Recent Results from the $\mathcal{K}_2\mathcal{K}$ Experiment

Jim Hill

Stonybrook University

Snowmass, Colorado

Zenith angle dependence (Multi-GeV)

\[ \chi^2 (\text{shape}) = 2.8 / 4 \text{ dof} \]
\[ \frac{\text{Up}}{\text{Down}} = 0.93 \pm 0.13 - 0.12 \]
\[ \chi^2 (\text{shape}) = 30 / 4 \text{ dof} \]
\[ \frac{\text{Up}}{\text{Down}} = 0.54 \pm 0.06 - 0.05 \]

(6.2\sigma !)

* Up/Down syst. error for \( \mu \)-like

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

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

[Diagram of the K2K Experiment]
K2K post-construction views

(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
The K2K ‘front detector suite’

Ground Level

Scint. fiber+water target

Lead Glass

Fe range stack

1 kt Water Cherenkov Detector

Neutrino Beam

To Super-Kamiokande

300m to pion production target
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

Measured Event Rates

Calendar time (1 data point / 5 days)

numu-Fe interactions / 5 X10^12 ppp

99Jun 99Nov 00Jan 00Feb 00Mar 00May 00Jun 01Jan 01Feb 01Mar 01Apr

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

Cos ΔΘ

MC (QE+nQE)

MC nQE

Data

Fit z α={(QE+nQE)}

α = 0.128 +/- 0.004
**summary (Preliminary)**

**selection criteria for $\pi^0$**
- 50t fiducial
- Fully Contained
- 2 rings
- both e-like
- $85\text{MeV/c}^2 < M_{\gamma\gamma} < 215\text{MeV/c}^2$

**selection criteria for $\mu$**
- 25t fiducial
- Fully Contained
- Evis $>30\text{MeV}$
- 1 ring
- $\mu$-like

**observed # of $\pi^0$: 4120**
**observed # of $\mu$: 16487**

\[
\frac{(\pi^0/\mu)_{\text{DATA}}}{(\pi^0/\mu)_{\text{MC}}} = 1.03 \pm 0.02 \pm 0.02 \pm 0.09
\]

<table>
<thead>
<tr>
<th>data stat.</th>
<th>MC stat.</th>
<th>sys.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Data Reduction for SK K2K Events

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

Fully Contained Event Analysis

- Event is not a decay electron
- Total PMT charge cut
- Vertex in fid. volume & No OD activity

70 Contained events
(44 in fiducial 22.5ktons)
Background \( \approx \mathcal{O}(\text{few} \cdot 10^{-3}) \)
(Solid dots are events with vertices in the fiducial volume; open are outside.)
**Uniformity of Arrival Times**

**Fine scale timing relative to beam:**

*Relative timing distribution for events*

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

**Overall arrival time through all runs**

*FC*

- *KS probability = 7.1%*
<table>
<thead>
<tr>
<th>18 25.5+4.3</th>
<th>3.5+1.4</th>
<th>2</th>
<th>24</th>
<th>34.9+5.5</th>
<th>26</th>
<th>38.4+5.5</th>
<th>RC 22.5+20</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0±1.8</td>
<td>13.3±3.4</td>
<td>11.6±1.9</td>
<td>19.3±3.5</td>
<td>22.3±3.4</td>
<td>27.4±3.1</td>
<td>41.5±4.7</td>
<td>63.9±6.1</td>
</tr>
</tbody>
</table>

\[ \text{Obs. No. Ophi.} \]

\[ 1999/06-2001/04 \]

# of observed events and expected events
### 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) $+7\%$  
    $-8\%$
  - Monitor based study (with some MC input)  
    $+6\%$  
    $-7\%$
- 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 $\pm 3\%$

$\implies$ Total estimated error on final prediction:

<table>
<thead>
<tr>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+9%$</td>
</tr>
<tr>
<td>$-10%$</td>
</tr>
</tbody>
</table>
$E_{\nu} \ F.C. \ 22.5kt \ 1$-ring $\mu$-like
 Statistical interpretation of a result

A hypothesis that *a priori* predicts a central value expected to be higher than that of competing scenarios is disfavored at a confidence level given by:

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

*where:*

- \(N_O\) is the number observed, and

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

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

This prescription gives a probability of approximately 3%
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!