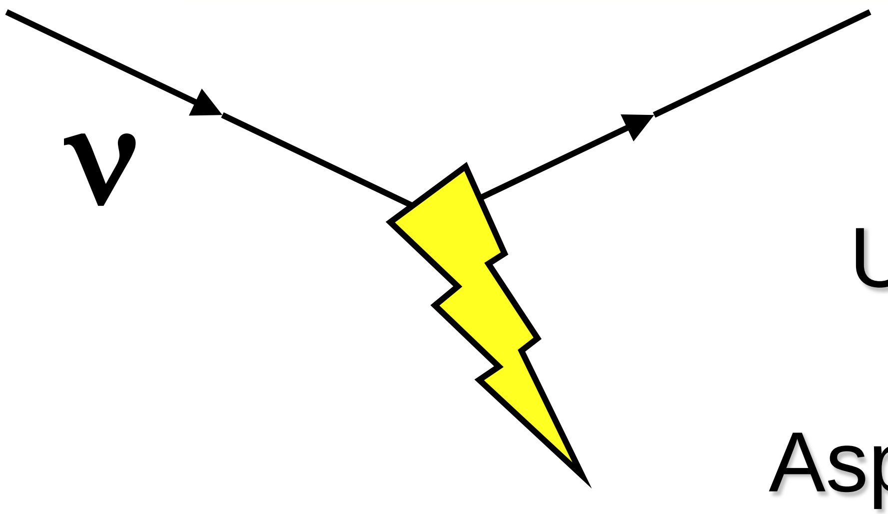
Neutrino Interactions and the Oscillation Program



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University of Rochester
ν New Directions
Aspen Center for Physics
7 February 2013

Lucky to Have this Problem

- Those of us working on neutrino masses and mixings are very fortunate
  - Recent major investments in new programs:
    - NuMI, T2K, Reactor Experiments
  - Serious discussion (with money) of next steps:
    - LBNE, Hyper-K, LBNO, Daya Bay II, INO ICAL, PINGU, ORCA, YAH (your acronym here)
  - Even nature is kind to us
    - If we'd had this experimental program, but θ_{13} had not been so enormous, דַּיֵּנוּ
- Sometimes good fortune leads to trouble

It’s a SuperYacht World

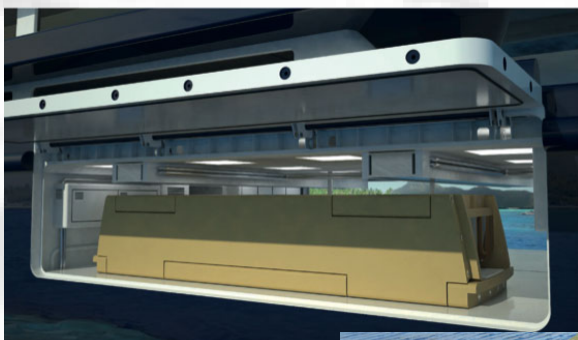
- Where better to contemplate the burdens of excess than Aspen?
- Prof. Walter was seated next to someone on his flight reading SuperYacht World magazine
  - “The global magazine for Superyacht owners”
- What problems do SuperYacht owners face?

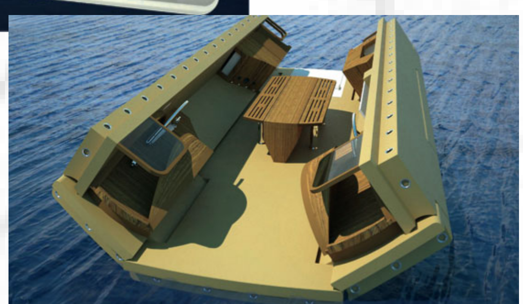
SuperYacht Burdens

- SuperYacht owners must be able to entertain their fabulously wealthy friends in the style to which they are accustomed
- However, aesthetics of design and needs for nuisances like engines frequently lead to limited deck space on your 60m yacht

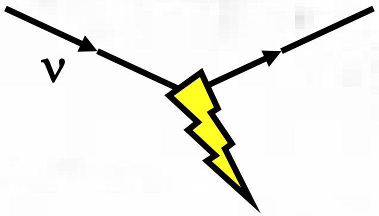
Capitalism to the Rescue!

- Fortunately, henrywarddesign [sic] has tackled this problem with solutions starting at £500,000
- Fully customized, stowable “recreational islands” that can be deployed from your SuperYacht!

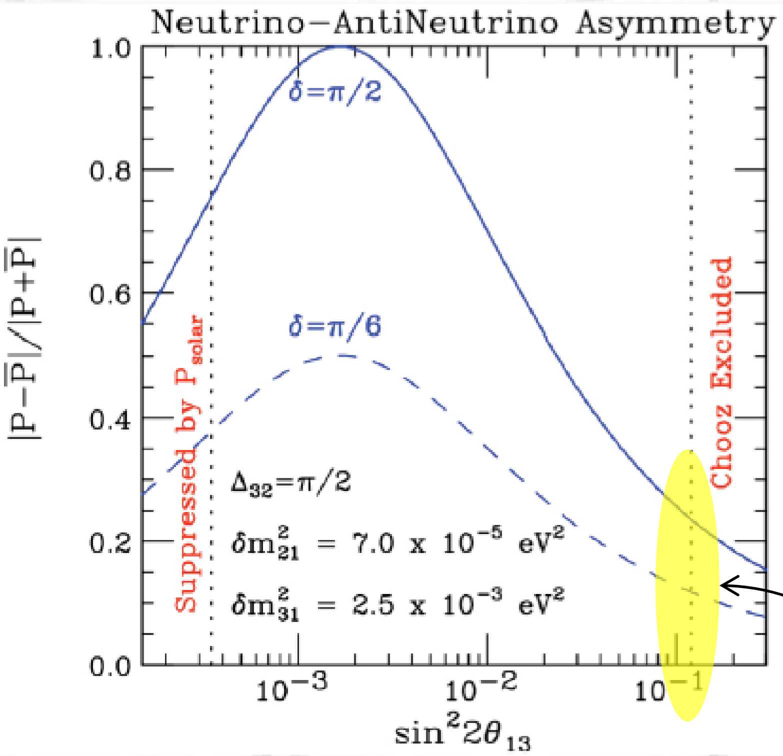




Be grateful for your burdens

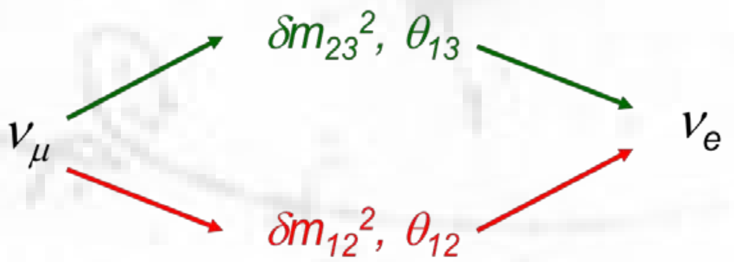


- Our burdens are not those of SuperYacht owners
- However, we do have some problems



(Parke 2003, arXiv:0710.554)

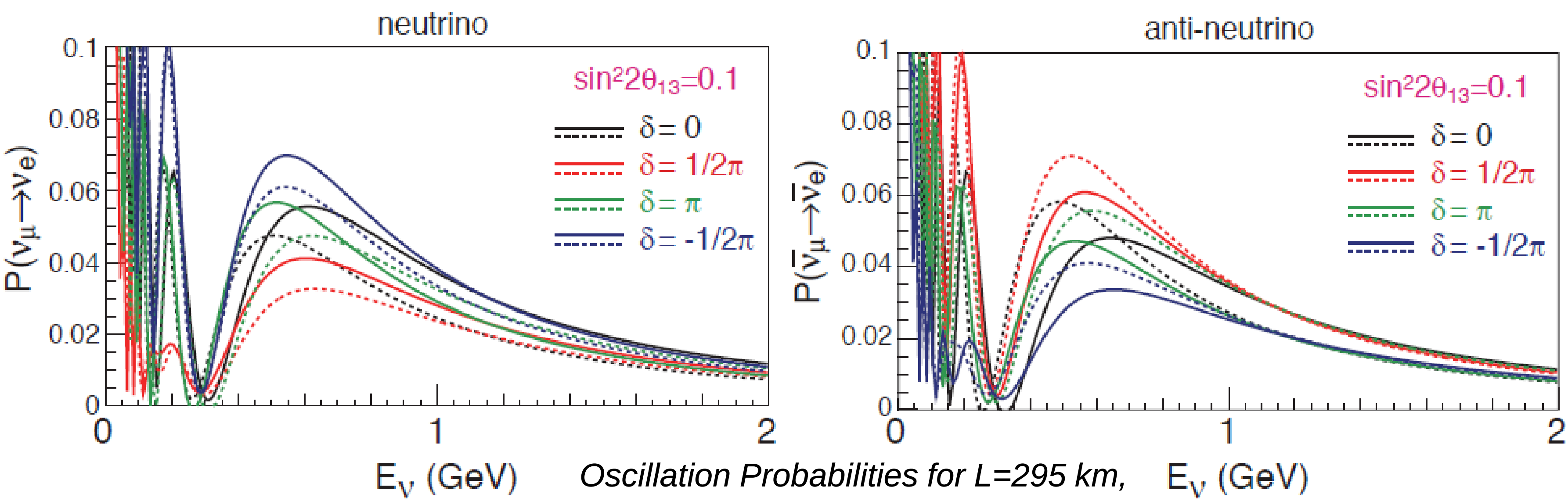
- Large θ_{13} means high rate of $\nu_\mu \rightarrow \nu_e$…
  - But fractional CP asymmetry decreases as θ_{13} increases



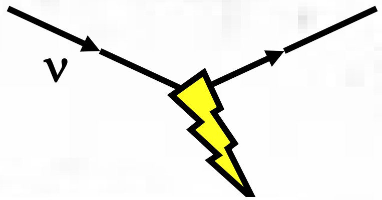
- Nature put us here
- Systematics become critical

Burdens (Hyper K)

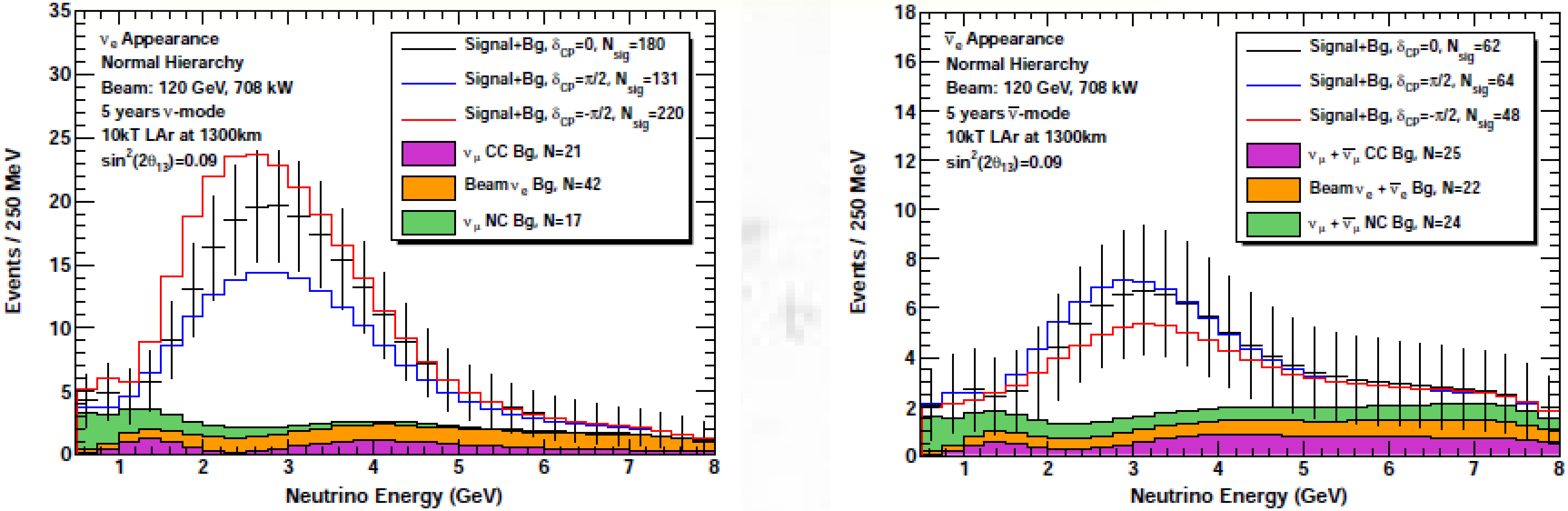
- Discovery of CP violation in neutrino oscillations in conventional beams requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy



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



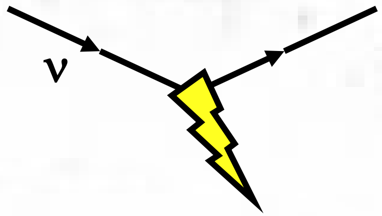
Burdens (LBNE)



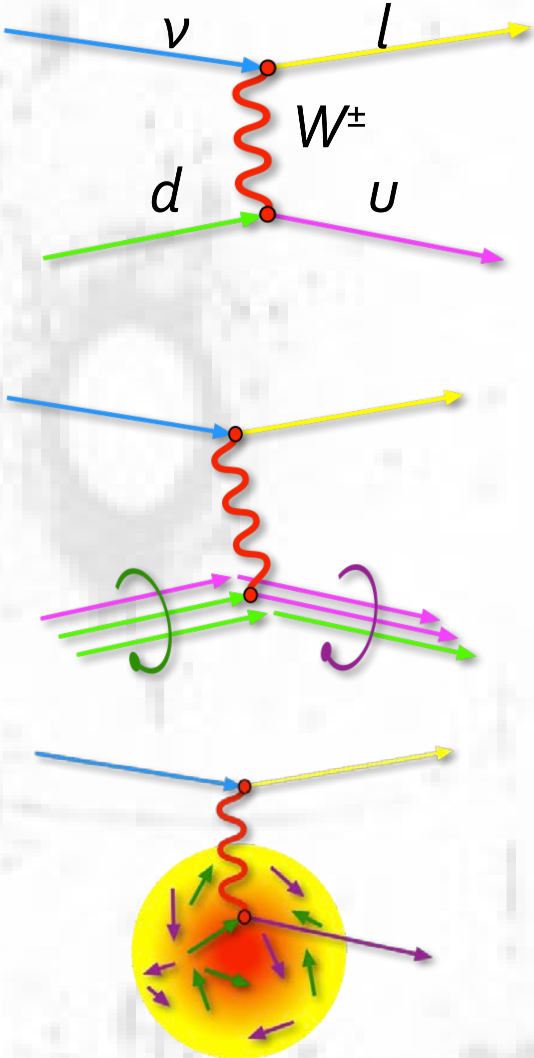
LBNE Phase 1 CDR

- 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

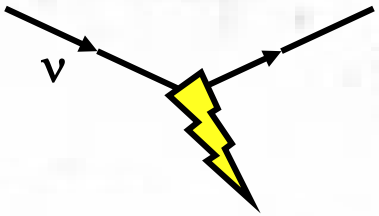
Burdens *(Interactions & Targets)*



- Although the weak interactions of neutrinos are, of course, well understood, application to our experimental needs is not
  - Nucleons have form factors
  - "Elastic" inside the nucleus probably isn't really elastic

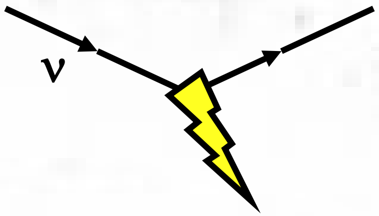


  - Inelastic reactions of strongly coupled systems are hard to calculate from first principles



What deficiencies of knowledge might ruin our future neutrino oscillation experiments?

Oscillation Experiments and Near Detectors



- The classic description of an oscillation experiment
  - Predict the neutrino interaction rate before oscillations
    - The product of flux and cross-section
  - Calculate an oscillation probability as a function of neutrino energy
  - Compare to the far detector to measure oscillations
- Near detectors are a powerful tool for constraining uncertainties
  - In principle, near detectors measure the rate without oscillations, eliminating flux and interaction uncertainties.
  - “Identical” near detectors have same detection strengths and weaknesses as far detector

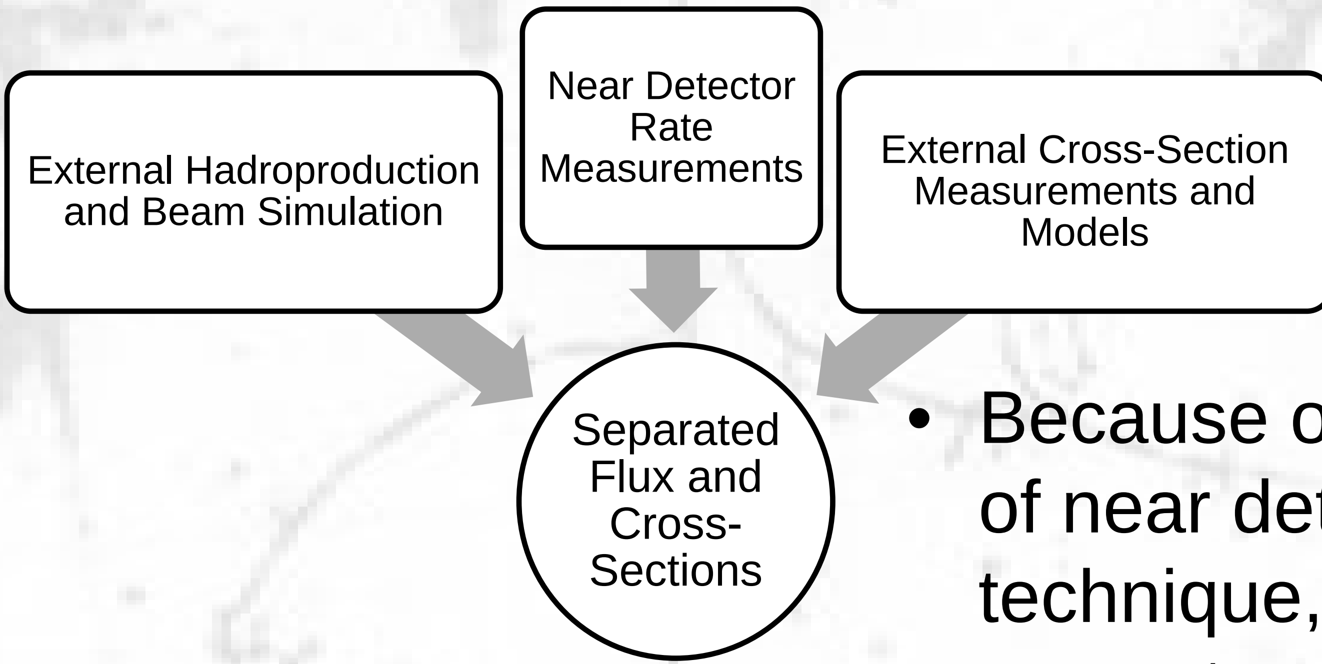
Limitations of Near Detectors

- 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).

- These limitations lead to the need to separate flux and cross-sections based on near detector measurements.

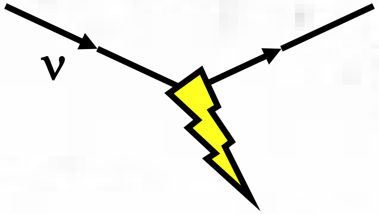
Flux & σ Degeneracy

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

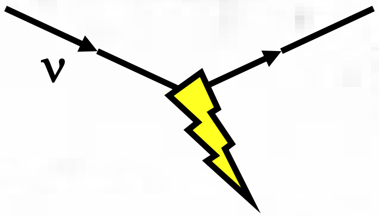


- Because of limitations of near detector technique, these rely on accurate models

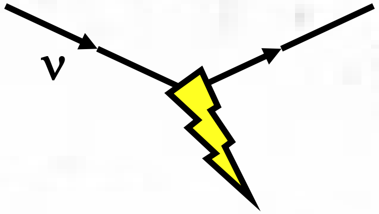
Limitations of Near Detectors



- 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.
- It is not straightforward to address #3 and #4 within your oscillation experiment

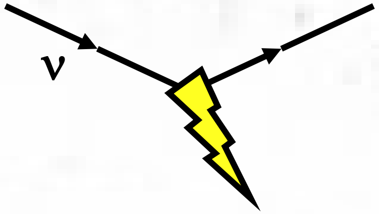


What can ease our burdens?



Our available toolkit

- Market forces alone are unlikely to solve our problems
- Improved theoretical models could lead to reliable calculations of interactions
- We could measure all the reactions in neutrino experiments or our near detectors
- We can make auxiliary (non-neutrino) measurements that indirectly constrain interaction models



Our available toolkit

- Improved theoretical models could lead to reliable calculations of interactions
  - QCD in the nucleus is not an exactly solvable problem
  - Models are effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions.
  - Effective theories are often only valid in a limited kinematic regime, or for a subset of possible final or intermediate states
  - Different approaches often give different results with sketchy guidance from first principles about which is "best"
- We could measure all the reactions in neutrino experiments or our near detectors
- We can make auxiliary (non-neutrino) measurements that indirectly constrain interaction models

Our available toolkit

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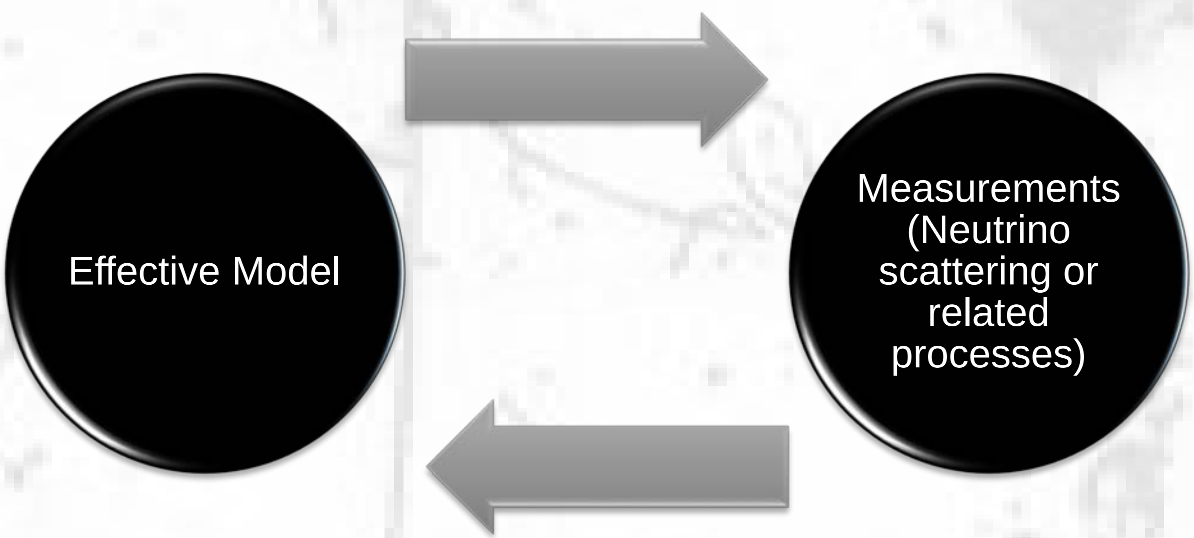
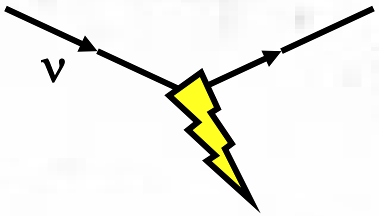
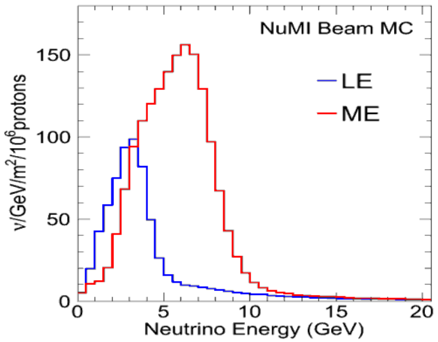
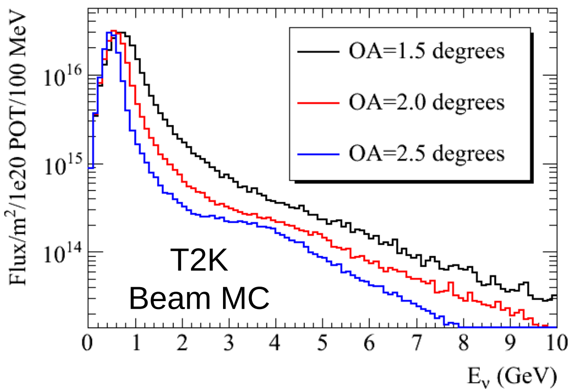


Our available toolkit

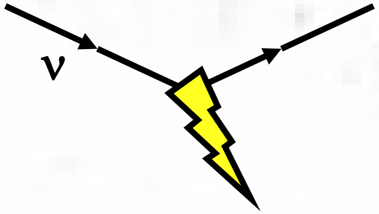


- Improved theoretical models could lead to reliable calculations of interactions
- We could measure all the reactions in dedicated neutrino experiments or our near detectors
  - Initial state energy of an event is typically not well known
  - High flux "narrow band" beams aren't.





  - Reconstructing the neutrino energy from the final state doesn't allow us to understand the bias that similar approaches would have in an oscillation experiment
- We can make auxiliary (non-neutrino) measurements that indirectly constrain interaction models

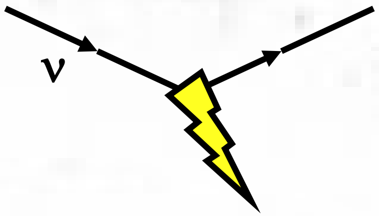


Our available toolkit

- Improved theoretical models could lead to reliable calculations of interactions
- We could measure all the reactions in neutrino experiments or our near detectors
- We can make auxiliary (non-neutrino) measurements that indirectly constrain interaction models
  - Electron scattering is a frequent input to most of the neutrino interaction models we use today
  - Wealth of data at JLab, for example, on elastic and inelastic processes on nuclei
  - But electron scattering can only probe the axial current indirectly, and sometimes access to kinematics relevant to neutrino scattering is difficult. E.g., $1/Q^4$ in propagator.

Lengthy Illustration: Modeling Quasi-Elastic Scattering

Quasi-Elastic Energy Reconstruction

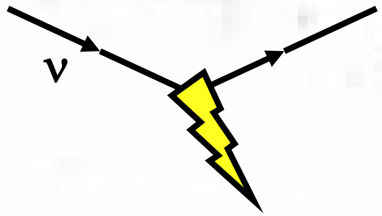


- Quasi-elastic reaction allows neutrino energy to be determined from only the outgoing lepton:

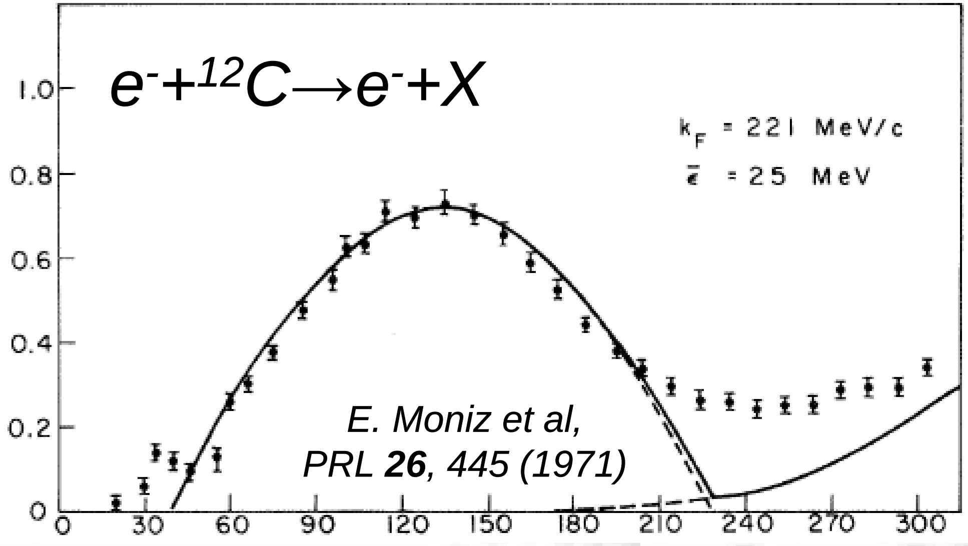
$$E_\nu^{\mathrm{rec}} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e \cos\theta_e)},$$

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

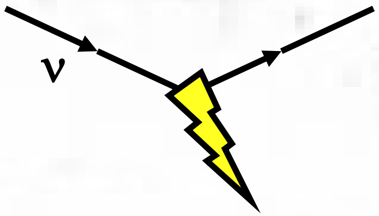
Modeling the Nucleon in a Nucleus



- 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.

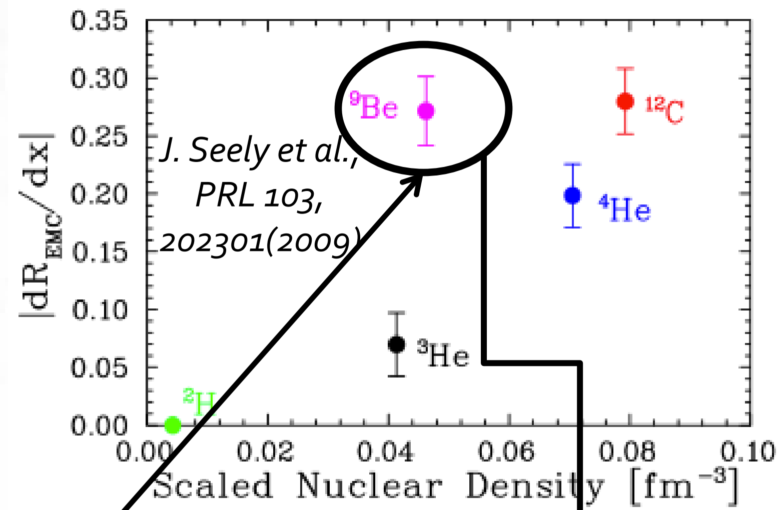


Mean Field Approximation?

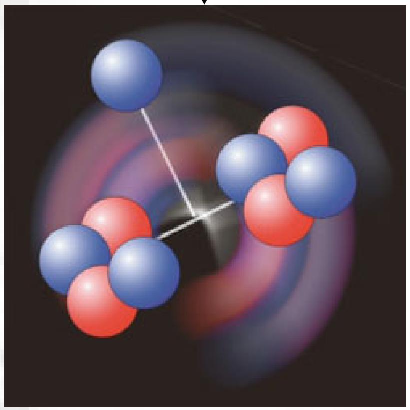


- There are many hints that the mean field approach isn't sufficient.

- *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*

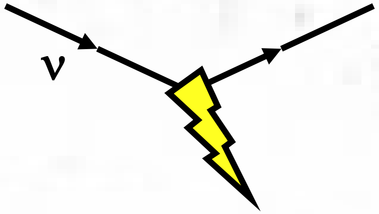


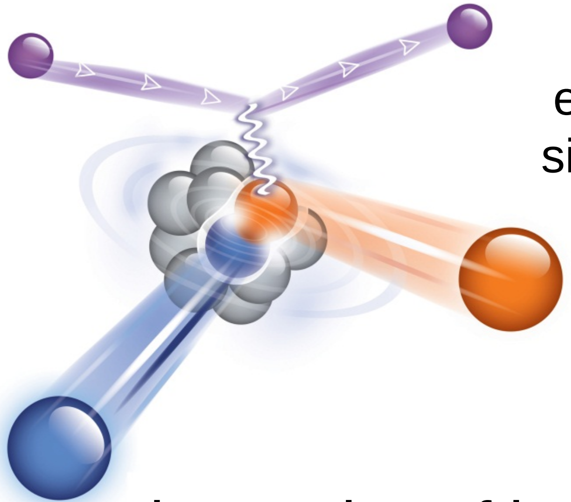
^{9}Be is two tightly bound α loosely held with a neutron



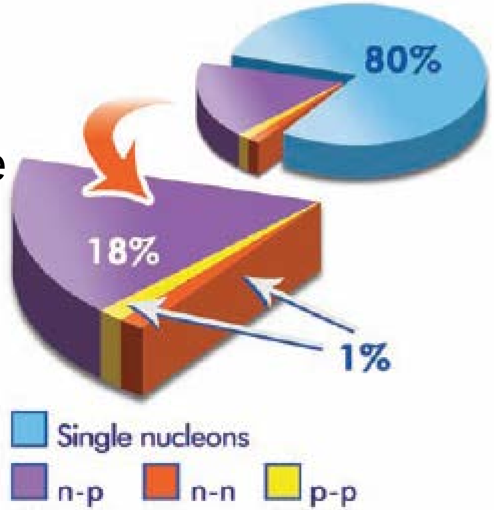
(Figure courtesy APS Phys Rev Focus)

Short-Range Correlations





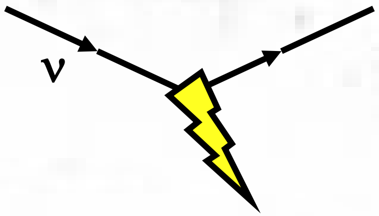
Recent Jlab studies of ^{12}C quasi-elastic scattering have demonstrated significant probabilities to see multiple nucleons knocked out beyond expectation from final state interactions.
*[R. Subedi et al., Science **320**, 1476 (2008)]*



- 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.

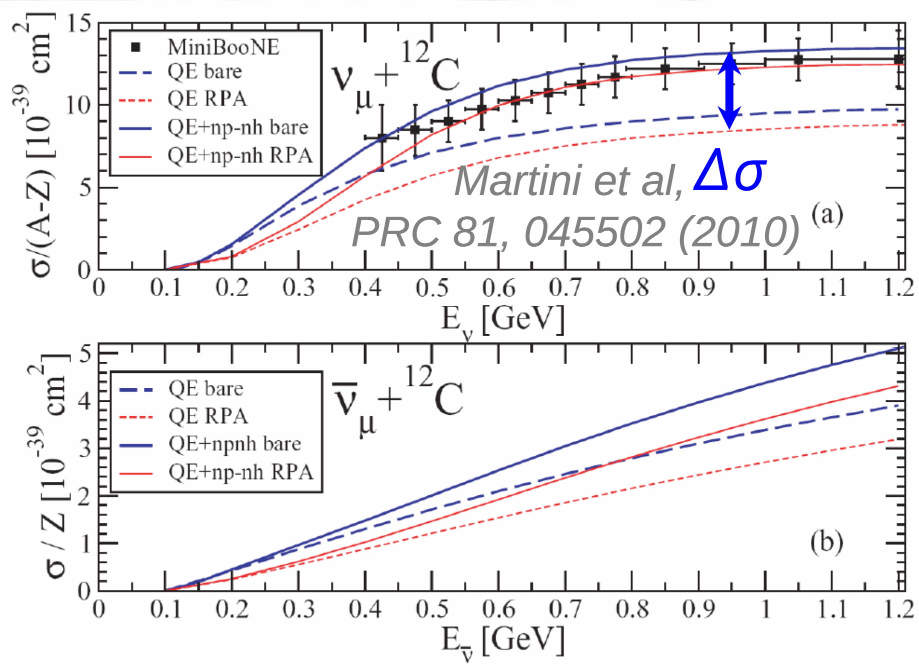
Dekker et al., PLB **266**, 249 (1991)
Singh, Oset, NP **A542**, 587 (1992)
Gil et al., NP **A627**, 543 (1997)
J. Marteau, NPPS **112**, 203 (2002)
Nieves et al., PRC **70**, 055503 (2004)
Martini et al., PRC 80, 065001 (2009)

Origin of MiniBooNE CCQE "Axial Mass"?



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

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

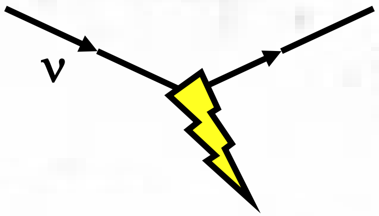


New work since Martini proposal

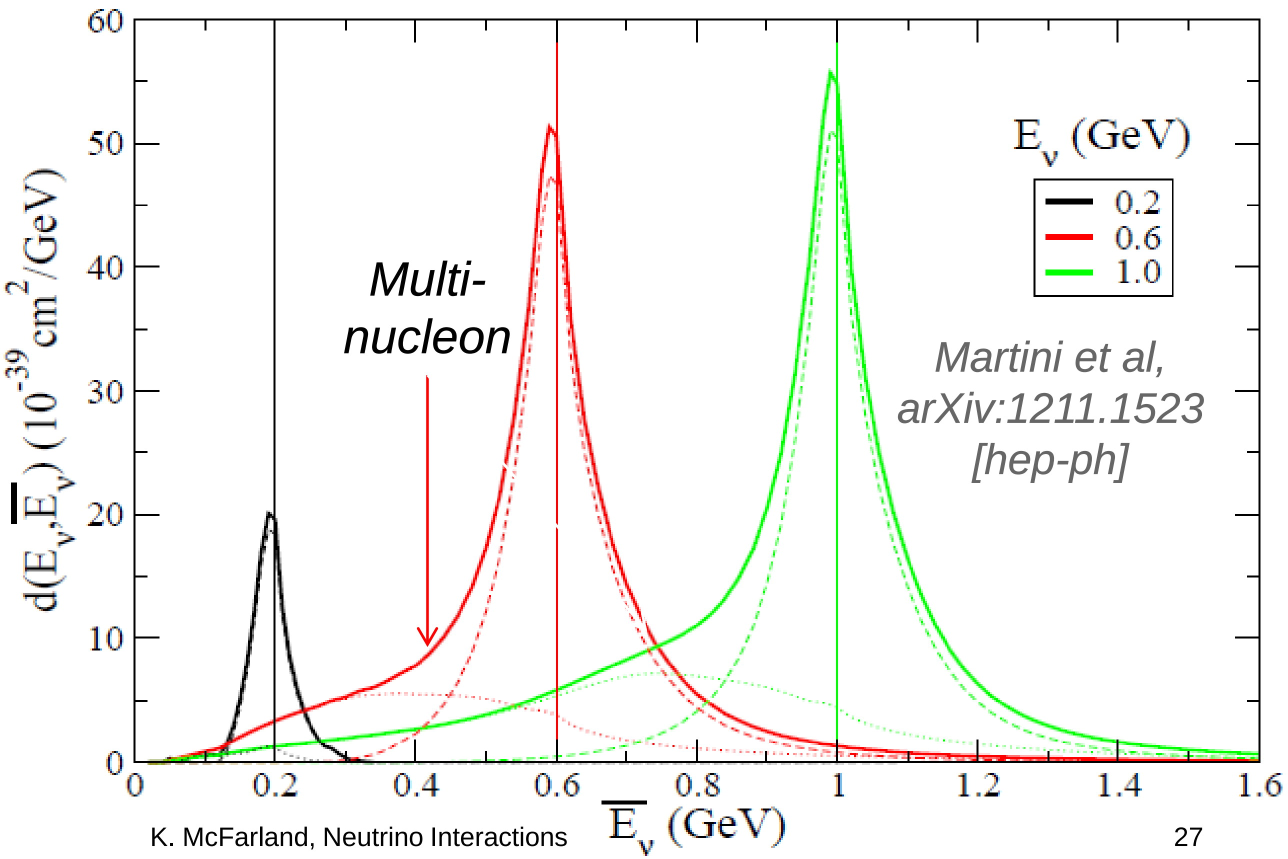
Nieves *et al*., arXiv:1106.5374 [hep-ph]
Bodek *et al*., arXiv:1106.0340 [hep-ph]
Amaro, *et al*., arXiv:1104.5446 [nucl-th]
Antonov, *et al*., arXiv:1104.0125
Benhar, *et al*., arXiv:1103.0987 [nucl-th]
Meucci, *et al*., Phys. Rev. **C83**, 064614 (2011)
Ankowski, *et al*., Phys. Rev. **C83**, 054616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

Energy Reconstruction: Quasi-Elastic



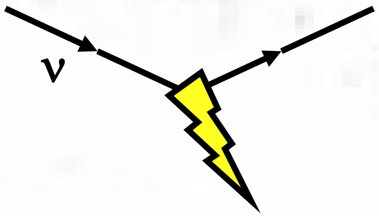
- How does it quantitatively matter if we model this as an effective axial mass or microphysically?
- Inferred neutrino energy changes if target is multinucleon.
- Recall that effect is ~20% of cross-section
- So the resulting energy bias is not small



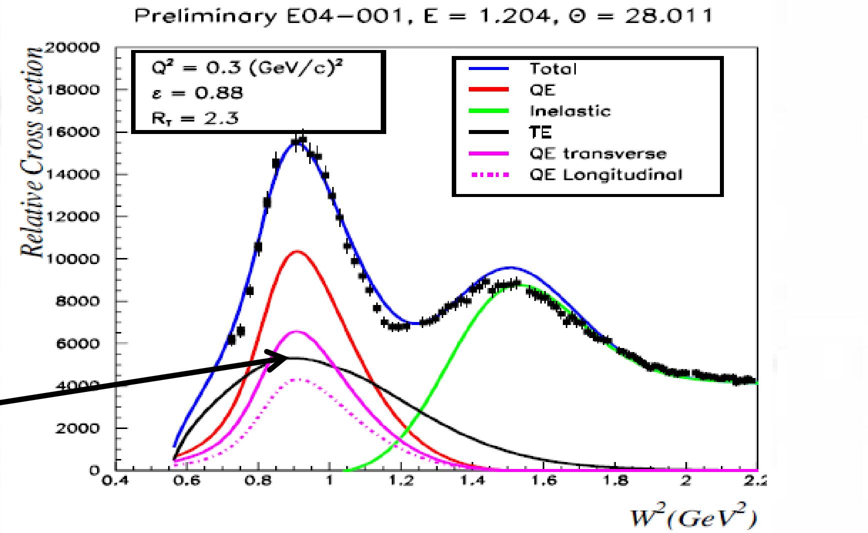
Modeling Multi-nucleon Correlations

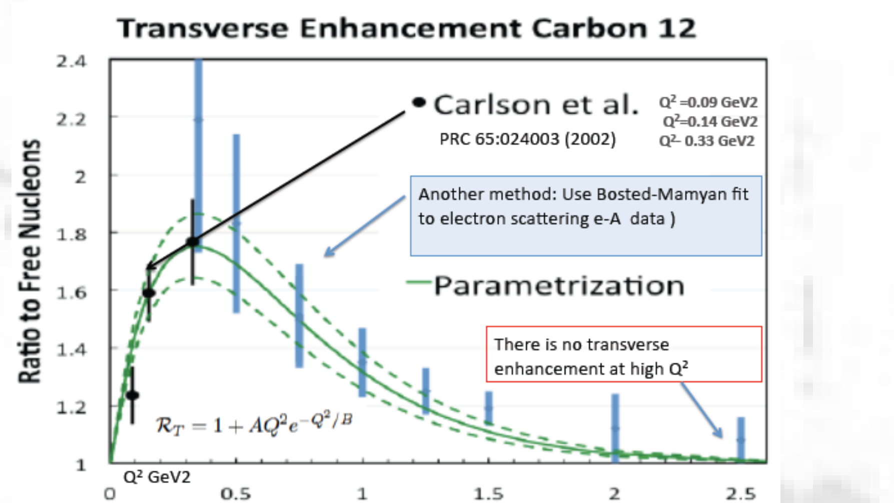
- There are several microphysical calculations on the market, but they share several key features.
  - They are all based on effective theories valid over limited ranges of energy, kinematics. Theoretical systematics are difficult to control.
  - Calculations are just starting to see effect in the right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



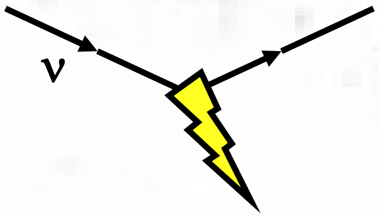
- Independent of models, can look for the effect in electron scattering
- Should show up as an enhancement to the transverse scattering cross-section on nuclei not seen on free nucleons
  - Do we learn enough from electron scattering data alone about the kinematic details? Probably not.



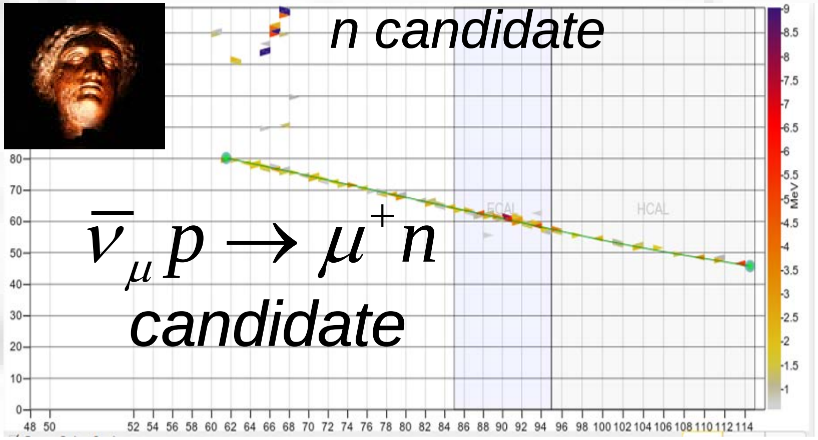


A. Bodek, H.S. Budd, M.E. Christy Eur.Phys.J. C71 (2011) 1726

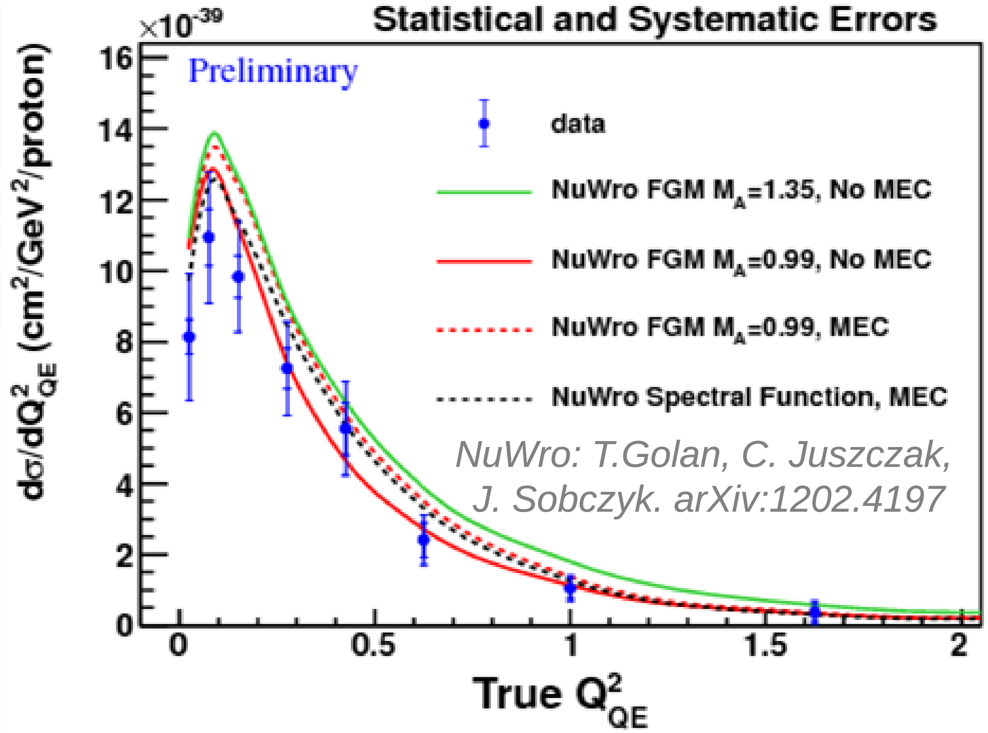
Neutrino Data

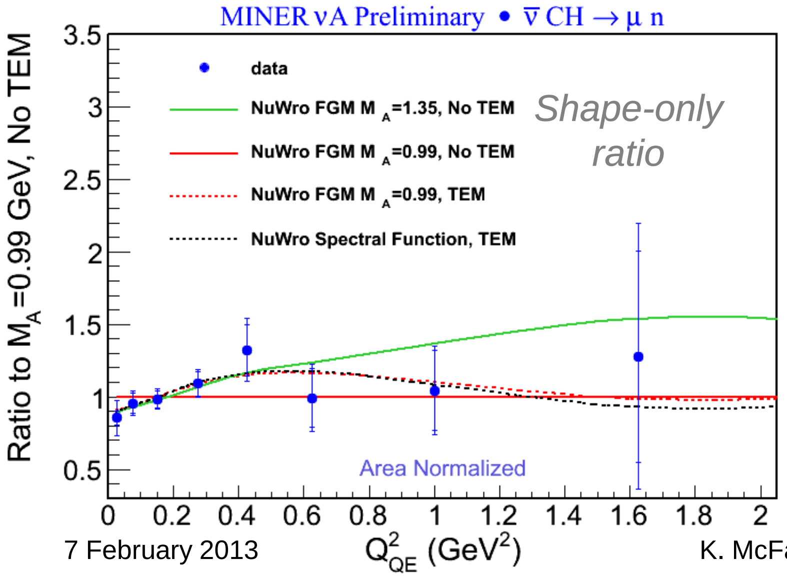


Anti-neutrino CCQE on scintillator (CH)



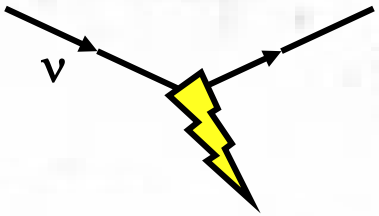
1/3 of data, partial detector, crude unfolding

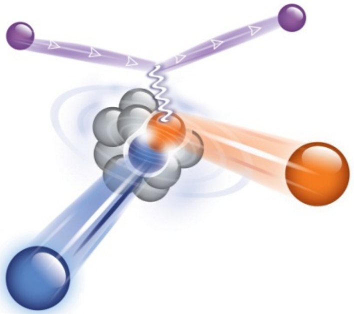




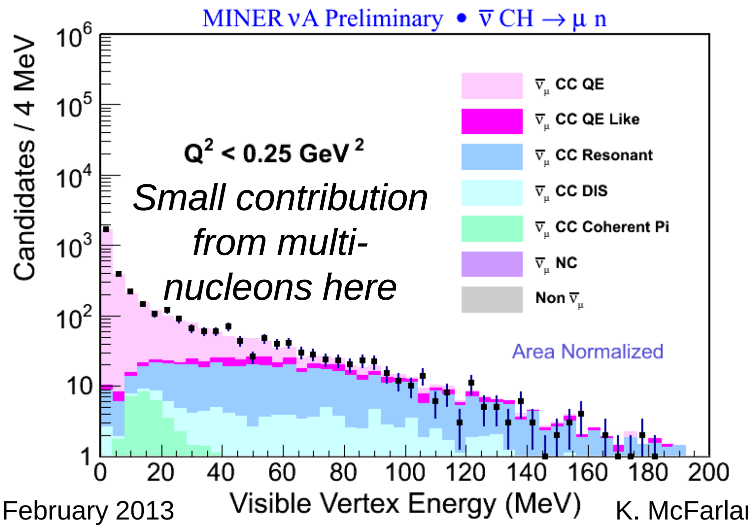
$d\sigma/dQ^2$ sensitive to these multi-nucleon effects. Agreement with Bodek-Budd-Christy parameterization is good. Need final result.

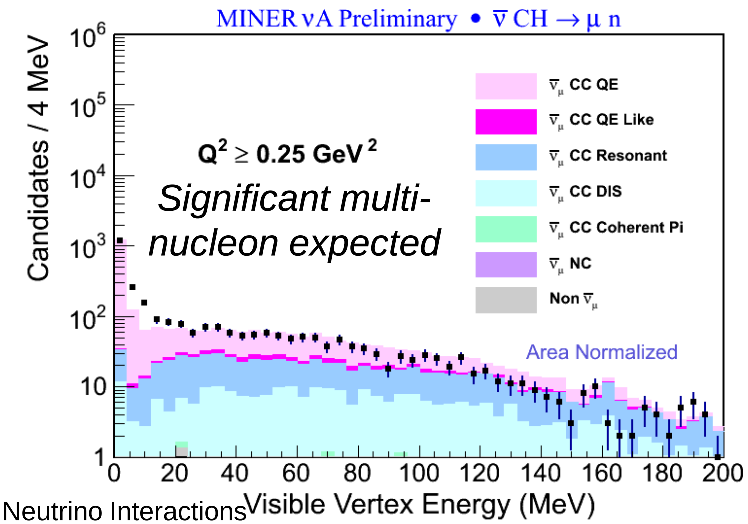
Neutrino Data



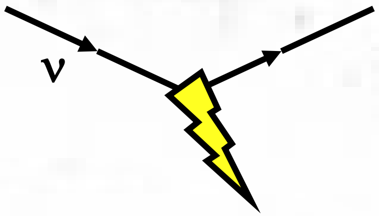


- Recall that multi-nucleon enhancements imply additional final state particles
- In MINERvA, additional protons would appear as enhanced energy near vertex, and additional neutrons as order(10) MeV "splashes" which are rare near vertex
- Teaser: anti-neutrino energy near vertex

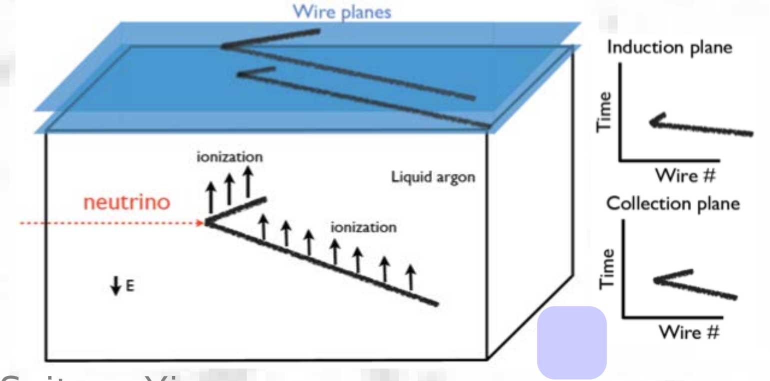




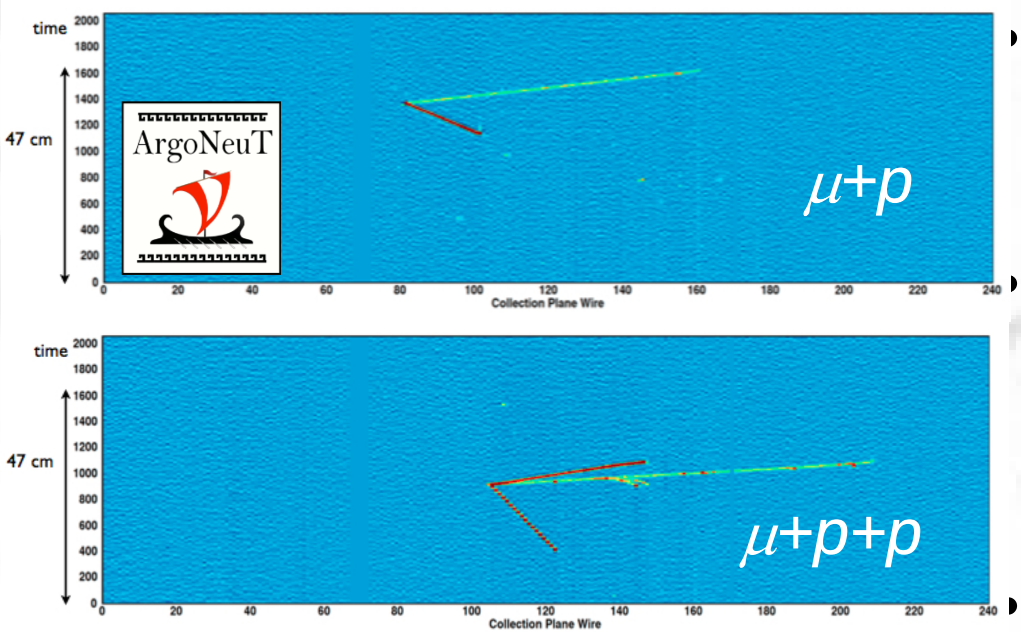
Neutrino Data



- Liquid argon has excellent resolution for final state
- Example: ArgoNeuT, a small liquid argon TPC test in NuMI beamline
- New results from Tingjun on Friday



J. Spitz, arXiv: 1009.2515v1



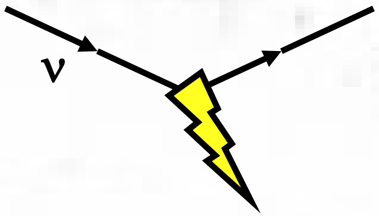
- Other detectors capable of seeing recoil protons can (and will) look for this
- *Difficulty will be separation of the effects of final state interactions from initial state correlations*
- Promising line of study

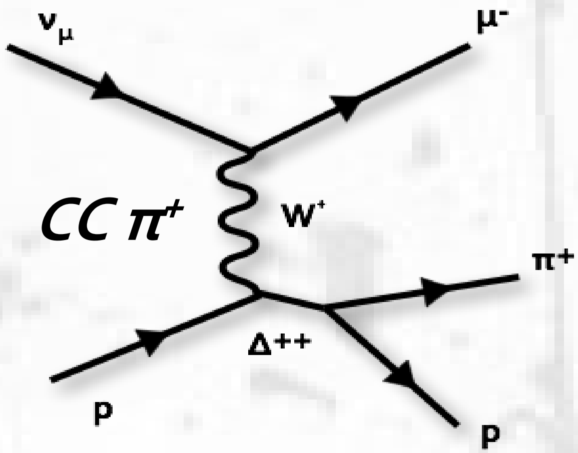
Other Puzzles and Progress

Energy Reconstruction: Inelastic

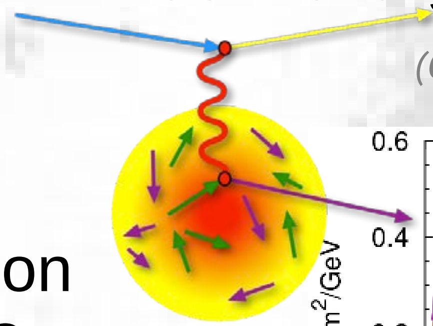
- This problem is worse than the elastic case
- Detector energy response varies
  - Neutrons often exit without interacting
  - Proton and alpha ionization saturates
  - π^- capture on nuclei at rest, π^+ decay, π^0 decay to photons and leave their rest mass in detector
- Any detector, even liquid argon, 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

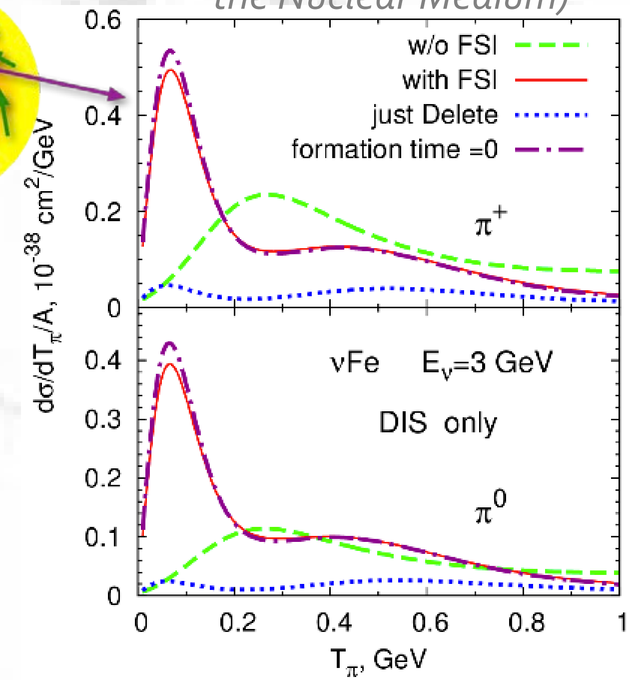




- What happens to our nucleon level prediction when you hide the target in a nucleus?



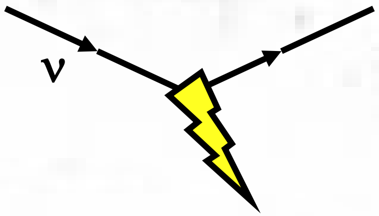
(O. Lalakulich, ECT, Hadrons in the Nuclear Medium)



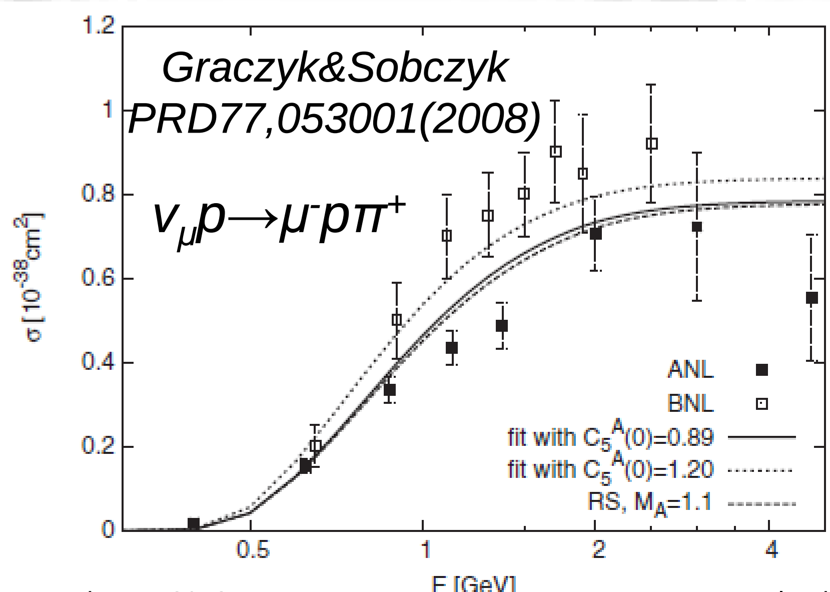
- Is our model of pion production from free nucleons accurate?
  [Rein & Sehgal, Ann. Phys. 133, 79-153 (1981)]

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

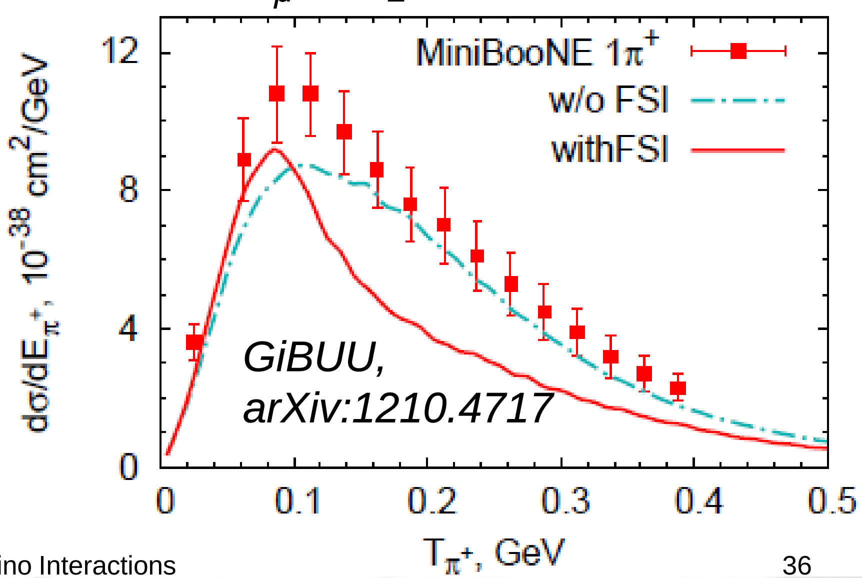
Pion Production Confronts Neutrino Data… and Fails



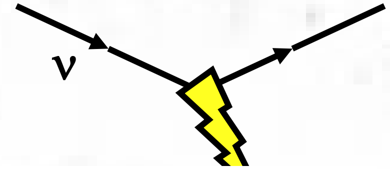
- Hydrogen datasets in conflict, so hard to have a definitive determination of axial form factor
- MiniBooNE CC pion production data gives an unexpectedly hard pion spectrum, as though the nucleus were transparent to the produced pion



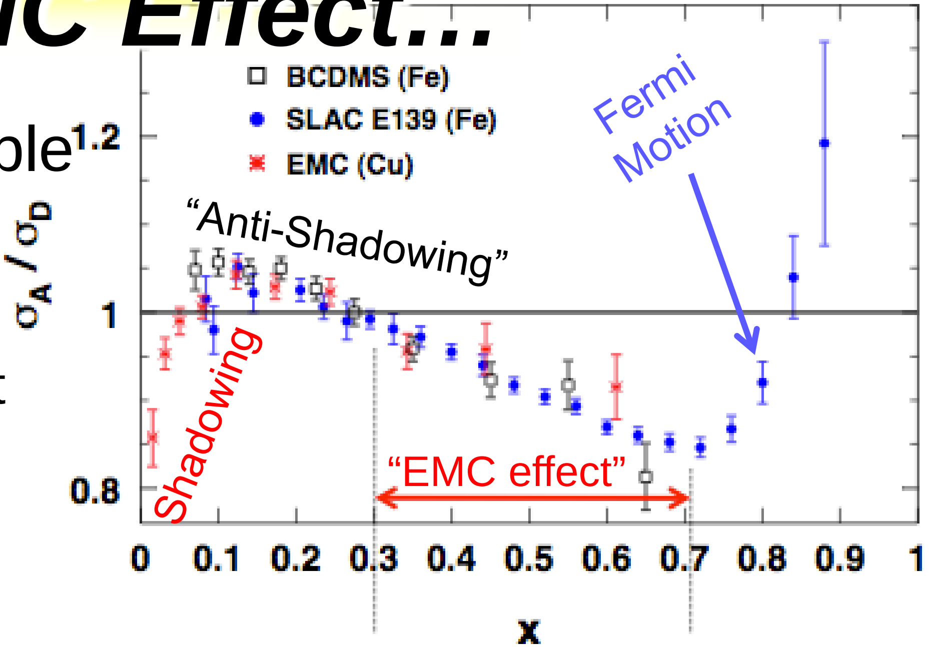
$\nu_\mu(CH_2) \rightarrow \mu^- \pi^+$+nucleons

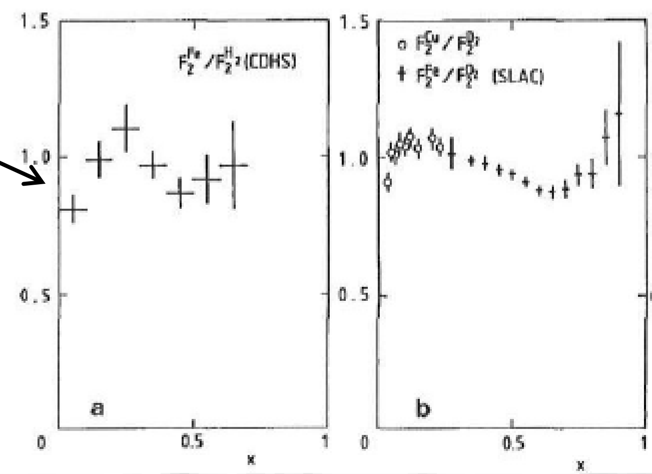


Models for Short-Range Correlations, EMC Effect…

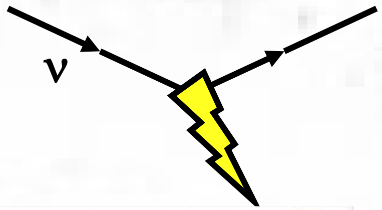


- A major goal is to make reliable measurements analogous to EMC in neutrino scattering
  - Different models of EMC effect have varying predictions for neutrinos
- Fe/D_2 ratio of F_2^{ν}.
  - Ratio of bubble chamber experiments (FNAL/CERN) to CDHS (CERN)
  - Challenging because of different beam flux,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

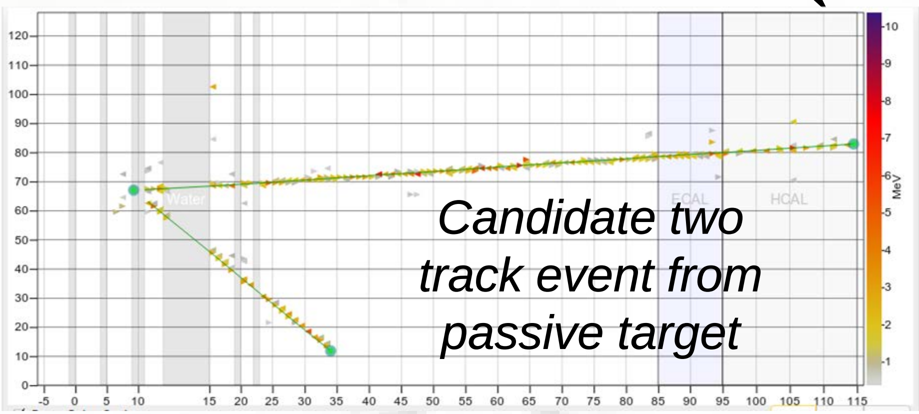


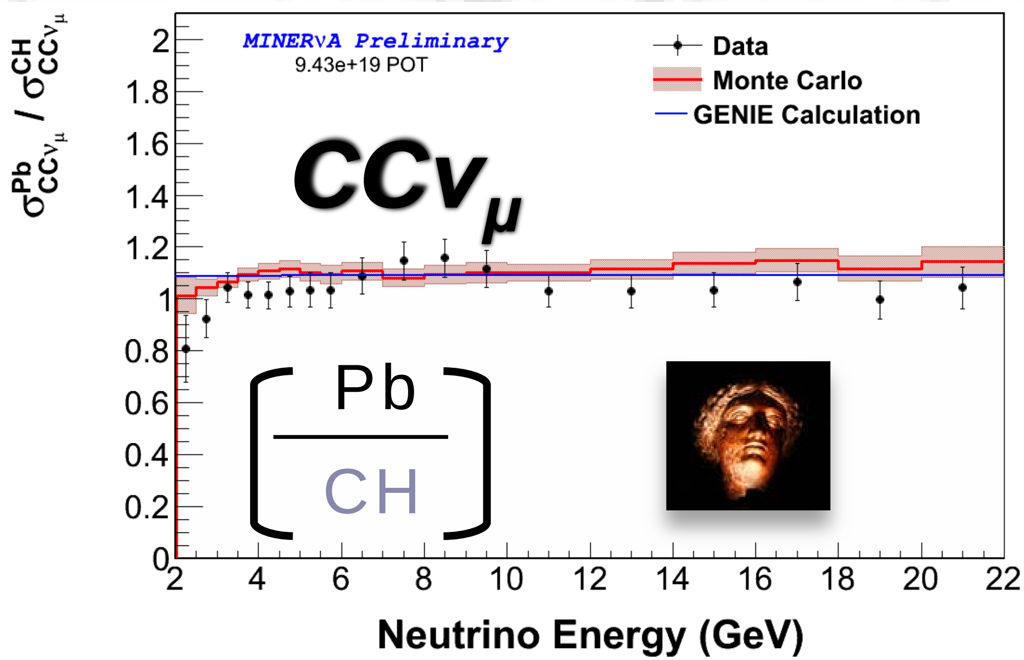


MINERvA's Pb/CH Ratio

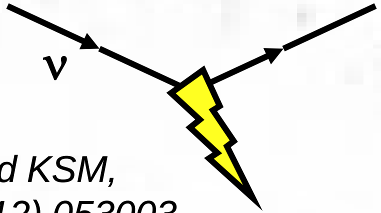


- Measure ratios of passive target to nearby scintillator
- Many reconstruction and flux uncertainties cancel
  - This preliminary result validates the approach
- Have a factor of four more data on tape and some tricks to play to increase acceptance
- Measurement becomes more interesting in NOvA era





Lepton Mass in Quasi-Elastic Scattering

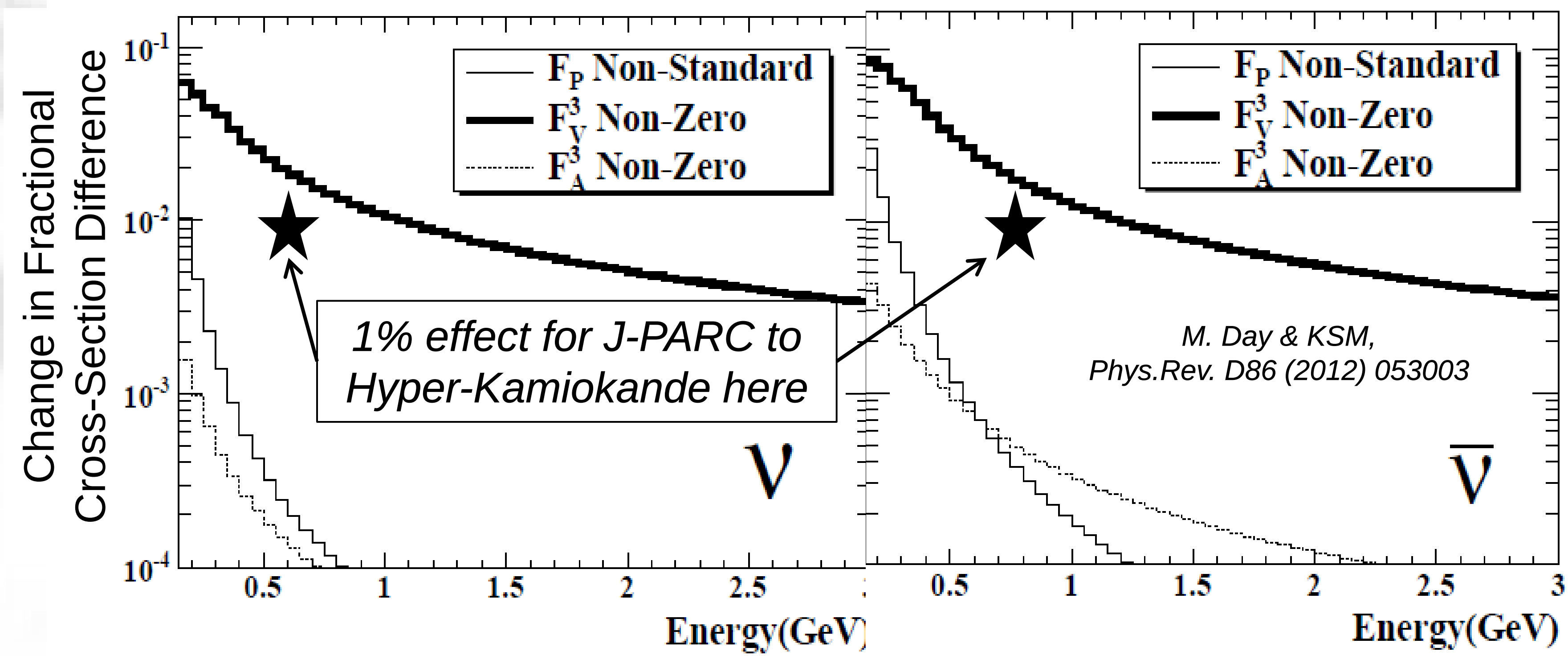


Melanie Day and KSM, Phys.Rev. D86 (2012) 053003

- 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

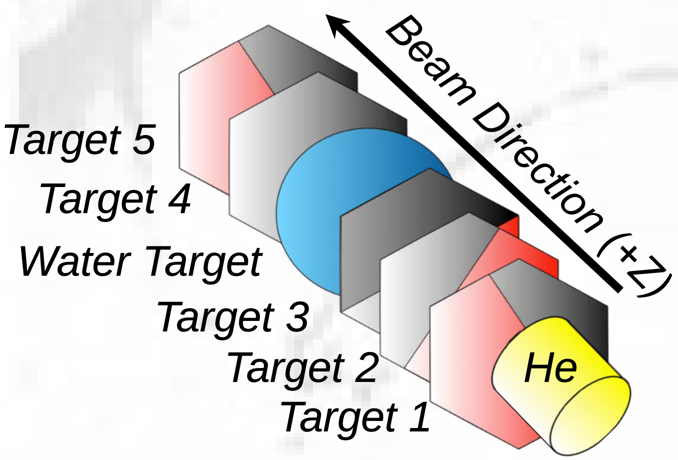
- Possible effect from F^3_V of few % at J-PARC to HK
  - Neutrino and anti-neutrino effects are opposite in sign for second class currents, so could fake a CP asymmetry.

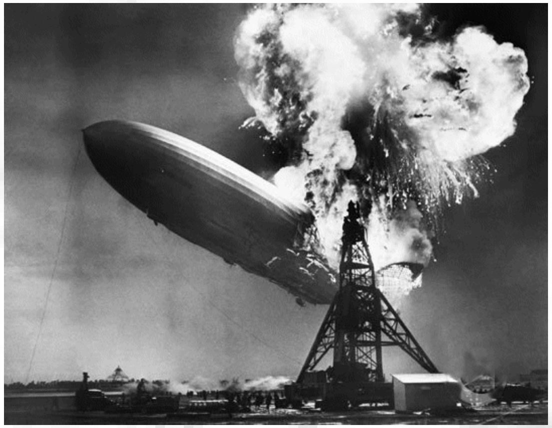


A few crazy ways forward for Neutrino Measurements

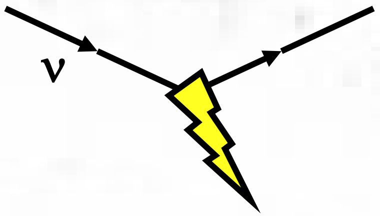
Back to the Future: Deuterium

- MINERvA approach of multiple targets in the same beam has a weakness: no free nucleons
  - MINERvA proposed a 0.25t fiducial volume passive target (He→D_2), but statistics were marginal in low energy beam and efficiencies are not ideal
  - Serious safety concerns even with 10^{-3} Hindenburgs in an underground cavern. Oh the humanity.

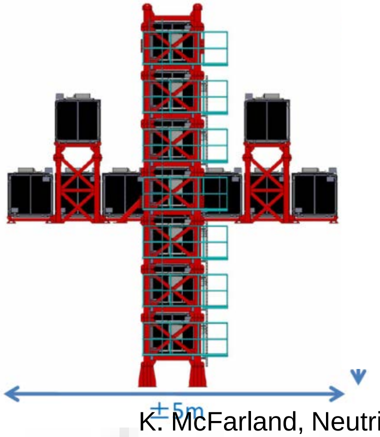


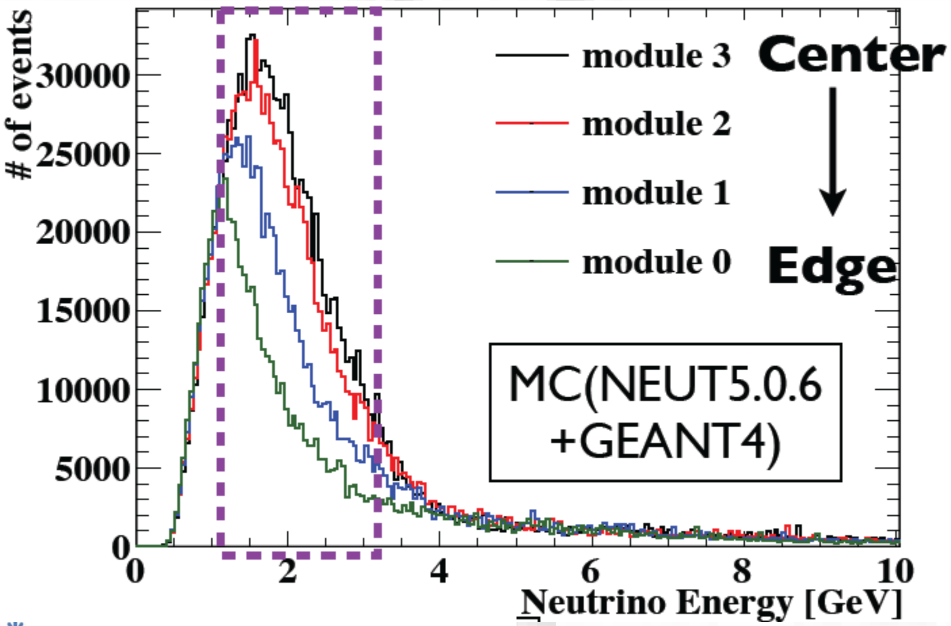


ANN: Artificially Narrowband Neutrinos

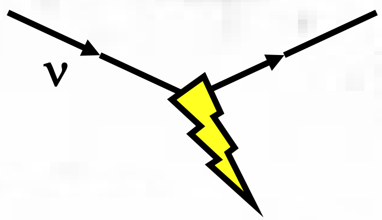


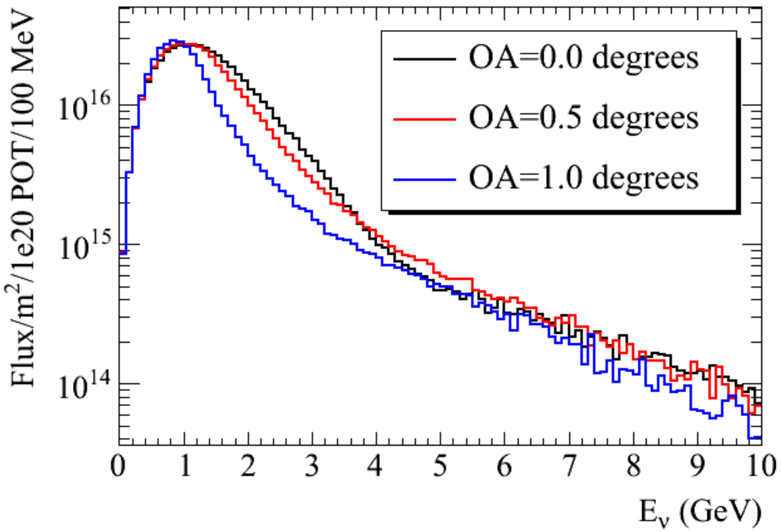
- Premise: detectors with a perfectly known, and preferably tunable, flux would allow a measurement of neutrino energy biases and smearing.
- Observation from T2K INGRID team (A. Ichikawa et al): low and high tails of flux similar as move off-axis
- Narrow range of neutrino energies where flux changes.

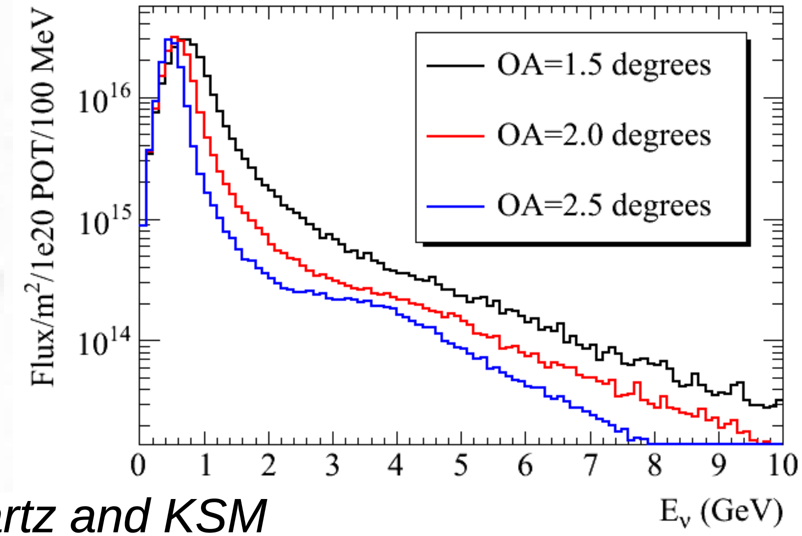




ANN: T2K Flux vs. Angle

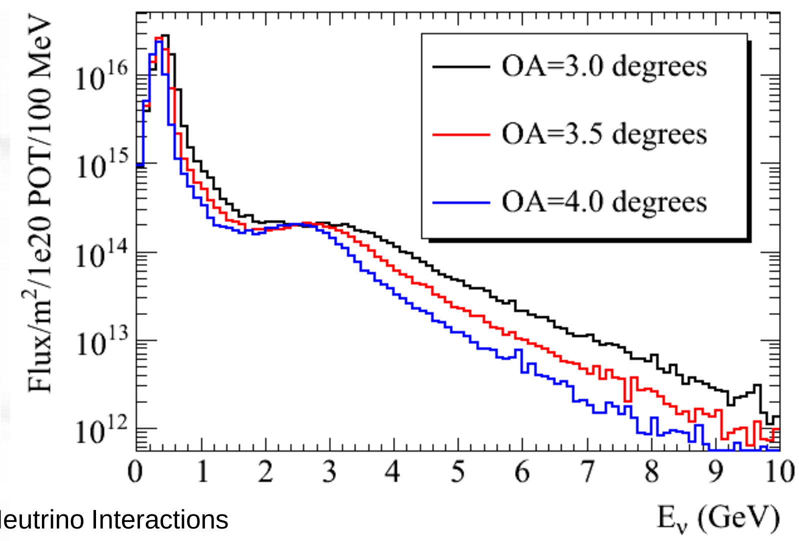






M. Hartz and KSM

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

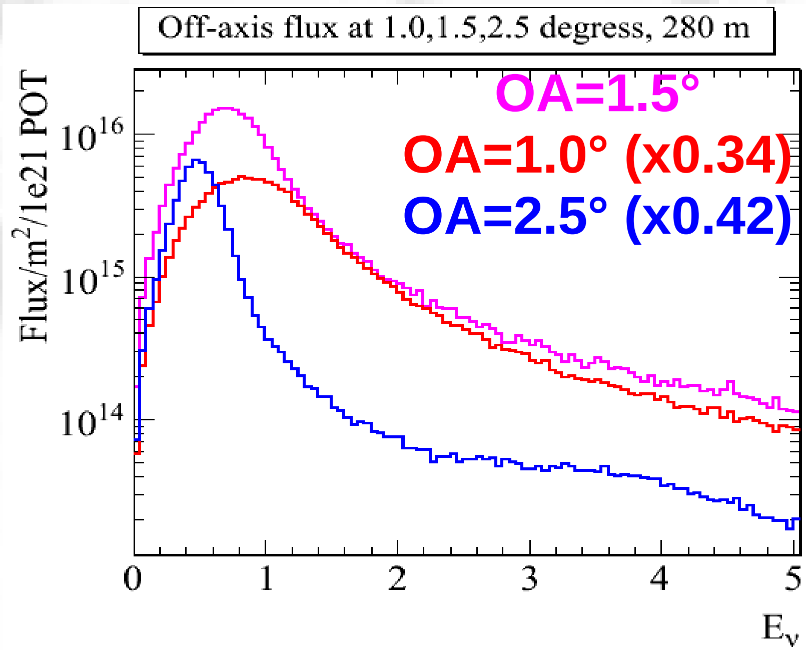


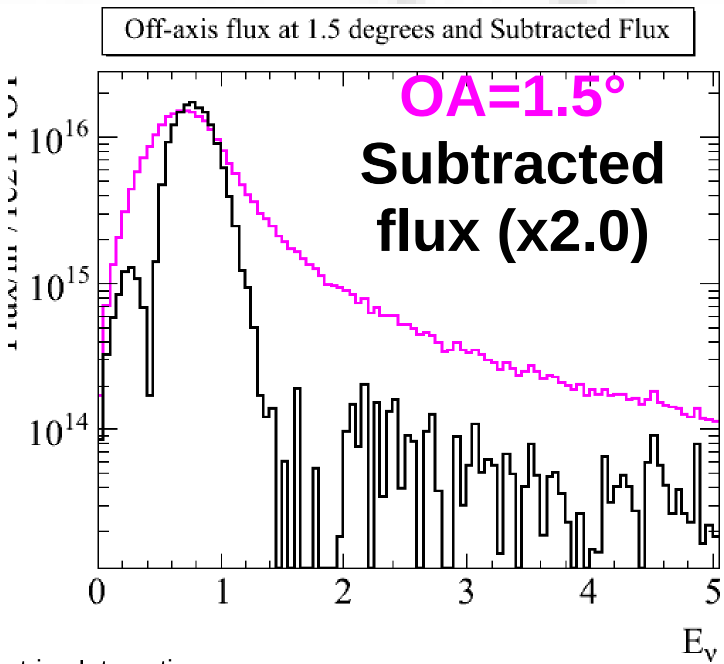
ANN: Proof of Principle

- Can do a reasonable job reducing the high energy and low energy fluxes with simple linear combinations of bins of nearby angles:

$$\varphi_{sub} = \varphi(1.5^\circ) - 0.34\varphi(1.0^\circ) - 0.42\varphi(2.5^\circ)$$

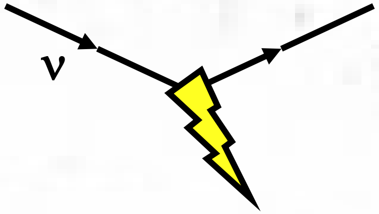
- Can narrow (in principle), by narrowing bins of angle (statistics)
- Also need to look at effect of hadroproduction uncertainties





M. Hartz and KSM

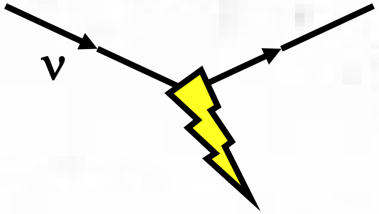
ANN: Near Detector Complex



- Turning this from a flux plot into reality?
  - Instrumenting 80mrad of off-axis angle at a reasonable distance from source is sobering

K2K 1kTon

ANN: Near Detector Complex



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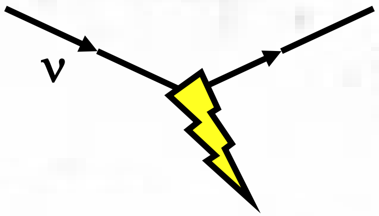

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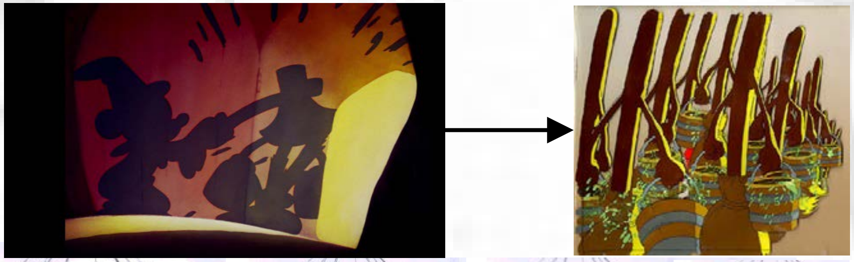
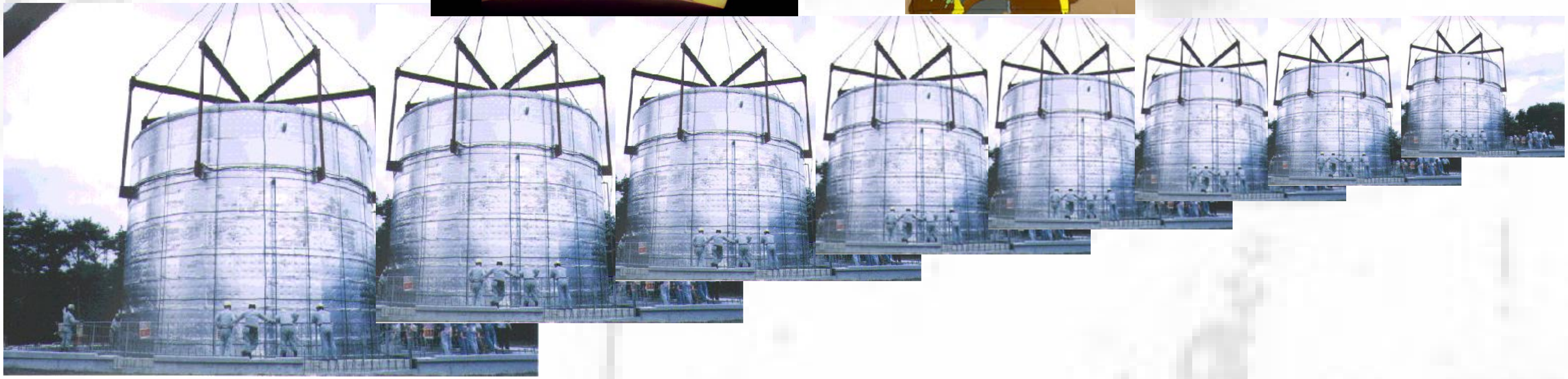


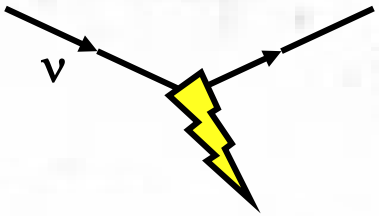
mmousedesign, purveyors of fine neutrino detectors

K2K 1kTon



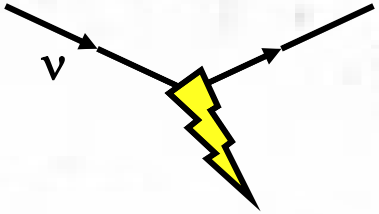
Conclusions

Interactions and Future Oscillation Experiments



- Large θ_{13} makes systematics a major problem for future ~GeV oscillation experiments
- Obtaining accurate models of neutrino interactions at required energies is a difficult problem.
- Interplay of data, including new data from MINERvA, T2K, ArgoNeuT/MicroBooNE, NOvA, with theory is essential to progress.

Interactions and Future Oscillation Experiments



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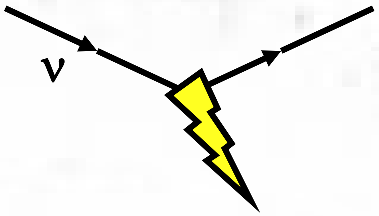
- Obtaining accurate models of neutrino interactions at required energies is a difficult problem.
- Interplay of data, including new data from MINERvA, T2K, ArgoNeuT/MicroBooNE, NOvA, with theory is essential to progress.
- Please continue to enjoy the challenge of landing your (metaphorical) helicopter on your (metaphorical) SuperYacht

Backup

Llewellyn Smith Quasi-Elastic Scattering



- Avert your gaze…

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

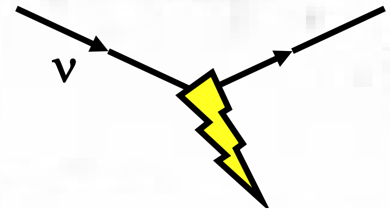
$$A(Q^2) = \frac{m^2+Q^2}{4M^2}\left[\left(4+\frac{Q^2}{M^2}\right)|F_A|^2 - \left(4-\frac{Q^2}{M^2}\right)|F_V^1|^2 + \frac{Q^2}{M^2}\xi|F_V^2|^2\left(1-\frac{Q^2}{4M^2}\right) + \frac{4Q^2 Re F_V^{1*}\xi F_V^2}{M^2} - \frac{Q^2}{M^2}\left(4+\frac{Q^2}{M^2}\right)|F_A^3|^2 - \frac{m^2}{M^2}\left(|F_V^1+\xi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

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

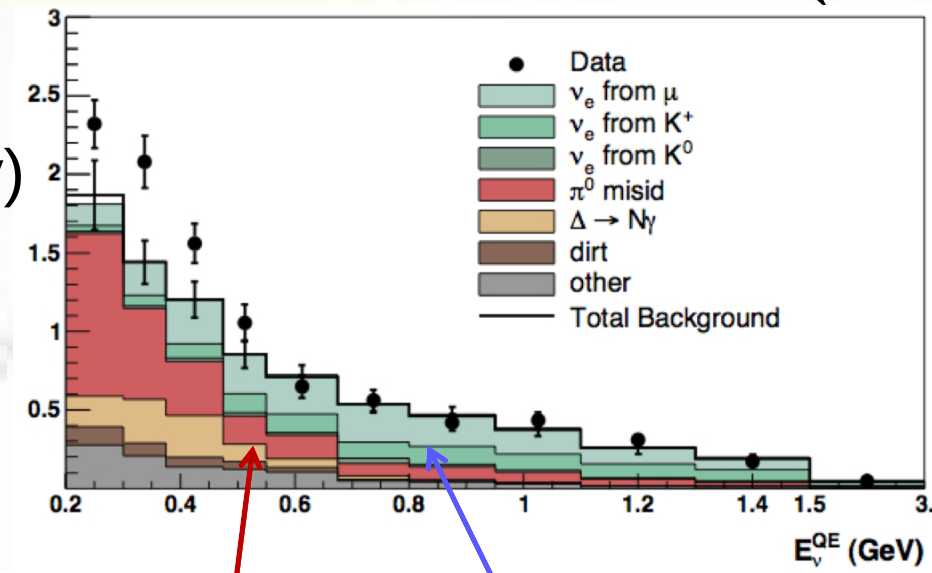
$$C(Q^2) = \frac{1}{4}\left(|F_A|^2 + |F_V^1|^2 + \frac{Q^2}{M^2}\left|\frac{\xi F_V^2}{2}\right|^2 + \frac{Q^2}{M^2}|F_A^3|^2\right).$$

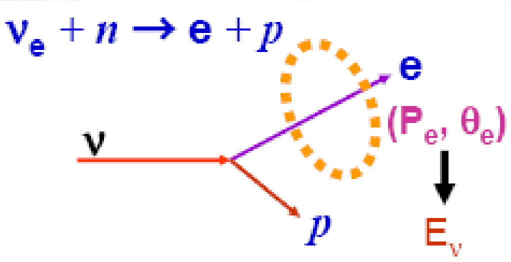
- Two terms, including those with F_P, and F^3_V, enter with a factor of m^2/M^2. These are relevant for muon neutrinos at low energies but not for electron neutrinos.

MiniBooNE

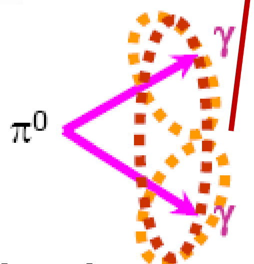


- ν_e appearance with a conventional (meson decay) wide-band beam
  - Significant backgrounds from neutral currents (π^0s), but are measured *in situ*





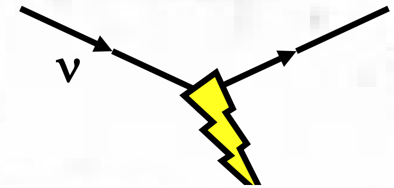
π^0 background from $E_\nu > E_\nu^{reco}$



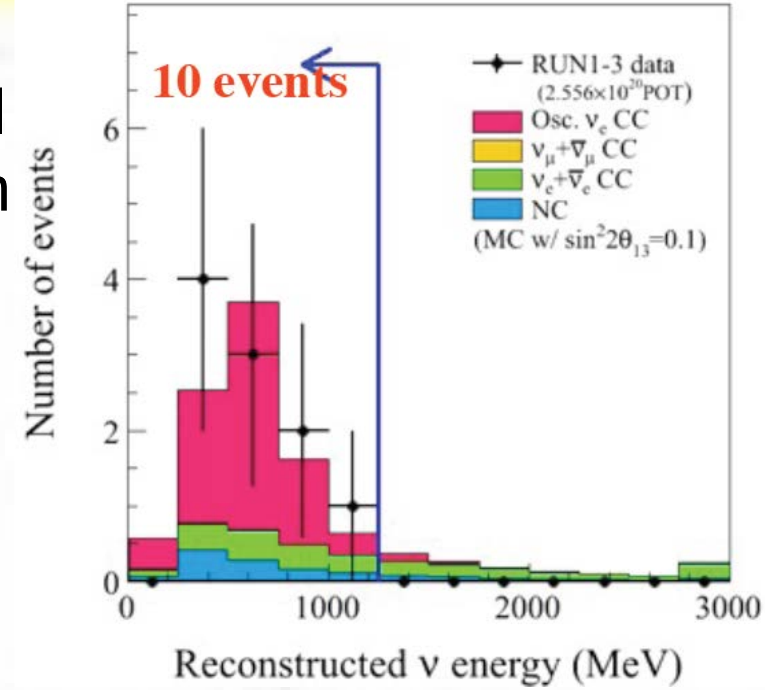
ν_e backgrounds

- 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.

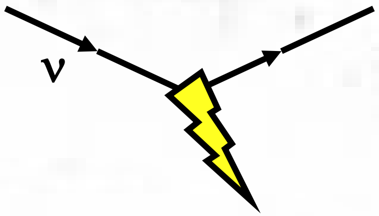


(T. Nakaya, Neutrino 2012)

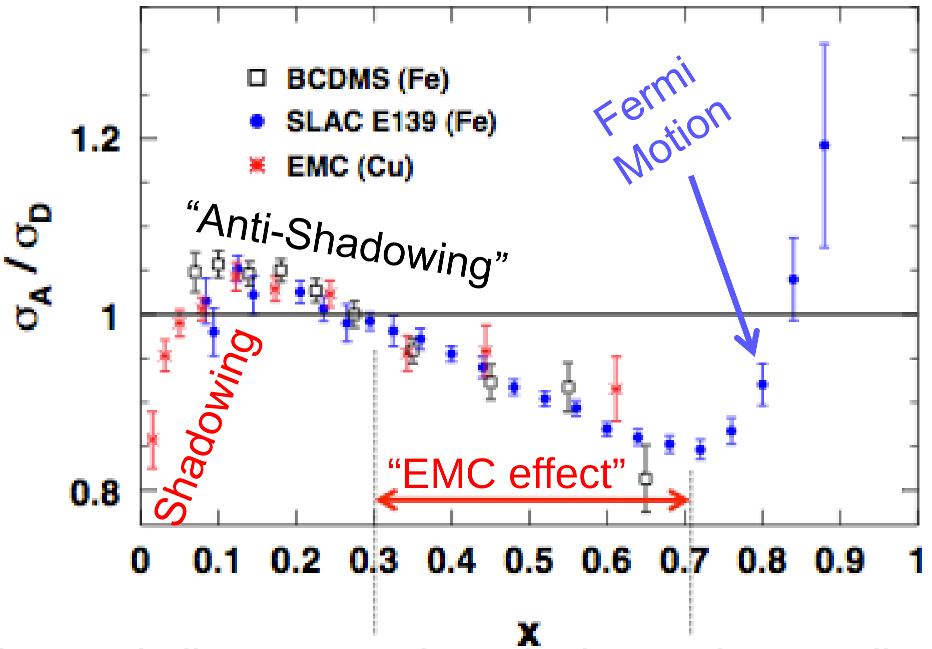
Systematic Errors

	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
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



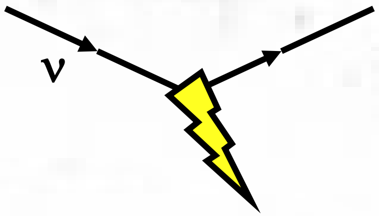
- Charged lepton F_2^A/F_2^D shows convincingly modification of quark distributions in a nucleus
  - No model of nucleus as an incoherent sum of nucleons can reproduce this effect.
  - No conclusive model of the collective behavior exists.



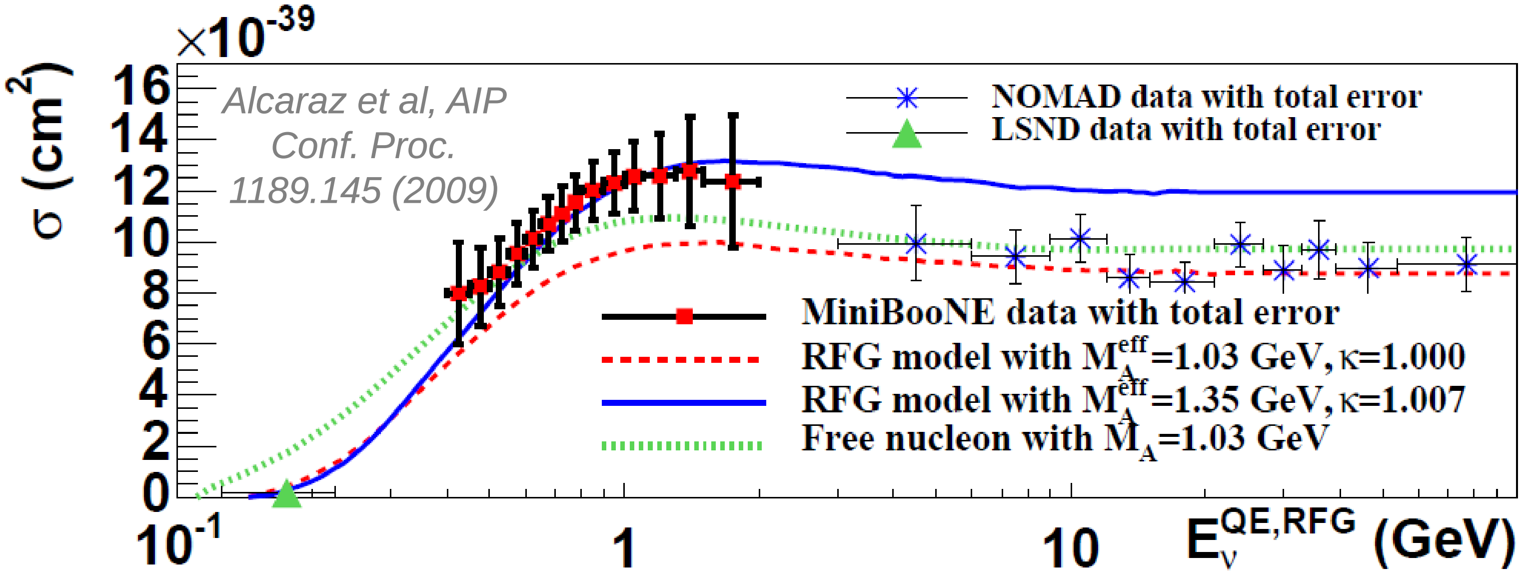
(D. Gaskell, ECT, Hadrons in the Nuclear Medium)*

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

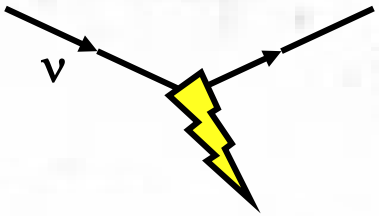
"Axial Mass Puzzle"

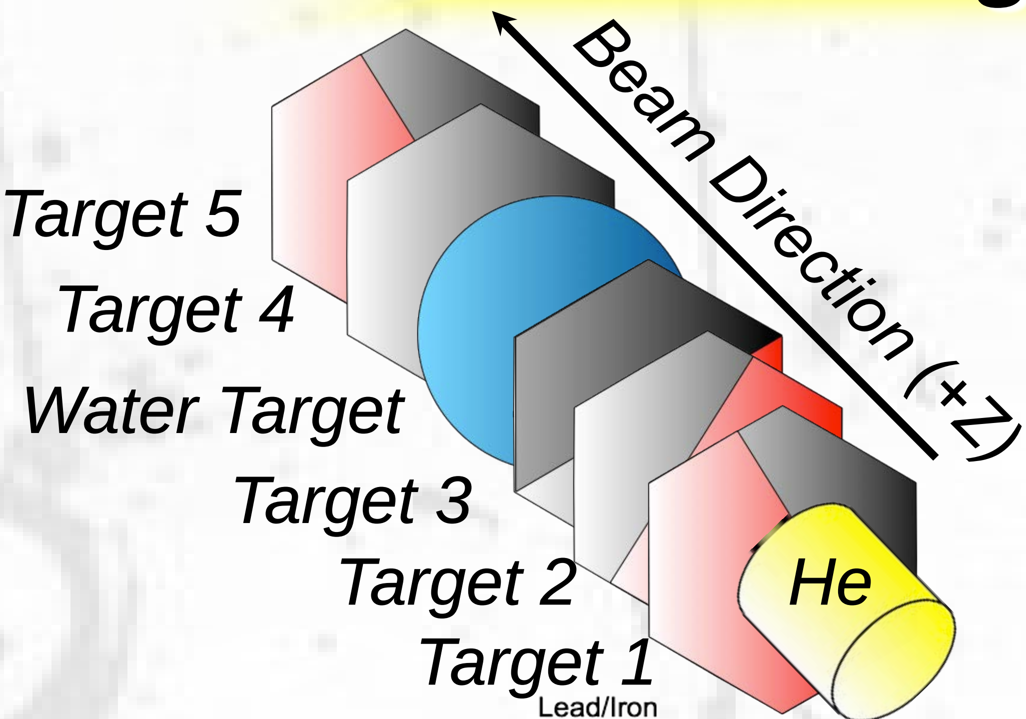


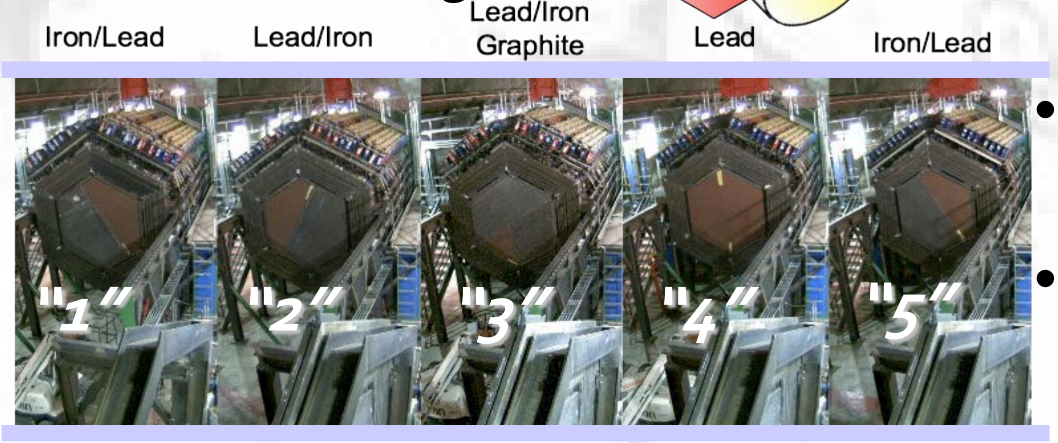
- As described earlier, M_A has been measured to be 1.03 GeV/c^2 in νD_2 and pion electroproduction
  - A slew of low energy data (MiniBooNE, SciBooNE, K2K) prefers a higher axial mass and therefore higher σ
  - What is going on in the nuclear environment to create this effect?



MINERvA's Targets

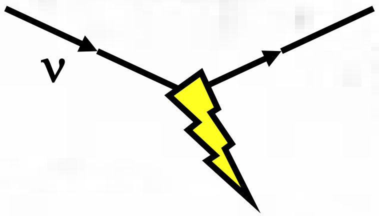






- Goal: High statistics ratios of Fe/Pb/C/O/He in identical flux
  - Extract x-dependent nuclear effects as a function of A!
- Targets surrounded by active scintillator.
- Some thick targets for "high" rate.
- Also thin targets for exclusive final states.

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
    - o Llewellyn Smith formalism for quasi-elastic scattering
    - o Rein-Sehgal calcluation/fit for resonance production
    - o Duality based models for deep inelastic scattering
  - Cascade models for final state interactions
    - o 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