Near Detector Considerations

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Outline

- A reminder of the current $\nu_e$ analysis at T2K
  - Addressing current strategy and systematic errors

- Constraints from ND280
  - Beam
  - Neutrino interactions
    - A focus on the $\sim 1$GeV region
    - Multi-nucleon effects

- Systematic error reduction in the spectrum propagation to SK
  - 2KM WC

- Topology identification
  - LAr (Ne?)
  - ND280
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$\nu_e$ Appearance Analysis Strategy

1. Neutrino Flux Predictions
2. Neutrino Cross Section Predictions
3. ND280 CCQE and CCnQE Data Samples
4. Cross-check intrinsic $\nu_e$ component at ND280

- Fit ND280 sample to tune $\nu_\mu$, flux and CCQE, CC1$\pi$ cross sections and reduce flux, cross section uncertainties.

- Apply rate correction to events at SK and fit to determine oscillation parameters.

$\nu_e$ appearance: $\theta_{13}$; $\nu_\mu$ disappearance: $\theta_{23}$, $\Delta m^2_{23}$
Selecting CC$\nu_\mu$ interactions at ND280

Measure un-oscillated $\nu_\mu$ (CC) rate in ND280 tracker (current analysis):

- Neutrino interactions in FGD1 FV
- Veto events with TPC1 tracks
- Select highest momentum, negative curvature track as $\mu^-$ (TPC PID)
- Further separate sample into two categories:
  - CCQE-enhanced
    - 1 TPC-FGD matched track
    - No decay electron in FGD1
  - CCnQE-enhanced
    - All other CC inclusive
  - The $(P_\mu, \cos \theta_\mu)$ spectrum used to constrain flux and xsection parameters used by SK

Measure intrinsic $\nu_e$ (CC) rate in ND280 tracker (current analysis):

- Similar selection to $CC\nu_\mu$
- Request an electron instead of a muon
- Use vertexes in the FGD2 as well to increase the statistics
- Use the ECAL to reject background reaching it.

Selected events:

- $\sim 80\% \, \nu_e$ are from kaon decays
- $\sim 78\%$ of the background is low energy electrons from $\gamma$ conversion in the FGD, where $\gamma$ come from $\pi^0$ from $\nu_\mu$ interactions either in the FGD or in the surrounding material

Notes on near detector needs:

- at least as good PID as we have now
- reduction background from gamma rays
After ND tuning, expect \((8.2 + 3.3 = ) 11.2\) events with \(\nu_\mu \rightarrow \nu_e\) oscillation, 3.3 without.

<table>
<thead>
<tr>
<th>Signal ((\nu_\mu \rightarrow \nu_e\ oscillation))</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta m^2_{32}=2.4 \times 10^{-3}) eV(^2), (\sin^2 2\theta_{23}=1.0) @ (\sin^2 2\theta_{13}=0.1, \delta CP=0)</td>
<td>8.2</td>
</tr>
</tbody>
</table>

\(\nu_e\) signal @ \(\Delta m^2_{32}=2.4 \times 10^{-3}\) eV\(^2\), \(\sin^2 2\theta_{23}=1.0\)

<table>
<thead>
<tr>
<th>Background</th>
<th># events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam (\nu_e + \bar{\nu}_e)</td>
<td>1.7</td>
</tr>
<tr>
<td>CC(\nu_\mu)</td>
<td>0.06</td>
</tr>
<tr>
<td>NC(\nu_\mu)</td>
<td>1.2</td>
</tr>
<tr>
<td>Osc through (\theta_{12})</td>
<td>0.18</td>
</tr>
<tr>
<td>Total</td>
<td>(3.3 \pm 0.43) (syst)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>(\nu_e) bkgd</th>
<th>(\nu_e) sig+bkgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu) flux + xsec (constrained by ND280)</td>
<td>±8.5%</td>
<td>±5.0%</td>
</tr>
<tr>
<td>(\nu) Xsec (no constraint by ND280)</td>
<td>±5.9%</td>
<td>±7.8%</td>
</tr>
<tr>
<td>Far Detector</td>
<td>±6.6%</td>
<td>±3.0%</td>
</tr>
<tr>
<td>Total</td>
<td>±13.0%</td>
<td>±9.9%</td>
</tr>
<tr>
<td>No ND measurement</td>
<td>18.3±</td>
<td>22.6±</td>
</tr>
</tbody>
</table>

[arXiv:1304.0841 [hep-ex]]
• A reminder of the current $\nu_e$ analysis at T2K
  • Addressing current strategy and systematic errors

• Constraints from ND280
  • Beam
  • Neutrino interactions
    • A focus on the $\sim$1GeV region
    • Multi-nucleon effects

• Systematic error reduction in the spectrum propagation to SK
  • 2KM WC

• Topology identification
  • LAr (Ne?)
  • ND280
The flux parametrization variation is described by normalization parameters in bins of $E_\nu$ and flavour at a given detector.

The ND280 $\nu_\mu$ and SK $\nu_\mu$ flux predictions have large correlations: the $\nu_\mu$ rate at the ND can constrain the unoscillated $\nu_\mu$ interaction rate at the FD.

The SK $\nu_e$ flux at SK is also correlated with the ND280 $\nu_\mu$ flux since they both originate from the $\pi \rightarrow \mu \nu_\mu$ decay.

<table>
<thead>
<tr>
<th>Propagated Neutrino Flux</th>
<th>Prior Value</th>
<th>Fitted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ 0.0-0.4 GeV</td>
<td>1.00±0.12</td>
<td>0.98±0.09</td>
</tr>
<tr>
<td>$\nu_\mu$ 0.4-0.5 GeV</td>
<td>1.00±0.13</td>
<td>0.99±0.10</td>
</tr>
<tr>
<td>$\nu_\mu$ 0.5-0.6 GeV</td>
<td>1.00±0.12</td>
<td>0.98±0.09</td>
</tr>
<tr>
<td>$\nu_\mu$ 0.6-0.7 GeV</td>
<td>1.00±0.13</td>
<td>0.93±0.08</td>
</tr>
<tr>
<td>$\nu_\mu$ 0.7-1.0 GeV</td>
<td>1.00±0.14</td>
<td>0.84±0.08</td>
</tr>
<tr>
<td>$\nu_\mu$ 1.0-1.5 GeV</td>
<td>1.00±0.12</td>
<td>0.86±0.08</td>
</tr>
<tr>
<td>$\nu_\mu$ 1.5-2.5 GeV</td>
<td>1.00±0.10</td>
<td>0.91±0.08</td>
</tr>
<tr>
<td>$\nu_\mu$ 2.5-3.5 GeV</td>
<td>1.00±0.09</td>
<td>0.95±0.07</td>
</tr>
<tr>
<td>$\nu_\mu$ 3.5-5.0 GeV</td>
<td>1.00±0.11</td>
<td>0.98±0.08</td>
</tr>
<tr>
<td>$\nu_\mu$ 5.0-7.0 GeV</td>
<td>1.00±0.15</td>
<td>0.99±0.11</td>
</tr>
<tr>
<td>$\nu_\mu$ &gt;7.0 GeV</td>
<td>1.00±0.19</td>
<td>1.01±0.15</td>
</tr>
</tbody>
</table>

Similarly for the $\nu_e$ and the antiparticles.
Neutrino Interactions at ND and SK

<table>
<thead>
<tr>
<th>Interaction Mode</th>
<th>Trkr. $\nu_\mu$ CCQE</th>
<th>Trkr. $\nu_\mu$ CCnQE</th>
<th>SK $\nu_e$ Sig.</th>
<th>SK $\nu_e$ Bgdnd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>76.6%</td>
<td>14.6%</td>
<td>85.8%</td>
<td>45.0%</td>
</tr>
<tr>
<td>CC1$\pi$</td>
<td>15.6%</td>
<td>29.3%</td>
<td>13.7%</td>
<td>13.9%</td>
</tr>
<tr>
<td>CC coh.</td>
<td>1.9%</td>
<td>4.2%</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>CC other</td>
<td>4.1%</td>
<td>37.0%</td>
<td>0.2%</td>
<td>0.7%</td>
</tr>
<tr>
<td>NC</td>
<td>1.5%</td>
<td>5.3%</td>
<td>-</td>
<td>39.7%</td>
</tr>
</tbody>
</table>

**CCQE** and **CC1$\pi$** are the largest interaction mode in ND, SK samples:

- Separation of CCQE and CCnQE ND samples gives additional power for fit to constrain cross section models
- Need to account for acceptance difference between ND (forward going selection) and SK (4$\pi$ selection) for identical changes to cross section to correlate the two samples
- Compared external (MiniBooNE, SciBooNE...) neutrino-nucleon cross sections with neutrino interaction models

**NC** is the largest background at SK after the selection
Sub-set of parameters which are substantially constrained by the ND280 data-set and relevant to the event rate prediction at SK

- $M_A^{QE}$ and $M_A^{RES}$: modify $Q^2$ distribution of QE and resonant $1\pi$ cross sections

- Normalizations provide overall scaling independent of $Q^2$ on a particular interaction

Apply cross section to observables at ND, SK using reweighting techniques

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prior Value</th>
<th>Fitted Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A^{QE}$ (GeV)</td>
<td>1.21±0.45</td>
<td>1.33±0.20</td>
</tr>
<tr>
<td>$M_A^{RES}$ (GeV)</td>
<td>1.16±0.11</td>
<td>1.15±0.10</td>
</tr>
<tr>
<td>CCQE norm 0-1.5 GeV</td>
<td>1.00±0.11</td>
<td>0.96±0.09</td>
</tr>
<tr>
<td>CC1(\pi) norm 0-2.5 GeV</td>
<td>1.63±0.43</td>
<td>1.61±0.29</td>
</tr>
<tr>
<td>CC1(\pi^0) norm</td>
<td>1.19±0.43</td>
<td>1.19±0.40</td>
</tr>
</tbody>
</table>

Parameter value, uncertainty are determined from the MiniBooNE single pion samples

Parameter value, uncertainty are extrapolated to the SK sample

A focus on the ~1GeV region

T2K flux around 0.5-1 GeV.
CC interactions dominated by CCQE

Minor fraction of xsection at ~1GeV is purely leptonic - exactly known in the SM. Majority of interactions occur on bound states (nucleon, nuclei).
A focus on the ~1GeV region

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CCQE Measurements

• Turning point is the high statistics MiniBooNE CCQE double differential cross section measurement:

• Cross section energy dependence in C is inconsistent between NOMAD and MiniBooNE.

• Experiments use a different definition of CCQE than theorists
  \( \nu_\mu + n \rightarrow \mu + p \) (see Feynman diagram)
  \( \nu_\mu + X \rightarrow \mu + X' + 0\pi \) (MB)
  \( \nu_\mu + X \rightarrow \mu + X' + 0\pi + \text{no vertex activity} \)
  \( \nu_\mu + X \rightarrow \mu + p + X' + 0\pi \) (NOMAD)

……

Based on what the experiments can observe
Introducing the Meson Exchange Current

Plenty of models have arisen to explain MiniBooNE CCQE data
Most popular is np-nh or meson exchange currents (MEC)
Can calculate from diagrams:

Also include pion-less $\Delta$ decays in models

Models good up to $\sim 1.5$ GeV - No prediction for nucleon kinematics

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

Martini et al
Reconstructed Energy Bias

- Not all the events (currently) reconstructed as CCQE are true CCQE, mainly due to multi-nucleon events.
- MEC events introduce a bias to the energy reconstruction.

Reconstructed neutrino energy bias in case not all the outgoing particles (nucleons, pions) are identified.

Mosel and Lalalukich arXiv:1208.3678 [nucl-th]

Martini et al, Phys. Rev. D87 (2013) 013009

To separate MEC from CCQE we need to analyze the final state nucleons.

More references:
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To reduce the errors at the FD we can concentrate on the following areas:

- Reduction of the differences between the ND and FD detectors:
  - Use same flux
  - Use same nucleus

- Improve the knowledge of the cross sections at the ND
  - We need to measure both CC and NC cross sections
  - We need to be able to measure multi-nucleon final states.

- Improve the measurement of the intrinsic $\nu_e$ contamination
Original proposal for a 2KM detector for T2K in 2007

A letter of intent to extend T2K with a detector 2 km away from the JPARC neutrino source, June 2007

The 2007 proposal includes:

- 1kton Water Cherenkov Detector
- 100ton LAr detector
- Iron muon range
• At 280m: neutrino source not point-like, spectral differences with respect to SK
• Neutrino spectra at SK and 2KM are almost the same: ~same beam → energy spectrum
• To improve our current precision we need to improve our errors on the flux predictions
• **Same nucleus** at the 2KM and SK.
  • Same neutrino interaction cross sections
  • Same energy bias
• **Neutrino energy tail** ~20% smaller than at ND280
  • Less contribution from non-CCQE events to the neutrino energy

ND280 and SK normalized to the same area:

As left plot but logarithmic scale:
• Full $4\pi$ coverage for 2KM and SK detectors
  • $\sim20\%$ of the SK events are backward.

• Measure rate of NC $\pi^0$ of NC single pion in water
• Much higher photocathode coverage $\rightarrow$ useful for systematics
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Main advantages of a LAr detector for HK are:

- Particles below Cherenkov threshold are visible, especially protons.
- Independent measure of off-axis flux and non-QE/QE event ratio.
- Exclusive measurement of NC and intrinsic electron neutrino background. Excellent PID will allow these to be separately measured.

**ARGONEUT DATA-MC COMPARISON (II)**

- Improve neutrino interaction understanding. It allows topology recognition with extraordinary sensitivity
- Many world-wide efforts in the LAr technology (test-beams and neutrino running)
Note of caution for HK:

• Different nucleus than Oxygen, so one needs to properly rescale between them.

• A slab of frozen Oxygen in the middle of the detector was introduced in the original 2KM proposal to allow to directly measure the interactions in the two nuclei.

• Some Dark Matter experiments, DEAP, CLEAN, miniCLEAN, are using both Ar and Neon. No further usage of Neon apart from DM, but we can look into it.

• Others?
• We need a detector that can perform precise studies of neutrino-nucleon scattering.
• Recent requirement for measuring the cross section is to resolve multi-nucleon final states.
• The detector needs very good vertexing and ability to identify the produced particles in multi-particle final states, track low energy charged particles etc.

We can improve the ND280 detector using a finely-segmented scintillator-based up-stream tracking region.
The ND280 Detector

- Using scintillator strips instead of water → MINERvA-type detector
- A nuclear target region will allow to measure the interactions in Oxygen.
- The current detector can be adapted with scintillator instead of water planes in the P0D.
- Possibly use 3 different orientations of planes (XUV) → 3D reconstruction
- The P0D-ECAL can be replaced by a more segmented ECAL, similarly to Barrel or DSECAL.
The ND280 refurbishment is on top of any possible upgrade we aim to do.

- ND280 will be more than 13y old and will need to last for another decade at least.
- There are several aspects related to aging and spares (same technology may not be available anymore) that we need to address:
  - Electronics ageing:
    - Minimize the possible replacements. Some electronic cards may be impossible to replace unless we fully dis-assemble the detector. We can concentrate on the RMMs (Readout Merger Modules) only for upgrade/replacement, not TFBs (Trip-t Front End Boards).
  - MPPCs aging should be OK, but new technology and no experiment used them for long time. Extremely low failure rate so far.
  - MicroMega aging should be OK.
  - Scintillator/fiber aging:
    - To check light yield reduction. Studies from MINOs available.
Conclusion

- We can learn from current T2K experience how to design the ND.

- ND very important to reduce errors at the FD
  - Flux: using the ND280 flux to reweight the SK flux
  - Neutrino interactions: MEC effect is important

- Near Detectors for HK:
  - We can look (again) at the 2KM near detector
    - Very important for having the same flux as at HK
    - Systematics will partially cancel due to the usage of the same nucleus
  - Possible LAr (or other nuclei) will help in precisely measuring neutrino interaction and intrinsic $\nu_e$ beam background
  - Upgraded ND280 with a fully active up-stream detector to measure neutrino interaction with high precision.
$N(\nu_e) = \Phi(E_\nu) \sigma(E_\nu) \epsilon P(\nu_\mu \rightarrow \nu_e)$

Fit the observed rate to determine $\sin^2 2\theta_{13}$. Also depends on

- Neutrino Flux Prediction
- Neutrino Cross Section Model
- Far Detector Selection, Efficiency

We decrease the error on the $\nu_e$ rate, with the near detector;

$N(\nu_\mu) = \Phi(E_\nu) \sigma(E_\nu) \epsilon$
A focus on the ~1GeV region

Minor fraction of xsection at ~1GeV is purely leptonic - exactly known in the SM. Majority of interactions occur on bound states (nucleon, nuclei).

Until recently, assumed neutrinos interaction with individual bound nucleons (Impulse Approximation)

ν interaction is a two-step process: a primary interaction followed by final states interactions (FSI) effects: before leaving nucleus, hadrons undergo re-interaction

Quark: Known.
Lepton: “Trivial.”

Nucleon: Parameterize w/ Form Factors.

Nucleus: Hard! Very complex nuclear physics. But this is where we want σ…
CCQE Measurements

- Turning point is the high statistics MiniBooNE CCQE double differential cross section measurement:

- Energy dependence of cross section of C is inconsistent between NOMAD and MiniBooNE.
- MiniBooNe measure $\mu 0\pi$, NOMAD selects $\mu p$
- Range of multinucleon models (extra process where neutrino interacts with more than a free nucleon) proposed:
  - Transverse enhancement to the cross section
  - Meson exchange current (MEC, simple Marteu process)
- Cross section also depends upon how nucleon is described within nuclear potential (nucleon is usually a relativistic gas model)
Introducing the Meson Exchange Current

One body basic intuition:

Fermi Gas: noninteracting nucleons, all states filled up to $k_F$

Two body basic intuition:
think about more Feynman diagrams

MEC events are suspected to introduce a strong bias to energy reconstruction:

To separate MEC from CCQE analyze final state nucleons.