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Neutrino-Nucleus Scattering "Grassroots" Discussion: The GENIE MC Event Generator

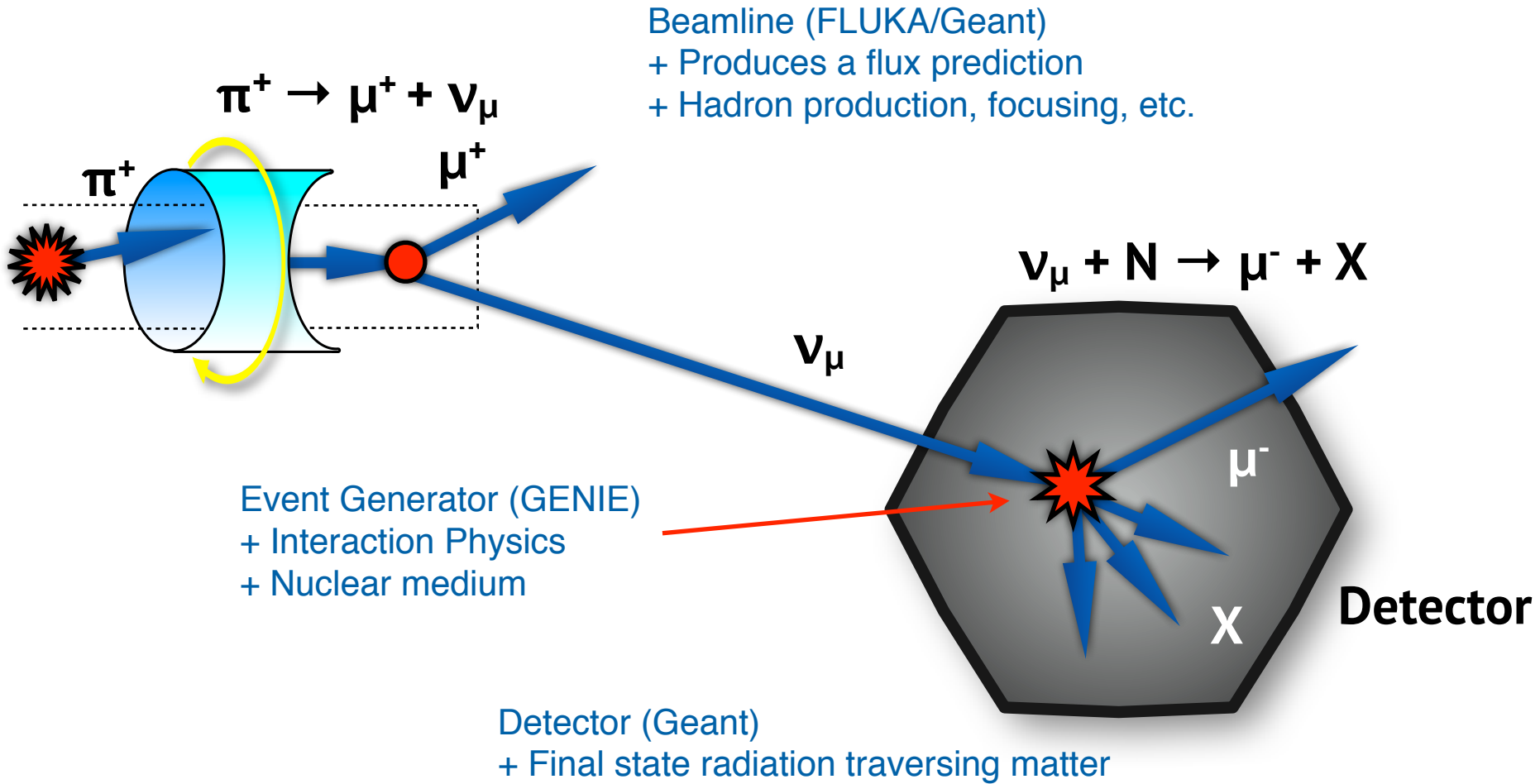
Gabriel Perdue

March 15, 2016

Overview

- How do we simulate neutrino experiments?
- What is GENIE?
- Data comparisons with MINERvA
 - Of course, many other fine data sets are available!
- What are our biggest needs?

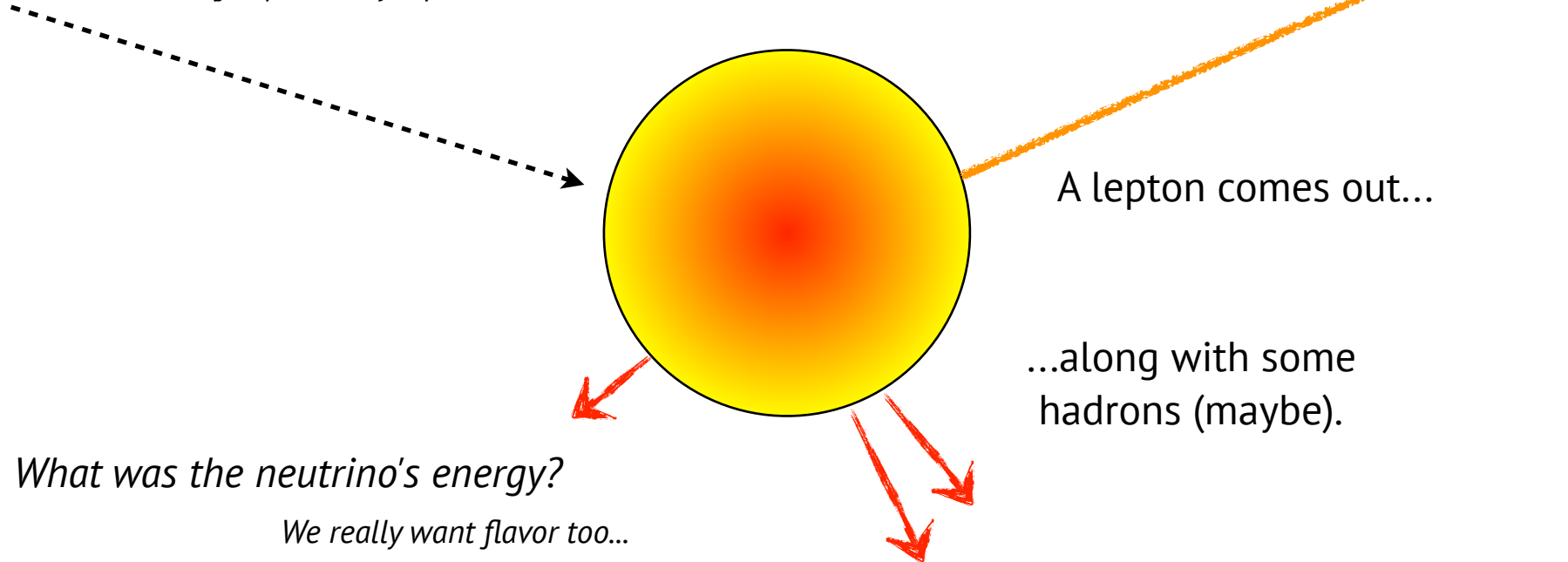
Neutrino Simulations: A Three-Part Software Stack



The Basic Problem

A neutrino comes in (unobserved).

This (flux) is a major problem which we will not consider much here....

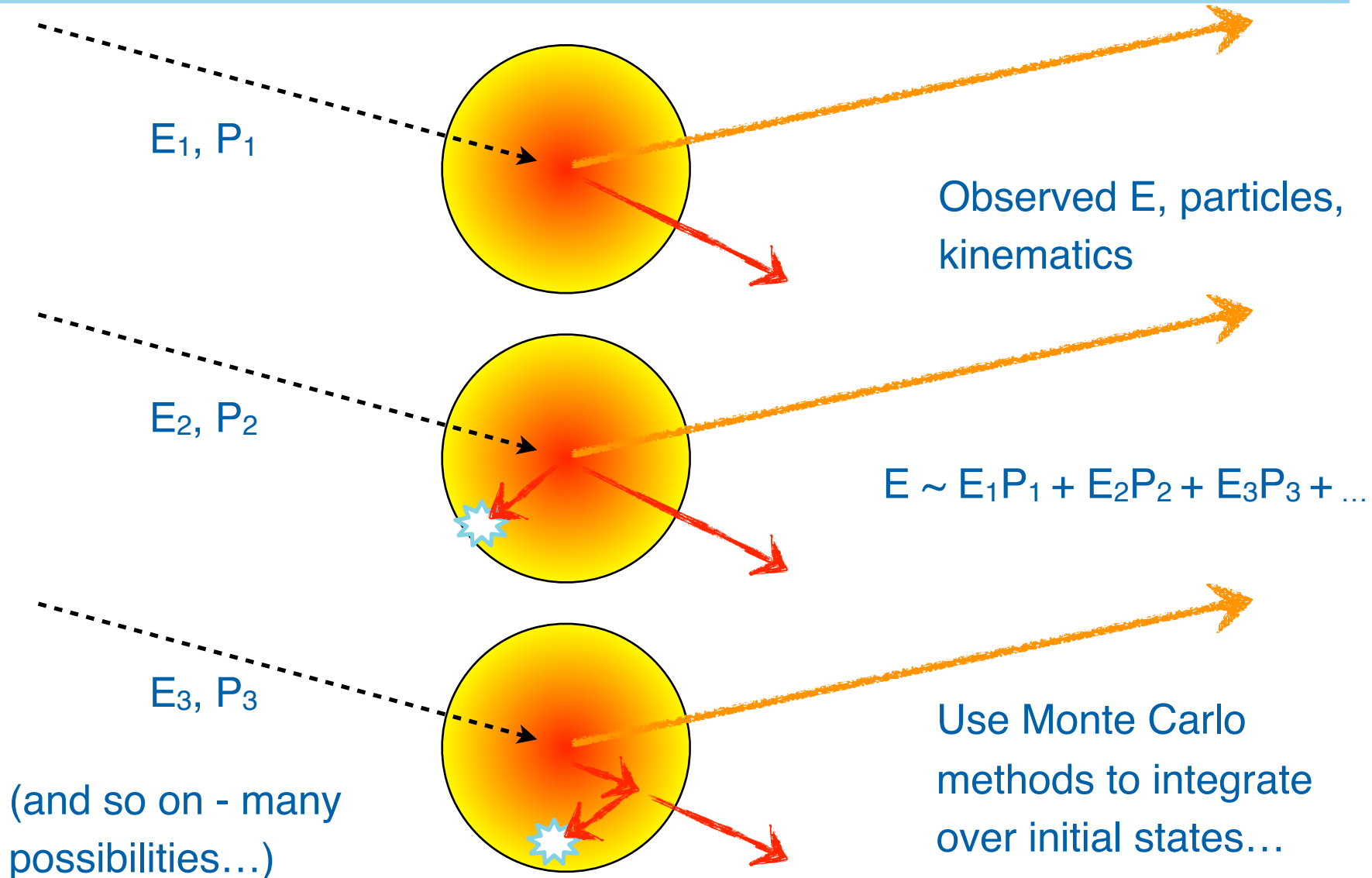


What was the neutrino's energy?

We really want flavor too...

We have an unknown incoming energy and “missing” energy in the final state (neutral current reactions, neutrons in the final state, nuclear rescattering, etc.). We must infer the energy from incomplete final state information.

The Basic Problem: The Best We Can Do



Neutrino MC Event Generators

- The generator must simulate all the types and momenta of every particle that appears in the final state.
- Some generators (MadGraph, Pythia, etc.) are computation aids for theorists, but GENIE is not.
- GENIE is maintained and built by experimentalists. *It is a computation aid for experimentalists.*
- Of course, many important contributions from theorists... but why is GENIE run by experimenters? How did the inmates get control of the asylum?

Neutrino MC Event Generators

- An ideal input theory would be internally consistent and provide fully-differential cross sections in the kinematics of every final state particle over all reaction mechanisms, energies, and targets.
- Modern theory typically provides final state kinematics for the lepton only, and only over limited ranges in energy or momentum transfer, and usually for exclusive or semi-inclusive channels only.
 - But the experiments must go on! So we must stitch together an ensemble that is consistent with all the data.

Ingredients: How to “Bake” a Generator...

- Good theoretical understanding of scattering from free nucleons.
- Large selection of well-grounded models based on effective degrees of freedom.
- Charged hadron scattering data (useful for understanding final state interactions).
- Charged lepton scattering data (provides very tight constraints on vector form factors and some guidance on nuclear effects).
- Neutrino scattering data
 - No "silver bullets" though: inferred quantities (neutrino energy, Q^2) must be computed using a model and energy-dependent observables are difficult to interpret (no comparison between experiments without a generator is possible).

GENIE



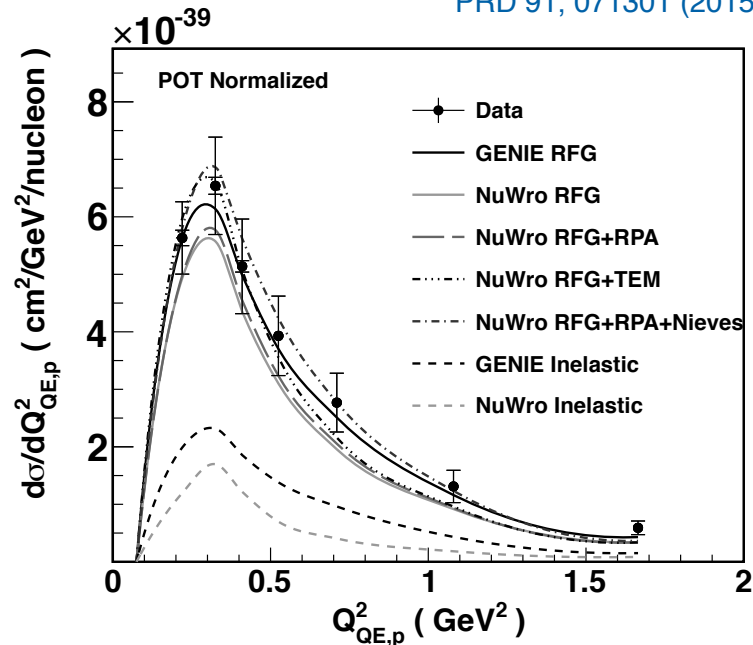
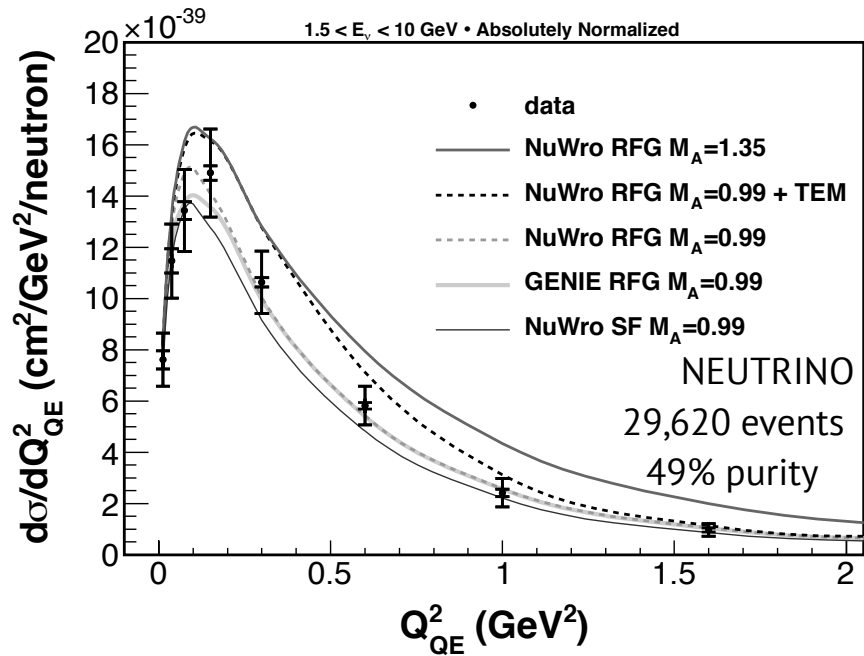
- <https://genie.hepforge.org>
- The software:
 - Created to be a “universal event generator”.
 - Additionally run in electron and hadron scattering modes.
 - Many tools for studying systematics, comparison to data, etc.
 - Event handling is decoupled from physics routines, easy to create arbitrary algorithm stacks.
- The collaboration:
 - International collaboration with about a half-dozen collaborators (essentially all experimentalists) and many more contributors.
 - Collaborators do service work (validation, distribution, user support, developer support, etc.)
 - Contributors (many theorists) offer individual models or pieces of validation software, sometimes consulting, etc.

GENIE at FNAL

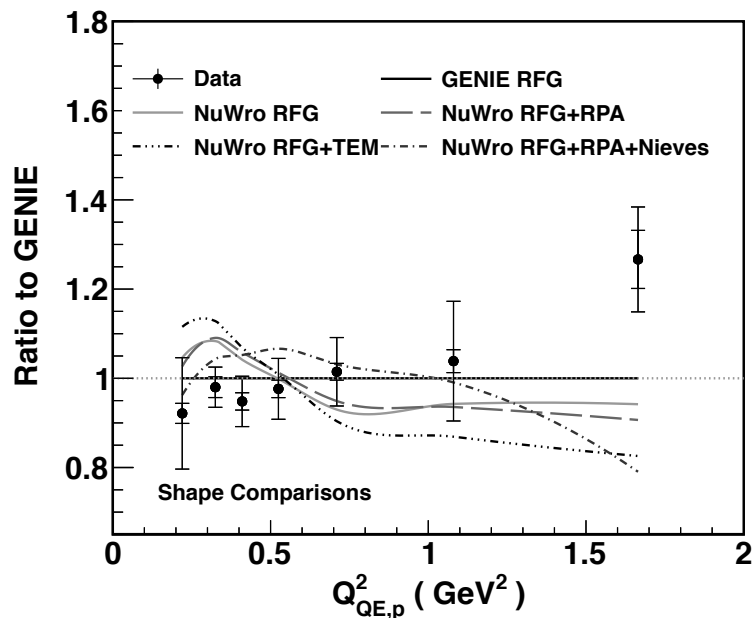
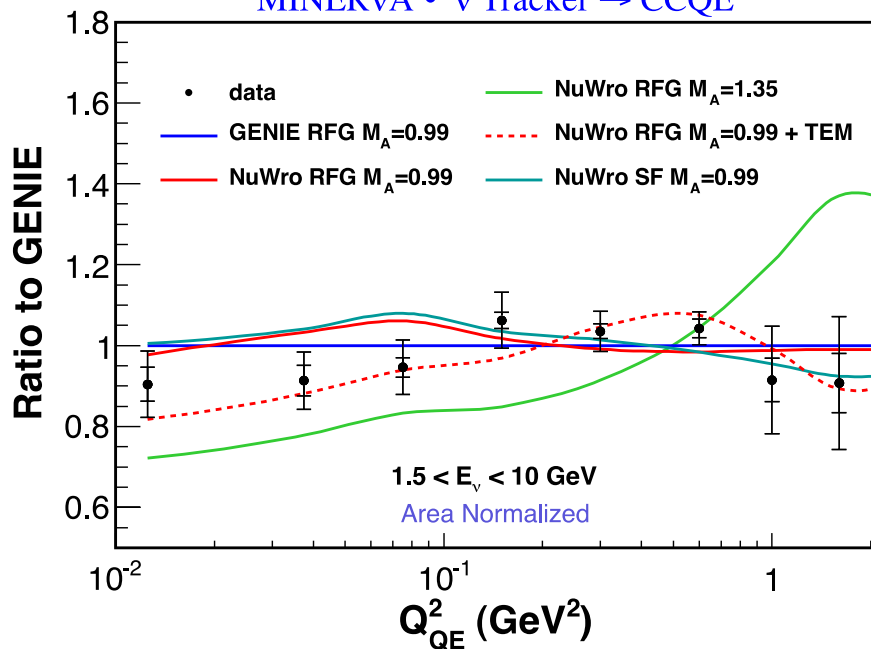
- GENIE is the primary event generator for:
 - ArgoNeuT
 - SBND
 - DUNE
 - MicroBooNE
 - MINERvA
 - NOvA
- GENIE is being considered for special studies by MINOS and MiniBooNE (they use previous generation software for their main generators).

Challenges for GENIE

- Two broad classes:
 - We need better theory.
 - We strongly support the efforts of our theory colleagues to improve our understanding of the nuclear model, transport, etc.
 - We need theory that operates over many regimes of kinematic phase space, and we need full predictions of the final state (hadronic side too!)
 - We need time / resources for model development, integration, and tuning.
 - All GENIE authors are experimentalists first - our day job is not to work on the generator and so it only improves when we have time. (Worse, really only when more than one of us has time at the same time.)
 - Difficult to dedicate large fractions of postdocs to GENIE - it isn't usually in their best interests, career wise, but small fractions (10-25%) leave people without domain expertise to develop code that passes internal review. We really need people who can comfortably dedicate 50% of their time over the course of a couple of years.
 - How to handle tensions between different datasets?



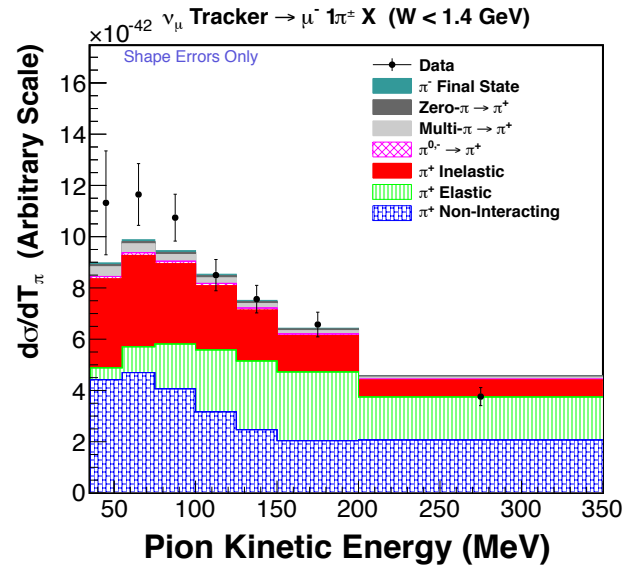
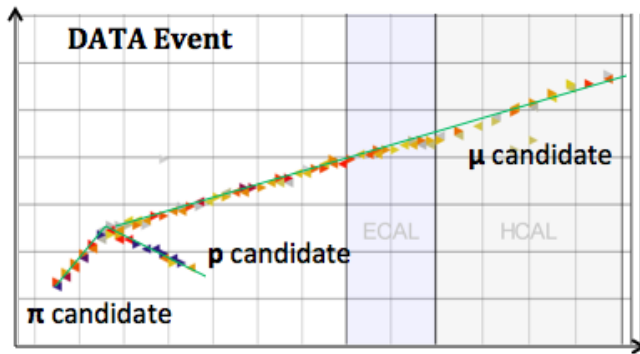
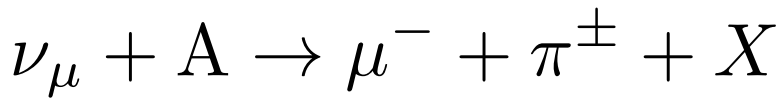
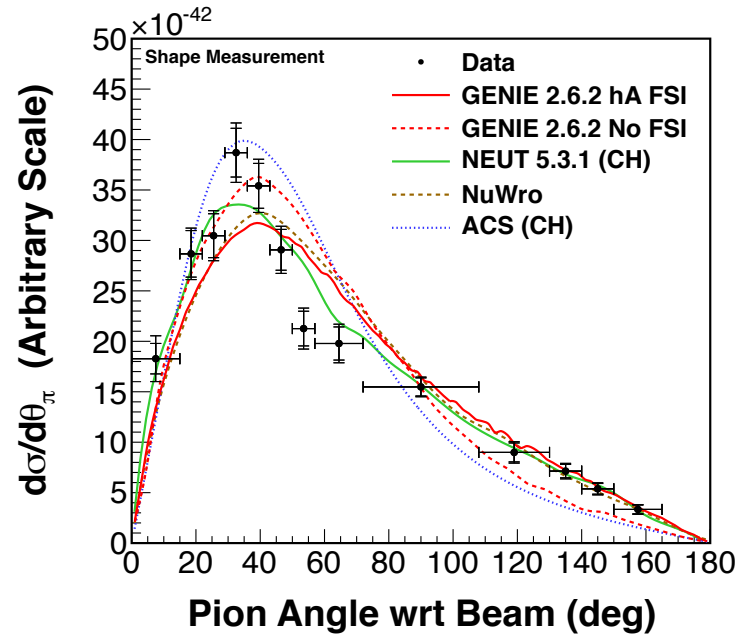
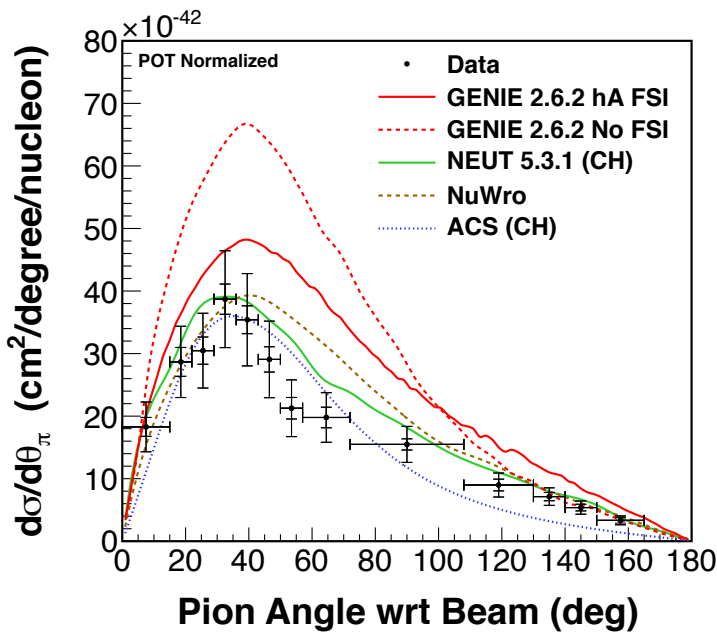
MINERvA • ν Tracker → CCQE



"Same" Channel, Same Detector, Same Flux - Prefer Different Models!

Muon Arm: NuWro Model	RFG	RFG +TEM	RFG	SF	Proton Arm: NuWro Model	RFG	RFG +RPA	RFG +RAP+Nieves	RFG +TEM
M_A (GeV/ c^2)	0.99	0.99	1.35	0.99	Rate χ^2 /d.o.f.	1.7	1.9	3.7	3.9
Rate χ^2 /d.o.f.	3.5	2.4	3.7	2.8	Shape χ^2 /d.o.f.	3.3	3.6	4.8	5.8
Shape χ^2 /d.o.f.	4.1	1.7	2.1	3.8					

- Not *quite* apples to apples, but “close”...
- Note that MINERvA used NuWro (not GENIE) for these comparisons (GENIE does not yet have some of these models implemented).
- Because the proton has different sensitivity to FSI, it isn't shocking that we get different results between the two analyses with respect to preferred nuclear models.
 - It is a bit surprising to see "worst to first."
- One consistent FSI model is applied across the results - an obvious next consideration is to vary both the nuclear and FSI models.



Even the "state of the art" leaves many questions.

Proxy for low-E protons at the vtx.

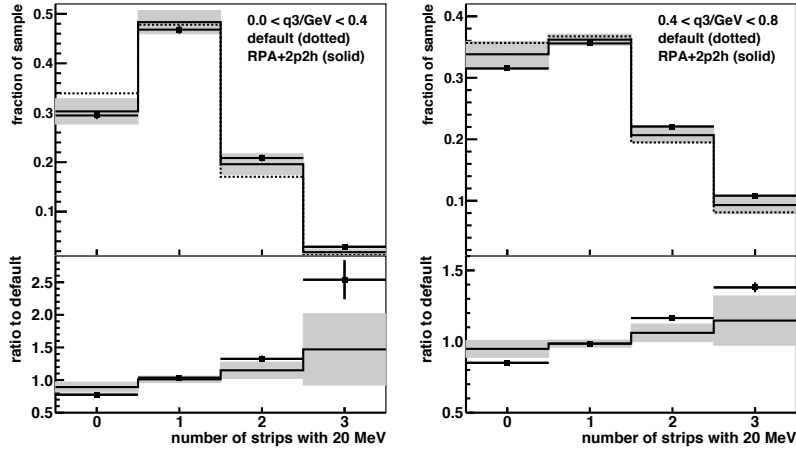


FIG. 3: Fraction of events with zero, one, two, and three or more strips with at least 20 MeV of activity near the interaction point. The samples are from the region between QE and Δ for two ranges of reconstructed three momentum transfer. The model with RPA and 2p2h is shown with the solid line and systematic uncertainty band; the data are shown with statistical uncertainties. The ratios are taken with respect to the default model, shown as a dotted line. RPA suppression negligibly modifies the default model for this quantity and is not shown.

RPA helps, but 2p2h models are still missing components.

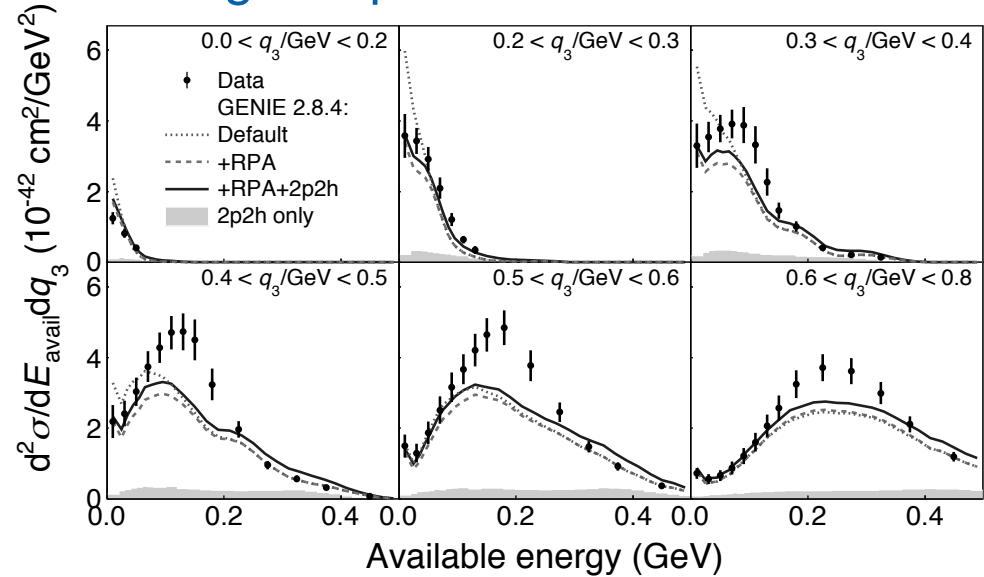


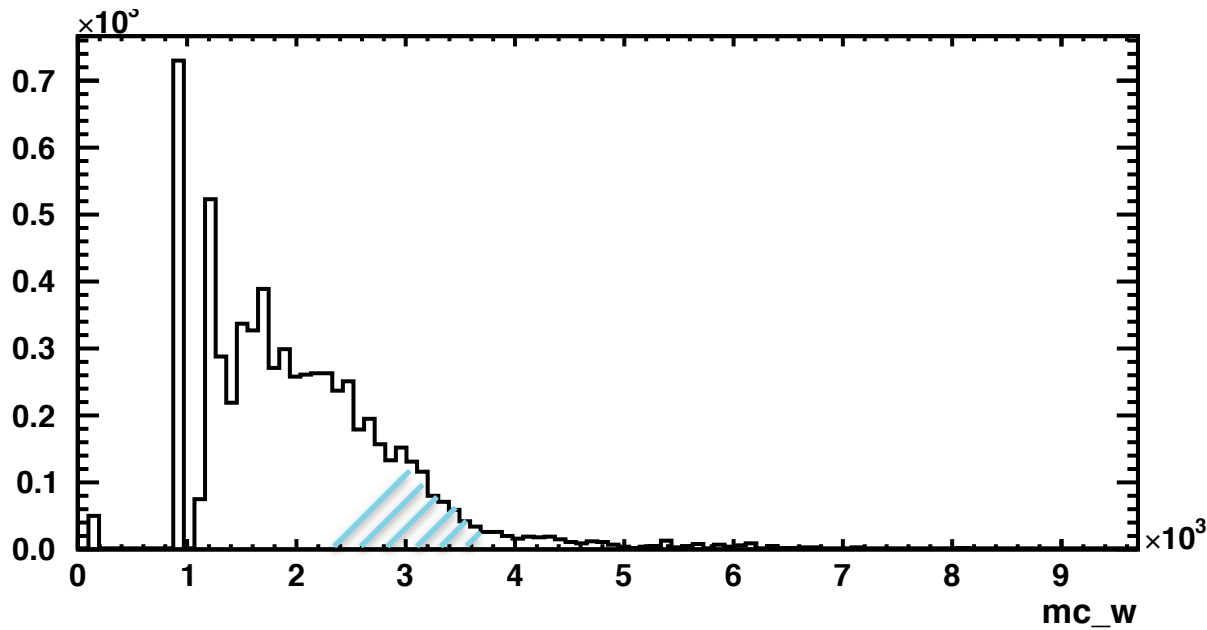
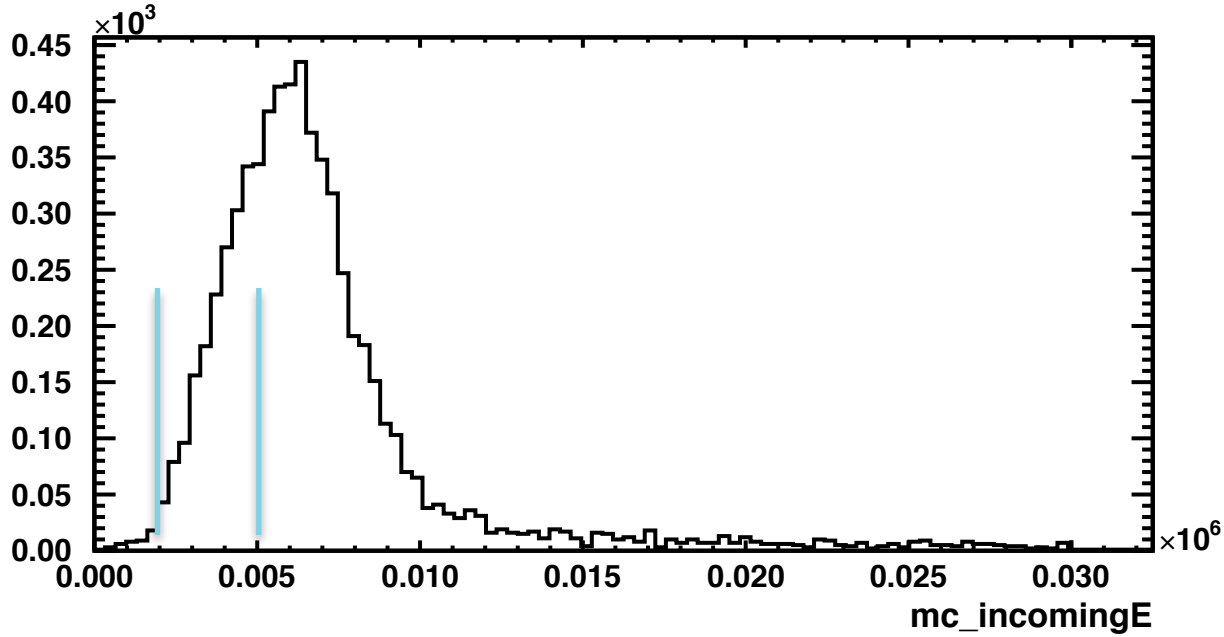
FIG. 2: The double-differential cross section $d^2\sigma/dE_{\text{avail}}dq_3$ in six regions of q_3 is compared to the GENIE 2.8.4 model with reduced pion production (small dot line), the same with RPA suppression (long-dashed), and then combined with a QE-like 2p2h component (solid). The 2p2h component is shown separately as a shaded region. GENIE predicts events with zero available energy (all neutrons in the final state), which are summed into the first bin in each q_3 range.

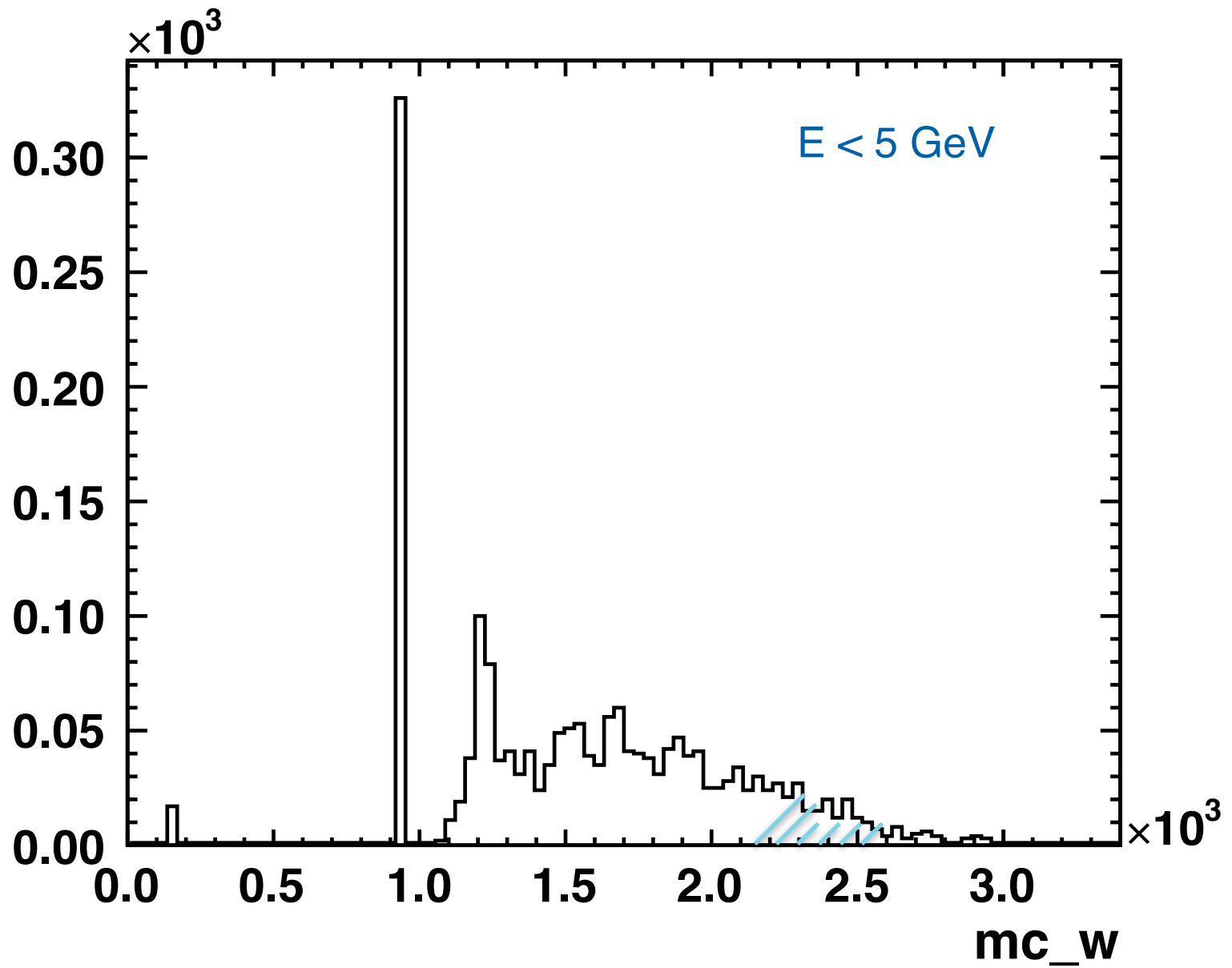
Plan of action

- This Spring we are undertaking a big "sprint" to incorporate new models (most of which were partially developed by members of the community).
- This Summer we have a large-scale tuning exercise planned.
 - Kicked off by a Workshop at Liverpool right after Neutrino, July 11-15.
- Also plan this Summer to introduce features to make it easier for experiments to change the default physics tune or create their own.
 - Theorists rightly cringe at this, but in GENIE we are trying to tune across a very wide collection of energies and targets. Any given experiment may not want to be sensitive to our choices for resolving tensions.

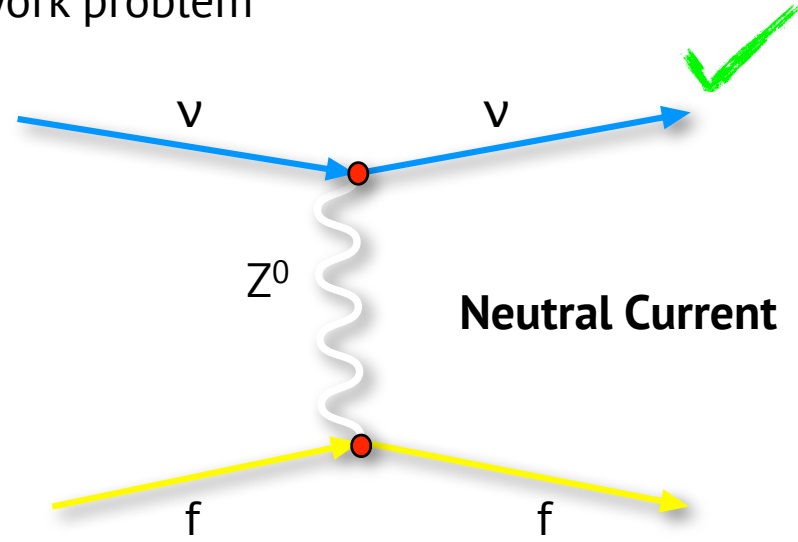
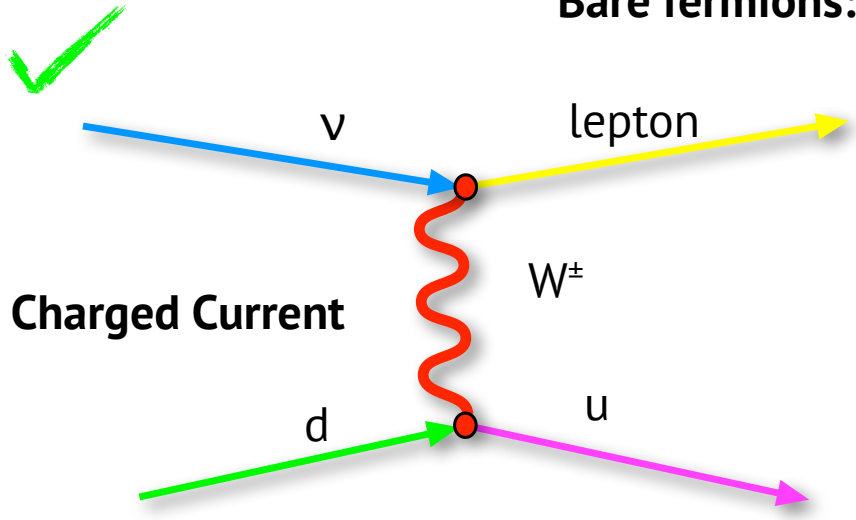


Back-up

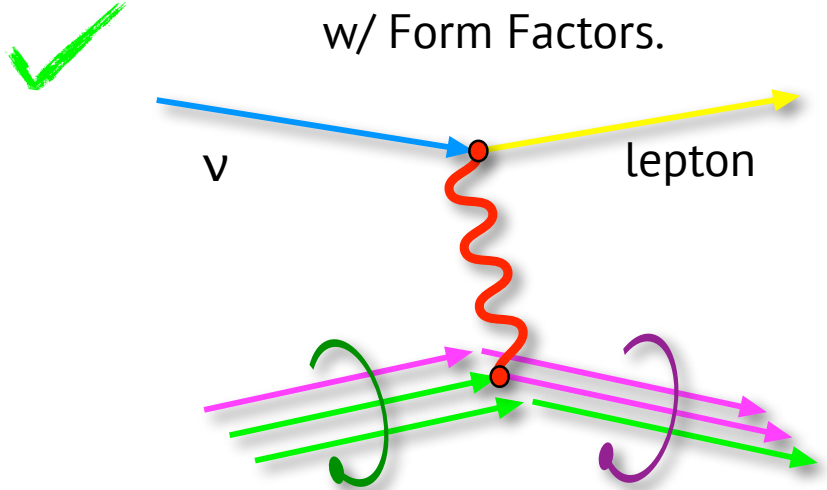




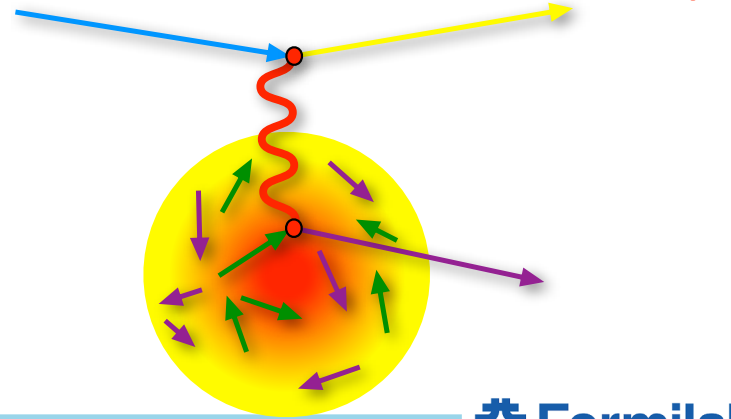
Bare fermions: Homework problem



Free Nucleon:
Parameterize
w/ Form Factors.

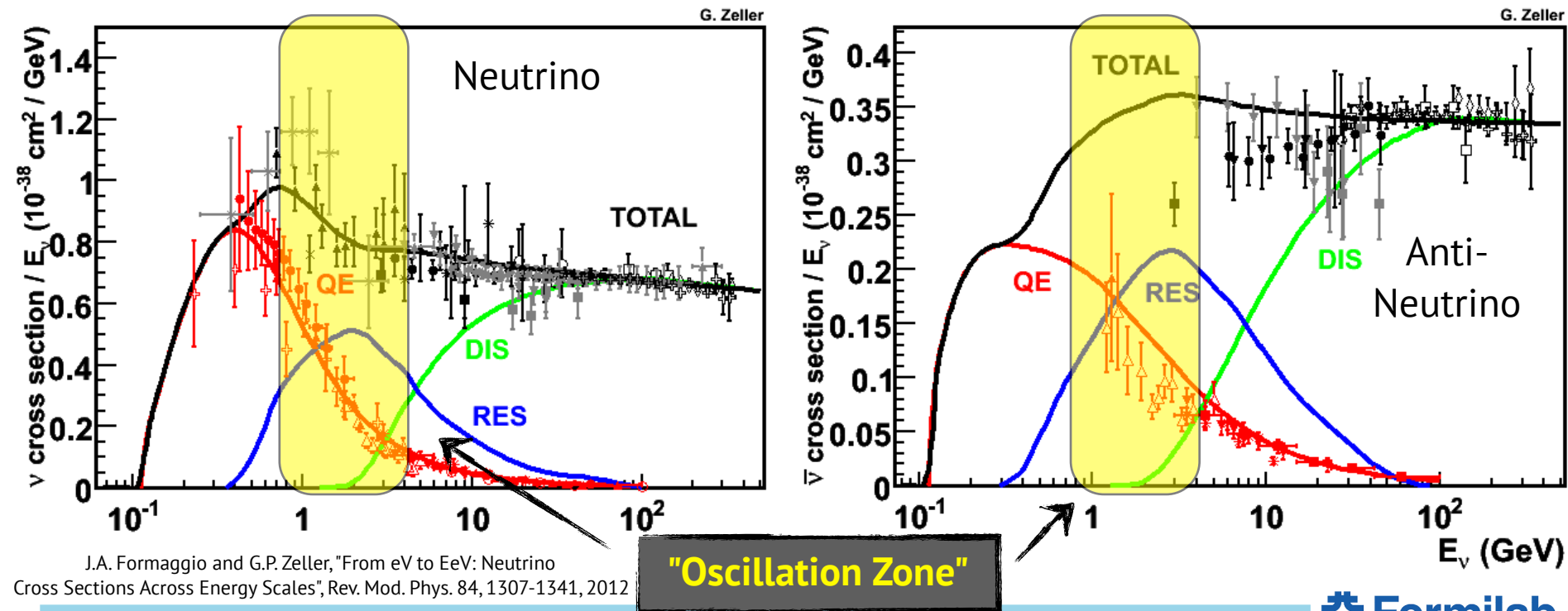


Nucleus:
What is the initial state?
What escapes the nucleus?



Embedded Assumptions

- There are a few facts that are often “hidden in plain sight” when discussing neutrino-nucleus interactions:
 - Your knowledge of the flux is typically only good to 10-20% and you have *no information event-by-event*.
 - Kinematic distributions are always integrated over a *specific* (barely known) flux.
 - Measurements are always convolutions of flux, cross section, nuclear effects, and detector efficiencies.



"Oscillation Zone"

The Basic Problem: The Best We Can Do

- The best we can do is build a map, weighted by probability, that provides all the possible initial states for an observed final state.
- With this map and a sample of events, we may infer a neutrino energy distribution (or some other kinematic distribution).
- How do we make any progress without an initial energy to begin with?
- For measurements, we use the generator to predict backgrounds and the efficiency.
 - We may constrain the backgrounds with data (at the price of a systematic uncertainty).
 - We must impose systematic uncertainties on our efficiency based on model estimates.
 - The more measurements we have, the better we may constrain these uncertainties and the better is our probability map.

Perspectives*

- Theorists: The model doesn't need to match the data, it just needs to be correct.
- Experimentalist: The model doesn't need to be correct, it just needs to match the data.
 - *(Both camps are quite pleased with their positions.)*
- Other generators:
 - NuWro (theorists)
 - GiBUU (theorists)
 - NEUT (mostly experimentalists)
 - NUANCE (mostly experimentalists, not actively supported)

*Attributed to U. Mosel

GENIE Physics Models

- GENIE 2.0 used identical physics models as NEUGEN, a Fortran generator that was developed over a number of years by a succession of physicists, and used by MINOS. GENIE has evolved with each subsequent release.
- There are currently over 20 different physics models.
- The default nuclear model is the relativistic Fermi gas with Bodek and Ritchie high-momentum tails. GENIE also has an Effective Spectral Function and an internally developed MEC model.
- The quasielastic process is Llewellyn-Smith.
- Excitation of nucleon resonances (decaying by meson emission) and coherent pion production are both described by models Rein and Sehgal.

GENIE Physics Models

- Bodek and Yang (2003) is used for nonresonant inelastic scattering.
- The custom "AGKY" hadronization model, developed internally, covers the transition between PYTHIA at high ($W > 3\text{GeV}/c^2$) invariant masses and an empirical model based on KNO-scaling at lower invariant masses.
- GENIE has two internally developed models for final-state interactions; one is a cascade model and the other (the default) parameterizes the cascade as a single effective interaction for easy re-weighting.
- GENIE uses the SKAT parametrization of formation zones (the effective distance over which a quark hadronizes).

Why do we need the energy?

- 3 x 3 Unitary Matrix
 - 3 “Euler Angles”, 1 Complex Phase*
- 3 Masses
 - 2 Independent Splittings



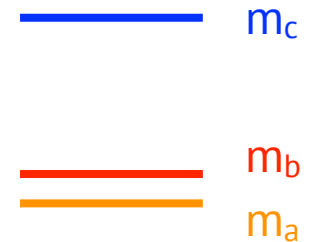
PMNS matrix...

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

ν_α = Flavor
Eigenstates

ν_i = Mass
Eigenstates

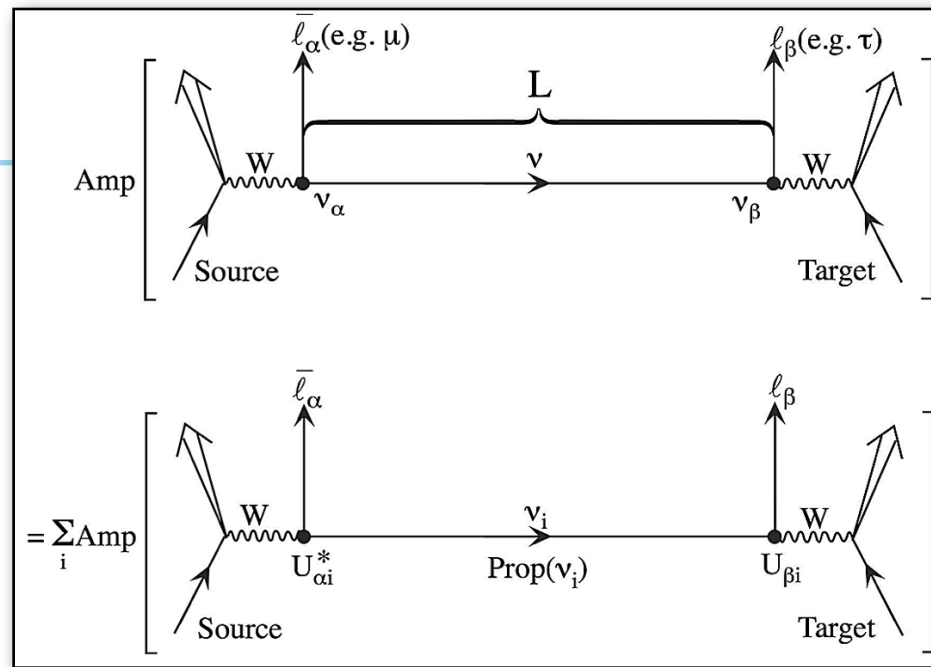
$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}$



*Plus two Majorana phases - Insanely important! (But, ignored here...)

$$\text{Prop}(\nu_j) \sim e^{-im_j \tau_j}$$

$$m_1 \neq m_2 \neq m_3$$



B. Kayser, arXiv
0804.1121

- Flavor eigenstates interact. Flavor states are superpositions of mass states.
 - Different masses \Rightarrow Different propagators.

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(L) \rangle|^2 = \left| \sum_j U_{\alpha j}^* e^{-im_j^2 \frac{L}{2E}} U_{\beta j} \right|^2$$

- \Rightarrow Flavor composition evolves with time.

How do we measure PMNS?

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= \left| U_{\mu 1}^* e^{-im_1^2 L/2E} U_{e1} + U_{\mu 2}^* e^{-im_2^2 L/2E} U_{e2} + U_{\mu 3}^* e^{-im_3^2 L/2E} U_{e3} \right|^2 \\ &= \left| 2U_{\mu 3}^* U_{e3} \sin \Delta_{31} e^{-i\Delta_{32}} + 2U_{\mu 2}^* U_{e2} \sin \Delta_{21} \right|^2 \\ &\simeq \left| \sqrt{P_{atm}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{sol}} \right|^2 \end{aligned}$$

- We beat these probabilities against each other.
- $\delta \rightarrow -\delta$ for antineutrinos.
- Compare neutrinos to antineutrinos to measure CP violation and the mass hierarchy.

$$\Delta_{ij} = 1.27 \Delta m_{ij}^2 L/E$$

Probabilities

- The probabilities are a function of the matrix parameters, the mass splittings, and the *neutrino energy*!

In MATTER:

$$P_{atm} \sim \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (\Delta_{31} - aL) \left(\frac{\Delta_{31}}{\Delta_{31} - aL} \right)^2$$




$$P_{sol} \sim \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 (aL) \left(\frac{\Delta_{21}}{aL} \right)$$

$$a = \pm G_F N_e / \sqrt{2} \sim (4000 \text{ km})^{-1}$$

$$\Delta_{ij} = 1.27 \Delta m_{ij}^2 L / E$$

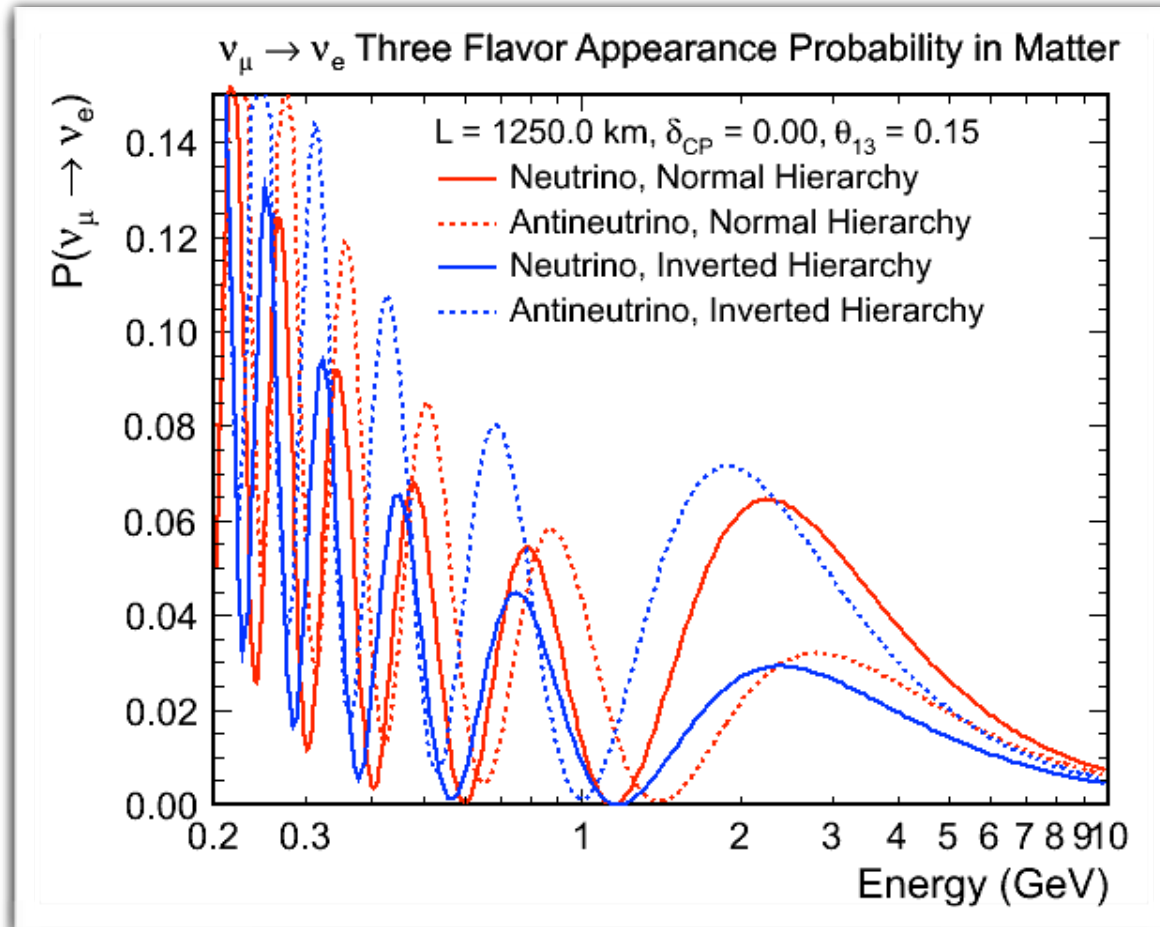
$$P \sim 2\sqrt{P'_{atm}}\sqrt{P'_{sol}} \cos \Delta_{32} \cos \delta_{CP} \mp 2\sqrt{P'_{atm}}\sqrt{P'_{sol}} \sin \Delta_{32} \sin \delta_{CP}$$




$$\delta_{CP} : 0 \rightarrow 2\pi$$

m_2 
 m_1 
 m_3 

Inverted

Antineutrino: $-\delta$



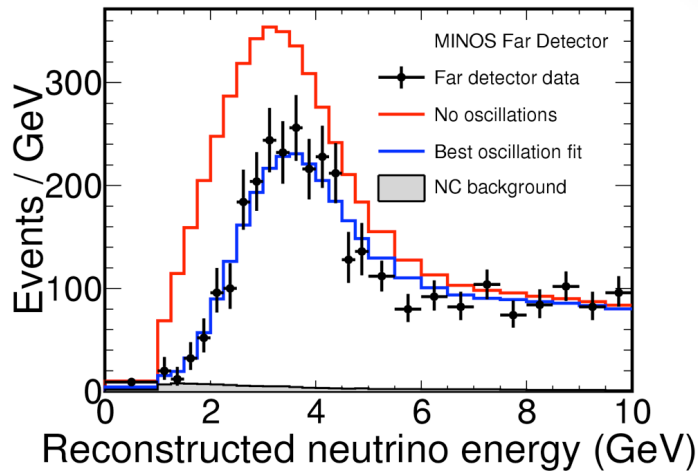
 m_3
 m_2
 m_1

Normal

Neutrino: δ

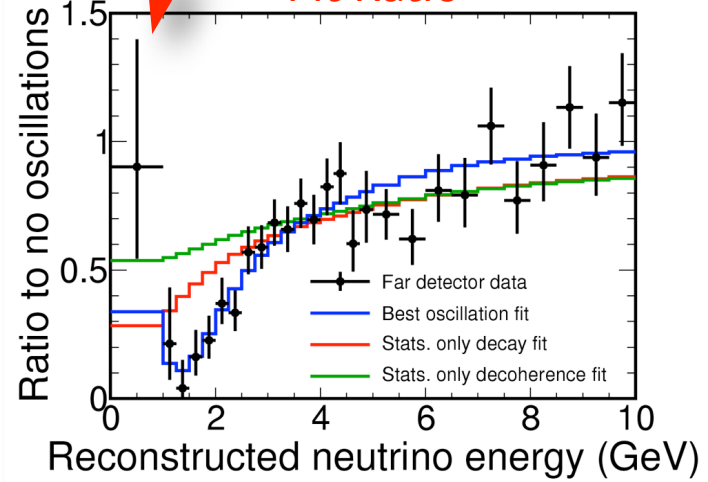
How do we measure these probabilities?

Measure "Near"/Far

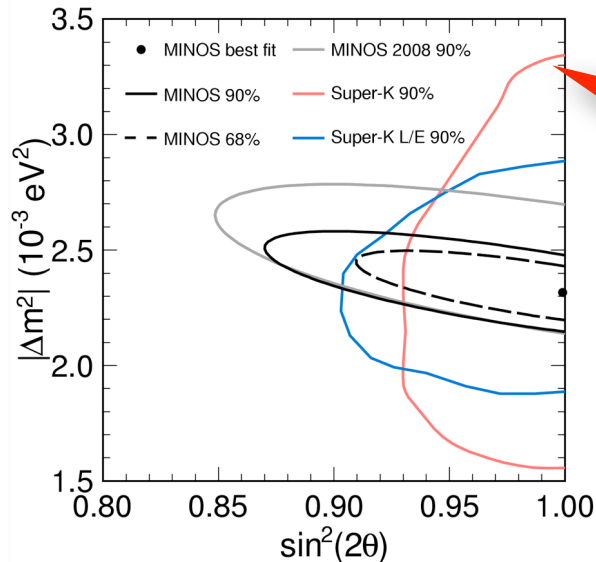


<http://www-numi.fnal.gov/PublicInfo/forScientists.html>

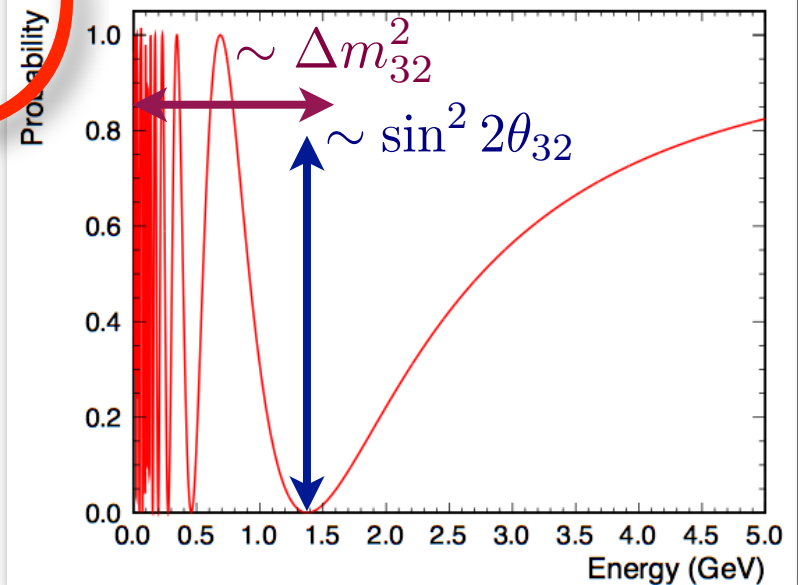
Fit Ratio

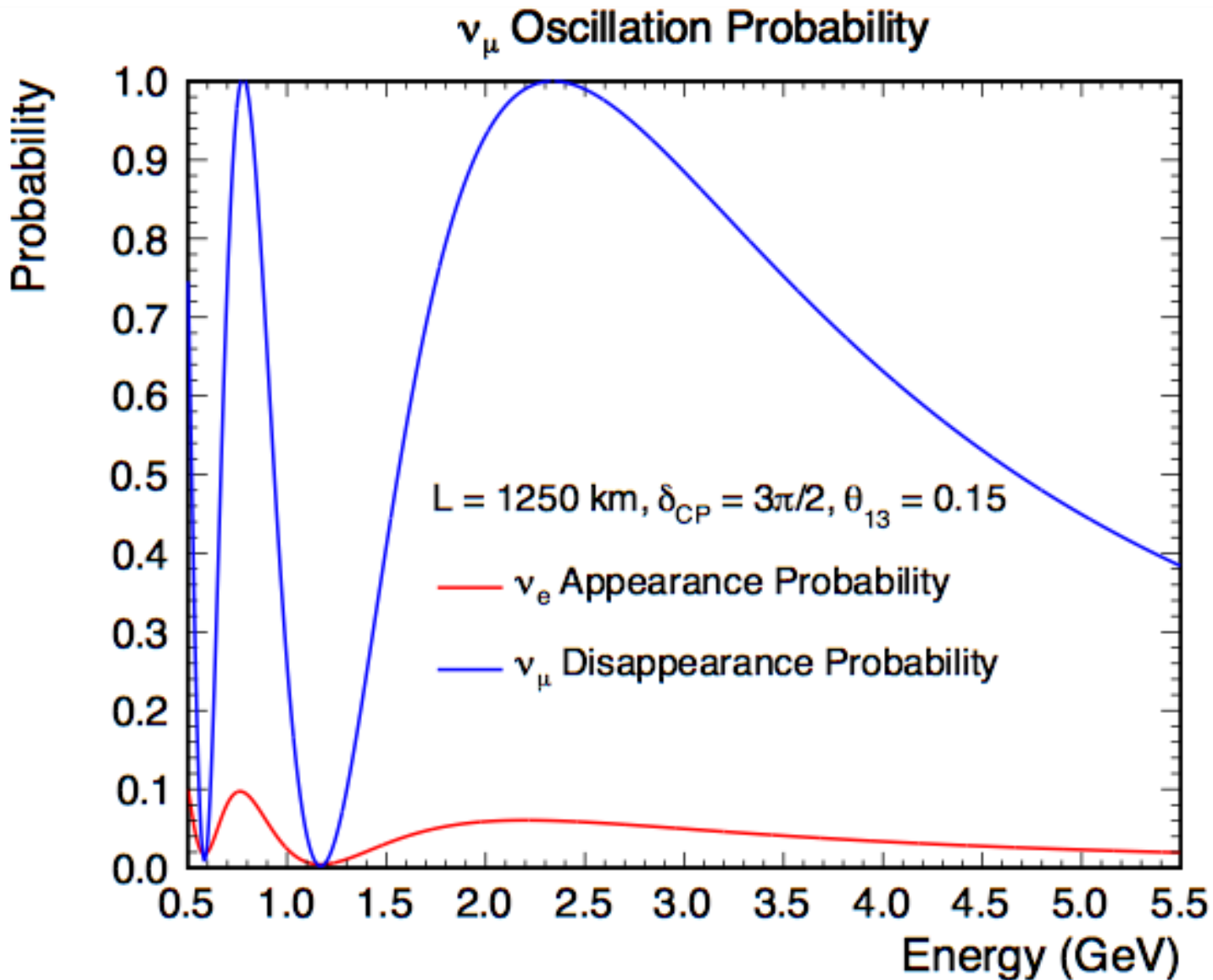


Extract Physics!



$\nu_\mu \rightarrow \nu_\mu$ Two Flavor Survival Probability





And remember, we need to do it all over again for antineutrinos!

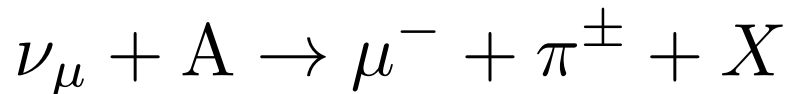
Review

- We need neutrino energy to high precision in our far detector.
- We need neutrino energy in our near detector.
 - These may feature different detector technologies. They *definitely* see different neutrino fluxes.
- We need to understand neutrinos and antineutrinos.
- We're looking for a tiny effect, so "large" systematic uncertainties will destroy the measurement.
- "Cross section uncertainties" are not simply level uncertainties. We need to know how to appropriately map an observed final state to a properly weighted distribution of possible initial states.

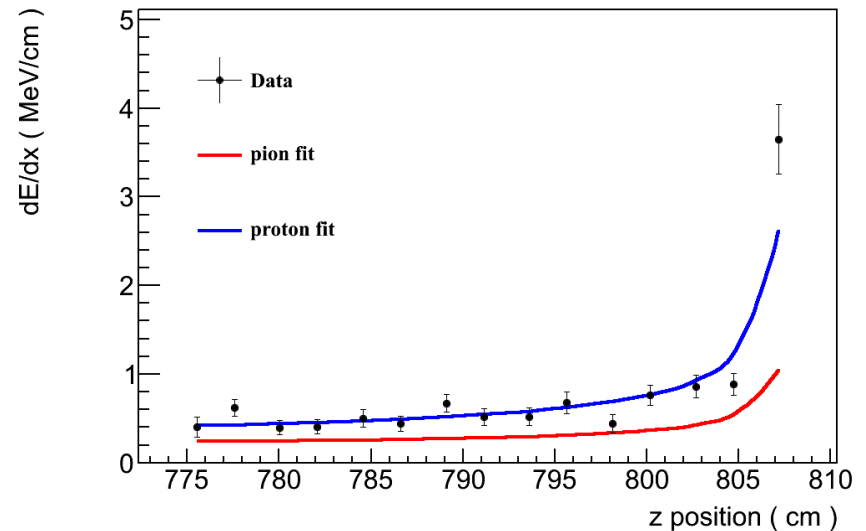
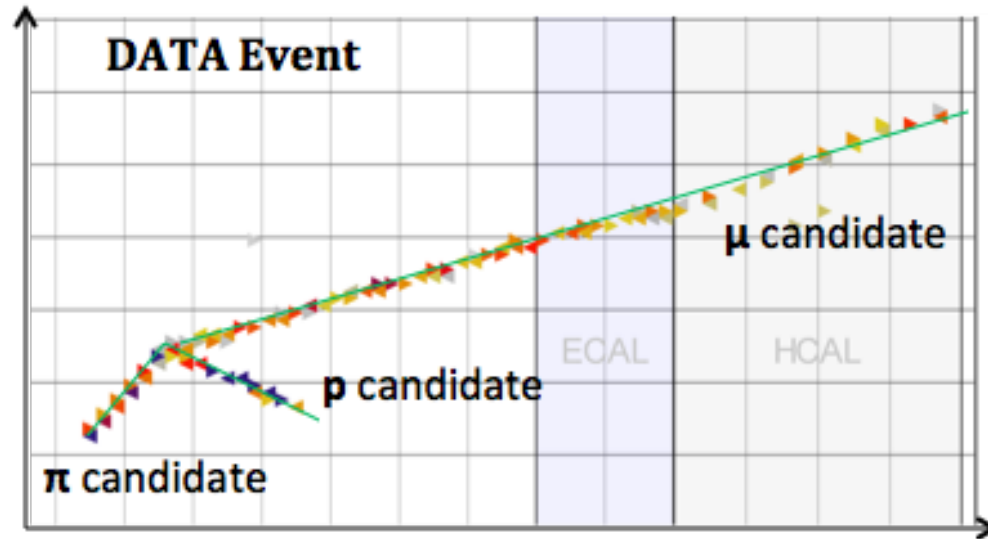


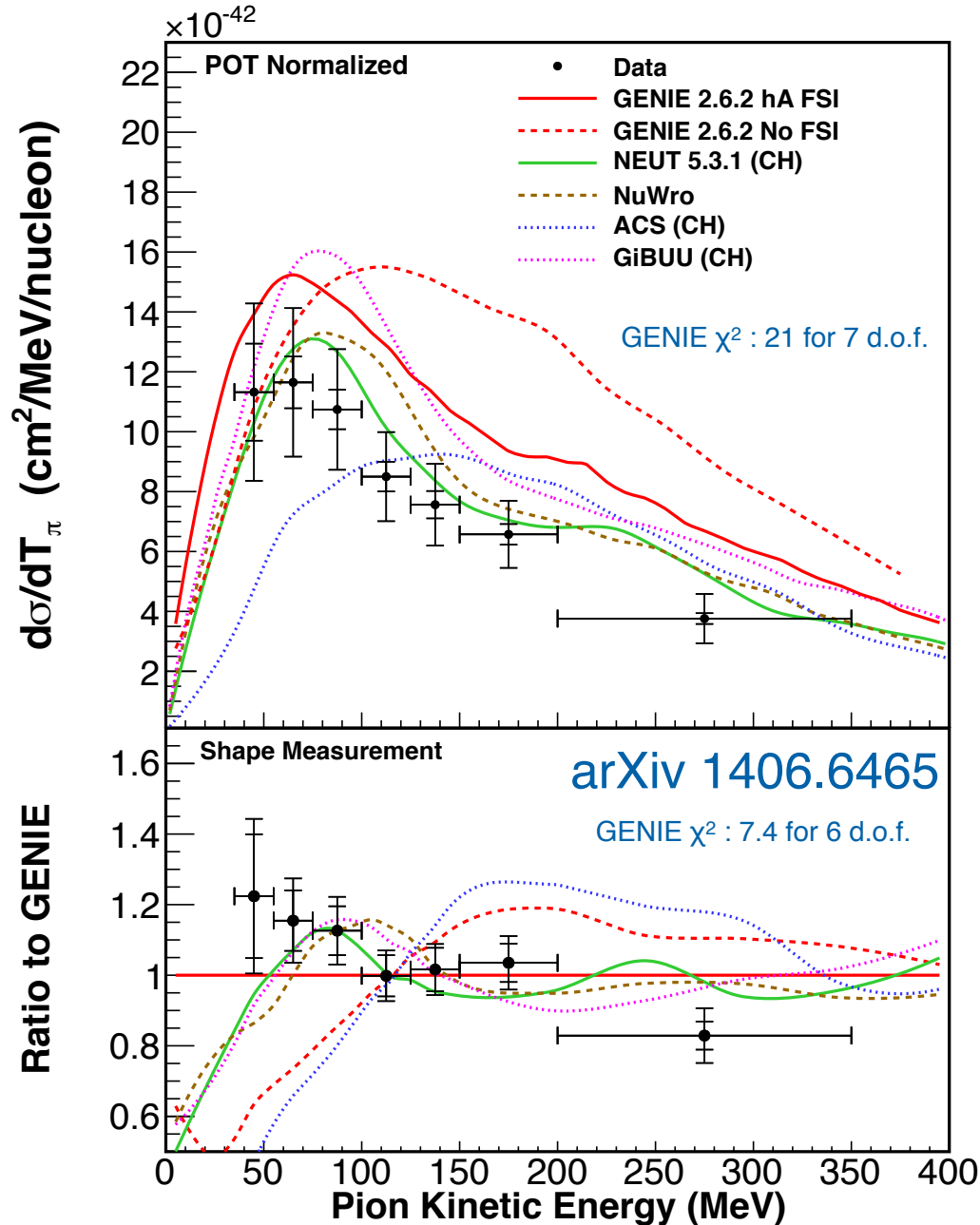
Testing FSI with Pion Production: Charged Pions

- Allow only **one** charged pion, however it is produced and any number of nucleons at $W < 1.4$ GeV (near the resonance region).
 - Max of two hadron *tracks*.
- Pions identified by dE/dX and a Michel electron tag.
 - Selection is tailored to avoid charge exchange, absorption, and hadronic showers in the detector for better energy resolution.



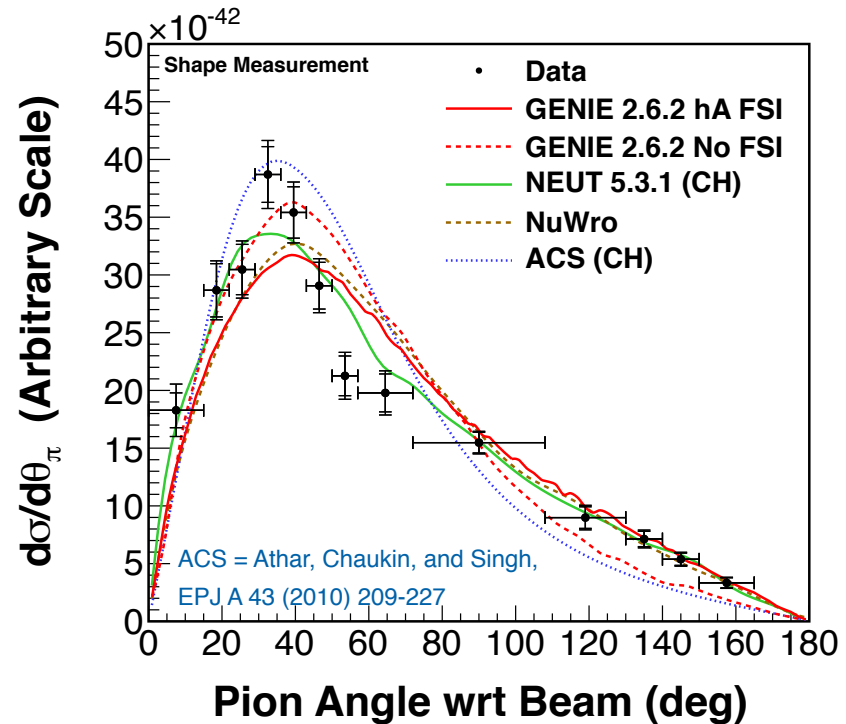
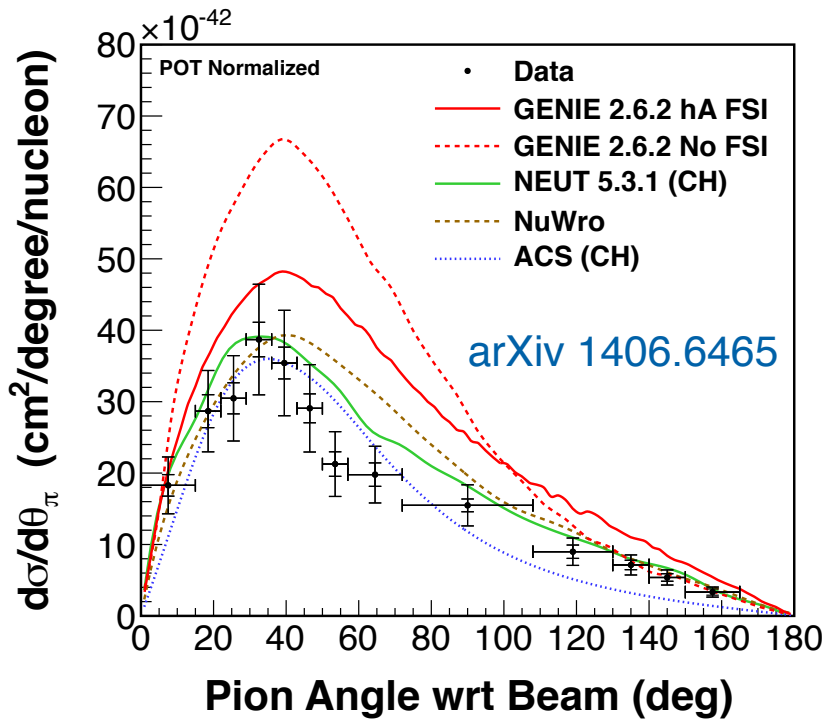
(A is ~95% CH; Final sample is 99% π^{+})

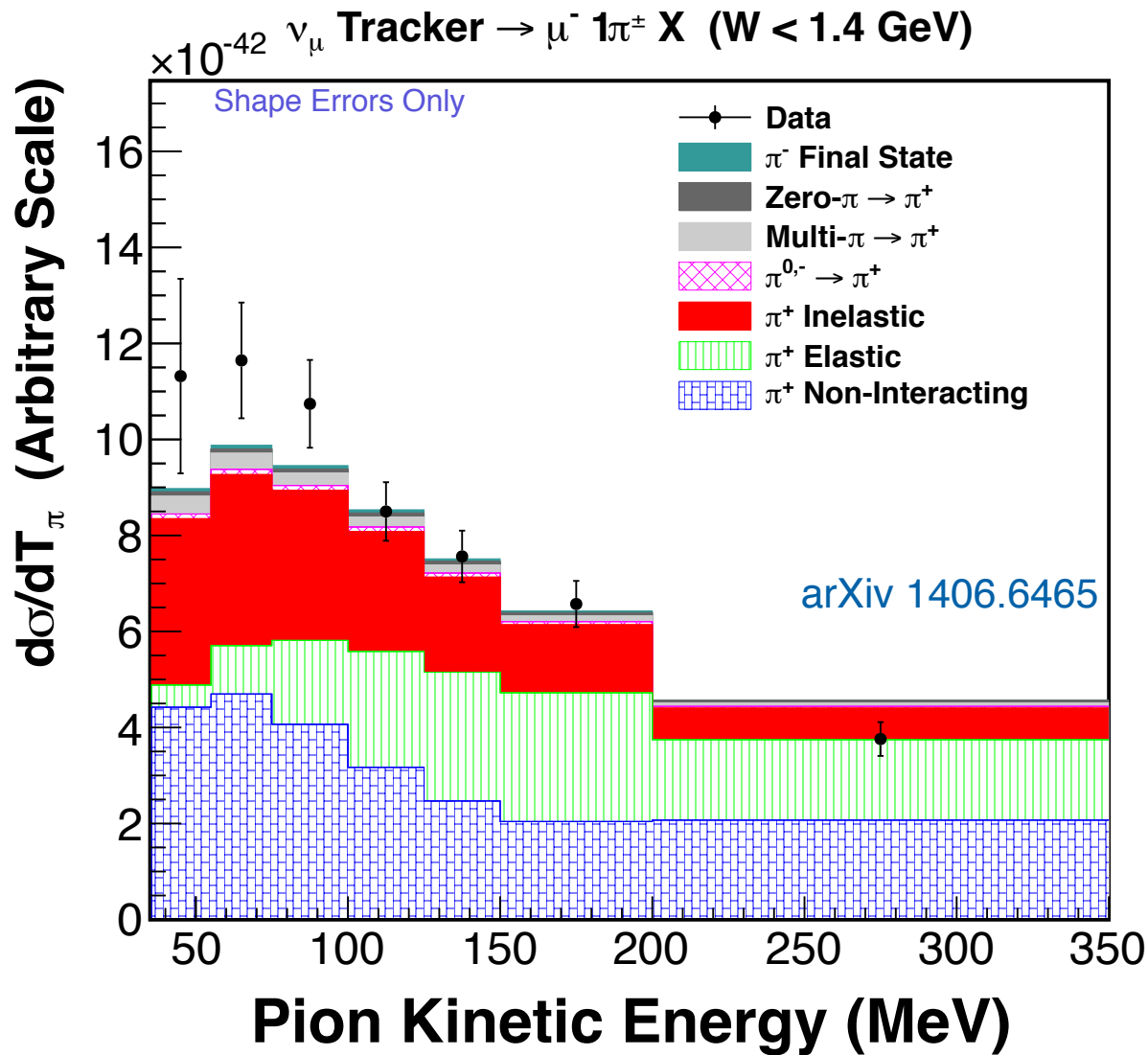




- 3,474 charged-pion event candidates.
- 77% purity. The largest background is events with a true W of more than 1.4 GeV ($\sim 17\%$ of total).
- Shape-only measurement is statistics limited in most bins.
- Dominant systematics are on flux, the pion energy response model in the detector, and on FSI (enters through the efficiency correction)
 - Dominant error changes as a function of energy.

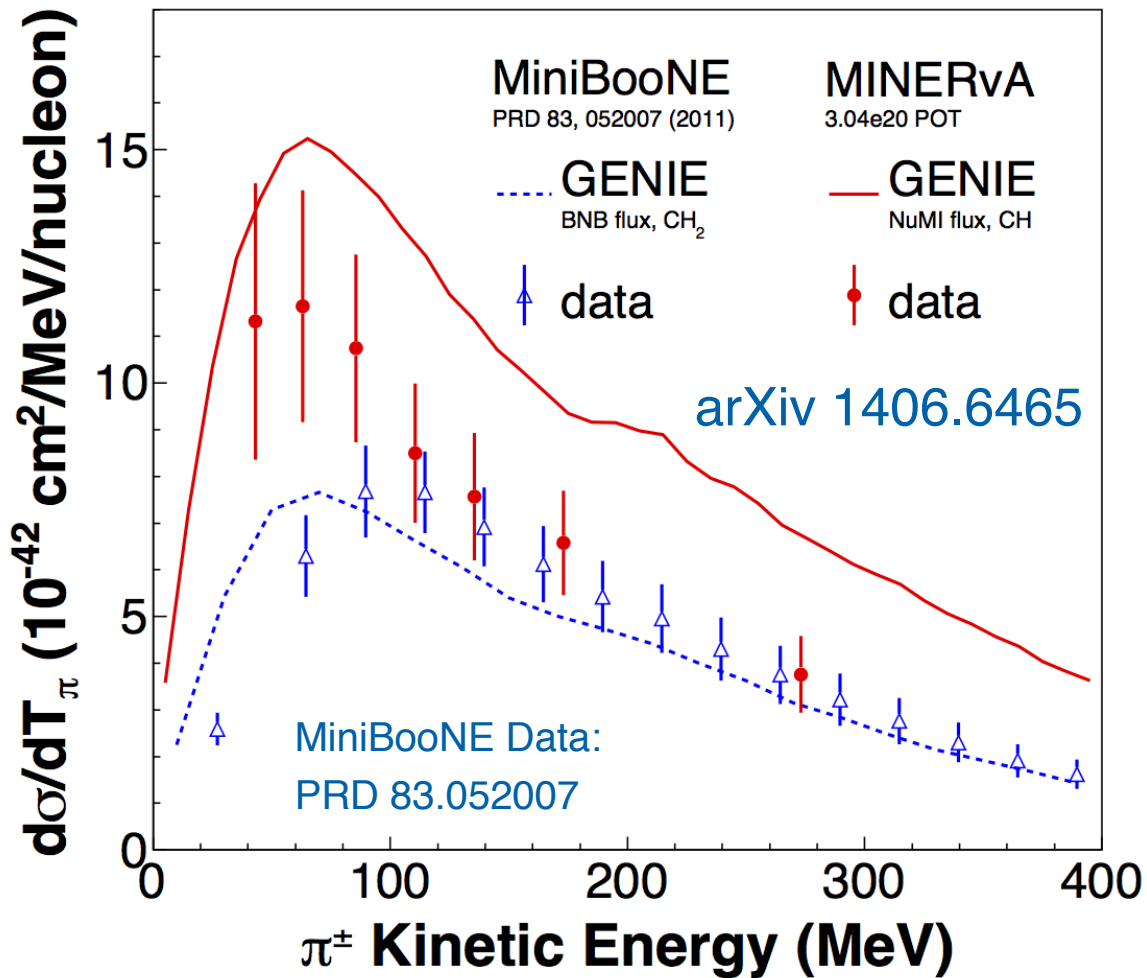
- GENIE and NuWro use an isotropic angular distribution for the Δ decay while NEUT uses the anisotropic model proposed by Rein and Sehgal.
- However, the FSI model dominates the (GENIE) response.





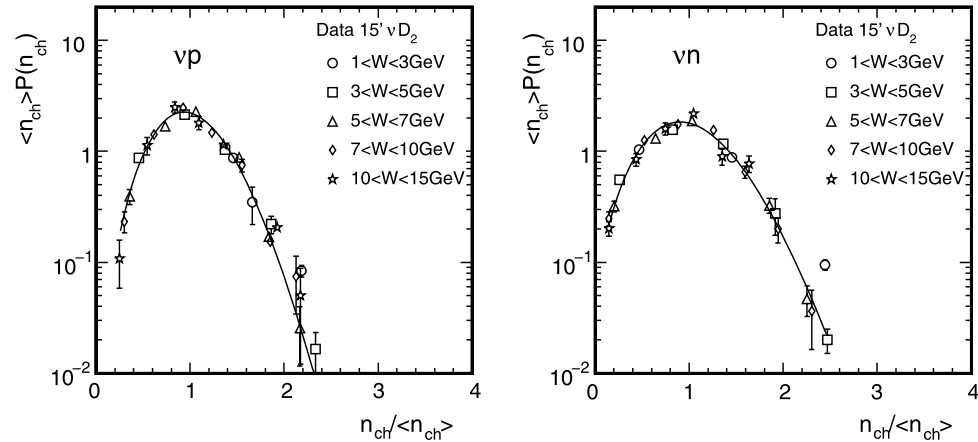
Shape agreement would improve if the inelastic scattering contribution were increased within the total error in the pion inelastic cross section data (40%).

- Because neutrino differential cross sections are flux integrated, they may only be compared through a generator model (like GENIE).
- *Within the context of the GENIE model, there is tension in these results:*
 - Inconsistent peaks
 - Different normalization shifts
 - "Agreement" also puzzling: MINERvA should see larger cross section since the pion production cross section rises with energy.



AGKY Hadronization

Fig. 1 KNO scaling distributions for νp (left) and νn interactions. The curve represents a fit to the Levy function. Data points are taken from [7]



The AGKY model, which is now the default hadronization model in the neutrino Monte Carlo generators NEUGEN [9] and GENIE-2.0.0 [10], includes a phenomenological description of the low invariant mass region based on Koba–Nielsen–Olesen (KNO) scaling [11], while at higher masses it gradually switches over to the PYTHIA/JETSET model. The transition from the KNO-based model to the PYTHIA/JETSET model takes place gradually, at an intermediate invariant mass region, ensuring the continuity of all simulated observables as a function of the invariant mass. This is accomplished by using a transition window $[W_{\min}^{\text{tr}}, W_{\max}^{\text{tr}}]$ over which we linearly increase the fraction of neutrino events for which the hadronization is performed by the PYTHIA/JETSET model from 0% at W_{\min}^{tr} to 100% at W_{\max}^{tr} . The default values used in the AGKY model are

$$W_{\min}^{\text{tr}} = 2.3 \text{ GeV}/c^2, \quad W_{\max}^{\text{tr}} = 3.0 \text{ GeV}/c^2.$$

Fig. 3 Average charged-hadron multiplicity $\langle n_{ch} \rangle$ as a function of W^2 . (a) νp events. (b) νn events. Data points are taken from [7, 20]

