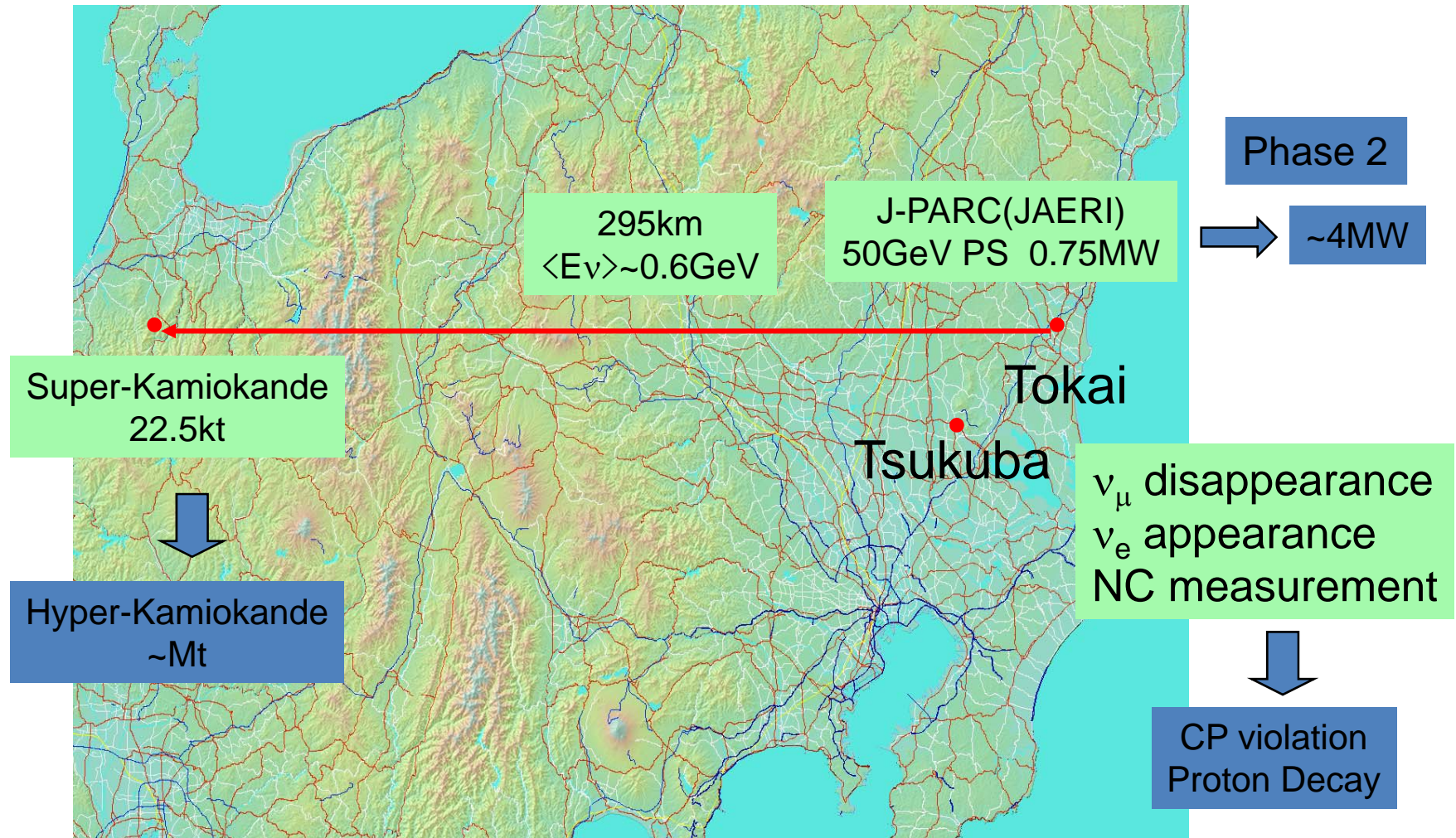


CP violation Physics at a J-PARC Beam – Water Cherenkov Detector

Kenji Kaneyuki
Univ. of Tokyo,
Institute for Cosmic Ray Research,
Research Center for Cosmic Neutrinos

What should be considered
and
improved for CP study.

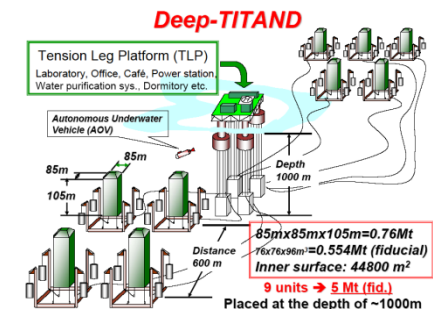
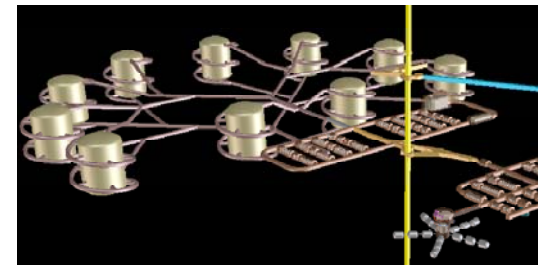
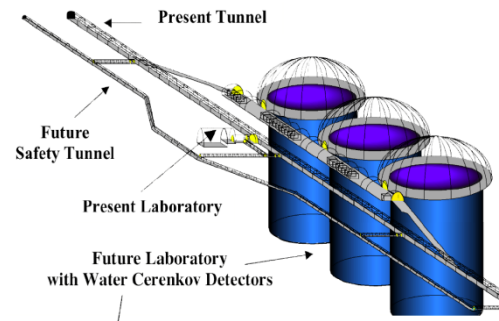
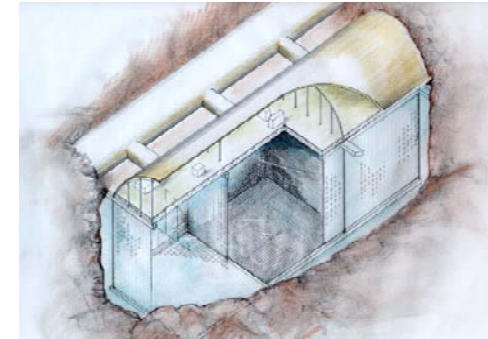
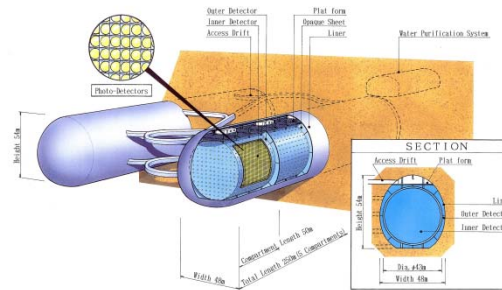
T2K Phase-II



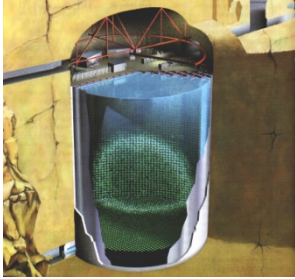
Next generation Water Cherenkov neutrino and proton decay detector

Characteristics of Water Cherenkov detector

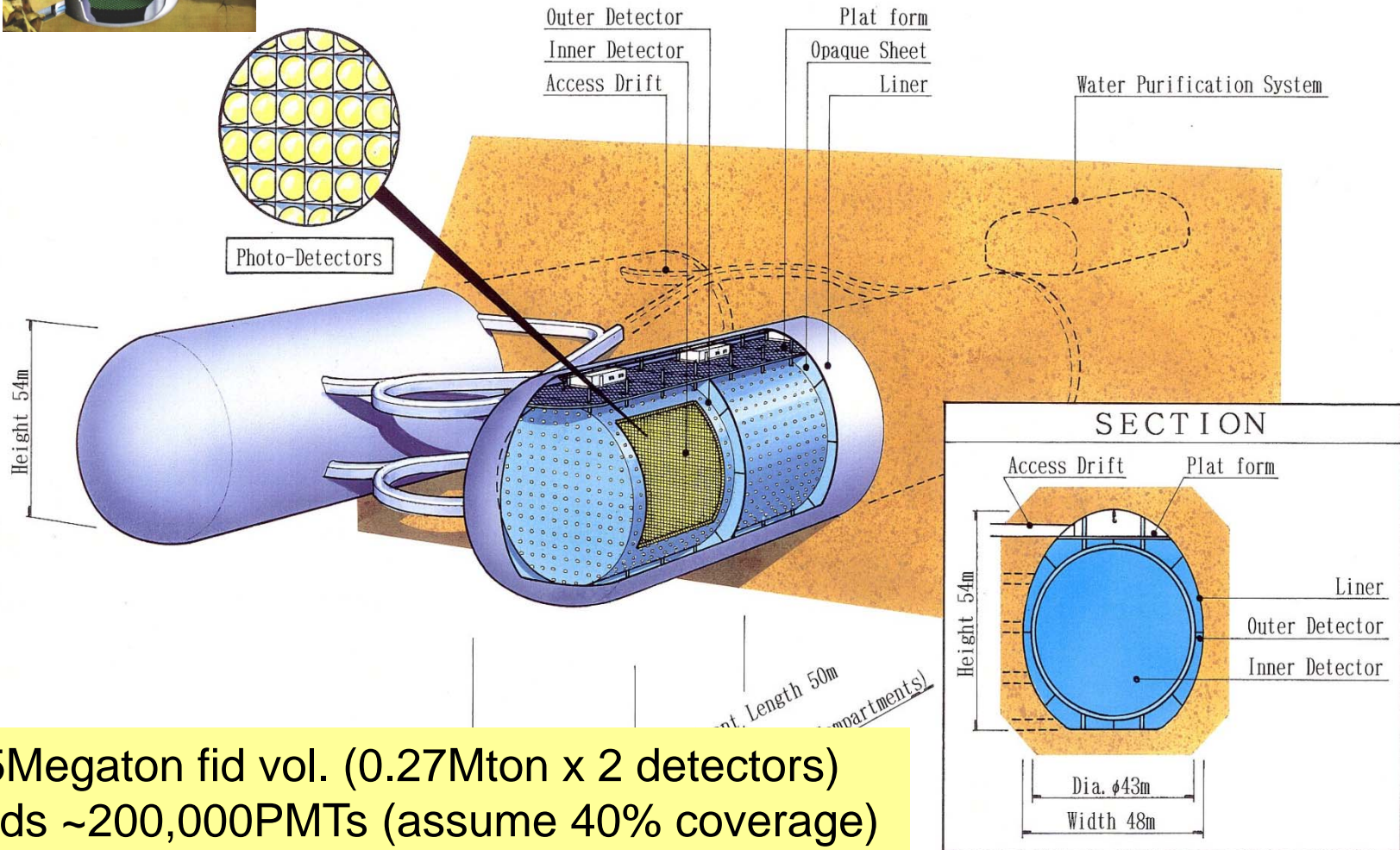
- Easy to enlarge
Mton class detector
- Good tracking at $\sim 1\text{ GeV}$
- Good Particle identification
- Good Energy resolution
- Hardware and Software are already well established.



Hyper-Kamiokande



Super-K 22kton



~0.5Megaton fid vol. (0.27Mton x 2 detectors)
Needs ~200,000PMTs (assume 40% coverage)

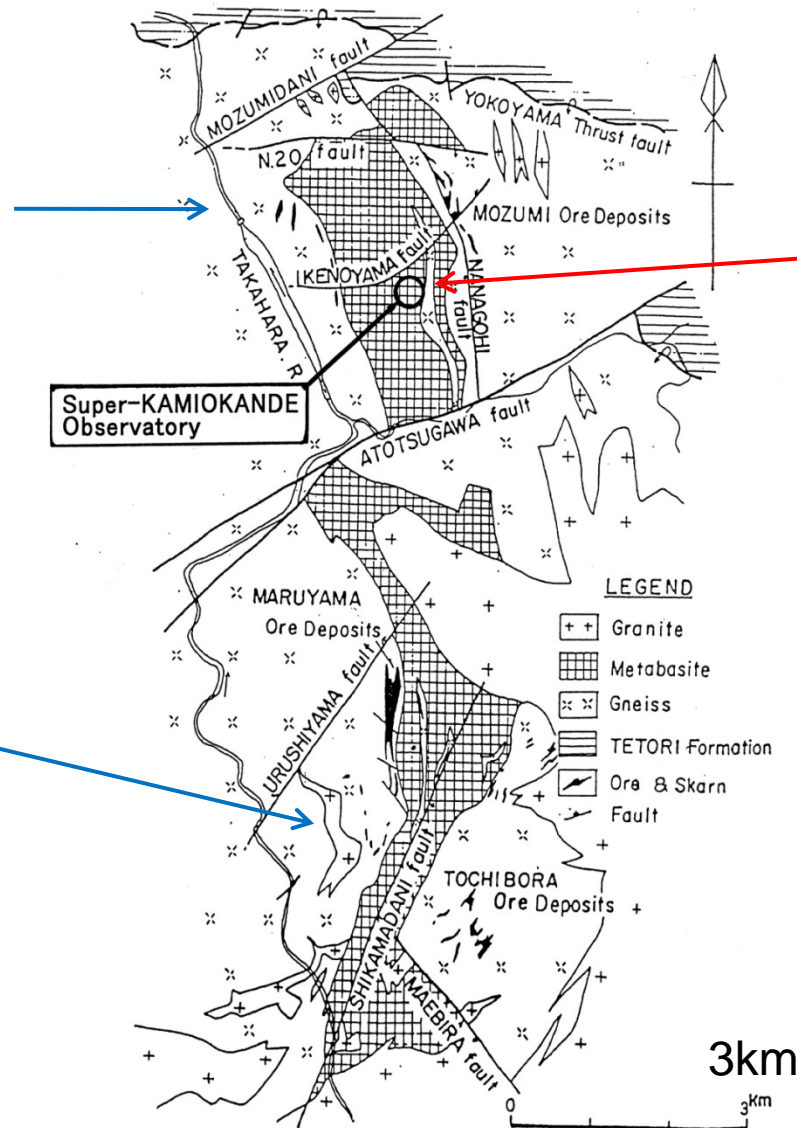
Geological map of Kamioka Mine

GEOLOGY AND ORE DEPOSITS OF KAMIOKA MINE

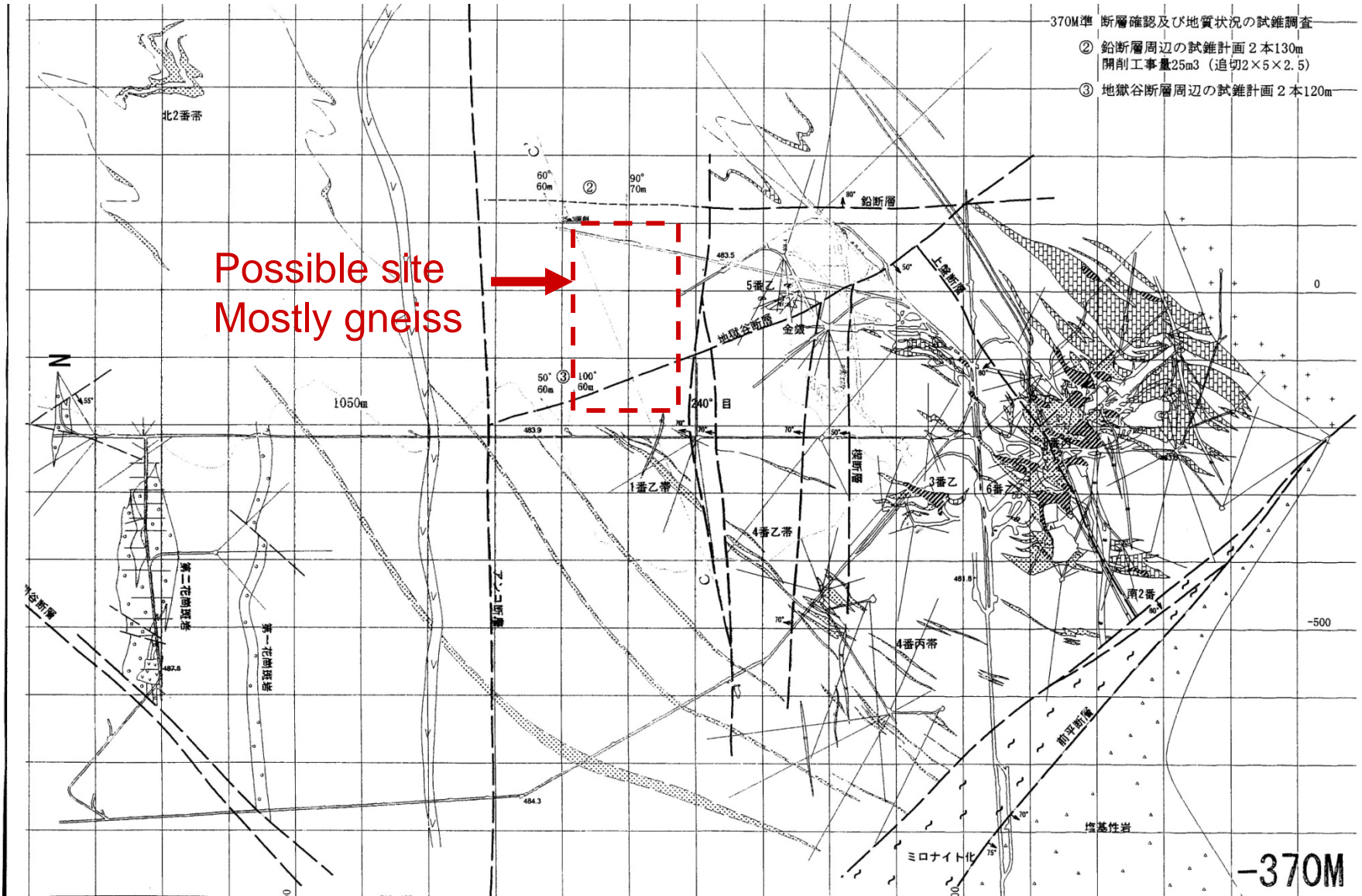
Mozumi Mine

Super-Kamiokande

Tochibora Mine

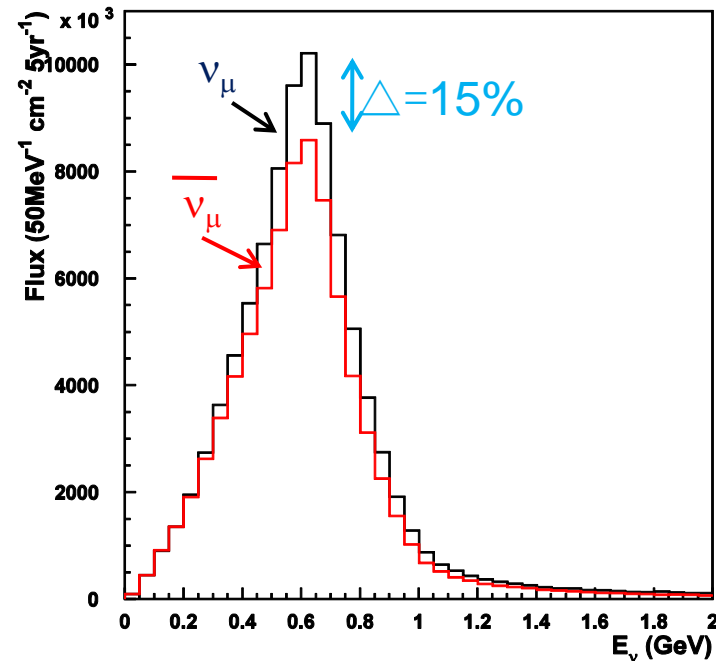
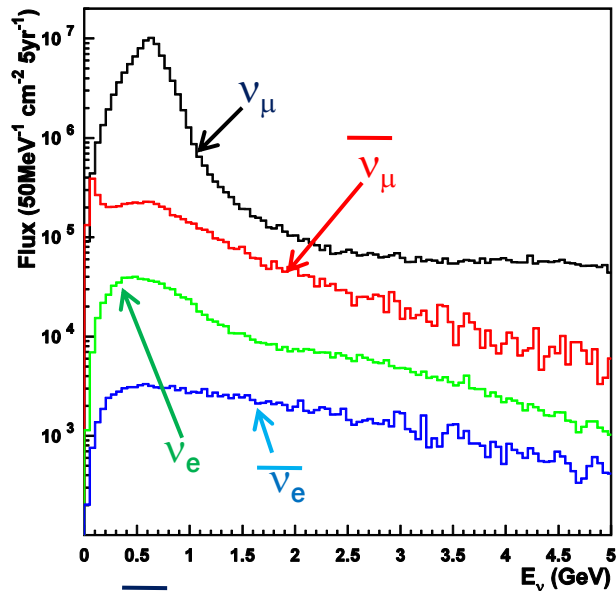


Tochibora Mine



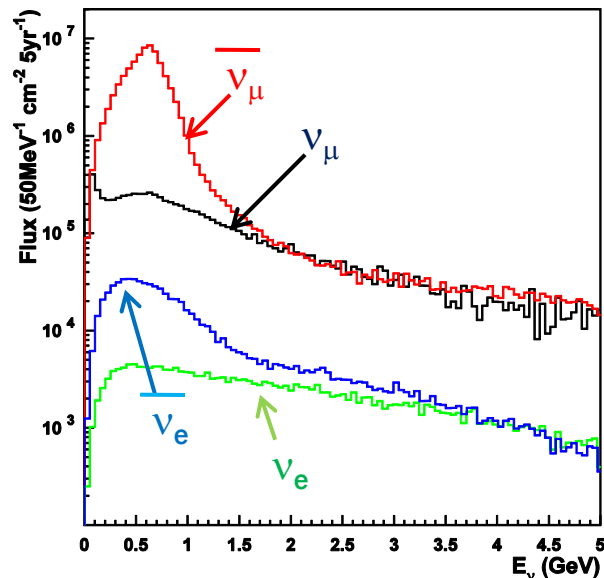
ν and $\bar{\nu}$ beam@J-PARC

ν run



ν_{μ} and ν_e contribution in $\bar{\nu}_{\mu}$ beam
flux difference btw ν_{μ} and $\bar{\nu}_{\mu}$ = 15%

$\bar{\nu}$ run



ν flux :

07a: $E_p=30\text{GeV}$, off-axis 2.5 degree

Decay volume : 110m

target diameter : 26mm

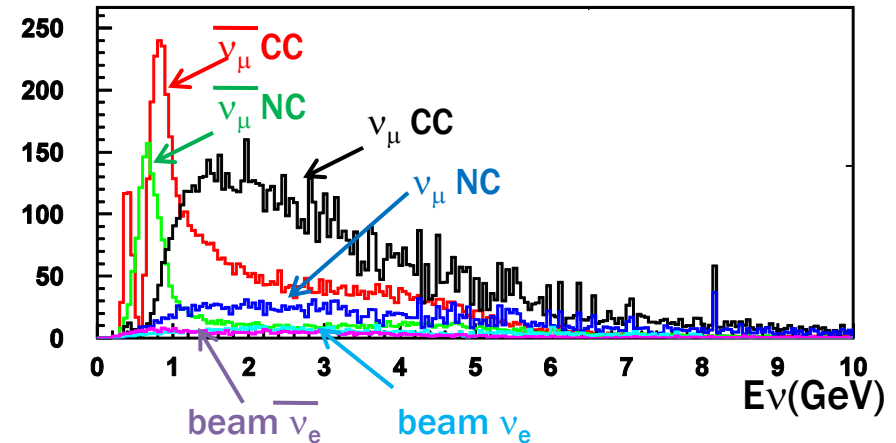
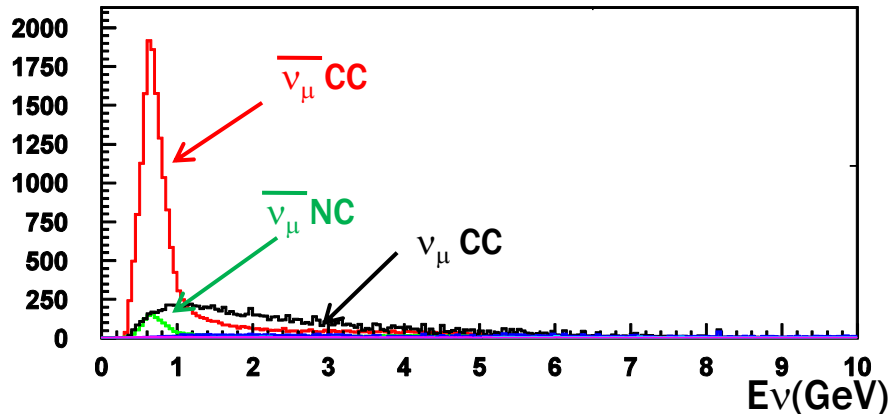
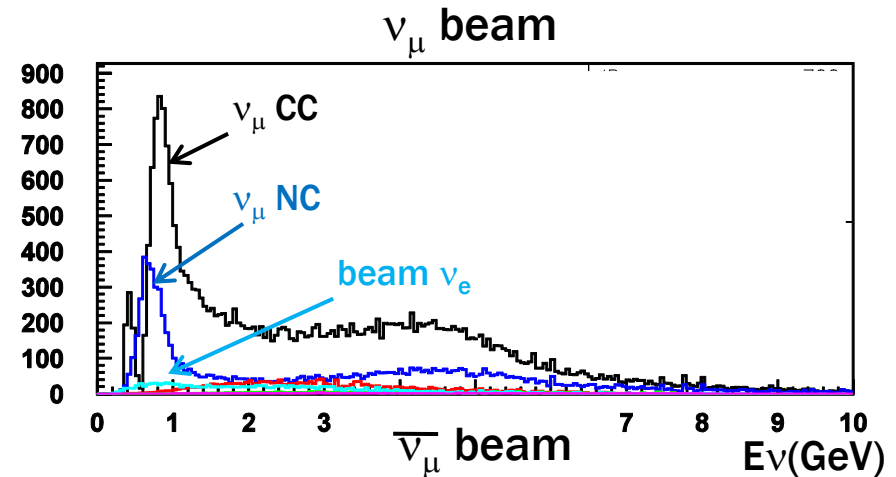
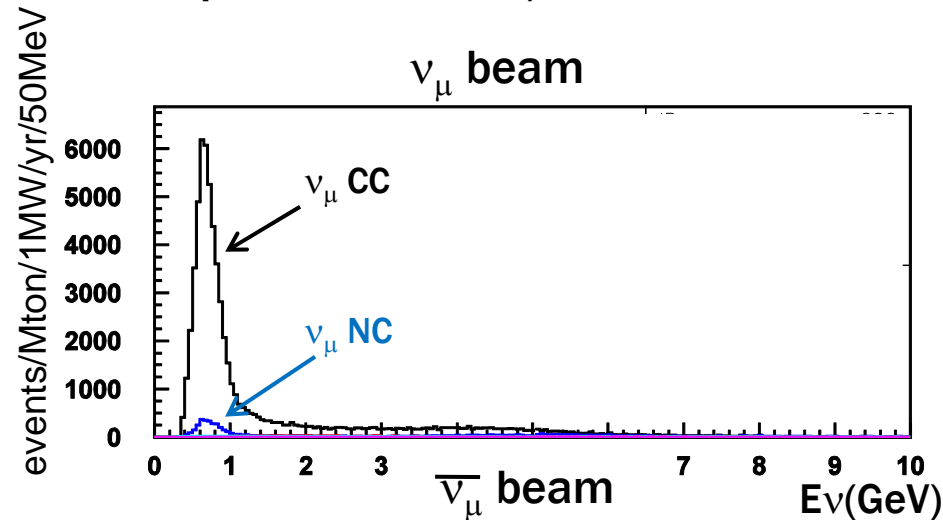
5yr = 8.33×10^{21} POT

(which corresponds to 5×10^{21} POT at 50GeV)

expected event rate @ Mton Water Cherenkov detector

expected events w/o ν oscillation

expected events with ν oscillation



ν_μ and ν_e in $\bar{\nu}_\mu$ beam should be carefully considered.

Assumed parameter for this study

- **$L=295\text{km}$ (J-PARC – Mozumi or Tochibora)**
- **$\Delta m_{12}^2=7.6 \times 10^{-5}\text{eV}^2$**
- **$\Delta m_{13}^2=2.4 \times 10^{-3}\text{eV}^2$**
- **$\sin^2\theta_{12}=0.32$**
- **$\sin^2\theta_{23}=0.50$**

Maltoni, Schwetz, Tortola, Valle,
hep-ph/0405172, 2007 updated

Oscillation probability

- $\nu_\mu \rightarrow \nu_\mu$

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_\mu) = & 1 - 4(C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 - 2C_{12} C_{23} S_{12} S_{13} S_{23} \cos \delta) S_{23}^2 C_{13}^2 \cdot \sin^2 \Delta_{23} \\
 & - 4(S_{12}^2 C_{23}^2 + C_{12}^2 S_{13}^2 S_{23}^2 + 2C_{12} C_{23} S_{12} S_{13} S_{23} \cos \delta) S_{23}^2 C_{13}^2 \cdot \sin^2 \Delta_{13} \\
 & - 4(C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 - 2C_{12} C_{23} S_{12} S_{13} S_{23} \cos \delta) \\
 & \times (C_{12}^2 C_{23}^2 + S_{12}^2 S_{13}^2 S_{23}^2 + 2C_{12} C_{23} S_{12} S_{13} S_{23} \cos \delta) \cdot \sin^2 \Delta_{12}
 \end{aligned}$$

- $\nu_\mu \rightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \left(1 + \frac{2a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \right) \cdot \sin^2 \Delta_{31}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \quad \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \quad \text{CP}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \quad \text{solar } \nu$$

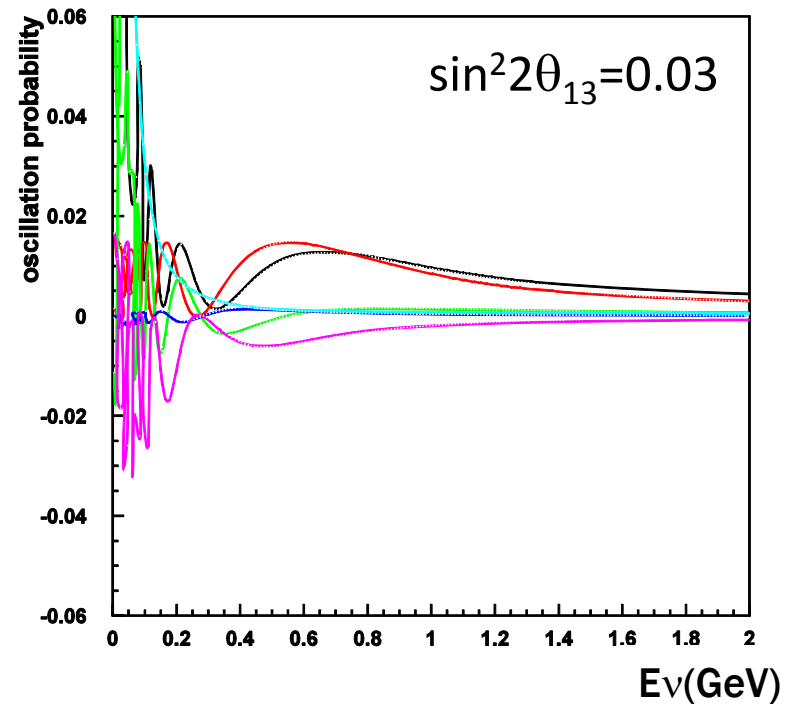
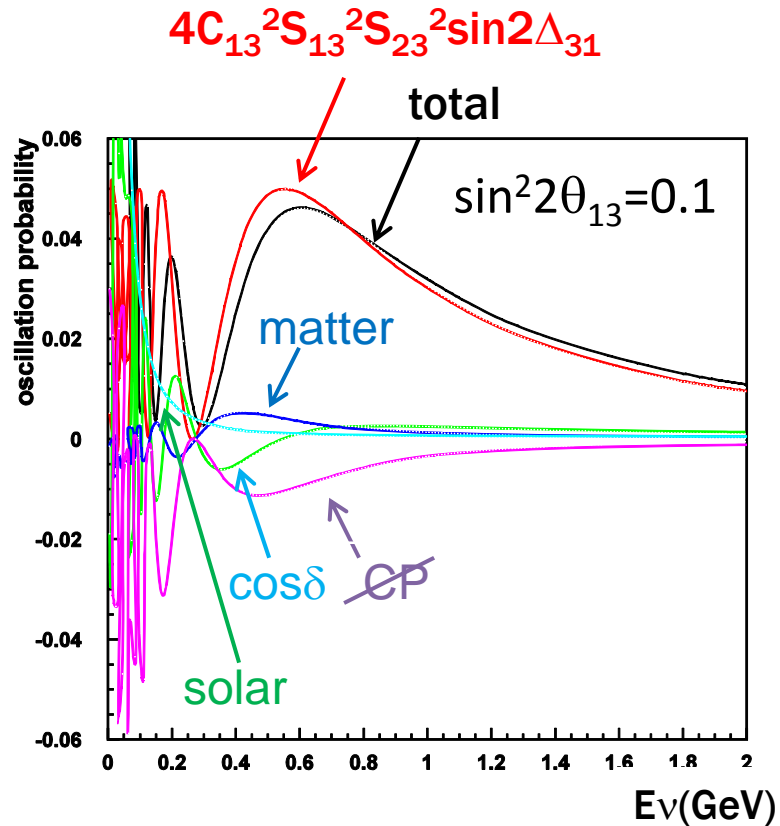
$$- 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \quad \text{matter effect}$$

- $\nu_e \rightarrow \nu_e$

$$P(\nu_e \rightarrow \nu_e) = 1 - 4C_{13}^2 S_{13}^2 \cdot (C_{12}^2 \sin^2 \Delta_{13} + S_{12}^2 \sin^2 \Delta_{23}) - 4S_{12}^2 C_{12}^2 C_{13}^4 \sin^2 \Delta_{12}$$

$$a = 7.6 \times \left(\frac{\rho}{[g/cm^3]} \right) \left(\frac{E}{[GeV]} \right) [eV^2]$$

Oscillation probability as a function of $E\nu$



$$\left[\begin{array}{l} L=295\text{km} \\ d=\pi/4 \end{array} \right]$$

~~CP~~ analysis

event selection

- Fully contained event in fiducial volume
- $E_{\text{vis}} > 100 \text{ MeV}$
- 1 ring e-like
- no decay electron
- reconstructed E_{ν} cut
- **e/π^0 separation**
- $\cos\theta_{\mu} < 0.9$ (only for ν_{μ} beam)
- $M_{\pi^0} < 100 \text{ MeV}$

using latest SK MC, tools

number of events on each step

(ν_μ beam 1.66MW 2.2yr $\sin^2 2\theta_{13}=0.1$)

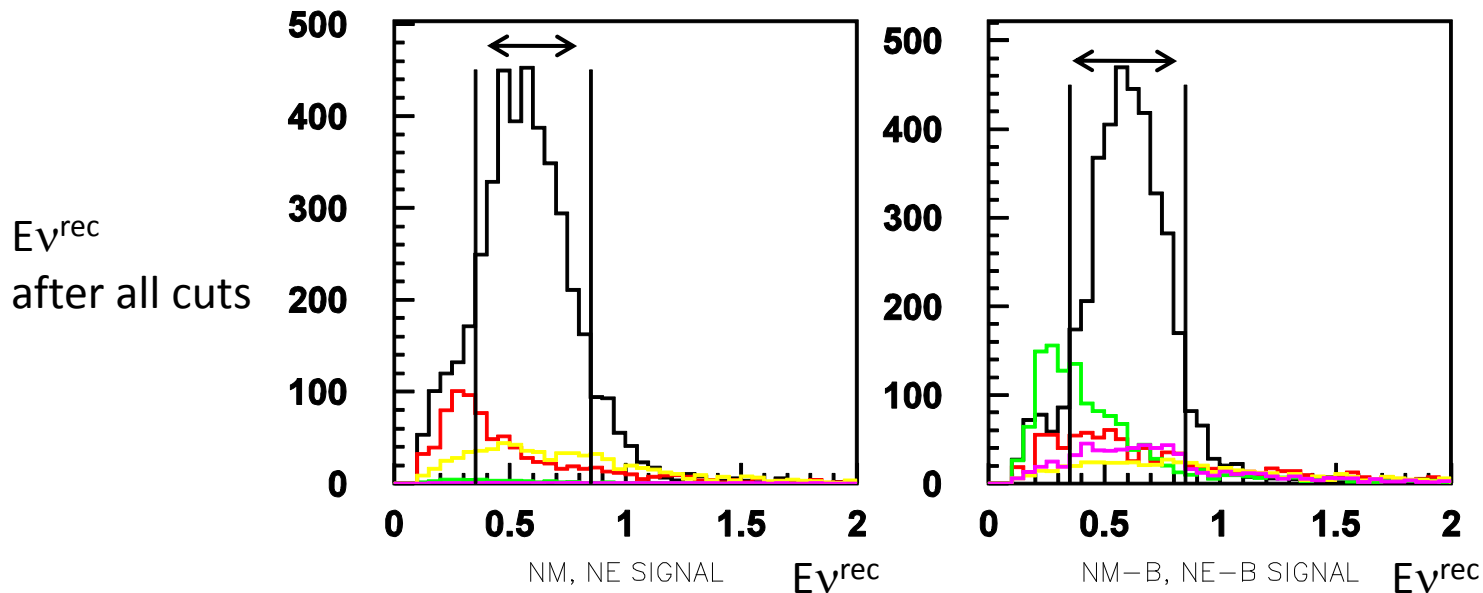
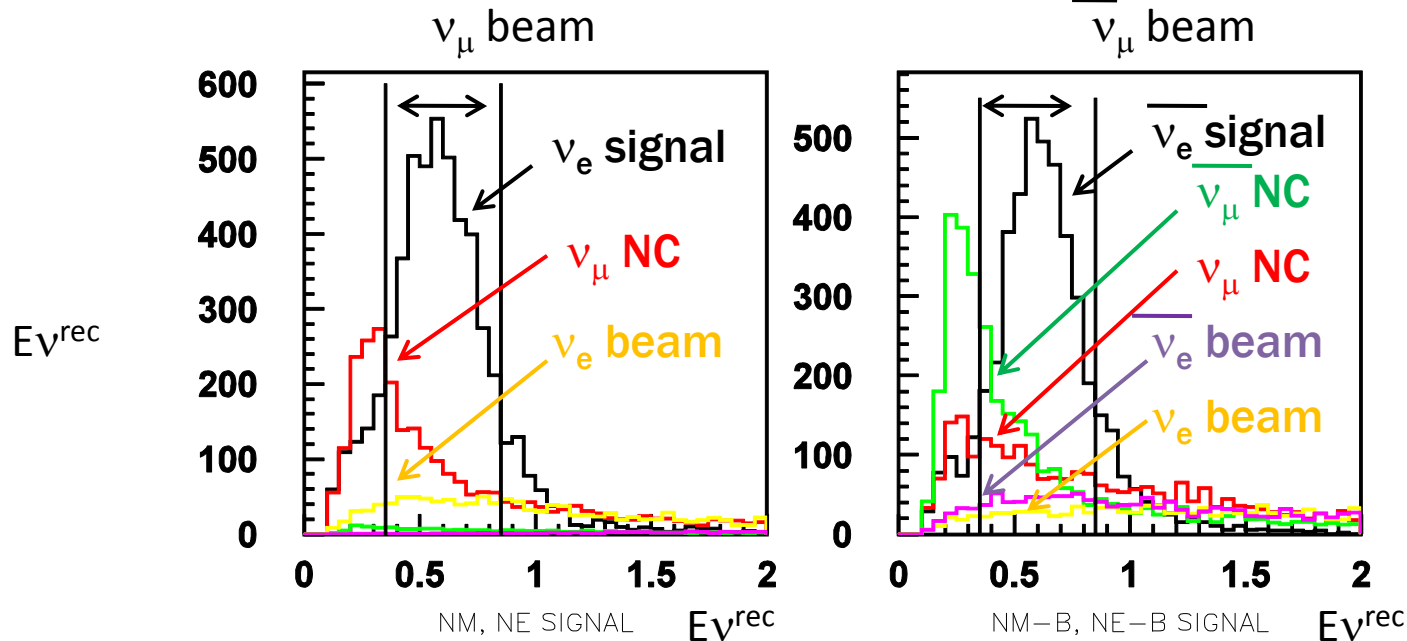
	ν_μ		$\bar{\nu}_\mu$		ν_e	$\bar{\nu}_e$	signal ν_e CC ($\sin^2 2\theta_{13}=0.1$)
	CC	NC	CC	NC			
in Fid. (vector)	72982	75118	7095	2855	4890	555	6756
FC, in Fid. vol. Evis>100MeV	51698 (71%)	18245 (24%)	4783 (67%)	1307 (46%)	4007 (82%)	437 (79%)	6529 (97%)
1ring	27596 (38%)	4316 (5.7%)	3005 (42%)	354 (12%)	2171 (44%)	277 (50%)	5779 (86%)
e-like	1053 (1.4%)	3254 (4.3%)	85 (1.2%)	245 (8.6%)	2112 (43%)	271 (49%)	5685 (84%)
no μ -e decay	373 (0.5%)	2912 (3.9%)	33 (0.5%)	220 (7.7%)	1807 (37%)	259 (47%)	5248 (78%)
$E_{\nu}^{\text{rec}} 0.35-0.85$	28 (0.04%)	1008 (1.3%)	0.9 (0.01%)	70 (2%)	455 (9.3%)	20 (4%)	3991 (59%)
$\cos\theta < 0.9$	22 (0.03%)	713 (1.0%)	0.2	49 (2%)	394 (8%)	12 (2%)	3513 (52%)
$M_{\pi^0} < 100\text{MeV}$	14 (0.02%)	340 (0.5%)	0.2	25 (0.9%)	358 (7%)	10 (2%)	3279 (49%)

number of events on each step

$$(\overline{\nu}_\mu \text{ beam } 1.66\text{MW } 7.8\text{yr } \sin^2 2\theta_{13}=0.1)$$

	ν_μ		$\overline{\nu}_\mu$		ν_e	$\overline{\nu}_e$	signal ν_e CC ($\sin^2 2\theta_{13}=0.1$)
	CC	NC	CC	NC			
in Fid. (vector)	89052	43053	58719	72428	6446	4389	5526
FC, in Fid. vol. Evis>100MeV	65825 (74%)	20041 (47%)	41435 (71%)	16659 (23%)	5498 (85%)	3333 (76%)	5302 (96%)
1ring	27443 (31%)	4878 (11%)	30652 (52%)	4249 (5.9%)	2589 (40%)	2293 (52%)	4783 (87%)
e-like	1486 (1.7%)	3355 (7.8%)	562 (1%)	3319 (8.6%)	2514 (40%)	2247 (51%)	4717 (85%)
no μ -e decay	586 (0.7%)	2801 (6.5%)	209 (0.4%)	3163 (4.5%)	2076 (32%)	2169 (49%)	4701 (85%)
$E_{\nu}^{\text{rec}} 0.35-0.85$	24 (0.03%)	885 (2%)	17 (0.02%)	1154 (2%)	268 (4%)	449 (10%)	3568 (65%)
$M_{\pi^0} < 100\text{MeV}$	9 (0.01%)	433 (1%)	12 (0.02%)	598 (0.8%)	229 (4%)	391 (9%)	3265 (59%)

reconstructed E_ν distribution

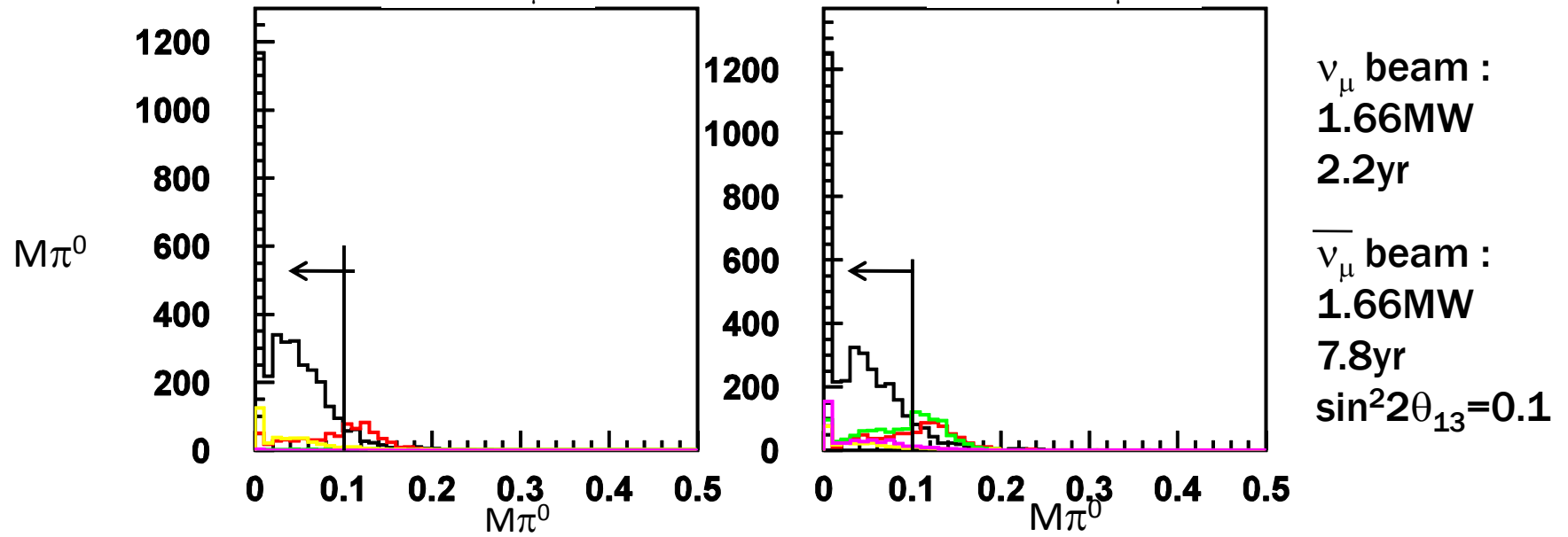
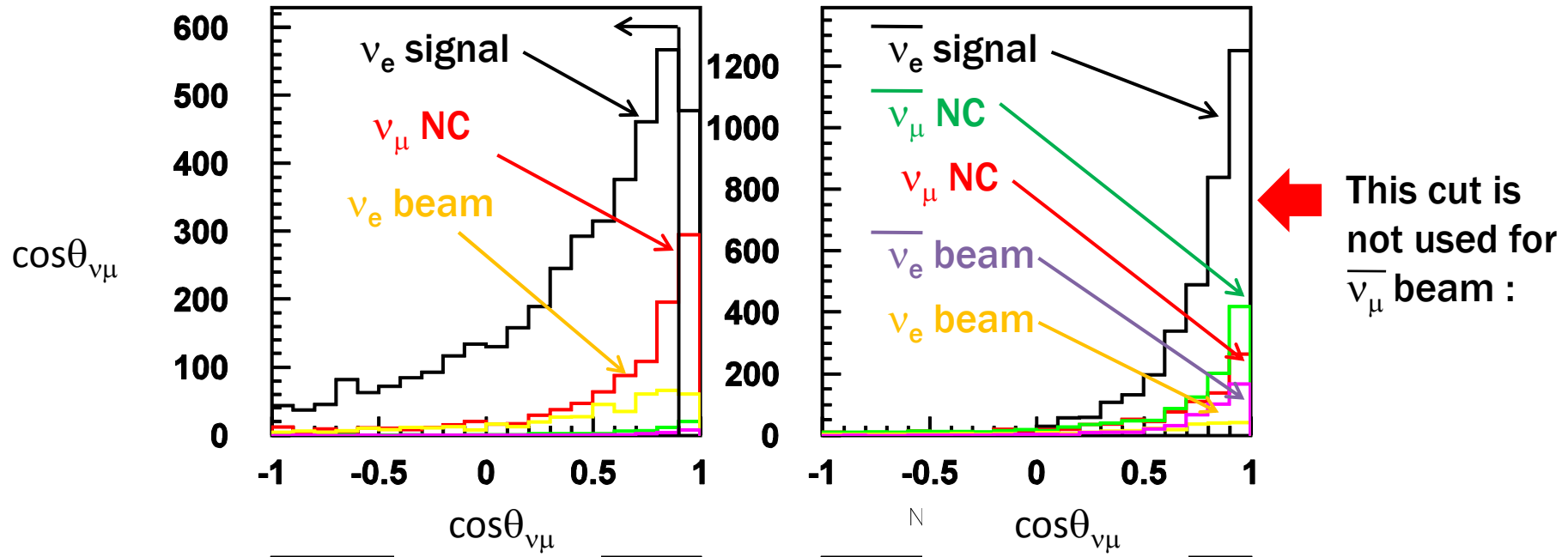


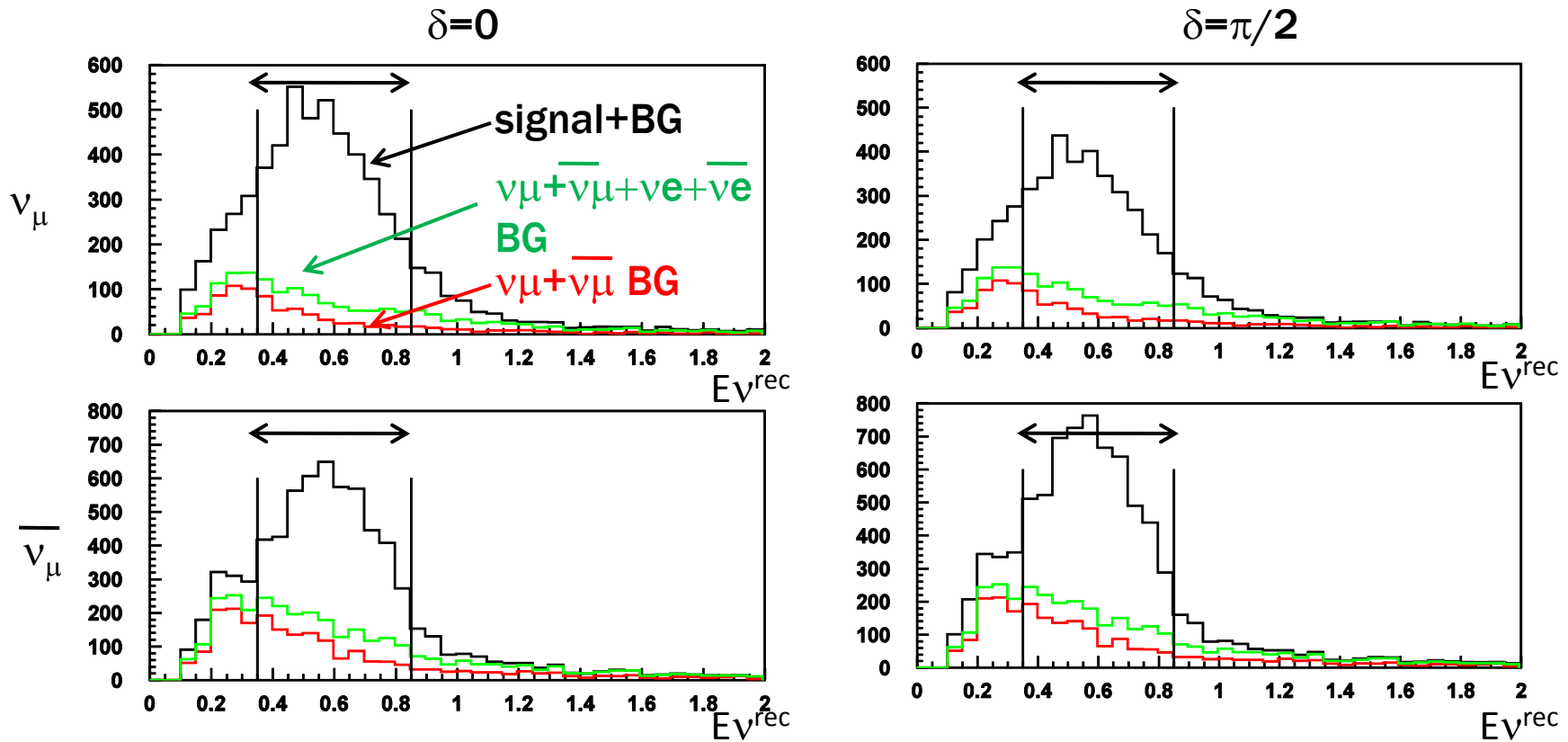
ν_μ beam :
1.66MW
2.2yr

$\bar{\nu}_\mu$ beam :
1.66MW
7.8yr
 $\sin^2 2\theta_{13} = 0.1$

reconstructed $\cos\theta_{\nu\mu}$ and M_{π^0} distribution

ν_μ beam $\bar{\nu}_\mu$ beam

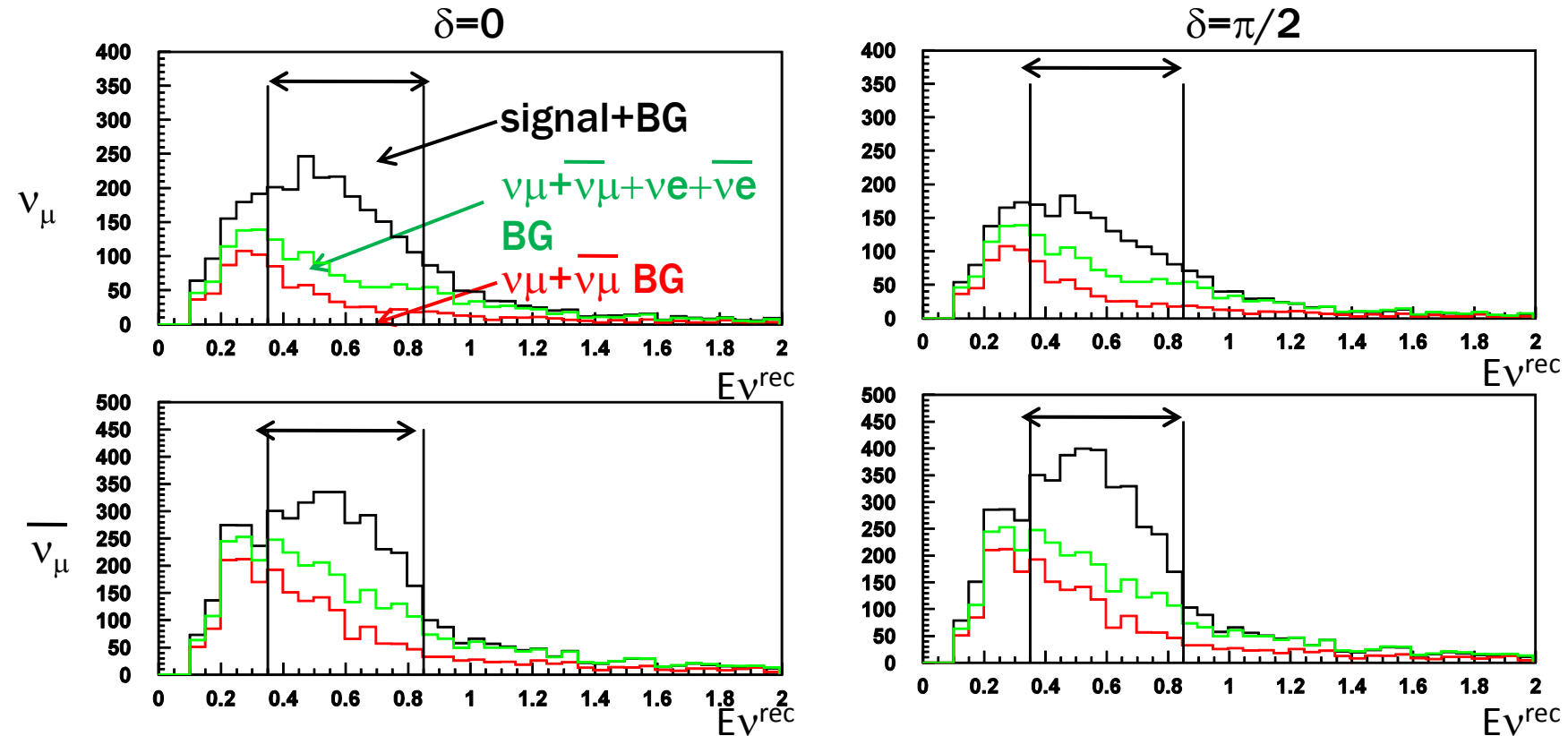


reconstructed E_ν distribution $(\sin^2 2\theta_{13}=0.1)$ 

	signal		background			
	$\delta=0$	$\delta=\pi/2$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
ν_μ	3279	2429	354	26	358	9
$\bar{\nu}_\mu$	3264	4065	443	610	229	391

reconstructed E_ν distribution

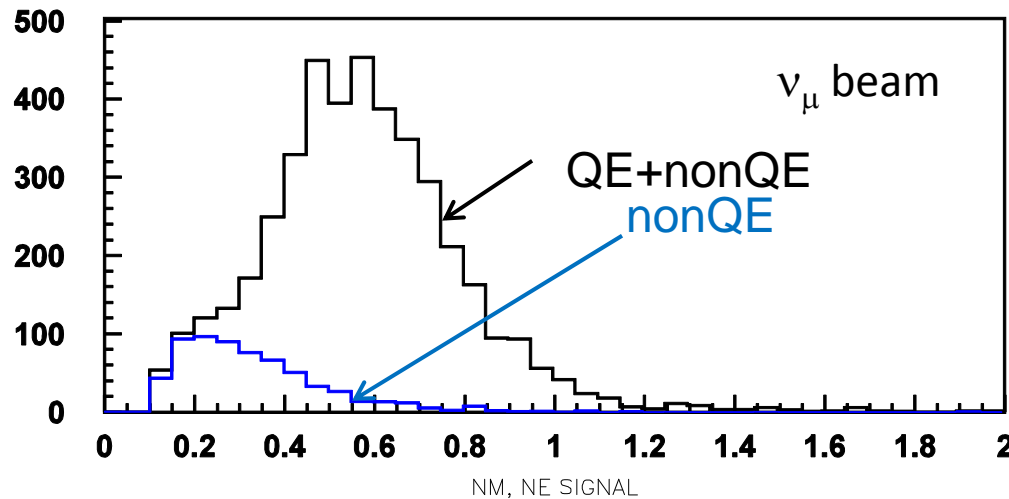
$(\sin^2 2\theta_{13} = 0.03)$



	signal		background			
	$\delta=0$	$\delta=\pi/2$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
ν_μ	1049	579	354	26	379	10
$\bar{\nu}_\mu$	1050	1493	443	610	241	415

uncertainty for ν_e ($\bar{\nu}_e$) signal

reconstructed E_ν distribution



Uncertainty

- ν_μ flux
- $\bar{\nu}_\mu$ flux
- $\sigma(\nu_\mu) \rightarrow \sigma(\nu_e)$
- $\sigma(\bar{\nu}_\mu) \rightarrow \sigma(\bar{\nu}_e)$
- non-QE/QE

ND

K2K

$$\delta(N_{\text{int}}^{1\text{kt}}) = 4.1\%$$

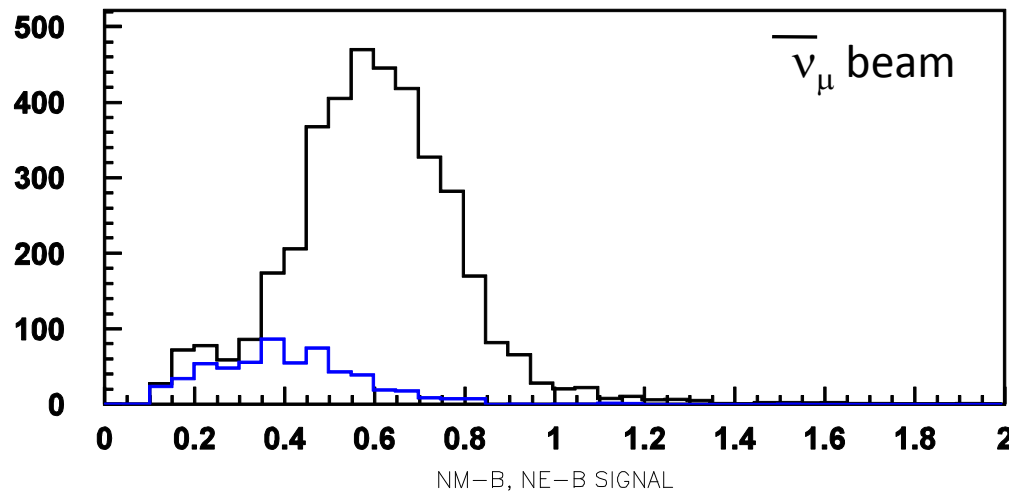
$$\delta(\text{nonQE/QE}) = \sim 6\%$$

$$\delta(\text{NC/CC}) = 5\%$$

• Far/near

NA61

$$\delta(\text{F/N}) = 3\%$$



- efficiency
- energy scale

FD

$$\delta(\text{E scale}) = \sim 2\%$$

$$\delta(\text{eff}) = \sim 5\%$$

cancelation between ν_μ and $\bar{\nu}_\mu$ beam is expected

background from ν_μ and $\bar{\nu}_\mu$

	ν_μ beam	$\bar{\nu}_\mu$ beam	
		$\bar{\nu}_\mu$	ν_μ
CC QE	10%	7%	3%
CC $1\pi^0$	6%	1%	1%
CC $1\pi^\pm$	2%	1%	2%
CC $\Delta \rightarrow \gamma N$	0.8%	0.3%	0%
CC $n\pi$	0.6%	0%	0.5%
NC elastic	0.2%	0.3%	2%
NC $1\pi^0$	61%	76%	68%
NC $1\pi^\pm$	4%	4%	6%
NC $\Delta \rightarrow \gamma N$	6%	5%	5%
NC $n\pi$	10%	6%	13%

mis PID
 mis PID
 or π^0

$\Delta \rightarrow \gamma N$

mis PID

π^0

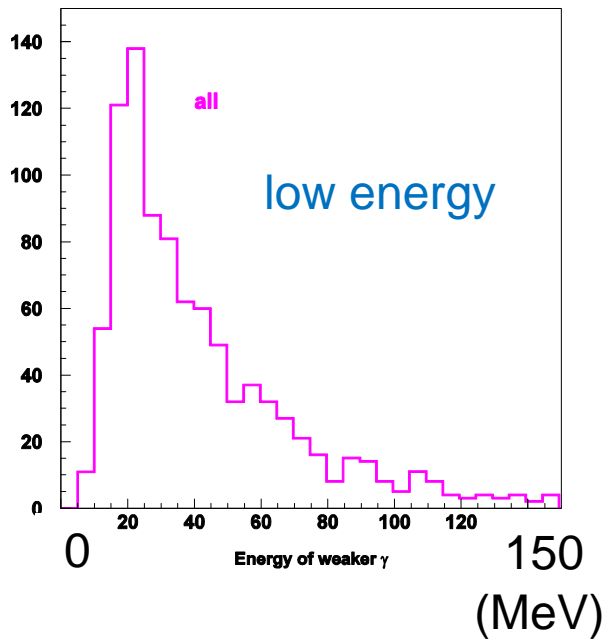
$\Delta \rightarrow \gamma N$

π^0

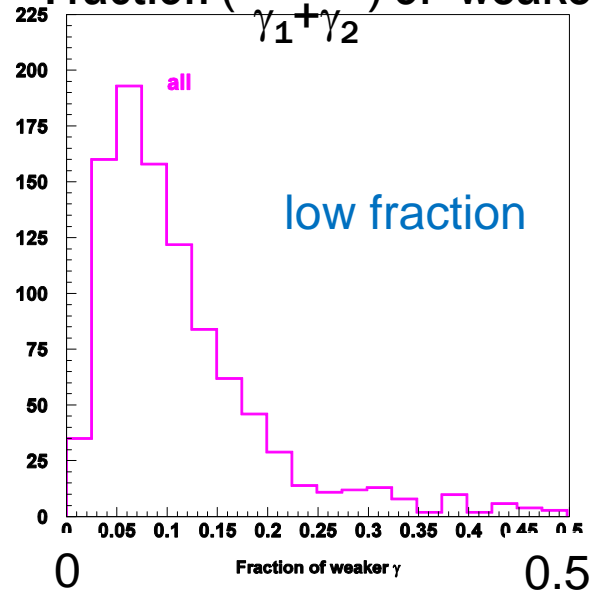
remained BG from ν_μ and $\bar{\nu}_\mu : \pi^0$

1 ring is still missed by e/π^0 separation.

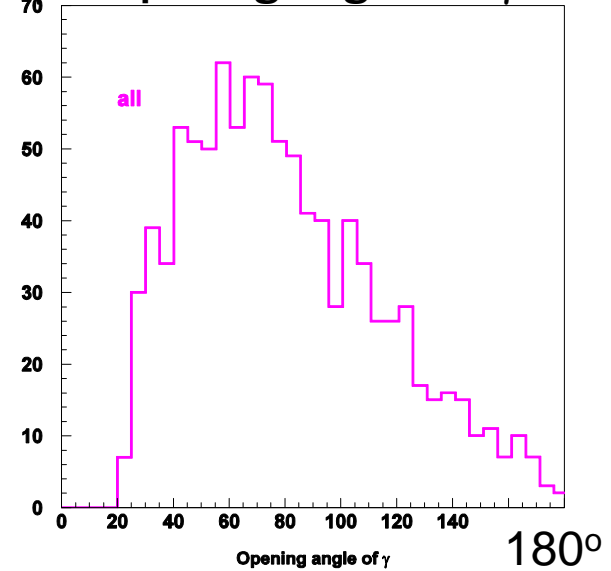
Energy of weaker γ



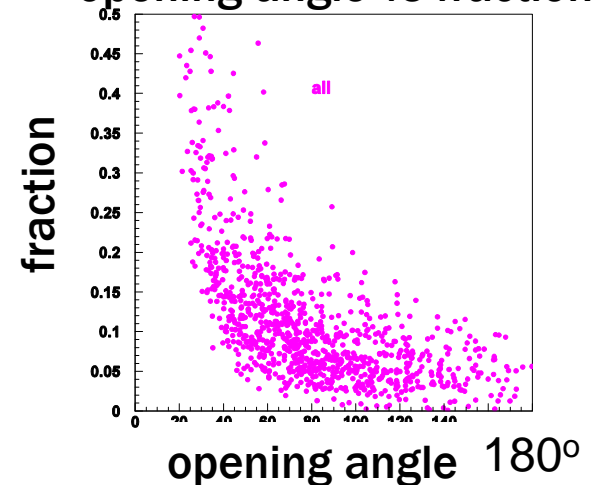
Fraction ($\frac{\gamma_1}{\gamma_1 + \gamma_2}$) of weaker γ



opening angle of 2γ

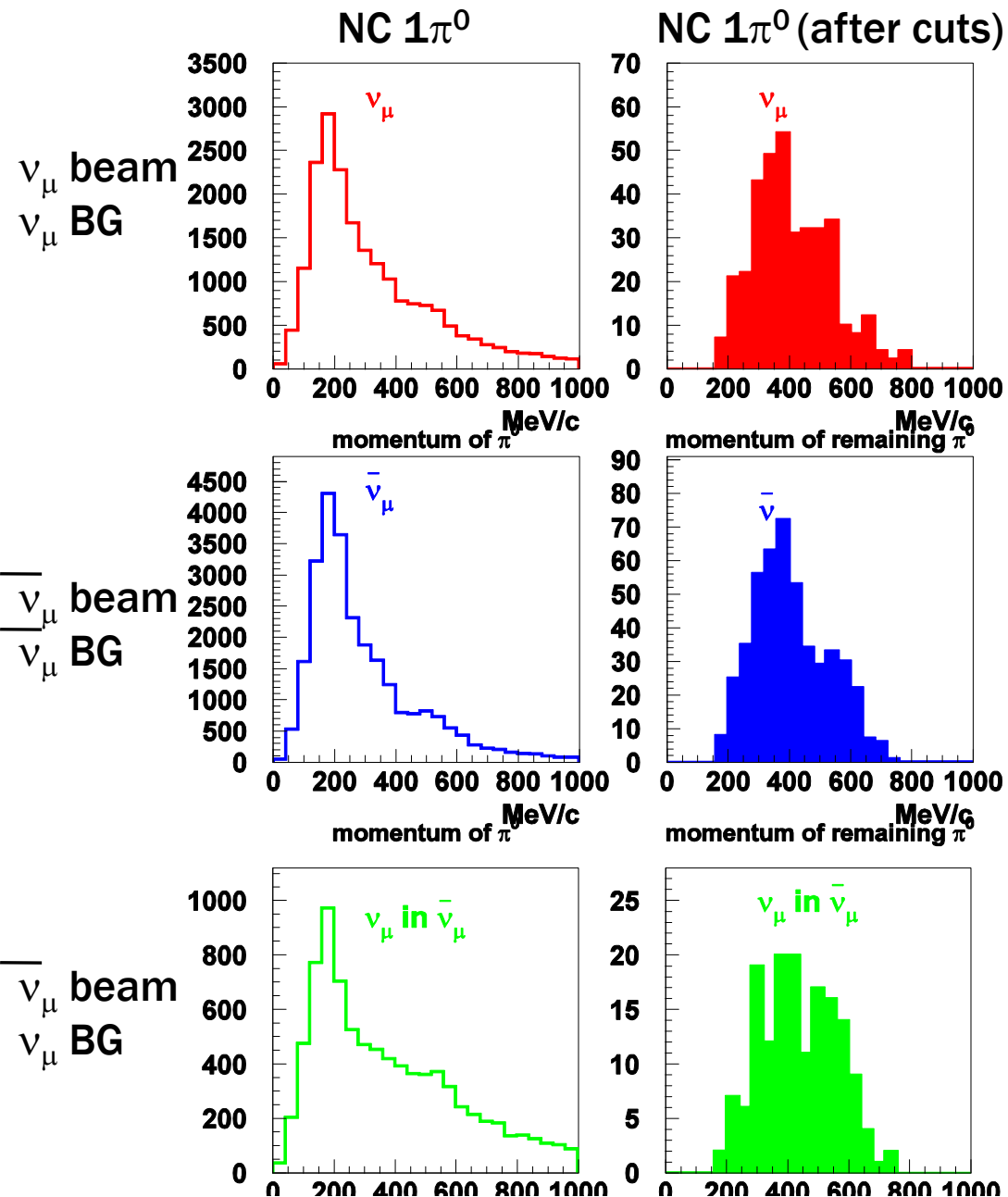


opening angle vs fraction



missed ring is low energy, low energy fraction γ .

momentum distribution of π^0 BG from $\nu_\mu, \bar{\nu}_\mu$



momentum distribution of π^0 background from ν_μ and $\bar{\nu}_\mu$ beam are similar.

difference of efficiency for π^0 BG from ν_μ and $\bar{\nu}_\mu$ are canceled.

uncertainty for ν_μ ($\bar{\nu}_\mu$) background

Main Uncertainty

- ν_μ flux
- $\bar{\nu}_\mu$ flux
- NC $\sigma(\nu\mu)$
- NC $\sigma(\bar{\nu}\mu)$

ND
measurement

K2K

$$\delta(N_{\text{int}}^{1\text{kt}})=4.1\%$$

$$\delta(\text{NC/CC})=7\%$$

- Far/near

NA61

$$\delta(\text{F/N})=2.7\%(0.5-1\text{GeV})$$

$$3.6\%(1-1.5\text{GeV})$$

(HARP)

- π^0 efficiency

FD

cancelation between
 ν_μ and $\bar{\nu}_\mu$ beam is
expected.

$$\delta(\pi^0 \text{ BG})=+37-26\%$$

π^0 mass cut : 19%

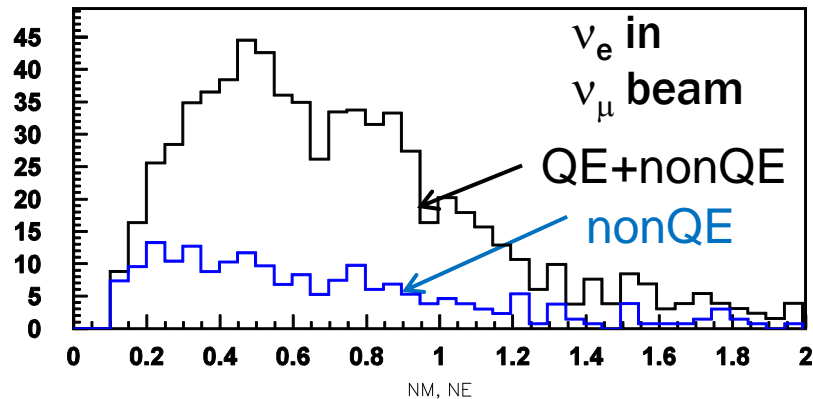
water property : 11%

coh. π model : +3-10%

**We need to improve e/π^0 separation
and to understand the performance in detail.**

uncertainty for beam ν_e and $\bar{\nu}_e$

reconstructed E_ν distribution



Uncertainty

- $\bar{\nu}_e$ flux
- ν_e flux
- $\sigma(\nu\mu) \rightarrow \sigma(\nu_e)$
- $\sigma(\bar{\nu}\mu) \rightarrow \sigma(\bar{\nu}_e)$
- non-QE/QE

} ND

K2K

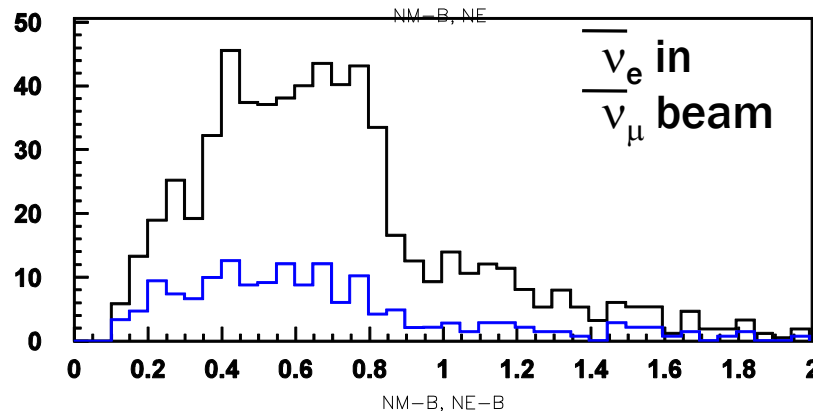
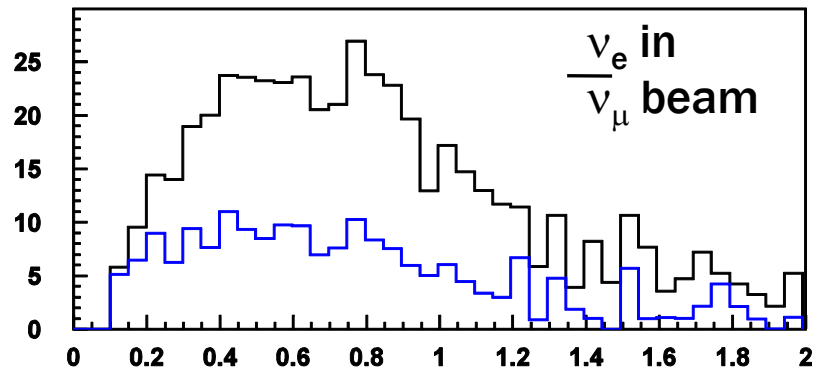
$$\delta(N_{\text{int}}^{1\text{kt}}) = 4.1\%(\nu_\mu)$$

$$\delta(\text{nonQE/QE}) = \sim 6\%$$

$$\delta(\pi \text{ production}) = \sim 15\%$$

$$\delta(\text{K production}) = \sim 16\%$$

• Far/near for $\nu_e, \bar{\nu}_e$ NA61



• efficiency

FD

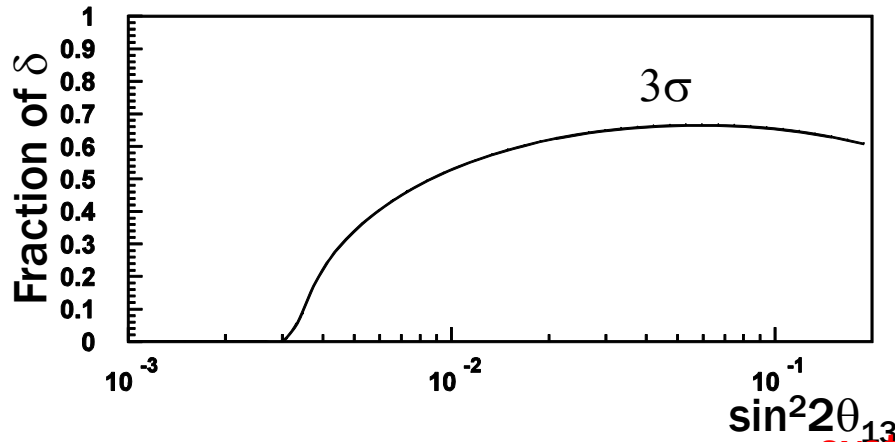
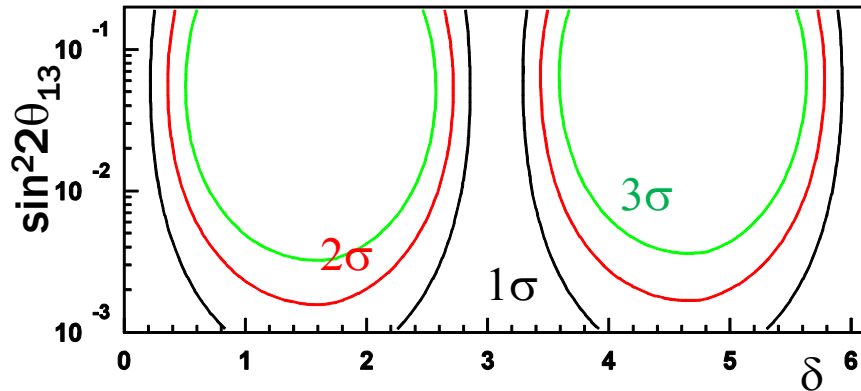
$$\delta(\text{eff}) = \sim 7\%$$

We need better understanding of beam $\nu_e, \bar{\nu}_e$.
(measurement at ND, NA61)

expected sensitivity

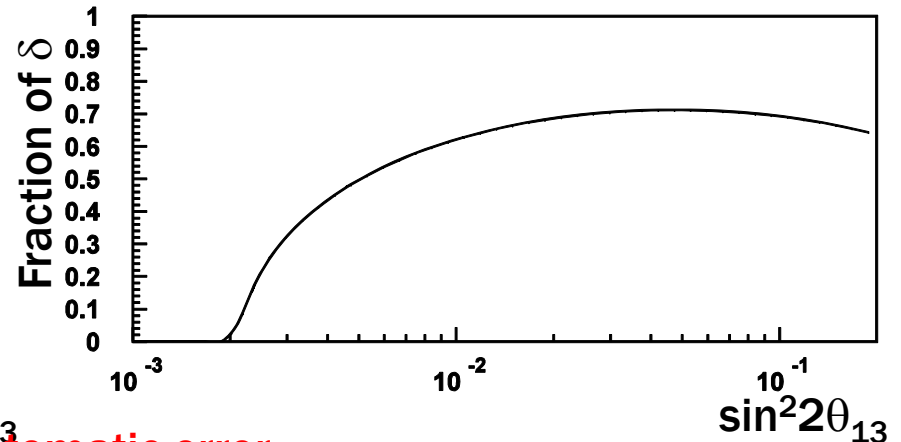
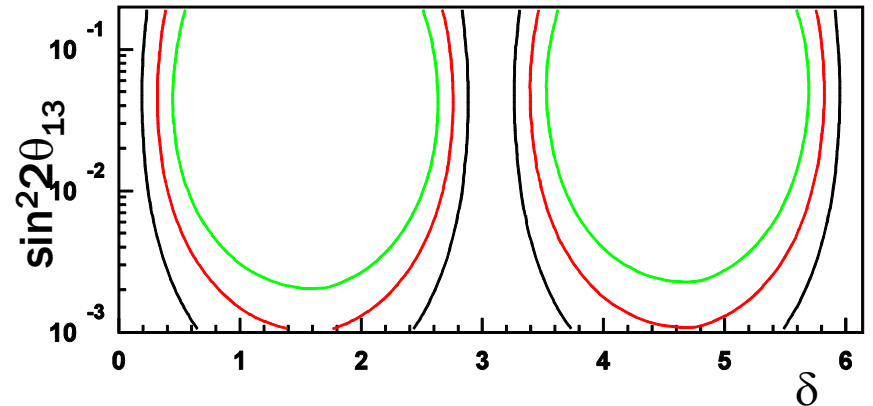
1.66MW ν_μ 1.1yr + $\bar{\nu}_\mu$ 3.9yr

CP sensitivity



1.66MW ν_μ 2.2yr + $\bar{\nu}_\mu$ 7.8yr

CP sensitivity



systematic error:

signal

5%

$\nu_\mu, \bar{\nu}_\mu$ BG

5%

beam $\nu_e, \bar{\nu}_e$ BG

5%

$\bar{\nu}_\mu/\nu_\mu$

5%

These errors are still challenging.

summary

- For CP study, ν_μ and ν_e in $\overline{\nu}_\mu$ beam should be carefully considered.
- Detailed flux and spectrum measurement at ND is necessary.
- We need to improve e/π^0 separation and to understand its performance in detail at SK.
- We need better understanding of beam ν_e and $\overline{\nu}_e$.
(measurement at ND, π and K production