Systematic in J-PARC/Hyper-K

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for Hyper-K WG

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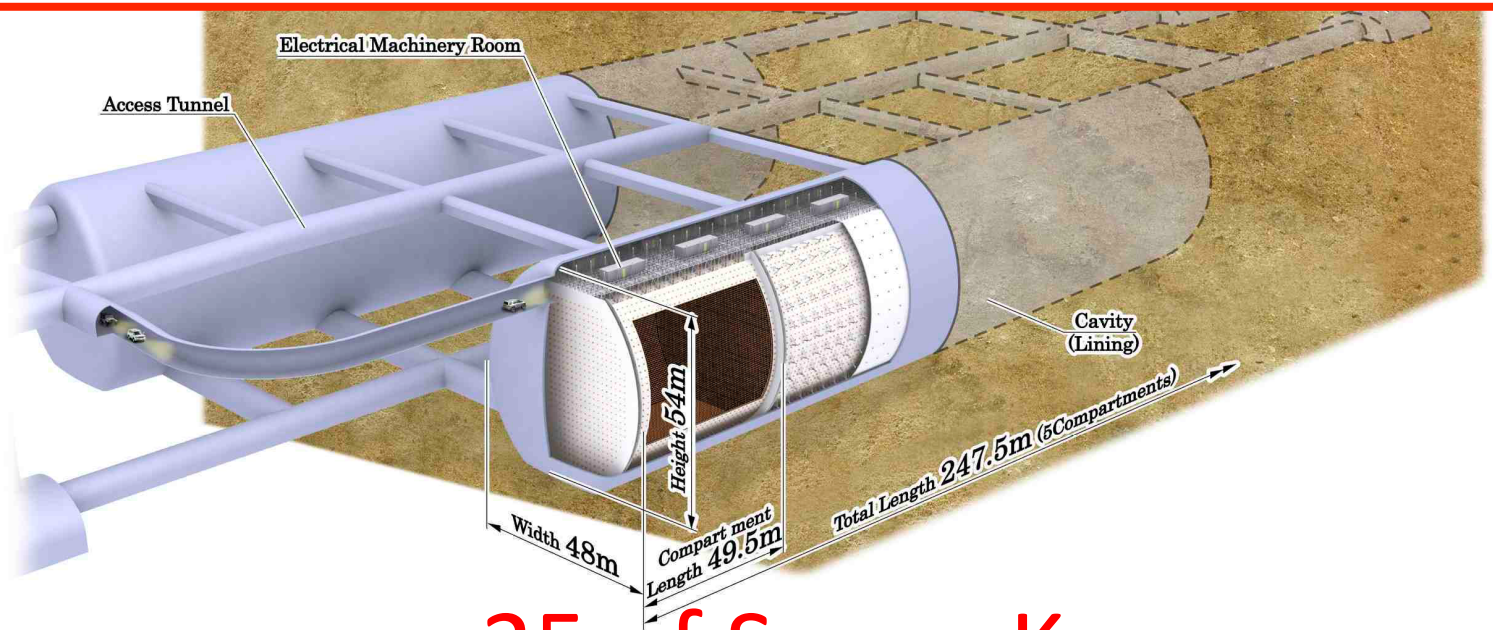
NuInt12@Rio de Janeiro

Hyper-K overview

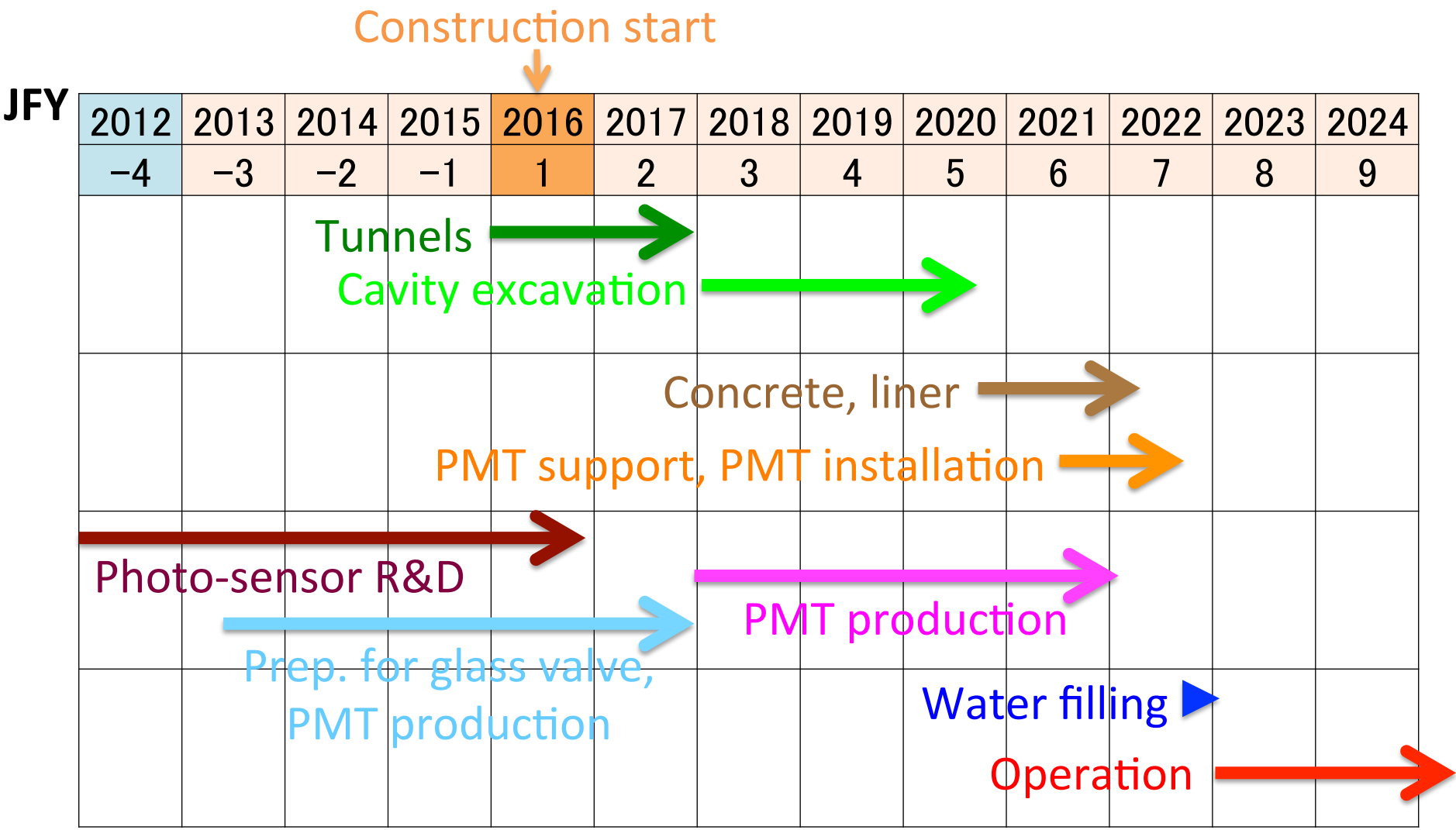
Total vol.	0.99 Mton
Fiducial vol.	0.56 Mton (0.056 Mton x 10 compartments)
Photo-sensors	99,000 of 20-inch PMTs for Inner Detector (20% photo-coverage)
	25,000 of 8-inch PMTs for Outer Detector



x 25 of Super-K

Schedule

assuming budget being approved from JPY2016



Physics topics in Hyper-K

LOI by Hyper-K WG, arXiv: 1109.3262 [hep-ex]

This talk

- Accelerator neutrino beam
- Atmospheric neutrinos
- Solar neutrinos
- Astrophysical neutrino
  - Supernova, Dark Matter, Solar flare, etc..
- Neutrino geophysics
- Nucleon decay

Neutrino oscillations w/ CPV

GUT

CP measurement with Hyper-K/J-PARC

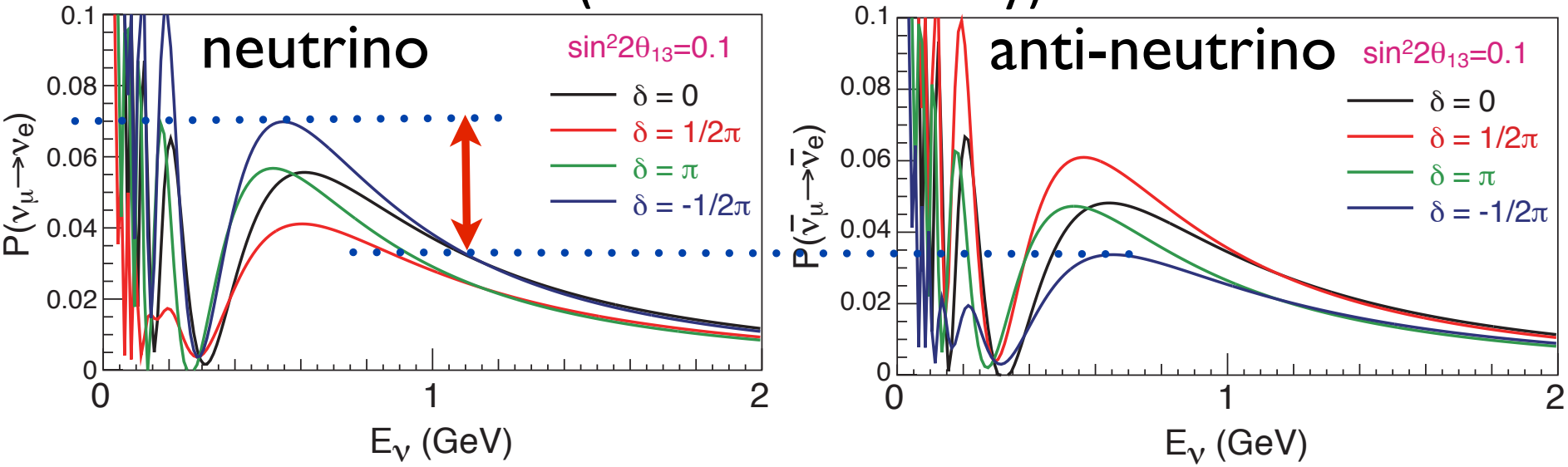
CP measurement with J-PARC/Hyper-K

- Strength of water Cherenkov detector
  - Large mass – statistics is always critical
  - Excellent reconstruction/PID performance especially in sub-GeV region (quasi-elastic ➔ single ring)
- Best matched with low energy, narrow band beam
  - Off-axis beam with relatively short baseline
    - Less matter effect
    - Complementary to other >1000km baseline experiments planned in EU/US

(natural extension of technique proved by T2K)

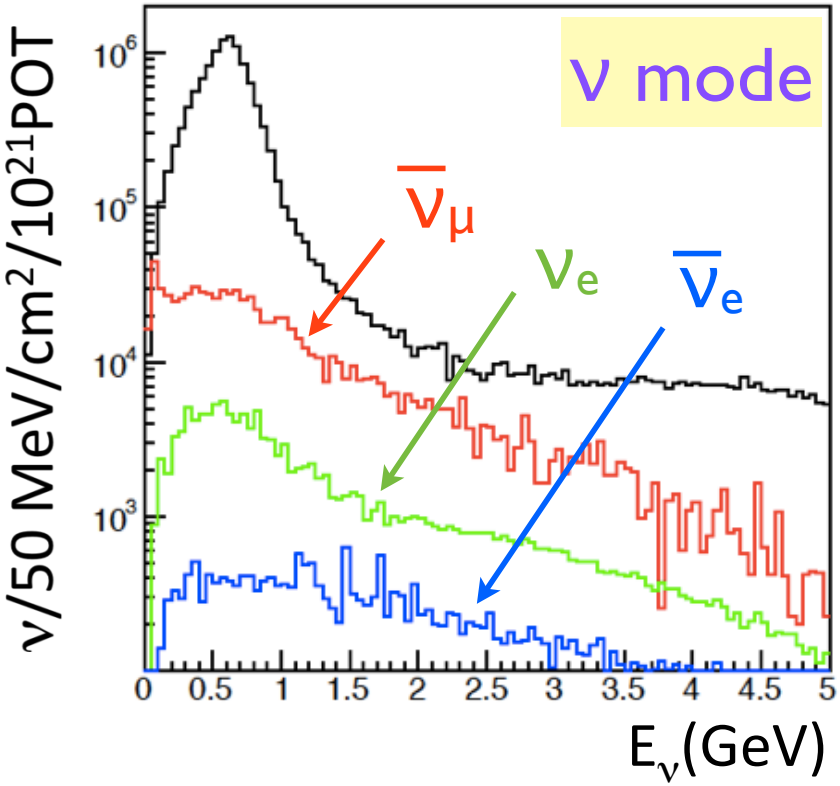
Measuring CP asymmetry

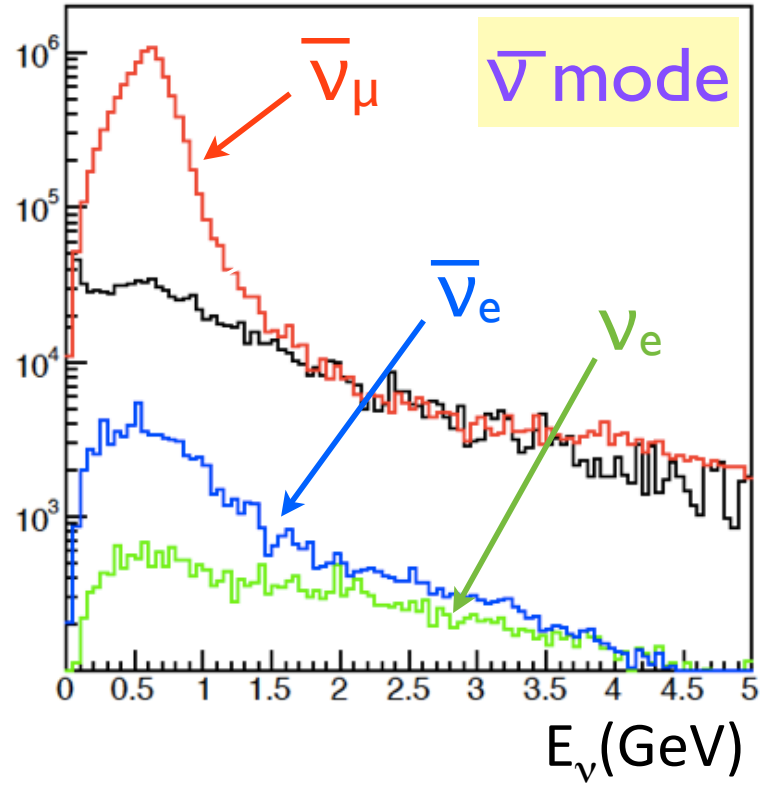
Appearance probability @ Hyper-K, L=295km
(normal hierarchy)



- Comp between $P(\nu_\mu \to \nu_e)$ and $P(\text{anti-}\nu_\mu \to \text{anti-}\nu_e)$
  - as large as ±25% from nominal
  - Sensitive to exotic (non-MNS) CPV

Expected ν flux @ Hyper-K (unoscillated)





- 2.5° off-axis beam from J-PARC
- Peaked at oscillation maximum
- Suppress BG from high energy component (ν_τ negligible)

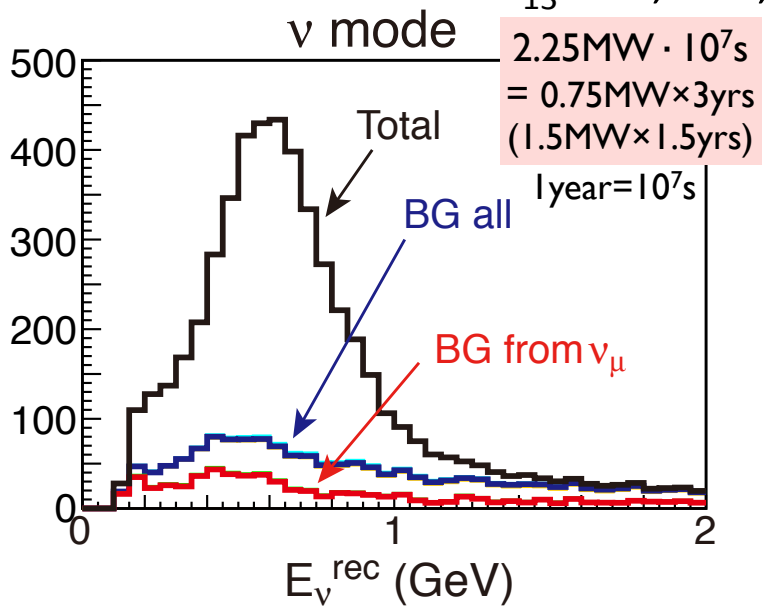
Full MC study

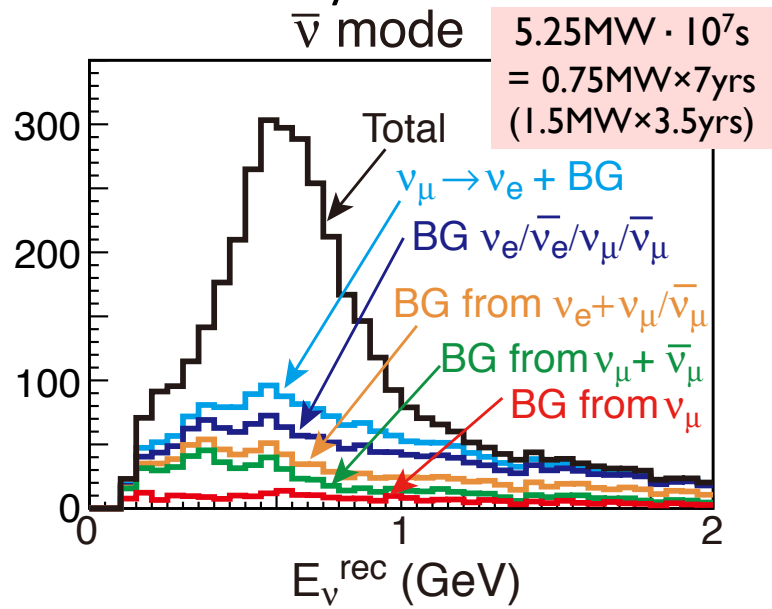
- Full simulation of ν beam, interaction, detector response and reconstruction
  - Photo-coverage: half of SK-4 (20% coverage)
- Event selection almost the same as T2K
  - Loose cut on E_ν to utilize spectrum information
- Assumed ten year running w/ 750kW power
  - We expect some beam power upgrades beyond 750kW
  - 3 year in ν run / 7 year in anti-ν run

Signal efficiency	64%
ν_μ CC BG rejection	>99.9%
NC π^0 BG rejection	95%

ν_e candidate events after selection

$\sin^2 2\theta_{13}$=0.1, δ=0, normal hierarchy





	Signal ($\nu_\mu \rightarrow \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν (2.25MW · 10^7s)	3,560	46	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	1,959	380	23	878	678

- 2000-4000 signal events expected for each of ν and anti-ν
- Beam ν_e/anti-ν_e and NCπ^0 are the dominant BG

CPV sensitivity study
in LOI, arXiv: 1109.3262 [hep-ex]

CPV sensitivity study in LOI

ν run & $\bar{\nu}$ run

Erec bin (50MeV/bin, 0-2GeV)

Expected number of events from

$\nu\mu \rightarrow \nu e + \bar{\nu}\mu \rightarrow \bar{\nu}e$ signal

$\nu\mu + \bar{\nu}\mu$ BG (mostly NC π^0)

$\nu e + \bar{\nu}e$ BG (mostly CC1e)

$$\chi^2 = \sum_{\nu,\bar{\nu}} \sum_i \left[N^i - \left\{ 1 \pm \frac{1}{2} f_{\nu/\bar{\nu}} \right\} \cdot \left((1 + f_{\rm sig}) \cdot n^i_{\rm sig} + (1 + f_{\nu_\mu}) \cdot n^i_{\nu_\mu} + (1 + f_{\nu_e}) \cdot n^i_{\nu_e} \right) \right]^2 / N^i$$
$$+ \frac{{f_{\rm sig}}^2}{{\sigma_{\rm sig}}^2} + \frac{{f_{\nu_\mu}}^2}{{\sigma_{\nu_\mu}}^2} + \frac{{f_{\nu_e}}^2}{{\sigma_{\nu_e}}^2} + \frac{{f_{\bar{\nu}/\nu}}^2}{{\sigma_{\nu/\bar{\nu}}}^2},$$

Energy dependent error not considered.

LOI assumption

$\sigma_{\rm sig}$: signal normalization (5%)

$\sigma_{\nu\mu}$: $\nu\mu$ BG normalization (5%)

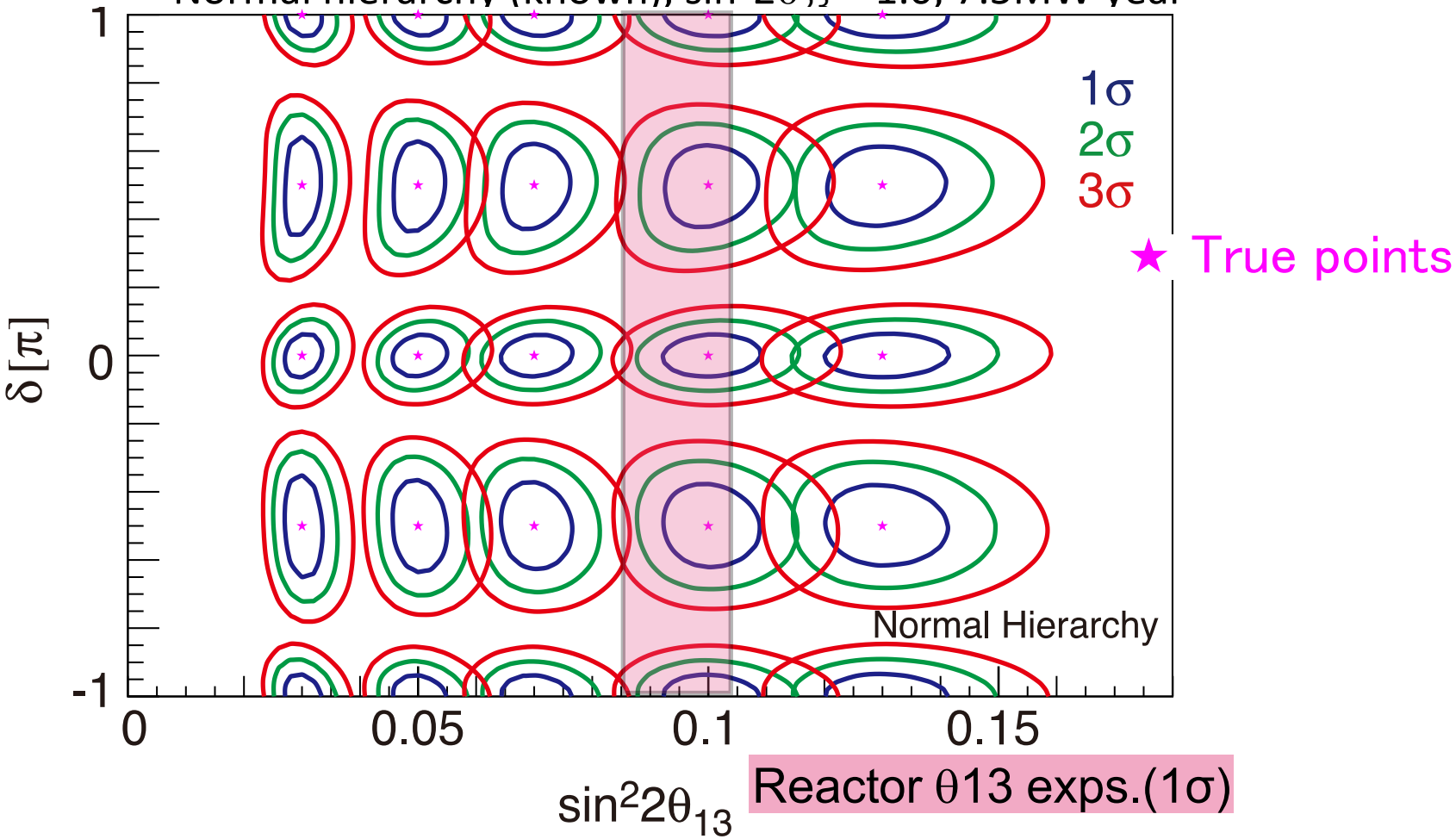
$\sigma_{\nu e}$: νe BG normalization (5%)

$\sigma_{\nu/\bar{\nu}}$: ν run/$\bar{\nu}$ run relative normalization (5%)

Expected Contours

assuming 5% systematics on signal, ν_μ BG, ν_e BG, ν/anti-ν

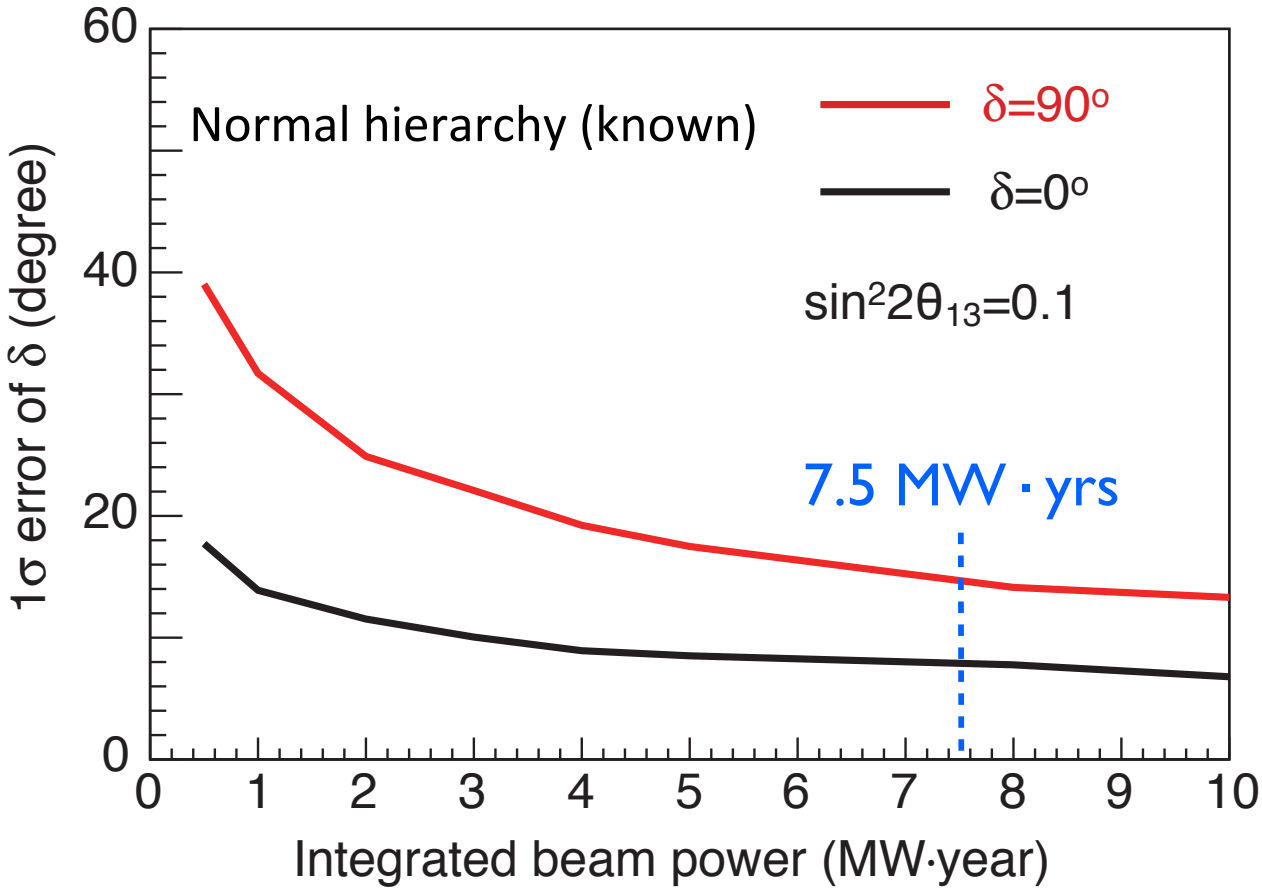
Normal hierarchy (known), $\sin^2 2\theta_{23}$ = 1.0, 7.5MW year



Good sensitivity for CPV!

δ resolution

assuming 5% systematics on signal, ν_μ BG, ν_e BG, ν/anti-ν



- δ precision < 20° (δ=90°)
  < 10° (δ=0°)
- modest dependence on θ_{13}

Ongoing study:
Effect of systematics on
CPV sensitivity
(with new systematic parameters)

Ongoing study: effect of systematics

- Assuming that normalization is given by Near Detector
  - For ν_μ in ν run,
  - For anti-ν_μ and ν_μ in anti-ν run
- Systematic parameters (total 11)
  - Normalization $f^{\nu}_{\mathrm{norm}}, f^{\bar{\nu}}_{\mathrm{norm}}, f^{\bar{\nu}}_{\mathrm{WS}}$
  - CCnon-QE/CCQE $f^{\nu}_{nQE}, f^{\bar{\nu}}_{nQE}$
  - ν_μ(~NC) $f^{\nu}_{\nu\mu}, f^{\bar{\nu}}_{\nu\mu}, f^{\bar{\nu}}_{\bar{\nu}_\mu}$
  - Intrinsic ν_e $f^{\nu}_{\nu e}, f^{\bar{\nu}}_{\nu e}, f^{\bar{\nu}}_{\bar{\nu}_e}$

WS: wrong sign appearance

Ongoing study: effect of systematics

ν run

$$\chi^2 = \sum_i^{for\,\nu} \Big[N^i - (1+f^{\nu}_{\rm norm}) \Big\{ n^i_{\nu_\mu\to\nu_e,QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu\to\nu_e,nQE} + n^i_{\bar{\nu}_\mu\to\bar{\nu}_e}$$

$$+(1+f^{\nu}_{\nu_\mu})(n^i_{\nu_\mu} + n^i_{\bar{\nu}_\mu}) + (1+f^{\nu}_{\nu_e})(n^i_{\nu_e} + n^i_{\bar{\nu}_e}) \Big\} \Big]^2 / N^i$$

antiν run

$$+ \sum_i^{for\,\bar{\nu}} \Big[N^i - (1+f^{\bar{\nu}}_{\rm norm}) \Big\{ n^i_{\bar{\nu}_\mu\to\bar{\nu}_e,QE} + (1+f^{\bar{\nu}}_{nQE}) n^i_{\bar{\nu}_\mu\to\bar{\nu}_e,nQE} + (1+f^{\bar{\nu}}_{\bar{\nu}_\mu}) n^i_{\bar{\nu}_\mu} + (1+f^{\bar{\nu}}_{\bar{\nu}_e}) n^i_{\bar{\nu}_e} \Big\}$$

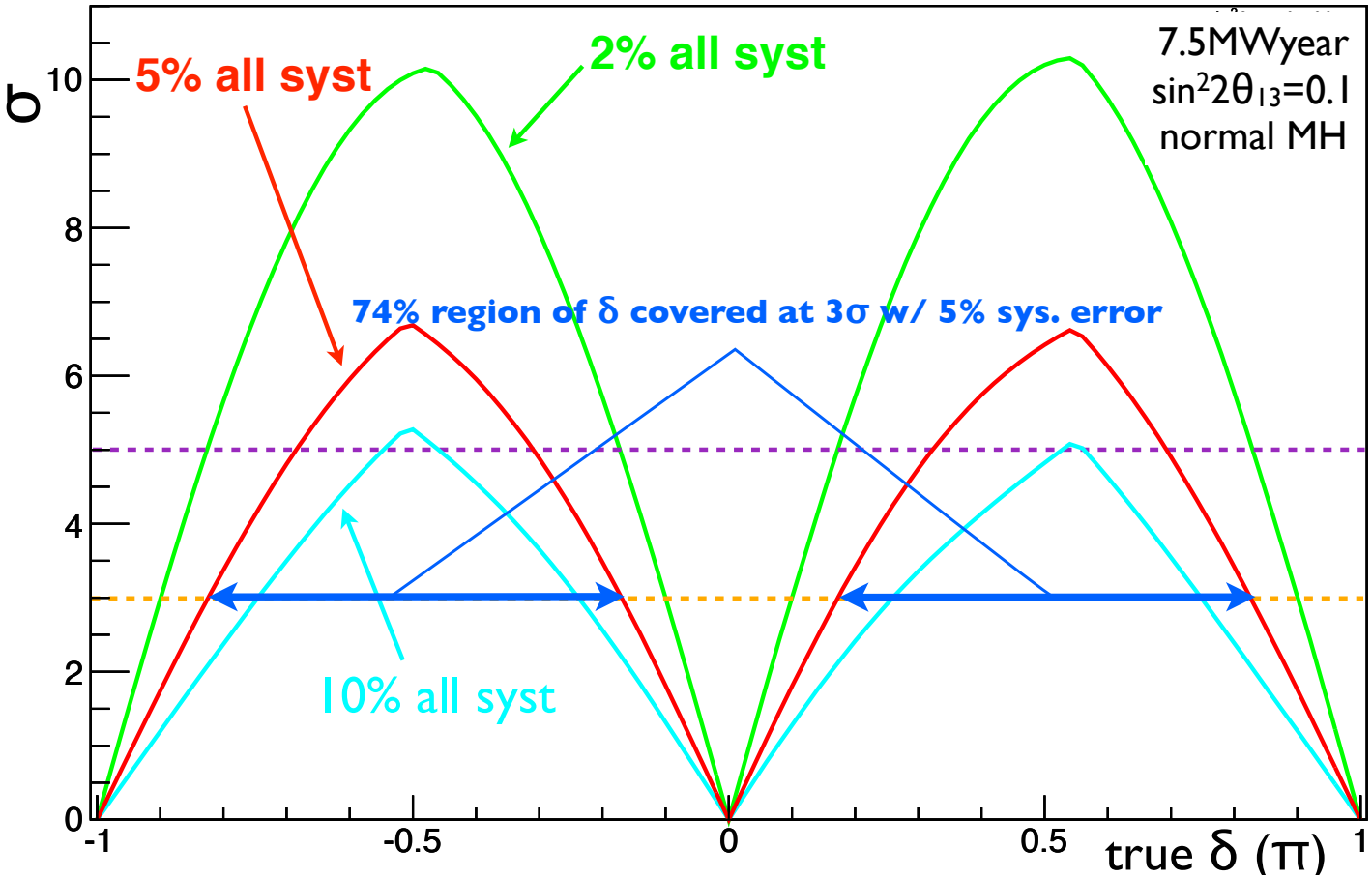
wrong sign

$$+(1+f^{\bar{\nu}}_{\rm WS}) \Big\{ n^i_{\nu_\mu\to\nu_e,QE} + (1+f^{\nu}_{nQE}) n^i_{\nu_\mu\to\nu_e,nQE} + (1+f^{\bar{\nu}}_{\nu_\mu}) n^i_{\nu_\mu} + (1+f^{\bar{\nu}}_{\nu_e}) n^i_{\nu_e} \Big\} \Big]^2 / N^i$$

$$+ \sum_{\text{syst. par}} \frac{f^2}{\sigma^2}$$

(Used E_ν^{rec}<1.2GeV)

CPV Discovery sensitivity
(w/ Mass hierarchy known)

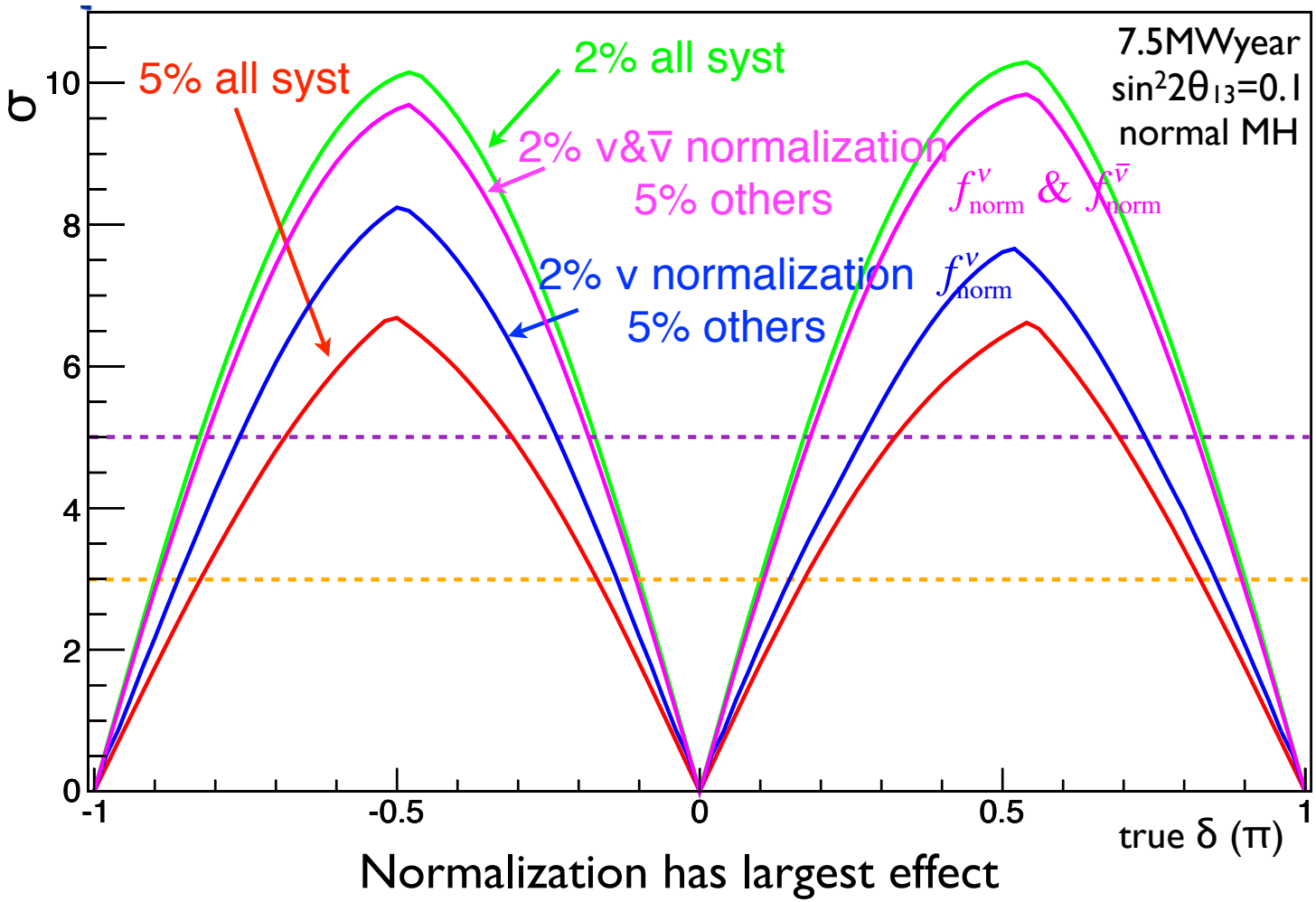


Effect of systematics is significant

High discovery potential to CPV w/ <~5% sys. errors

CPV Discovery sensitivity

Effect of normalization

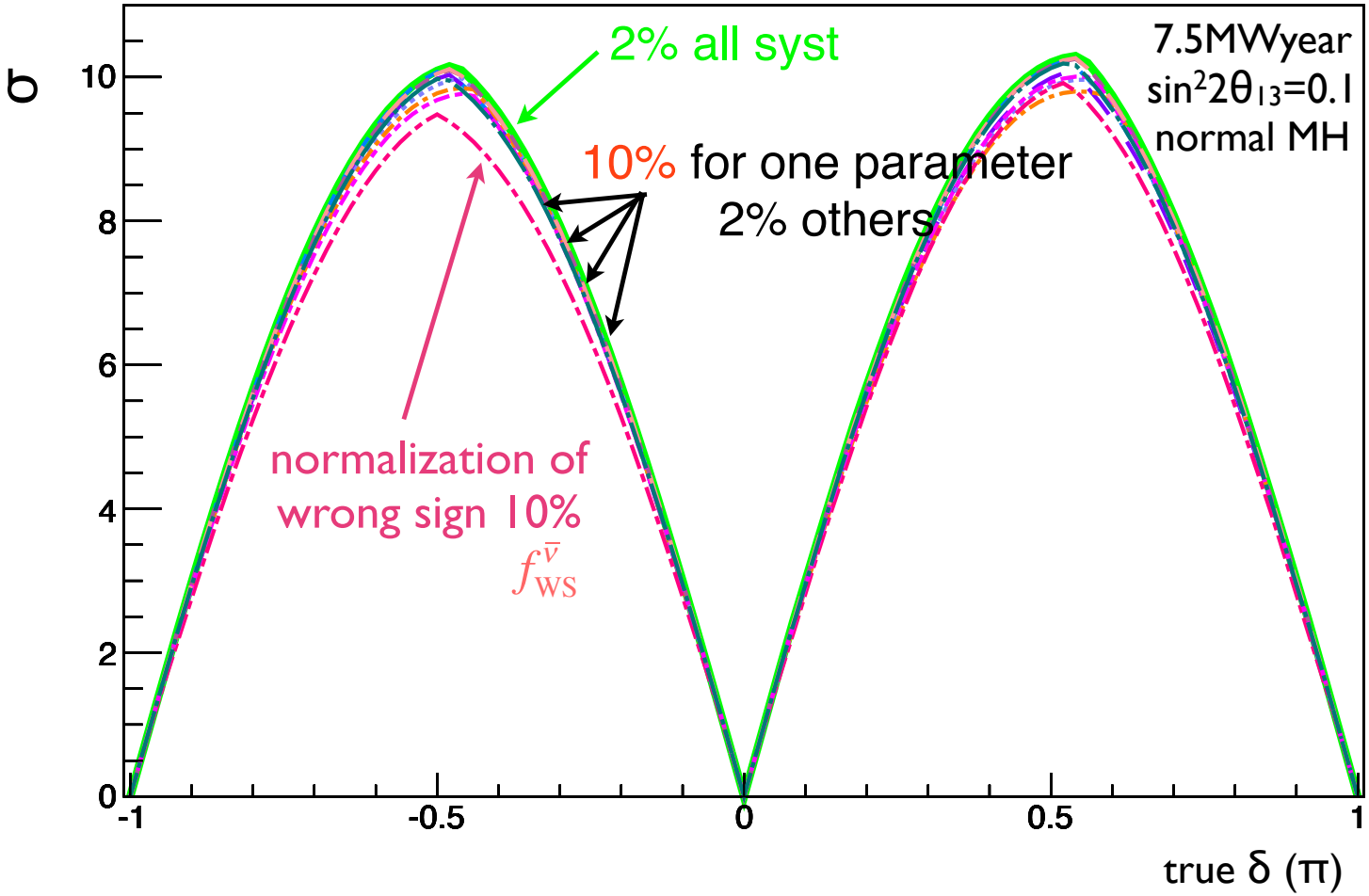


Normalization has largest effect

Normalization has largest effect

CPV Discovery sensitivity

Other systematics



Effect may be small

Note: preliminary study with simple parametrization, study ongoing

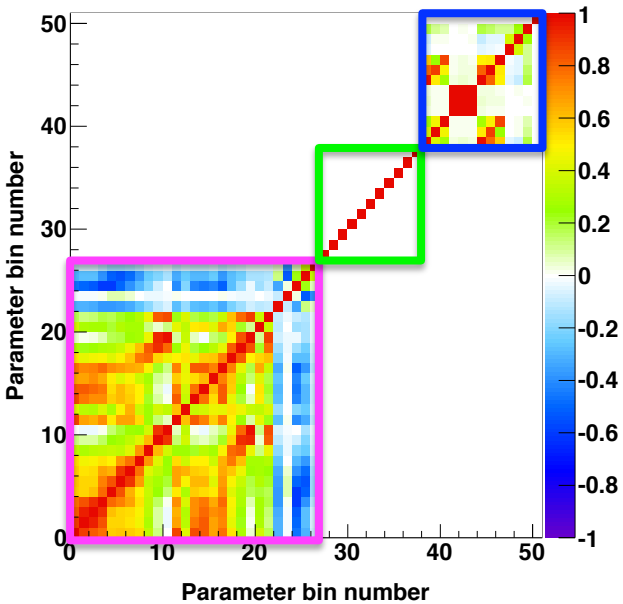
T2K experience
(only ν run, so far)

ND: Near Detector

T2K: Systematic errors on N_{SK}

$\sin^2 2\theta_{13} = 0.1$	Individual	Group
Flux	8.0	Flux+Xsec w/ ND fit 5.0%
M_A^{QE} (GeV)	6.7	
M_A^{RES} (GeV)	1.8	
CCQE norm ($E_\nu < 1.5$ GeV)	6.2	
CC1π norm ($E_\nu < 2.5$ GeV)	3.5	
NC1π^0 norm	2.2	
CC other shape (GeV)	0.1	Xsec w/o ND fit 7.4%
Spectral function	5.5	
p_F (MeV)	0.1	
CC coherent norm	0.2	
NC coherent norm	0.6	
NC1$\pi^\pm$+NC other norm	0.8	
$\sigma_{\nu_e \mathrm{CC}}/\sigma_{\nu_\mu \mathrm{CC}}$	2.7	
W shape (MeV)	0.9	
Pionless delta decay	3.2	
1π E_ν shape	1.2	
SK detector efficiency	3.1	SK det. +FSI/SI 3.9%
FSI+SI	2.4	
SK energy scale	0.6	
Total	9.8%	

Correlation matrix of sys. errors



T2K: How to reduce Systematic errors (1)

Sys. errors on N_{SK}

$\sin^2 2\theta_{13} = 0.1$	Individual	Group
Flux	8.0	Flux+Xsec w/ ND fit 5.0%
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Total	9.8%	

ND: Near Detector

Flux + Xsec w/ND fit

- NA61 measurement
  - K prod. (w/ higher stat.)
  - 2nd. Proton
  - Replica target
- ND measurement
  - Higher statistics
  - More event categories CCQE, CC1π, CCNπ, …
  - Larger phase-space analysis
  - New ND with 4π acceptance

T2K: How to reduce Systematic errors (2)

Sys. errors on N_{SK}

$\sin^2 2\theta_{13} = 0.1$	Individual
Flux	8.0
M_A^{QE} (GeV)	6.7
M_A^{RES} (GeV)	1.8
CCQE norm ($E_\nu < 1.5$ GeV)	6.2
CC1π norm ($E_\nu < 2.5$ GeV)	3.5
NC1π^0 norm	2.2
CC other shape (GeV)	0.1
Spectral function	5.5
p_F (MeV)	0.1
CC coherent norm	0.2
NC coherent norm	0.6
NC1$\pi^\pm$+NC other norm	0.8
$\sigma_{\nu_e CC}/\sigma_{\nu_\mu CC}$	2.7
W shape (MeV)	0.9
Pionless delta decay	3.2
1π E_ν shape	1.2
SK detector efficiency	3.1
FSI+SI	2.4
SK energy scale	0.6
Total	9.8%

Group

- Flux+Xsec w/ ND fit 5.0%
- Xsec w/o ND fit 7.4%
- SK det. +FSI/SI 3.9%

ND: Near Detector

Xsec errors w/o ND fit

Common goals

- ND measurement
  - More event categories CCQE, CC1π, CCNπ, …
  - Larger phase-space analysis
  - Using Water target
  - New water target ND w/ 4π acceptance
- Incorporate into ND fit

Spectral function error

- Change nucleon mom. model used in ν event generator from FG(Fermi gas) to SF
- Electron scattering exp.

T2K: How to reduce Systematic errors (3)

Sys. errors on N_{SK}

$\sin^2 2\theta_{13} = 0.1$	Individual	Group
Flux	8.0	Flux+Xsec w/ ND fit 5.0%
M_A^{QE} (GeV)	6.7	
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CCQE norm ($E_\nu < 1.5$ GeV)	6.2	
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FSI+SI	2.4	
SK energy scale	0.6	
Total	9.8%	

SK det. errors

- Higher stat. of control samples

FSI errors

- π scattering exp.
- ND measurement
  - Using Water target
  - New water target ND w/ 4π acceptance
- Incorporate into ND fit

ND: Near Detector

Corresponding T2K Systematic errors to J-PARC/Hyper-K errors

T2K sys. Errors (only ν run)

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Group

Flux+Xsec w/ ND fit 5.0%

Xsec w/o ND fit 7.4%

SK det. +FSI/SI 3.9%

Hyper-K sys. errors

Large effect errors (target value = 5.0%)

8.8%

f^{ν}_{norm}, $f^{\bar{\nu}}_{\text{norm}}$, $f^{\bar{\nu}}_{\text{WS}}$

f^{ν}_{nQE}, $f^{\bar{\nu}}_{nQE}$

$f^{\nu}_{\nu\mu}$, $f^{\bar{\nu}}_{\nu\mu}$, $f^{\bar{\nu}}_{\bar{\nu}_\mu}$

$f^{\nu}_{\nu e}$, $f^{\bar{\nu}}_{\nu e}$, $f^{\bar{\nu}}_{\bar{\nu}_e}$

Small effect errors

We will demonstrate J-PARC/Hyper-K feasibility with T2K.

Summary

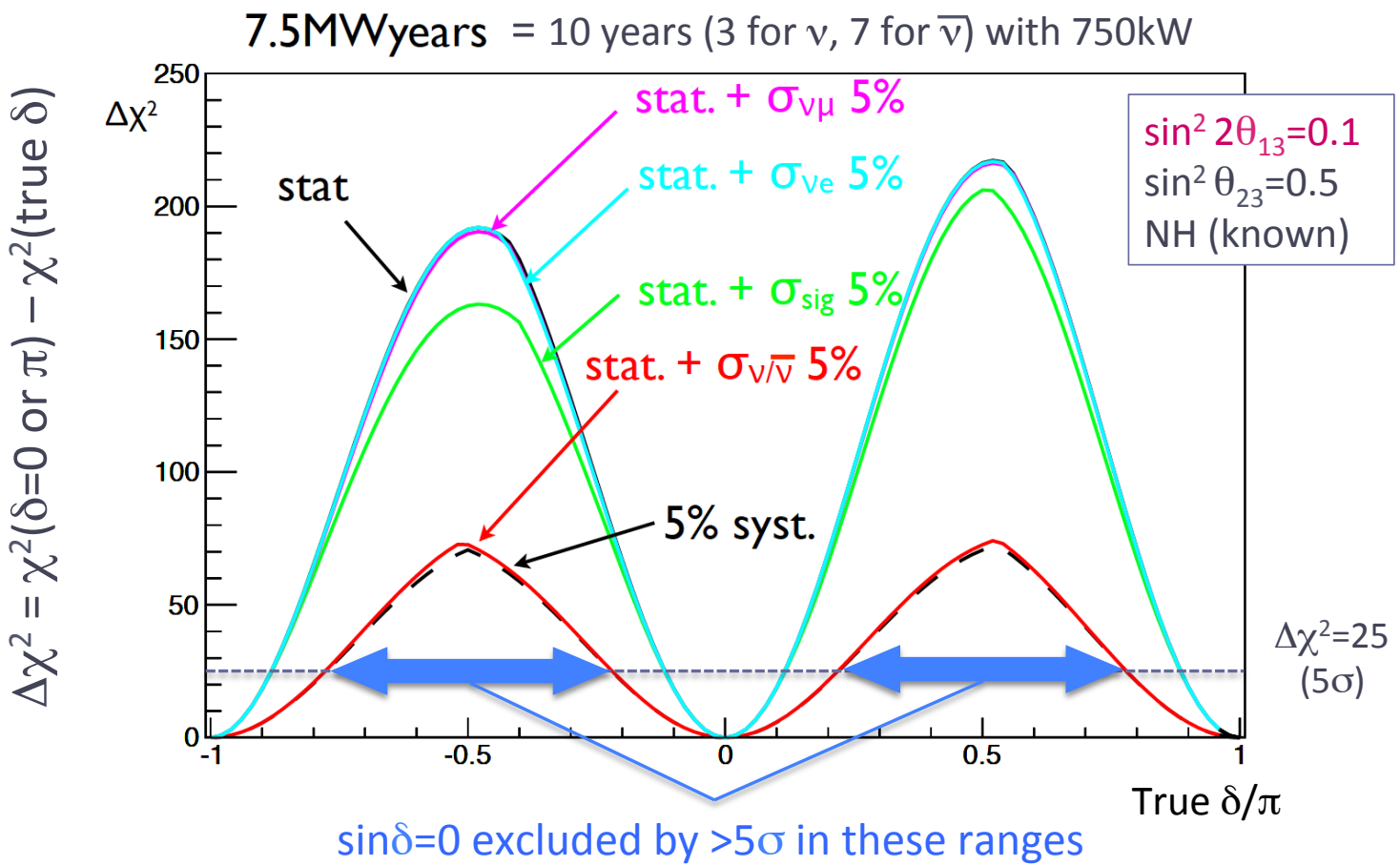
- J-PARC + Hyper-K LBL experiment has potential to reveal full picture of neutrino oscillation.
  - CPV > $3\sigma(5\sigma)$ for 74(55)% of δ

- Systematic uncertainties are important for study of sub-leading CPV effect.
  - We will demonstrate J-PARC/Hyper-K feasibility with T2K.

Backup

CPV Discovery sensitivity
(w/ Mass hierarchy known)

LOI assumption



Effect of systematics is significant

ν run/anti-ν run relative normalization has largest effect

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@ICHEP2012

Systematic errors in T2K

The predicted number of events and systematic uncertainties

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

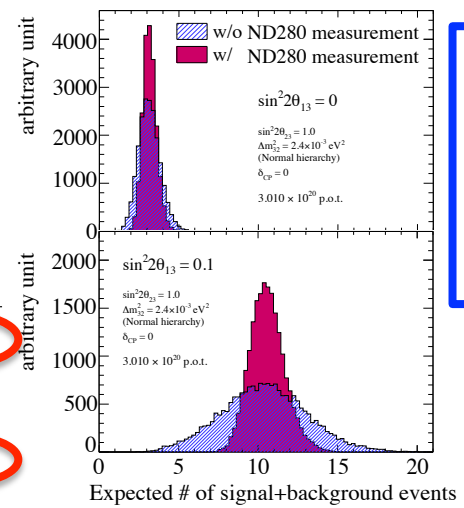
Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ^0)	1.21	1.21
$\bar{\nu}_\mu + \bar{\nu}_e$ background	0.16	0.16

Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

big improvement from the T2K 2011 results

the predicted # of event distribution



Uncertainties are reduced using ND280 measurement

Upcoming Cross-section measurements in T2K-ND280 and the cross section model improvements are critical.

T2K flux extrapolation and the detector uncertainties almost reach the Hyper-K requirement.

- Total sys. error for $\sin^2 2\theta_{13}$=0.1: ~10%
  - Beam flux + ν int. constraint in T2K: 5.7%
  - ν cross section uncertainty from other experiment: 7.5%
  - Super-K detector uncertainty: 3.1%

T2K: Neutrino flux at ND

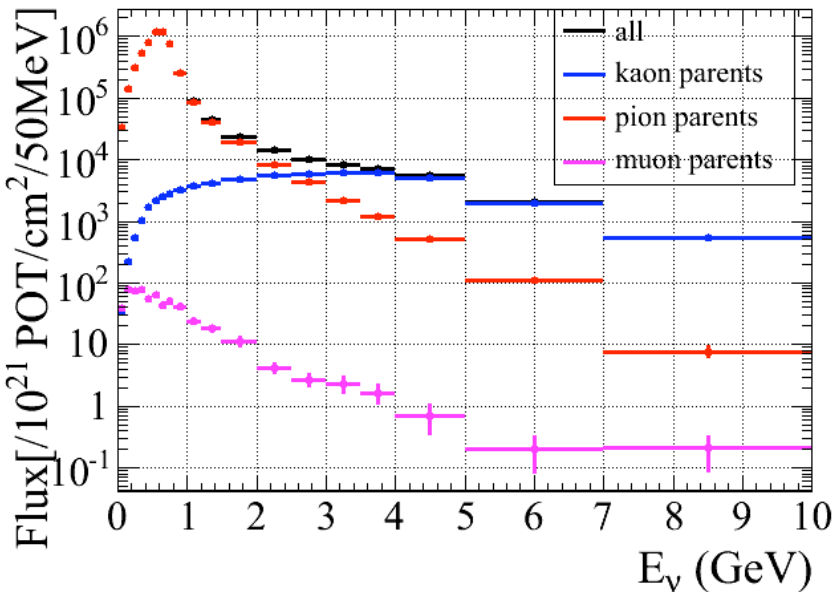
Neutrino Mode	ND ν_μ CCQE	ND ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_μ NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu}_\mu$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

ν_μ from π decay

- CCQE enriched sample
- CCnQE enriched sample

ν_μ from K decay

- CCnQE enriched sample



T2K: ν flux correlation btw. ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_μ NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

SK signal/NC background events strongly correlate with ν_μ flux measured at ND.

ND: Near Detector

T2K: How to reduce Systematic errors

Sys. errors on N_{SK}

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FSI+SI	2.4	
SK energy scale	0.6	
Total	9.8%	

Flux errors

- NA61 measurement
  - K production
  - 2nd. Proton
  - Replica target
- ND measurement

Xsec errors w/ ND fit

- ND measurement

Xsec errors w/o ND fit

- Higher acceptance (4π) ND with water target

SK det. Errors

- Higher stat. of control samples

FSI errors

- π scattering exp.

T2K sys. errors on Neutrino flux

	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.56	1.90
Proton Beam, Alignment & Off-axis Angle	3.45	2.08	1.75
Horn Current and Magnetic Field	1.40	1.16	1.39
Total	10.04	10.94	4.78

Summary

- J-PARC + Hyper-K LBL experiment has potential to reveal full picture of neutrino oscillation.
  - CPV > $3\sigma(5\sigma)$ for 74(55)% of δ
- Systematic uncertainties are important for study of sub-leading CPV effect.
  - Ongoing work: quantifying the effect from each systematic error and making a strategy for achieving the Hyper-K requirement.
    - Cross-section measurements in T2K Near Detector and the cross section model improvements
    - Anti-ν run in T2K
    - Improve (upgrade) Near Detector