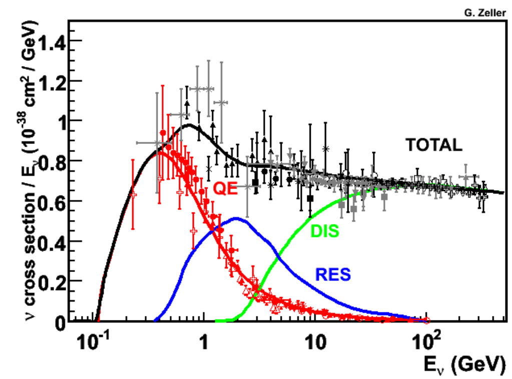
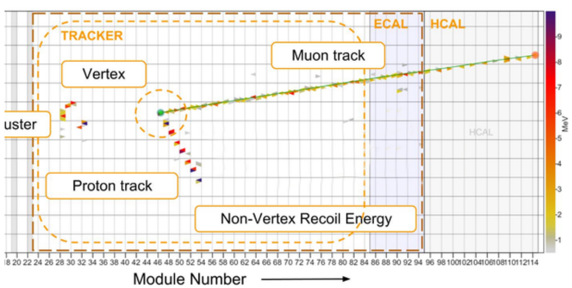
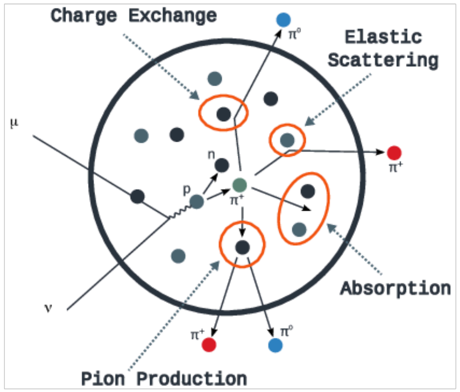
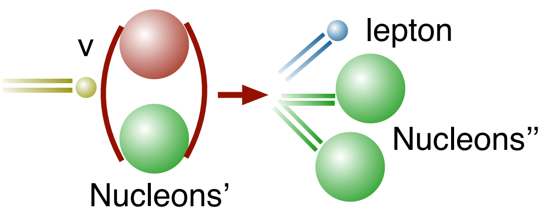


Neutrino-Nucleus Scattering

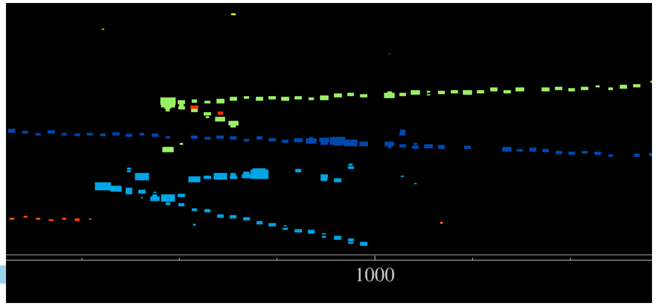




Jonathan Paley
Fermilab Neutrino Division



June 18, 2025
Neutrino University
Fermilab

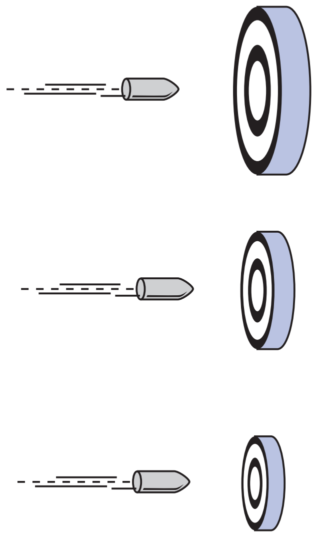


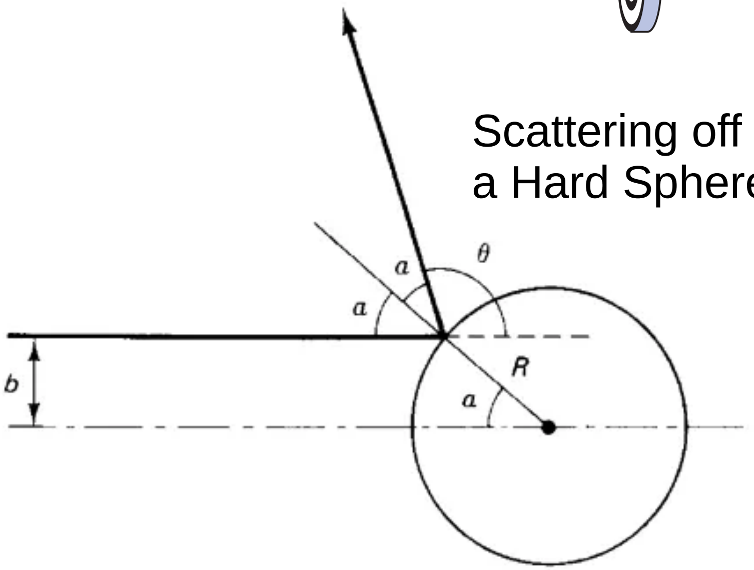
Outline

- Reminder: what is a cross section?
- Why do we care about neutrino scattering?
- The role of neutrino event generators
- What goes into a cross section measurement?
- Review of [some of] the experiments, and [some] measurements
- What we need to put it all together, and a look to the future

What is a cross section?

- A cross section is the probability of an interaction occurring. The bigger the target, the more likely the interaction will occur.
- Given in units of area
  - Hard sphere scattering target
  - Analogy to cross sectional area

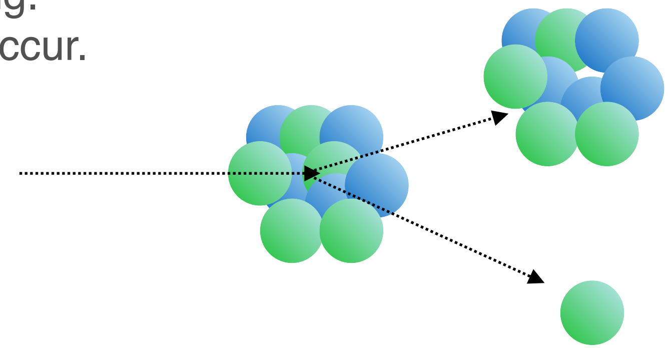




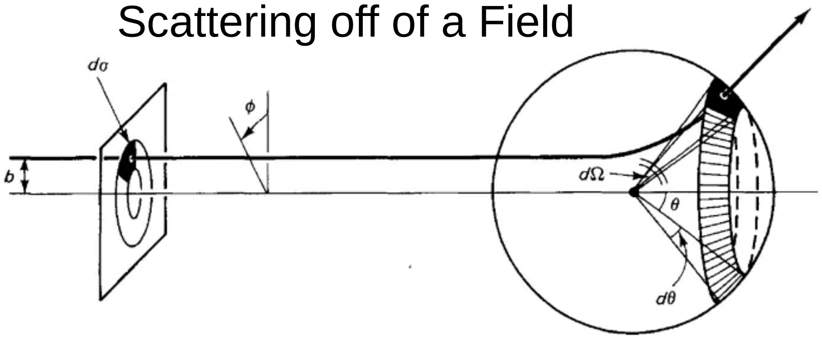
Scattering off of a Hard Sphere

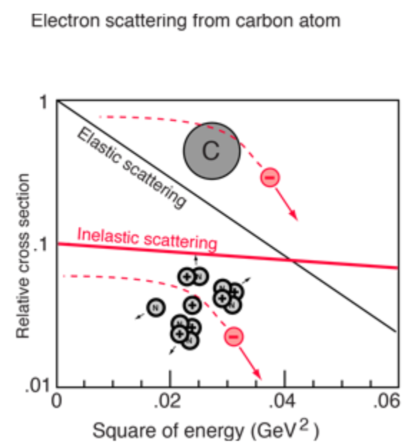
What is a cross section?

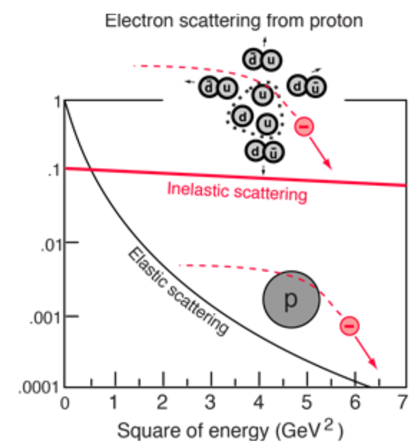
- A cross section is the probability of an interaction occurring. The bigger the target, the more likely the interaction will occur.
- Given in units of area
  - Hard sphere scattering target
  - Analogy to cross sectional area
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target



Scattering off of a Field







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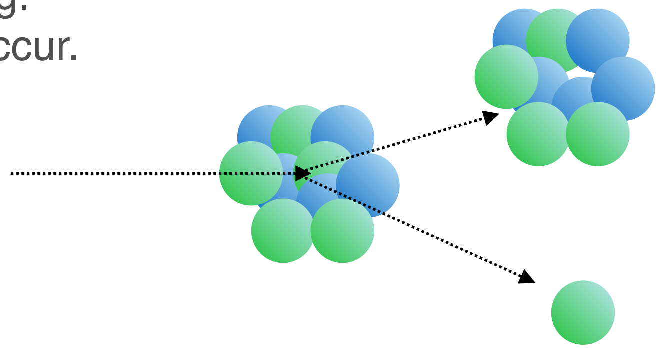
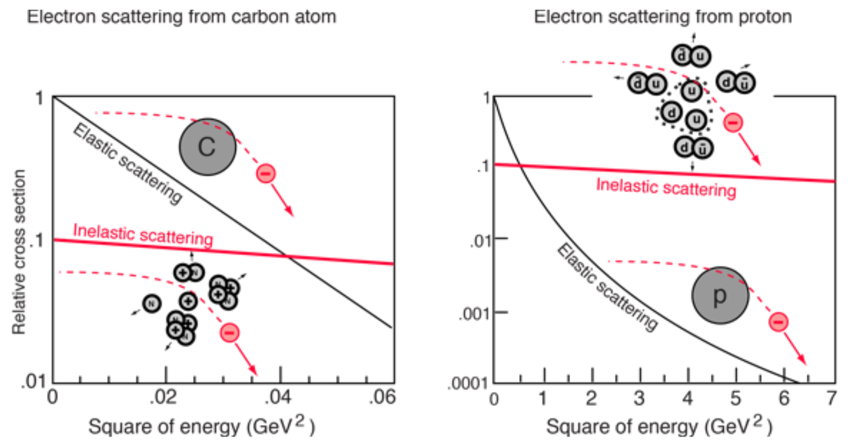
What is a cross section?

- A cross section is the probability of an interaction occurring. The bigger the target, the more likely the interaction will occur.
- Given in units of area
  - Hard sphere scattering target
  - Analogy to cross sectional area
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target
- For a single target (eg, nucleon):



$$\sigma = \frac{N_{\text{int}}}{\Phi}$$



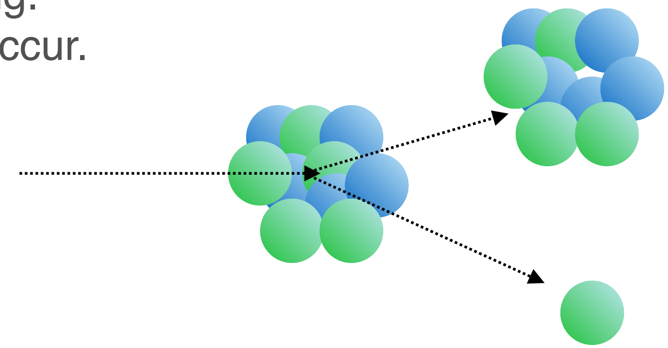
where

N_{int} = number of interactions

Φ = number of incoming particles/unit area

What is a cross section?

- A cross section is the probability of an interaction occurring. The bigger the target, the more likely the interaction will occur.
- Given in units of area
  - Hard sphere scattering target
  - Analogy to cross sectional area
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target
- For a “real” target made of many nuclei:



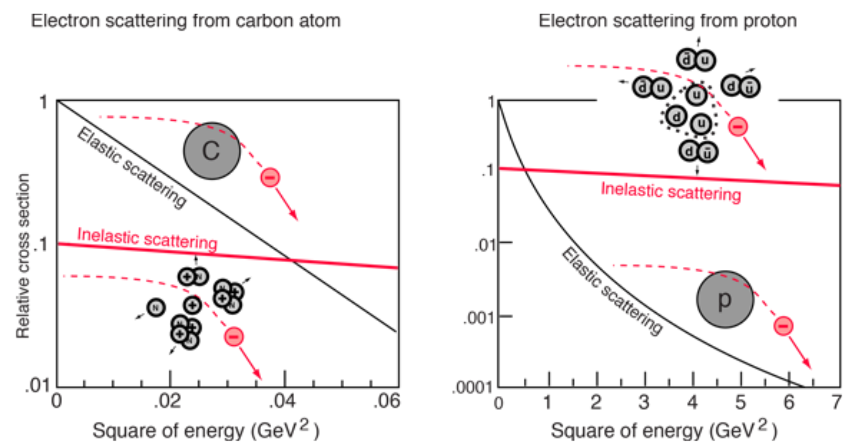
$$\sigma = \frac{N_{\rm int}}{\Phi N_{\rm tar}}$$

where

N_{int} = number of interactions

N_{tar} = number of nuclear targets

Φ = number of incoming particles/unit area



What is a cross section?

- In a real experiment, we have to “select” what we think are our signal interactions from the data. This is an imperfect process, and so we have some corrections to make:

$$P = \frac{N_{\rm int}^{\rm true,sel}}{N_{\rm int}^{\rm sel}}$$

$$\sigma = \frac{N_{\rm int}^{\rm sel} P}{\epsilon \Phi N_{\rm tar}}$$

$$\epsilon = \frac{N_{\rm int}^{\rm true,sel}}{N_{\rm int}^{\rm true}}$$

where

N^{sel}_{int} = number of selected interactions

N_{tar} = number of nuclear targets

Φ = number of incoming particles/unit area

P = “purity” of the selection (background subtraction)

ϵ = “efficiency” of the selection

- We often rely on our simulations to determine the efficiency and purity. One must never forget:

SIMULATION IS ALWAY WRONG

- The important question is “how wrong is it” (we need to quantify our uncertainty!), and can we develop a measurement that is minimally sensitive to the biases in the simulation?

What is a cross section?

- Total cross sections are nice to have, but what we really want and need in order to improve our neutrino scattering models are differential cross sections:

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

$$P = \frac{N_{\mathrm{int}}^{\mathrm{true,sel}}}{N_{\mathrm{int}}^{\mathrm{sel}}}$$

$$\epsilon = \frac{N_{\mathrm{int}}^{\mathrm{true,sel}}}{N_{\mathrm{int}}^{\mathrm{true}}}$$

where

x = some useful variable

i = i^{th} bin in “true” space

j = j^{th} bin in “reconstructed” space

N^{sel}_j = number of selected interactions

P_j = “purity” of the selection (background subtraction) in reco space

U_{ij} = smearing matrix, true -> reco

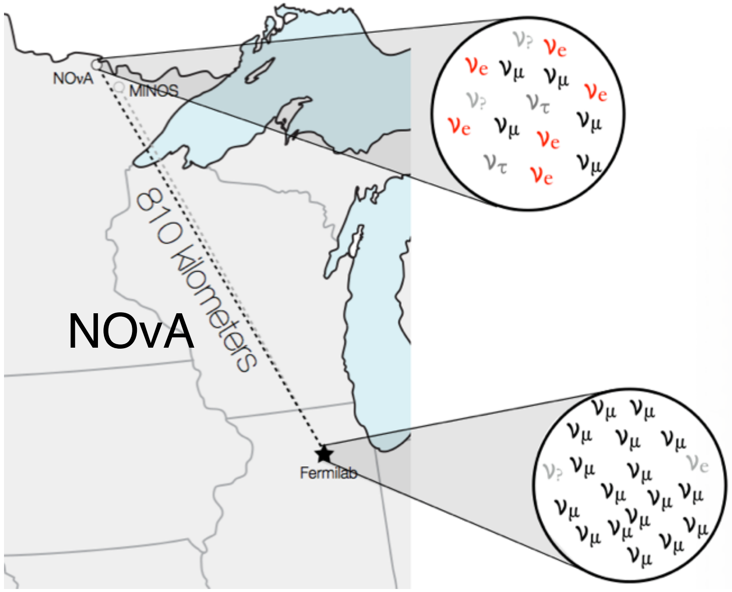
ϵ_i = “efficiency” of the selection in true space

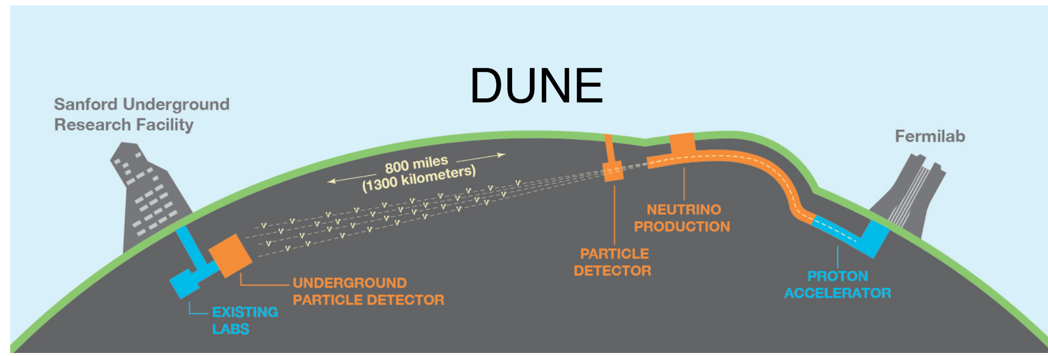
N_{tar} = number of nuclear targets

Φ = number of incoming particles/unit area

Neutrino Scattering and Oscillations

$$N_\nu^{\rm obs}(E_\nu^{\rm reco}) \sim \vec{U}(E_\nu^{\rm true} \to E_\nu^{\rm reco})\Big(\Phi(E_\nu^{\rm true}) \times \sigma(E_\nu^{\rm true}) \times \epsilon(E_\nu^{\rm true}) \times P^{\rm osc}(E_\nu^{\rm true})\Big)$$

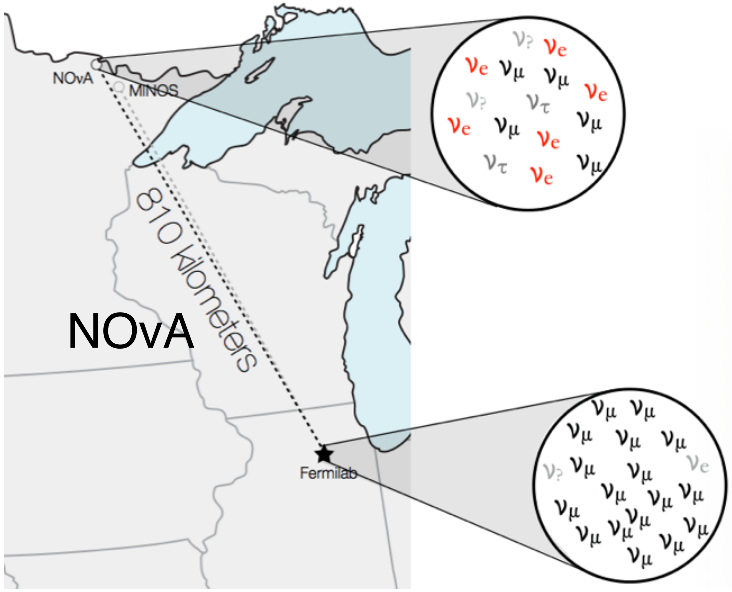


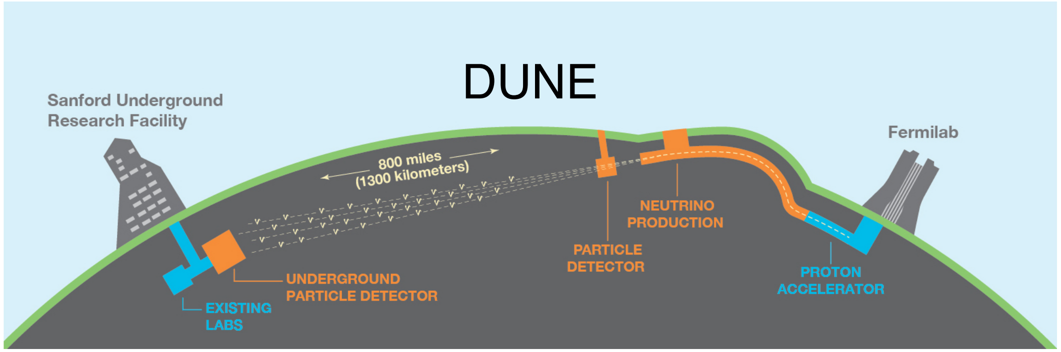


- Remember, we “see” neutrinos because they scatter off nuclei, producing charged particles that deposit energy in our detectors.

Neutrino Scattering and Oscillations

$$N_\nu^{\text{obs}}(E_\nu^{\text{reco}}) \sim \vec{U}(E_\nu^{\text{true}} \to E_\nu^{\text{reco}})\Big(\Phi(E_\nu^{\text{true}}) \times \boxed{\sigma(E_\nu^{\text{true}})} \times \epsilon(E_\nu^{\text{true}}) \times P^{\text{osc}}(E_\nu^{\text{true}})\Big)$$



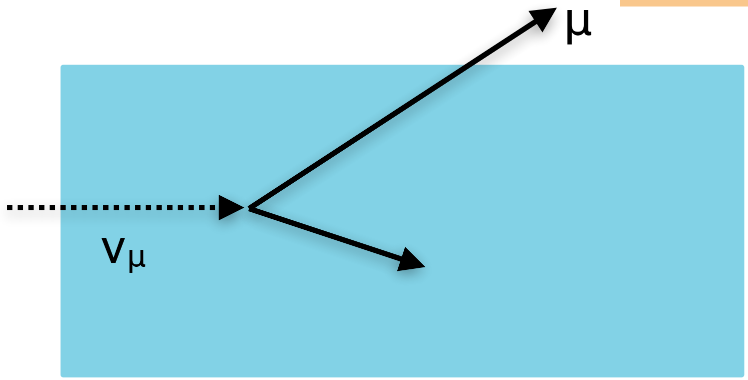


- Remember, we “see” neutrinos because they scatter off nuclei, producing charged particles that deposit energy in our detectors.
- The probability that a neutrino scatters is the cross-section.

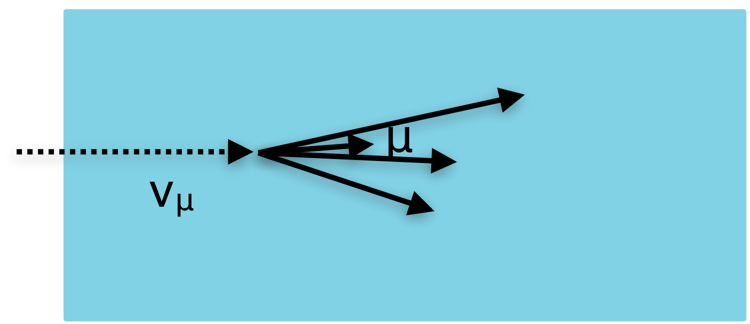
Neutrino Scattering and Oscillations

$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \rightarrow E_\nu^{\mathrm{reco}})\left(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}})\right)$$

$$\epsilon(E_{\nu_\mu}^{\mathrm{true}}) \propto \frac{d^N\sigma(E_{\nu_\mu}^{\mathrm{true}})}{d\vec{X}}$$



geometric acceptance corrections



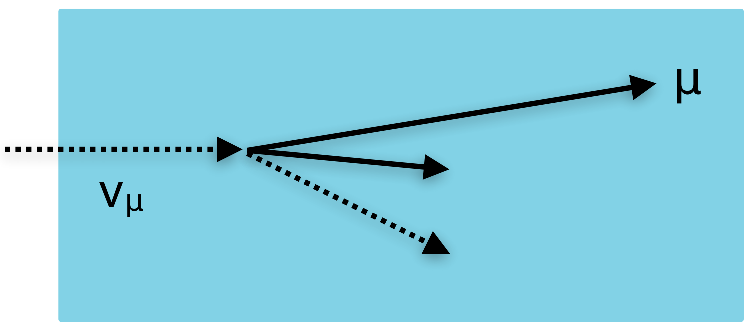
missed signal event

- We have to select our signal interactions (eg, ν_μ CC interactions), but our selection is imperfect. The rate at which we select signal events is our *efficiency*.
- The efficiency depends on the differential cross section for producing all the final-state particles for all interactions at a given energy.

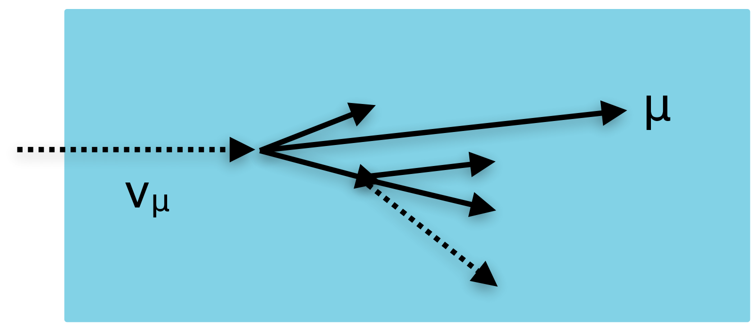
Neutrino Scattering and Oscillations

$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \rightarrow E_\nu^{\mathrm{reco}})\Big(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}})\Big)$$

$$\vec{U}(E_{\nu_\mu}^{\mathrm{true}}, E_{\nu_\mu}^{\mathrm{reco}}) \propto \frac{d^N\sigma(E_{\nu_\mu}^{\mathrm{true}})}{d\vec{X}}$$



corrections for unobserved final-state particles



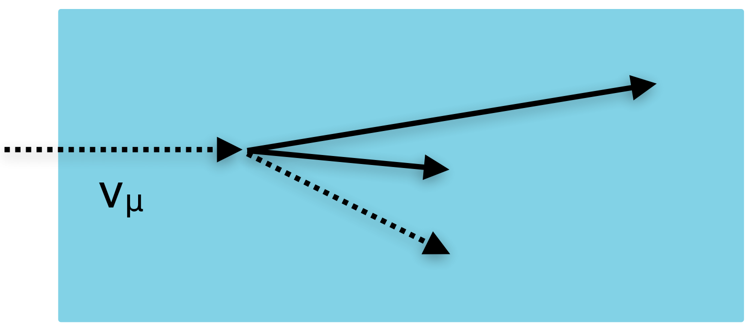
corrections for particles that further interact in the detector

- We don’t know the energy of the neutrino coming in, so we have to reconstruct it based on the measurements of the final-state particles we see.
- Smearing matrix accounts for unobserved particles and detector resolution.

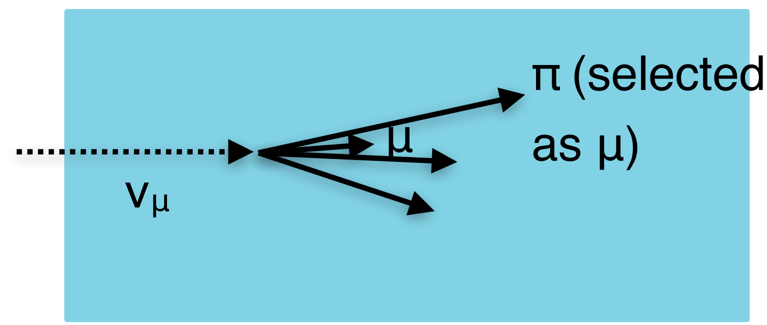
Neutrino Scattering and Oscillations

$$N_\nu^{\text{obs}}(E_\nu^{\text{reco}}) \sim \vec{U}(E_\nu^{\text{true}} \to E_\nu^{\text{reco}})\Big(\Phi(E_\nu^{\text{true}}) \times \sigma(E_\nu^{\text{true}}) \times \epsilon(E_\nu^{\text{true}}) \times P^{\text{osc}}(E_\nu^{\text{true}})\Big)$$

$$\vec{U}(E_{\nu_\mu}^{\text{true}}, E_{\nu_\mu}^{\text{reco}}) \propto \frac{d^N\sigma(E_{\nu_\mu}^{\text{true}})}{d\vec{X}}$$



corrections for unobserved final-state particles



corrections for particles that further interact in the detector

- We don't know the energy of the neutrino coming in, so we have to reconstruct it based on the measurements of the final-state particles we see.
- Smearing matrix accounts for unobserved particles and detector resolution.

Event Generators

$$N_\nu^{\mathrm{obs}}(E_\nu^{\mathrm{reco}}) \sim \vec{U}(E_\nu^{\mathrm{true}} \to E_\nu^{\mathrm{reco}})\Big(\Phi(E_\nu^{\mathrm{true}}) \times \sigma(E_\nu^{\mathrm{true}}) \times \epsilon(E_\nu^{\mathrm{true}}) \times P^{\mathrm{osc}}(E_\nu^{\mathrm{true}})\Big)$$

- We rely on models to determine these corrections. The models are implemented in neutrino event generators to simulate neutrino interactions and the kinematics of all final-state particles.
- For ~GeV neutrino energy-scale experiments, there are 5 generators on the market:

Used by Fermilab experiments

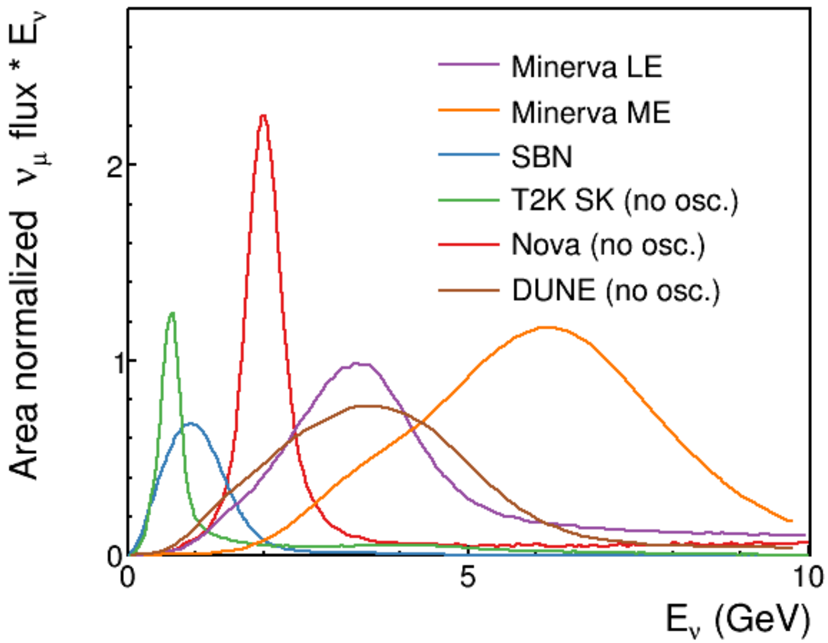
Used by T2K, SK and H2K

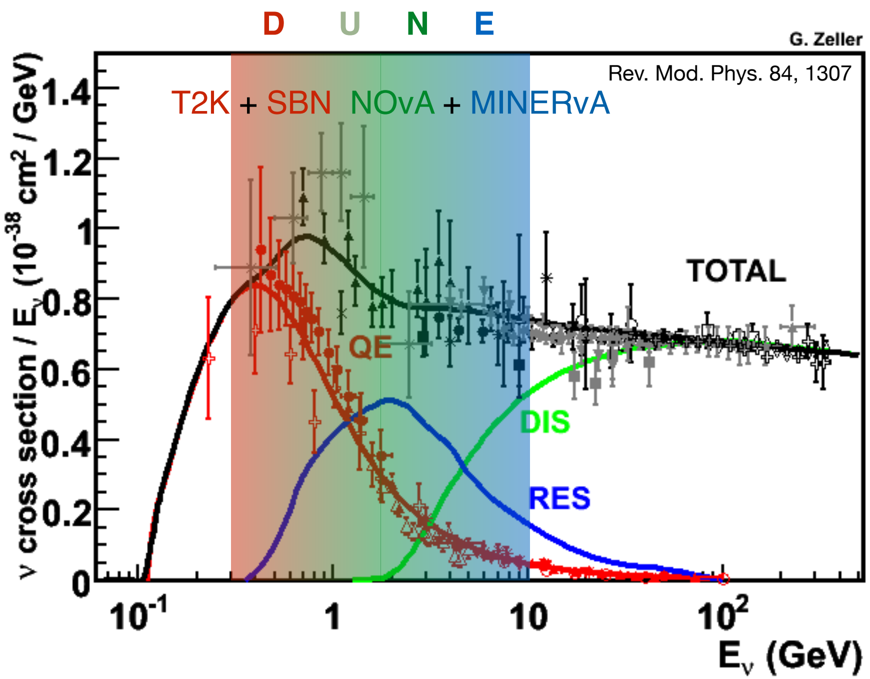
Very new, theory-driven event generator, Fermilab-led

Theory-driven event generator, most sophisticated FSI model.

Theory-driven with many model options, early adopter of new theory developments.

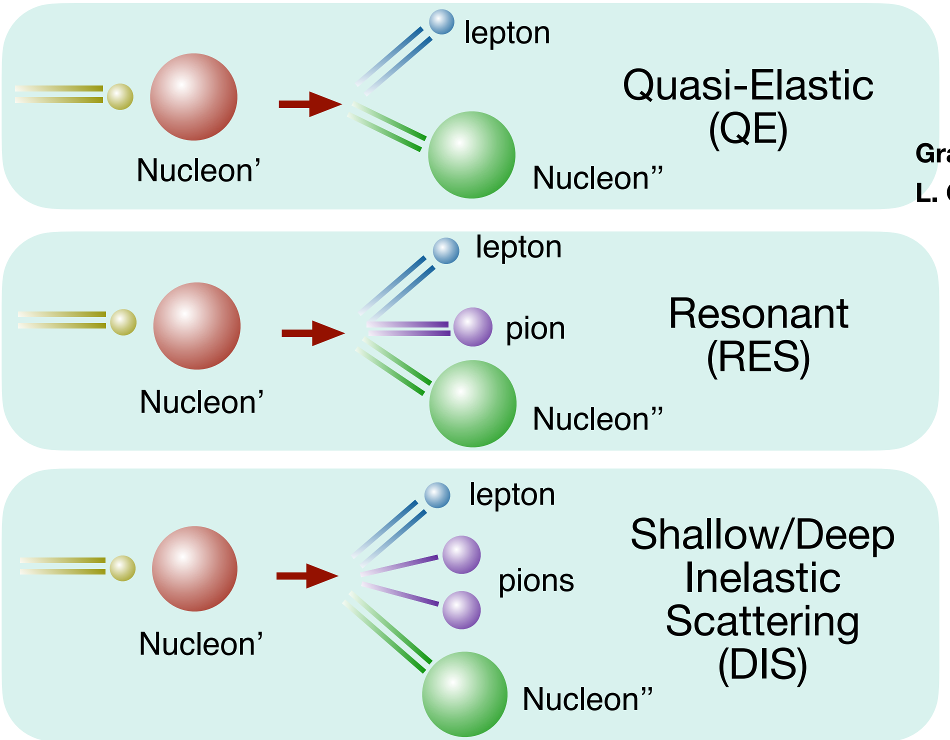
Event Generators





- Current neutrino experiments cover nearly two orders of magnitude of neutrino energies.
- Life is made more interesting because over this range, there are several types of scattering modes.

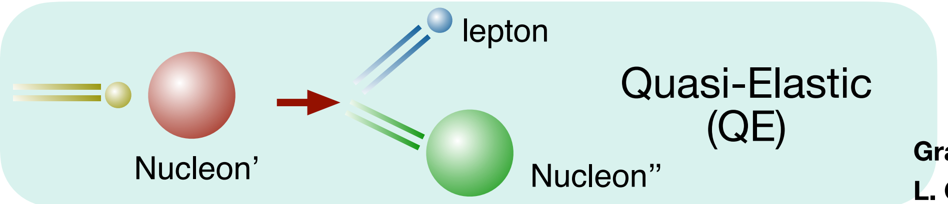
Neutrino Interactions



Graphics by L. Cremonesi

- Interactions at the ~GeV scale are often categorized by their scattering off of bound nucleons and their final state.

Neutrino Interactions



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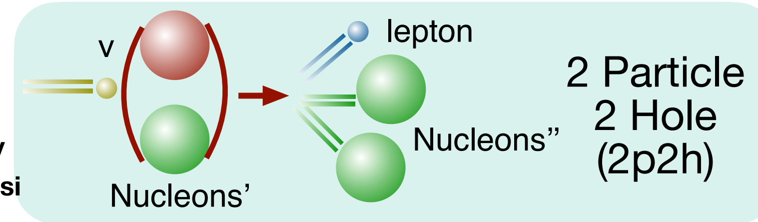
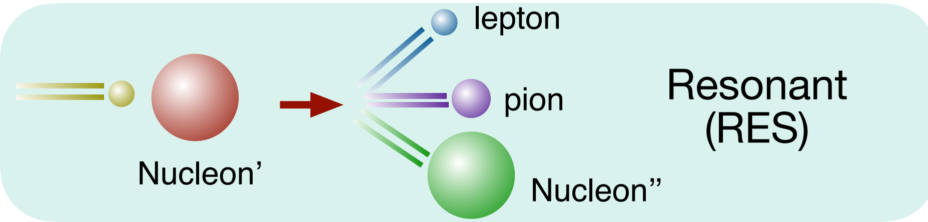
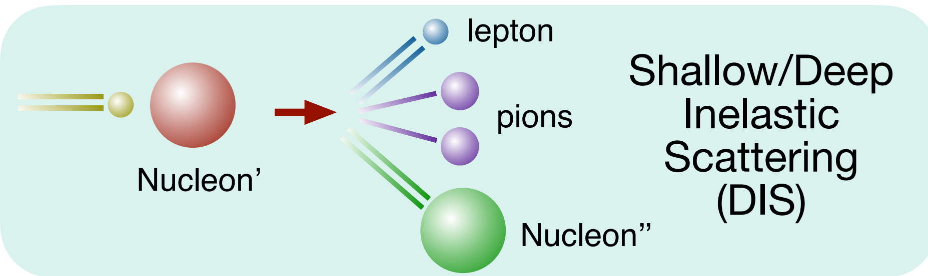
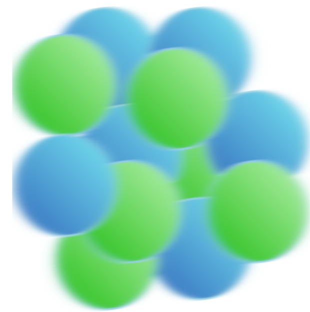
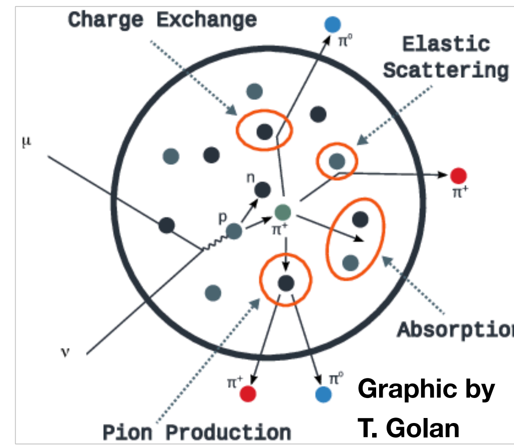








Initial State - nucleons bound but not at rest



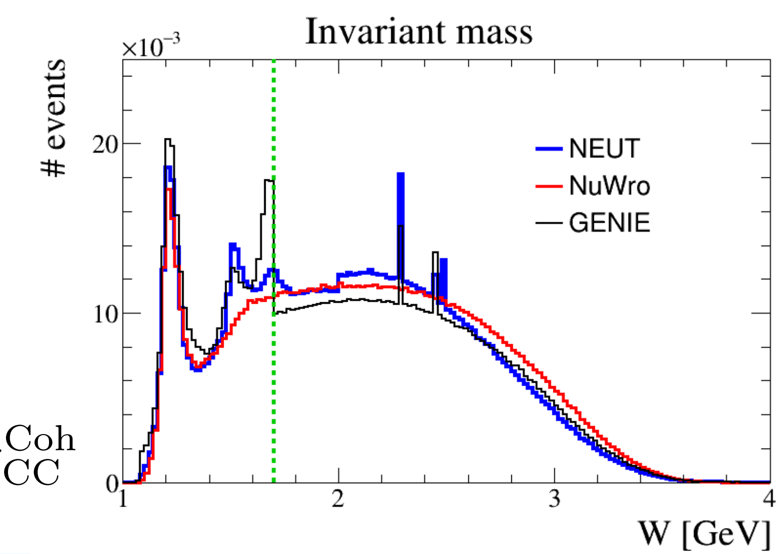
- Interactions at the ~GeV scale are often categorized by their scattering off of bound nucleons and their final state.
- But all of this happens in a nuclear environment, which impacts both the initial state and the particles we observe in the final state. Things like nucleon binding energy, momentum distribution of nucleons, and intranuclear scattering and absorption have to be modeled!

Neutrino Interactions

	Initial State	QE	2p2h	Res	DIS	FSI
GENIE v3.00.06	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 6	hN
NEUT 5.4.0	LFG	Valencia (Nieves, et al)	Valencia (Nieves, et al)	B-S	PYTHIA 5	Oset (low mom. pions) + ext. data
NuWro 2019	LFG	L-S + RPA	Valencia (Nieves, et al)	NuWro	PYTHIA 6	Oset (pions) + NuWro (nucleons)
GiBUU 2019	LFG	GiBUU Model				BUU equations

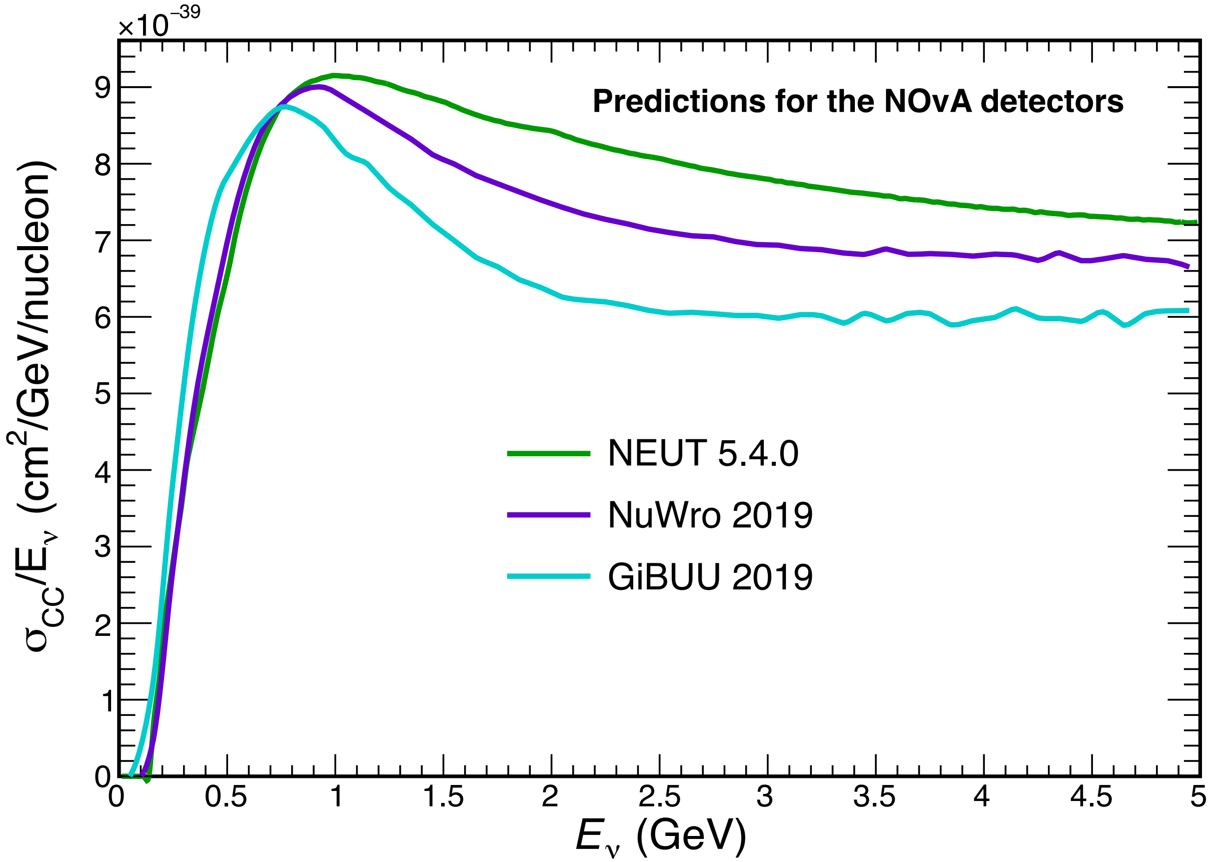
- Generators use very similar (often the same) models for exclusive differential cross sections. However, their implementation can be quite different.
- The models then have to be stitched together:

$$\sigma_{\mathrm{CC}}^{\mathrm{inclusive}}(E_\nu) = \sigma_{\mathrm{CC}}^{\mathrm{QE}} + \sigma_{\mathrm{CC}}^{\mathrm{MEC}} + \sigma_{\mathrm{CC}}^{\mathrm{Res}} + \sigma_{\mathrm{CC}}^{\mathrm{DIS}} + \sigma_{\mathrm{CC}}^{\mathrm{Coh}}$$



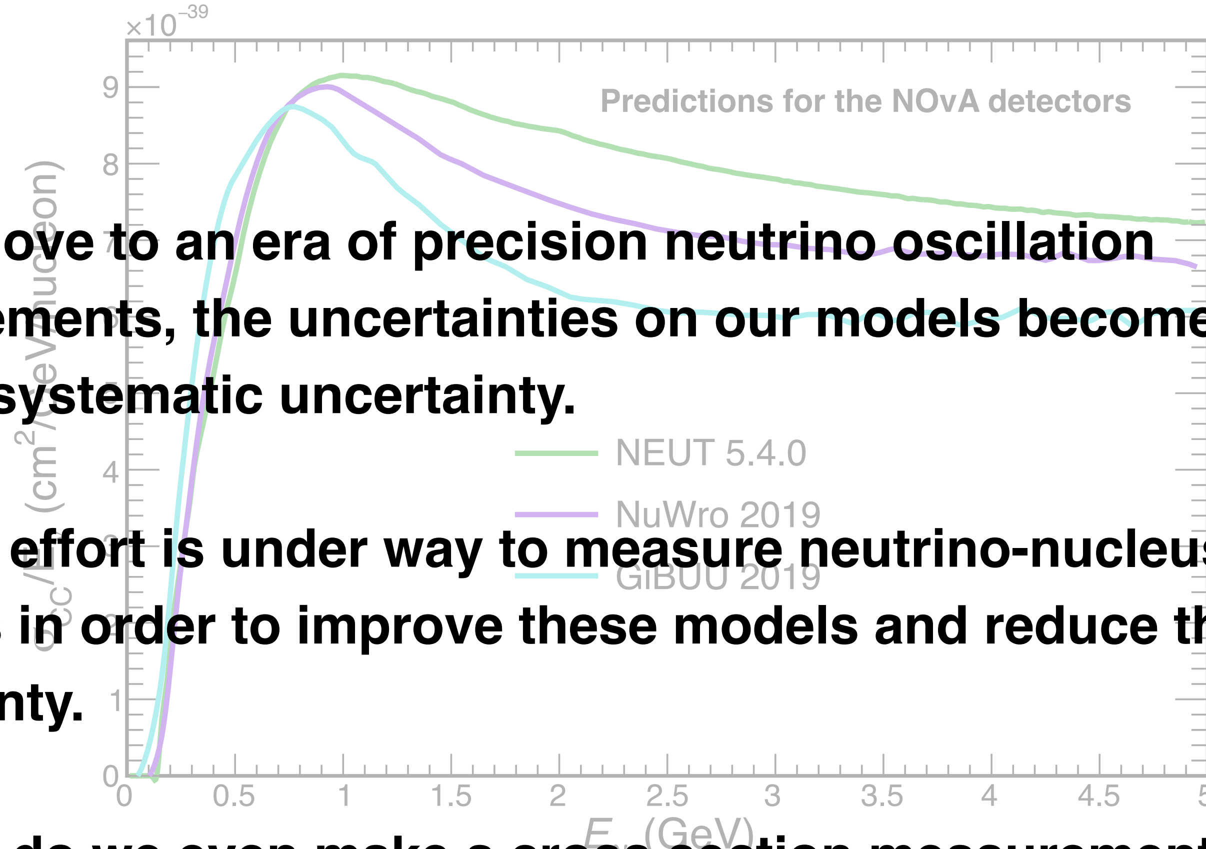
C. Bronner, NuSTEC 2018 Workshop Presentation

Neutrino Interactions



- Implementation and stitching differences between the generators is reflected in the spread of inclusive predictions from various generators.
- Cross section measurements are critical to improve our understanding of the individual processes and how all the pieces fit together.

Neutrino Interactions



As we move to an era of precision neutrino oscillation measurements, the uncertainties on our models become a leading systematic uncertainty.

A global effort is under way to measure neutrino-nucleus cross sections in order to improve these models and reduce the uncertainty.

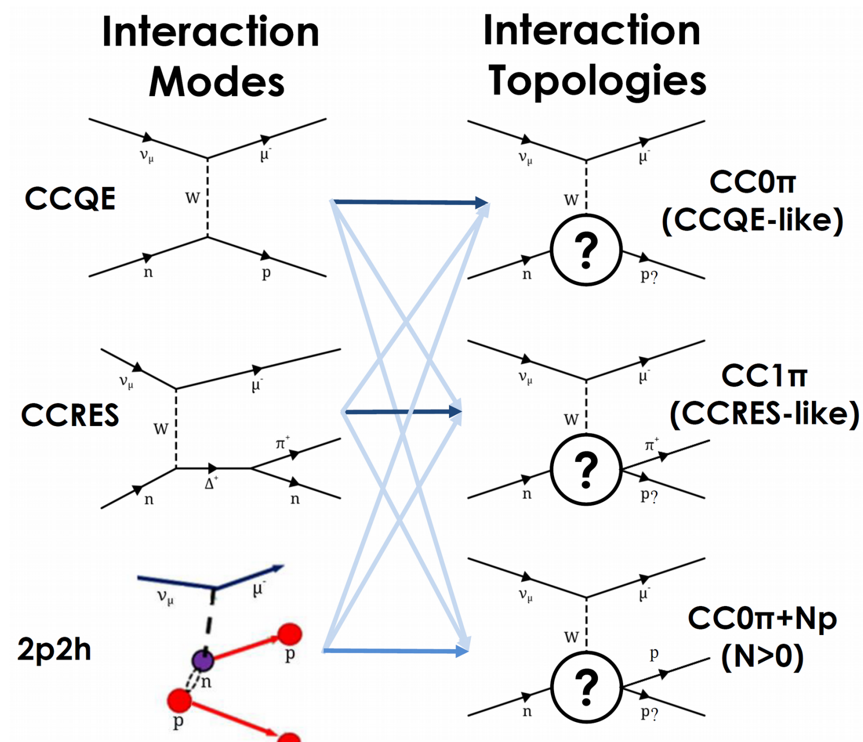
But how do we even make a cross section measurement?

- Implementation and stitching differences between the generators is reflected in the spread of inclusive predictions from various generators.
- Cross section measurements are critical to improve our understanding of the individual processes and how all the pieces fit together.

What Variables to Report?

- First, we must define our signal.
- Theorists and model builders typically think in terms of “QE”, “Resonance”, “2p2h”, etc. But final-state interactions (eg, pion absorption or charge exchange) and our own detector limitations (resolution), it is impossible for us to measure these processes directly! Eg: consider a case where we see only one muon and one proton in the final state. This could be:
  - a CC QE interaction or,
  - a CC Res interaction where the pion is absorbed in the nucleus or,
  - a 2p2h interaction where one proton has energy below our detection threshold (100 MeV)
- Instead, we should be honest and clear about what we are measuring, eg: “CC interactions with a single proton about 100 MeV in the final state”.

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$



Graphic by S. Dolan

What Variables to Report?

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$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

- Again, theorists love to see cross sections reported as functions of E_ν, Q^2 and W, but these are all cross-section **model-dependent** variables, which:
  - Makes them hard to interpret at face-value
  - Can introduce potential bias
- The cleanest measurements are those that report the final-state particle kinematics, eg those that we can measure directly:
  - lepton energy and angle (or longitudinal and transverse momenta)
  - hadron energy and angle (or longitudinal and transverse momenta)

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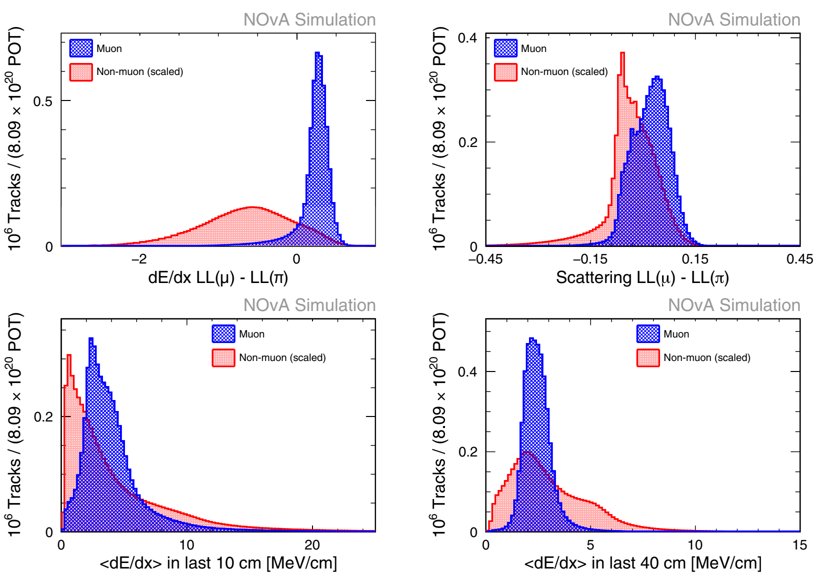
Developing and Optimizing The Event Selection

- Event selection is all about maximizing both your efficiency and purity.
- Best to use observables that characterize particles in the final-state, eg, particle-id based on dE/dx, scattering, time-of-flight, Ckov light, etc.
- Eg, in NOvA, we use dE/dx and scattering information of the reconstructed charged particle trajectories to isolate muons from other particle:



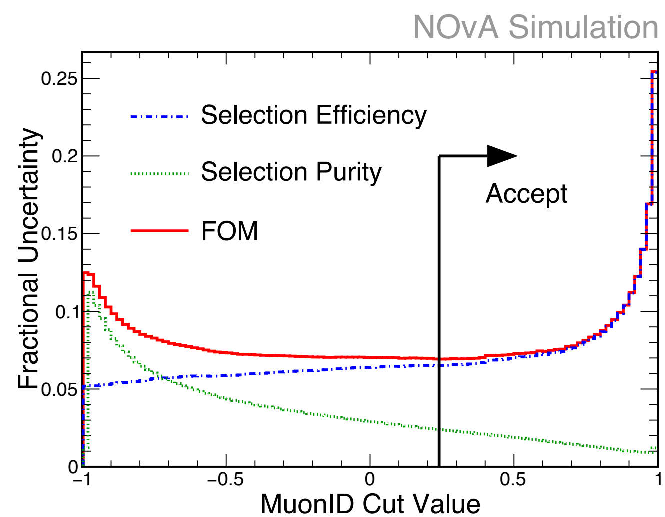
Multivariate

"MuonID"

$$\sigma = \frac{N_{\rm int}^{\rm sel} P}{\epsilon \Phi N_{\rm tar}}$$

- Figure of Merit (FoM) is used to maximize sensitivity of the measurement:

$$\left(\frac{\delta\sigma}{\sigma}\right)^2 = \frac{1}{N_{\rm int}^{\rm sel}} + \left(\frac{\delta P}{P}\right)^2 + \left(\frac{\delta\epsilon}{\epsilon}\right)^2$$



Understanding and Constraining the Selection Efficiency

- Be sure to check that the selection efficiency doesn't drop too strongly for the things you are measuring. Eg, if muons cannot be identified below a certain energy (say, 400 MeV), then consider changing the phase space of your signal to include only muons above this threshold.

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\mathrm{sel}} P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

- Be sure to check that the selection efficiency doesn't depend too strongly on things that you are not measuring but also have large uncertainties. Eg:
  - Muon selection efficiency as a function of hadronic energy in the final-state
  - Pion selection efficiency as a function of lepton momentum transfer (Q^2)
- Whenever possible, compare your efficiency with real data (but not the data you are using to make your measurement). Eg:
  - Check muon selection with cosmic rays
  - Check EM shower selection with bremsstrahlung showers of cosmic rays

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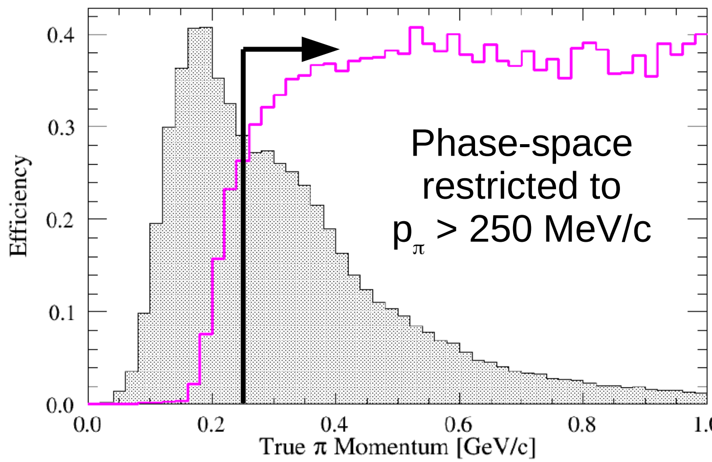

Don't measure π momentum well

Find flat region and redefine signal

p_π > 250 MeV/c

19

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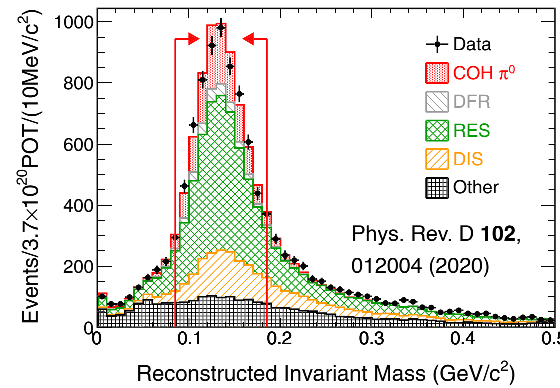
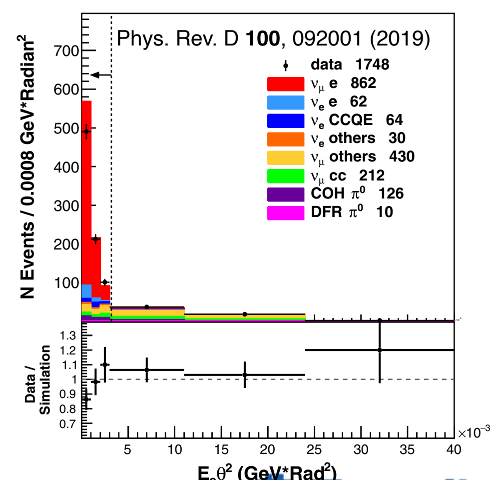
Constraining Backgrounds

- Remember, SIMULATIONS ARE ALWAY WRONG, and in the case of neutrino interactions, the uncertainties in our backgrounds can be quite large.
- When the backgrounds are significant, a general approach adopted by most experiments is to use data “sidebands” (events that are not selected) to validate the modeling of, or even constrain the backgrounds.
- Ideally the events in the sideband have similar or overlapping kinematics as the background in the signal selection. But this can be tricky, since background events that “look” like your signal were probably already selected!
- Nevertheless, sidebands can be used to not only validate the simulation, they can be used to reduce the uncertainty associated with modeling the backgrounds.
- Some examples:
  - ν_μ CC π0 interactions when measuring NC π0 or ν_e CC interactions
  - NC π+ interactions when measuring CC π+

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}\left(N_j^{\mathrm{sel}} P_j\right)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

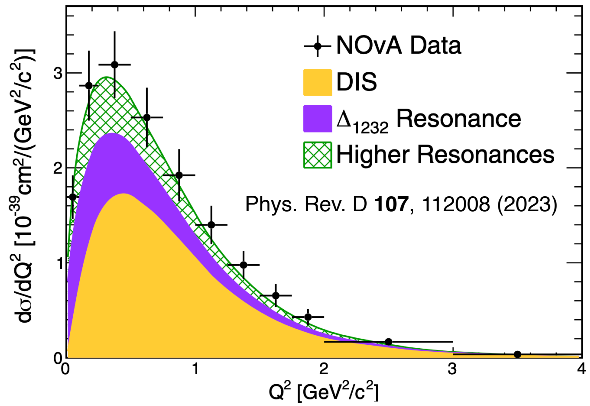


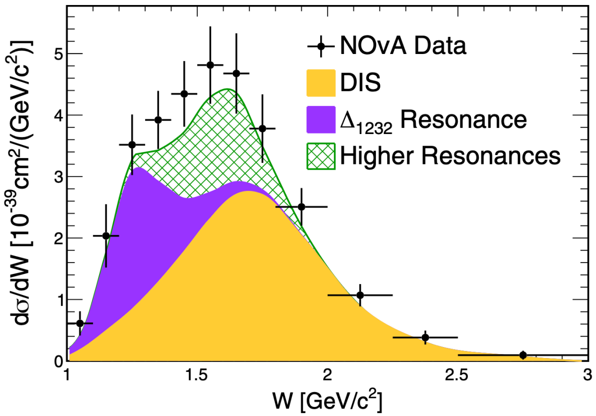


Analysis Variables and Binning

- As I mentioned earlier, measurements involving direct observables (eg, measured kinematics of final-state particles) are the least susceptible to the impact of model bias.
- But that does not mean that we should never look at derived variables! Studying how the cross section behaves as a function of E_ν, Q^2, W or anything else that relies on some reasonable model can still be qualitatively informative.

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U^{-1}_{ij}(N^{\rm sel}_j P_j)}{\epsilon_i \Phi N_{\rm tar}\Delta x_i}$$





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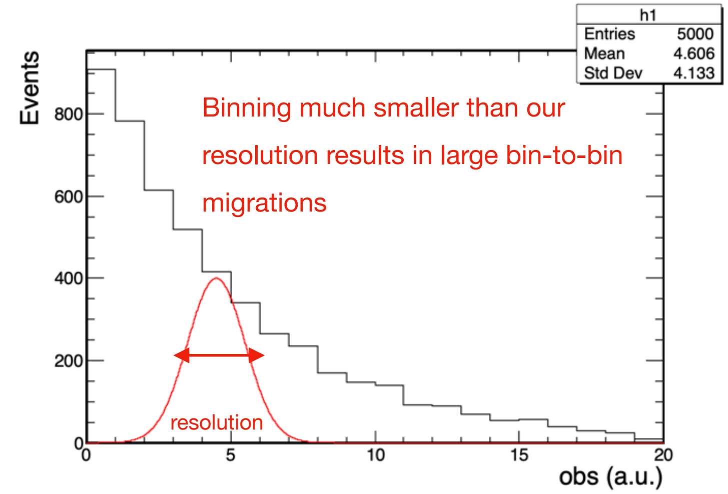
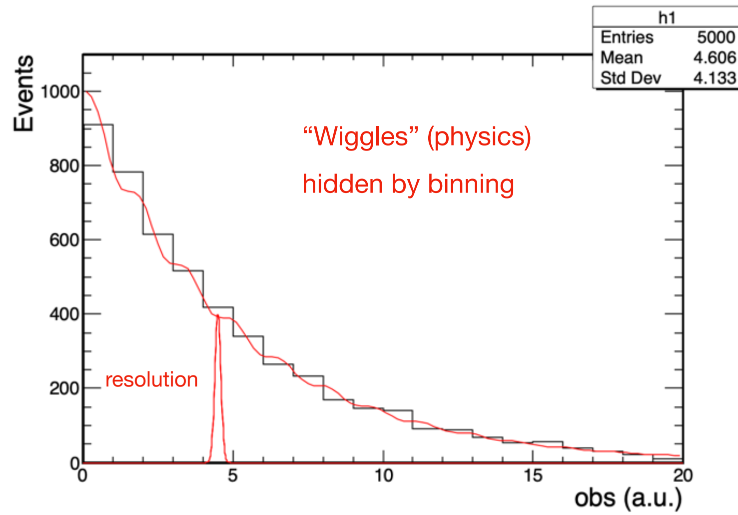
  - Never be smaller than our detector resolution.
  - But small enough to capture the physics we're after





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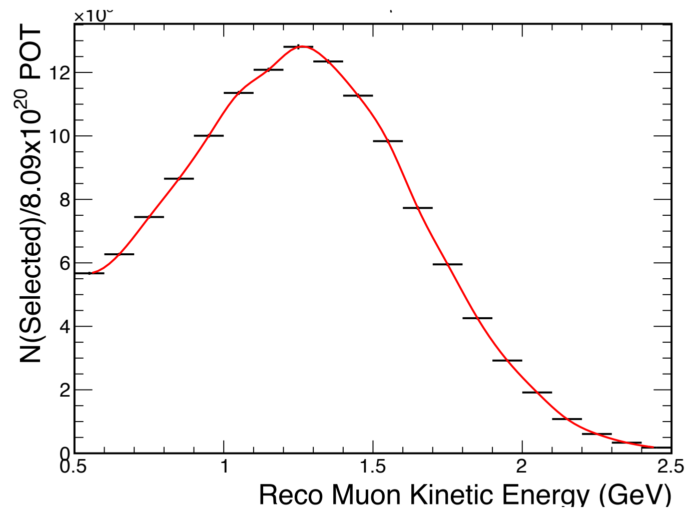
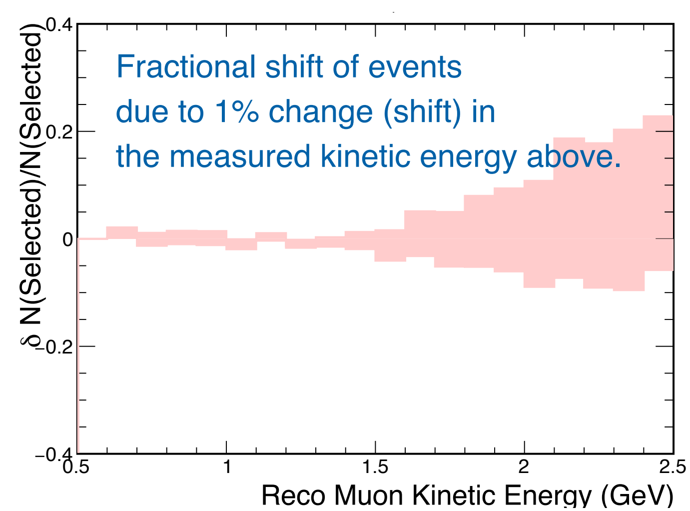
- We also need to take care when deciding how to bin (discretize) our data. Bin-widths should:
  - Never be smaller than our detector resolution.
  - But small enough to capture the physics we're after
  - Consider bin-to-bin migration due to systematic uncertainties. Events in a distribution with a rapidly-changing slope will migrate asymmetrically across bins and can result in magnifying the effect!





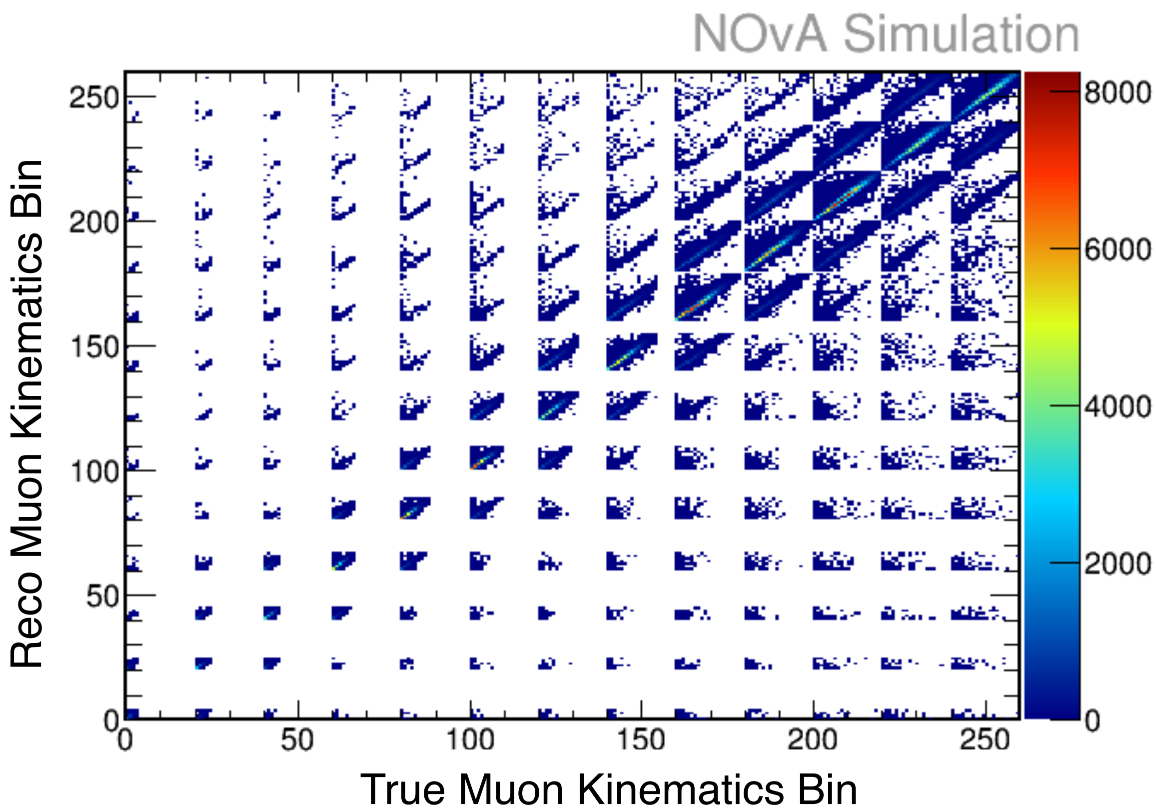
Fermilab

Unfolding… A Necessary Evil?

- Our detectors have finite resolution. Furthermore, we have to reconstruct the events in our detector, and our algorithms can systematically get things wrong.

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U^{-1}_{ij}(N^{\text{sel}}_j P_j)}{\epsilon_i \Phi N_{\text{tar}} \Delta x_i}$$

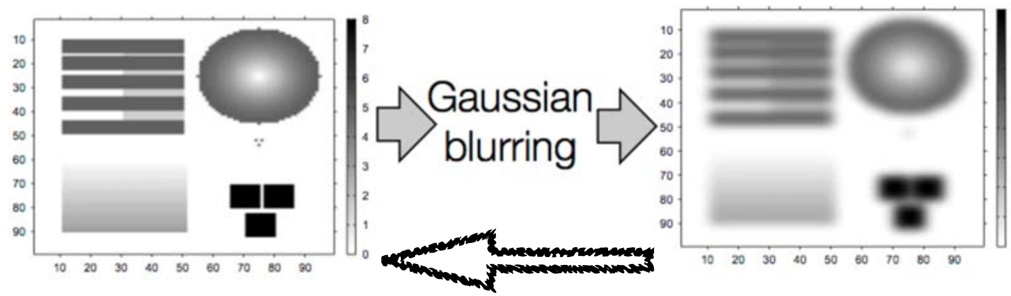
- We wish to report measurements that are useful to the community, therefore we need to "convert" our reconstructed observable to a "true" observable.
- We rely on our simulations to get our "smearing right", as it can be a very complicated process and often not "Gaussian" in nature.
- We can construct smearing matrix by recording the reconstructed variable as a function of its true value.
- We then have to "undo" the smearing, which is an inverse problem, and **ill-posed**!

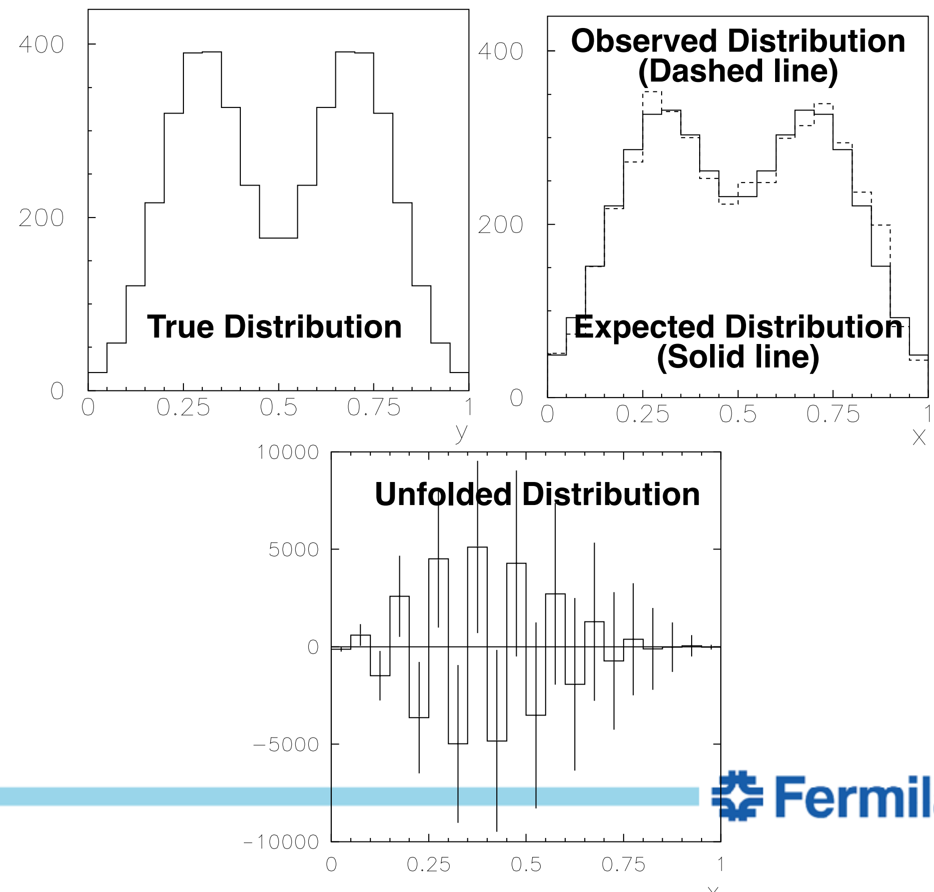


Fermilab

Unfolding… A Necessary Evil?

- I like to think of this as starting with a blurry image and trying to extract sharp details from it.
  - The blurred image has less information.
  - To recover, one must make some assumptions. In our case, the assumptions are our model.
- But even if the model were perfect, we can't simply "invert" the matrix. This can give disastrous results!
  - Bin-to-bin correlations and limited statistics can introduce wild oscillatory behavior in the unfolded spectrum.
  - One has to apply some kind of dampening to reduce these effects.
  - The level of dampening is often left to the discretion of the analyzer.





http://dx.doi.org/10.1051/epjconf/20135503002

To Unfold or Not To Unfold? That is the question…

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} P_j)}{\epsilon_i \Phi N_{\text{tar}} \Delta x_i}$$

Most theorists

Some experimentalists

$$\frac{dN}{dx_j} + \mathbf{U}, \vec{P}, \vec{\epsilon}, N_T, \Phi$$

This experimentalist

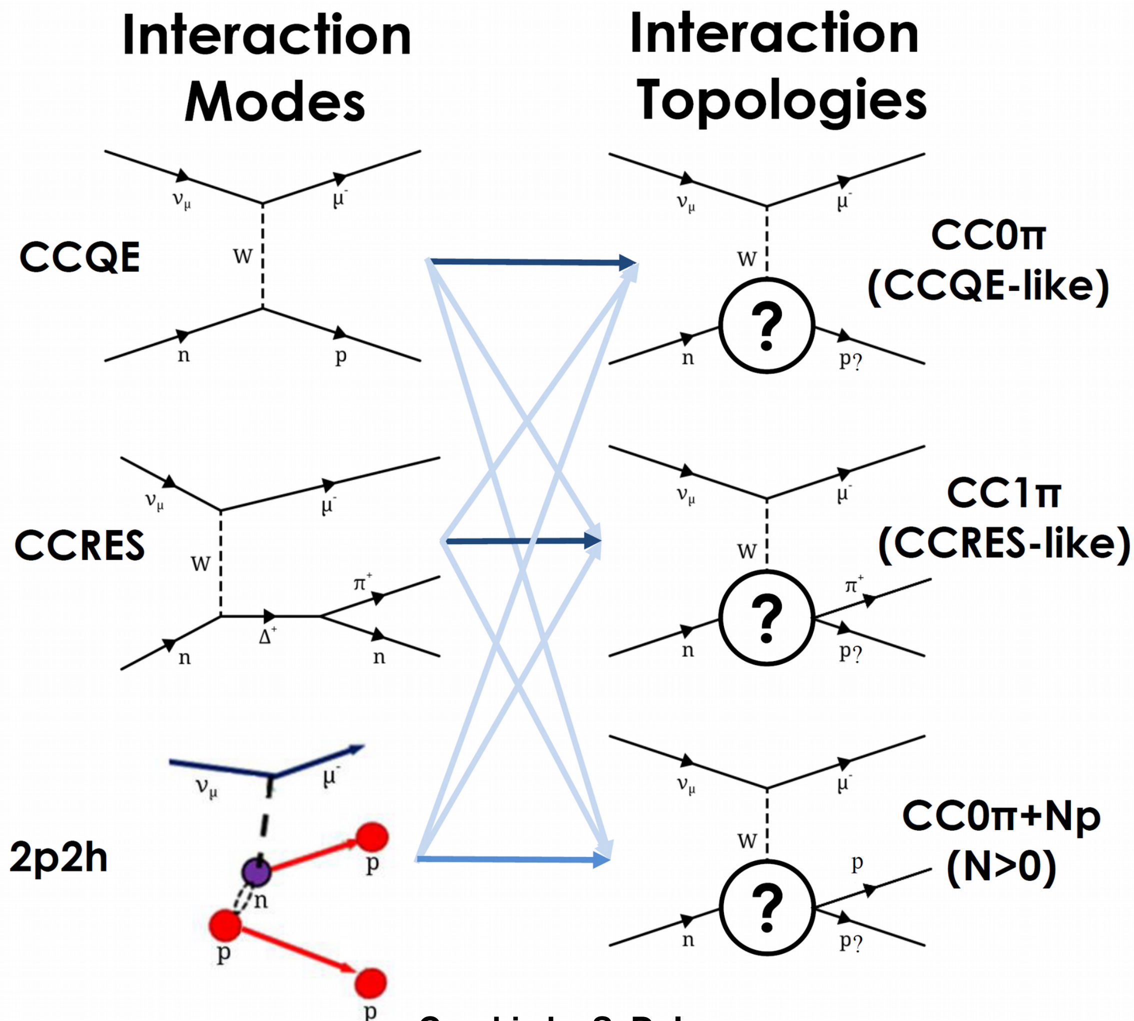
Most theorists

- Alternatively, we can simply measure our event rate and provide the community the rest of the information they need to compare predictions.
- Note, both involve unavoidable model-dependencies. Again, the challenge is to keep this to a minimum.
- In both cases, it is important to make all of the pieces that go into a measurement available, as they may be needed for future re-analysis.

A Reminder…

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U_{ij}^{-1}(N_j^{\text{sel}} P_j)}{\epsilon_i \Phi N_{\text{tar}} \Delta x_i}$$

- Most neutrino cross sections are reported based on their final-state topology, eg:
  - CC inclusive (all interactions)
  - CC 0π (mostly CC QE + 2p2h)
  - CC 1π (mostly CC Res)
  - CC Nπ (mostly higher resonances + SIS/DIS)



Graphic by S. Dolan

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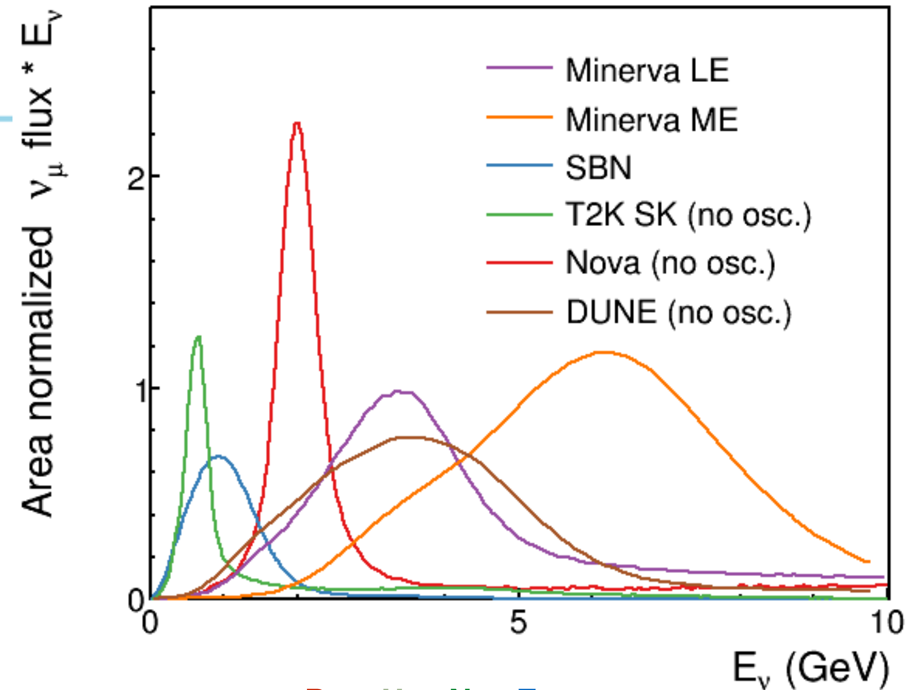
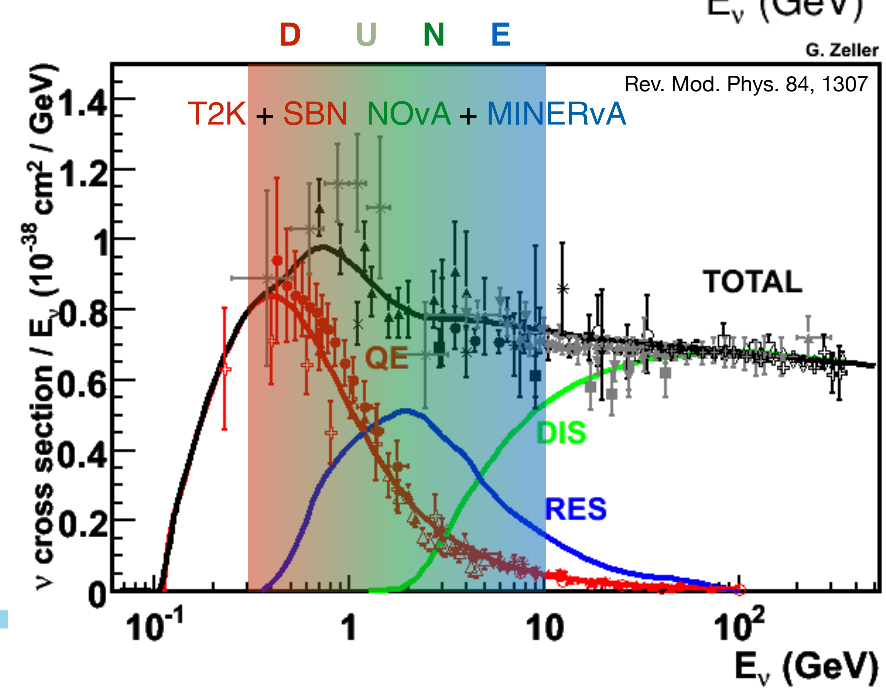
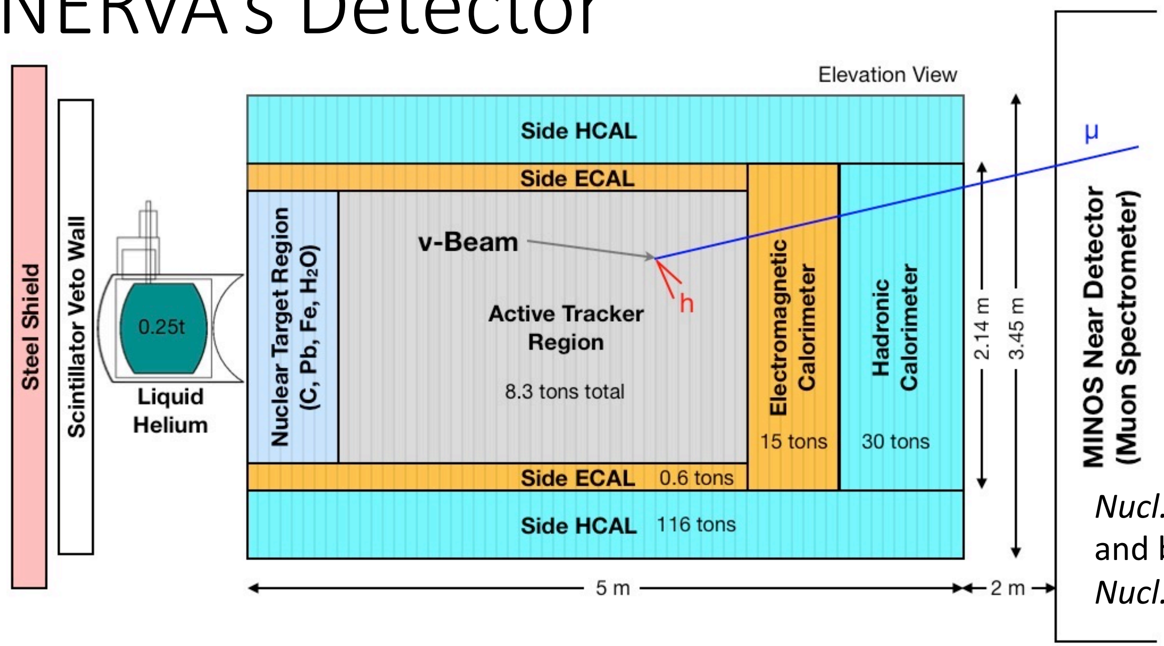
  - CC 1π (mostly CC Res)
  - CC Nπ (mostly higher resonances + SIS/DIS)
- The experiments making cross section measurements have different sensitivities (levels) of the topologies. In particular, T2K and SBN are dominated by QE and 2p2h interactions.





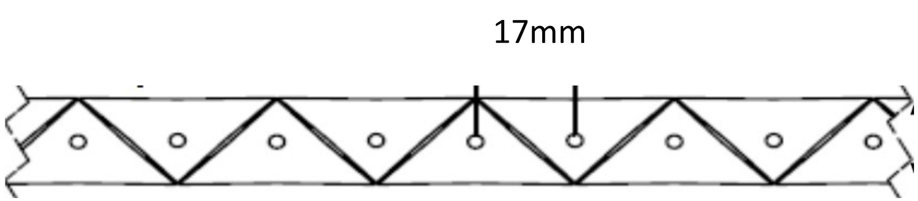
The Experiments and Their Detectors

MINERvA's Detector



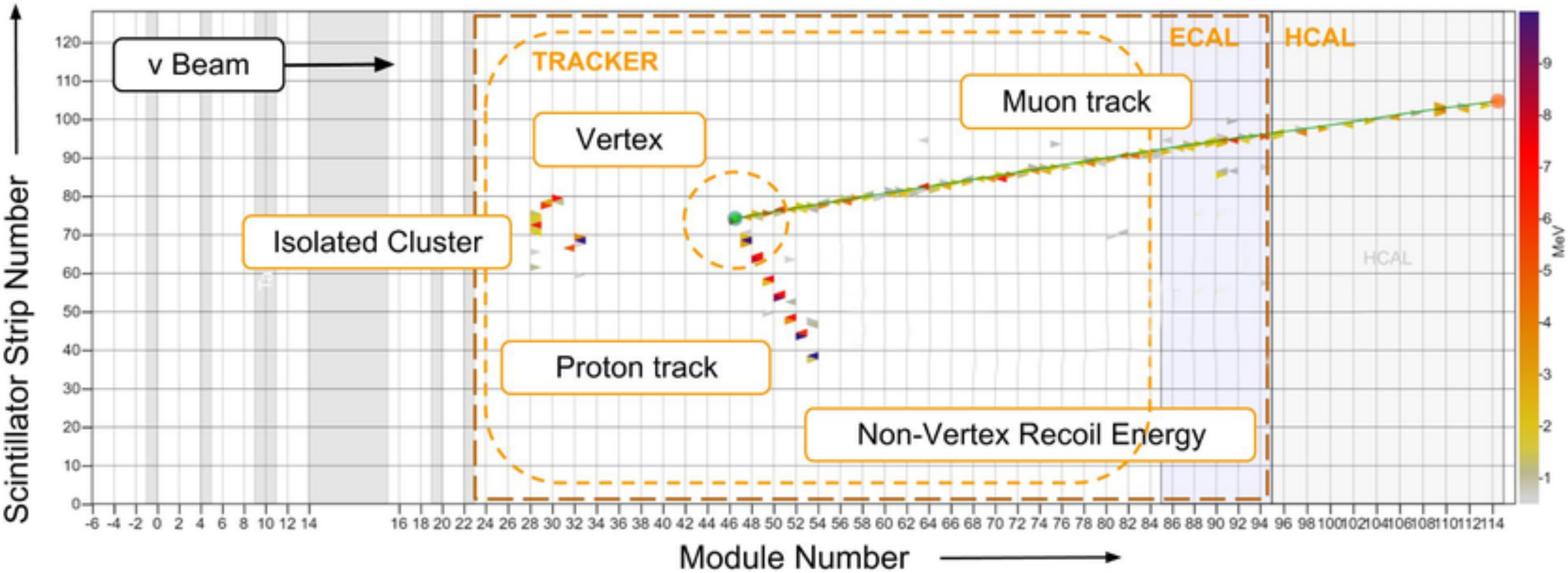
Nucl.Instrum.Meth.A 743 (2014) 130
and beam test
Nucl.Instrum.Meth.A 789 (2015) 28

Three views:
X: Vertical
U,V: $\pm$60



Spatial resolution ~3mm
Timing resolution ~3ns

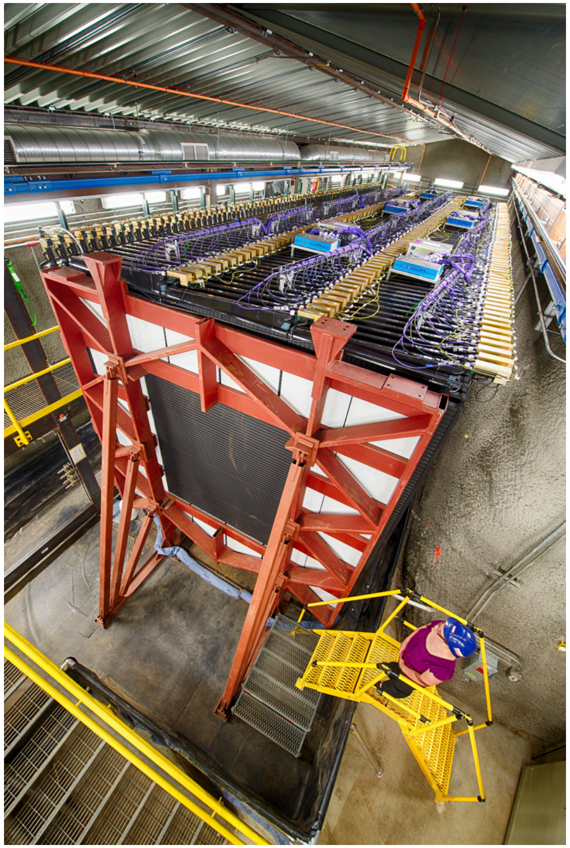
MINERvA

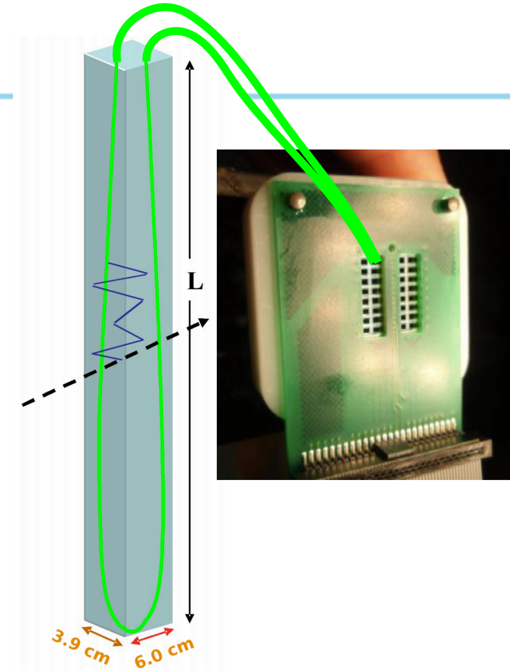


- Particle id mostly via dE/dx in the active tracker region.
- Limited angular acceptance since muons must enter the downstream MINOS near detector.
- A variety of nuclear targets upstream enables cross-section A-dependence.

Fermilab

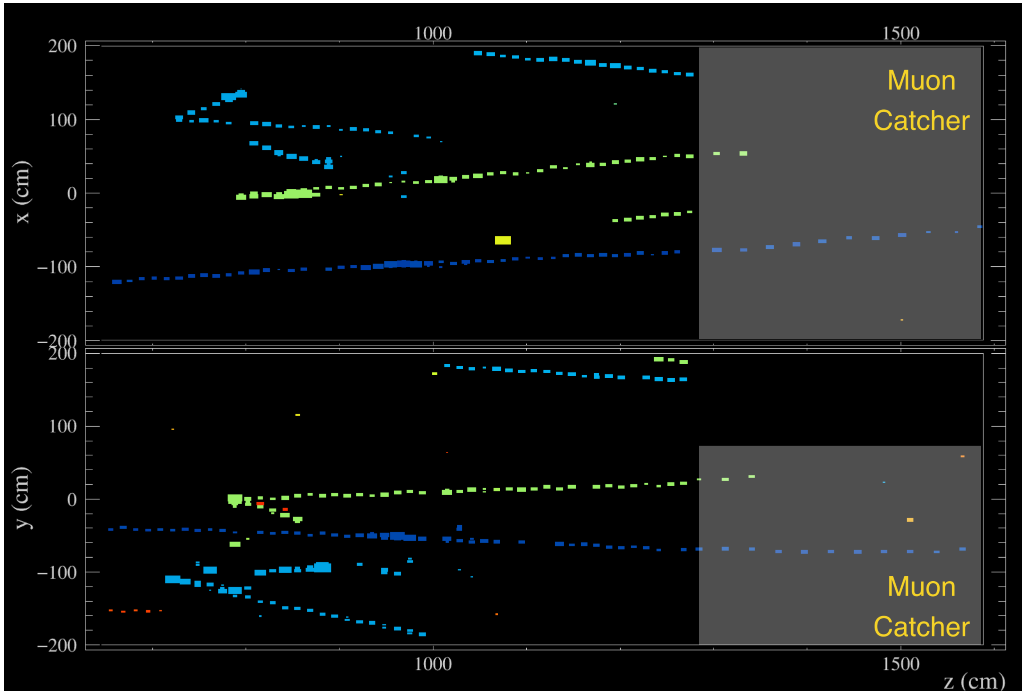
NOvA Near Detector

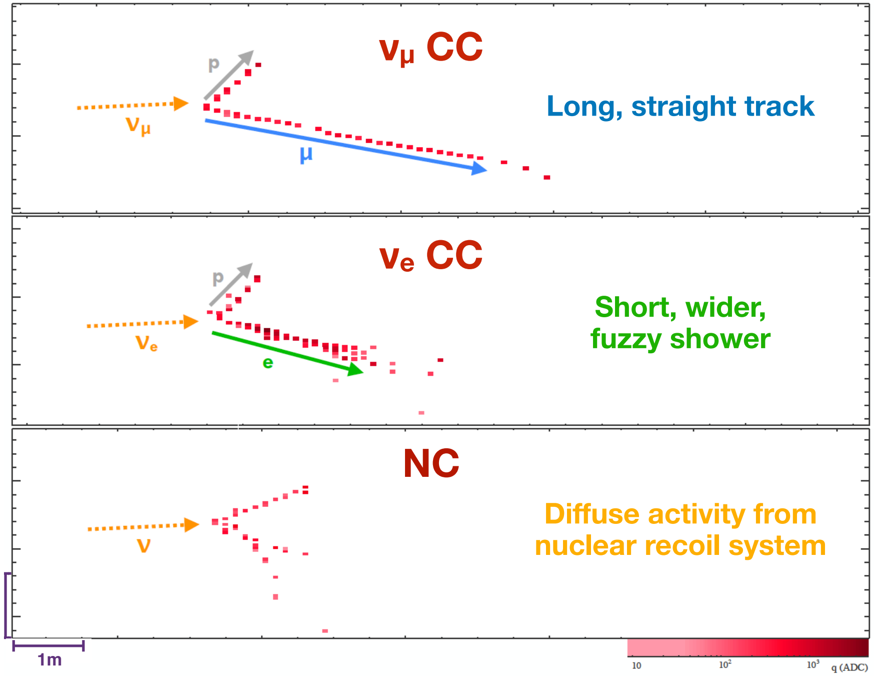




- 300t tracking calorimeter, constructed from extruded PVC cells filled with liquid scintillator.
- Scintillation light captured and routed to APDs via WLS fibers.
- 0.07 X_0 per layer
- **77% CH_2, 16% chlorine, 6% TiO_2 by mass**

NOvA Near Detector

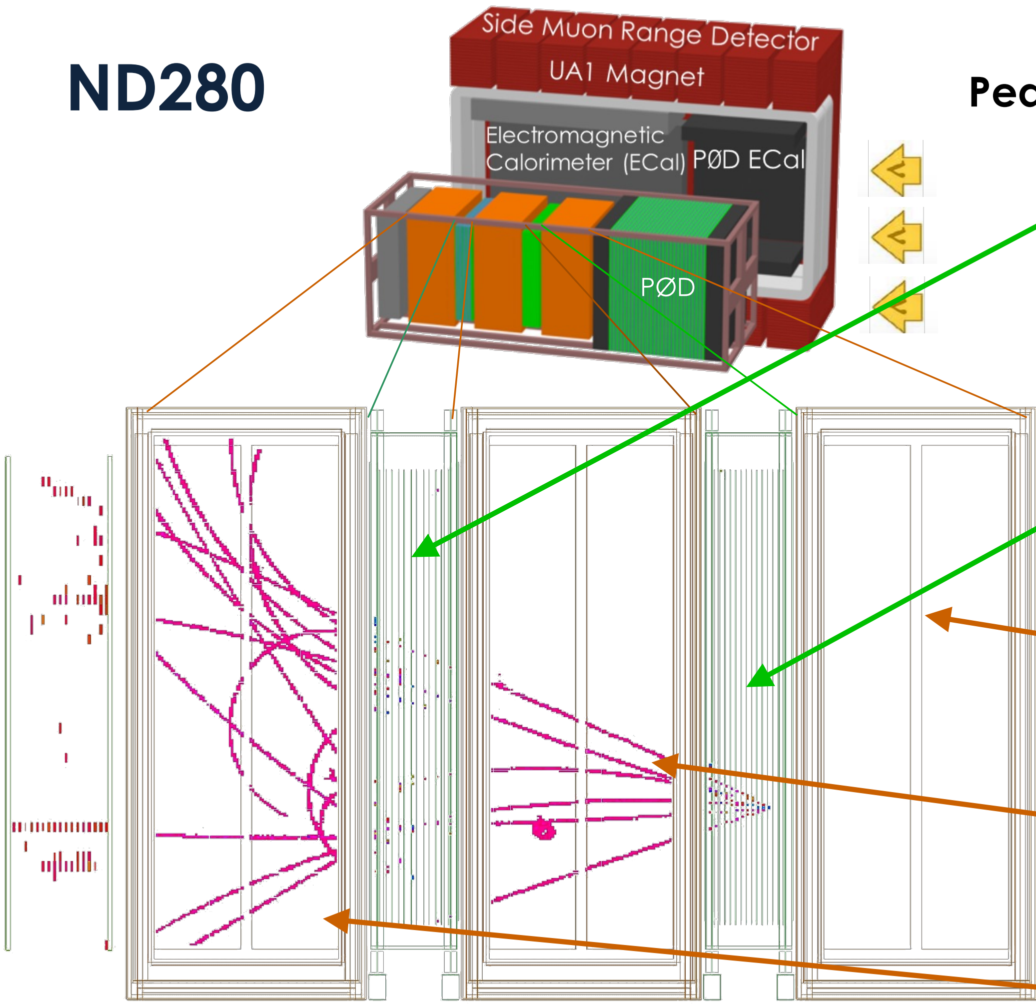




- Muon catcher (steel + NOvA cell at the downstream end ranges out ~2 GeV muons.
- 5 ns hit-level timing resolution used to separate the many neutrino interactions per 10 us spill.
- NOvA is an oscillation experiment and the detectors and reconstruction are designed to optimize muon and EM-shower measurements. So, very good at identifying and measuring the energies of muons, electrons and π0s in the final state, improvements to reconstruction of other particles are underway.

T2K ND280

ND280



On Axis ~ 1.1 GeV

Peak E_ν

Off Axis ~ 0.6 GeV

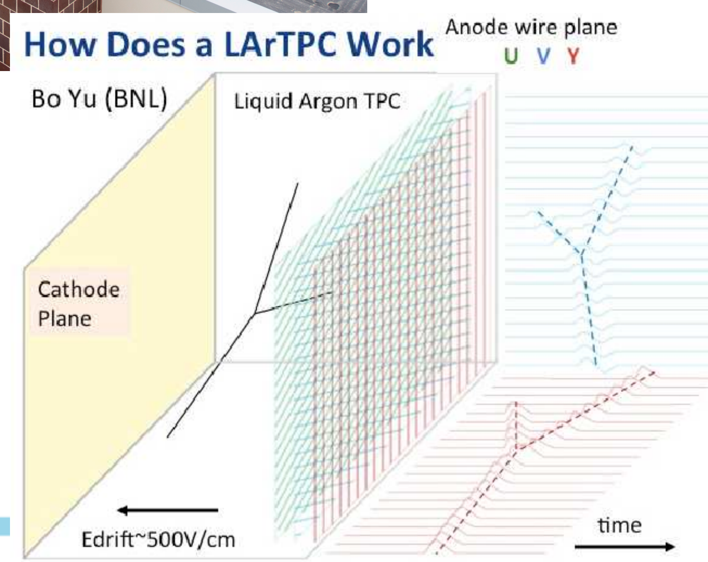
Fine-Grained Detectors (FGD 1 & 2):

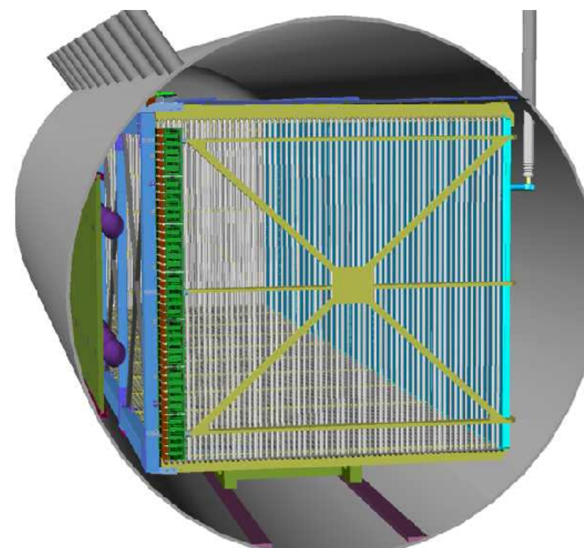
- CH scintillator tracker
- Target for ν
- FGD2 contains water

Time Projection Chambers (TPC):

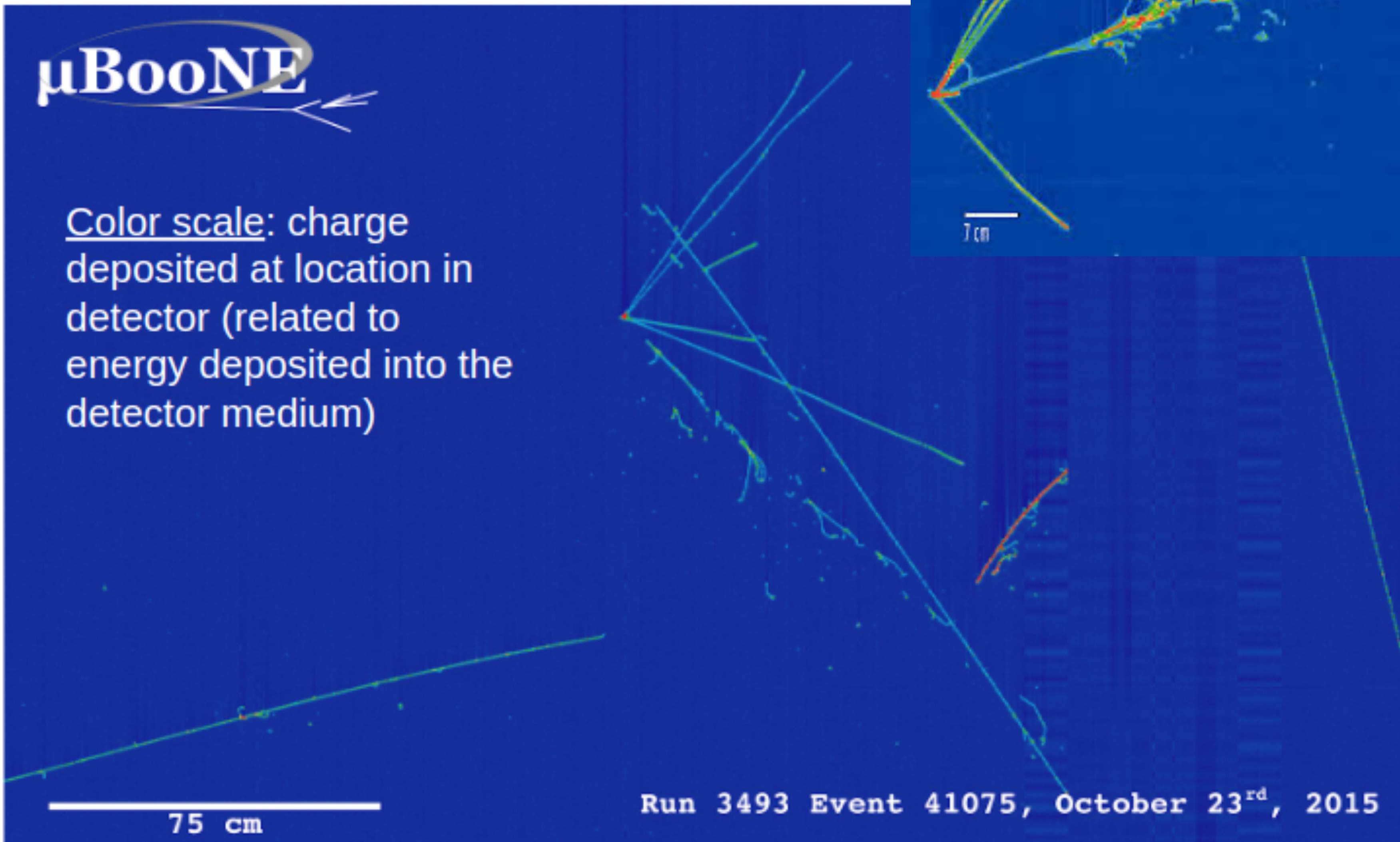
- Excellent tracking
- High-res charged-particle momenta
- Accurate particle ID

MicroBooNE


How Does a LArTPC Work
Anode wire plane
U V Y
Bo Yu (BNL)
Liquid Argon TPC
Cathode
Plane
Edrift~500V/cm
time



MicroBooNE



<u>Color scale</u>: charge deposited at location in detector (related to energy deposited into the detector medium)

A Brief Survey of Some Measurements And Their Comparisons to Event Generator Predictions

Note: the news is not so great… in general, generator predictions are pretty far off from our measurements.

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A Brief Survey of Some Measurements And Their Comparisons to Event Generator Predictions

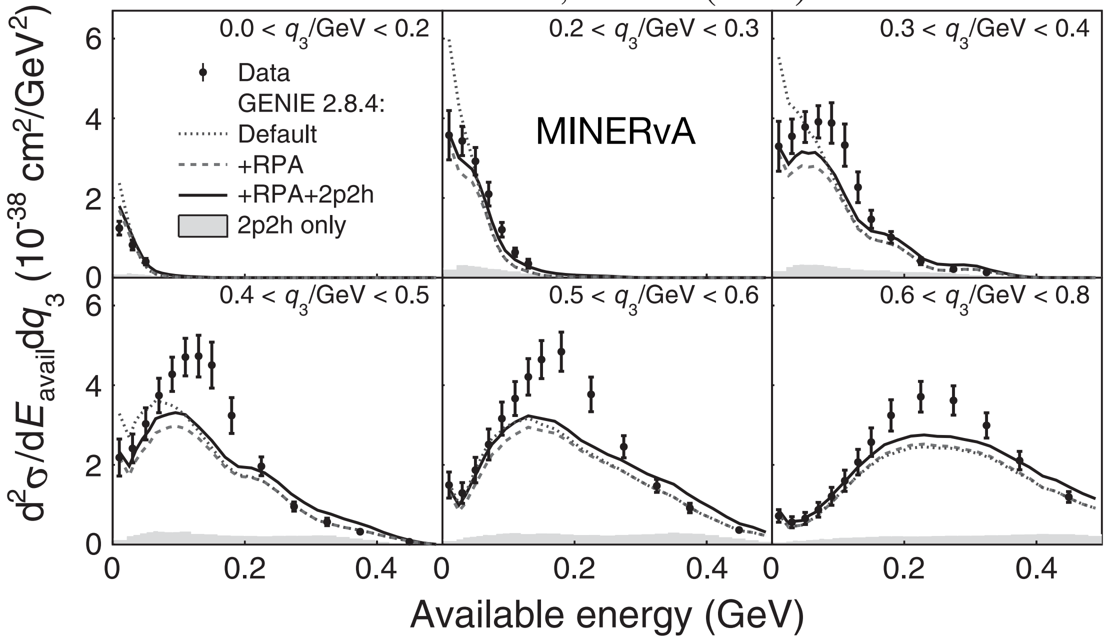
Note 2: this is a huge topic, and I simply can't cover everything in this one lecture. If you are interested in learning more, I suggest:

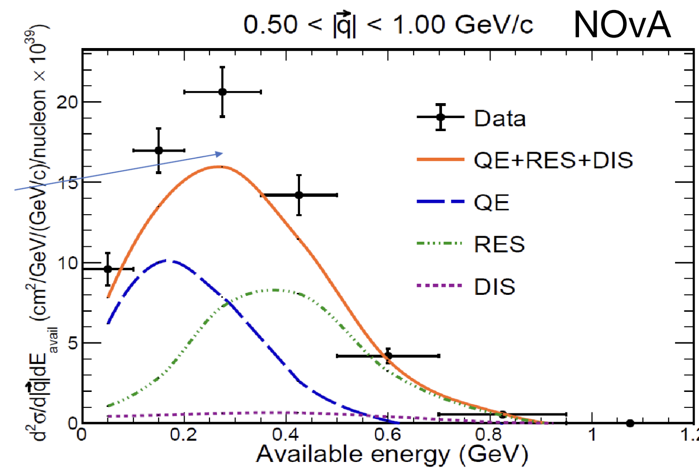
- **check out/get involved in NuSTEC (nustec.fnal.gov)**
- **Join the NuSTEC-new email list (see https://nustec.fnal.gov/nustec-news/ for instructions)**
- **Read the NuSTEC 2017 White Paper (http://inspirehep.net/record/1604295)**
- **Read the new NuSTEC White Paper when it comes out**
- **Checkout the talks in the most recent NuInt Workshop**

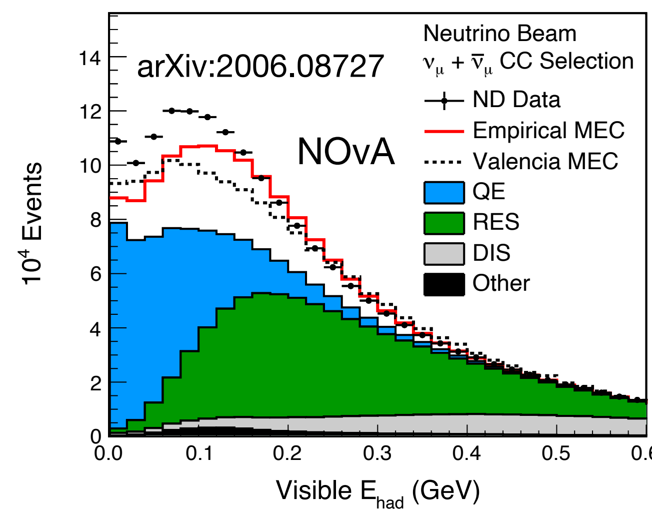
Fermilab

The 2p2h Saga…

PRL **116**, 071802 (2016)

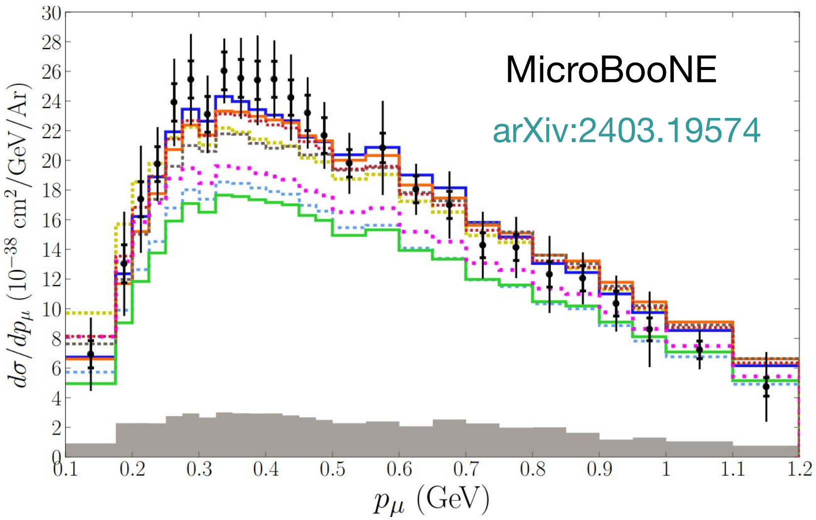


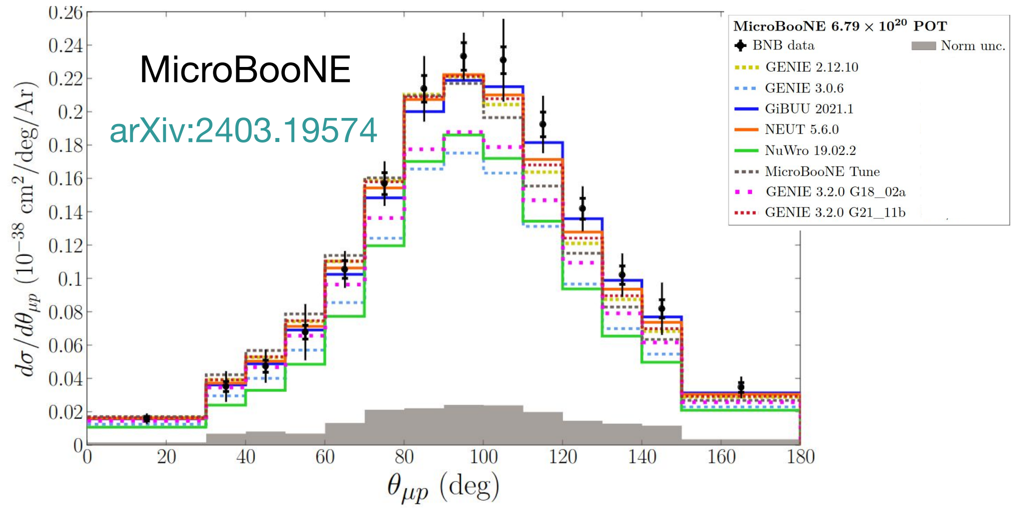




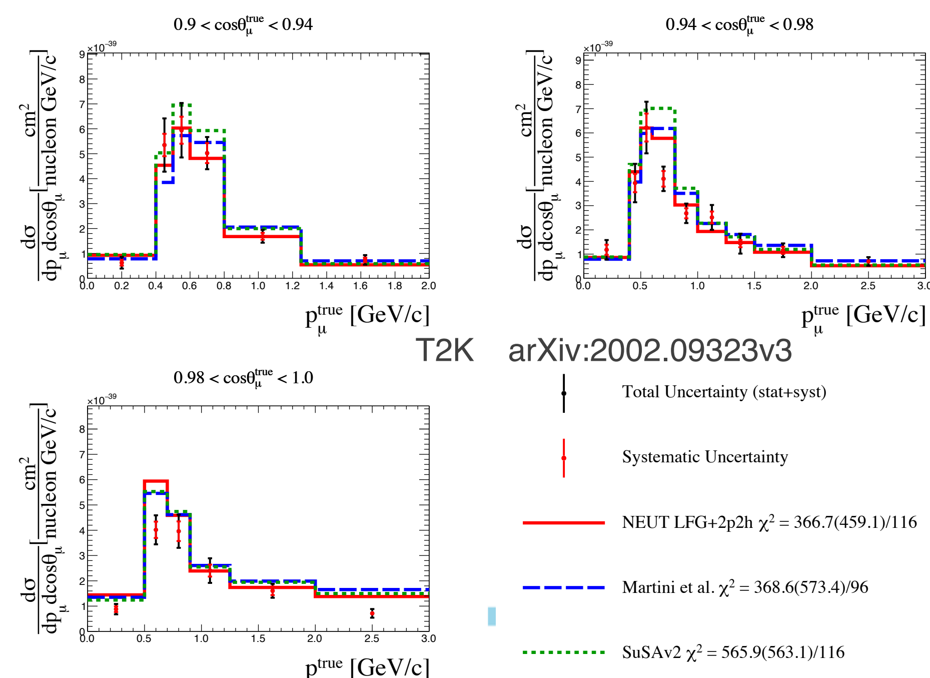
- In 2016, MINERvA published results showing a measured cross section much larger than was predicted in the their event generator at low momentum transfer.
- The excess of events appears at momenta transfer consistent with 2p2h interactions (a process already known from electron scattering experiments).
- NOvA showed a similar discrepancy in their data soon after. Studies show that no theory model is able to “fill in this gap”.

The 2p2h Saga…

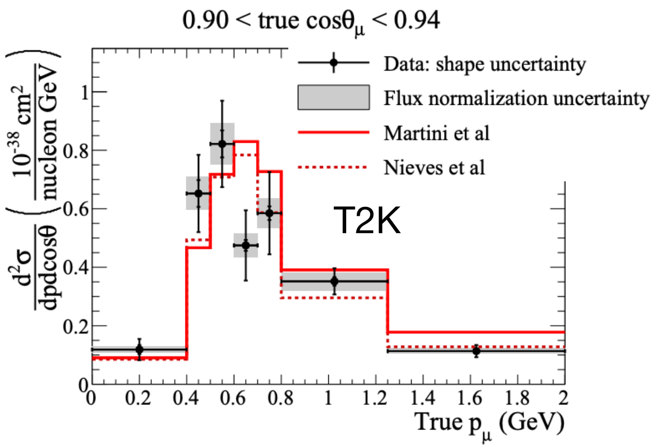


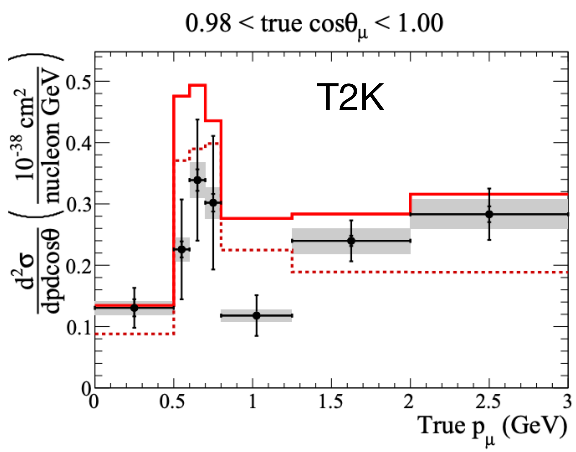


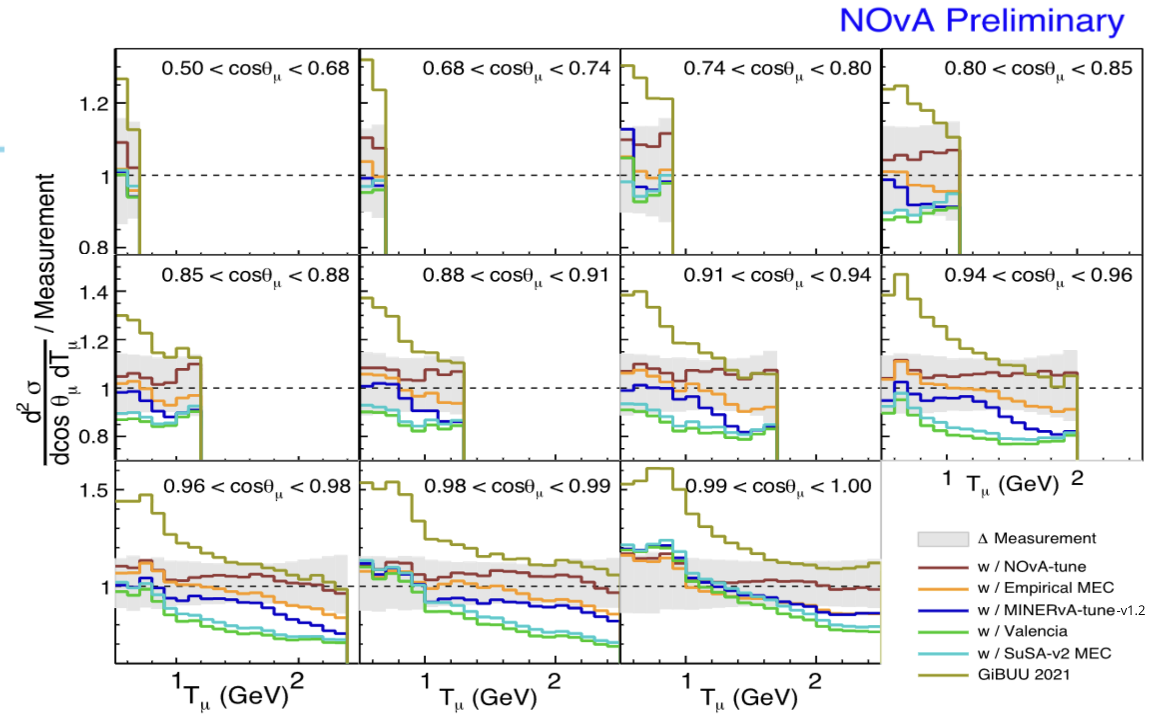
- And yet the models seem to work pretty well for both MicroBooNE and T2K.
  - This may not appear to be the case looking at the MicroBooNE plots above, but the chi2 comparisons between the data and predictions are all very reasonable.
- **So either there is an unaccounted neutrino-energy dependence in 2p2h interactions, or there is something else that we are not modeling at higher energies.**

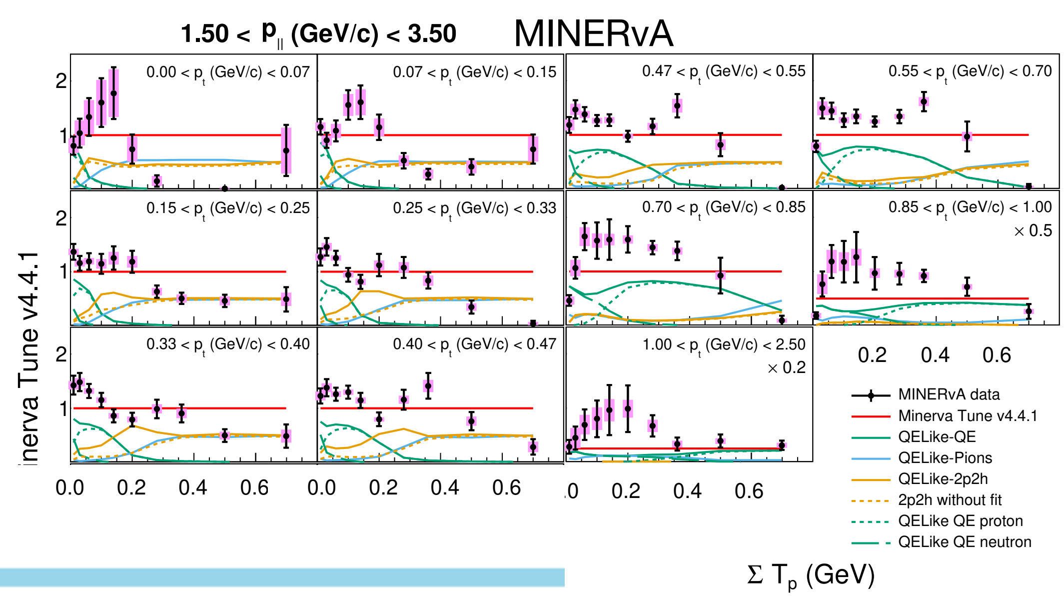


CC 0π Measurements



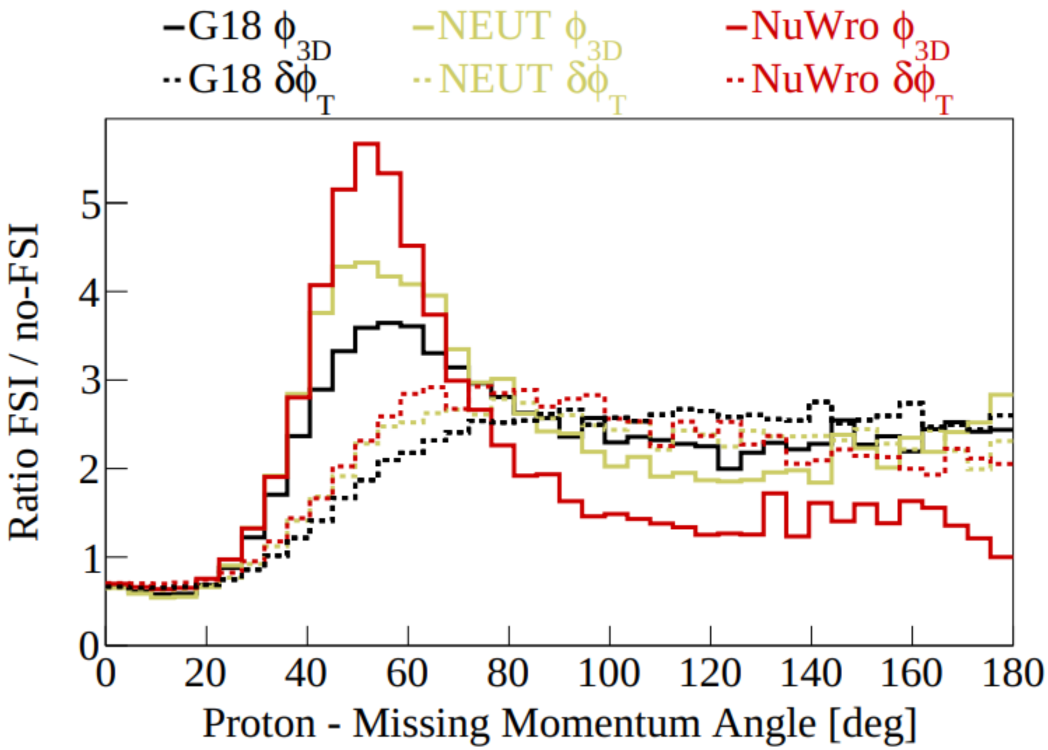


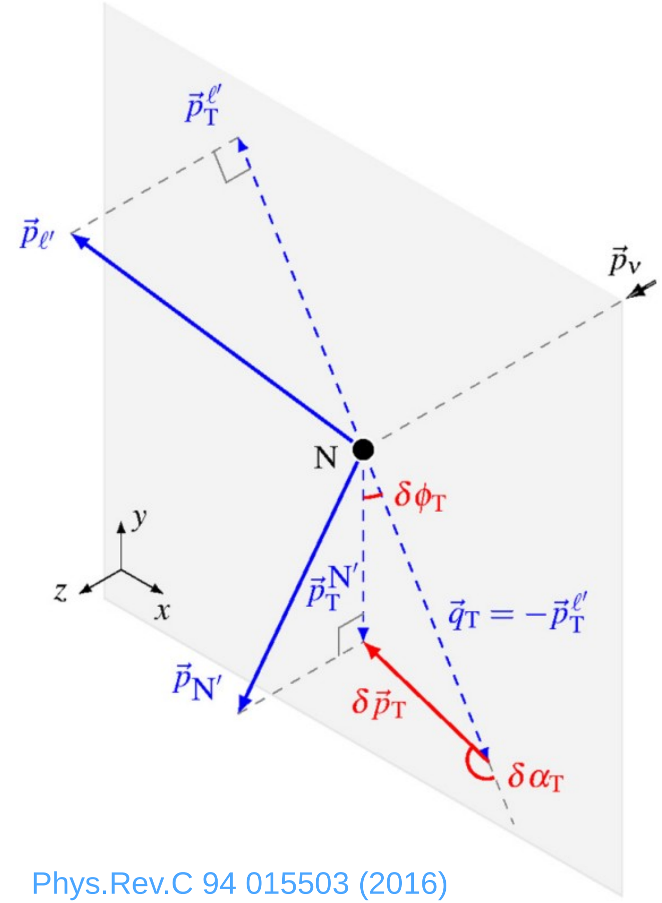




CC 0π Measurements - Transverse Kinematic Imbalance

- The idea: look for imbalance in the transverse momenta of the final-state particles.
- These observables are sensitive to effects of final state kinematics!





Phys.Rev.C 94 015503 (2016)

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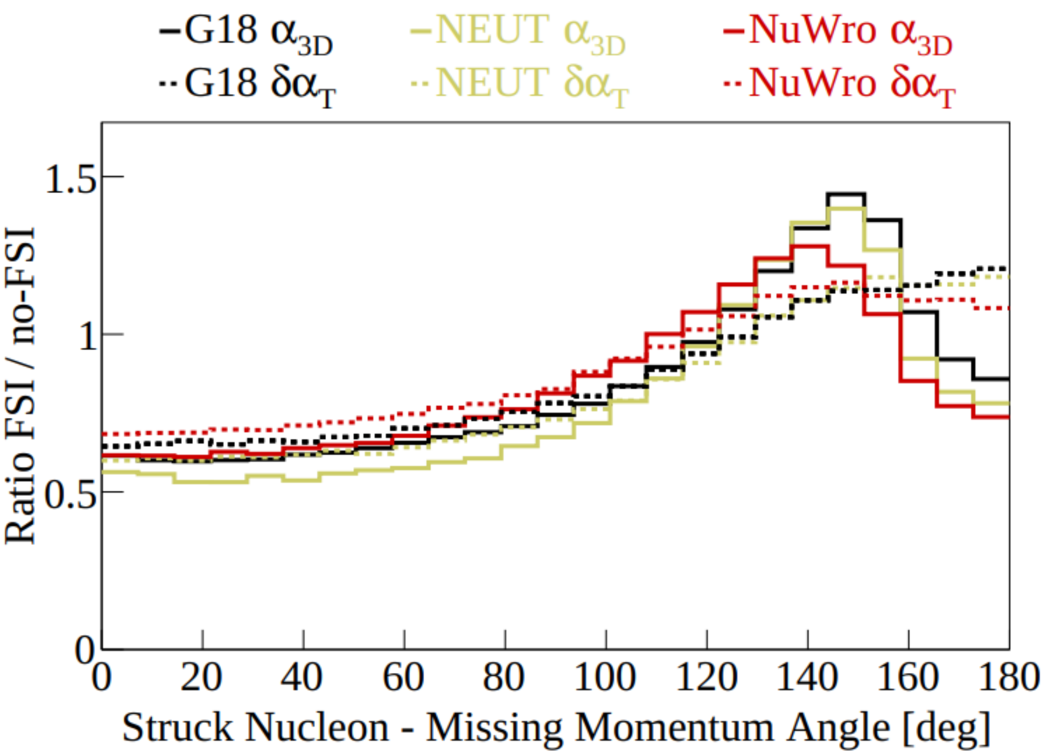

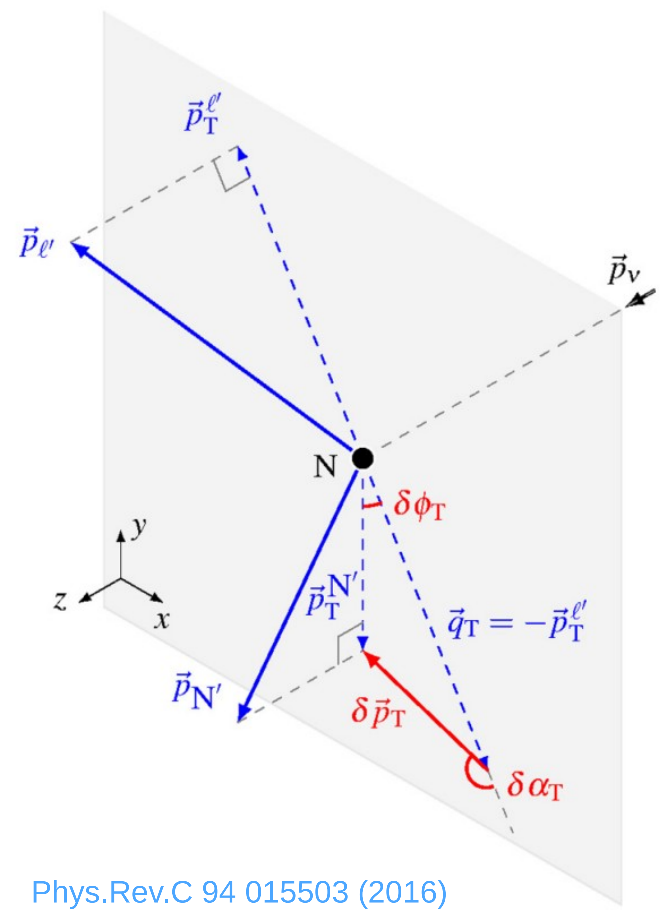

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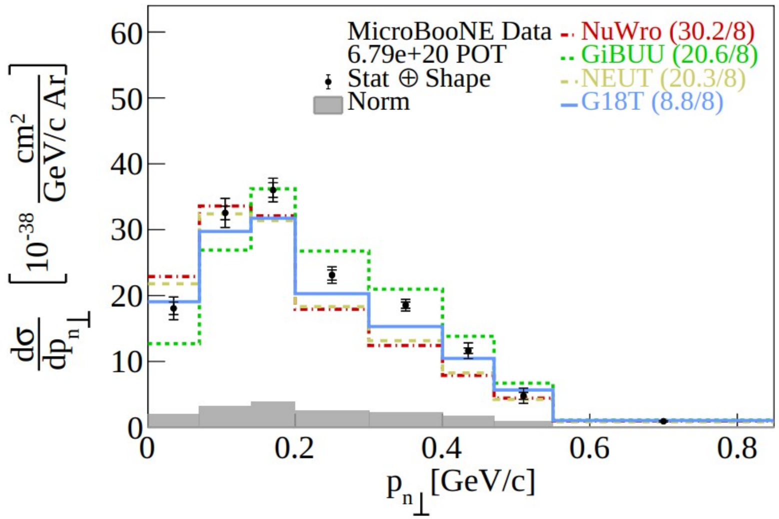
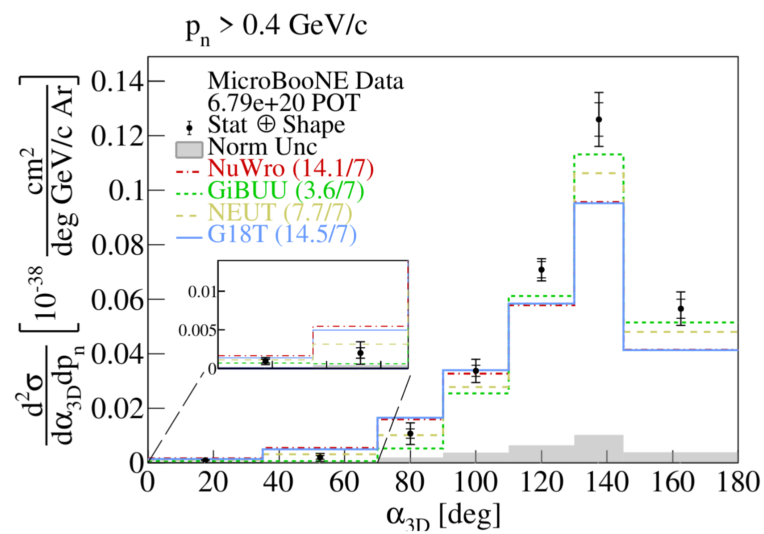
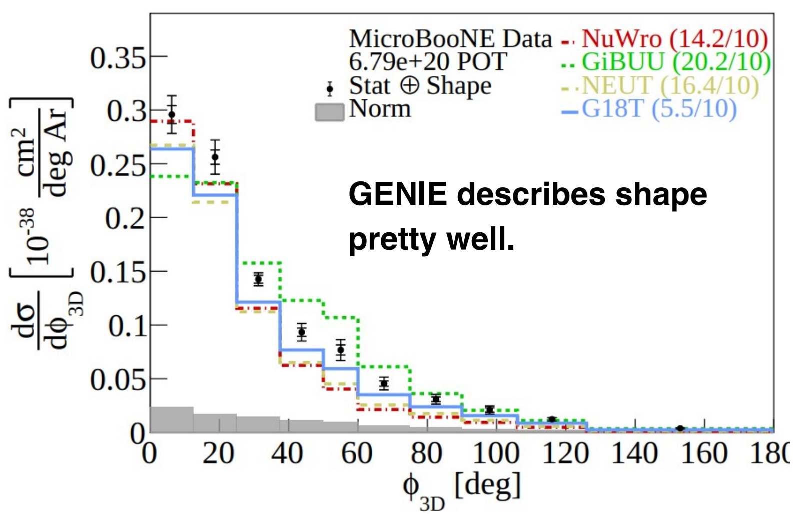
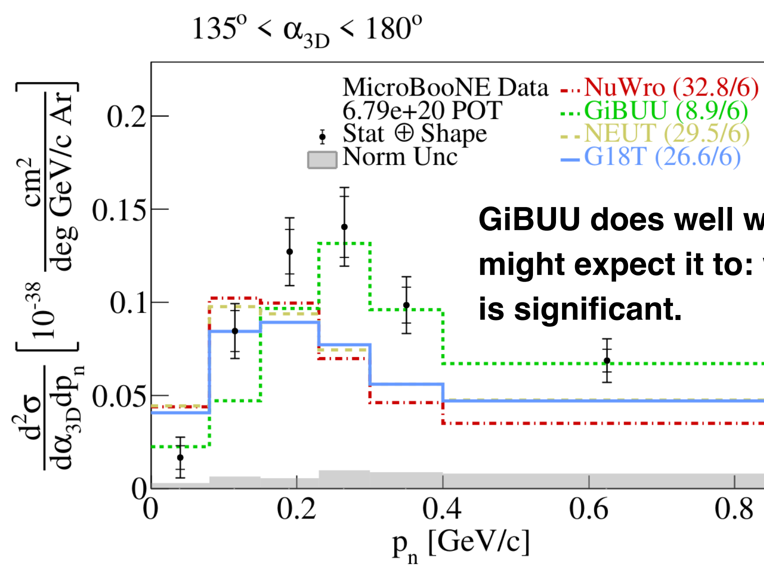
CC 0π Measurements - Transverse Kinematic Imbalance







GENIE describes shape pretty well.



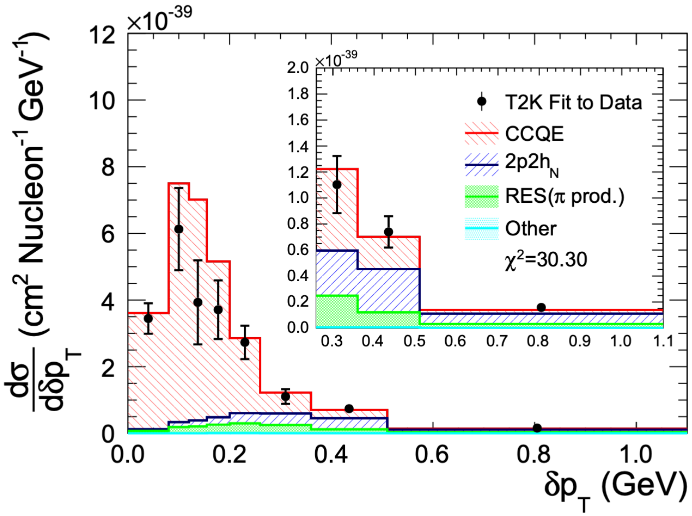
GiBUU does well where we might expect it to: where FSI is significant.

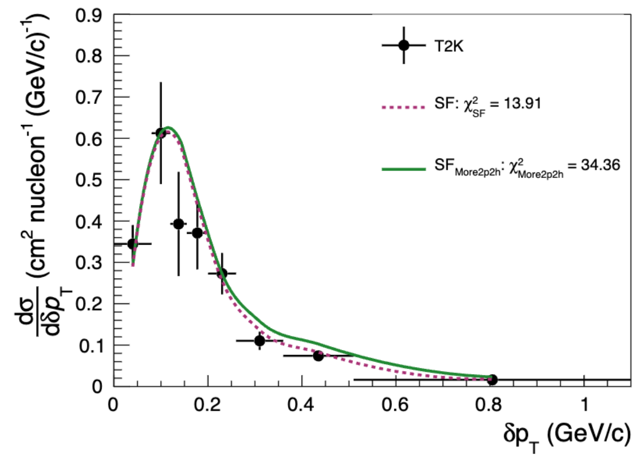
CC 0π Measurements - Transverse Kinematic Imbalance

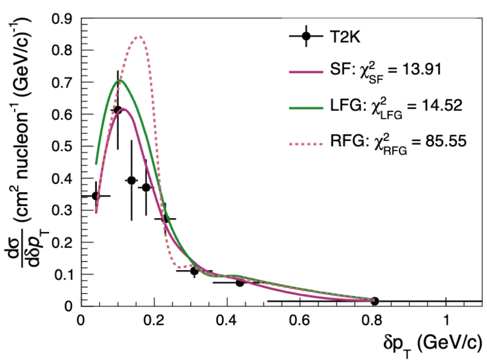
T2K Measuring muon+proton kinematics

Youthful optimism

- Measuring muon-proton correlations (2018) Phys. Rev. D **98**, 032003







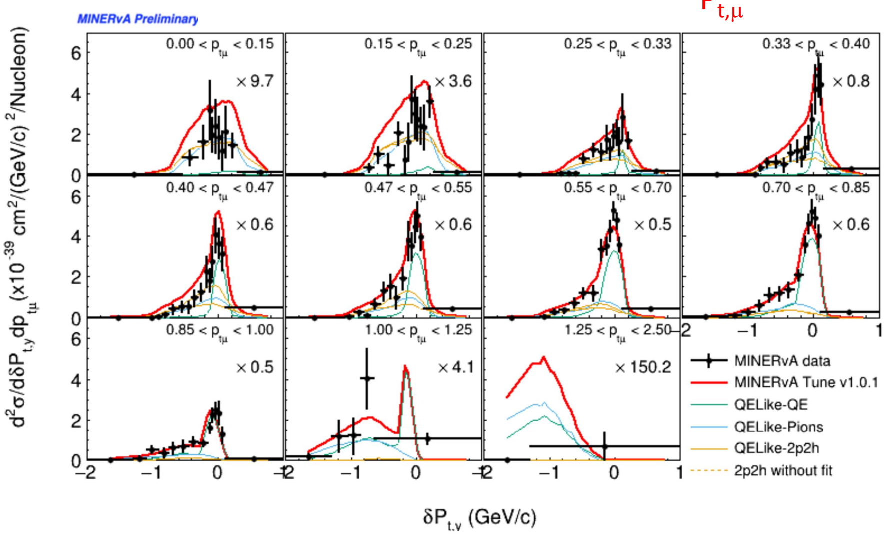
What we've learnt

- No model quantitatively describes measurements
- RFG models clearly rejected
- Robust estimation of QE vs non-QE in CC0π+Np
- Clear requirement for 2p2h+π abs not much scope to alter one without changing the other

CC 0π Measurements - Transverse Kinematic Imbalance

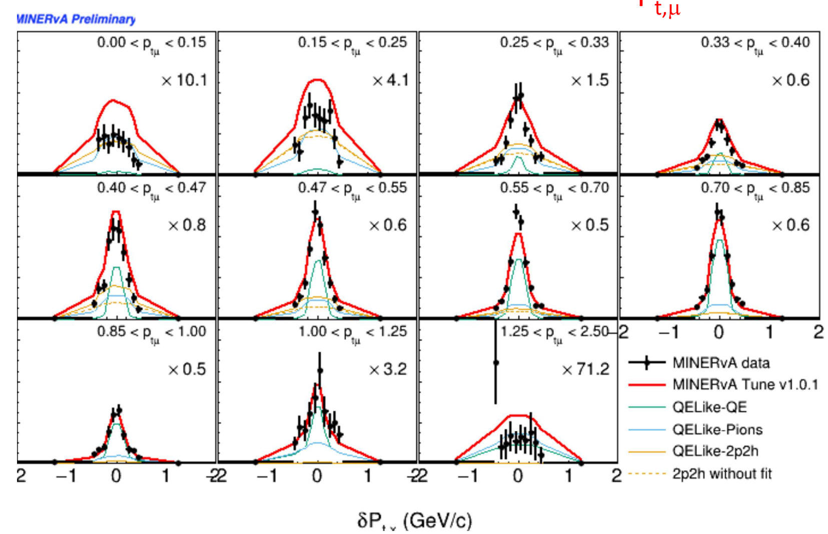
$\delta_{pt,y}$

Question: What is the peak position, width, and symmetry as a function of $P_{t,\mu}$



$\delta_{pt,x}$

Question: What is the peak position, width, and symmetry as a function of $P_{t,\mu}$



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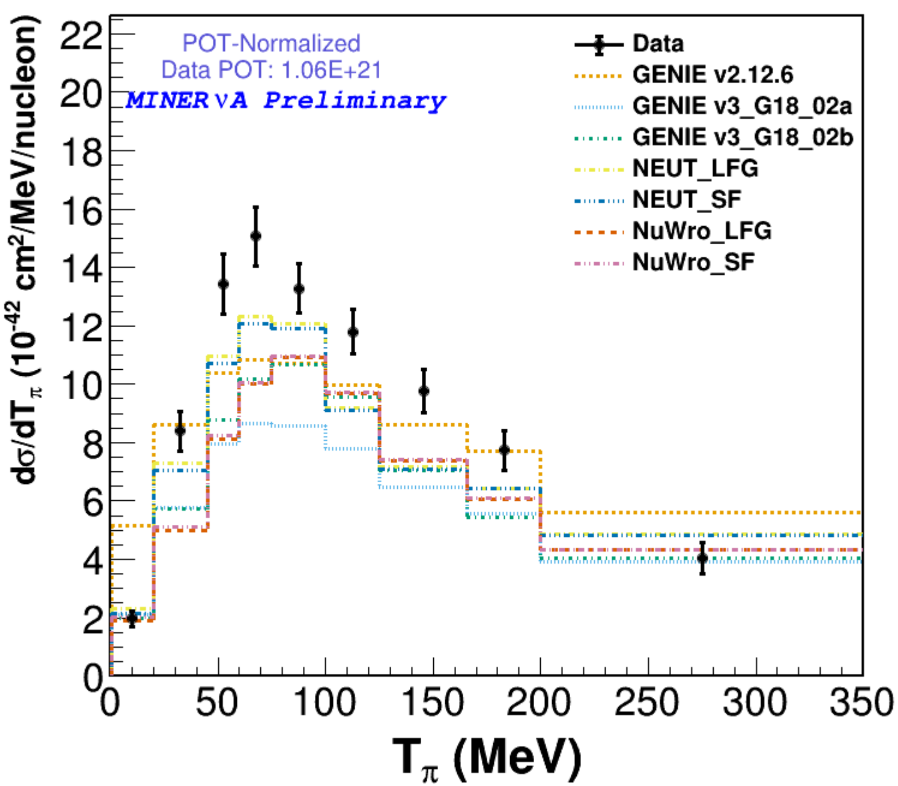
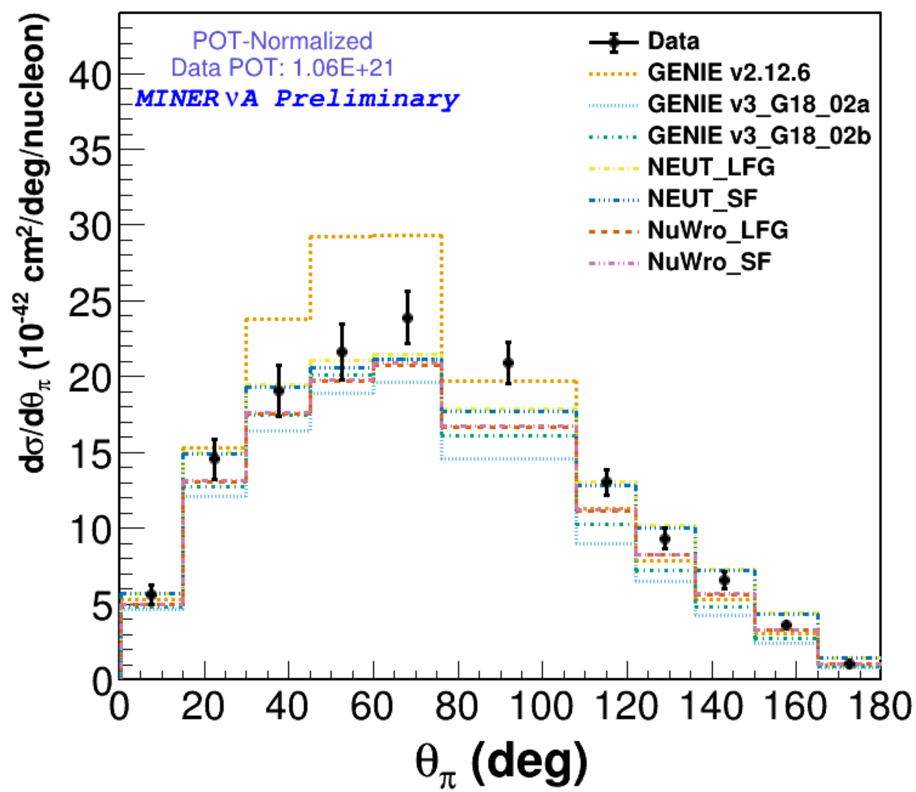
MINERvA: tuned cross section model (to their own data, but not using these observables) does ok in some regions of phase space, but does not do so well in others.

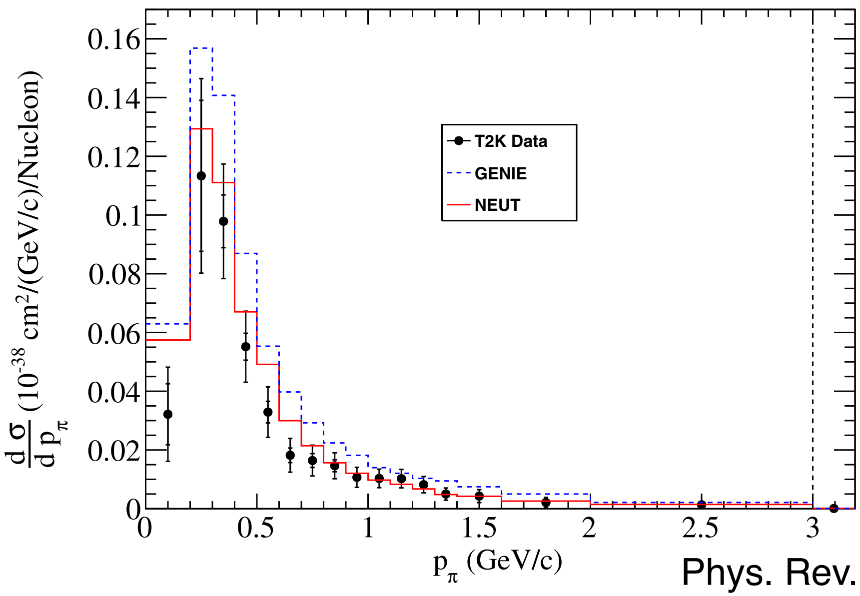
CC 1π Measurements

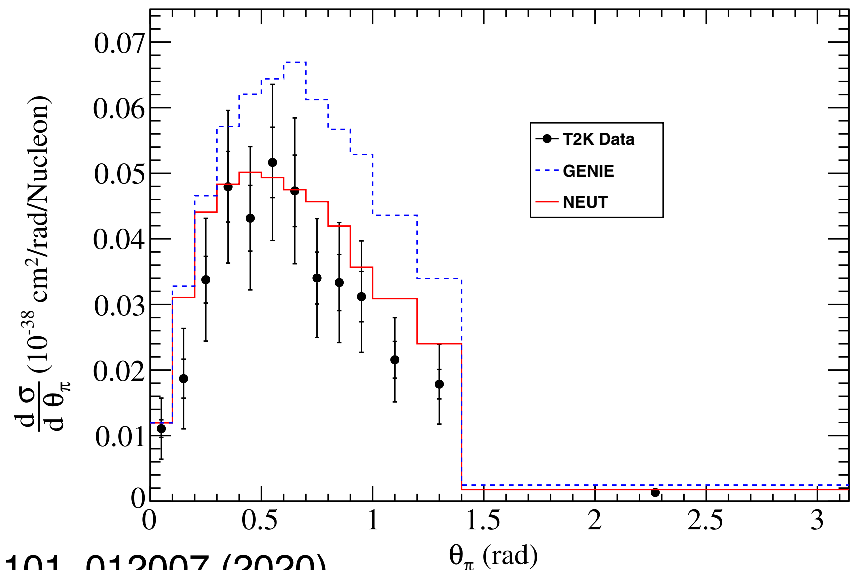




- Angular distribution of pions seems to be relatively well modeled. The energy distribution is peaked at lower energies than most models.

CC 1π Measurements

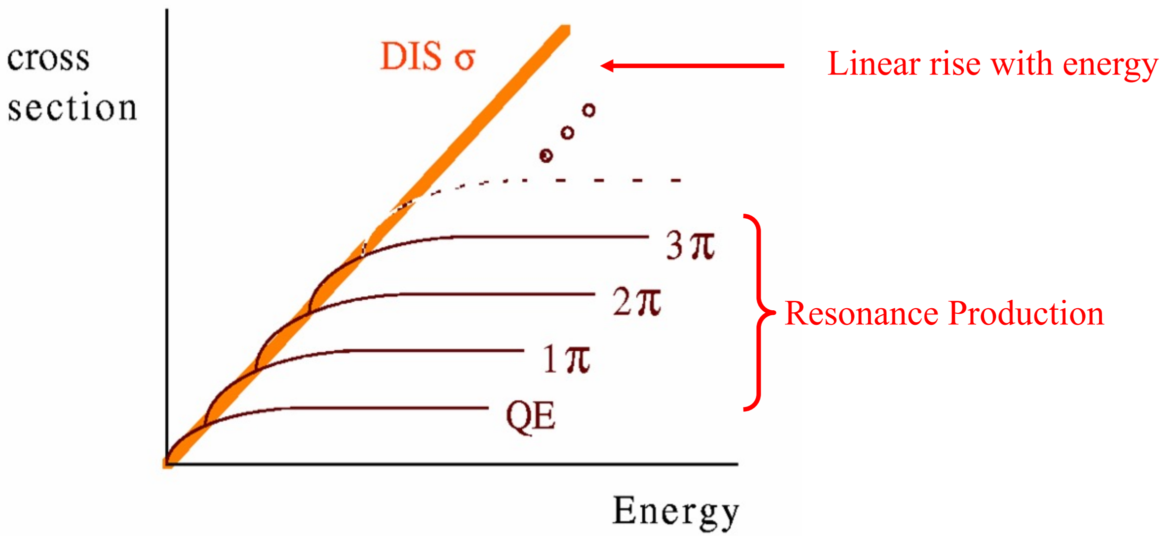


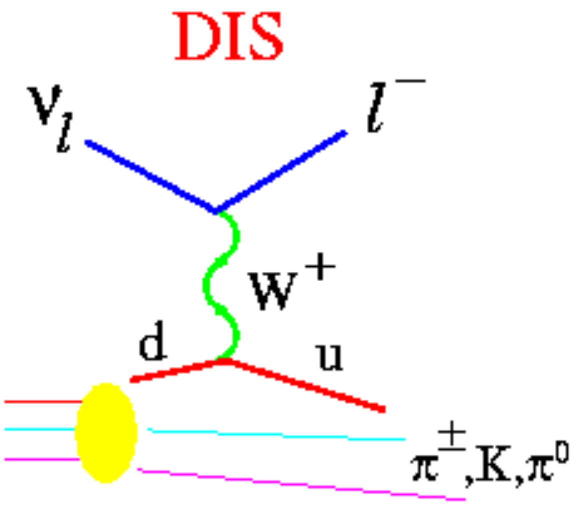


Phys. Rev. D 101, 012007 (2020)

- NEUT seems to be doing a good job predicting the pion kinematics.
- The GENIE cross section seems a bit high, and predicts higher momenta and larger angles than the data.

CC Nπ Measurements

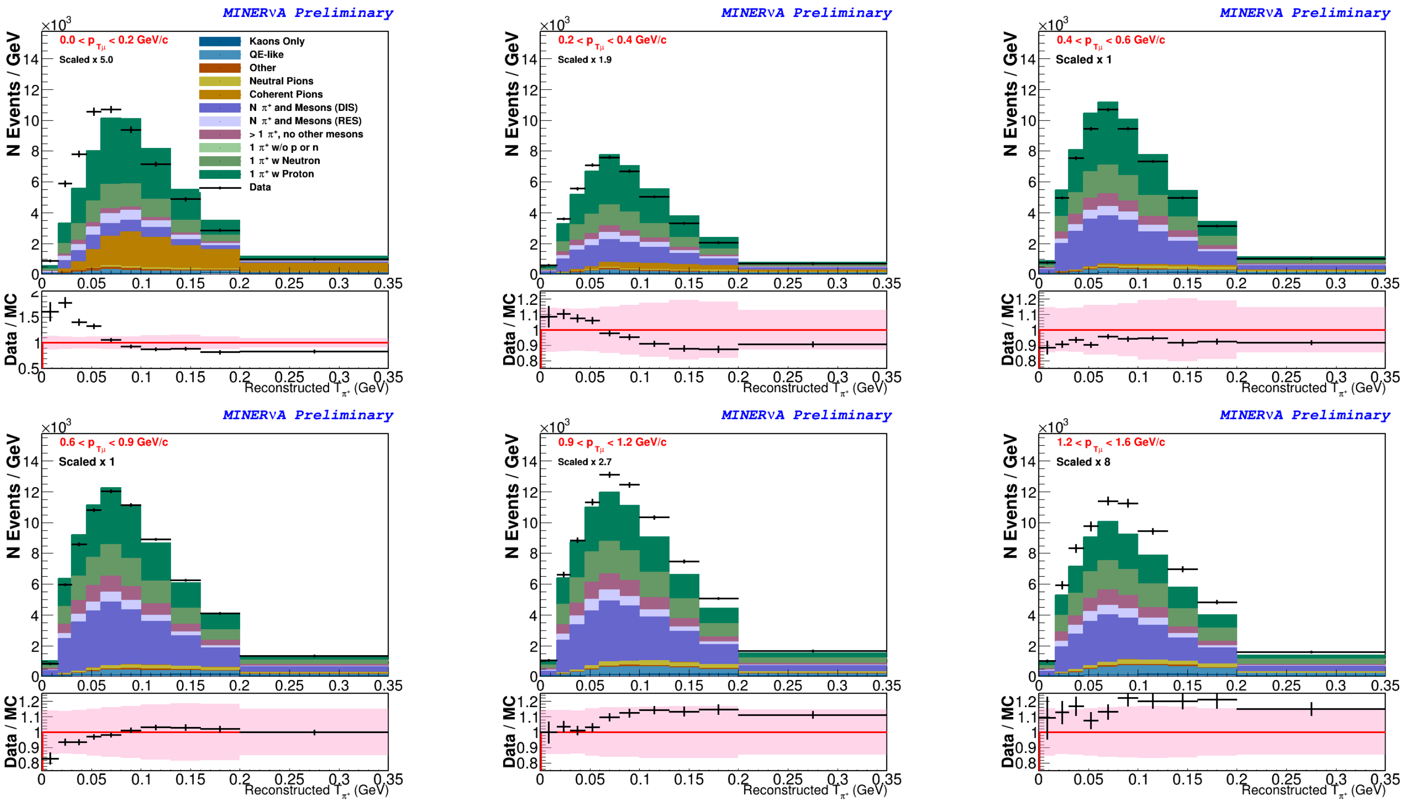




- As we go to higher energies, shallow- and deep-inelastic scattering can produce more than one pion in the final state.
- Most interactions in NOvA and DUNE involve pion production.
- The energy to create the pion needs to be accounted for when reconstructing the neutrino energy - important for oscillation measurements!
- Pions are susceptible to FSI

CC Nπ Measurements

CC≥1π^+ Events versus T_π and $p_{t\mu}$ with tune

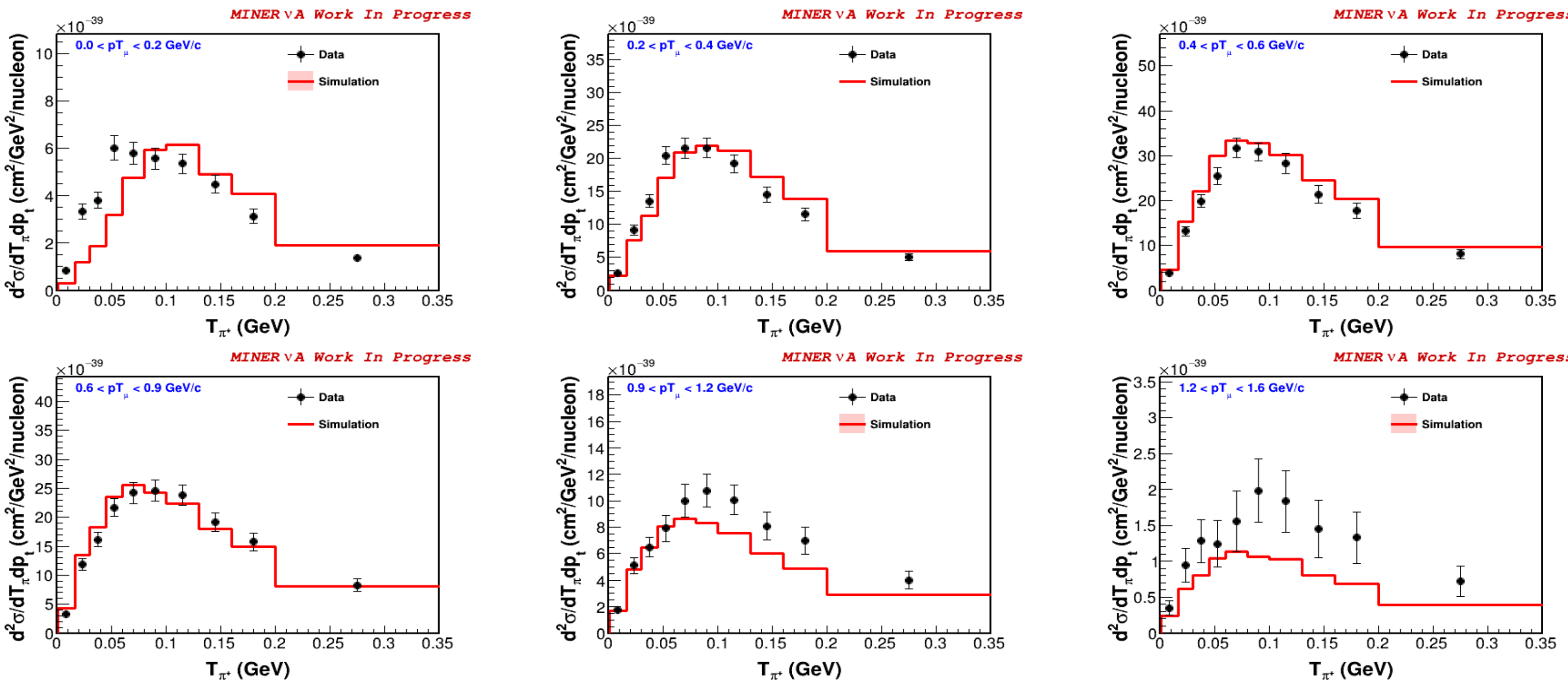


- Notice many contributing processes at each pion momentum
- Statistical error only on data points

18 April 2024 D. Harris for M. Sultana, Pions at MINERvA 17

CC Nπ Measurements

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

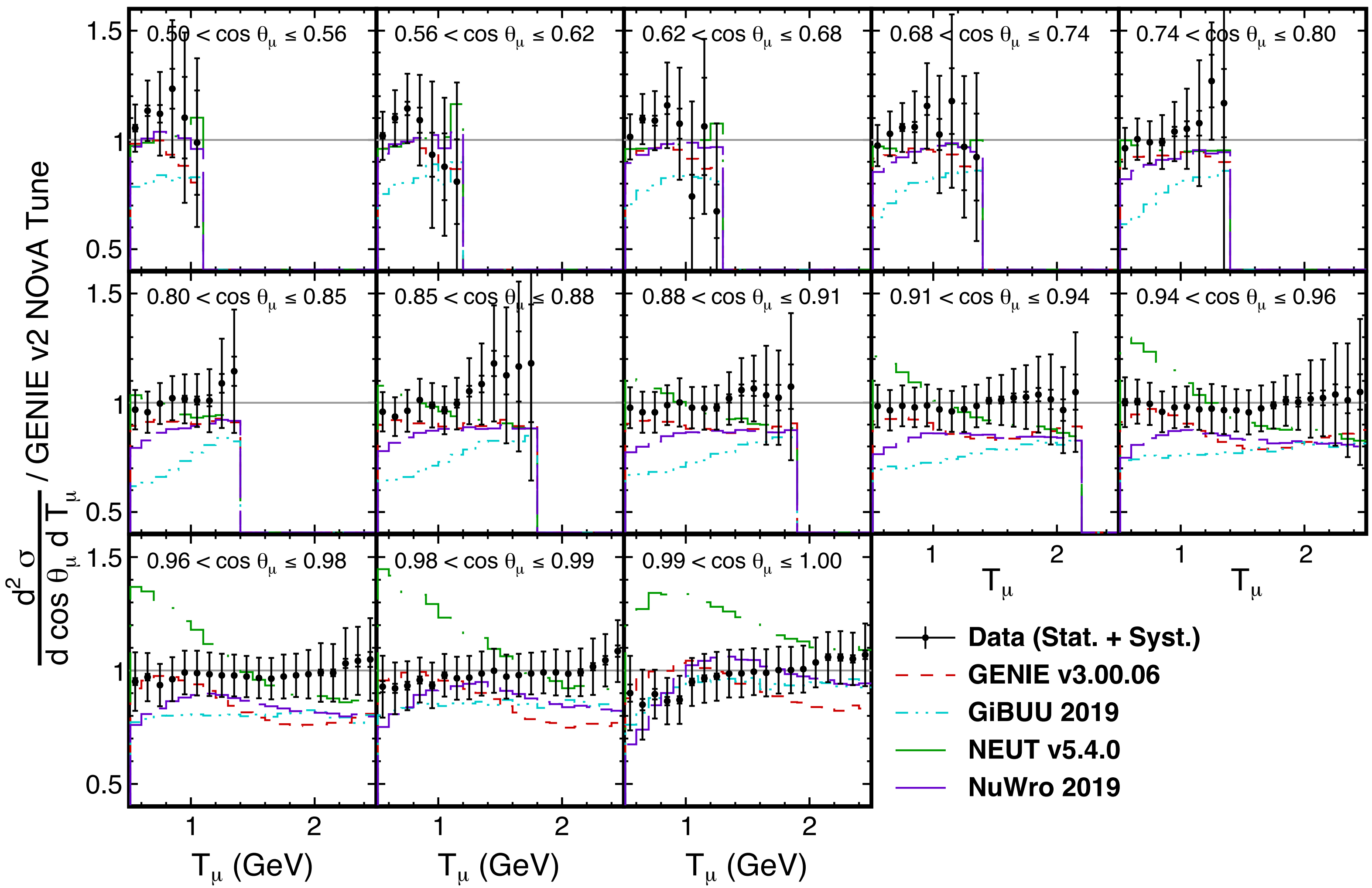


- Can look at transition from resonance to SIS to DIS

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

CC Inclusive Measurements

Phys. Rev. D 107, 052011 (2023)



CC Inclusive Measurements

$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

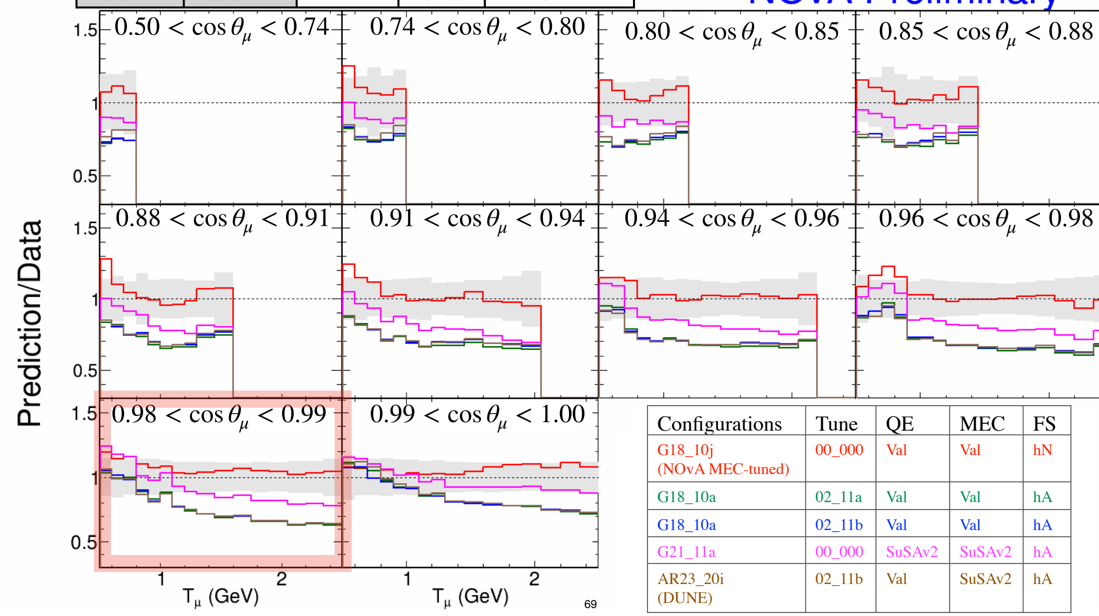
0 < E_{avail} < 100 MeV

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
59.4	35.4	4.4	0.6	0.2

Events: 48%

- None of the theory-based models fully reproduce our measurements
- SuSA-v2 model better reproduces data than Valencia for QE
- For MEC, Valencia and Susa-v2 are very similar and neither model matches the data



Configurations	Tune	QE	MEC	FS
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	hN
G18_10a	02_11a	Val	Val	hA
G18_10a	02_11b	Val	Val	hA
G21_11a	00_000	SuSAv2	SuSAv2	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	hA

Matt Wetstein, Iowa State University NUINT 2024, April 2024 22

$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

100 MeV < E_{avail} < 300 MeV

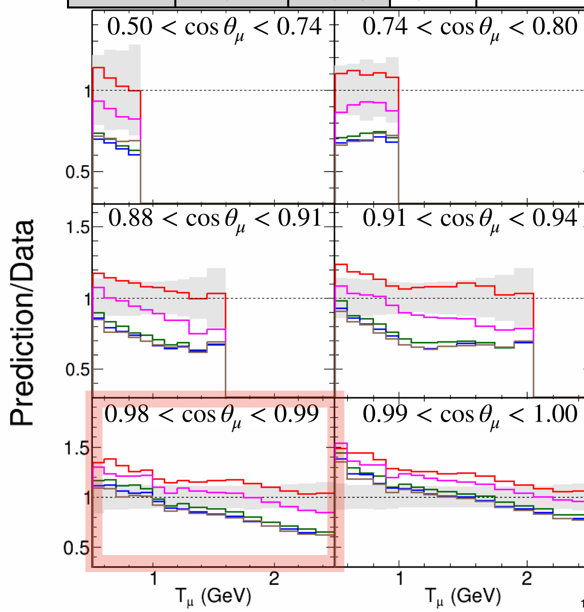
- Similar conclusions can be drawn in the 100-300 MeV E_{avail} bin as that 0-100 MeV bin wrt Data/MC ratios:
  - SuSA-v2 better describes QE physics
  - Both theory models poorly describe MEC

Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
21.4	18.2	48.0	8.4	4.1

Events: 22%

NOvA Preliminary



Configurations	Tune	QE	MEC	RES	FSI
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	BS	hN
G18_10a	02_11a	Val	Val	BS	hA
G18_10a	02_11b	Val	Val	BS	hA
G21_11a	00_000	SuSAv2	SuSAv2	BS	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	BS	hA

$\bar{\nu}_\mu$ Charge Current Inclusive Measurement

GENIE MC/Data Ratios

300 MeV < E_{avail} < 600 MeV

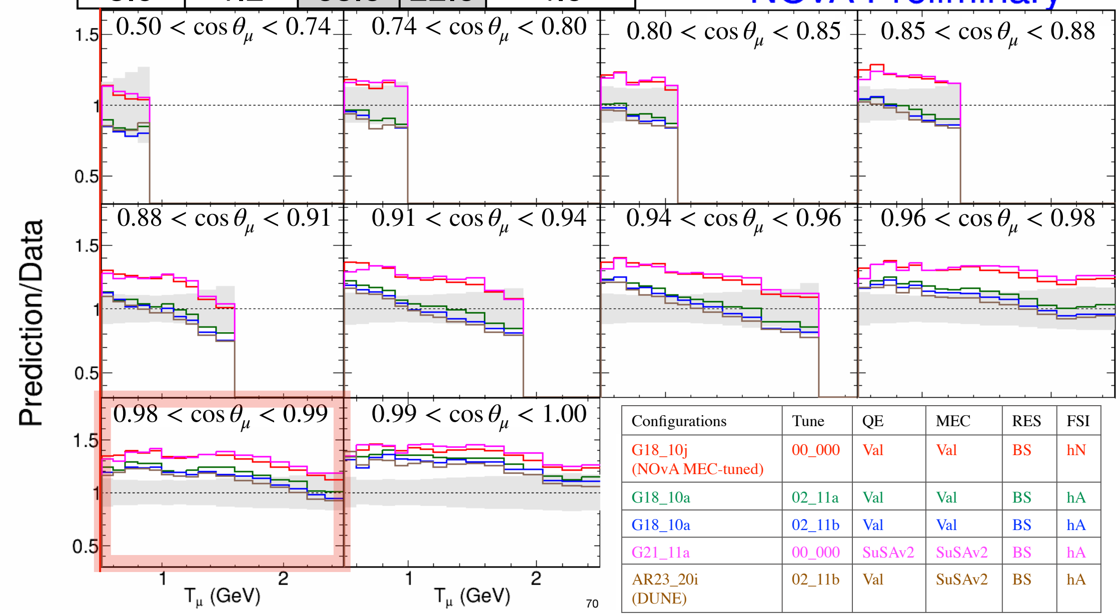
Table from NOvA-tuned GENIE

QE (%)	MEC (%)	RES (%)	DIS (%)	Others (%)
3.9	1.2	68.0	22.0	4.9

Events: 14%

NOvA Preliminary

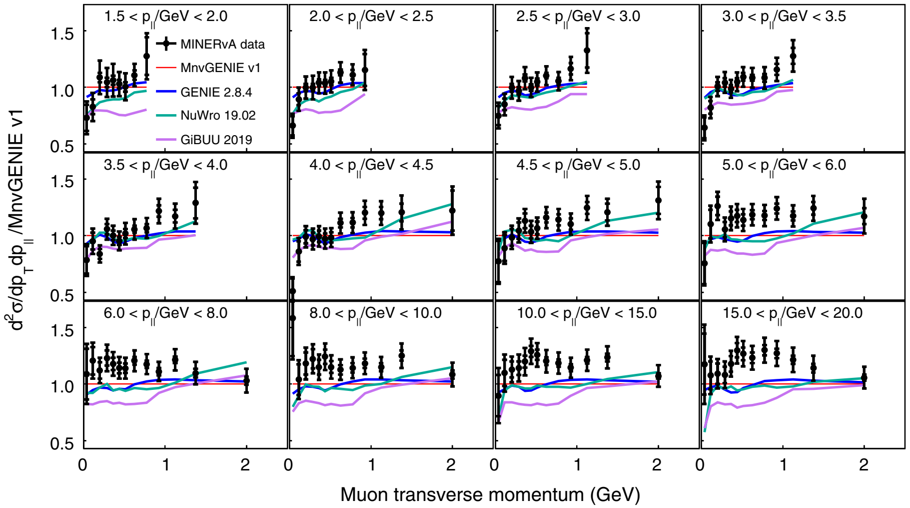
- Differences between the CMCs
  - GENIE tune 00_000 has no external data tune applied
  - 02_11a/b tunes adjust the model to match external single-nucleon data in modeling RES event
- We find that the 02_11 tunes to external data perform do perform better than the 00_0000 in this RES enhanced region



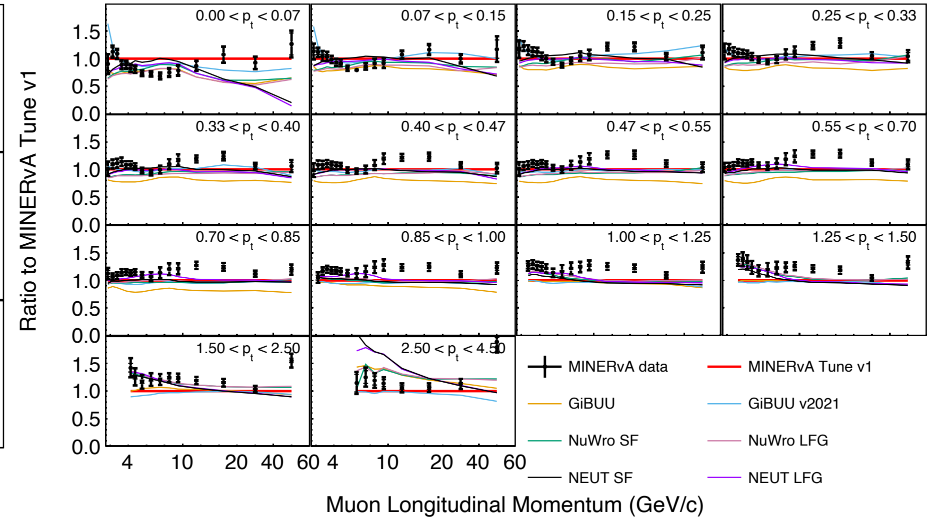
Configurations	Tune	QE	MEC	RES	FSI
G18_10j (NOvA MEC-tuned)	00_000	Val	Val	BS	hN
G18_10a	02_11a	Val	Val	BS	hA
G18_10a	02_11b	Val	Val	BS	hA
G21_11a	00_000	SuSAv2	SuSAv2	BS	hA
AR23_20i (DUNE)	02_11b	Val	SuSAv2	BS	hA

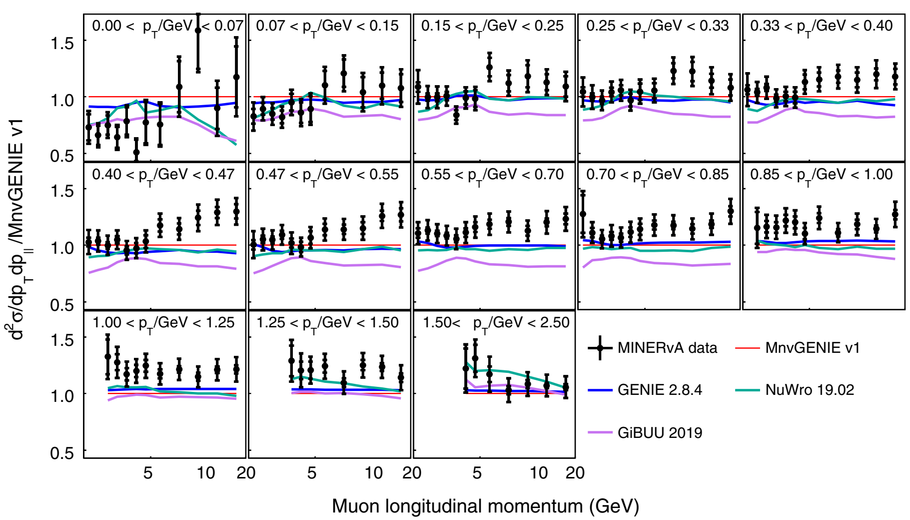
CC Inclusive Measurements

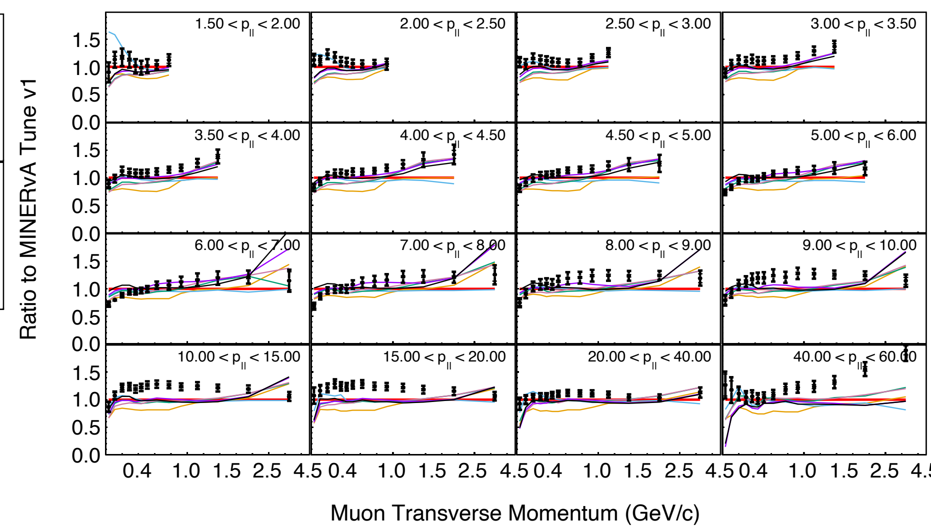
MINERvA <Eν> ~ 3.5 GeV



MINERvA <Eν> ~ 6 GeV



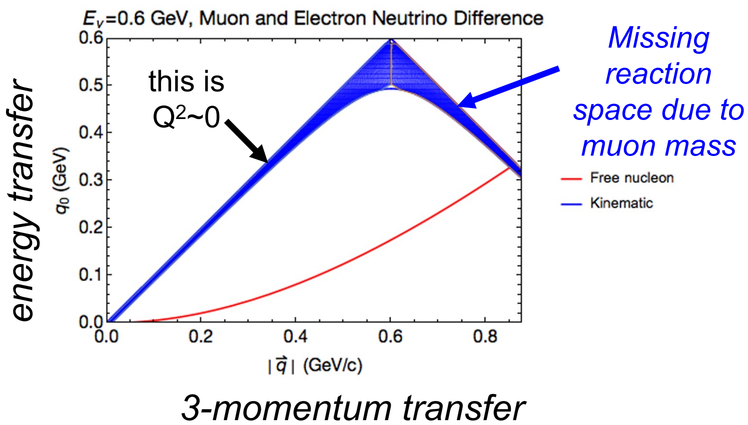


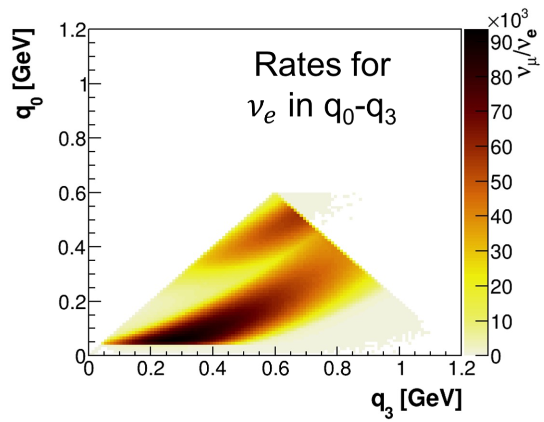


ν_e CC Inclusive Measurements

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.



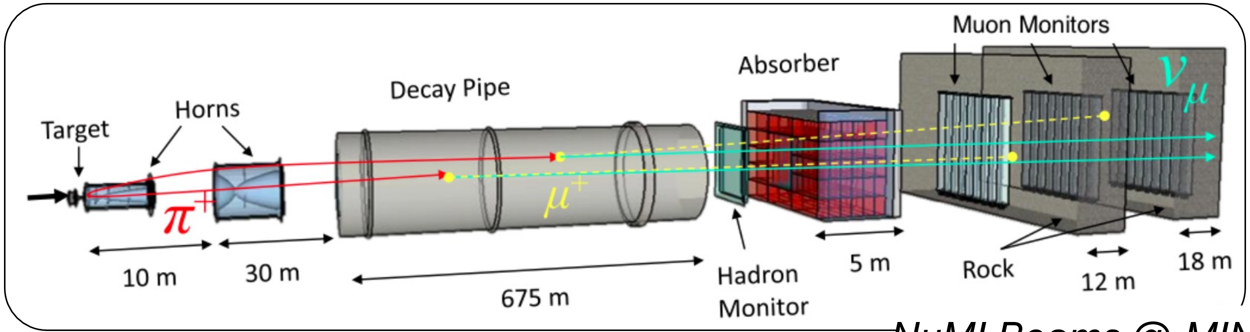


Radiative corrections:
O. Tomalak et al., Nature Commun. 13 (2022) 1, 5286 and Phys.Rev.D 106 (2022) 9, 093006

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

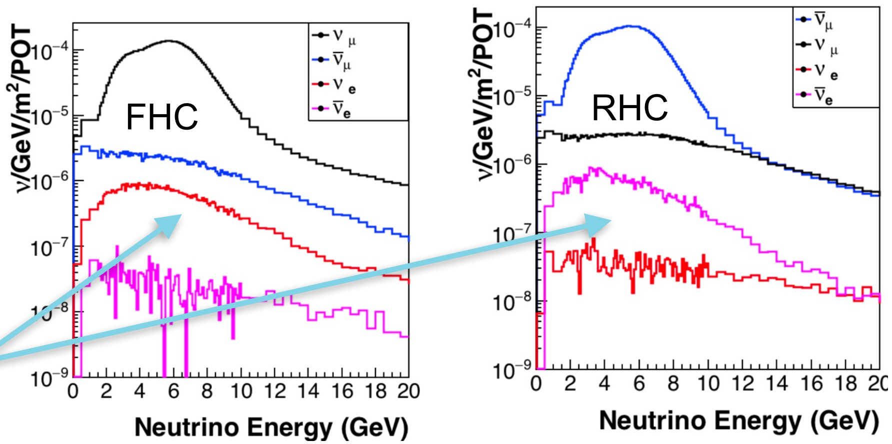
ν_e CC Inclusive Measurements

The NuMI Beam: Electrons



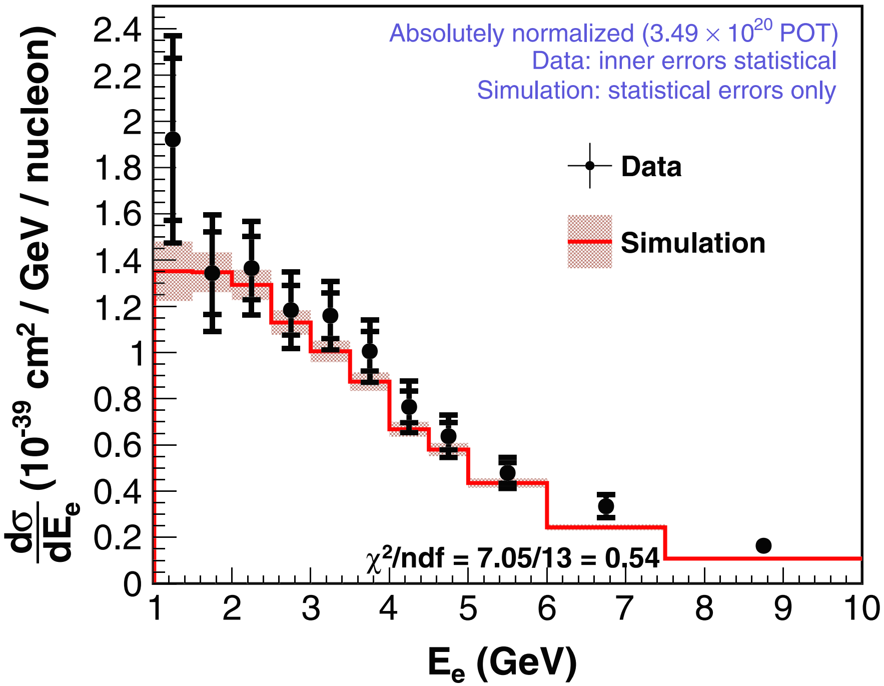
- NuMI is a "conventional" neutrino beam, with most neutrinos produced from focused pions.
- Pions decay mostly to muons, but weak decays involving electrons come from daughter muons, kaons, and so forth.
- ~1% contribution of the beam.

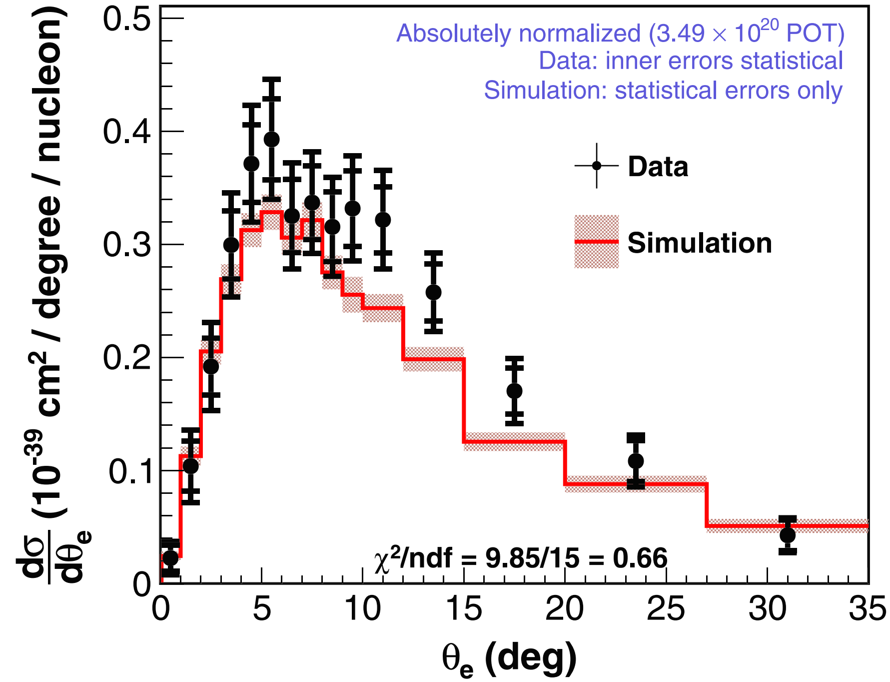
NuMI Beams @ MINERvA



ν_e CC Inclusive Measurements

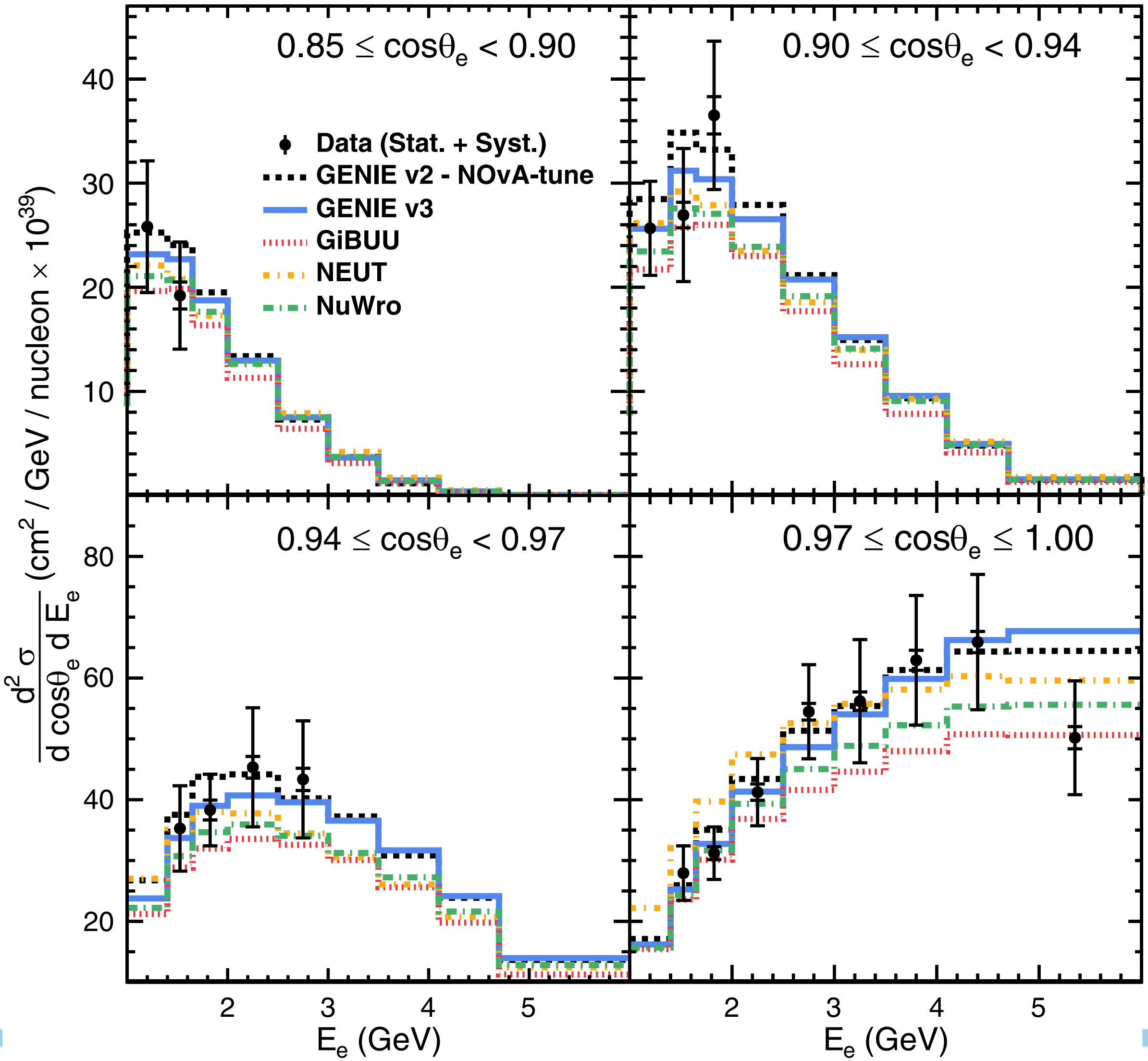
MINERvA, PRL 116, 081802 (2016)





ν_e CC Inclusive Measurements

NOvA, PRL 130, 051802 (2023)



Fermilab

ν_e CC Inclusive Measurements

NOvA, PRL 130, 051802 (2023)

What we really care about is the $\sigma(\nu_e)/\sigma(\nu_\mu)$ ratio… our current uncertainty on this is ~3%.

Measuring this ratio to better than 3% in the current generation of experiments is probably unlikely, but we're working on it!

Summary of Measurements

- Overall most generators seems to okay predicting muon kinematics.
- When measuring pions directly, the predictions seem to be not too bad. But inclusive cross section measurements seem to imply that pion production is under-predicted at higher muon energies.
- There is something going on either with 2p2h or some other interaction that produces an enhancement of “available energy” at low momentum transfer for the higher energy experiments.
- How to make sense of all this?

Making sense of all these Measurements

- We are now faced with an enormous amount of data, some of which have few-percent uncertainties in the shape.
- Many generator developers are implementing some kind of global fit of their models to these data (and to electron scattering data too, but I don't have time to get into that).
  - Exclusive final-state measurements are easier to deal with.
  - GENIE uses the "Professor" tool (also used by Geant4)
  - NUISANCE is another great tool for comparing different data sets to different generator predictions.
- This is an enormously challenging task, and we are just getting started!

A Look to the Future

- There was much that I did not talk about:
  - Neutron measurements by MINERvA, ANNIE and others
  - Measurements of interactions in the SIS/DIS regime by MINERvA (and maybe NOvA someday)
  - Using electron scattering to constrain the vector components of our models (e4nu, electron scattering in neutrino generators)
  - Hadron scattering measurements to improve our understanding of FSI, secondary interactions in our detectors, and reducing flux uncertainties (ProtoDUNE, LArIAT, EMPHATIC, NA61, etc.)
  - BSM, NSI, LDM…
  - T2K ND280 Upgrade
  - DUNE 2x2, SBND
- Furthermore, all of the experiments will continue to analyze and improve upon existing measurements

A Look to the Future

- As we saw from the data, we have our work cut out for us to make sense of it all.
- But the future is bright, and we need smart people like you to help us…
- Come join the fun!