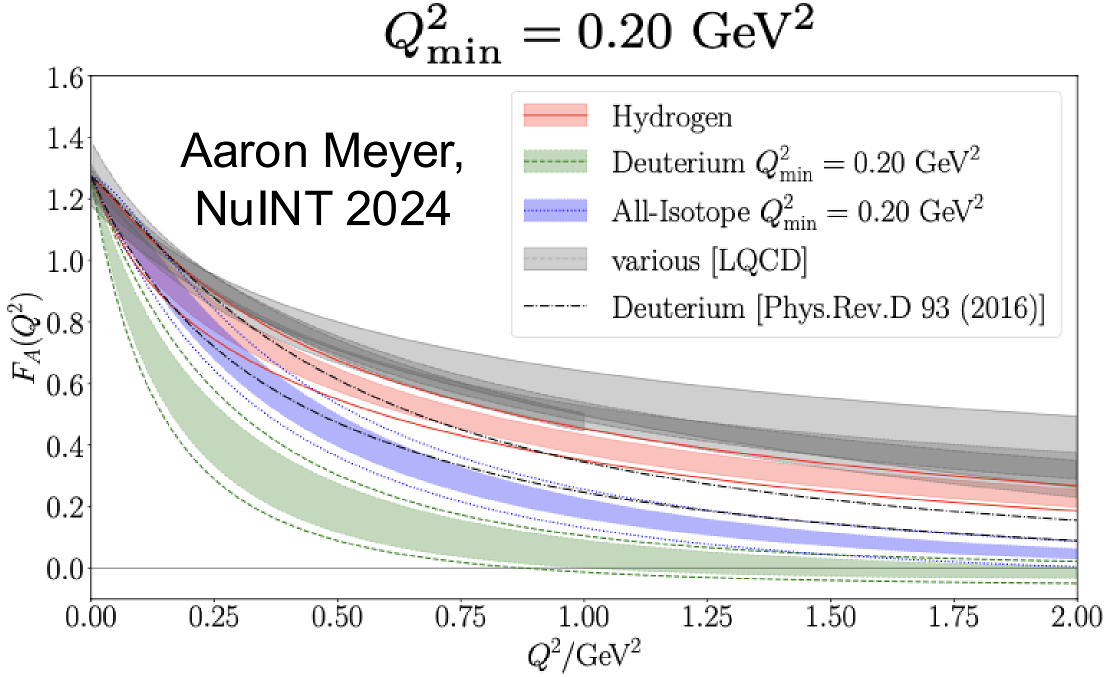
*But a second conclusion is that all nuclei exhibit the **same** unexpected transverse momentum dependence.*



$$Q^2 \approx p_T^2(1 + \mathcal{O}(\nu/E_\nu))$$

Nucleons vs Nuclei

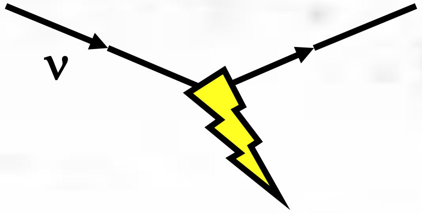
- By contrast, we are struggling to understand cross-sections on free nucleons as a base for calculating cross-sections on nucleons.
- In $F_A(Q^2)$, there are significant tensions between the deuterium bubble chamber legacy data, and either the MINERvA hydrogen or lattice QCD calculations.
- Why? It's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



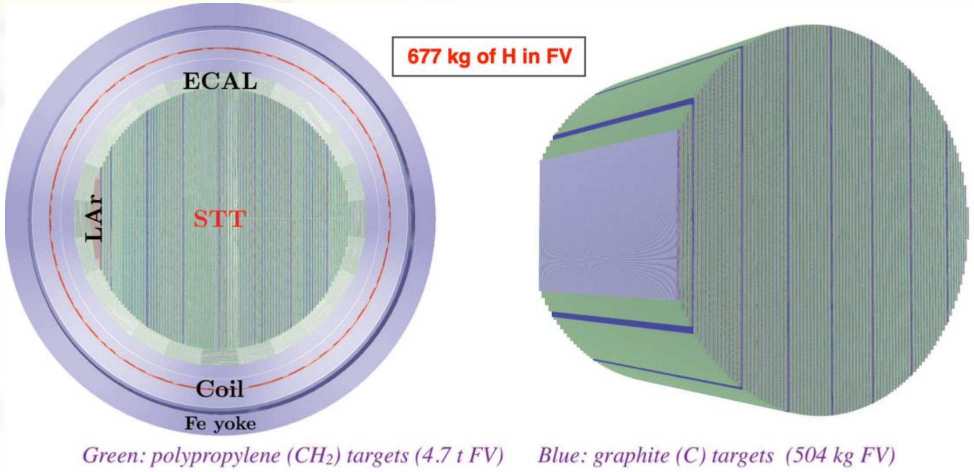
	$\{a_k\}_D$	p_D	$\{a_k\}_H$	p_H
χ^2_D/DoF_D	94.9/94	0.45	167.7/96	8.3×10^{-6}
χ^2_H/DoF_H	23.3/15	0.08	10.0/13	0.69

Deuterium is incompatible with hydrogen, LQCD

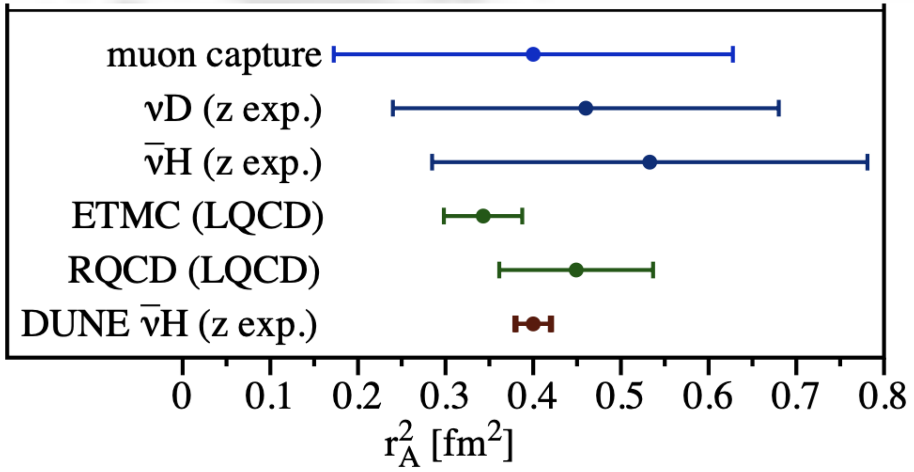
DUNE-ND "Solid Hydrogen"



- Recall that the DUNE SAND near detector includes 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.")*

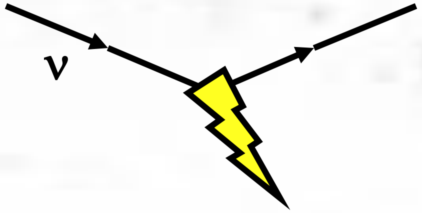


one realization of the SAND low-density tracker

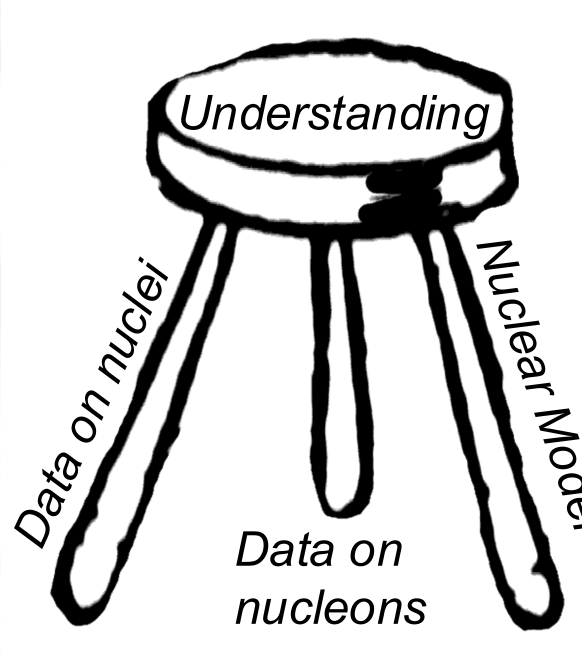


Phys.Rev.D 109 (2024) 5, L051301

Nucleons and Nuclei



- 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 are important!
  - Critical to carry out DUNE ND CH_n-C plan, **and** to supplement it with other ideas like modular hydrogen and bubble chambers now under development.



Closing Thoughts

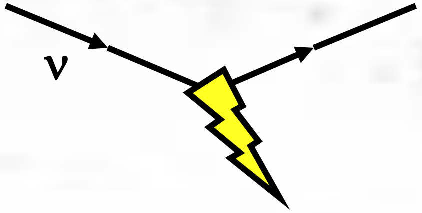
Conclusions

- Motivated by high statistics oscillation experiments at accelerators, the two decades have seen a resurgence of interest in studying and modeling inelastic neutrino interactions on nuclei.
  - Complementary to programs in GeV lepton scattering @ JLab.
- Experiments have reached – or are well past – the point that we are challenging the fidelity of our current modeling, even for seemingly “simple” reactions.
  - A similar renaissance of theoretical work has followed.
- The program to unify these two, as they challenge each other, will be a critical ingredient to our long (and short) baseline futures.

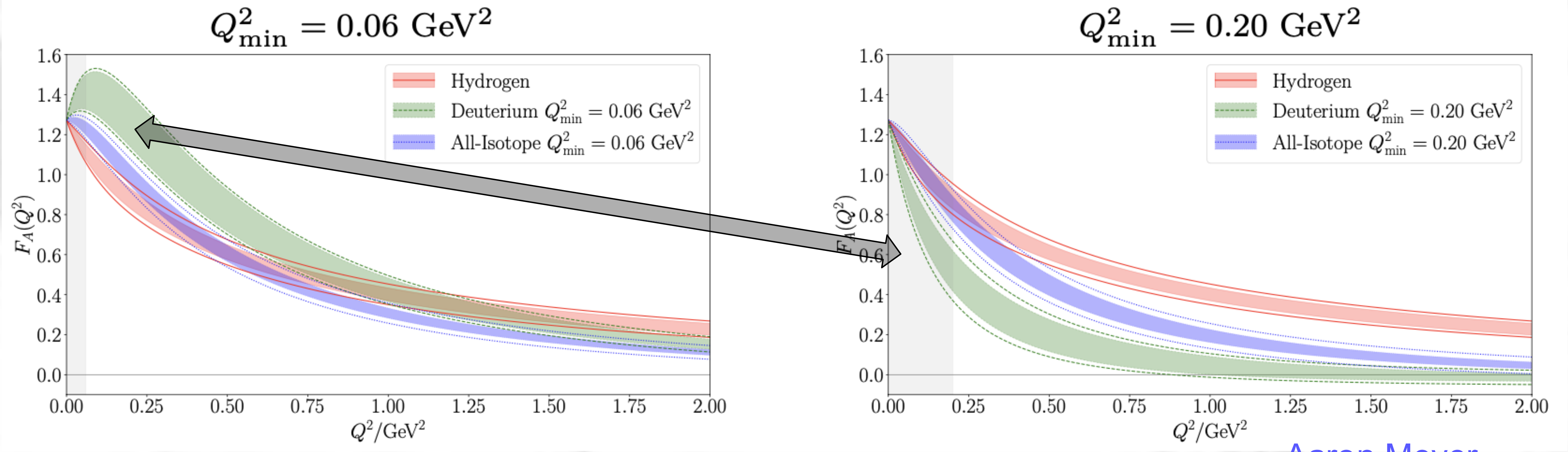
Backup

Axial Form Factor

More on the Deuterium Data…



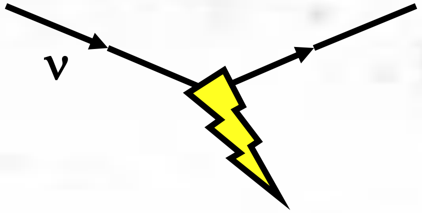
- The deuterium bubble chamber data gives self-inconsistent fits for $F_A(Q^2)$, unless overregularized to force sensible results, like a reasonable value for the axial radius (slope at $Q^2 = 0$).
  - Below is the effect of choices of how low in Q^2 to fit the data.



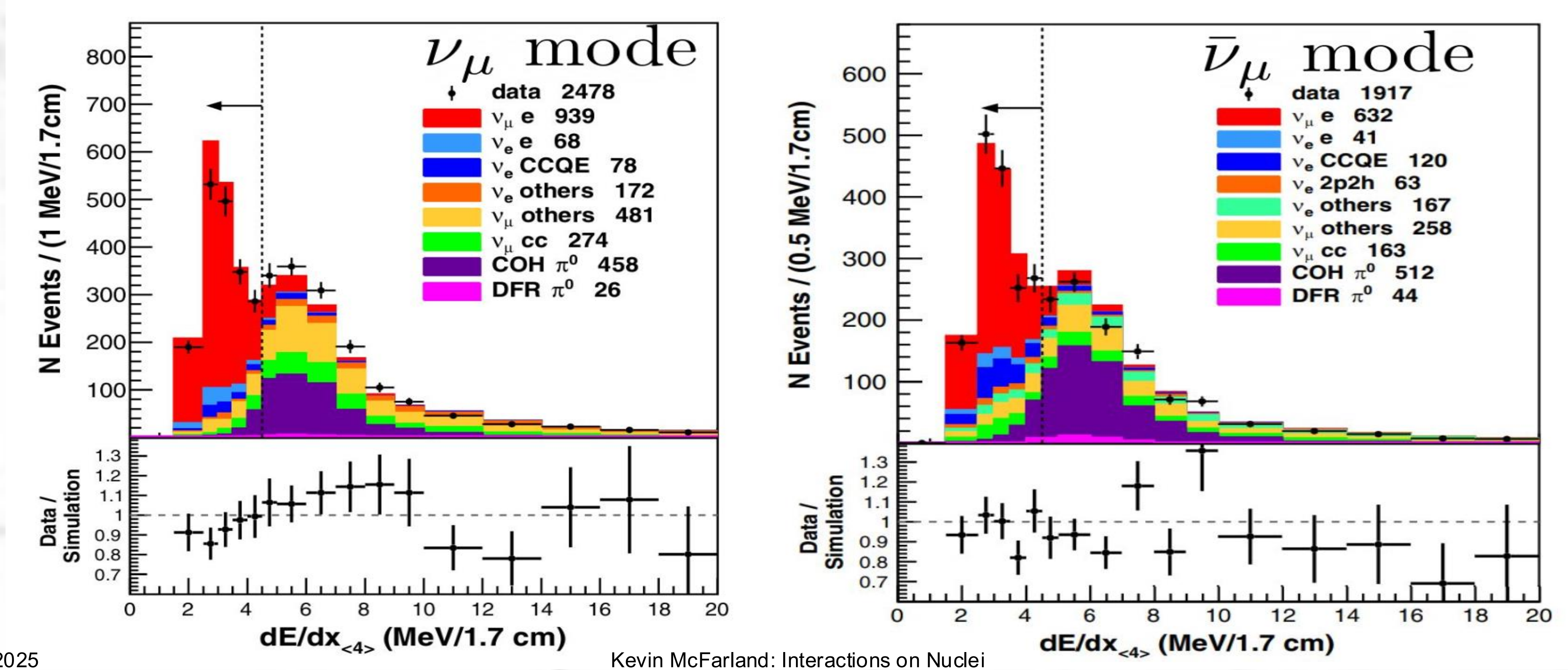
Aaron Meyer, NuINT 2024

MINERvA Electrons

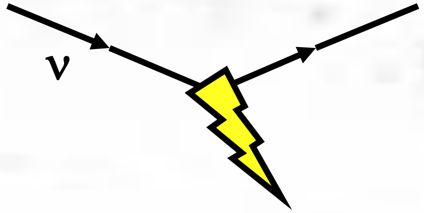
Electron/Photon in $\nu e^- \rightarrow \nu e^-$

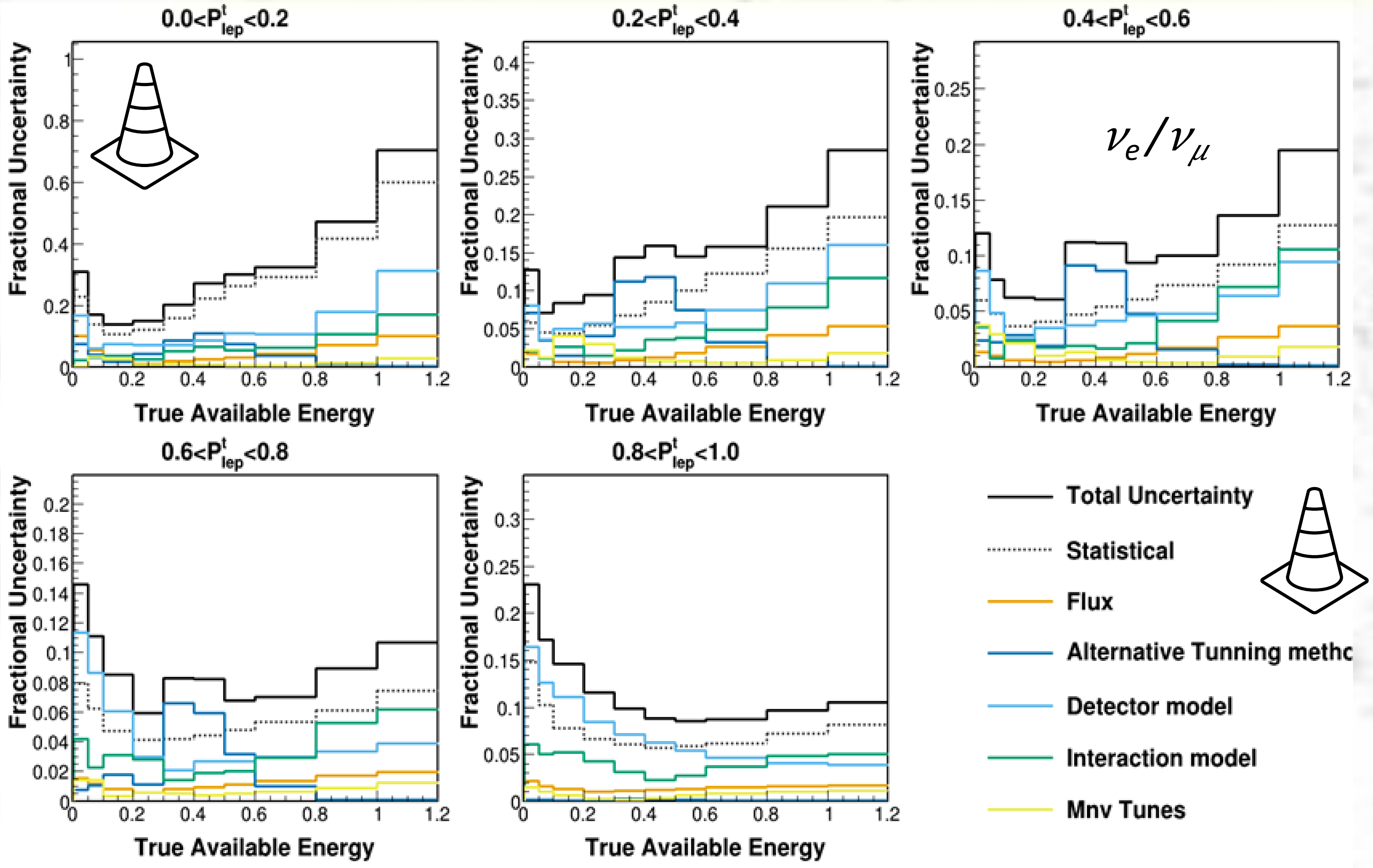


- Background from production neutral pions is manageable with dE/dx, even with an electron energy threshold of 800 MeV.



MINERvA: Uncertainties on ν_e/ν_μ

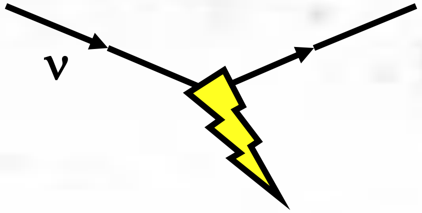




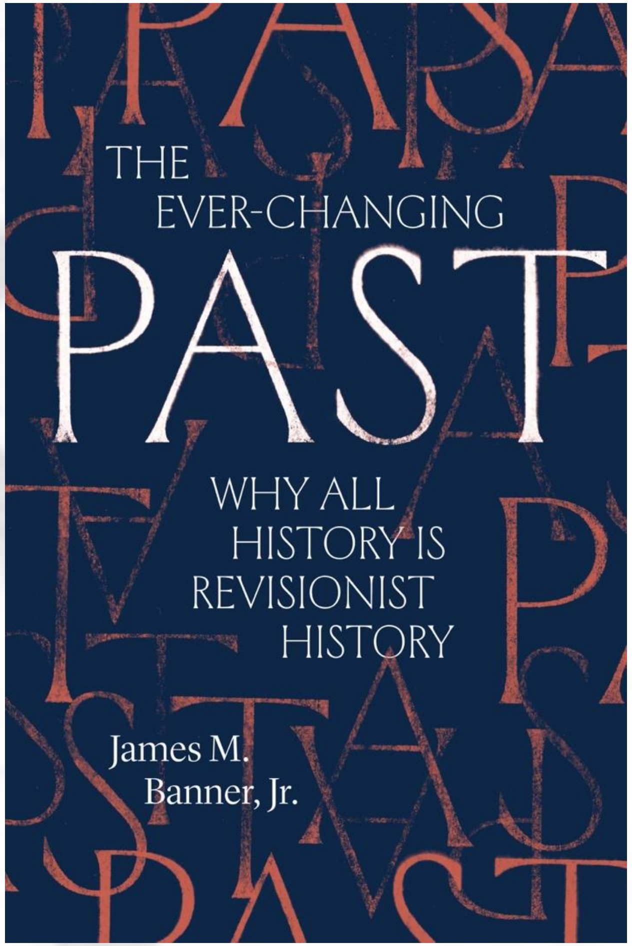
- These are preliminary, and so far only for neutrinos.
- Systematic uncertainties are ~subdominant, at least in any given bin.
- Detector model (muon energy scale) becomes significant. But flux and interaction models are small uncertainties.

MINERvA Data Preservation

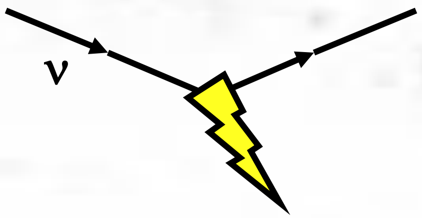
Revisionist History



- In the past, our field has found value in reanalyzing old data sets. The deuterium bubble chamber data is an excellent example.
- As I postulated, some of that data seems to be inconsistent with modern hydrogen data.
- Wouldn't it be great to go back and reanalyze it with different techniques to investigate why?



Data Preservation



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

Data Preservation (cont’d)

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

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

→

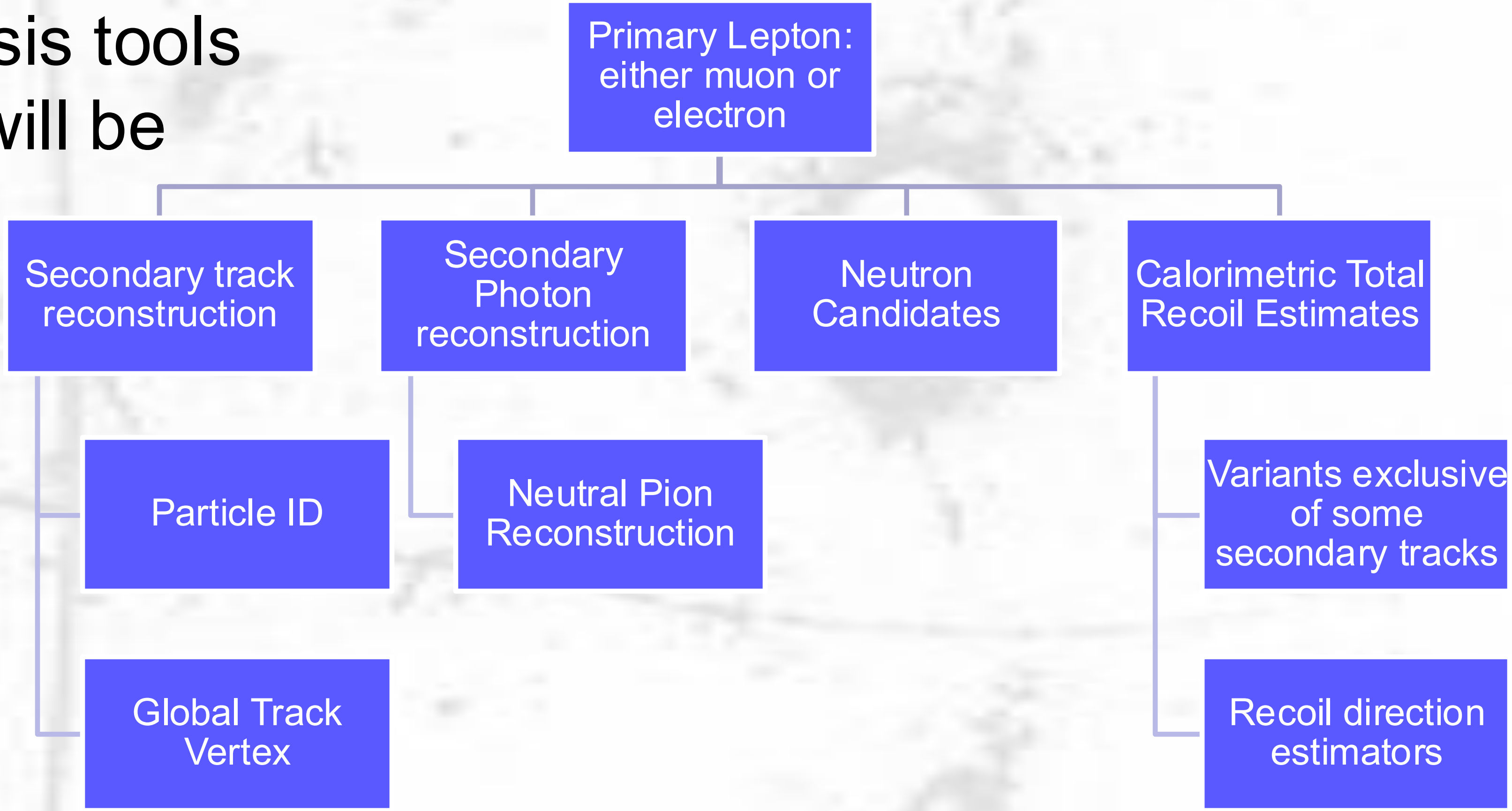
Event Loop Macros

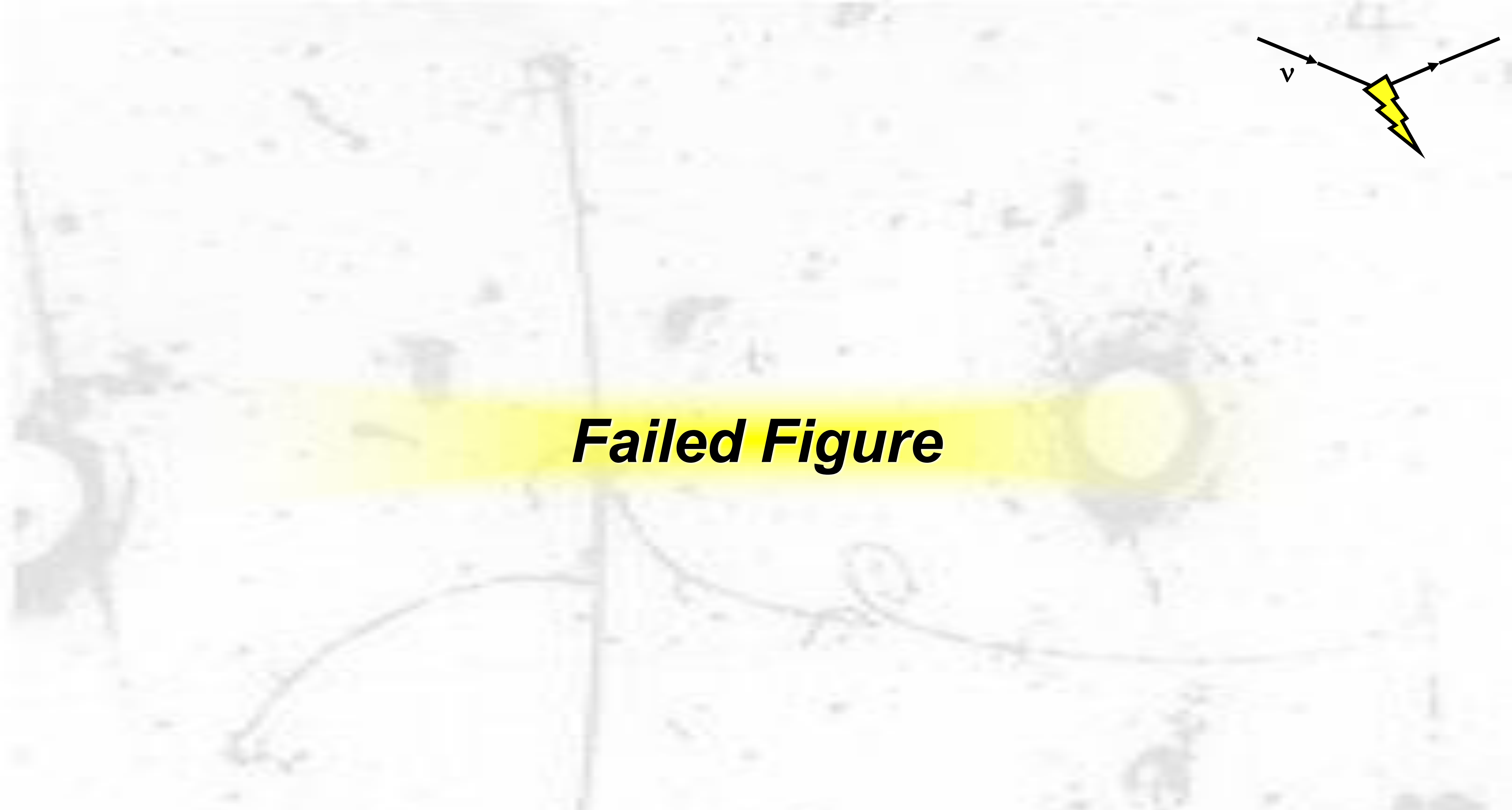
→

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

Data Preservation (cont'd)

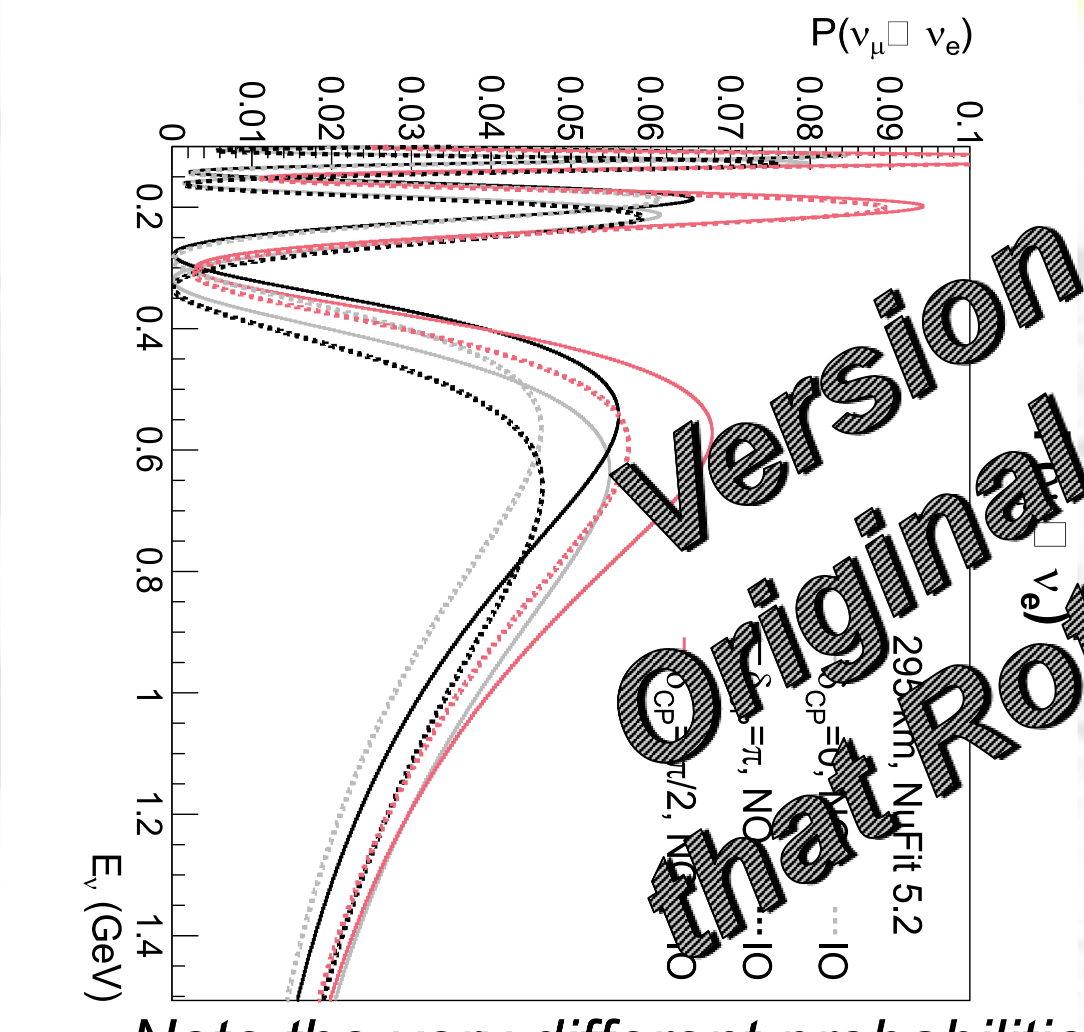
- What is in the reconstruction?
- All macros and analysis tools are public, and data will be shortly.
- Documentation with analysis examples.
- May serve as a useful starting point for more experiments to do something similar.

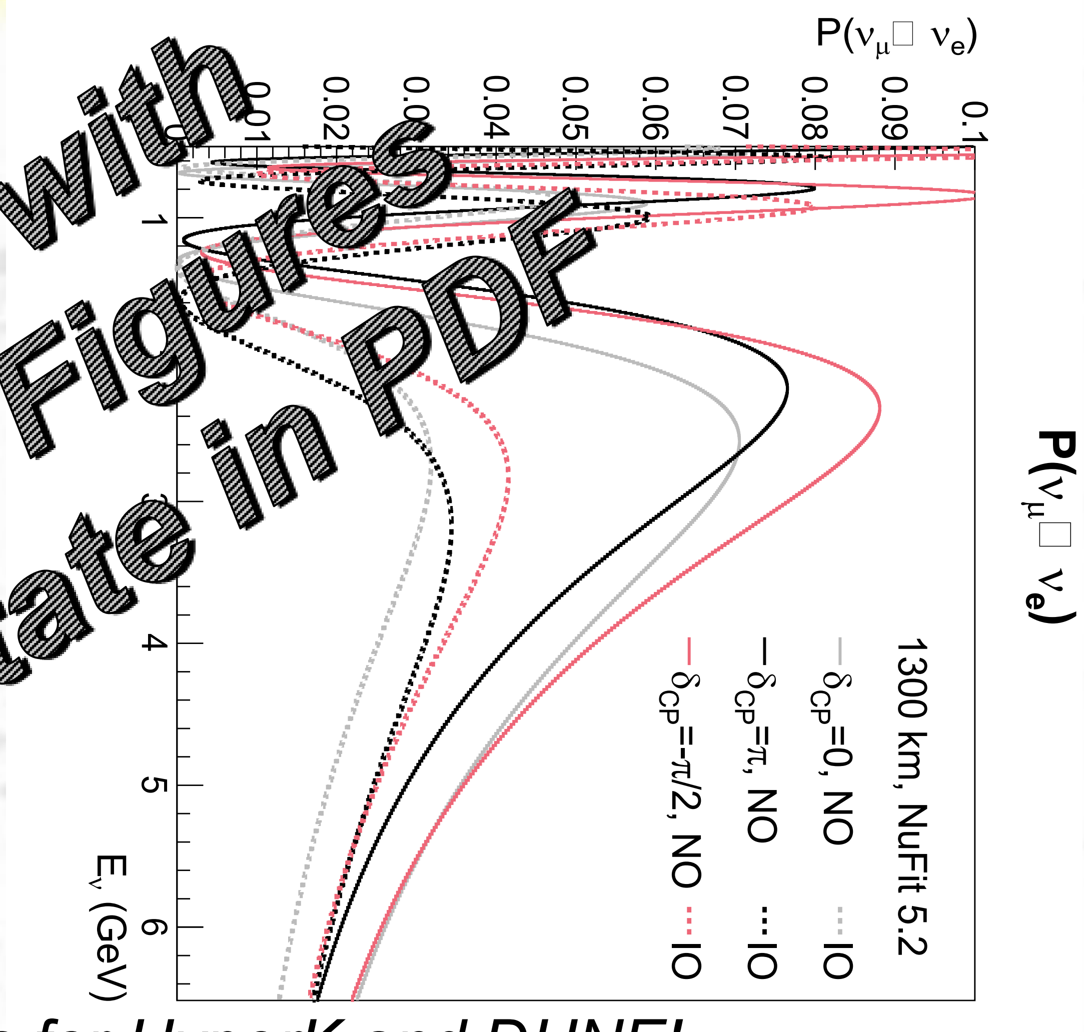




Failed Figure

Oscillation at Hyper-K and DUNE





NO: Normal Mass Ordering
IO: Inverted Mass Ordering

Version with Original Figures that Rotate in PDF

- *Note the very different probabilities for HyperK and DUNE!*