Neutrino Scattering - Why and How

Jonathan Paley
Fermilab Neutrino Division

April 30, 2024
ICTS Understanding Universe with Neutrinos
Summer School

Please Note…

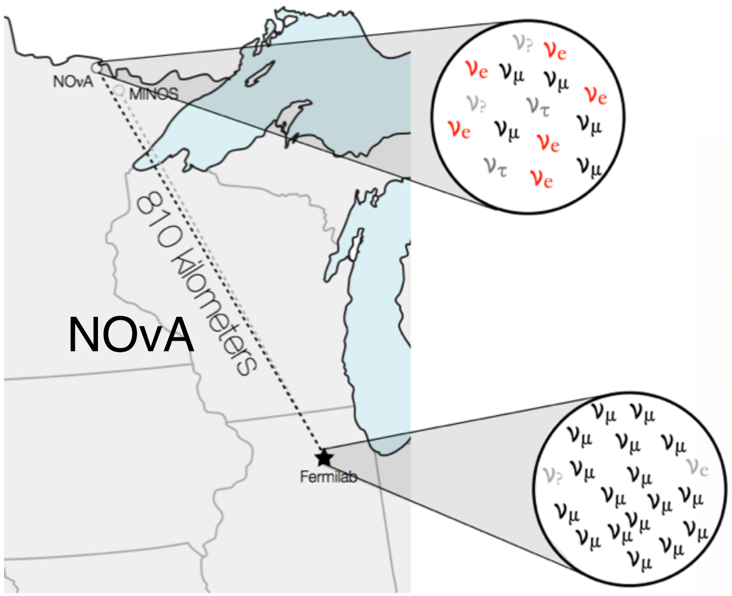
- I sincerely apologize that I cannot be there in person to meet and talk with you all!
- Since this is a school:
  - I have some questions throughout my slides that I would like you to answer afterward.
  - Please send me at least 1 follow-up question after each lecture. I will answer at least 1 question from each of you and post them in Slack (#flux-and-xsec-exp).
  - You may send me questions either via email (jpaley@fnal.gov) or Slack (@Jon Paley)

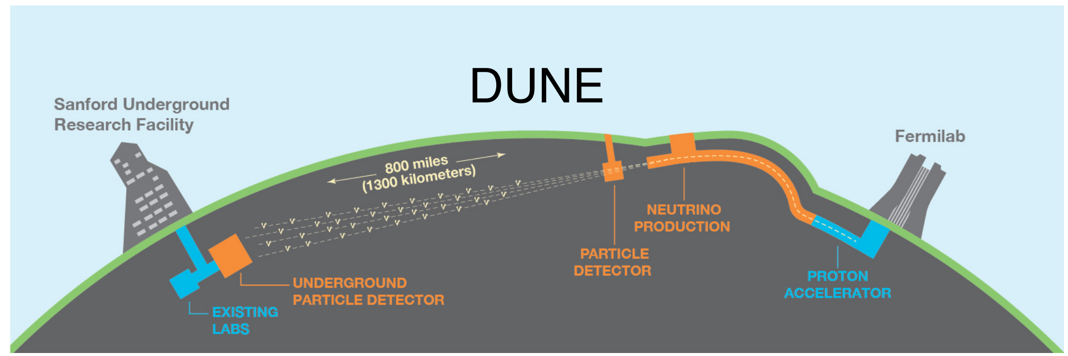
Outline

- Why do we care about neutrino scattering?
- The role of neutrino event generators
- What goes into a cross section measurement?
- How to avoid cross section model dependency and model bias?

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.

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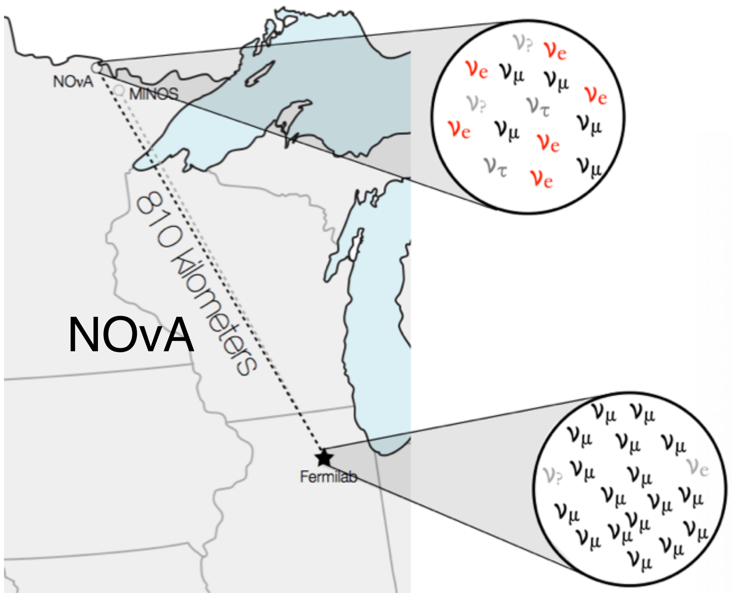
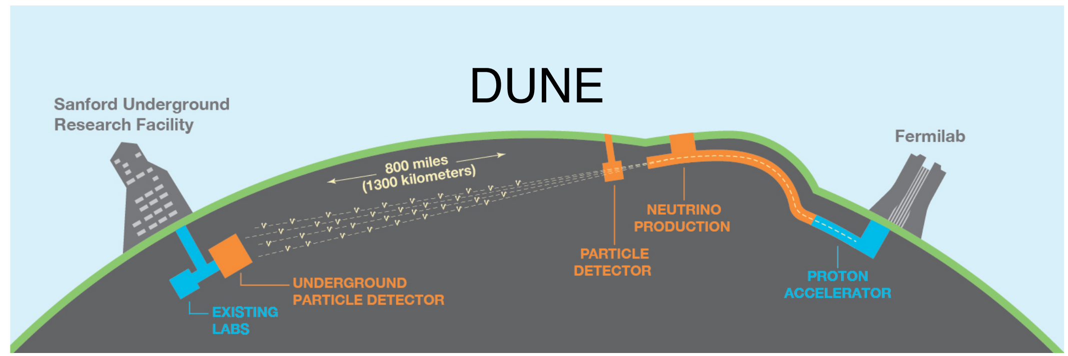
Neutrino Scattering and Oscillations

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



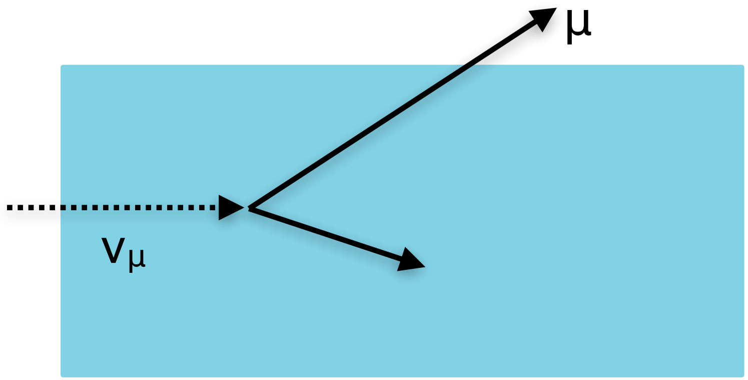


- Remember, we "see" neutrinos because they scatter off nuclei, producing charged particles that deposit energy in our detectors.
- The probability that a neutrino scatters is the cross-section.

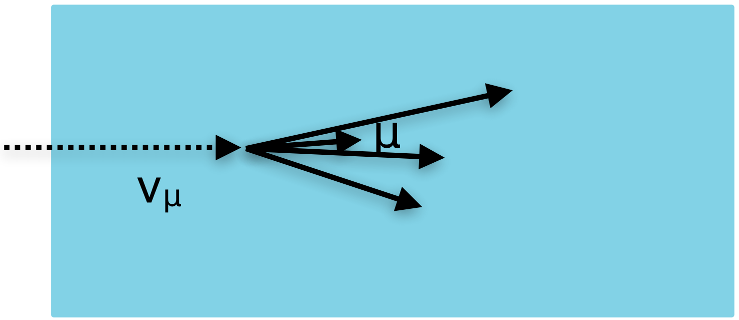
Neutrino Scattering and Oscillations

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

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



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.

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Neutrino Scattering and Oscillations

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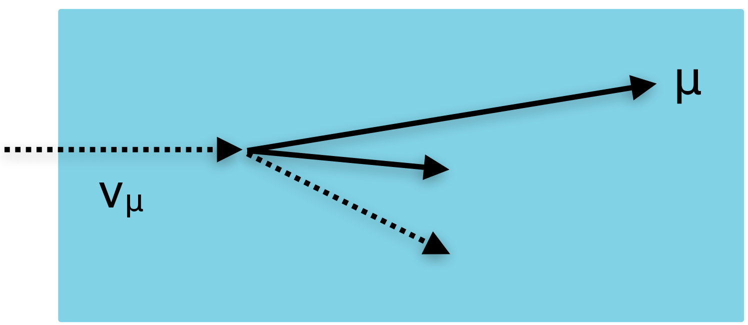
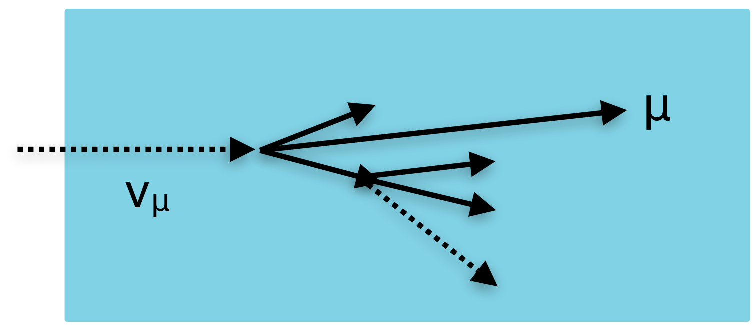
$$\vec{U}(E_{\nu_\mu}^{\text{true}}, E_{\nu_\mu}^{\text{reco}}) \propto \frac{d^N\sigma(E_{\nu_\mu}^{\text{true}})}{d\vec{X}}$$



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.

Neutrino Scattering and Oscillations

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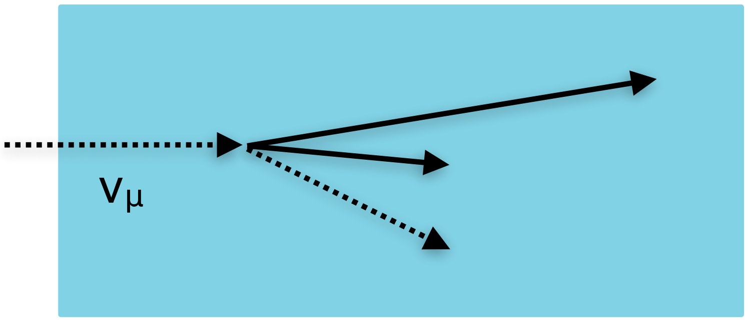

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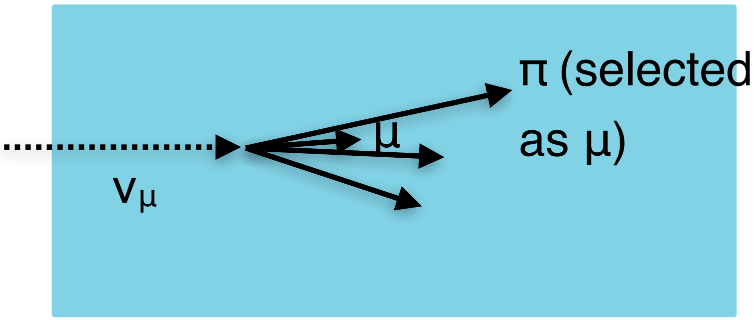

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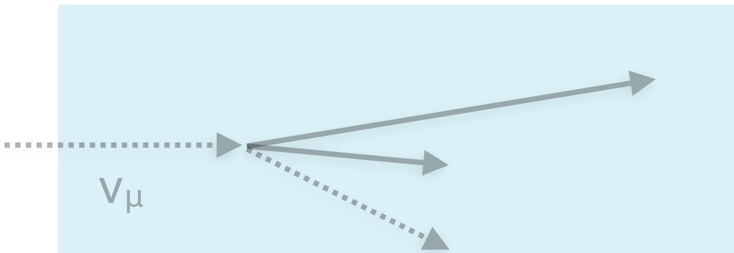
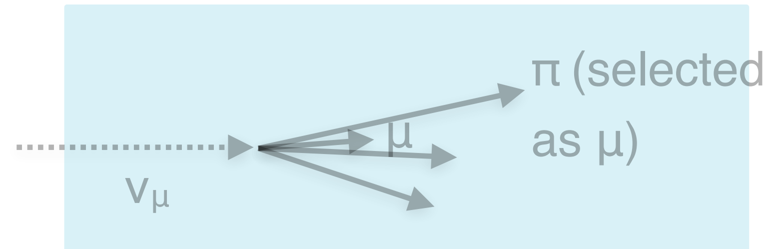




What else could go wrong with our event selection?

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

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

- 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

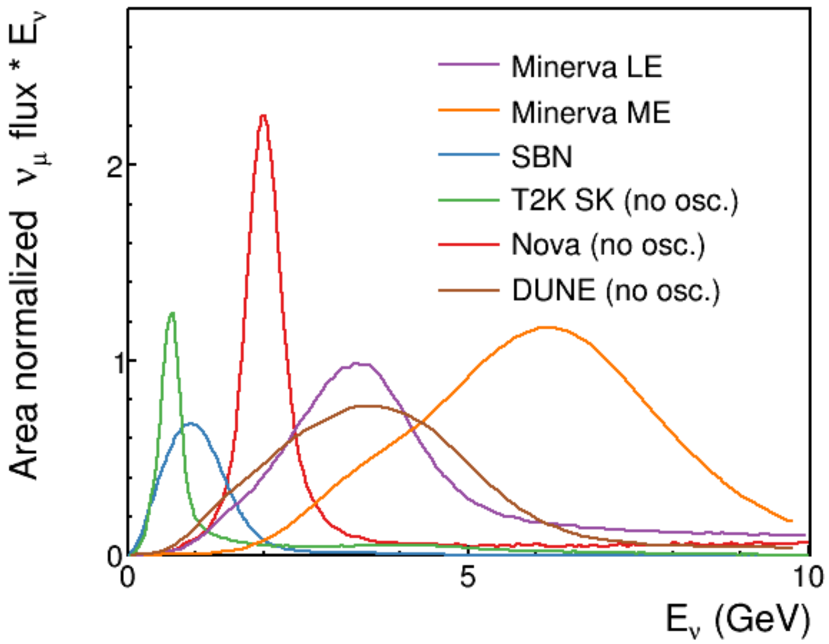
Used by T2K, SK and H2K

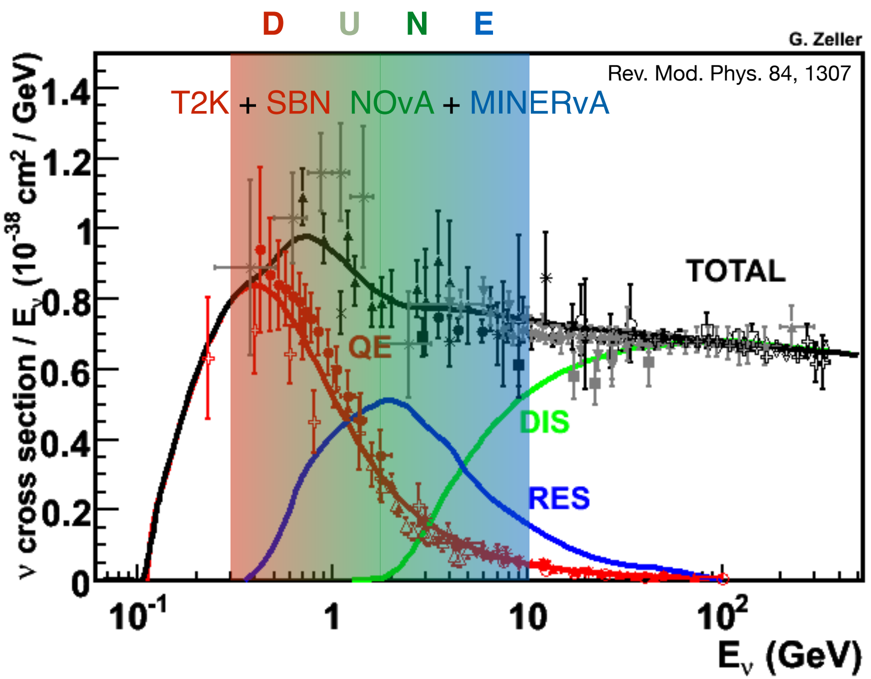
Very new, theory-driven event generator, Fermilab-led

Theory-driven event generator, most sophisticated FSI model.

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

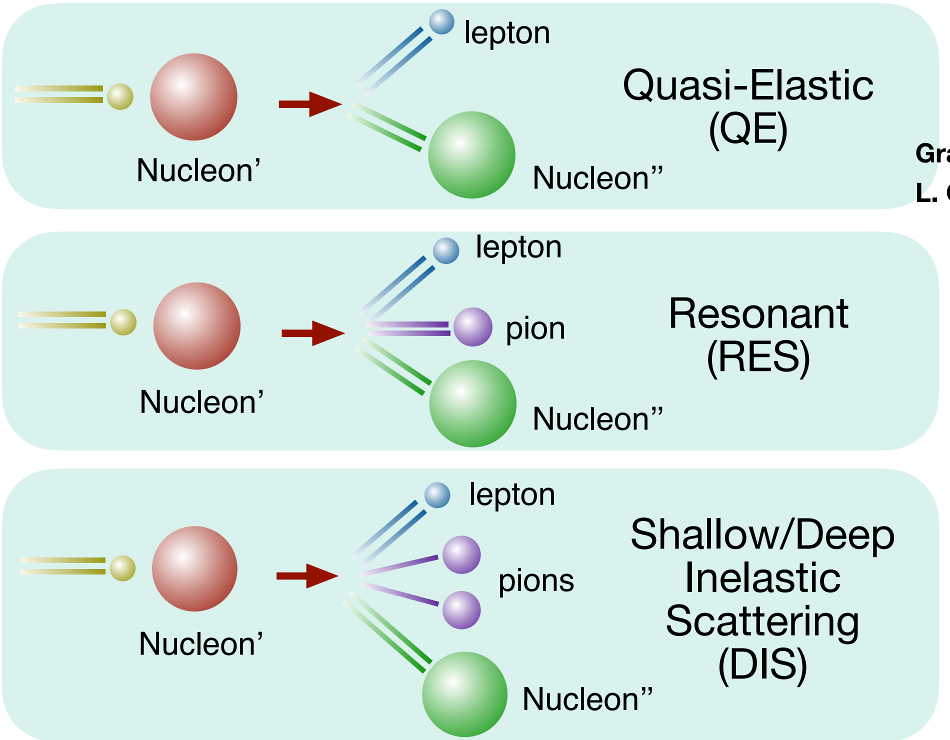
Event Generators





- 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.

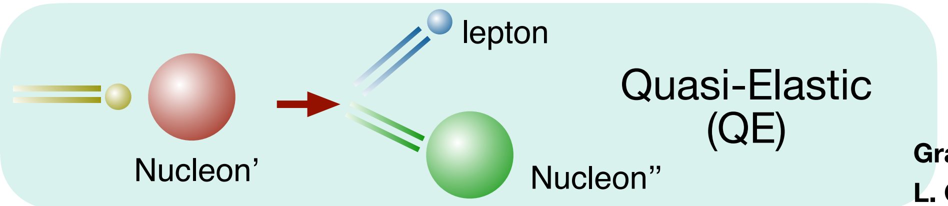
Neutrino Interactions

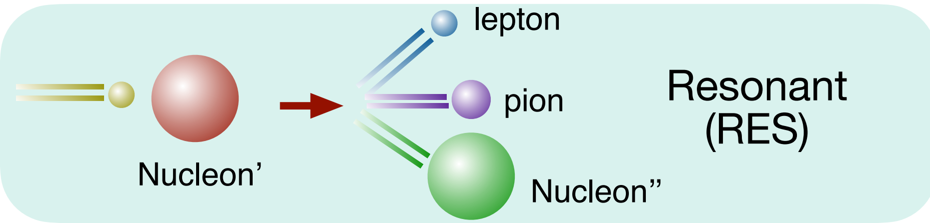


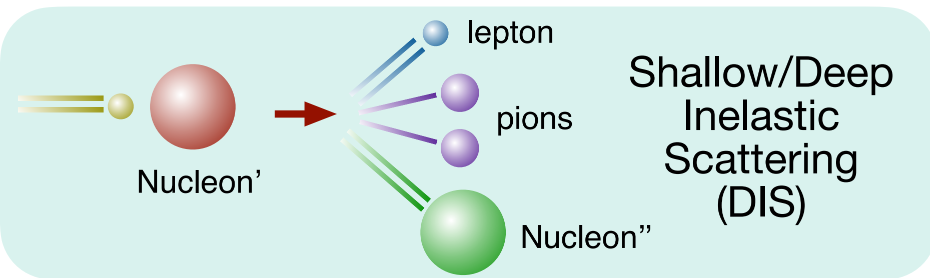
Graphics by L. Cremonesi

- 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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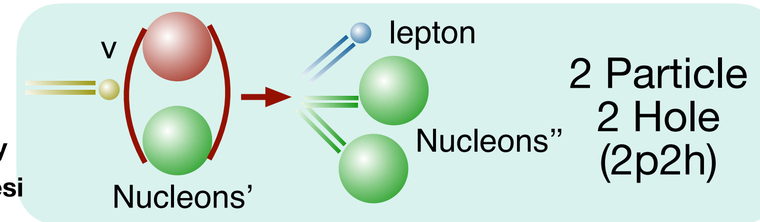
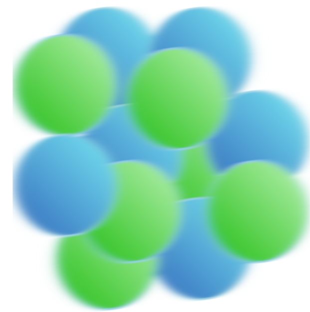
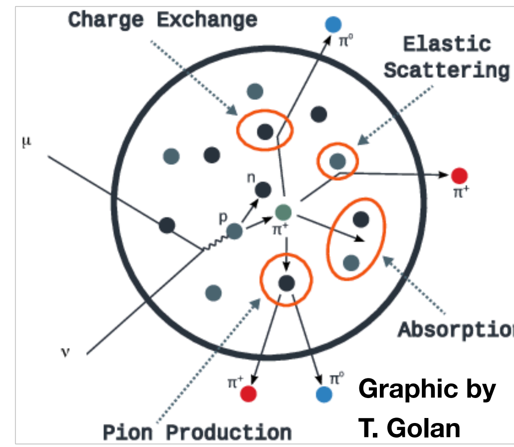




Initial State - nucleons bound but not at rest



Graphic by T. Golan

- 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!

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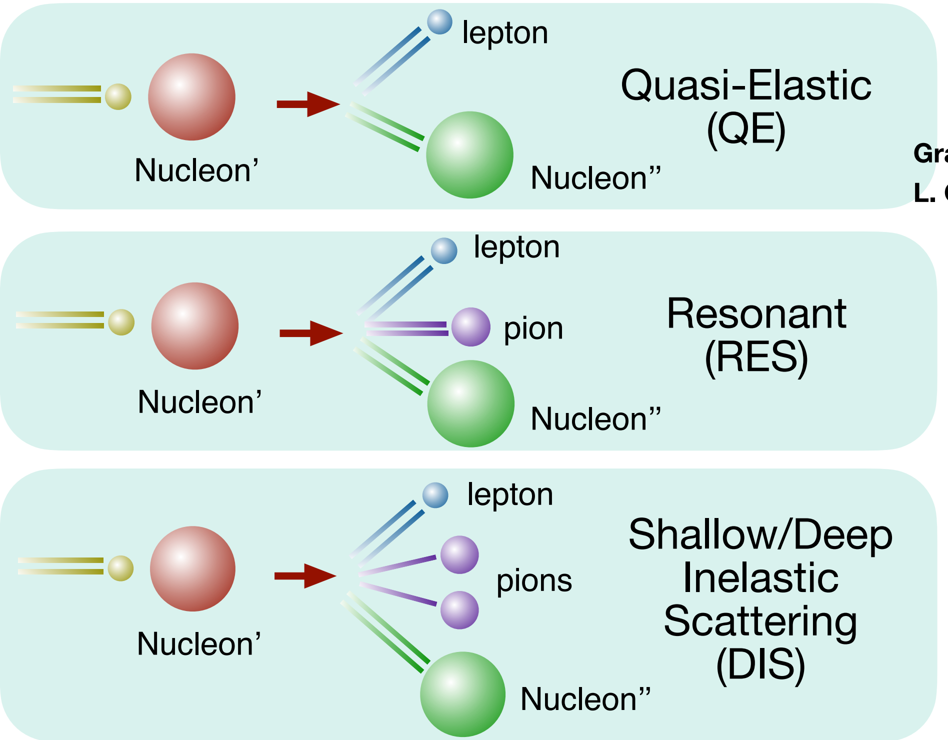
Neutrino Interactions



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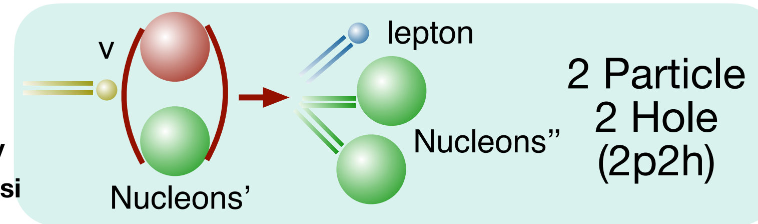

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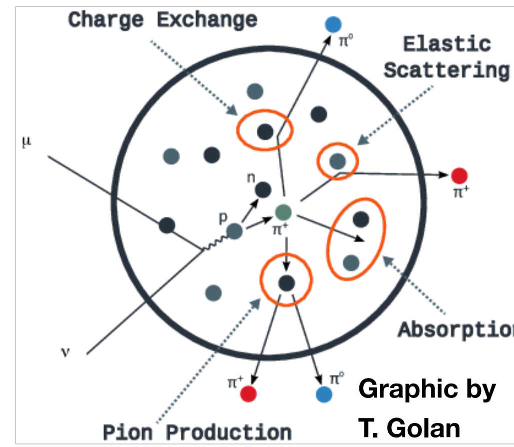

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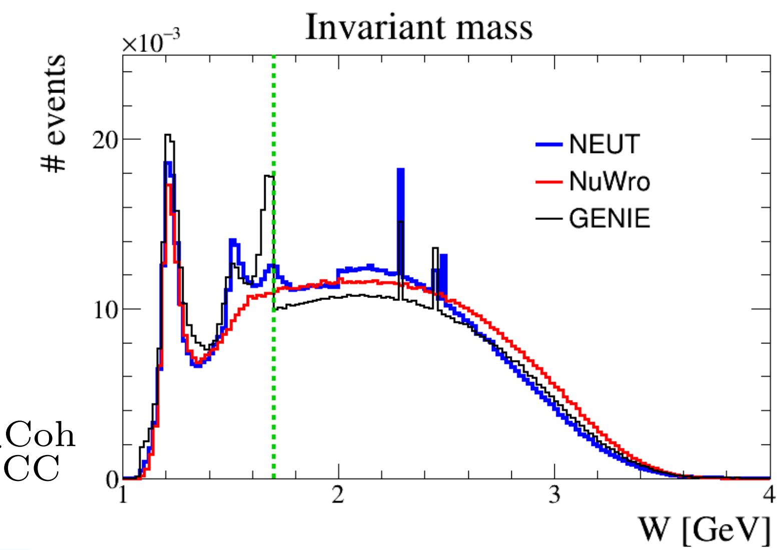
What else has to be modeled?

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

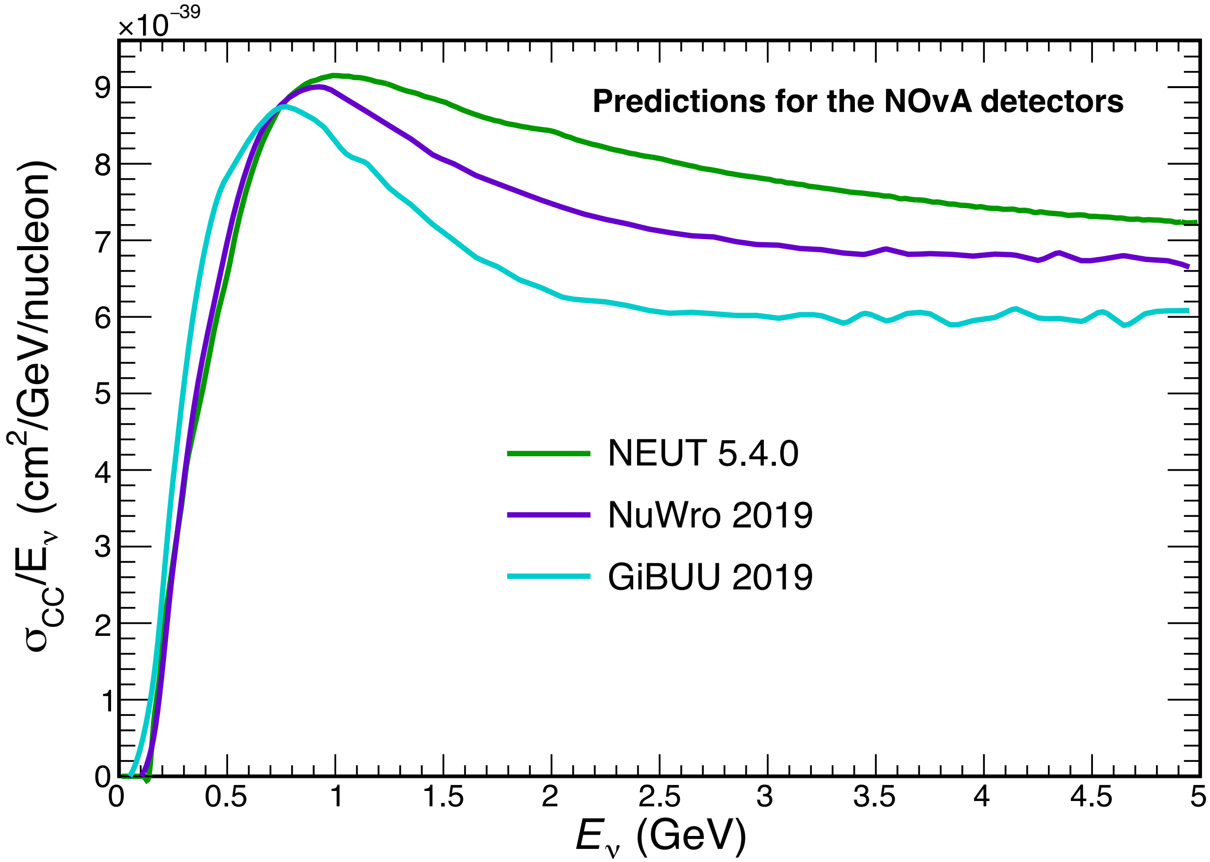
- Generators use very similar (often the same) models for exclusive differential cross sections. However, their implementation can be quite different.
- The models then have to be stitched together:

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



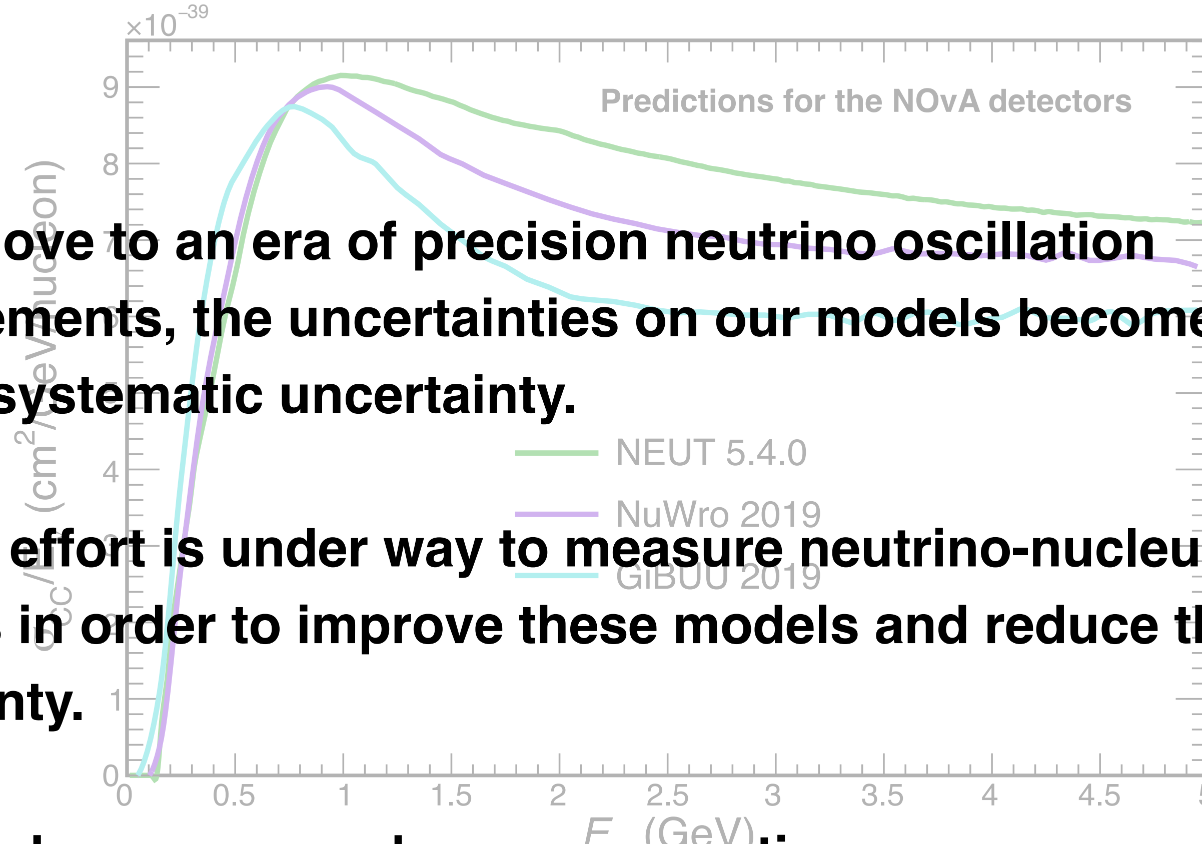
C. Bronner, NuSTEC 2018 Workshop Presentation

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.

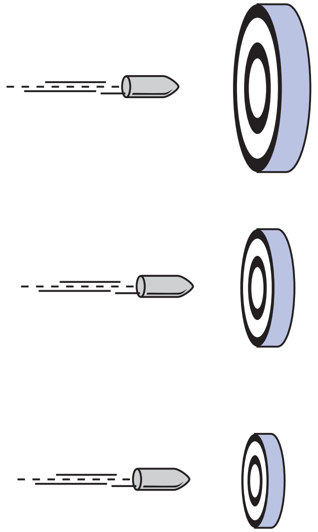
A global effort is under way to measure neutrino-nucleus cross sections in order to improve these models and reduce the uncertainty.

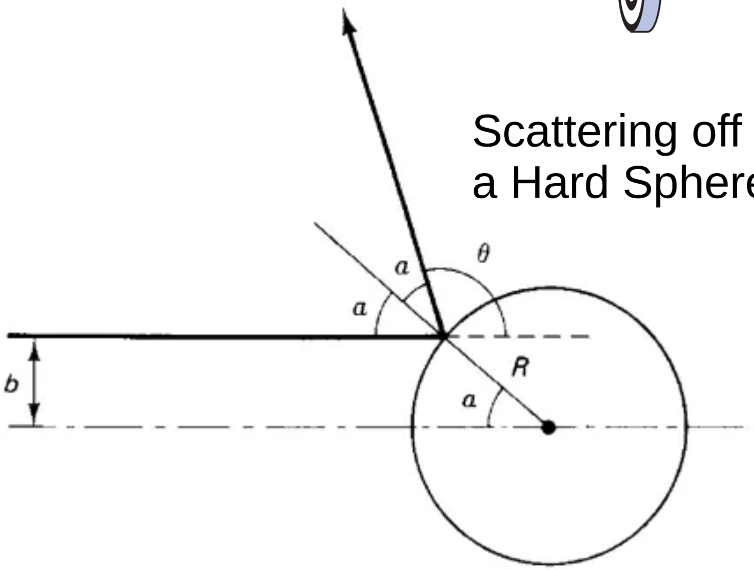
But how do we even make a cross section measurement?

- 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 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.
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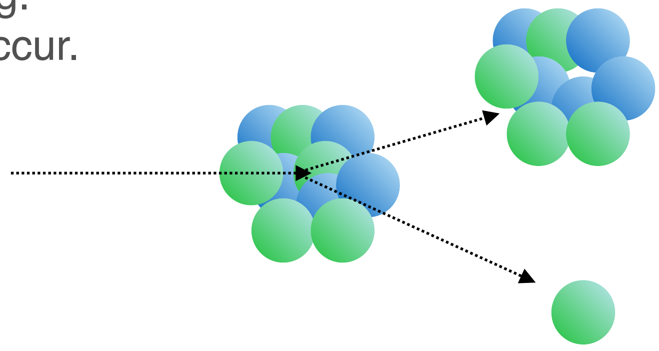
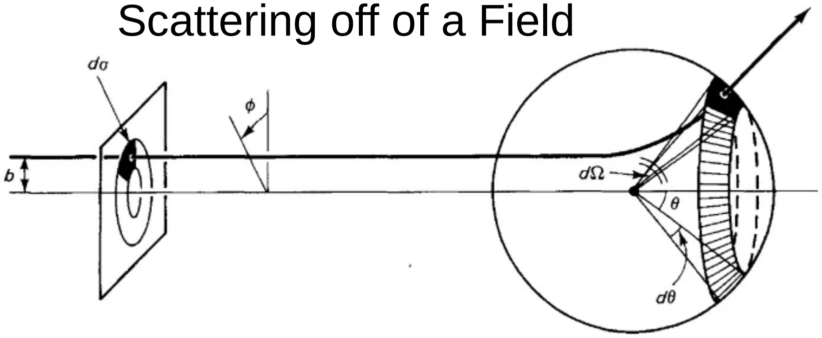
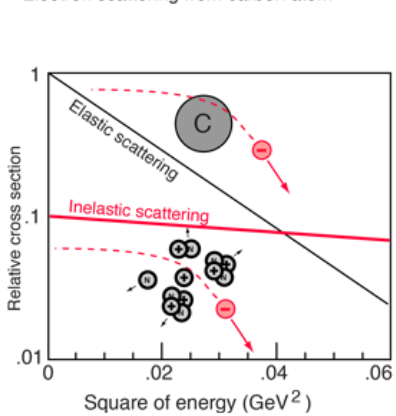
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target



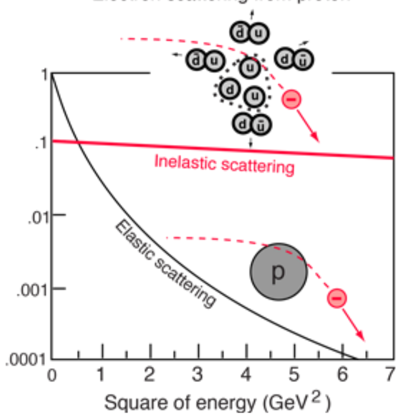
Scattering off of a Field



Electron scattering from carbon atom



Electron scattering from proton



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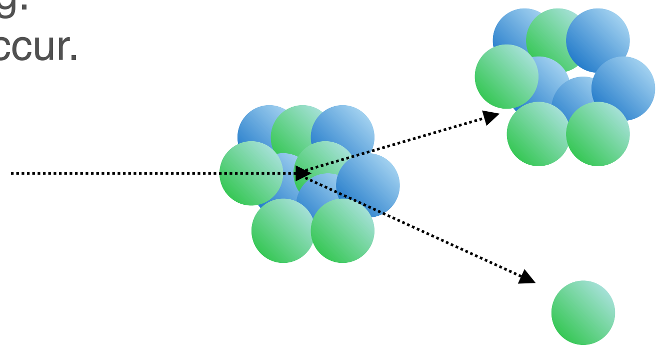
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target
- For a single target (eg, nucleon):

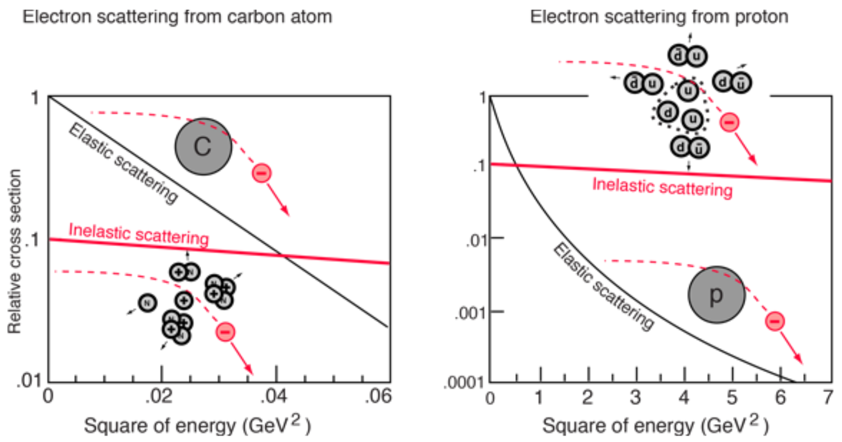


$$\sigma = \frac{N_{\text{int}}}{\Phi}$$

where

N_{int} = number of interactions

Φ = number of incoming particles/unit area



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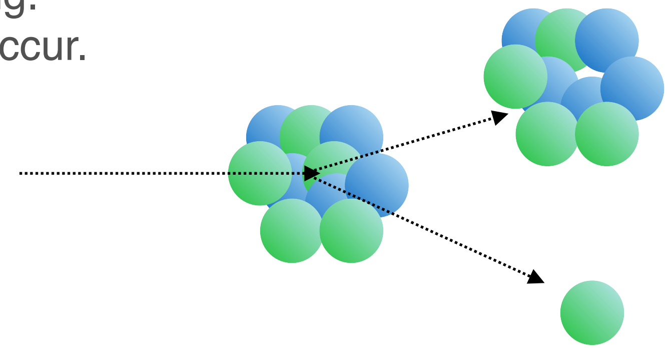
- Elastic scattering is a measure of the strength of a field
- Inelastic scattering is a measure of the internal structure of the target
- For a “real” target made of many nuclei:



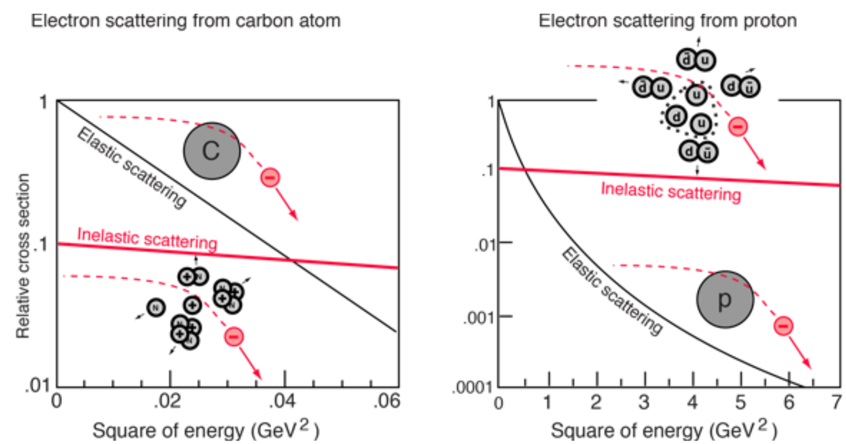
$$\sigma = \frac{N_{\mathrm{int}}}{\Phi N_{\mathrm{tar}}}$$

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:

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

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

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

  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:

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

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

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

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

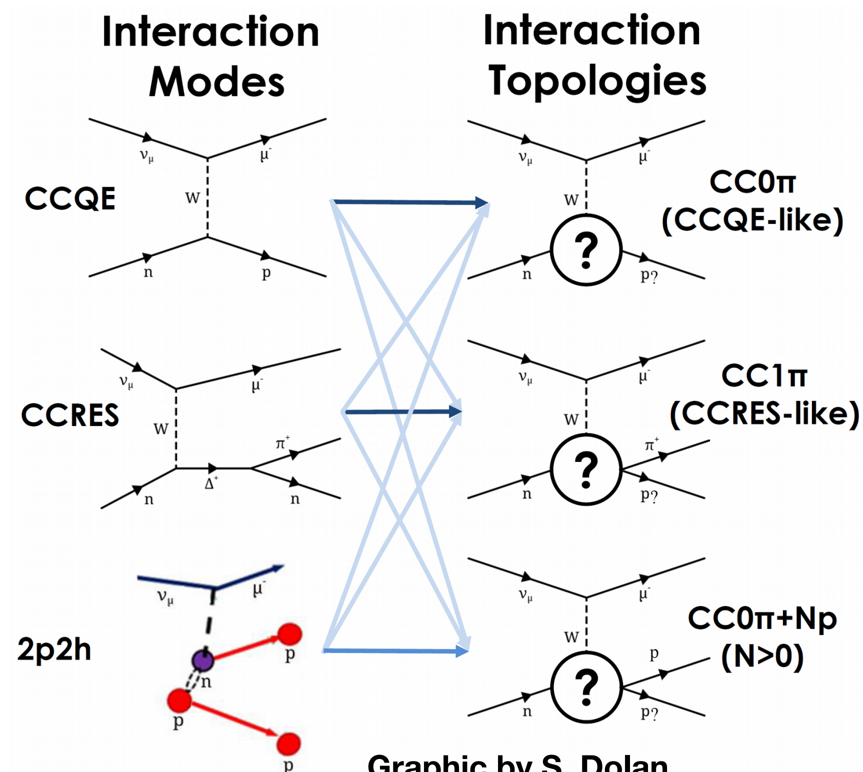
N_{tar} = number of nuclear targets

Φ = number of incoming particles/unit area

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".

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



Graphic by S. Dolan

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

- 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)

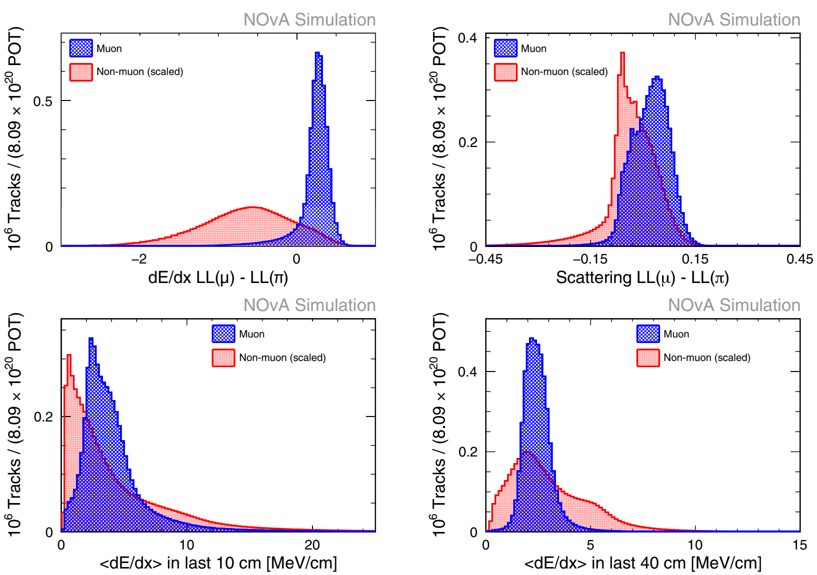
Developing and Optimizing The Event Selection

- 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:

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

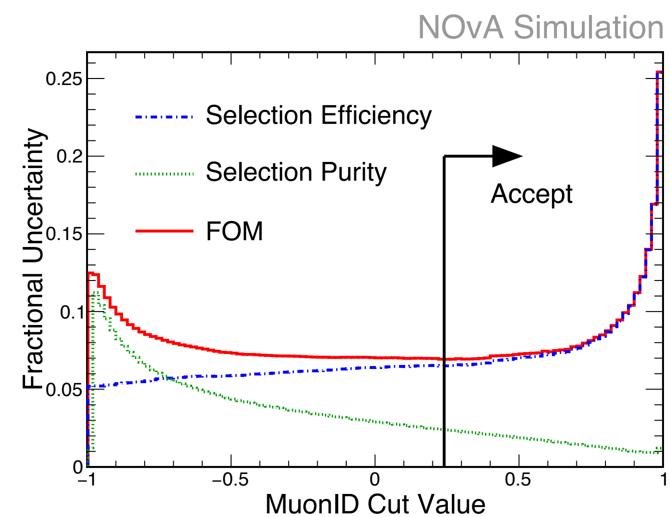
- Figure of Merit (FoM) is used to maximize sensitivity of the measurement:

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



Multivariate

"MuonID"



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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
  - **Q: What are some other sources of data in neutrino detectors that we can use for this?**

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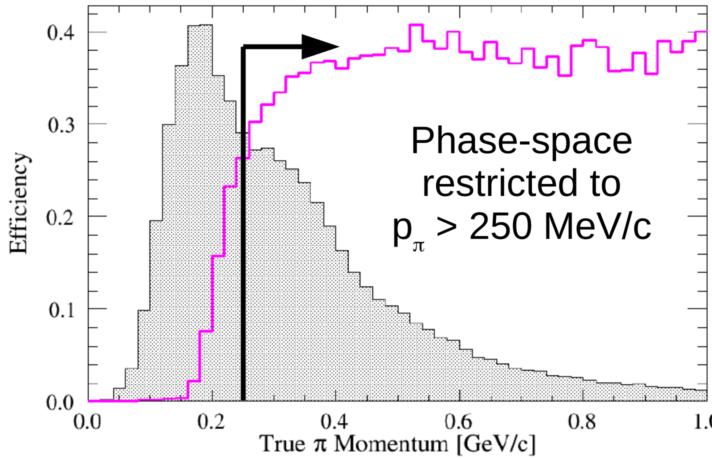

Don't measure π momentum well

Find flat region and redefine signal

p_π > 250 MeV/c

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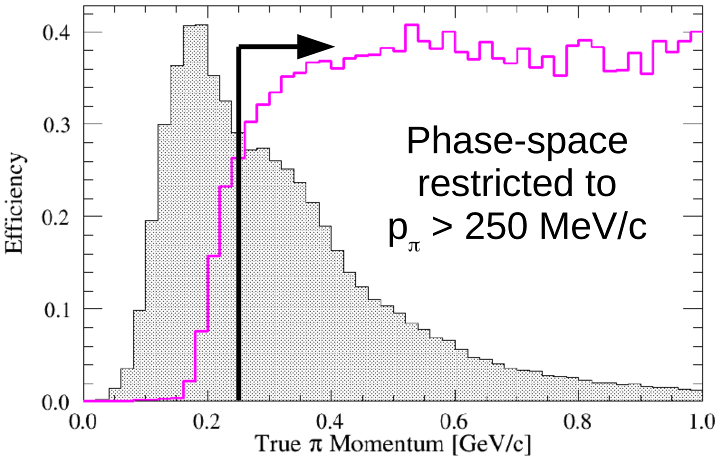

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Constraining Backgrounds

- 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+

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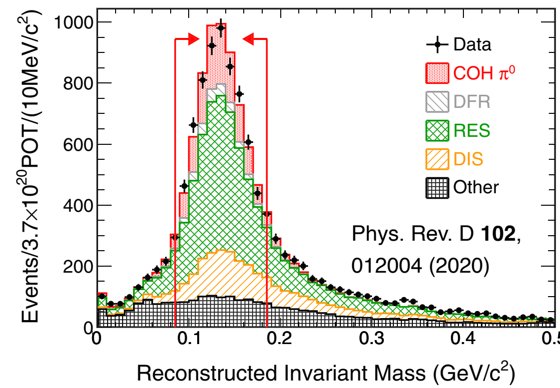

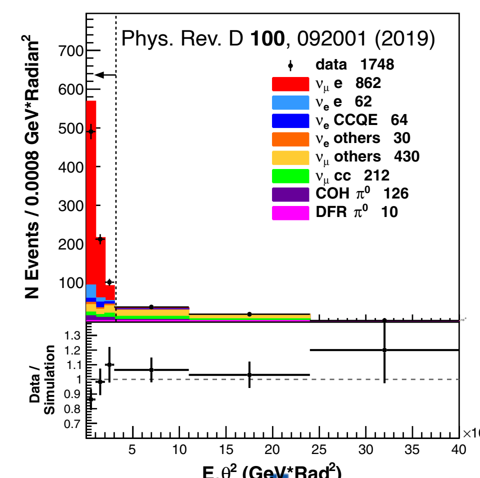

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    - NC π+ interactions when measuring CC π+
    - **Q: What are some other examples?**

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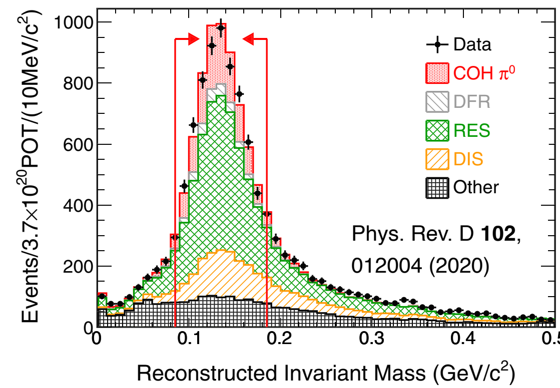

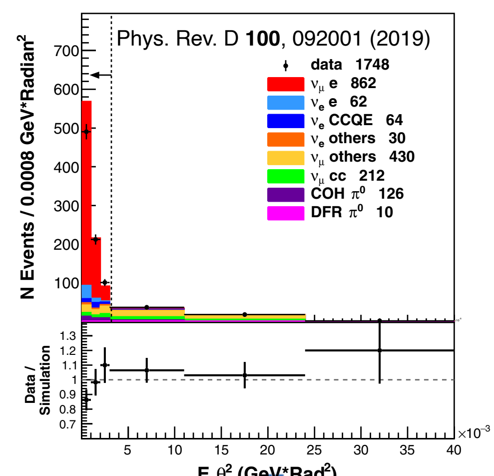

Analysis Variables and Binning

- 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.

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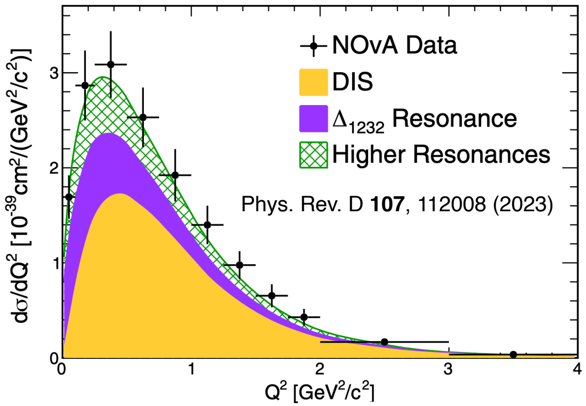

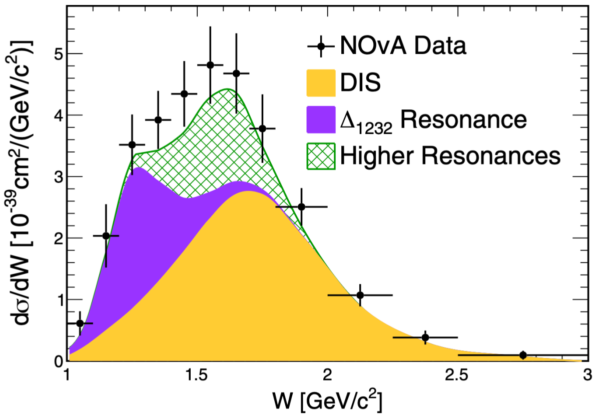

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- We also need to take care when deciding how to bin (discretize) our data. Bin-widths should:
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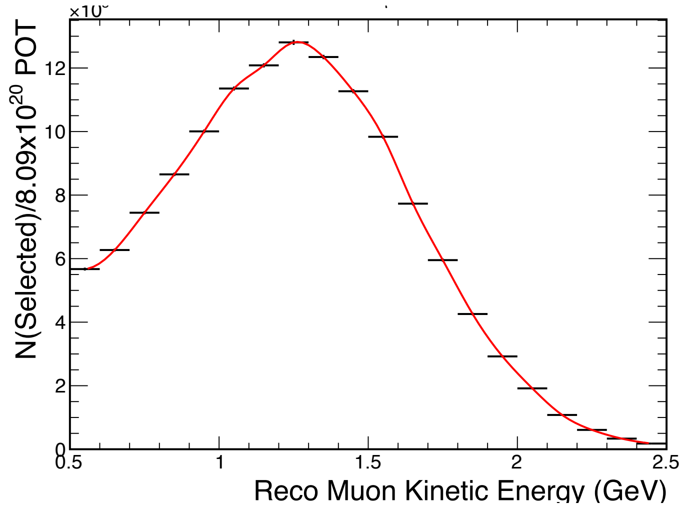
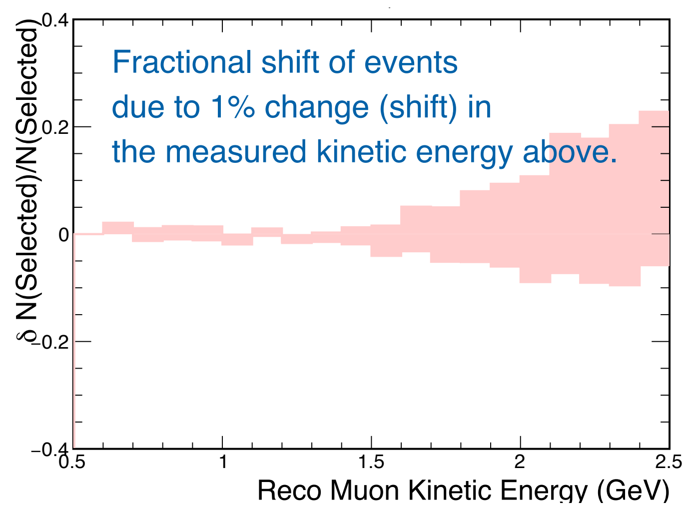
  - Consider bin-to-bin migration due to systematic uncertainties. Events in a distribution with a rapidly-changing slope will migrate asymmetrically across bins and can result in magnifying the effect!





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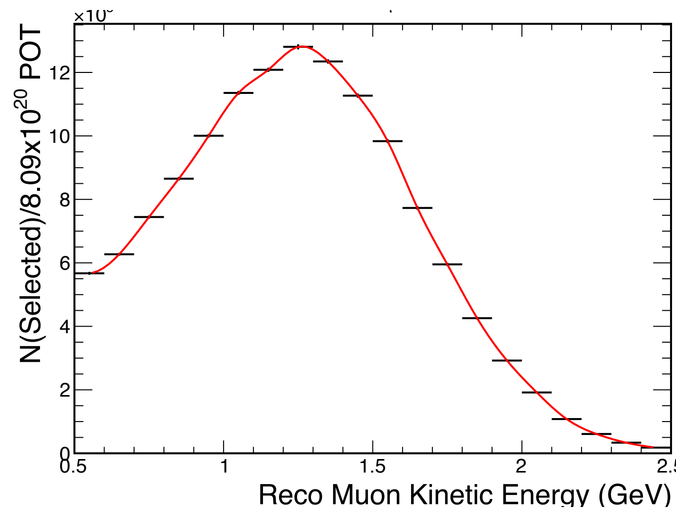
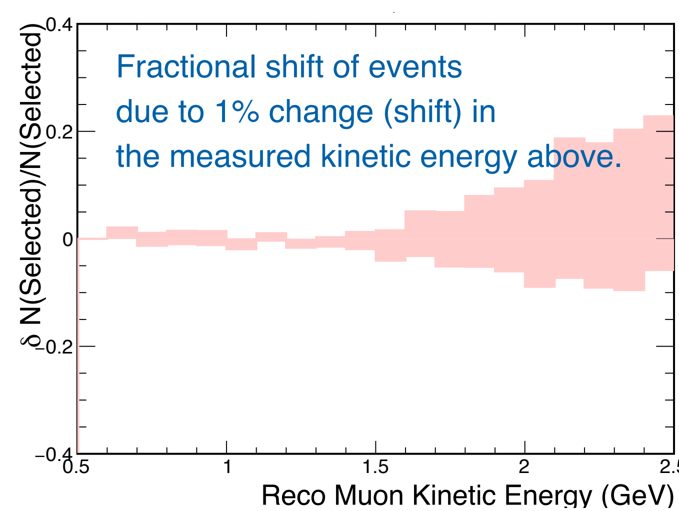
  - **Q: Will smaller or wider bins avoid this issue?**





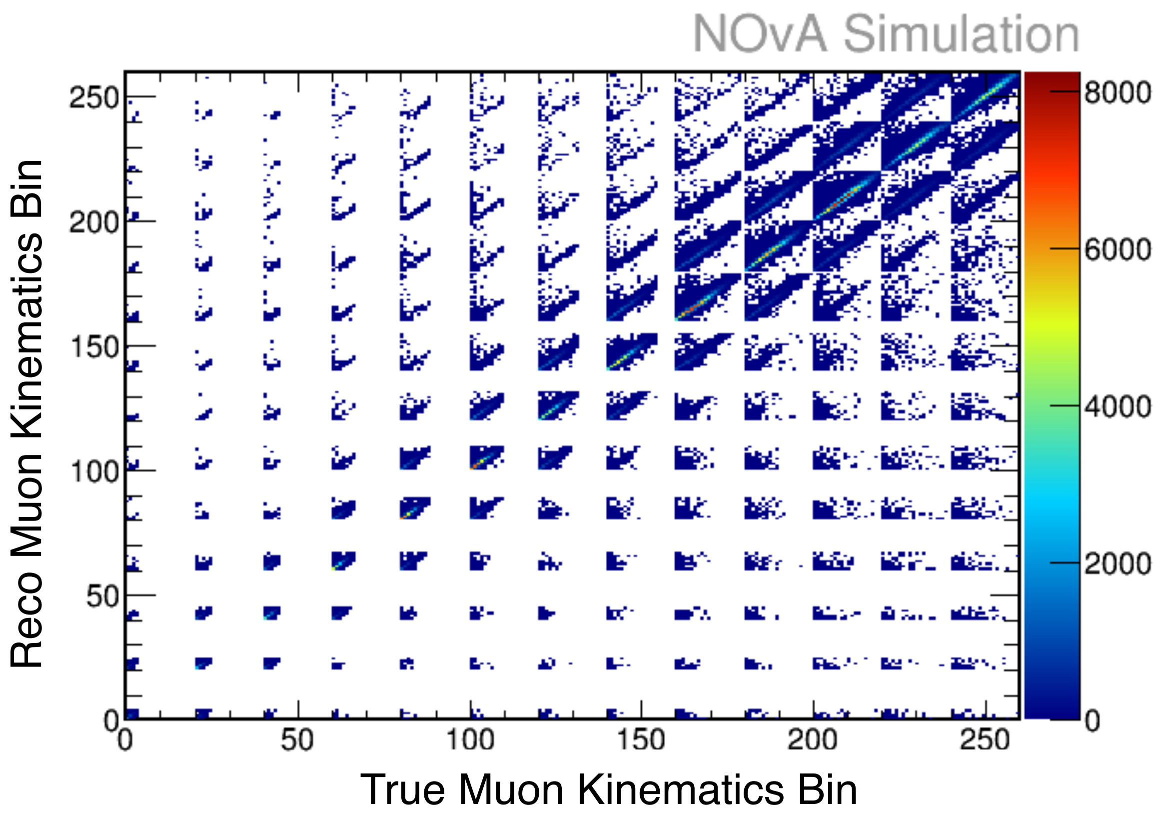
Fermilab

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.

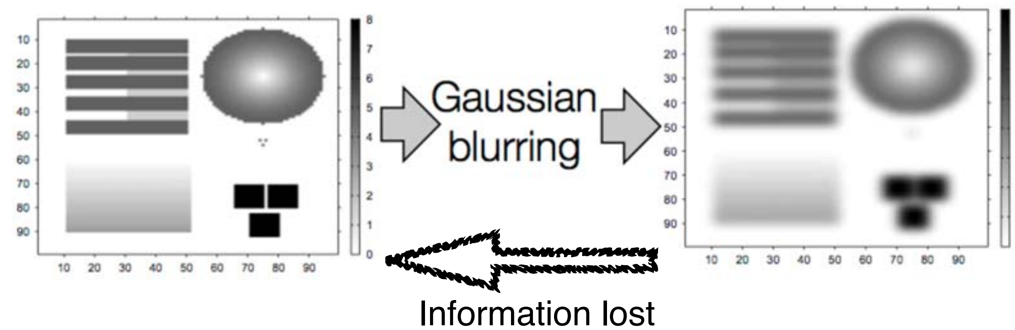
$$\left(\frac{d\sigma}{dx}\right)_i = \frac{\sum_j U^{-1}_{ij}(N^{\mathrm{sel}}_j P_j)}{\epsilon_i \Phi N_{\mathrm{tar}} \Delta x_i}$$

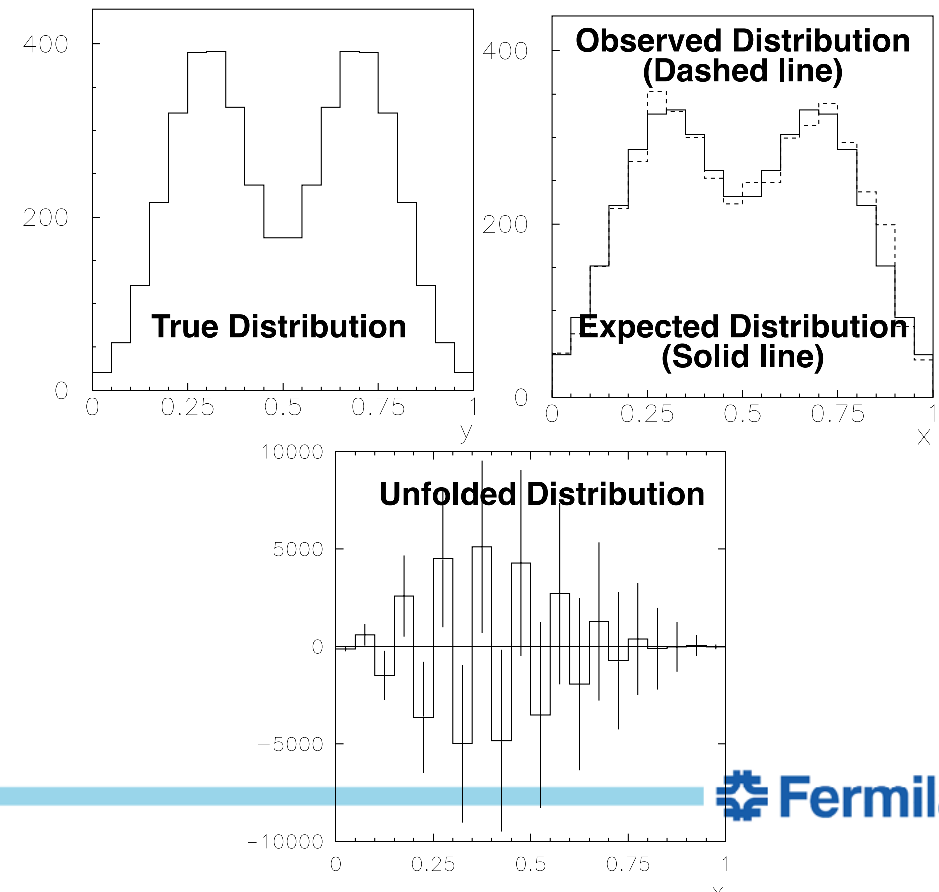
- We wish to report measurements that are useful to the community, therefore we need to "convert" our reconstructed observable to a "true" observable.
- We rely on our simulations to get our "smearing right", as it can be a very complicated process and often not "Gaussian" in nature.
- We can construct 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**!



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…

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

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.

Tomorrow, I will cover what we know, and what we know we don't know, about neutrino-nucleus scattering at the GeV scale.

Please send me questions via email or Slack!