Re-evaluation of the T2KK physics potential with simulations including backgrounds

NuFact09 @ IIT
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N. Okamura (KEK)

Based on JHEP07(2009)031
K. Hagiwara, NO

T2KK??

- T2KK: one of the extension of the T2K exp.
- Neutrino beam of the T2K experiment automatically reaches south part of Korea.
- When we observe neutrino beam from J-PARC at Korea, what we can do??

K. Hagiwara
K. Hagiwara, K. Senda, NO,
K. Hagiwara, NO,

hep-ph/0410229
JHEP 01 022 (2008) and ref. there in
Digest of our previous work

The best combination of OAB for mass hierarchy determination is SK(295km):3.0° (NBB) and Kr(1000km):0.5°(WBB) with $5 \times 10^{21}$ POT exposure, 22.5kton@SK and 100kton@Korea, and include the results from “reactor exp.”

\[ \Delta \chi^2 = 22 \text{ (input : normal)} \]

CP phase

\[ 1\sigma \sim \pm 30^\circ \text{ w/o anti-neutrino} \]

NBB for SK $L\sim O(2)$km
WBB for Korea $L\sim O(3)$km

motivation

<table>
<thead>
<tr>
<th></th>
<th>Previous work</th>
<th>this work</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>CCQE only</td>
<td>CCQE + $\Delta$-Res.</td>
</tr>
<tr>
<td>NC</td>
<td>no</td>
<td>$\pi^0$ background</td>
</tr>
<tr>
<td>binning energy</td>
<td>Neutrino</td>
<td>Reconstructed</td>
</tr>
<tr>
<td>$\rho$ (SK/Korea)</td>
<td>2.8/3.0 (g/cm$^3$)</td>
<td>2.6/3.0 (g/cm$^3$)</td>
</tr>
<tr>
<td>error of $\rho$</td>
<td>3%</td>
<td>6%</td>
</tr>
<tr>
<td>resolution</td>
<td>no</td>
<td>include</td>
</tr>
<tr>
<td>miss ID ($\mu \rightarrow e$)</td>
<td>no</td>
<td>1%($\pm$1%)</td>
</tr>
<tr>
<td>efficiency ($e$)</td>
<td>100%</td>
<td>90%($\pm$5%)</td>
</tr>
<tr>
<td>efficiency($\mu$)</td>
<td>100%</td>
<td>100%(-1%)</td>
</tr>
</tbody>
</table>

We study the robustness of the results, best combination, hierarchy ($\Delta \chi^2$), CP phase ($\Delta \delta_{MNS}$).
CC

1. MC
2. Resolution
3. Smearing function

event selection

- Selection criteria
  - only one $\mu (e)$
  - $|p| > 200\text{MeV}$
  - no high energy $\pi^+/\pi^-$
  - $|p| < 200\text{MeV}$
  - no high energy $\gamma$
  - $|p| < 30\text{MeV}$
  - no $\pi^0/K_s/K^+/K^-$
Resolution

- We include the resolution effect to determine the reconstruct energy.

<table>
<thead>
<tr>
<th></th>
<th>$\delta p/p$</th>
<th>$\delta \theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>1.7+0.7/$\sqrt{p}$ %</td>
<td>1.8°</td>
</tr>
<tr>
<td>$e$</td>
<td>0.6+2.6/$\sqrt{p}$ %</td>
<td>3.0°</td>
</tr>
</tbody>
</table>

(from SK)

Blue : w/o resolution
Red : w/ resolution

Smearing functions

For $E_v \rightarrow E_{\text{rec}}$ conversion

- CCQE(RED) : 3 Gaussians ($E_v$ = 0.4-6.0GeV)
- Resonance (Blue) : 3 or 4 Gaussians ($E_v$ = 0.7-1.2, 1.2-6.0GeV)
- Normalized for each functions.

- ●, ◆ : MC by nuance
- Lines : smearing function

Full parameterizations in paper.
NC

1. MC
2. Event selection

Event selection

- Selection criteria
  - only one $\pi^0$
  - no $\mu/e$
  - no high energy $\pi^0/\pi^-$
    - $|p| < 200$MeV
  - no high energy $\gamma$
    - $|p| < 30$MeV
  - no $Ks/K^+/K^-$

- 0.5° OAB
  - 480 events at 0.2-0.4GeV
  - 300 events at 0.4-0.6GeV

nuance Ver.3.504 (Apr/25,2006)
D. Casper (UC.Irvine)
\( \pi^0 \) event cut

- \( \pi^0 (\gamma \gamma) \) sometimes seems an “e-like” event.
- energy ratio (\( E_1 > E_2 \))
  \[ E_2 / (E_1 + E_2) < 0.2 : 100\% \text{ missed} \]
- opening angle (\( \cos \theta_{\gamma\gamma} \))
  \[ \cos \theta_{\gamma\gamma} > \cos 17^\circ = 0.956 \]

\[
f \left( p_x, \cos \hat{\theta} \right) = 1 - \left( \frac{E_2 / (E_1 + E_2) - 0.2}{0.3} \right)^{0.5} \left( \frac{\cos \theta_{\gamma\gamma} - 1.0}{\cos 17 - 1.0} \right)^{1.5}
\]

\[
P_{\pi^0} \left( |p_\pi| \right) = \int_0^1 F \left( p_x, \cos \hat{\theta} \right) d \cos \hat{\theta}
\]

\[
F \left( p_x, \cos \hat{\theta} \right) = \Theta \left( 0.2 - E_2 / (E_1 + E_2) \right)
\]

\[
+ f \left( p_x, \cos \hat{\theta} \right) \cdot \Theta \left( E_2 / (E_1 + E_2) - 0.2 \right) \cdot \Theta \left( \cos \theta_{\gamma\gamma} - \cos 17 \right)
\]
TYPICAL EVENTS

There is a difference between hierarchies on $e$-like event
Typical events at SK

The difference between $\mu$-like events can be compensated by $\delta m^2_{13}$. 

NUMERICAL ANALYSIS
**Condition**

- **fiducial volume** (efficiency: $\epsilon:90\% \ \mu:100\%$)
  - SK : 22.5 kton
  - Korea : 100 kton
- **exposure**
  - $5 \times 10^{21}$ POT
  - no anti-neutrino phase
- **base-line and off-axis**
  - SK : $L=295\text{km}$ with $\theta=2.5^\circ$ or $3.0^\circ$
  - Korea: $L=1000-1200 \text{ km}$ with $\theta=(0.5^\circ \sim 3.0^\circ) / 0.5^\circ \text{ step}$
  - Because of geometry, $0.5^\circ$ OAB cannot reach Korea when $2.5^\circ$ OAB for SK.

**Input and systematic**

- **solar**
  - $\sin^22\theta = 0.83 \pm 0.07$, $\delta m^2 = (8.2 \pm 0.6) \times 10^{-5} \text{ eV}^2$
- **atmospheric**
  - $\sin^22\theta = 1.00$, $\delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$
- **matter density (systematic error 6%)**
  - $\rho = 2.6 / 3.0 \ (\text{g/cm}^3) \ (\text{SK/Korea})$
- **Systematic errors**
  - flux normalization (3%) (each flavor to SK/Kr)
  - fiducial volume (3%) (SK / Kr)
  - CCQE $\sigma$ (3%) ($\nu/\overline{\nu}$)
  - Resonance (20%) ($\nu/\overline{\nu}$)
  - $\pi^0$ (50%) ($\nu$)
  - efficiency ($\mu:100-1\%, \epsilon:90\pm5\%$)
  - miss PID (1±1%)

#total:26
The best combination is still $\text{SK}(3.0) + Kr(0.5) L=1000\text{km}$

$\Delta \chi^2=13$ (input : normal)

$\Delta \chi^2=11$ (input : inverted)

Contribution to $\Delta \chi^2$ (normal)

- Previous Setup 22.9
- matter density (SK) 0.5 positive
- resonance 2.7
density error -0.6
miss ID ($\mu$-$e$) -1.0
reconstruction -2.3
efficiency ($e$) -2.3
$P^{\mu,e}$ background -6.5

$\sin^2 \theta^\text{RCT}=0.1, \delta^\text{MNS}=0.0$

Reactor experiments helps T2KK to solve the degeneracy.
1σ region is changed from ±30° to ±45°
3σ region is not closed even if sin²θ₁₃=0.10.
There appears a shadow island for sin²θ₁₃=0.04, covers large area.
These feature common for the other CP phases.

summary

<table>
<thead>
<tr>
<th>hierarchy</th>
<th>CP phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC (Δ res.)</td>
<td><img src="image" alt="positive" /> negative <img src="image" alt="negative" /></td>
</tr>
<tr>
<td>NC(π⁰)</td>
<td>negative <img src="image" alt="negative" /> negative <img src="image" alt="negative" /></td>
</tr>
</tbody>
</table>

The others, reconstruction, matter profile, and so on, do not change the results drastically.

“3.0 at SK and 0.5 at 1000km” is still the best.

Δχ²  23 → 13 (input : normal)
Δδ_MNS  ±30° → ±45° (3σ → 2σ)