Energy Reconstruction and Near Detectors

Mark Hartz, University of Toronto
Kevin McFarland, University of Rochester

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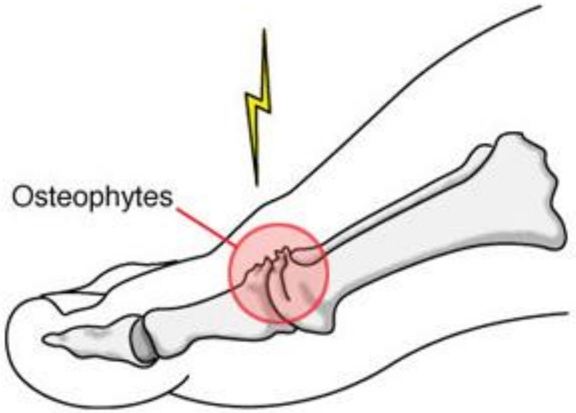
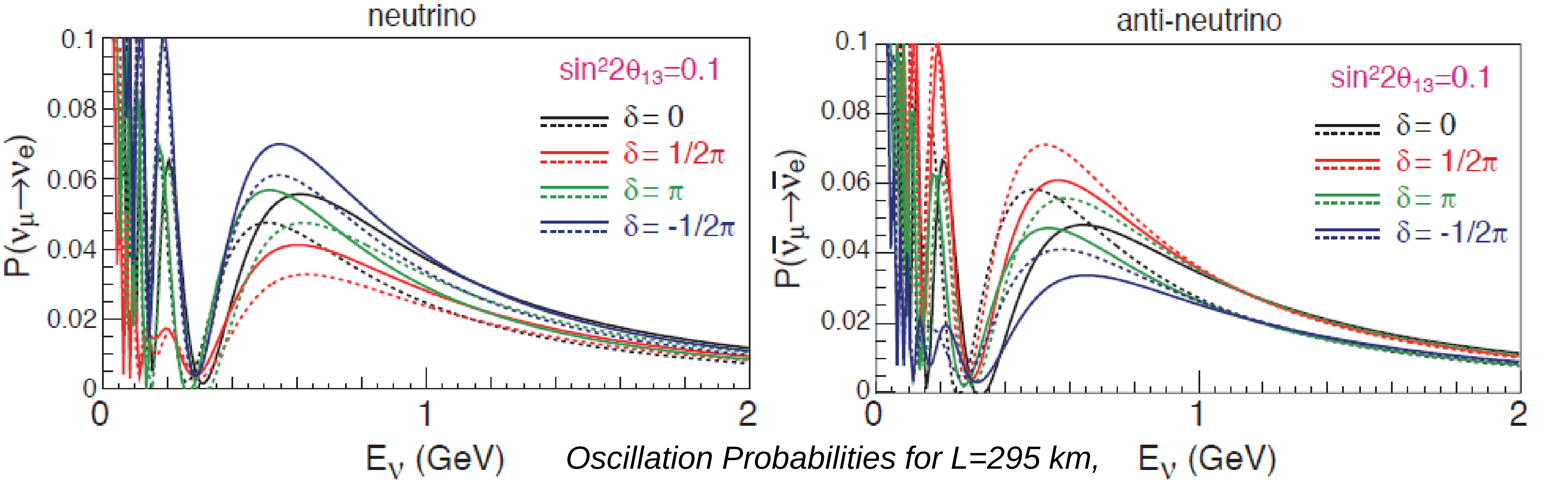
A Time-saving Announcement

- I had surgery on my right foot three weeks ago to attempt to improve symptoms of degeneration of my toe
- Removed osteophytes and resurfaced what little cartilage I have left
- I will be fine as long as no one steps on my foot. ☺



Role of Energy Reconstruction

* Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy



Oscillation Probabilities for L=295 km, Hyper-K LOI

Quasi-Elastic Energy Reconstruction

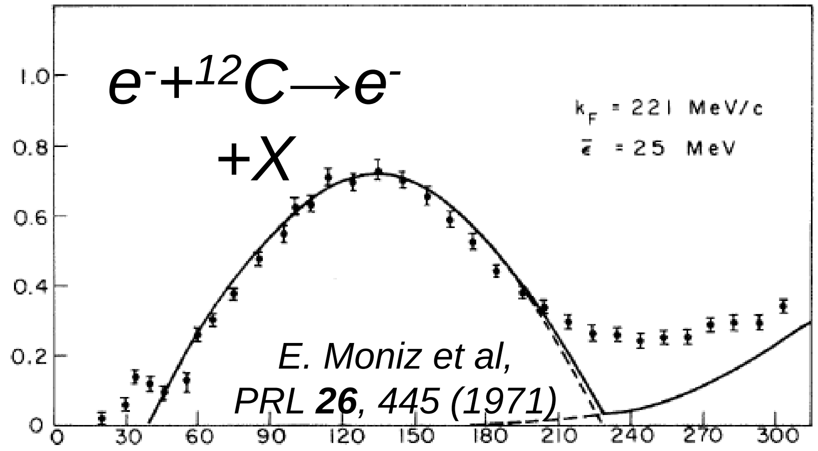
- The quasi-elastic reaction allows neutrino energy to be determined from only the outgoing lepton:

$$E_\nu^{\mathrm{rec}} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e \cos\theta_e)},$$

- This assumes a single target nucleon, motionless in a potential well (the nucleus)
- Smearing due to Fermi motion (and Pauli suppression) are typically built into the cross-section model since smearing cannot be removed on an event-by-event basis.

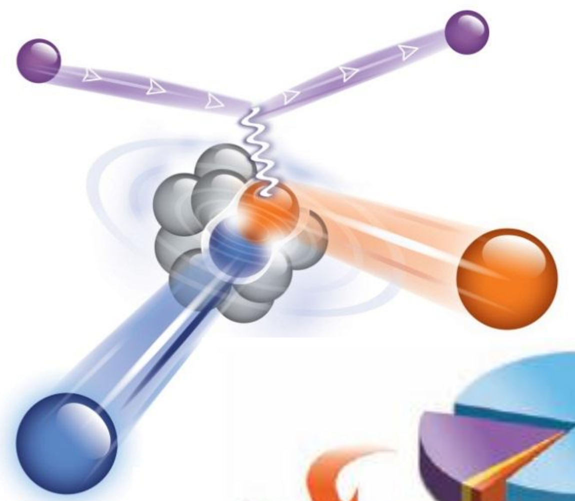
Modeling the Nucleon in a Nucleus

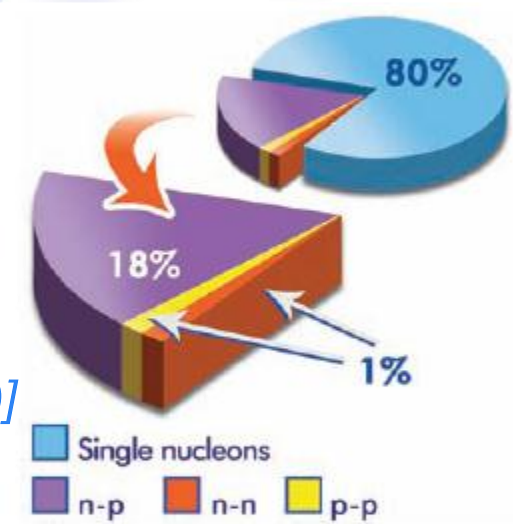
- Our models come from theory tuned to electron scattering
- Generators usually use Fermi Gas model, which takes into account effect of the mean field.
- Corrections to electron data from isospin effects in neutrino scattering.



Short-Range Correlations

- Direct evidence for multi-nucleon correlations exists
- ^{12}C quasi-elastic scattering at Jlab final state studies see multiple nucleons ~20% of the time, mostly pn
  - Have to demonstrate an excess over final state effects

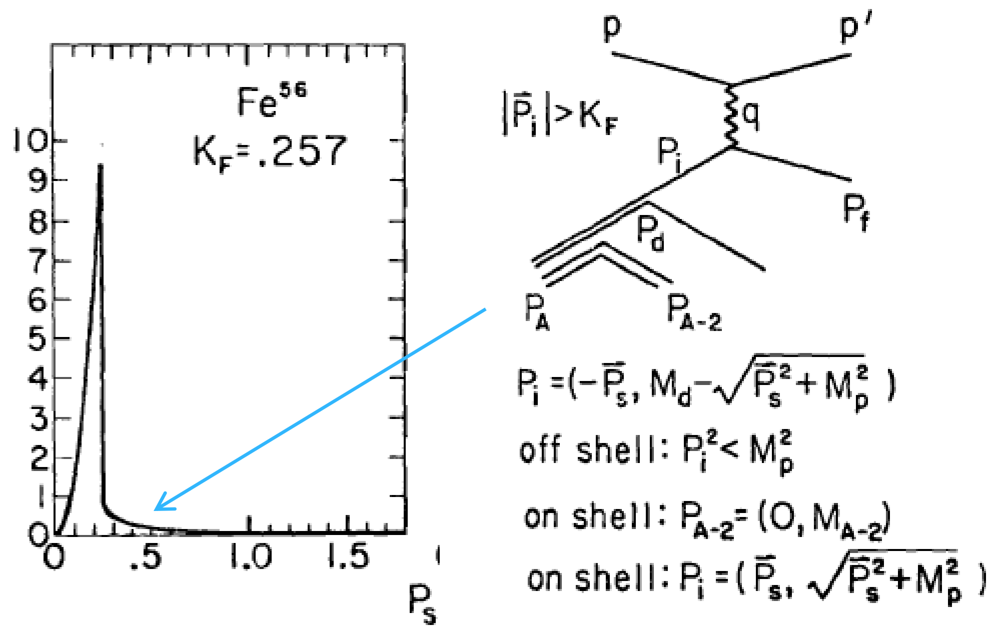




*[R. Subedi et al., Science **320**, 1476 (2008)]*

Quasi-Deuterons?

* In fact, part of this effect has been known for a long time and is accounted for in (some of) our generators



Bodek and Ritchie Phys.Rev. D23 (1981) 1070

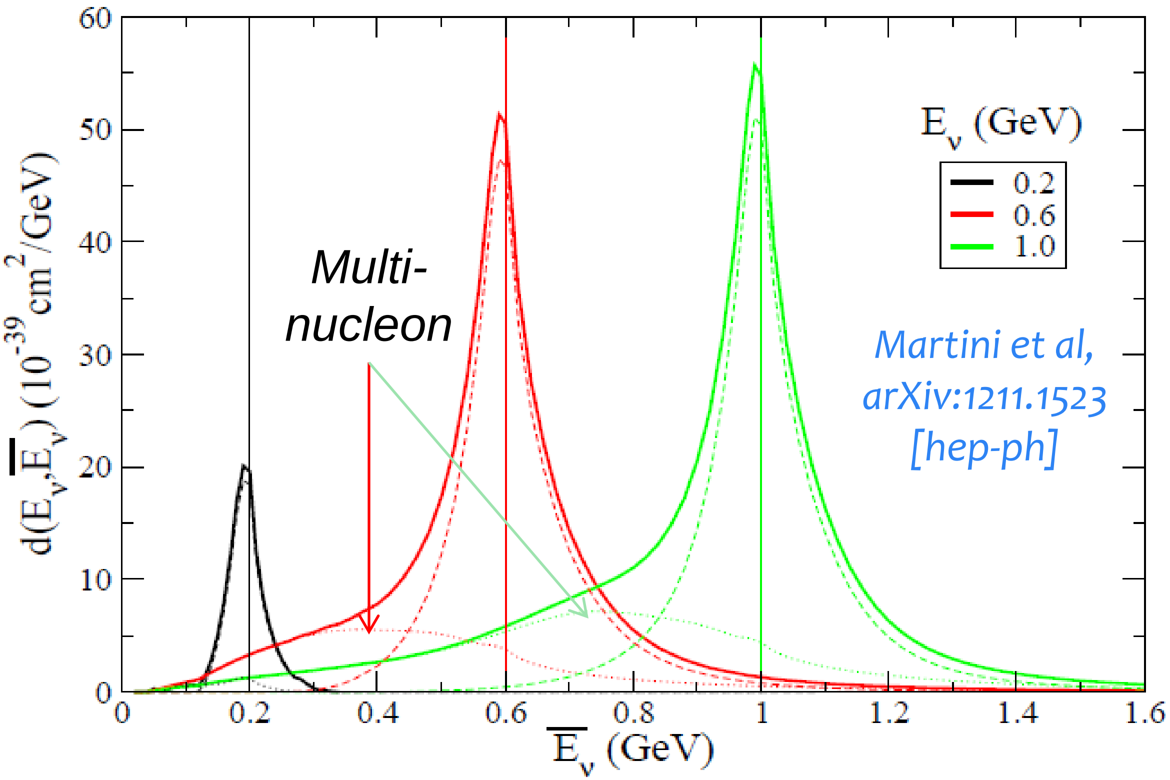
Kinematics of Short-Range Correlations

* Kinematics of interaction may be altered because scattering in nuclear environment occurs from a correlated pair ~20% of the time.
* Not a new idea to apply to quasi-elastic scattering.
* Evidence in charged lepton scattering now strengthens the case for doing so.
* Generally, expect a bias and additional smearing from multi-nucleon effects.

Dekker et al., PLB **266**, 249 (1991)
Singh, Oset, NP **A542**, 587 (1992)
Gil et al., NP **A627**, 543 (1997)
J. Marteau, NPPS **112**, 203 (2002)
Nieves et al., PRC **70**, 055503 (2004)
Martini et al., PRC 80, 065001 (2009)

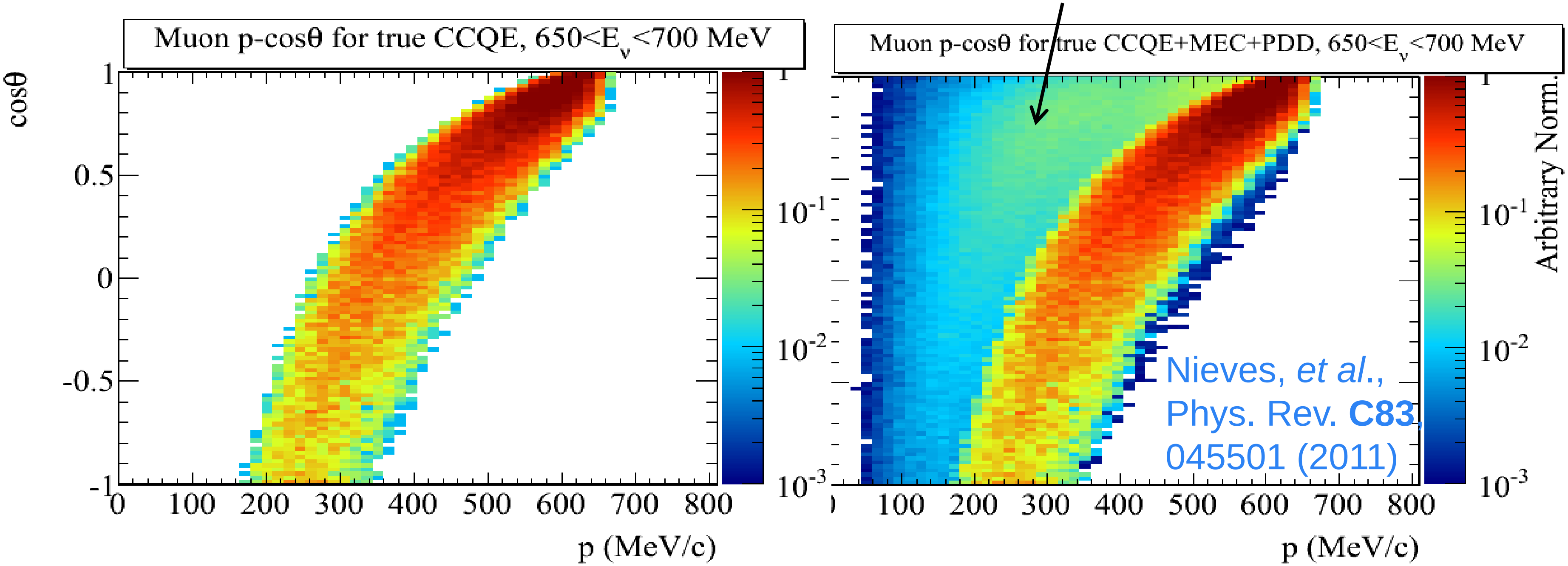
Quantitative Effect on Energy Measurement

- Detailed effect depends on the microphysical models used to calculate effects of multi-nucleon correlations
- No prescription for knowing effect independent of models.



Quantitative Effects in Lepton Kinematics

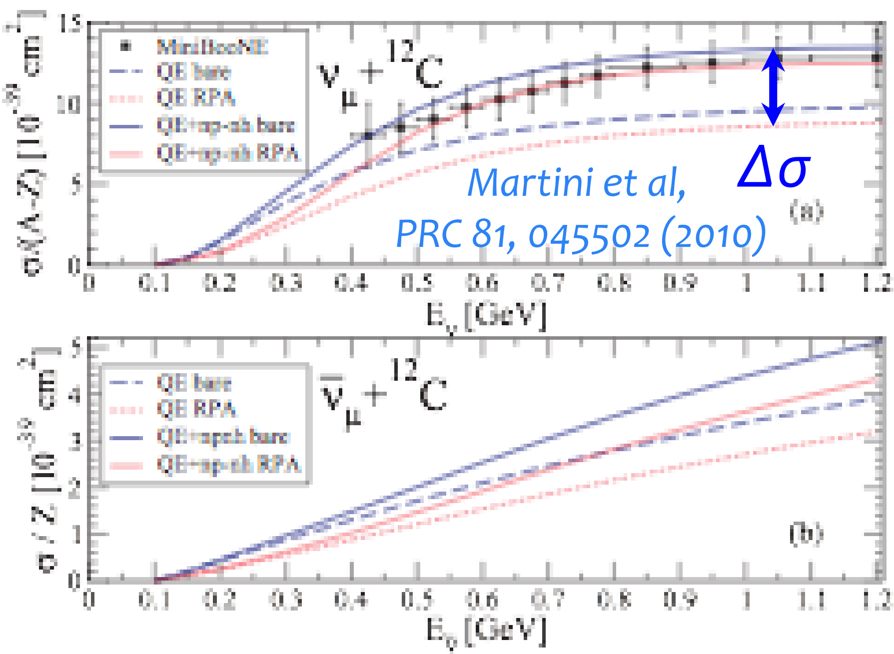
- More instructive to look at effect in space of lepton p-θ
- Nieves model of meson exchange currents
  - This includes processes that give "pionless delta decay" in NEUT



Do we know that these processes affect neutrino scattering?

- Correlations are predicted to increase cross-section. Consistent with MiniBooNE data.

$\nu_\mu n \rightarrow \mu^- p \quad + \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$



Recent Work

Nieves *et al*., arXiv:1106.5374 [hep-ph]
Bodek *et al*., arXiv:1106.0340 [hep-ph]
Amaro, *et al*., arXiv:1104.5446 [nucl-th]
Antonov, *et al*., arXiv:1104.0125
Benhar, *et al*., arXiv:1103.0987 [nucl-th]
Meucci, *et al*., Phys. Rev. **C83**, 064614 (2011)
Ankowski, *et al*., Phys. Rev. **C83**, 054616 (2011)
Nieves, *et al*., Phys. Rev. **C83**, 045501 (2011)
Amaro, *et al*., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]
Martinez, *et al*., Phys. Lett **B697**, 477 (2011)
Amaro, *et al*., Phys. Lett **B696**, 151 (2011)
Martini, *et al*., Phys. Rev **C81**, 045502 (2010)
[compilation by G.P. Zeller]

Limitations of Microphysical Models

- There are several microphysical calculations on the market, but they share several key features.
  - They are all based on effective theories valid over limited ranges of energy, kinematics. Theoretical systematics are difficult to control.
  - Calculations are just starting to see effect in the right set of variables (inclusive lepton energy and angle) for high precision comparison with data, prediction of kinematic effects.
- My personal conclusion: calculations need more experimental validation before they are reliable.

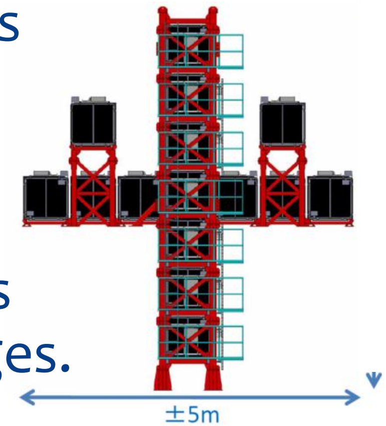
Near Detectors

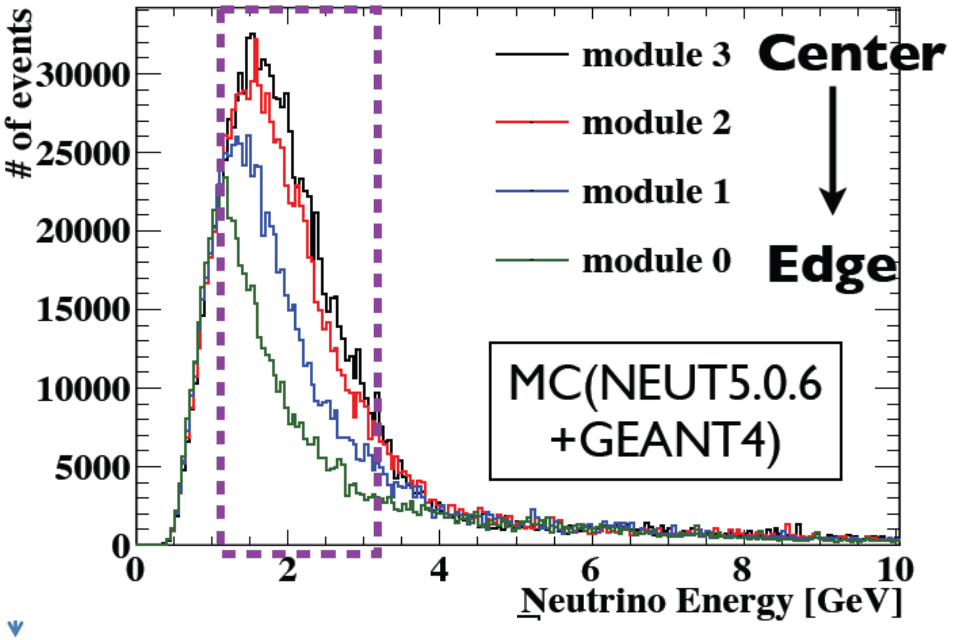
Near Detectors and Oscillations

* Near detectors measure an event rate
  * Convolution of flux and cross-section
* Converting from a near detector rate to a far detector prediction with oscillations has limitations
  * In particular, if there is a common mistake in energy reconstruction, then the oscillation probability will not be correctly applied
* Backgrounds and differences in flux only make the problem more difficult to disentangle

Can we address the Energy Reconstruction Problem?

- Near detectors with a perfectly known, and preferably tunable, flux would allow a measurement of neutrino energy biases and smearing.
- How to get this?
- Observation from T2K INGRID team: Low and high tails of flux similar as move off-axis
- Narrow range of neutrino energies where flux changes.

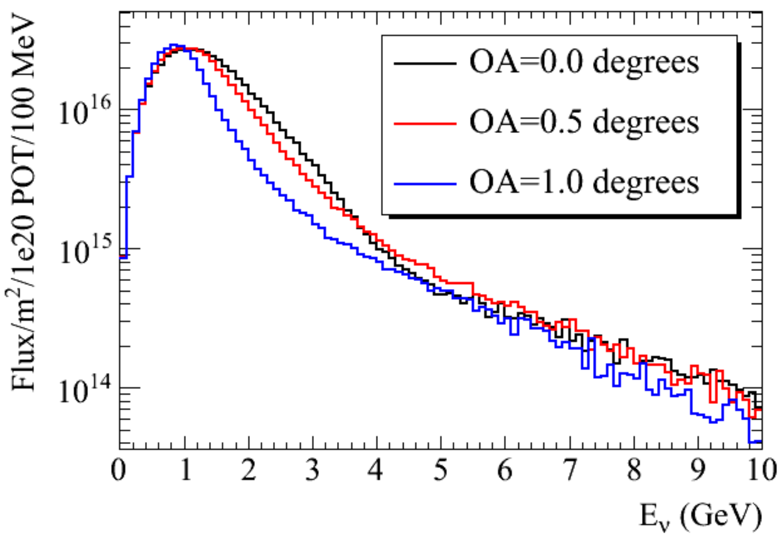


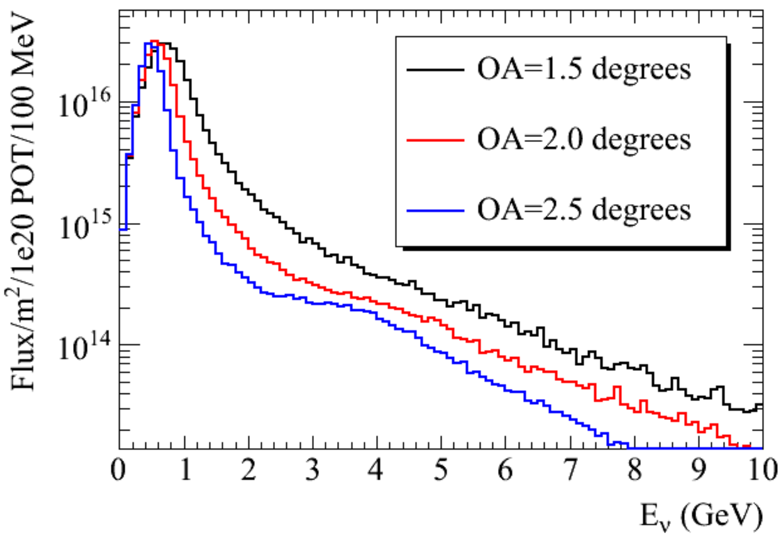


First Study: 280m Near Detector

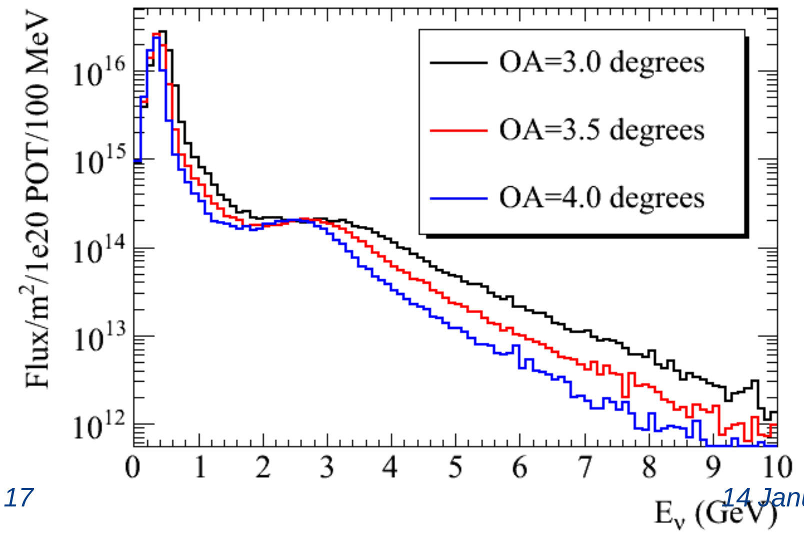
* Situate 1mx1m detectors every 0.5 degrees of off-axis angle at the 280m location
  * 2.5m spacing: could reduce this spacing
* Eventual strategy would be to make detailed measurements as a function of position and use the correlation of position with neutrino energy to derive response functions vs. neutrino energy
* This first analysis is a much simpler proof of principle.

Flux at Different Angles



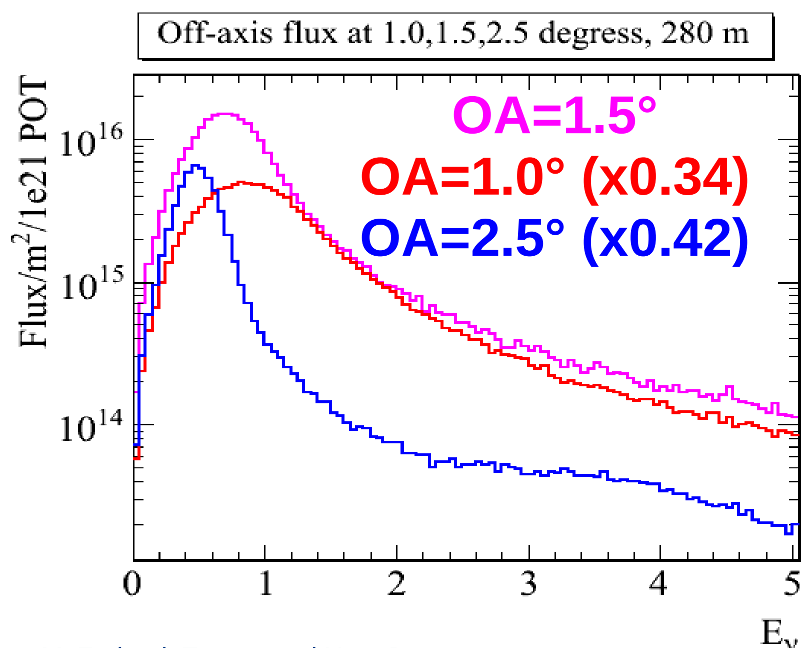


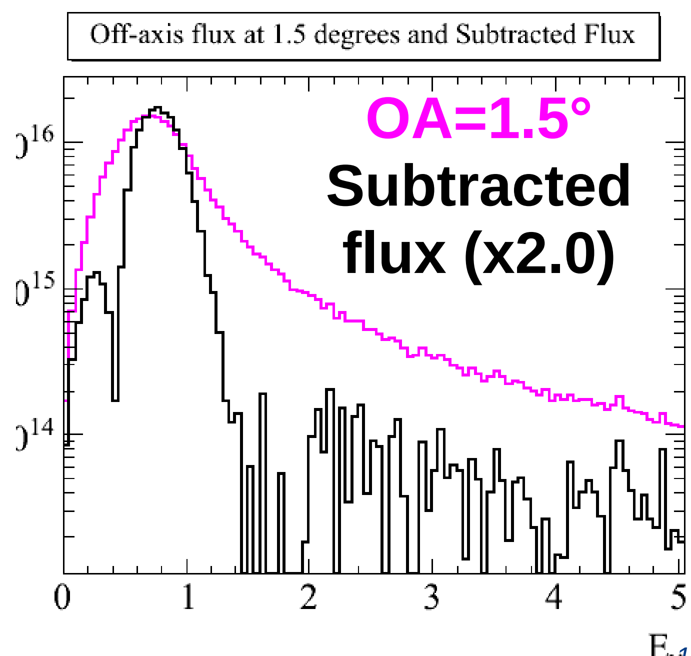
- Cancelations are simplest closest to the axis
- At large angles, more complicated, but combinations of angles still select definite energies



First Study: Simple Linear Combinations

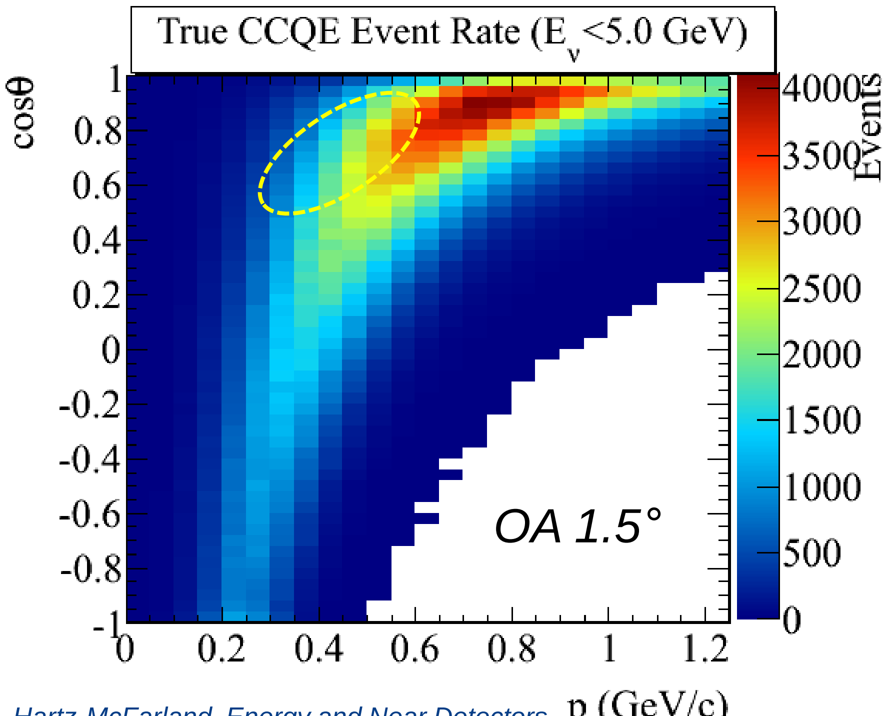
* Can do a pretty good job reproducing the high energy and low energy fluxes with simple linear combinations of nearby angles: $\varphi_{sub} = \varphi(1.5^{\circ}) - 0.34\varphi(1.0^{\circ}) - 0.42\varphi(2.5^{\circ})$

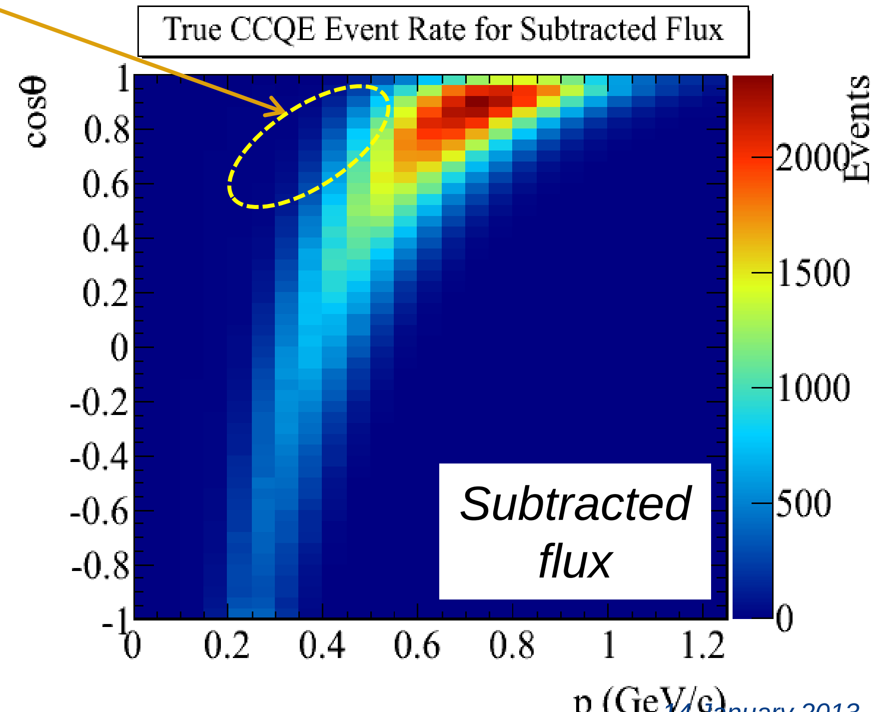




Comparison of "True CCQE" Lepton Kinematics

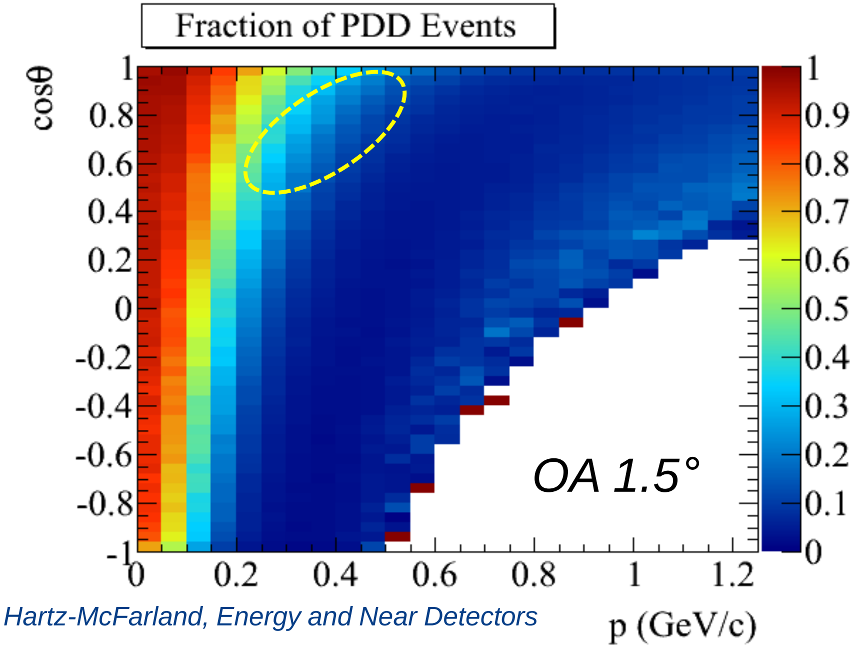
- Narrower "subtracted flux"
  more sharply peaked lepton p-θ, as expected
- More sensitivity to region of altered multinucleon kinematics

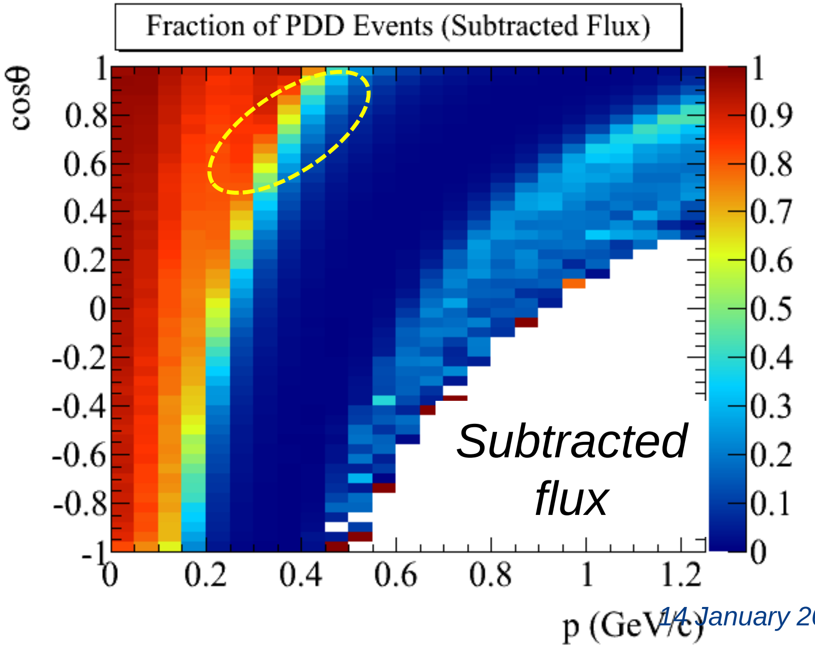




Metric of Sensitivity

- Use the NEUT model for pionless delta decay (PPD)
  - Chose this for convenience… microphysical models are not complete for neutrino energies above 1.5 GeV
- Look at ratio of PPD to total cross-section





Conclusions

Major Points

- Neutrino energy reconstruction is most likely altered by multi-nucleon effects
  - Models of these effects are difficult to construct and are "effective" models. Perhaps not sensible to trust our success to these models without testing.
- By looking at ensembles of water target detectors at different off-axis angles, can construct a "narrow band" derived beam
- First demonstration of the idea in a simple way.

Next Steps

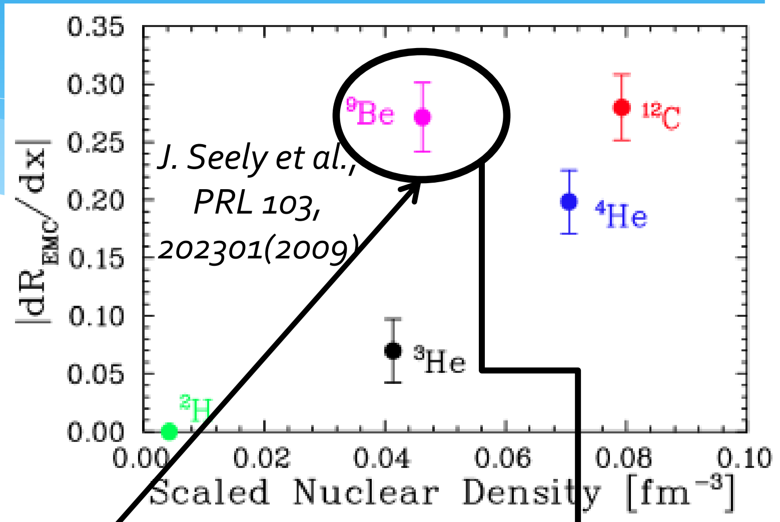
* Optimize off-axis angles and fitting procedure for effective "narrow band" beam
* Repeat sensitivity study with different multi-nucleon models (not just NEUT pionless delta decay)
* Update studies with all interaction modes to understand the effect of backgrounds
* Make some reasonable assumptions about detector efficiencies and resolutions
* Proceed to detector design

Backup

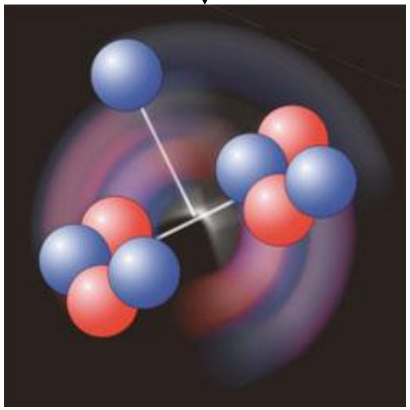
Mean Field Approximation?

* There are many hints that the mean field approach isn't sufficient.

- *EMC effect: modification of inclusive cross-section*
- *Recently, study of "size" of EMC effect in nuclei led to the conclusion that effect seems to vary with local rather than global density of nucleus*



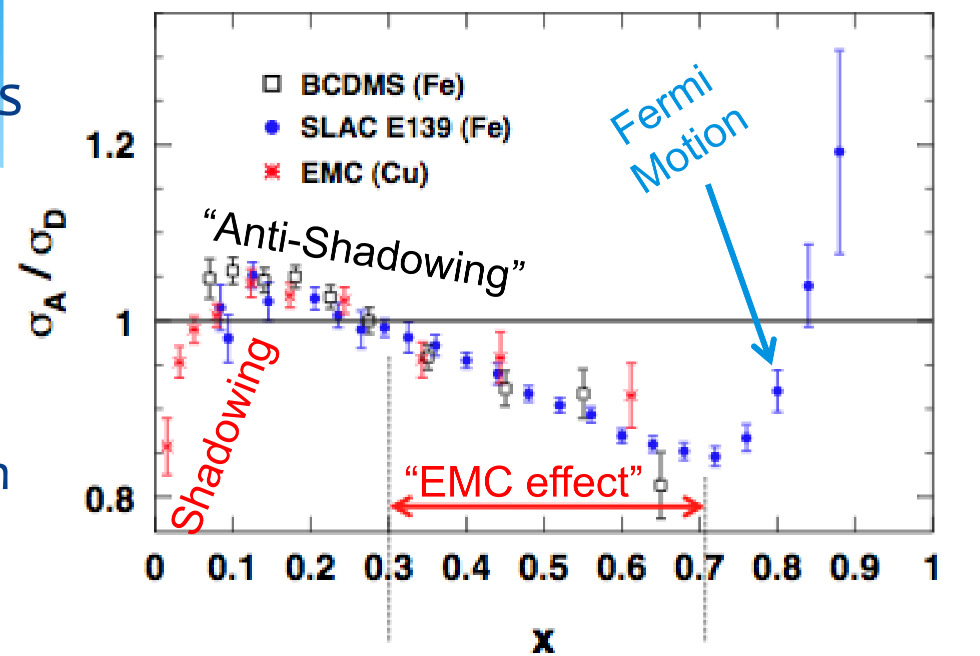
^{9}Be is two tightly bound α loosely held with a neutron



(Figure courtesy APS Phys Rev Focus)

A Long-Standing Puzzle: The EMC Effect

- Charged lepton F_2^A/F_2^D shows convincingly modification of quark distributions in a nucleus
  - No model of nucleus as an incoherent sum of nucleons can reproduce this effect.
  - No conclusive model of the collective behavior exists.

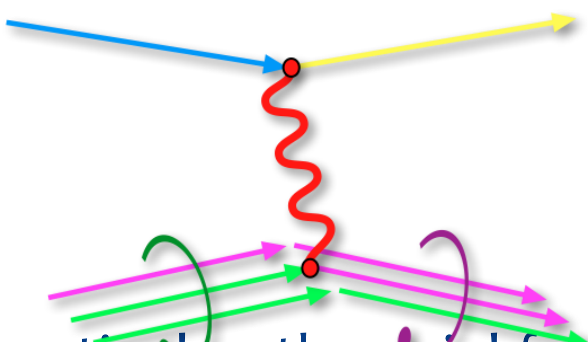


(D. Gaskell, ECT*, Hadrons in the Nuclear Medium)

- Empirically, we know that the qualitative dependence on x is the same for all nuclei
  - But size of effect varies with the nucleus studied

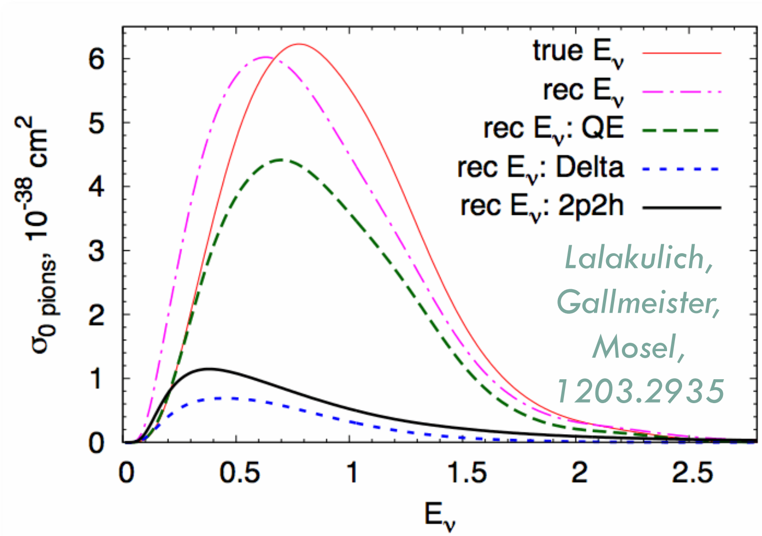
Quasi-Elastic Questions

* Cross-section depends on empirical form factors



* In particular, the axial form factor, $F_A(Q^2)$, from M_A
  * Vector form factors measured precisely in e- scattering (Bodek, Budd, Bradford, Arrington Nucl.Phys.Proc.Suppl.159:127-132,2006)
  * PCAC gives pseudoscalar $F_P(Q^2)$

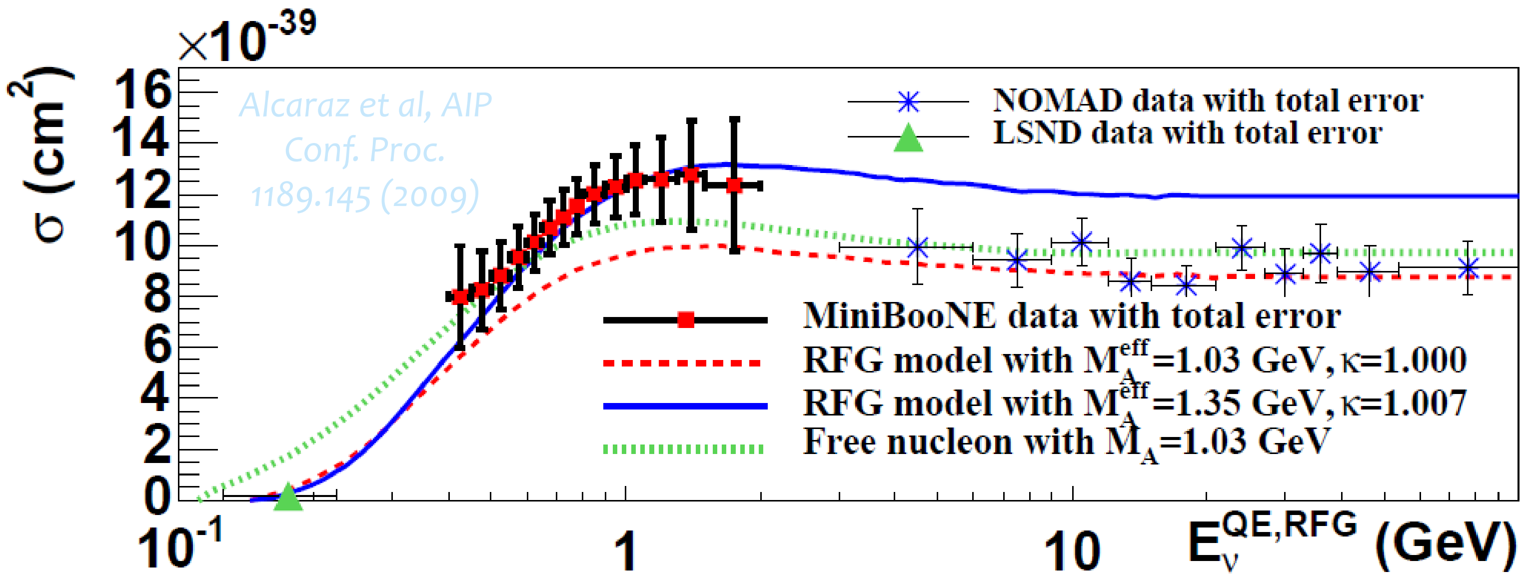
* Oscillation experiments use CCQE to estimate energy from reconstructed lepton
* Nuclear physics can modify estimated energies



ex: Mosel/Lalakulich 1204.2269, Martini et al. 1202.4745, Lalakulich et al. 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

"Axial Mass Puzzle"

- As described earlier, M_A has been measured to be 1.03 GeV/c² in νD_2 and pion electroproduction
  - A slew of low energy data (MiniBooNE, SciBooNE, K2K) prefers a higher axial mass and therefore higher σ
  - What is going on in the nuclear environment to create this effect?



Posters:

MINOS 205-1 *(progress report)*

MiniBooNE 119-2 *(outside fits to MiniBooNE)*