Analysis and Background Aspects in Large Water Cerenkov Detectors

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Outline

• T2K signal and background rates

• Water Čerenkov response model
  – Cross-sections and efficiencies
  – Neutrino energy reconstruction
  – Background rejection

• Systematic uncertainties
  – Near detector(s)
  – Fast global fit technique
40-50 GeV protons create off-axis $\nu_\mu$ beam
Neutrino flux at Super-K

(2.5° off-axis beam from 0.75 MW, 40 GeV protons, assumes 5 years x 10^{21} POT)

\[ \Delta m^2 = 0.0025 \]

Unoscillated \( \nu_\mu \) flux

Oscillated \( \nu_\mu \) flux \( (\sin^2 2\theta_{23} = 1.0) \)

Oscillated \( \nu_e \) flux \( (\sin^2 2\theta_{13} = 0.1) \)
Signal and Backgrounds
• From off-axis $\nu_\mu$ beam at Super-K

**Disappearance Experiment**
Selection:
Fully contained, single-ring, $\mu$-like events

**Appearance Experiment**
Selection:
Fully contained, single-ring, e-like (showering) no decay electron

**Signal:**
CCQE: $\nu_\mu + n \rightarrow p + \mu^-$

**Backgrounds:**
- CC single $\pi$: $\nu_\mu + N \rightarrow N' + \mu^- + \pi$
- CC multi $\pi$’s: $\nu_\mu + N \rightarrow N' + \mu^- + \pi$
- NC: $\nu + N \rightarrow N' + \nu + \pi^0$
- Beam $\nu_e$
- Misidentified muons
Reconstructing $\nu_\mu$ Energy
For T2K disappearance

True Neutrino Energy

(1.0, 0.0025)

Interaction spectrum =
Flux $\times$ Cross section $\times$ Efficiency

y-axis: Events / 5 years / 22.5 kton / 50 MeV bin
ν_e Appearance Background

- Largest background is from NC π^0 production

- The π^0 fitter (POLfit) finds a second ring by testing:
  Likelihood(2γ) vs. Likelihood(1e)
  Then fits direction and energy fraction of 2^{nd} ring

Plot from S. Mine

500MeV/c π^0
true Pγ_2 = 55.5MeV/c
rec.Mπ^0 =140.4MeV/c^2
**ν_e signal vs. background after π^0 fitter**

(For Δm^2=0.0025  sin^22θ_{23}=1.0  θ_{13}=9°)

**Before π^0 fitter:**
NC background ~ 40 events

**After π^0 fitter:**
NC background ~ 10 events

Background estimates by M. Fechner

![Graph showing signal vs. background after π^0 fitter](image)
$\nu_e$ signal for varied $\theta_{13}$ values

(For $\Delta m^2=0.0025$ $\sin^22\theta_{23}=1.0$)

$\theta_{13}=3^\circ$

(sin$^22\theta_{13}=0.01$)
Systematic uncertainties

- Precision measurement of $\theta_{23}$ and $\Delta m_{23}^2$ and appearance background subtraction require careful control of systematic uncertainties.
  - Čerenkov detector reconstruction:
    - Energy scale ($\sim 3\%$)
    - Fiducial volume ($\sim 3\%$)
  - Cross sections
    - CCQE ($\sim 10\%-20\%$)
    - Other ($\sim 20\%-50\%$)
  - Flux normalization and shape
    - Hadron production model
    - Beam geometry
    - Beam $\nu_e$
Near Detector(s)

• Systematics may be controlled by using one or more near detectors.

• Fine-grained detector placed near the target.
  - Ability to measure relative amounts of CCQE and nonQE interactions

• Water Cerenkov 2km away from target.
  - Flux shape matches that at far detector.
  - Close to identical response at both near and far detectors.
Global oscillation fit

- A fit has been developed to determine oscillation parameters with the following capabilities:
  - varying systematic effects
  - inclusion of near and far detectors
  - inclusion of both signal and background
  - parameterized detector response (cross-sections, efficiency, reconstruction)

A similar approach has been used in the Super-K atmospheric neutrino oscillation analysis.

References:
Para and Szleper (hep-ex/0110001)
Example global oscillation fit

$\Delta m^2 = 0.0025$

$\sin^2 2\theta_{23} = 0.95$

$\theta_{13} = 0^\circ$

Data

Prediction

Best fit Prediction

+ Systematics

Fit $\Delta m^2$

Fit $\sin^2 2\theta_{23}$

Uncertainty:

$\sim 2\%$ on $\Delta m^2_{23}$

$\sim 1.2\%$ on $\sin^2 2\theta_{23}$

Preliminary example: no inclusion of 280m detector.
Conclusions

• Global fit of oscillation parameters including systematics, near detectors, and backgrounds is a work in progress.

• Current goals are
  – Perform sensitivity analysis for oscillation parameters using different detector configurations.
  – Determine effect of systematic uncertainties on T2K sensitivity.

• Method is not limited to Water Cerenkov detectors or to T2K-I experiment