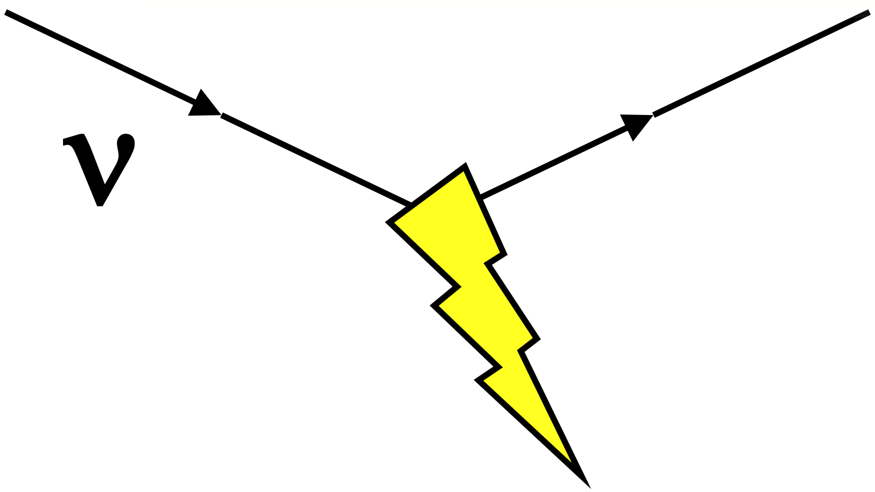
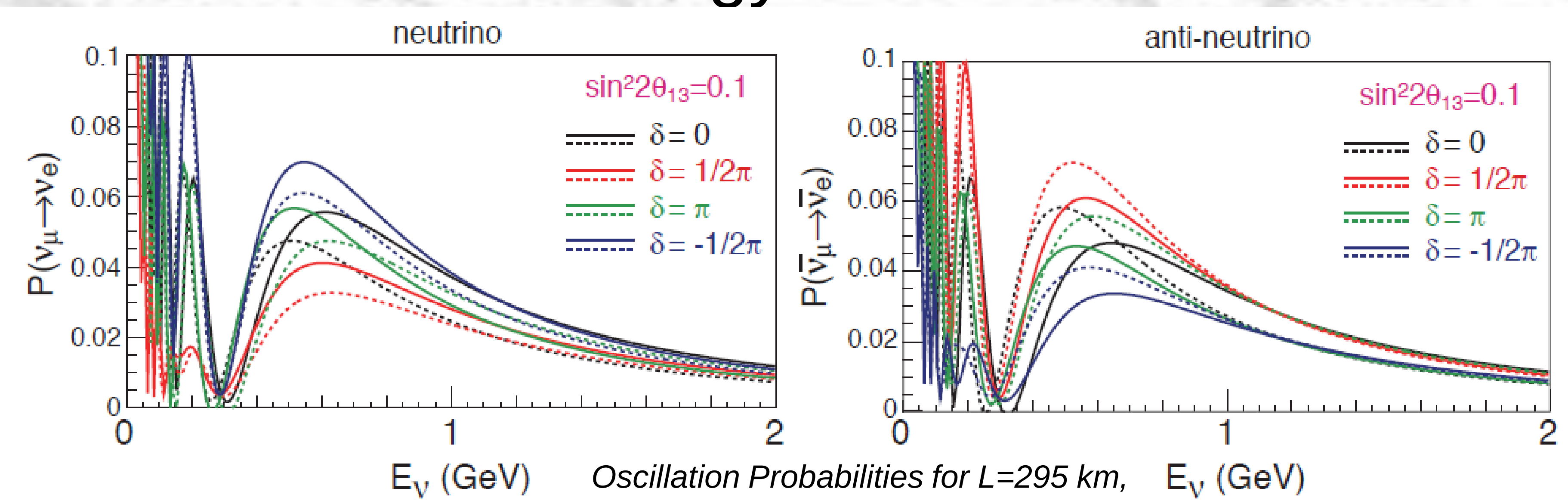
Irreducible Systematics from Neutrino Interactions?



Kevin McFarland
University of Rochester
HyperK Open Meeting
Kavli IPMU
22 August 2012

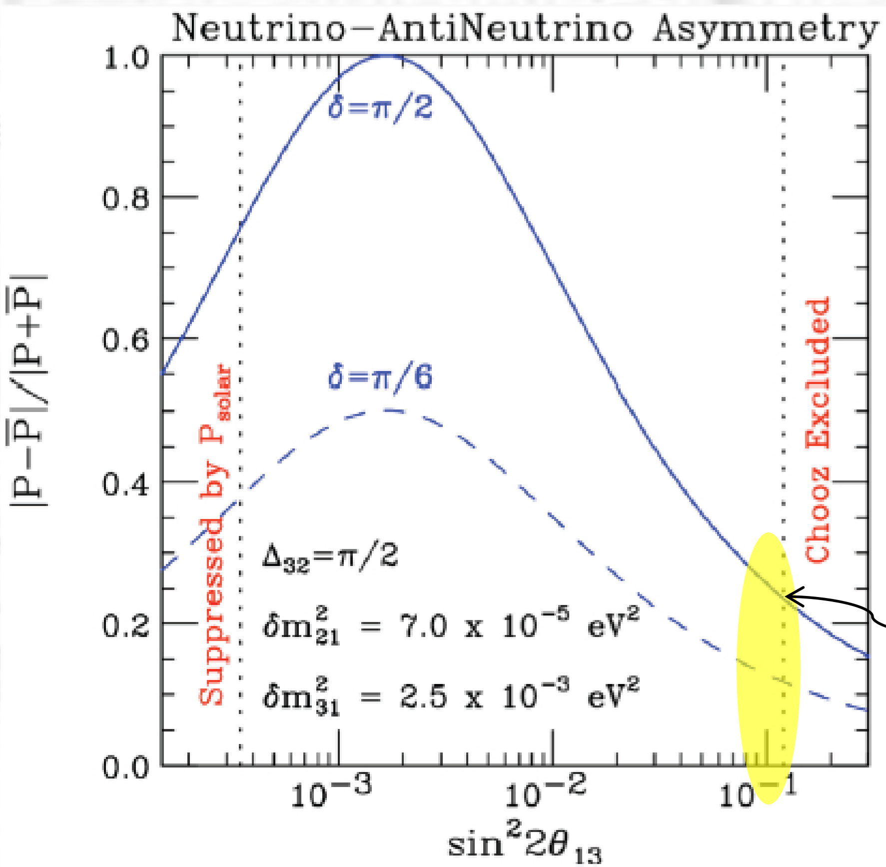
Introduction: Needs

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



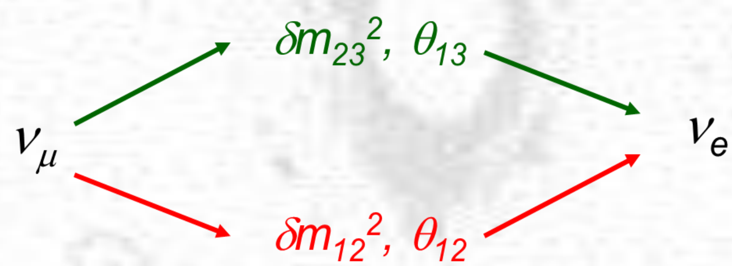
Oscillation Probabilities for L=295 km, Hyper-K LOI

Introduction: Large θ_{13}



(Parke 2003, arXiv:0710.554)

- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases



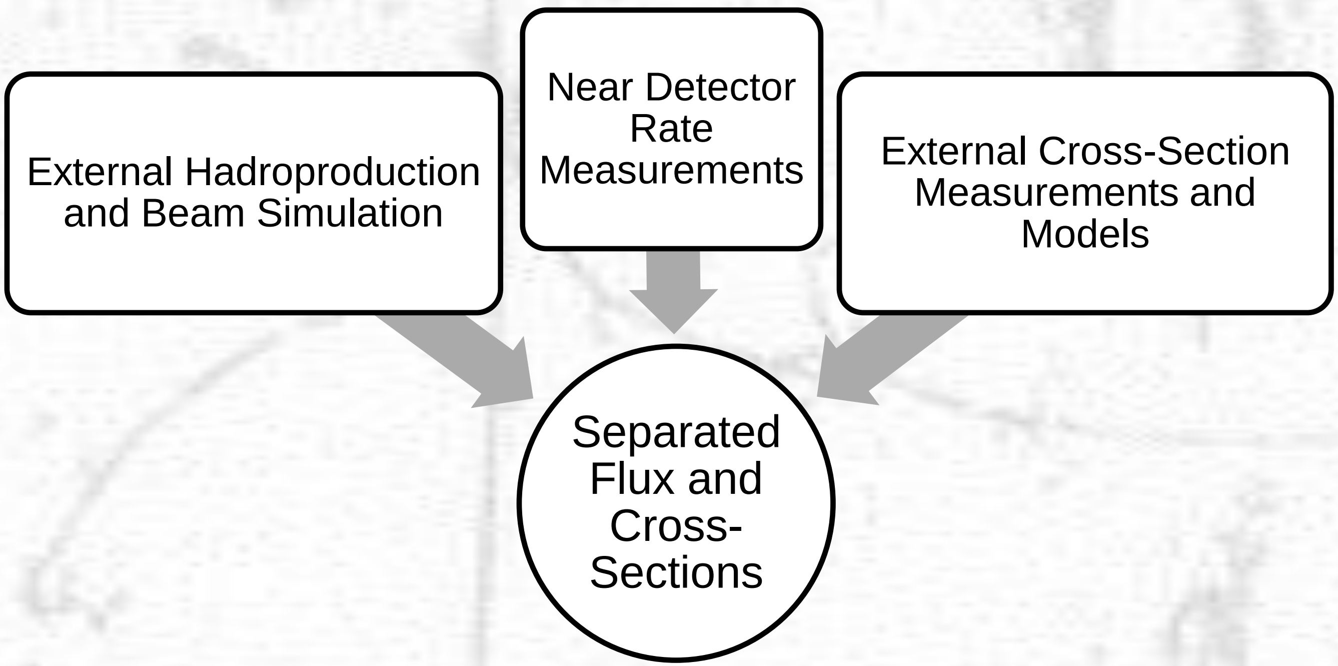
- Nature put us here
- As we all know, that puts us in the position of having good statistics, but systematics become more important.

Introduction: Near Detectors

- Near detectors are a powerful tool for constraining uncertainties in flux and cross-sections
- Limitations of even “perfect” near detectors:
  1. Flux is never identical near and far, because of oscillations if for no other reason.
  2. Neutrino energy may be smeared or biased.
  3. Near detector has backgrounds to reactions of interest.
  4. Near detectors measure (dominantly) interactions of muon neutrinos when signal is electron neutrinos.

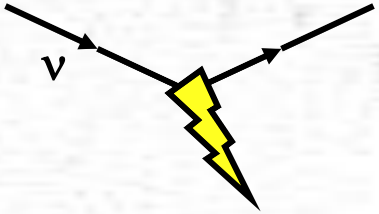
Introduction: Breaking the Flux & σ Degeneracy

- As Mark Hartz just told you, T2K has developed a process for using the near detector data to get flux and cross-section



Introduction: Irreducible?

- Use of near detector to measure flux and cross-sections is particularly vulnerable to deficiencies in the cross-section model.
- Two examples may be of concern in the Hyper-Kamoikande era
  - Differences between muon and electron neutrino cross-sections.
  - Inability to reconstruct energy due to nuclear effects.

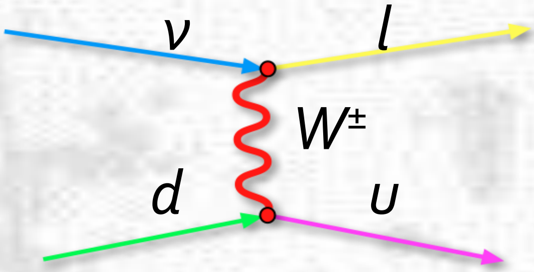


LEPTON MASS IN NEUTRINO CROSS-SECTIONS

Based on Melanie Day and Kevin McFarland,
"Differences in Quasi-Elastic Cross-sections of Muon and Electron Neutrinos", http://arxiv.org/abs/1206.6745,
to appear in PRD.

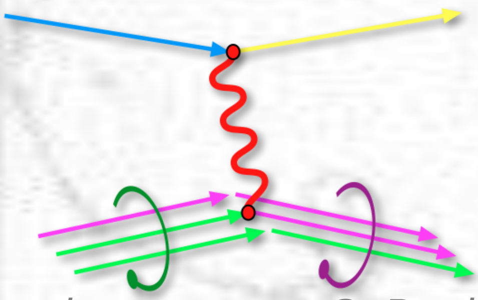
Models of Neutrino Interactions

Fermi theory (plus parity violation) is still a successful effective theory for point-like targets.



Leptonic current is perfectly predicted in SM…
…as is the hadronic current if we had free quarks.

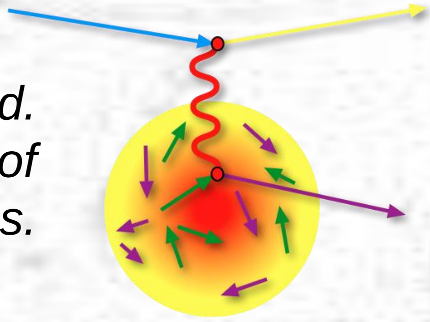
For inclusive scattering from a nucleon, add PDFs for a robust high energy limit prediction



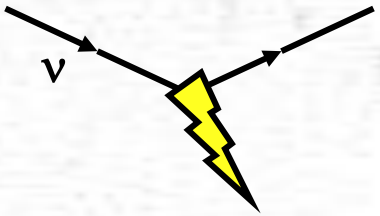
For exclusive, e.g., quasi-elastic scattering, hadron current requires empirical form factors.

(drawings courtesy G. Perdue)

If the nucleon is part of a nucleus, it may be modified. Also, exclusive states are affected by interactions of final state hadrons within the nucleus.

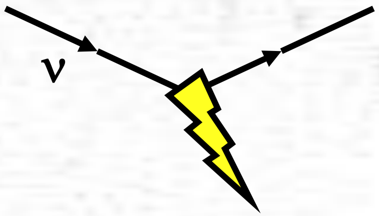


Quasi-Elastic Scattering



- Straightforward to write framework for quasi-elastic scattering on nucleon, e.g., Ch. Llewellyn-Smith, Phys˙Rept. 3C, 261–379 (1972).
- There are many cross-section differences that we understand. But uncertainties in form factors of nucleon lead to uncertainties in the differences of muon and electron neutrino reaction rates.
- Six allowed form factors of the nucleon that enter:
  - Two “ordinary” vector and one axial form factor
    - Vector form factors can be measured in electron scattering. Axial form factor from pion leptoproduction, neutrino CCQE on D_2.
  - One pseudoscalar form factor
    - Predicted by PCAC and Goldberger-Treiman to be small.
  - One vector and one axial “second class” current
    - Assumed to be zero because they violate charge symmetry (not a perfect symmetry, e.g., $m_n \neq m_p$) in nucleon system.

Quasi-Elastic Scattering (cont'd)



- Avert your gaze…

$$\frac{d\sigma}{dQ^2}\left({}^{\nu n\to l^- p}_{\overline{\nu} p\to l^+ n}\right) = \left[A(Q^2) \mp B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\right] \times \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}$$

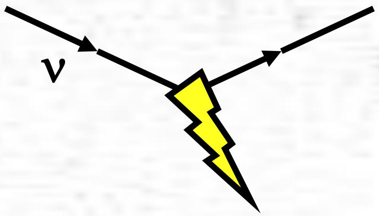
$$\begin{aligned} A(Q^2) = \frac{m^2+Q^2}{4M^2}\Bigg[&\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\xi|F_V^2|^2\left(1-\frac{Q^2}{4M^2}\right) + \frac{4Q^2 ReF_V^{1*}\xi F_V^2}{M^2} \\ &- \frac{Q^2}{M^2}\left(4+\frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi F_V^2|^2 + |F_A+2F_P|^2 - \left(4+\frac{Q^2}{M^2}\right)\left(|F_V^3|^2+|F_P|^2\right)\right)\Bigg], \end{aligned}$$

$$B(Q^2) = \frac{Q^2}{M^2} ReF_A^*\left(F_V^1+\xi F_V^2\right) - \frac{m^2}{M^2} Re\left[\left(F_V^1 - \frac{Q^2}{4M^2}\xi F_V^2\right)^* F_V^3 - \left(F_A - \frac{Q^2 F_P}{2M^2}\right)^* F_A^3\right] \text{ and}$$

$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right).$$

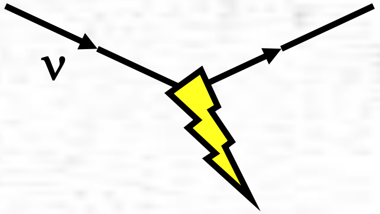
  - Two terms, including those with F_P, and $F^3{}_V$, enter with a factor of m^2/M^2. These are relevant for muon neutrinos at low energies but not for electron neutrinos.

Know Nothing Approach

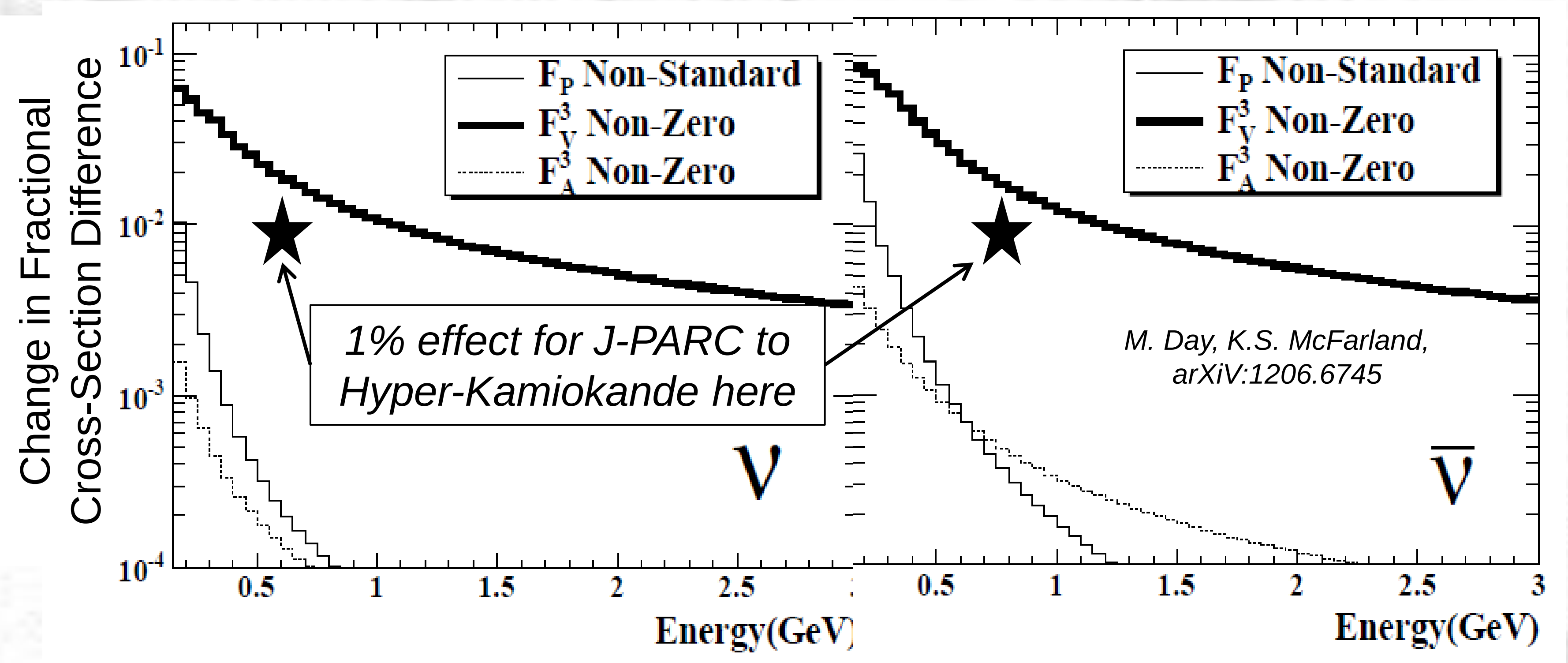


- We decided to look at how large the possible effects of non-standard or unconstrained form factors could be, independent of theoretical prejudice.
  - Constraints on second class currents primarily from beta decay and muon capture.
  - Pseudoscalar form factors and axial form factor measured in pion electroproduction.
  - Vector form factors from electron-nucleon elastic scattering.

Results for Neutrino Cross-Section Differences



- Possible effect from F^3_V of few % at J-PARC to HK
  - Neutrino and anti-neutrino effects are opposite in sign for second class currents, so could fake a CP asymmetry.

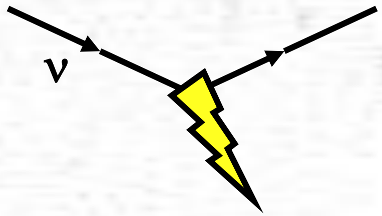


Can we reduce this uncertainty?

- Yes, on the timescale of J-PARC to HK, by studying neutrino interactions.
- High statistics neutrino and anti-neutrino muon neutrino CCQE has potential to constrain second-class currents
  - Effect is distinctive in Q^2 and energy.
  - Only seen in muon neutrinos.
  - MINERvA, T2K, NOvA should have useful data.
- Can study muon and electron neutrinos together with a muon decay source, e.g., NuStorm.

NUCLEAR EFFECTS IN ENERGY RECONSTRUCTION

Quasi-Elastic Energy Reconstruction

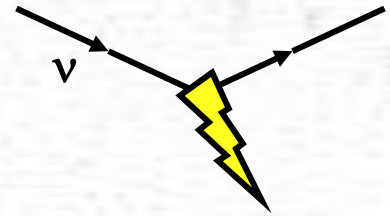


- Quasi-elastic reaction allows neutrino energy to be determined from only the outgoing lepton:

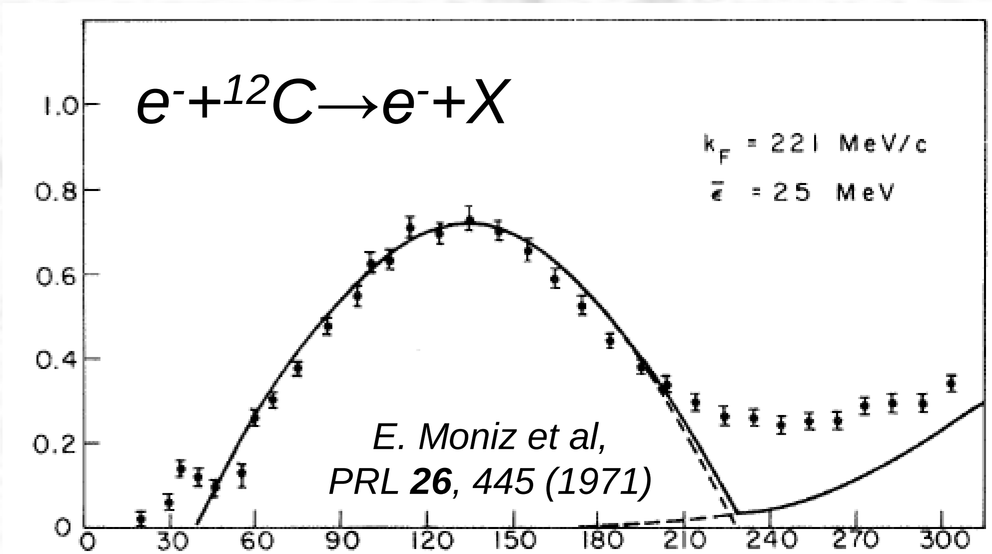
$$E_\nu^{\text{rec}} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e \cos\theta_e)},$$

- This assumes:
  - A single target nucleon, motionless in a potential well (the nucleus)
  - Smearing due to the nucleus is typically built into the cross-section model since it cannot be removed on an event-by-event basis.

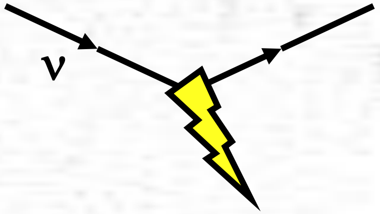
Modeling the Nucleon in a Nucleus



- 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.

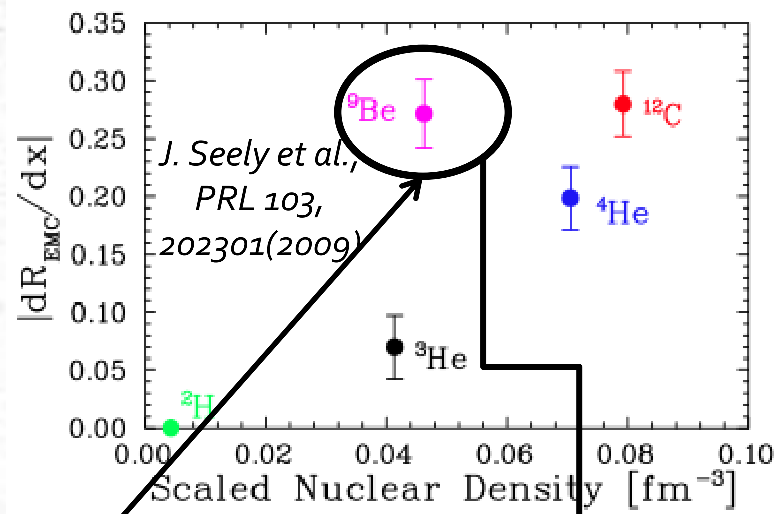


Mean Field Approximation?

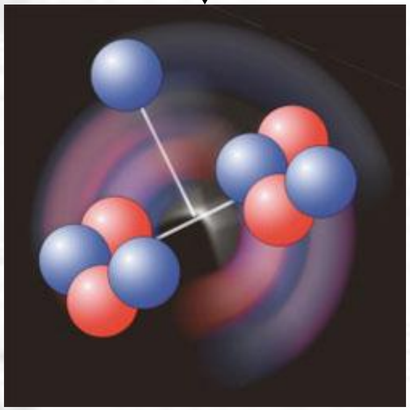


- There are many hints that the mean field approach isn't sufficient.

- *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*

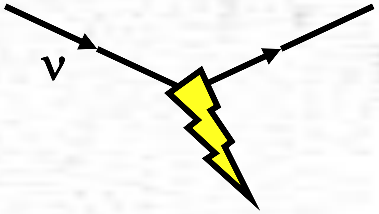


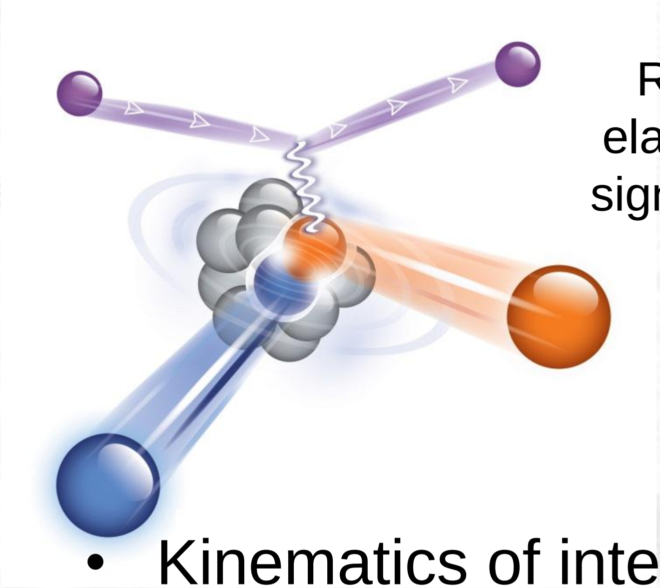
^{9}Be is two tightly bound α loosely held with a neutron



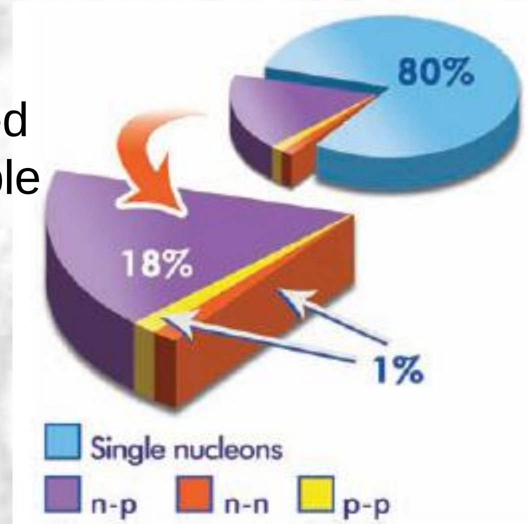
(Figure courtesy APS Phys Rev Focus)

Short-Range Correlations



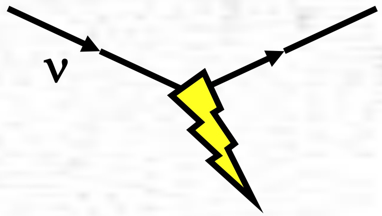


Recent Jlab studies of ^{12}C quasi-elastic scattering have demonstrated significant probabilities to see multiple nucleons knocked out beyond expectation from final state interactions.
*[R. Subedi et al., Science **320**, 1476 (2008)]*



- 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.

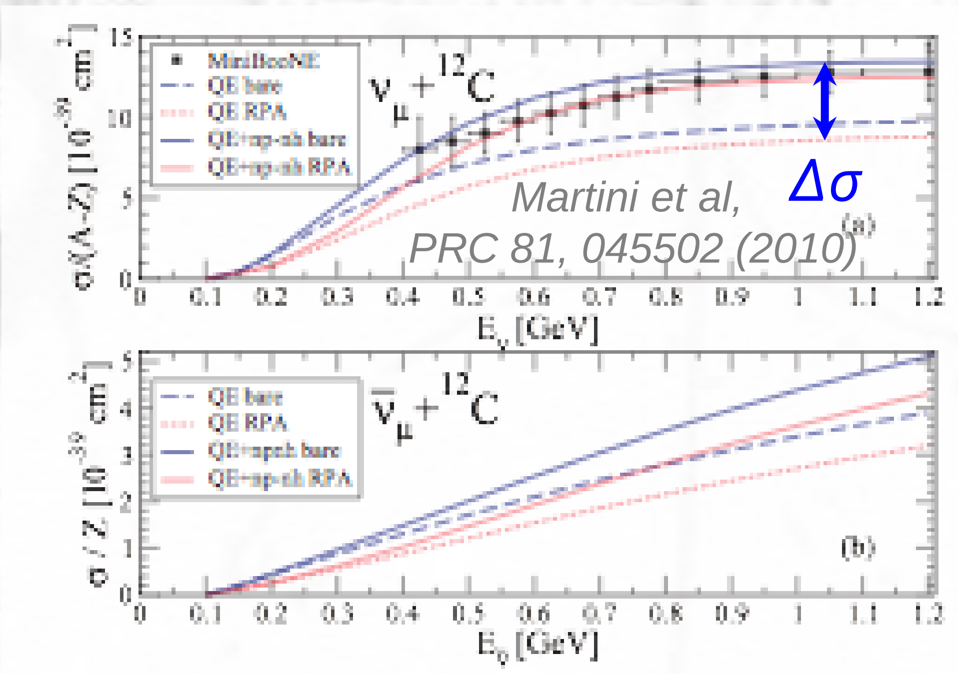
Dekker et al., PLB **266**, 249 (1991)
Singh, Oset, NP **A542**, 587 (1992)
Gil et al., NP **A627**, 543 (1997)
J. Marteau, NPPS **112**, 203 (2002)
Nieves et al., PRC **70**, 055503 (2004)
Martini et al., PRC 80, 065001 (2009)



Seen in MiniBooNE CCQE?

- From the ^{12}C experiment and calculations, expect a cross-section enhancement from correlated process:

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



New work since Martini proposal

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)

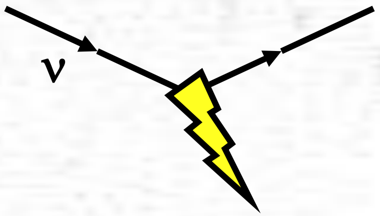
[compilation by G.P. Zeller]

Modeling Short-Range Correlations

- 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…
  - … or to predict the kinematic effects!
- My personal conclusion: calculations need more experimental validation before they are reliable.
  - Good news: lots of data soon to be available.
  - Bad news: difficult to directly observe energy smearing.

CONCLUSIONS

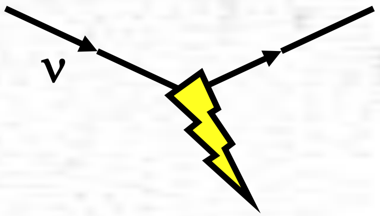
Irreducible?



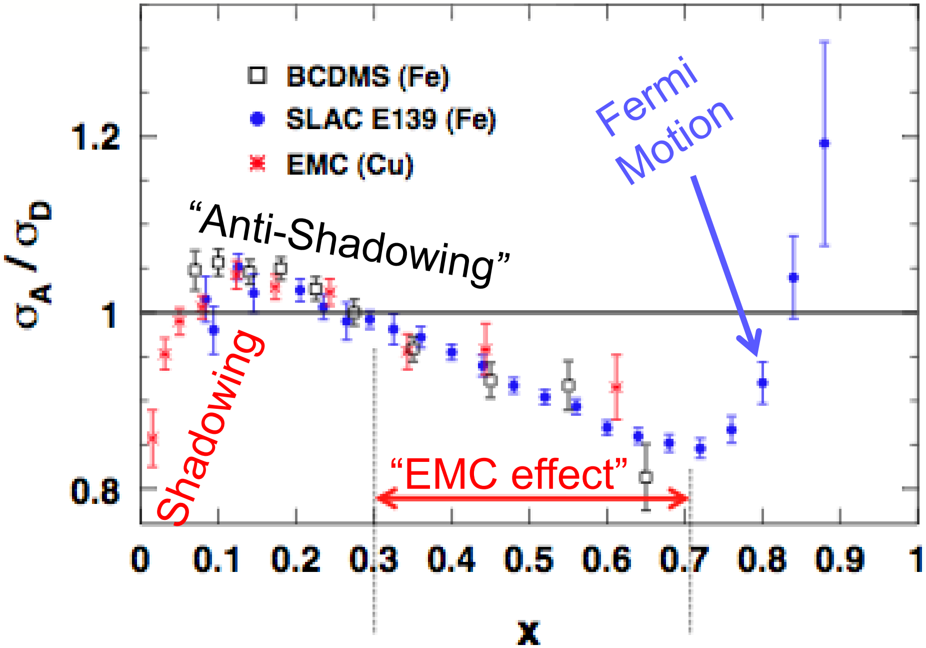
- Near detector constraints flux and cross-sections require input from cross-section models.
- There are some vulnerabilities in models.
  - *Unknown form factors of nucleon*
  - *Effects of nucleus on energy reconstruction*
- Wealth of new cross-section data from current program should help to reduce uncertainties
  - Will required detailed analysis of data and interplay between models and data.
  - Outcome will determine if uncertainties will impact physics potential of next generation experiments.

BACKUP

A Long-Standing Puzzle: The EMC Effect



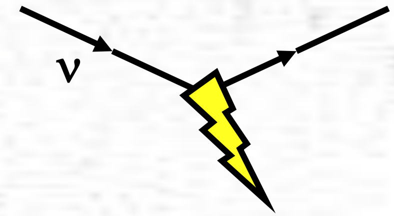
- Charged lepton F_2^A/F_2^D shows convincingly modification of quark distributions in a nucleus
  - No model of nucleus as an incoherent sum of nucleons can reproduce this effect.
  - No conclusive model of the collective behavior exists.



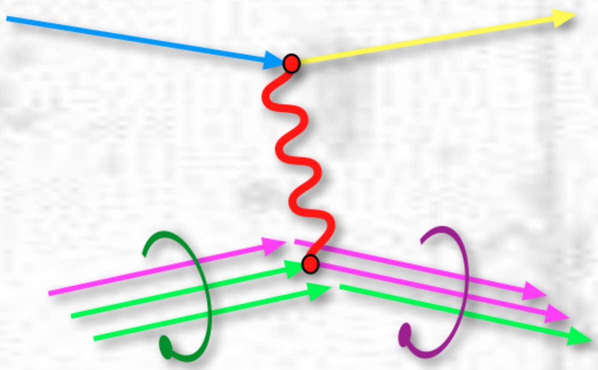
(D. Gaskell, ECT, Hadrons in the Nuclear Medium)*

- 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

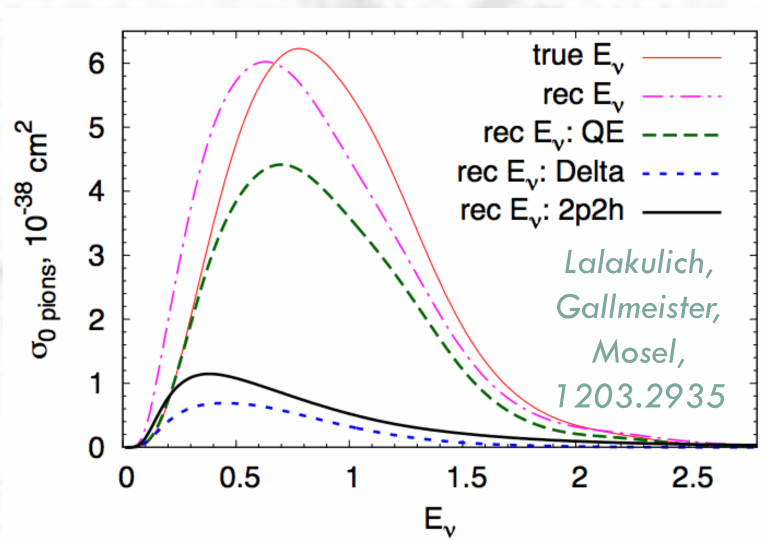


- Cross-section depends on empirical form factors



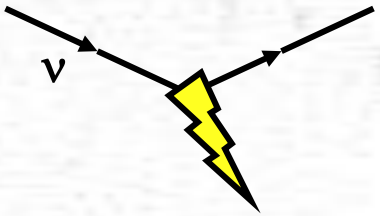
- In particular, the axial form factor, $F_A(Q^2)$, from M_A
  - Vector form factors measured precisely in e- scattering (Bodek, Budd, Bradford, Arrington Nucl.Phys.Proc.Suppl.159:127-132,2006)
  - PCAC gives pseudoscalar $F_P(Q^2)$

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

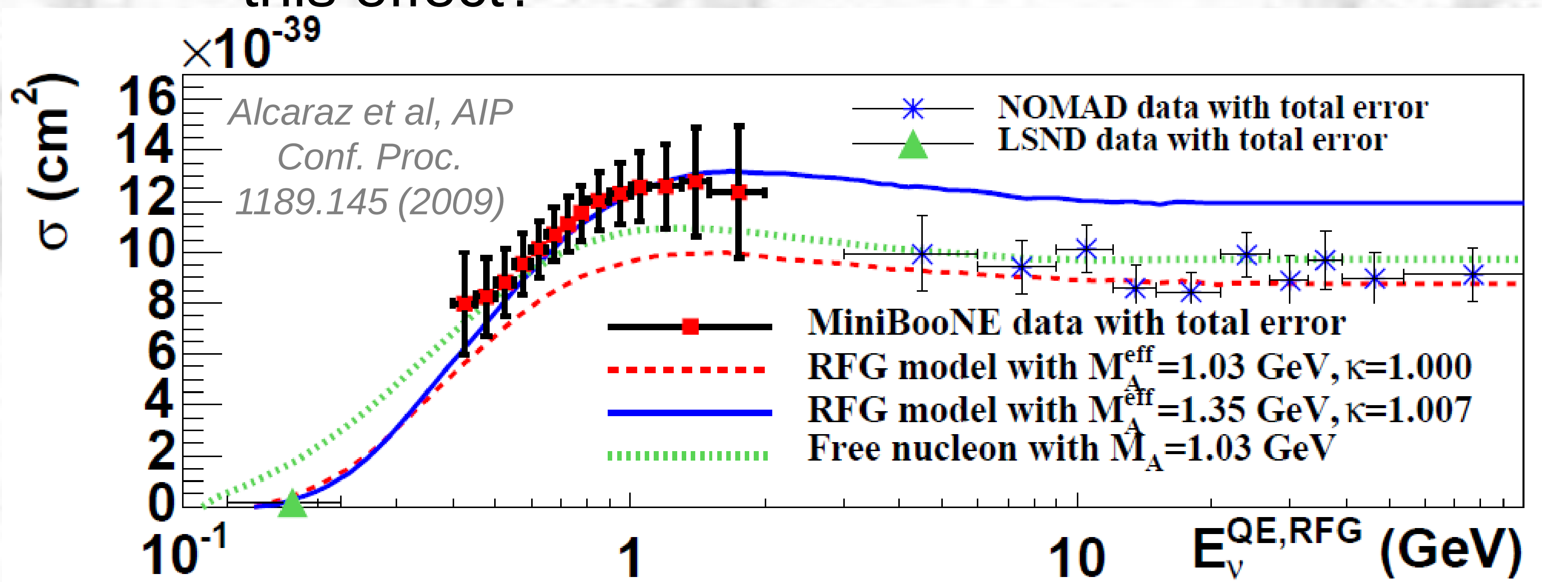


ex: Mosel/Lalakulich 1204.2269, Martini et al. 1202.4745, Lalakulich et al. 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

"Axial Mass Puzzle"



- As described earlier, M_A has been measured to be 1.03 GeV/c^2 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)