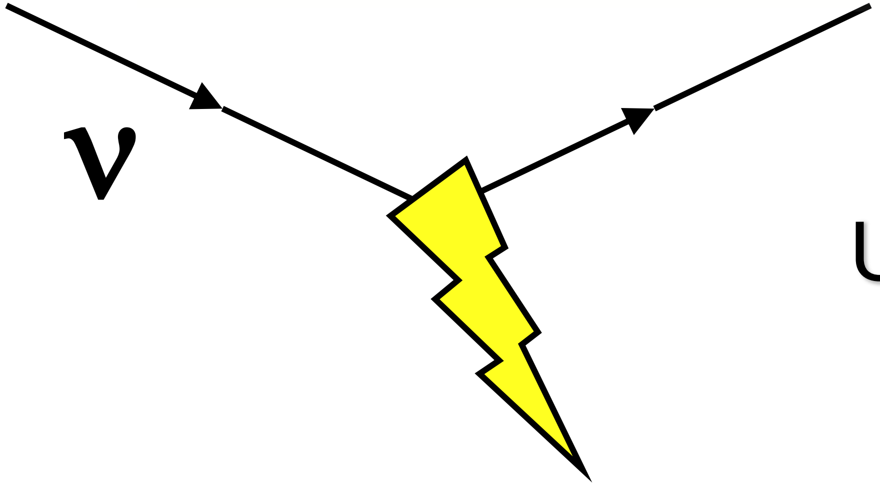
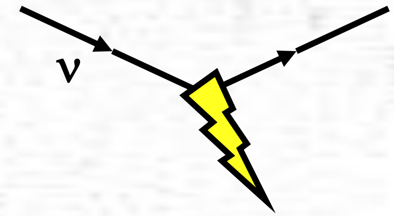
Neutrino Interactions and the Oscillation Program

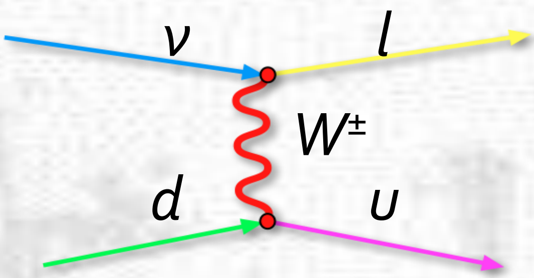


Kevin McFarland
University of Rochester
NNN 2012
6 October 2012

Neutrinos Interactions

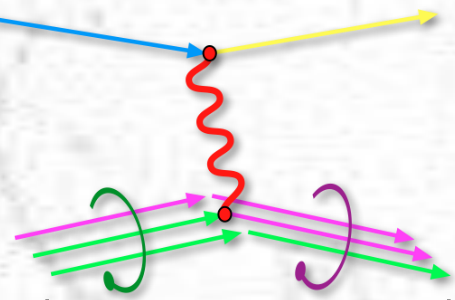


Neutrinos interactions are simple… until they aren't.



Leptonic current is perfectly predicted in SM…
…as is the hadronic current for free quarks.

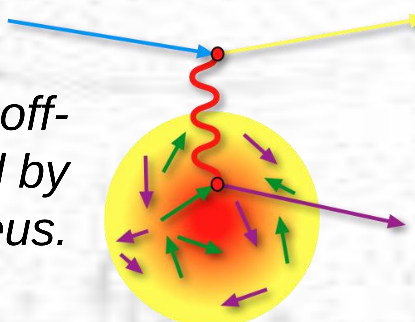
For inclusive scattering from a nucleon, add PDFs for a robust high energy limit prediction



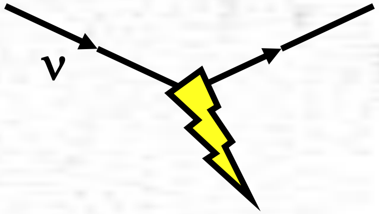
For exclusive, e.g., quasi-elastic scattering, hadron current requires empirical form factors.

(drawings courtesy G. Perdue)

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

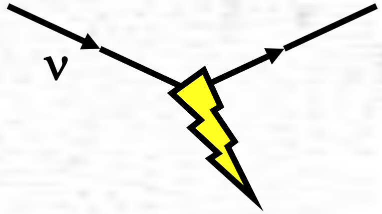


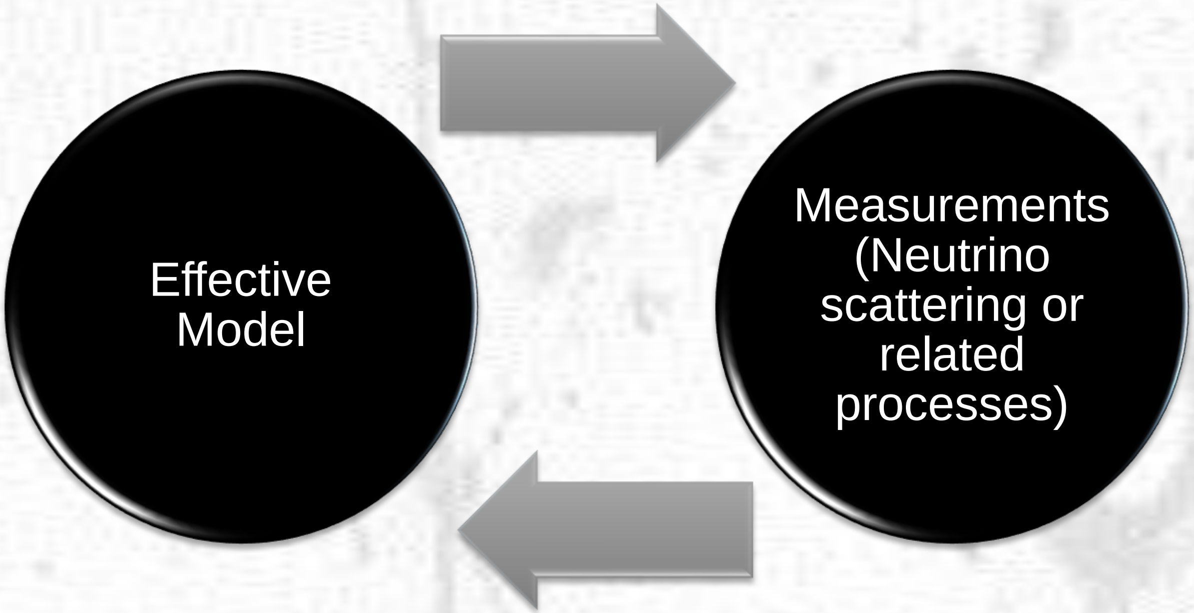
Where's My Spoonful of Sugar?



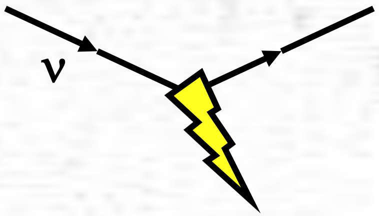
- Complications of interactions are not always appealing.
- Accelerator oscillation experiments require beam energies of 0.3-5 GeV
  - Nuclear response in this region makes the transition between inelastic and elastic processes.
- First-principles calculations of strongly bound target are impossible or unreliable.

How do we Understand and Model Interactions?



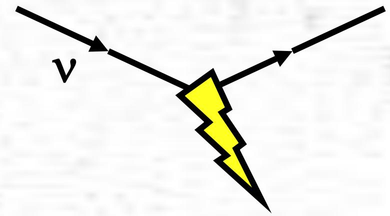


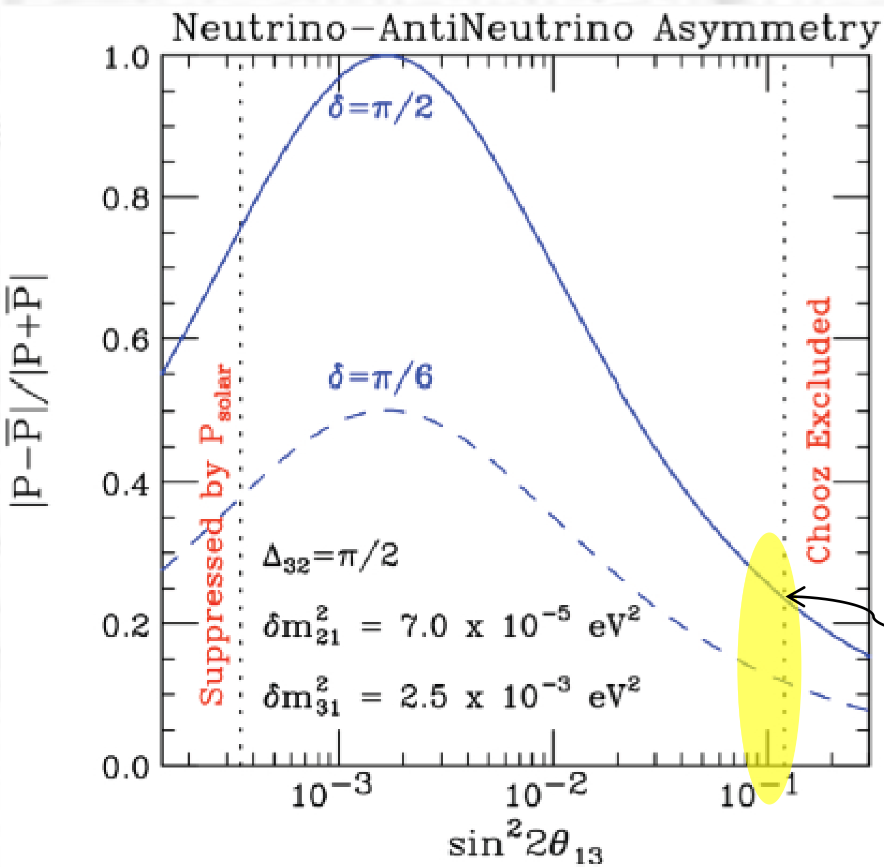
- Iterative process, using data to improve models
- Models are effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions.



How do Oscillation Experiments use Models?

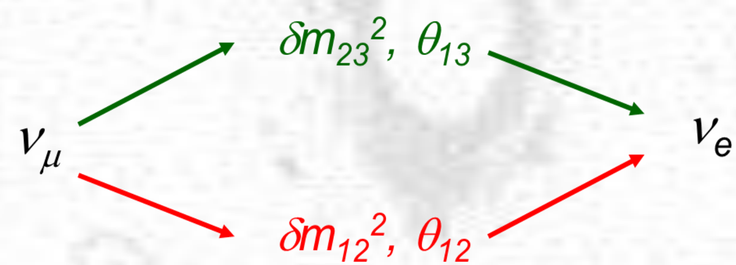
Oscillations: Large θ_{13}





(Parke 2003, arXiv:0710.554)

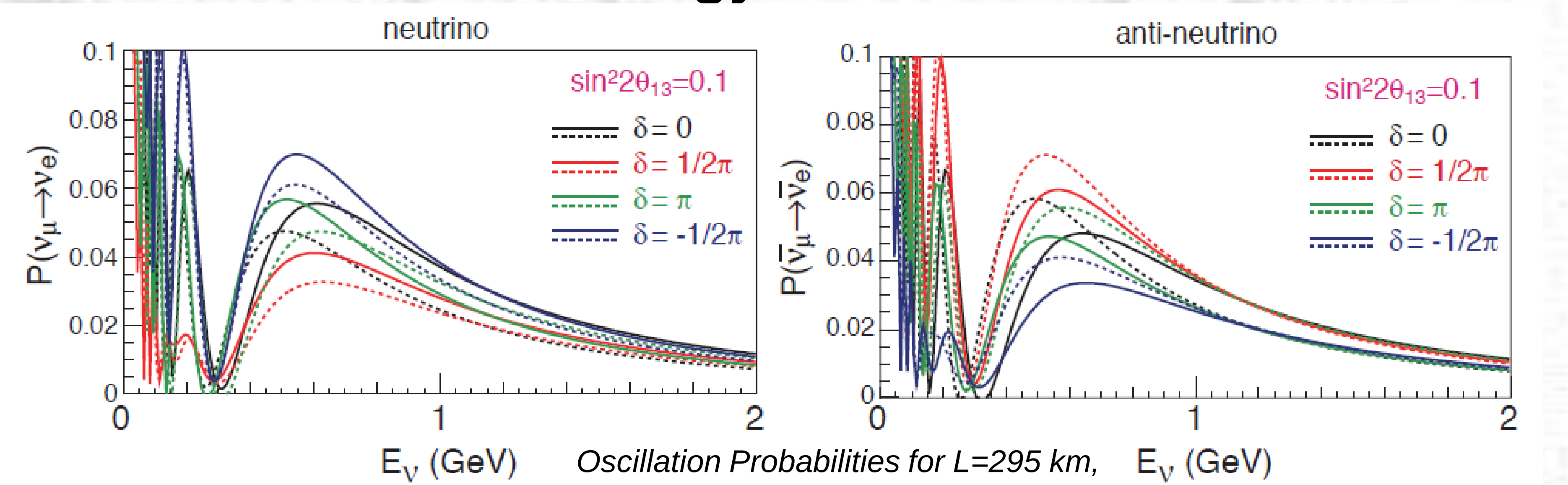
- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases



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

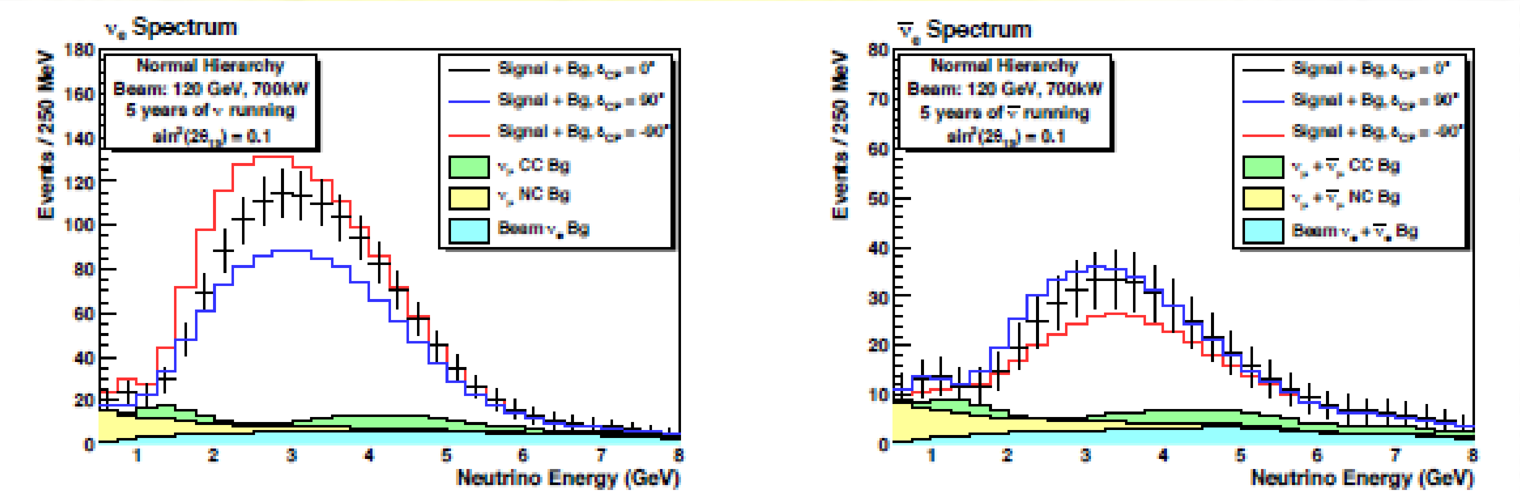
Oscillations: Needs (Hyper K)

- 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

Oscillations: Needs (LBNE)



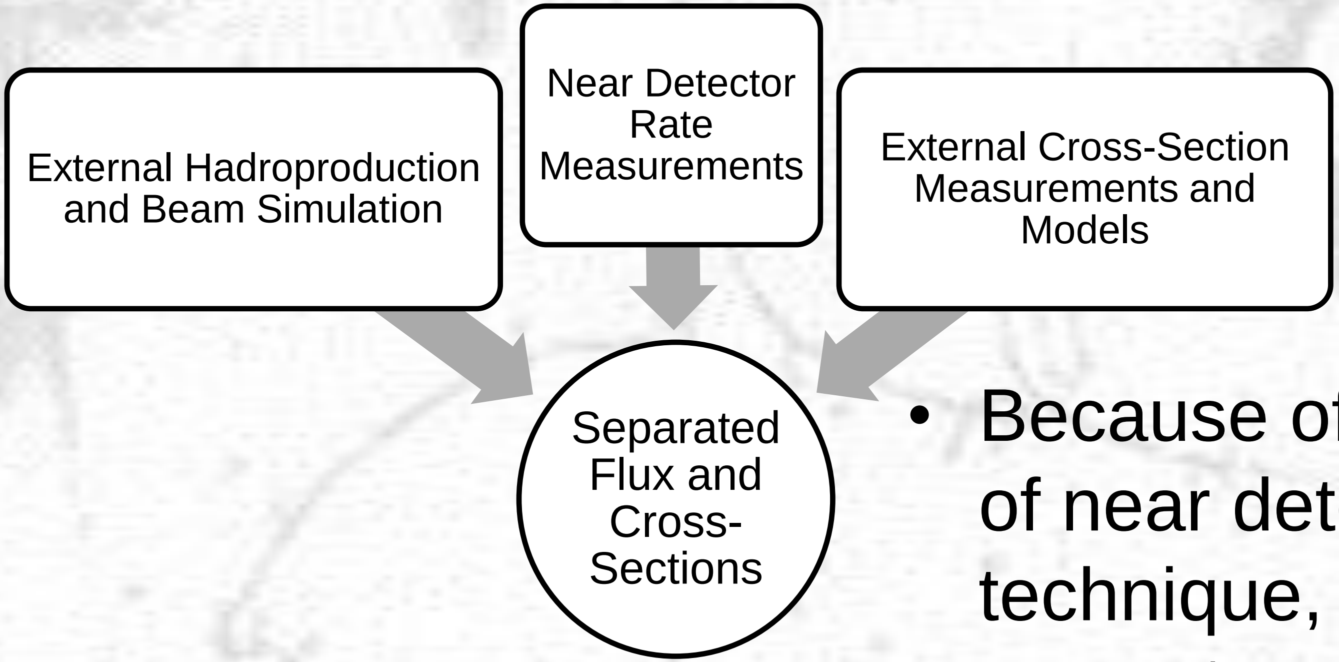
- Maximum CP effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Pileup of backgrounds at lower energy makes 2nd maximum only marginally useful in optimized design
- Spectral information plays a role
  - CP effect may show up primarily as a rate decrease in one beam and a spectral shift in the other

Oscillations: 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. Near detector has backgrounds to reactions of interest which may not be identical to far detector (see #1).
  3. Neutrino energy, on which the oscillation probability depends, may be smeared or biased.
  4. Near detectors measure (dominantly) interactions of muon neutrinos when signal is electron neutrinos.

Oscillations: Breaking the Flux & σ Degeneracy

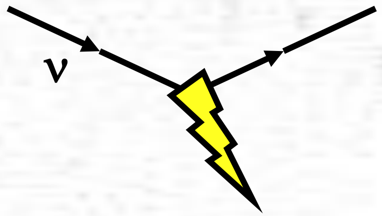
- Experiments have a, more or less, universal scheme for using the near detector data to get flux and cross-section



- Because of limitations of near detector technique, these rely on accurate models

Current Practices

Neutrino Generators: "State of the Art"



- GENIE, NUANCE, NEUT, NuWro are the generators currently used in neutrino oscillation experiments.
- Share same approach, with minor variations
  - Relativistic Fermi Gas in Initial State
  - Free nucleon cross-sections
    - Llewellyn Smith formalism for quasi-elastic scattering
    - Rein-Sehgal calcluation/fit for resonance production
    - Duality based models for deep inelastic scattering
  - Cascade models for final state interactions
    - Roughly, propagate final state particles through nucleus and allow them to interact. Constrained by πN, NN measurements.
- Improvements (nuclear model, reaction models) are in progress, but behind "best" theory models.

Llewellyn-Smith, PhysRept. 3C, 261–379 (1972)

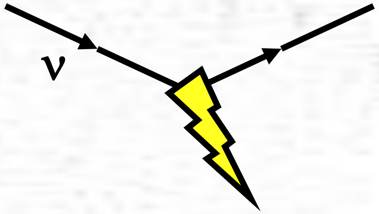
Rein-Sehgal [Ann. Phys. 133, 79-153 (1981)]

Bodek-Yang arXiV:1011.6592

The Essential Tension

- Ulrich Mosel's brilliant observation at NuINT11:
  - Theorist's paradigm: "A good generator does not have to fit the data, provided [its model] is right"
  - Experimentalist's paradigm: "A good generator does not have to be right, provided it fits the data"
- Most of the generators currently used by oscillation experiments (NUANCE, GENIE, NEUT) are written and tuned by experimentalists
  - *See above!* Our generators are wrong. WRONG!
- Models do not fit (all) the data, although they provide insight into features of this data

What is Useful about Generators?

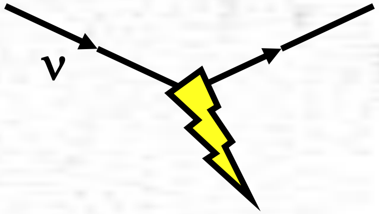


- This approach gives a set of four vectors for every particle leaving the nucleus
  - Essential for oscillation experiments where limited detectors have responses that vary wildly depending on final state particle
- Many tunable parameters, and it is always easy to add more
  - Why? Initial model isn't self-consistent anyway, so experimenters just tune knobs to make data agree
    - o *Which of course only applies to data we have and may or may not be predictive for the future.*

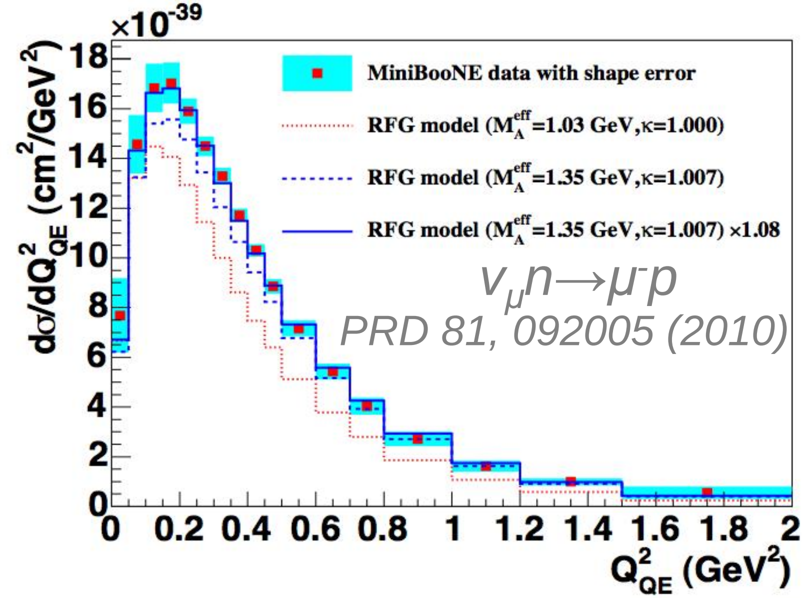
What is Deadly About Generators?

- Difficult or impossible to put in a complete calculation for a single exclusive or semi-inclusive final state.
  - *Even if that calculation is better, it may not be clear how to factorize from the ensemble of reactions and effects in the generator*.
  - As a result, generators lag developments in theory.
- No way to know *a priori* if range of tunable parameters that external data seems to allow is really spans the difference between the generator and truth.

What to do when models and data don't agree?



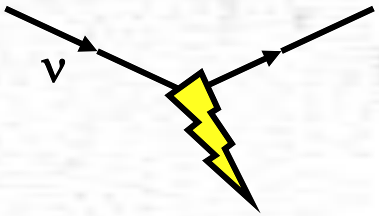
- Most of these models give absolute predictions. So how to make them agree with data?
- MiniBooNE oscillation analysis approach:
  - Modify the dipole axial mass and Pauli blocking until model fits data.
  - But there is nothing fundamental behind this approach. It's a mechanical convenience. Dipole form factor is unlikely to be right, and changes in Pauli blocking are masking deficiencies in models!

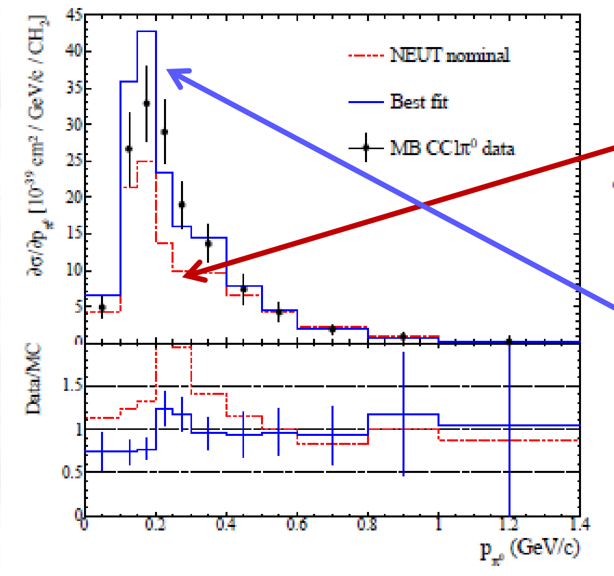


$\nu_\mu n \rightarrow \mu^- p$

PRD 81, 092005 (2010)

What to do when models and data don't agree? (cont'd)

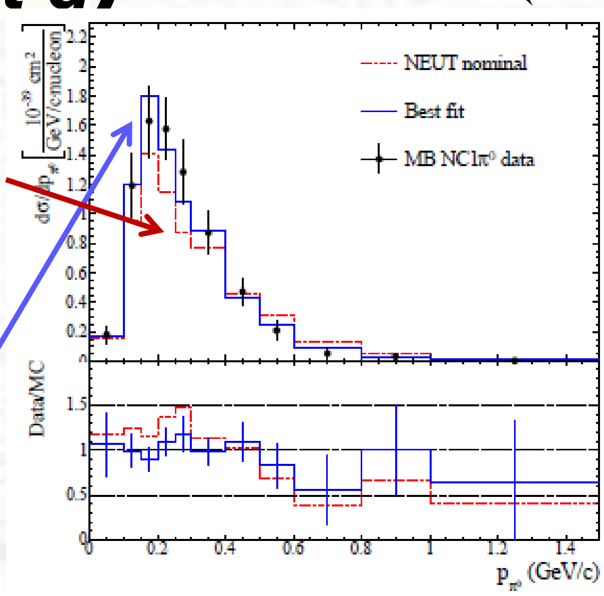




(a) CC1π^0 $|\mathbf{p}_{\pi^0}|$

Rein-Sehgal
[Ann. Phys. 133, 79-153 (1981)]
implementation in NEUT

"Tuned" Rein-Sehgal
to modify Q^2 distribution,
pion spectrum, rate

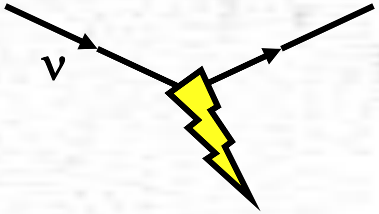


(c) NC1π^0 $|\mathbf{p}_{\pi^0}|$

- T2K studies $\nu_\mu N \to \mu^- \pi^{(+)0} N^{(\prime)}$ and $\nu_\mu N \to \nu_\mu \pi^0 N$ and finds poor agreement between Rein-Sehgal calculation and MiniBooNE data
- Adds *ad hoc* tuning that "breaks" assumptions of underlying model, e.g. CC-NC universality of process and relation among resonances, to force good agreement.

Example of Progress: Quasi-Elastic Models

Quasi-Elastic Energy Reconstruction

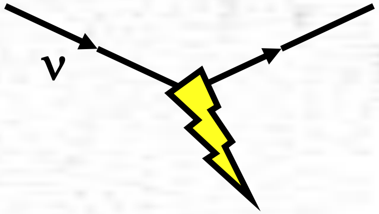


- Quasi-elastic reaction allows neutrino energy to be determined from only the outgoing lepton:

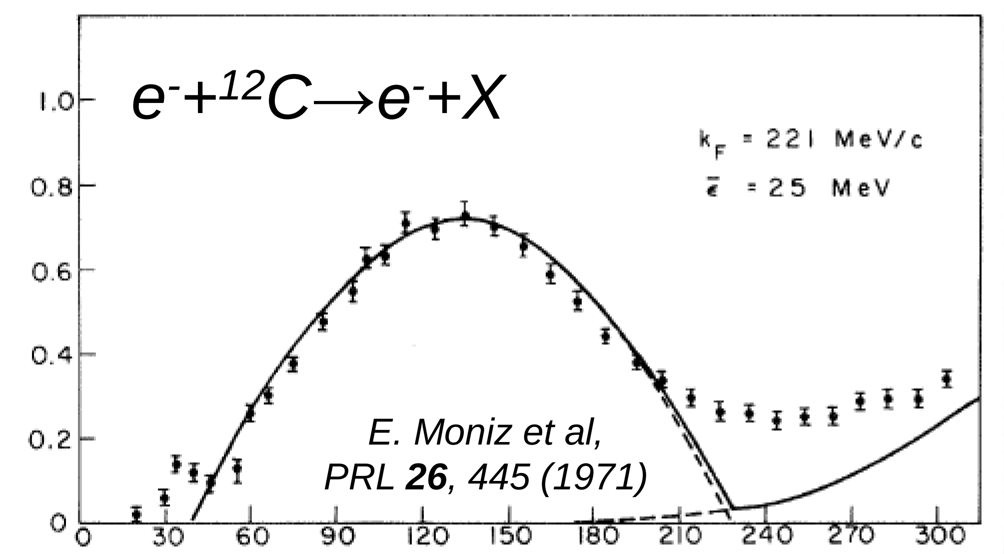
$$E_\nu^{\rm rec} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e\cos\theta_e)},$$

- 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



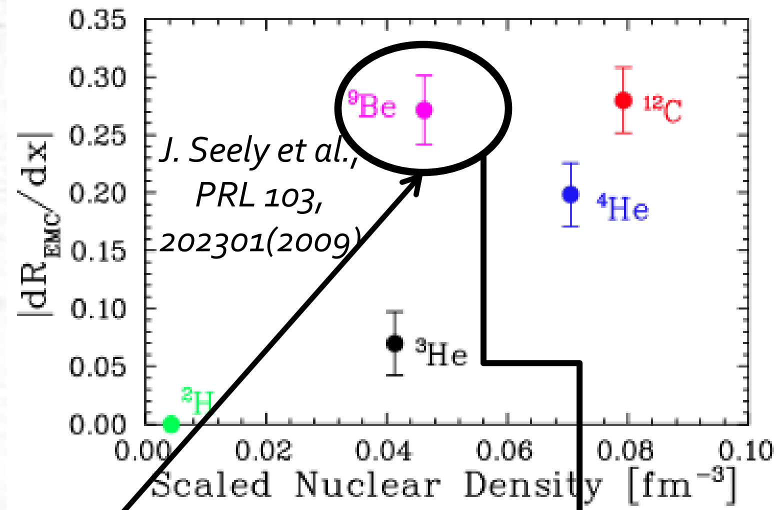
- Our models come from theory tuned to electron scattering
- Generators usually use Fermi Gas model, which takes into account effect of the mean field.
  - Corrections to electron data from isospin effects in neutrino scattering.



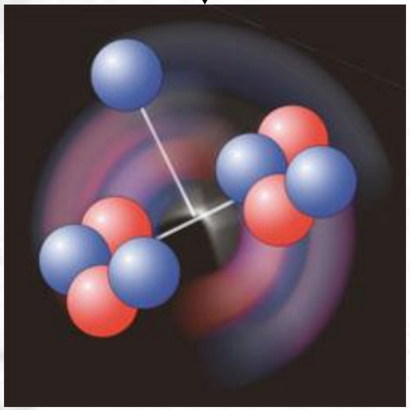
Mean Field Approximation?

- 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*

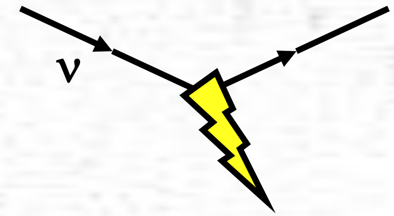


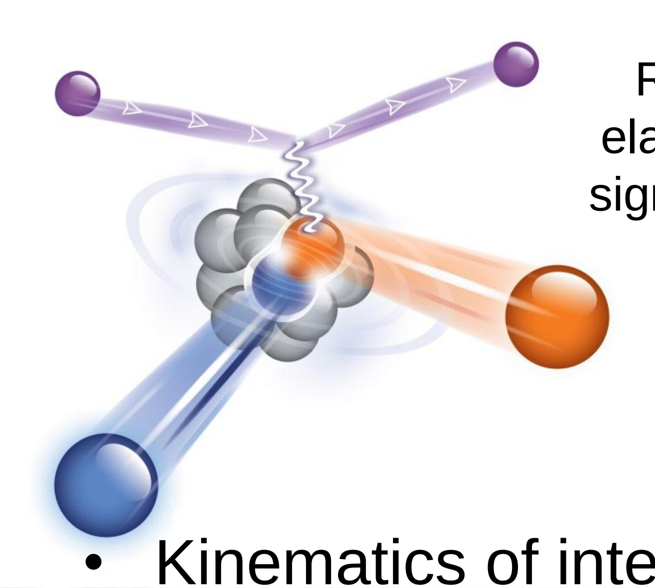
^{9}Be is two tightly bound α loosely held with a neutron



(Figure courtesy APS Phys Rev Focus)

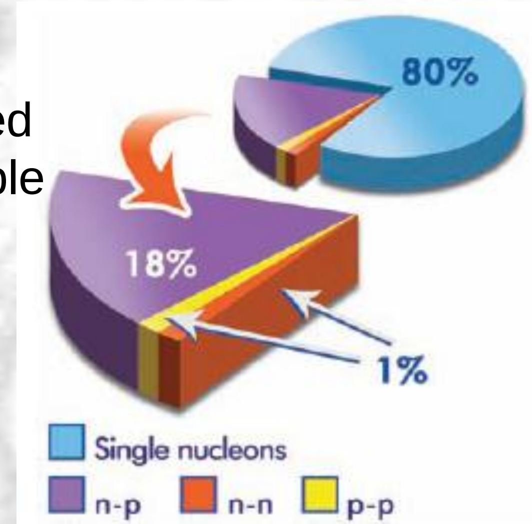
Short-Range Correlations





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.

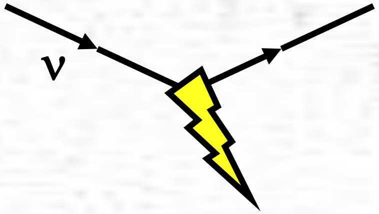
*[R. Subedi et al., Science **320**, 1476 (2008)]*



- 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.

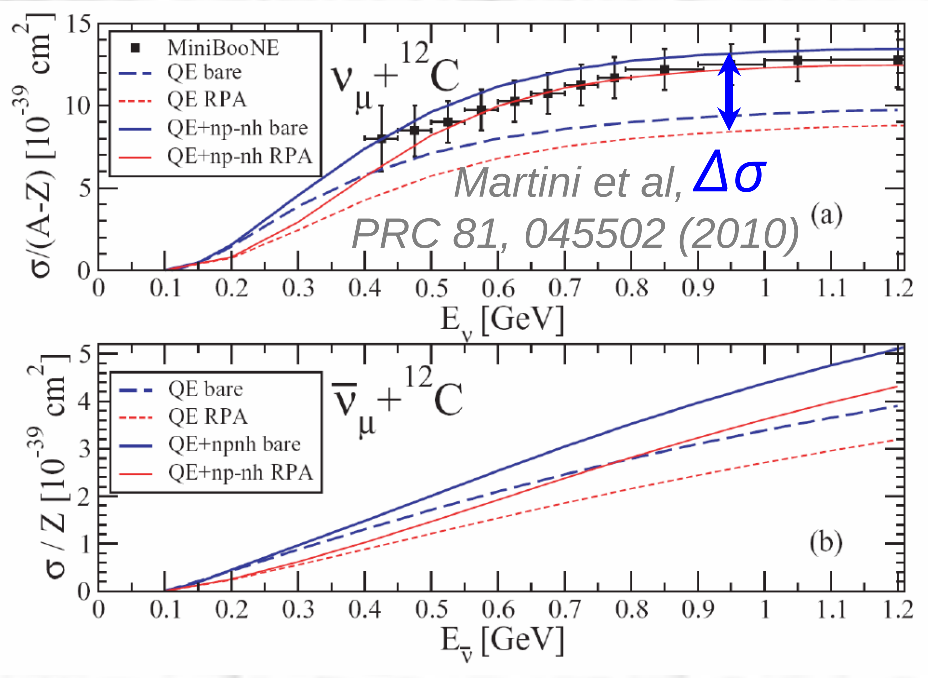
Dekker et al., PLB **266**, 249 (1991)
Singh, Oset, NP **A542**, 587 (1992)
Gil et al., NP **A627**, 543 (1997)
J. Marteau, NPPS **112**, 203 (2002)
Nieves et al., PRC **70**, 055503 (2004)
Martini et al., PRC 80, 065001 (2009)

Origin of MiniBooNE CCQE "Axial Mass"?



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

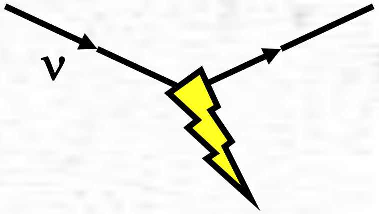
$$\nu_\mu n \rightarrow \mu^- p \quad + \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$$



New work since Martini proposal

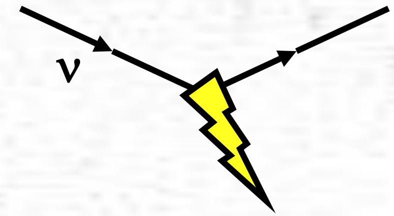
Nieves *et al*., arXiv:1106.5374 [hep-ph]
Bodek *et al*., arXiv:1106.0340 [hep-ph]
Amaro, *et al*., arXiv:1104.5446 [nucl-th]
Antonov, *et al*., arXiv:1104.0125
Benhar, *et al*., arXiv:1103.0987 [nucl-th]
Meucci, *et al*., Phys. Rev. **C83**, 064614 (2011)
Ankowski, *et al*., Phys. Rev. **C83**, 054616 (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 Multi-nucleon Correlations



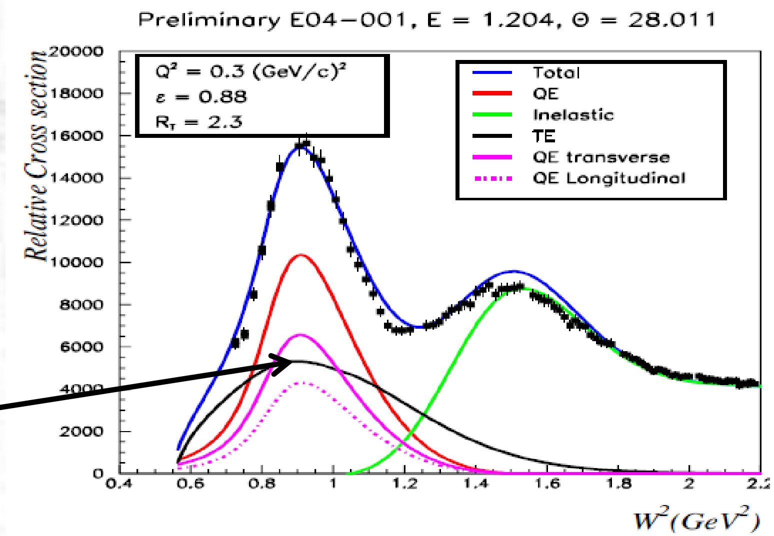
- There are several microphysical calculations on the market, but they share several key features.
  - They are all based on effective theories valid over limited ranges of energy, kinematics. Theoretical systematics are difficult to control.
  - Calculations are just starting to see effect in the right 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.

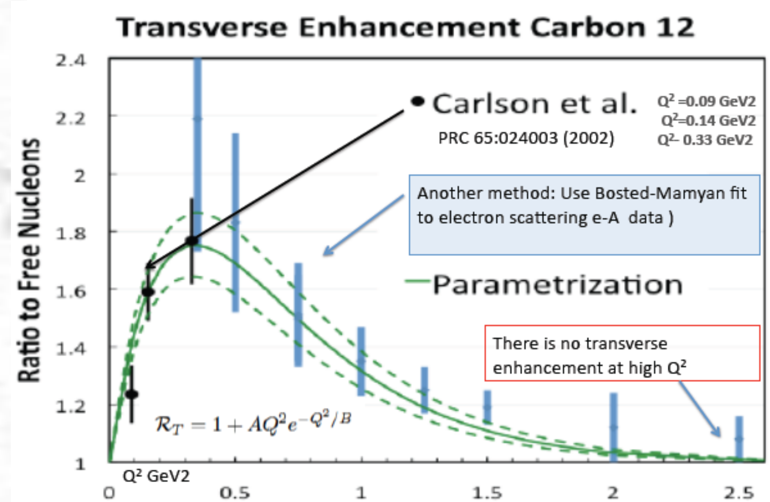
Parameterizing Multi-Nucleon Correlations



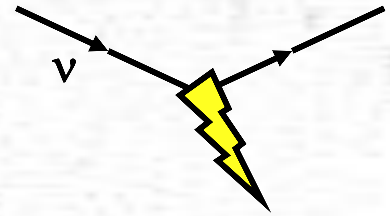
- Independent of models, can look for the effect in electron scattering
- Should show up as an enhancement to the transverse scattering cross-section on nuclei not seen on free nucleons
    - Do we learn enough from electron scattering data alone about the kinematic details? Probably not.

A. Bodek, H.S. Budd, M.E. Christy Eur.Phys.J. C71 (2011) 1726

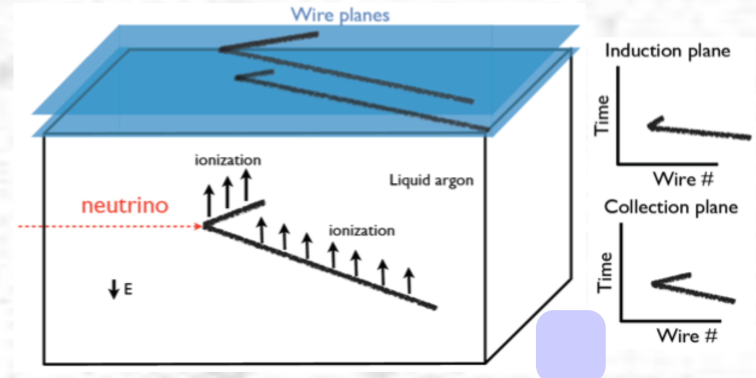




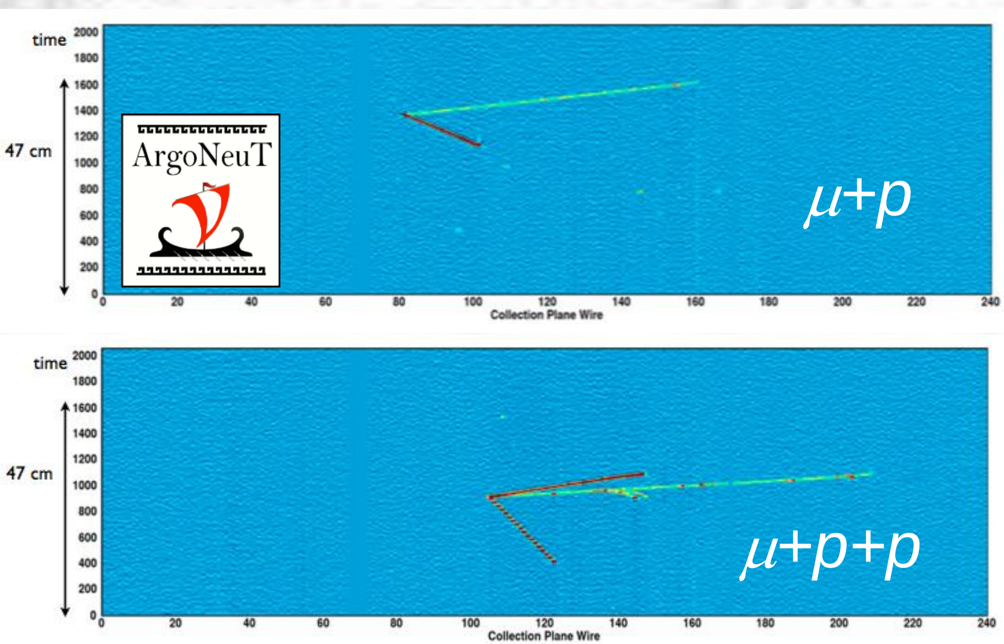
Can we see this with neutrinos?



- Liquid argon has excellent resolution for final state
  - Example: ArgoNeuT, a small liquid argon TPC test in NuMI beamline

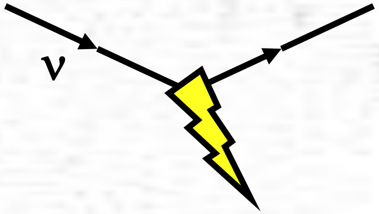


J. Spitz, arXiv: 1009.2515v1

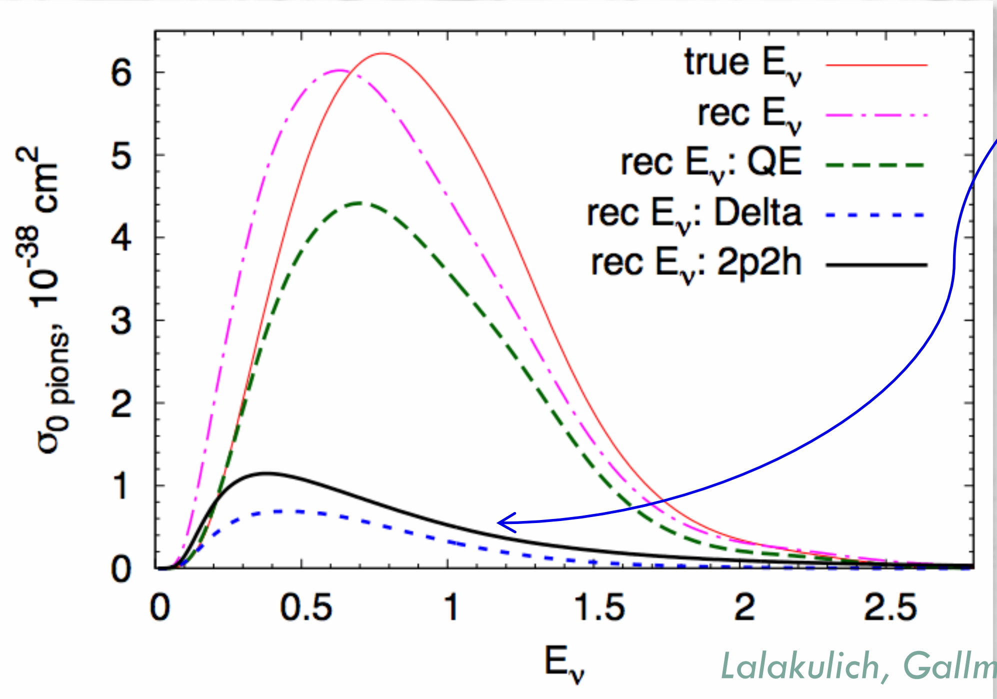


- Other detectors capable of seeing recoil protons can (and will) look for this
- *Difficulty will be separation of the effects of final state interactions from initial state correlations*
- Promising line of study

Energy Reconstruction: Quasi-Elastic



- How does it quantitatively matter if we model this as an effective axial mass or microphysically?
- Inferred neutrino energy changes if target is multinucleon.

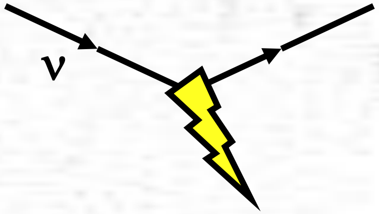


Lalakulich, Gallmeister, Mosel,1203.2935

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

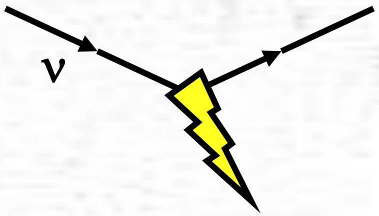
Other Puzzles and Progress

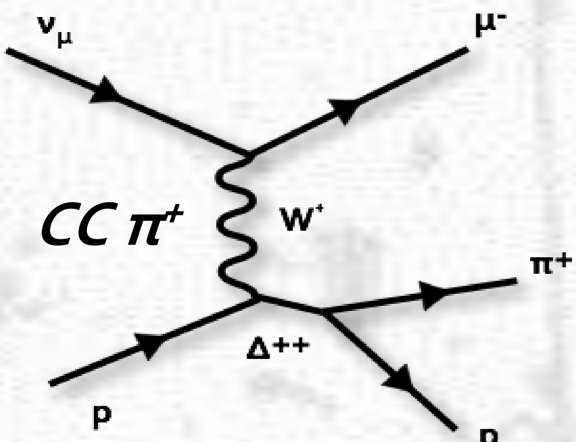
Energy Reconstruction: Inelastic



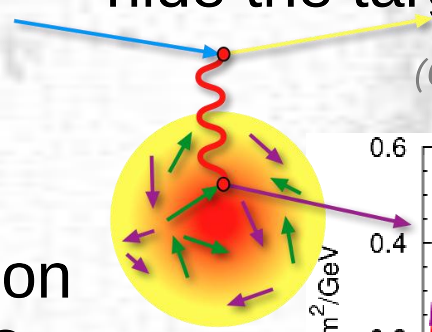
- Here the problem is actually worse
- Detector energy response varies
  - Neutrons often exit without interacting
  - Proton and alpha ionization saturates
  - π^- capture on nuclei at rest, π^+ decay, π^0 decay to photons and leave their rest mass in detector
- Any detector, even liquid argon, will only correctly identify a fraction of the final state
  - Need to know details of final state in four vector and particle content to correct for response

What We Want to Know about Pions

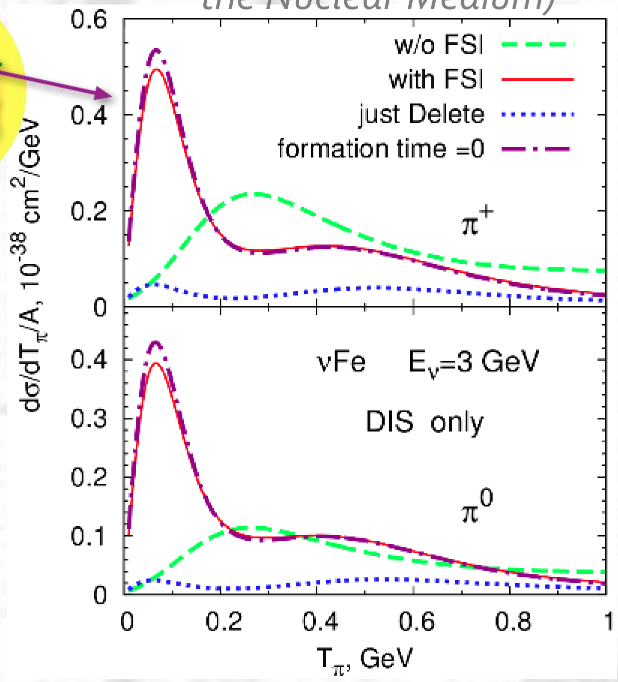




- What happens to our nucleon level prediction when you hide the target in a nucleus?



(O. Lalakulich, ECT, Hadrons in the Nuclear Medium)

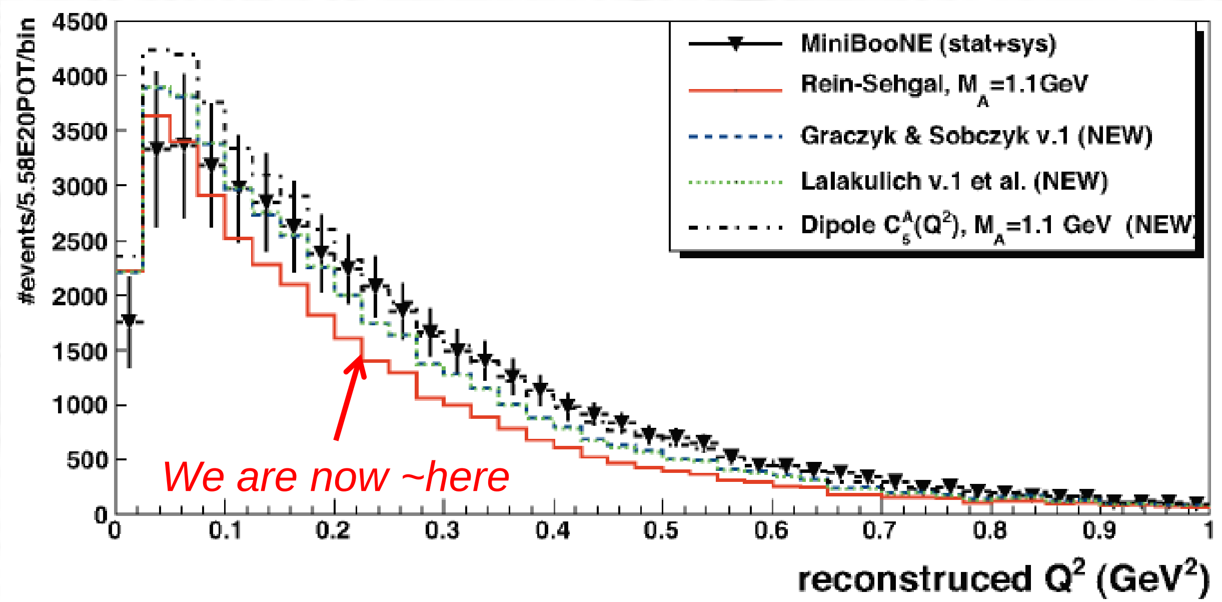


- Is our model of pion production from free nucleons accurate?
[Rein & Sehgal, Ann. Phys. 133, 79-153 (1981)]

If we only study pion production on nuclei, can we ever cleanly separate the free-nucleon cross-section from final state effects?

Updating Rein-Sehgal?

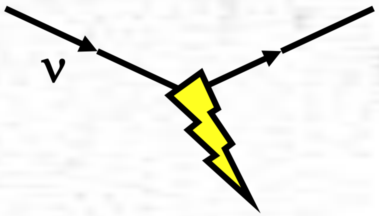
- Vector form factors can be updated to give improvement



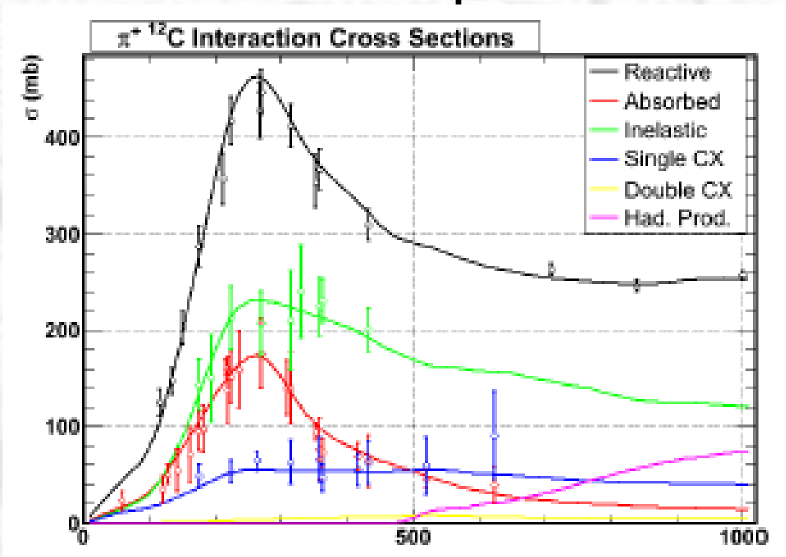
J. Nowak, NuInt09: Comparisons between several updated form factors and (prelim.) MB CC1π+ data. Also added lepton mass.

- Can retune to D_2 data, particularly to improve non-resonant component

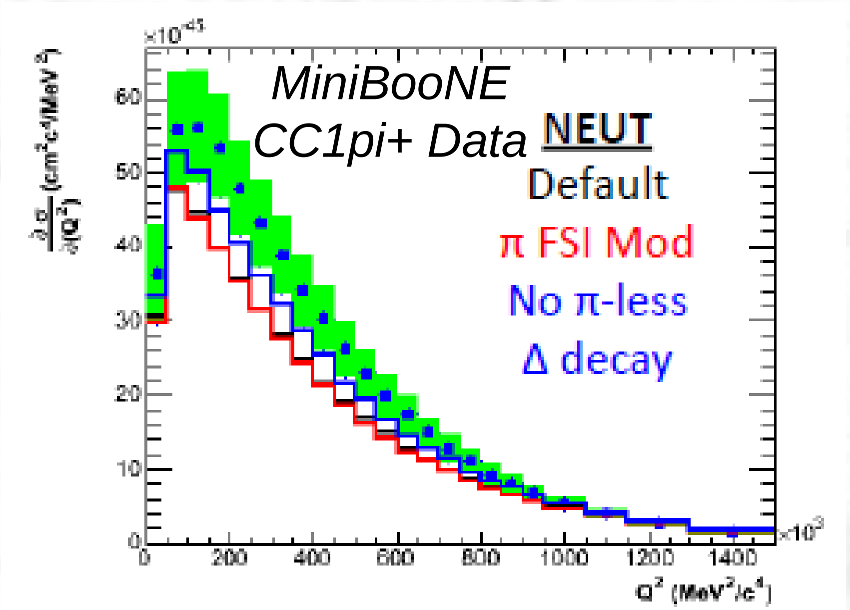
Final State Interactions



- Most generators implement a semi-classical cascade model of transport for FSI. E.g., NEUT:



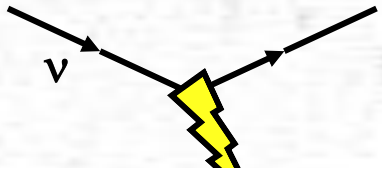
Pion-C scattering data compared to NEUT's tuned model



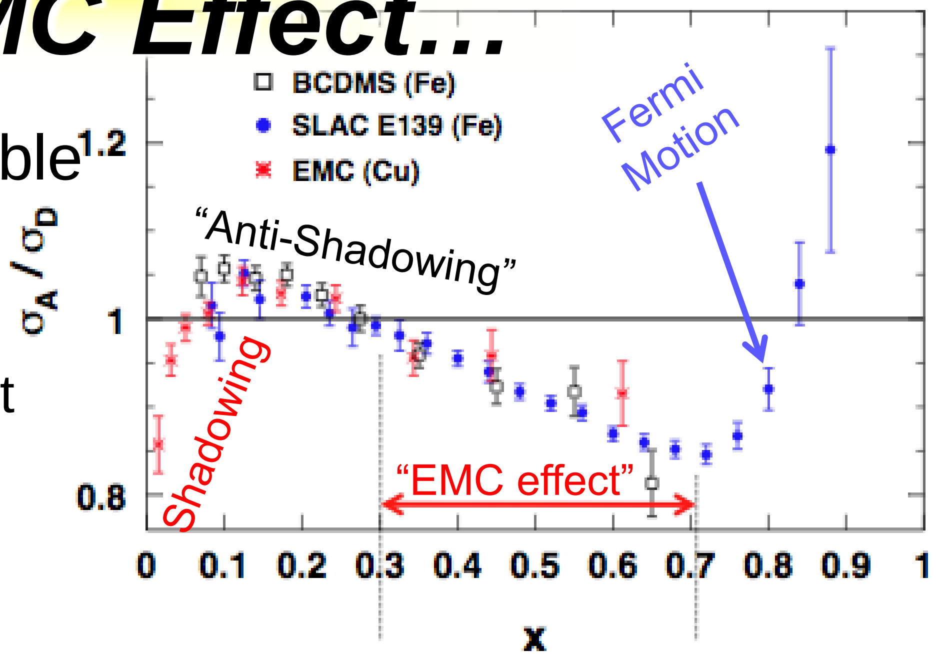
Figures and analysis from P. dePerio, NuINT11

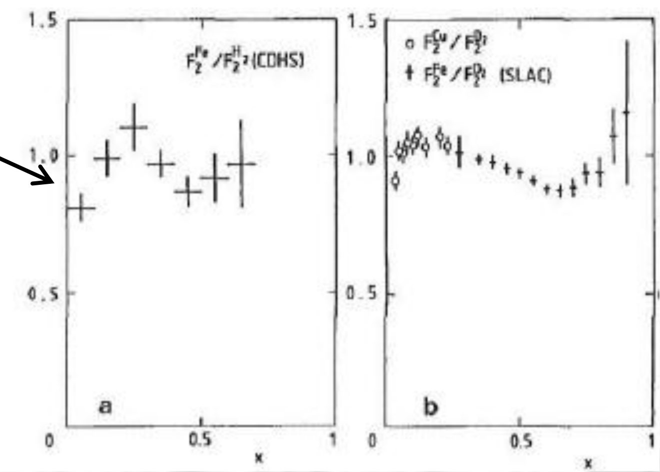
- But attempts to retune still don't reproduce precise data. Is it nucleon-level model or is it simplicity of FSI model?
  - How can we distinguish between the two problems?

Models for Short-Range Correlations, EMC Effect…



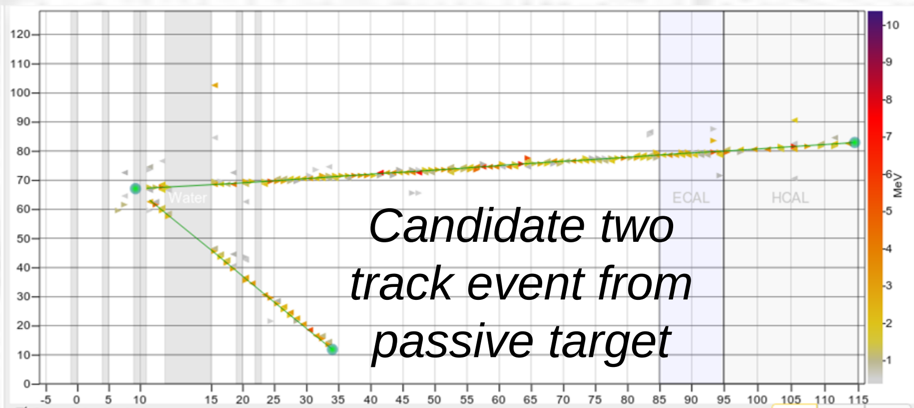
- A major goal is to make reliable measurements analogous to EMC in neutrino scattering
  - Different models of EMC effect have varying predictions for neutrinos
- Fe/D_2 ratio of F_2^{ν}.
  - Ratio of bubble chamber experiments (FNAL/CERN) to CDHS (CERN)
  - Challenging because of different beam flux, low statistics in bubble chambers.
  - After 30 years, time to advance.





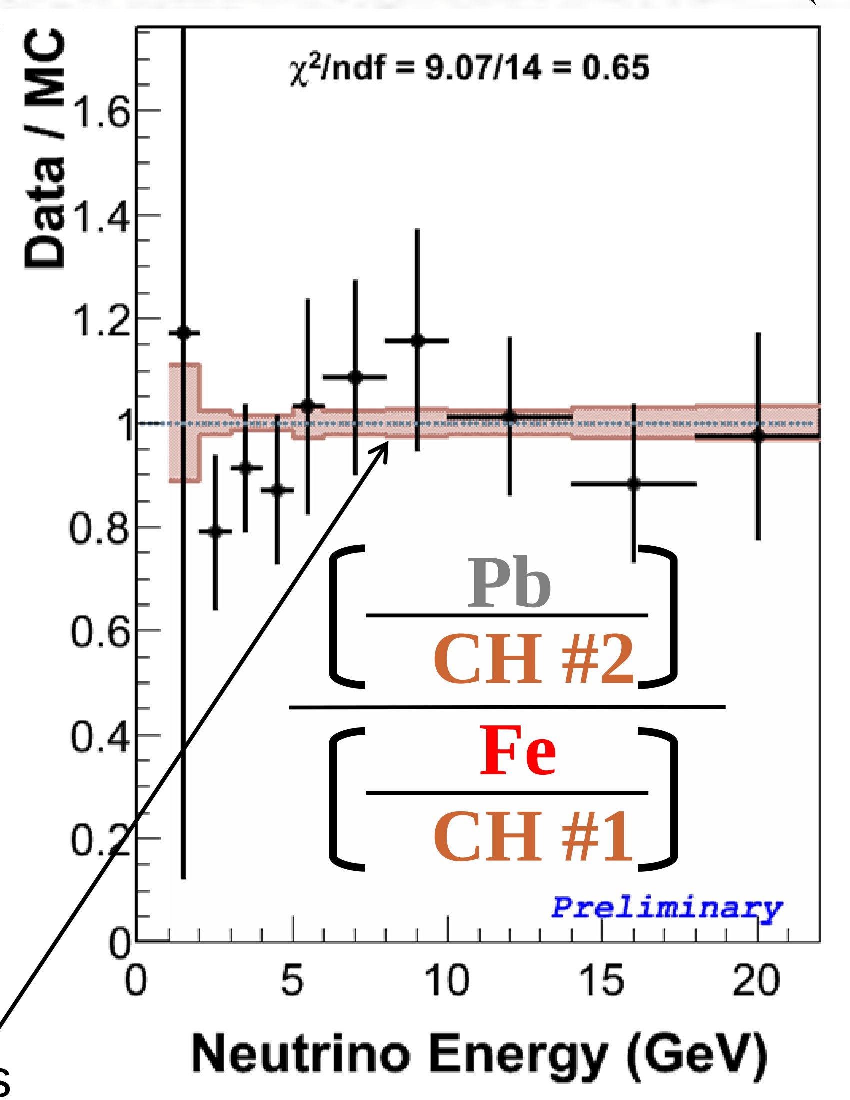
MINERvA's Fe/Pb Ratio

- Measurement technique uses ratios of passive target to nearby scintillator to reduce uncertainties

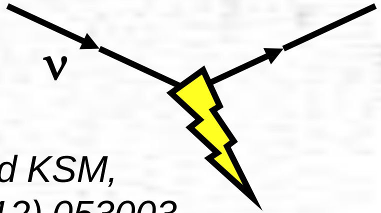


Candidate two track event from passive target

- Early days… so far, Pb/Fe few% of exposure to validate the experimental technique
  - Also, MINERvA plans a long run at higher beam energy
- Ratios, as expected, largely free of reconstruction and flux uncertainties



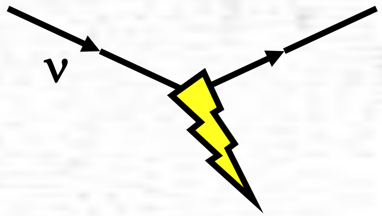
Lepton Mass in Quasi-Elastic Scattering



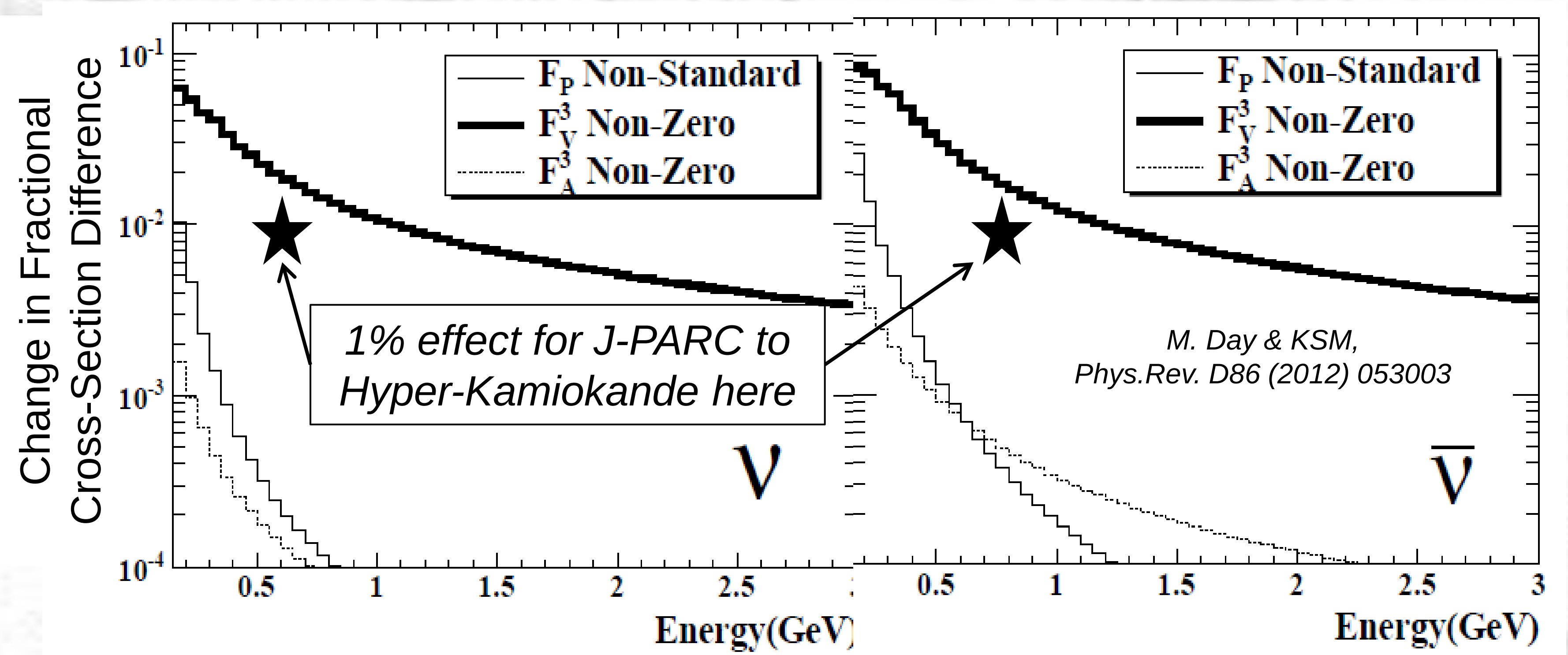
Melanie Day and KSM, Phys.Rev. D86 (2012) 053003

- Differences arise from kinematic limits and mass-dependent terms.
- 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
    - Experimental tests of these assumptions exist.
  - 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.
    - Constrained (poorly) from beta decay and muon capture.

Results for Neutrino Cross-Section Differences

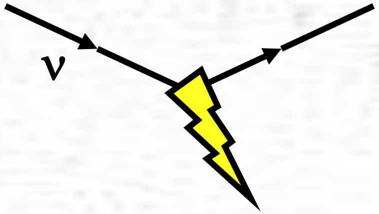


- Possible effect from F^3_V of few % at J-PARC to HK
  - Neutrino and anti-neutrino effects are opposite in sign for second class currents, so could fake a CP asymmetry.



Conclusions

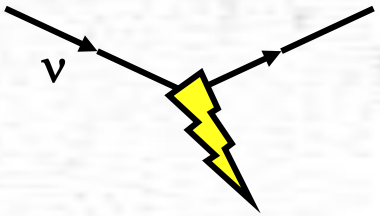
Interactions and Future Oscillation Experiments



- Models of neutrino interactions are necessary for oscillation experiments.
- Obtaining accurate models of neutrino interactions at required energies is a difficult problem.
- Interplay of data, including new data from MINERvA, T2K, MicroBooNE, NOvA, with theory is essential to progress.

Backup

Llewellyn Smith Quasi-Elastic Scattering



- Avert your gaze…

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

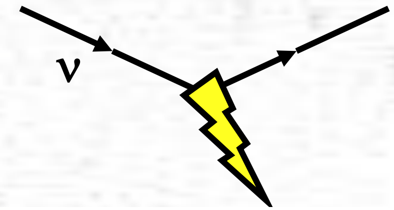
$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\xi|F_V^2|^2\left(1-\frac{Q^2}{4M^2}\right) + \frac{4Q^2 ReF_V^{1*}\xi F_V^2}{M^2} - \frac{Q^2}{M^2}\left(4+\frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi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

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

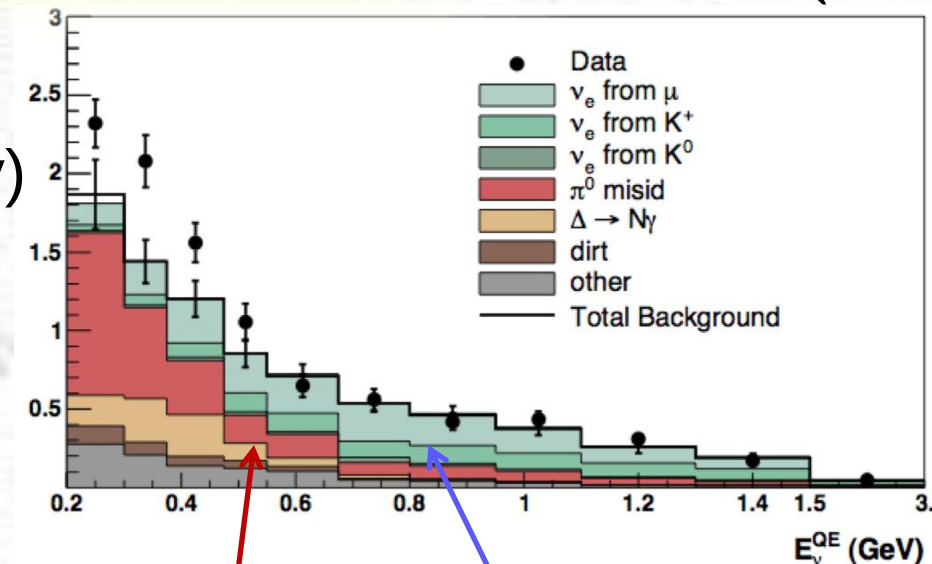
$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right).$$

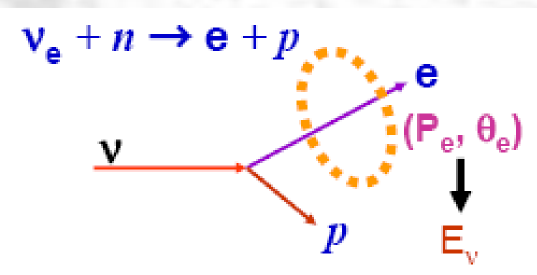
  - Two terms, including those with F_P, and F^3_V, enter with a factor of m^2/M^2. These are relevant for muon neutrinos at low energies but not for electron neutrinos.

MiniBooNE

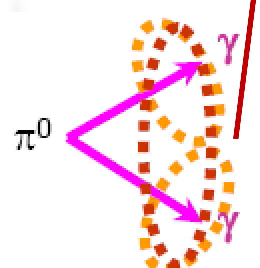


- ν_e appearance with a conventional (meson decay) wide-band beam
  - Significant backgrounds from neutral currents (π^0s), but are measured *in situ*





π^0 background from $E_\nu > E_\nu^{reco}$



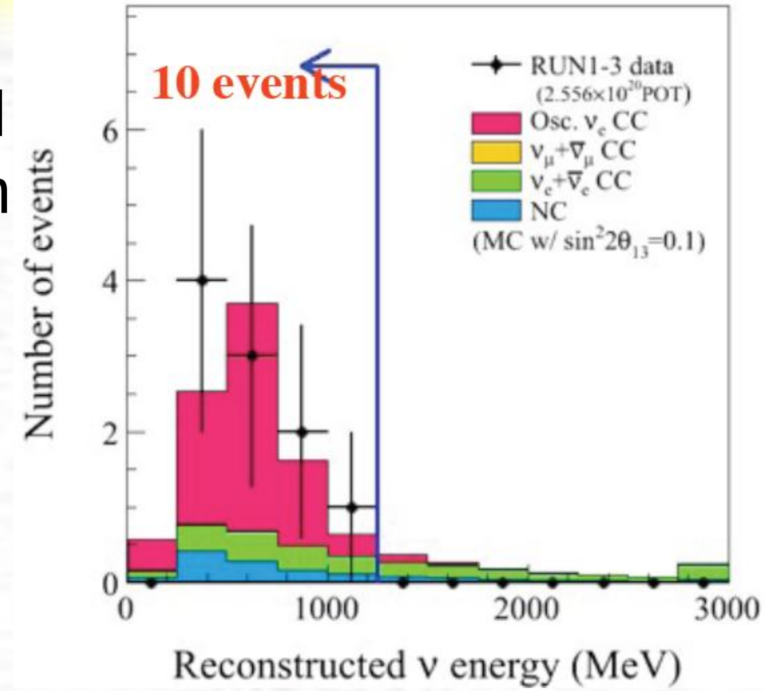
(G.P. Zeller)

ν_e backgrounds

- Signal identification is exclusive quasi-elastic. Lepton kinematics used to infer neutrino energy.
  - Parameters of signal reaction constrained with muon neutrino quasi-elastic sample

T2K

- ν_e appearance with a conventional (meson decay) narrow-band beam
  - Backgrounds from neutral currents (π^0s), but here rate is too low to constrain in far detector
    - Fit external data to constrain production
  - Signal identification is also restrictive and use lepton kinematics to infer neutrino energy, as with MiniBooNE
- Even after near detector constraint, still have significant uncertainties from interactions.

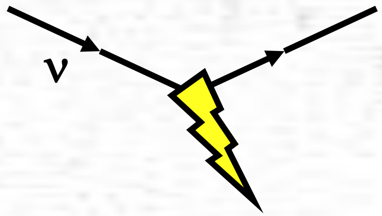


(T. Nakaya, Neutrino 2012)

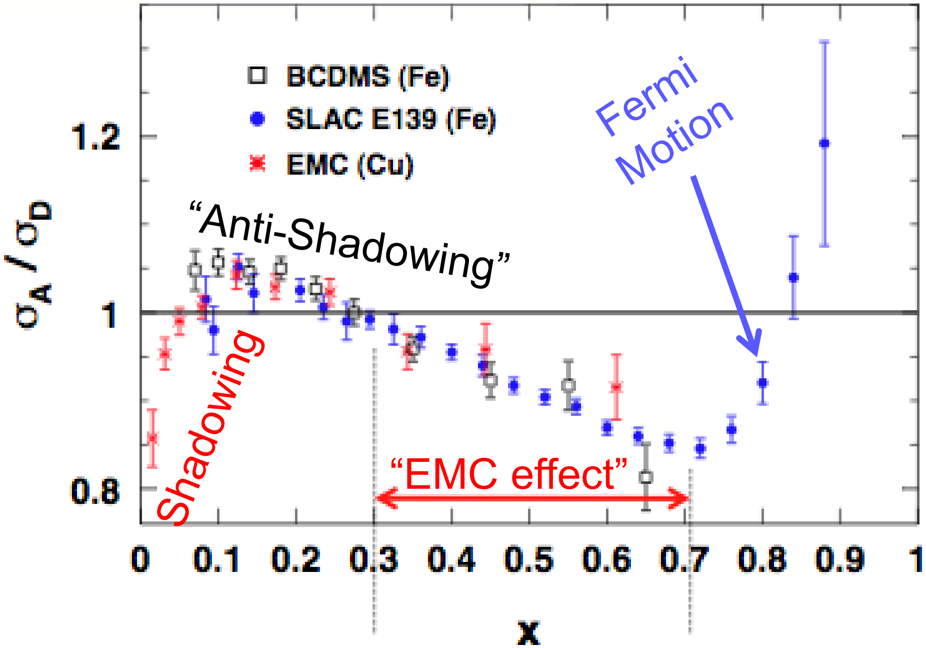
Systematic Errors

	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
Flux+Xsec in T2K fit	5.7%	8.7%
Xsec (from other exp.)	7.5%	5.9%
SK + FSI	3.9%	7.7%
Total	**10.3%**	**13.4%**

A Long-Standing Puzzle: The EMC Effect



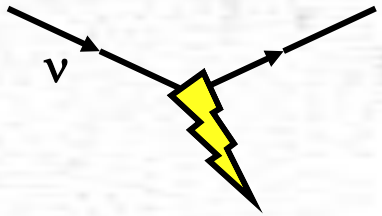
- Charged lepton F_2^A/F_2^D shows convincingly modification of quark distributions in a nucleus
  - No model of nucleus as an incoherent sum of nucleons can reproduce this effect.
  - No conclusive model of the collective behavior exists.



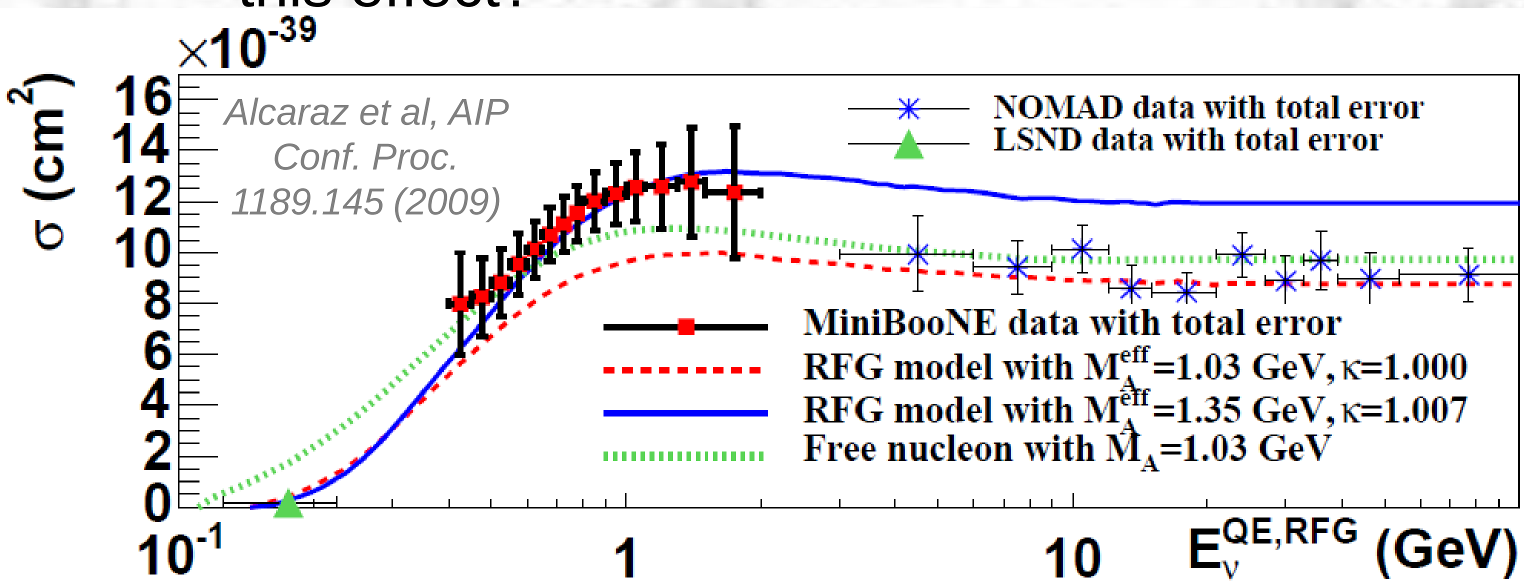
(D. Gaskell, ECT, Hadrons in the Nuclear Medium)*

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

"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?

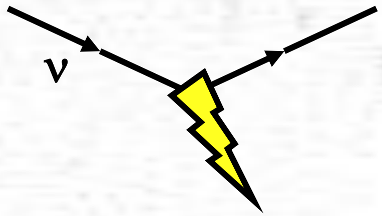


Posters:

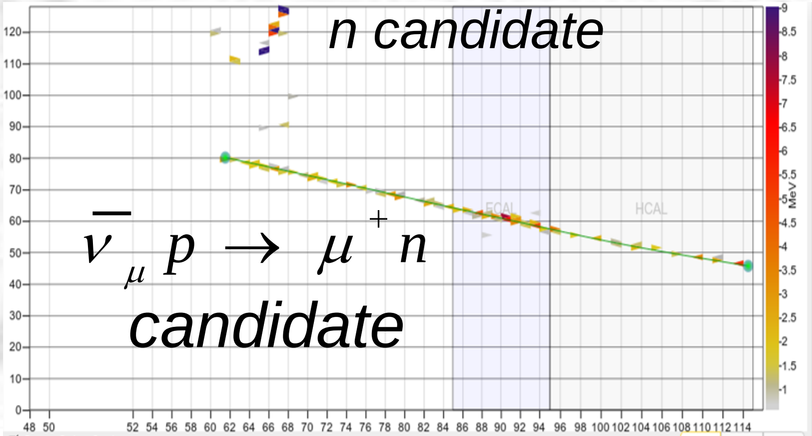
MINOS 205-1
(progress report)

MiniBooNE 119-2
(outside fits to MiniBooNE)

First MINERvA Result!

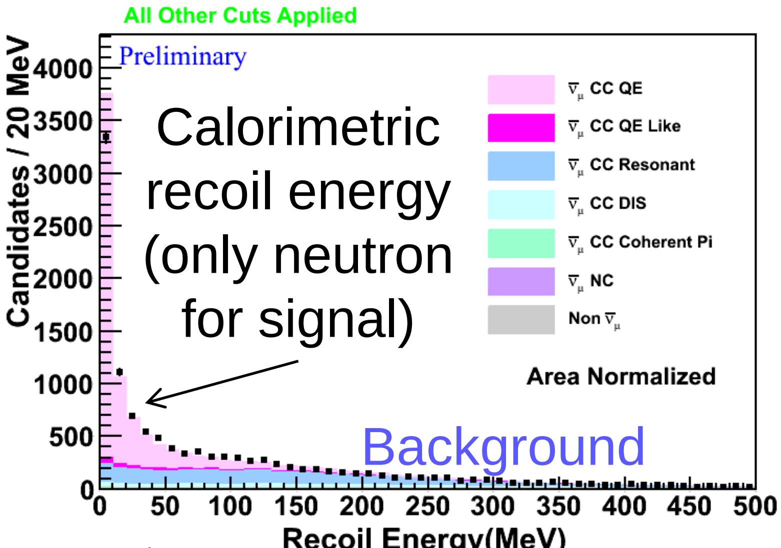


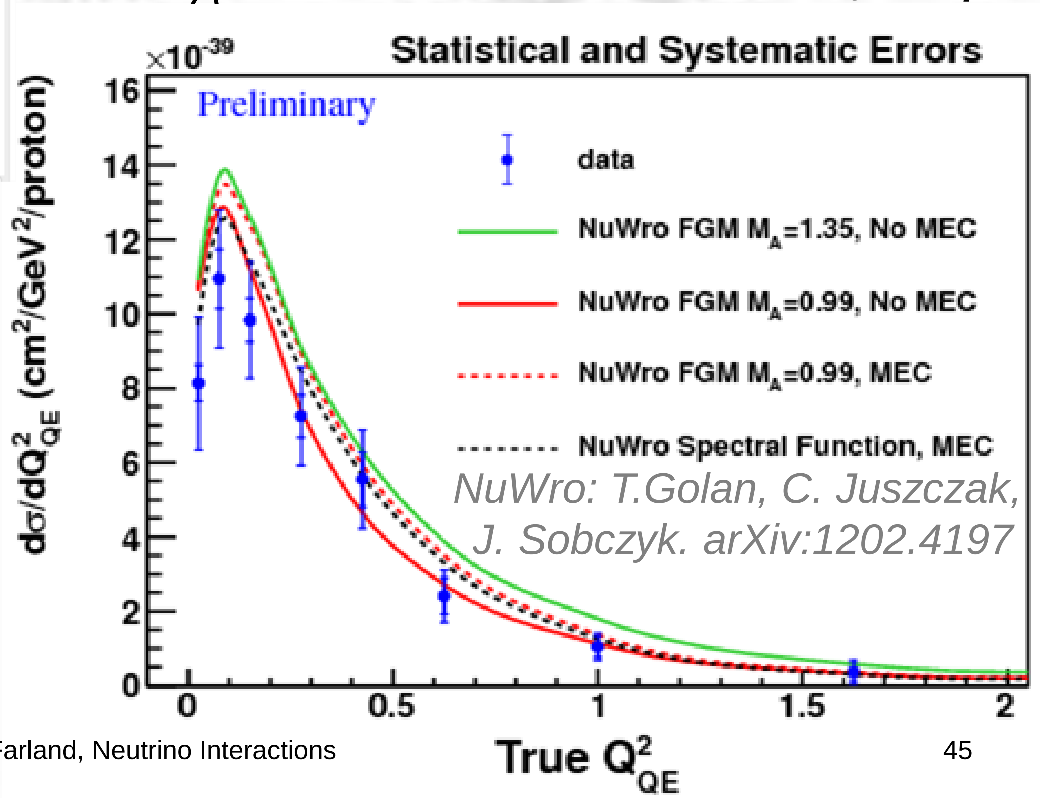
Anti-neutrino CCQE on scintillator (CH)



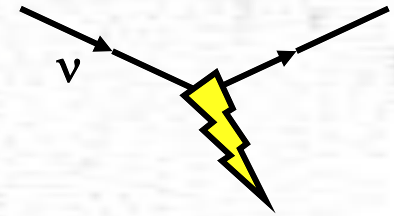
Even with current systematics (will improve), clear trends in data

- *M_A 1.35 disfavored; low Q^2 dip*



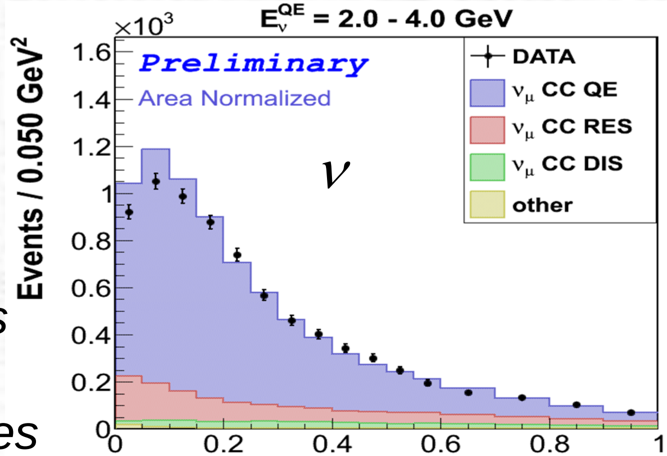


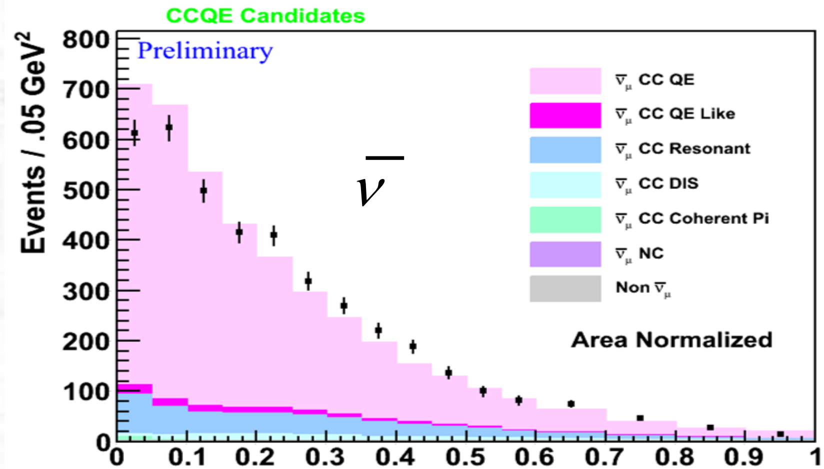
Neutrino and Anti-Neutrino in Energy Bins



Q^2 distributions compared to GENIE, M_A=0.99 GeV/c^2

Low Energy, 2-4 GeV



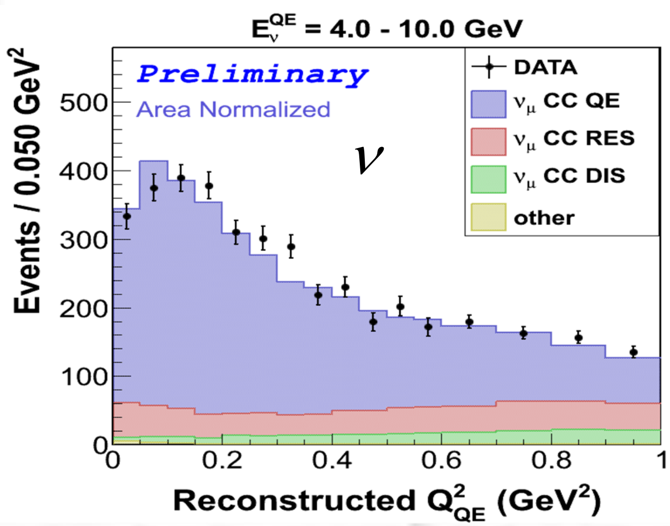


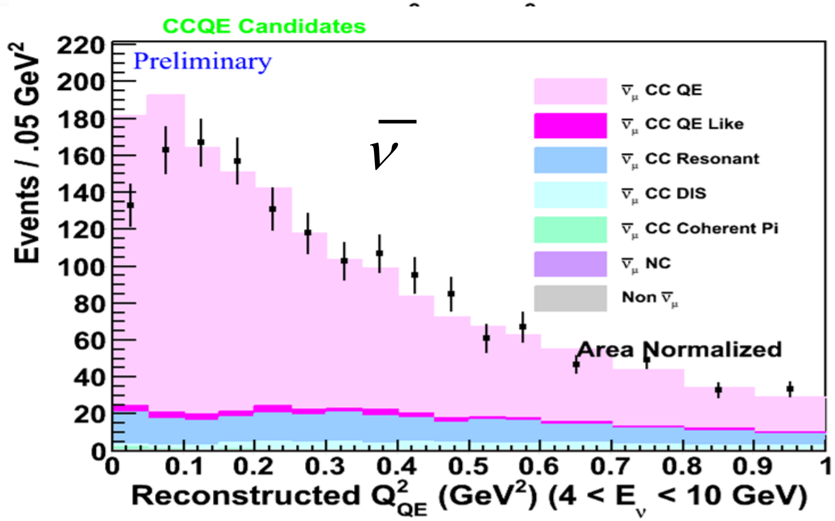
Similar trends in Q^2 in both beams, energies

Poster 132-3

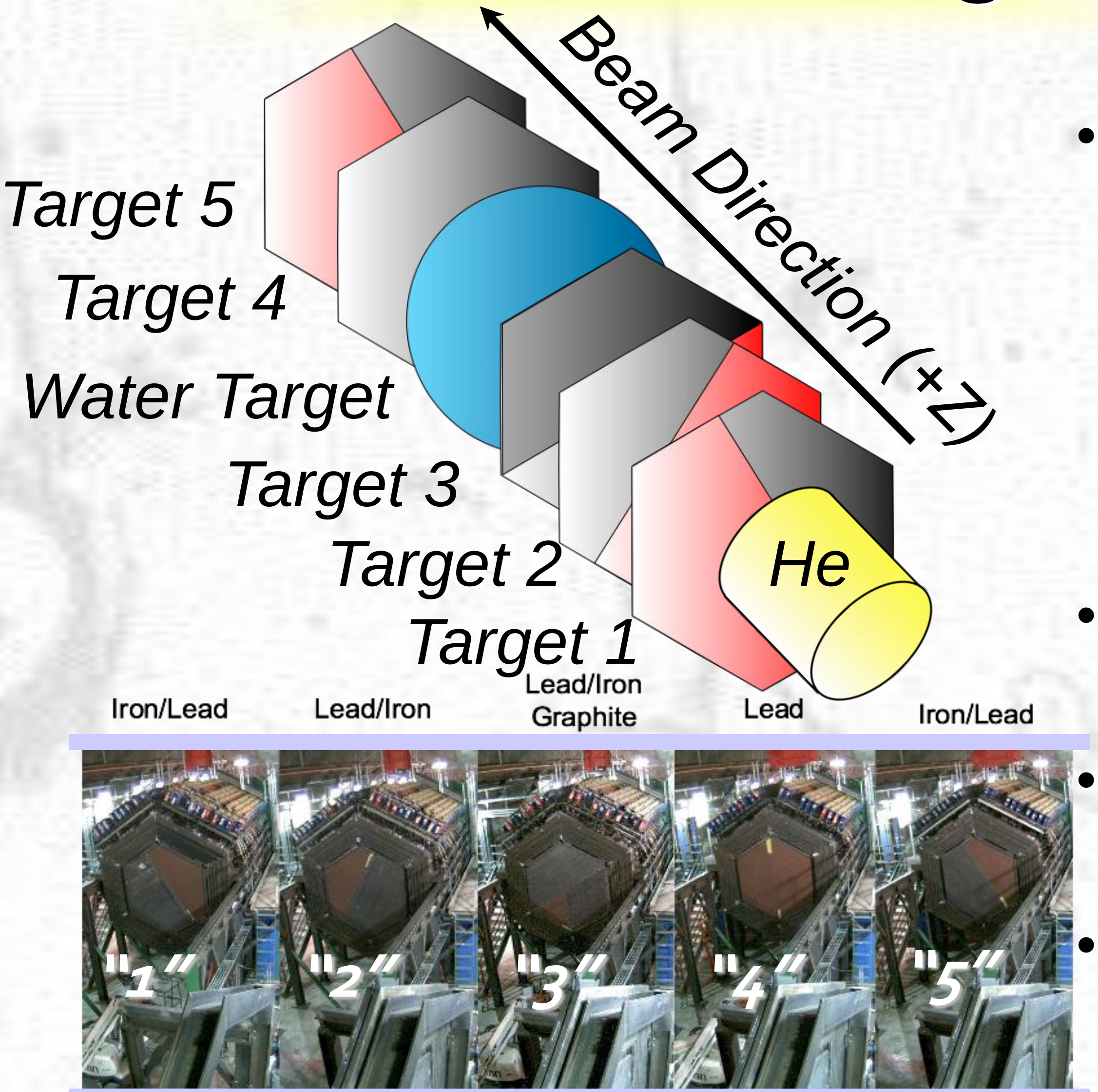
20% of our data on CH

High Energy, 4-10 GeV





MINERvA's Targets



- Goal: High statistics ratios of Fe/Pb/C/O/He in identical flux
  - Extract x-dependent nuclear effects as a function of A!
- Targets surrounded by active scintillator.
- Some thick targets for "high" rate.
- Also thin targets for exclusive final states.