ν-Nucleus Scattering Systematics: Interplay of Neutrino Flux, Cross sections and Nuclear Effects

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Neutrino Experimental Systematics

- Detector Systematics:
  - Muon energy scale
  - Hadron energy scale
  - Muon tracking – reconstruction
  - Neutron and proton response
  - Target mass
  - Cross-talk
  - …….
- Flux Systematics
- Interaction Model Systematics
  - Cross section
  - Nuclear Effects

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Neutrino Nucleus Scattering

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:

$Y_{c\text{-like}}(E) \,\alpha\, \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

- $\mathbf{Y_{c\text{-like}}(E)}$ is the event energy and channel / topology of the event observed in the detector. It is called c-like since it appears to be channel c but may not have been channel c at interaction.

- That is the topology measured in the detector is what we observe in the detector and not necessarily what was produced at the initial interaction.

- The energy E is not given by knowing the E of the incoming particle as in charged particle scattering, but is the sum of energies coming out of the nucleus and measured in the detector.

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- **$\phi(E)$** is the energy dependent neutrino flux that enters the detector.

- With traditional meson-decay-source neutrino beams we can, with considerable effort, estimate the incoming neutrino energy distribution to ≤ 10% absolute and ≤ 7% energy bin-to-bin accuracy. **Significant contribution to systematics.**

- With muon-decay-source neutrino beams (NuSTORM and Neutrino Factory) we could know the **energy dependent absolute flux to order 1%**.

Neutrino Nucleus Scattering

What do we observe in our detectors?

- The events we observe in our detectors are convolutions of:
  $Y_{c\text{-like}}(E) \propto \phi(E' \geq E) \otimes \sigma_{c,d,e..}(E' \geq E) \otimes Nuc_{c,d,e..\rightarrow c}(E' \geq E)$

- $\sigma_{c,d,e..}(E' \geq E)$ is the measured or the Monte Carlo (model) energy dependent neutrino cross section off a **nucleon within a nucleus**.

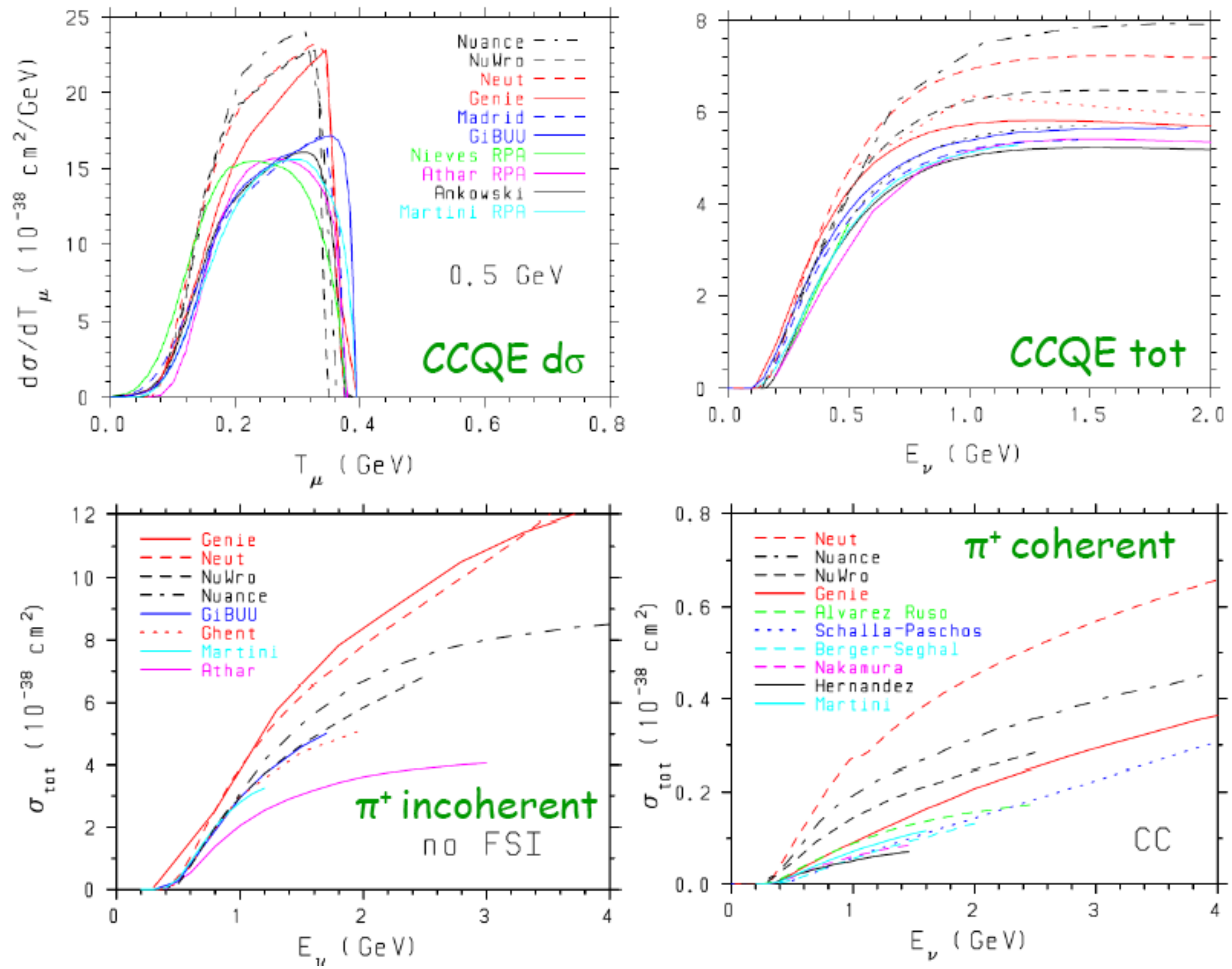
- Form factors are modified within a nucleus compared to a nucleon. Analogous to the difference between PDFs and nuclear NPDFs

- The width of resonances, i.e the Δ, changes within a nucleus.

- **Significant contribution to systematics**.

Range of Existing Model (MC) Predictions off C

NuInt09 – Steve Dytman



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- **$Nuc_{c,d,e..\rightarrow c}(E' \geq E)$ – Nuclear Effects**
  - In contemporary neutrino experiments the interactions do not occur on a free nucleon but rather nucleon(s) within a nucleus and there are many nuclear effects that have to be considered.
  - In general the interaction of a neutrino with energy E' creating initial channel d,e… can appear in our detector as energy E and channel c.
  - **Nuclear Effects** – a migration matrix that mixes produced/observed channels and energy. **Significant contribution to systematics.**
  - A bit tricky to measure the cross section off a nucleon within a nucleus because of these nuclear effects.

What are these Nuclear Effects **$Nuc_{c,d,e..\rightarrow c}$ (E'≥ E)** in Neutrino Nucleus Interactions? (Partial List)

- Target nucleon in motion – classical Fermi gas model or the superior spectral functions (Benhar et al.)
- Multi-nucleon initial states: Short-range correlations, meson exchange currents.
- Form factors, structure functions, resonance widths, parton distribution functions and, consequently, cross sections are modified within the nuclear environment. (Butkevich / Kulagin, Tsushima et al., Kovarik et al.)
- Produced topologies are modified by final-state interactions modifying topologies and possibly reducing **detected** energy.
  - Convolution of $\delta\sigma(n\pi) \otimes$ formation zone uncertainties $\otimes$ π-charge-exchange/ absorption probabilities and nuclear density uncertainties.
- **Systematics associated with each of these effects.**

  - Monte Carlos – like GENIE – try to include all these effects.

GENIE needs improvements! GENIE group needs additional help from the community.

Example Model Uncertainties

Cross Section Model Uncertainties

Uncertainty	1 σ
M_A (Elastic Scattering)	± 25%
Eta (Elastic scattering)	± 30%
M_A (CCQE Scattering)	+25% −15%
CCQE Normalization	+20% −15%
CCQE Vector Form factor model	on/off
CC Resonance Normalization	± 20%
M_A (Resonance Production)	± 20%
M_V (Resonance Production)	± 10%
1pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
1pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
2pi production from $\nu p / \bar{\nu} n$ non-resonant interactions	± 50%
2pi production from $\nu n / \bar{\nu} p$ non-resonant interactions	± 50%
Modify Pauli blocking (CCQE) at low Q^2 (change PB momentum threshold)	± 30%

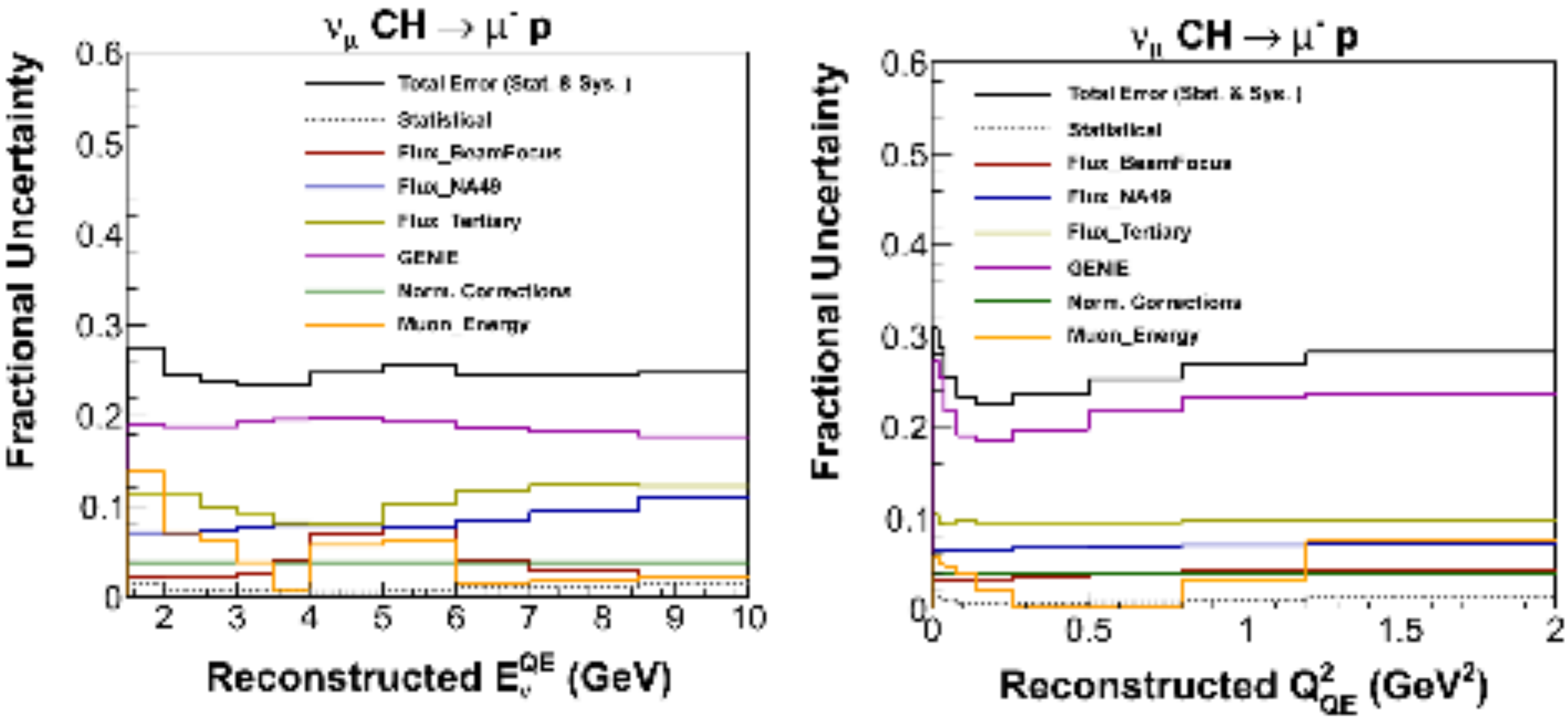
•*Intranuclear Rescattering Uncertainties*

Uncertainty	1 σ
Pion mean free path	± 20%
Nucleon mean free path	± 20%
Pion fates – absorption	± 30%
Pion fates – charge exchange	± 50%
Pion fates – Elastic	± 10%
Pion fates – Inelastic	± 40%
Pion fates – pion production	± 20%
Nucleon fates – charge exchange	± 50%
Nucleon fates – Elastic	± 30%
Nucleon fates – Inelastic	± 40%
Nucleon fates – absorption	± 20%
Nucleon fates – pion production	± 20%
AGKY hadronization model – x_F distribution	± 20%
Delta decay angular distribution	On/off
Resonance decay branching ratio to photon	± 50%

Hugh Gallagher

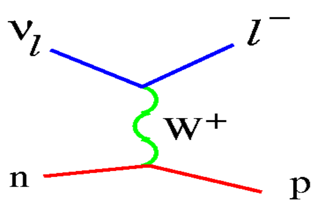
References: (1) www.genie-mc.org, (2) arXiv:0806.2119, (3) D. Bhattacharya, Ph. D Thesis (U. Pittsburgh) 2009.

Example: Uncertainty on Exclusive Prediction

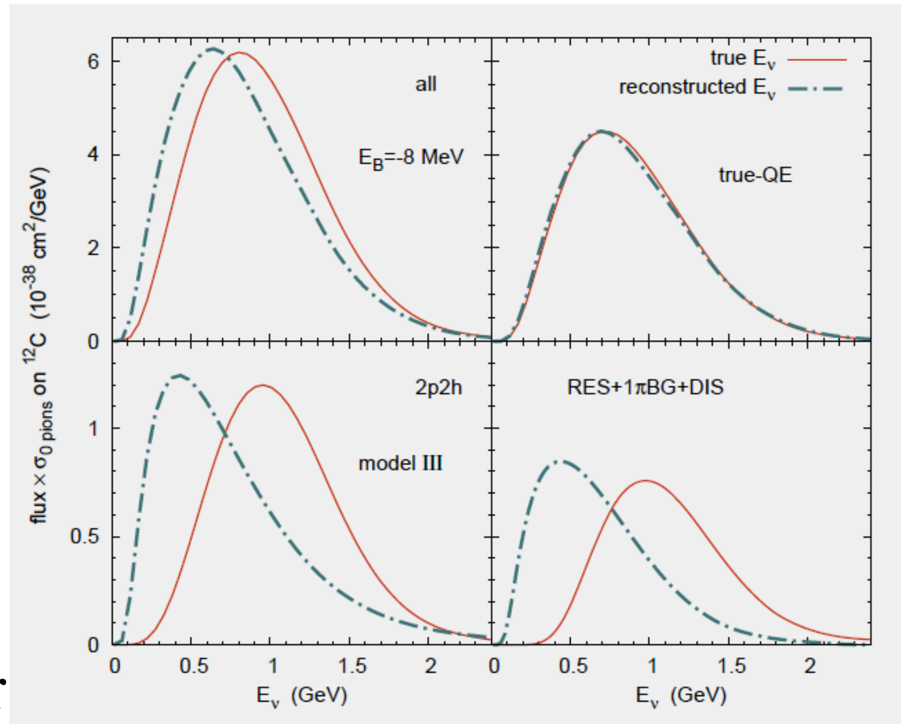


Nuclear Effects can Change the Energy Reconstruction for "QE" Events

- In pure QE scattering on nucleon at rest, the outgoing lepton can determine the neutrino energy:



$$E_\nu = \frac{2M_N E_\mu - m_\mu^2}{2(M_N - E_\mu + p_\mu \cos\theta_\mu)}$$

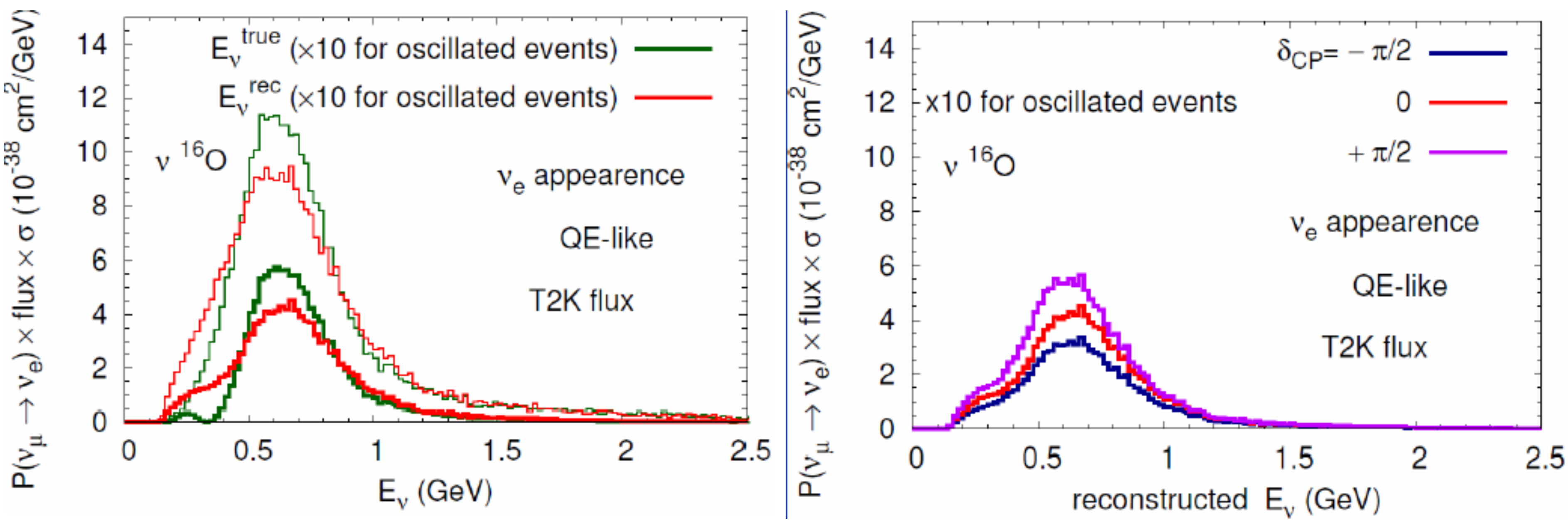


U. Mosel GiBUU

However, all neutrino oscillation experiments contain nuclei as targets. Reconstructed energy shifted to lower energies for all processes other than true QE off nucleon at rest

Nuclear Effects and Oscillation Measurements

Ulrich Mosel using his Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) Transport Model looking at T2K



A Nuclear Theorist's View

From Ulrich Mosel – Nuclear Theorist from University of Giessen, Germany

…. **these neutrino experiments are - from a nuclear physicist's point of view - unique in the sense that their analysis has to rely on nuclear structure and nuclear reaction theory more so than any other nuclear physics experiment that I know of (the closest is the extraction of properties of the quark-gluon plasma from ultra-relativistic heavy ion collisions)**

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effective $\sigma_c^A(E)$

- Experimentally, the last two terms convoluting the initial nucleon (within a nucleus) cross section and nuclear effects are combined into an effective cross section $\sigma_c^A(E)$.

- Note that the **effective cross section $\sigma_c^A(E)$ measured depends on the incoming neutrino energy spectrum and the involved nuclear effects that populate the yield $Y_c^A(E)$.**

- This implies that, for example, the effective $\sigma_{\pi 0}^C$ (1 GeV) measured in the MiniBooNE Booster beam **will be different** than the same effective $\sigma_{\pi 0}^C$ (1 GeV) observed by MINERvA in the higher energy NuMI beam due to, for example, more feed down from multi-pi events via pion absorption in the NuMI beam.

Significant Implications for Oscillation Experiments

- Can not simply plug in effective $\sigma_{\pi 0}{}^{A}$ from experiments in a significantly different beam.

- In a two-detector oscillation experiment the neutrino flux entering the far detector is altered from the neutrino flux at the near detector due to oscillations.

- The $\sigma_c{}^{A}$ (E) effective that should be applied to expectations (Monte Carlo) at the far detector is NOT the same as that which we would measure at the near detector. **However, the near detector results give us an excellent starting point for calculating the difference.**

- **The convoluted $\phi(E' \geq E)$ ⓧ $\sigma(E)$ ⓧ Nuc(E'≥ E) systematics need to be correctly incorporated in determining the systematics of oscillation parameter measurements.**

Summary and Conclusions

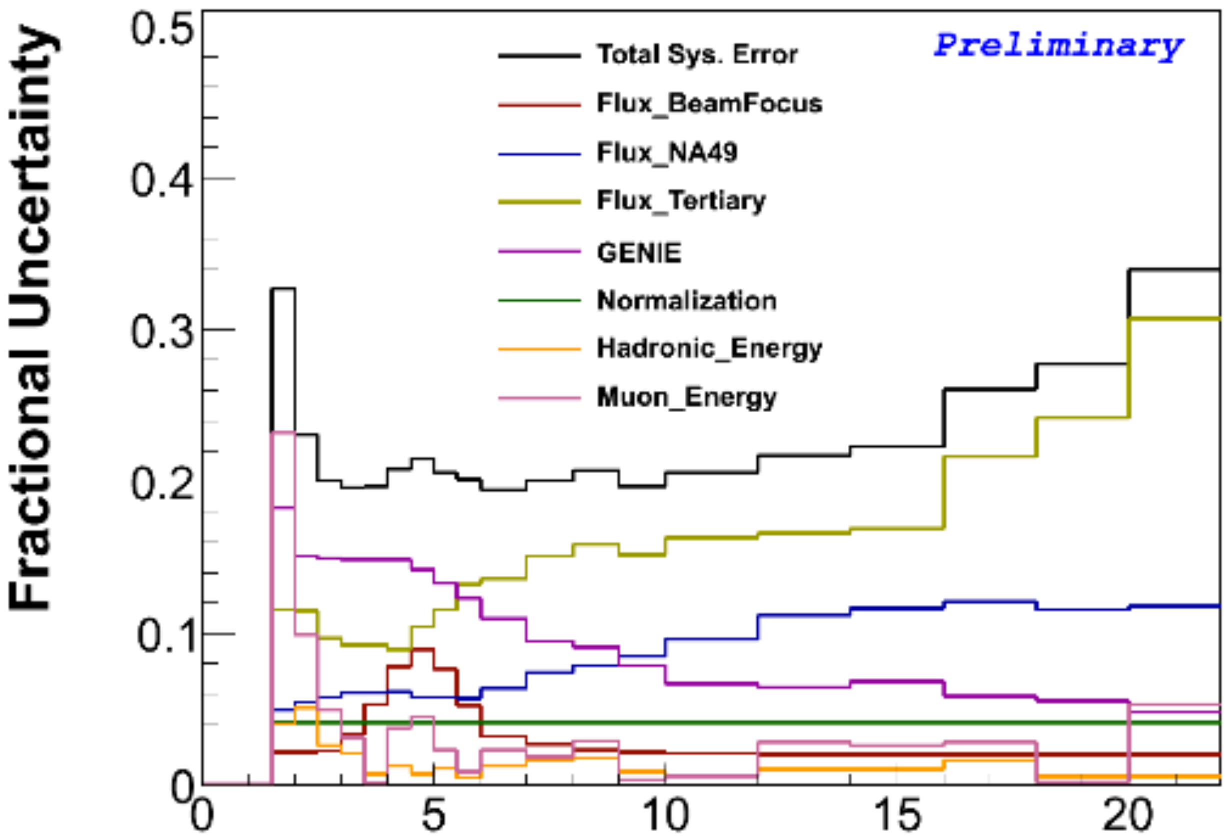
- Nuclear effects, present in the data of all contemporary neutrino oscillation experiments, **mixes channels and changes energy between produced and final (observed) states**.
- Nuclear effects couples with the initial cross section and incoming neutrino spectrum such that an observed result for a specific channel from one detector does not transfer to another detector unless they are using the same nucleus AND same neutrino beam. **What is a "standard candle"?**
- GENIE generator that tries to model these coupled effects **needs additional help.**
- To untangle these effects experimentally, a significant step forward would be a **high-statistics neutrino-hydrogen /deuterium experiment in a neutrino beam with a flux that we know to ≈ 1% such as from NuSTORM or NuFact.**

- **The U. S. neutrino physics community is in need of a significant increase of neutrino physics phenomenologists. Currently, need to go to Europe where a thriving phenomenologists community exists.**

Backup

Example: Uncertainty on an Inclusive Prediction

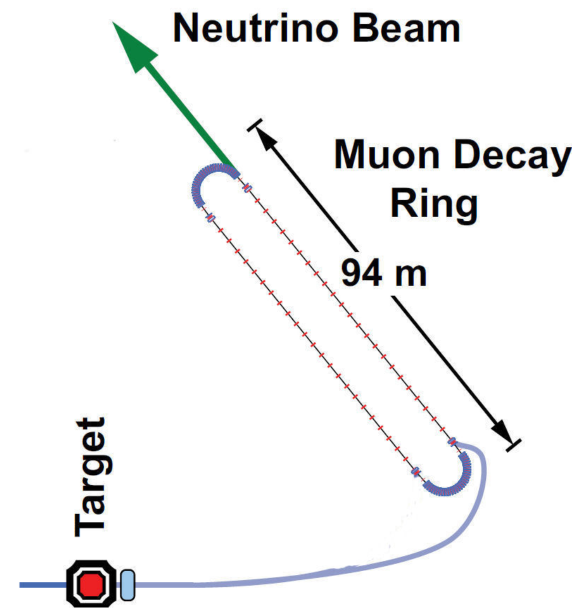
Uncertainty on the energy spectrum from Fe



Can we Actually MEASURE these Differences in the 0.5 – 4 GeV region

νSTORM Neutrinos from Stored Muons

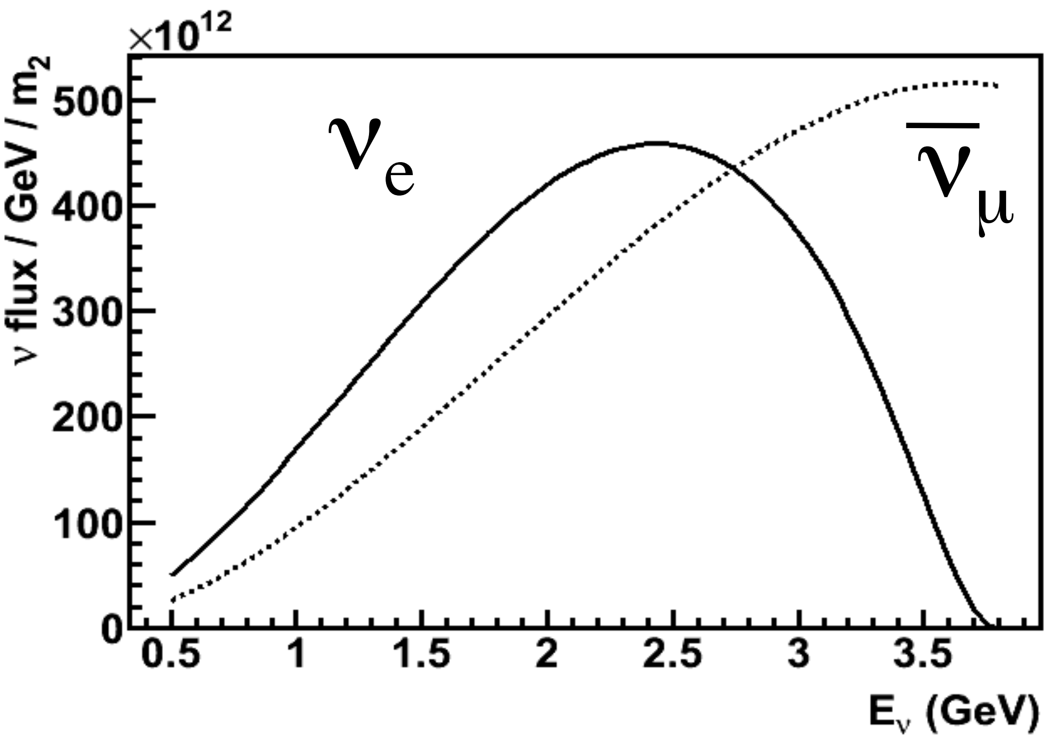
- High-Precision ν interaction physics program.
  - The νSTORM beam will provide a very well-known ($\delta\,\phi(E) \approx 1\%$) beam of ν and $\bar{\nu}$.
    - ν_e and $\bar{\nu}_e$ cross-section measurements.
    - ν_μ and $\bar{\nu}_\mu$ cross-section measurements
- Address the large Δm^2 oscillation regime, mak major contribution to the study of sterile neutri
  - Either allow for precision study (in many channels), if they exist in this regime.
  - Or greatly expand the dis-allowed region.
- Provide a μ decay ring test demonstration and μ beam diagnostics test bed.
- Provide a precisely understood ν beam for detector studies.
- **Change the conception of the neutrino factory.**



The νSTORM Neutrino Beam

$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$ $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

- A high-intensity source of ν_e events for experiments.



3.8 GeV μ^+ stored, 150m straight, flux at 100m

(thanks to Sam Zeller and Chris Tunnell!)

μ^+

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

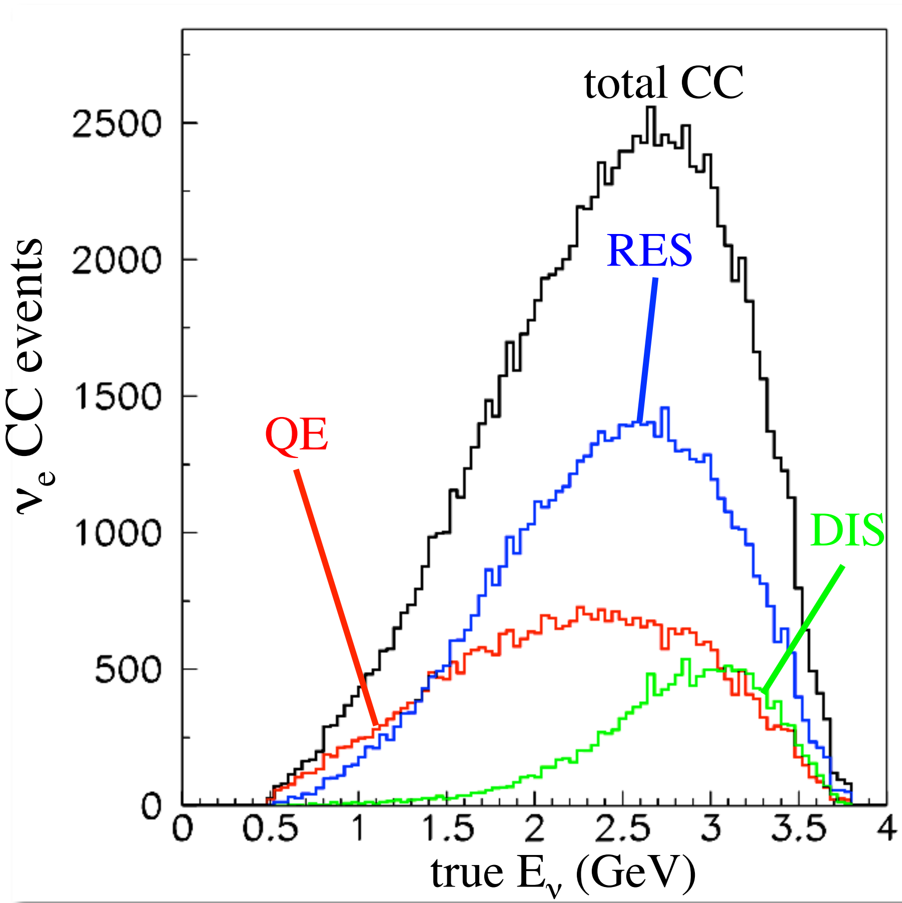
μ^-

Channel	N_{evts}
$\bar{\nu}_e$ NC	709,576
ν_μ NC	1,584,003
$\bar{\nu}_e$ CC	1,784,099
ν_μ CC	4,626,480

event rates per 1E21 POT -
100 tons at 50m

ν_e Event Fractions in νSTORM

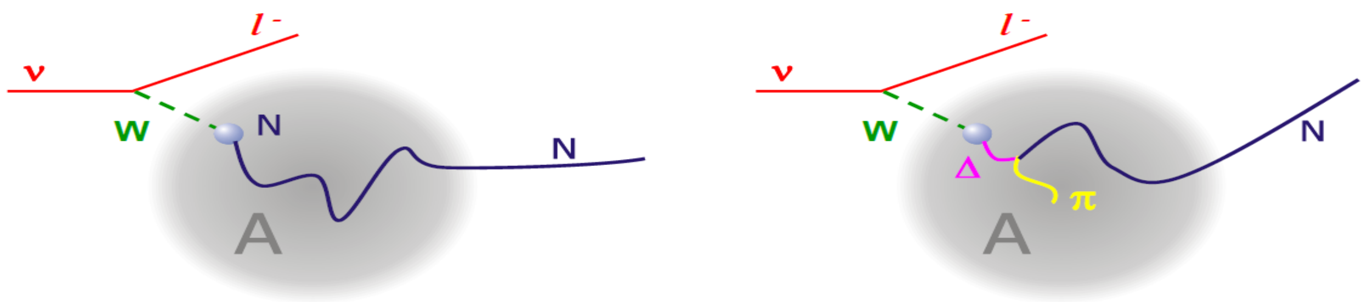
- ν_e produced by 3.8 GeV μ^+ beam.



out of the CC modes:
- * 56% resonant
- * 32% QE
- * 12% DIS

- For $\overline{\nu}_e$ sample, 52% resonant, 40% QE, 8% DIS)

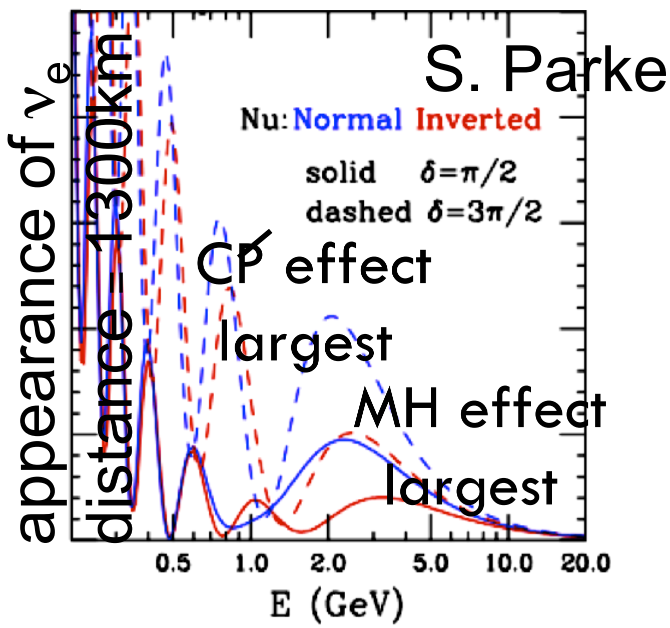
Final State Interactions can mimic a QE event



- Define a class of events as **"QE-like"** that have the apparent topology but can have been produced as something other than QE.

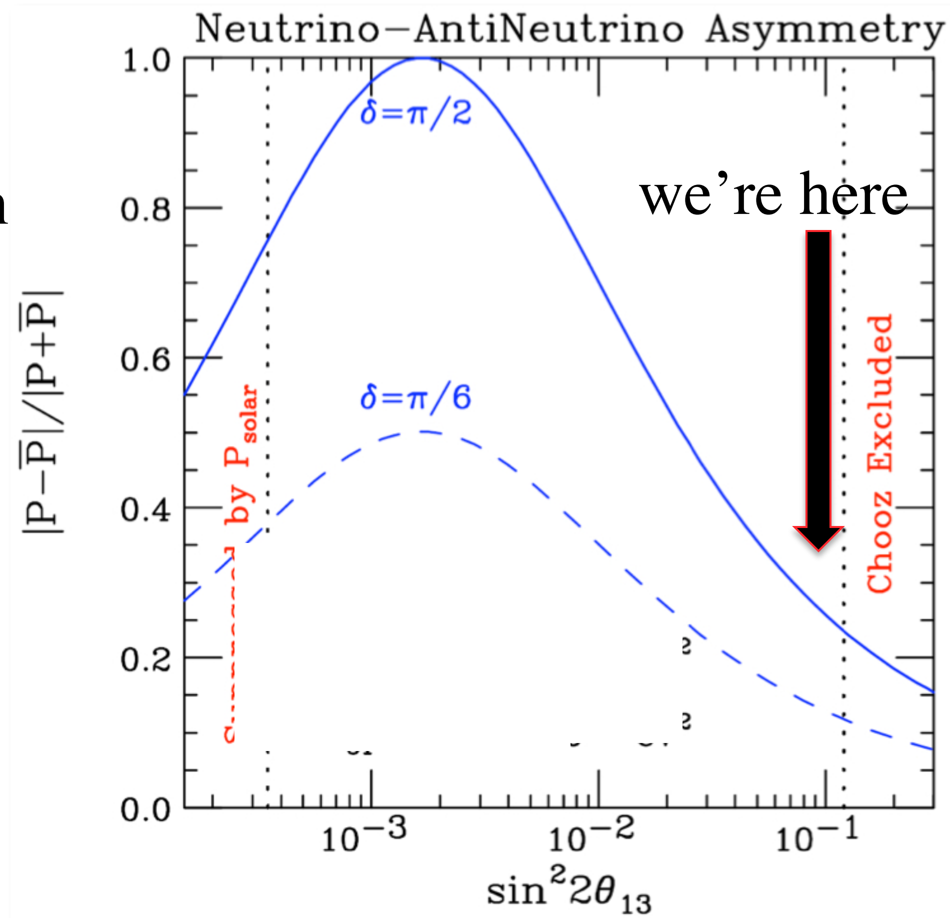
Why are ν_e Cross Sections Important?

- ν_e A – scattering results are interesting on their own.
- Recent determination of large θ_{13} has opened up possibilities of
  - Determining ν mass ordering.
  - Searching for CP-violation in the ν sector.
- To be sensitive to these effects, current/near-future long-baseline experiments will be looking for ν_μ to ν_e and $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillations over a range of energies.
- These will no longer be only "counting" experiments but rather will depend on observing distortions in the far detectors neutrino energy spectrum in **both neutrino and anti-neutrino samples.**



Why are ν_e and $\overline{\nu}_e$ Cross Sections Important?

- Large θ_{13} means we could have reasonable statistics.
- However, as the now-well-known plot at right suggests, the asymmetry between ν and $\overline{\nu}$ will be small and the goal of constraining the range of δ will demand minimal systematic errors.
- One of these systematics will be our knowledge of ν_e and $\overline{\nu}_e$ cross sections in the relevant energy range.



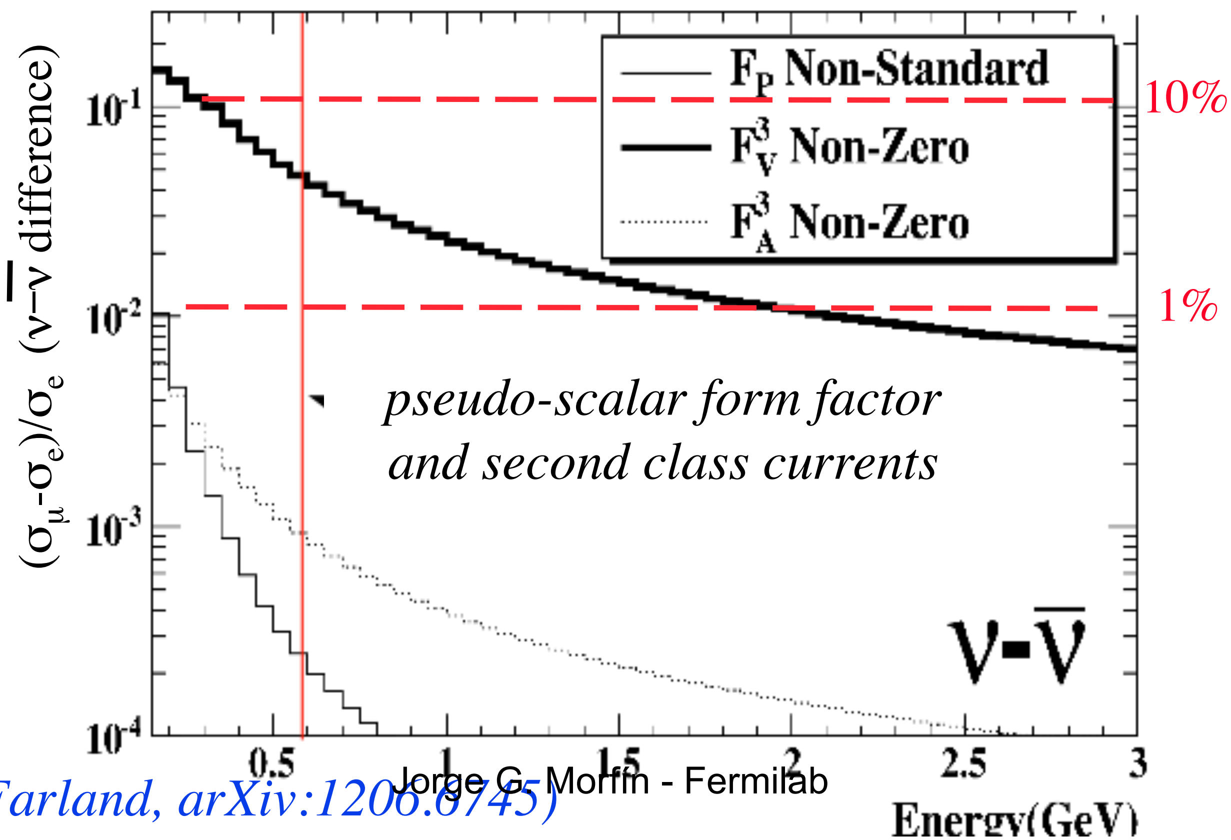
(not including matter effects & backgrounds)

(S. Parke)

What are the Differences $\sigma_{\nu\mu}(E)$ and $\sigma_{\nu e}(E)$? Quasi-elastic Scattering

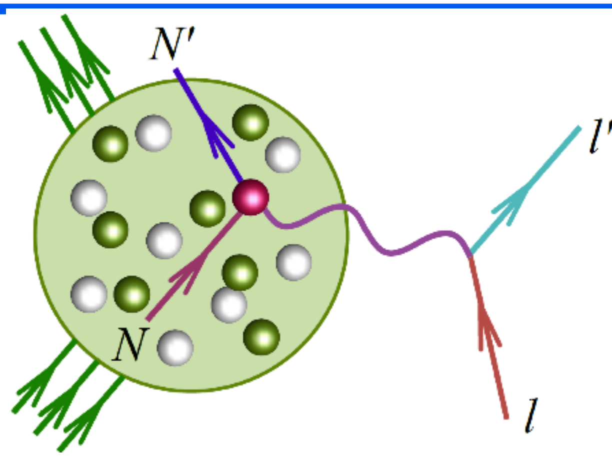
Day-McFarland study: Phys.Rev. D86 (2012) 053003

- Sources of possible differences: form factor uncertainties entering through lepton mass alterations - much more subtle:
  - Form factor contributions – both Axial and Pseudoscalar
  - Second class current contributions to vector and axial-vector form factors
- Possible contribution to CP uncertainties: effect on the FF could be different for ν and $\bar{\nu}$



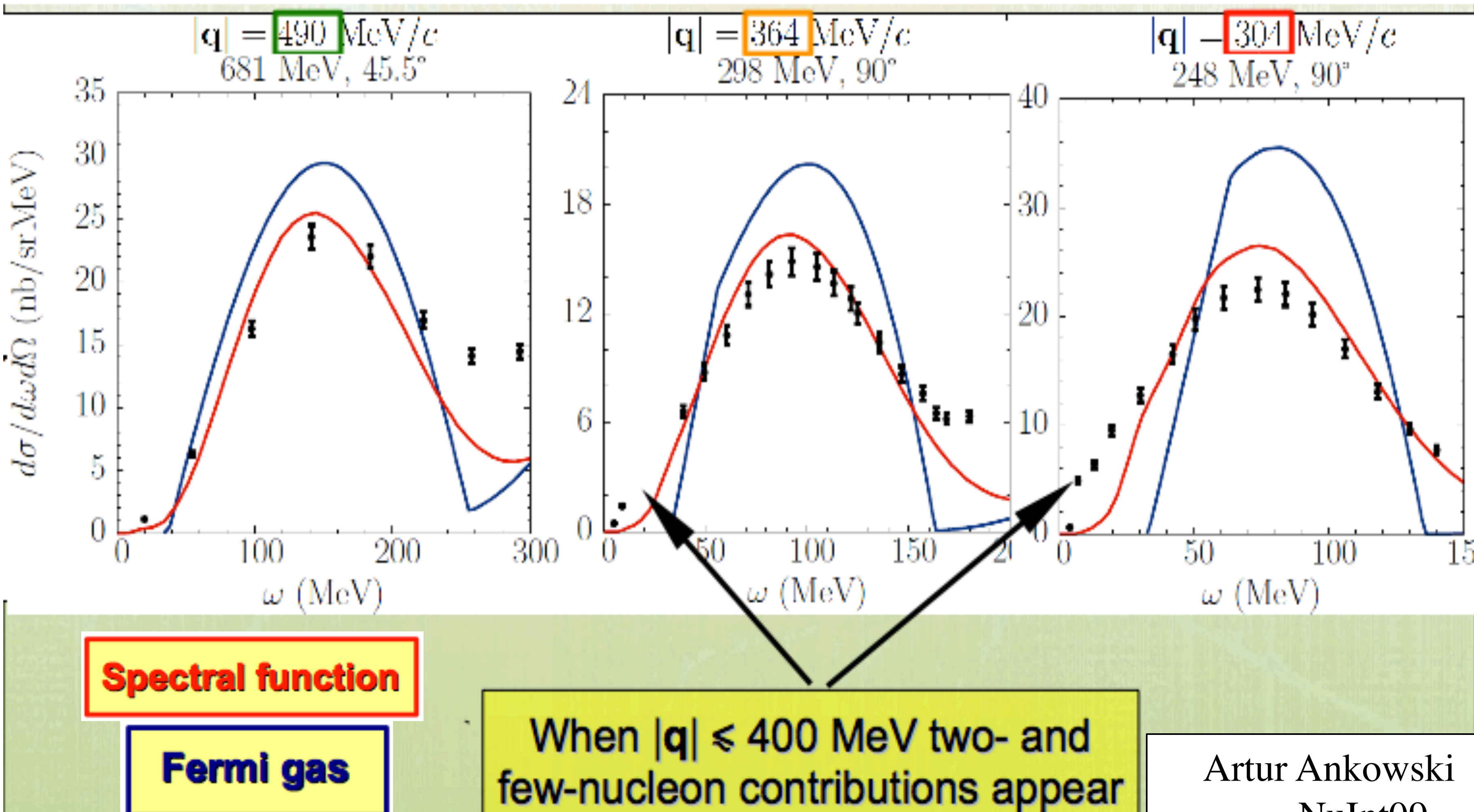
(M. Day, K. McFarland, arXiv:1206.6745)

Target Nucleon in Motion – Classical Fermi Gas Model or the Superior Spectral Functions



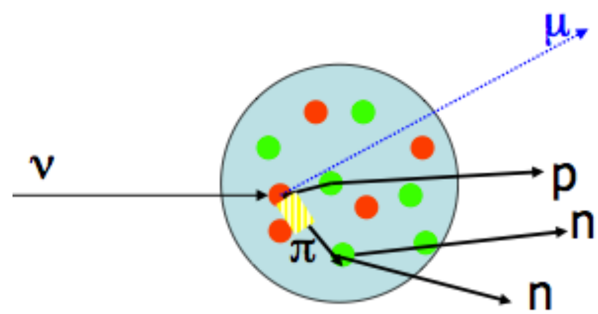
- Impulse Approximation (IA) – nucleus treated as a collection of independent nucleons – no collective excitations
  - breaks down as Q decreases with spatial resolution decreasing as 1/Q
- In the IA the nucleus is fully described by its spectral function
  - The spectral function gives the distribution of momenta and energies of the nucleons inside the nucleus
- The original model to describe this distribution is the Fermi Gas model

Spectral Function Approach Superior – Particularly as Q Decreases



Artur Ankowski
NuInt09

Final State Interactions (FSI)

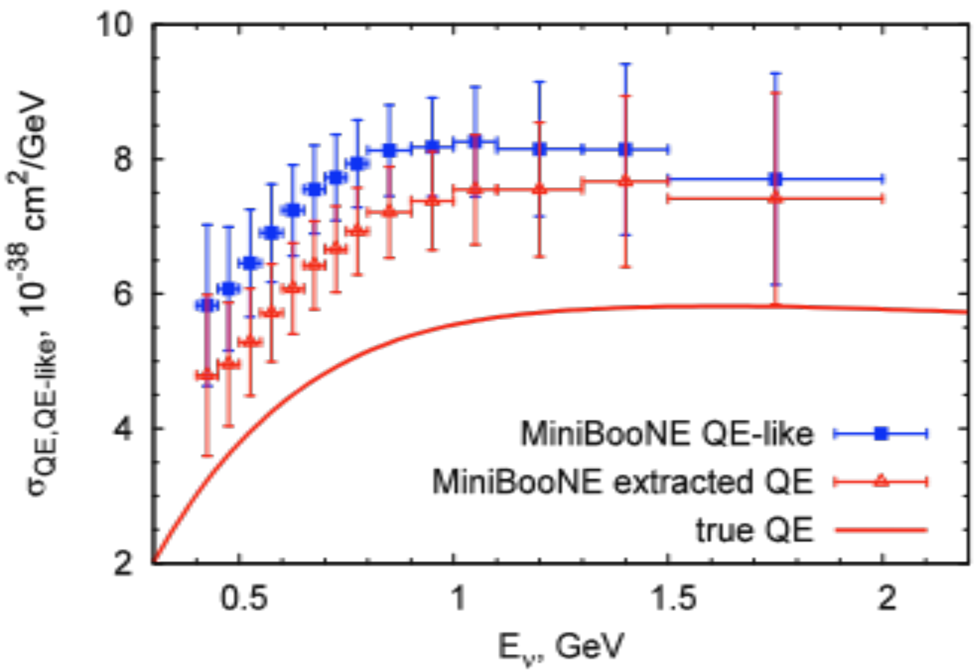


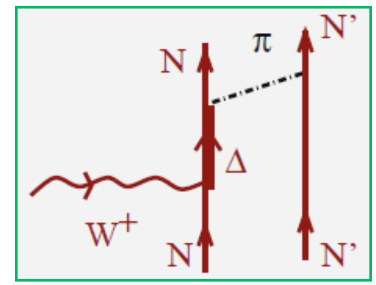
- Components of the initial hadron shower interact within the nucleus changing the apparent final state configuration and even the detected energy.
- For example, an initial pion can charge exchange or be absorbed on a pair of nucleons and an initial nucleon can scatter producing a pion

Example numbers	**Final μ p**	**Final μ p π**
Initial μ p	90%	10%
Initial μ p π	25%	75%

Attempt to Remove Resonance Background

MiniBooNE Experiment example



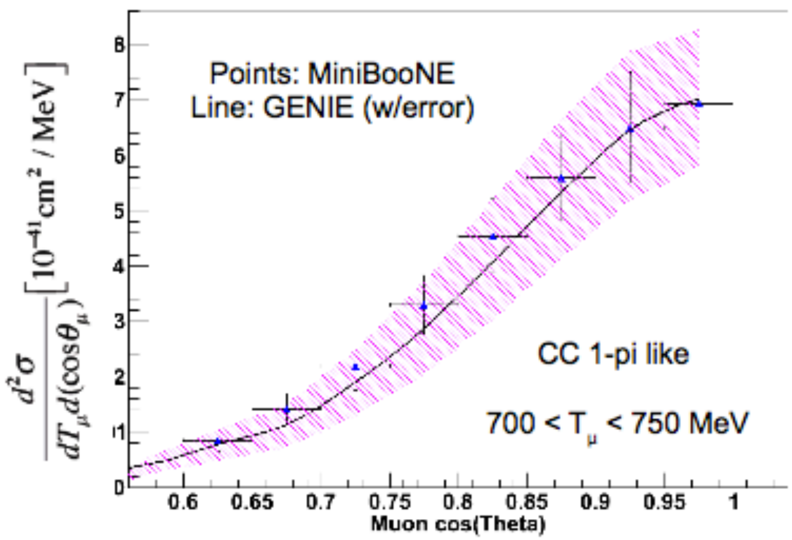


Event generator – a particular model - is used to remove QE-like background (pion absorption) from QE-like Xsect (blue) yielding an extracted QE Xsect (red)→ large pion absorption model dependence of QE result.

Example: Interplay of Cross section and Nuclear Effects

- Challenges to QE analyses at MINERνA:

Laura Fields, NuInt12



- Measurements depend heavily on the simulation of backgrounds, obtained from GENIE:
  - QEL: BBA05 FF, M_A = 0.99 GeV
  - Resonance: Rein-Segal
  - Coherent: Rein-Segal
  - DIS: GRV94/GRV98 with Bodek-Yang
  - DIS & QEL charm (Kovalenko, Sov.J.Nucl.Phys.52:934 (1990))

Nuclear Model

RFGM with NN correlations
Hadronization Model: AGKY – transitions between KNO-based and JETSET T. Yang, AIP Conf. Proc.967:269-275 (2007))
Formation zone: SKAT μ^2 = 0.08 GeV^2
Intranuclear Rescattering: cascade model; INTRANUKE-hA (*S. Dytman, AIP Conf Proc, 896, pp. 178-184 (2007)*) anchored to π,p/n-Fe data

- **Improvements to GENIE are severely man-power limited! GENIE group needs additional help from the community.**