E61: The J-PARC Intermediate Water Cherenkov Detector

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How to Measure Neutrino Oscillations

In a near/far experiment, $\sigma$ uncertainties will cancel?

\[
ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND} \\
FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{osc}
\]
How to Measure Neutrino Oscillations

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Unfortunately, “cancelation” does not work!
How to Measure Neutrino Oscillations

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\[
ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND} \times M_{E_{rec}}^{E_{true}}
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\]
How to Measure Neutrino Oscillations

In a near/far experiment, $\sigma$ uncertainties will cancel?

Unfortunately, “cancelation” does not work!

**Near Detector Measures:**
- $\nu_\mu$ energy spectrum
- Small $\nu_e$ component

**Far Detector Measures:**
- Osc. $\nu_\mu$ energy spectrum
- Large $\nu_e$ appearance signal

$$ND(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{ND} \times M_{E_{\text{rec}}}^{E_{\text{true}}}$$

$$FD(\nu_\mu) = \Phi(E_\nu) \times \sigma(E_\nu, A) \times \epsilon_{FD} \times P_{\text{osc}} \times M_{E_{\text{rec}}}^{E_{\text{true}}}$$
How to Measure Neutrino Oscillations

In a near/far experiment, $\sigma$ uncertainties will cancel?

Unfortunately, “cancelation” does not work!

- $E_{\text{true}} \rightarrow E_{\text{rec}}$ migration matrix is (quite) non-diagonal! (next slides)
- Several important cross section uncertainties will not cancel
Measuring $E_\nu$

**Lepton Only:**

- $\nu$ direction known
- $n$ at rest? not observed (but mass is assumed)
- $\mu$ fully reconstructed
- $p$ or $\Delta$

Must assume mass of recoiling hadron(s)

Problematic! due to Multi-nucleon interactions

**Lepton + Hadronic Energy:**

- $\nu$ Energy measurement
- $\mu$ fully reconstructed
- $p, \pi^+, \pi^0, n, n$ Missing energy
- $\Pi^+$ Missing energy

Missing hadronic energy from $n$, unseen $\pi^+$, etc.

Energy loss is different for $\nu$ and anti-$\nu$

- Both effects lead to underestimating the neutrino energy (feed down)
- Need to calibrate both leptonic ($e$ & $\mu$) & hadronic energy scales and shapes (e.g. long $E_{\text{rec}}$ tails)

Martini et al. arXiv:1311.1523

GEANT4 Simulation of a large LAr volume

(True deposited hadronic energy)/
(True initial hadronic energy)
**Eν Feed Down**

- Feed down & o are poorly understood
- Factor of ~3 disagreements in existing (effective theory) models
- Different for ν & anti-ν
- Eν feed down fills in the νμ disappearance dip
- Results in large biases in θ23 and Δm232 measurements

**Conventional near detectors lack sensitivity** to feed down tail
- Many degenerate solutions
- Cannot constrain effect at far detector
Fake Data Studies

- If we had a **model we could believe** at the sub-% level (in rate and shape), our jobs would be much easier.
  
  - We would simply design a near detector to constrain the parameters of that model.
  
- However, our models are **not very good**.
  
  - It is unlikely that any combination of model parameters will reproduce our data.
  
- We can try to probe this using **fake data studies**, where the data contains features not accessible by the MC model in the fit.
  
  - In T2K, such studies show that, even with a standard near detector constraint, **large biases occur** in the fitted oscillation parameters.
Example Fake Data Study

- Create fake data samples with flux and cross section variations
  - 2 versions: with and without multi-nucleon events (i.e. T2K 2013 model vs 2015 model)
- For each fake data set, full T2K near/far oscillation fit is performed
  - For each variation, plot difference with and without multi-nucleon events
- Resulting error on $\theta_{23}$ at the ~4% level
  - This is would be one of the largest systematic uncertainties for T2K
- But this is not a “real” systematic uncertainty; it is just the comparison of 2 models

Summary of Cross Section Model

Difficulties for Conventional Near Detectors

1. If your fluxes are different at the near and far detectors
   - ...they will be, due to oscillations

2. Then you can introduce cross section parameters that are:
   A. Important at the far detector
   B. Largely degenerate at the near detector

3. This produces systematic errors that your near detector can no longer help with
   - We already know of some such parameters, and more are likely to be introduced in the future (unknown unknowns)

This problem goes away if we can measure $E_{\text{true}} \rightarrow E_{\text{rec}}$ experimentally.
E61 Detector Concept
E61 Detector Concept
E61 Detector Concept

ν-Beam
ν Interactions
ν Interactions
ν Interactions

4.0° Off-axis Flux
2.5° Off-axis Flux
1.0° Off-axis Flux
E61 Detector Concept

Muon p&θ

ν Interactions

ν Interactions

ν Interactions

ν Interactions
E61 Detector Concept

v-Beam

Take linear combinations!

-0.5 *

+1.0 *

-0.2 *

 ν Interactions

ν Interactions

ν Interactions

Muon p&θ

ν Interactions

ν Interactions

ν Interactions

-0.5 *

+1.0 *

-0.2 *
E61 Detector Concept

Take linear combinations!

-0.5

+1.0

-0.2

Muon p&θ

Muon p&θ

Muon p&θ

Muon p&θ from a monoenergetic beam

Linear Combination, 0.6 GeV Mean

1 Ring u Event Spectrum
Absolute Flux Error
Shape Flux Error
Statistical Error
Fit Mean: 0.60 GeV
Fit RMS: 0.08 GeV
E61 Detector Concept

-0.5 *

Take linear combinations!

600 MeV Monoenergetic Beam using 60 slices in off-axis angle

600 MeV Monoenergetic Beam using 60 slices in off-axis angle

Take linear combinations!

Muons p&\theta

From a monoenergetic beam

Linear Combination, 0.6 GeV Mean

Muon p&\theta

Muon p&\theta

Muon p&\theta

from a monoenergetic beam
E61 in an Oscillation Experiment

Muon p&θ

ν Interactions

ν Interactions

ν Interactions
E61 in an Oscillation Experiment

ν-Beam

Take different linear combinations!

+1.0*

-0.8*

+0.2*

ν Interactions

ν Interactions

ν Interactions

ν Interactions
E61 in an Oscillation Experiment

Take different linear combinations!

Measured oscillated $p&\theta$ spectrum in a near detector!
E61 in an Oscillation Experiment

Oscillated Flux Produced at the Near Detector!

Oscillated p&θ Measured at the Near Detector!

Match Super-K Oscillated Flux

Measured oscillated p&θ spectrum in a near detector!
E61 in an Oscillation Experiment

Oscillated Flux Produced at the Near Detector!

Oscillated $p&\theta$ Measured at the Near Detector!

This technique is robust against existing fake data studies.

Match Super-K Oscillated Flux

Measured oscillated $p&\theta$ spectrum in a near detector!
“Oscillations” in a Near Detector

- Red region is directly measured by E61
- Blue region is flux difference correction
- Green is SK non-CC0π background
- Partially cancels with already-subtracted E61 CC0π background
- Magenta is acceptance correction
  (geometric muon acceptance)
- SK prediction is largely from directly measured component
Beam Uncertainties

- Haven’t we just replaced **unknown cross section errors** with **unknown flux errors**?
  - Yes! But only relative flux errors are important!
- Significant cancelation between E61 and far detector variations
- **Normalization uncertainties will cancel** in the E61 analysis
  - Cancelations persist, even for the E61 linear combination
- **T2K without E61**: hadron prod. errors dominate; **T2K with E61**: hadron prod. errors are negligible
- Variations that affect off-axis angle shape are most important
  - Horn current, beam direction, alignment, etc.
- For T2K, beam uncertainties do not significantly contribute to the $\nu_\mu$ disappearance sensitivity
Disappearance Constraint

**Martini Model**
(with Nieves final states)

- Bias = -2.9%
- RMS = 3.2%

**Nieves Model**

- Bias = 0.3%
- RMS = 3.6%

Standard T2K Analysis
E61 $\nu_\mu$ Disappearance Constraint

**Martini Model**
- Bias = -2.9%
- RMS = 3.2%

**Nieves Model**
- Bias = -0.06%
- RMS = 1.0%

**Standard T2K Analysis**
- Martini Model (with Nieves final states)
  - Bias = -2.9%
  - RMS = 3.2%

**E61 Analysis**
- Nieves Model
  - Bias = 0.3%
  - RMS = 3.6%

- Martini Model (with Nieves final states)
  - Bias = -0.1%
  - RMS = 1.2%

Entries: 300
Mean: -0.0002917
RMS: 0.005395

Entries: 300
Mean: -0.000475
RMS: 0.006014
Fake data studies show the bias in $\theta_{13}$ is reduced from $4.3\%/3.6\%$ to $1.2\%/1.0\%$.

More importantly, this is now based on a data constraint, rather than a model-based guess.

Expect the E61 constraints to get significantly better as additional constraints are implemented (very conservative errors).
A Phased Approach

- **Phase 1**
  - Moveable instrumented detector, placed in a ~50 m deep pit, ~1 km away from the neutrino target

- **Phase 0**
  - Instrumented portion of phase 1 is placed in a water tank near ND280
  - Physics goal: measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ to ~3% precision
  - Can demonstrate detector performance & calibration precision
  - Provides a test detector for Hyper-K R&D
Phase 0 $\sigma(v_e)/\sigma(v_\mu)$ Measurement

- The best $\sigma(v_e)/\sigma(v_\mu)$ measurements have ~20% errors
  - Theoretical uncertainty at 3% level
  - Default uncertainty for osc. experiments, and already significant for $\delta_{CP}$
- Nice overview given by Kevin McFarland at NuINT 2 weeks ago: https://meetings.triumf.ca/indico/event/6/session/2/contribution/78
- $v_e/v_\mu$ Flux ratio uncertainties grow at larger off-axis angles due to increase in $v_e$ from kaon decay
  - Few percent uncertainties up to ~8°
- Expect to make a few percent measurement of $\sigma(v_e)/\sigma(v_\mu)$ in several $v_e$ kinematic bins
Gd Loading

- Aim to load E61 with Gd to study n-capture
- Super-K will soon be loaded with Gd
  - Some separation of ν/anti-ν may be possible
  - But, to utilize this information for high-energy analysis, must constrain neutron emission/capture
- Phase 1 can measure neutron capture rate as a function of Eν and muon kinematics (Hyper-ANNIE?)
- Phase 0 can provide initial constraints, and is an important demonstrator for Phase 1
  - 93% of muons in the FV capture in the Phase 0 detector (88% Gd, 12% H)
- Extensive studies are underway
  - Simulation and reconstruction tools
  - Studies of radioactive backgrounds and external neutron signals

Neutron flux measurements at ND280:
E61 was granted Stage-1 approval in July, 2016

- A Technical Design Report is under development for Stage-2 (final) approval in 2018

- Phase 0 start is driven by mPMT development & production
  - Plan to take at least 2 years of beam data in Phase 0
  - Aim to begin Phase 1 ~3 years after Phase 0 start
  - Data taking over the last 2-3 years of T2K-II run
Summary

- Long-baseline neutrino oscillation experiments are beginning to face limitations due to cross section uncertainties
  - Poorly understood “feed down” can bias oscillation parameter measurements
    - ...due to very different near & far detector $\nu_e$ & $\nu_\mu$ fluxes
- The E61 experiment (Phase 1) at J-PARC can provide an experimental solution to $E_{\text{rec}} \rightarrow E_{\text{true}}$ problem
  - Phase 0 can make a precise measurement of $\sigma(\nu_e)/\sigma(\nu_\mu)$
    - Also a demonstrator for Phase 1, and hardware test detector for Hyper-K
- Variety of other measurements: $n$-Gd capture rates, sterile neutrino search, and a rich cross section program with mono-energetic beams
Supplement
**Phase 1 $\nu_e$ Appearance (CPV)**

### 3 step approach:

**Step 1:** Measure *Super-K $\nu_e$* response with *E61 $\nu_\mu$*

- If $\sigma(\nu_e)/\sigma(\nu_\mu) = 1$ this fit is all that is needed

**Step 2:** Measure *E61 $\nu_e$* response with *E61 $\nu_\mu$*

- High-$E$ is above muon acceptance
- Measure $\sigma(\nu_e)/\sigma(\nu_\mu)$

**Step 3** uses the slice of E61 in the far detector direction to measure NC backgrounds with the same energy spectrum as the far detector (reduces background systematics)

- **Step 1** is the $\nu_e$ version of the $\nu_\mu$ disappearance analysis
  - Reduces FSI/SI and SK detector uncertainties, and improves ND280 flux+xsec constraint

- **Step 2** uses only E61 to measure $\sigma(\nu_e)/\sigma(\nu_\mu)$
  - Constrains the $\sigma(\nu_e)/\sigma(\nu_\mu)$ uncertainty