

Physics Potential of The T2KK Experiment

Pyungwon Ko (KIAS)

Based on the work in preparation
with K. Hagiwara, N. Okamura, Y. Takaesu

KAERU Conference @ IPMU
March 25-26 (2014)

Neutrino Physics

- Many important questions unanswered yet
- Masses (and their origin) ? (NH or IH ?) CP phase(s) ?
- Dirac or Majorana ?
- Sterile neutrinos ?
- Neutrino DM connection ? (Yong Tang, PKo, I404.0236)
- Need new experimental data to answer them

Contents

- Origin of mass of neutrinos (and all other particles) ?
- Physics potential of the T2KK experiment (Many thanks to Yoshitaro Takaesu and Naotoshi Okamura for their help for preparation of this talk)

Origin of mass

- Higgs discovery : Origin of the SM particles come from Higgs VEV and strong interaction (confinement)
- Still the origin of Higgs VEV unknown....
- Neutrino mass : seesaw (tree level or radiative) ?
- Neutrino mass from strong dynamics ?
- DM mass from strong dynamics ?
- Let me present one model of such a kind

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including v's and CDM masses)
from hidden sector strong dynamics,
and CDM long lived by accidental sym

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)

Hur, Ko : arXiv:1103.2517, PRL (2011)

Proceedings for workshops/conferences
during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

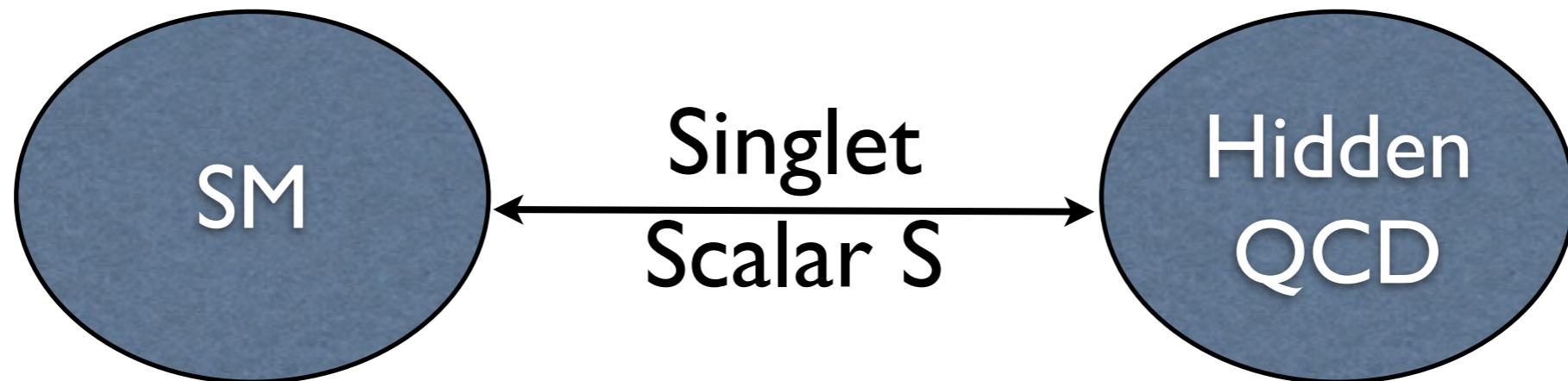
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations :
accidental symmetries of QCD (pion is
stable if we switch off EW interaction;
proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by “S”

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

$$\begin{aligned}
 \mathcal{L}_{\text{SM}} = & \mathcal{L}_{\text{kin}} - \frac{\lambda_H}{4} (H^\dagger H)^2 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H - \frac{\lambda_S}{4} S^4 \\
 & + \left(\bar{Q}^i H Y_{ij}^D D^j + \bar{Q}^i \tilde{H} Y_{ij}^U U^j + \bar{L}^i H Y_{ij}^E E^j \right. \\
 & \left. + \bar{L}^i \tilde{H} Y_{ij}^N N^j + S N^{iT} C Y_{ij}^M N^j + h.c. \right)
 \end{aligned}$$

Hidden sector lagrangian with new strong interaction

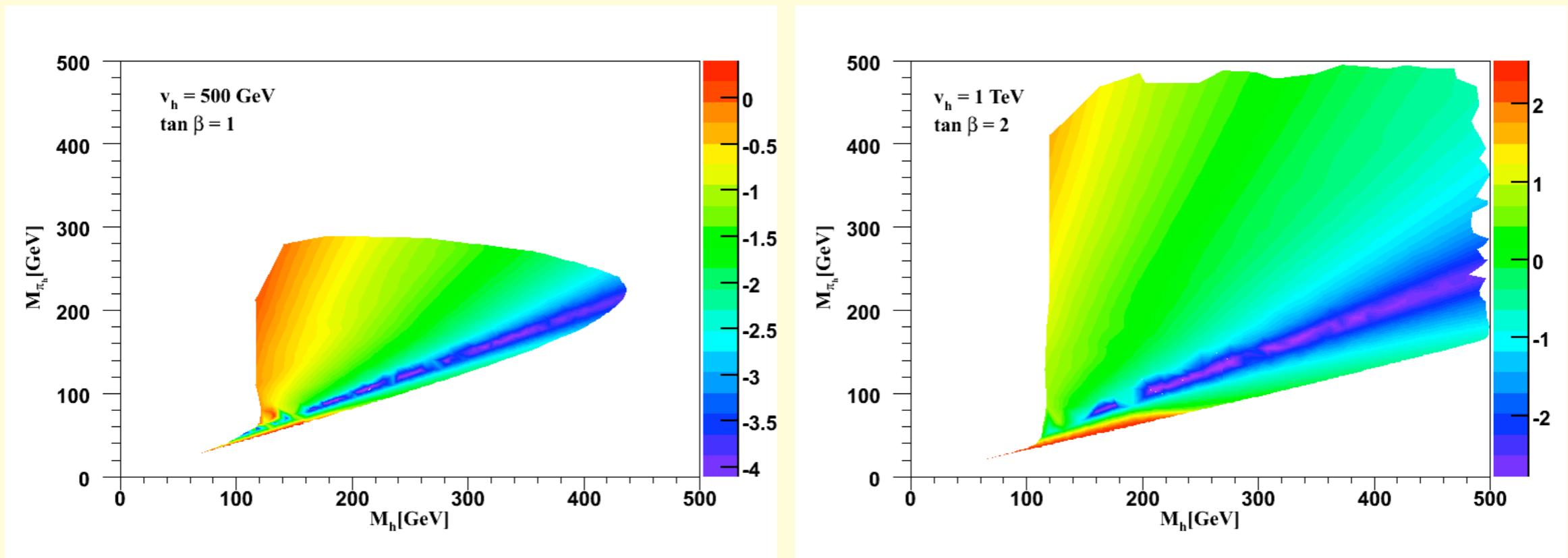
$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \sum_{k=1}^{N_{HF}} \bar{Q}_k (i \mathcal{D} \cdot \gamma - \lambda_k S) Q_k$$

3 neutral scalars : h , S and hidden sigma meson
 Assume h -sigma is heavy enough for simplicity

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

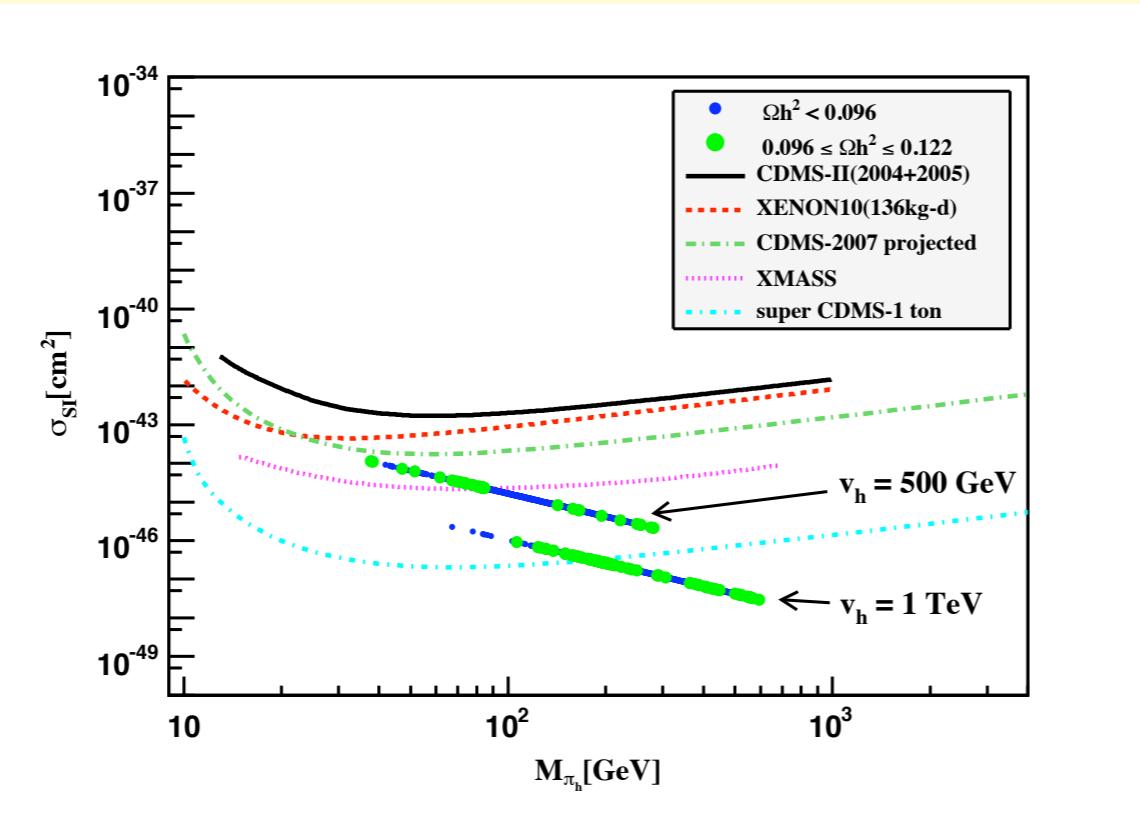
$$\begin{aligned}
 \mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
 \mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
 \mathcal{L}_{\text{SM}} &= -\frac{\lambda_1}{2} (H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
 \mathcal{L}_{\text{mixing}} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa'_S \frac{S}{\Lambda_h} \right. \\
 &\quad \left. + O\left(\frac{SH_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}\right) \right] \\
 &\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa'_S S \right]
 \end{aligned}$$

Relic density



$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for
(a) $v_h = 500 \text{ GeV}$ and $\tan \beta = 1$,
(b) $v_h = 1 \text{ TeV}$ and $\tan \beta = 2$.

Direct Detection Rate



$\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$ as functions of m_{π_h} .

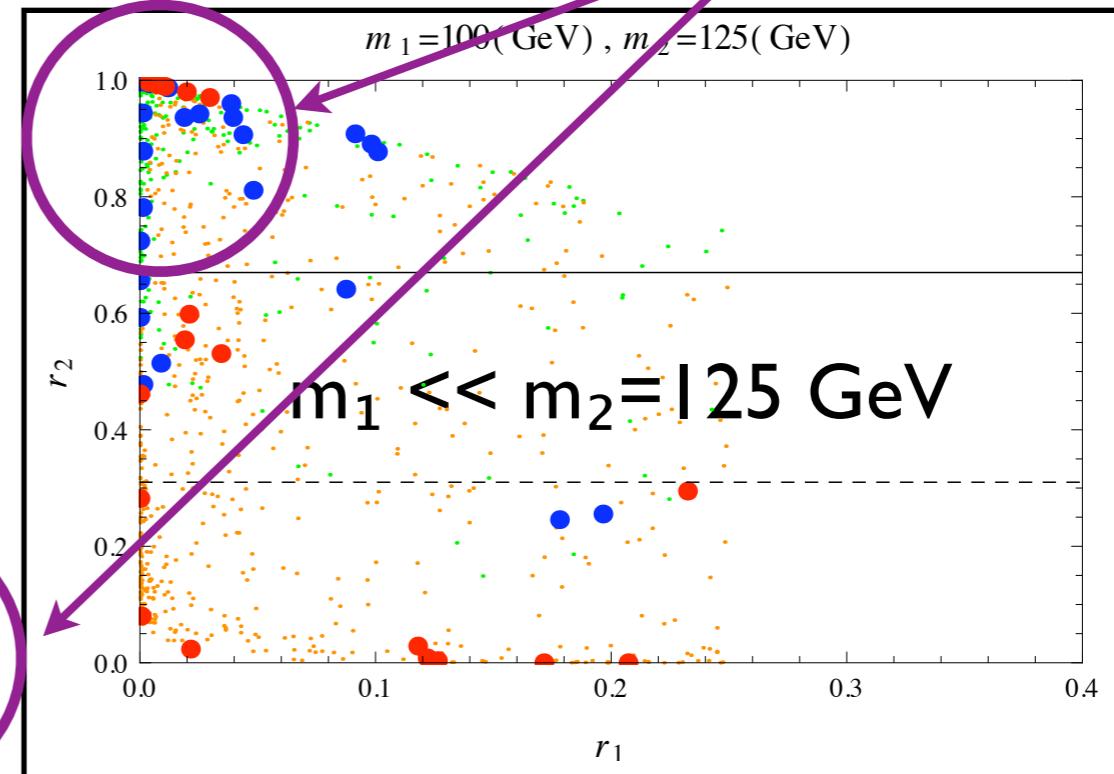
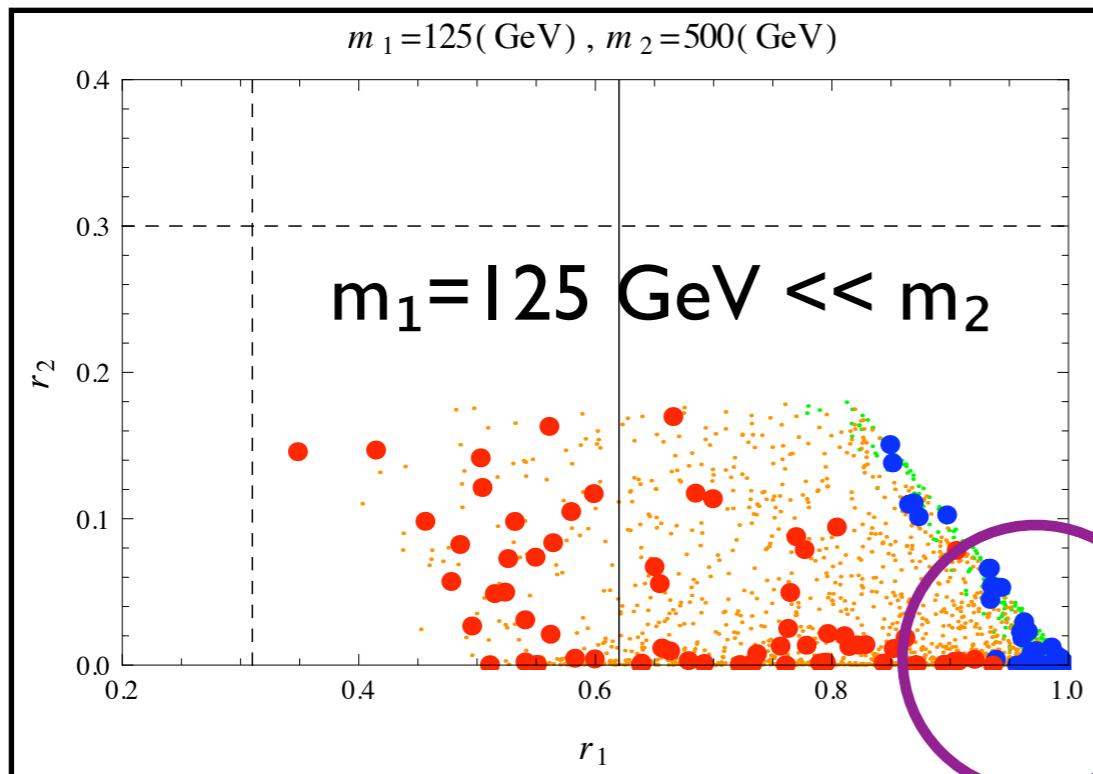
the upper one: $v_h = 500 \text{ GeV}$ and $\tan \beta = 1$,

the lower one: $v_h = 1 \text{ TeV}$ and $\tan \beta = 2$.

Discovery possibility

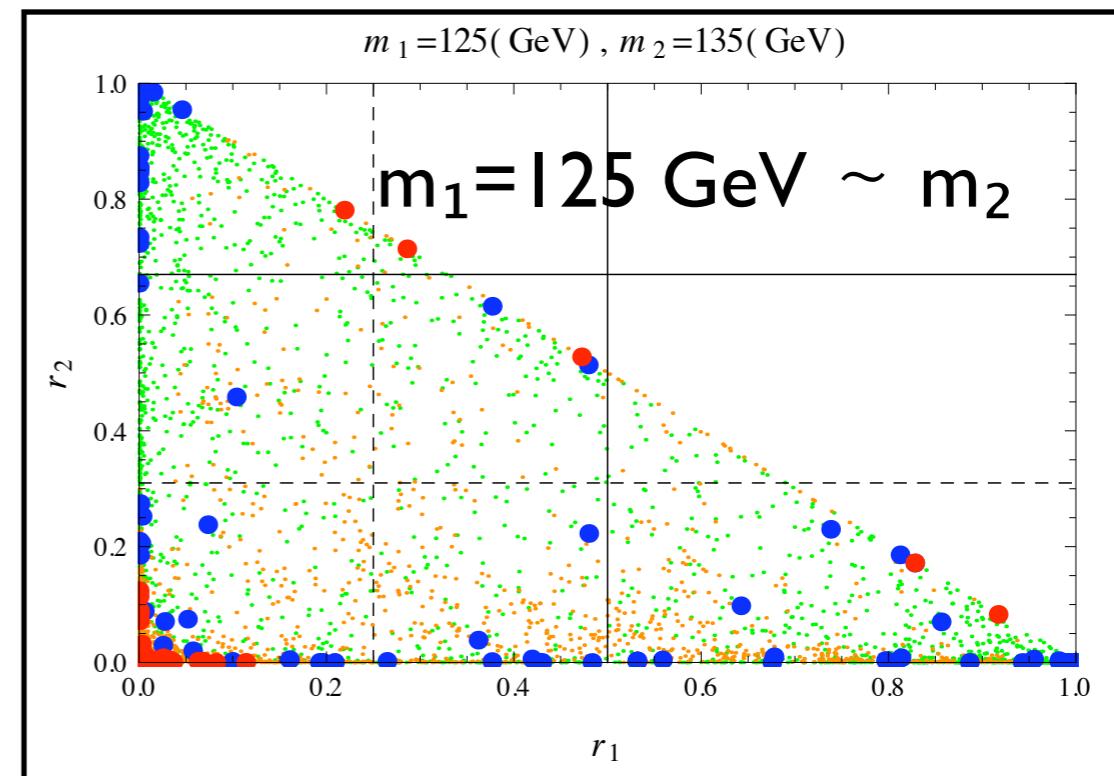
- Signal strength (r_2 vs r_1)

LHC data for 125 GeV resonance



- : $L = 5 \text{ fb}^{-1}$ for 3σ Sig.
- : $L = 10 \text{ fb}^{-1}$ for 3σ Sig.

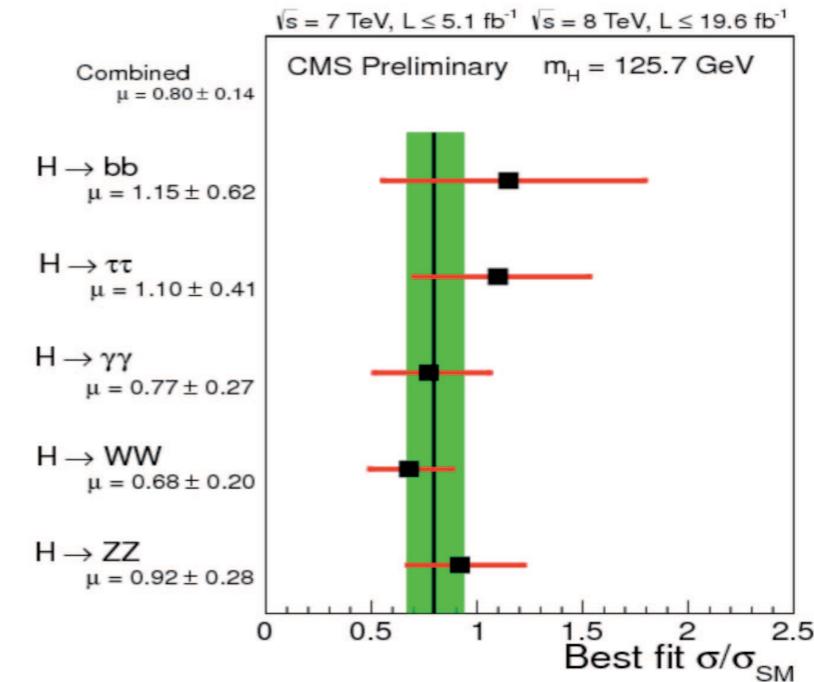
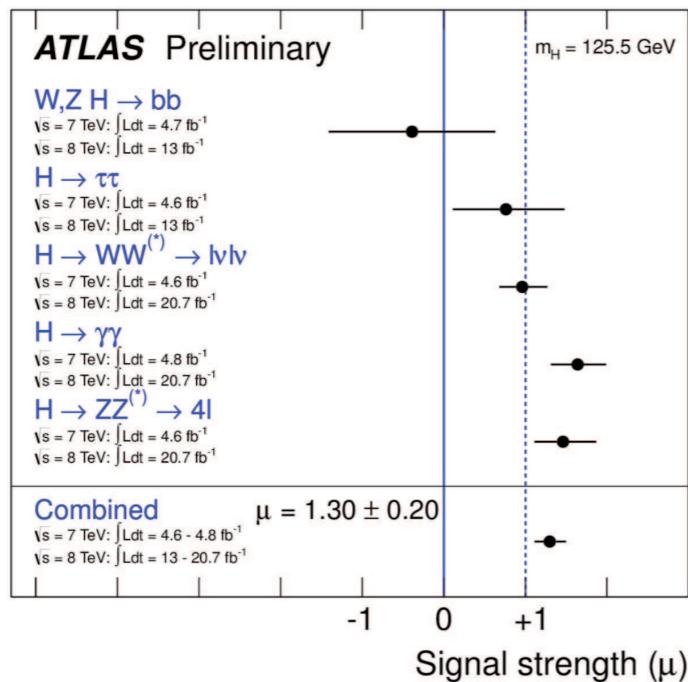
- : $\Omega(x), \sigma_p(x)$
- : $\Omega(x), \sigma_p(o)$
- : $\Omega(o), \sigma_p(x)$
- : $\Omega(o), \sigma_p(o)$



Updates@LHCb by Pich

Signal Strengths

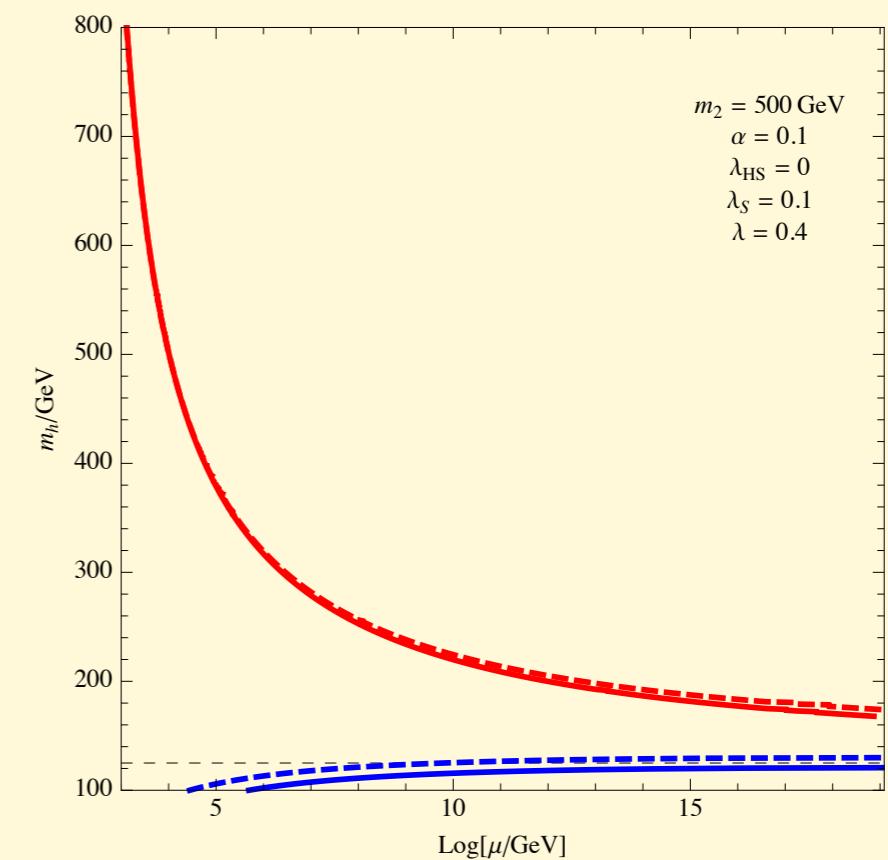
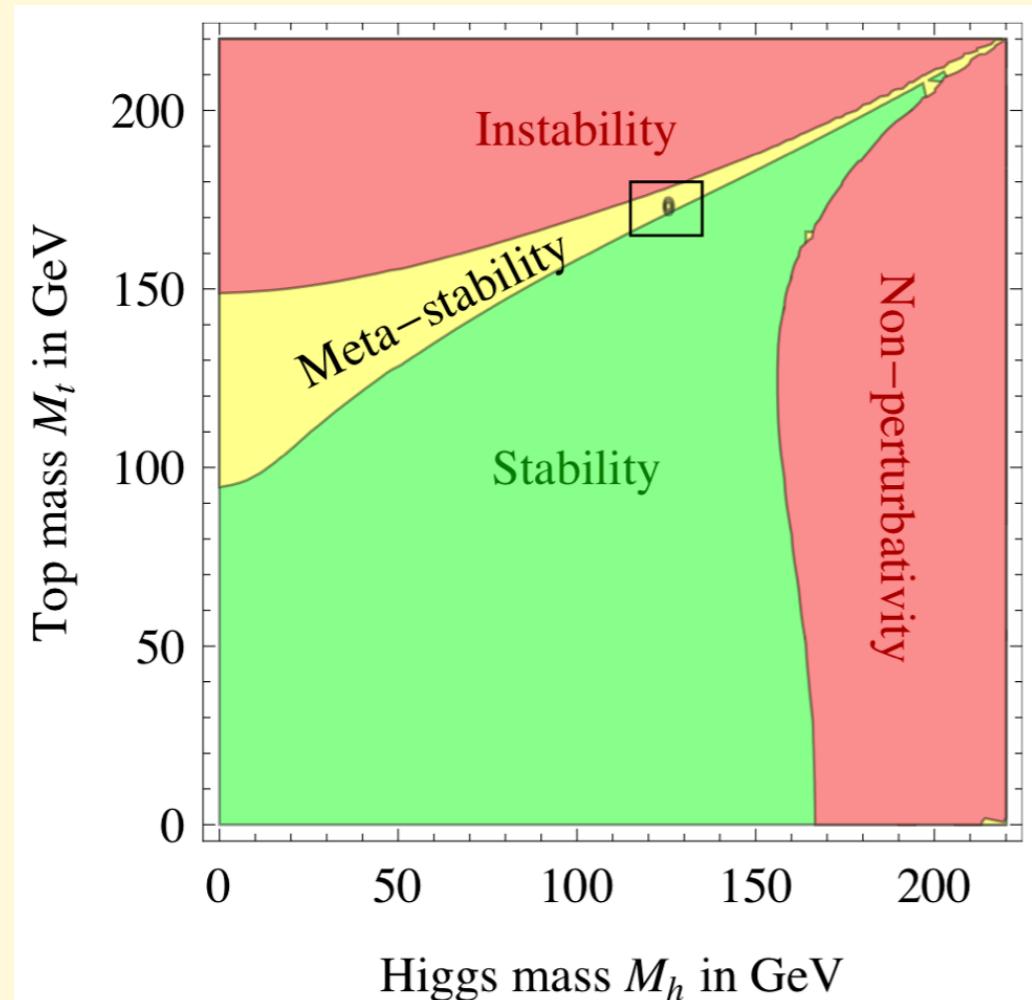
$$\mu \equiv \frac{\sigma \cdot \text{Br}}{\sigma_{\text{SM}} \cdot \text{Br}_{\text{SM}}}$$



Decay Mode	ATLAS ($M_H = 125.5 \text{ GeV}$)	CMS ($M_H = 125.7 \text{ GeV}$)
$H \rightarrow bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \rightarrow \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \rightarrow \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \rightarrow WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \rightarrow ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	1.30 ± 0.20	0.80 ± 0.14

$$\langle \mu \rangle = 0.96 \pm 0.12$$

Vacuum Stability Improved by the singlet scalar S



A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Also “S” can be used to explain the GC gamma ray excess

Naturalness Problem ?

- Scale Symmetry is explicitly broken only by dim-4 operators (beta functions)
- Our model is renormalizable when dim regularization is used, and no quadratic divergence
- Logarithmic sensitivity to high energy scale
- OK up to Planck scale as long as no new particles at high energy scale

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long lived because of accidental symmetries), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- WZW term : 3->2 for 3 or more flavors
- Could consider SUSY version of it

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Better approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; Form factor effects by MTanabashi and SOkawa; HHatanaka, DWJung, PKo in AdS/QCD approach in preparation)

Physics Potential of the T2KK Experiment

Based on the work in preparation
with Hagiwara, Okamura, Takaesu

For the probe for new physics in the neutrino sector at T2KK,
Cipriano Ribeiro, Kajita, Ko, Minakata, Nakayama, Nunokawa,
hep-ph:0712.4314, PRD

Our knowledge of neutrino oscillation

Three light flavor mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Reactor/Interference Solar

$$\sin^2 2\theta_{23} \sim 1 \quad \theta_{13} \simeq 9^\circ \quad \theta_{12} \simeq 35^\circ$$

Mass differences

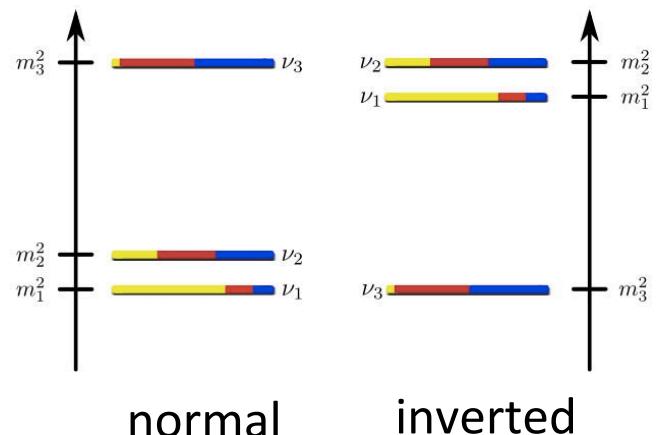
$$m_2^2 - m_1^2 = 7.5 \times 10^{-5} [\text{eV}^2]$$

$$|m_3^2 - m_1^2| = 2.32 \times 10^{-3} [\text{eV}^2]$$

δ_{CP} : unknown

Next targets

Mass hierarchy: NH or IH



[PDG:Phys. Rev. D86 (2012) 010001]

Oscillation probability

$$P_{\nu_\mu \rightarrow \nu_\mu} \simeq 1 - \sin^2 2\theta_{\text{atm}} \sin^2 (\Delta_{31} + \Delta_{21} \cos^2 \theta_{12})$$

$$P_{\nu_\mu \rightarrow \nu_e} \simeq 4 \sin^2 \theta_{13} \sin^2 \theta_{23} (1 + A^e) \sin^2 (\Delta_{31} + B^e)$$

$$\sin \theta_{\text{atm}} = \sin \theta_{23} \cos \theta_{13}, \quad \Delta_{ij} = \frac{\delta m_{ij}^2 L}{4E}$$

$$a = 2\sqrt{2}G_F E n_e \simeq 7.56 \times 10^{-5} [\text{eV}^2] \left(\frac{\rho(x)}{\text{g/cm}^3} \right) \left(\frac{E}{\text{GeV}} \right)$$

$$A^e \simeq \frac{aL}{2\Delta_{31}E} - \Delta_{21} \frac{\sin 2\theta_{12}}{\tan \theta_{23} \sin \theta_{13}} \sin \delta_{\text{CP}}$$

$$B^e \simeq -\frac{aL}{4E} + \frac{\Delta_{21}}{2} \frac{\sin 2\theta_{12}}{\tan \theta_{23} \sin \theta_{13}} (\cos \delta_{\text{CP}} - 2 \sin^2 \theta_{12})$$

(Up to linear terms of Δ_{21} , $\sin^2 \theta_{13}$, $\frac{aL}{4E}$ are retained in A and B)

Matter effect terms enhances sign difference of Δ_{31} .

→ Longer baseline L has better sensitivity to the mass hierarchy.

$\sin \delta_{\text{CP}}$ term typically has larger coefficient than $\cos \delta_{\text{CP}}$ term.

→ More sensitive to $\sin \delta_{\text{CP}}$ than $\cos \delta_{\text{CP}}$.



Amplitude
correction

↑
Phase
correction

T2KK and T2KO proposals

- Longer baseline than T2K to enhance sensitivity to the MH
- Wide band beam for sensitivity to $\cos \delta_{CP}$ (phase) as well as $\sin \delta_{CP}$ (amplitude).

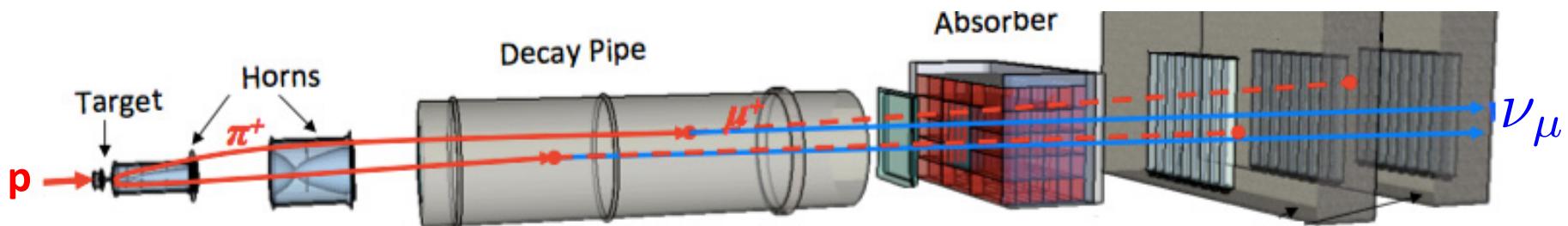


T2KK: 100 kton in [Korea](#) and **SK** [hep-ph/0410229, 0504026, 0901.1517, 1001.5165]

T2KO: 100 kton in [Oki island](#) and **SK** [0804.2111, 1209.2763]

* **SK** (22.5kton) is also used as a second detector

ν_μ ($\bar{\nu}_\mu$) focusing beam



Neutrino beam is produced by colliding protons on target.

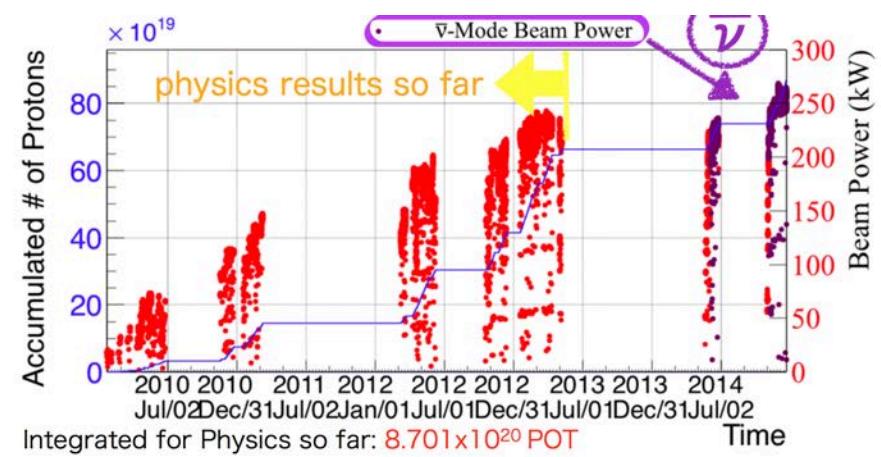
The total neutrino flux is expressed by **POT** (Protons On Target).
(like Luminosity @ collider)

We assume 10^{21} POT/year (10^7 sec)
with 40 GeV proton beam.

↔ 0.64 MW

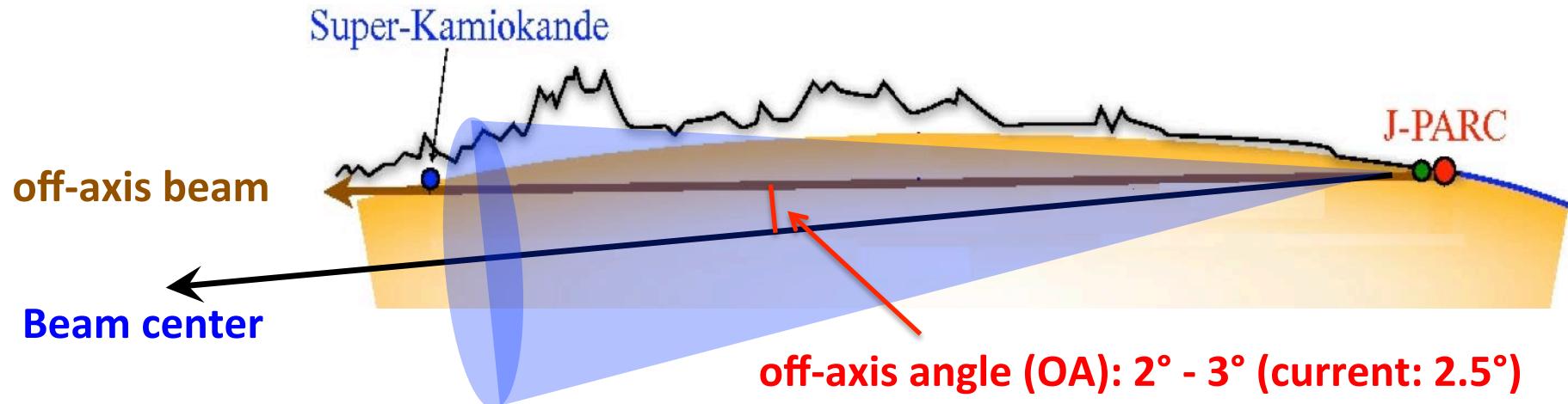
Current: 0.32 MW

Plan: 0.75 MW in 5years (Talk by T.Nakaya @Flavor of New Physics (2015.3.9))

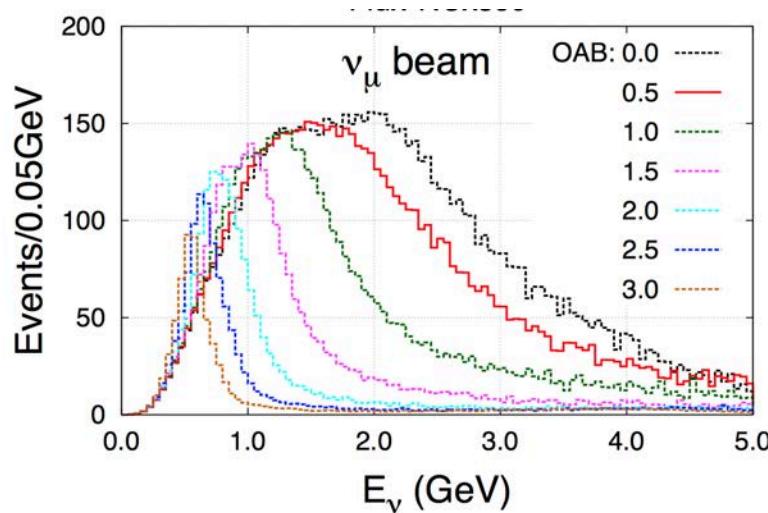


Off-axis beam

- Neutrino beam spreads.
- A detector receives spreaded beam (**off-axis beam: OAB**)



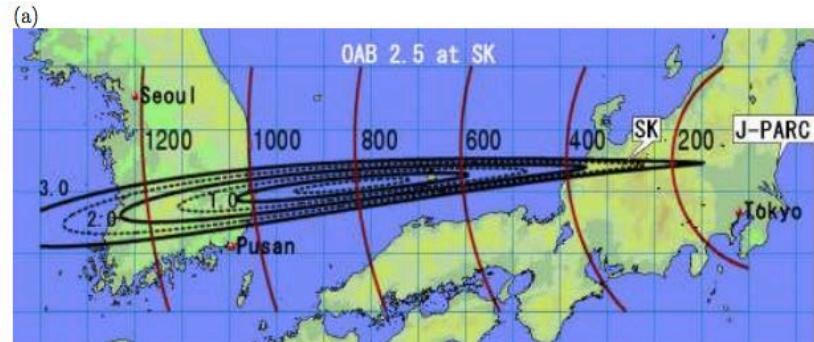
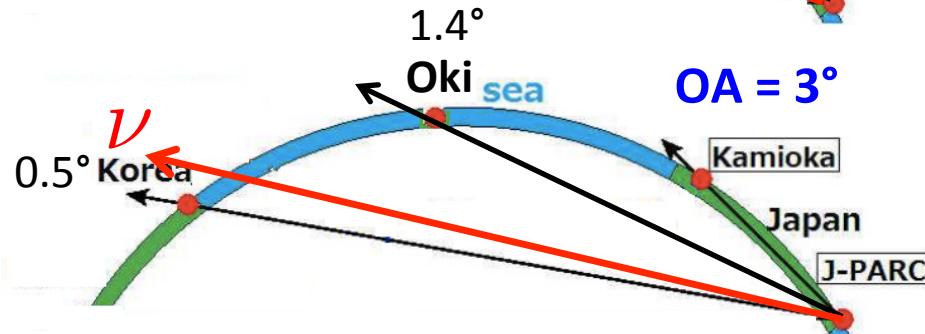
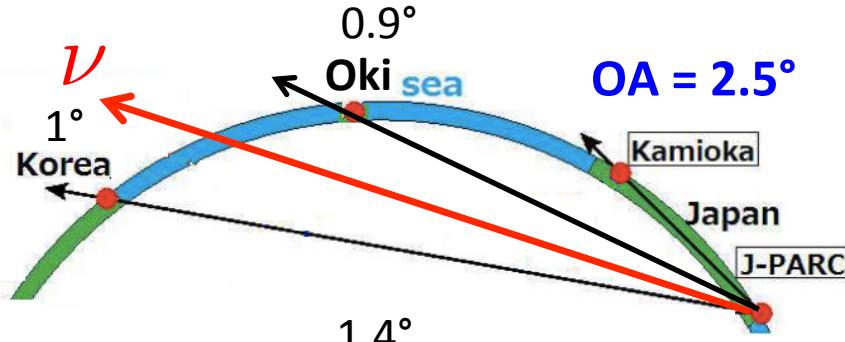
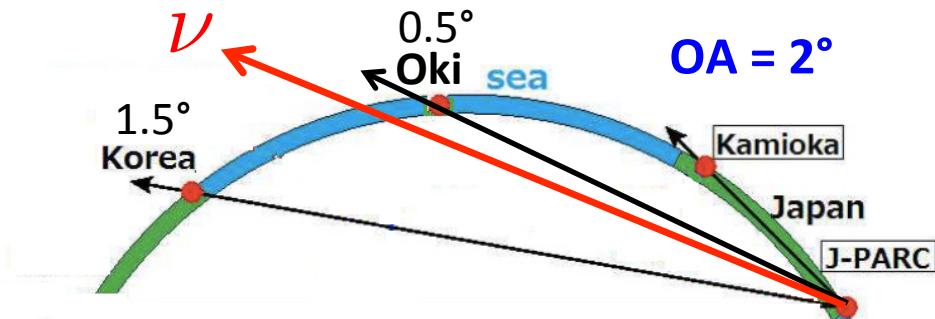
(The direction of neutrino beam is specified by OA at SK in this talk.)



Neutrino beam energy distribution depends on OA.

Off-axis angle @ SK, Oki, Korea

OAB set up in our study 2.5° OAB @SK \rightarrow 0.9° @Oki and 1° @Korea
 3.0° OAB @SK \rightarrow 1.4° @Oki and 0.5° @Korea



Beam profiles

SK: 2°

T2KO: 0.5°

T2KK: 1.5°

SK: 2.5°

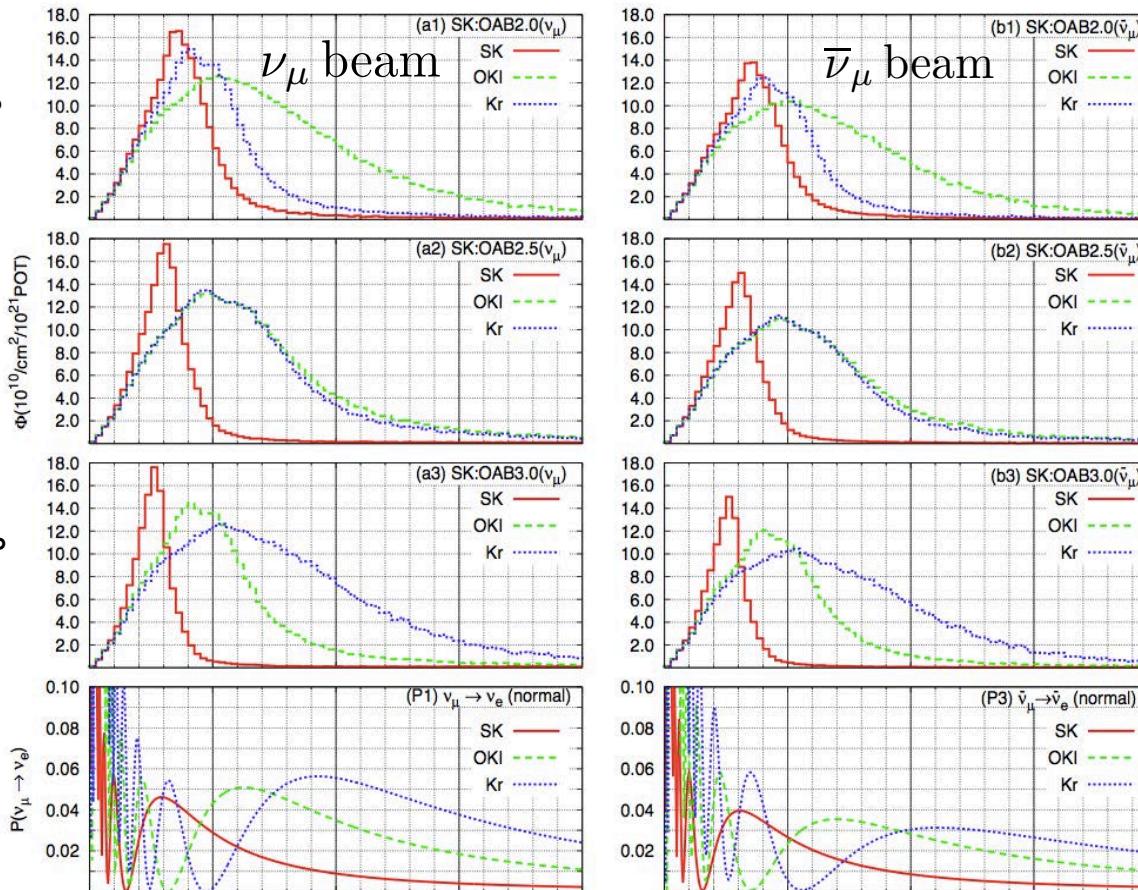
T2KO: 1°

T2KK: 1°

SK: 3°

T2KO: 1.5°

T2KK: 0.5°



Flux * Cross section

K.Hagiwara, T.Kiwanami, N.Okamura, K.Senda hep-ph/1209.2763

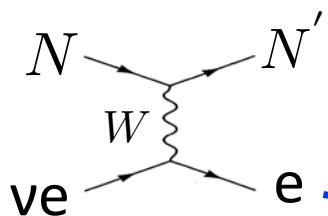
Korea and Oki detectors cover wider energy range than SK.

→ sensitive to $\cos \delta_{CP}$ term (phase) as well as $\sin \delta_{CP}$ term (Amp.).

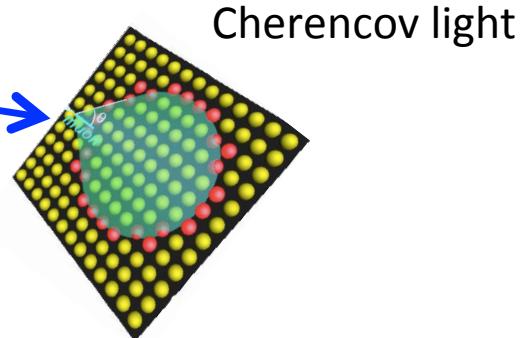
But more NC π^0 BG from the high energy tail

NC π^0 background

Signal



Charged Current Quasi-Elastic
(CCQE) scattering



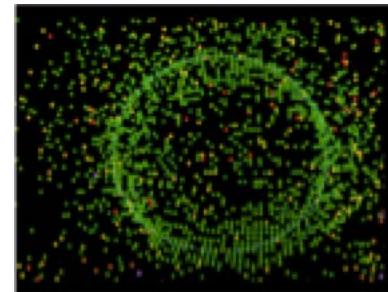
Electrons and π^0 can be very similar in a water Cherenkov detector.

e : one fuzzy ring

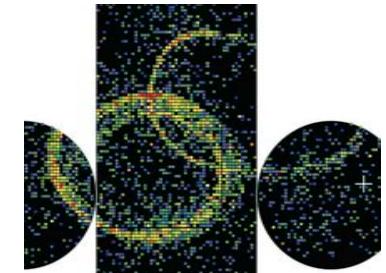
$\pi^0 \rightarrow \gamma\gamma$: two fuzzy rings

If π^0 is highly boosted or
one of the photons is missed,
 π^0 looks like an electron.

Electron

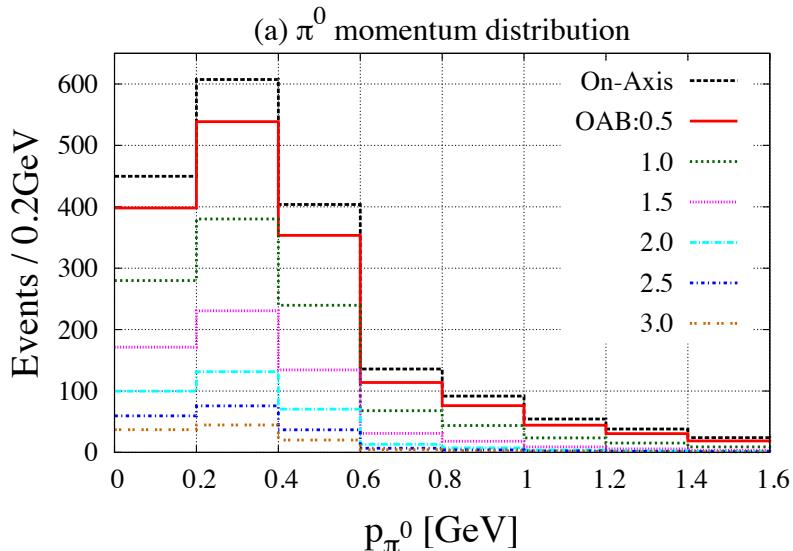


π^0

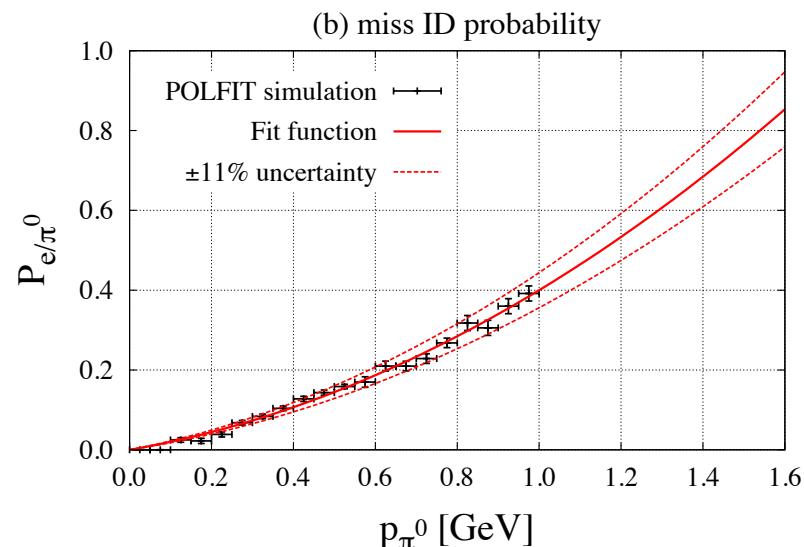


→ NC π^0 events can be major backgrounds
for the $\bar{\nu}_e$ appearance signal.

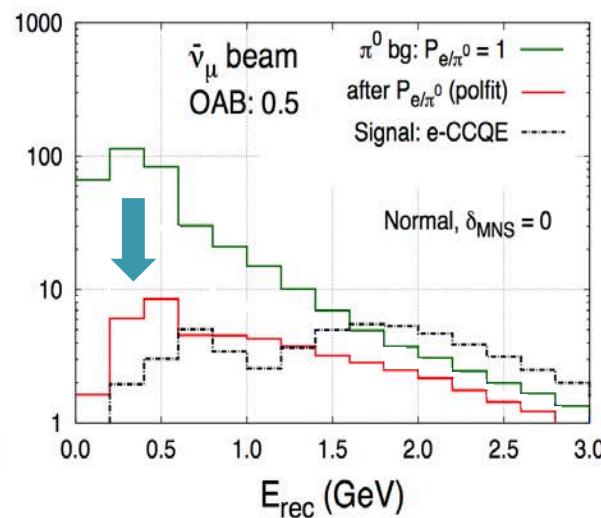
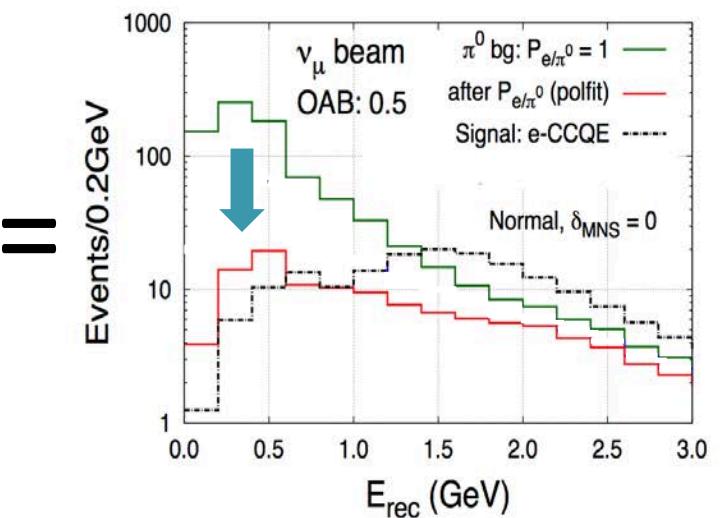
NC π^0 background



Smaller OA angle gives more NC π^0 events.



We use **POLfit** π^0 ID algorithm developed by T2K collaboration.
[T. Barszczak, Ph.D. thesis (2005)]



NC π^0 BG can be reduced significantly.



helpfull especially for smaller OA beam

Aim of Current study

Analysis details between previous and current studies
for the same two detector setups (T2KK and T2KO).

	T2KK (0901.1517)	T2KK,T2KO (1001.5165, 1209.2763)	T2KK, T2KO (current study)
Neutrino beam	ν beam	ν and anti- ν beam	ν and anti- ν beam
Signal evnets	All CC events	CCQE events	All CC events
Backgrounds	NC π^0 /miss-ID mu(e) /secondary ν	Secondary ν	NC π^0 /miss-ID mu(e) /secondary ν
Detector smearing	yes	no	yes
Efficiency (e)	$90\% \pm 5\%$	100%	$90\% \pm 5\%$
Efficiency (mu)	100% -1%	100%	100% -1%
Bin size	200 MeV	200 MeV	50 MeV

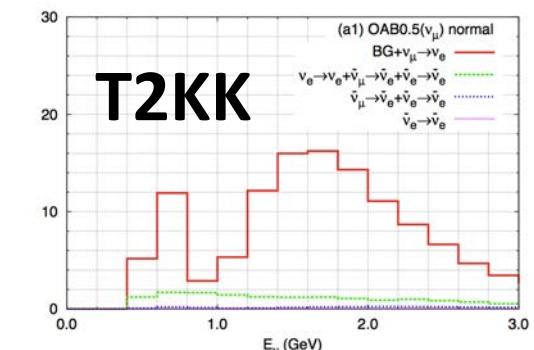
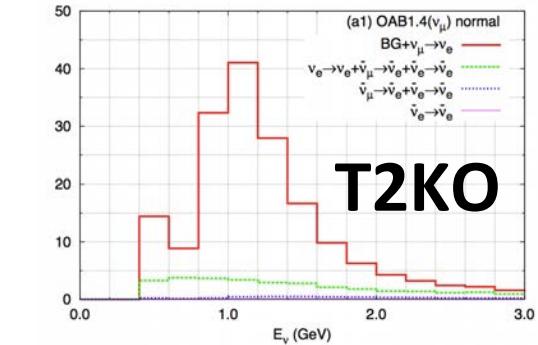
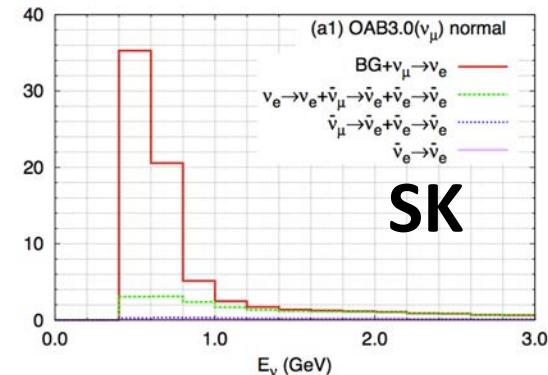
We study effects of anti- ν beam on sensitivities to MH and CP phase with NC π^0 BG by updating previous studies.

Points of this study, comparing to previous works

- We study SK (22.5 kton) + 100 kton detector at Korea/Oki as in Hagiwara, Okamura et.al. [hep-ph/0410229, 0504061, 0607255, 0901.1517, 1107.5857, 1209.2763] as **economical setup** for MH & CP phase.
 - ↔ Minakata, Kajita et. al. considered 270 kton (Kamioka) + 270 kton (Korea) detectors as an optional configuration of Hyper-K (540 kton at Kamioka). [hep-ph/0504026, 0609286, 1001.5165]
 - T2KK, but different philosophy
- We study effects of **anti- ν beam** systematically in addition to ν beam with **NC π^0 BG**.
 - ↔ Hagiwara, Okamura et.al. [hep-ph/0901.1517(T2KK)] **only** used ν beam. → Rooms to be improved with anti- ν beam
 - ↔ Hagiwara, Okamura et. al. [hep-ph/1107.5857(T2KK), 1209.2763(T2KK & T2KO)] used anti- ν beam ($\nu : \text{anti-}\nu = 1:1$ only) but **did not consider NC π^0 BG**. → Optimistic results.

Analysis method χ^2 analysis

- Signal: $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_\mu \rightarrow \nu_e$ *Improvements from 0901.1517
1209.2763
- Backgrounds
 - Secondary beam: ν_e , $\bar{\nu}_e$, $\bar{\nu}_\mu(\nu_\mu)$
 - miss-ID muon/electron
 - π^0 BG with improved ID algorithm (POLfit)
- Oscillation parameters (updated)
 - $\delta m_{12}^2 = (7.5 \pm 0.2) \times 10^{-5} \text{ eV}^2$
 - $\delta m_{13}^2 = \pm 2.35 \times 10^{-3} \text{ eV}^2$
 - $\sin^2 2\theta_{12} = 0.857 \pm 0.024$
 - $\sin^2 2\theta_{13} = 0.095 \pm 0.005$
 - $\sin^2 \theta_{23} = 0.5 \pm 0.1$ δ_{CP}
- Systematics
 - matter density: 6%
 - Cross section, normalization: 3% - 20%
 - fiducial volume: 3%
 - NC π^0 BG modeling (π^0 ID, axial masses)



chi^2 function and sensitivity measures

$$\chi^2 \equiv \chi_{\text{SK}}^2 + \chi_{\text{Oki/Kr}}^2 + \chi_{\text{sys}}^2 + \chi_{\text{para}}^2$$

$$\chi_D^2 = \sum_i \left\{ \left(\frac{(N_{\mu,D}^i)^{\text{fit}} - (N_{\mu,D}^i)^{\text{input}}}{\sqrt{(N_{\mu,D}^i)^{\text{input}}}} \right)^2 + \left(\frac{(\bar{N}_{\mu,D}^i)^{\text{fit}} - (\bar{N}_{\mu,D}^i)^{\text{input}}}{\sqrt{(\bar{N}_{\mu,D}^i)^{\text{input}}}} \right)^2 \right. \\ \left. + \left(\frac{(N_{e,D}^i)^{\text{fit}} - (N_{e,D}^i)^{\text{input}}}{\sqrt{(N_{e,D}^i)^{\text{input}}}} \right)^2 + \left(\frac{(\bar{N}_{e,D}^i)^{\text{fit}} - (\bar{N}_{e,D}^i)^{\text{input}}}{\sqrt{(\bar{N}_{e,D}^i)^{\text{input}}}} \right)^2 \right\}$$

MH sensitivity measure:

$$\Delta\chi_{\min}^2 = \chi_{\min}^2(\text{wrong MH}) - \chi_{\min}^2(\text{true MH})$$

CP phase sensitivity measure:

$$\Delta\chi_{\min}^2 = \chi_{\min}^2(\text{test } \delta_{\text{CP}}) - \chi_{\min}^2(\text{true } \delta_{\text{CP}})$$

Difference between
Data and prediction

$$\chi_{\text{sys}}^2 = \sum_{D=\text{SK,Oki,Kr}} \left\{ \left(\frac{f_V^D - 1}{0.03} \right)^2 + \left(\frac{f_\rho^D - 1}{0.06} \right)^2 + \sum_{\nu_\alpha = \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e} \left(\frac{f_{\nu_\alpha}^D - 1}{0.03} \right)^2 \right. \\ \left. + \left(\frac{\varepsilon_e^D - 0.9}{0.05} \right)^2 + \left(\frac{\varepsilon_\mu^D - 1}{0.01} \right)^2 + \left(\frac{P_{e/\mu}^D - 0.01}{0.01} \right)^2 + \left(\frac{P_{\mu/e}^D - 0.01}{0.01} \right)^2 \right\} \\ + \sum_{\nu_\beta = \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e} \left\{ \left(\frac{f_{\nu_\beta}^{\text{CCQE}} - 1}{0.03} \right)^2 + \left(\frac{f_{\nu_\beta}^{\text{non-CCQE}} - 1}{0.20} \right)^2 \right\} \\ + \left(\frac{f_{\pi^0}^{\text{NC}} - 1}{0.11} \right)^2 + \left(\frac{f_{\pi^0}^{\text{NCRes}} - 1}{0.13} \right)^2 + \left(\frac{f_{\pi^0}^{\text{NCCoh}} - 1}{0.15} \right)^2 . \quad (3)$$

Systematic uncertainty

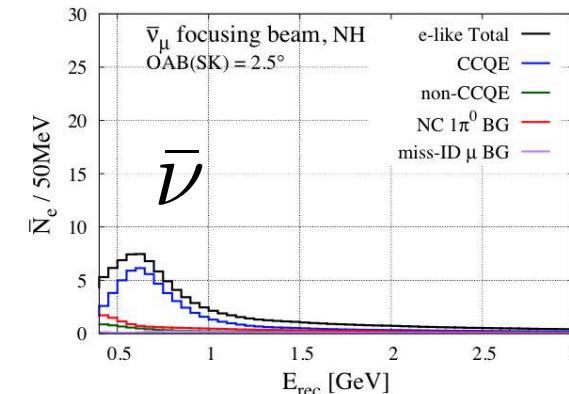
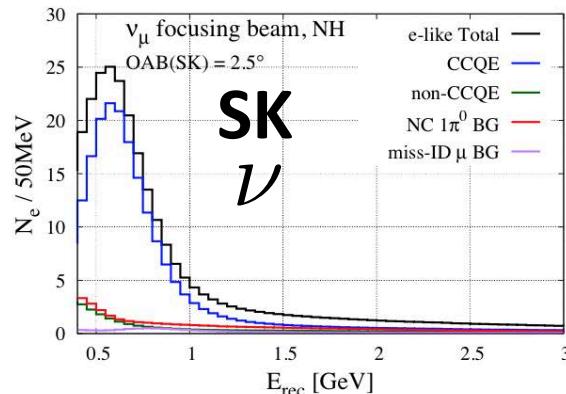
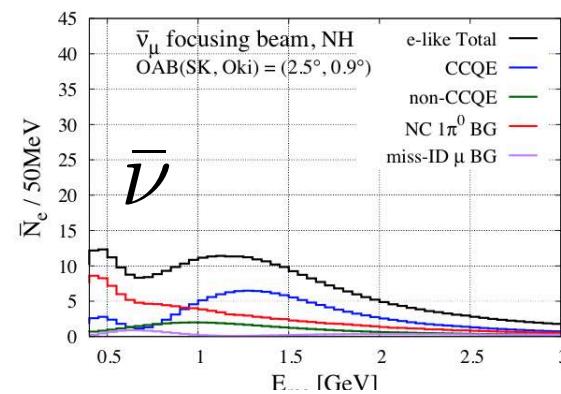
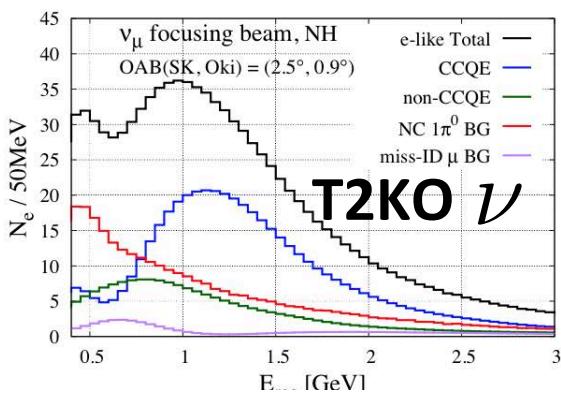
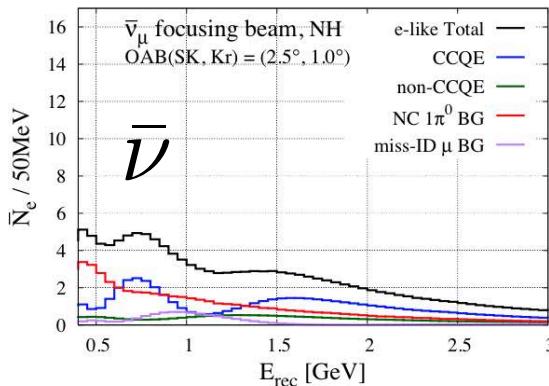
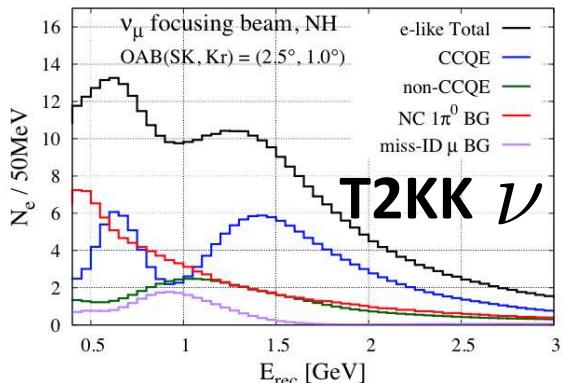
External constraints on
oscillation parameters

$$\chi_{\text{para}}^2 = \left(\frac{\sin^2 2\theta_{12}^{\text{fit}} - 0.875}{0.024} \right)^2 + \left(\frac{\sin^2 2\theta_{13}^{\text{fit}} - 0.095}{0.005} \right)^2 + \left(\frac{\sin^2 \theta_{23}^{\text{fit}} - 0.5}{0.1} \right)^2 \\ + \left(\frac{(\delta m_{21}^2)^{\text{fit}} - 7.5 \times 10^{-5} [\text{eV}^2]}{0.20 \times 10^{-5} [\text{eV}^2]} \right)^2 + \left(\frac{(|\delta m_{32}^2|)^{\text{fit}} - 2.32 \times 10^{-3} [\text{eV}^2]}{0.10 \times 10^{-3} [\text{eV}^2]} \right)^2 \quad (3)$$

Parameters in chi^2 analysis (summary)

Fitting parameters	Input Value	Uncertainty
$\sin^2 2\theta_{12}$	0.875	0.024 [28]
$\sin^2 2\theta_{13}$	0.095 [28]	0.005 [4]
$\sin^2 \theta_{23}$	0.5	0.1 [28]
δm_{21}^2 [eV] ²	7.50×10^{-5}	0.20×10^{-5} [28]
$ \delta m_{32}^2 $ [eV] ²	2.32×10^{-3}	0.10×10^{-3} [28]
δ_{CP}	0°	-
$\bar{\rho}^{\text{SK}}$ [g/cm ³]	2.60	6% [21]
$\bar{\rho}^{\text{Oki}}$ [g/cm ³]	2.75	6% [21]
$\bar{\rho}^{\text{Kr}}$ [g/cm ³]	2.9	6% [21]
fiducial volume of detectors (f_V^D)	1.00	0.03
neutrino flux at a detector ($f_{\nu_\alpha}^D$)	1.00	0.03
CCQE cross sections ($f_{\nu_\beta}^{\text{CCQE}}$)	1.00	0.03
non-CCQE cross sections ($f_{\nu_\beta}^{\text{non-CCQE}}$)	1.00	0.20
missidentified NC π^0 events ($f_{\pi^0}^{\text{NC}}$)	1.00	0.11
missidentified NC resonant π^0 events ($f_{\pi^0}^{\text{NCRes}}$)	1.00	0.13
missidentified NC coherent π^0 events ($f_{\pi^0}^{\text{NCcoh}}$)	1.00	0.15
detection efficiency of e^\pm (ϵ_e^D)	0.90	0.05
detection efficiency of μ^\pm (ϵ_μ^D)	1.00	0.01
μ -to- e miss-ID probability ($P_{e/\mu}^D$)	0.01	0.01
e -to- μ miss-ID probability ($P_{\mu/e}^D$)	0.01	0.01

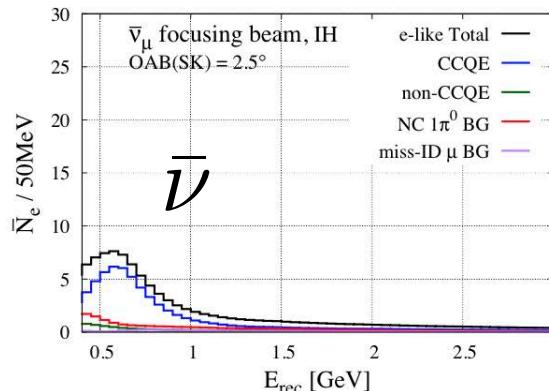
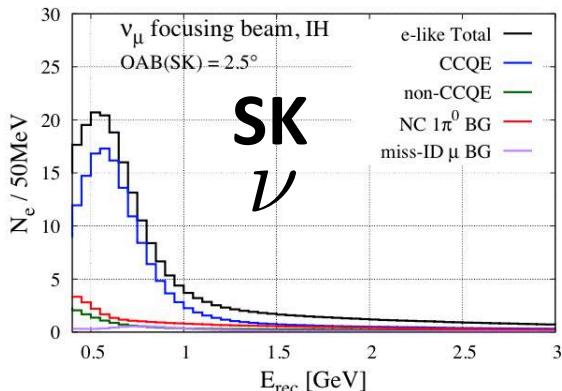
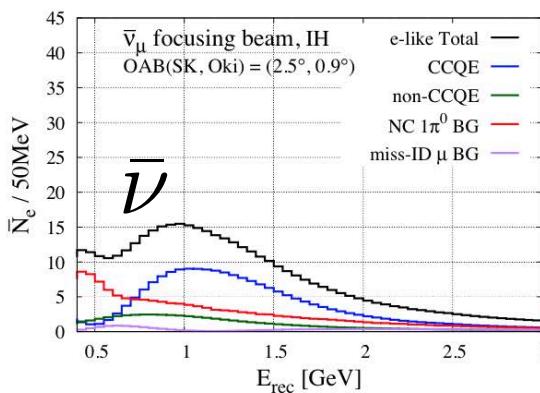
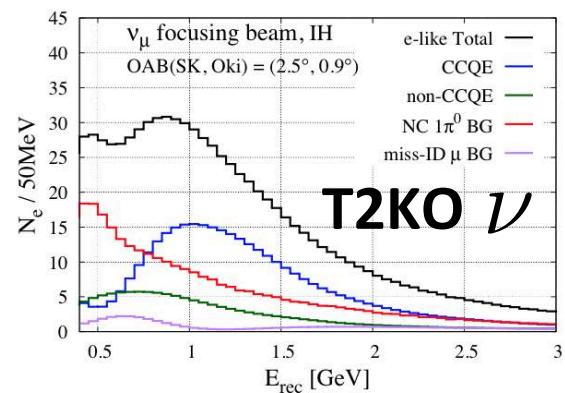
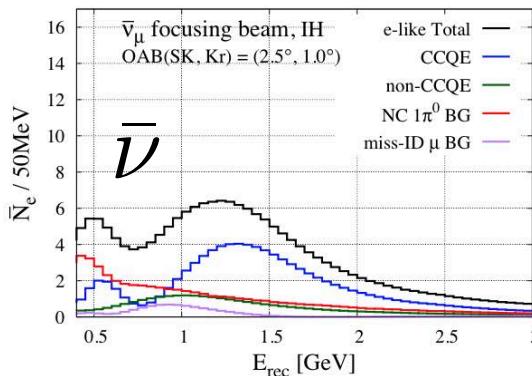
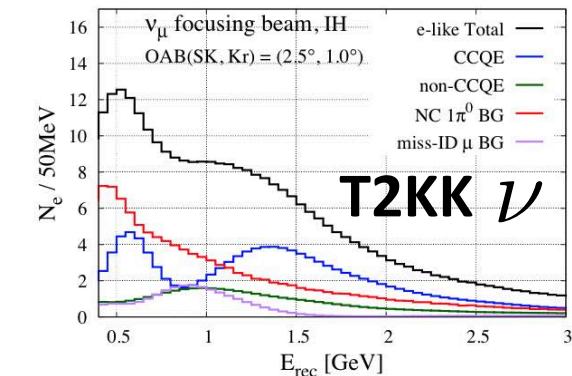
Energy distributions: ve appearance mode (NH)



Total events
 CCQE signal
 non-CCQE signal
 NC π^0 BG
 miss-ID neutrino BG

T2KK and T2KO
 can observe the
 2nd oscillation peak
 as well as the 1st peak.

Energy distributions: ve appearance mode (IH)



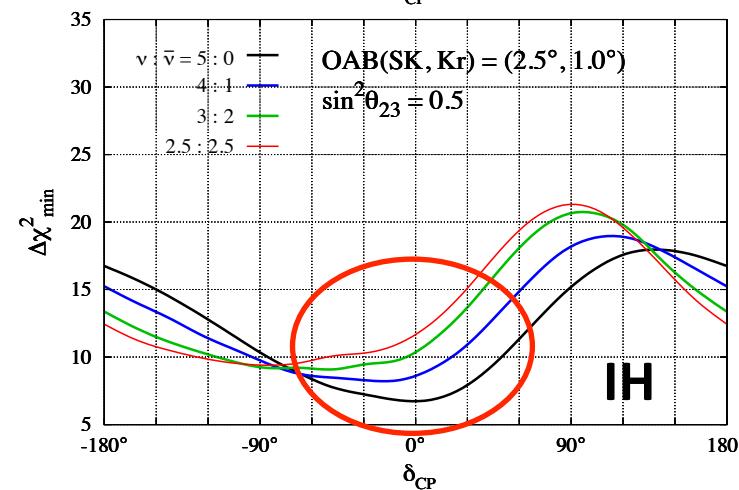
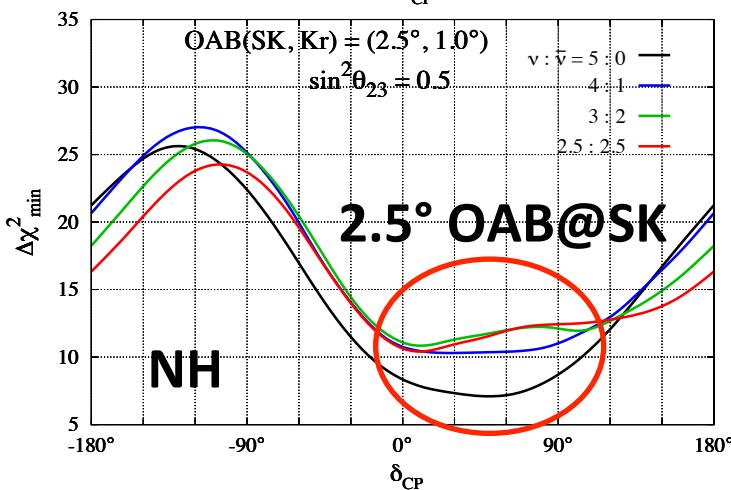
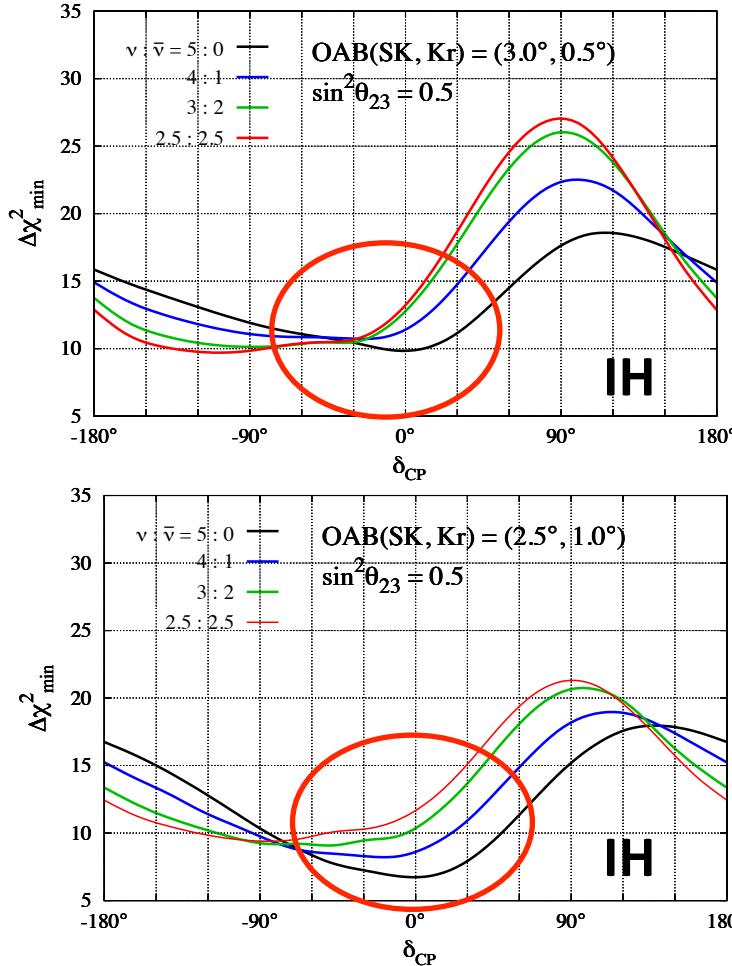
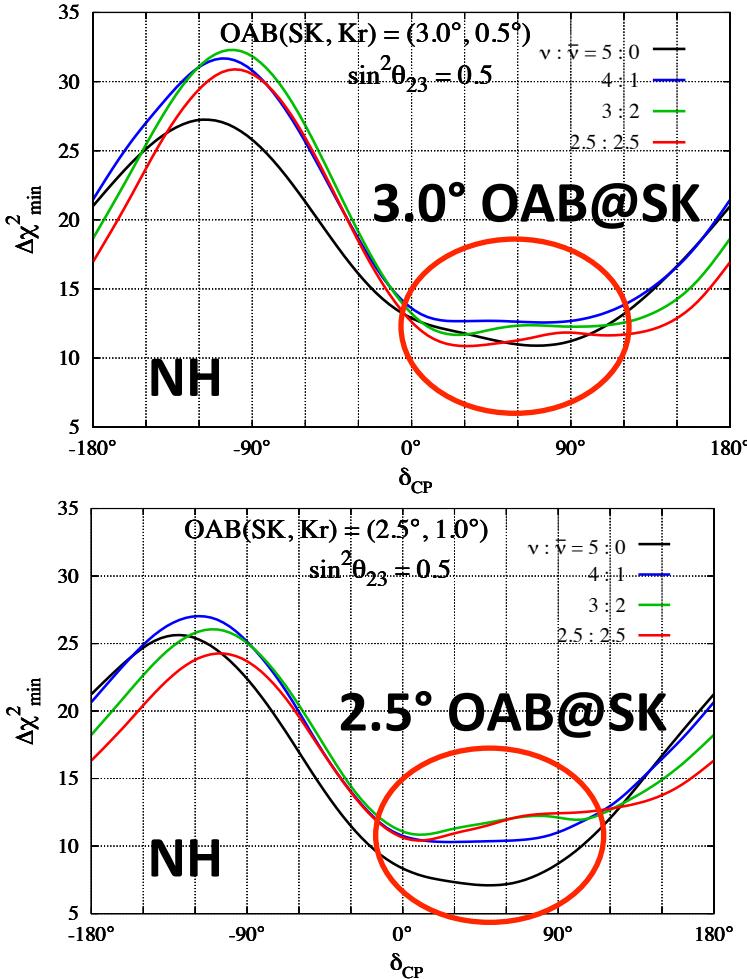
Total events
CCQE signal
non-CCQE signal
NC π^0 BG
miss-ID neutrino BG

T2KK and T2KO
can observe the
2nd oscillation peak
as well as the 1st peak.

Results

MH sensitivity with ν and $\bar{\nu}$ beam (T2KK)

The lowest sensitivity can be improved by including $\bar{\nu}_\mu$ beam.



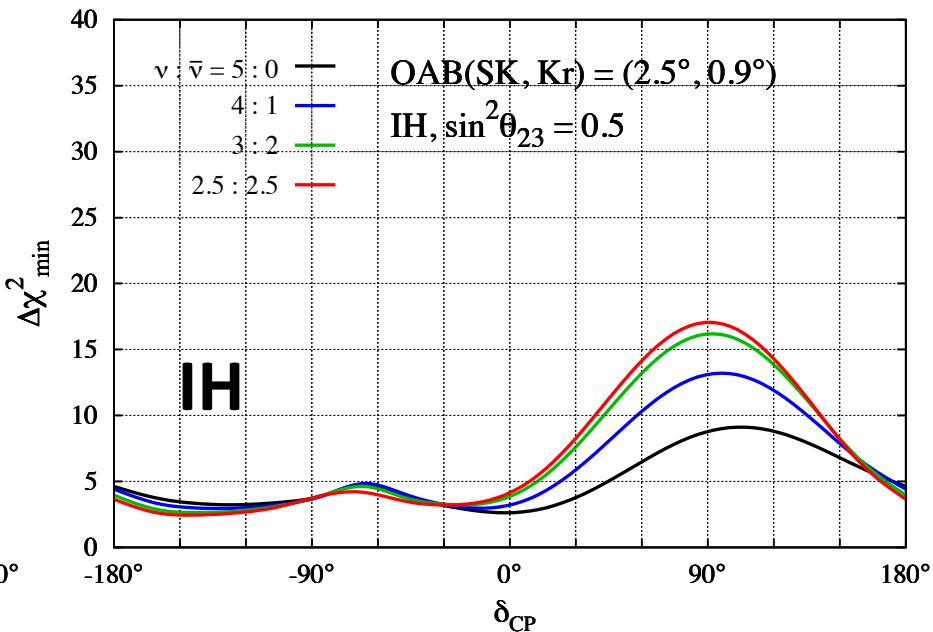
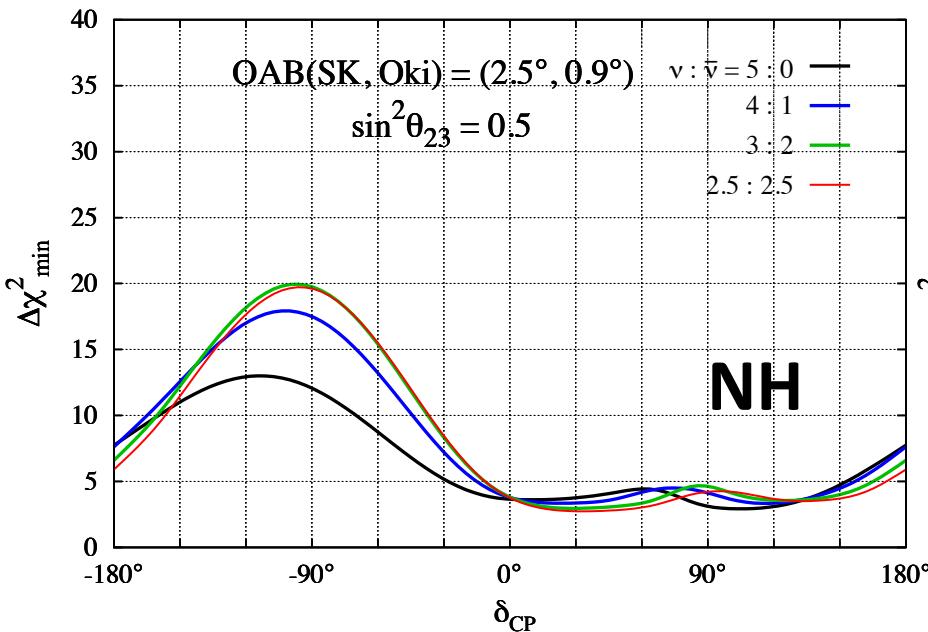
~20% improvement for 3.0° OAB@SK (4:1) in 5 years run.

~40% improvement for 2.5° OAB@SK (3:2 – 2.5:2.5) in 5 years run.

MH sensitivity with ν and $\bar{\nu}$ beam (T2KO)

The lowest sensitivity is not improved by including $\bar{\nu}_\mu$ beam.

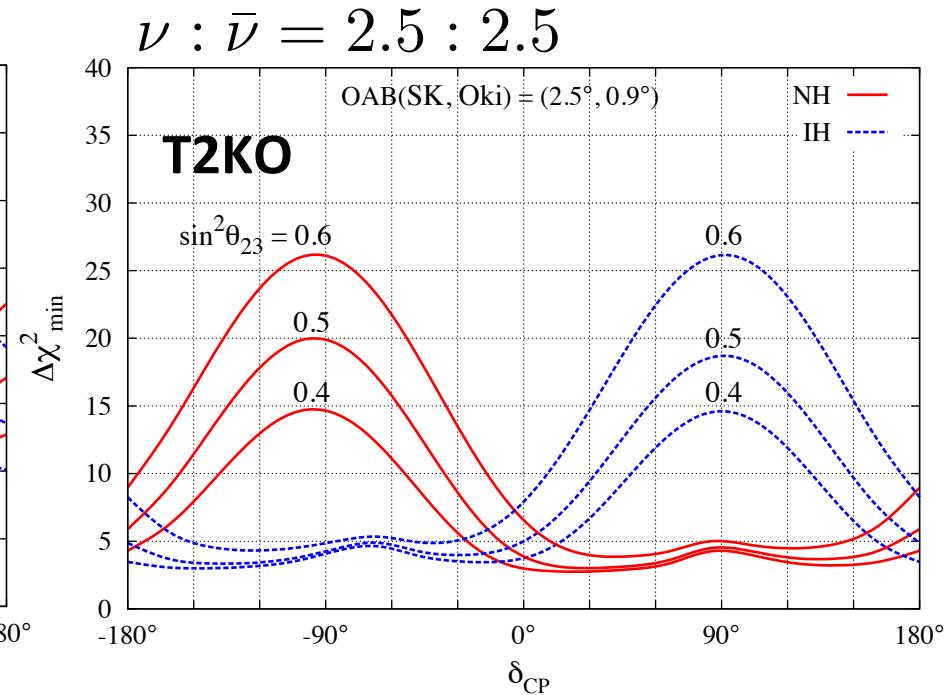
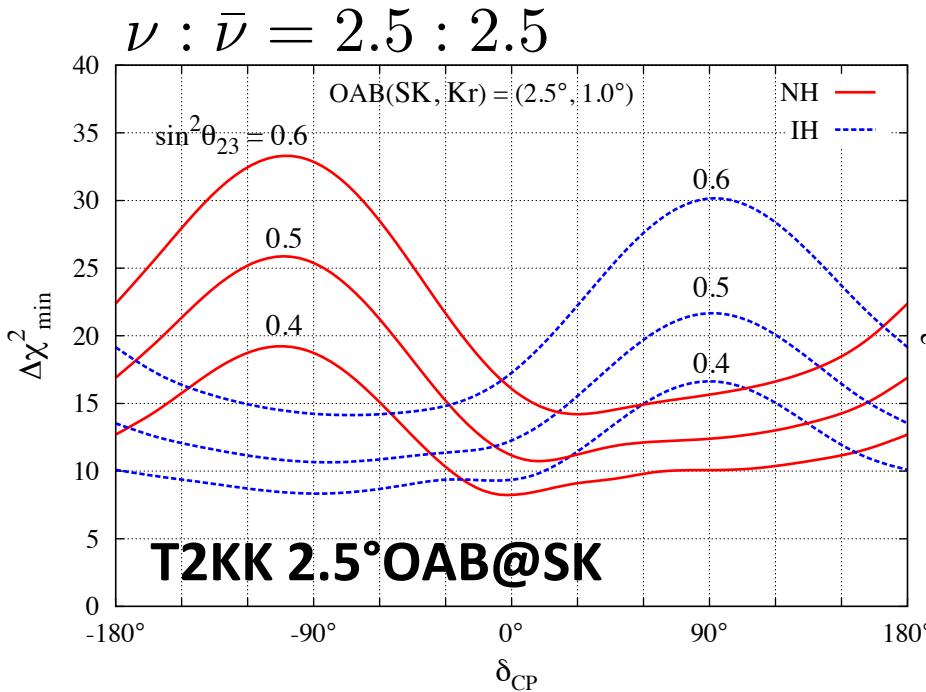
But over all sensitivity tends to be improved.



3:2 – 2.5:2.5 beam ratio is preferred for T2KO.

θ_{23} dependence

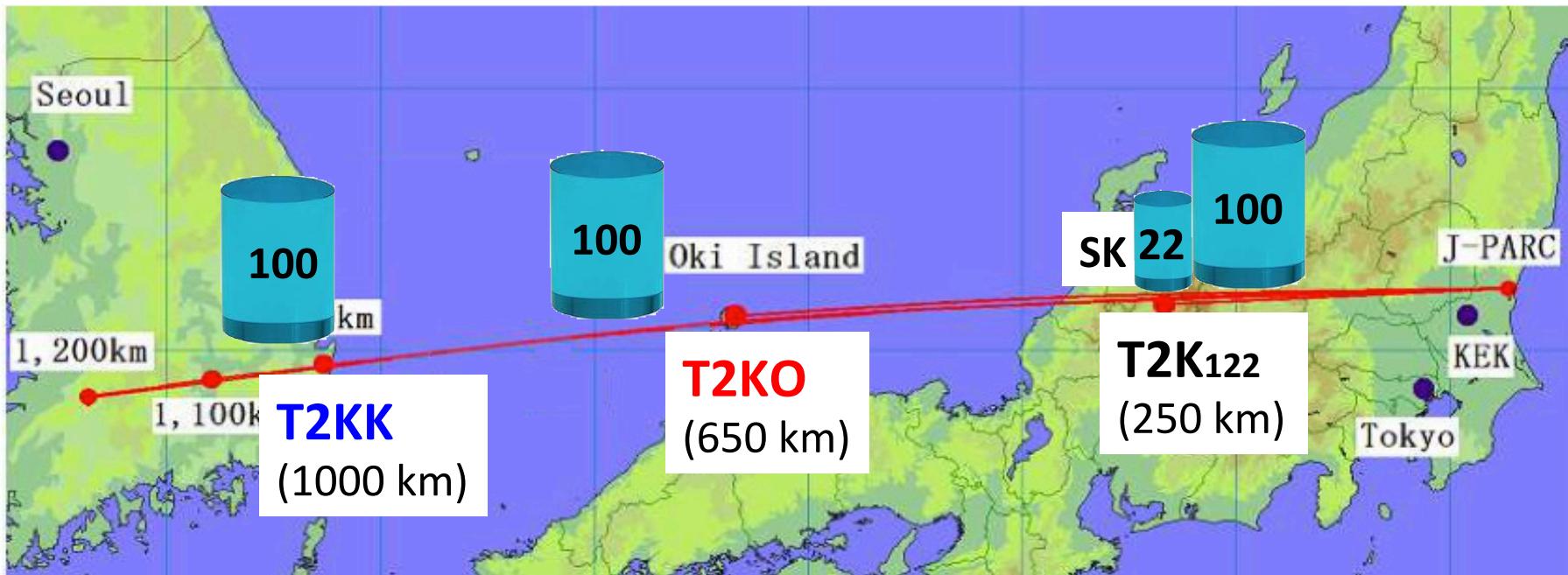
The sensitivity to the mass hierarchy depends on θ_{23} .



$\Delta\chi^2_{\min}$ degrades 30% – 40% when $\sin^2\theta_{23}$ decreases by 0.1.

Sensitivity to CP phase

We also consider T2K (22.5kton) +100kton experiment
@ Kamioka (**T2K₁₂₂**) as a reference for CP phase sensitivity.



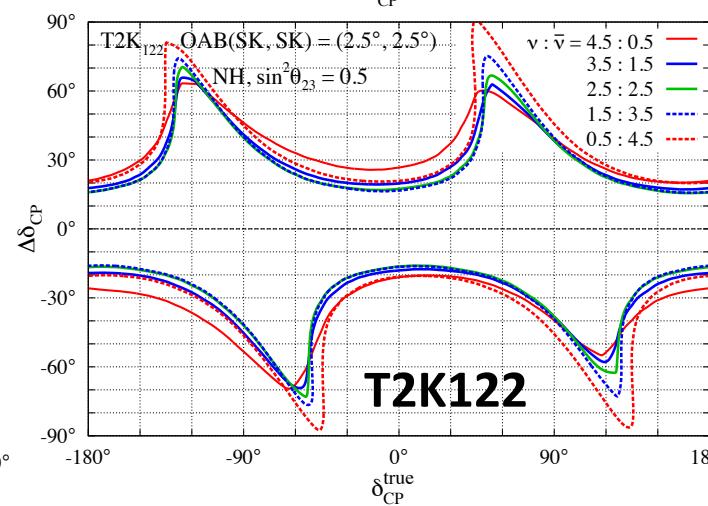
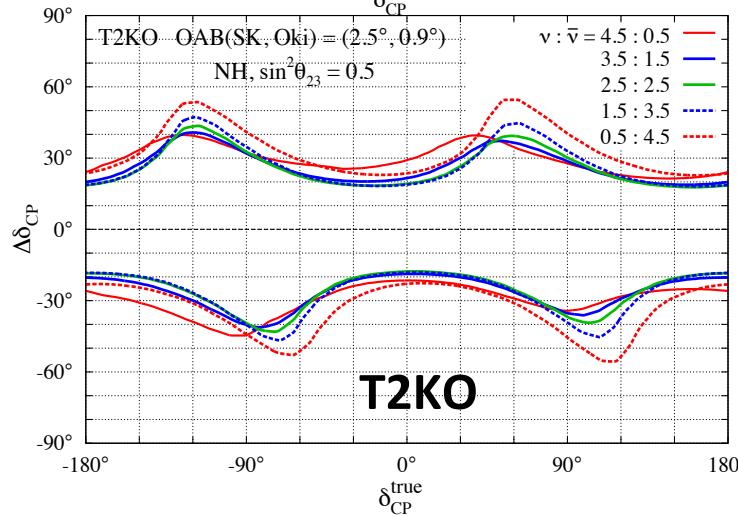
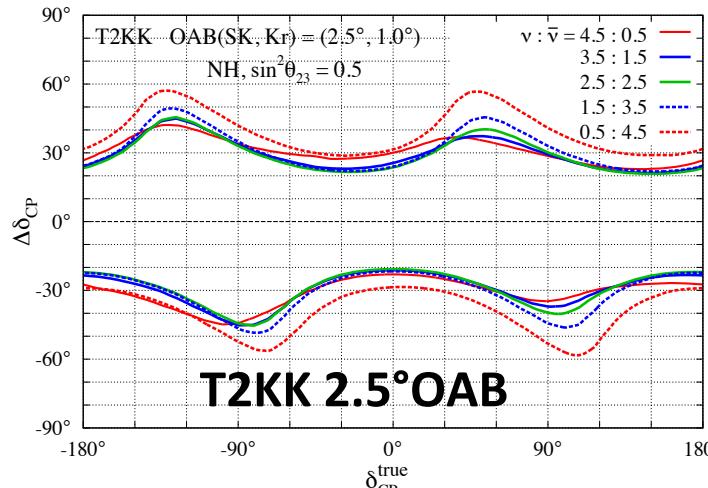
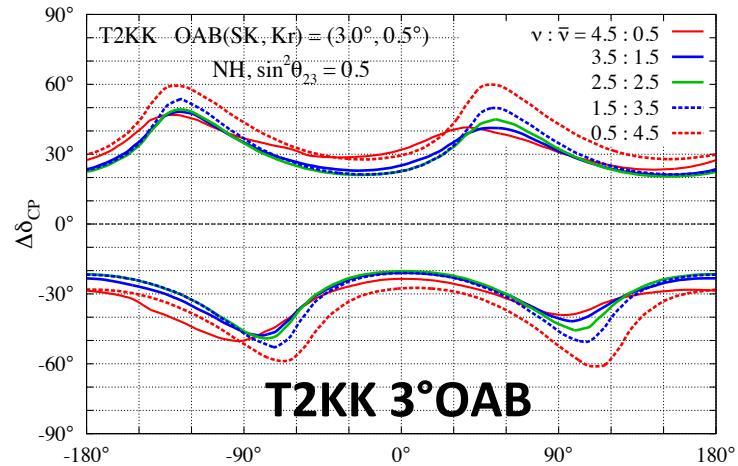
T2KK: 100 kton in **Korea** [hep-ph/0410229, 0504026, 0901.1517, 1001.5165]

T2KO: 100 kton in **Oki island** [0804.2111, 1209.2763]

* **SK** (22.5kton) is also used as a second detector

CP measurement with ν and $\bar{\nu}$ beam

CP phase measurement is also affected by including $\bar{\nu}_\mu$ beam.



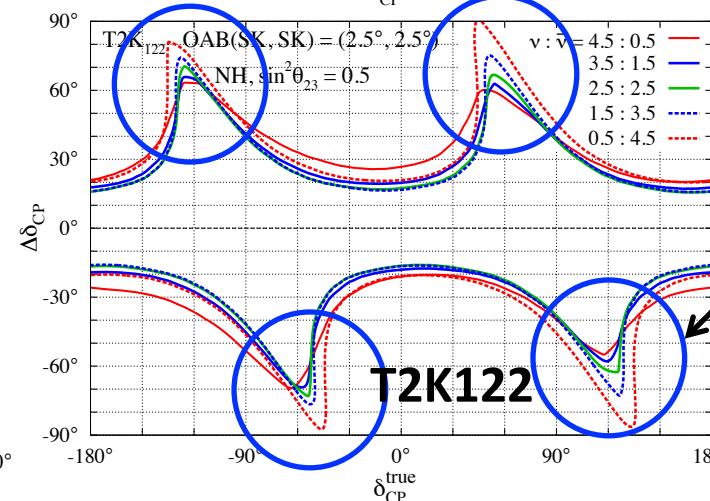
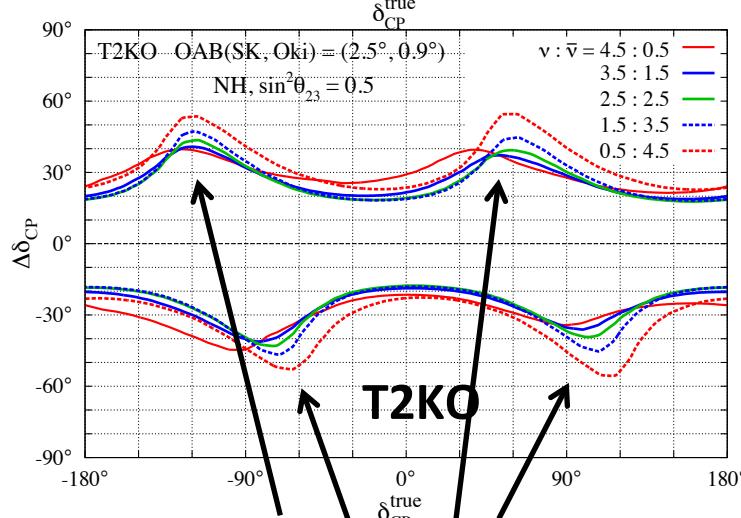
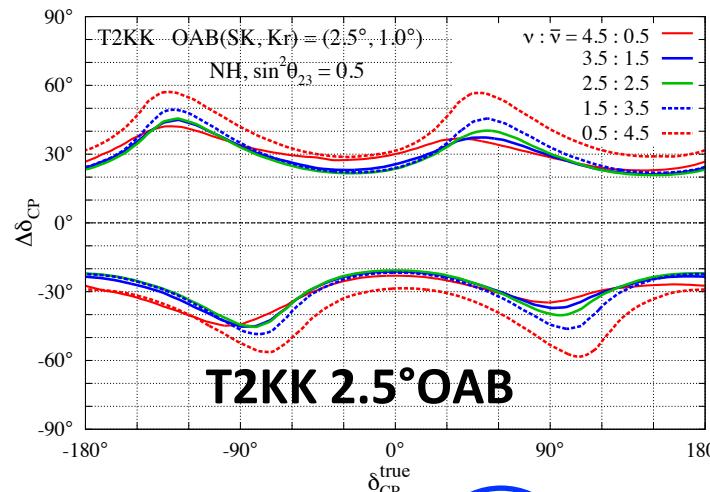
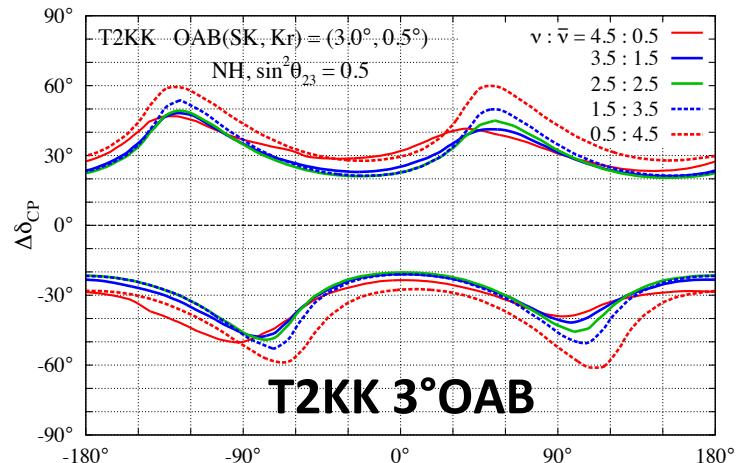
δ_{CP} measurement around 0° , 180° is improved.
 around $\pm 60^\circ$, $\pm 120^\circ$ is degraded.



due to
 $\sin \delta_{CP}$ term

CP measurement with ν and $\bar{\nu}$ beam

Longer baseline helps to resolve δ_{CP} and $\pi - \delta_{\text{CP}}$ degeneracy in $\sin \delta_{\text{CP}}$.



Poor accuracy
due to the
degeneracy

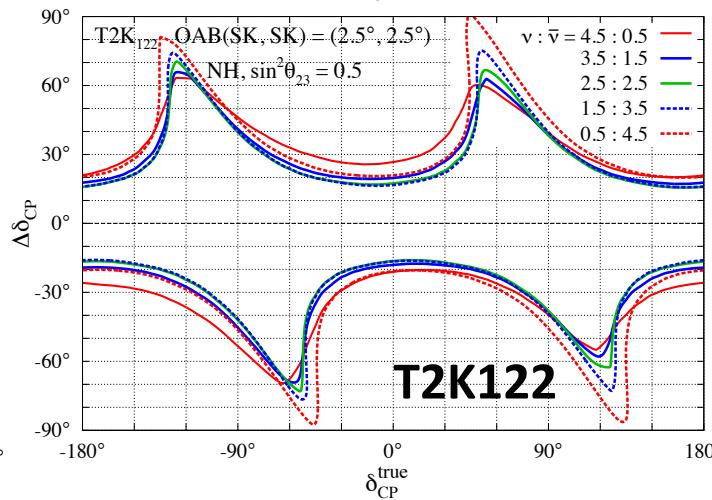
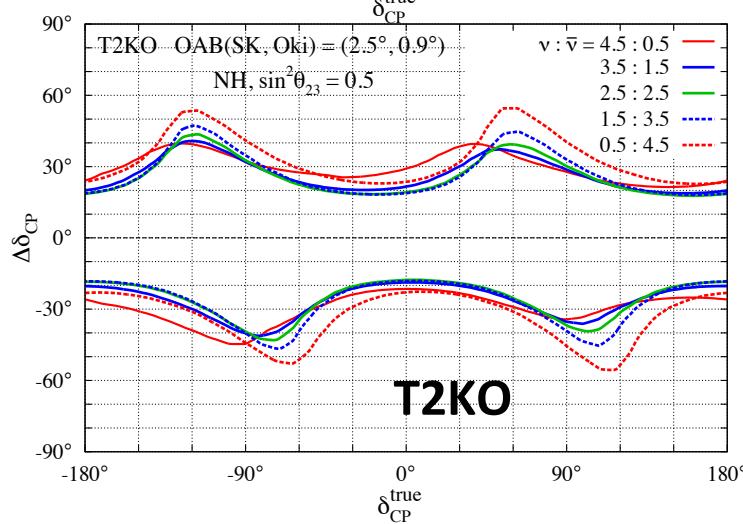
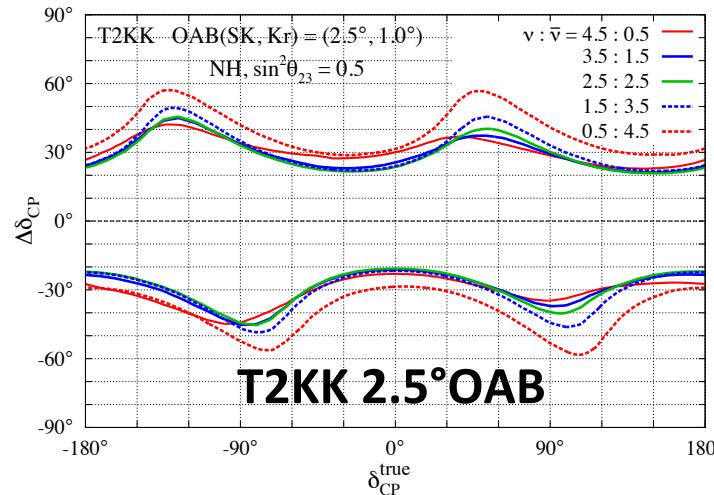
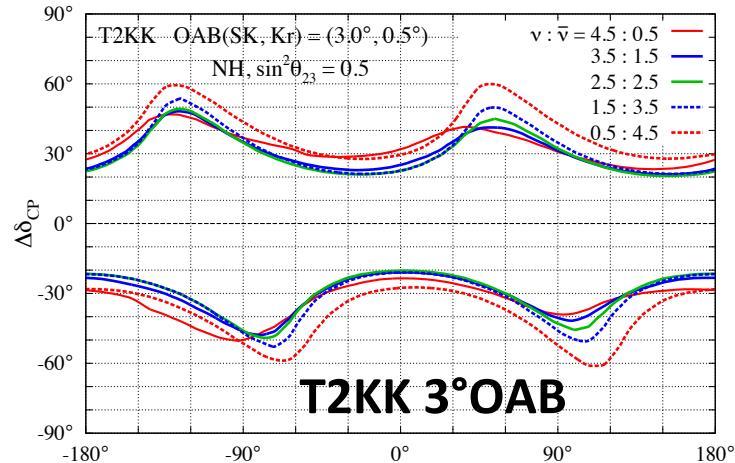
T2KK & T2KO have better sensitivity than T2K122
around $\pm 60^\circ, \pm 120^\circ$.



due to
 $\cos \delta_{\text{CP}}$ term

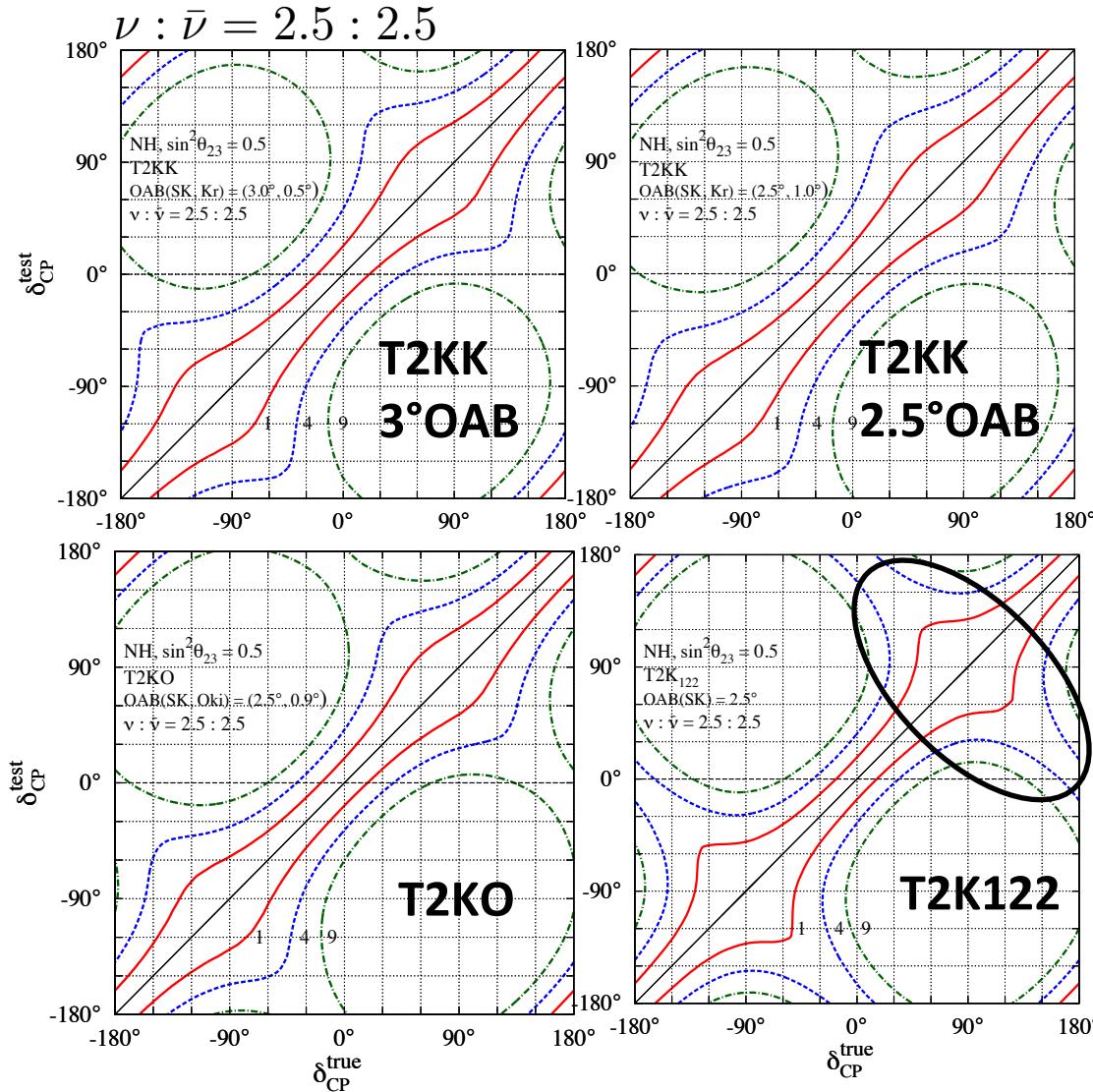
CP measurement with ν and $\bar{\nu}$ beam

Using around **2.5:2.5** beam ratio, CP phase can be measured with $20^\circ - 50^\circ$ (T2KK) and $20^\circ - 45^\circ$ (T2KO) accuracy.



Sensitivity to CP phases (global picture)

The sensitivity to the CP phase measurement is fully expressed in test δ_{CP} vs. true δ_{CP} plane.



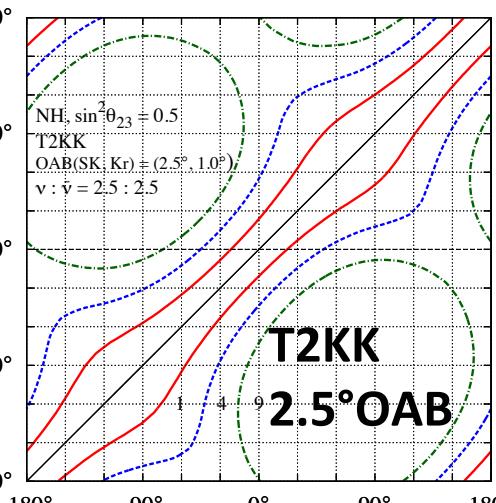
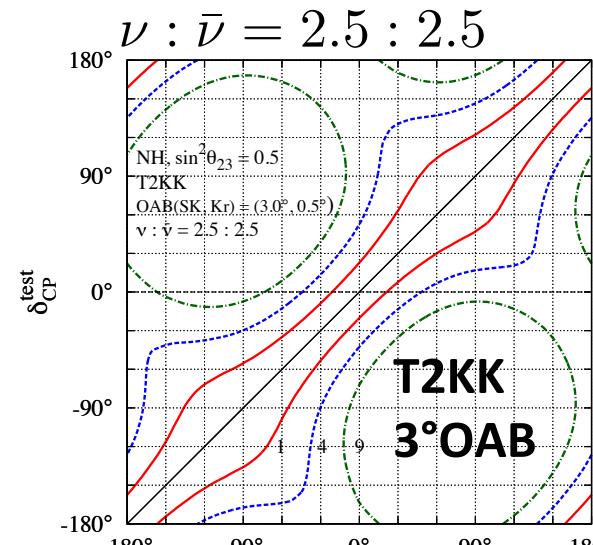
Exclusion contours

— $\Delta\chi^2_{\min} = 1$ — $\Delta\chi^2_{\min} = 4$ — $\Delta\chi^2_{\min} = 9$

↑ corresponds to
CP measurement accuracy
in previous slides

δ_{CP} and $\pi - \delta_{\text{CP}}$
degeneracy is clearly seen.

Sensitivity to CP violation detection

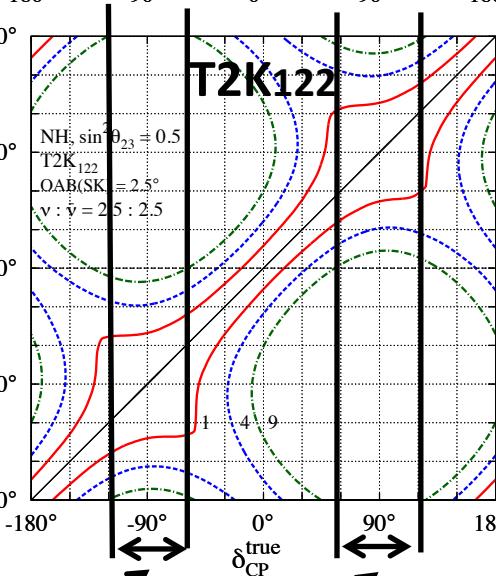
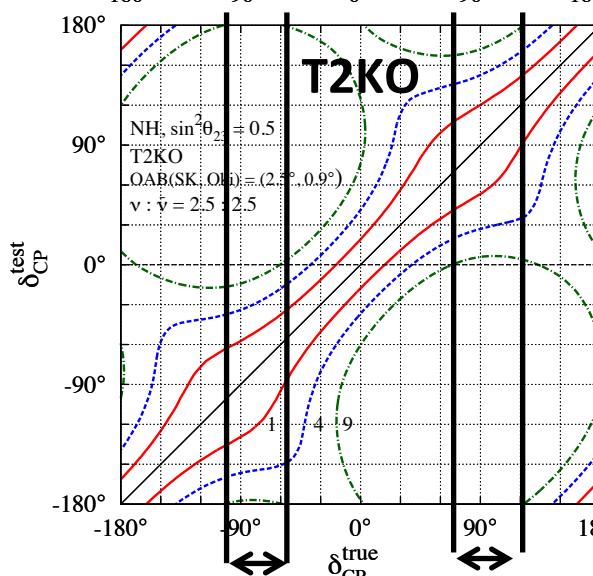


Exclusion contours

- $\Delta \chi^2_{\min} = 1$
- $\Delta \chi^2_{\min} = 4$
- $\Delta \chi^2_{\min} = 9$

$\sin \delta_{CP} \neq 0 \rightarrow \text{CPV}$

The region of the CPV detection is also clearly seen.



CPV detection with $\Delta \chi^2_{\min} > 9$

Sensitivity to CPV in 5years

$$\Delta \chi^2_{\min} > 9$$

for 33% of δ_{CP} (T2K₁₂₂)

for 25% of δ_{CP} (T2KO)

$$\Delta \chi^2_{\min} > 4$$

for 45% of δ_{CP} (T2KK)

CPV sensitivity:

T2K₁₂₂ > T2KO > T2KK

→ Statistics matters

Summary of this study

We revisited the sensitivity of T2KK and T2KO proposals to neutrino mass hierarchy and leptonic CP phase with
nu and anti-nu beam
realistic pi0 background estimation

MH

The sensitivity is significantly improved by including anti-nu beam ($\text{nu} : \text{anti-nu} = 4:1 - 2.5:2.5$ (in 10^{21} POT)). Especially for CP phase of -90 deg. (NH) and 90 deg. (IH).

T2KK has sensitivity of $\Delta\chi^2_{\min} = 10 - 30$ (3° OAB @ SK, $\text{th23} = 0.5$).
T2KO has sensitivity of $\Delta\chi^2_{\min} = 3 - 20$ (2.5° OAB @ SK, $\text{th23} = 0.5$).

CP phase

The sensitivity is slightly improved.

If MH is determined,

T2KK measures δ_{CP} with $\pm 20^\circ - \pm 50^\circ$ uncertainty.
T2KO measures δ_{CP} with $\pm 20^\circ - \pm 45^\circ$ uncertainty.

Many thanks to Kaoru

- for collaboration on this subject
- for his help for me and other Korean colleagues working in phenomenology during the past ~20 years