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

NuFact09 @ IIT

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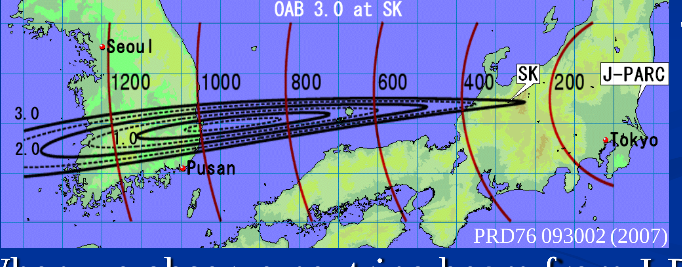
N.Okamura (KEK)

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.



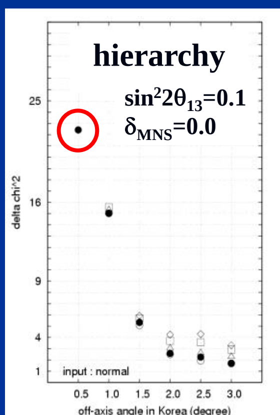
3.0°@SK

- When we observe neutrino beam from J-PARC at Korea, what we can do??

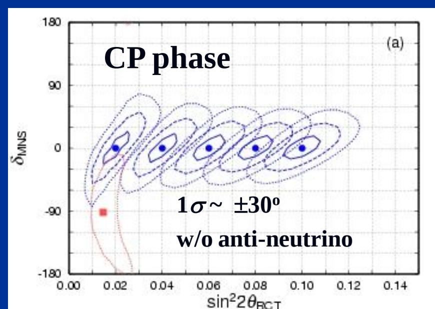
K.Hagiwara	hep-ph/0410229
K.Hagiwara, K.Senda, NO,	PLB637 266 (2006), PRD76 093002 (2007)
K.Hagiwara, NO,	JHEP01 022 (2008) and ref. there in

Digest of our previous work

The best combination of OAB for mass hierarchy determination is
SK(295km):3.0^o (NBB) and Kr(1000km):0.5^o(WBB)
with $5x10^{21}$POT exposure, 22.5kton@SK and 100kton@Korea,
and include the results from "reactor exp."



$\Delta\chi 2$ = 22 (input : normal)



NBB for SK L~O(2)km
WBB for Korea L~O(3)km

motivation

	Previous work	this work
CC	CCQE only	CCQE + Δ-Res.
NC	no	π^0 background
binning energy	Neutrino	Reconstructed
ρ (SK/Korea)	2.8/3.0 (g/cm^3)	2.6/3.0 (g/cm^3)
error of ρ	3%	6%
resolution	no	include
miss ID ($\mu \rightarrow e$)	no	1%(±1%)
efficiency (e)	100%	90%(±5%)
efficiency(μ)	100%	100%(-1%)

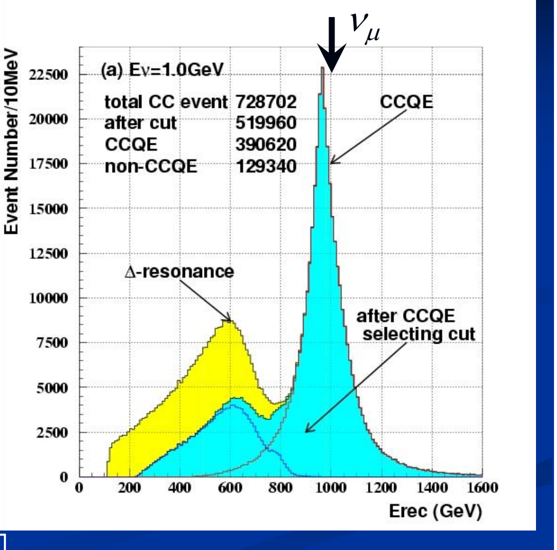
We study the robustness of the results,
best combination, hierarchy ($\Delta\chi 2$), CP phase ($\Delta\delta_{MNS}$).

CC

1. MC
2. Resolution
3. Smearing function

event selection

- Selection criteria
  - only one μ (e)
    $|p| > 200$MeV
  - no high energy π^+/π^-
    $|p| < 200$MeV
  - no high energy γ
    $|p| < 30$MeV
  - no $\pi^0/Ks/K^+/K^-$



nuance Ver.3.504 (Apr/25,2006)
D. Casper (UC.Irvine)

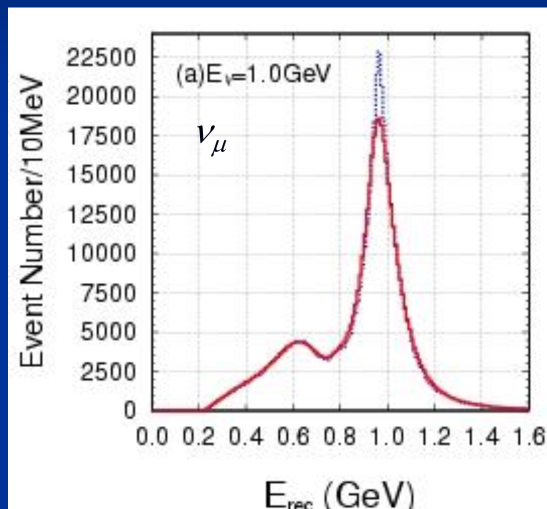
Resolution

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

	$\delta p/p$	$\delta\theta$
μ	$1.7+0.7/\sqrt{p}$ %	1.8°
e	$0.6+2.6/\sqrt{p}$ %	3.0°

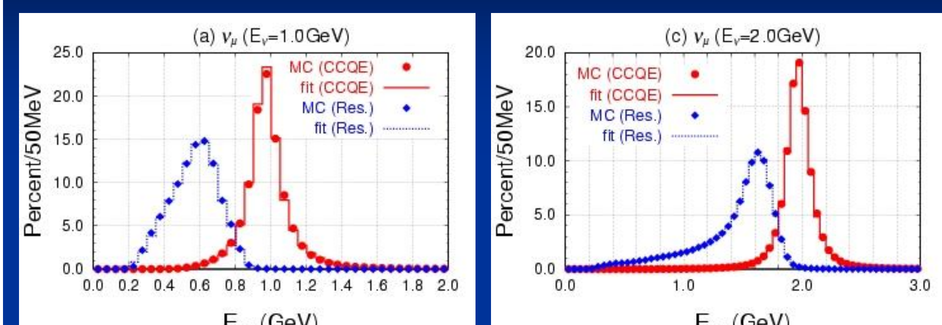
(from SK)

Blue : w/o resolution
Red : w/ resolution



Smearing functions

For $E_\nu \rightarrow E_{rec}$ conversion



- CCQE(RED) : 3 Gaussians (E_ν=0.4-6.0GeV)
- Resonance (Blue) : 3 or 4 Gaussians (E_ν=0.7-1.2, 1.2-6.0GeV)
- Normalized for each functions.
  - ●, ◆: MC by nuance
  - Lines : smearing function

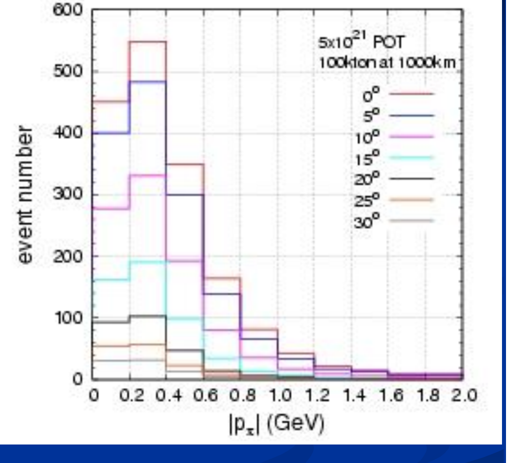
Full parameterizations in paper.

NC

1. MC
2. Event selection

event selection

- Selection criteria
  - only one π^0
  - no-μ / e
  - no high energy π^+/π^-
    $|p| < 200$MeV
  - no high energy γ
    $|p| < 30$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)

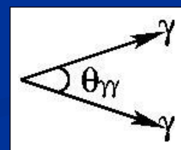
π^0 event cut

- π^0 ($\gamma\gamma$) sometimes seems an "e-like" event.
  - energy ratio ($E_1 > E_2$)

    $E_2/(E_1+E_2) < 0.2$: 100% missed

  - opening angle ($\cos\theta_{\gamma\gamma}$)

    $\cos\theta_{\gamma\gamma} > \cos 17^{o} = 0.956$



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

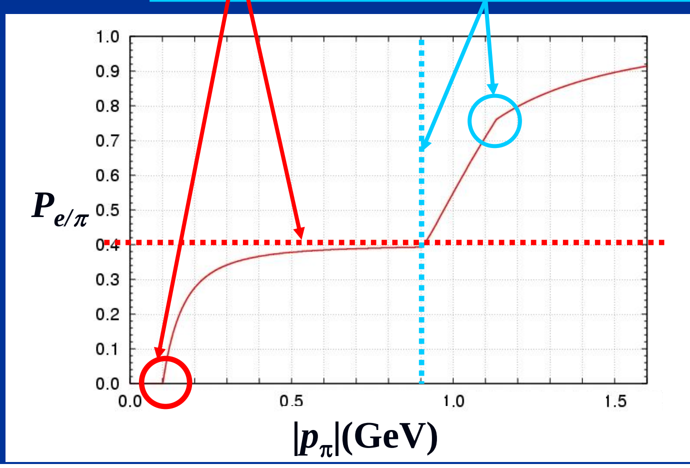
$$P_{e/\pi}\left(|p_\pi|\right) = \int_0^1 F\left(|p_\pi|, \cos\hat{\theta}\right) d\cos\hat{\theta}$$

$$F\left(|p_\pi|, \cos\hat{\theta}\right) = \Theta\left(0.2 - E_2/(E_1+E_2)\right) + f\left(|p_\pi|, \cos\hat{\theta}\right)\cdot\Theta\left(E_2/(E_1+E_2) - 0.2\right)\cdot\Theta\left(\cos\theta_{\gamma\gamma} - \cos 17\right)$$

$P_{e/\pi}(|p_\pi|)$

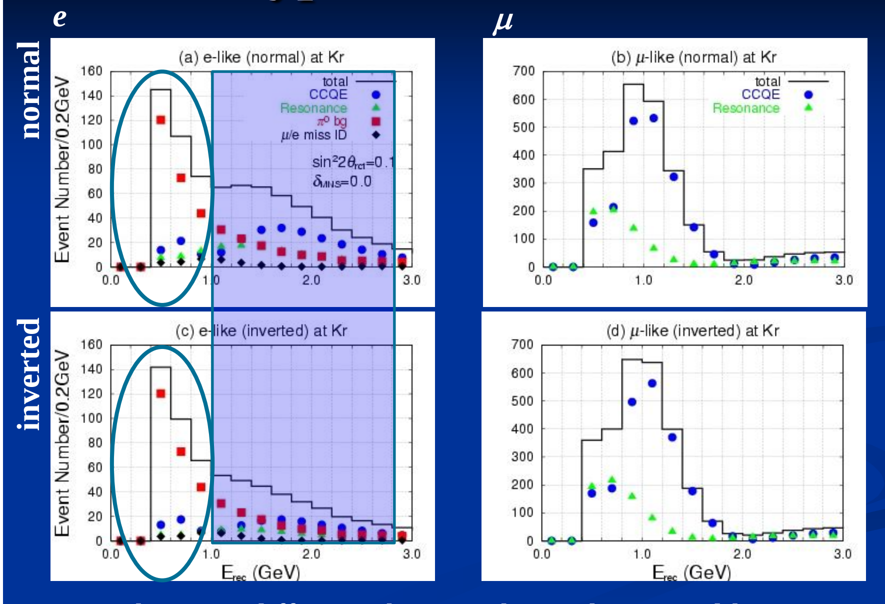
$$P_{e/\pi}\left(|p_\pi|\right) = \int_0^1 F\left(|p_\pi|, \cos\hat{\theta}\right) d\cos\hat{\theta}$$

$$F\left(|p_\pi|, \cos\hat{\theta}\right) = \Theta\left(0.2 - E_2/(E_1+E_2)\right) + f\left(|p_\pi|, \cos\hat{\theta}\right)\cdot\Theta\left(E_2/(E_1+E_2) - 0.2\right)\cdot\Theta\left(\cos\theta_{\gamma\gamma} - \cos 17\right)$$



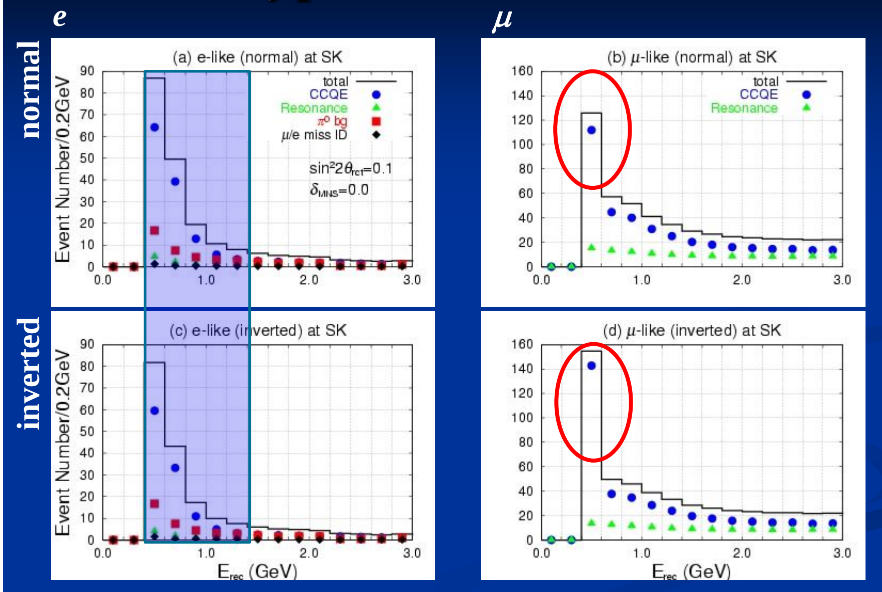
TYPICAL EVENTS

Typical events at Kr



There is a difference between hierarchies on *e*-like event

Typical events at SK



The difference between μ-like events can be compensated by δm^2_{13}

NUMERICAL ANALYSIS

Condition

- **fiducial volume** (efficiency: e:90% μ:100%)
  - SK : 22.5 kton
  - Korea : 100 kton
- **exposure**
  - 5 x 10^{21} POT
  - no anti-neutrino phase
- **base-line and off-axis**
  - SK : L=295km with θ=2.5º or 3.0º
  - Korea: L=1000-1200 km with θ=(0.5º ~ 3.0º) / 0.5º step
  - Because of geometry, 0.5º OAB cannot reach Korea when 2.5º OAB for SK.

Input and systematic

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

#total:26

χ^2 -rule of the game-

$$\chi^2 = \sum_{\substack{\text{bin} \\ \alpha = e,\mu}} \left(\frac{\left(N_\alpha^i\right)^{\text{fit}} - \left(N_\alpha^i\right)^{\text{input}}}{\sqrt{\left(N_\alpha^i\right)^{\text{input}}}} \right)^2$$

$$+ \sum_{\nu,\bar{\nu}} \left\{ \left(\frac{f_{\nu_\alpha}^{\text{CCQE}} - 1.0}{0.03} \right)^2 + \left(\frac{f_{\nu_\alpha}^{\text{Res}} - 1.0}{0.10} \right)^2 \right\} + \left(\frac{f^{\pi} - 1.0}{0.50} \right)^2 + \left(\frac{P_{\mu/e} - 0.01}{0.01} \right)^2$$

$$+ \sum_{\text{SK,Kr}} \left\{ \left(\frac{f_\rho - 1.0}{0.06} \right)^2 + \left(\frac{f_V^{\text{SK/Kr}} - 1.0}{0.03} \right)^2 + \left(\frac{f_{\nu_\mu}^{\text{flux}} - 1.0}{0.03} \right)^2 \right\} + \left(\frac{\varepsilon_\mu - 1.0}{0.01} \right)^2 + \left(\frac{\varepsilon_e - 0.9}{0.05} \right)^2$$

$$+ \left(\frac{\left(m_2^2 - m_1^2\right)^{\text{fit}} - 8.2\times 10^{-5}\left(\text{eV}^2\right)}{0.6\times 10^{-5}\left(\text{eV}^2\right)} \right)^2 + \left(\frac{\left(\sin^2 2\theta_{\text{sun}}\right)^{\text{fit}} - 0.83}{0.07} \right)^2$$

$$+ \left(\frac{\left(\sin^2 2\theta_{\text{rct}}\right)^{\text{fit}} - \left(\sin^2 2\theta_{\text{rct}}\right)^{\text{input}}}{0.01} \right)^2$$

statistics

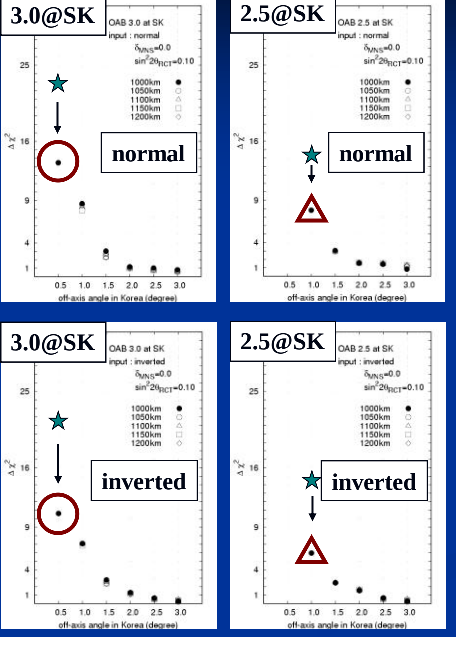
systematic

input

expected error of reactor exp.

Reactor experiments helps T2KK to solve the degeneracy.

Results



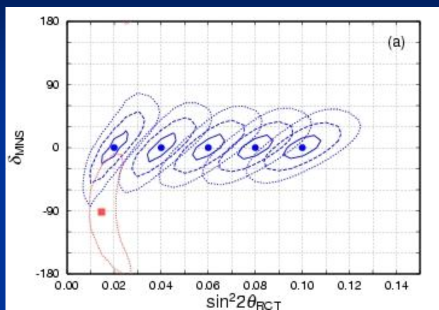
- The best combination is still SK(3.0) ＋Kr(0.5) L=1000km
  - $\Delta\chi 2$=13 (input : normal)
  - $\Delta\chi 2$=11 (input : inverted)
- Contribution to $\Delta\chi 2$ (normal)

Previous Setup	22.9	
matter density (SK)	0.5	positive
resonance	2.7	positive
density error	-0.6	negative
miss ID (μ-e)	-1.0	negative
reconstruction	-2.3	negative
efficiency (e)	-2.3	negative
π^0 background	-6.5	negative
total	13.4	

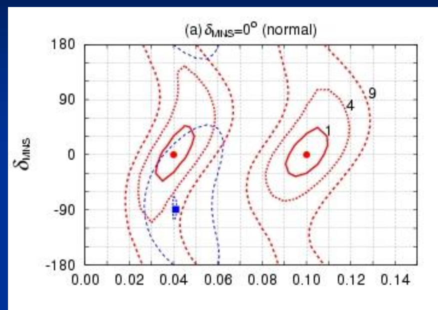
$\sin^2 2\theta_{RCT}$=0.1, δ_{MNS}=0.0

CP phase

Previous Results



This Results



- 1σ region is changed from ±30° to ±45°
- 3σ region is not closed even if $\sin^2 2\theta_{13}=0.10$.
- There appears a shadow island for $\sin^2 2\theta_{13}=0.04$, covers large area.
- These feature common for the other CP phases.

summary

	hierarchy	CP phase
CC (Δ res.)	positive	negative
NC(π^0)	negative	negative

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.

$\Delta\chi 2$	23 → 13	(input : normal)
	21 → 11	(input : inverted)
$\Delta\delta_{MNS}$	±30° → ±45°	($3\sigma \rightarrow 2\sigma$)