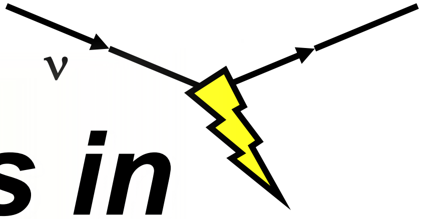
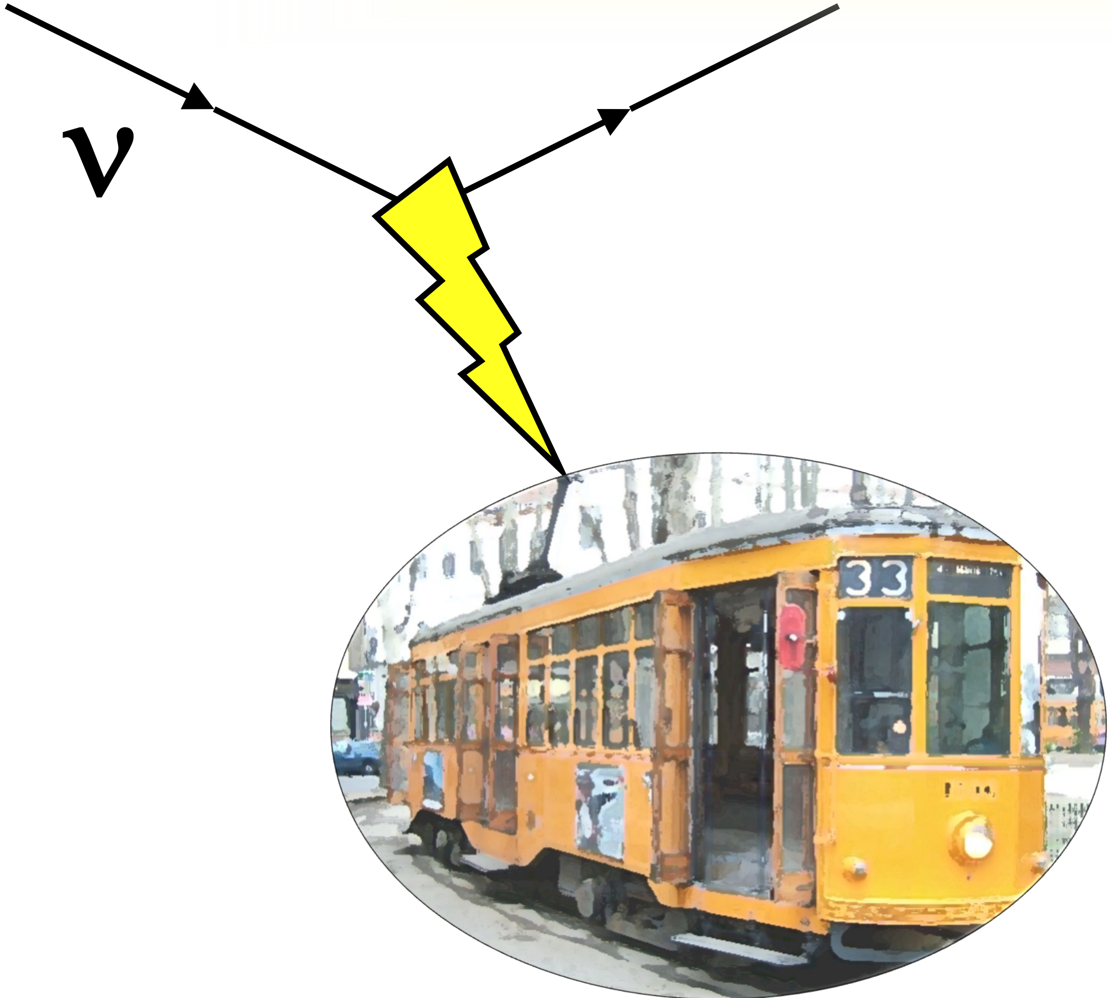
Future Prospects for Experiments in Neutrino Interactions





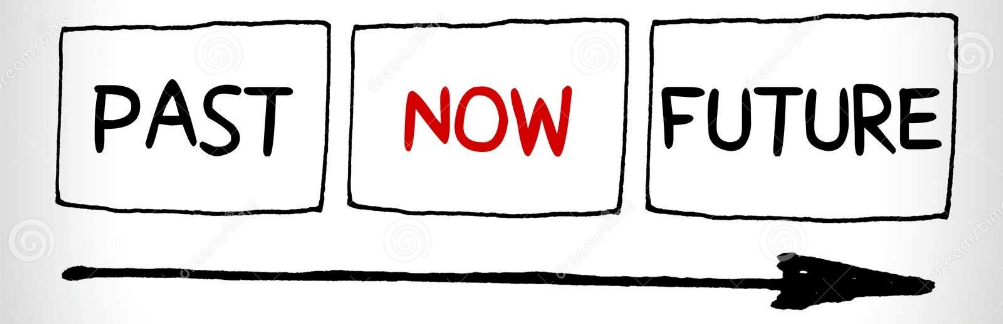
Kevin McFarland
University of Rochester

Neutrino 2024, Milano

20 June 2024

Future... Difficult?

- Several of your speakers, including me, have been tasked with predicting the future. This comes with several difficulties.



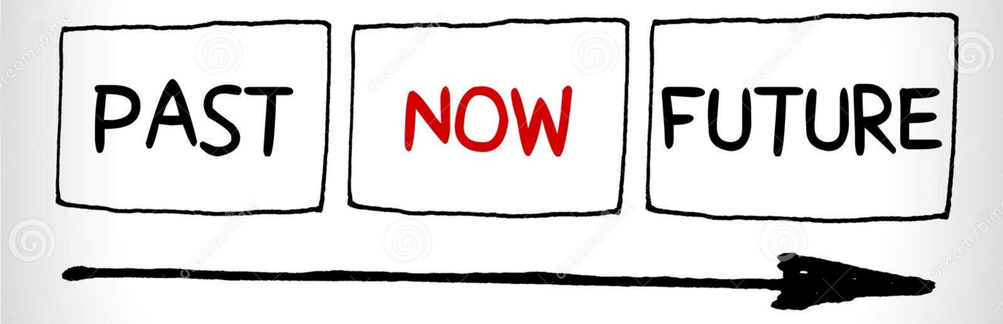
Talks covering "Current" or "Recent" or even "Past" results cover a finite interval, since there is always a natural start time.

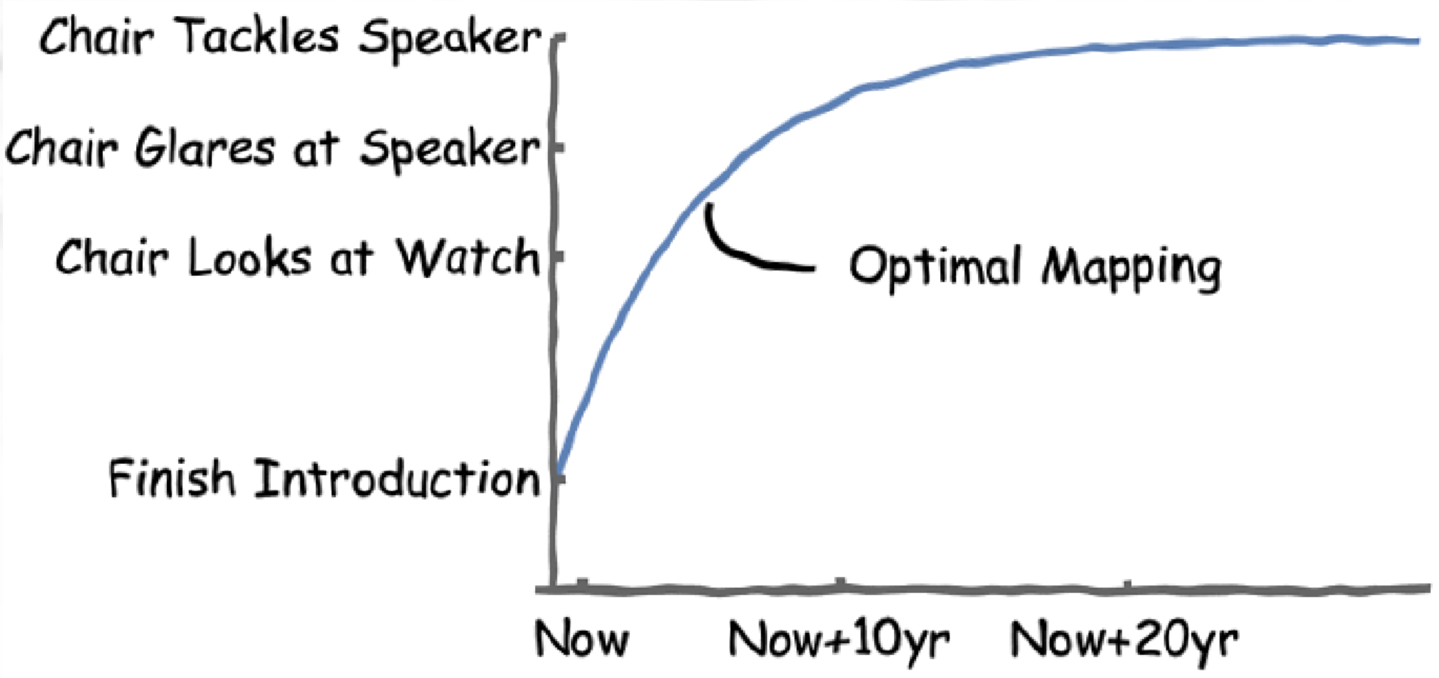
The Birth of Science

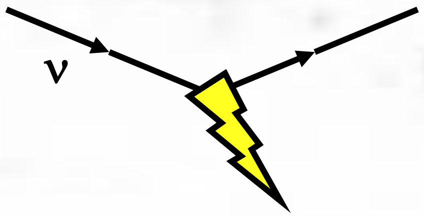
Future... Difficult?

- Several of your speakers, including me, have been tasked with predicting the future. This comes with several difficulties.

By contrast, "future" is a semi-infinite time interval. So, in a 25 minute talk, time management is a challenge.

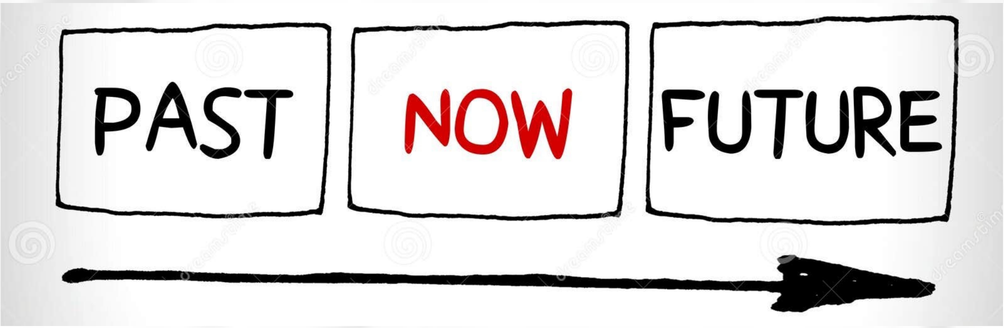






Future... Difficult?

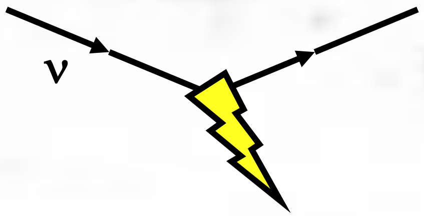
- Several of your speakers, including me, have been tasked with predicting the future. This comes with several difficulties.



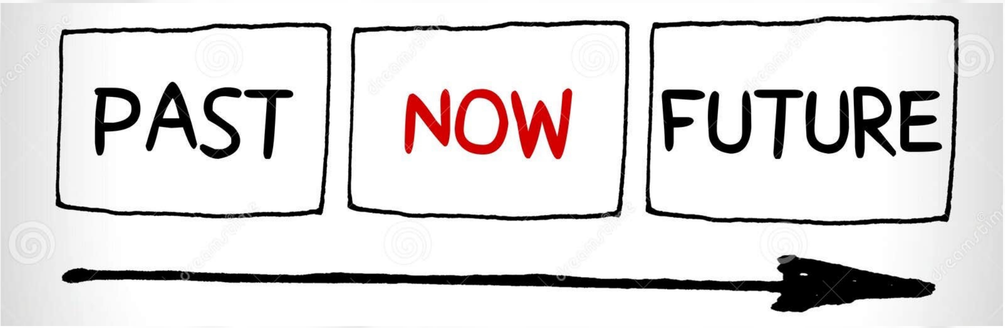
It's also been said many times, and credited to many individuals, that, ***"it is difficult to make predictions, especially about the future."***

Det er vanskeligt at spaa, især naar det gælder Fremtiden.

Future... Easy?



- Several of your speakers, including me, have been tasked with predicting the future. This comes with one great opportunity.

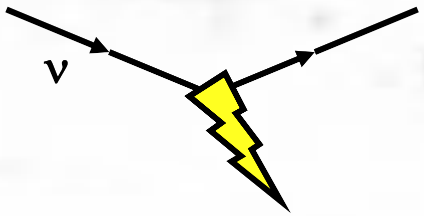


Since the task itself it impossible by construction, I can talk about anything I choose, constrained only by my need to keep you coming back for more.

Today's Plan

- Trends in technology
  - Beams, locations, detectors
- Emerging scientific opportunities
  - Energy dependence
  - Flavor dependence
  - Neutrons
  - Nucleons and nuclei
  - Revisionist History
- Banquet

Some day soon, you will meet a dark and intense beam.
Your detectors will grow and become ever more convoluted.
Your detectors will be in strange locations relative to the beam.
Some of them will move, sloshing liquids as they slowly travel.
Some cost less because they are a byproduct of freezing ground beef.
Some will be made of materials you abandoned long ago, but I see worries of a fireball and hear someone sobbing, "oh the humanity".



Neutrino Beams

(it all begins here)

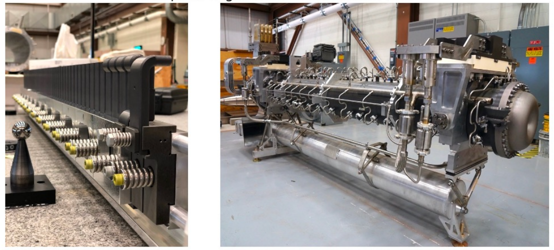
Neutrino Beams: Intensity

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

The NuMI neutrino beam

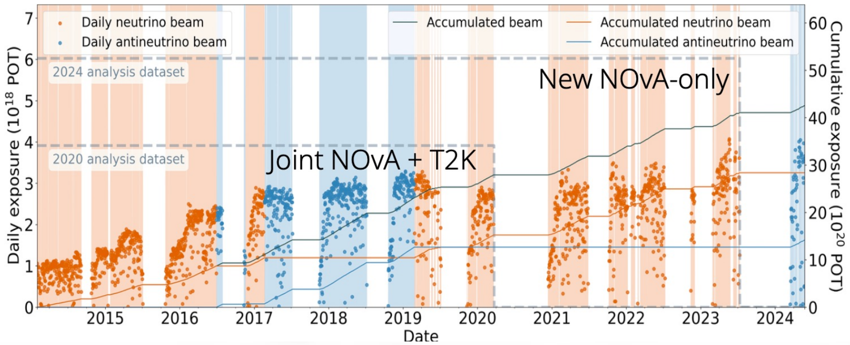
Wolcott, NOvA

MW capable target, horn installed in 2019-2020



Approaching megawatt beam!

- Typically ~900 kW
- Record 959 kW



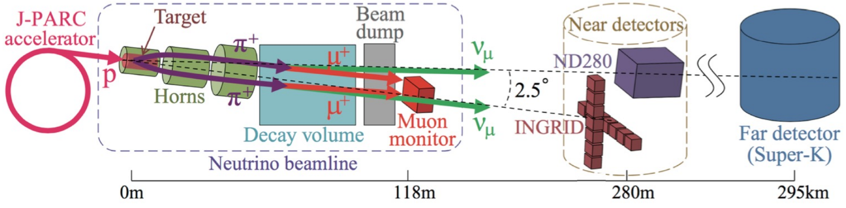
2014-2023:
10 years of beam to NOvA!

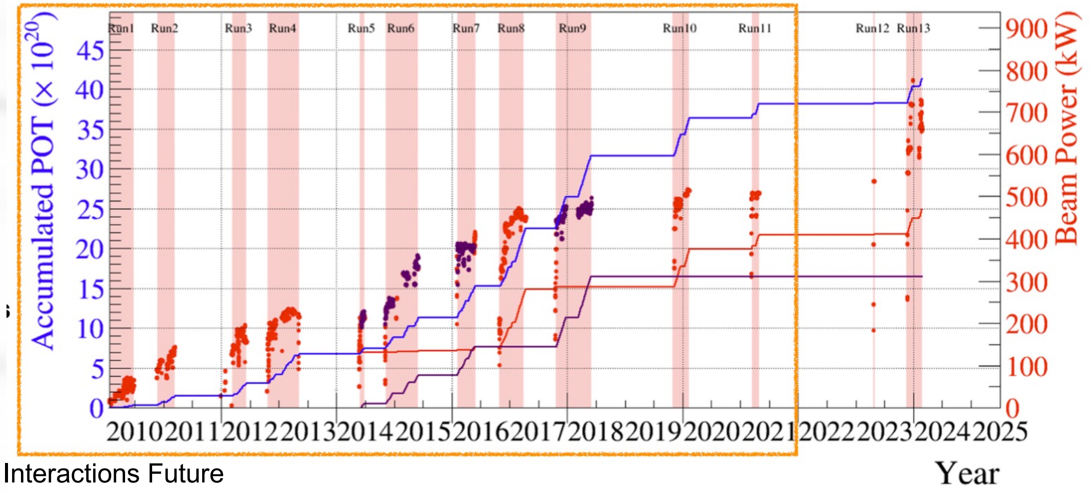
This analysis:
+96% neutrino beam

ν: 26.61×10^{20} POT
$\bar{\nu}$: 12.50×10^{20} POT

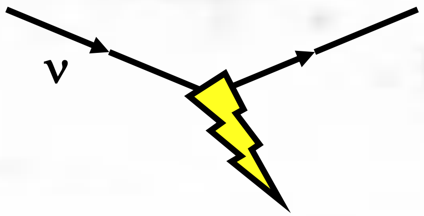
T2K beamline

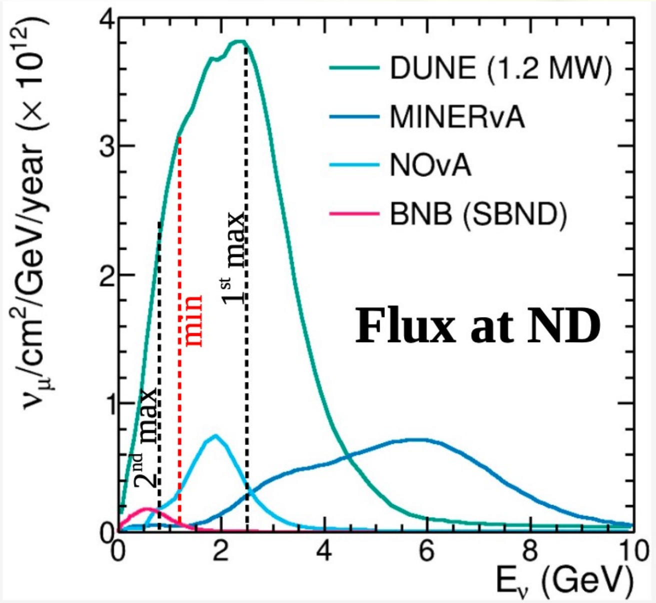
Giganti, T2K





Neutrino Beams: Intensity

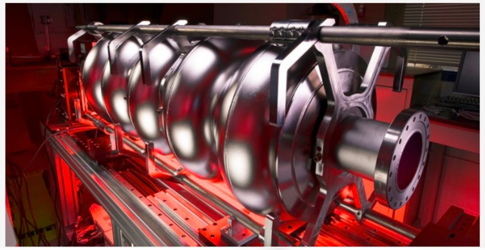




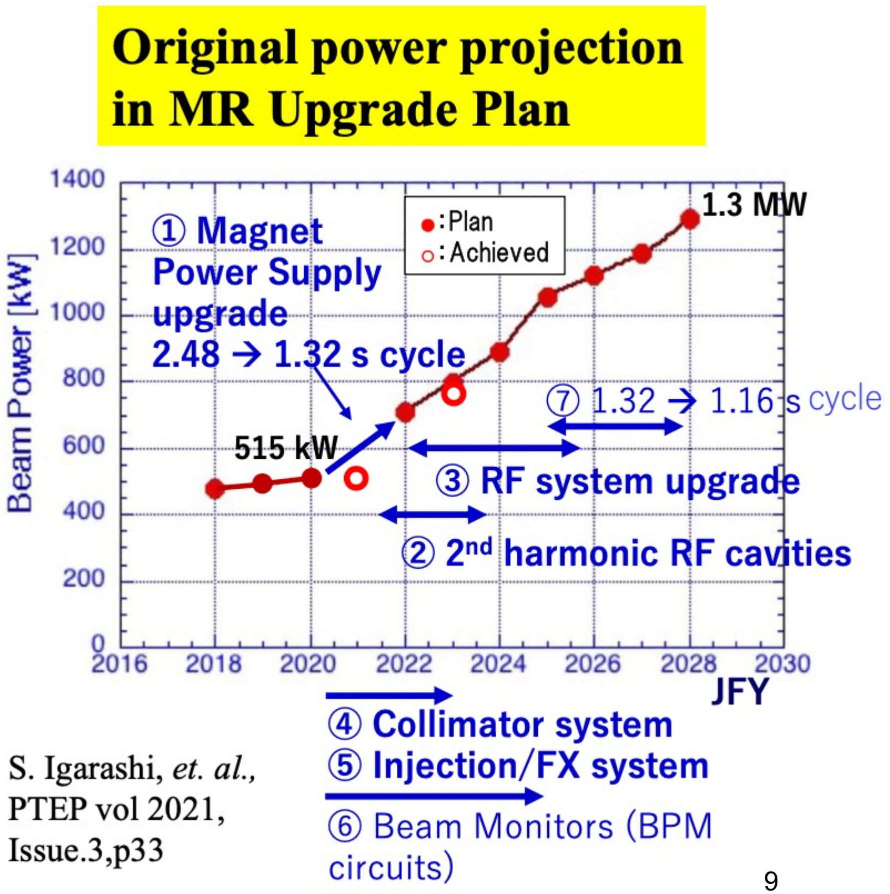
- Both FNAL and J-PARC have paths to significant increases in what is now the visible future.

Marshall, DUNE

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



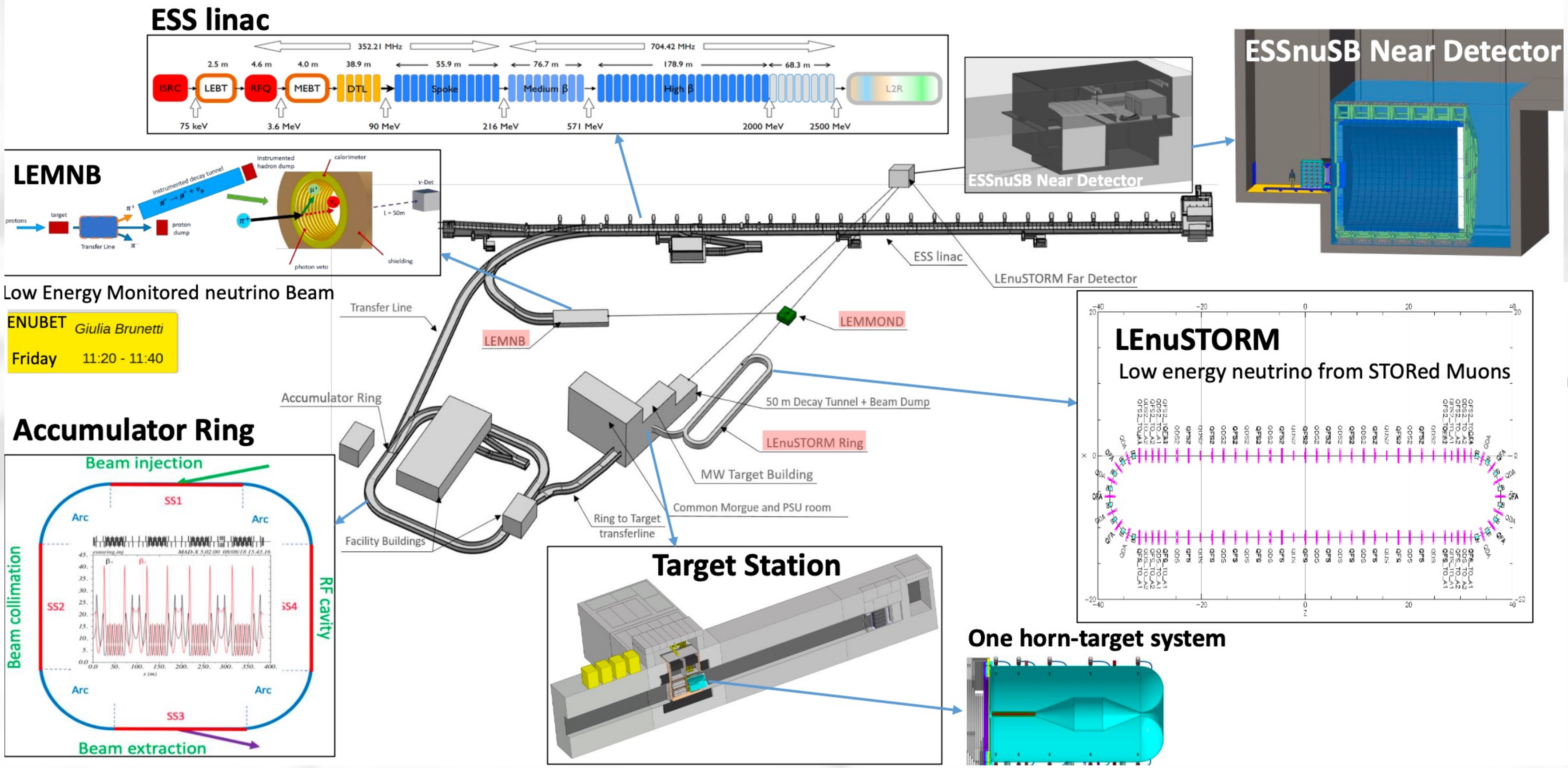
Moriyama, HyperKamiokande



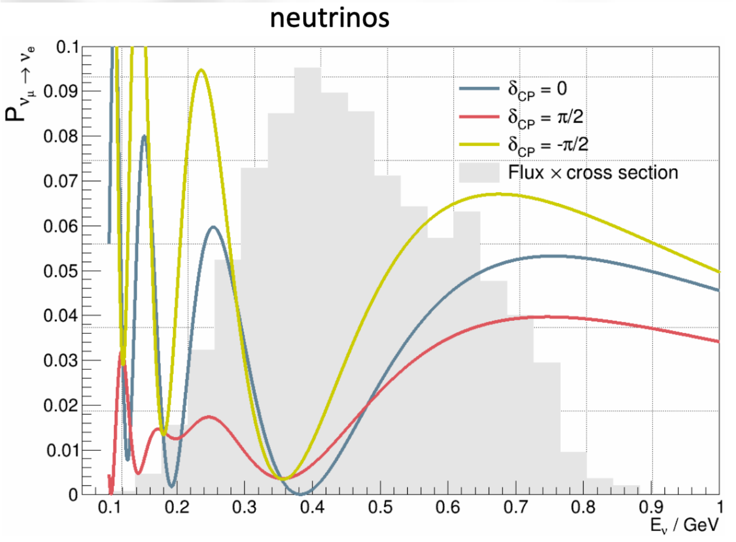
S. Igarashi, *et. al.*, PTEP vol 2021, Issue.3,p33

Neutrino Beams: Intensity

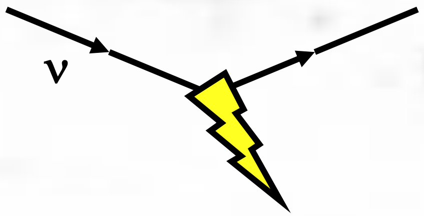
- And there may be plausible, and *complementary*, ways to reach higher power at lower energies with spallation sources.



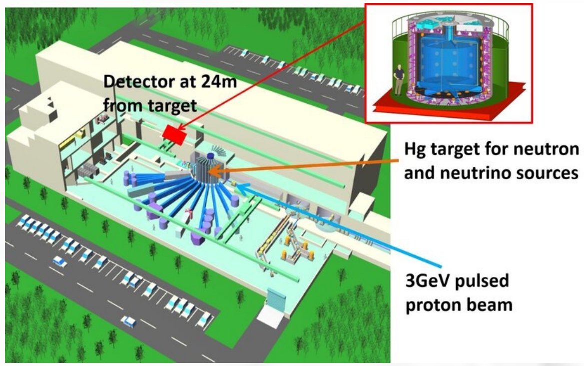
Tolba, ESSnuSB



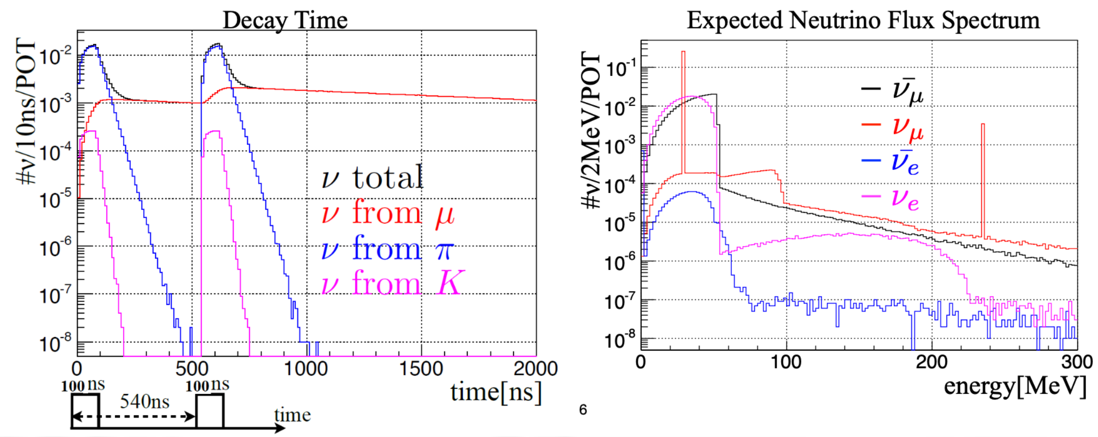
Neutrino Beams: Flavor

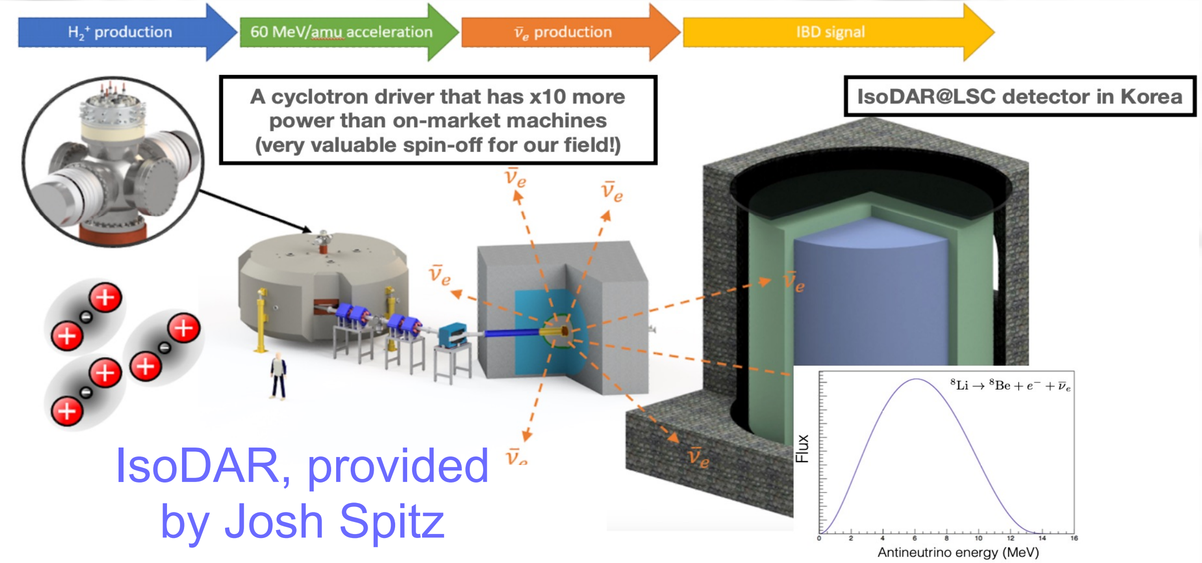


- Our conventional beams are muon neutrinos. But…
- …can produce *electron neutrinos* through decay-at-rest of leptons or ions, and even tackle the challenging task of capturing and accelerating them (nuSTORM).

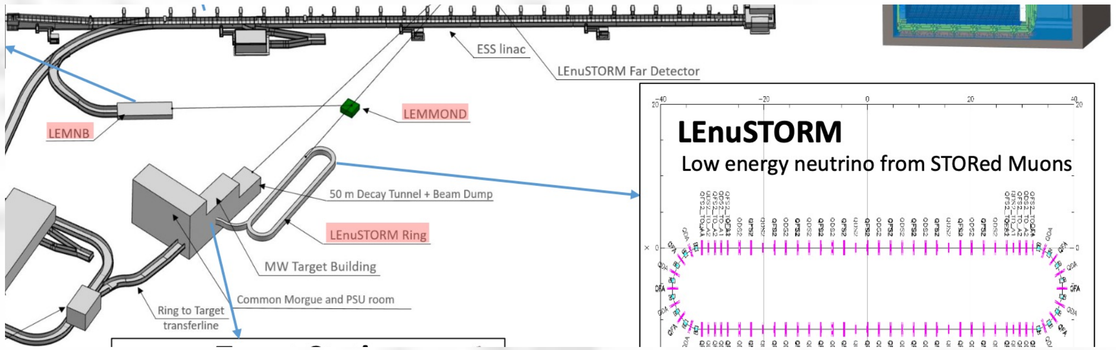


Marzec, JSNS

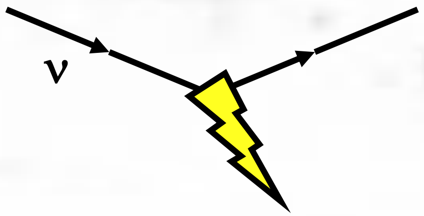




IsoDAR, provided by Josh Spitz



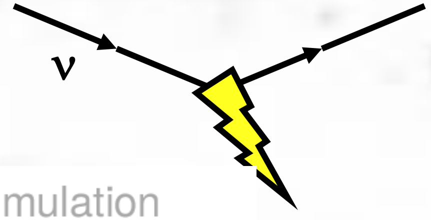
Tolba, ESSnuSB



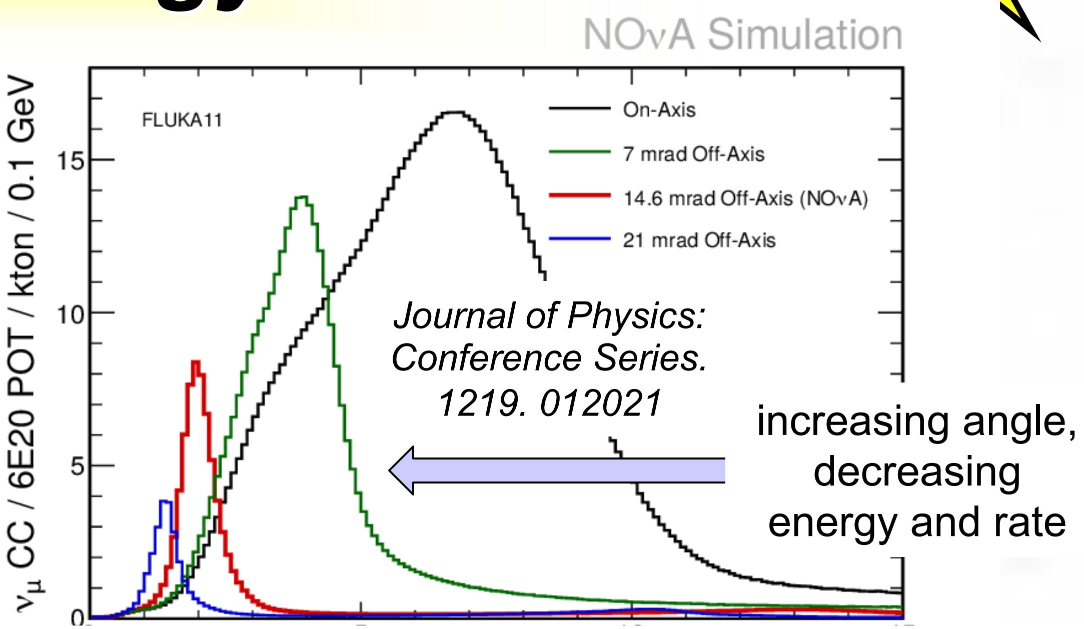
Location

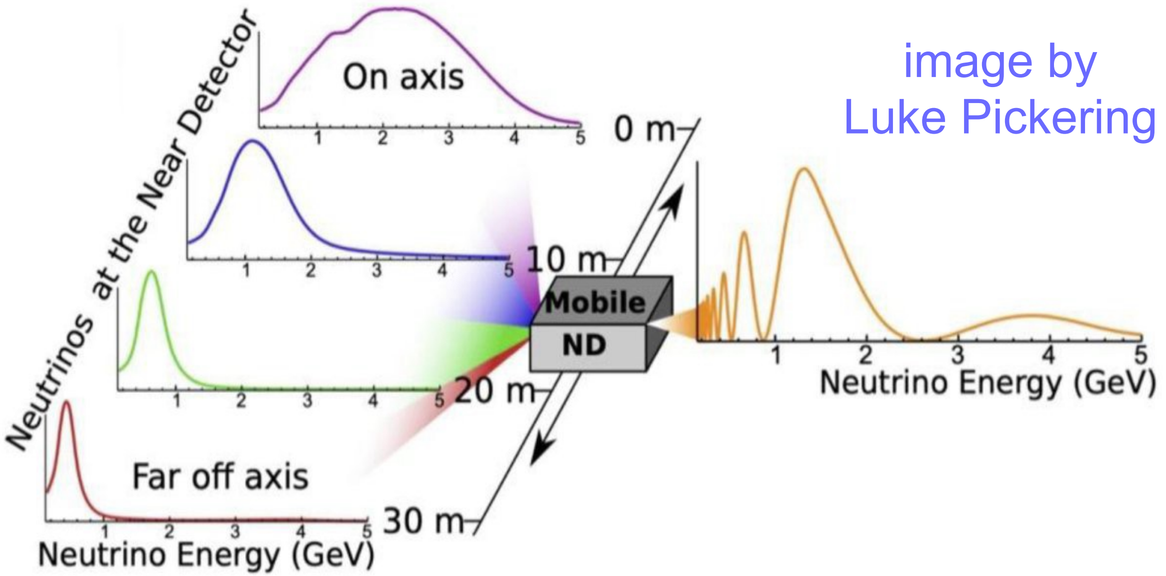
(location, location…)

Location… for energy

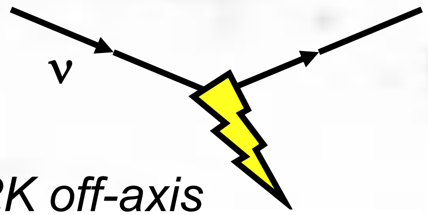


- Beams (like NuMI) can be tuned to produce different energies.
- But also, NOvA and T2K use the "off-axis" technique, pointing the beam away from the detector to select neutrino energy.
- PRISM: measure many off-axis angles in the same near detector to study beams of different energies.



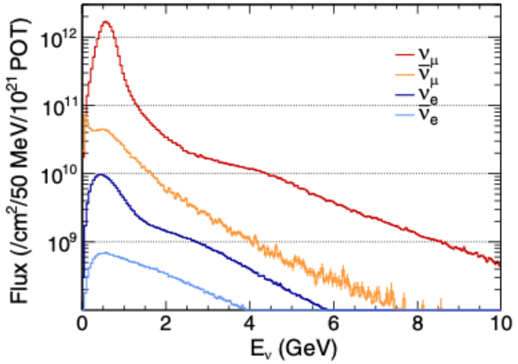


Location… for energy

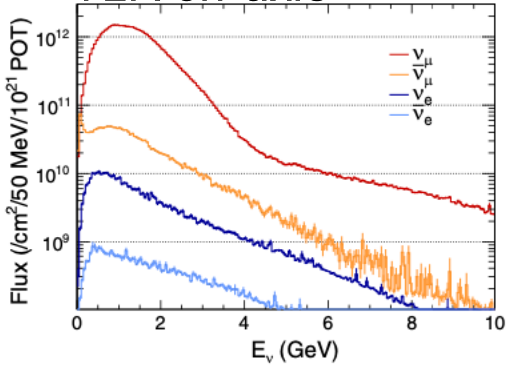


- T2K and MINERvA have both produced first results exploiting this to measure energy dependence.
  - T2K by using different detectors in different locations.

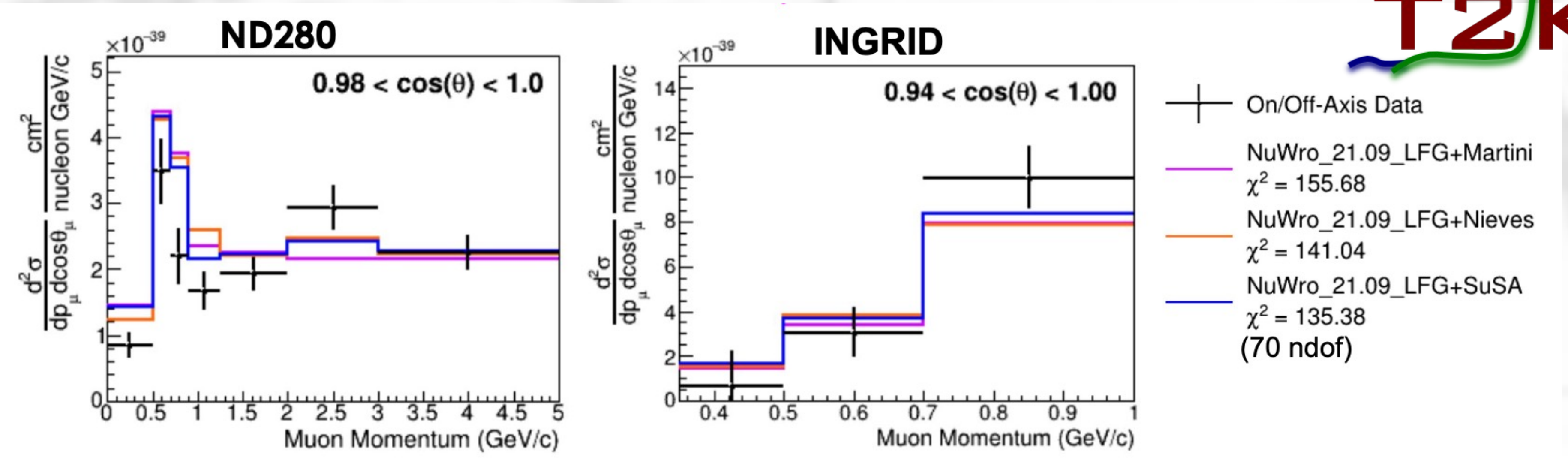
T2K off-axis



T2K on-axis



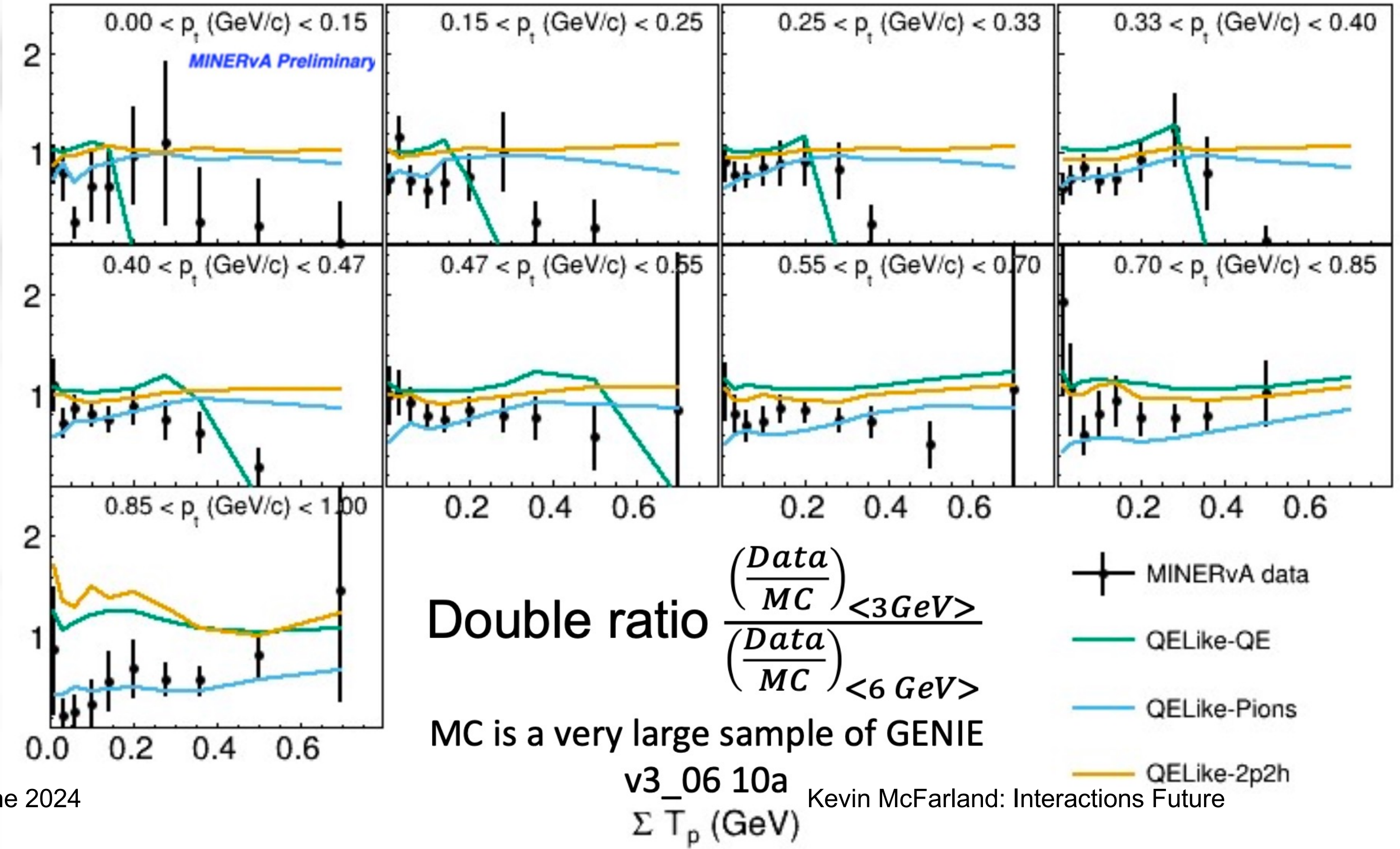
Phys Rev D108, 112009 (2023)

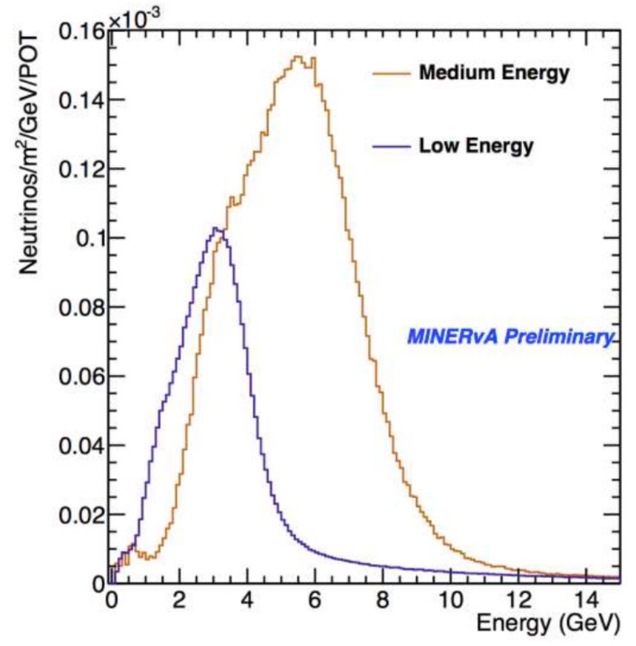


Buizza Avanzini, summarizing T2K result

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!

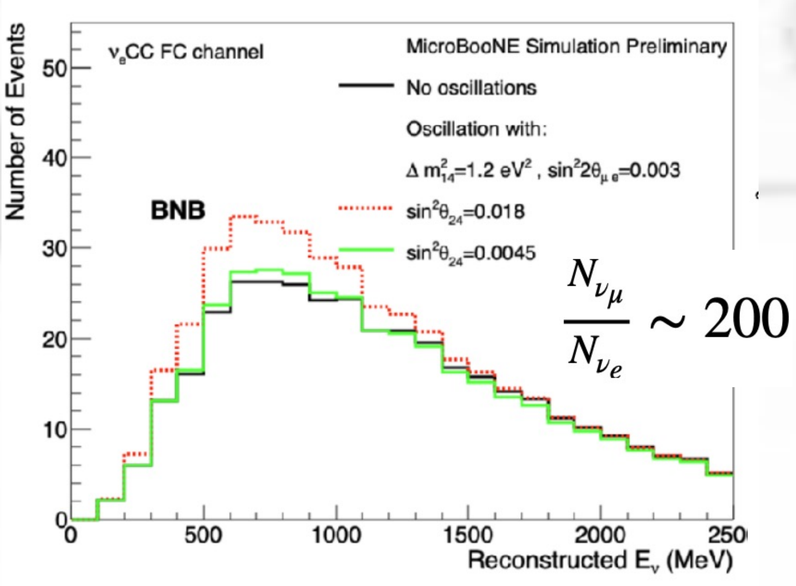


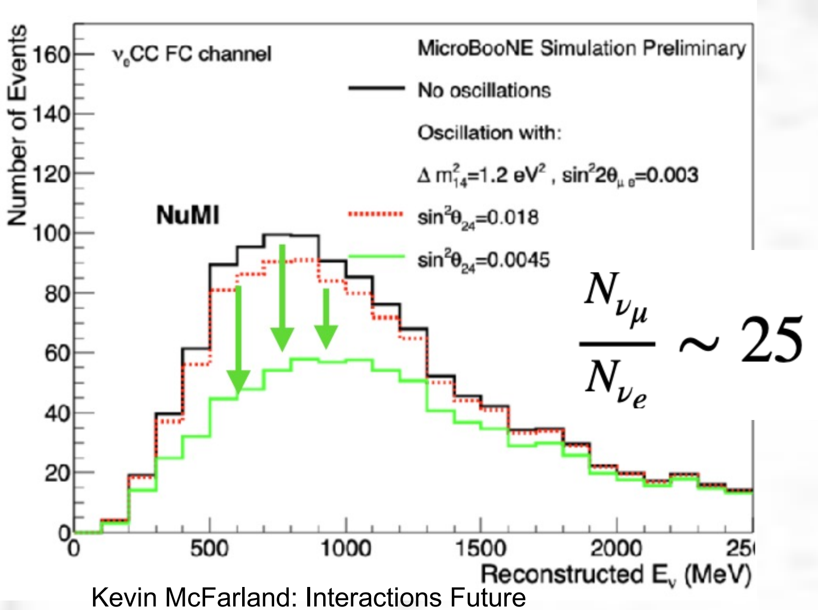


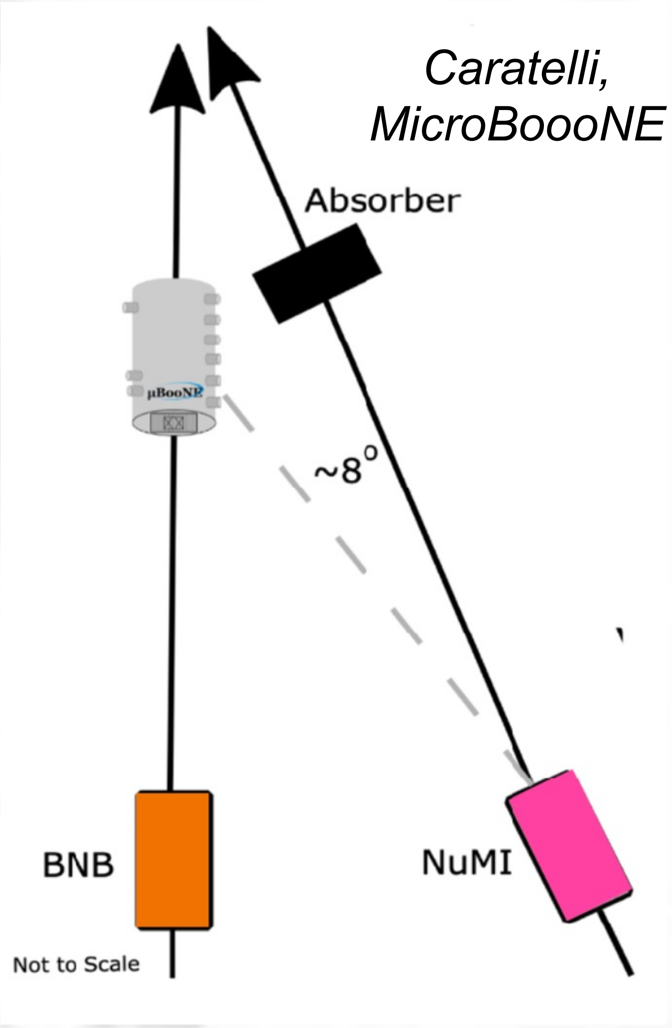
Dan Ruterbories, NuINT 2024

Location… for flavor

- 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.

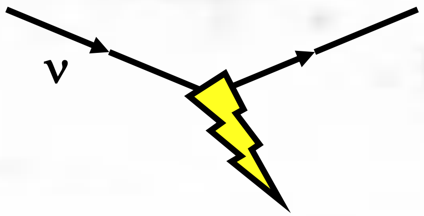






Intensity and Location commentary

- Neutrino beams continue to grow in intensity, increasing statistics for neutrino interaction measurements, and allowing smaller target/detectors.
- Off-axis beams, to tune neutrino energy and flavor, are a luxury of the very intense beams that we are producing at accelerators.
- Today we are seeing early results from experiments.
- But I'll *predict* that this technique will become increasingly critical in our control of flavor and energy dependence of neutrino interactions for oscillation experiments.
  - *More on this later.*

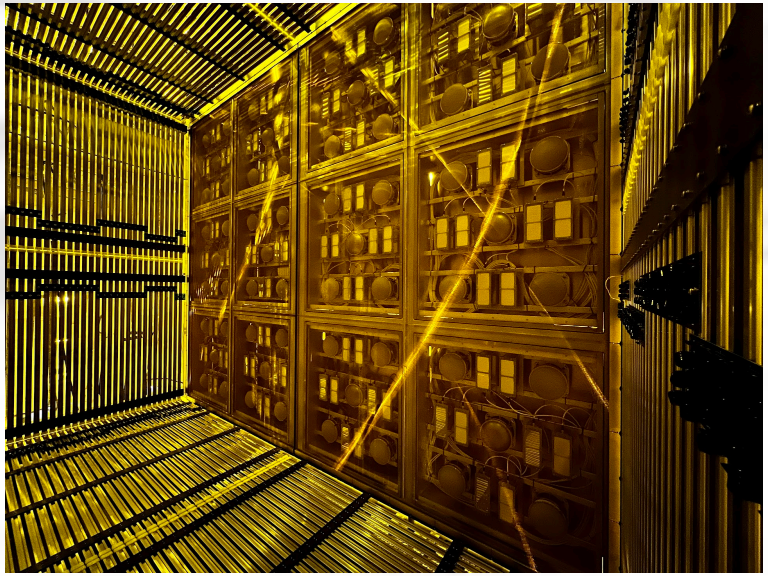


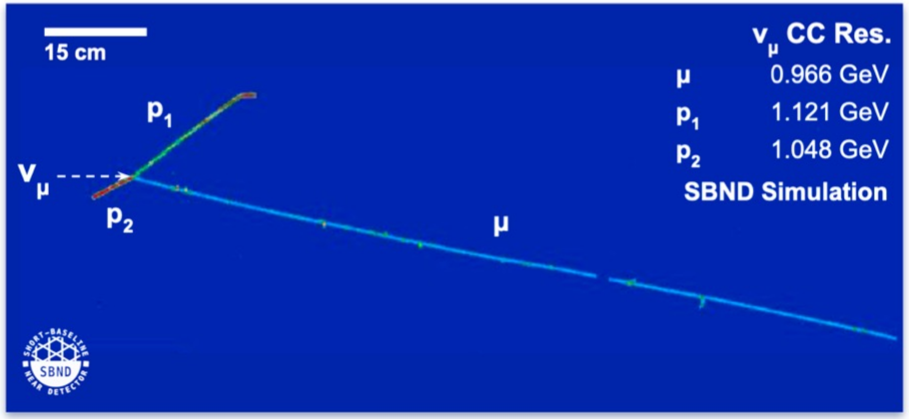
Detectors

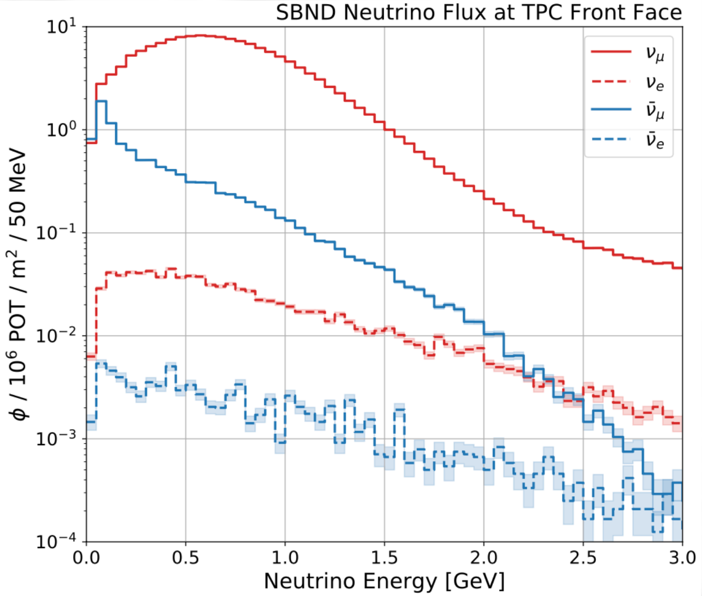
(like the Duomo di Milano, detectors are designed by committees, parts are outsourced, and they take time to build)

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 NOvA near detector or MINERvA sized statistics on an argon target.

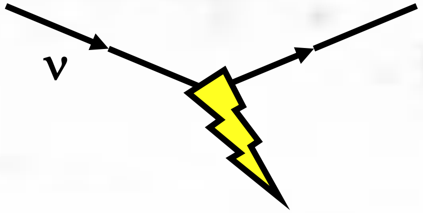




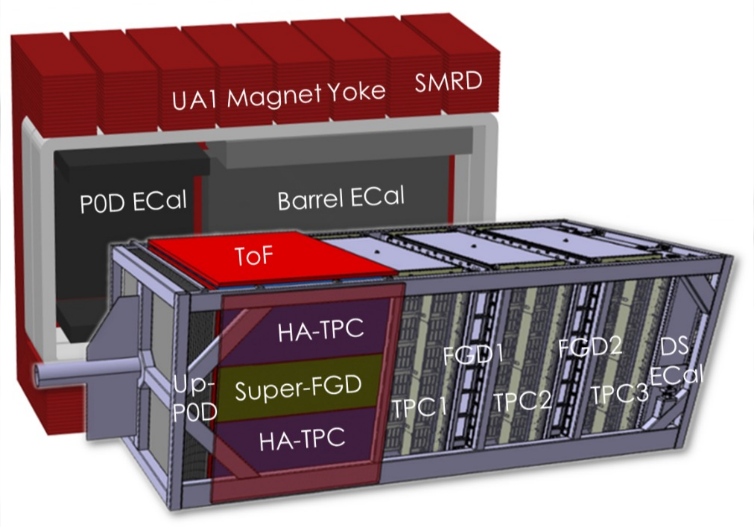


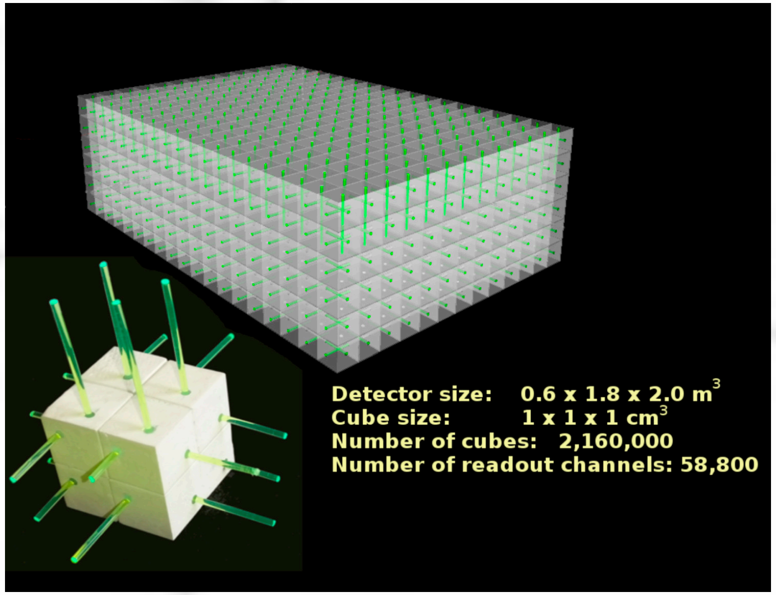
figures courtesy Vishvas Pandey

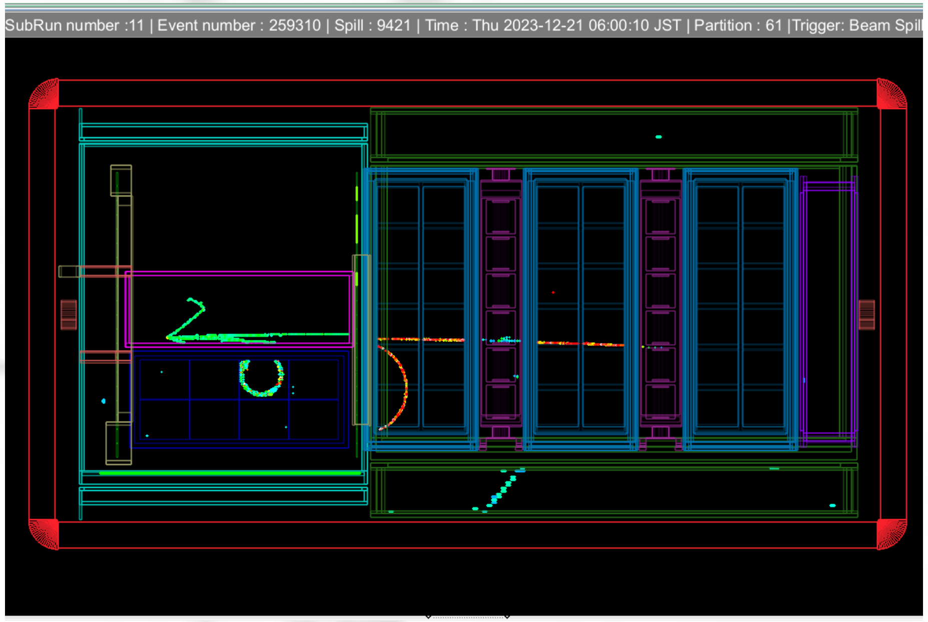
T2K/HyperKamiokande SuperFGD



- 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.



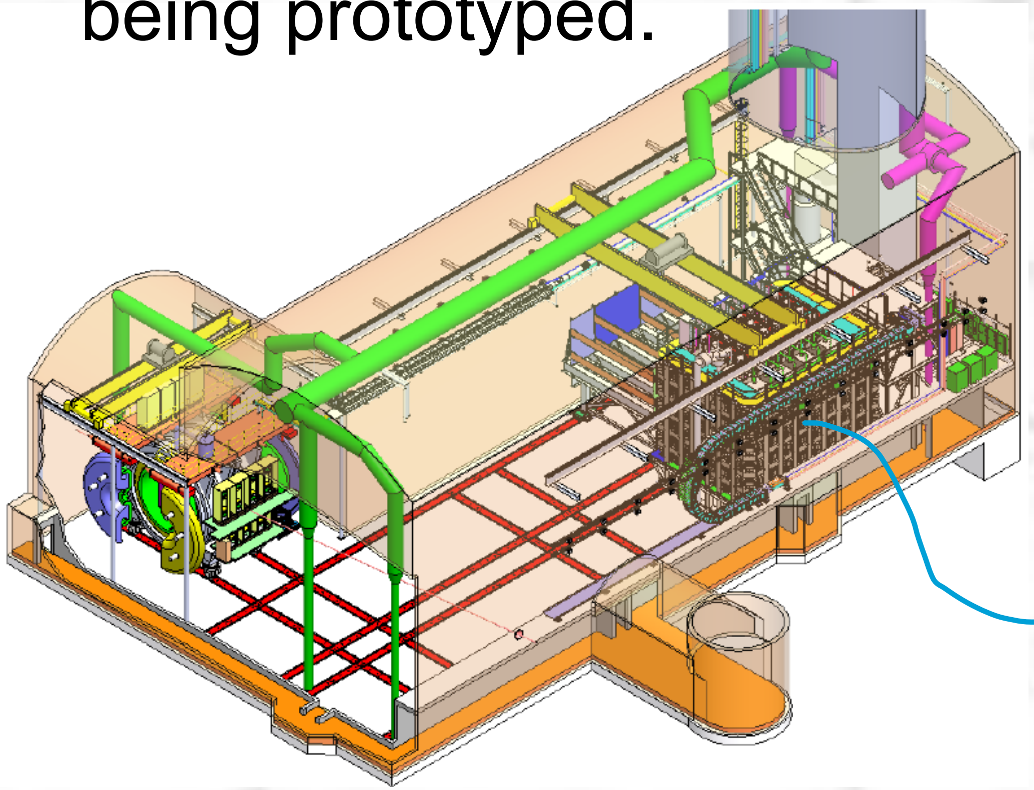


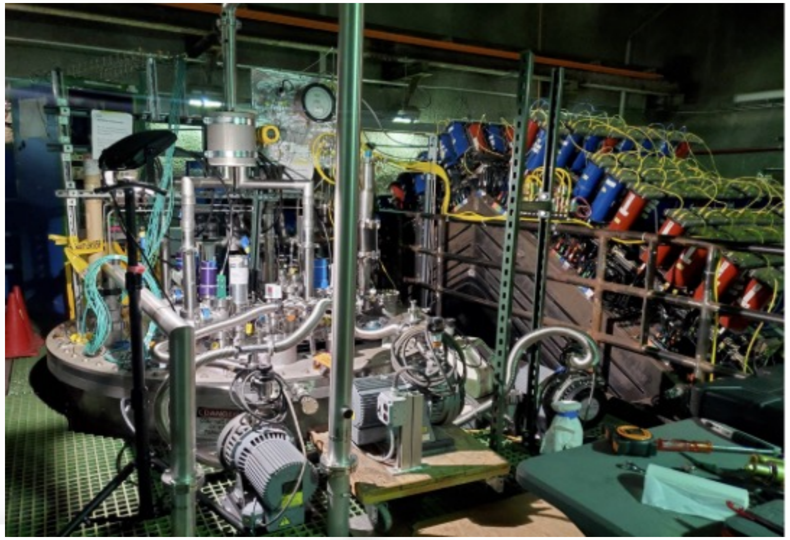


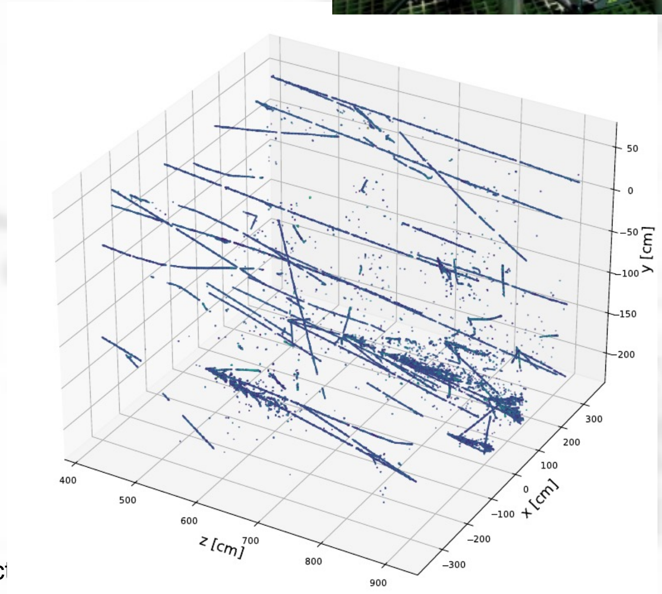
Giganti, T2K

DUNE Phase One Near Detector

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



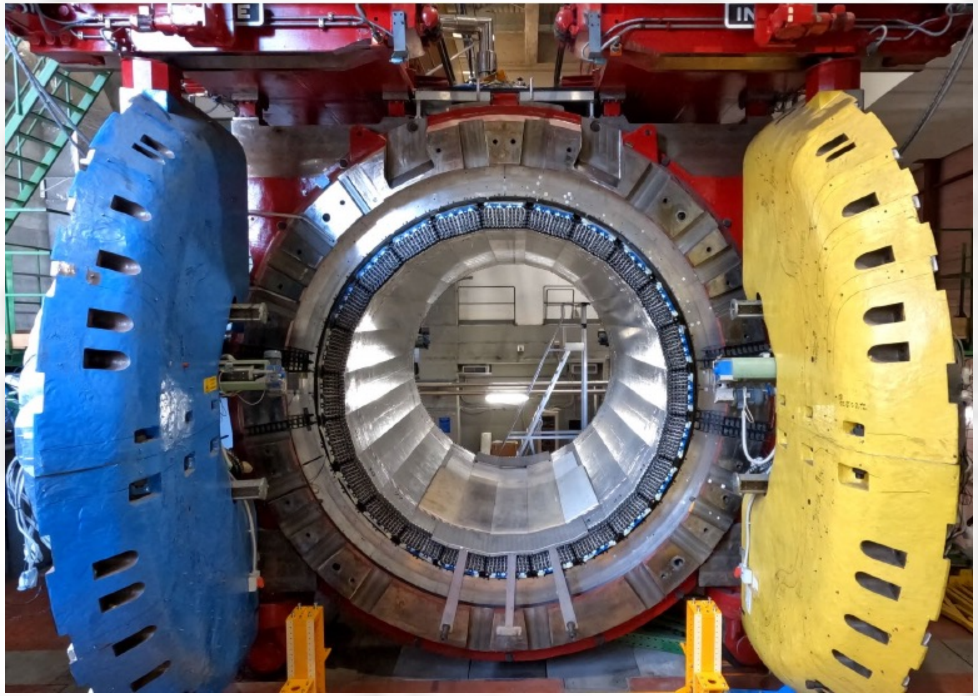


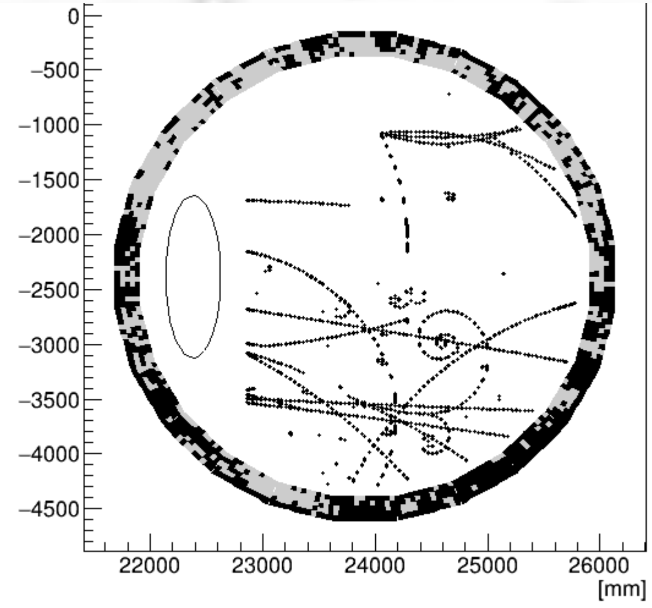


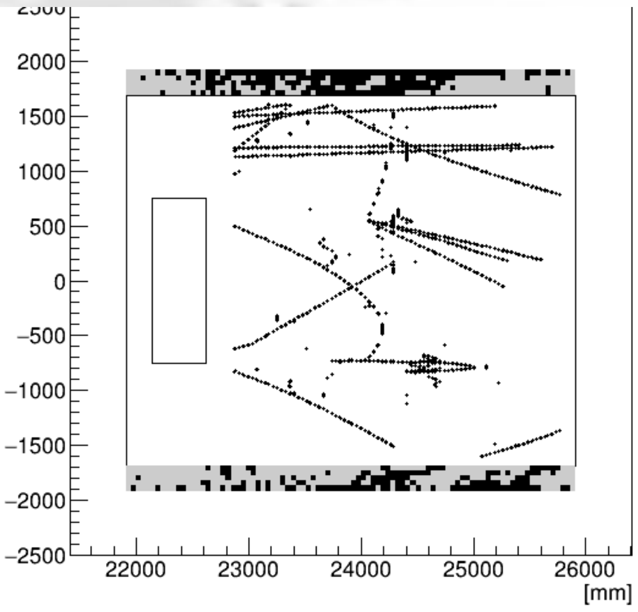
Marshall, DUNE

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.

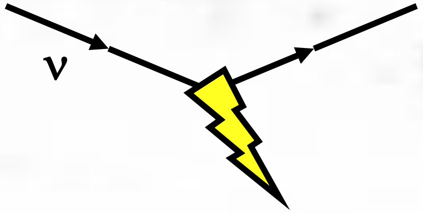




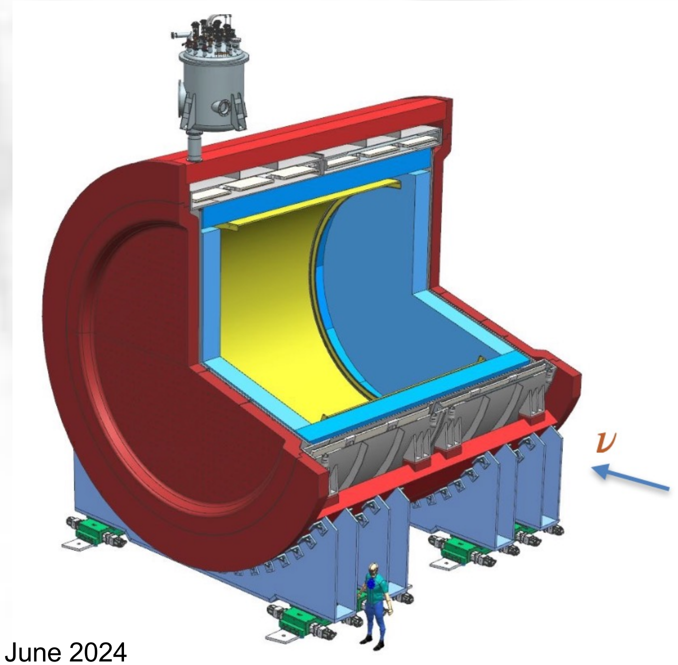


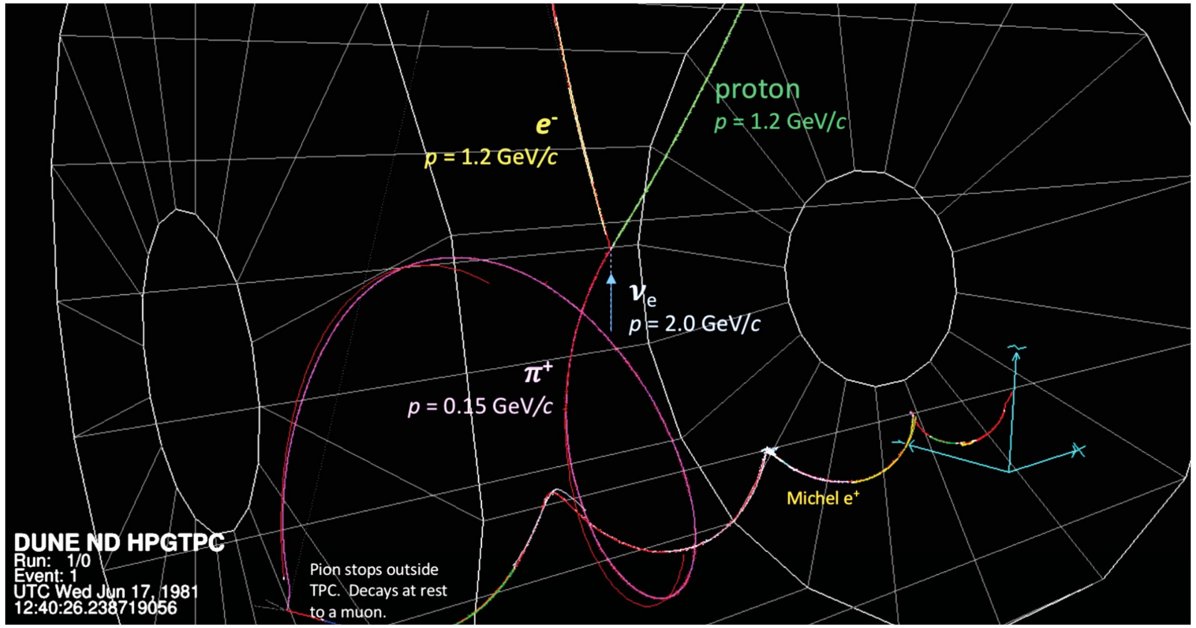
Marshall, DUNE

DUNE Phase Two Gaseous *“more capable”* ND



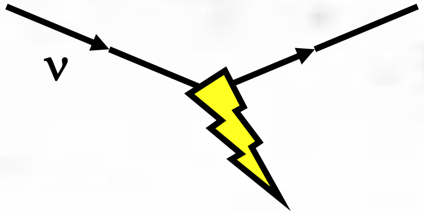
- A future gaseous argon detector would provide bubble-chamber like low thresholds for reconstruction of charged particles.
- Valuable information about energy lost to nuclear final states.



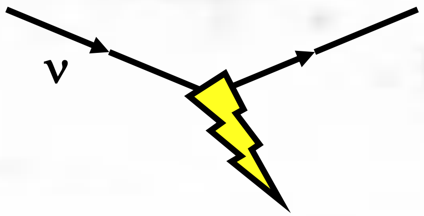


Tanaka, P5 Town Hall March 2023

Detector commentary



- The intensity allowing for smaller mass detectors also opens up a wide variety of increased capabilities.
  - Only some of which I've highlighted here today!
- We have also, as a field, benefitted from learning what worked and what didn't in past experiments.
- Detectors come with long lead times, so it's easy to *predict* we will see increased capability for neutrons, multiple target nuclei, lower thresholds and better particle identification. All of these will break new ground in understanding of interactions.
  - *More on that later.*



Neutrino Energy

(it's what oscillation experiments need to measure)

DUNE and HyperKamiokande PRISM

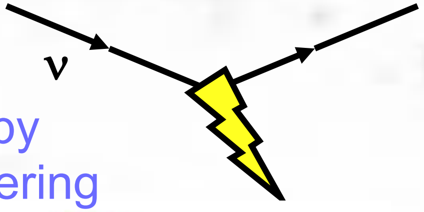
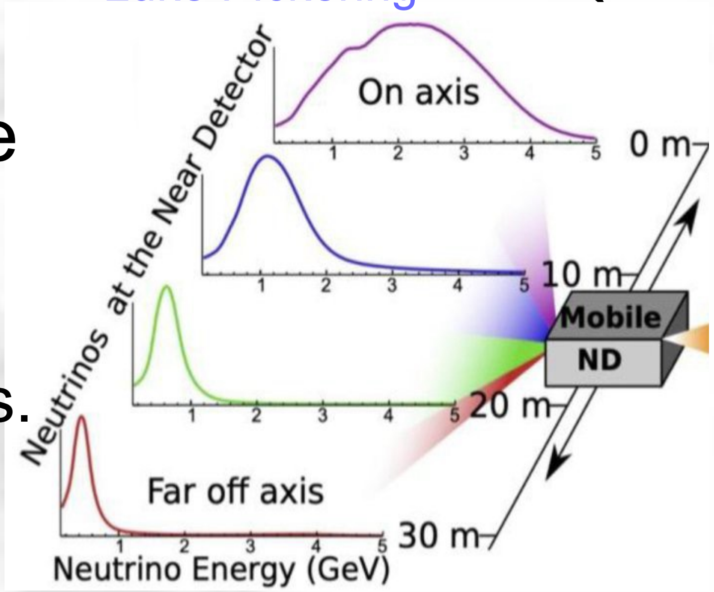
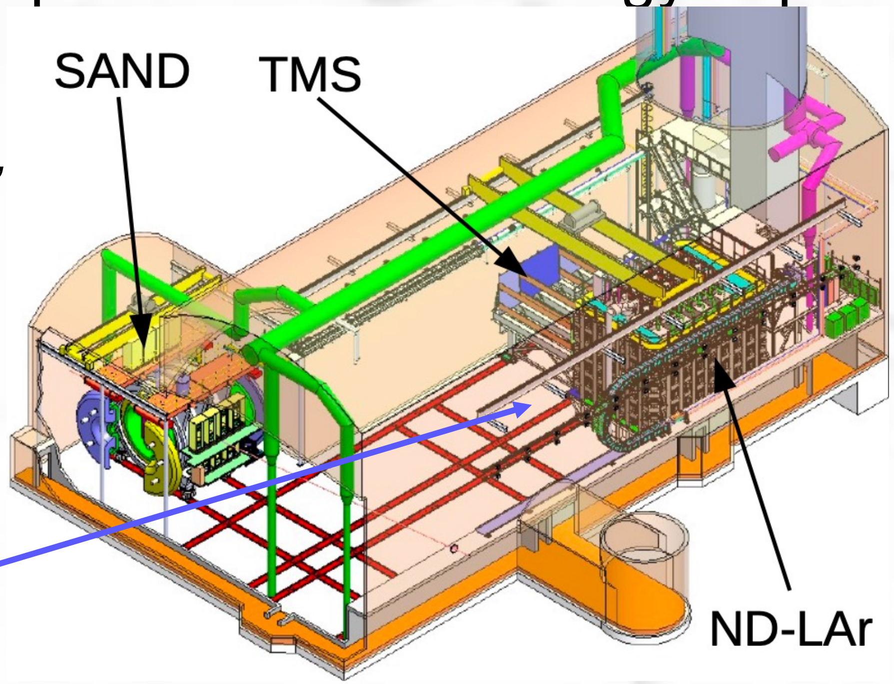


image by
Luke Pickering



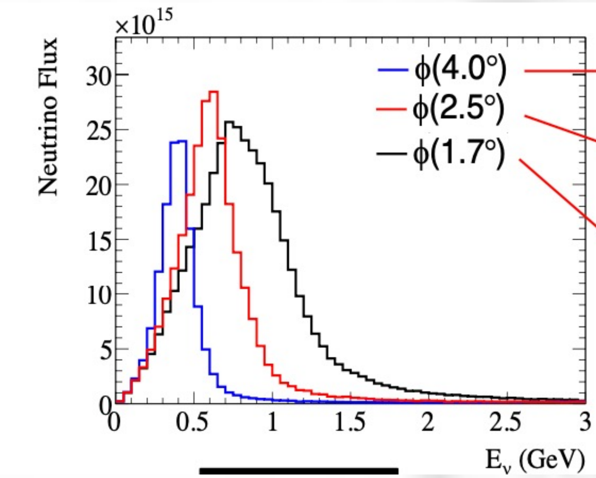
- DUNE and HyperKamiokande both intend to have movable detectors for the PRISM technique.
  - While framed as a tool directly applied to oscillations, this probes neutrino energy dependence of interactions.

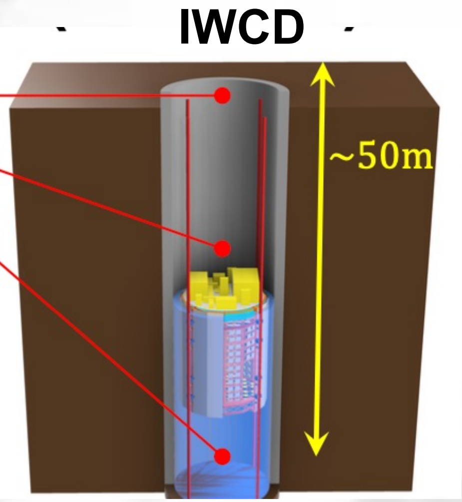
Marshall, DUNE



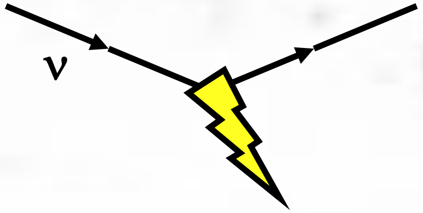
movable, for PRISM

Moriyama, HyperKamiokande

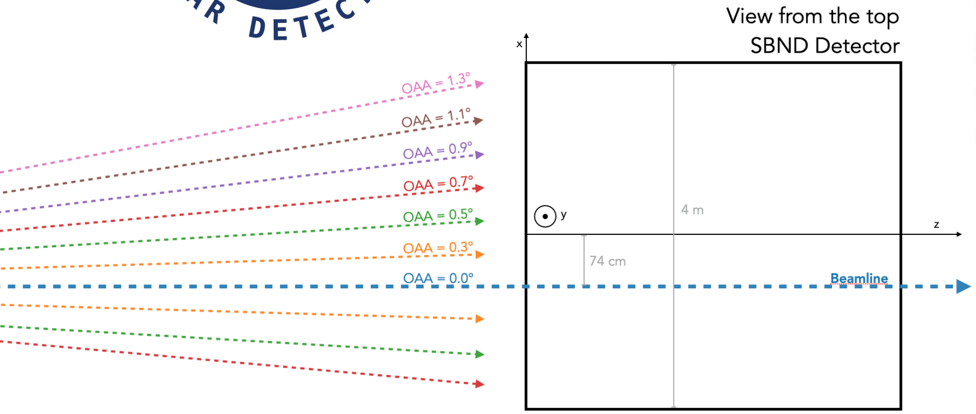


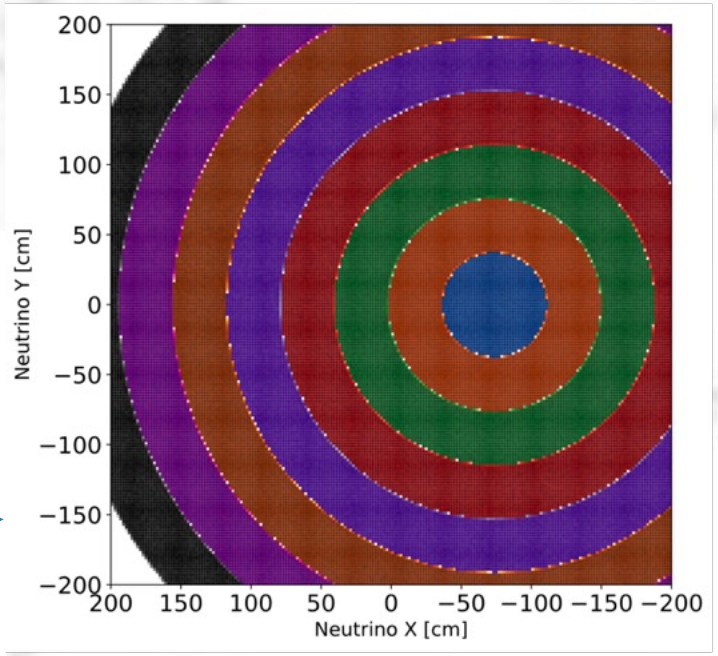


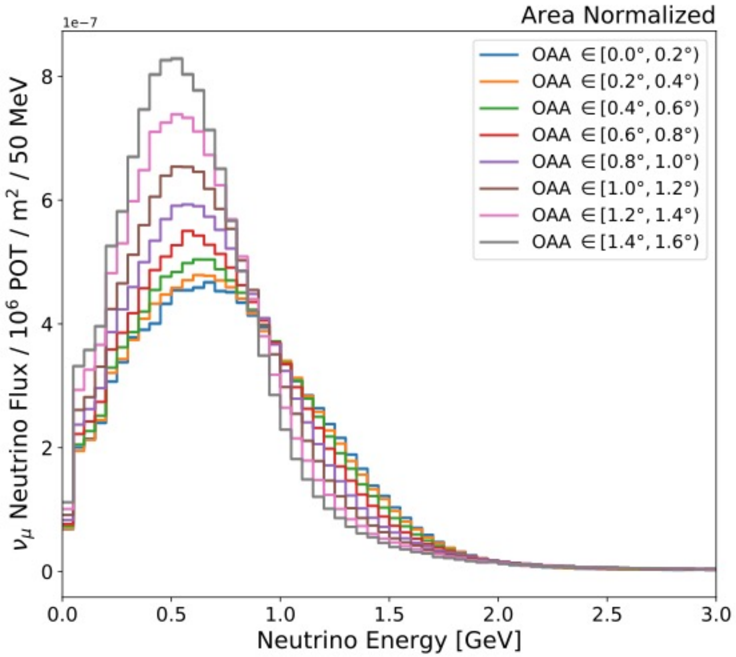
SBND "Mini" (my word) PRISM



- 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.



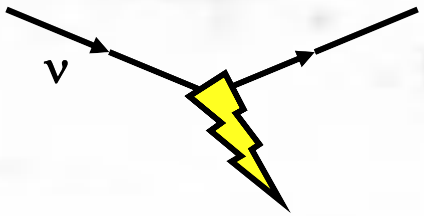




figures from Vishvas Pandey

Energy commentary

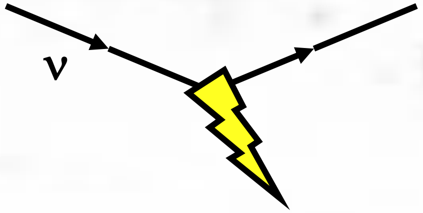
- It is a limitation of our wideband beams that we have had very few tools to cleanly probe neutrino energy dependence of interactions.
- That is problematic when neutrino oscillations requires measurement of neutrino energy and flavor.
  - Current experiments probe this effect indirectly and minimize its impact with narrow band beams and near to far detector comparisons.
- Direct capability to probe energy dependence of a wide variety of interactions is novel and, I *predict, a* critical capability of our next generation of experiments



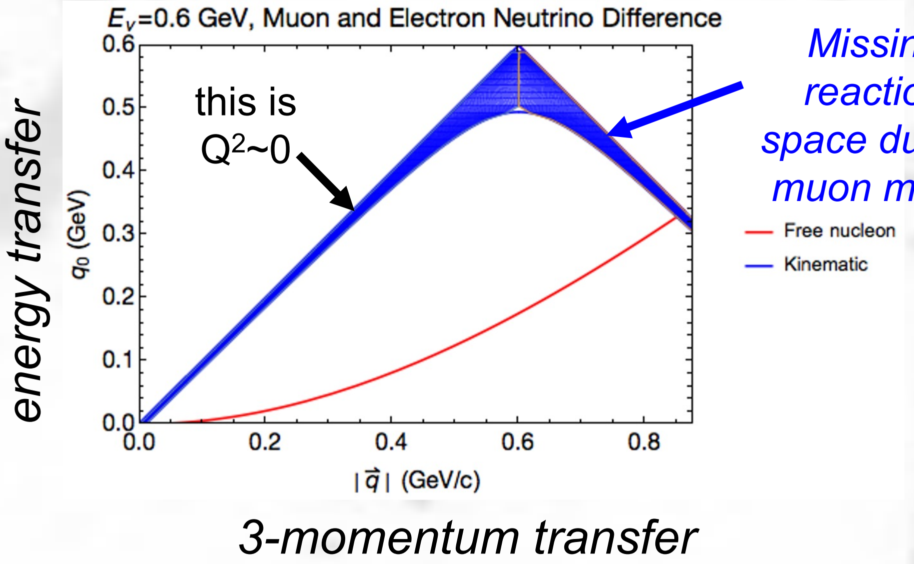
Neutrino Flavor

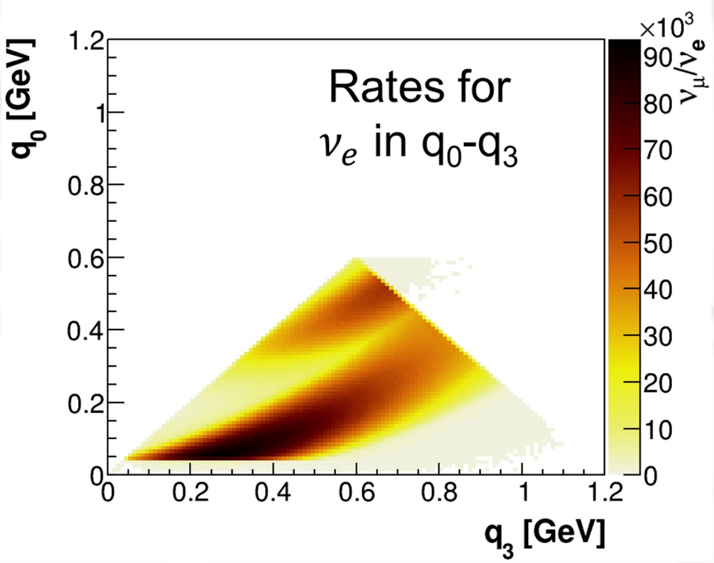
(in American English,
there is no "u" in "flavor")

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.

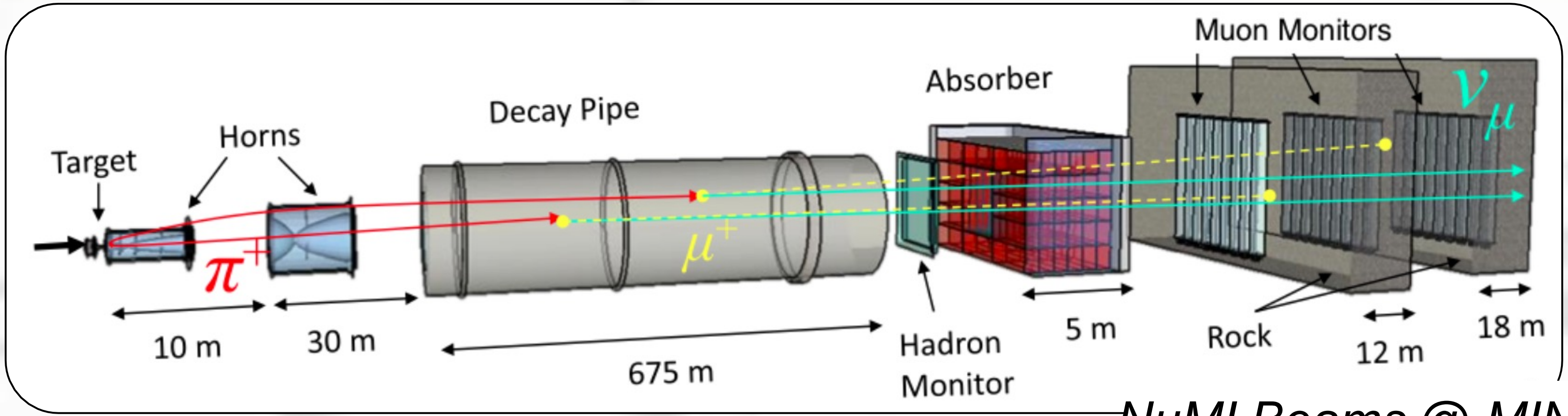




Radiative corrections:
O. Tomalak et al.,
Nature Commun. 13 (2022) 1, 5286
and Phys.Rev.D 106 (2022) 9, 093006

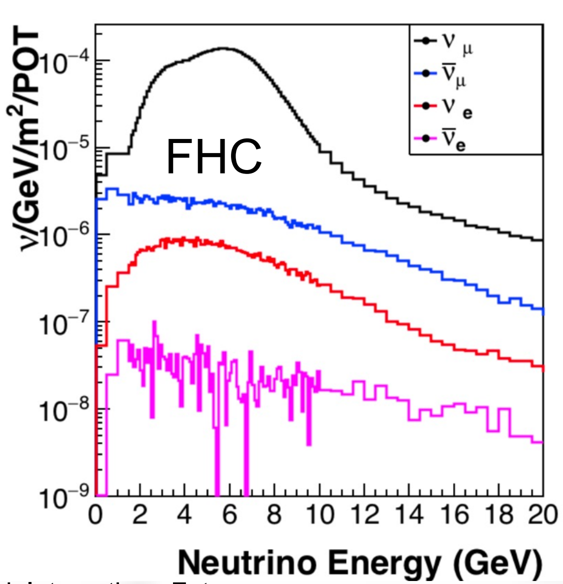
Nuclear effects:
T. Dieminger et al.,
Phys.Rev.D 108 (2023) L031301

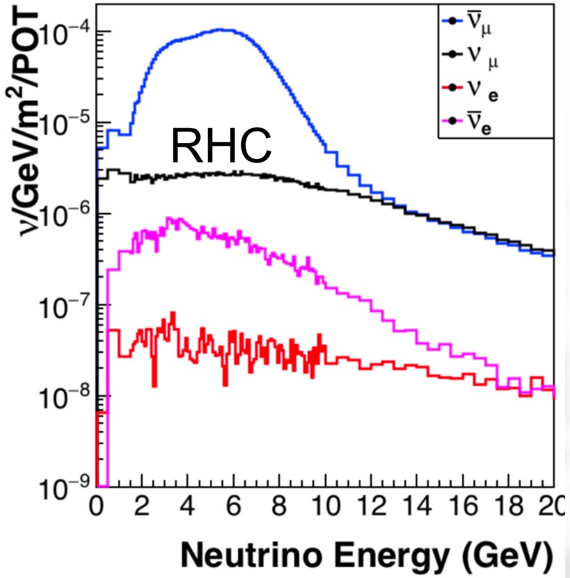
MINERvA: Electron Neutrino Flux



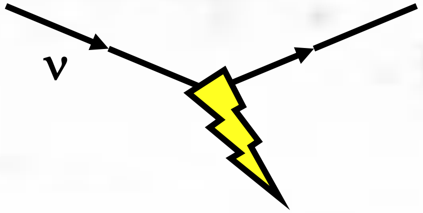
NuMI Beams @ MINERvA

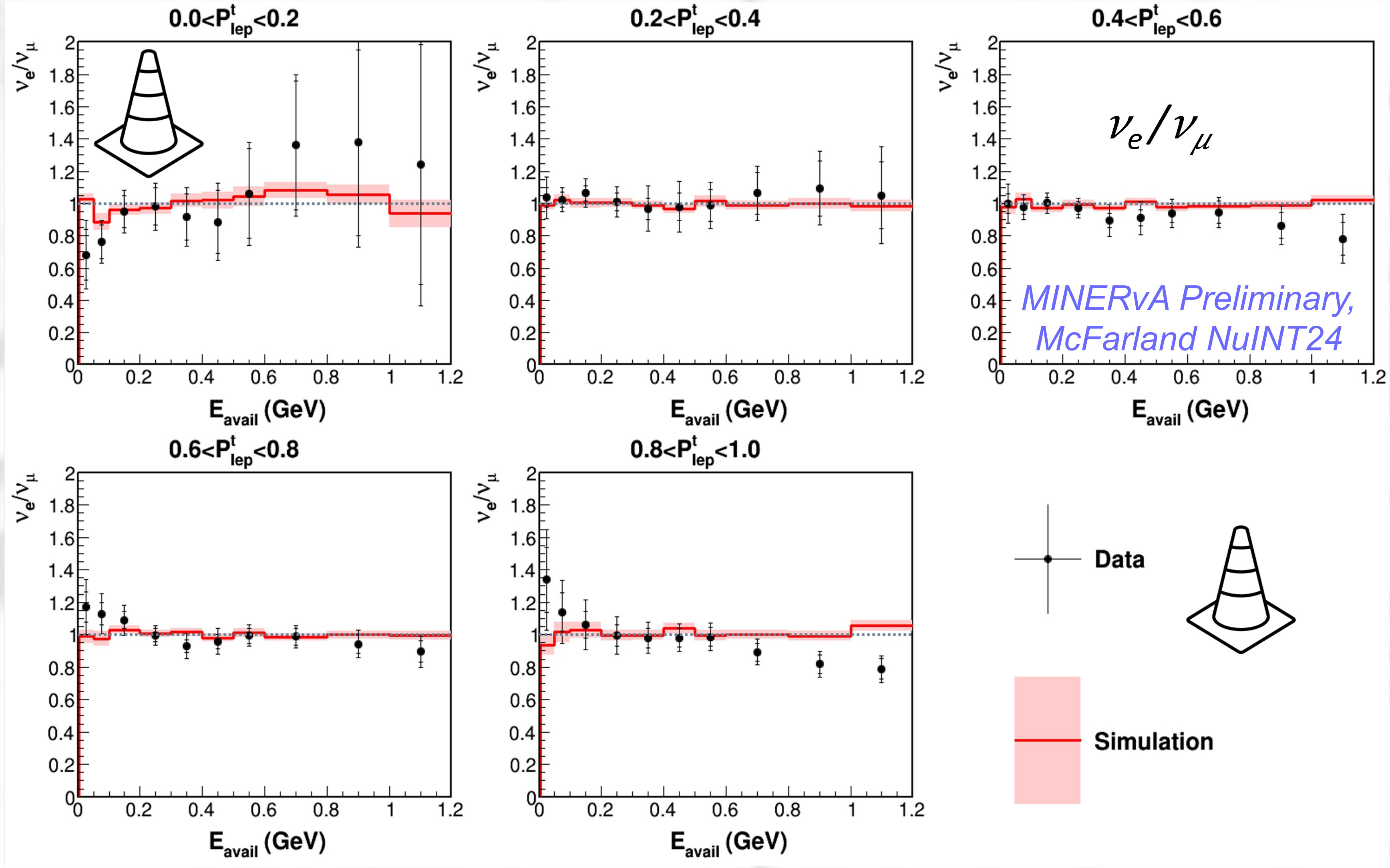
- NuMI is a "conventional" neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons or kaons.
- ~1% contribution of the beam.





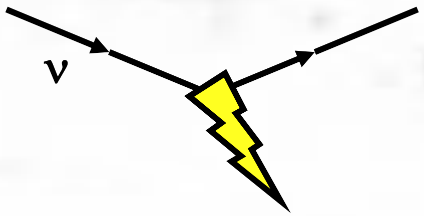
MINERvA ν_e/ν_μ Ratios





- 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 ☺.

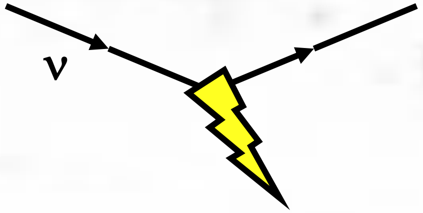
Flavor (or color?) commentary



- 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.
- Very high statistics of future beams, supplemented by far off-axis samples from SBN (ICARUS) and MicroBooNE, should allow this.

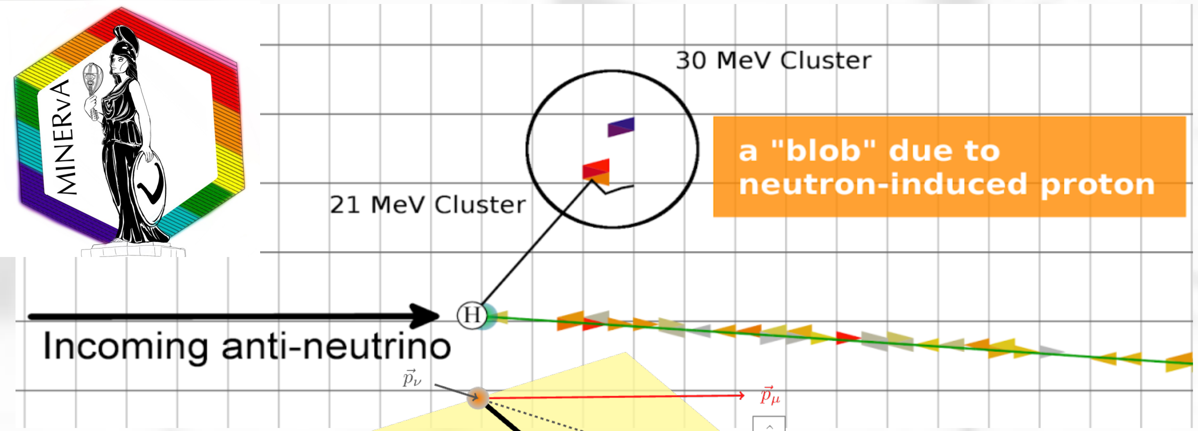
Neutrons

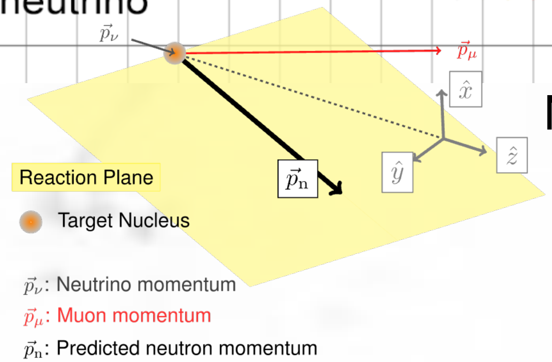
(we've made friends with light neutral long-lived particles, so maybe we should try these too)



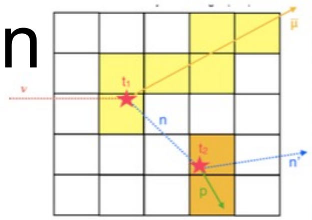
Neutron reconstruction

- 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.

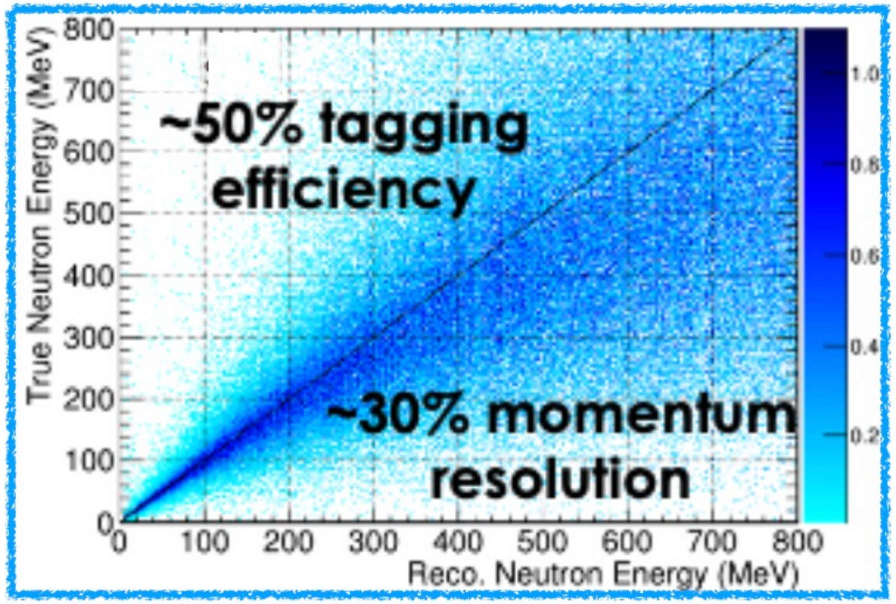


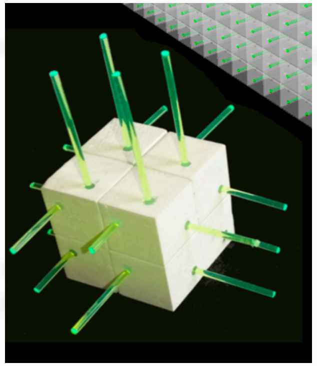


Nature, 614, 48-53



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

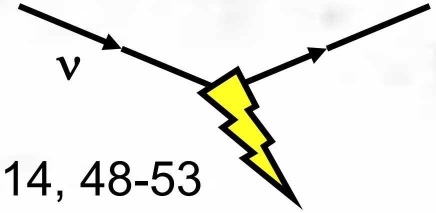




Phys. Rev. D101 (2020) 9, 092003

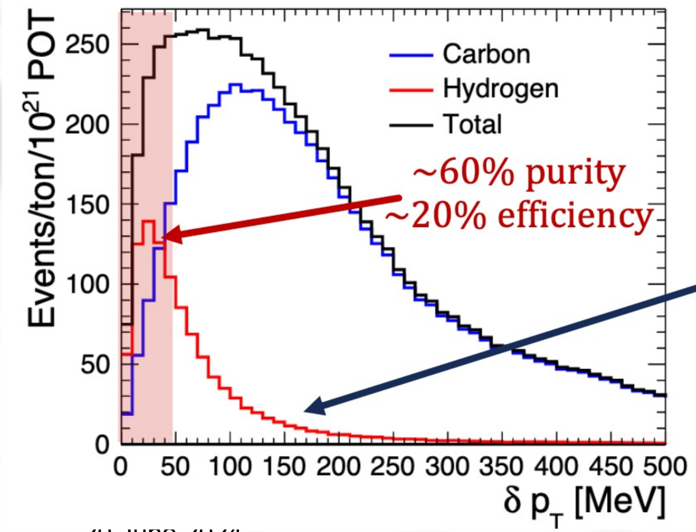
Giganti, T2K

Neutron and Axial Form Factor



Nature, 614, 48-53

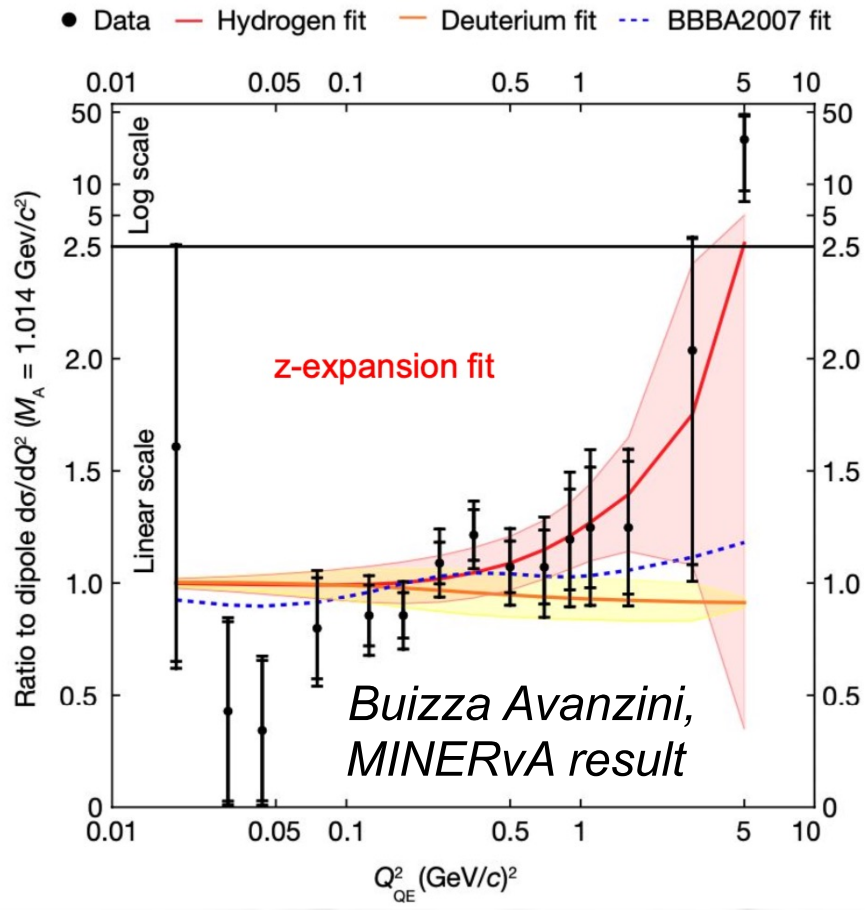
- MINERvA used neutron reconstruction and ability to isolate events on hydrogen (only with direction!) to measure $F_A(Q^2)$ with useful precision $0.06 < Q^2 < 2$ GeV².
- SuperFGD will have two handles, direction and energy, to isolate hydrogen scattering.



Antineutrinos:
Peak from interactions on hydrogen

No nuclear effects

Possible thanks to **neutron detection**!



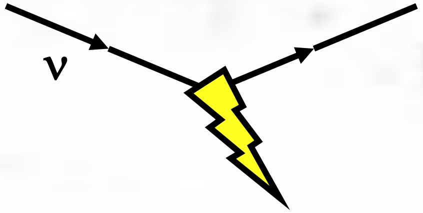
Phys. Rev. D 101, 092003 (2020), assembled figure from L. Munteanu

Neutron commentary

- I can confidently *predict* that neutron measurement techniques developed in recent years, through detector and analysis technologies, will have multiple impacts.
  - I emphasized 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 low and requires capable detectors; thus high power neutrino beams are another enabling technology.

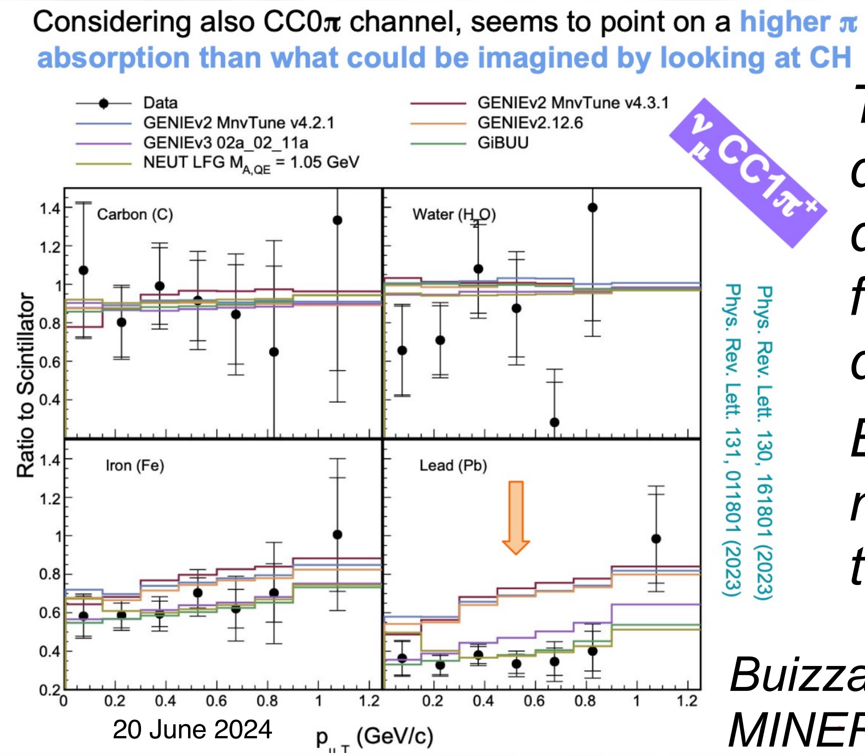
Nucleons and Nuclei

(hydrogen is the most special of the nuclei?)



Is a nucleus a nucleus a nucleus?

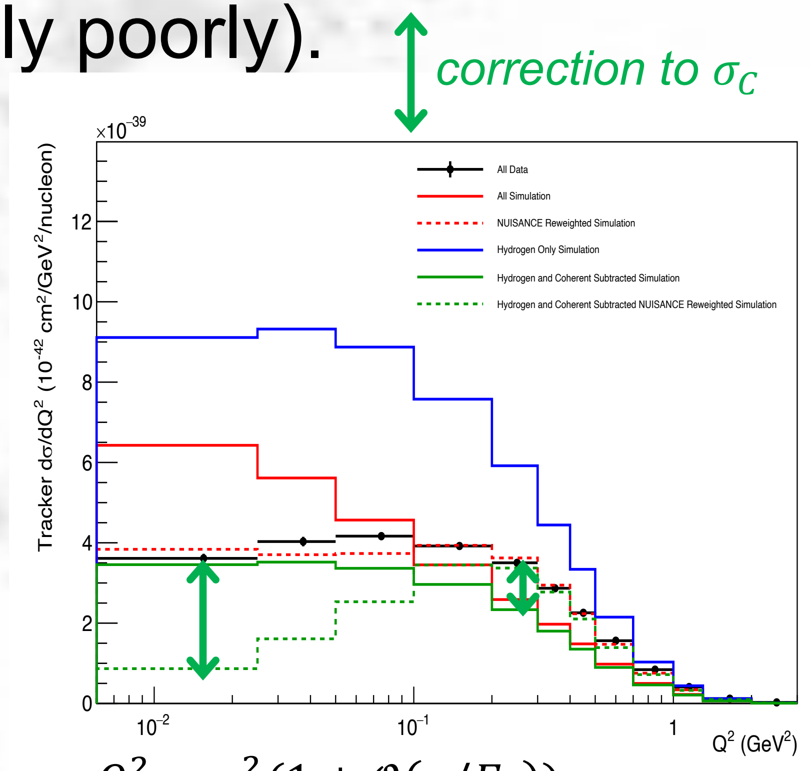
- Details of nuclei, such as energies and momenta of individual nucleons within the nucleus, vary.
- But we are beginning to see some consistencies in how models describe different nuclei equally well (or equally poorly).



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.*

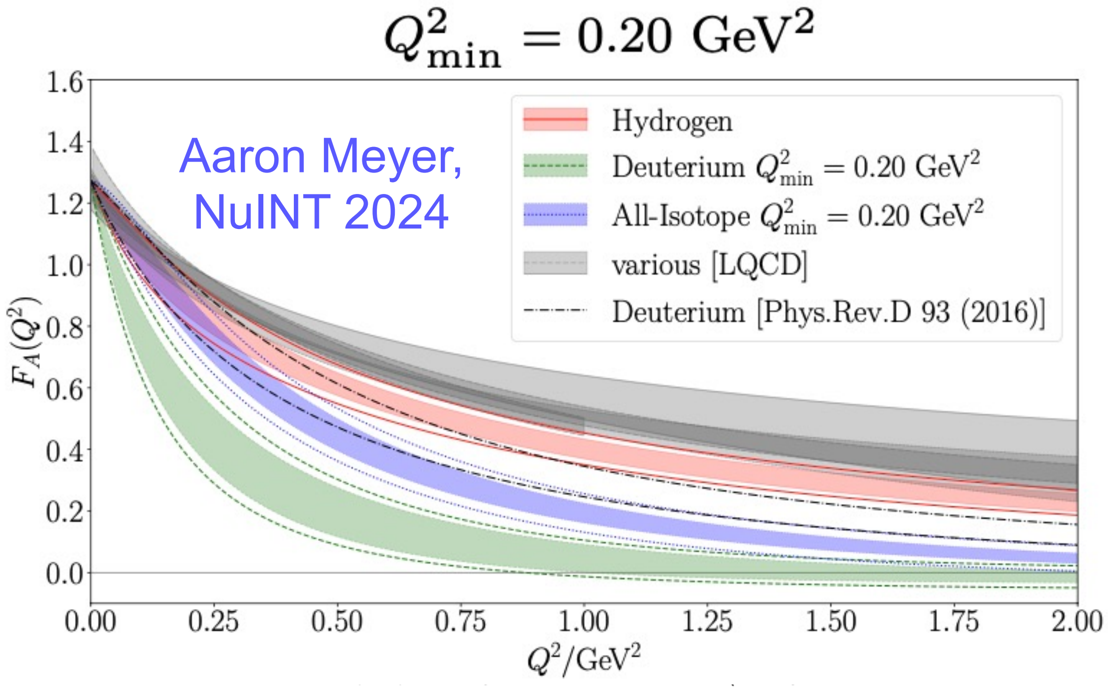
Buizza Avanzini, MINERvA result



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

Nucleons vs Nuclei

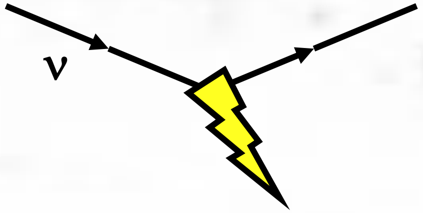
- By contrast, we are struggling to understand cross-sections on free nucleons as a base for calculating cross-sections on nucleons.
- In $F_A(Q^2)$, there are significant tensions between the deuterium bubble chamber legacy data, and either the MINERvA hydrogen or lattice QCD calculations.
- Why? It's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



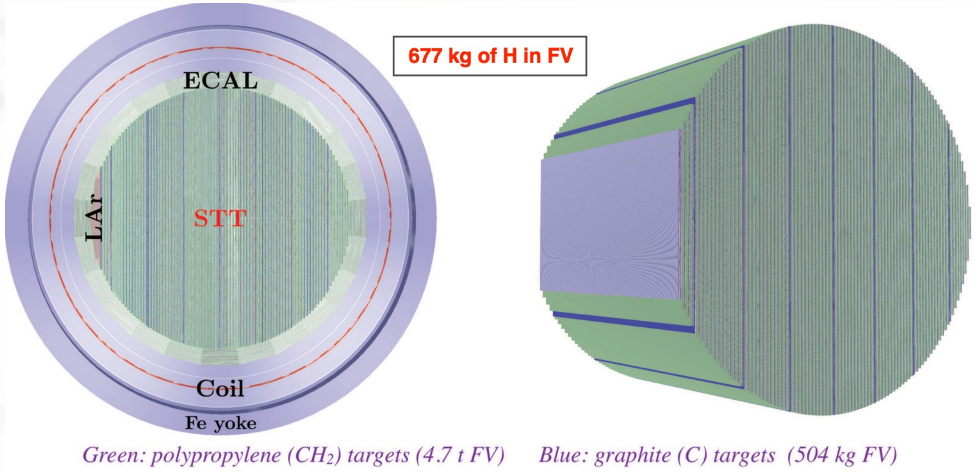
	$\{a_k\}_{\rm D}$	$p_{\rm D}$	$\{a_k\}_{\rm H}$	$p_{\rm H}$
$\chi^2_{\rm D}/{\rm DoF}_{\rm D}$	94.9/94	0.45	167.7/96	8.3×10^{-6}
$\chi^2_{\rm H}/{\rm DoF}_{\rm H}$	23.3/15	0.08	10.0/13	0.69

Deuterium is incompatible with hydrogen, LQCD

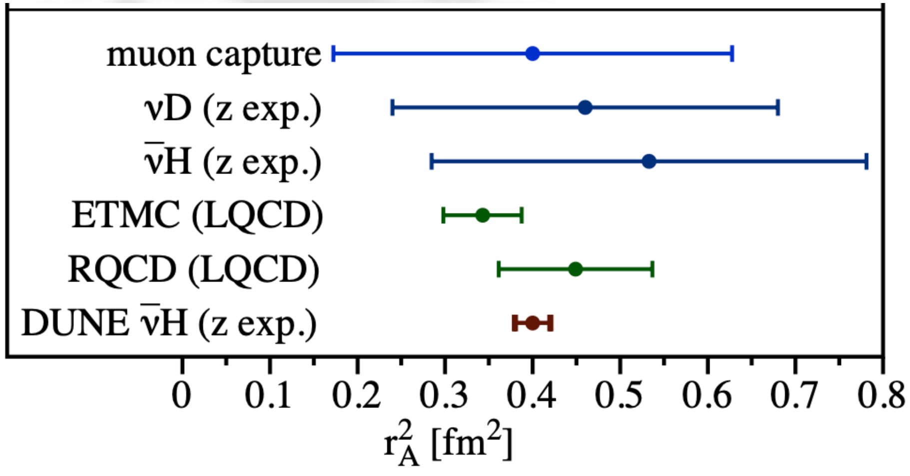
DUNE-ND "Solid Hydrogen"



- 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.")*

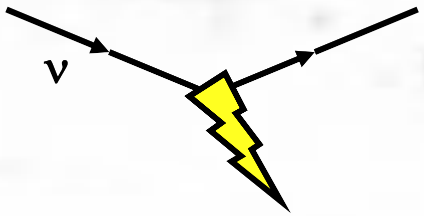


one realization of the SAND low-density tracker

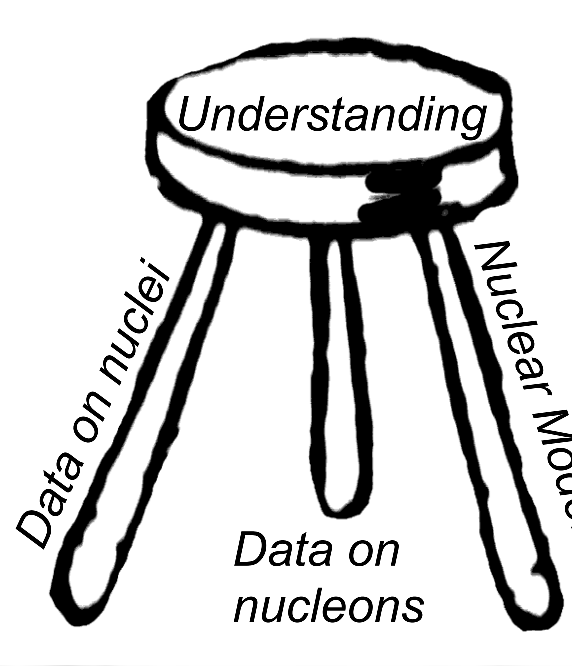


Phys.Rev.D 109 (2024) 5, L051301

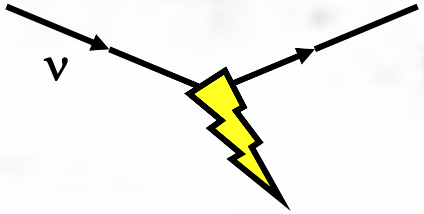
Nucleon and Nuclei commentary



- 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.



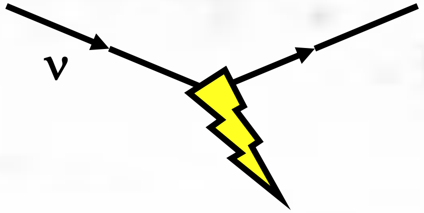
- I *predict* that experiments that can measure or theory that can calculate free-nucleon interactions, will become increasingly important.
  - Critical to carry out DUNE ND CH_n-C plan, **and** to supplement it with other ideas like modular hydrogen and deuterium bubble chambers now under development.



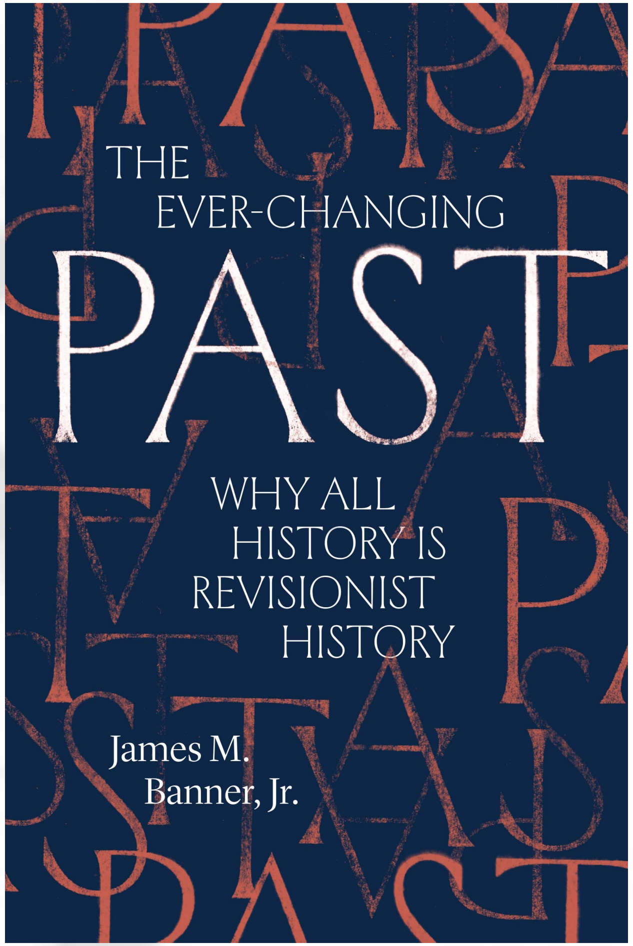
Revisionist History

(because sometimes we don't get it right on the first try. as in the deuterium story, perhaps…)

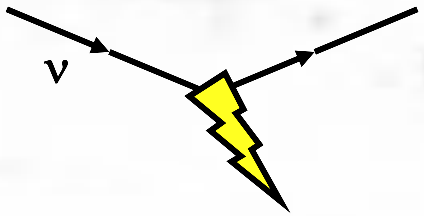
Revisionist History



- 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?

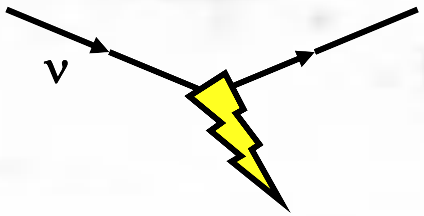


Data Preservation



- 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

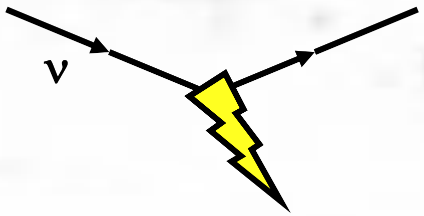
→

Event Loop Macros

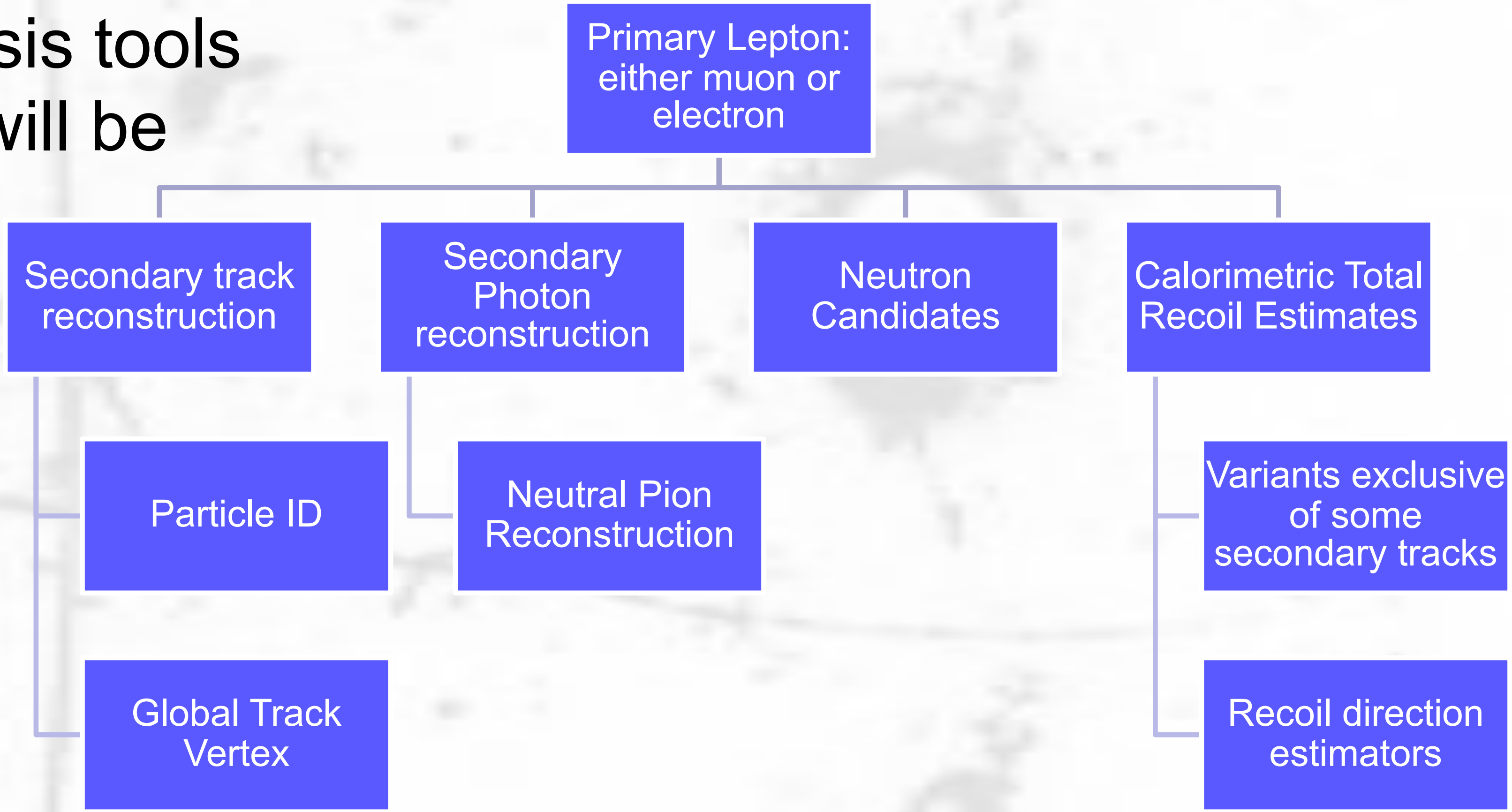
→

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

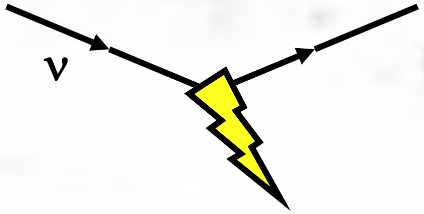
Data Preservation (cont'd)



- 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.



Closing Thoughts

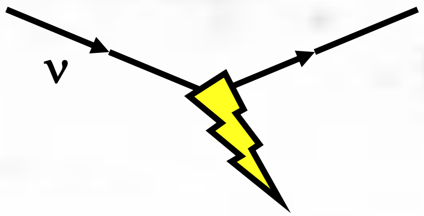


Conclusions

- The future is still the subject of the most difficult predictions.
- Nevertheless, we can *predict* that a confluence of beam and detector capabilities will enable high impact and novel measurements as new facilities begin to acquire data.
  - I've given some of my favorite examples. That may have been *exhausting*, but it was far from *exhaustive*†.

- These measurements will complement developments in theory that will support reduced uncertainties for precision oscillation measurements, and they will allow our new facilities to realize their full potential.

†Apologies for the subtle wordplay. An explanation is in the backup if you don't know the difference between these two words.

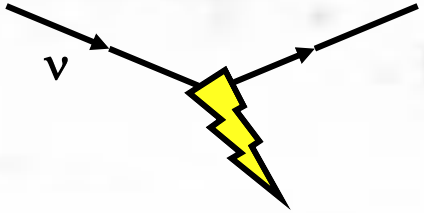


Thanks to…

- I'm grateful to the many individuals who, knowingly or unknowingly, provided materials and suggestions for this talk.

Luis Alvarez-Ruso, Margherita Buizza Avanzini, Anatael Cabrera, David Caratelli, Stephen Dolan, Daniele Gibin, Claudio Giganti, Deborah Harris, Chris Marshall, Eric Marzec, Aaron Meyer, Laura Munteanu, Shigetaka Moriyama, Vishvas Pandy, Greg Pawloski, Luke Pickering, Josh Spitz, Tamer Tolba, Sasha Tomalak, Jeremy Wolcott

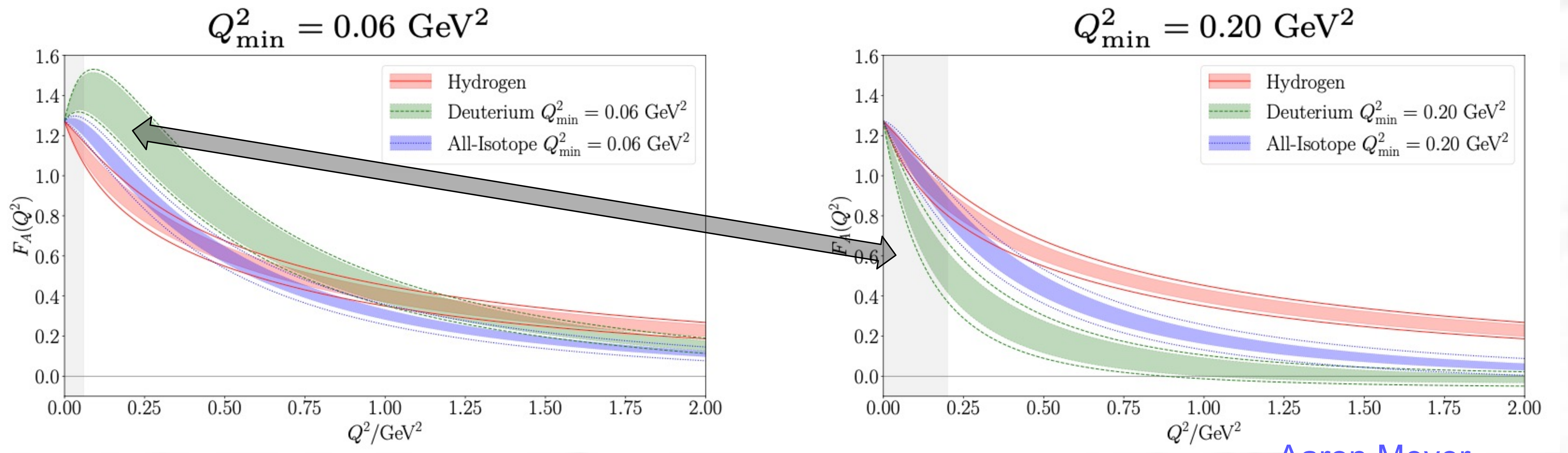
Backup



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

A Subtle Piece of the English Language

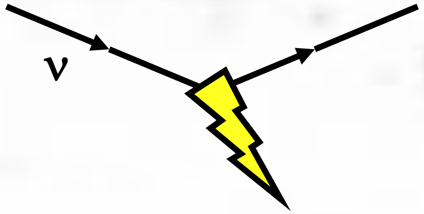
"Exhausting" and "Exhaustive"

Exhausting (adjective): making one feel very tired; very tiring.

example use: "a long and exhausting journey"

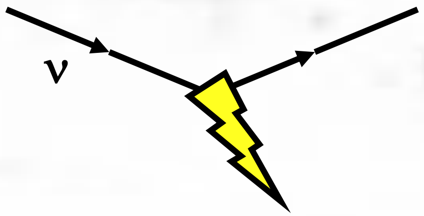
Exhaustive (adjective): examining, including, or considering all elements or aspects; fully comprehensive.

example use: "she has undergone exhaustive tests since becoming ill"

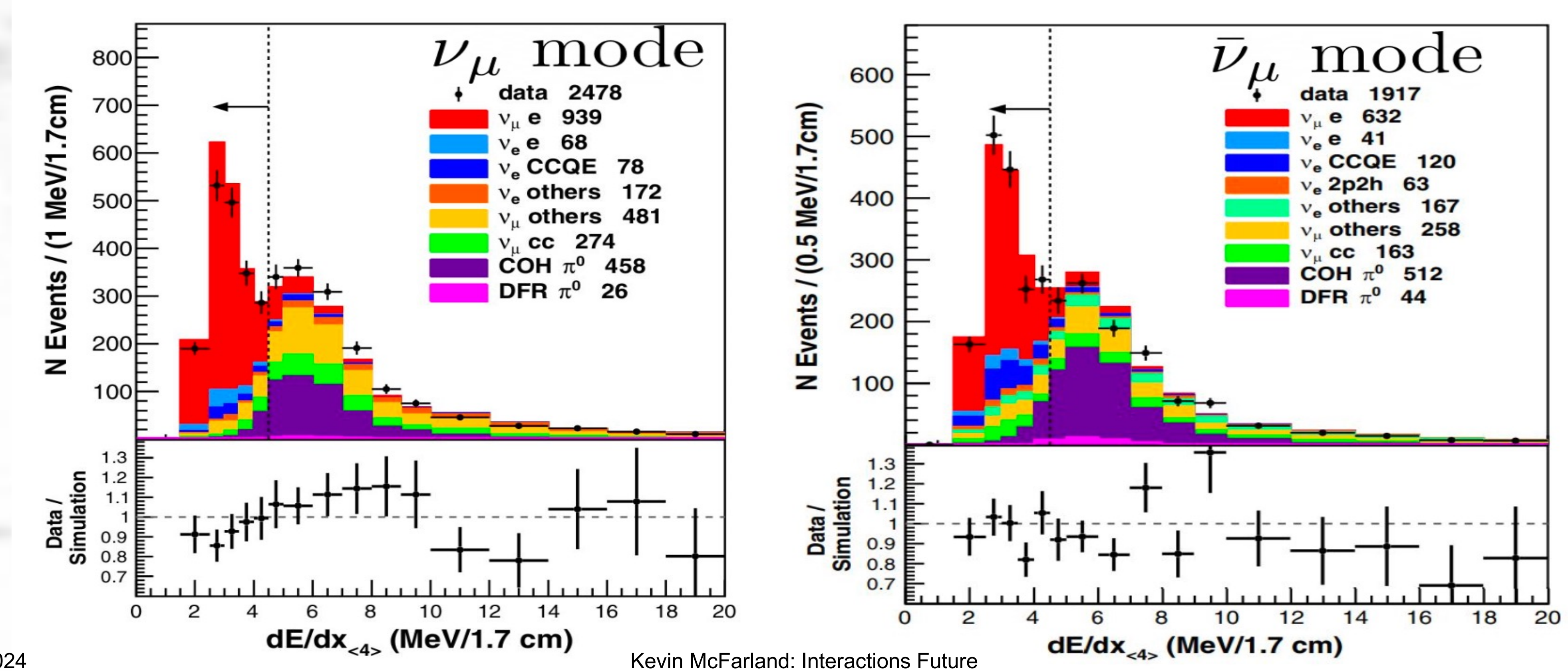


MINERνA Electrons

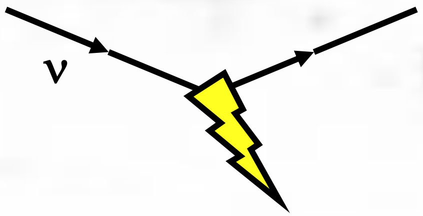
Electron/Photon in $\nu e^- \rightarrow \nu e^-$

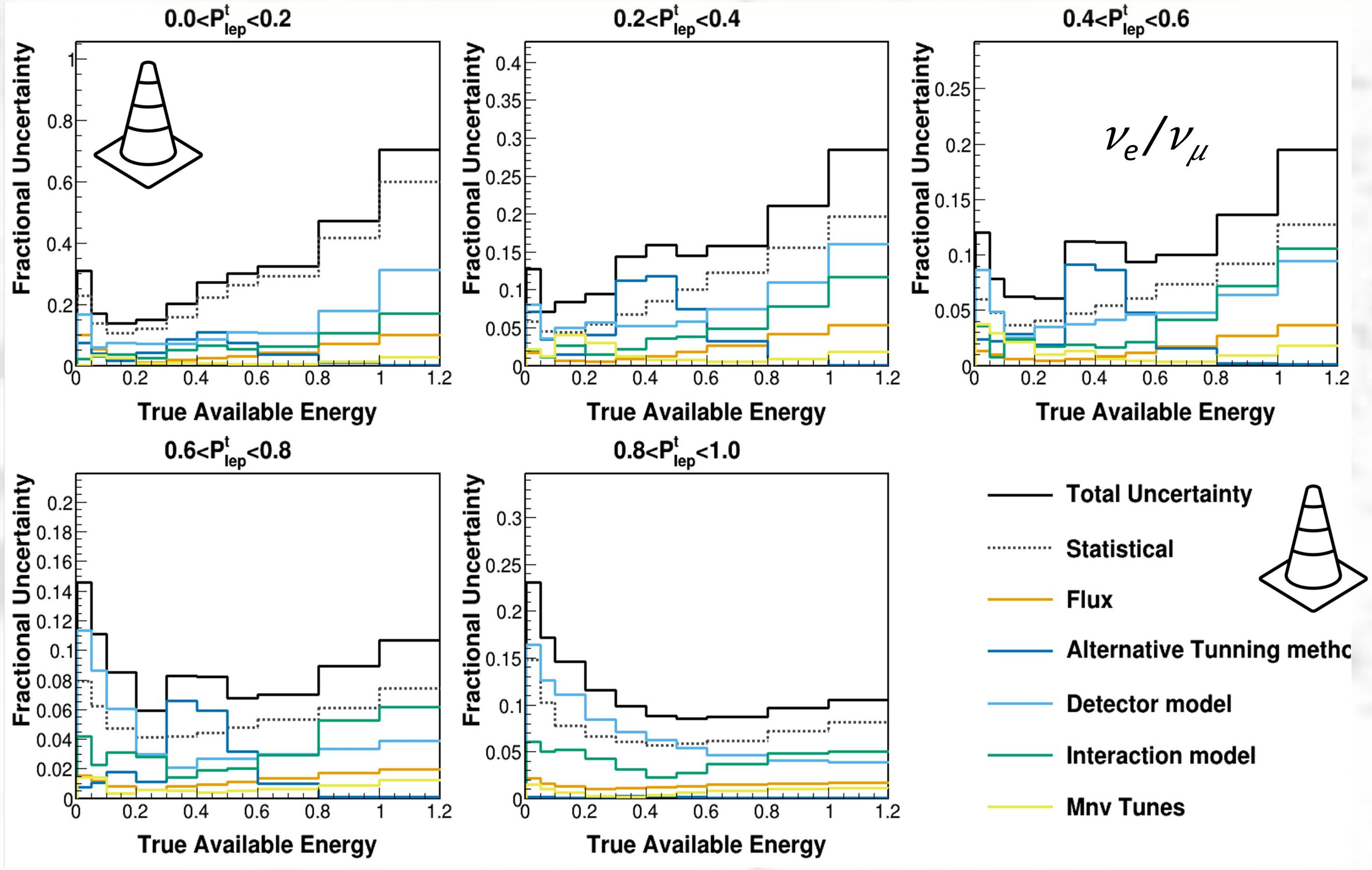


- Background from production neutral pions is manageable with dE/dx, even with an electron energy threshold of 800 MeV.



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.