Recent Results from the $K^2K$ Experiment

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Zenith angle dependence (Multi-GeV)

(a) FC e-like
- Data
- MC + MC stat
- Up-going
- Down-going

\[ X^2(\text{shape}) = 2.8/4 \text{ dof} \]
\[ \frac{\text{Up}}{\text{Down}} = 0.93 \pm 0.13 - 0.12 \]

(b) FC μ-like + PC
- Number of Events
- \( \cos \Theta \)
- Up/Down syst. error for μ-like

\[ X^2(\text{shape}) = 30/4 \text{ dof} \]
\[ \frac{\text{Up}}{\text{Down}} = 0.54 \pm 0.06 - 0.05 \]  
(6.2σ!!)

Prediction (flux calculation \( \leq 1\% \))
- 1 km rock above SK \( \leq 1.5\% \)
- \( 1.8\% \)

Data (Energy calib. for \( \uparrow \downarrow \) \( \leq 0.7\% \))
- Non ν Background \( \leq 2\% \)
- \( 2.1\% \)
The MNS matrix

\[ \tilde{\nu}_{weak} = \mathcal{M} \circ \tilde{\nu}_{mass} \]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
M_{1,e} & M_{2,e} & M_{3,e} \\
M_{1,\mu} & M_{2,\mu} & M_{3,\mu} \\
M_{1,\tau} & M_{2,\tau} & M_{3,\tau}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[ \mathcal{M} \rightarrow \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}, \quad \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}, \quad \begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\]

Solar, reactor analyses \quad Atm., K2K analyses \quad terms probed by future experiments
Far site event rate prediction in two steps:

- **Measure the neutrino flux nearby**
  - Multiple measurements at the KEK site.

- **Modeling the beam:**
  - Our MC

This is used to extrapolate from the nearby measurement.
K2K post-construction views

12 GeV protons

Decay tunnel

(These & more available at http://neutrino.kek.jp/)
A few such detectors exist; here is one:
Expected $\nu_\mu$ flux at 250 km, on axis and far from it

- On axis flux expected
- Flux expected 1km (4mr) away
- Flux expected 2km (8mr) away
- Flux expected 3km (12mr) away

\[ \Phi_{\nu_\mu} \text{ (arbitrary units, log scale)} \]

\[ P_{\nu_\mu} \text{ (GeV/c)} \]
The K2K ‘front detector suite’

Ground Level

Scint. fiber+water target

Lead Glass

Fe range stack

1 kt Water Cherenkov Detector

300m to pion production target
The Water Cherenkov Spectral Measurement

Start with basic reconstructed muon information:

Assuming Q.E. kinematics, make a neutrino spectrum:

Subtract background, correct for efficiencies and acceptance:

Voila!
The MRD: A nearly perfect stability monitor

Neutrino beam aiming

CC–Interaction Rate

Calendar time (1 data point / 5 days)

Calendar time (1 data point / 2 days)
Two Views of a Rather High Energy Event

K2K Fine-Grained Detector (Hall-Side View)

Run 2379 Spill 54330 TRGID 1
100 2 16 7 31 54 0
Nvtx 0

K2K Fine-Grained Detector (Hall-Top View)

Run 2379 Spill 54330 TRGID 1
100 2 16 7 31 54 0
Nvtx 0
Measuring the Backgrounds with 2–Track Events

Neutrino direction

Measured 2nd track

'Δ(θ)'

Expected proton direction in Q.E.

Measured muon direction

Nv99-J101/N4.3XFSieta_x_3h, N(MRD_3D+1L)

Entries: 2218
Mean: 0.6676
RMS: 0.3590

Number of Events

2track-cosθ_zen

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

-1 -0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8 1
π₀ summary (Preliminary)

selection criteria for π₀
- 50t fiducial
- Fully Contained
- 2 rings
- both e-like
- 85MeV/c² < M_{γγ} < 215MeV/c²

selection criteria for μ
- 25t fiducial
- Fully Contained
- Evis > 30MeV
- 1 ring
- μ-like

observed # of π₀ : ~5K
observed # of μ : ~20K

$$\frac{(π₀/μ)_{\text{DATA}}}{(π₀/μ)_{\text{MC}}} = 1.04 \pm 0.02 \pm 0.02 \pm 0.09$$

data stat.  MC stat.  sys.
Data Reduction for SK K2K Events

\[ \Delta t \equiv T_{SK} - T_{KEK} \quad \text{time of flight} \]

56 Contained events in fiducial 22.5ktons
(91 total contained events)

Background \( \approx O(\text{few} \cdot 10^{-3}) \)
Uniformity of Arrival Times

Fine scale timing relative to beam:

Relative timing distribution for events

- Data (box = stat. err.)
- Idealized model (normalized to data)

Selection window

Overall arrival time through all runs

Fully Contained, 22.5kt

POT vs events

KS probability = 43.1%
### # of observed events and expected events

**1999/06-2001/07**

<table>
<thead>
<tr>
<th></th>
<th>Obs.</th>
<th>No Ocsi.</th>
<th>$\Delta m^2 (\times 10^{-3} eV^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>FC</td>
<td>56</td>
<td>80.6 $^{+7.3}_{-8.0}$</td>
<td>52.4</td>
</tr>
<tr>
<td>1-ring</td>
<td>32</td>
<td>48.4±6.7</td>
<td>28.1</td>
</tr>
<tr>
<td>$\mu$-like</td>
<td>30</td>
<td>44.0±6.8</td>
<td>24.4</td>
</tr>
<tr>
<td>e-like</td>
<td>2</td>
<td>4.4±1.7</td>
<td>3.7</td>
</tr>
<tr>
<td>multi ring</td>
<td>24</td>
<td>32.2±5.3</td>
<td>24.3</td>
</tr>
</tbody>
</table>
About those error estimates...

For the front detector (Water Cherenkov) overall flux estimation:
- Stat. error is very small: (< 1/2%).
- Leading systematic terms are from energy scale and background subtraction.  
  Sum of known systematics  \(\pm 5\%\)

For the extrapolation from near measurement to far expectation:
- Error can be estimated two ways:
  MC study only (with monitor inputs)  \(\pm 7\%\)
  Monitor based study (with some MC input)  \(\pm 6\%, -7\%\)
- Leading terms come basically from lack of knowledge of the pion kinematic distribution after production.

For the event rate estimation at SK:
- Leading term is from systematic vertex fit shifts,
- Sum of known systematics  \(\pm 3\%\)

\[\Rightarrow \text{Total estimated error on final prediction:} \]
\[\begin{array}{c}
+9 \% \\
-10 \%
\end{array}\]
$E\nu_{\nu}$ F.C. 22.5kt 1-ring $\mu$-like

no osci.

$\Delta m^2 = 3 \times 10^{-3} \text{eV}^2$
A hypothesis that \textit{a priori} predicts a central value expected to be higher than that of competing scenarios is disfavored at a confidence level given by:

\[
\text{C.L.} \equiv 1 - \int_0^\infty \left( e^{-\lambda} \sum_{i=0}^{N_O} \frac{\lambda^i}{i!} \right) \times P(\lambda) \, d\lambda
\]

\textit{where:}

\(N_O\) is the number observed, and

\[
P(\lambda) \approx \left( \sigma_L \sqrt{2\pi} \right)^{-1} e^{-\frac{1}{2} \left( \frac{\lambda - \mu}{\sigma_L} \right)^2}
\]

for an expectation of \(\mu\) with a lower side error of \(\sigma_L\).

\textbf{This prescription gives a probability of approximately 3\%}
A Simple Probability to Calculate

The “two-tailed” probability for a gaussian distribution with a calculated mean and $\sigma$ can easily be calculated as:

$$1 - \text{erf} \left( \frac{|N_{\text{Obs}} - N_{\text{Exp}}|}{\sqrt{2\sigma}} \right)$$

This is more conservative than the “no-oscillations case” already cited.
Observed/Expected Counts Oscillation Analysis
Gaussian tail hypothesis test

Contour definitions:

- 68%
- 90%
- 99%

Disfavored at 90% CL.

SK Atmospheric
“FC + PC”
Allowed, 99%
Conclusions

- This year’s data are consistent with the previous set and add to its statistical power.
- K2K has gathered sufficient data to begin to explore spectral shape analysis.
- Other physics is being pursued with the near detector data.
- We will more than double our statistics in the next few years and have a full spectral analysis for oscillations.

- The hypothesis of no oscillations is disfavored at approximately the 2σ level.

It works!