Toward realistic evaluation of the T2KK physics potential

Preliminary

T2KK07 @ Univ. of Tokyo
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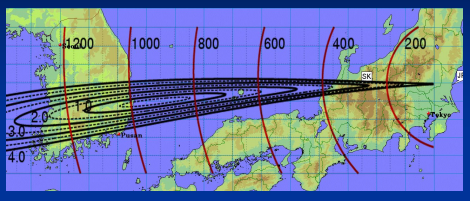
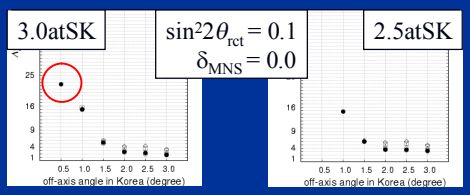
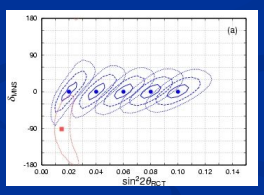
Digest of our previous work

Neutrino beam of T2K automatically reaches Korea.



- 22.5 kton at Kamioka
- 100 kton at Korea
- 5x10^{21}POT exposure
- include the "reactor exp."





- 3.0 OAB at SK
- 0.5 OAB at Korea (1000km)
- $\Delta\chi 2 = 22$ (input : normal)

- $1\sigma \sim \pm 30^{o}$
- w/o anti-neutrino

motivation

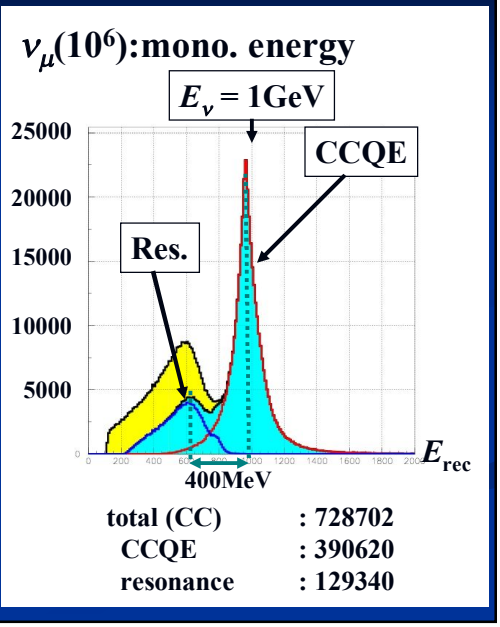
	previous work	this work
CC	CCQE only	CCQE + Δ-Res.
NC	no	π^0 background
binning energy	Neutrino	Reconstructed
ρ (SK/Kr)	2.8/3.0 (g/cm^3)	2.6/3.0 (g/cm^3)
error of ρ	3%	6%
miss ID ($\mu \rightarrow e$)	no	1%
efficiency (e)	100%	90%

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

event selection

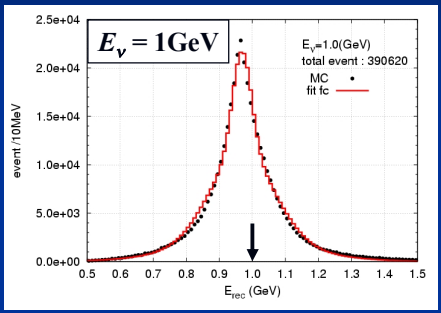
- only one μ (e)
  $|p| > 200$MeV
- no high energy π^+/π^-
  $|p| < 200$MeV
- no high energy γ
  $|p| < 30$MeV
- no π^0/Ks/K^+/K^-

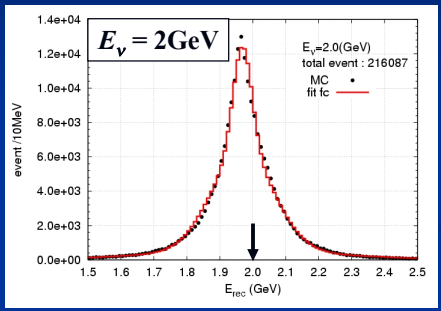
nuance Ver.3.504 (Apr/25,2006)
D. Casper (UC.Irvine)



CCQE mode

For $E_\nu \rightarrow E_{\mathrm{rec}}$ conversion : fit function





$$f(E_\nu) = A\{G(E_0,\sigma_1) + r_2 G(E_0,\sigma_2) + r_3 G(E_0,\sigma_3)\}$$

$$G(E_0,\sigma_i) = \exp\left(-(E-E_0)^2/2\sigma_i^2\right)$$

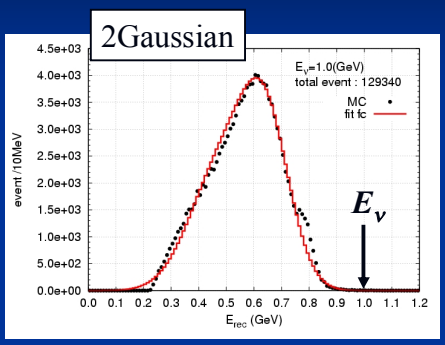
E_0, σ_i, r_i : function of E_ν

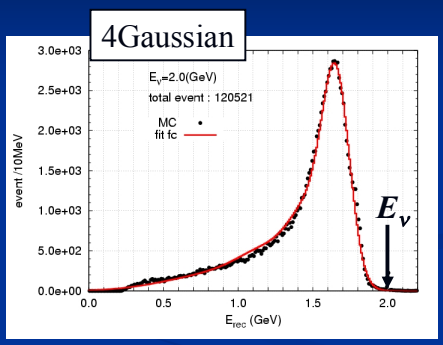
A : normalization factor

coverage: E_ν=0.4 – 6.0GeV

Resonance mode

For $E_\nu \rightarrow E_{\mathrm{rec}}$ conversion : fit function





$$f(E_\nu) = A\{G(E_1,\sigma_1) + r_2 G(E_2,\sigma_2) + r_3 G(E_3,\sigma_3) + r_4 G(E_4,\sigma_4)\}$$

$$G(E_i,\sigma_i) = \exp\left(-(E-E_i)^2/2\sigma_i^2\right)$$

E_i, σ_i, r_i : function of E_ν

A : normalization factor

#G depends on the E_ν

coverage: E_ν=0.7 – 6.0GeV

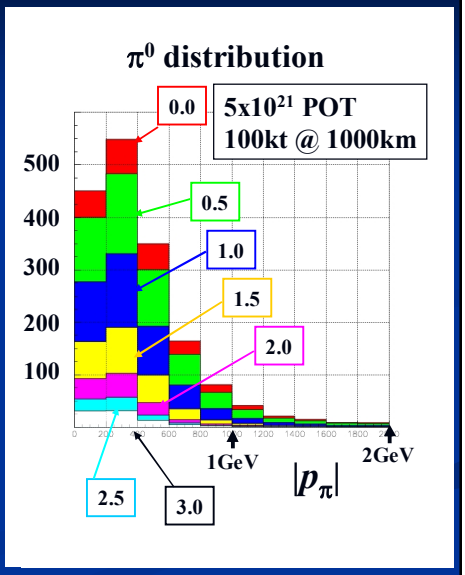
NC

- π^0 event

event selection

- 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 event at 0.2-0.4GeV
  - 300 event at 0.4-0.6GeV

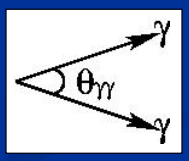


π^0 event cut

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

    $E_2/(E_1+E_2) < 0.2$: 100% missed
  - opening angle ($\cos\theta_{\gamma\gamma}$)

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



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

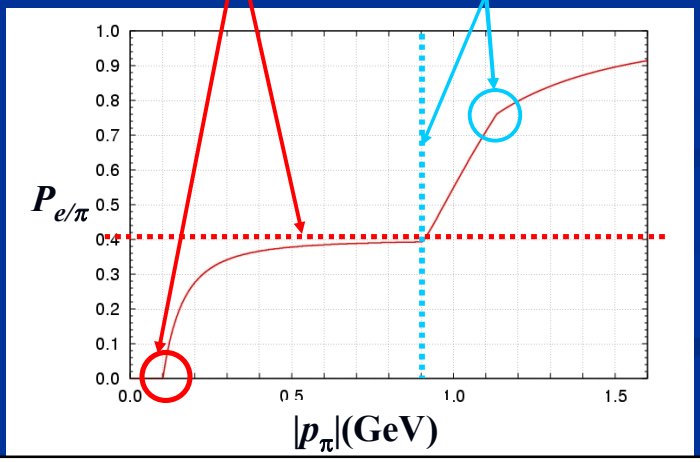
$$P_{e/\pi}\left(|p_\pi|\right)=\int_0^1 F\left(|p_\pi|,\cos\hat{\theta}\right)d\cos\hat{\theta}$$

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

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

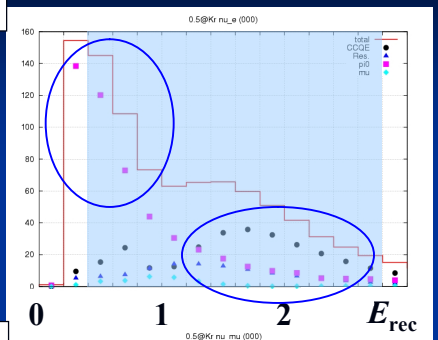
$$P_{e/\pi}\left(|p_\pi|\right)=\int_0^1 F\left(|p_\pi|,\cos\hat{\theta}\right)d\cos\hat{\theta}$$

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

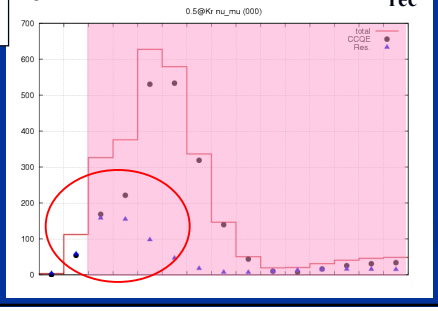


events at Korea

e



μ

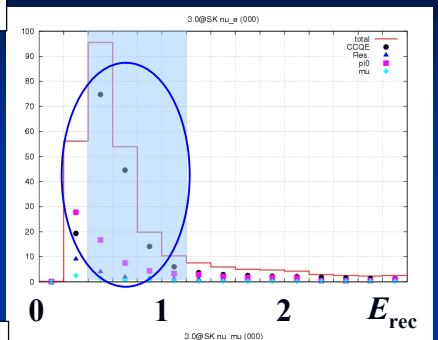


- e
  - π^0 dominates at low energy (E_{rec}<1GeV)
  - CCQE event is larger than the others
  - E_{rec}=0.4-2.8GeV
- μ
  - Almost CCQE
  - Resonant mode is comparable at low energy
  - E_{rec}=0.4-5.0GeV

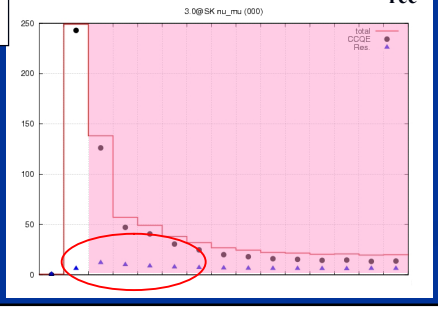
$\sin^2 2\theta_{RCT}$=0.1, δ_{MNS}=0.0

events at SK

e



μ



- e
  - CCQE event is dominant
  - E_{rec}=0.4-1.2GeV
- μ
  - Event from resonance is smaller.
  - E_{rec}=0.4-5.0GeV

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

$\Delta\chi 2$

- Best combination
  - mass hierarchy
  - CP phase ($\Delta\delta_{MNS}$)
- Effect
  - π^0, resonance mode

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**
  - $\sin^2 2\theta = 1.00 \Leftrightarrow 0.96$, $\delta m^2 = 2.5 \times 10^{-3}$ eV^2
- **matter density** (uncertainty 6%)
  - $\rho = 2.6 / 3.0$ (g/cm^3) (SK/Korea)

- **Systematic**
  - flux normalization (3%) (ν_μ for SK/Korea)
  - fiducial volume (3%) (SK / Korea)
  - CCQE σ (3%) ($\nu/\bar{\nu}$)
  - Resonance (10%) ($\nu/\bar{\nu}$)
  - π^0 (30%) ($\nu=\bar{\nu}$)

#total:17

χ^2 -rule of the game-

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

statistics

systematic

$$+ \sum_{\nu,\nu} \left\{ \left(\frac{f_{\nu_\alpha}^{\text{CCQE}} - 1.0}{0.03} \right)^2 + \left(\frac{f_{\nu_\alpha}^{\text{Res}} - 1.0}{0.10} \right)^2 \right\} + \left(\frac{f^{\pi} - 1.0}{0.30} \right)^2$$

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

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

input

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

expected error of reactor exp.

Reactor experiments helps T2KK to solve the degeneracy.

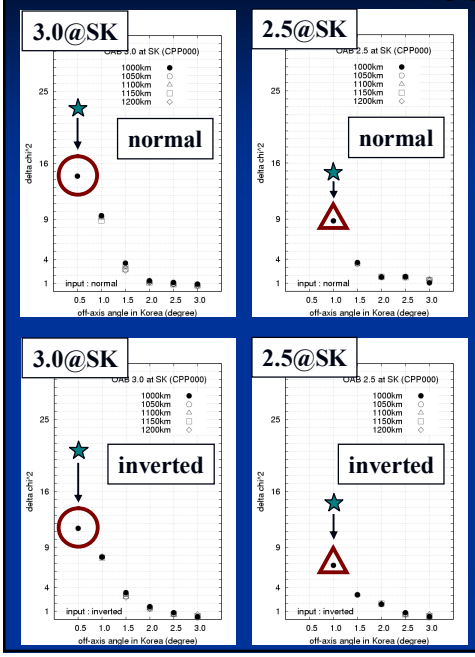
Condition

- **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=2.5° or 3.0°
  - KR: L=1000-1200 km with θ=(0.5° ~ 3.0°) / 0.5° step
- **Previous results for mass hierarchy**
  - 3.0@SK and 0.5@Kr (L=1000km) is the best combination

    $\Delta\chi 2 = 22$, input : normal, $\sin^2 2\theta_{\text{rct}} = 0.10$, $\delta_{\text{MNS}}=0.0$

    $\Delta\chi 2 = 21$, input : inverted, $\sin^2 2\theta_{\text{rct}} = 0.10$, $\delta_{\text{MNS}}=0.0$

Results

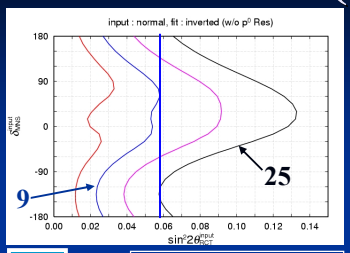


- Best combination is still SK(3.0) and Kr(0.5) L=1000
  - $\Delta\chi2$=14 (input : normal)
  - $\Delta\chi2$=11 (input : inverted)
- contribution to $\Delta\chi2$ (normal)
  - Previous Setup 22.9
  - matter density (SK) 0.5
  - resonance 2.7
  - density error -0.6
  - miss ID (μ-e) -0.7
  - reconstruction -1.7
  - efficiency (e) -2.0
  - π^0 background -6.7
  - total 14.4

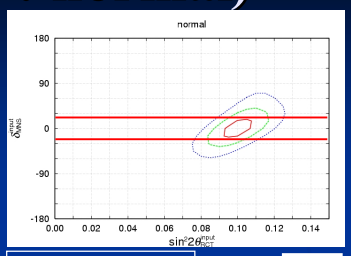
positive / negative

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

Contour (input : normal)



w/o res. & π^0

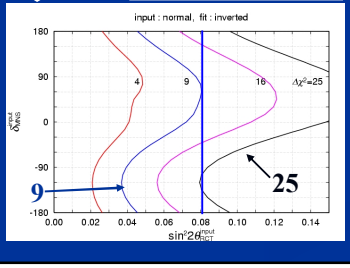


$\sin^2 2\theta_{rct} \sim 0.06$

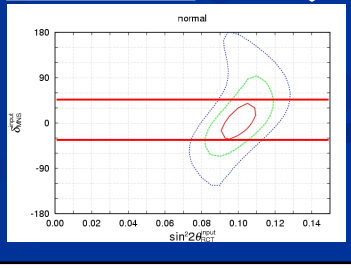
$\Delta\delta_{MNS} = \pm 30^o$

$\sin^2 2\theta_{rct} \sim 0.08$

$\Delta\delta_{MNS} = \pm 45^o$



with res. & π^0



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 → 14	(input : normal)
	21 → 11	(input : inverted)
$\Delta\delta_{MNS}$	$\pm 30^o$ → $\pm 45^o$	($3\sigma \rightarrow 2\sigma$)

Thank you for your attention

Q u e s t i o n

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