K2K results

Results of
Total Event Rate &
Spectrum Shape Analysis

K2K collaboration

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K2K Collaboration

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  University of Hawaii, Manoa
Massachusetts Institute of Technology
State University of New York at Stony Brook
  University of Washington at Seattle

Warsaw University
  Solton Institute for Nuclear Study
KEK to Kamioka Neutrino Oscillation Experiment

Super-K (far detector)
50 kton Water
Cherenkov detector

Ev ~ 1.3 GeV
νμ
250 km

12 GeV PS@KEK
- ν beam line
- Beam monitor
- Near detectors
**Principle of K2K**

Fixed distance, direction

(E$_v$\~1.3 GeV, L=250km)

(99% $\nu_\mu$, $\sigma_\tau$\ll$\sigma_\mu$)

prob. = $\sin^2 2\theta \cdot \sin^2 \left(\frac{1.27\Delta m^2 L}{E_v}\right)$

**Observations**
- Reduction of events
- Spectrum distortion

**Goal**
- Does $\nu_\mu$ decrease?
- Does it depend on $E_v$?
- Is it consistent to $\sin^2(1/E_v)$?
- What is $\Delta m^2$?
Bird's Eye Neutrino Beam Line

- Front (Near) Detector
- Pion monitor
- 
- Direction ($\pi \rightarrow \mu$) spectrum, rate
- Direction ($\nu$)

Front detector

- $\nu_{\mu}$

12 GeV PS

- $>5 \times 10^{13}$ ppp
- 2.2 sec/pulse

Target/Double Horn

- $\sim 20 \times$ flux

North Counter Hall

Primary beam line

- 200 m

Decay section ($\pi \rightarrow \mu \nu_{\mu}$)

Pion monitor
Near Detectors at KEK

1kt Water Cherenkov detector (KT)  
Water tube + Scintillation fiber detector (SciFi)  
Muon range detector (MRD)  
Lead glass detector (LG)

 fiducial
25 ton  ~ SK
6 ton  1, 2, >2 tracks
~700 ton  \( \nu \) beam monitor
Pion Monitor: measure \((p_\pi, \theta_\pi)\) distribution

Gas Cherenkov detector: (insensitive to primary protons)

Measure momentum and angular distribution of pions, \(N(p_\pi, \theta_\pi)\) just after the horns. \(p_\pi > 2\)GeV/c

Choice of \(\pi\) Production model and error estimate
Index of refraction: $n_\pi$ threshold $\theta_\pi$

Position of ring: $\theta_\pi$

$p_\pi, \theta_\pi$ gives two C-light peaks

Fit with $\Sigma (w_i \cdot C\text{-light})$

**Pion Monitor Fitting (November)**

![Graphs showing PMT number vs. ADC counts for different measurements](image)

π production

Good agreement with old data. (Cho et.al.)

- Beam MC
- Error assignment
Super-Kamiokande

50,000 ton water Cherenkov detector  (22.5 kton   fiducial volume)
Optically separated INNER and OUTER detector
e-like and $\mu$-like events in Super-Kamiokande

Total rate with low threshold (>30MeV) ~100% efficient for CC
Identification of $\mu$ (1R$\mu$), e (1Re)
Super-K Event selection

\[-0.2 \leq \Delta T \equiv T_{SK} - T_{Spill} - \text{TOF} \leq 1.3 \mu \text{sec}\]

\[\begin{align*}
&\text{GPS} \\
&T_{spill} \\
&T_{SK} \\
&T_{Spill}: \text{Abs. time of spill start} \\
&T_{SK}: \text{Abs. time of SK event} \\
&\text{TOF: 0.83ms (KEK to Kamioka)} \\
&\text{FC: fully contained} \\
&\text{(No activity in Outer Detector)} \\
&\text{FV: 22.5kt Fiducial Volume} \\
&\text{Expected Atm. } \nu \text{ BG} < 10^{-3} \text{ within 1.5} \mu \text{s.}
\end{align*}\]
Summary of K2K results 2001

- Neutrino beam is well under control
  - Beam direction < 1 mrad. ⇔ 3~4 mrad required
  - Stable $E_\mu$ spectrum from $\nu$ interactions
- Accumulated $4.8 \times 10^{19}$ POT @ SK from Jun ’99 to July ’01.
  - No change (obvious reason !)
- # of fully contained events in fiducial volume (FCFV) @ SK
  Observed: 56, Expected with null oscillation 80 (+7.3 -8.0)
  Probability of null oscillation < 3% (F/N, KT fid)

This year

Full error treatment (correlation, etc.)
Re-calibration KT, SciFi, MRD
Rate + Shape
- Null oscillation prob.
- Allowed region
Flow of Neutrino Oscillation Analysis

Observed \((p_\mu, \theta_\mu)\) distributions at Near Detectors
\[\downarrow \nu \text{ Int. Model}\]
Neutrino Spectrum at Near detector \(\phi_{\text{near}}(E\nu),\)
\[\downarrow\]
Far/Near Extrapolation vs \(E\nu\) \(R_{\text{FN}}(E\nu)\)
Neutrino Spectrum w/o oscillation at SK \(\phi_{\text{SK}}(E\nu)\)
\(\phi_{\text{SK}}(E\nu) \otimes \text{Oscillation} \ (\sin^2 2\theta, \Delta m^2) \otimes \text{Int. Model}\)

Prediction
- \(N_{\text{SK}}(\text{exp't})\) : Expected no. of SK events
- \(S_{\text{SK}}(E_{\nu \text{rec}})\) : 1R\(\mu\) \(E_{\text{rec}}\) distribution(shape)

SK observation
- \(N_{\text{SK}}(\text{obs})\)
- 1R\(\mu\) \(E_{\text{rec}}\) distribution

Maximum Likelihood Fit in \((\sin^2 2\theta, \Delta m^2)\)
1R\(\mu\) events in water Cherenkov detector
QE-like events in SciFi

\[ \nu_{\mu} + n \rightarrow \mu^- + p + (E_{\mu}, p_{\mu}) \]  
- **CC QE**
  - \(\sim 100\%\) efficiency for \(N_{SK}\)
  - can reconstruct \(E_{\nu} \leftarrow (\theta_{\mu}, p_{\mu})\)

\[ \nu_{\mu} + n \rightarrow \mu^- + p + \pi^- + (E_{\mu}, p_{\mu}) \]  
- **CC nQE**
  - \(\sim 100\%\) efficiency for \(N_{SK}\)
  - Bkg. for \(E_{\nu}\) measurement

\[ \nu_{\mu} + n \rightarrow \nu + p + \pi^- + \pi^+ \]  
- **NC**
  - \(\sim 40\%\) efficiency for \(N_{SK}\)
QE and nQE in SciFi 2track events

SciFi 2 track $\cos(\Delta \Theta_p)$ distribution

- Data
- MC
- (CCQE)

$>30^\circ$ $<25^\circ$

nQElike QElike
Used data for $\phi_{\text{near}}(E\nu)$

**KT**
- Fully Contained Fiducial Volume (FCFV) events
- No. of events ($E_{\text{vis}} > 100\text{MeV}$)
  - (1) Single $\mu$–1 e events
- 4 sets of ($p_\mu$, $\theta_\mu$) distributions

**SciFi**
- (2) 1-track $\mu$ events
- (3) 2-track QE-like events
- (4) 2-track nonQE-like events

**Pion monitor & Beam simulation**
- $\pi$ distribution in ($p_\pi$, $\theta_\pi$) $\rightarrow$ flux estimate $\phi_{\text{near}}(E\nu)$ w. error

$\nu$ flux $\phi_{\text{near}}(E\nu)$ (8 bins)
$\nu$ interaction model (param. as $n\text{QE}/\text{QE}$ ratio)
CC Quasi Elastic(QE) & Other Processes(nQE)

Not well known

Used Parameters
MA(QE)=1.11 GeV
MA(1π)=1.21 GeV
Coherent π: Marteau et.al.
Multi-π: use hep-ex/0203009

Checked

MA(QE)=1.01-1.11
MA(1p)=1.01-1.51
GRV94-Mod.GRV94

Very small effect on oscillation analysis
Fitting method

\[(p_\mu, \theta_\mu) \rightarrow \phi(E\nu), \text{nQE/QE}\]

\[E\nu \quad \text{QE (MC)} \quad \text{nQE(MC)}\]

- 0-0.5 GeV
- 0.5-0.75 GeV
- 0.75-1.0 GeV
- 1.0-1.5 GeV

MC templates

1kt DATA: \(P_\mu\) vs \(\theta_\mu\) Distribution

Also \((p_\mu, \theta_\mu)\) dist. in SciFi
1track, 2track(QE-like), 2track(nQE-like)

\(\chi^2=227\) for 197 d.o.f.
Fit result of Neutrino Flux at KEK Site
KT \((p_\mu, \theta_\mu)\) distribution using \(\phi_{\text{fit}}, \text{QE/nQE}_{\text{fit}}\)

1kt: \(\mu\)-momentum Distribution (Fid.25t FC 1-Ring \(\mu\)-like)

1kt: \(\mu\)-angular Distribution (Fid.25t FC 1-Ring \(\mu\)-like)
Scifi \( p_\mu, \theta_\mu \) distributions using \( \phi_{fit}, QE/nQE_{fit} \)
Expected $E_{\nu}^{\text{rec}}$ spectrum for $1R\mu$ at SK if no oscillation

Initial $1R\mu$ spectrum w/ all syst. err. incl. E-scale

\[ E_{\nu}^{\text{rec}} = \frac{m_N E_\mu - m_\mu^2 / 2}{m_N - E_\mu + p_\mu \cos \theta_\mu} \]
Oscillation analysis

Neutrino flux @SK ∝ Int. Model ∝ Oscillation \( (\sin^2 2\theta, \Delta m^2) \)

Separated into No of event & Renormalized \( E_{\text{rec}} \) shape

- \( N_{\text{SK}}(\text{exp’t}) \): Expected no. of SK events
- \( S_{\text{SK}}(E_{\nu \text{rec}}) \): 1R\( \mu \) \( E_{\text{rec}} \) distribution(shape)

SK observation
- Observed no. of events in FCFV \( N_{\text{SK}}(\text{obs}, >30\text{MeV}) \)
- 1R\( \mu \) events \( E_{\nu \text{rec}} \) spectrum shape

Maximum Likelihood Fit in \( (\sin^2 2\theta, \Delta m^2) \)

1. Rejection of Null oscillation hypothesis
2. Contour of allowed region
   - Number of events observed/expected
   - Obs./exp. neutrino energy spectrum shape
Delivered Protons on Target (POT)

Accumulated POT ($10^{18}$)

200kA

250kA

5.6x$10^{19}$ POT (July 12, 2001)

4.8x$10^{19}$ POT for Analysis
Data set

• Data sets
  • **June 99-July 01** FCFV, Evis>30 MeV
    • total number of events
    • 56 events observed
  • **Nov 99-July 01** 1Rμ events
    • $E_{\nu}^{\text{rec}}$ shape
    • 29 events observed

• Running condition
  • June 99
    • Target=2 cmφ Horn current=200kA (~6.5% of POT)
    • Larger systematic errors in ‘near’ measurements
  • Nov 99~July 01
    • Target=3cmφ Horn current=250kA
    • Full analysis of systematic errors
Systematic parameters

\[ f = (f_\Phi, f_{nQE}, f_{F/N}, f_{ESK}, f_{Esk}, f_{\text{n6}}, f_{n11}) \]

- \( f_\Phi \): Flux (8 energy bins)
- \( f_{nQE} \): QE/nQE ratio
- \( f_{F/N} \): Far/Near ratio
- \( f_{ESK} \): SK reconstruction (Fid, PID, Nring)
- \( f_{Esk} \): SK energy scale
- \( f_{\text{n6}} \): Norm. for June 99
- \( f_{n11} \): Norm. Nov 99 ~ Jul 01
Likelihood

\[ L_{tot} = L_{\text{norm}}(f) \cdot L_{\text{shape}}(f) \cdot L_{\text{syst}}(f) \]

Normalization term

\[ L_{\text{norm}} = \text{Poisson}(N_{\text{obs}}, N_{\text{exp}}(f)) \]

Shape term for FCFV 1Rμ

\[ L_{\text{shape}} \equiv \prod_{i=1}^{29} P((f_{\text{Esk}} \cdot E_i), \Delta m^2, \sin^2 2\theta, f) \]

Systematic parameter constraint term

\[ L_{\text{syst}} \equiv \exp\left( -\Delta f_{\Phi,nQE}^{T} \cdot M_{FD}^{-1} \cdot \Delta f_{\Phi,nQE} / 2 \right) \cdot \cdots \cdot \exp\left( -f_{n6}^2 / 2\sigma_{n6}^2 \right) \exp\left( -f_{n11}^2 / 2\sigma_{n11}^2 \right) \exp\left( -\Delta f_{\text{Esk}}^2 / 2\sigma_{\text{Esk}}^2 \right) \]

\[ N_{\text{obs}} = 56 \quad N_{\text{exp}} = 80.1 \pm 6.2 \pm 5.4 \]
3d plots of $\Delta \ln L$ for shape+norm & definition of L

$L$ at $(\Delta m^2, \sin^2 2\theta)$

- **method-1**
  Maximize $L$ by adjusting systematic parameters.

- **method-2**
  The MC generation of the systematic parameters & $L$=the mean values.
## Null Oscillation Probability

<table>
<thead>
<tr>
<th></th>
<th>method-1</th>
<th>method-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{SK}}$ only</td>
<td>1.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Shape only</td>
<td>15.7%</td>
<td>14.3%</td>
</tr>
<tr>
<td>$N_{\text{SK}}+\text{Shape}$</td>
<td>0.7%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

### Best fit ($\sin^2 2\theta , \Delta m^2$)

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<thead>
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</thead>
<tbody>
<tr>
<td>Shape only ( (\text{Allowing unphys.}) )</td>
<td>((1.0, \ 3.0\times10^{-3}\text{eV}^2))</td>
<td>((1.0, \ 3.2\times10^{-3}\text{eV}^2))</td>
</tr>
<tr>
<td>$N_{\text{SK}}+\text{Shape}$ ( (\text{Allowing unphys.}) )</td>
<td>((1.0, \ 2.8\times10^{-3}\text{eV}^2))</td>
<td>((1.0, \ 2.7\times10^{-3}\text{eV}^2))</td>
</tr>
</tbody>
</table>
Allowed regions

Total no. of Events only

Spectrum Shape only

Shape and $N_{SK}$ +Shape indicate consistent parameter region
Is best fit point also for $1R\mu$ shape & Nsk?

Best fit point ($\sin^22\theta, \Delta m^2$)

**Method 1**

KS test prob. (shape) = 79%
$N_{SK}$ prediction = 54 (obs 56)

**Method 2** KS-test

$N_{SK}$ 82%
shape 93%
$N_{SK}+$shape 50%
Comparison with diff. L & ν interaction model

Reasonable agreement btw definition of L

Change of ν interaction model has small effect
Comparison with SK atm ν observation

Allowed Region - Total Number + Shape

Super-K 1489 day prelim.

K2K Preliminary
1999-2001 Data
$\Delta m^2$ for $\sin^2 2\theta = 1$
K2K Allowed region (Shape+Norm)

$1.5 \sim 3.9 \times 10^{-3} \text{eV}^2$

@ $\sin^2 2\theta = 1$

@ 90% CL
Conclusion

• K2K Oscillation analysis on June99 ~July01 data
  – Full error analysis

1. Null oscillation probability is less than 1%
2. Both SK rate reduction and $E_v^{\text{rec}}$ shape indicate consistent oscillation parameters region
3. $\Delta m^2=1.5\sim3.9\times10^{-3}\text{eV}^2$ for $\sin^22\theta=1$ @ 90% CL
4. $\sin^22\theta$, $\Delta m^2$ are consistent with atmospheric neutrino results

The best fit point ($\sin^22\theta=1.0$, $\Delta m^2=2.8\times10^{-3}$ eV$^2$)

cf. Atmospheric neutrino results

$\Delta m^2=(1.6\sim3.8)\times10^{-3}$ eV$^2$ for $\sin^22\theta=1.0$

best fit ($\sin^22\theta=1.0$, $\Delta m^2=2.5\times10^{-3}$ eV$^2$)

• Data taking will resume within this year