Looking Forward to the Future QE*
Needs of Oscillation Experiments

Deborah Harris
Fermilab
December 3, 2013
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

• $\nu_\mu$ Disappearance Parameters
  – $\Delta m^2_{23}$
  – $\sin^2 2\theta_{23}$
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
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
  – $\nu_e$ Cross Section (signal processes)
  – Predicted $\nu_\mu$ flux at far detector
    • Which comes from $\nu_\mu$ events at near detector
  – Predicted efficiency for $\nu_e$ events

• 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 $\nu_e$ flux is very different from the far detector $\nu_\mu$ flux

• And if you think that’s hard, now you have to do the same thing for anti-neutrinos…

Red color indicates some knowledge about QE processes
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 $\nu_\mu$ to $\nu_e$ QE cross sections
  - Uncertainties for antineutrinos assumed to be the same (and uncorrelated?)

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”
$\nu_\mu / \nu_e$ QE cross section ratios alone

- Already considered in 2007!
- What measurements can we do before NuStorm?
- Need to see how $\nu_e$ QE cross sections compare to predictions that come from detailed flux simulations anchored on $\nu_\mu$ flux measurements
- Challenge/opportunity: today’s beams have $\nu_e + \bar{\nu}_e$ bar
  - But different data sets have different combinations of $(\nu_e \times \bar{\nu}_e)/\nu_\mu$

P. Huber, M. Mezzetto, T. Schwetz
arXiv: 0711.2950
Can’t we just derive $\nu_\mu/\nu_e$ QE cross section ratio from a priori principles?

- 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 $\nu_\mu$ cross section ratios,
Also need this for $\nu_e$
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!
What we need for $\nu_\mu$ Disappearance

- In principle this is an easier task
- Near detector has healthy flux of $\nu_\mu$'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 $\nu_\mu$ 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
what do we want?

• QE Cross section*efficiencies at 1-2% level for
  – $\nu_\mu$
  – $\bar{\nu}_\mu$
  – $\nu_e$
  – $\bar{\nu}_e$
  – 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, H₂O, 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 Čerenkov detector won’t see their energy depositions at all
  - Liquid Argon detector should see them with very low energy threshold (Argonneut 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
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

### Error source

<table>
<thead>
<tr>
<th>From ND280</th>
<th>sin^2 2\theta_{13} = 0.1</th>
<th>w/o ND280 fit</th>
<th>w/ ND280 fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam only</td>
<td>11.6</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>(M_A^{QE})</td>
<td>21.5</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>(M_A^{RES})</td>
<td>3.3</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>CCQE norm. ((E_\nu &lt; 1.5) GeV)</td>
<td>9.3</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>CC1(\pi) norm. ((E_\nu &lt; 2.5) GeV)</td>
<td>4.2</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>NC1(\pi^0) norm.</td>
<td>0.6</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>CC other shape</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Spectral Function</td>
<td>6.0</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>pF</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>CC coh. norm.</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>NC coh. norm.</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>NC other norm.</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>(\sigma_{\nu_e}/\sigma_{\nu_\mu})</td>
<td>2.9</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>W shape</td>
<td>0.2</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>pion-less (\Delta) decay</td>
<td>3.7</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>SK detector eff.</td>
<td>2.4</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>FSI</td>
<td>2.3</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>PN</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>SK momentum scale</td>
<td>0.6</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>28.1</td>
<td>8.8</td>
<td></td>
</tr>
</tbody>
</table>

units: percentage error on N_{SK}
# T2K Oscillation Systematics, II

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Interaction Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{A\text{QE}}$</td>
<td>axial mass</td>
<td>CCQE</td>
</tr>
<tr>
<td>$M_{A\text{RES}}$</td>
<td>axial mass</td>
<td>$1\pi$</td>
</tr>
<tr>
<td>CCQE (3)</td>
<td>normalization</td>
<td>CCQE</td>
</tr>
<tr>
<td>CC$1\pi$ (2)</td>
<td>normalization</td>
<td>CC$1\pi$</td>
</tr>
<tr>
<td>NC$\pi^0$</td>
<td>normalization</td>
<td>NC$1\pi$</td>
</tr>
<tr>
<td>$p_f$</td>
<td>fermi momentum</td>
<td>CCQE/RFG</td>
</tr>
<tr>
<td>$E_b$</td>
<td>binding energy</td>
<td>CCQE/RFG</td>
</tr>
<tr>
<td>spectral function</td>
<td>model comparison</td>
<td>CCQE/SF</td>
</tr>
</tbody>
</table>

**Figure 1:**
- World Average (n,p)
- K2K SciFl (C)
- K2K SciBar (C)
- MiniBooNE (C)
- MINOS (Fe)
- NOMAD (C)
- T2K Prior

For $M_{A\text{QE}}$ (GeV/c$^2$):

- But allow normalizations in 3 energy bins

---

Asher Kaboth, NuFact2013
What about just measuring the intrinsic beam $\nu_e$’s at T2K?

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

Find good agreement between this sample and the expectation from the $\nu_\mu$ analysis

$$f(\nu_e) = 1.055 \pm 0.058{\text{(stat.)}} \pm 0.079{\text{(syst.)}}$$
T2K Systematics in $\nu_\mu$ disappearance


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

<table>
<thead>
<tr>
<th>Source of uncertainty (no. of parameters)</th>
<th>$\delta n_{\text{SK}}^{\text{exp}} / n_{\text{SK}}^{\text{exp}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ND280-independent cross section (11)</td>
<td>6.3%</td>
</tr>
<tr>
<td>Flux &amp; ND280-common cross section (23)</td>
<td>4.2%</td>
</tr>
<tr>
<td>Super-Kamiokande detector systematics (8)</td>
<td>10.1%</td>
</tr>
<tr>
<td>Final-state and secondary interactions (6)</td>
<td>3.5%</td>
</tr>
<tr>
<td>Total (48)</td>
<td>13.1%</td>
</tr>
</tbody>
</table>
What data we have “in hand”  
(not including SciBooNE)

<table>
<thead>
<tr>
<th>Characteristics of $\nu_\mu$ QE events</th>
<th>Mini-BooNE</th>
<th>MINERvA</th>
<th>Argoneut</th>
<th>T2K ND280</th>
<th>MINOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE Event Selection</td>
<td>1$\mu$, 1 Michel</td>
<td>1$\mu$, low recoil</td>
<td>1$\mu$ + no $\pi$, p counting</td>
<td>1$\mu$ + no $\pi$</td>
<td>1$\mu$, $\nu$&lt;225MeV</td>
</tr>
<tr>
<td>Nuclear Target</td>
<td>CH$_2$</td>
<td>He, C,CH, Pb, Fe, H$_2$O</td>
<td>Ar</td>
<td>C$_8$H$_8$ (FGD)</td>
<td>Fe</td>
</tr>
<tr>
<td>$\nu$ flux range (GeV)</td>
<td>0.4&lt;E&lt;2</td>
<td>1.5&lt;E&lt;10</td>
<td>1.5&lt;E&lt;10</td>
<td>0.2&lt;E&lt;30</td>
<td>1.5&lt;E&lt;20</td>
</tr>
<tr>
<td>Sign selection?</td>
<td>no</td>
<td>For MINOS $\mu$’s</td>
<td>For MINOS $\mu$’s</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Muon angular range</td>
<td>all</td>
<td>All or $\theta$&lt;20 (MINOS $\mu$’s)</td>
<td>$2\pi$ forward</td>
<td>$\theta$&lt;80</td>
<td>$\theta$&lt;180</td>
</tr>
<tr>
<td>p detection thresh. (MeV)</td>
<td>n/a</td>
<td>50/80 shwr/trk</td>
<td>21</td>
<td>Not yet known</td>
<td>n/a</td>
</tr>
<tr>
<td>$E(\nu)$ reconstruction</td>
<td>$E_{\nu}$ $^{QE,RFG}$ ($\mu$ or p arm)</td>
<td>$E_{\nu}$ $^{QE,RFG}$</td>
<td>$E_\mu + \Sigma T_{pi} + T_X + E_{miss}$</td>
<td>Template fit to $\mu$ kinmtx</td>
<td>$E_{\nu}$ $^{QE,RFG}$</td>
</tr>
</tbody>
</table>

12/3/2013
Deborah Harris
What we will have in the longer term (+NOMAD)

<table>
<thead>
<tr>
<th>Characteristics of $\nu_\mu$ QE events</th>
<th>MicroBooNE</th>
<th>NOvA</th>
<th>LBNE-ND (straw trkr)</th>
<th>NOMAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE Event Selection</td>
<td>$1\mu + \text{no } \pi$, p counting</td>
<td>$1\mu + \text{mltvr selection}$</td>
<td>$1\mu + \text{no } \pi$</td>
<td>$1\mu + 1p \text{ or } 1\mu + \text{no trk}$</td>
</tr>
<tr>
<td>Nuclear Target</td>
<td>Ar</td>
<td>CH</td>
<td>C$_3$H$_6$</td>
<td>Mainly C</td>
</tr>
<tr>
<td>$\nu$ flux range (GeV)</td>
<td>0.4$&lt; E &lt;$2.5</td>
<td>.5$&lt; E &lt;$2.5</td>
<td>0.2$&lt; E &lt;$30</td>
<td>24GeV</td>
</tr>
<tr>
<td>Sign selection?</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Muon angular range</td>
<td>??</td>
<td>$\theta &lt; 22.5$</td>
<td>$4\pi$</td>
<td>$\theta &lt; 180 \text{ trk}$ $\theta &lt; 50 \mu \text{ ID}$</td>
</tr>
<tr>
<td>$p$ detection thresh. (MeV)</td>
<td>21</td>
<td>n/a</td>
<td>Very low?</td>
<td>200</td>
</tr>
<tr>
<td>$E(\nu)$ reconstruction</td>
<td>$E_\mu + \sum T_{pi} + T_x + E_{\text{miss}}$</td>
<td>$E_{\nu}^{QE, \text{RFG mod}}$</td>
<td>Many options</td>
<td>Many options</td>
</tr>
</tbody>
</table>

12/3/2013
Deborah Harris
What could we hope to measure?

• Absolute QE* cross sections vs “Eν” (flux-willing)
  – MINERvA: C, CH, Fe, Pb, H2O broad energy range
  – NOvA: CH, 2GeV
  – Argoneut and MicroBooNE: Ar 1,3GeV
  – T2K ND: H2O, CH 700MeV
  – want ν and ν̄ν, νμ and νe
  – Could also get to cross sections vs pμ θμ
  – 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 $\nu_e$ 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