Looking Forward to the Future QE* Needs of Oscillation Experiments

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INT Workshop

*U. Mosel, INT 2013: "One always has to talk about QE and pions together"

Outline

- Theoretical perspective
- Experimental perspective
  - Case Study: T2K appearance and disappearance
- Summary of detectors and beamlines we have in hand to make QE analyses

What you need depends on what oscillation parameter you are measuring

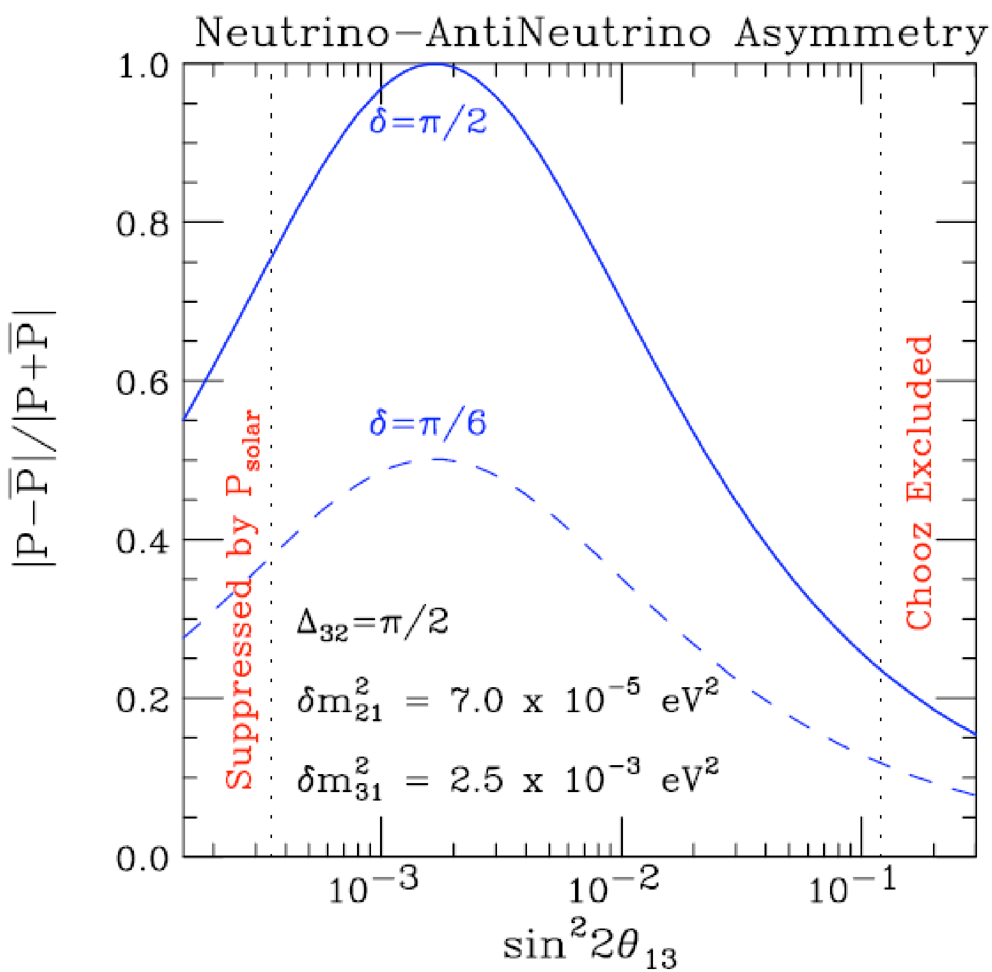
- $\nu_\mu \rightarrow \nu_e$ Appearance Parameters
  - "$\sin^2 2\theta_{13}$"
  - CP violation
  - Mass Hierarchy

Must compare neutrino and antineutrino measurements for the last two of these!

- ν_μ Disappearance Parameters
  - Δm^2_{23}
  - $\sin^2 2\theta_{23}$

Example: CP violation

- Measurements of CP violation and Mass Hierarchy:
  - QE process provides most if not all of the signal
  - "QE-like" is in the eye of the beholder
  - Usual demonstration of why we need "QE measurements"
  - Maximal CP violation means you need to measure probability differences at the 10-20% level



S. Parke, INSS 2009

Where do QE processes come into $\nu_\mu \rightarrow \nu_e$ Probability Measurement?

- Recall the ingredients of an appearance measurement:
  - Number of measured signal events
  - Predicted background event count
  - ν_e Cross Section (signal processes)
  - Predicted ν_μ flux at far detector
    - Which comes from ν_μ events at near detector
  - Predicted efficiency for ν_e events

Red color indicates some knowledge about QE processes

- And we're going to have to get the total uncertainty on all these quantities to a few %
- And since $\sin^2 2\theta_{13}$ is large, the near detector ν_e flux is very different from the far detector ν_μ flux
- And if you think that's hard, now you have to do the same thing for anti-neutrinos…

Theoretical Attempt to Explore this issue

- Coloma, Huber, Kopp, Winter: see sensitivity differences between "optimistic" and "pessimistic" assumptions about cross sections
- Energy dependence of different processes assumed to be known perfectly
- Quasi-elastic cross sections appear three times:
  - For signal cross section
  - Signal efficiency
  - Ratio of ν_μ to ν_e QE cross sections
  - Uncertainties for antineutrinos assumed to be the same (and uncorrelated?)

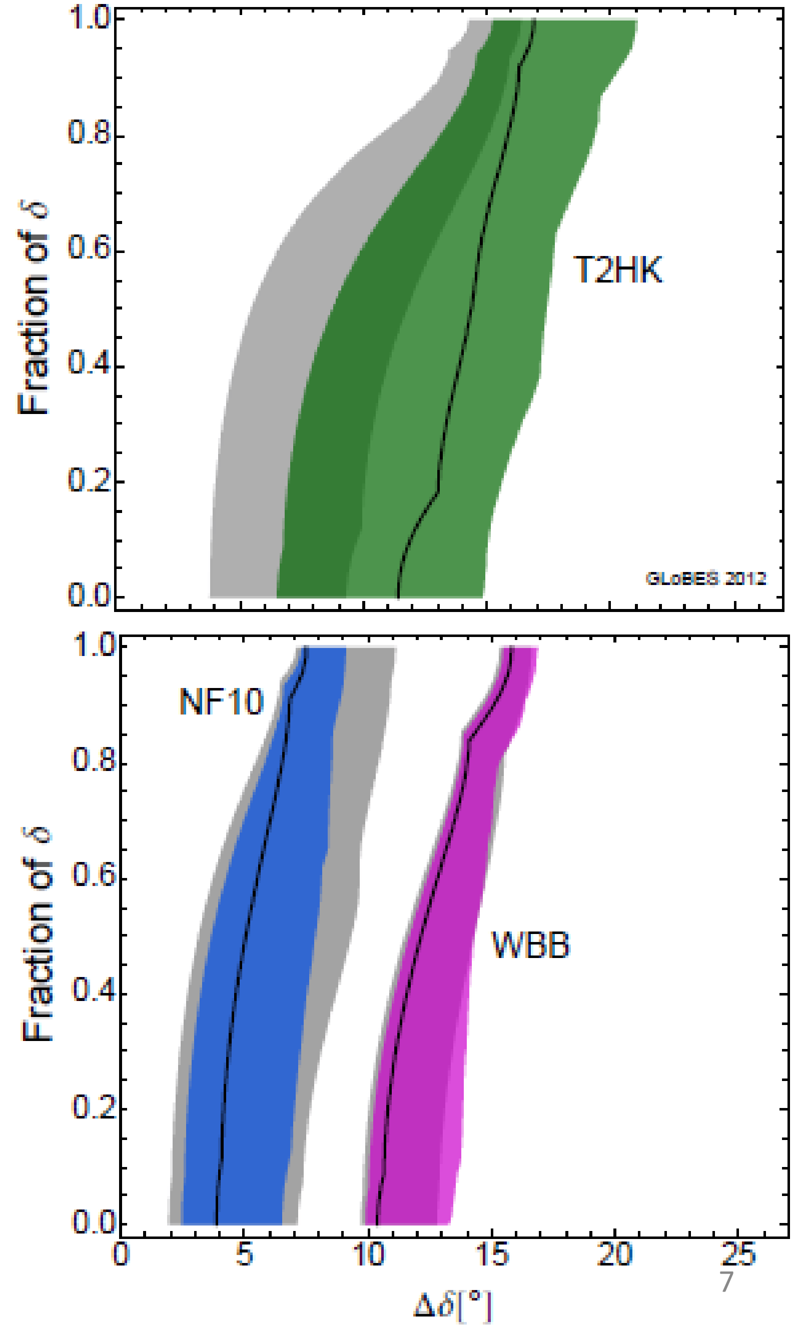
	SB		
Systematics	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%
Flux error background ν	10%	15%	20%
Flux error signal $\bar{\nu}$	10%	15%	20%
Flux error background $\bar{\nu}$	20%	30%	40%
Background uncertainty	5%	7.5%	10%
Cross secs × eff. QE†	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%
Cross secs × eff. DIS†	5%	7.5%	10%
Ratio ν_e/ν_μ QE*	3.5%	11%	–
Ratio ν_e/ν_μ RES*	2.7%	5.4%	–
Ratio ν_e/ν_μ DIS*	2.5%	5.1%	–
Matter density	1%	2%	5%

theoretical constraint

Phys.Rev. D87 (2013) 3, 033004

Effects of Systematics

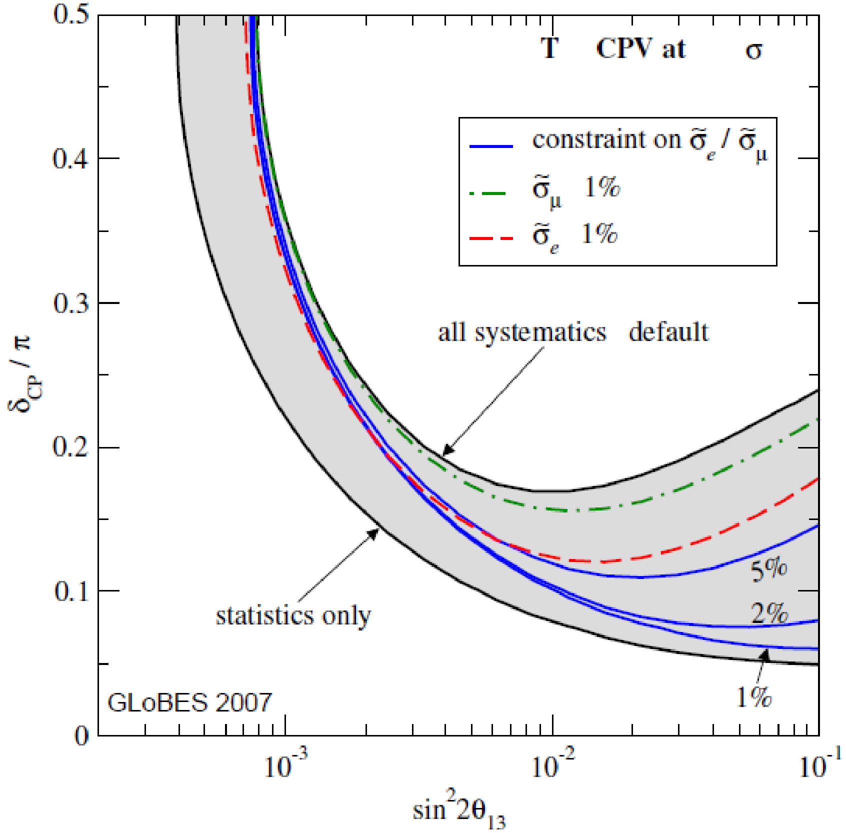
- Grey/color band: no near detector/ correlated ND
- Colored Band Width: optimistic to pessimistic systematic uncertainties
- Grey Band Width: 0 systematic uncertainties to 5%/10% signal background
- T2HK: 295km, 700MeV neutrino beam. WBB: “wide band ~2-3GeV beam”, long baseline, liquid argon detector”



Phys.Rev. D87 (2013) 3, 033004

ν_μ / ν_e QE cross section ratios alone

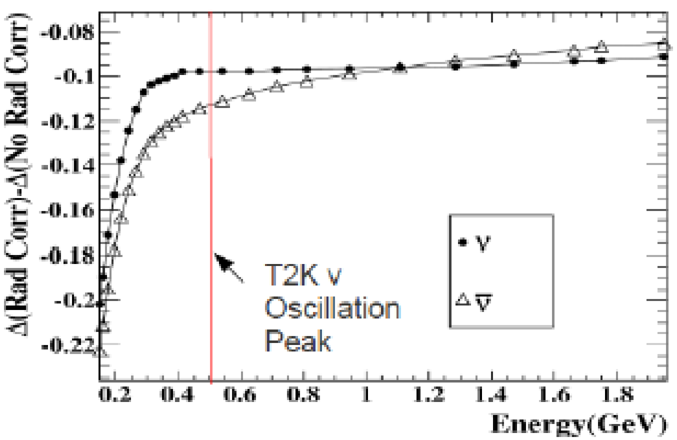
- Already considered in 2007!
- What measurements can we do before NuStorm?
- Need to see how ν_e QE cross sections compare to predictions that come from detailed flux simulations anchored on ν_μ flux measurements
- Challenge/opportunity: today's beams have ν_e + ν_e bar
  - But different data sets have different combinations of (ν_e * ν_e bar)/ ν_μ



P. Huber, M. Mezzetto, T. Schwetz
arXiv: 0711.2950

Can't we just derive ν_μ/ν_e QE cross section ratio from a priori principles?

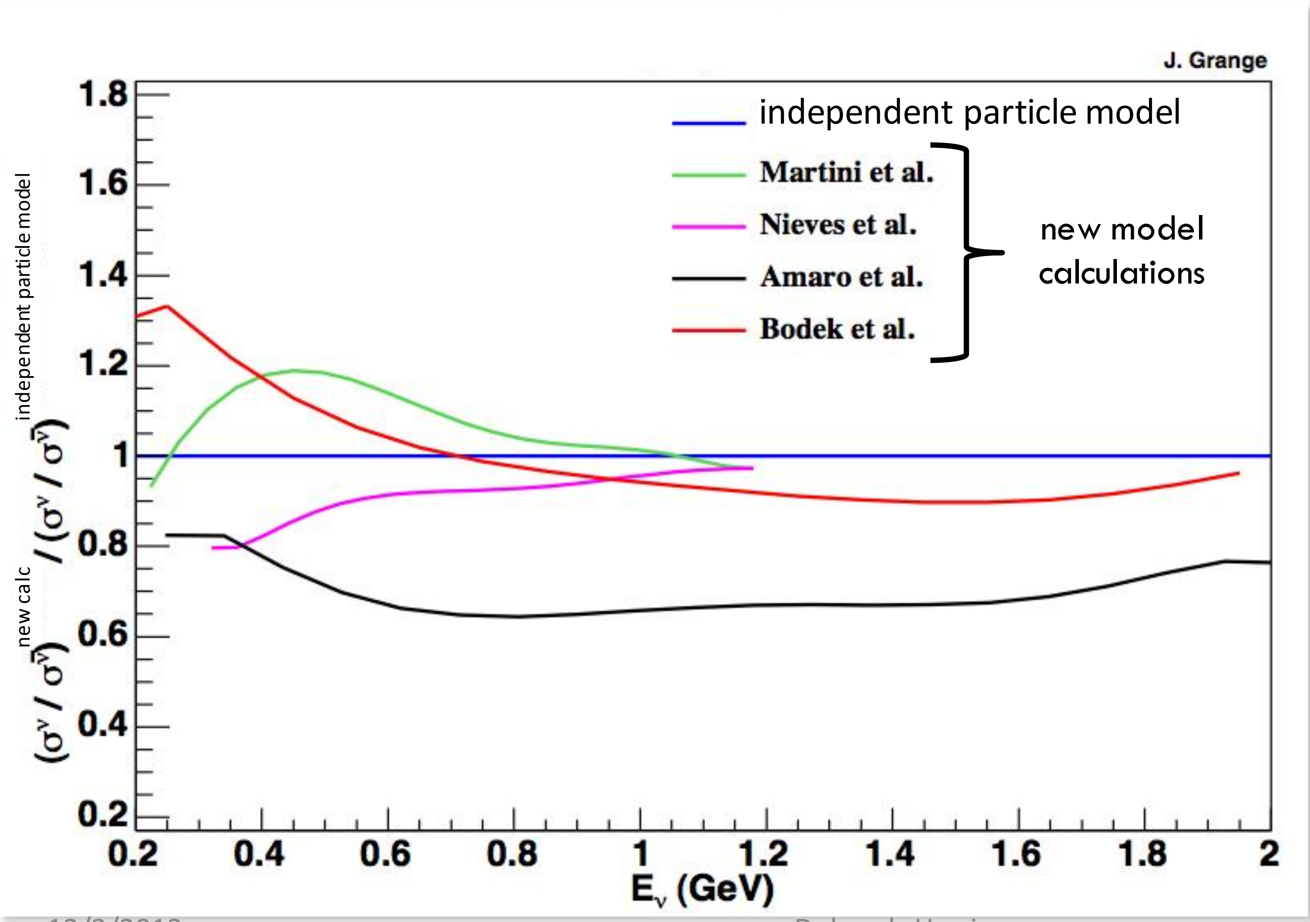
- See M. Day's talk at NuFact 2012 (or M. Day & K.S. McFarland, *Phys.Rev.* ***D****86 (2012))*
- Long list of effects need to be incorporated
  - Kinematic Limits
  - Axial Form Factor Contributions
  - Pseudoscalar Form Factor Contributions
    - Pole mass uncertainty
    - Goldberger-Treiman Violation
  - Second Class Current Contributions
    - Vector and Axial Form Factors
  - Radiative Corrections



- Need Better Calculations: note that there is not a "what QE theory do we need for oscillations", the answer might be simply what's in the rest of today's and tomorrow's talks)

What about neutrino/antineutrino cross section ratios?

- Different models predict different ratios



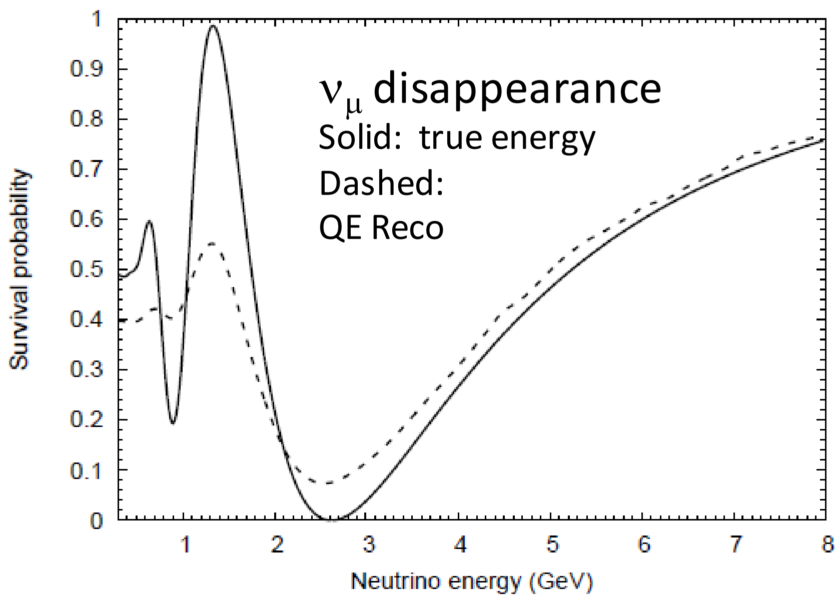
And these are ν_μ cross section ratios,
Also need this for ν_e

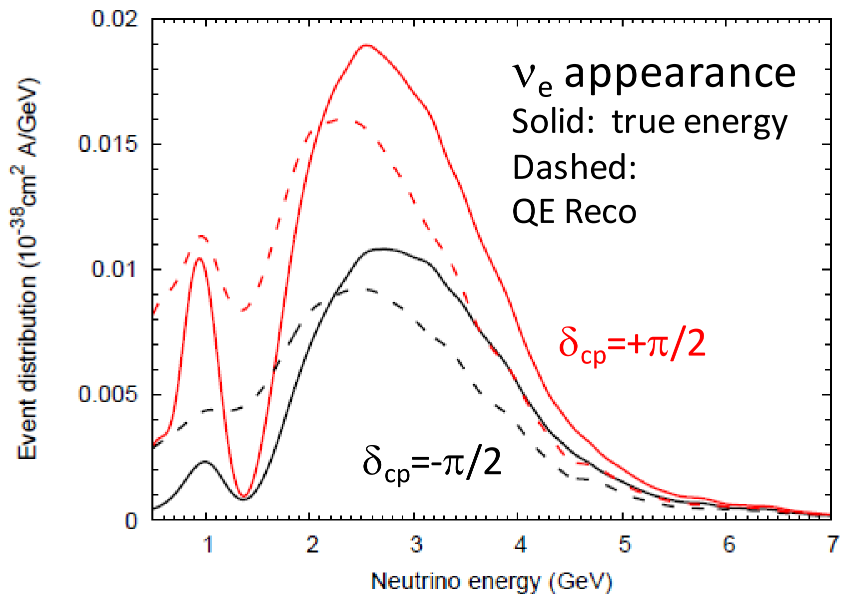
And the theorists are assuming we'll know these ratios (times acceptances) to 1-3% each…

Slide courtesy G. Zeller

Wide Band Beam Challenges

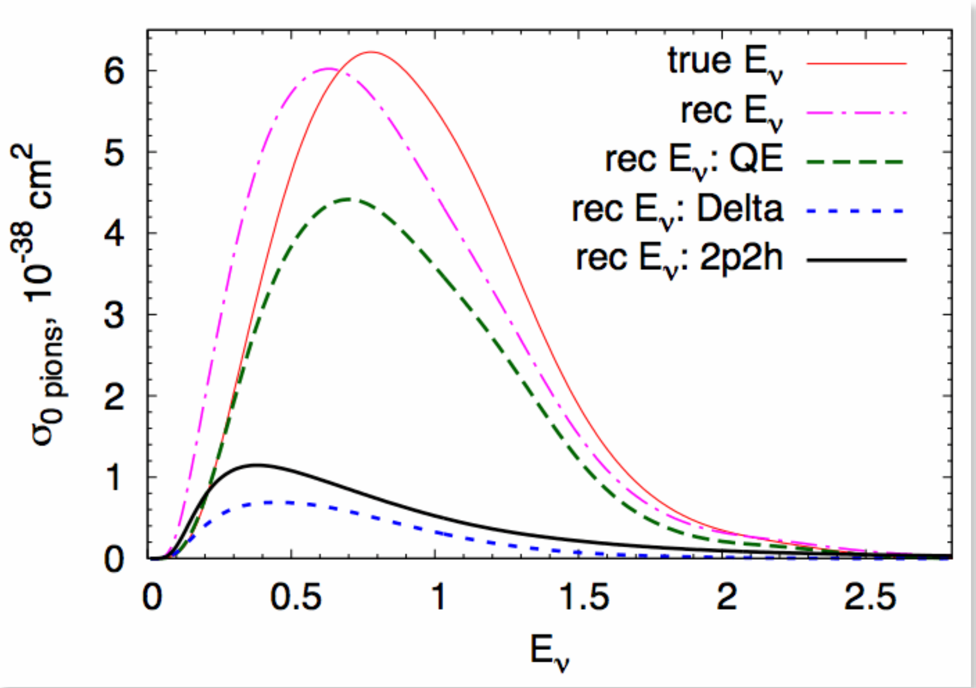
- For a narrow band beam, the flux is roughly narrow enough so that you are not going to be inferring much from the energy spectrum, once the events pass some loose energy cut
- For a wide band beam, significant leverage from looking at "second oscillation peak", or at least over broad range of neutrino energies
- Need to understand energy dependence of all of the above parameters
- Thanks to Ulrich for submitting paper to arXiv in time for this meeting!
- U, Mosel, O, Lalakulich, K. Gallmeister, arXiv:1311.7288: consider LBNE





What we need for ν_μ Disappearance

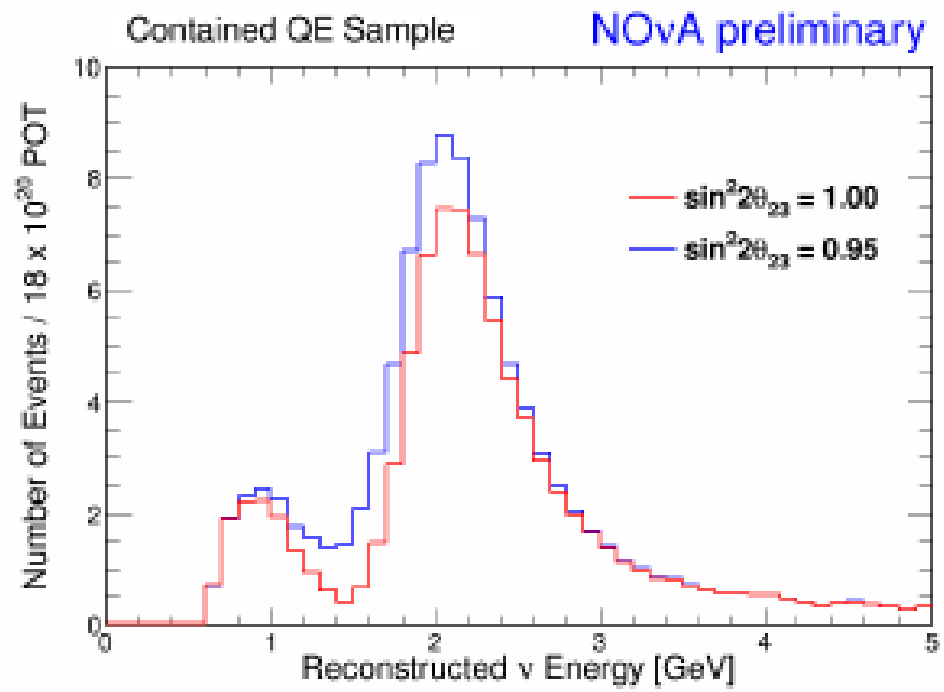
- In principle this is an easier task
- Near detector has healthy flux of ν_μ's
- But precision needed is much higher: have the statistical precision to do per cent level mass splitting measurements
- How can we get to sub-per cent level energy scale uncertainties?

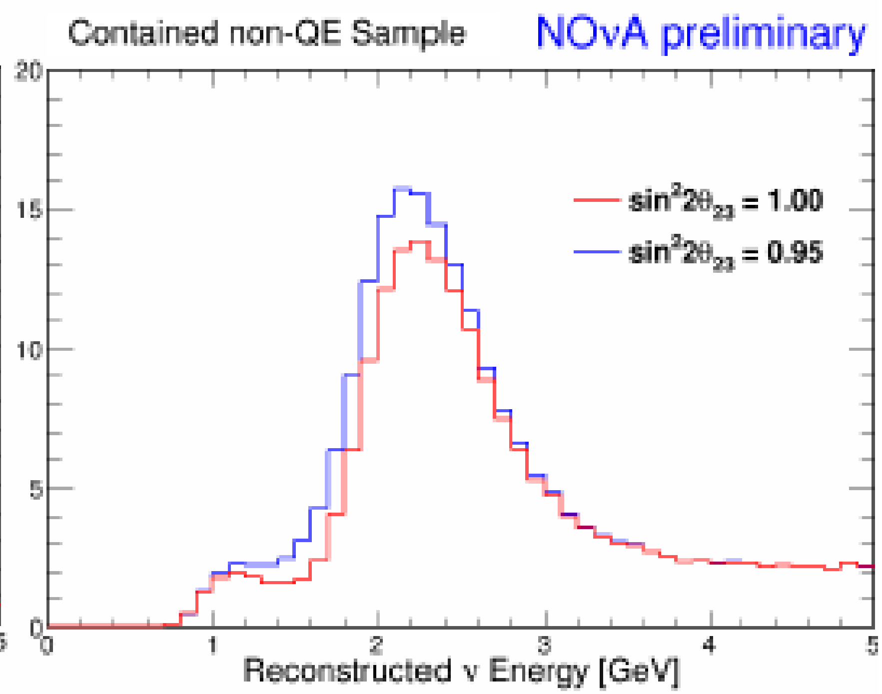


one example from Lalakulich, Gallmeister, Mosel, arXiv:1203.2935

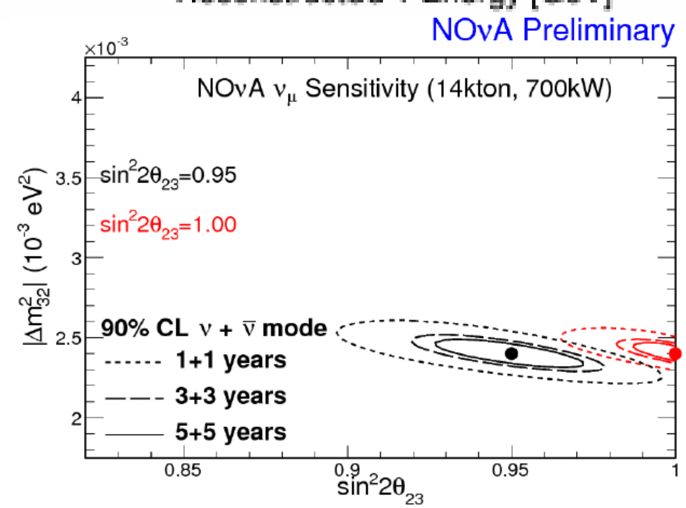
Slide courtesy G. Zeller

NOvA Expected ν_μ Disappearance Sensitivity





- NOvA Energy Reconstruction: add muon and proton energies
- Event samples: QE, non-QE, and "uncontained" events
- Statistical power: 2% at 1 sigma

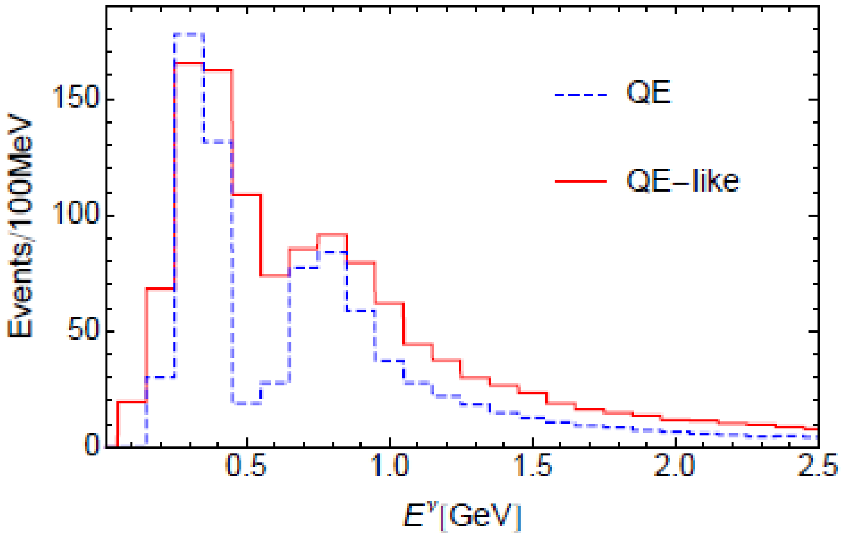


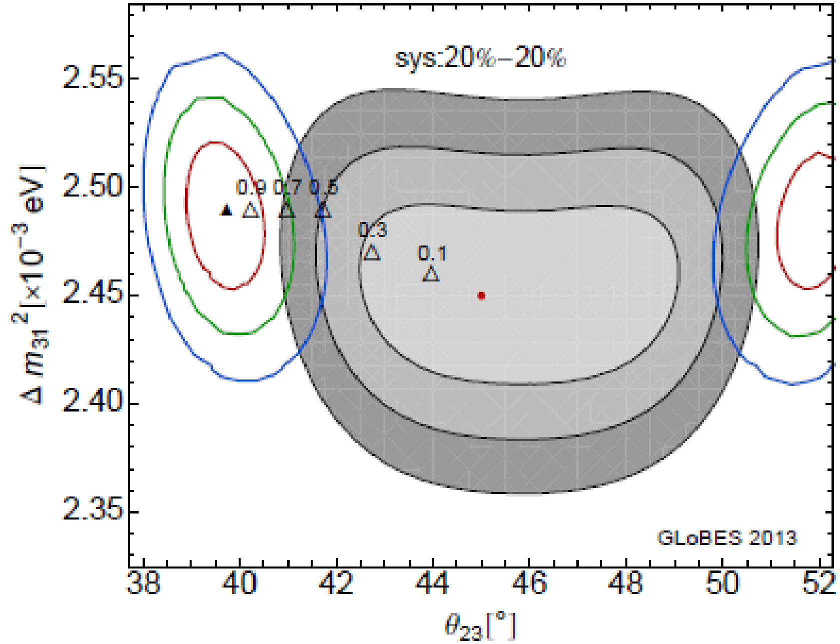
From Nucleons to Nuclei

- In addition, nuclear effects for quasi-elastic processes need to be measured (neutrino and antineutrino)
- Specifically: how much QE-like contamination is there in the QE sample?
- Plots below for "T2K-like" experiment

$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$

where $\alpha = 0$ corresponds to perfectly known nuclear effects and $\alpha = 1$ to entirely unknown nuclear effects in the fit.





Ref: P. Coloma and P. Huber, arXiv:1307.1243

View Shopping Cart… what do we want?

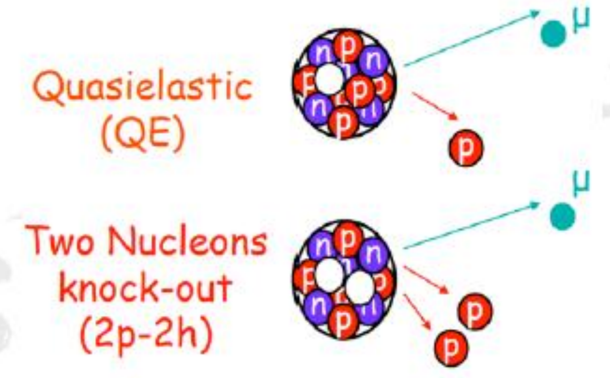
- QE Cross section*efficiencies at 1-2% level for
  - ν_μ
  - $\nu_\mu$bar
  - ν_e
  - $\nu_e$bar
  - As a function of neutrino energy…
- Would like the same thing as above for “QE-like” events
- Determination of absolute energy scale for particular neutrino reconstruction technique at the 1-2% level
  - Because of initial state nucleon not correctly specified
  - Because of migration from resonance to QE-like events
  - Because of other final state effects hiding energy from protons
- In principle, this absolute energy scale could be determined by Muon energy and angular spectra, and proton multiplicity and energy spectra

From theorist to experimentalist

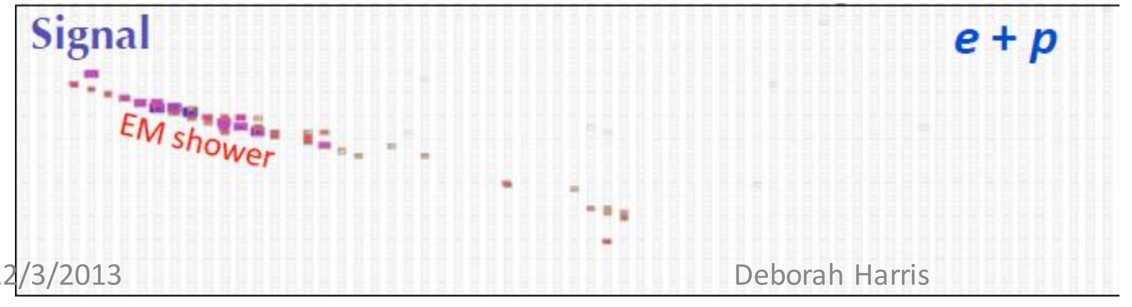
- We don’t have a magic neutrino test beam that will let us get the items in our shopping cart
- What we do have…
  - Beamlines: Booster Beamline, NuMI, T2K
  - Neutrino Energies: 200MeV through 20GeV
  - Detectors: Scintillator, Mineral Oil, Liquid Argon TPC, Gas TPC
  - Target nuclei: He, C, CH, H_2O, Ar, Fe, Pb
- How can we get from what we can measure to what we need to know?

Enter Experimentalist… What QE measurements we need depends on the detector technology

- Example: let's say there are extra protons that are knocked out of a nucleon in the QE scattering process: how well do those protons need to be modeled?
  - Water Cerenkov detector won't see their energy depositions at all
  - Liquid Argon detector should see them with very low energy threshold (Argoneut detection threshold: 21MeV)
  - Totally active Scintillator detector will measure the extra energy but may not be able to distinguish the proton energy from the electron energy, and dE/dx cut at beginning of electron track is used to remove photon background



Graphic courtesy M. Wascko



NOvA Event Display (MC)

Case Study: T2K Oscillation Systematics

- Current State of the Art in evaluating Cross Section Systematics for Oscillation Experiment
- Nothing like having data to force you to figure out what matters most…
- Asher Kaboth, NuFact2013

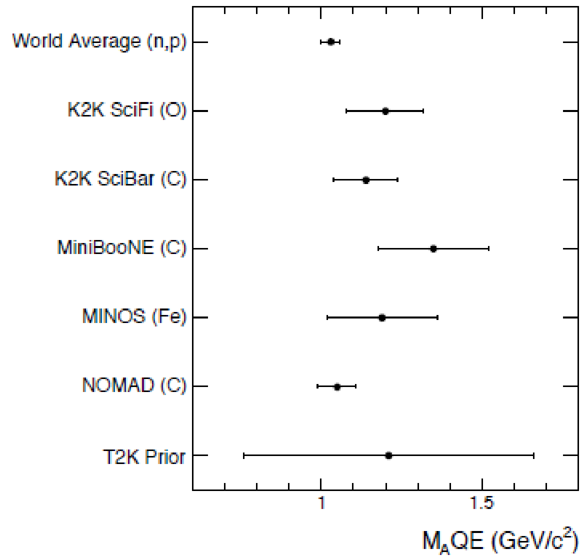
From ND280 (Correlated) / SK only (Uncorrelated)

Error source	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	11.6	7.5
M_A^{QE}	21.5	3.2
M_A^{RES}	3.3	0.9
CCQE norm. ($E_\nu < 1.5$ GeV)	9.3	6.3
CC1π norm. ($E_\nu < 2.5$ GeV)	4.2	2.0
NC1π^0 norm.	0.6	0.4
CC other shape	0.1	0.1
Spectral Function	6.0	6.0
p_F	0.1	0.1
CC coh. norm.	0.3	0.2
NC coh. norm.	0.3	0.2
NC other norm.	0.5	0.5
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.9	2.9
W shape	0.2	0.2
pion-less Δ decay	3.7	3.5
SK detector eff.	2.4	2.4
FSI	2.3	2.3
PN	0.8	0.8
SK momentum scale	0.6	0.6
Total	28.1	8.8

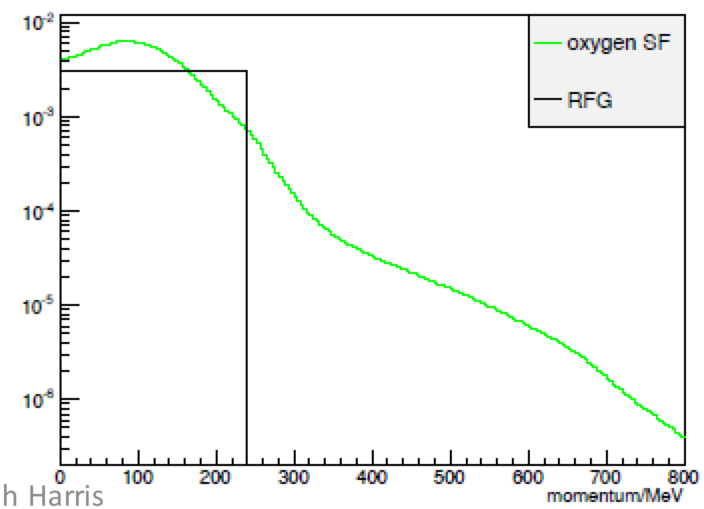
units: percentage error on N_{SK}

T2K Oscillation Systematics, II

Parameter	Type	Interaction Type
M_AQE	axial mass	CCQE
M_ARES	axial mass	1π
CCQE (3)	normalization	CCQE
CC1π (2)	normalization	CC1π
$NC\pi^0$	normalization	NC1π
p_f	fermi momentum	CCQE/RFG
E_b	binding energy	CCQE/RFG
spectral function	model comparison	CCQE/SF

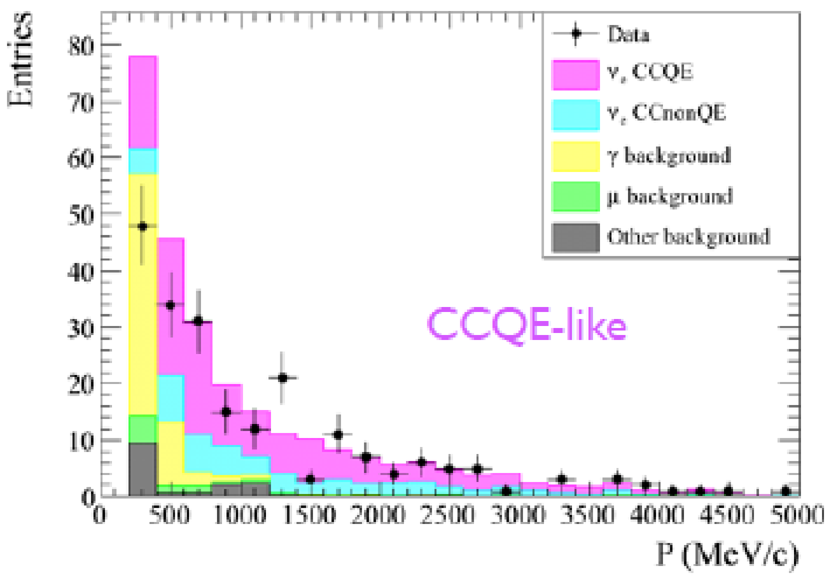


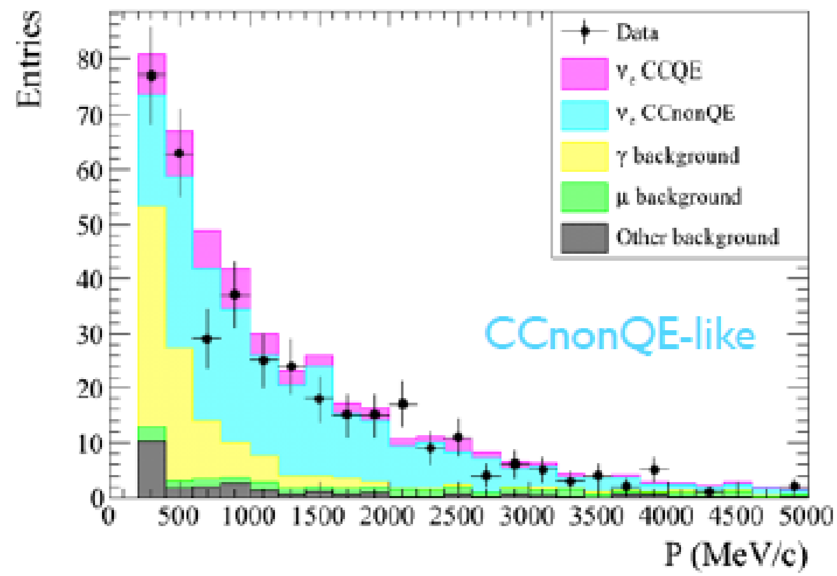
But allow normalizations in 3 energy bins



Asher Kaboth, NuFact2013

What about just measuring the intrinsic beam ν_e's at T2K?





Use a selection of electron neutrino events and fit for the ratio of observed to expected ν_e events.

Asher Kaboth, NuFact2013

Find good agreement between this sample and the expectation from the ν_μ analysis

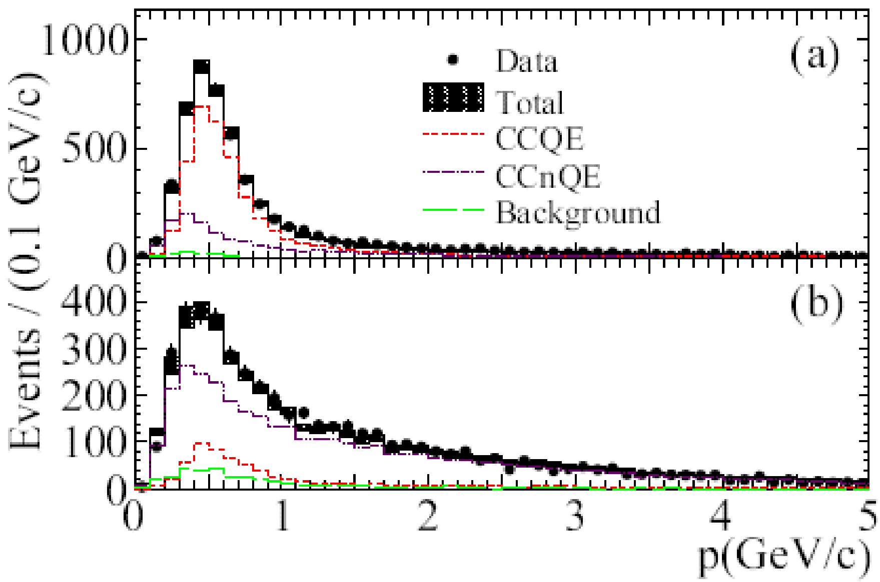
$$f(\nu_e) = 1.055 \pm 0.058(\text{stat.}) \pm 0.079(\text{syst.})$$

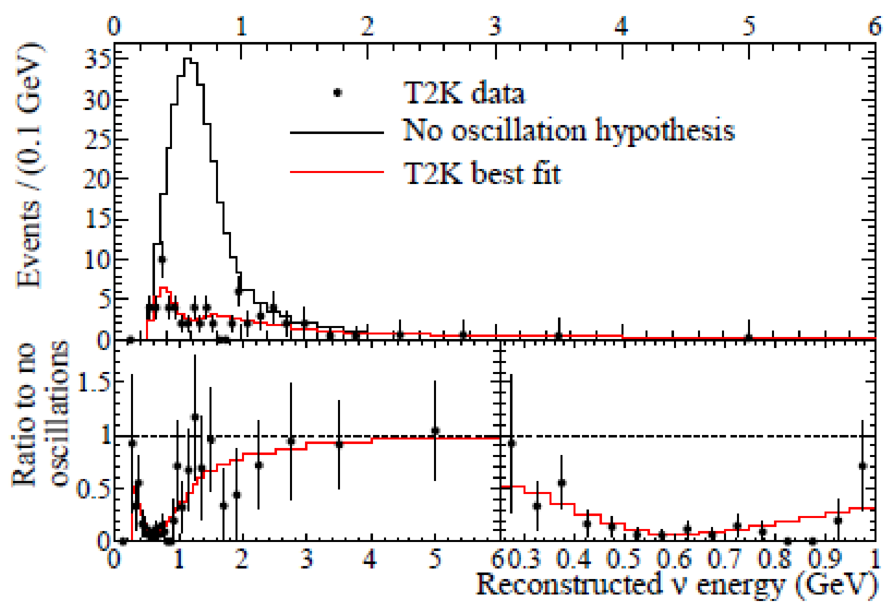
T2K Systematics in ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2(\theta_{13})\sin^2(\theta_{23})[1 - \cos^2(\theta_{13}) \times \sin^2(\theta_{23})]\sin^2(1.27\Delta m^2_{32}L/E_\nu),$$

- Phys. Rev. Lett. 111, (2013)

Source of uncertainty (no. of parameters)	$\delta n^{\rm exp}_{\rm SK} / n^{\rm exp}_{\rm SK}$
ND280-independent cross section (11)	6.3%
Flux & ND280-common cross section (23)	4.2%
Super-Kamiokande detector systematics (8)	10.1%
Final-state and secondary interactions (6)	3.5%
Total (48)	13.1%





What data we have "in hand"

(not including SciBooNE)

Characteristics of ν_μ QE events	Mini-BooNE	MINERvA	Argoneut	T2K ND280	MINOS
QE Event Selection	1μ, 1 Michel	1μ, low recoil	1μ + no π, p counting	1μ + no π	1μ, ν<225MeV
Nuclear Target	CH_2	He, C,CH, Pb, Fe, H_2O	Ar	C_8H_8 (FGD)	Fe
ν flux range (GeV)	0.4<E<2	1.5<E<10	1.5<E<10	0.2<E<30	1.5<E<20
Sign selection?	no	For MINOS μ's	For MINOS μ's	yes	yes
Muon angular range	all	All or θ<20 (MINOS μ's)	2π forward	θ<80	θ<180
p detection thresh. (MeV)	n/a	50/80 shwr/trk	21	Not yet known	n/a
E(ν) reconstruction	$E_\nu^{QE,RFG}$	$E_\nu^{QE,RFG}$ (μ or p arm)	$E_\mu + \Sigma T_{pi} + T_X + E_{miss}$	Template fit to μ kinmtx	$E_\nu^{QE,RFG}$

What we will have in the longer term (+NOMAD)

Characteristics of ν_μ QE events	MicroBooNE	NOvA	LBNE-ND (straw trkr)	NOMAD
QE Event Selection	1μ + no π, p counting	1μ + mltvr selection	1μ + no π	1μ + 1p or 1μ + no trk
Nuclear Target	Ar	CH	C_3H_6	Mainly C
ν flux range (GeV)	0.4<E<2.5	.5<E<2.5	0.2<E<30	24GeV
Sign selection?	no	no	yes	yes
Muon angular range	??	θ<22.5	4π	θ<180 trk θ<50 μ ID
p detection thresh. (MeV)	21	n/a	Very low?	200
$E(\nu)$ reconstruction	$E_\mu + \Sigma T_{pi} + T_X + E_{miss}$	$E_\nu^{QE,RFG\ mod}$	Many options	Many options

What could we hope to measure?

- Absolute QE* cross sections vs "E_ν" (flux-willing)
  - MINERvA: C, CH, Fe, Pb, H_2O broad energy range
  - NOvA: CH, 2GeV
  - Argoneut and MicroBooNE: Ar 1,3GeV
  - T2K ND: H_2O, CH 700MeV
  - want ν and νbar, ν_μ and ν_e
  - Could also get to cross sections vs p_μ θ_μ
  - Getting to cross sections vs electron kinematics not feasible any time soon
- Proton Information for QE* events
  - Argoneut, MicroBooNE: p multiplicity and momenta
  - MINERvA: leading proton kinematics for many nuclei
  - NOvA and T2K: some leading proton acceptance
- Comparisons between proton arm and muon arm information
  - MINERvA, Argoneut, MicroBooNE, T2K, NOMAD, will be hard in NOvA
- Will not get to absolute cross sections at few % without more efforts on understanding fluxes from these beamlines

*U. Mosel, INT 2013: "One always has to talk about QE and pions together"

Summary

- Theory predictions describe need for "cross section times efficiency" uncertainties at 10% levels for next generation
- Also need to better understand Neutrino Energy Reconstruction Issues
- Experiments tend to classify their uncertainties on the cross sections and efficiencies separately: need external data and models!
- The analyses we saw today are primarily systematics limited—need theory AND more measurements to get to what future Oscillation Experiments need

- T2K currently gets to ~8% far detector prediction uncertainty on ν_e events from cross sections
  - CCQE Normalization, Spectral Function uncertainty
- Various experiments currently operating as (mostly) independent entities
- Need to talk among experiments more to see what each experiment can learn from the other, and with theorists to figure out how to limit future uncertainties