

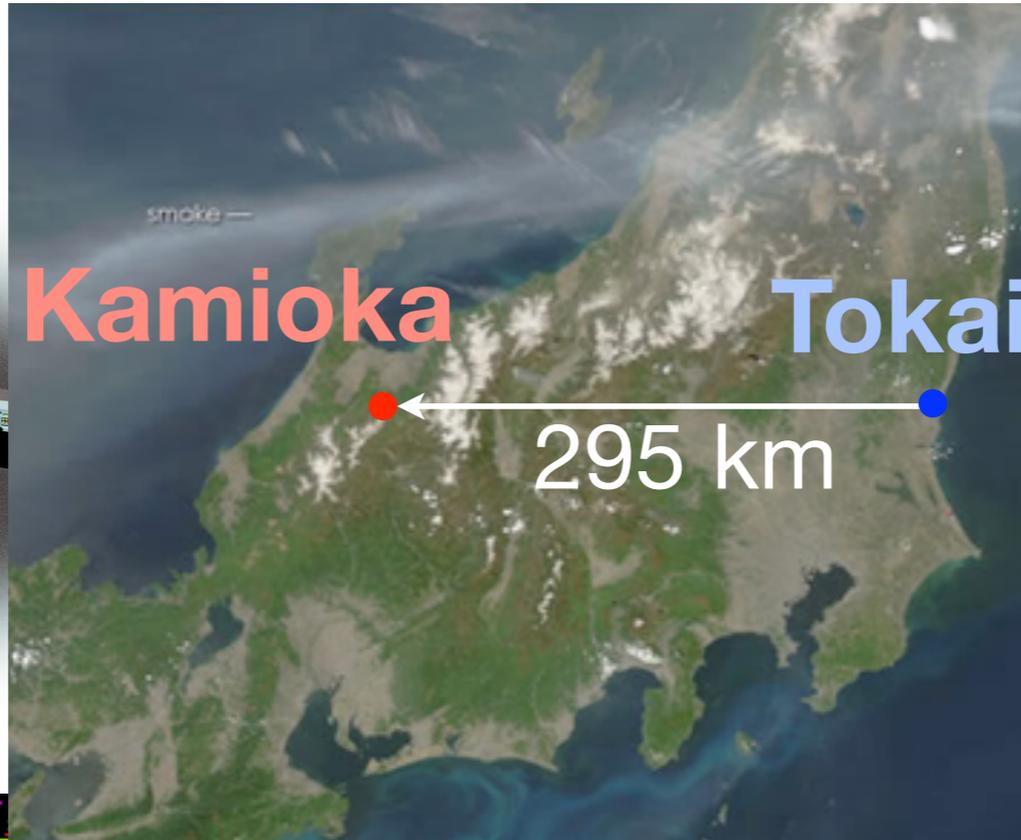
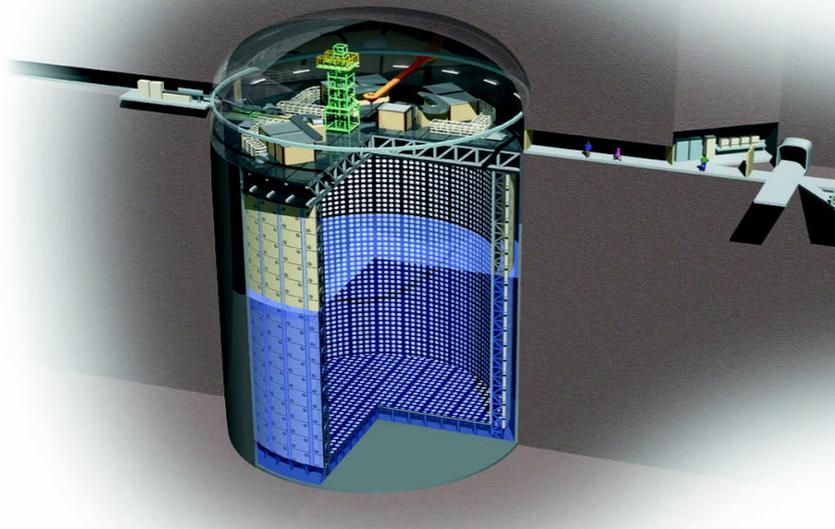
*T2K*実験とスーパーカミオカンデ実験による「ニュートリノ *CP*の測定」

中家 剛 (京大理/東大Kavli-IPMU)

T2K Neutrino Oscillation Experiment

Very Intense Neutrino Beam for $(\bar{\nu})_{\mu} \rightarrow (\bar{\nu})_{e}$ study

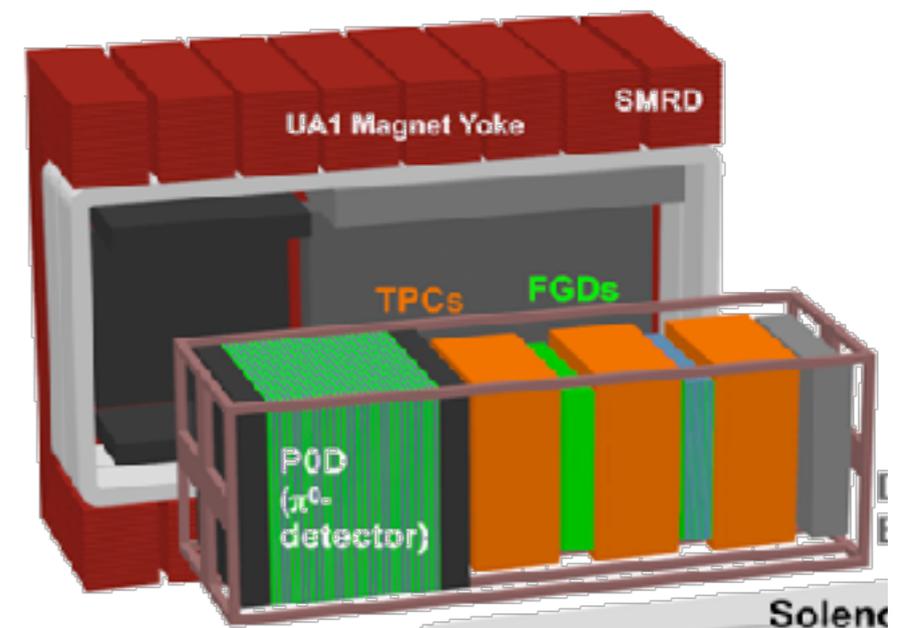
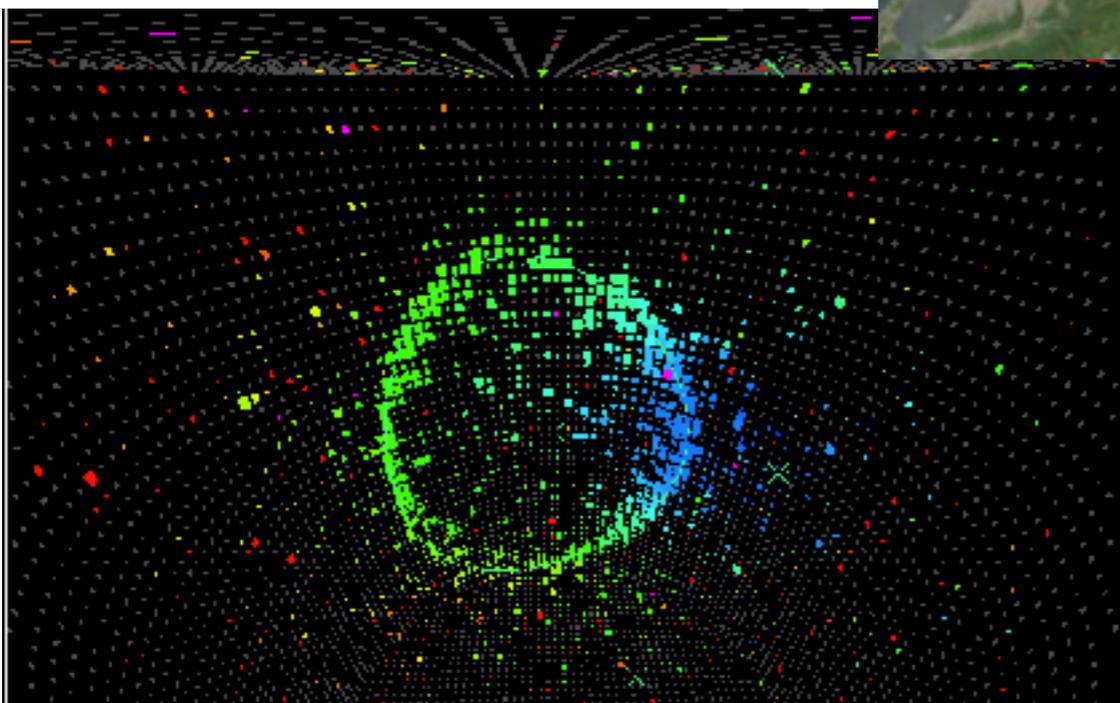
Super-K



J-PARC



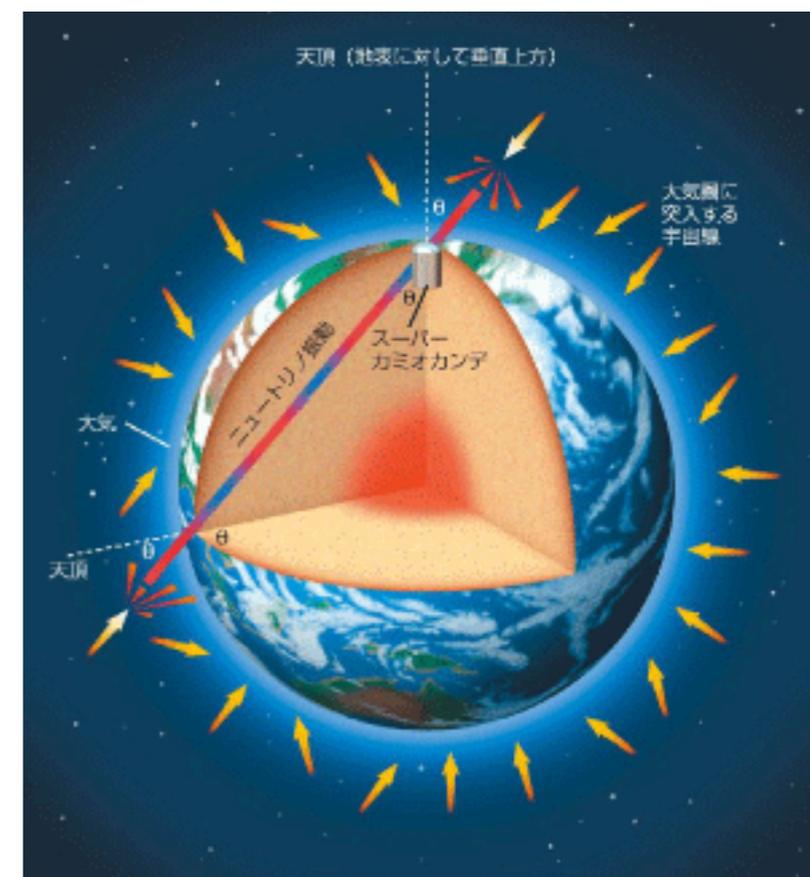
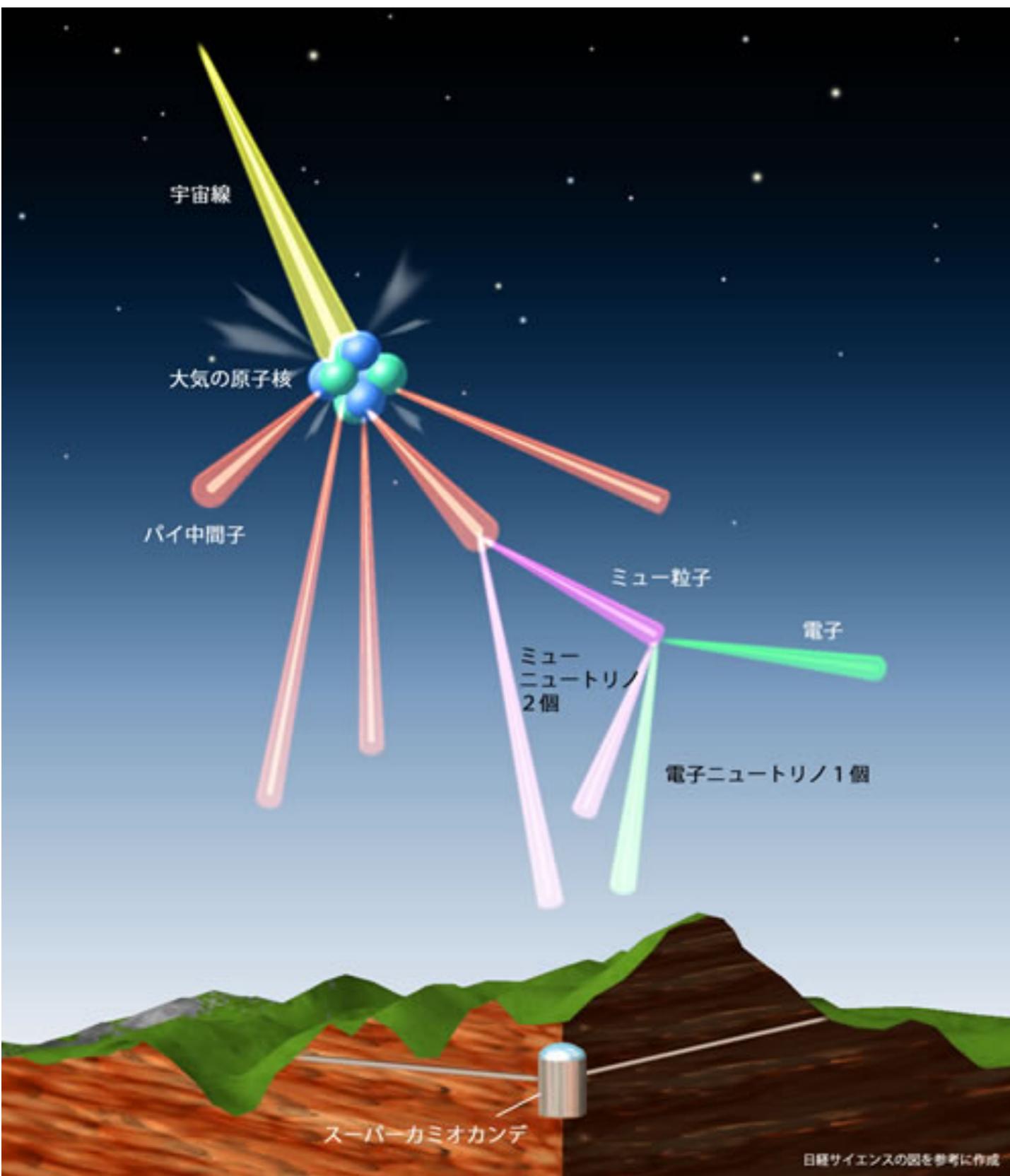
- 470 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)



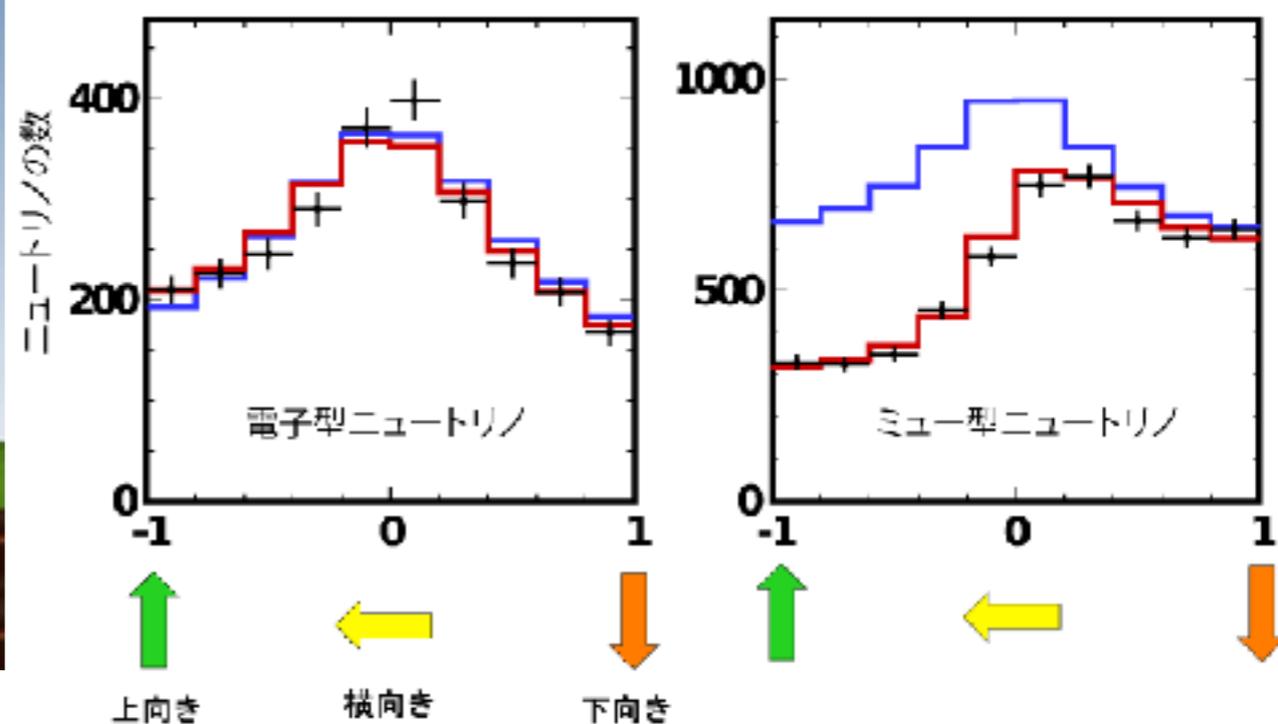


~500 members, 59 Institutes, 11 countries

Super-K Atmospheric Neutrinos



— ニュートリノ振動がない場合の期待値
— ニュートリノ振動がある場合の期待値
+ SKの実測値



Today's Topics

- CP violation in neutrino oscillation
- Neutrino oscillation parameters
 - 3 neutrinos or more?
 - Mass hierarchy
 - $\sin^2 \theta_{23}$
- T2K and Super-K results
- In future, T2K-II \rightarrow Hyper-Kamiokande

Introduction

Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar, Reactor
Atmospheric, Accelerator

$$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$$

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

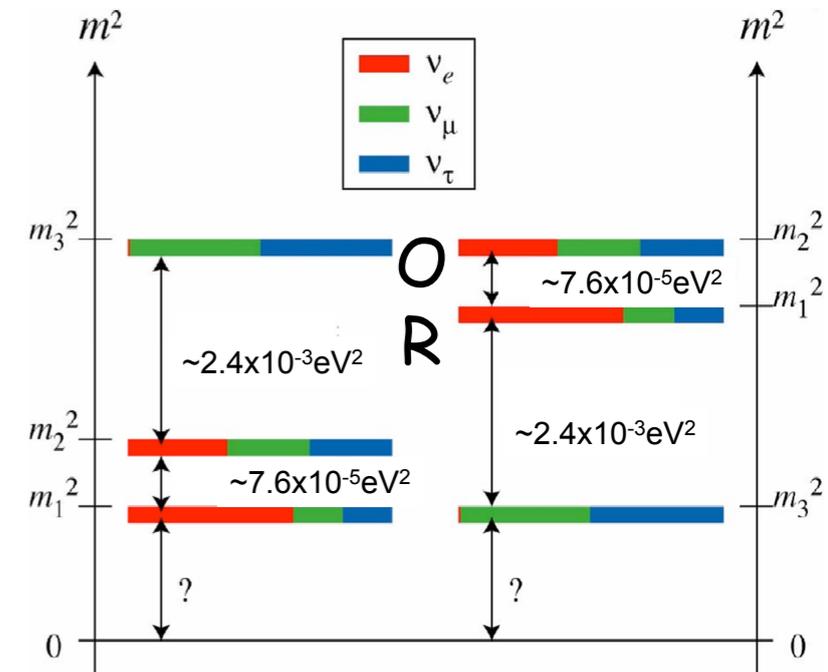
**Atmospheric
Accelerator**

**Accelerator
Reactor
Atmospheric**

**Solar
Reactor**

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad \delta \sim \text{unknown}$$

$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix} \quad \delta = 60^\circ$$



• In the framework of 3 neutrinos, the unknowns are

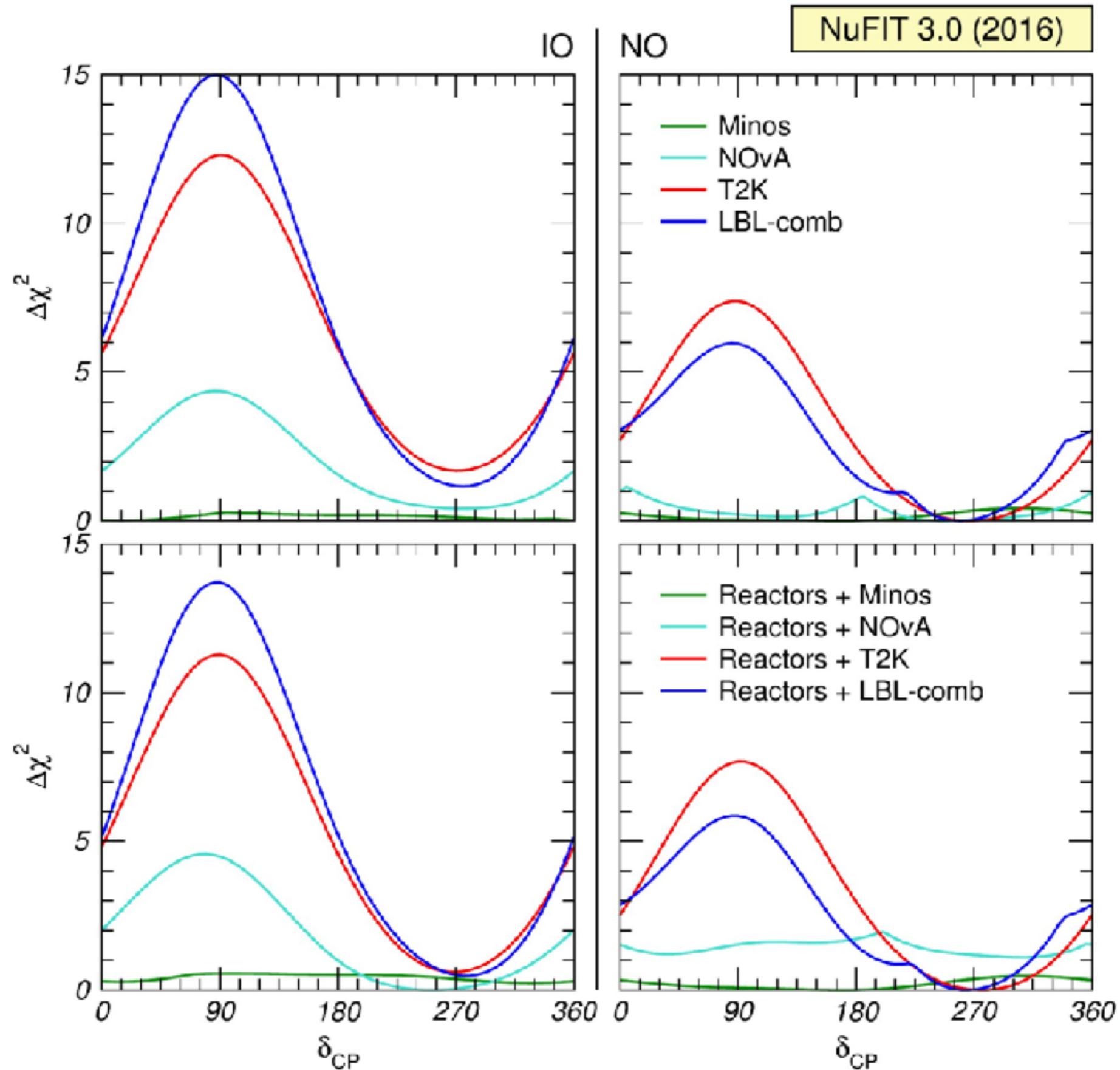
- mass ordering
- CP violation parameter: δ_{CP}

Current values of the oscillation parameters

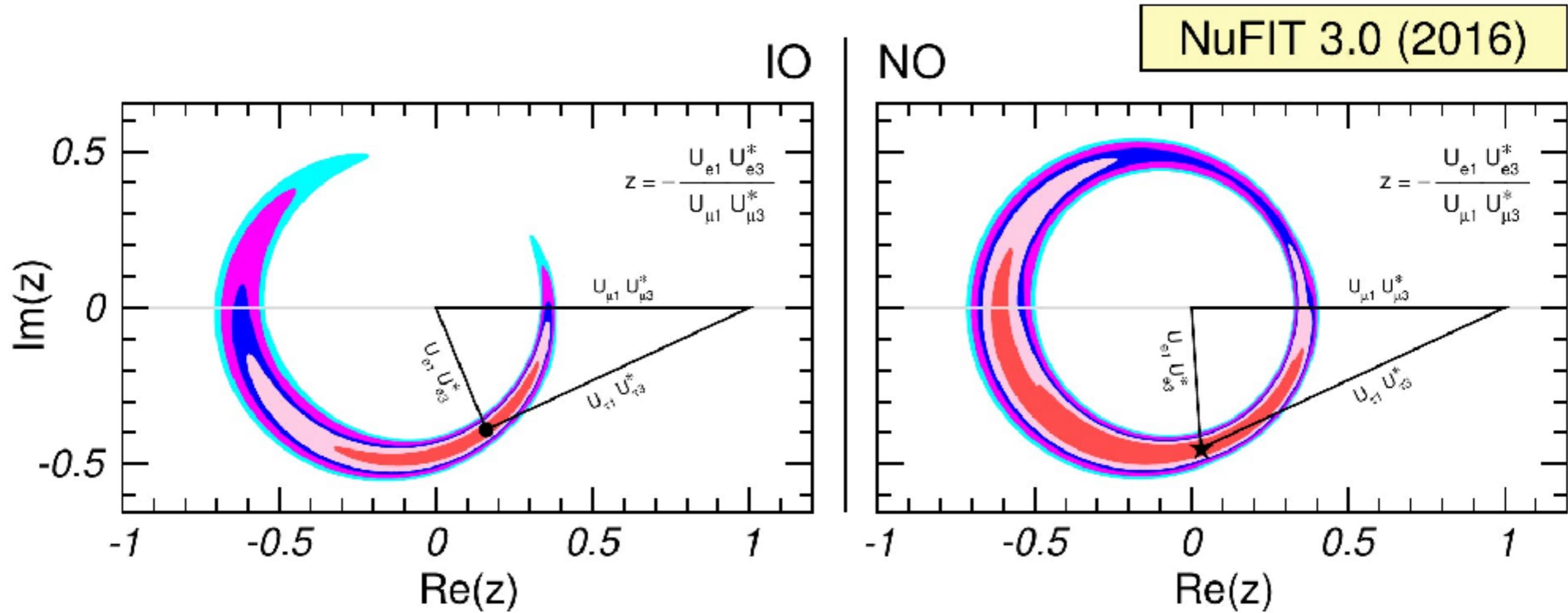
NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2 \theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \rightarrow 0.345$	$0.271 \rightarrow 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \rightarrow 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \rightarrow 35.99$	$31.38 \rightarrow 35.99$
$\sin^2 \theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \rightarrow 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \rightarrow 0.640$	$0.385 \rightarrow 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \rightarrow 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \rightarrow 53.1$	$38.4 \rightarrow 53.0$
$\sin^2 \theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \rightarrow 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \rightarrow 0.02408$	$0.01934 \rightarrow 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \rightarrow 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \rightarrow 8.93$	$7.99 \rightarrow 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \rightarrow 360$	277^{+40}_{-46}	$145 \rightarrow 391$	$0 \rightarrow 360$
$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \rightarrow 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \rightarrow 8.09$	$7.03 \rightarrow 8.09$
$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \rightarrow +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \rightarrow -2.399$	$\left[+2.407 \rightarrow +2.643 \right]$ $\left[-2.629 \rightarrow -2.405 \right]$

Status of δ_{CP}



Three neutrinos and Beyond



Assuming unitarity (3 neutrinos)

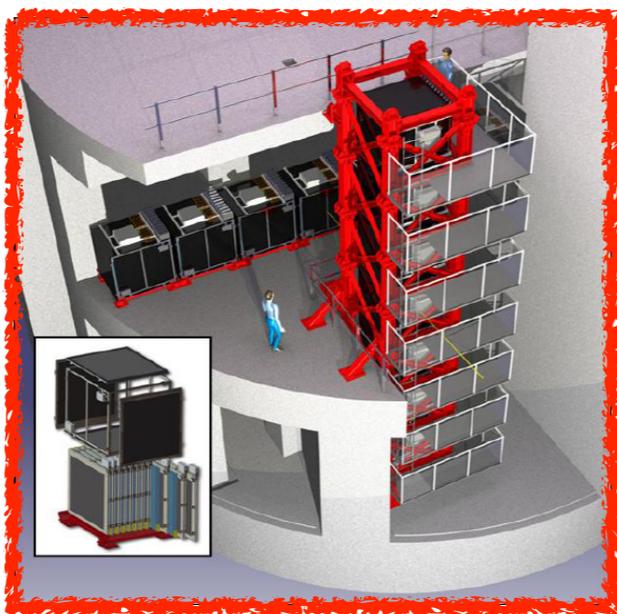
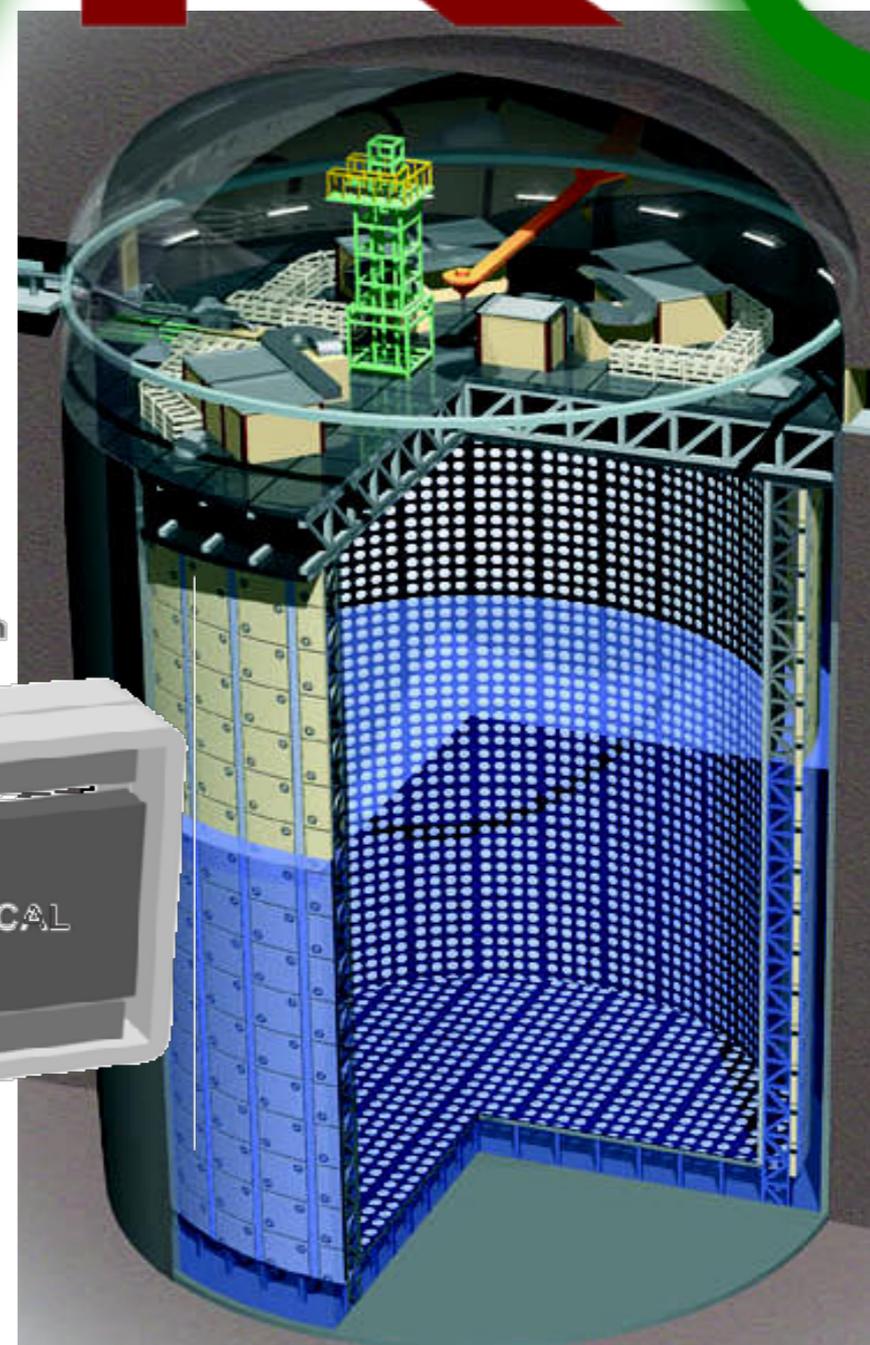
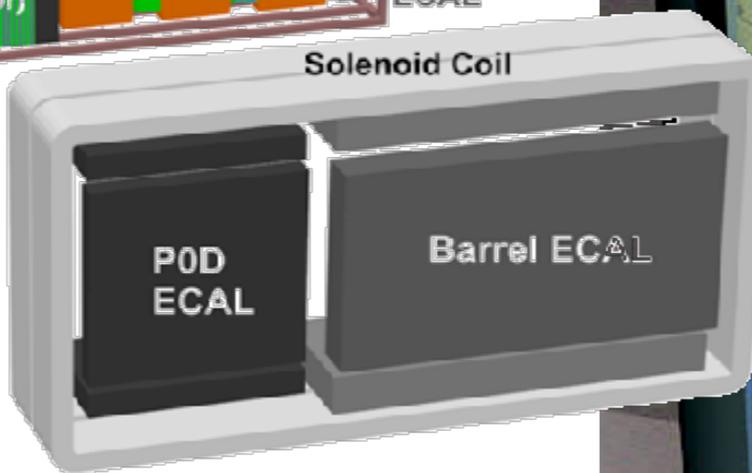
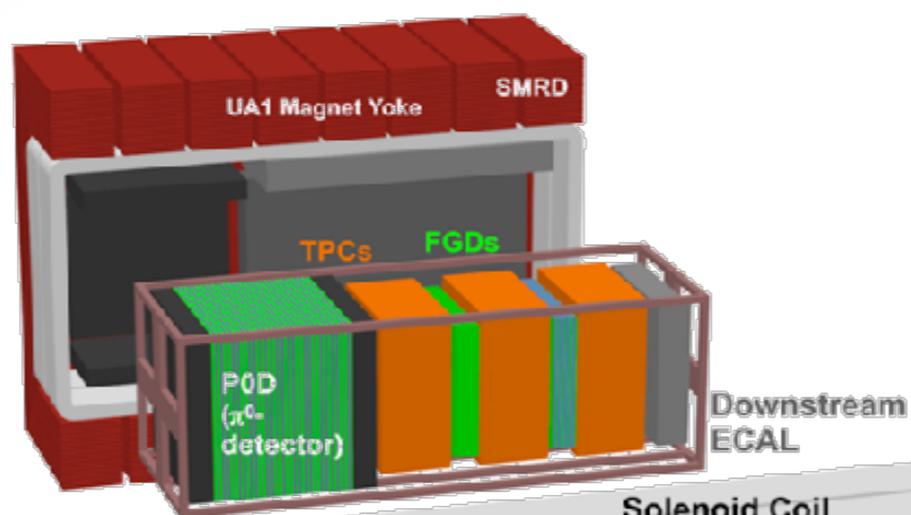
Through neutrino oscillations, we want to know

- CP violation
 - PMNS matrix or beyond. Any source of new CP violation?
 - the relation with leptogenesis and a quest of the matter - antimatter asymmetry in our universe.
- A pattern of the PMNS matrix and the mass of neutrinos
 - A relation with a GUT model

T2K results

- **The new T2K results will be announced at the KEK Colloquium at 10:00 JST on Friday, August 4th.**
 - Title:
 - T2K neutrino oscillation results with data up to 2017 Summer
 - Abstract:
 - In 2016, T2K reported the results of neutrino oscillation measurements based on the data accumulated with 7.5×10^{20} protons-on-target from the J-PARC Main Ring (MR) for each of the neutrino beam run and the antineutrino beam run. One of the highlights then was an indication of CP violation with 90% C.L. Since then, the J-PARC MR beam power was increased up to 470kW and T2K accumulated another 7.2×10^{20} protons-on-target with neutrino beam in a half-year run. In addition, approximately a 30% increase in statistics was achieved by improvements to the event selection at Super-Kamiokande, the T2K far detector. In this colloquium, we will present the results of the neutrino oscillation measurements with all of the data collected up to now and with the new event selection.

TRZKK



Formula of Oscillation Probability with CP violation

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \text{ Leading} \\
 & + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
 & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \cdot \sin \Delta_{32} \cdot \sin \Delta_{31} \cdot \sin \Delta_{21} \\
 & + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta) \cdot \sin^2 \Delta_{21} \text{ Solar} \\
 & - 8C_{13}^2 S_{13}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos \Delta_{32} \cdot \sin \Delta_{31} \\
 & + 8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31} \text{ Matter effect}
 \end{aligned}$$

Leading

$$\sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

CPV

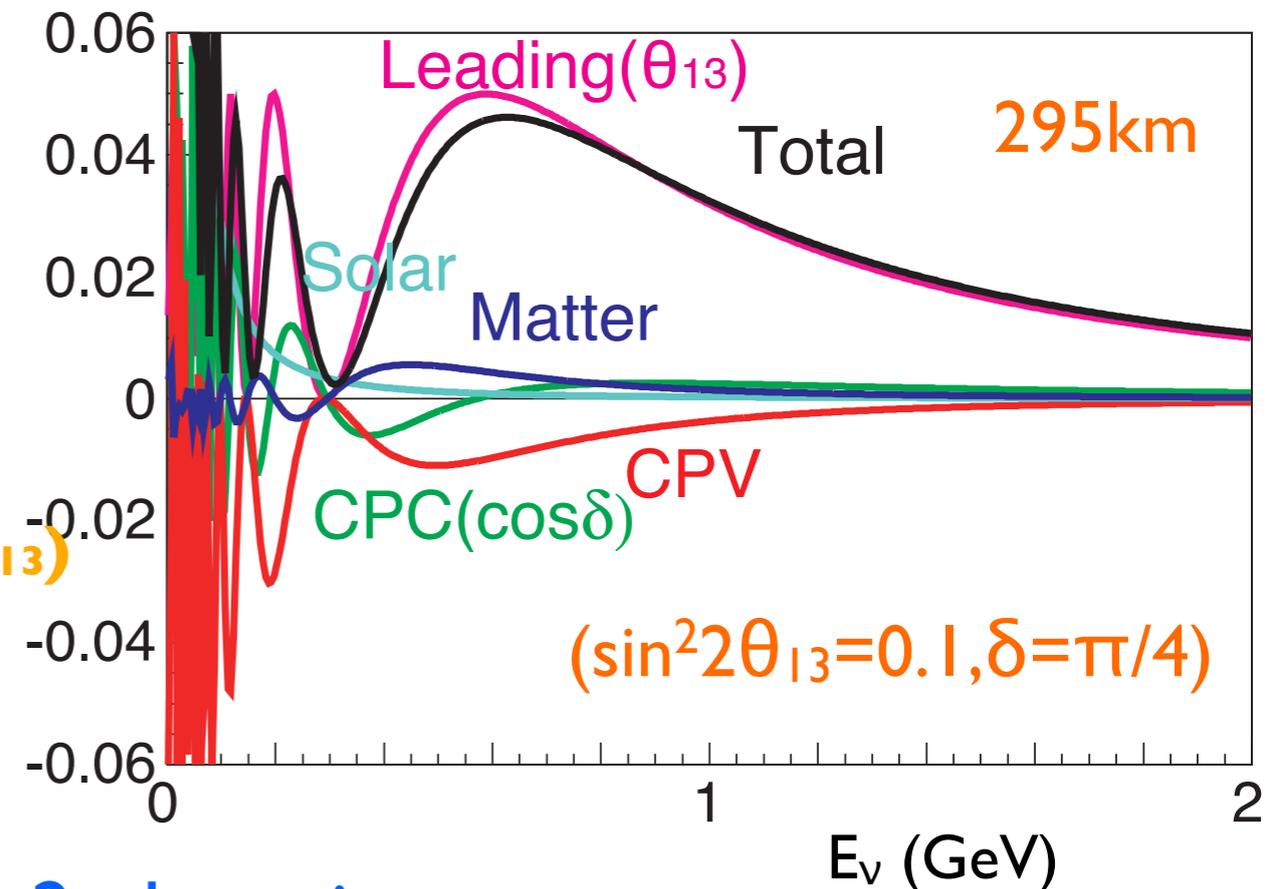
$$\frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \delta$$

$$\sim 0.03 \sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2 \theta_{23} \sin \theta_{13}} \frac{E_{1st \max}}{E} [leading] \sin \delta \sim 1.8 \text{ (6.4 from } 1/\sin \theta_{13})$$

$$\sim 0.27 \times [leading] \times \frac{E_{1st \max}}{E} \times \sin \delta$$

27%

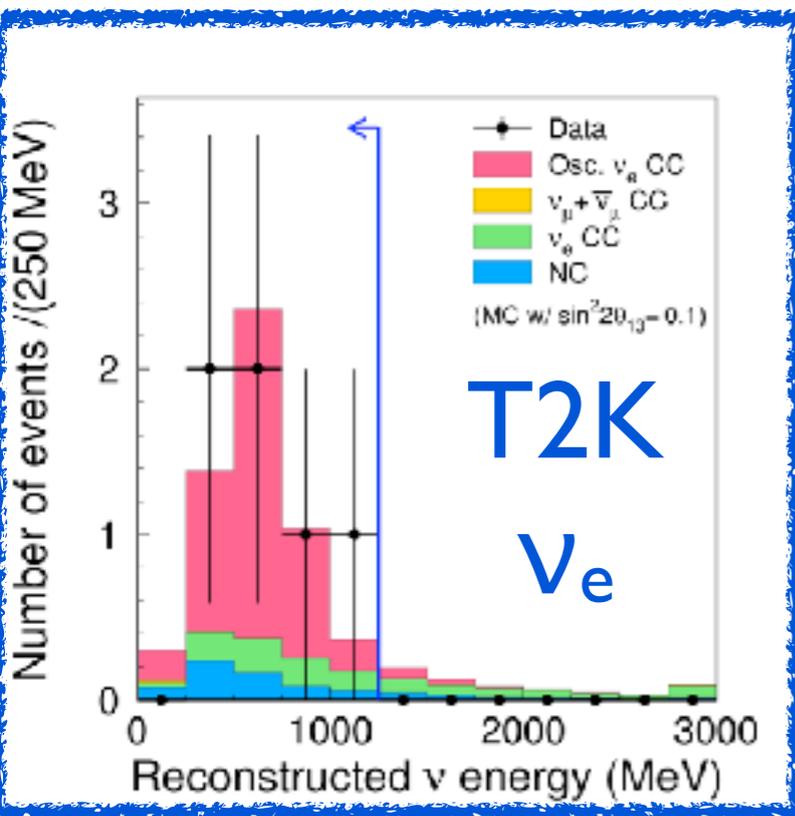
- No magic for the 2nd maximum.
- Energy dependence is important.



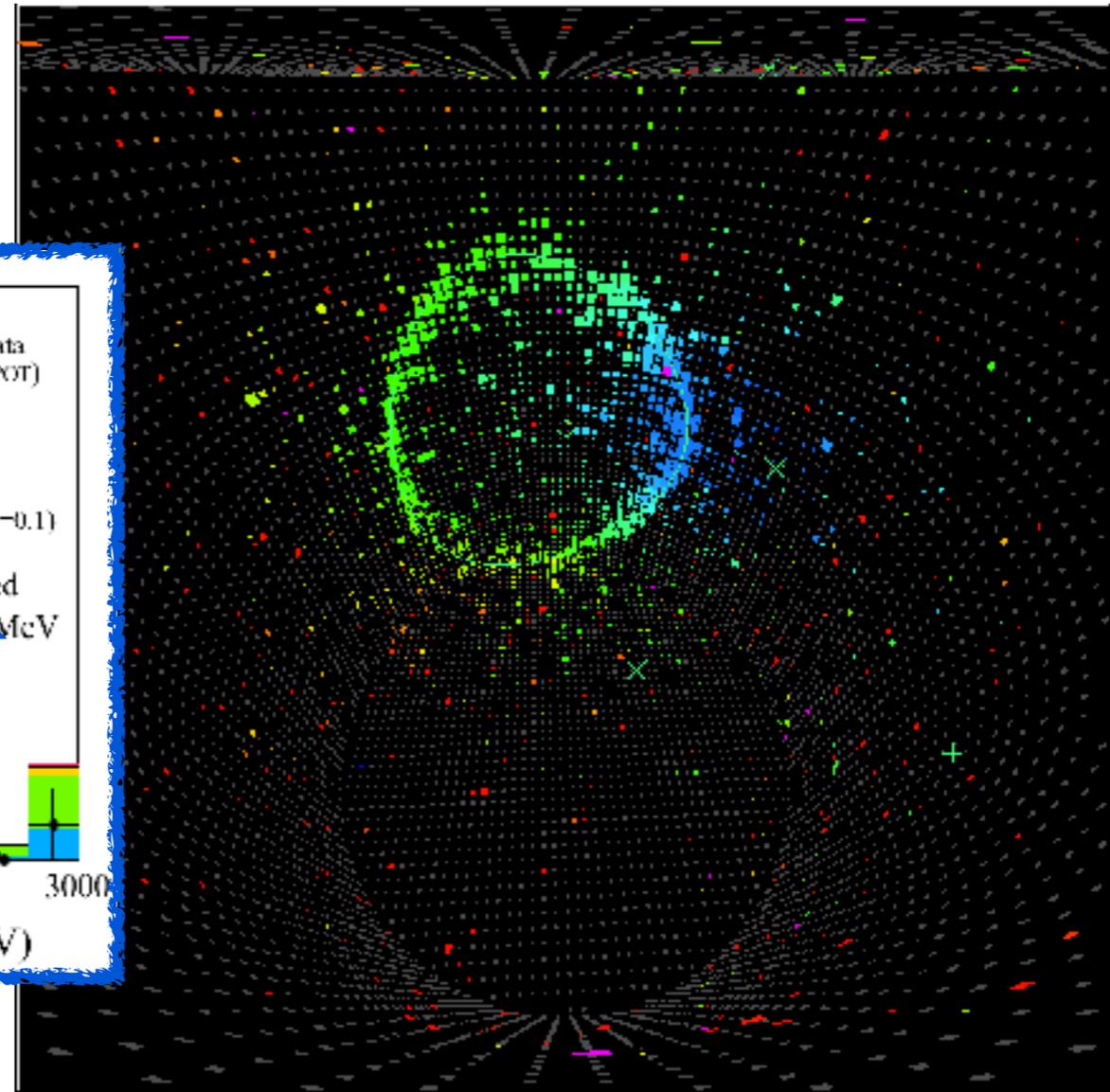
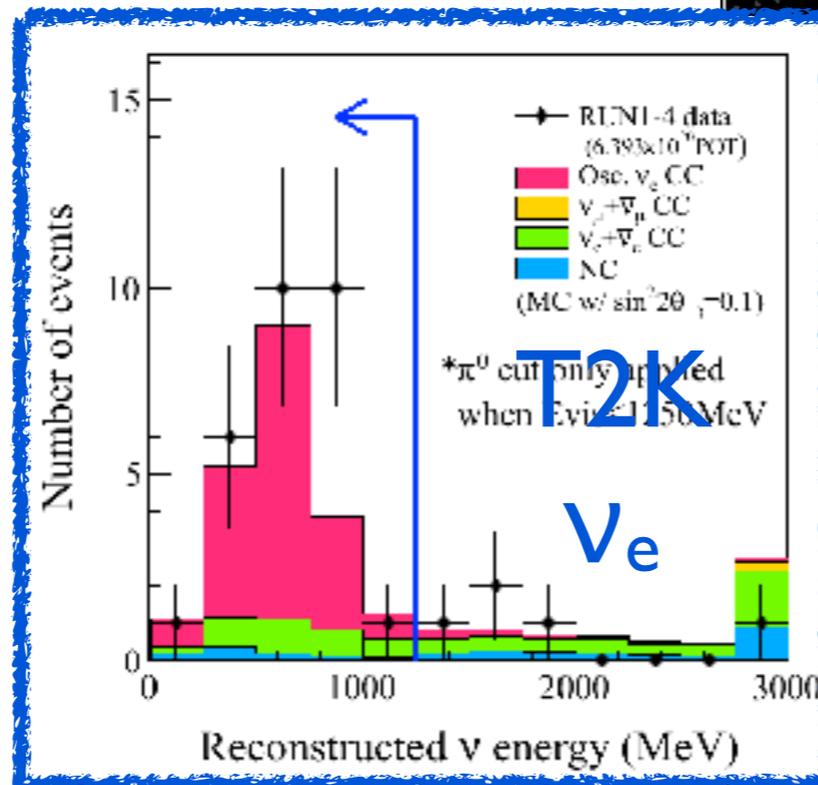
A door to Neutrino CP violation is opened

- $\nu_{\mu} \rightarrow \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
 - Indication in 2011 [PRL 107, 041801 (2011)]
 - Observation in 2013 [PRL 112, 061802 (2014)]

2011



2013



FRAMEWORK

- Four modes of observation observed at T2K
 - $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
 - $\nu_\mu \rightarrow \nu_\mu, \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ disappearance
 - use all information to constrain oscillation parameters

Parameters	Asimov A
$\sin^2 2\theta_{12}$	0.846
$\sin^2 2\theta_{13}$	0.0849
$\sin^2 \theta_{23}$	0.528
Δm_{21}^2	7.53×10^{-5}
Δm_{32}^2	2.509×10^{-3}
δ_{cp}	-1.601

constrain by reactor

$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \times \boxed{\sin^2 \theta_{23}} \times \frac{\sin^2 [(1-x)\Delta_{31}]}{(1-x)^2} \times \sin \Delta_{31} \frac{\sin[x\Delta_{31}]}{x} \frac{\sin[(1-x)\Delta_{31}]}{1-x} + \mathcal{O}(\alpha^2)$$

switches sign for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$- \alpha \sin \delta_{CP} + (\text{CP even})$$

constrain by ν_μ disp.

$$\alpha = \left| \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \right| \sim \frac{1}{30} \quad \Delta \equiv \frac{\Delta m_{31}^2 L}{4E} \quad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$$

M. Freund, Phys.Rev. D64 (2001) 053003

$$P(\nu_\mu \rightarrow \nu_\mu) \sim 1 - (\cos^4 2\theta_{13} \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \sin^2 \theta_{23}) \sin^2 \Delta m_{31}^2 \frac{L}{4E}$$

- Large θ_{23} : enhances both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\delta_{CP} = -\pi/2$: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\Delta m_{31}^2 > 0$ (normal hierarchy): enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$$N_{\text{signal}} = \Phi \times \sigma \times N_{\text{target}} (\times \epsilon)$$

Oscillation Analysis in T2K

Φ

ND280 ν_{μ} measurements

Neutrino flux prediction
w/CERN NA61 result

Flux
+Cross Section Fit

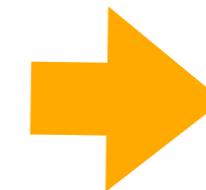
Neutrino Cross Section
Uncertainties

σ

$N_{\text{target}} (\times \epsilon)$

SK Detector/Selection
Uncertainties

Osc. Fit:
 $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$, Δm_{32}^2 ,
 δ_{CP}



Result

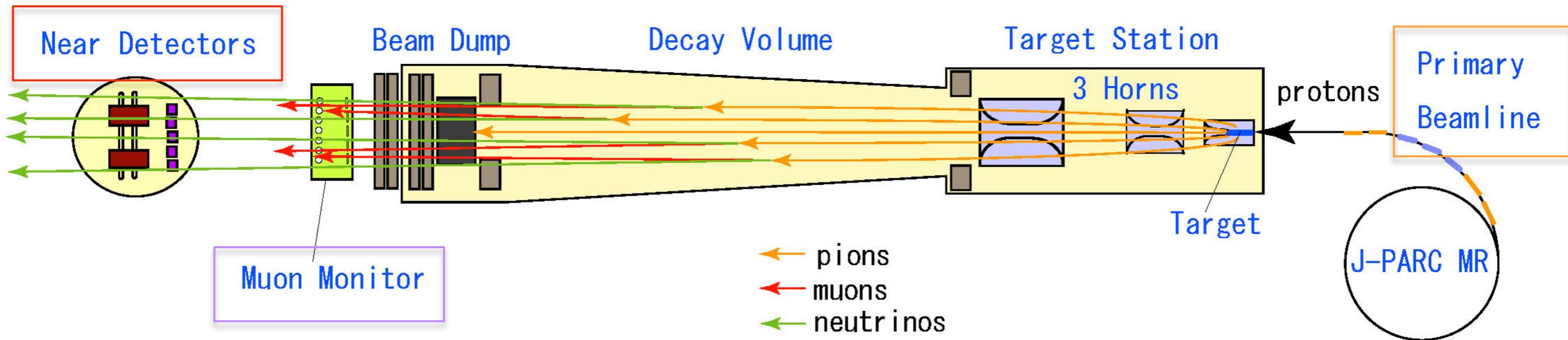
Neutrino Cross Section
Uncertainties

σ

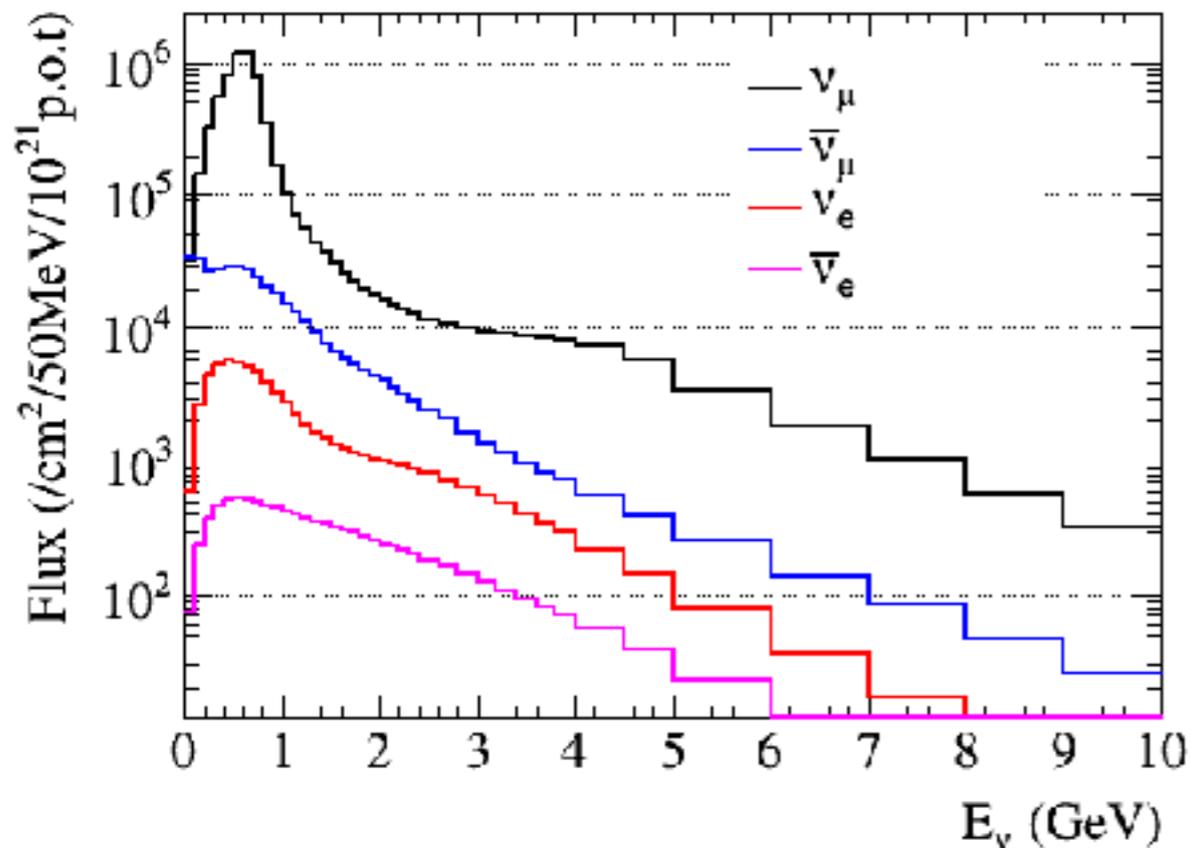
ν oscillation parameters fixed:

- $\Delta m_{12}^2 = 7.6 \times 10^{-5} \text{ eV}^2$
- $\sin^2 \theta_{12} = 0.32$

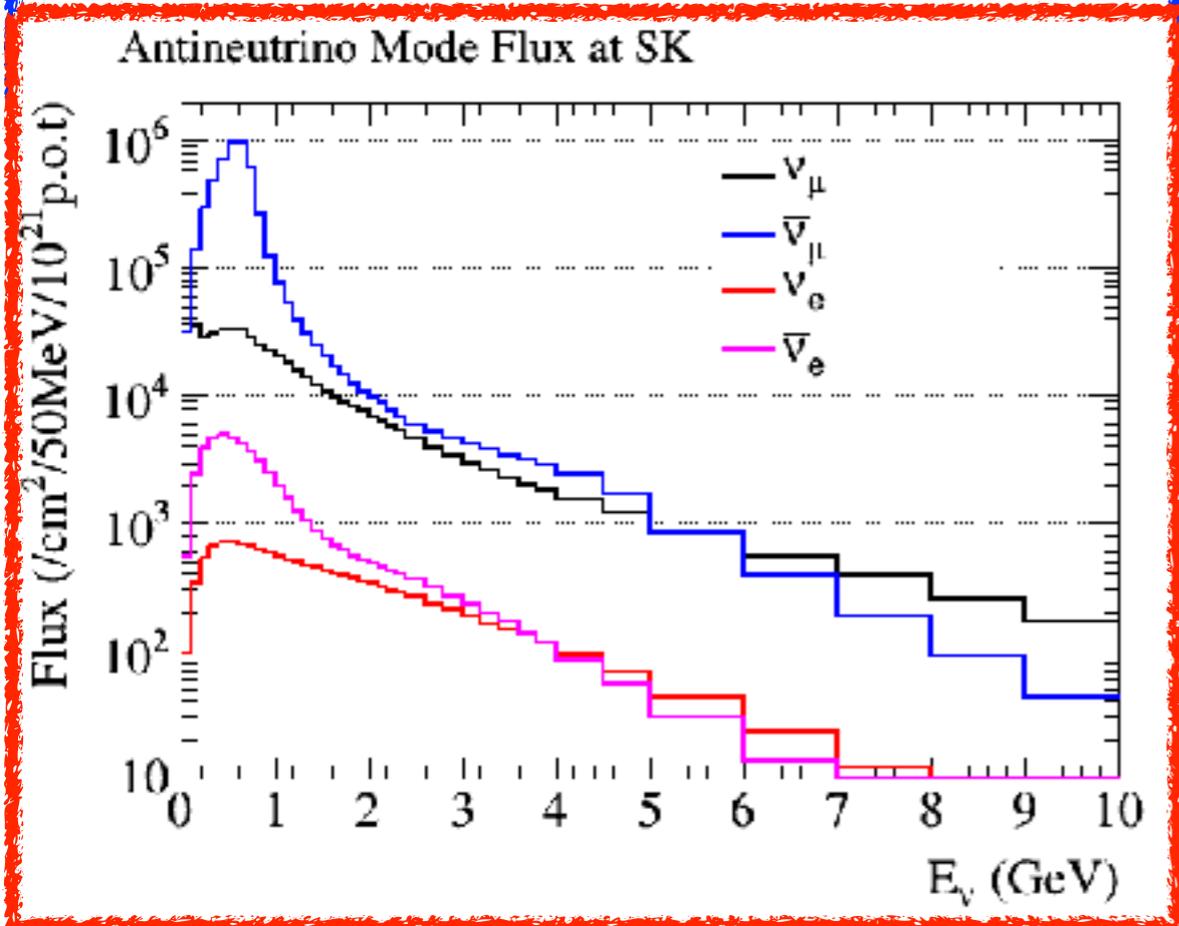
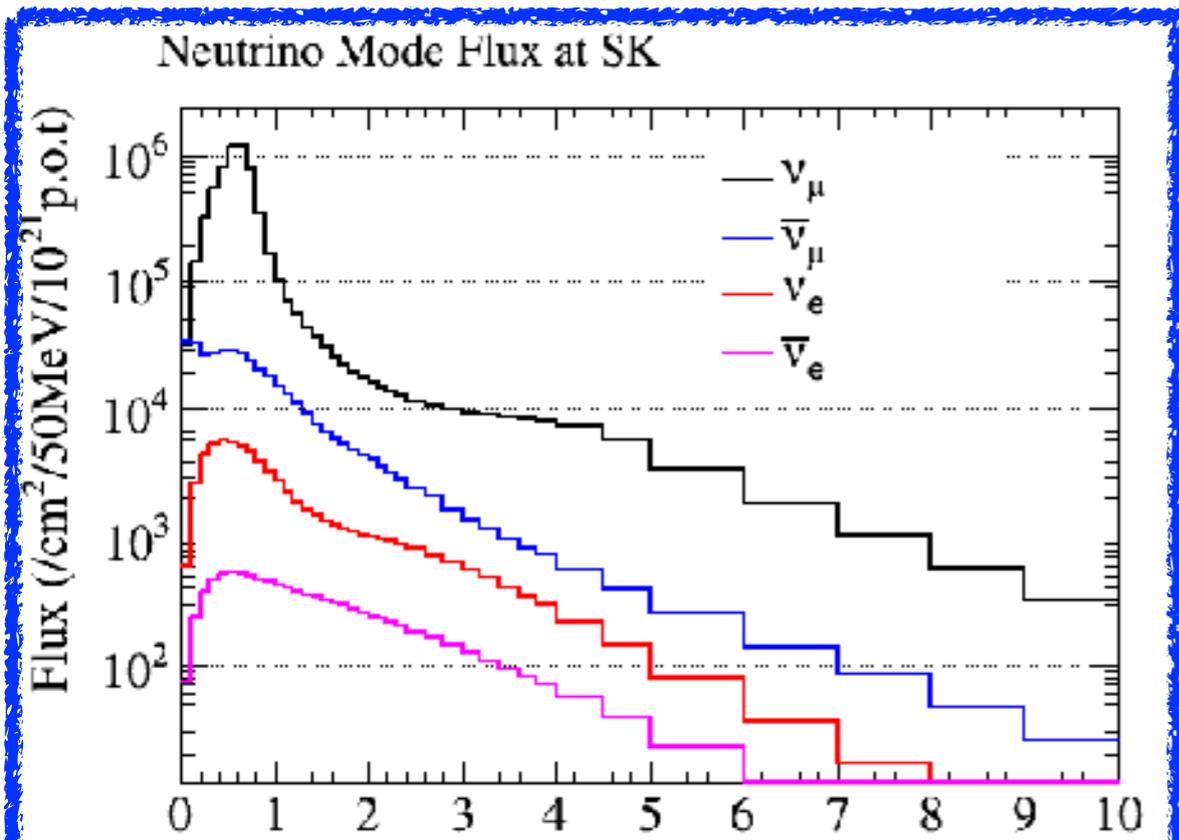
T2K neutrino beam



Neutrino Mode Flux at SK

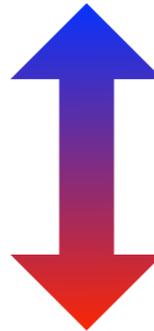


Predicted Neutrino Flux

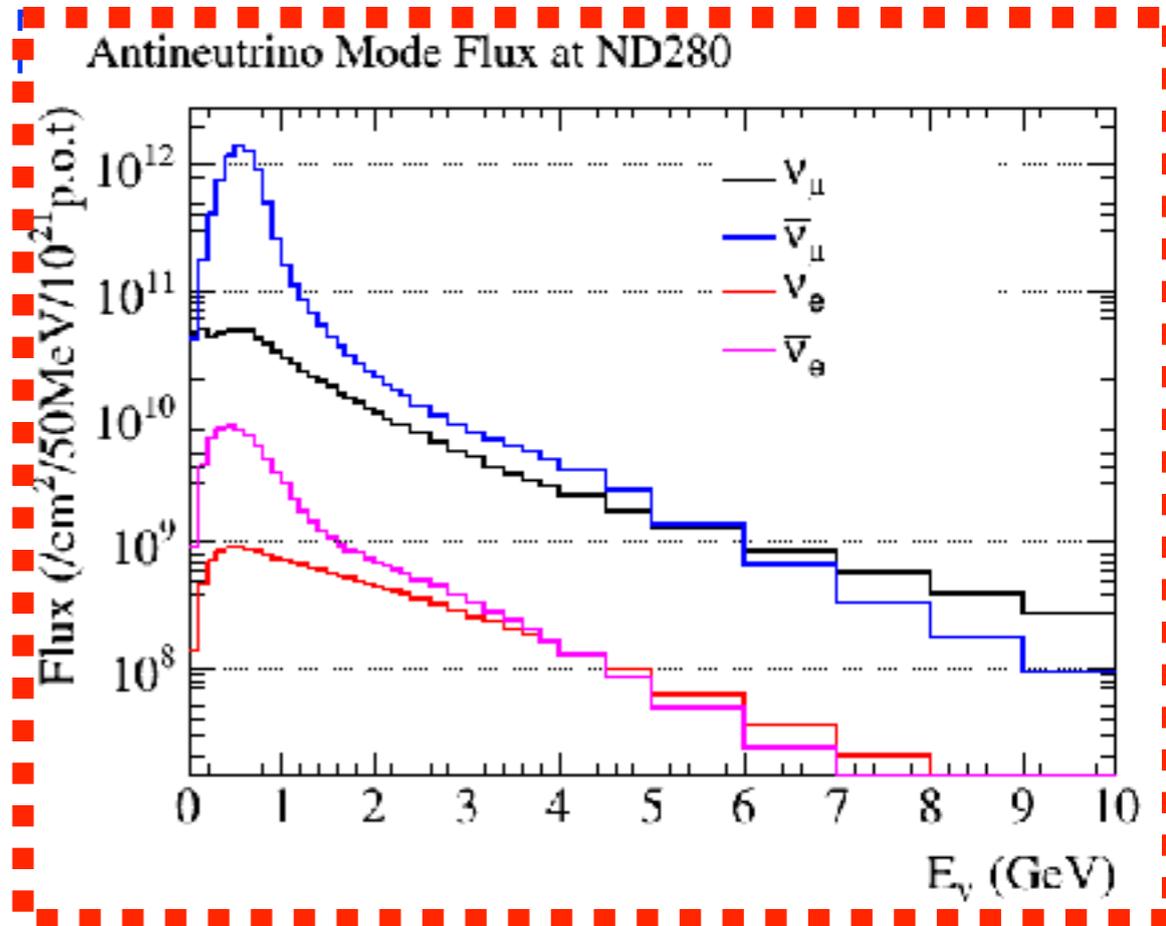
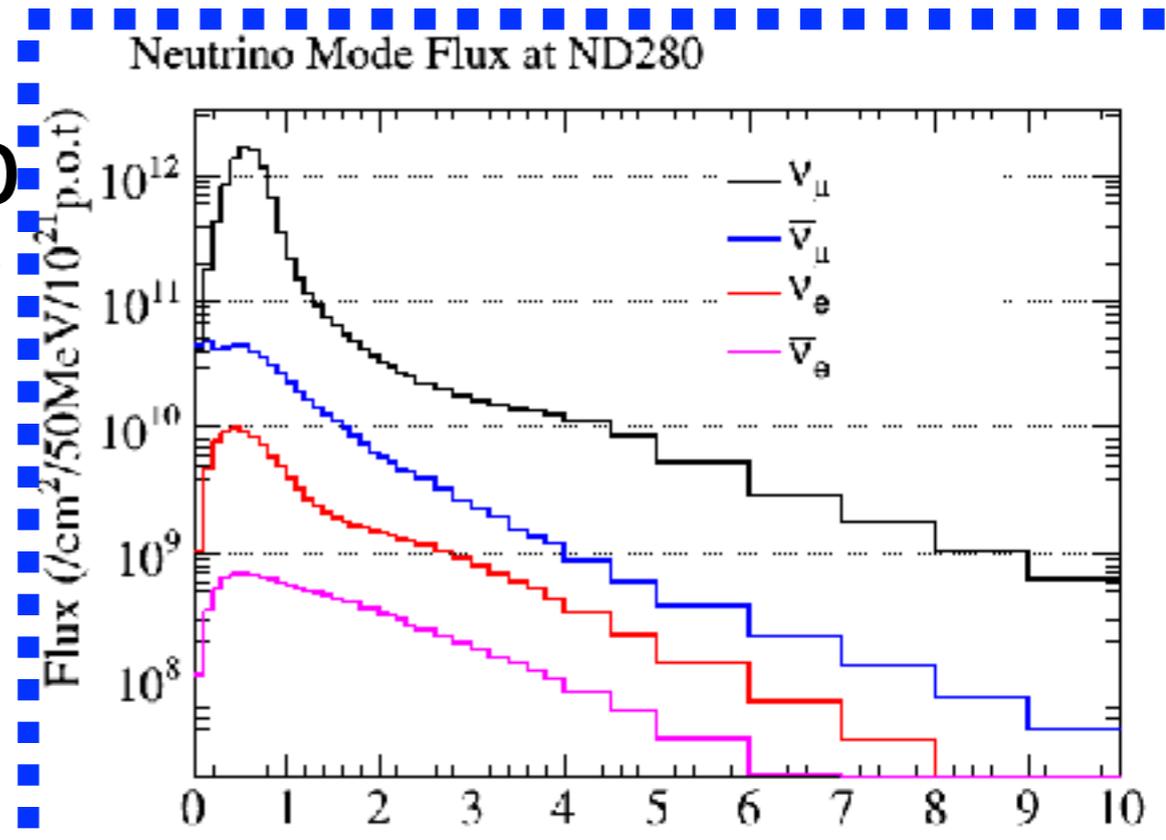


SK \longleftrightarrow ND280

ν

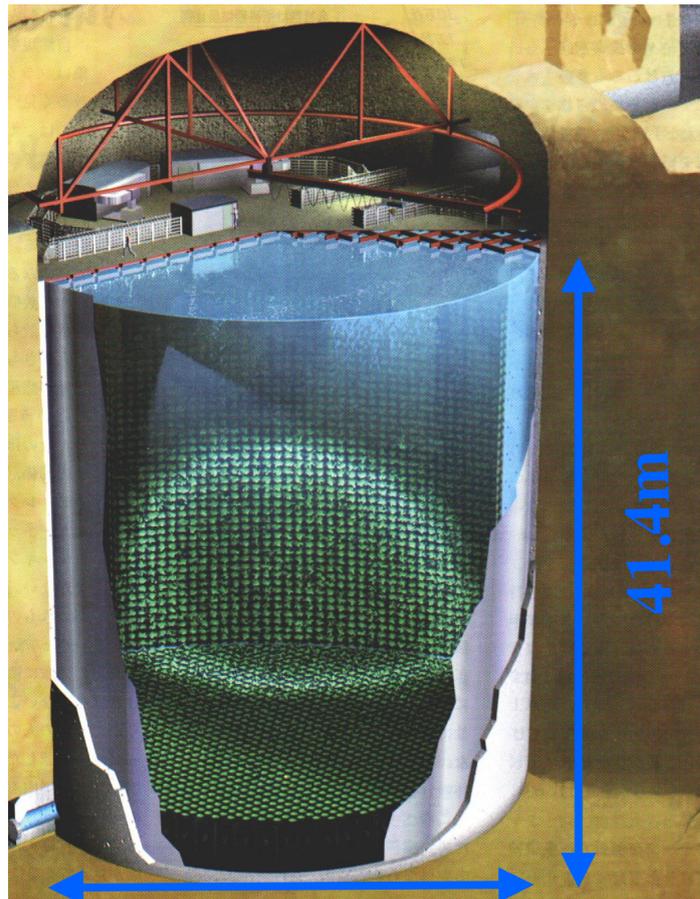


$\bar{\nu}$



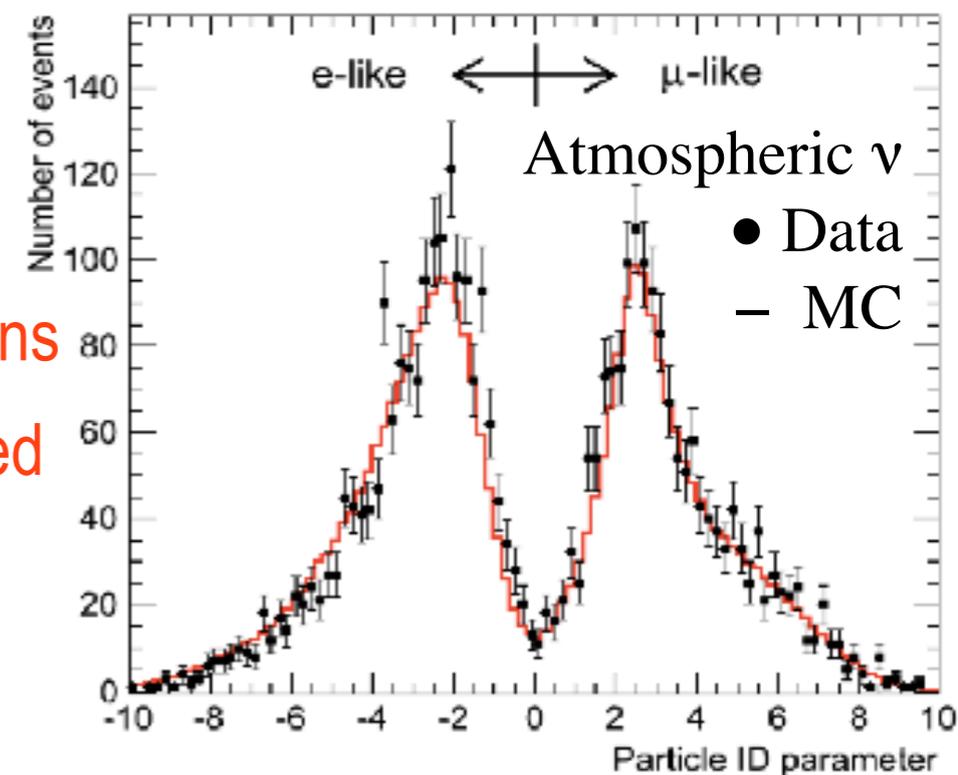
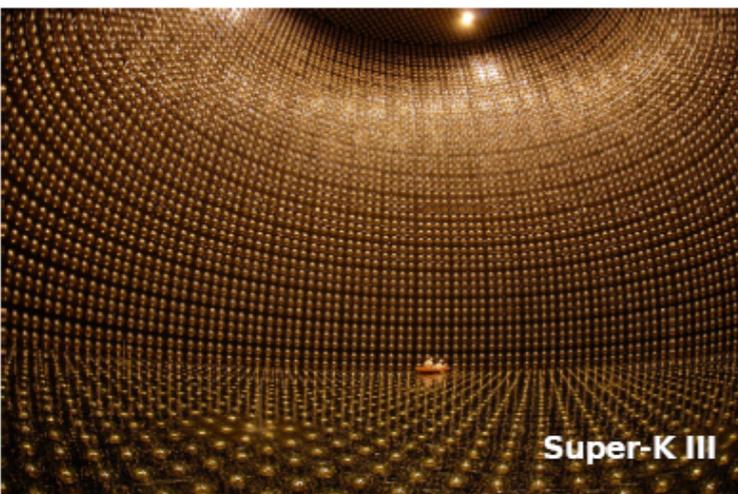
Super-Kamiokande

- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
 - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
 - [Typical] 61% efficiency for T2K signal ν_e with 95% NC- $1\pi^0$ rejection
 - Inner tank (32 kton) :11,129 20inch PMT
 - Outer tank:1,885 8inch PMT
- Dead-time-less DAQ
- GPS timing information is recorded real-time at every accelerator spill
- T2K recorded events: All interactions within a $\pm 500\mu\text{sec}$ window centered on the the neutrino arrival time.



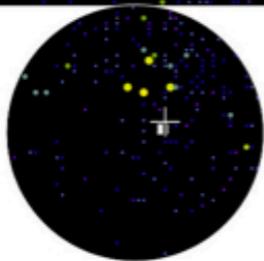
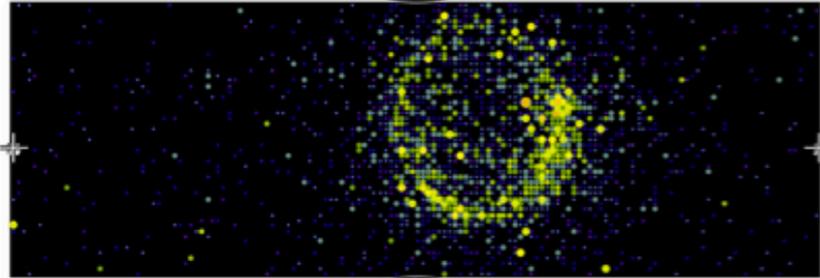
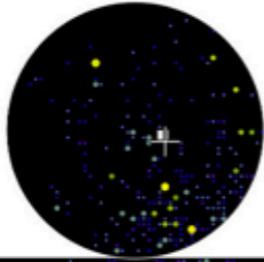
39.3m

41.4m

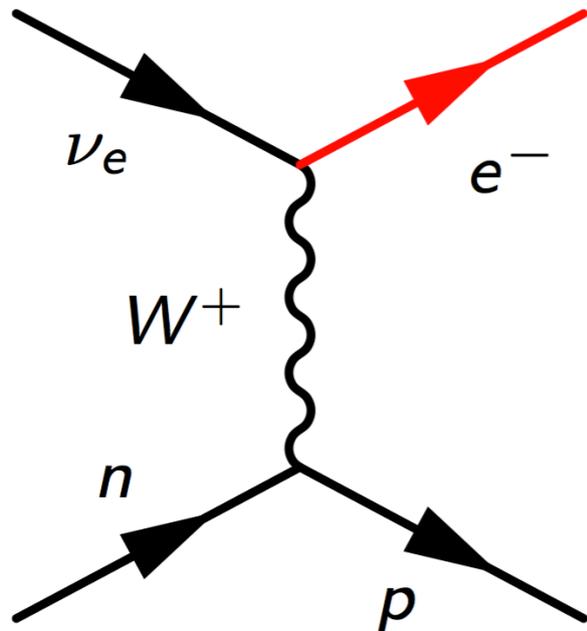


Neutrino Detection at SK Far Detector

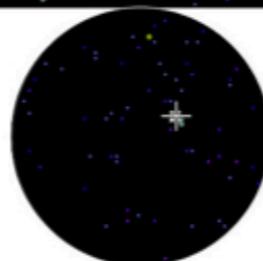
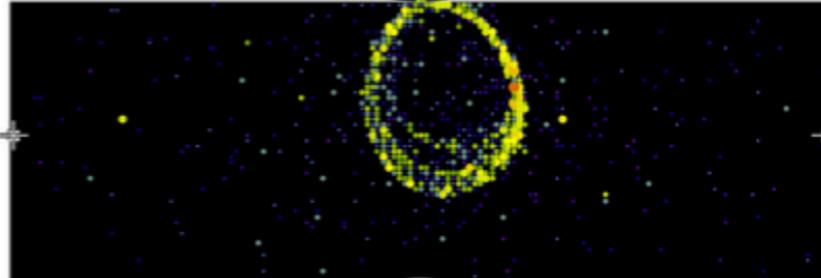
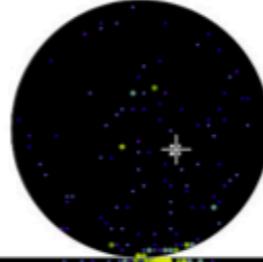
Signal (ν_e)



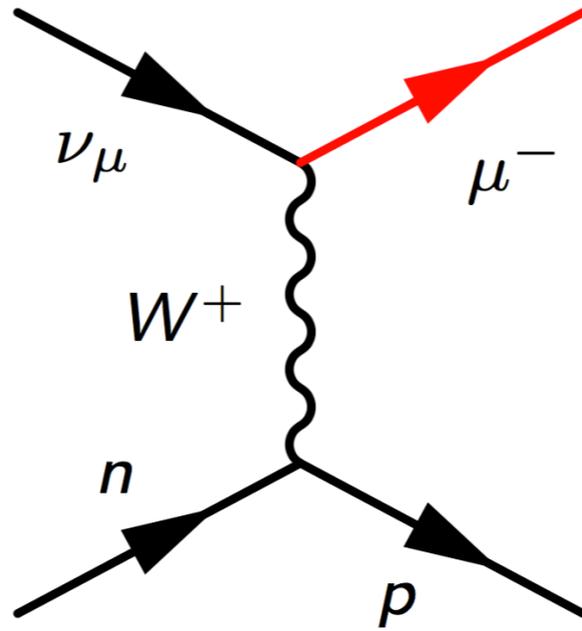
ν_e CCQE



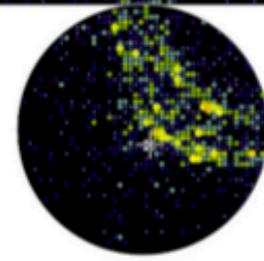
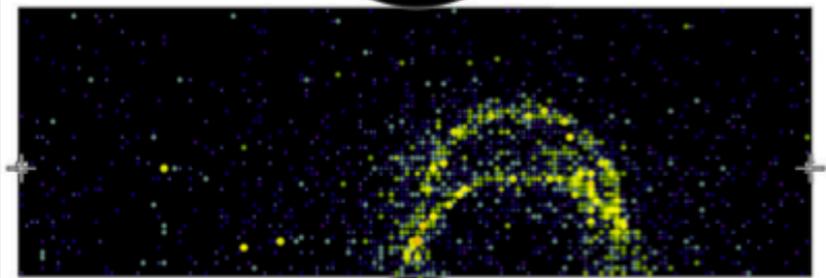
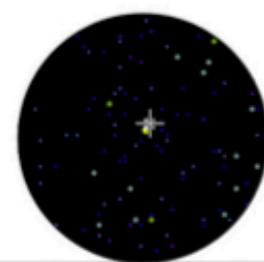
Signal (ν_μ)



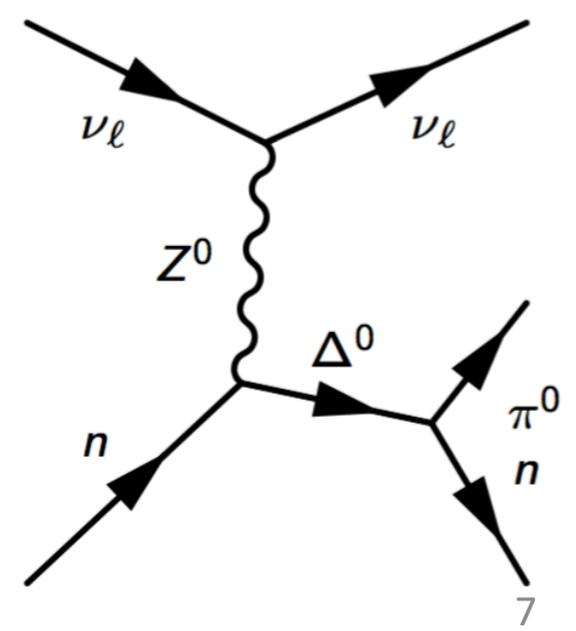
ν_μ CCQE



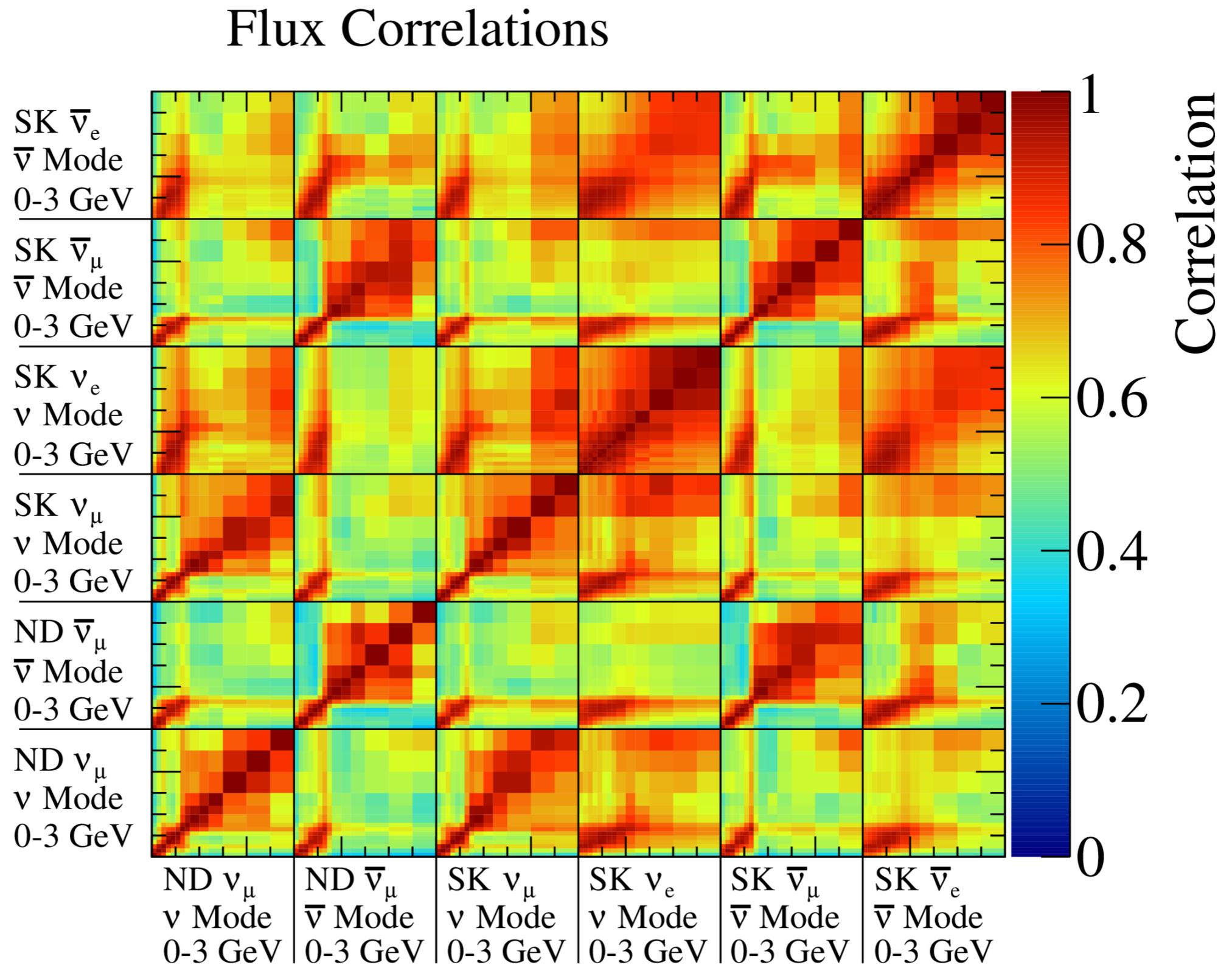
Background



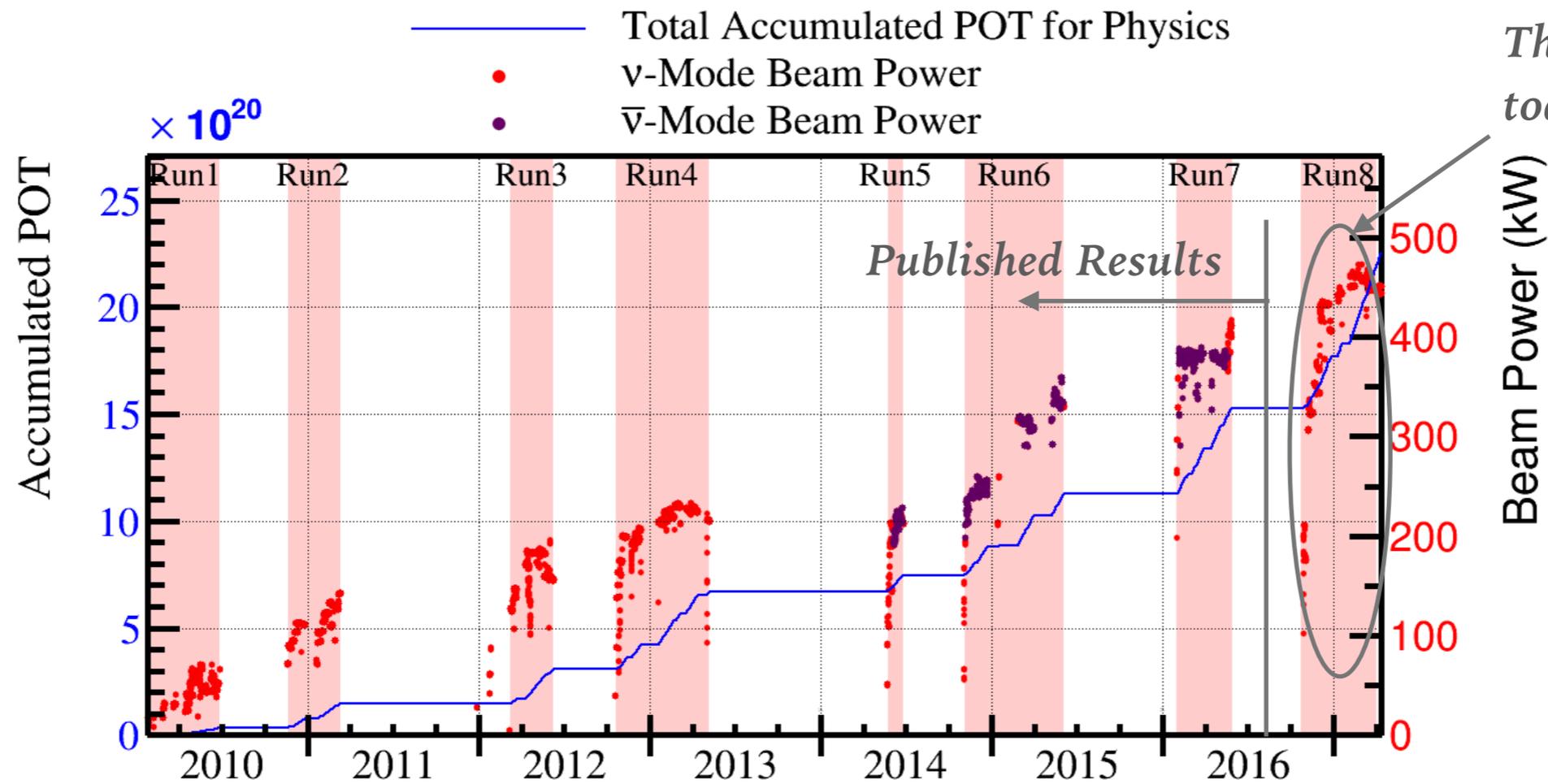
ν_ℓ NC1 π^0



Flux correlations before ND280 fit : zoom



T2K DATA COLLECTION HISTORY



- Accumulated 14.7×10^{20} protons-on-target (POT) in neutrino mode and 7.6×10^{20} POT in antineutrino mode - full data set presented here
 - **29% of the approved T2K POT**
 - 7.5×10^{20} neutrino mode, 7.5×10^{20} antineutrino mode for published results
 - **Phys. Rev. Lett. 118 (2017) no.15, 151801 - PRL Editor's Suggestion**
- Accelerator has achieved stable operation with **470 kW beam power**
 - **Thanks to high power operation, double neutrino data in 1 year!**

Today's results

- Based on

High Energy Physics – Experiment

Measurement of neutrino and antineutrino oscillations by the T2K experiment including a new additional sample of ν_e interactions at the far detector

K. Abe, J. Amey, C. Andreopoulos, M. Antonova, S. Aoki, A. Ariga, Y. Ashida, S. Ban, M. Barbi, G.J. Barker, G. Barr, C. Barry, M. Batkiewicz, V. Berardi, S. Berkman, S. Bhadra, S. Bienstock, A. Blondel, S. Bolognesi, S. Bordoni, S.B. Boyd, D. Brailsford, A. Bravar, C. Bronner, M. Buizza Avanzini, R.G. Calland, T. Campbell, S. Cao, S.L. Cartwright, M.G. Catanesi, A. Cervera, A. Chappell, C. Checchia, D. Cherdack, N. Chikuma, G. Christodoulou, J. Coleman, G. Collazuol, D. Coplowe, A. Cudd, A. Dabrowska, G. De Rosa, T. Dealtry, P.F. Denner, S.R. Dennis, C. Densham, F. Di Lodovico, S. Dolan, O. Drapier, K.E. Duffy, J. Dumarchez, P. Dunne, S. Emery-Schrenk, A. Ereditato, T. Feusels, A.J. Finch, G.A. Fiorentini, M. Friend, Y. Fujii, D. Fukuda, Y. Fukuda, A. Garcia, C. Giganti, F. Gizzarelli, T. Golan, et al. (230 additional authors not shown)

(Submitted on 4 Jul 2017 (v1), last revised 5 Jul 2017 (this version, v2))

The T2K experiment reports an updated analysis of neutrino and antineutrino oscillations in appearance and disappearance channels. A sample of electron neutrino candidates at Super-Kamiokande in which a pion decay has been tagged is added to the four single-ring samples used in previous T2K oscillation analyses. Through combined analyses of these five samples, simultaneous measurements of four oscillation parameters, $|\Delta m_{32}^2|$, $\sin^2(\theta_{23})$, $\sin^2(\theta_{13})$, and δ_{CP} and of the mass ordering are made. A set of studies of simulated data indicates that the sensitivity to the oscillation parameters is not limited by neutrino interaction model uncertainty. Multiple oscillation analyses are performed, and frequentist and Bayesian intervals are presented for combinations of the oscillation parameters with and without the inclusion of reactor constraints on $\sin^2(\theta_{13})$. When combined with reactor measurements, the hypothesis of CP conservation ($\delta_{CP} = 0$ or π) is excluded at 90% confidence level. The 90% confidence region for δ_{CP} is $[-2.95, -0.44]$ ($[-1.47, -1.27]$) for normal (inverted) ordering. The central values and 68% confidence intervals for the other oscillation parameters for normal (inverted) ordering are $\Delta m_{32}^2 = 2.54 \pm 0.08$ (2.51 ± 0.08) $\times 10^{-3}$ eV²/c⁴ and $\sin^2(\theta_{23}) = 0.55_{-0.09}^{+0.05}$ ($0.55_{-0.08}^{+0.05}$), compatible with maximal mixing. In the Bayesian analysis, the data weakly prefer normal ordering (Bayes factor 3.7) and the upper octant for $\sin^2(\theta_{23})$ (Bayes factor 2.4).

Comments: 50 pages, 50 figures

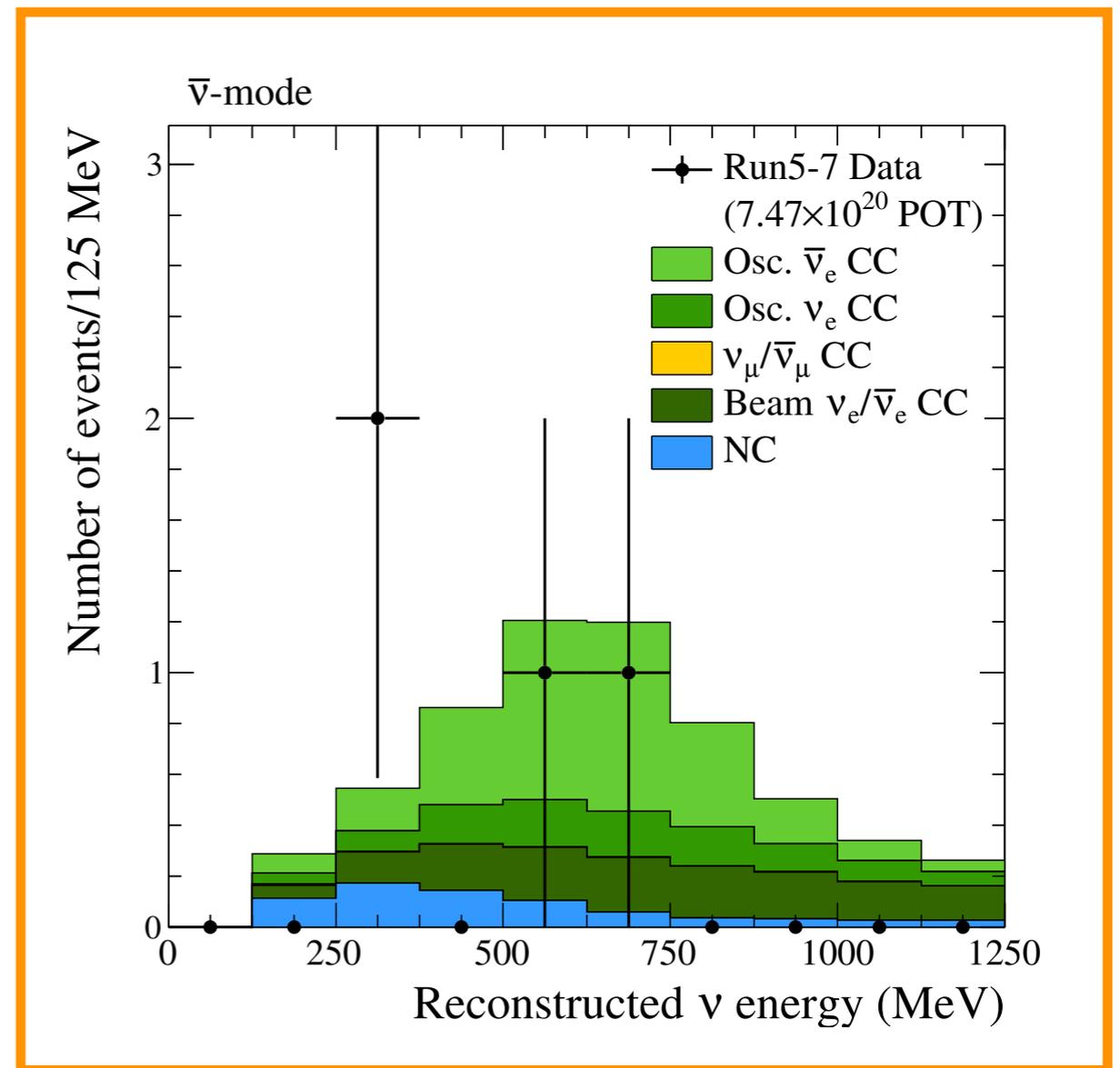
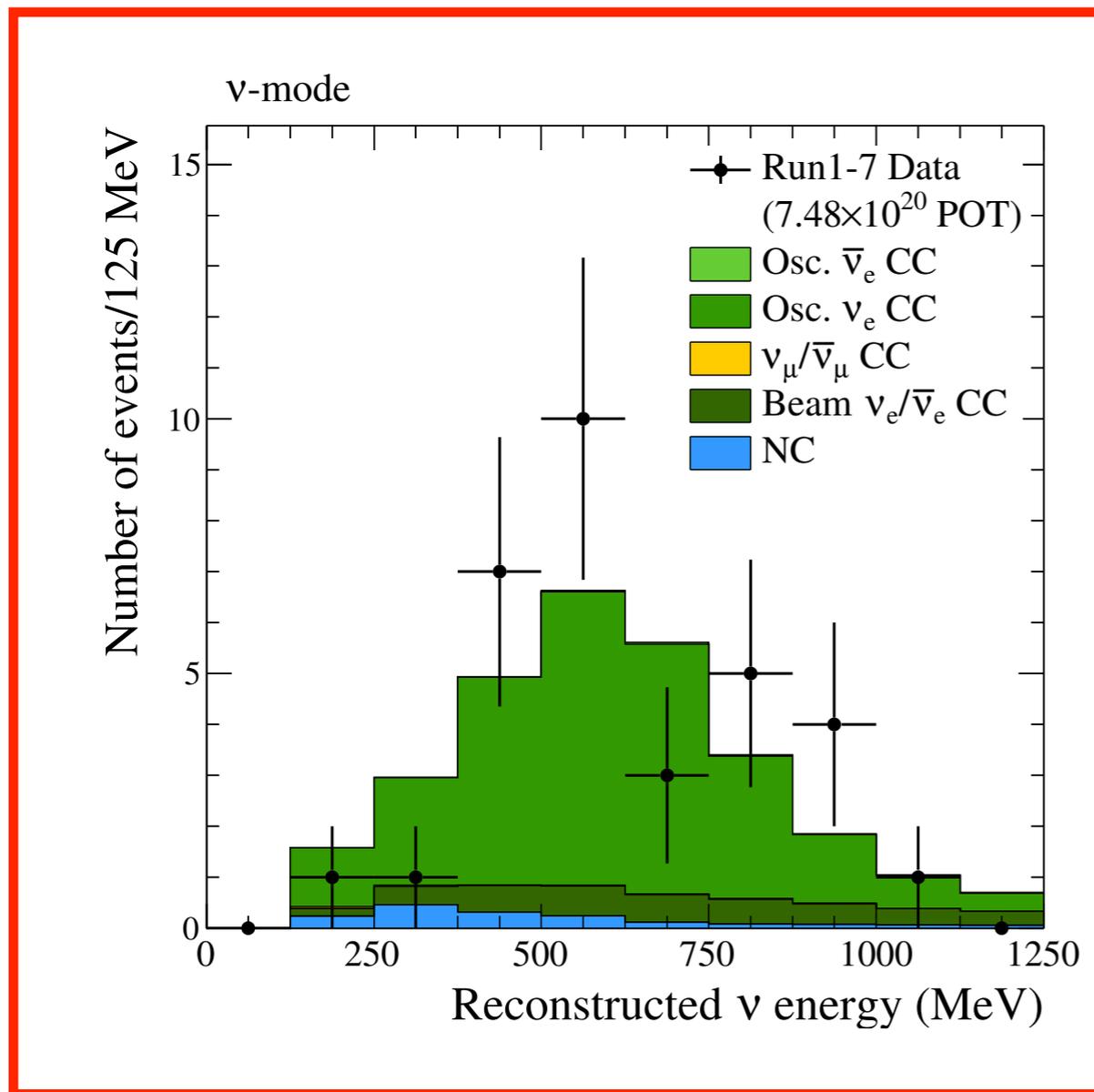
Subjects: High Energy Physics – Experiment (hep-ex)

Cite as: arXiv:1707.01048 [hep-ex]

(or arXiv:1707.01048v2 [hep-ex] for this version)

Submitted to PRD

FINAL Electron (anti-)neutrino events



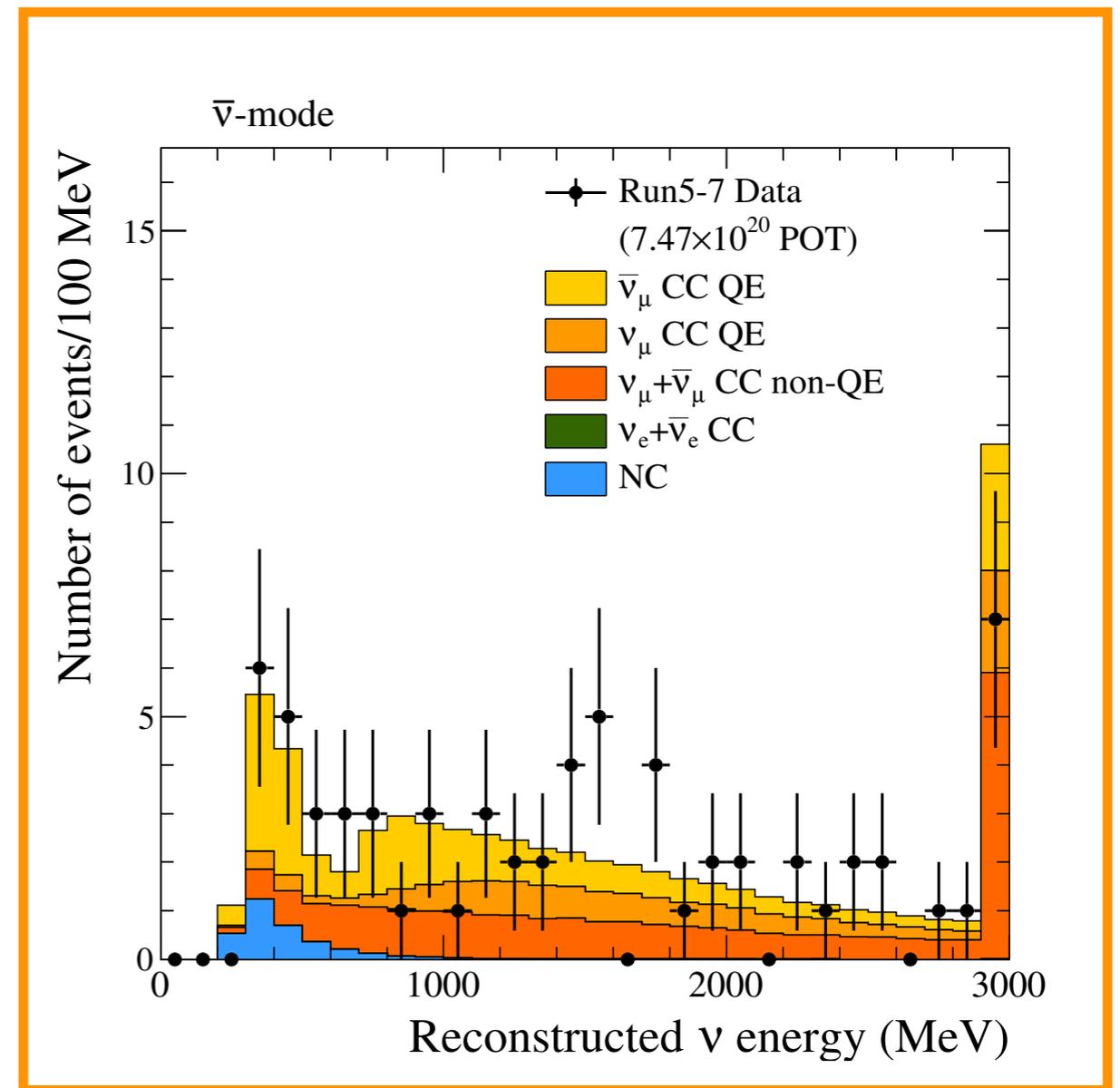
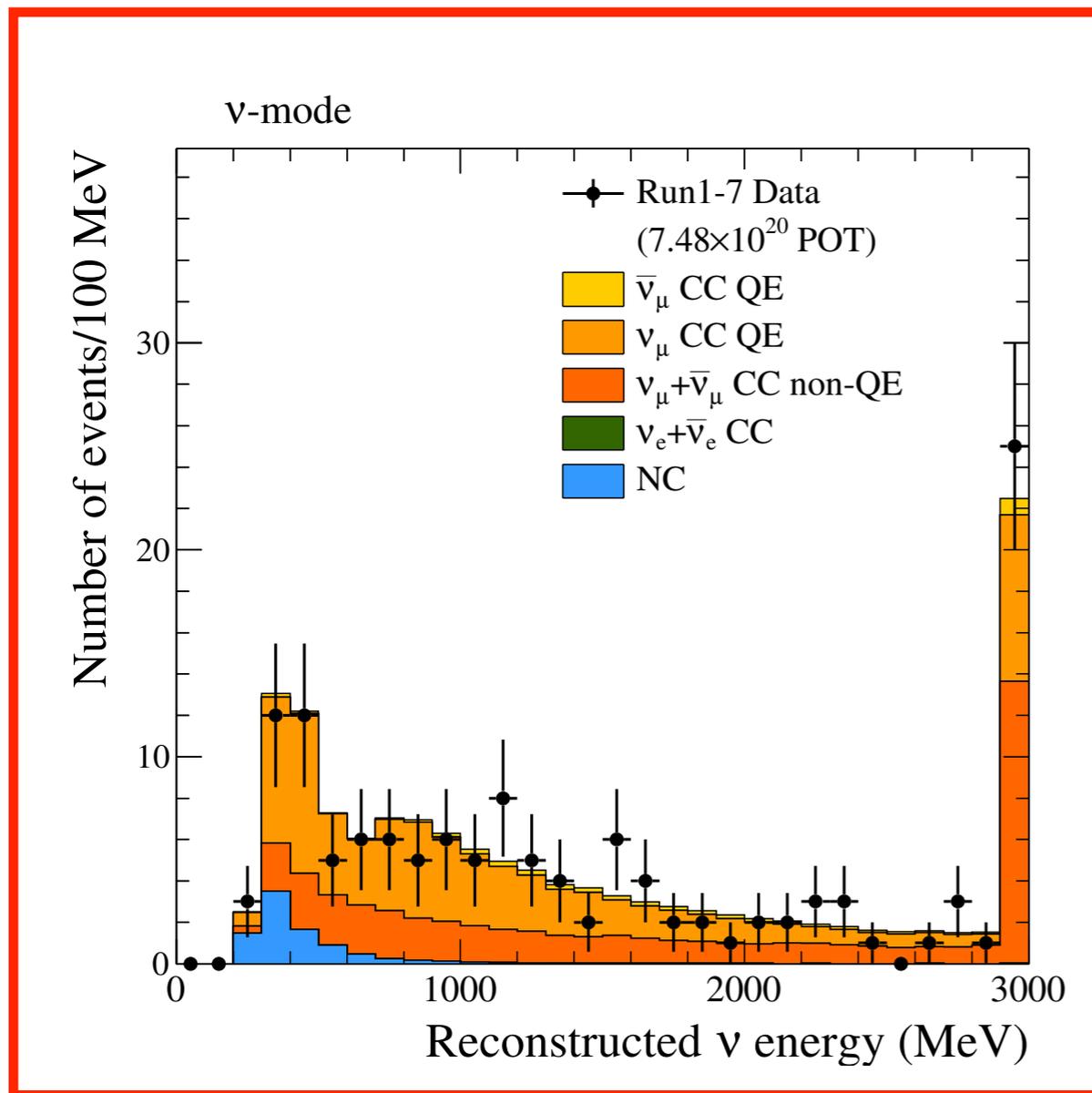
- Neutrino:

- Data: 32
- MC: 28.55

- Anti-neutrino:

- Data: 4
- MC: 6.28

FINAL muon (anti-)neutrino events



- Neutrino:

- Data: 135

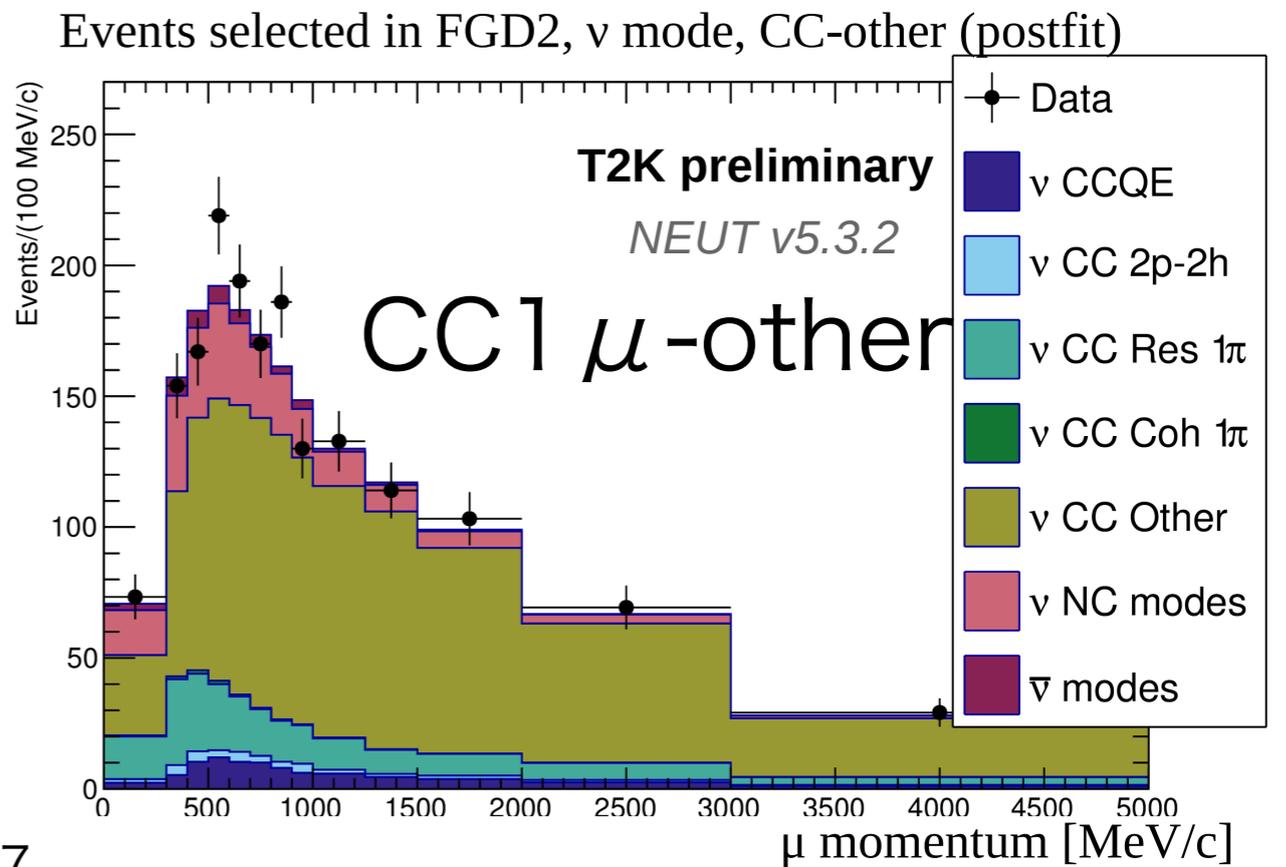
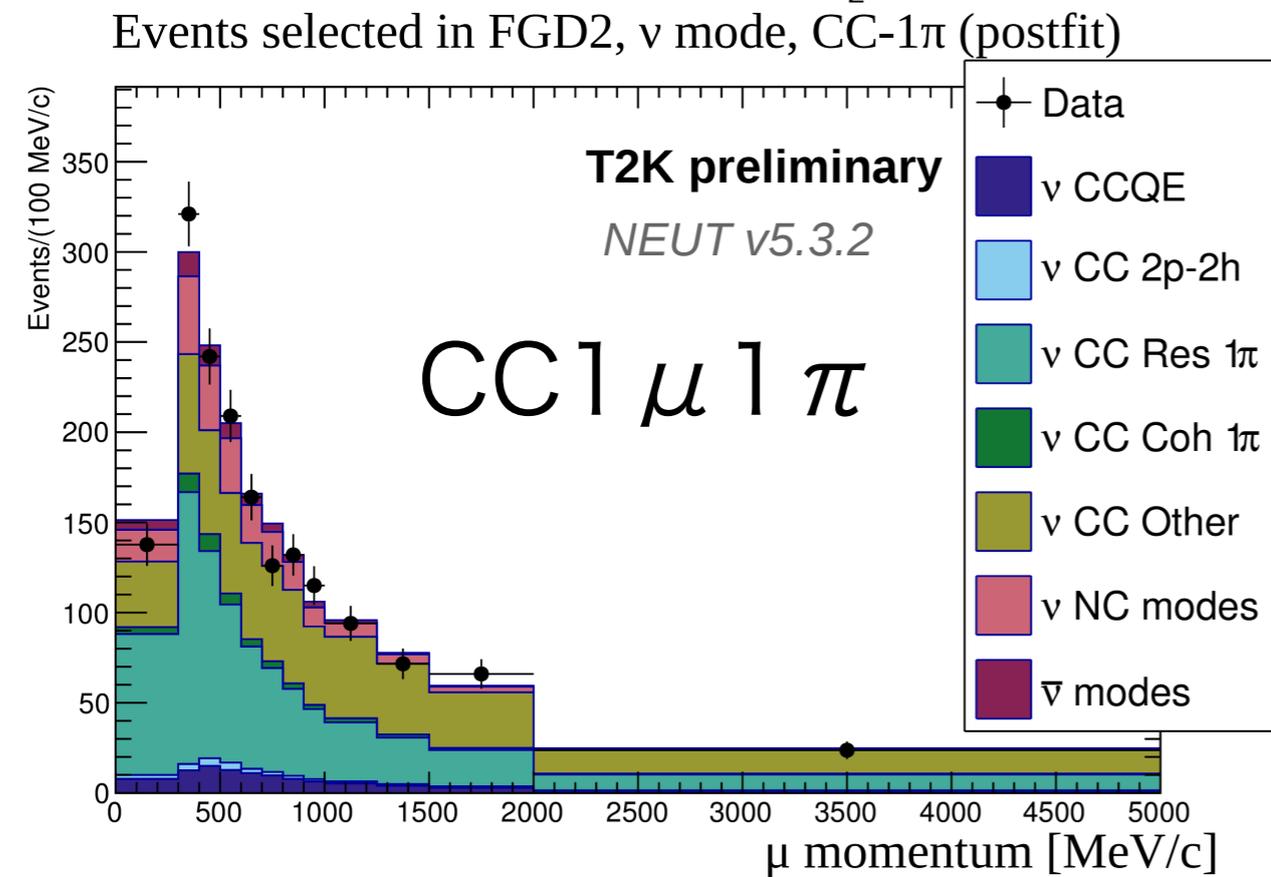
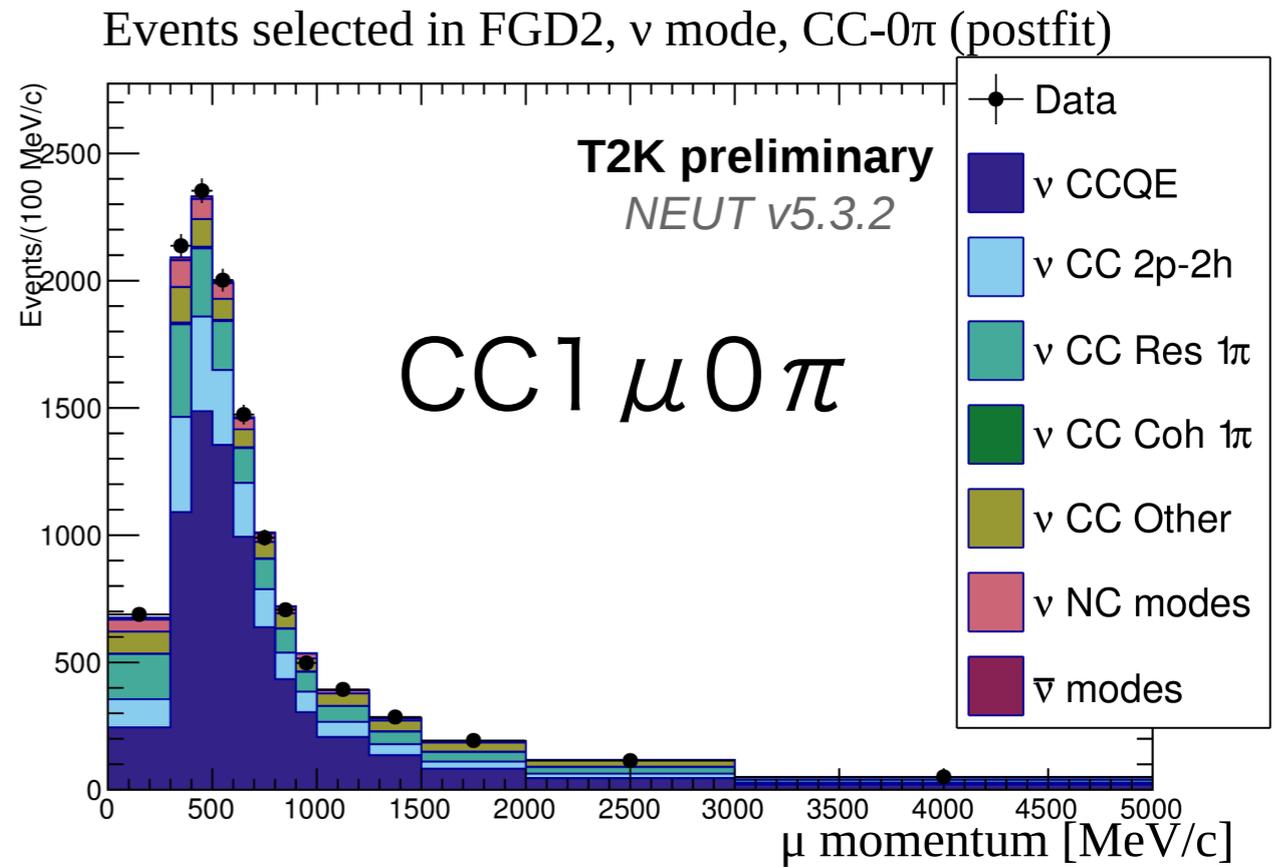
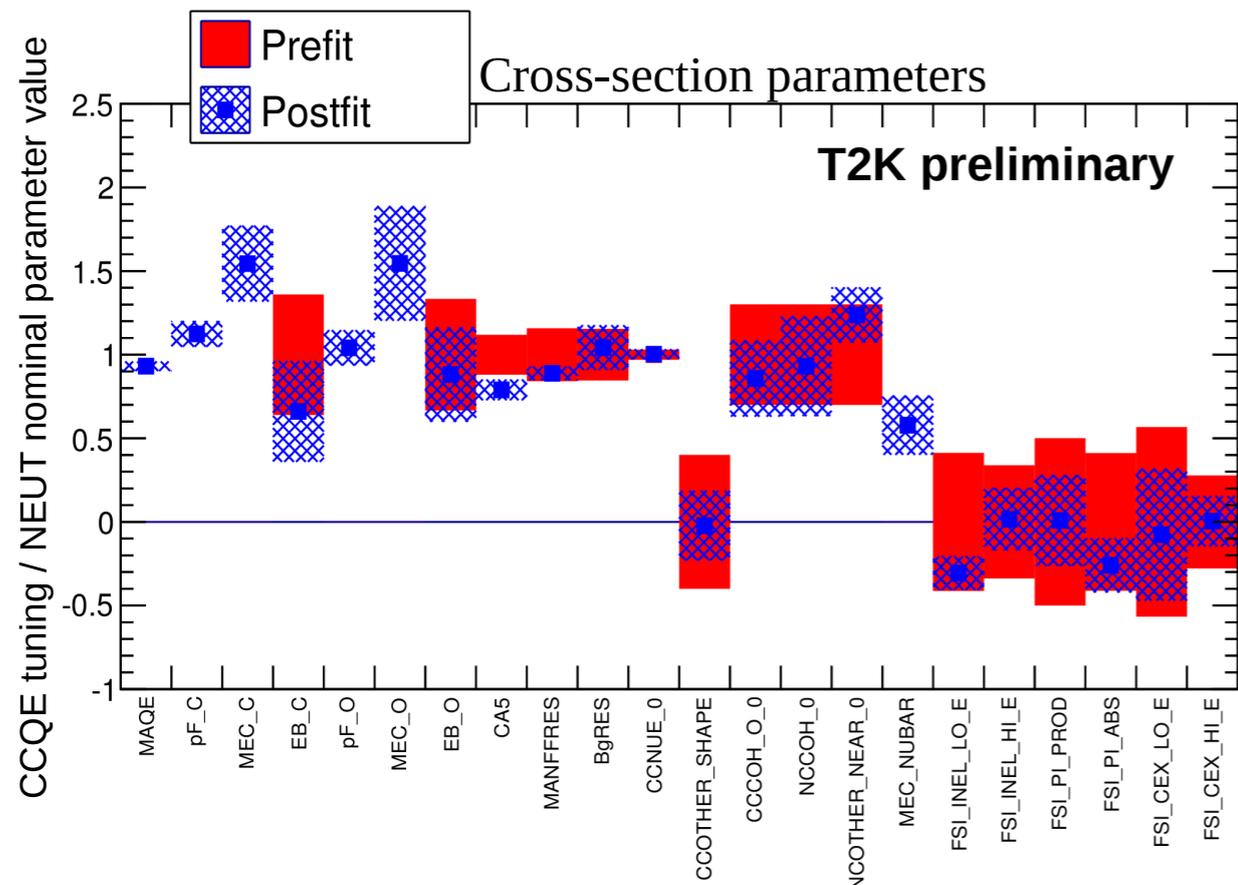
- MC: 137.76

- Anti-neutrino:

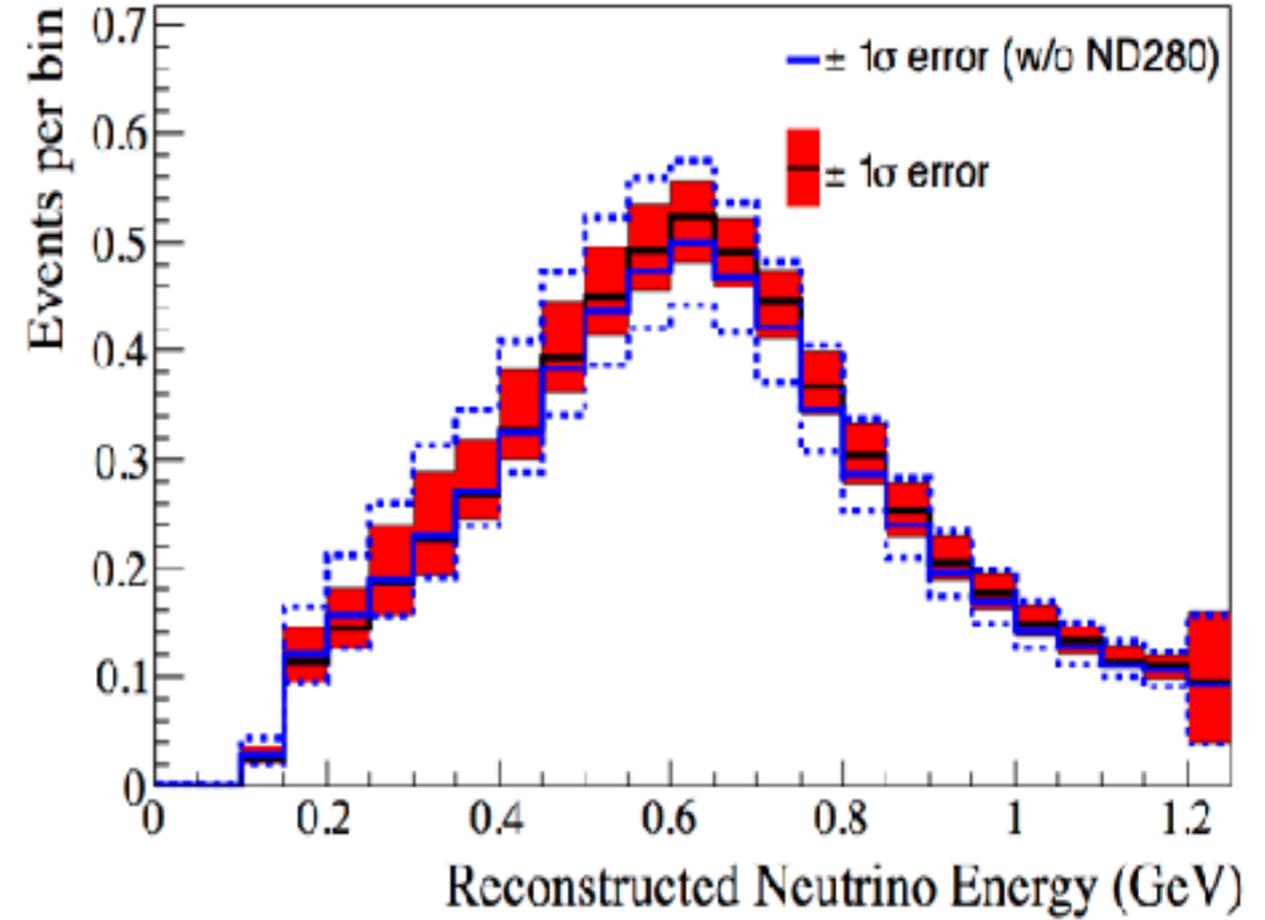
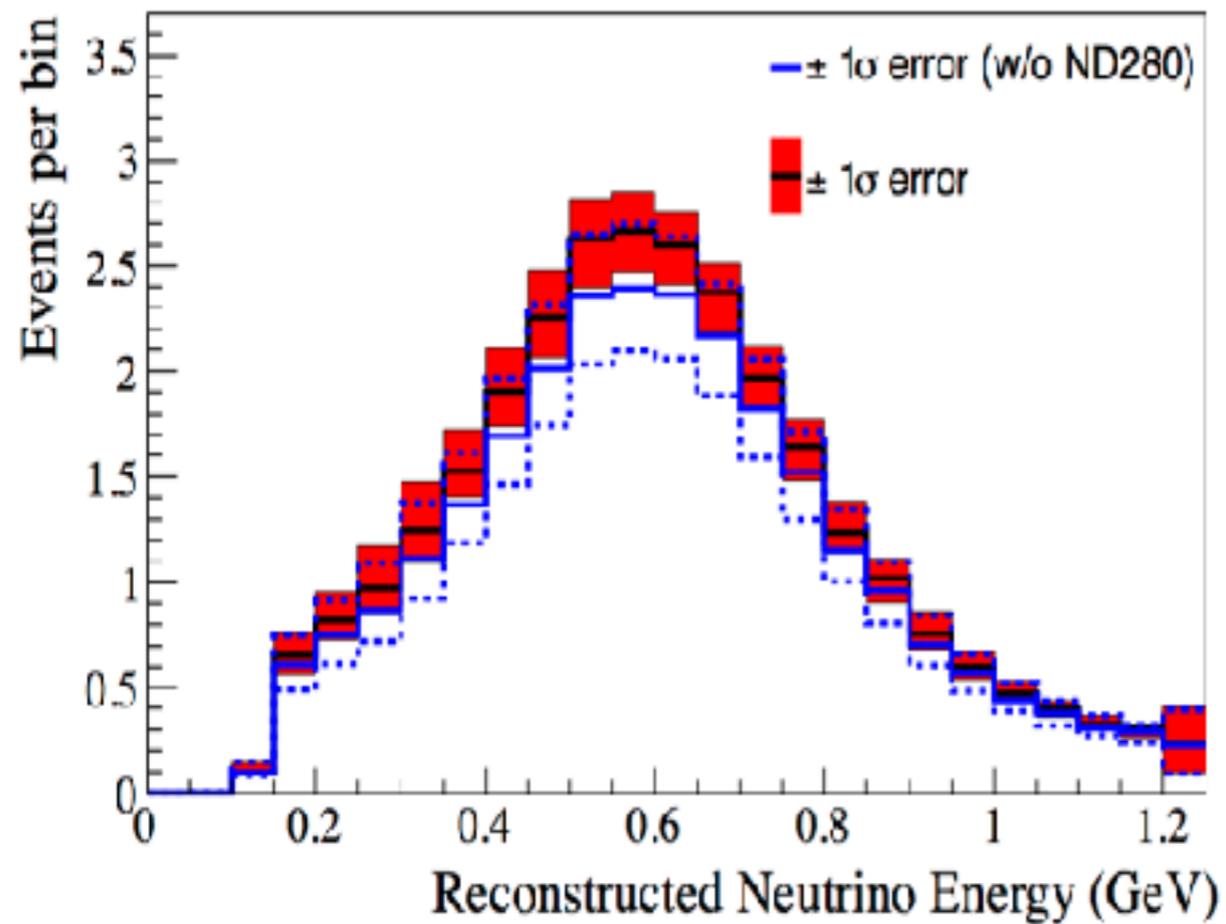
- Data: 66

- MC: 68.26

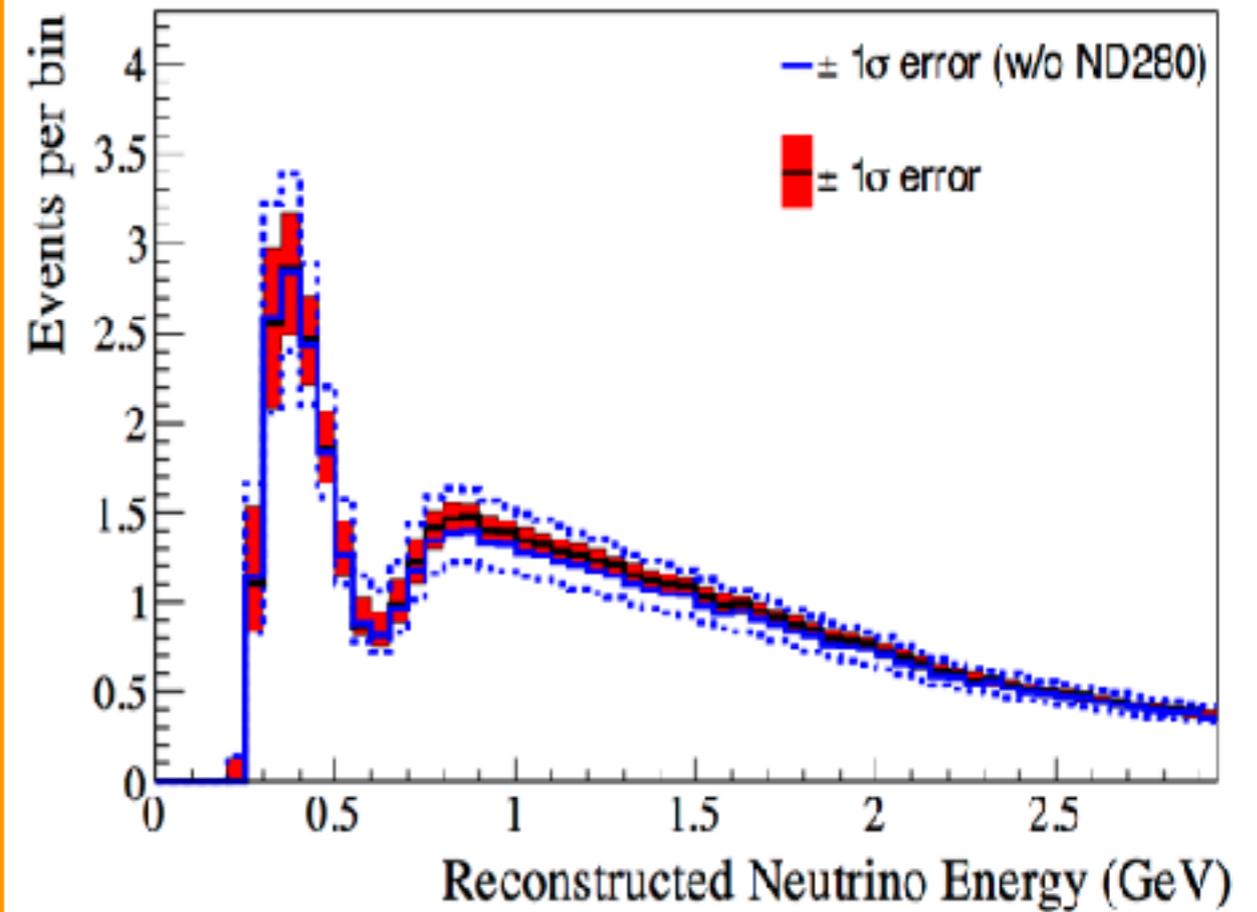
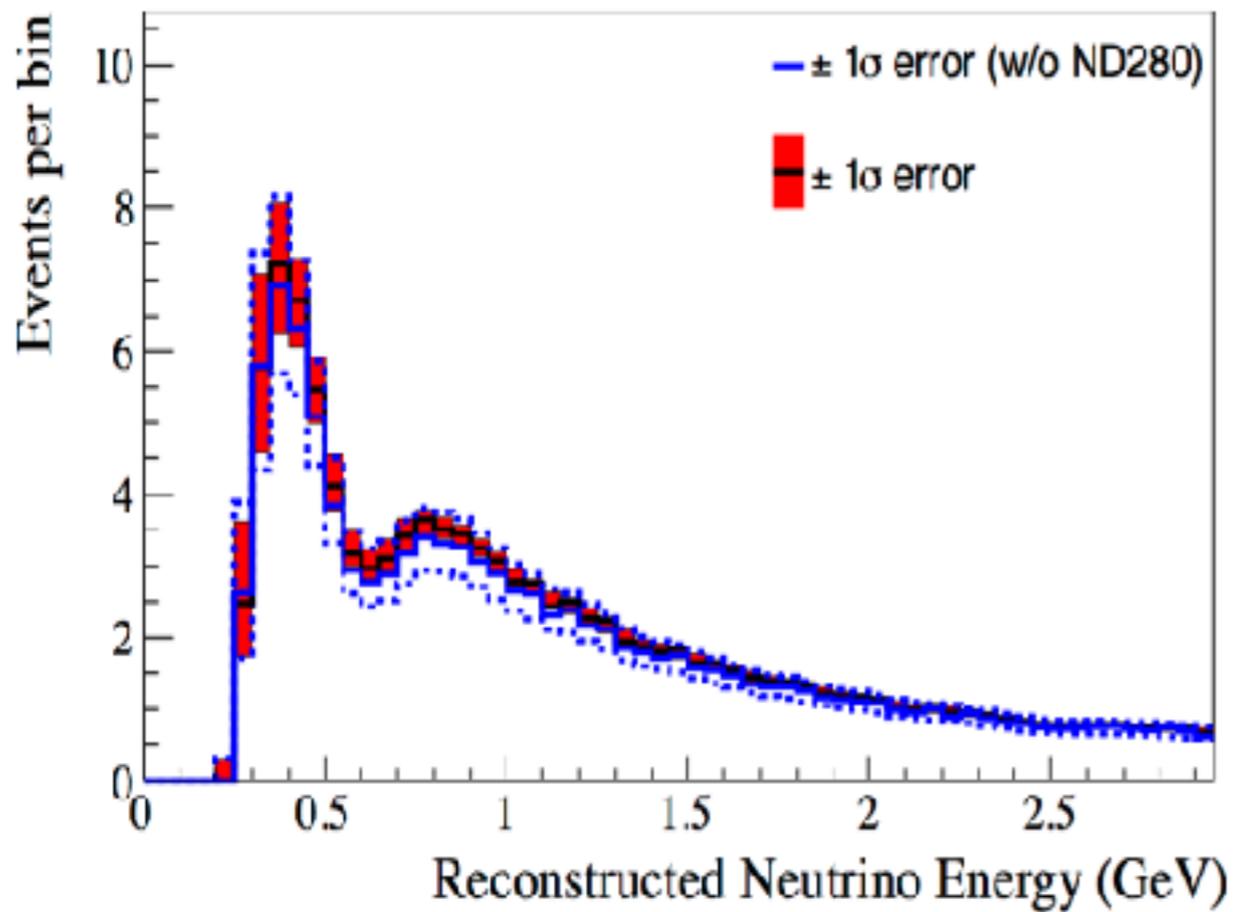
Near Detector measurements \rightarrow constraints



Electron Neutrino Predictions



Muon Neutrino Predictions



Systematic uncertainties

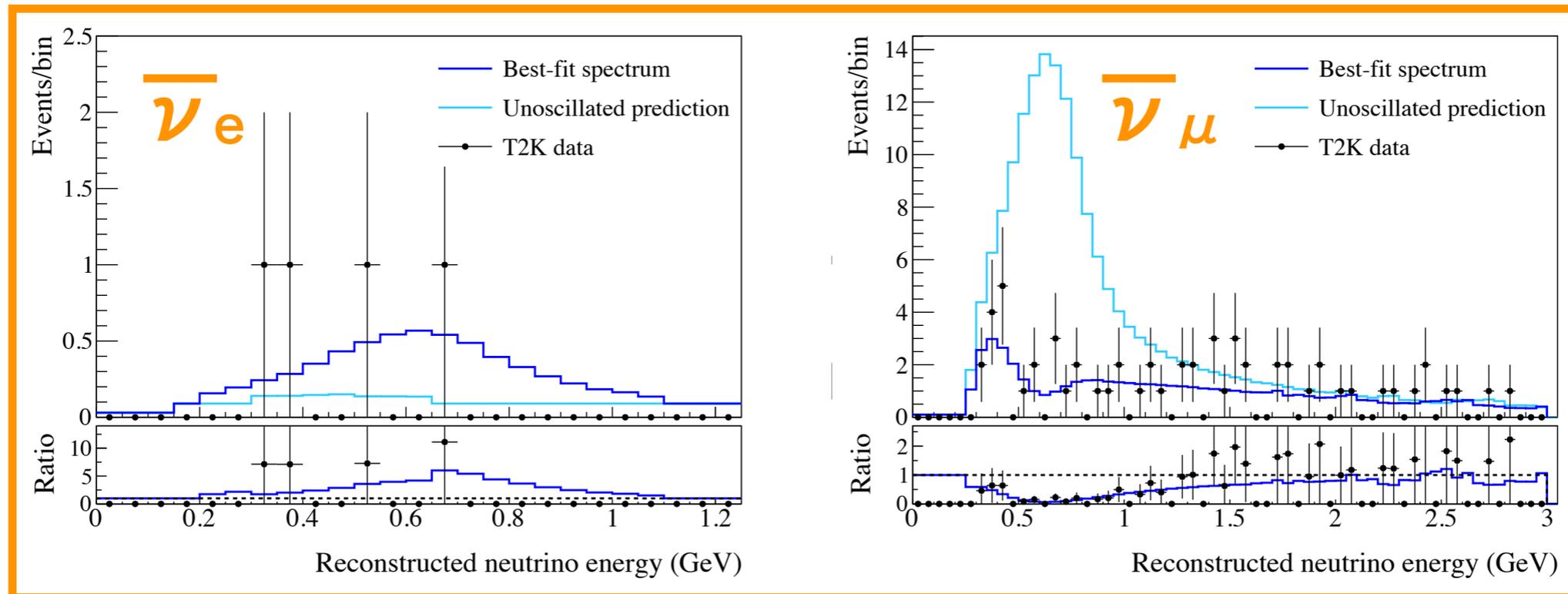
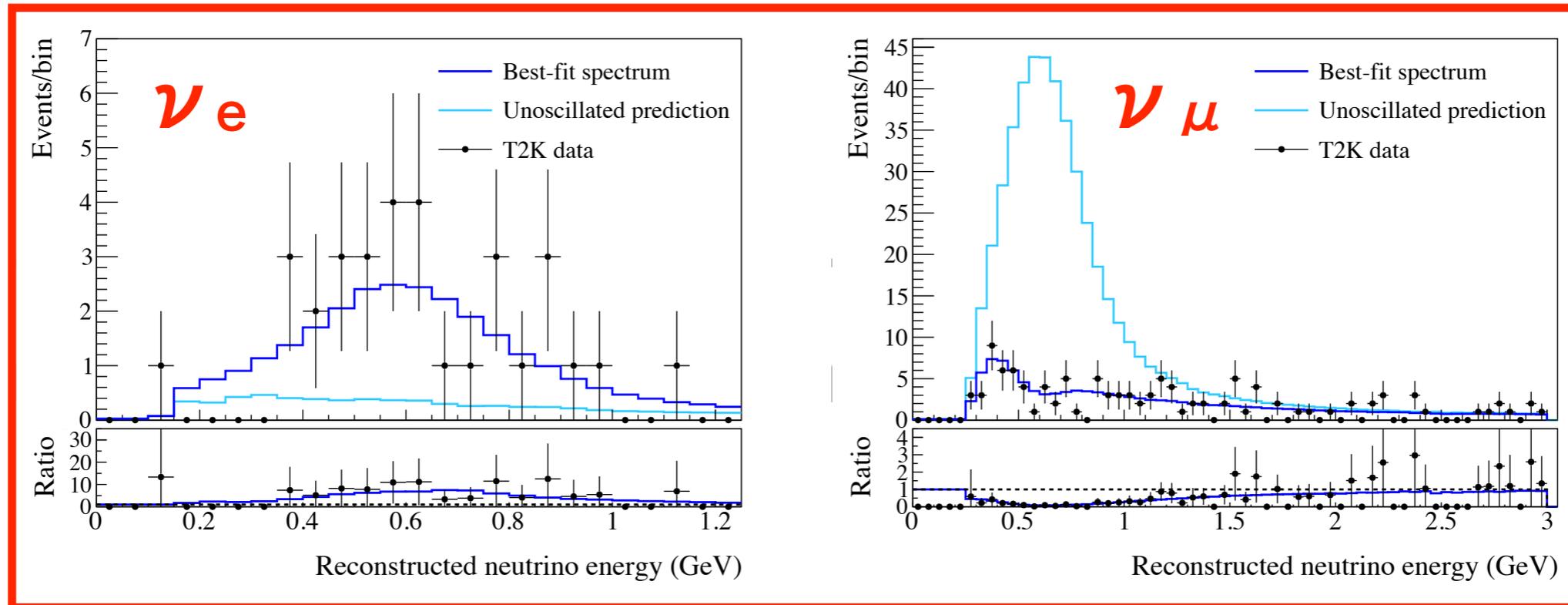
Total $\delta N_{SK}/N_{SK}$			
Beam mode	sample	ND280 constrained	W/o ND280
neutrino	μ -like	5.11%	12.02%
neutrino	e -like	5.53%	12.06%
antineutrino	μ -like	5.19%	12.88%
antineutrino	e -like	6.31%	14.06%
neutrino	CC1 π^+ -like	14.84%	21.84%

Systematic uncertainties

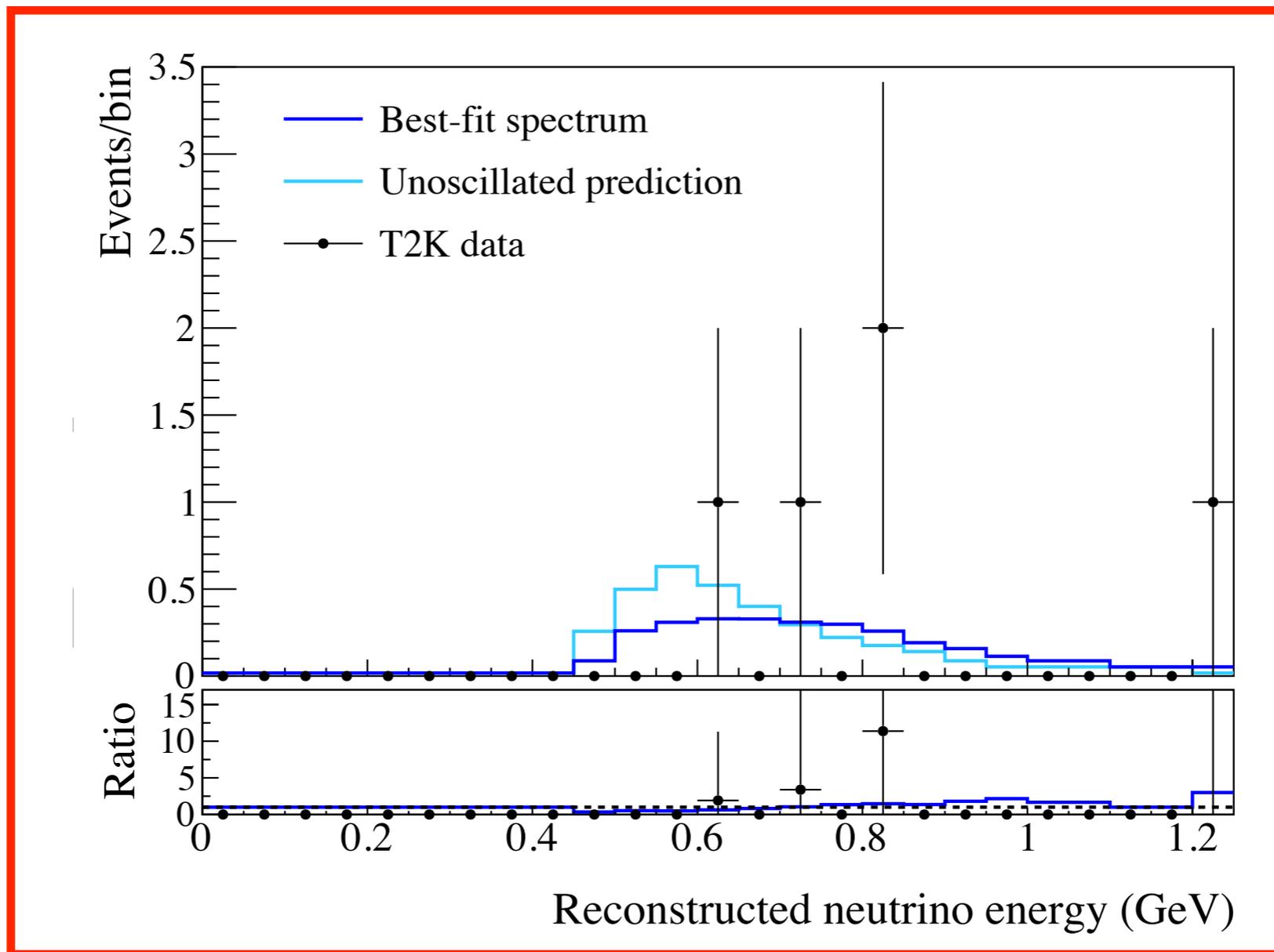
Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1 π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross-section (w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI+SI+PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All (w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%

Source of uncertainty	$\bar{\nu}_e$ CCQE-like $\delta N/N$	$\bar{\nu}_\mu$ $\delta N/N$
Flux (w/ ND280 constraint)	3.8%	3.8%
Cross section (w/ ND280 constraint)	5.5%	4.2%
Flux+cross-section (w/o ND280 constraint)	12.9%	11.3%
(w/ ND280 constraint)	4.7%	3.5%
FSI+SI+PN at SK	3.0%	2.1%
SK detector	2.5%	3.4%
All (w/o ND280 constraint)	14.5%	12.5%
(w/ ND280 constraint)	6.5%	5.3%

Oscillation FIT



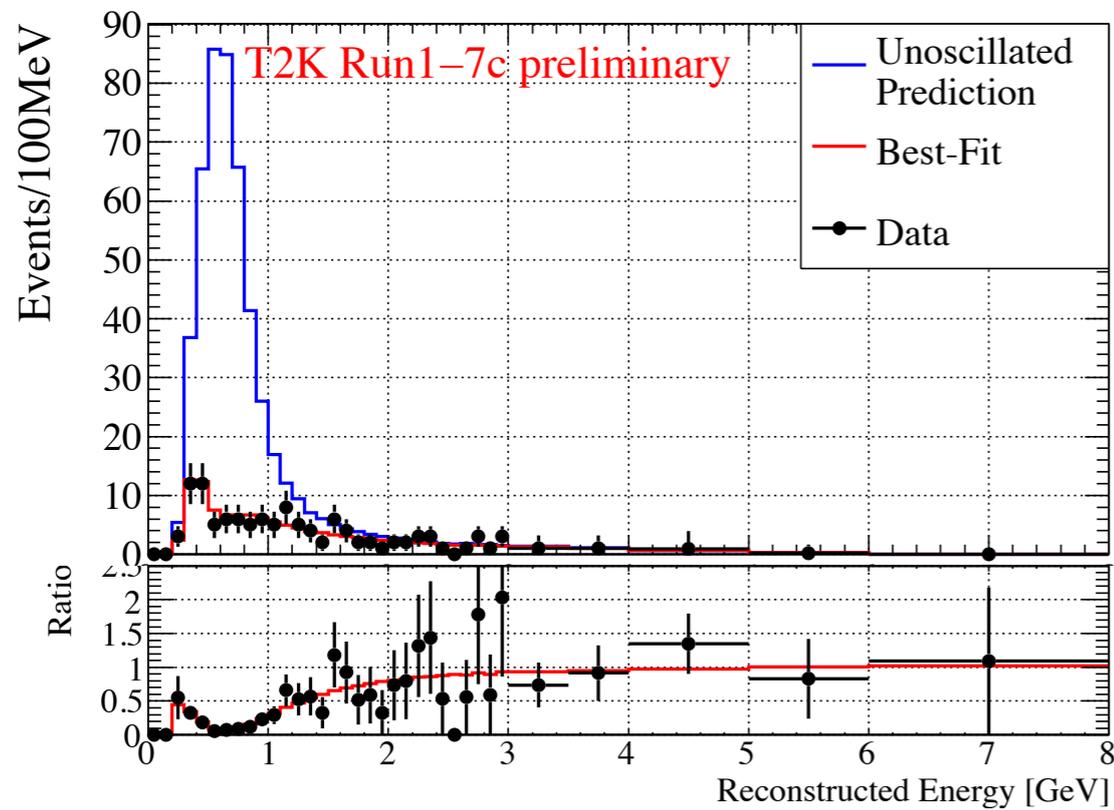
Oscillation FIT w/ CC $\nu_{e-1} \pi^+$



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

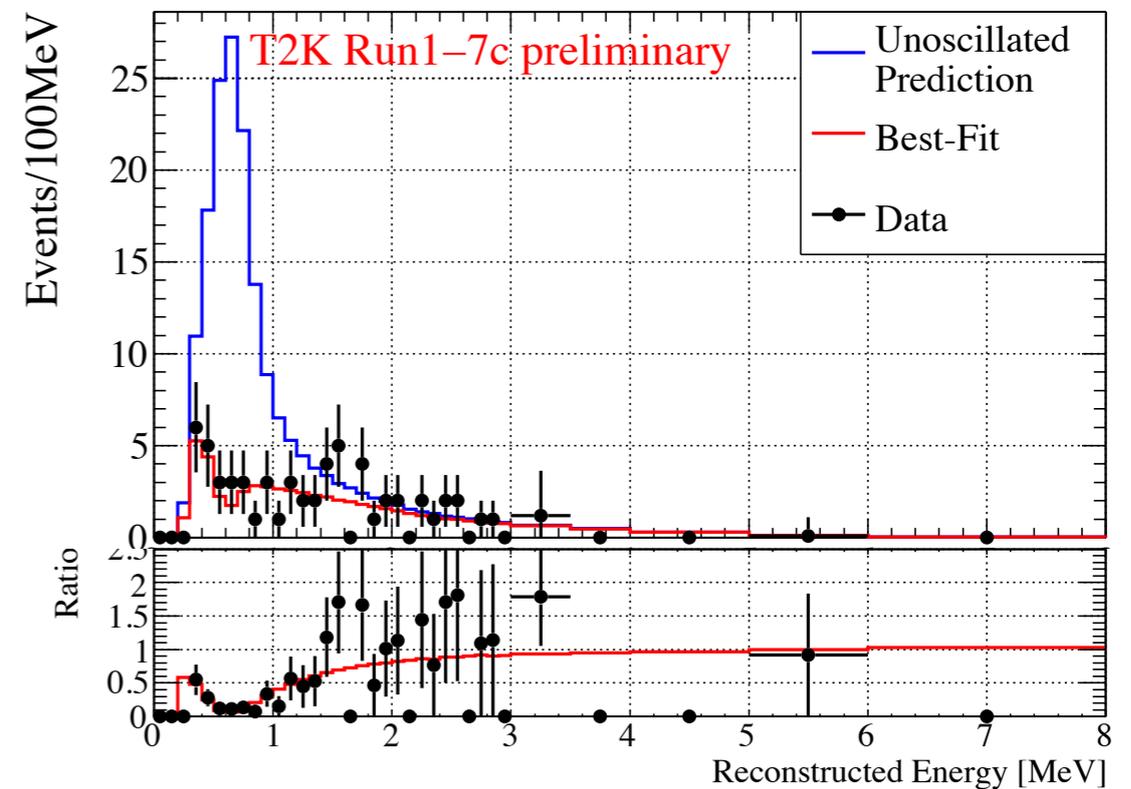
- CPT test by comparing ($\nu_\mu \rightarrow \nu_\mu$) and ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$) modes

ν_μ



135 events observed
(135.8 events expected)

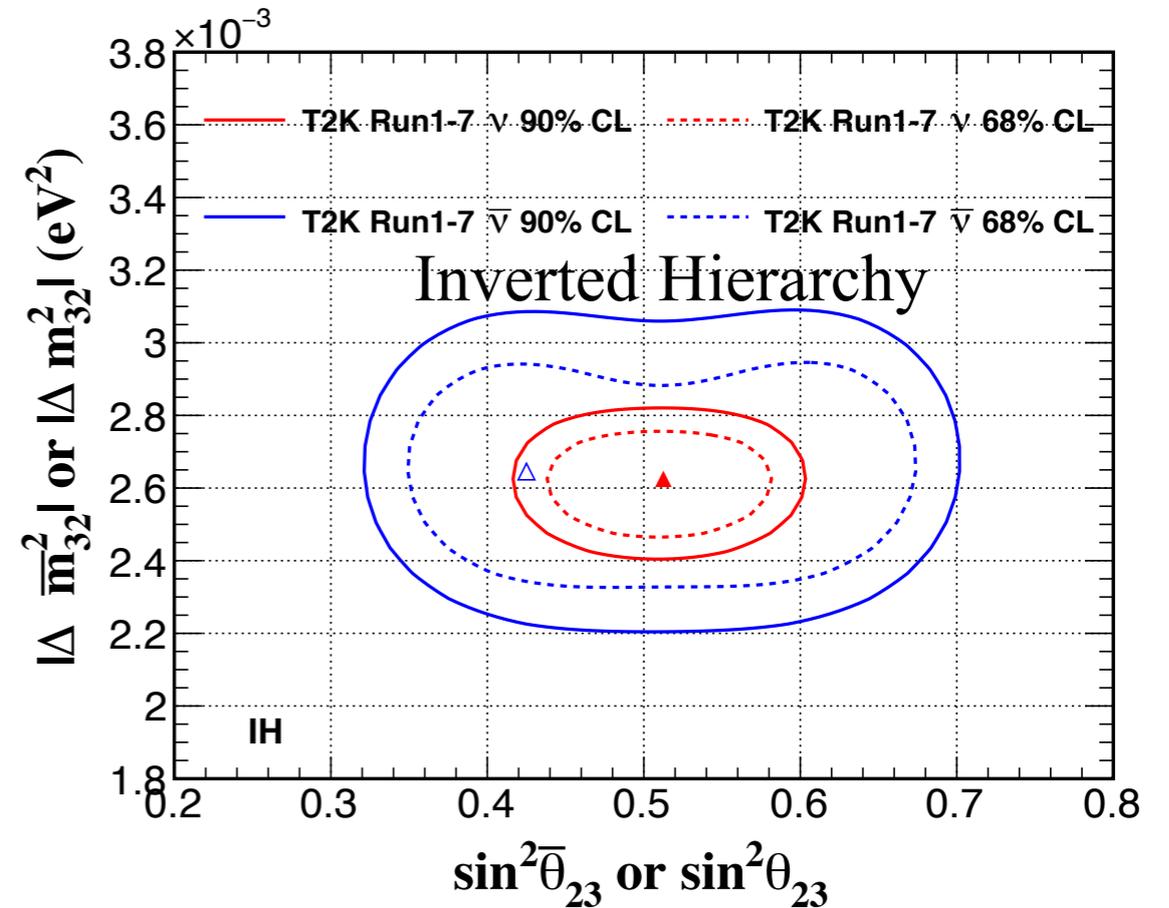
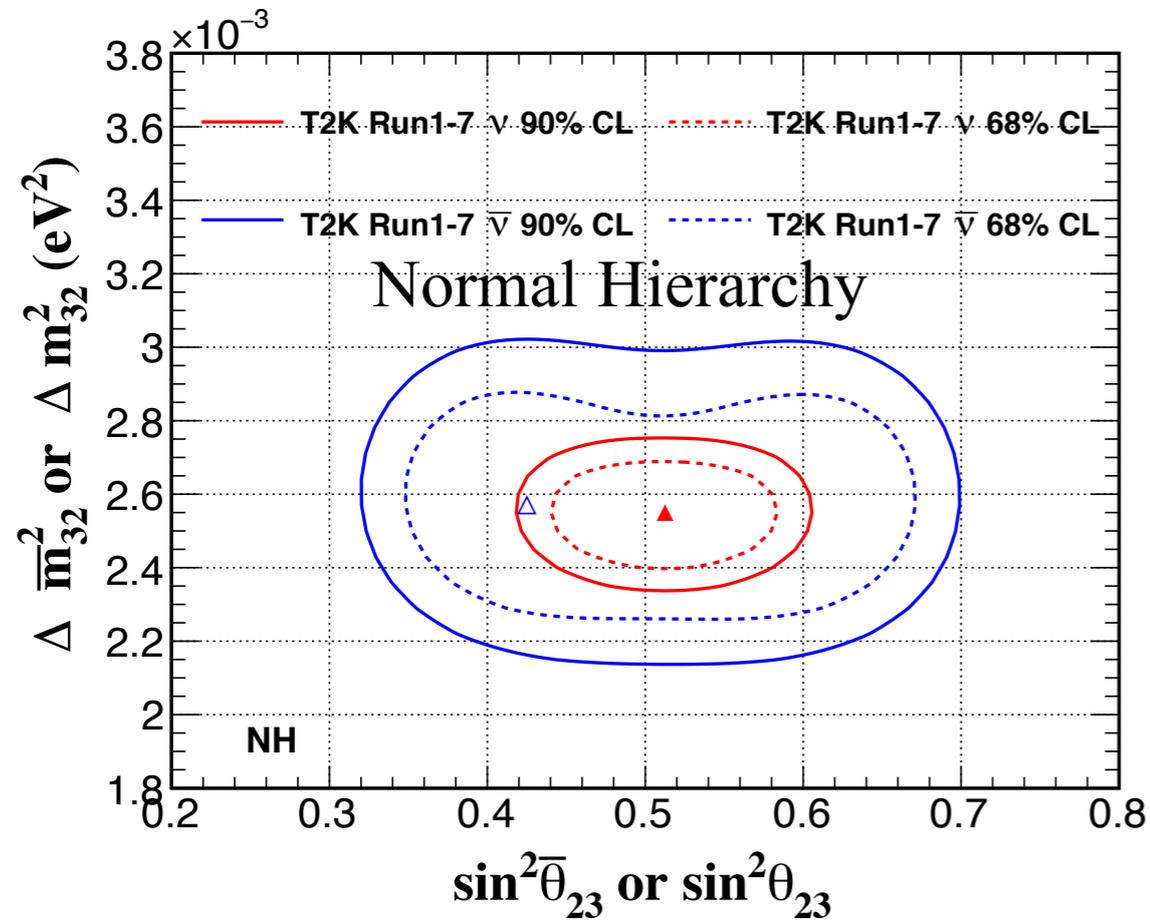
$\bar{\nu}_\mu$



66 events observed
(64.2 events expected)

θ_{23} and Δm_{32}^2 Comparison

- No hint of CPT violation



$$\Delta \bar{m}_{32}^2 = [2.16, 3.02] \times 10^{-3} eV^2 (NH) \text{ at } 90\% \text{ CL}$$

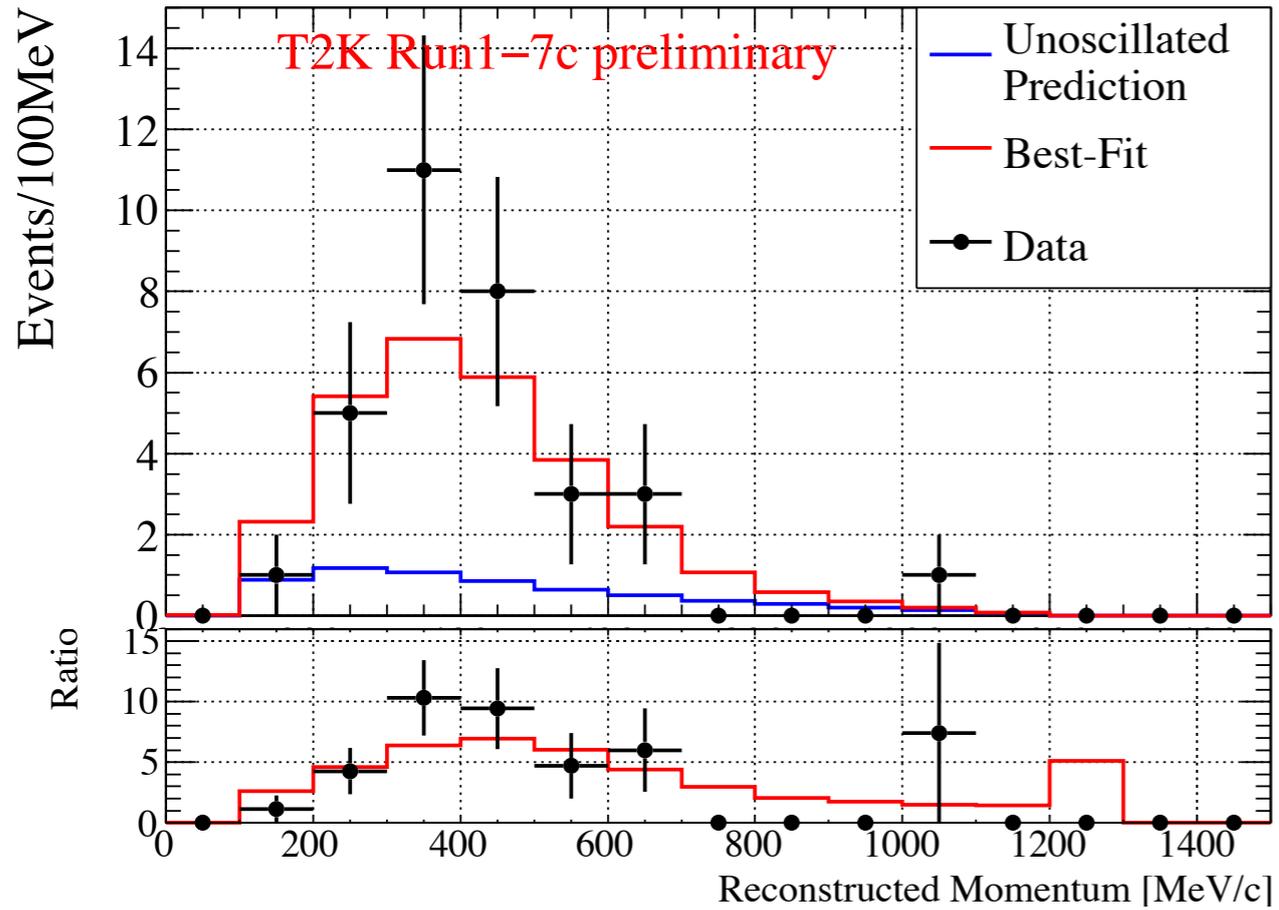
$$\sin^2 \bar{\theta}_{23} = [0.32, 0.70] (NH) \text{ at } 90\% \text{ CL}$$

$$\Delta m_{32}^2 = [2.34, 2.75] \times 10^{-3} eV^2 (NH) \text{ at } 90\% \text{ CL}$$

$$\sin^2 \theta_{23} = [0.42, 0.61] (NH) \text{ at } 90\% \text{ CL}$$

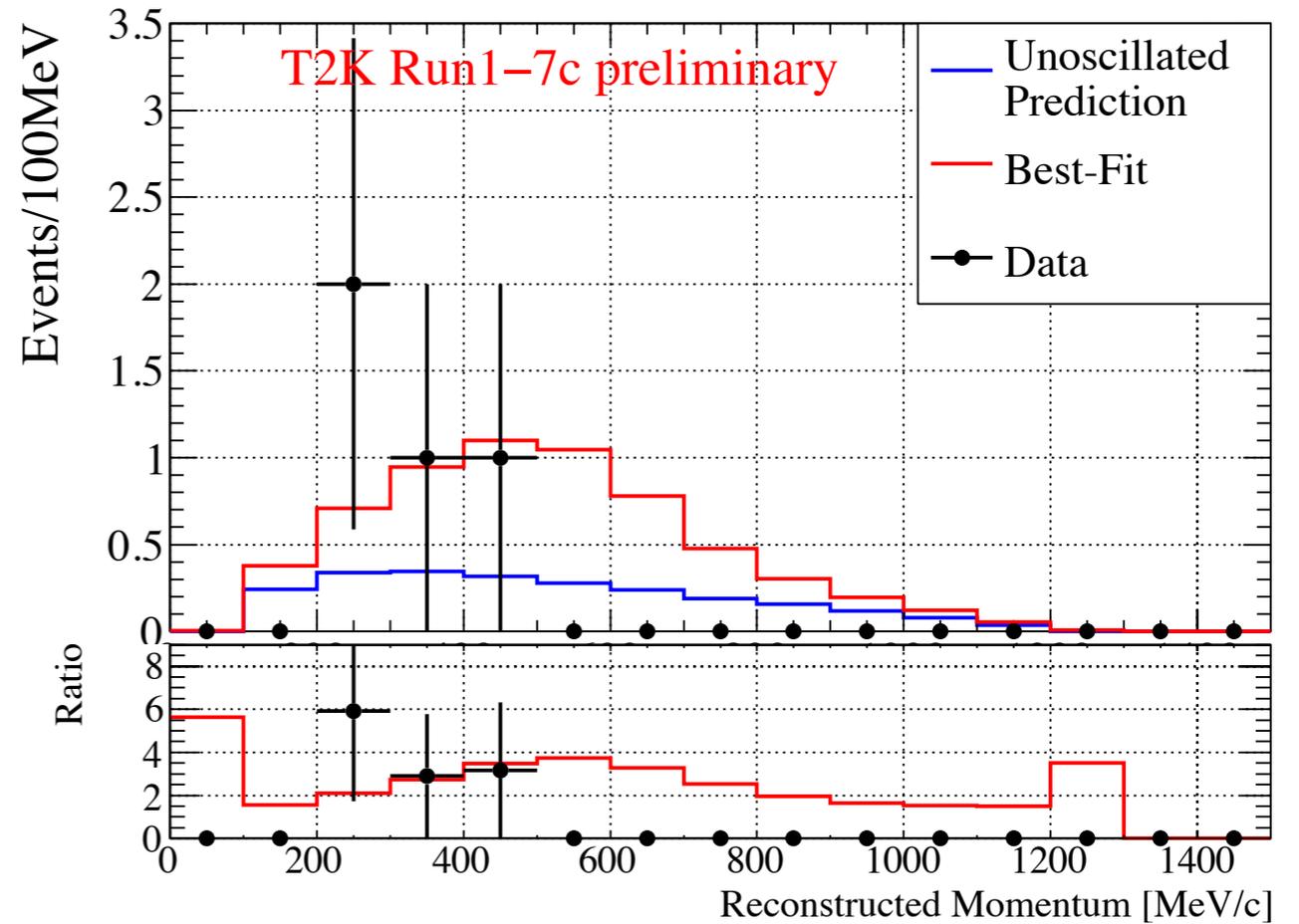
Full Joint Fit Analysis

ν_e



32 events observed

$\bar{\nu}_e$

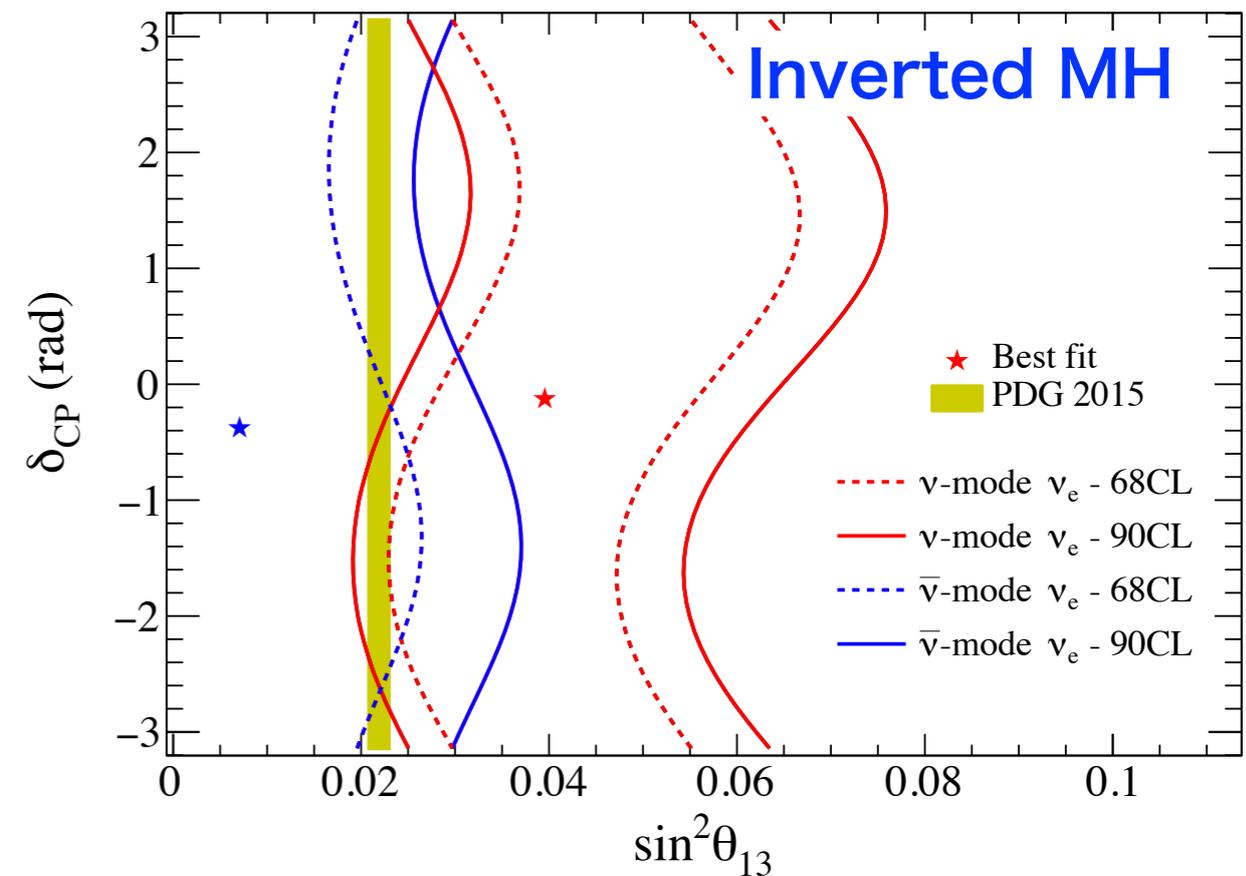
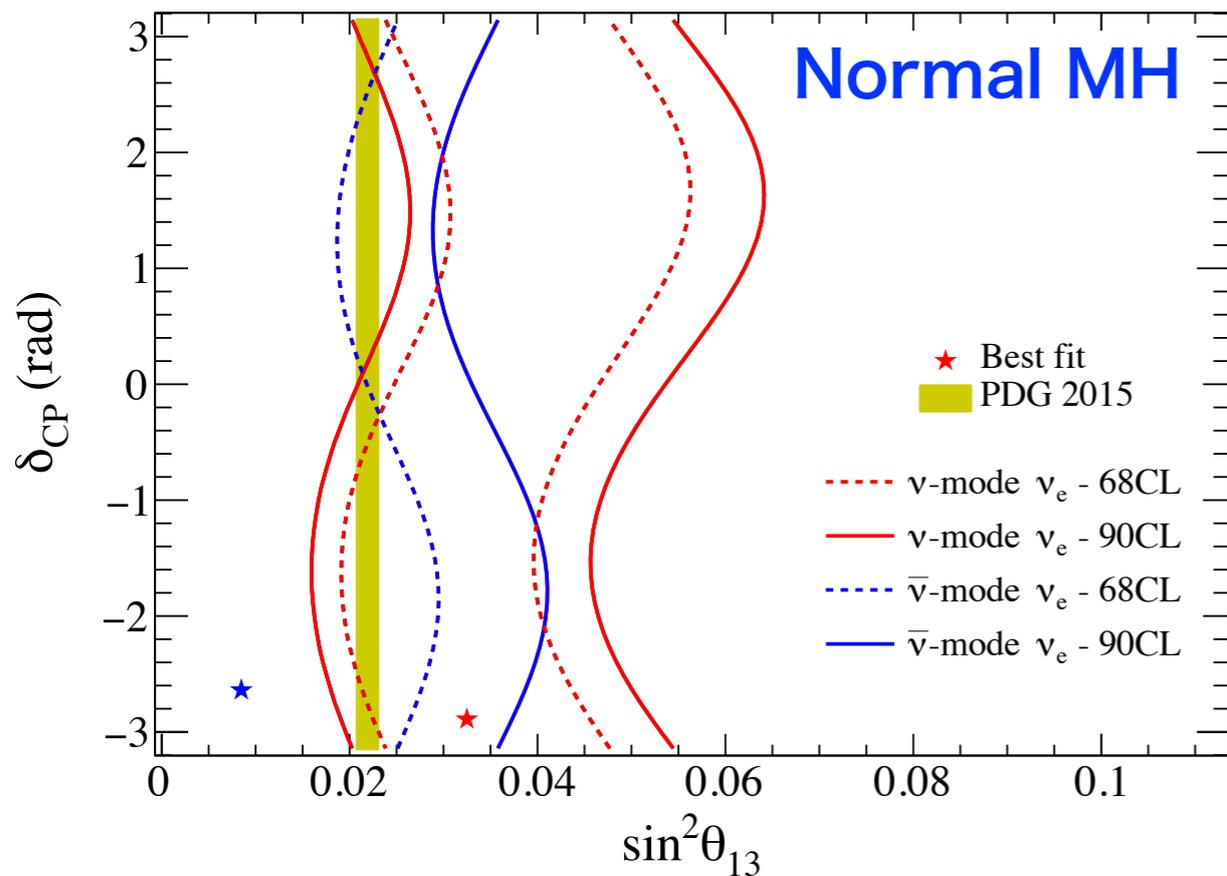


4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	36 7.7	6.8	4

OA Fit results with T2K only data

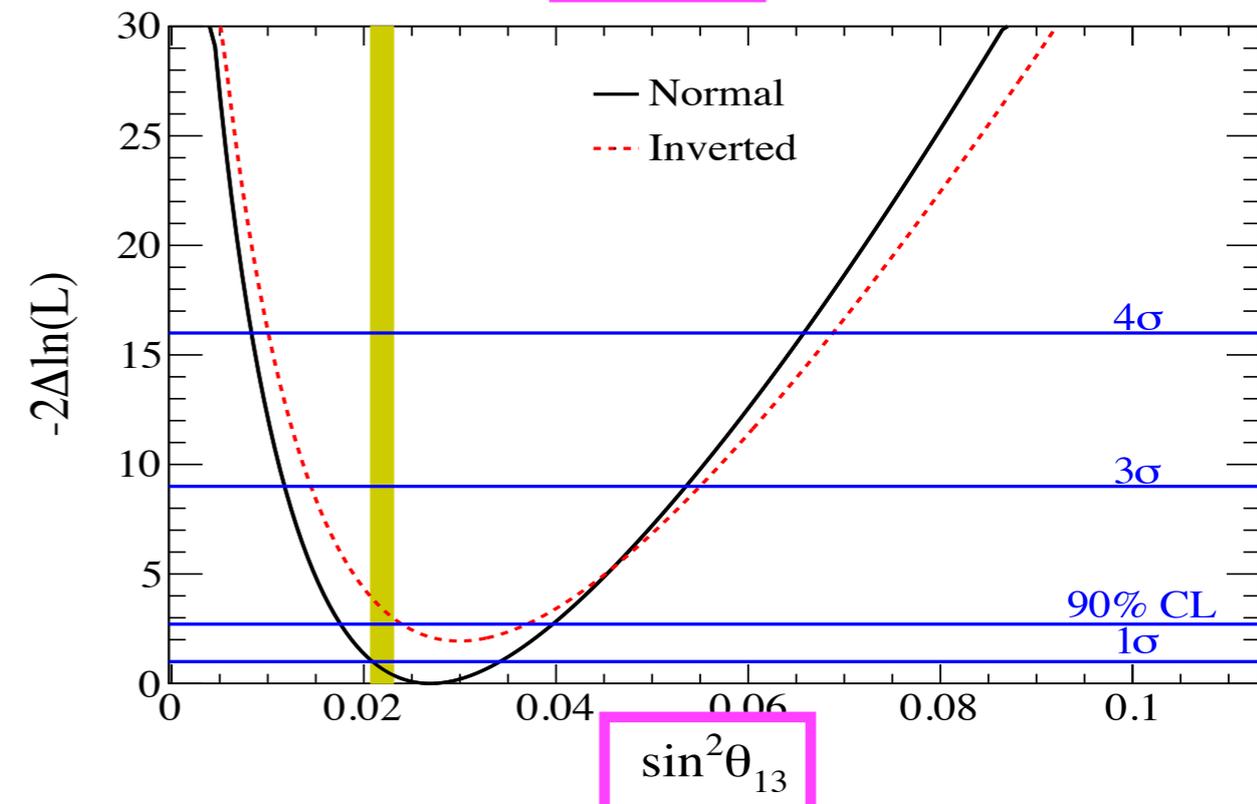
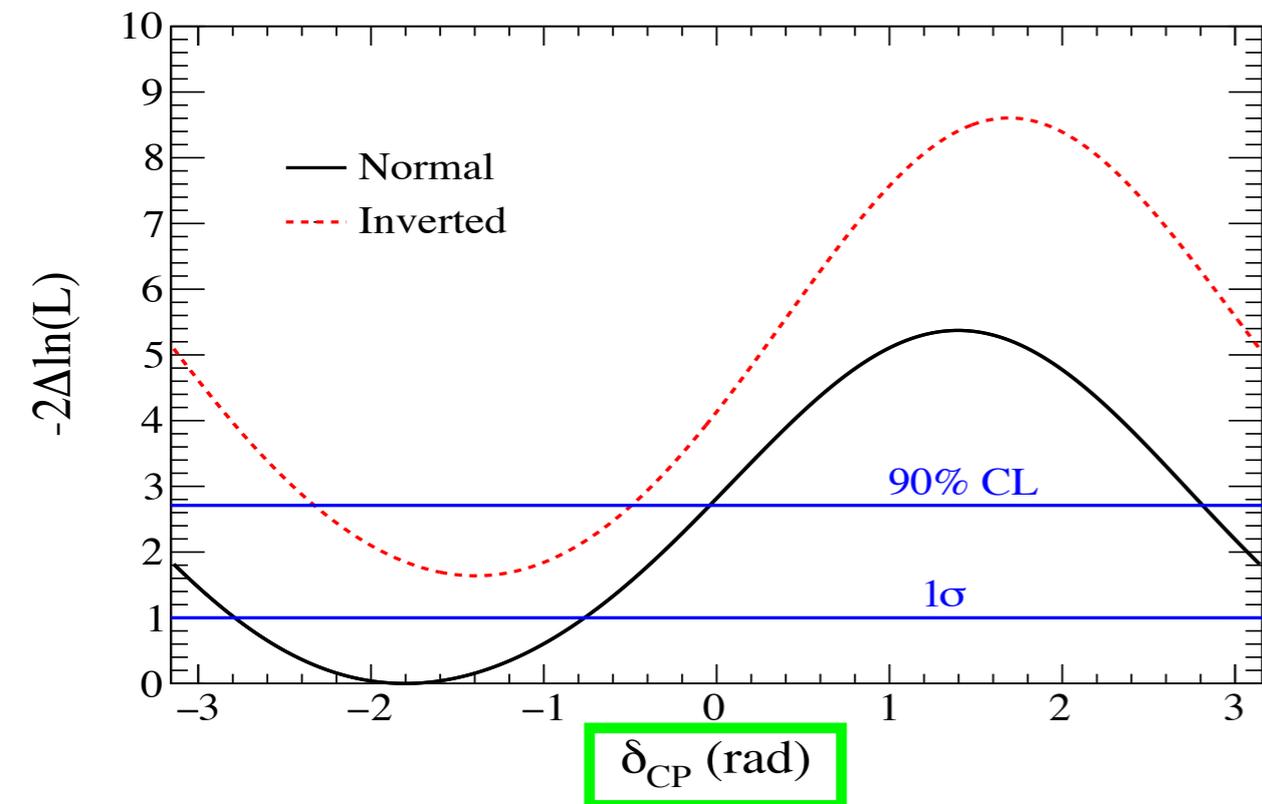
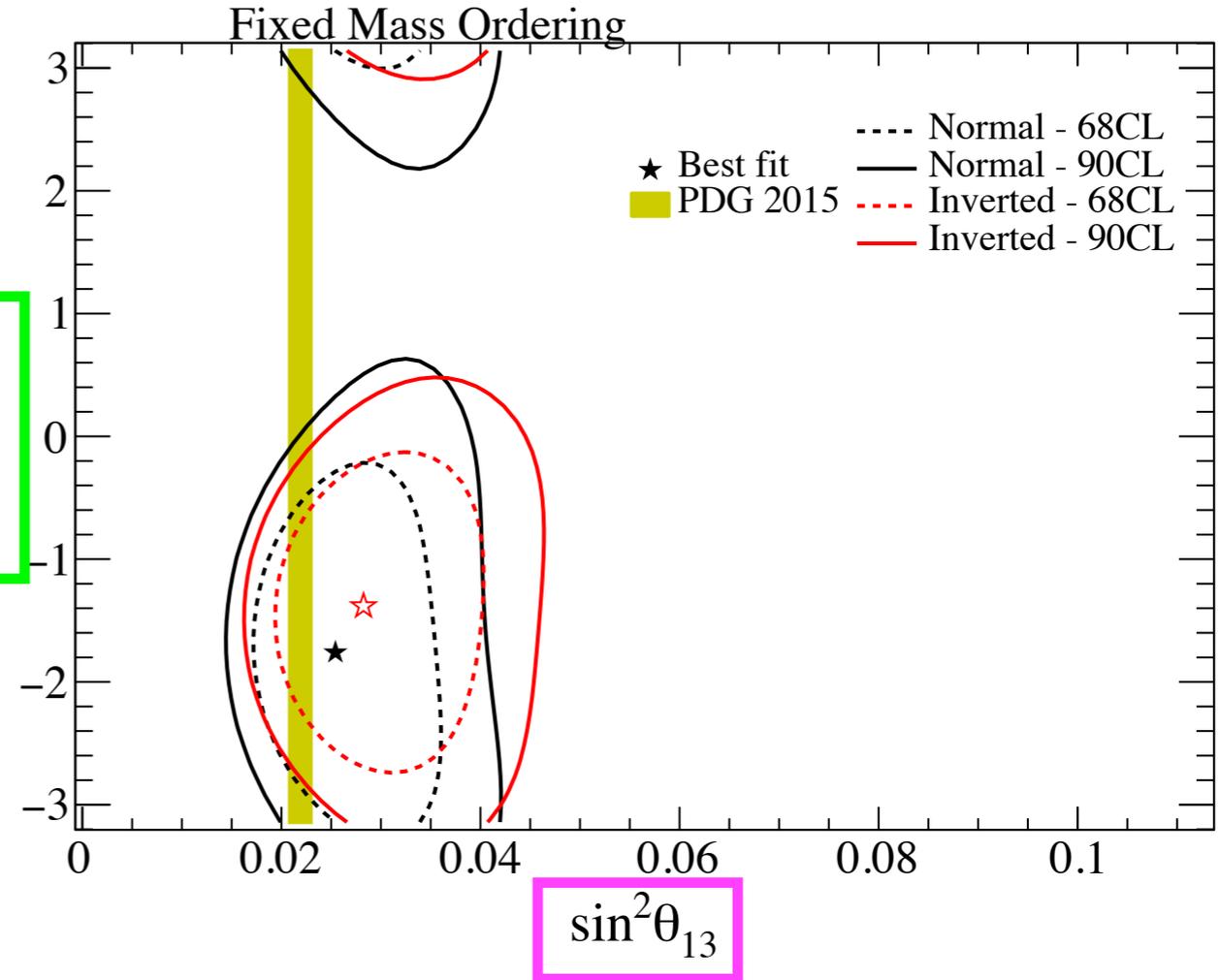
- FIT **neutrino** and **anti-neutrino** data separately.



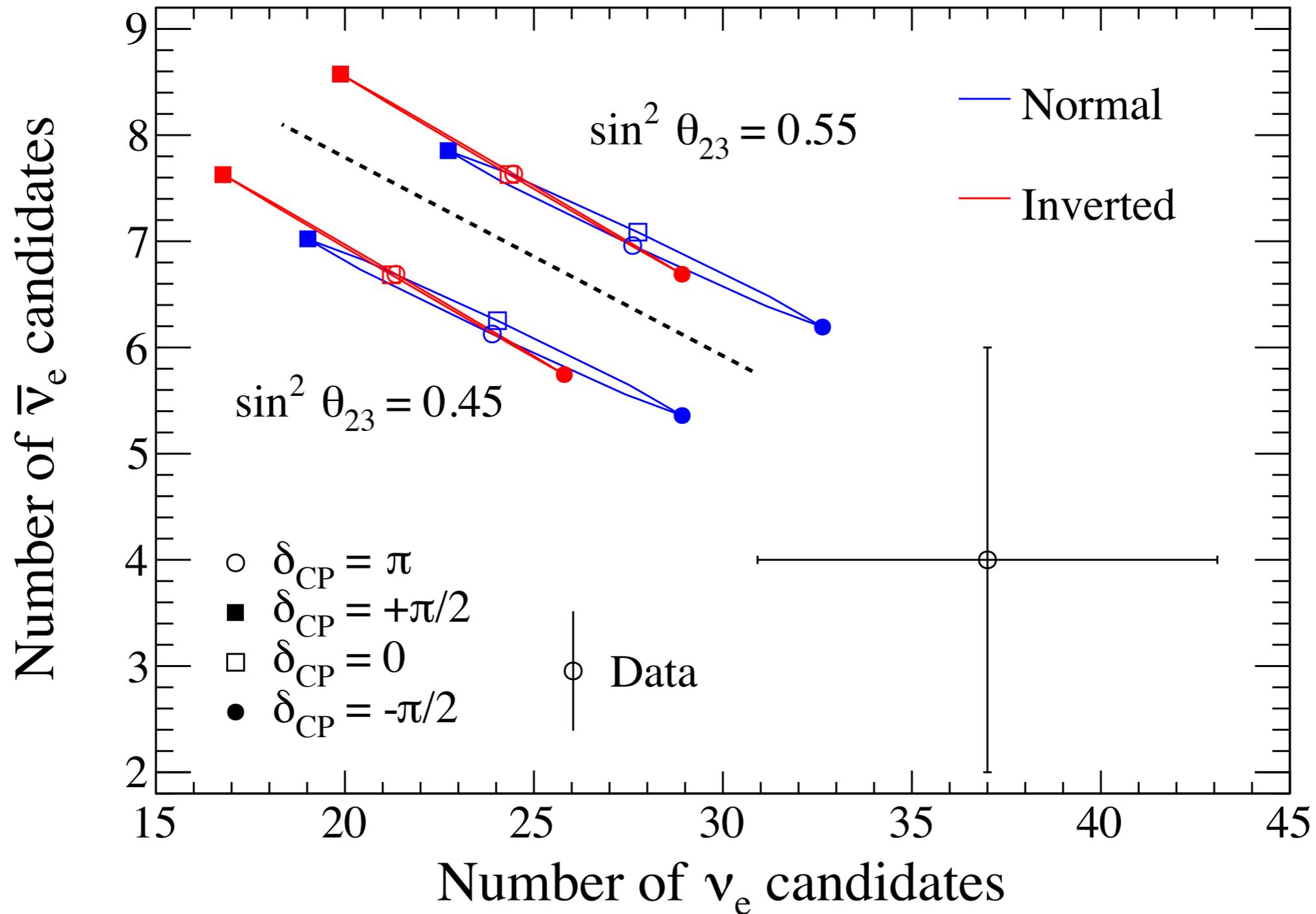
OA Fit results with T2K only data

Parameter	Normal ordering		Inverted ordering	
	Best-fit	$\pm 1\sigma$	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.791	[-2.789; -0.764]	-1.382	[-2.296; -0.524]
$\sin^2 \theta_{13}$	0.0271	[0.0209; 0.0342]	0.0299	[0.0232; 0.0380]

δ_{CP} (rad)

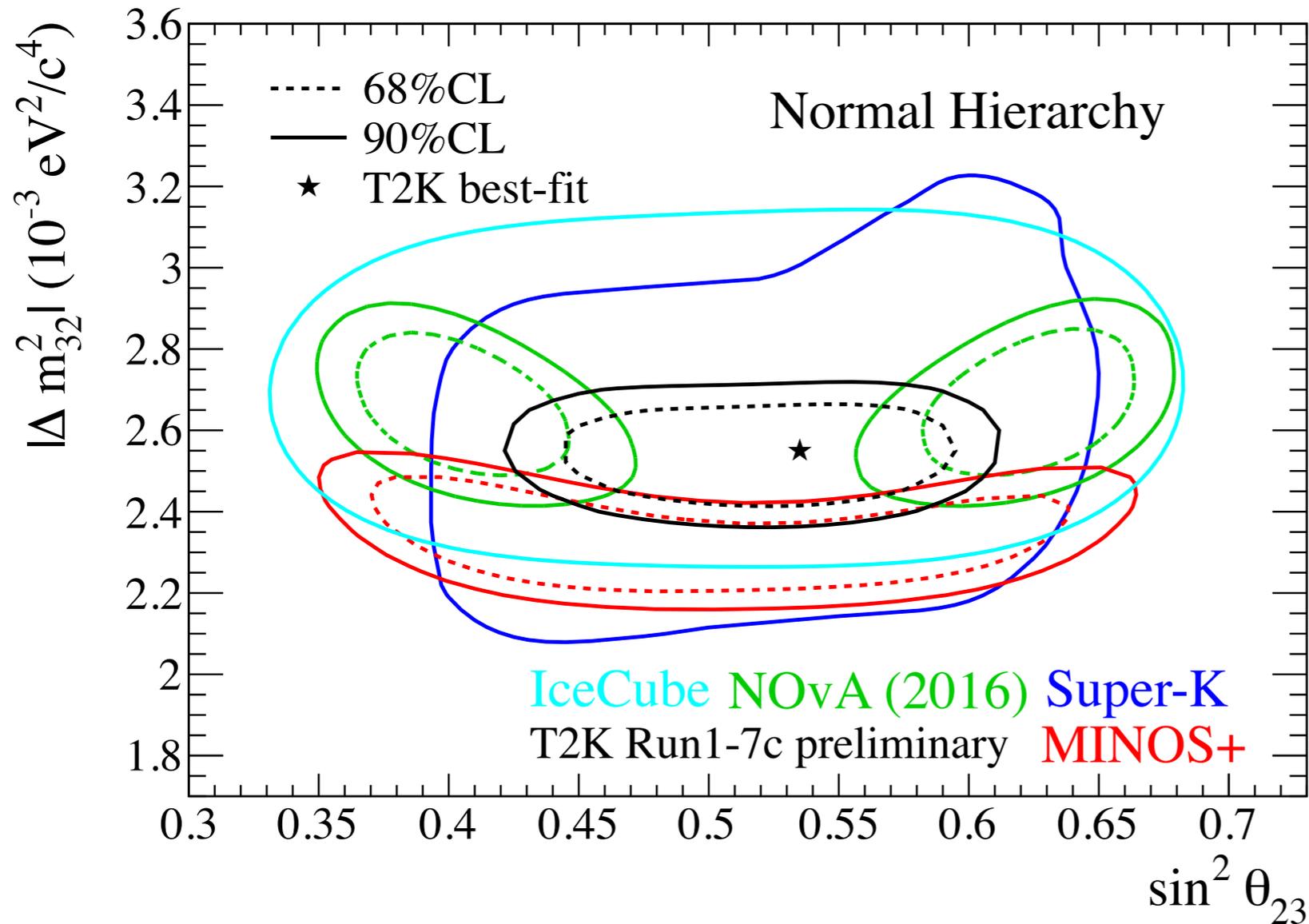


Number of events as a function of θ_{23}



θ_{23} and Δm_{32}^2

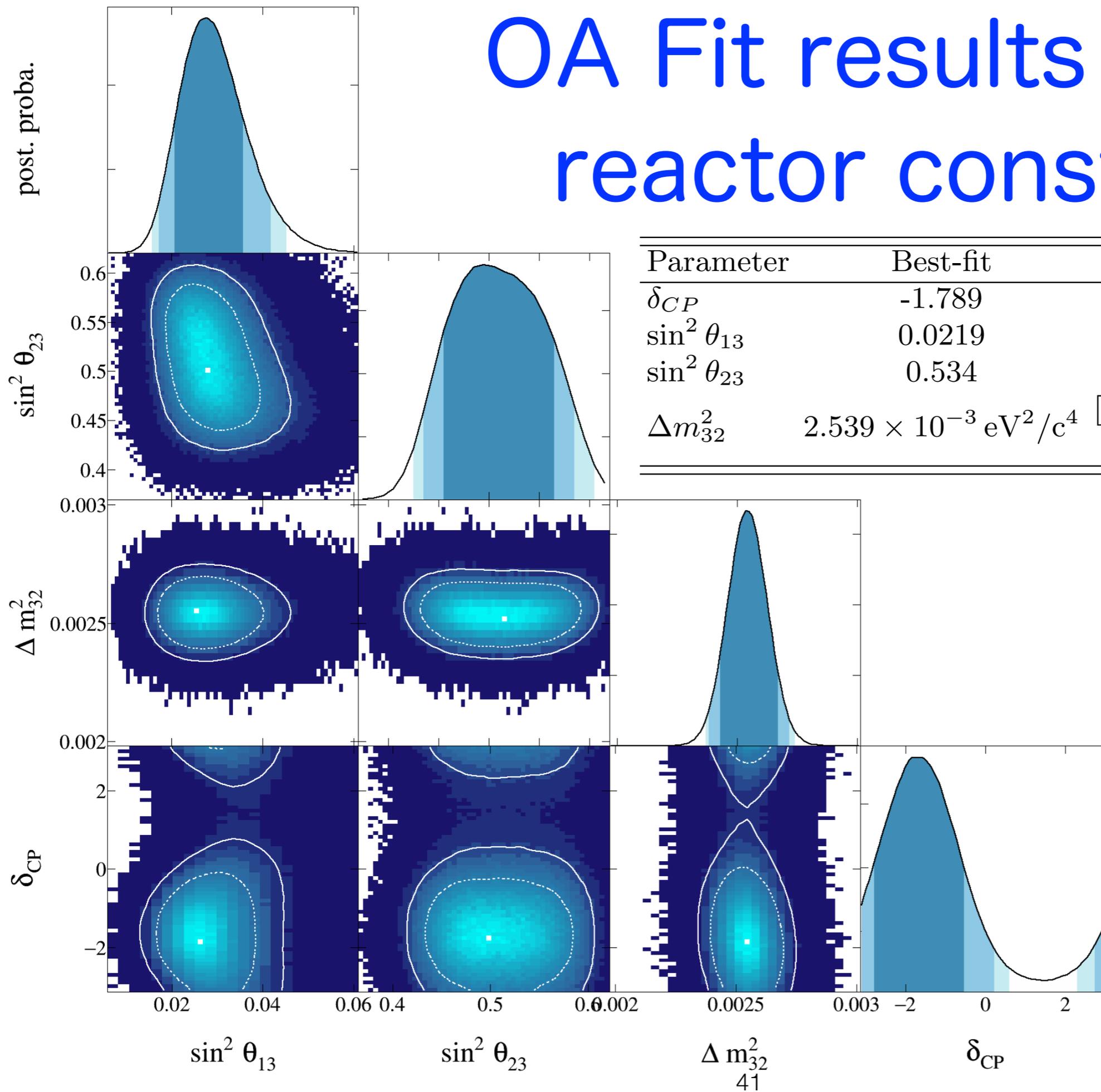
- Consistent with maximal mixing



\updownarrow **Daya Bay:**
 $|\Delta m_{ee}^2| = (2.45 \pm 0.08) \times 10^{-3} eV^2$
 90% CL (NH)

	NH	IH
$\sin^2 \theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$ \Delta m_{32}^2 [10^{-3} eV^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$

OA Fit results w/ the reactor constraint

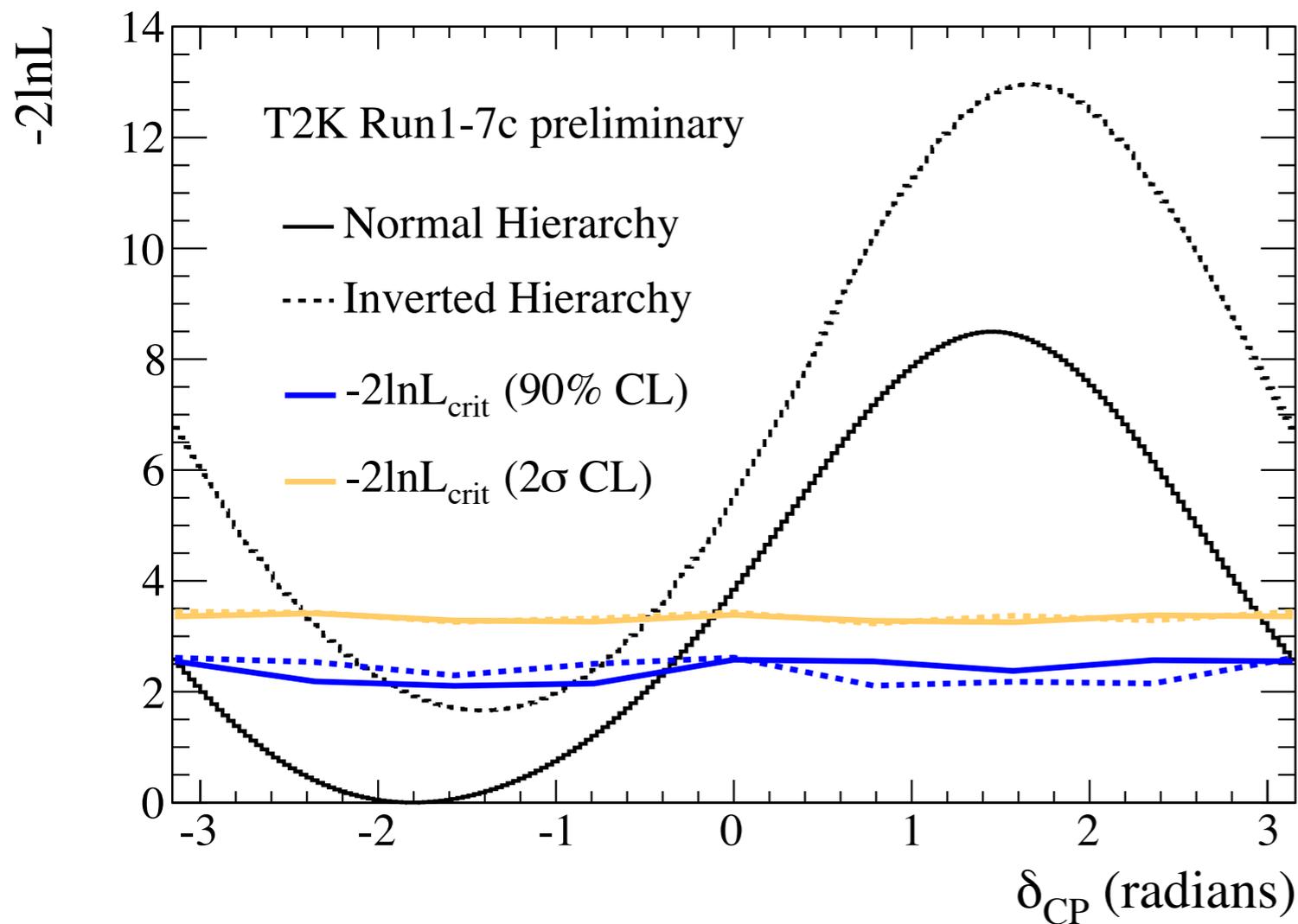


Parameter	Best-fit	$\pm 1\sigma$
δ_{CP}	-1.789	[-2.450; -0.880]
$\sin^2 \theta_{13}$	0.0219	[0.0208; 0.0233]
$\sin^2 \theta_{23}$	0.534	[0.490 ; 0.580]
Δm_{32}^2	$2.539 \times 10^{-3} \text{ eV}^2/c^4$	$[-3.000; -2.952] \times 10^{-3} \text{ eV}^2/c^4$ $[2.424; 2.664] \times 10^{-3} \text{ eV}^2/c^4$

δ_{CP} with reactor θ_{13}

with $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

Measurement (Data)

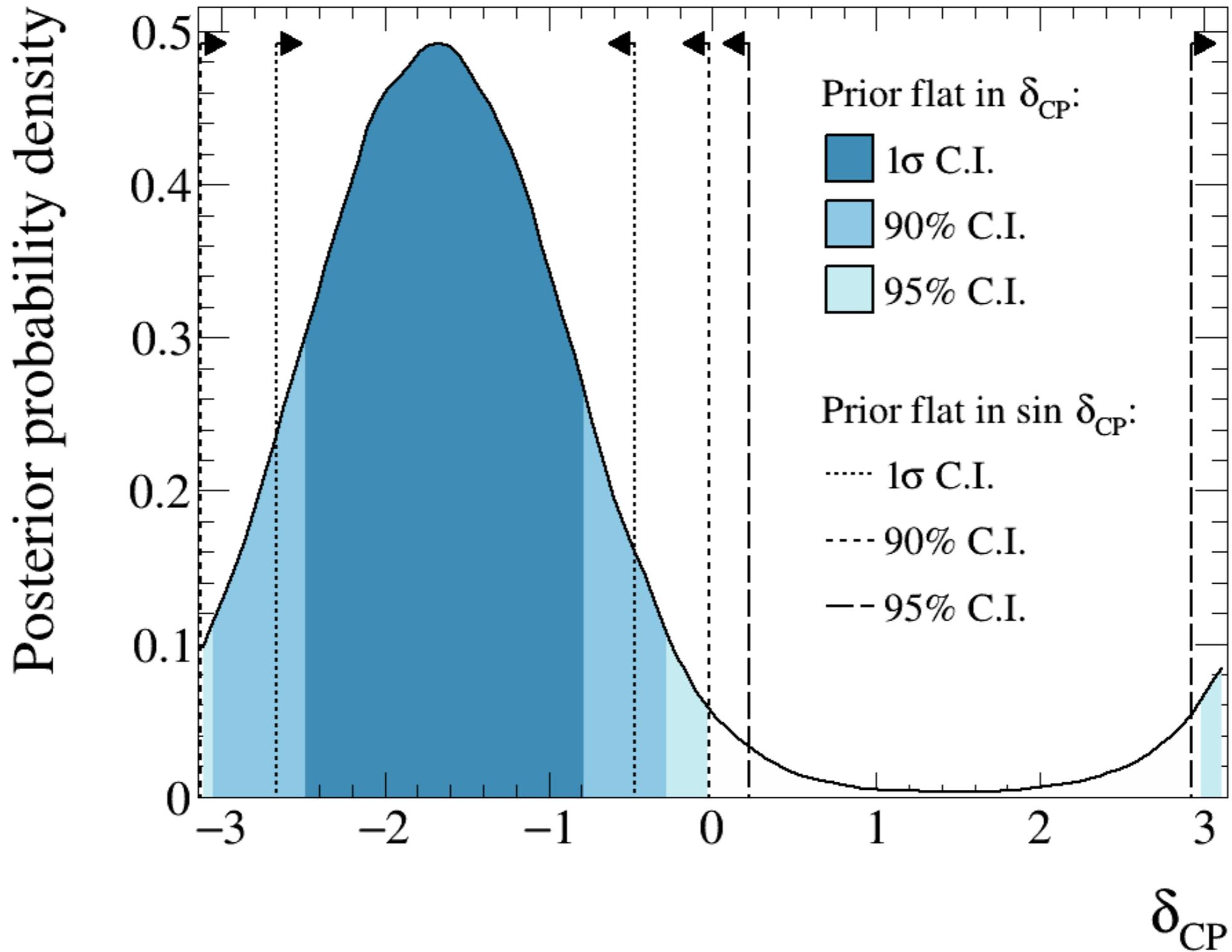


True: $\delta_{CP} = -\pi/2$ — normal ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.243	0.131
π	Normal	0.216	0.105
0	Inverted	0.542	0.425
π	Inverted	0.559	0.436
True: $\delta_{CP} = 0$ — normal ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.104	0.0490
π	Normal	0.130	0.0591
0	Inverted	0.229	0.137
π	Inverted	0.205	0.122
True: $\delta_{CP} = -\pi/2$ — inverted ordering			
δ_{CP}	Ordering	90% CL	2σ CL
0	Normal	0.124	0.0515
π	Normal	0.102	0.0413
0	Inverted	0.290	0.194
π	Inverted	0.308	0.207

- A constraint of neutrino CPV at 90% CL

- $\delta_{CP} = [-3.13, -0.39]$ (NH), $[-2.09, -0.74]$ (IH) at 90% CL

Posterior probability on δ_{CP}



Posterior probabilities for the mass ordering and $\sin^2 \theta_{23}$

	$\sin^2 \theta_{23} < 0.5$	$\sin^2 \theta_{23} > 0.5$	Line Total
Inverted ordering	0.060	0.152	0.212
Normal ordering	0.235	0.553	0.788
Column total	0.295	0.705	1

Super-K atmospheric ν results

Complementarity with atmospheric neutrinos

NuclPhysB669,255(2003)

NuclPhysB680,479(2004)

$$\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx P_2(r \cdot \cos^2 \theta_{23} - 1) \quad \text{Solar term}$$

$$-r \cdot \sin \tilde{\theta}_{13} \cdot \cos^2 \tilde{\theta}_{13} \cdot \sin 2\theta_{23} (\cos \delta \cdot R_2 - \sin \delta \cdot I_2) \quad \text{Interference term } (\delta\text{CP})$$

$$+2 \sin^2 \tilde{\theta}_{13} (r \cdot \sin^2 \theta_{23} - 1) \quad \theta_{13} \text{ resonance term} \quad (3)$$

r : μ/e flux ratio (~ 2 at low energy)

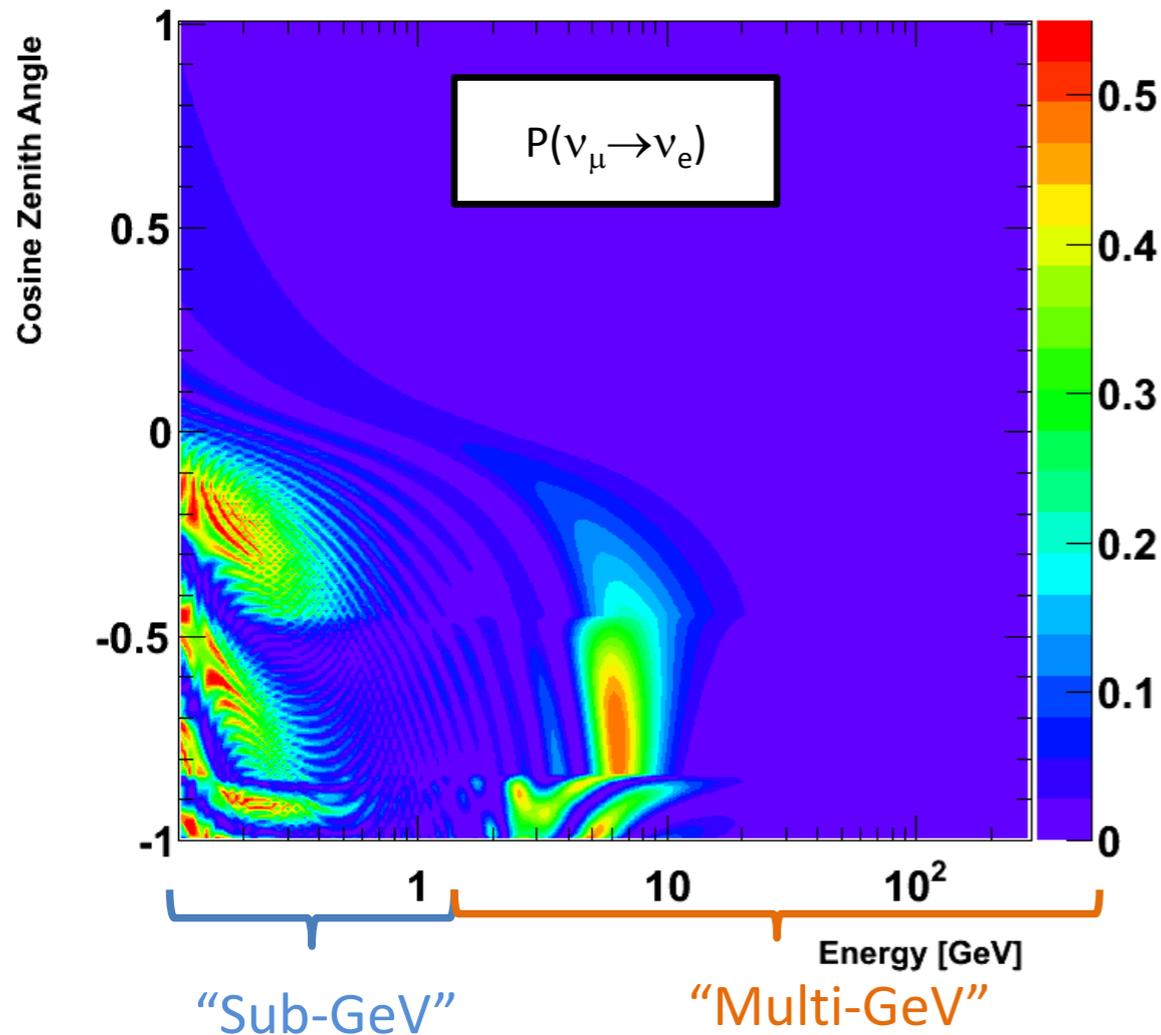
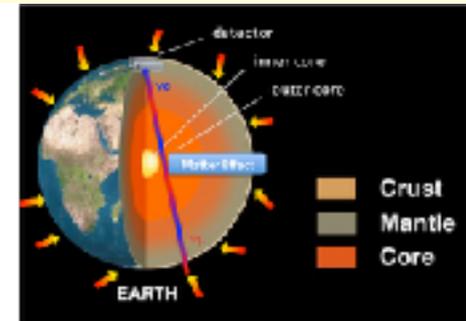
$P_2 = |A_{e\mu}|^2$: 2ν transition probability $\nu_e \rightarrow \nu_{\mu\tau}$ in matter

$$R_2 = \text{Re}(A_{ee}^* A_{e\mu})$$

$$I_2 = \text{Im}(A_{ee}^* A_{e\mu})$$

A_{ee} : survival amplitude of the 2ν system

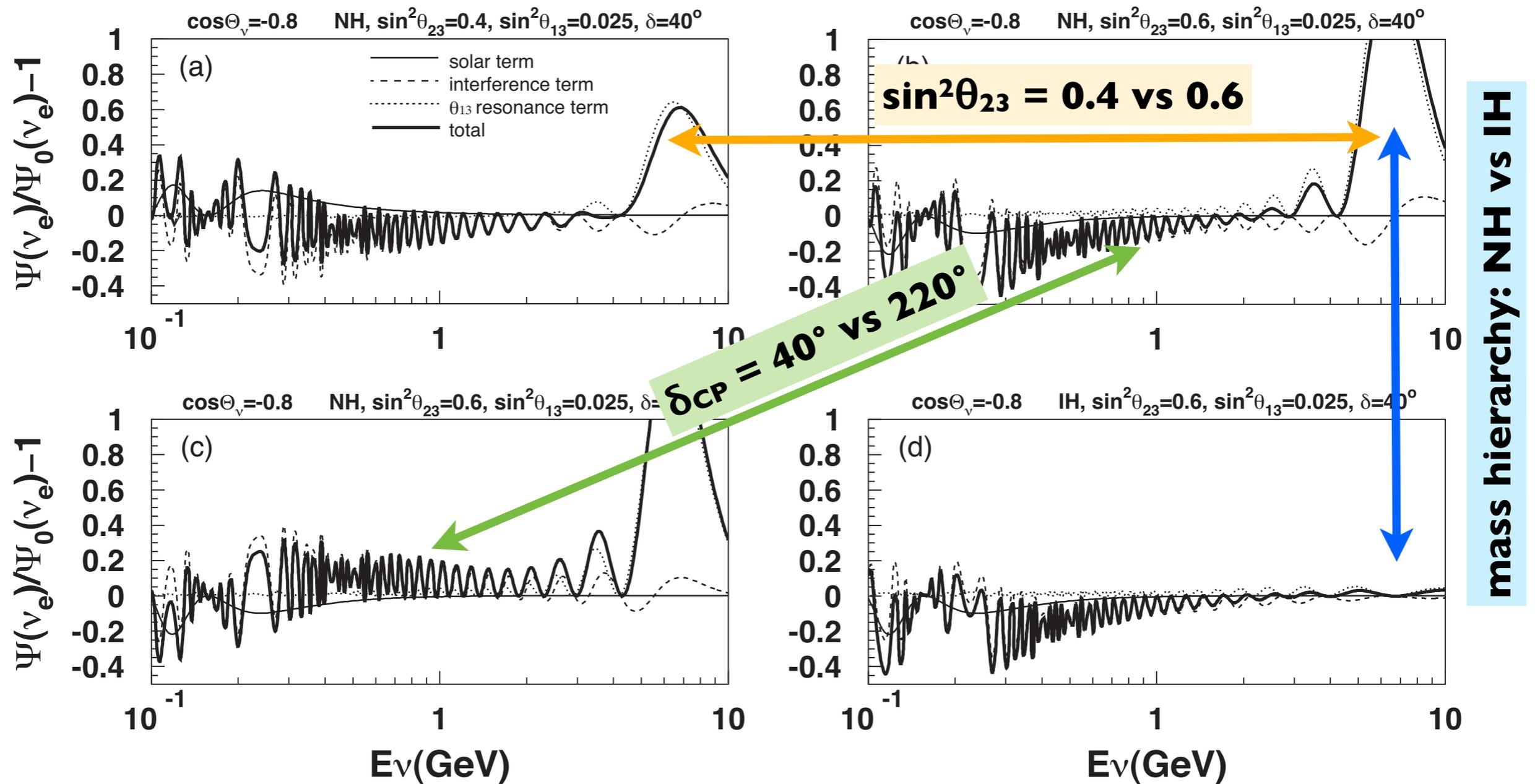
$A_{e\mu}$: transition amplitude of the 2ν system



ν_e appearance (and ν_{μ} distortion) is expected due to MSW effect in the Earth's matter

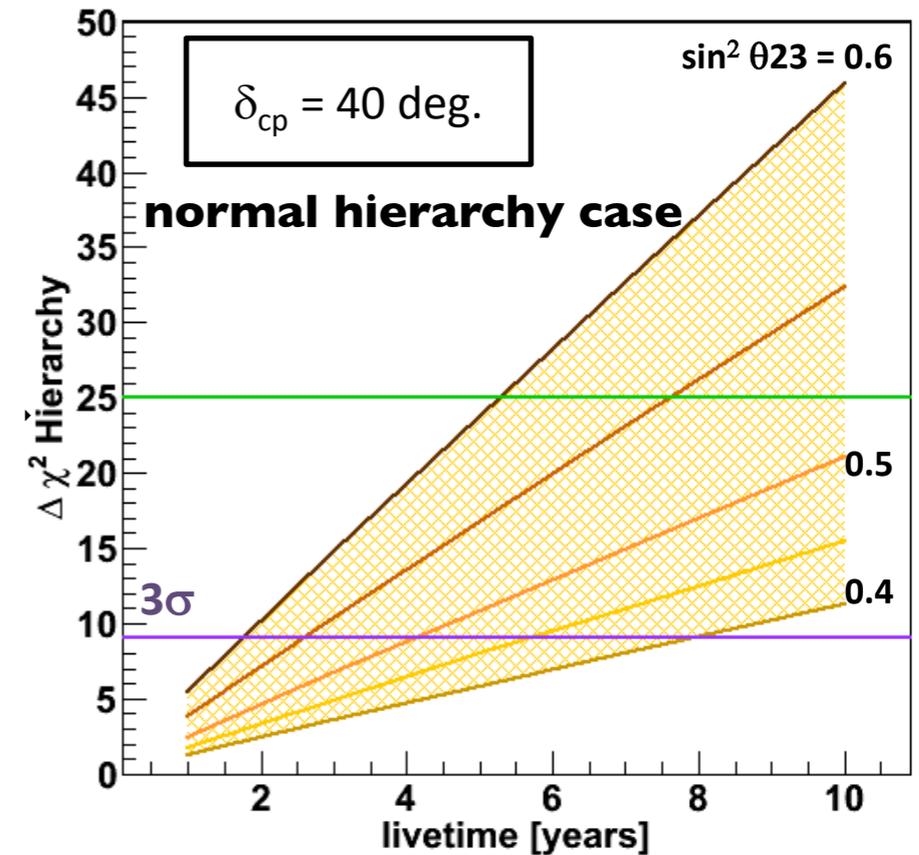
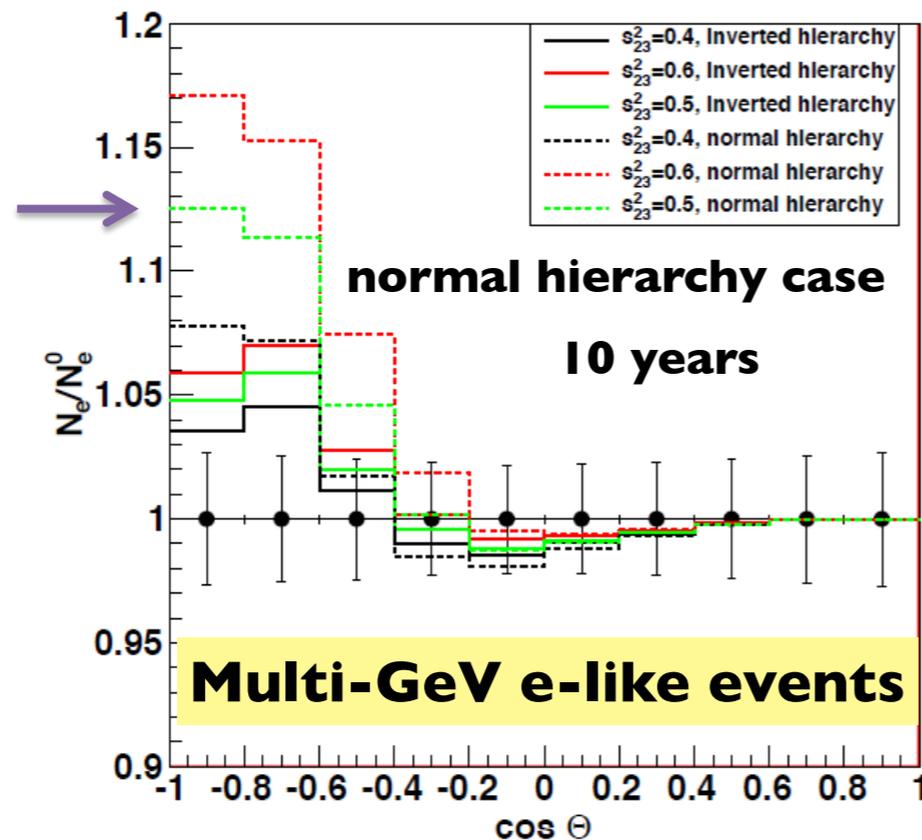
- happens in ν in the case of normal mass hierarchy
- in anti- ν in inverted mass hierarchy

Large θ_{13} value gives us a good chance to discriminate mass hierarchy.

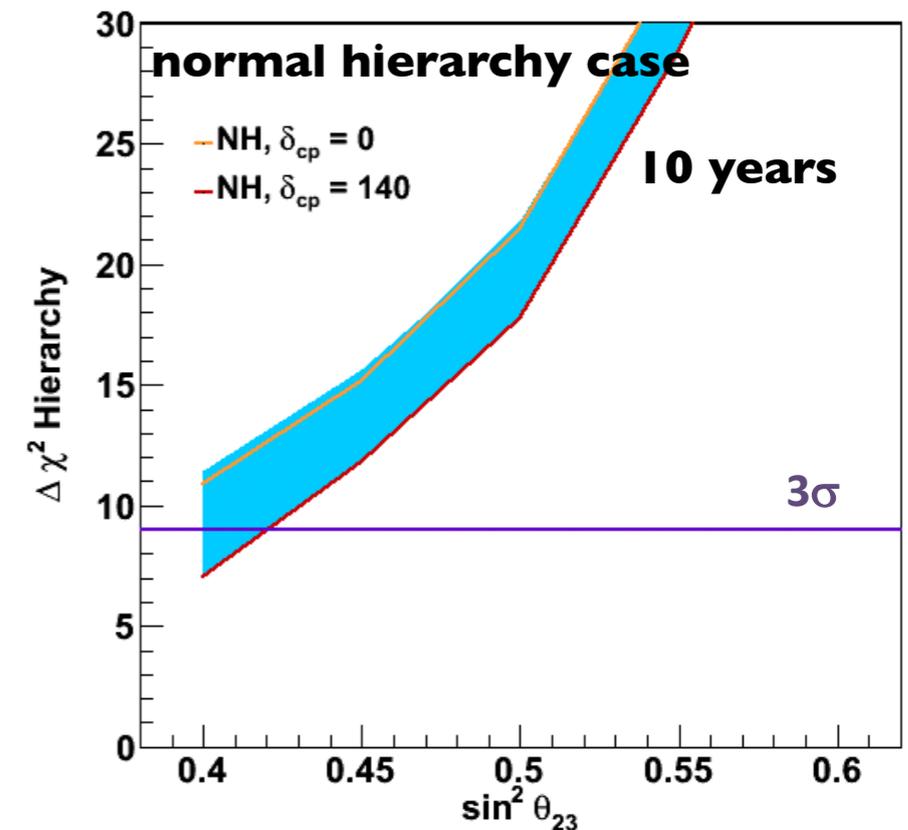


- Through matter effect (MSW), we study
 - Mass hierarchy \Rightarrow Asymmetry between neutrinos and antineutrinos.
 - Octant of θ_{23} \Rightarrow Magnitude of resonance effect
Appearance (and $\nu_\mu \rightarrow \nu_\mu$ disappearance) interplay
 - δ_{CP} (and θ_{13}) \Rightarrow Interference effects in \sim GeV energy region

Mass Hierarchy Sensitivity of Hyper-K

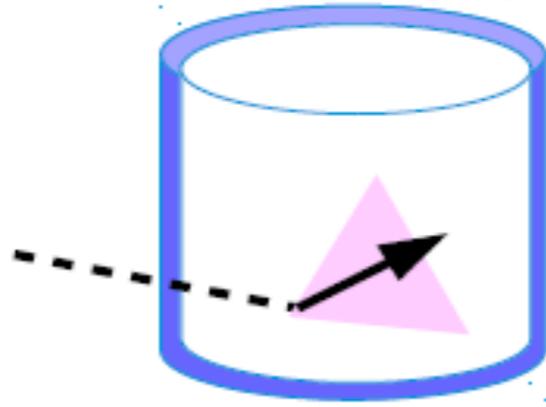


- Sensitivity depends on θ_{23} , δ and mass hierarch (a little).
- 3σ mass hierarchy determination for $\sin^2 \theta_{23} > 0.42$ (0.43) in the case of normal (inverted) hierarchy.

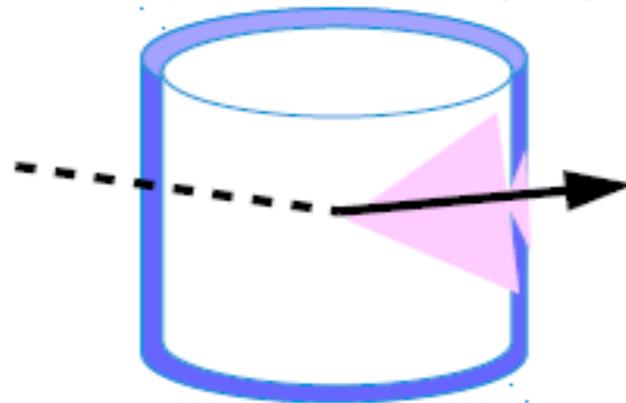


Super-K atm ν analysis

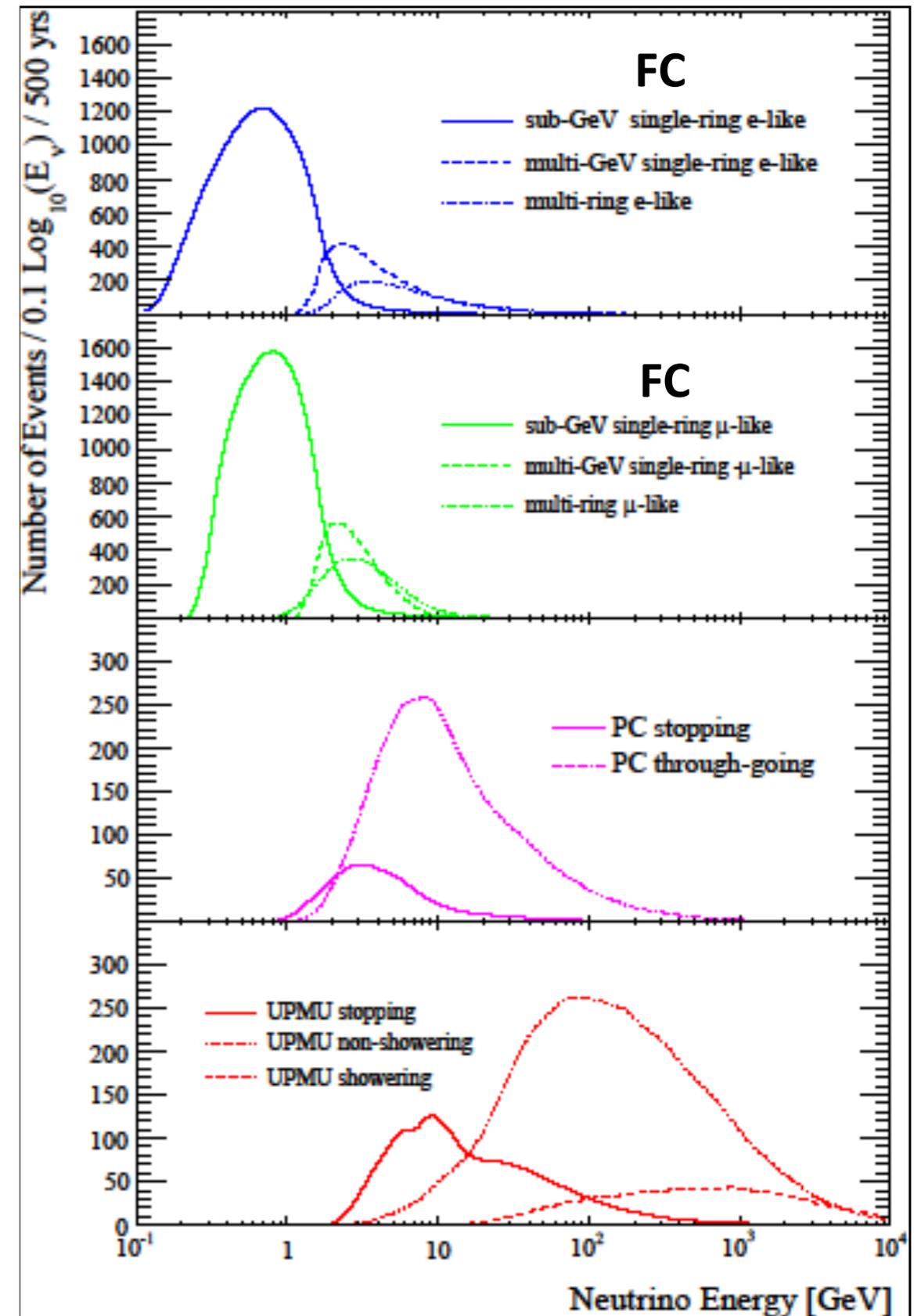
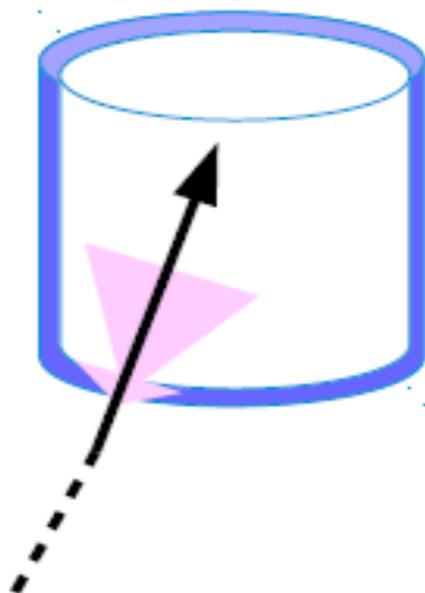
Fully Contained (FC)



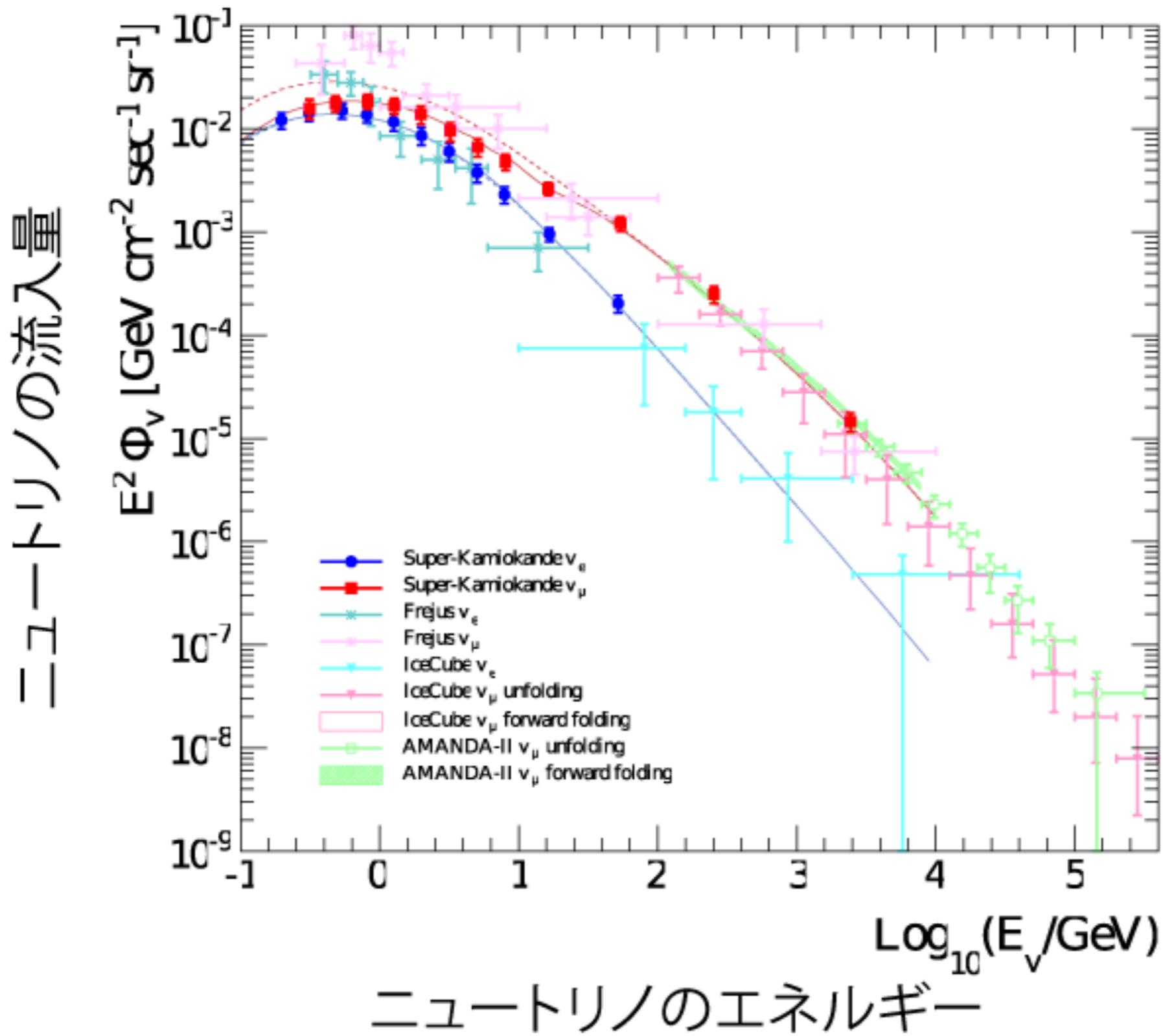
Partially Contained (PC)



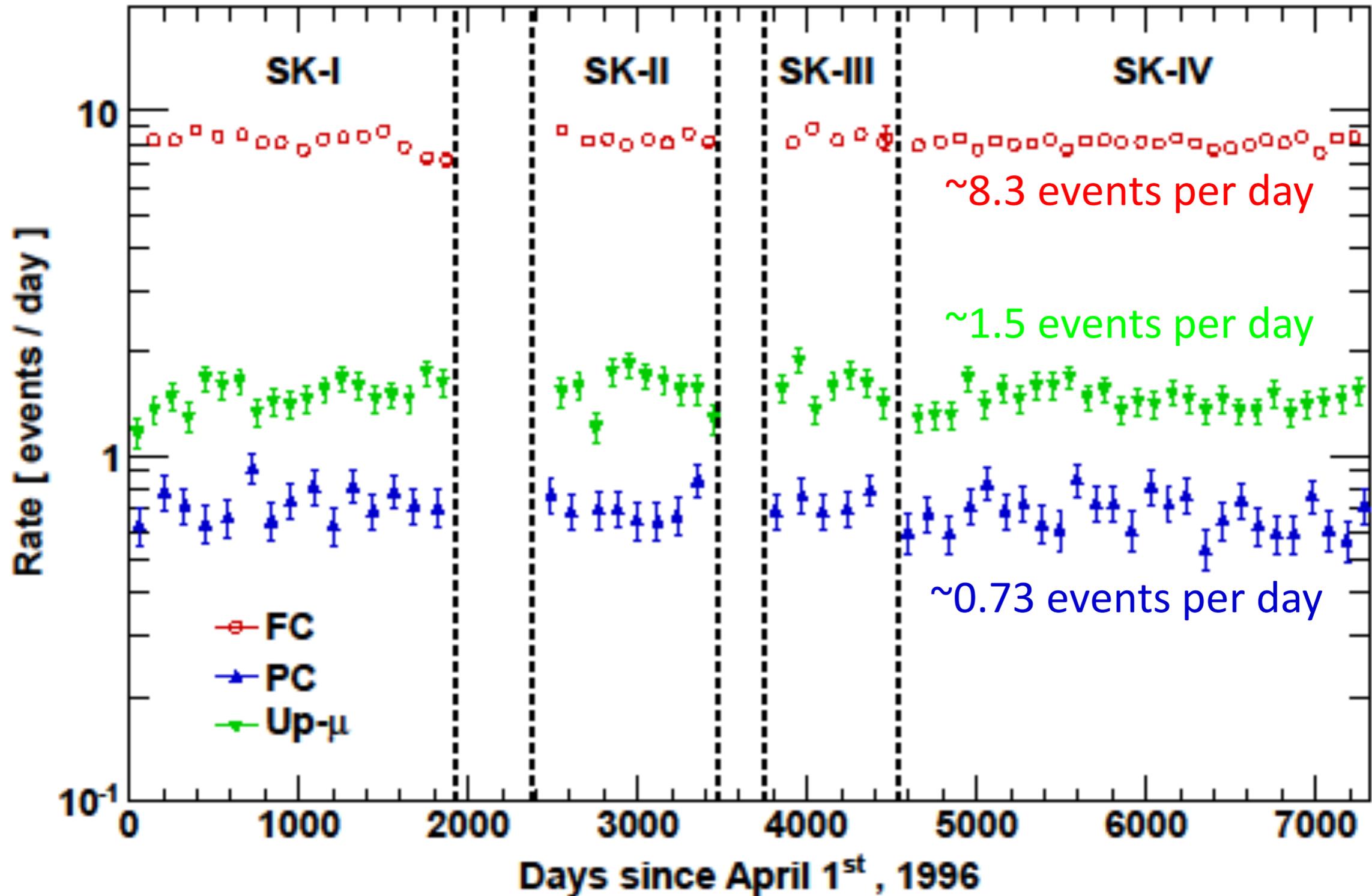
Upward-going Muons (Up- μ)



Atm. ν flux



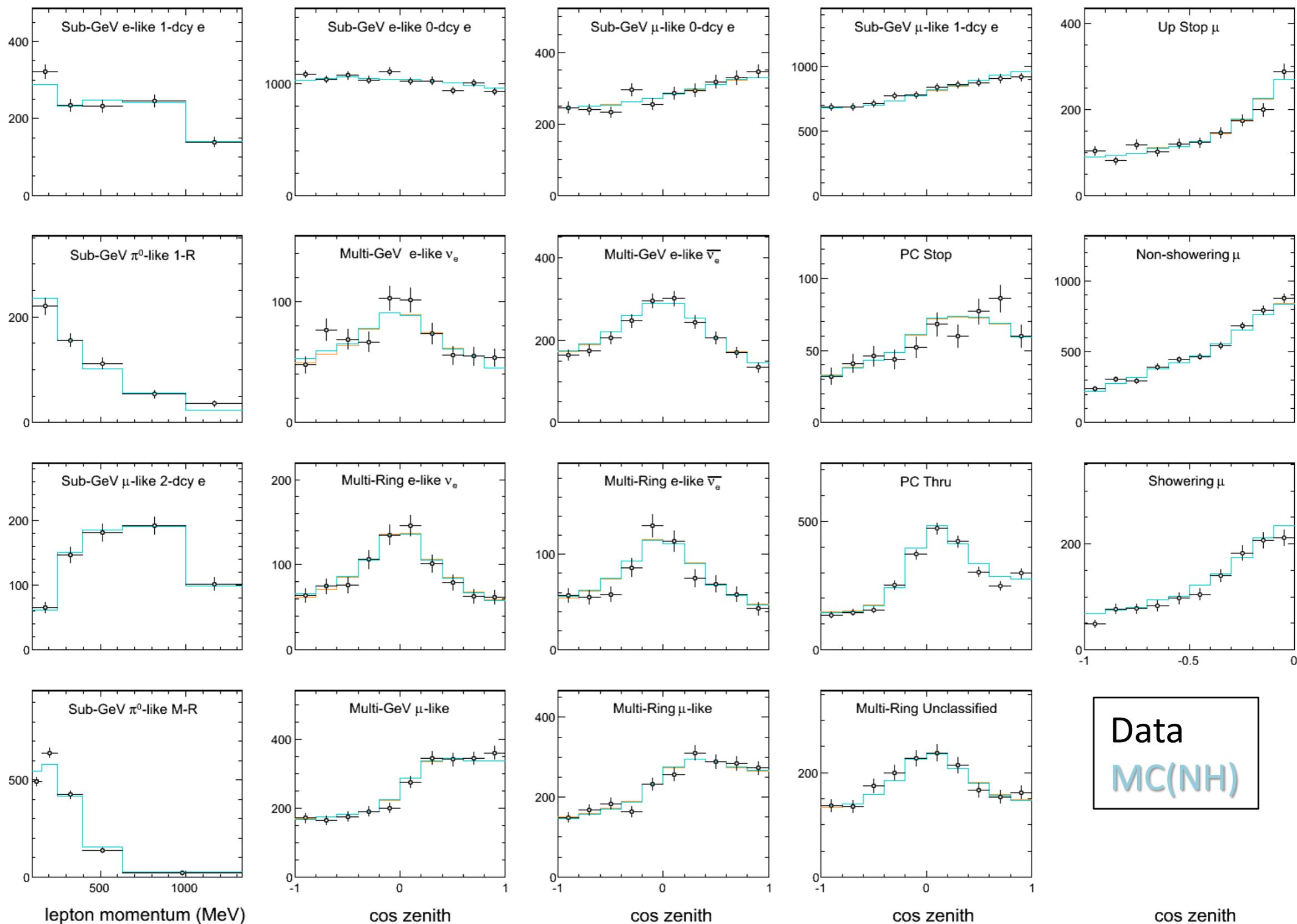
Atm. ν event rate @ Super-K



Atm. ν event sample @ Super-K

(19 analysis samples for 3- ν oscillation analysis)

SK Preliminary



Oscillation Analysis w/ ν_e and $\bar{\nu}_e$ samples

Standard 3 flavor analysis

- Take into account all the sub-leading effects (Δm^2_{21} & matter)
- Presence of **matter: matter effect on θ_{13} \rightarrow resolving mass hierarchy**
- Presence of Δm^2_{21} : $\nu_\mu \leftrightarrow \nu_e \rightarrow$ resolving octant θ_{23}
- Presence of **interference \rightarrow CP violating phase**

ν_e sample

Multi-GeV e-like ne
Multi-Ring e-like ne

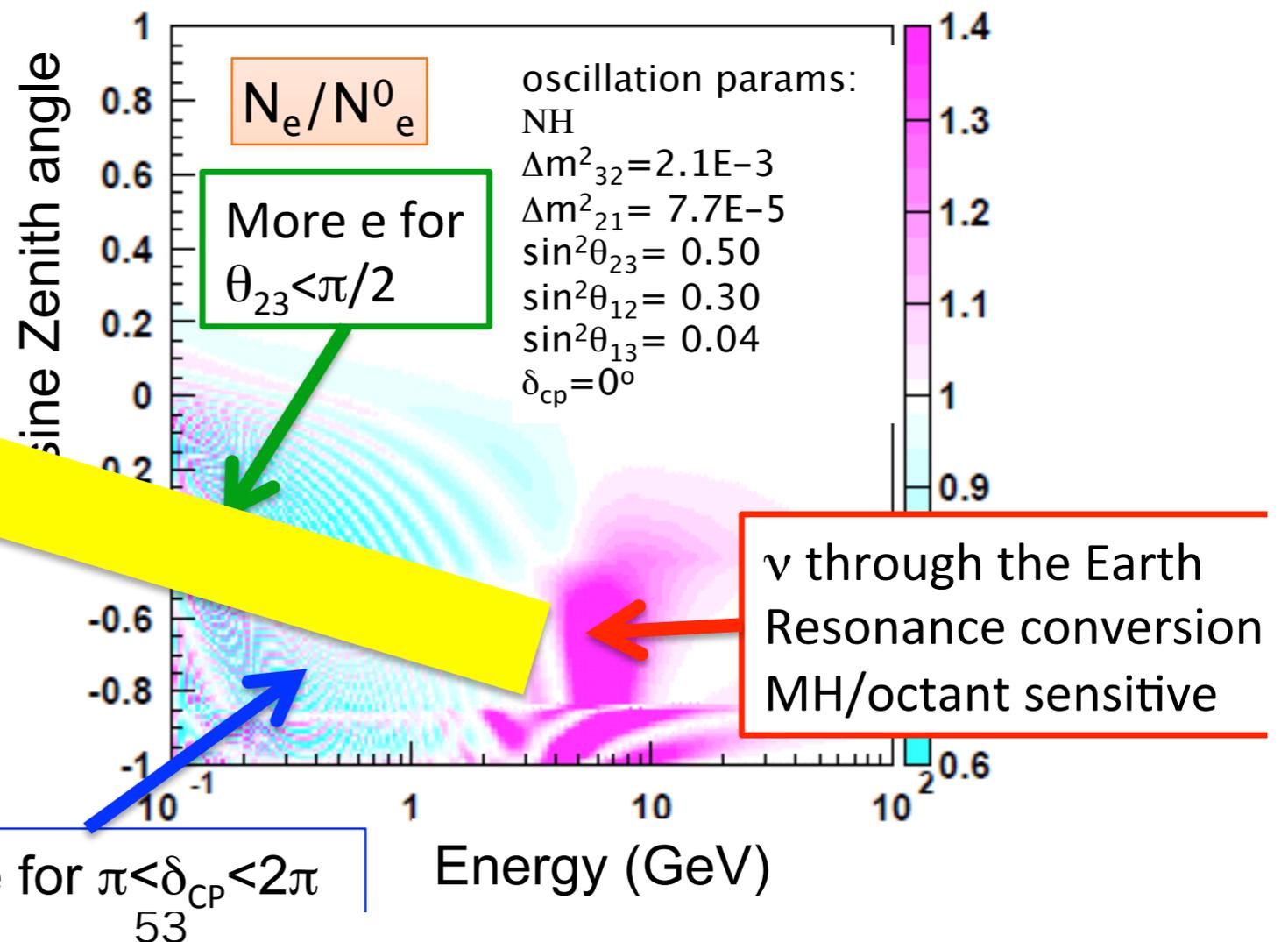
$\bar{\nu}_e$ sample

Multi-GeV e-like ne
Multi-Ring e-like ne

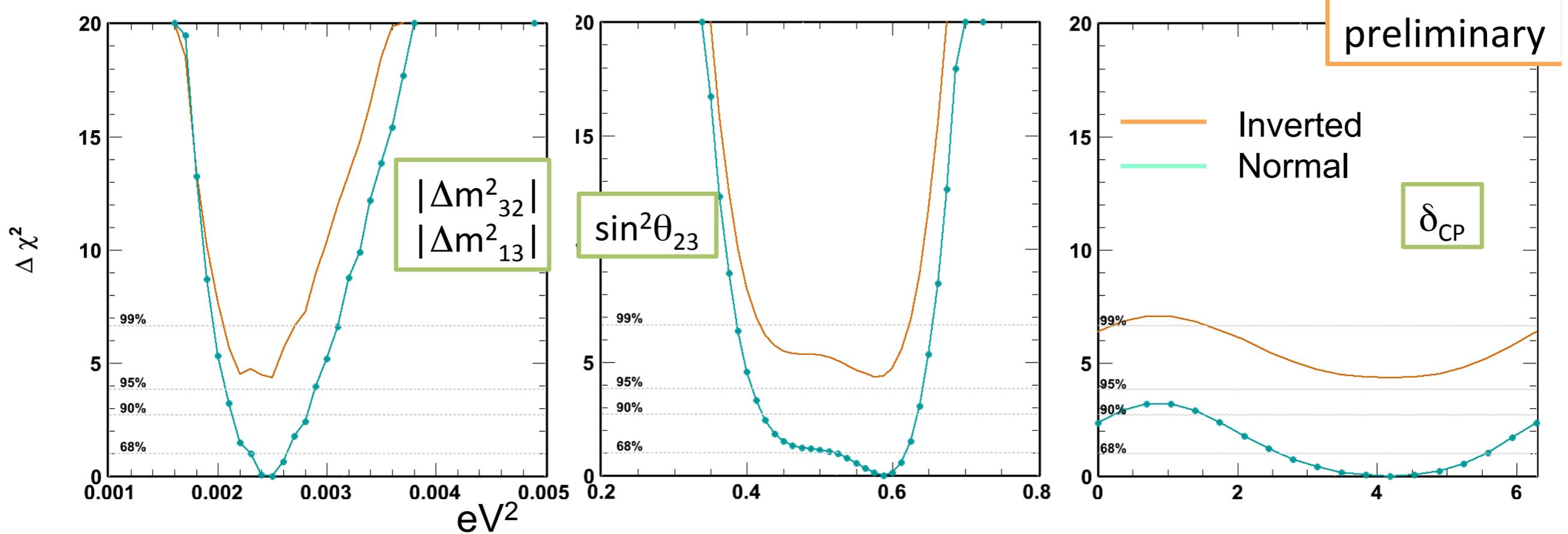
Multi-Ring other

statistical separation based on

- # of decay e
- # of rings
- transverse mom.



SK only Results



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$ \Delta m^2_{32} \text{ eV}^2$
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

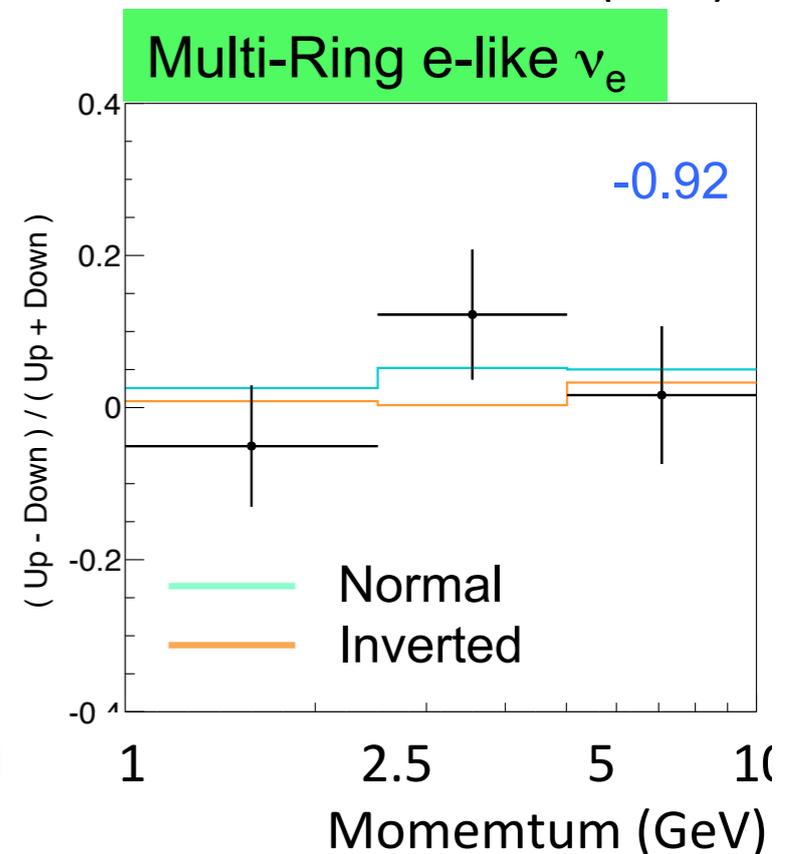
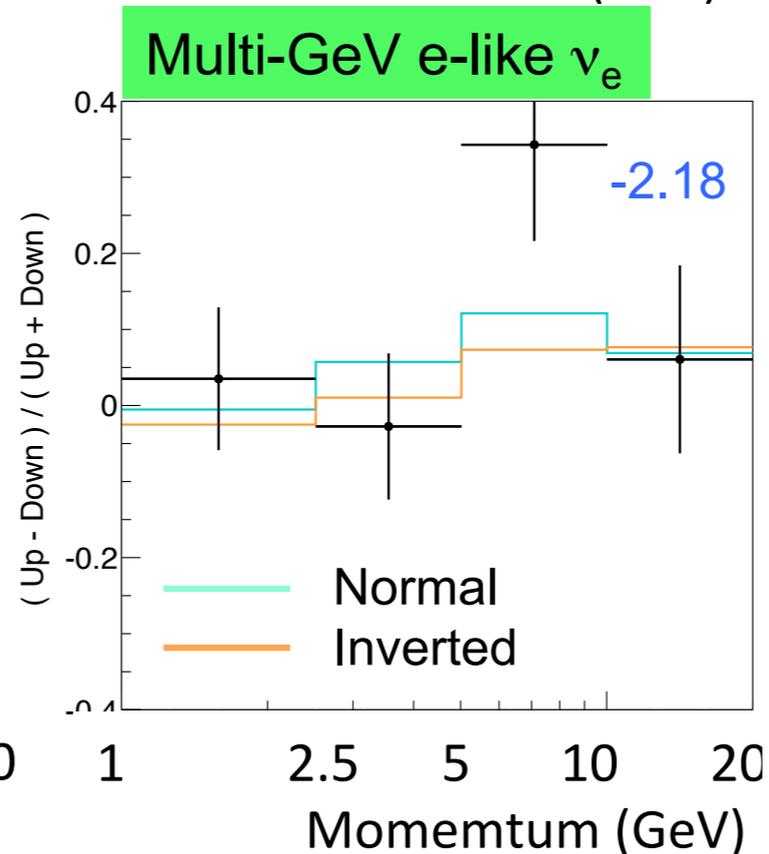
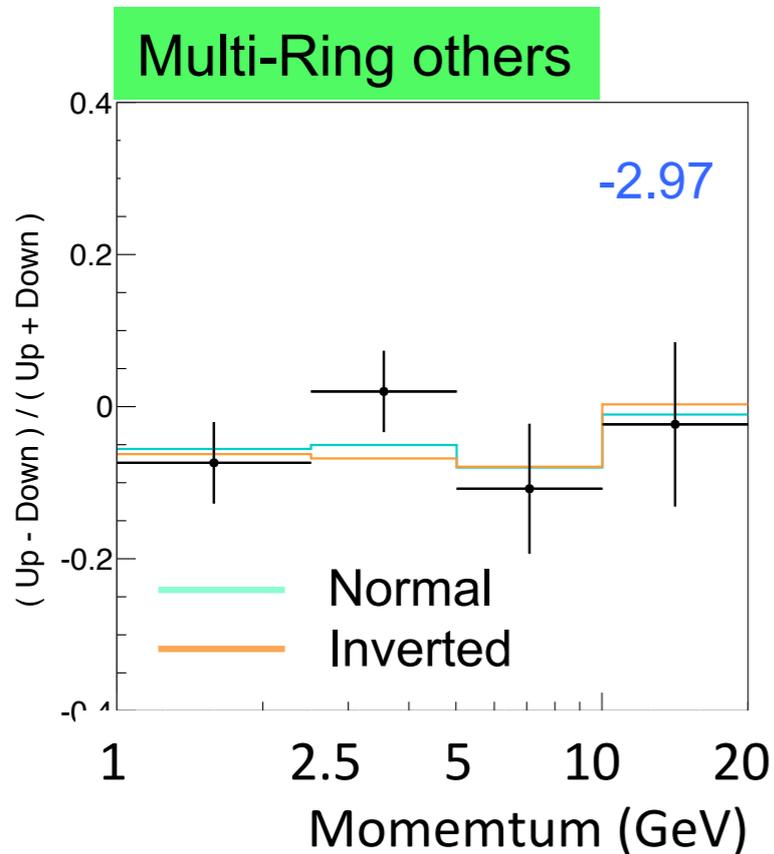
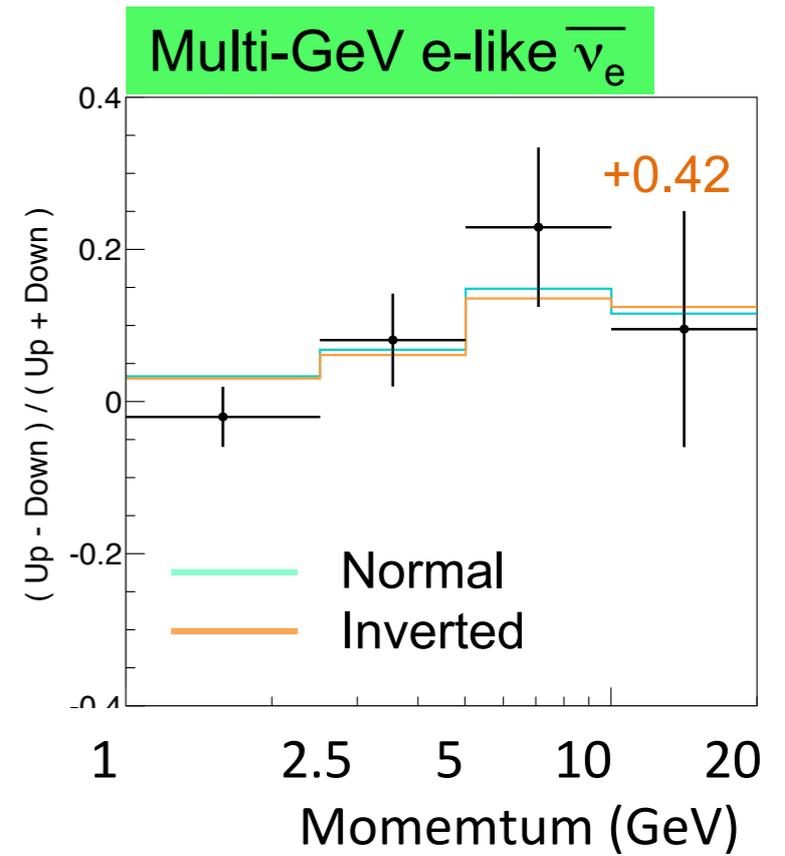
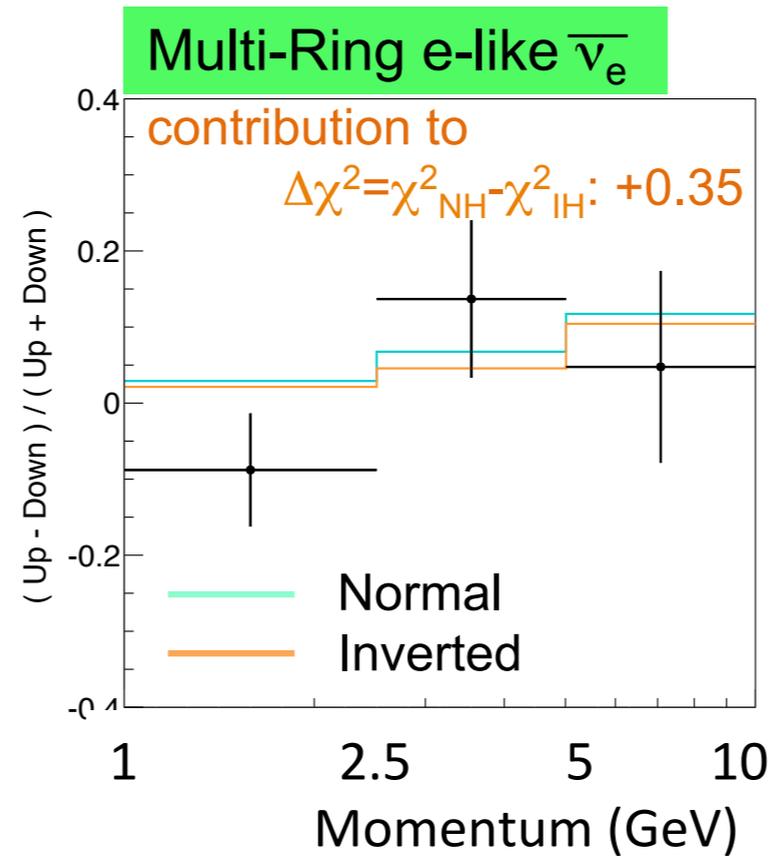
- SK only (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}=0.6$) and 0.007 ($\sin^2\theta_{23}=0.4$). Under NH hypothesis, the probability is 0.45 ($\sin^2\theta_{23}=0.6$).

Samples with large contributions

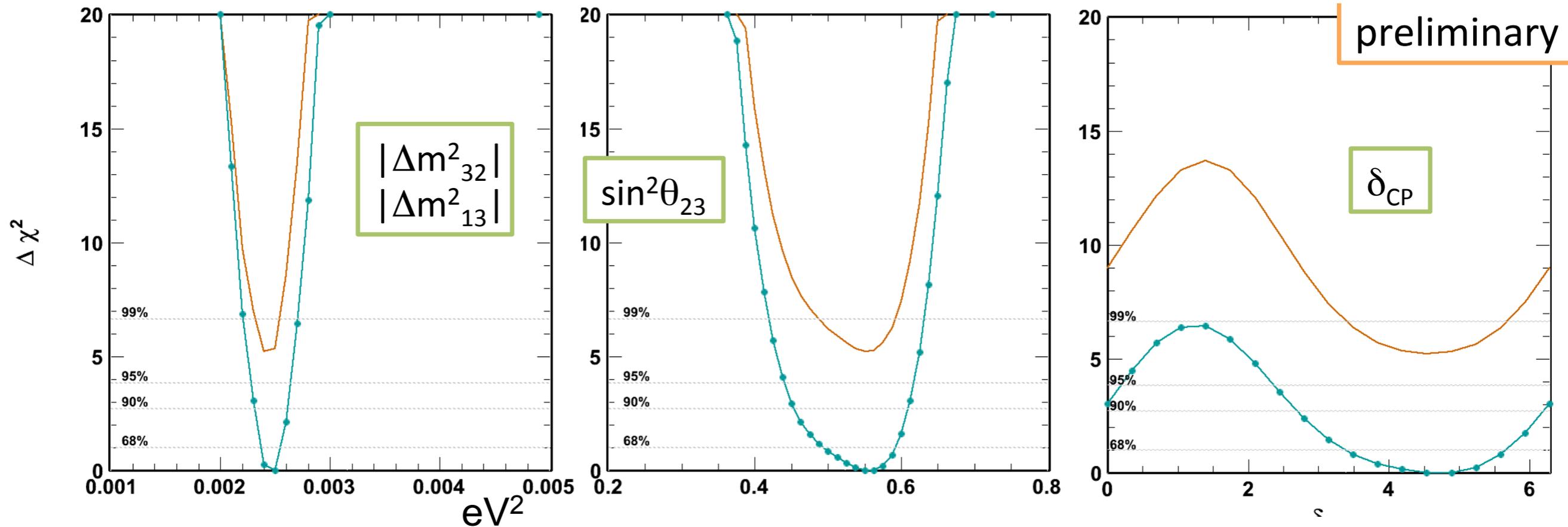
Hierarchy
Sensitive
Samples

UP-DOWN

UP+DOWN
as a func. of p



SK Results with T2K inputs



Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$ \Delta m^2_{32} \text{ eV}^2$
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$
 (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}=0.6$) and 0.001 ($\sin^2\theta_{23}=0.4$). NH: 0.43 ($\sin^2\theta_{23}=0.6$)

Future

Seamless program to ν CPV

From T2K to T2K-II and

Hyper-Kamiokande

CP Violation Sensitivity in T2K-II

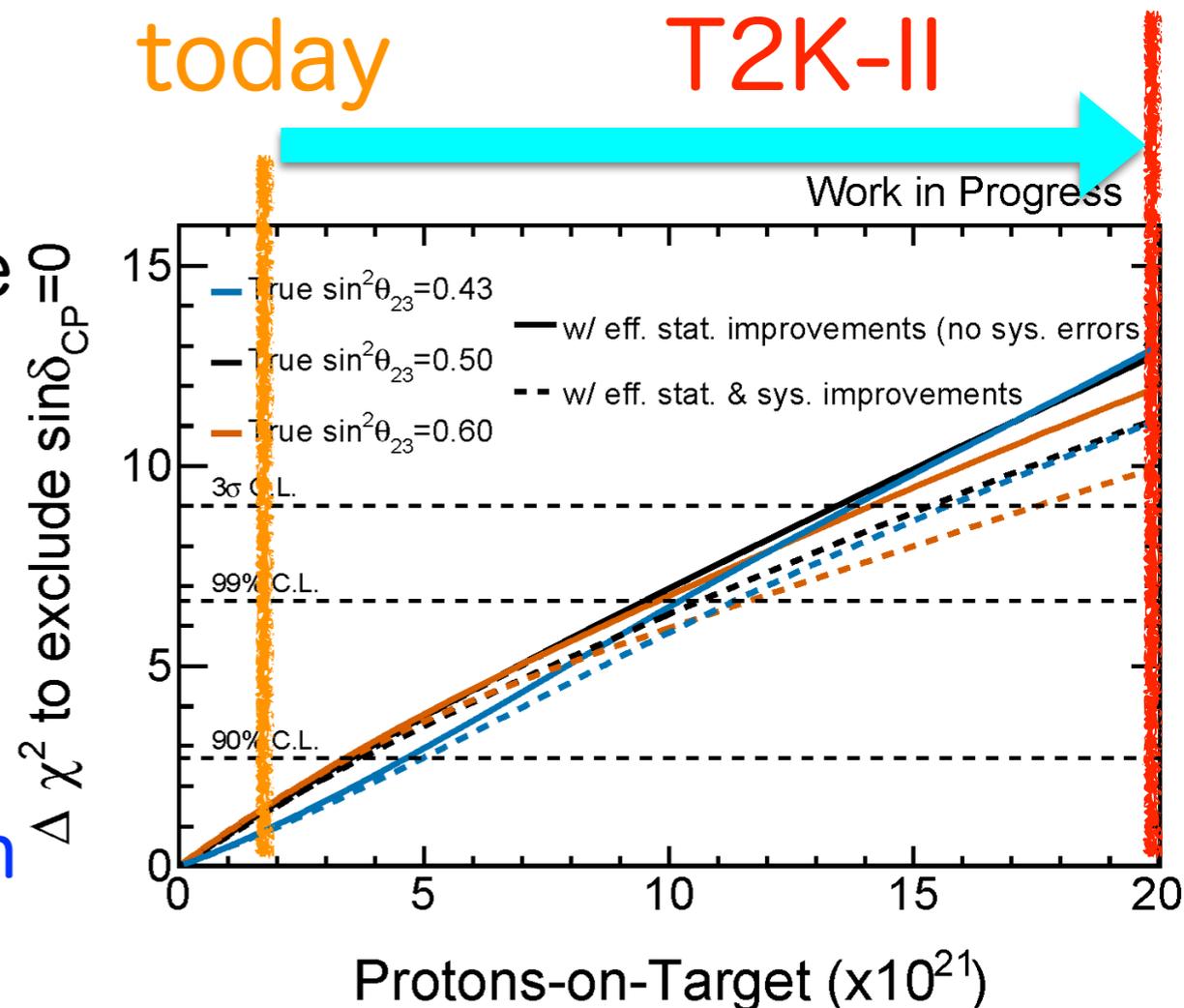
T2K-II w/ improved stat. (10E21 POT for nu and 10E21 POT for anti-nu)

	True δ_{CP}	Total	Signal $\nu_{\mu} \rightarrow \nu_e$	Signal $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_{\mu} + \bar{\nu}_{\mu}$	NC
ν -mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$ -mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

3 σ sensitivity to CP violation for favorable parameters based on

- 20×10^{21} Protons on Target with the upgrade of J-PARC to 1.3MW (~10 year long run) before year 2026.

J-PARC PAC gives Stage 1 approval. We are preparing the Technical Design Report.

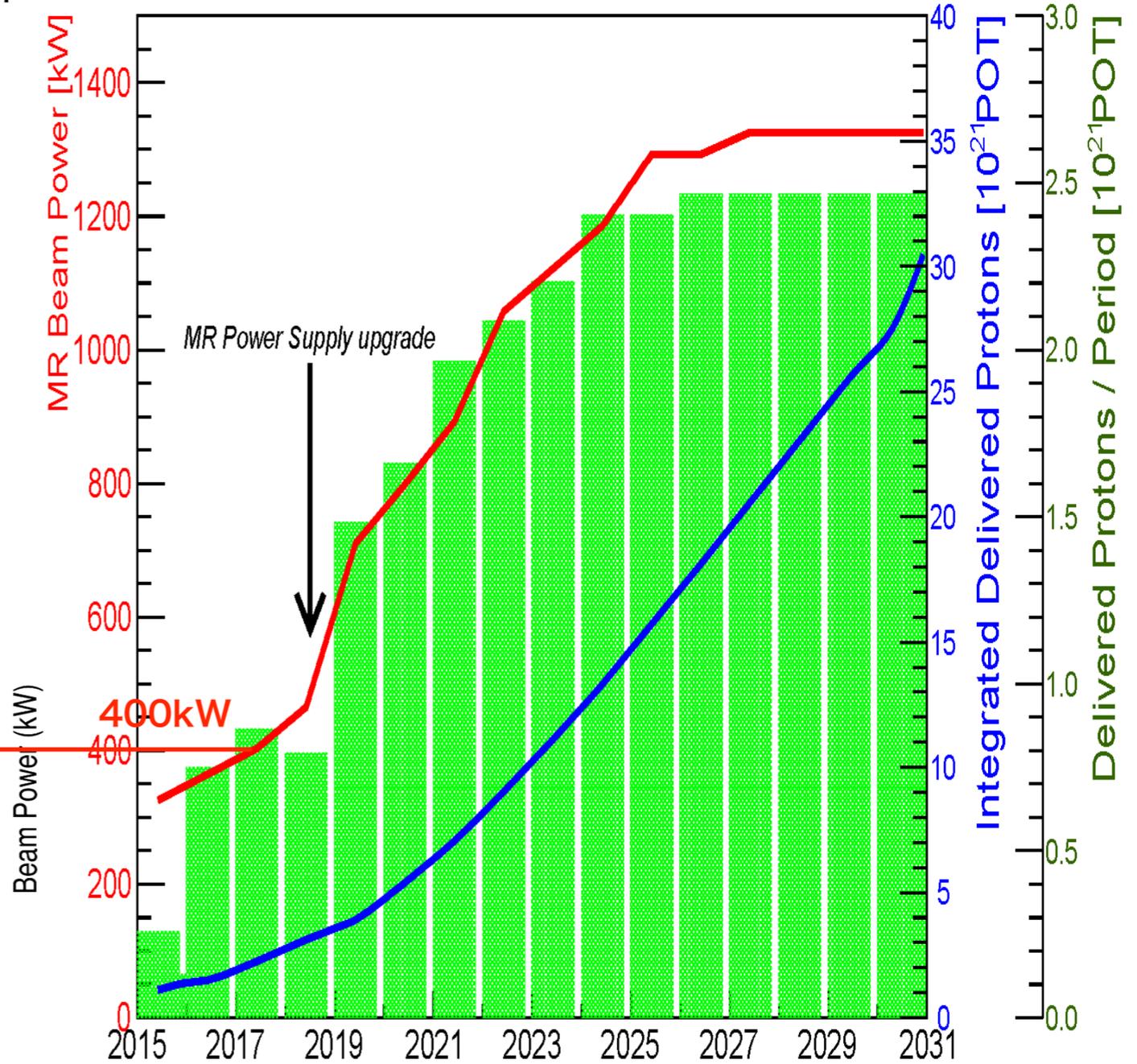
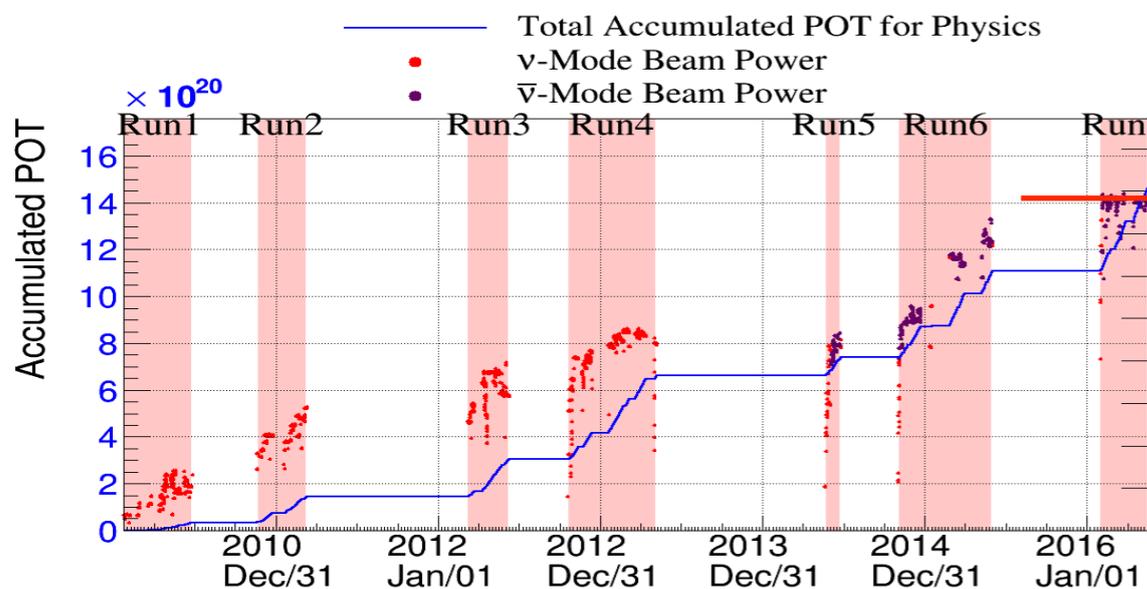


Accelerator Improvement

T2K-II to Hyper-K

- J-PARC MR has achieved **420 kW** operation
- MR Power Supply Upgrade** is scheduled on 2018.
- J-PARC demonstrated **3.41E13 ppb** operation [1 MW equivalent]
- After the upgrade, the aim is **1.3MW or higher**.

Today



T2K

T2K-II

Hyper-K

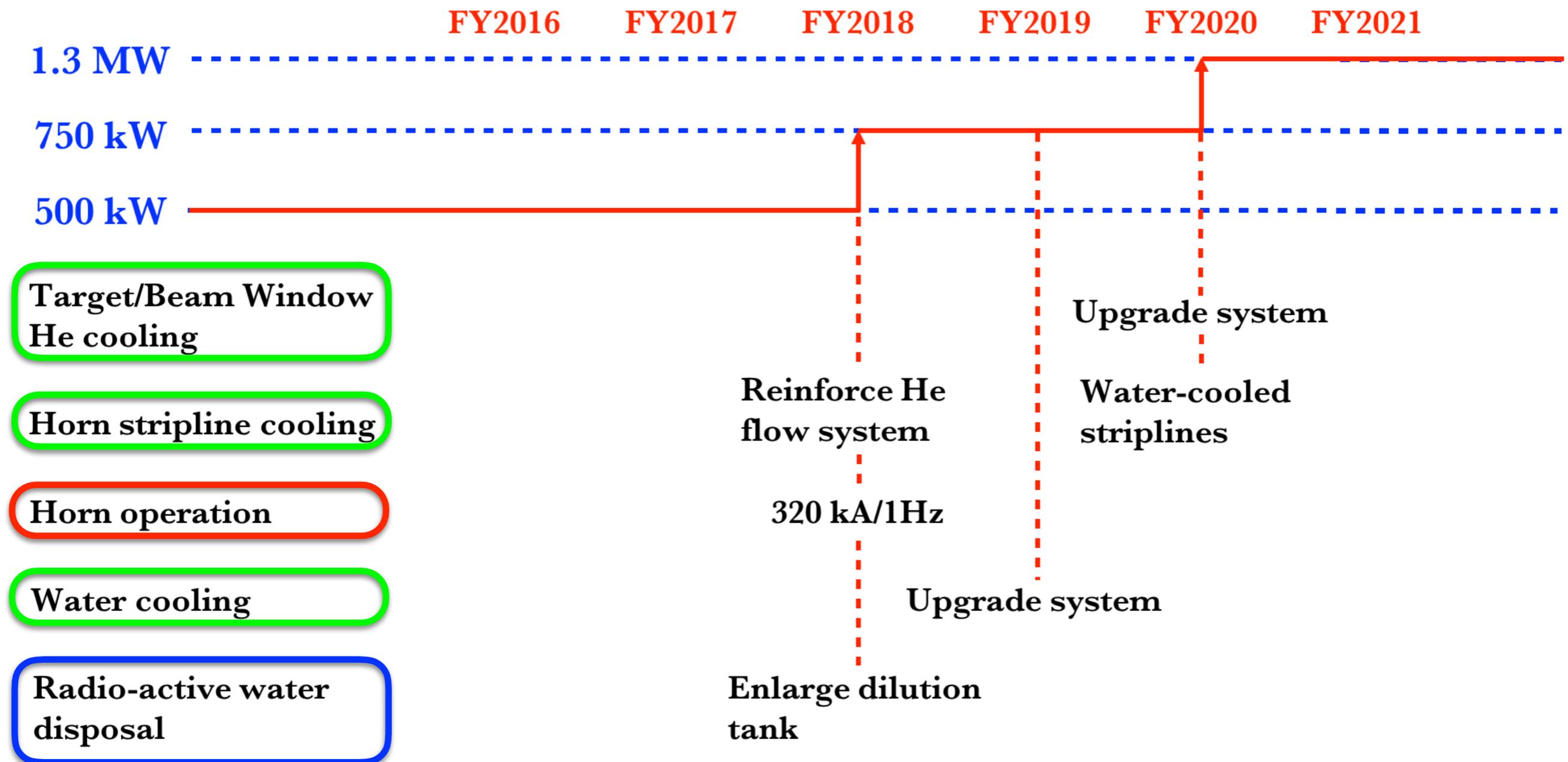
J-PARC Secondary Beamline Upgrades

However, need upgrades to improve cooling capacity, radiation containment, and irradiated cooling water disposal for 1+ MW

Component	Limiting Factor	Current Acceptable Value	Upgraded Acceptable Value
Target	Thermal Shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling Capacity	0.75 MW	>1.5 MW
Horn	Conductor Cooling	2 MW	2 MW
	Stripline Cooling	0.54 MW	>1.25 MW
	Hydrogen Production	1 MW	>1 MW
	Operation	2.48 s & 250 kA	1 s & 320 kA
He Vessel	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Decay Volume	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Beam Dump	Thermal Stress	3 MW	3 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Radiation	Radioactive Air Disposal	1 MW	>1 MW
	Radioactive Water	0.5 MW	0.75 → 1.3 or 2 MW

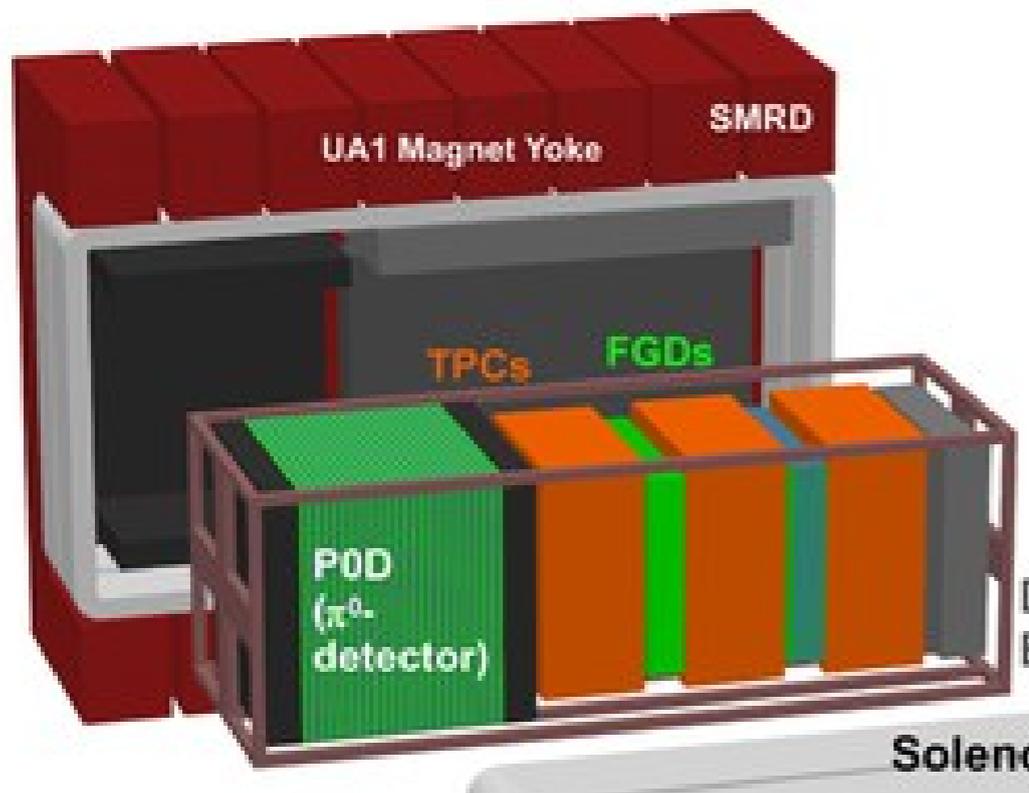
Improvement of Neutrino Flux with Upgrade

- 320kA horn current, Radio-active water disposal, cooling, cooling, and cooling
 - +10% more neutrino flux expected

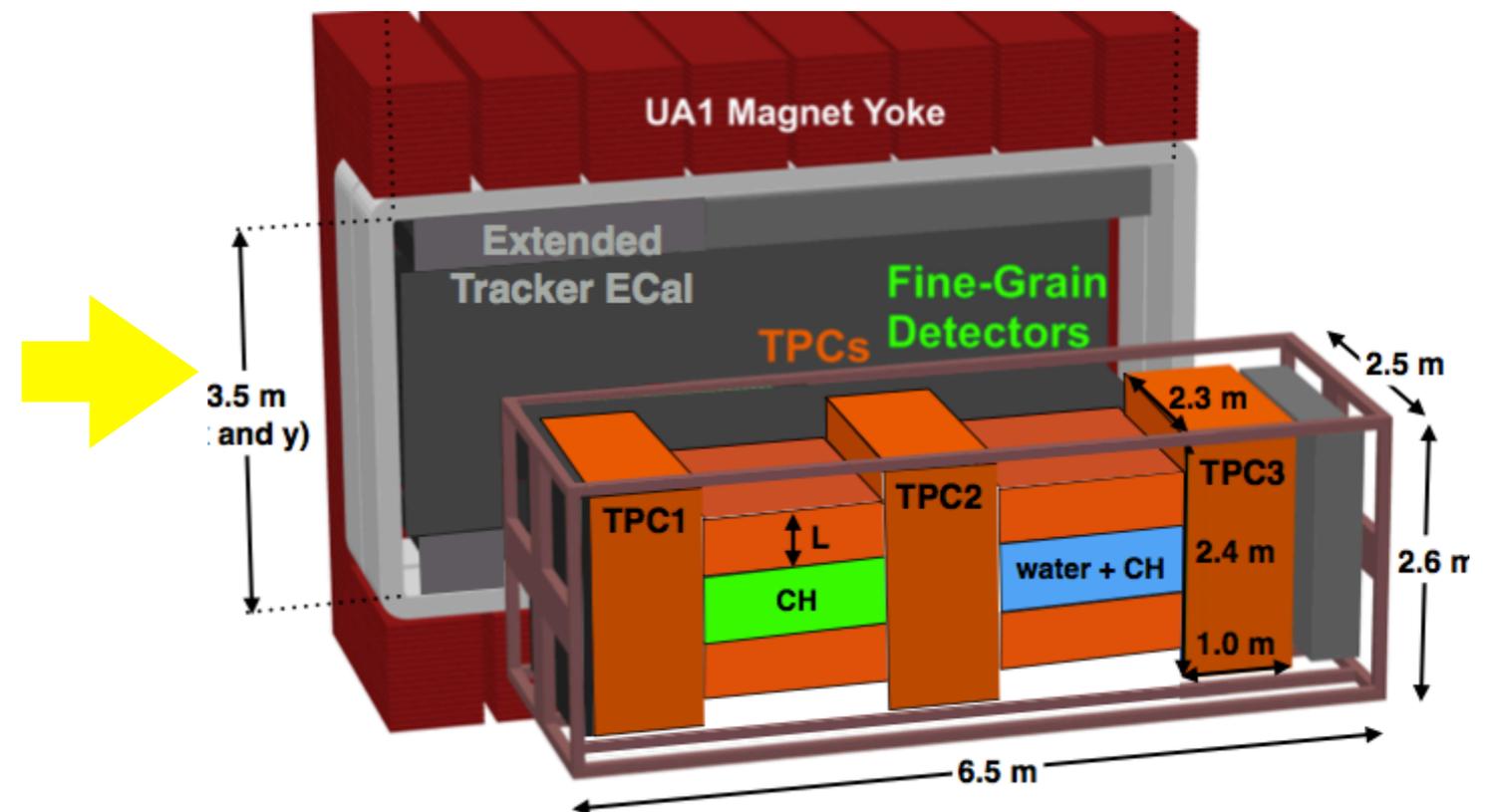


Near Detector Upgrade

ND280 (NOW)



ND280 (Upgrade)



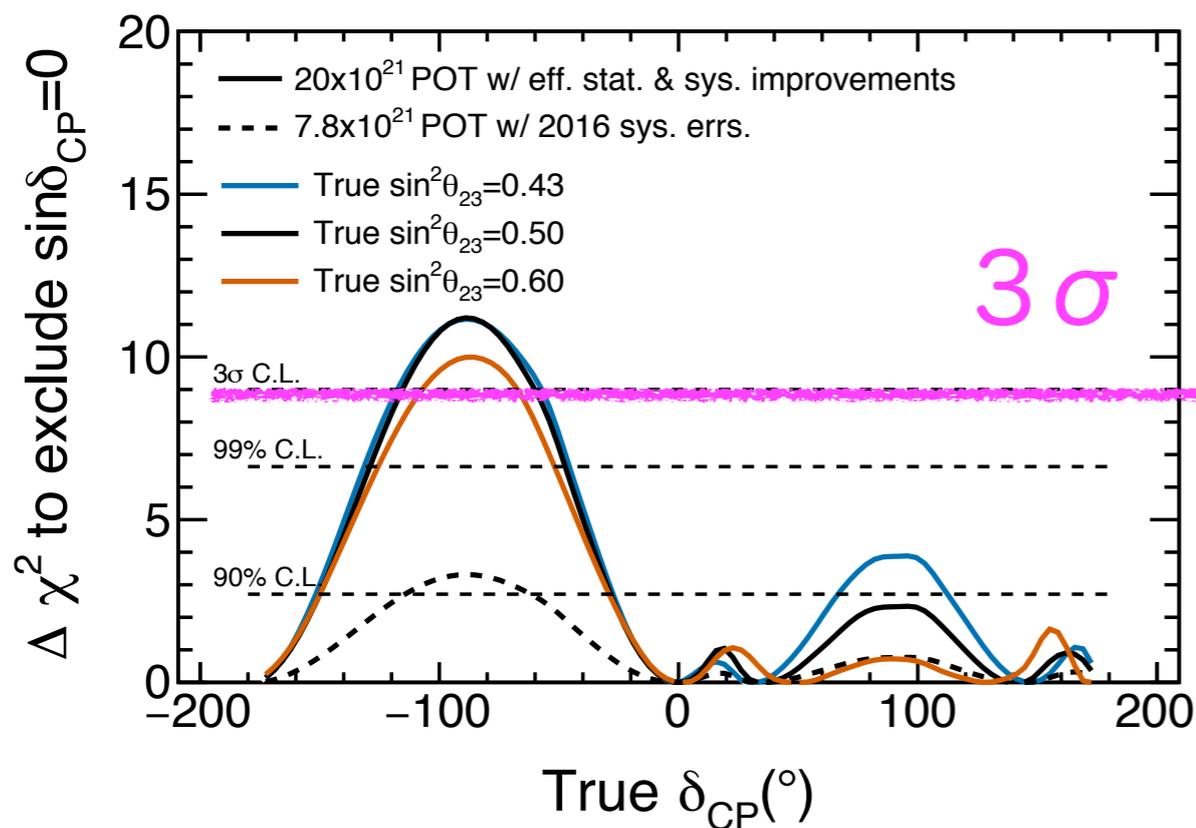
This is just an image, and the details are under discussions in the T2K collaboration.

- T2K steadily improves the systematic uncertainty.
 - **~18% (2011) → ~9% (2014) → ~6% (2016) [→ ~3% (2020)]**
- Understanding of Neutrino Interactions is essential for future experiments (T2K-II and Hyper-K)

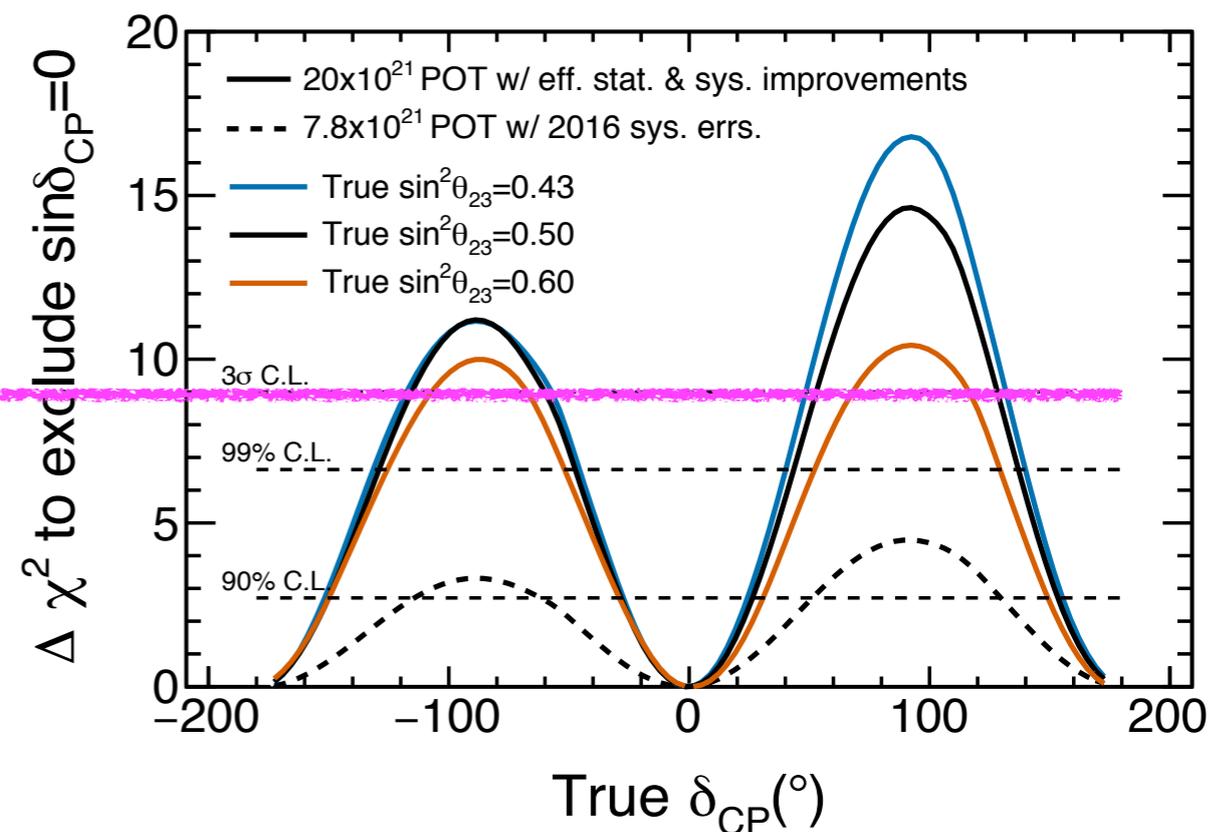
T2K-II Physics Sensitivity

- For which true δ_{CP} values can we find CP violation assuming true $\sin^2 \theta_{23}=0.43$, 0.50, 0.60?
 - The fractional region for which $\sin \delta_{CP}=0$ can be excluded at the 99% (3σ) C.L. is 49% (36%) of possible true values of δ_{CP} assuming the MH is known.

assuming MH unknown



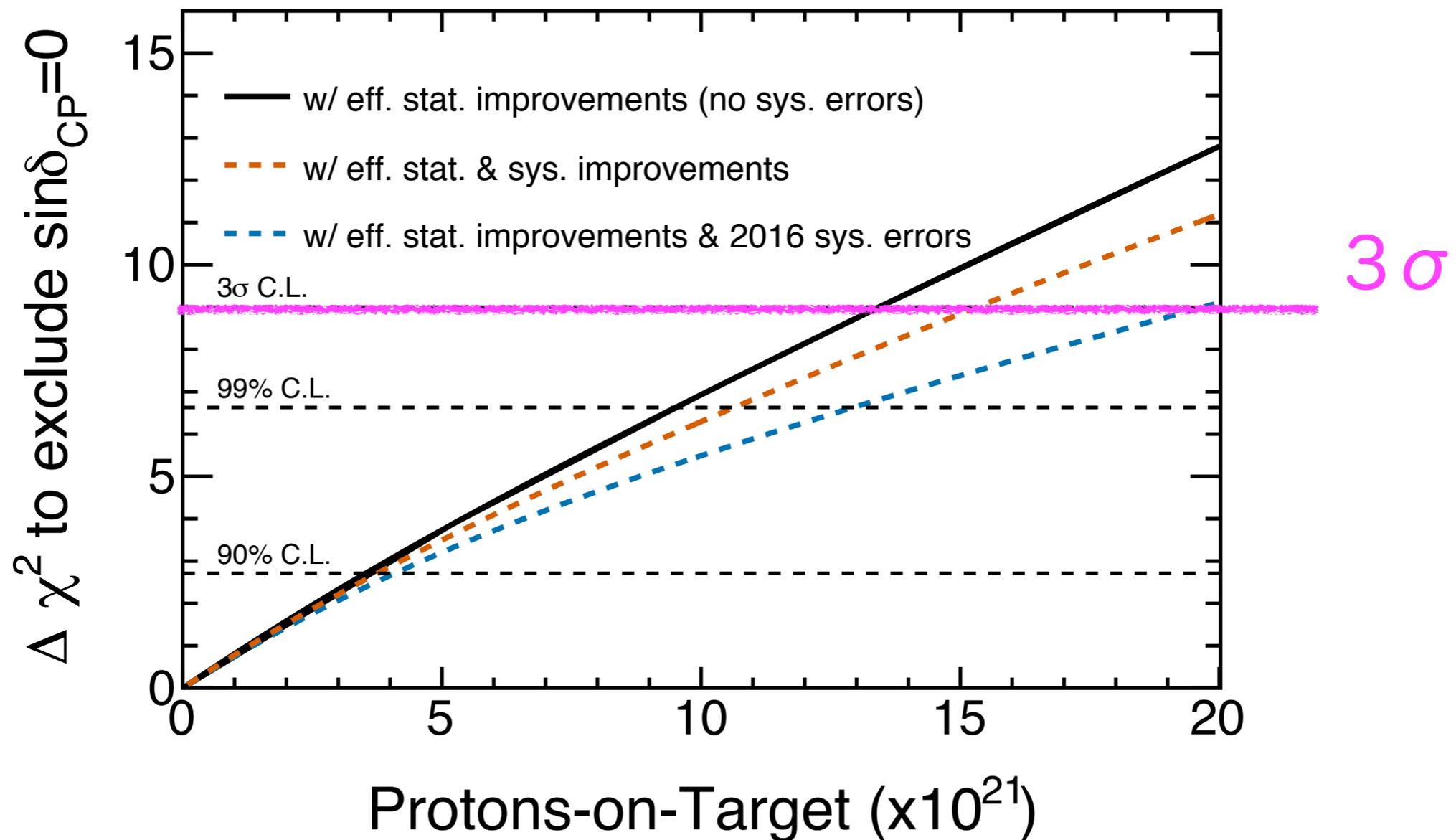
assuming MH known



(Note) Although T2K alone can't measure MH, we can help with the MH measurement by, ie, combining T2K + NOVA

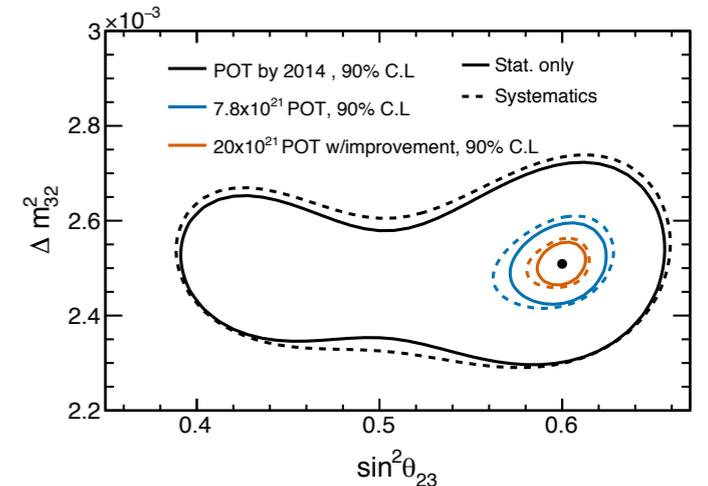
T2K-II Physics Sensitivity

- As a function of POT in the case of $\sin^2 \theta_{23}=0.5$, $\delta_{CP}=-\pi/2$ and normal MH

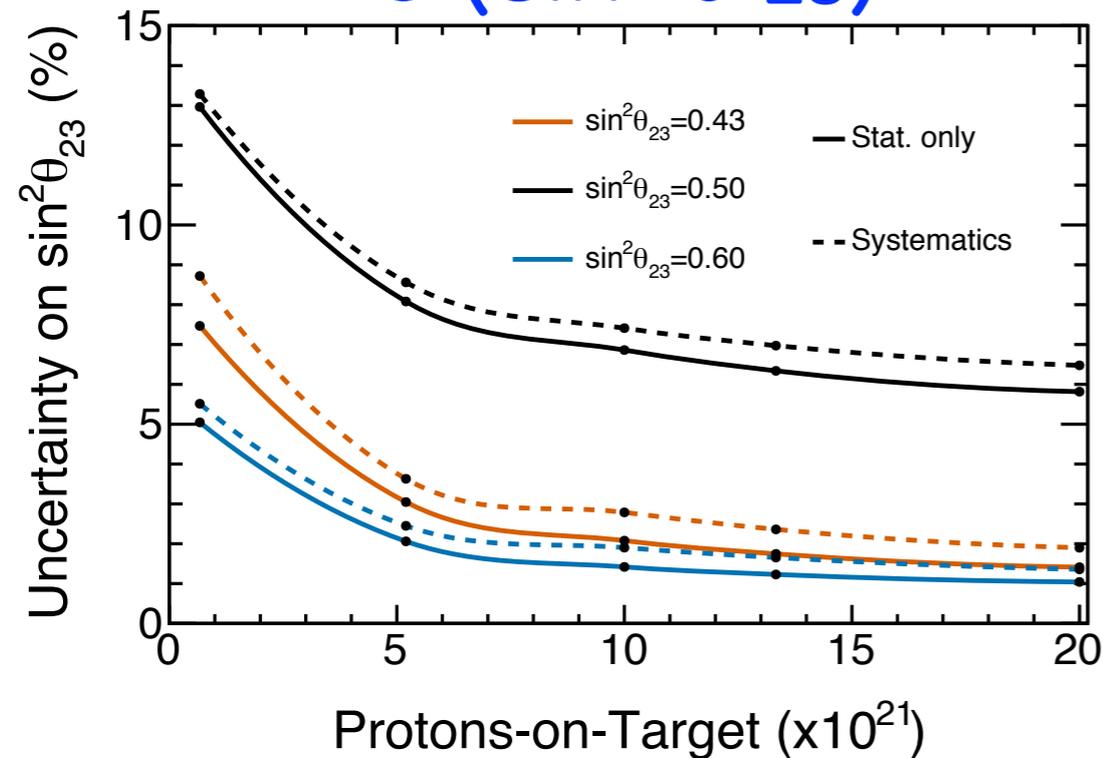


T2K-II Physics Sensitivity

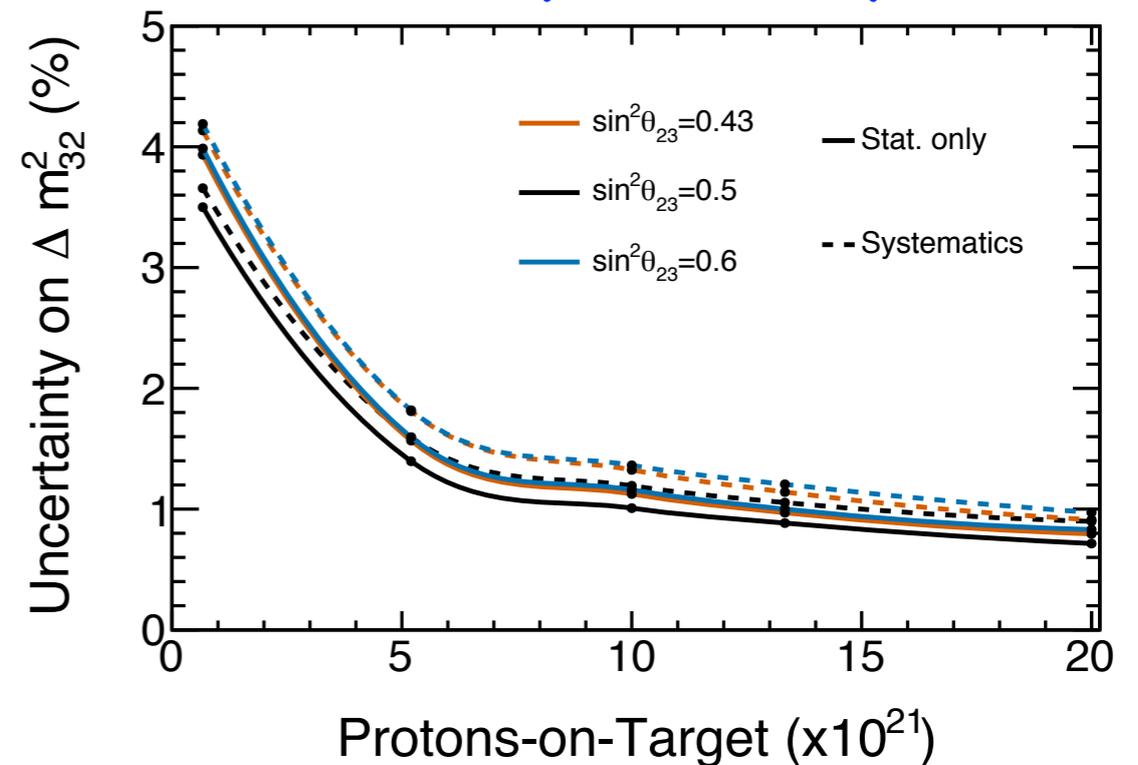
- Precisions of $\sin^2 \theta_{23}$ and Δm_{32}^2



$\delta(\sin^2 \theta_{23})$



$\delta(\Delta m_{32}^2)$



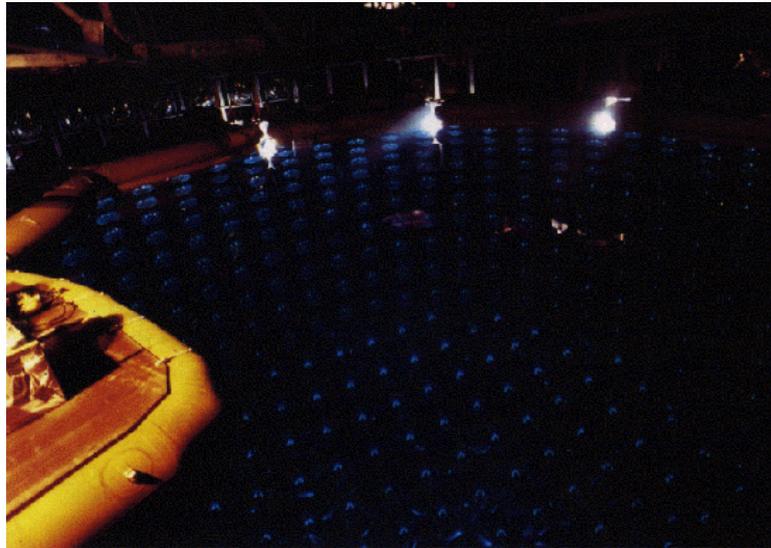
- More physics for Neutrino Interactions and non-standard models

Hyper-Kamiokande

Kamiokande family

Kamiokande (1983-1996)

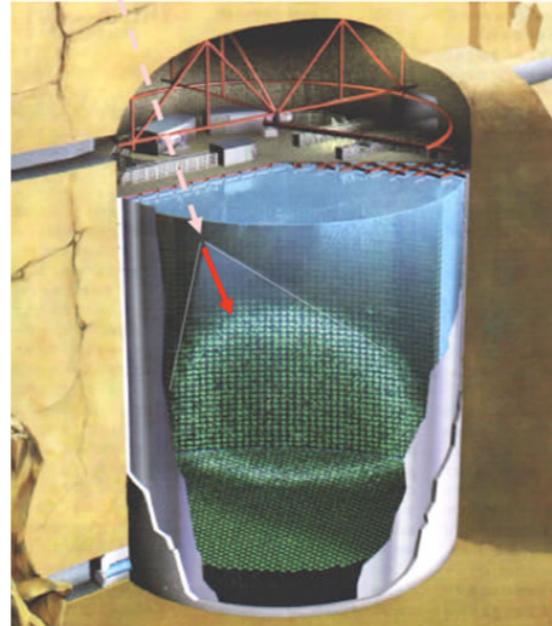
3000 ton



- Neutrinos from SN1987a.
- Atmospheric neutrino deficit.
- Solar neutrinos.

Super-Kamiokande (1996-)

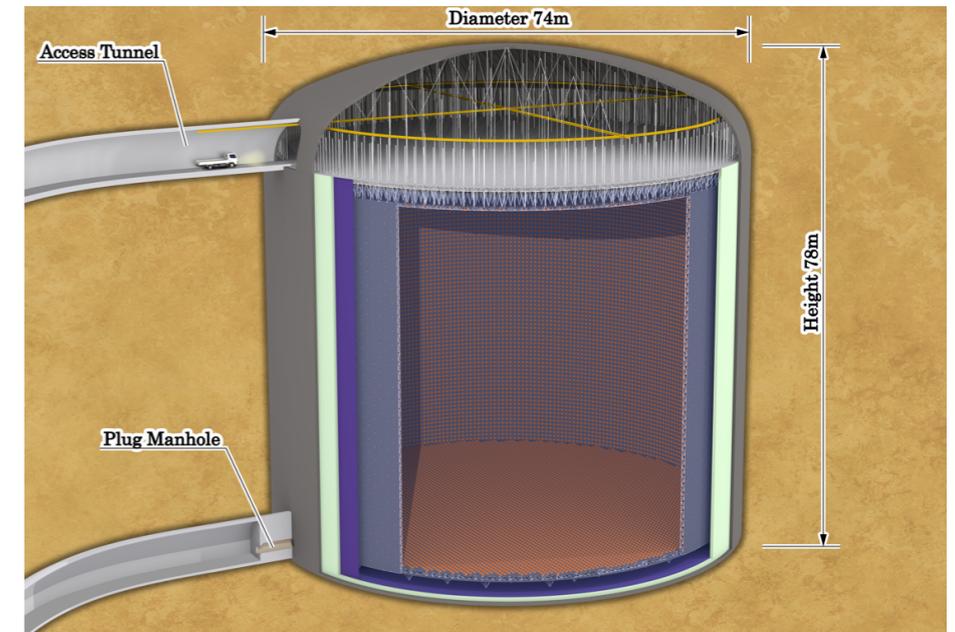
50,000 ton



- Atmospheric neutrino oscillation.
- Solar neutrino oscillation with SNO.
- Far detector for KEK-PS (K2K) and J-PARC beam (T2K): electron neutrino appearance.
- World leading limit on proton lifetime $> 10^{34}$ years.

Hyper-Kamiokande ($\sim 2026-$)

$2 \times 260,000$ ton



Physics programme:

- Neutrino oscillations: Mass Hierarchy, Leptonic CP violation, θ_{23} Octant, ...
- Nucleon decay: $p \rightarrow e^+ \pi^0$, $p \rightarrow K^+ \bar{\nu}$, ...
- Neutrino astrophysics: Solar neutrinos, Supernova neutrinos, WIMP searches

Hyper-Kamiokande (New Design)

<http://www.hyperk.org>



The screenshot shows the Hyper-Kamiokande website. At the top, there is a navigation bar with links for Home, For the Public, For Scientists, For Collaborators, and Hyper-K Wiki. Below this is a large banner image of the detector tanks with the text "Hyper-Kamiokande" and "A gigantic detector to confront elementary particle unification theories and the mysteries of the Universe's evolution". A navigation menu below the banner includes DETECTOR, PHYSICS, PRESENTATIONS, ARTICLES, and COLLABORATION. A search bar is also present. The main content area features a "HYPER KAMIOKANDE PUBLIC DESIGN REPORT RELEASED" announcement, dated October 6, 2016, and a "RECENT NEWS" section with three items: "Hyper Kamiokande Public Design Report Released October 6, 2016", "The Hyper-Kamiokande Advisory Committee Report July 22, 2016", and "7th Open Meeting for the Hyper-Kamiokande Project July 1, 2016".

One tank

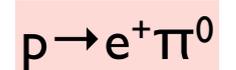
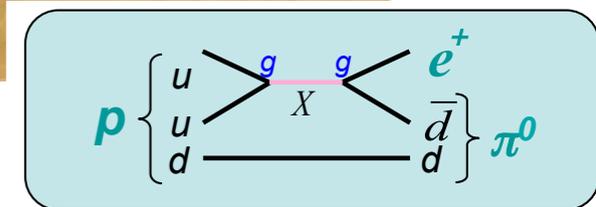
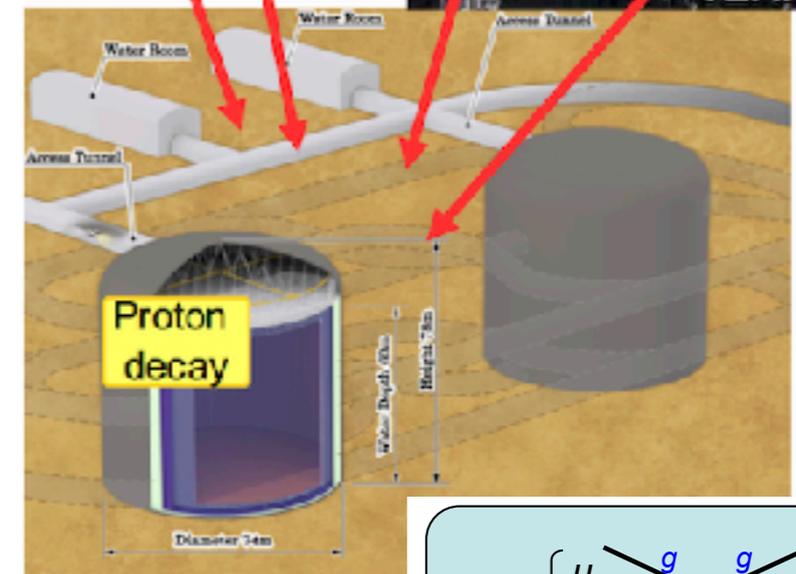
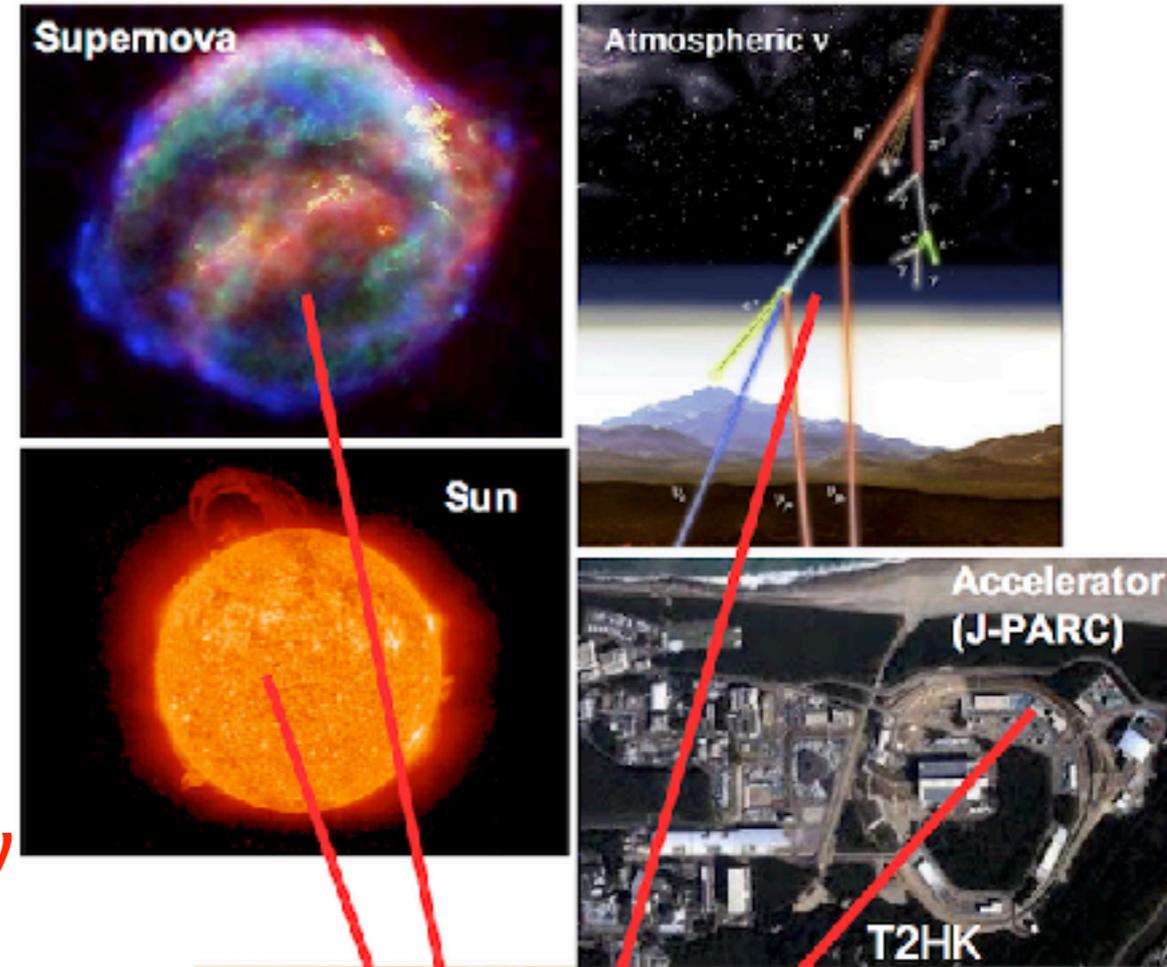
- ▶ 60m (high) × 74m (diameter)
- ▶ Total Volume: 260 kton.
- ▶ Fiducial Volume: 190 kton (~ 10× Super-K).
- ▶ 40% PMT coverage.
- ▶ 40,000 50cm ID PMTs, 6,700 20cm OD PMTs.

- Cost saving and quick start with one tank first
- Improving the performance
 - A new PMT has x2 better Photon sensitivity
- A new design was reviewed by the international advisory committee, and endorsed.

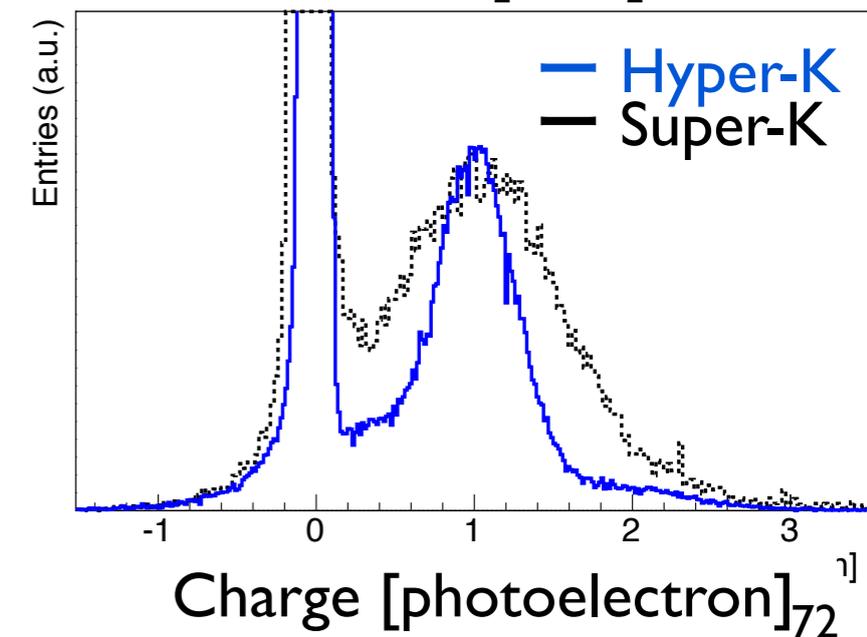
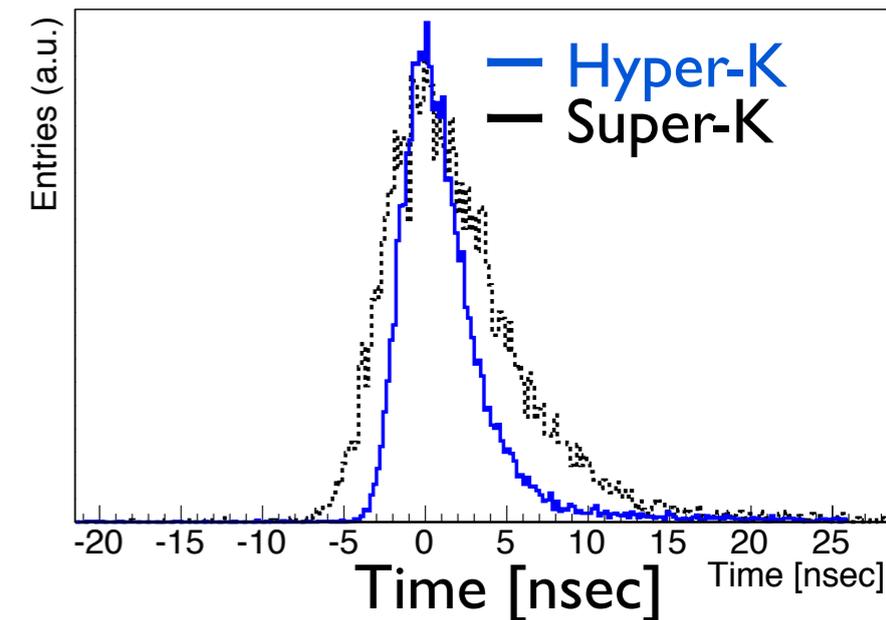
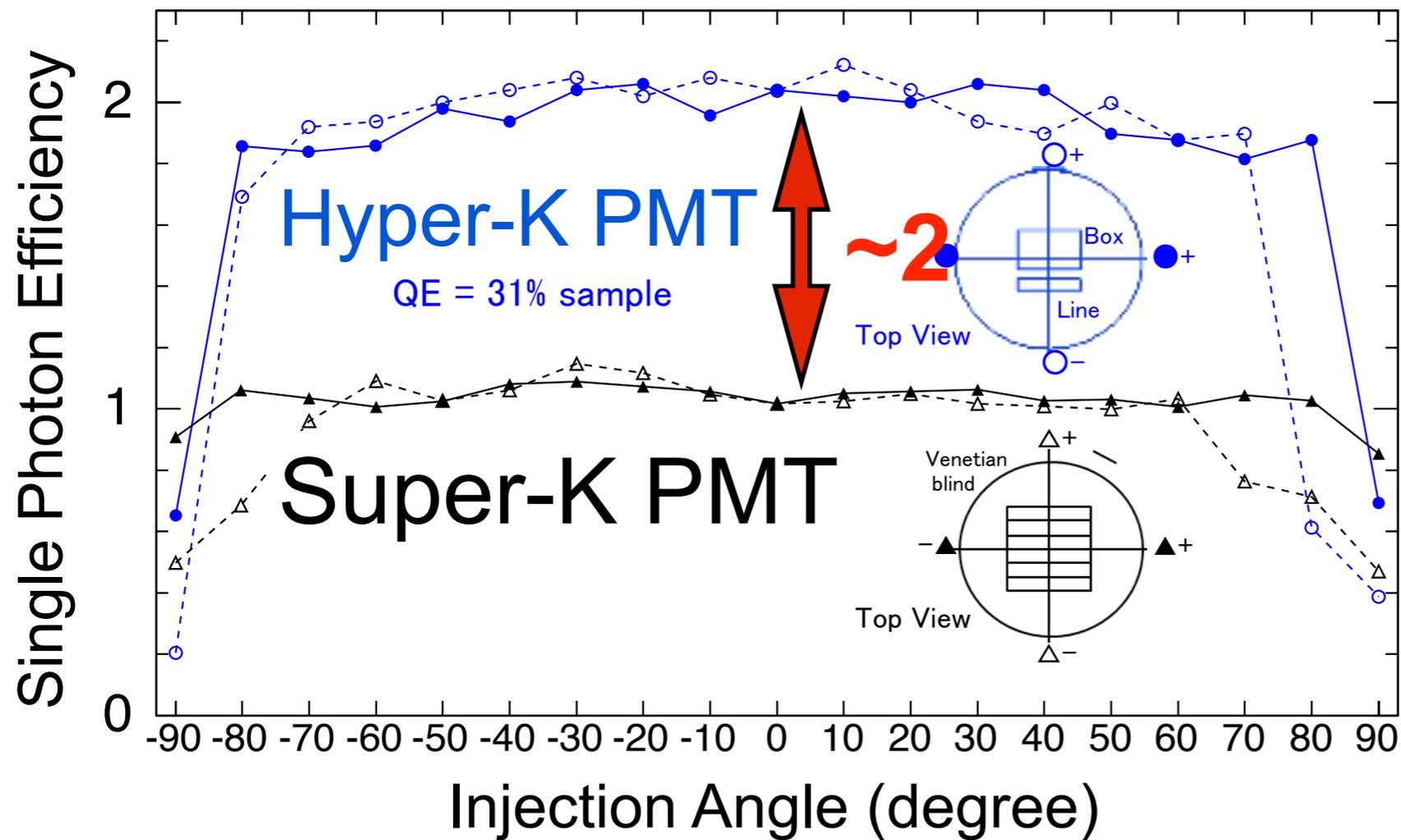


Broad science program with Hyper-K

- Neutrino oscillation physics
 - Comprehensive study with beam and atmospheric neutrinos
- Search for nucleon decay
 - Possible discovery with $\sim \times 10$ better sensitivity than Super-K
- Neutrino astrophysics
 - Precision measurements of solar ν
 - High statistics measurements of SN burst ν
 - Detection and study of relic SN neutrinos
- Geophysics (neutrinoigraphy of interior of the Earth)
- Maybe more (unexpected)



Hyper-K New Technology



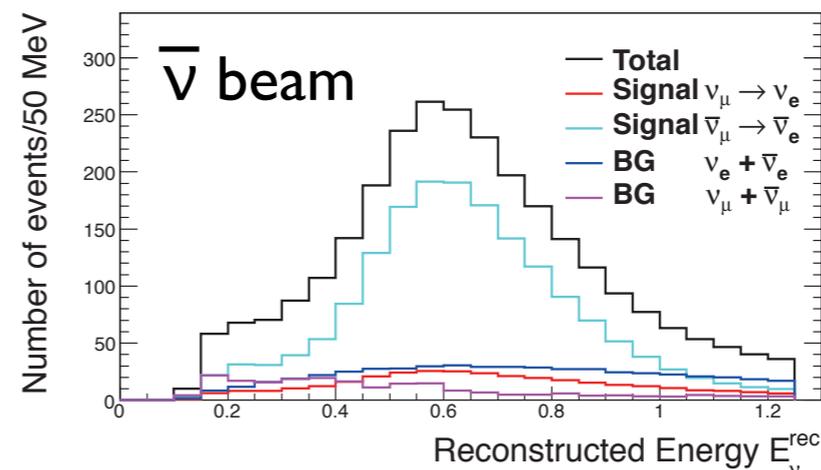
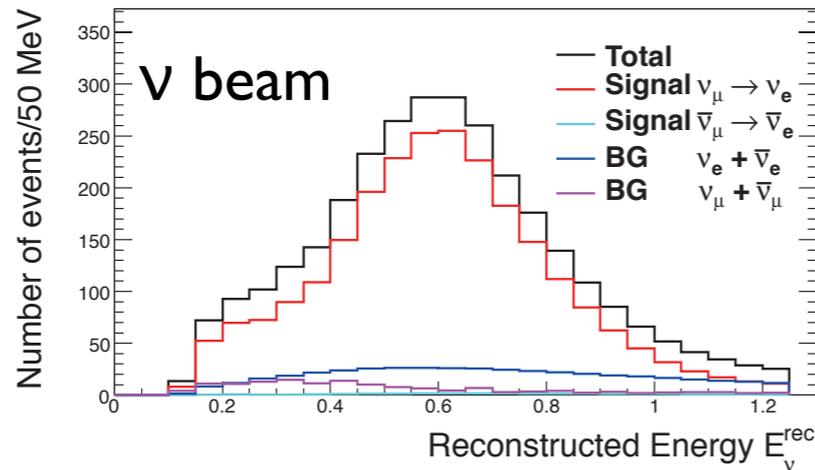
- Single Photon Efficiency: **x2**
- Time Resolution: **x2**
- Charge Resolution: **x2**
- Better Physics Sensitivity with the improved detector performance

Expected events

1.3MW, 10×10^7 sec, $\nu:\bar{\nu}=1.3$

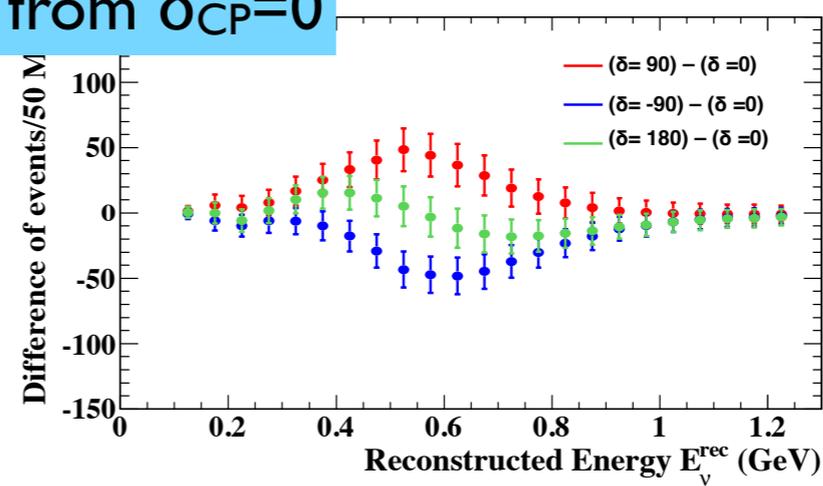
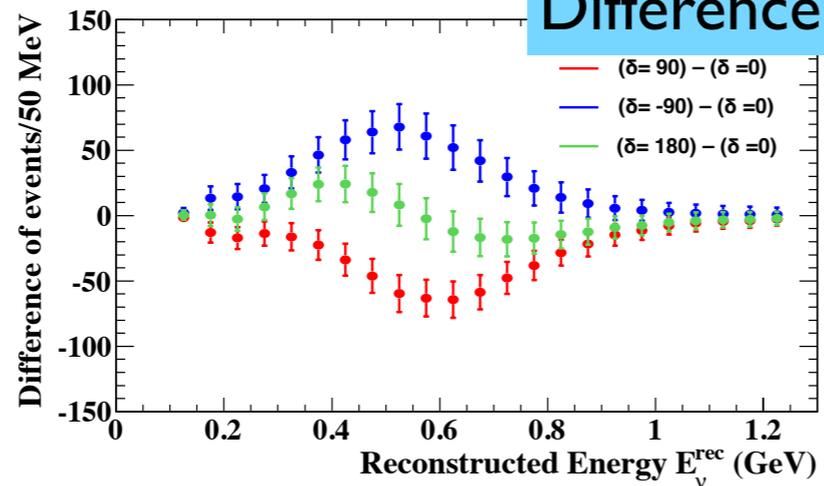
ν_e candidates

Using fiTQun for π^0 rejection



for $\delta=0$	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 beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

Difference from $\delta_{CP}=0$

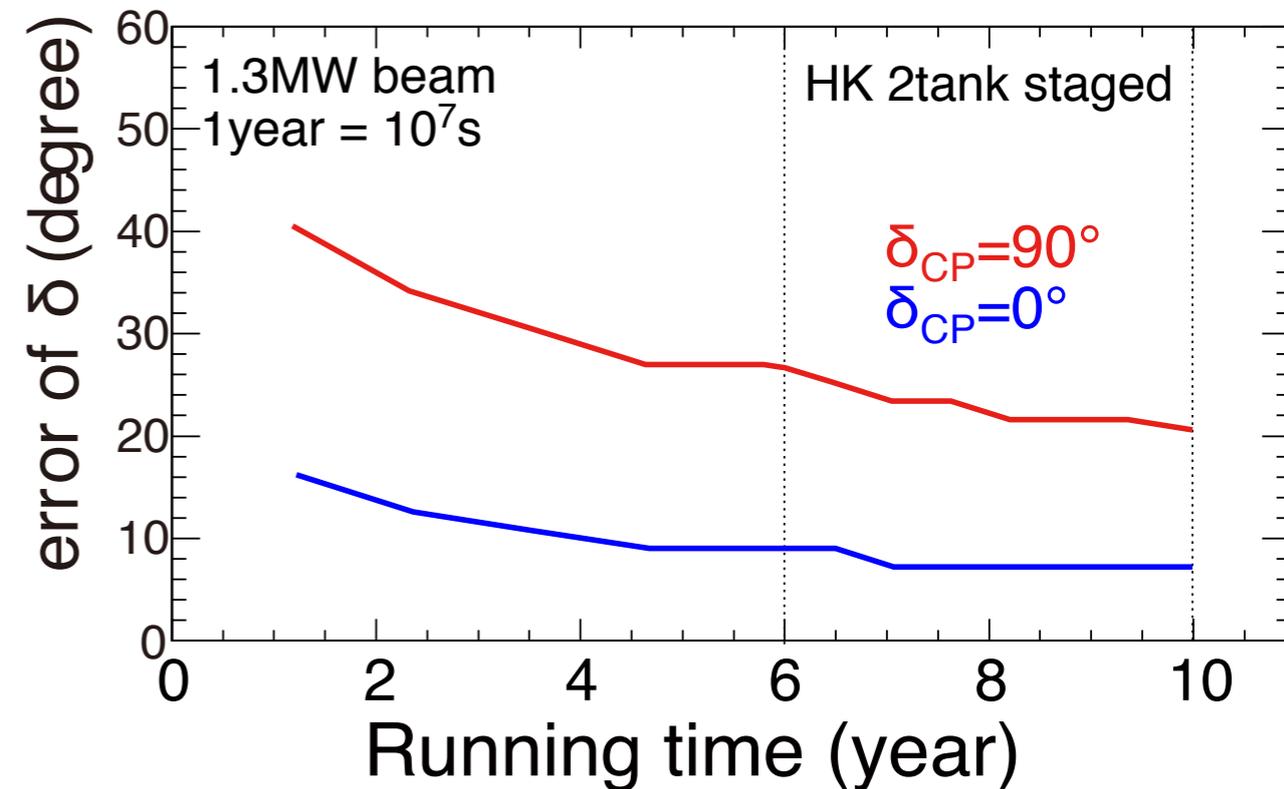
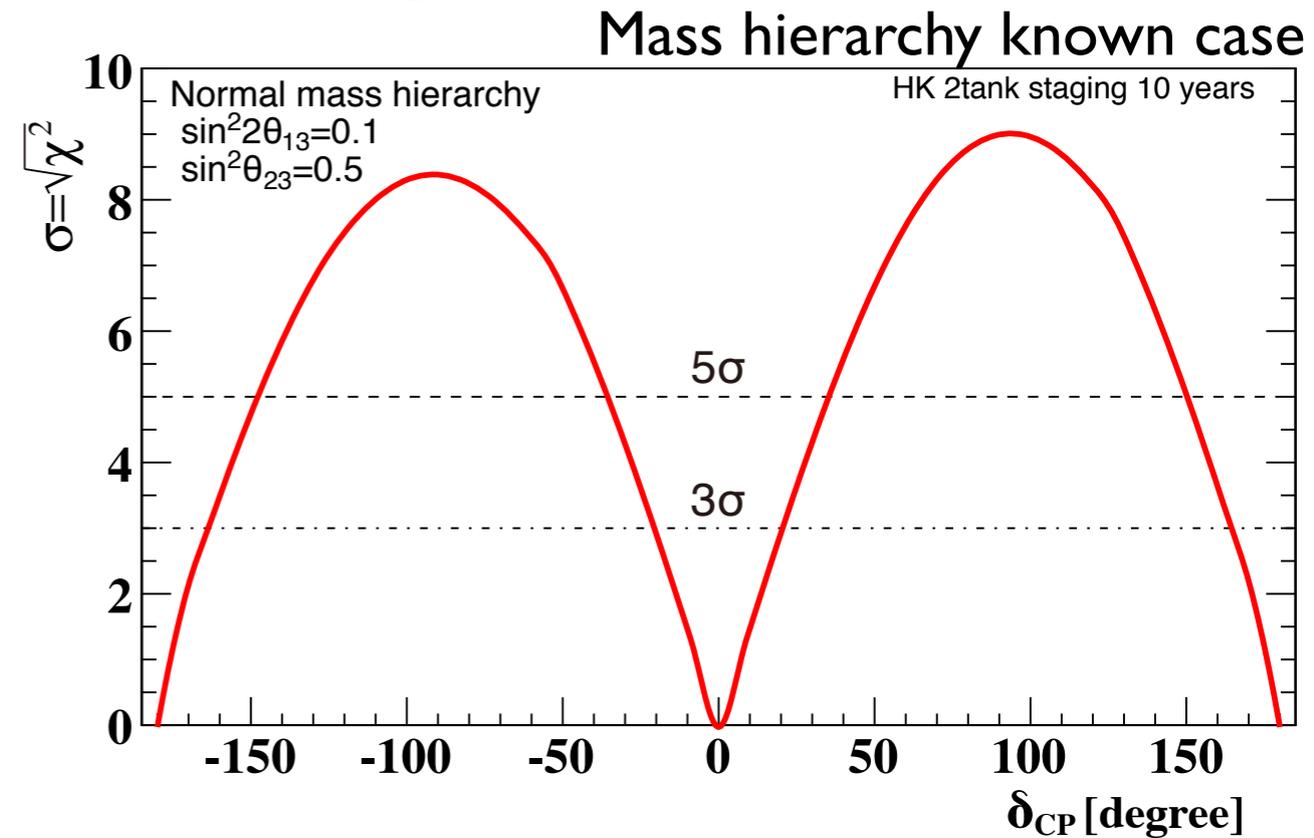


$\delta=0$ and 180° can be distinguished using shape information

CPV sensitivity

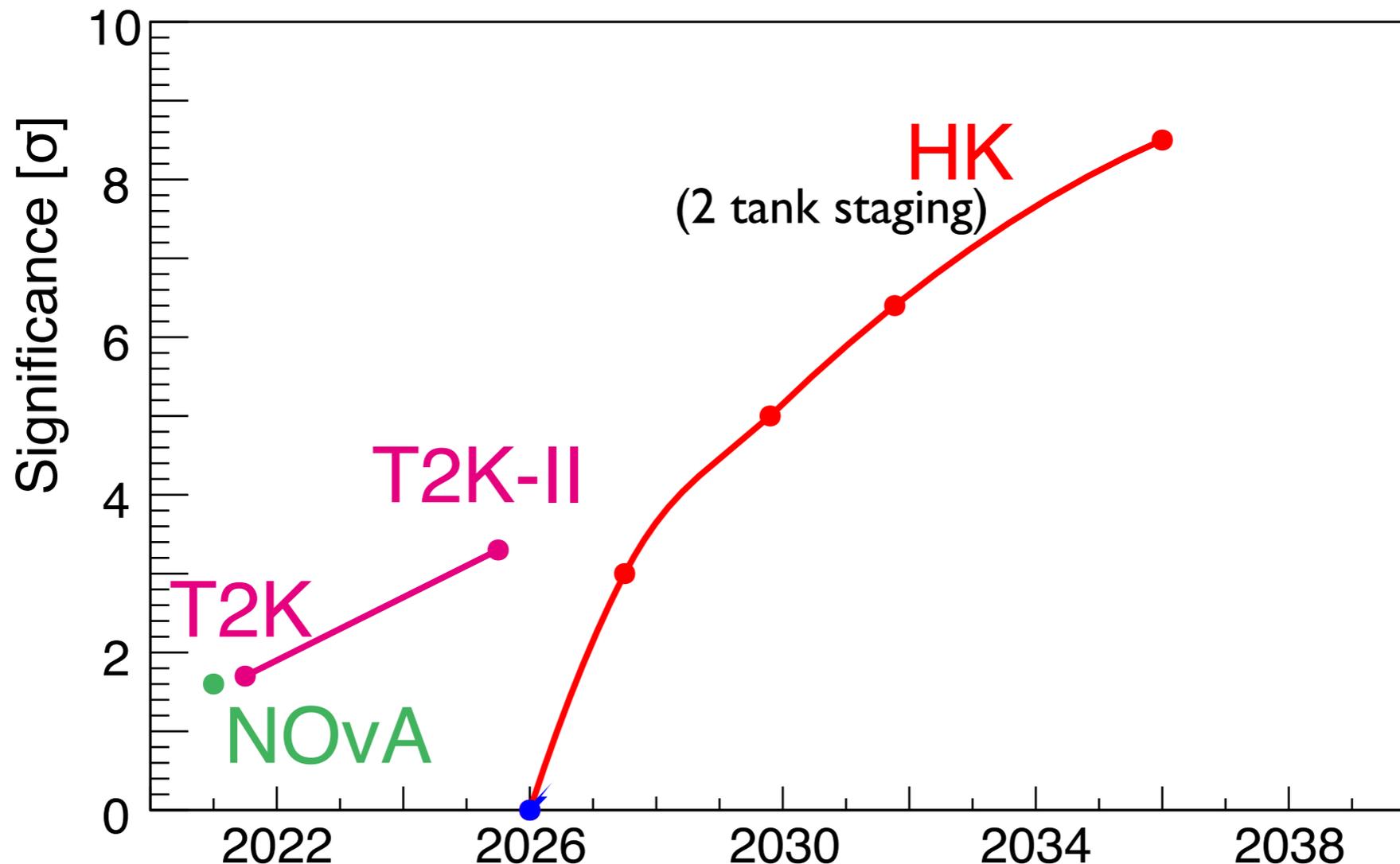
- Exclusion of $\sin\delta_{CP}=0$
 - $>8\sigma$ (6σ) for $\delta=-90^\circ$ (-45°)
 - $\sim 80\%$ coverage of δ parameter space with $>3\sigma$
- From discovery to δ_{CP} measurement:
 - $\sim 7^\circ$ precision possible

sin $\delta=0$ exclusion		error	
$>3\sigma$	$>5\sigma$	$\delta=0^\circ$	$\delta=90^\circ$
78%	62%	7.2°	21°



Towards leptonic CP asymmetry

CPV significance for $\delta=-90^\circ$, normal hierarchy



Strategy of Japan-based program

~3σ evidence with T2K → T2K-II,

>5σ discovery and measurement with HK

Note: “exact” comparison sometimes difficult due to different assumptions

θ_{23} and Δm^2_{32}

$$\delta(\Delta m^2_{32}) \sim 1.4 \times 10^{-5} \text{eV}^2$$

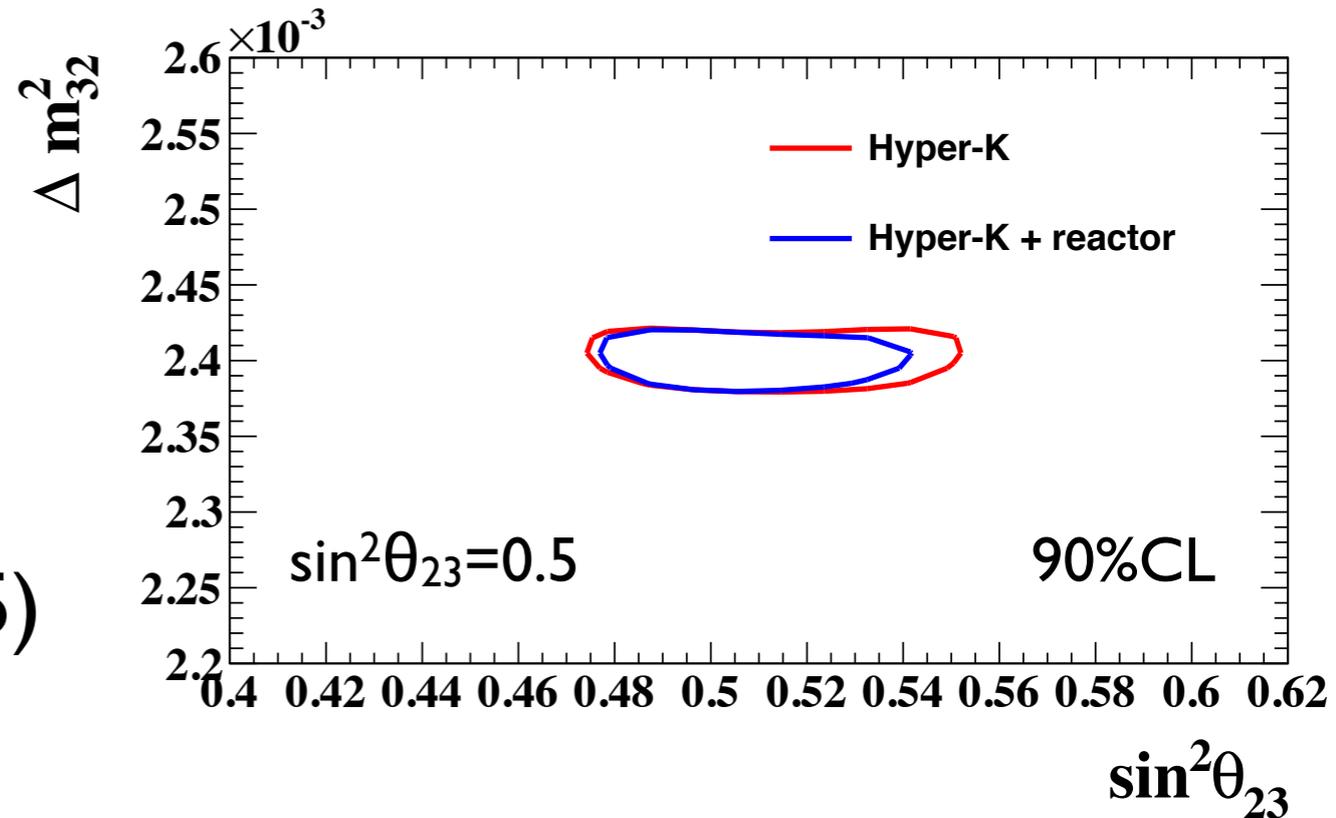
→ Mass hierarchy sensitivity
in combination with reactor

$$\delta(\sin^2 \theta_{23}) \sim 0.015 \text{ (for } \sin^2 \theta_{23} = 0.5)$$

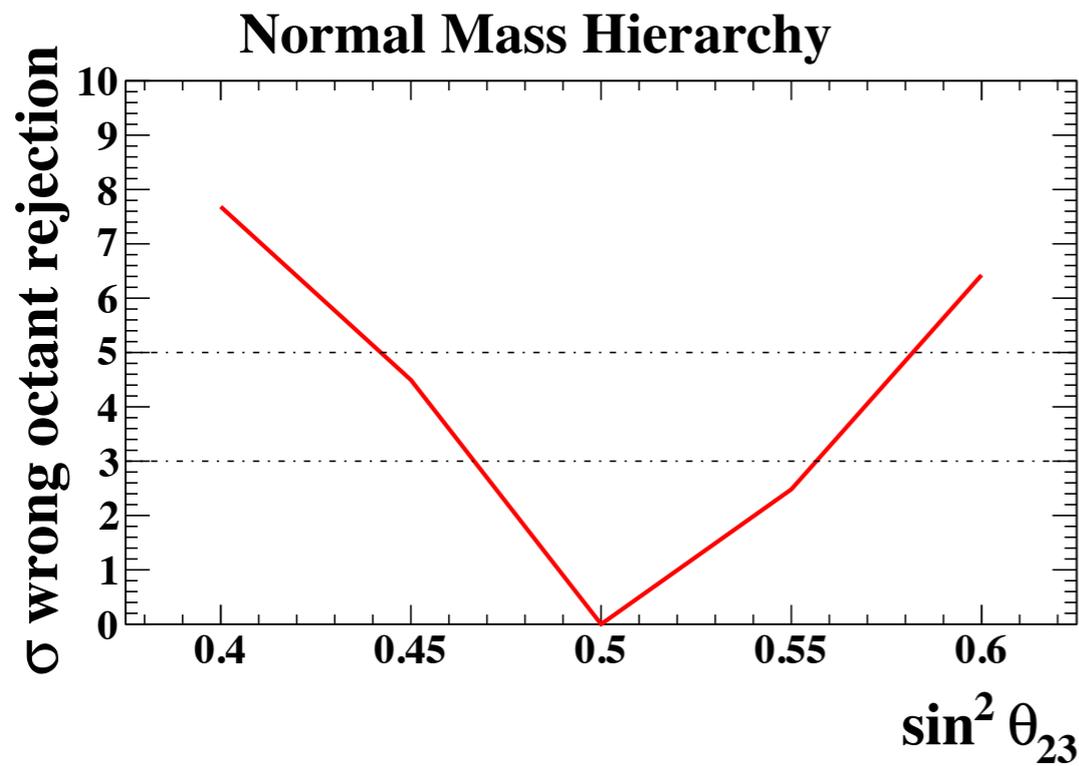
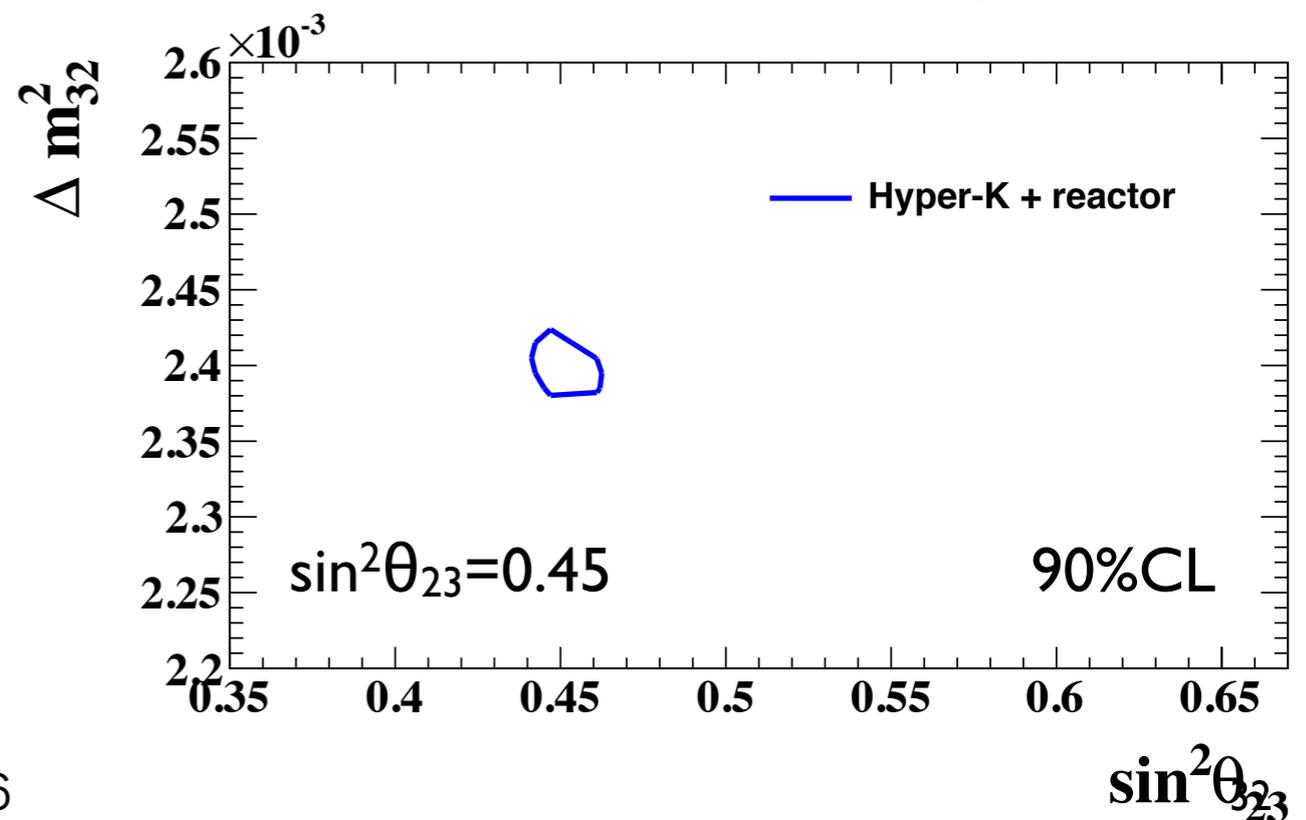
$$\sim 0.006 \text{ (for } \sin^2 \theta_{23} = 0.45)$$

→ Octant determination,
input to models

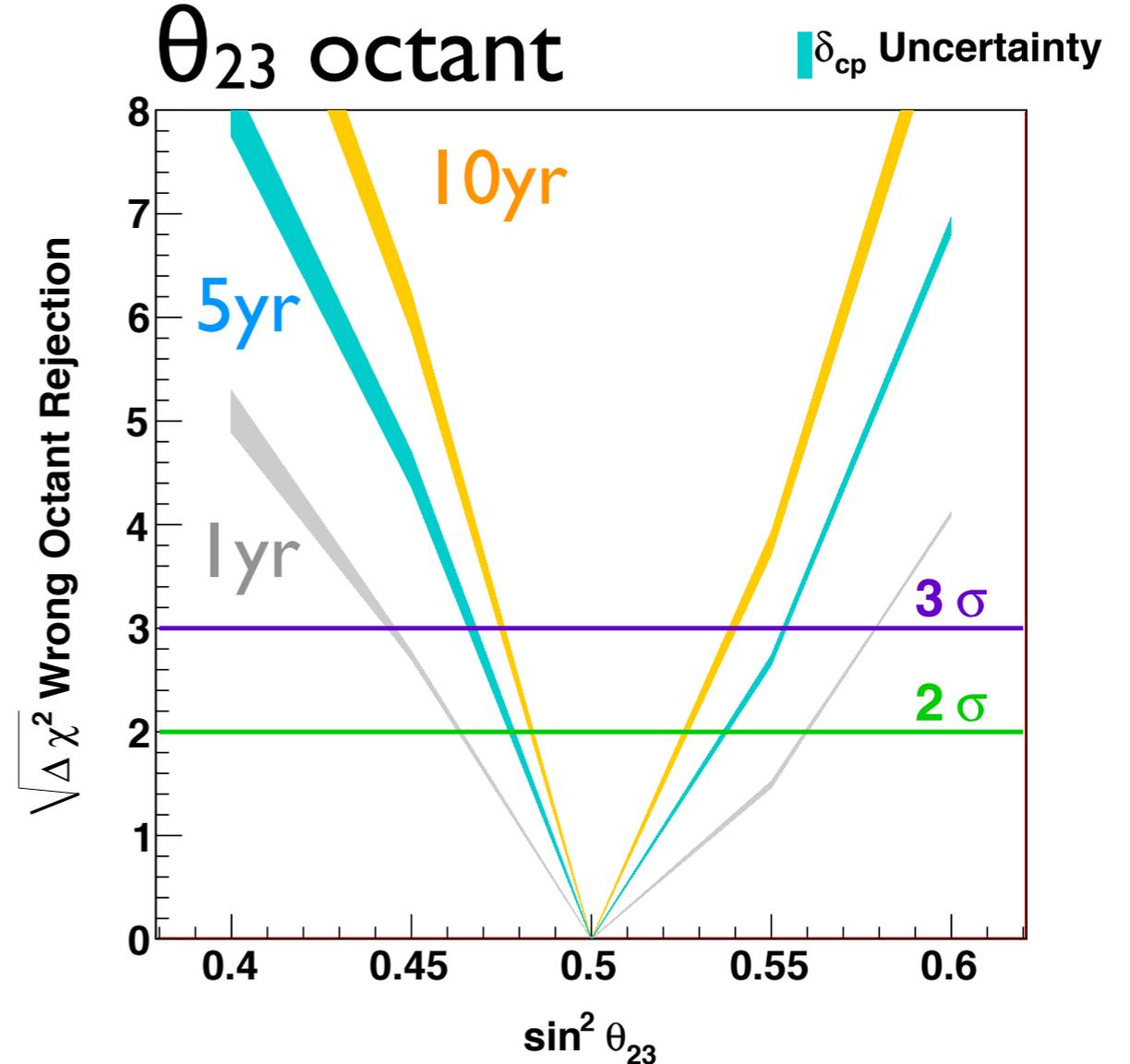
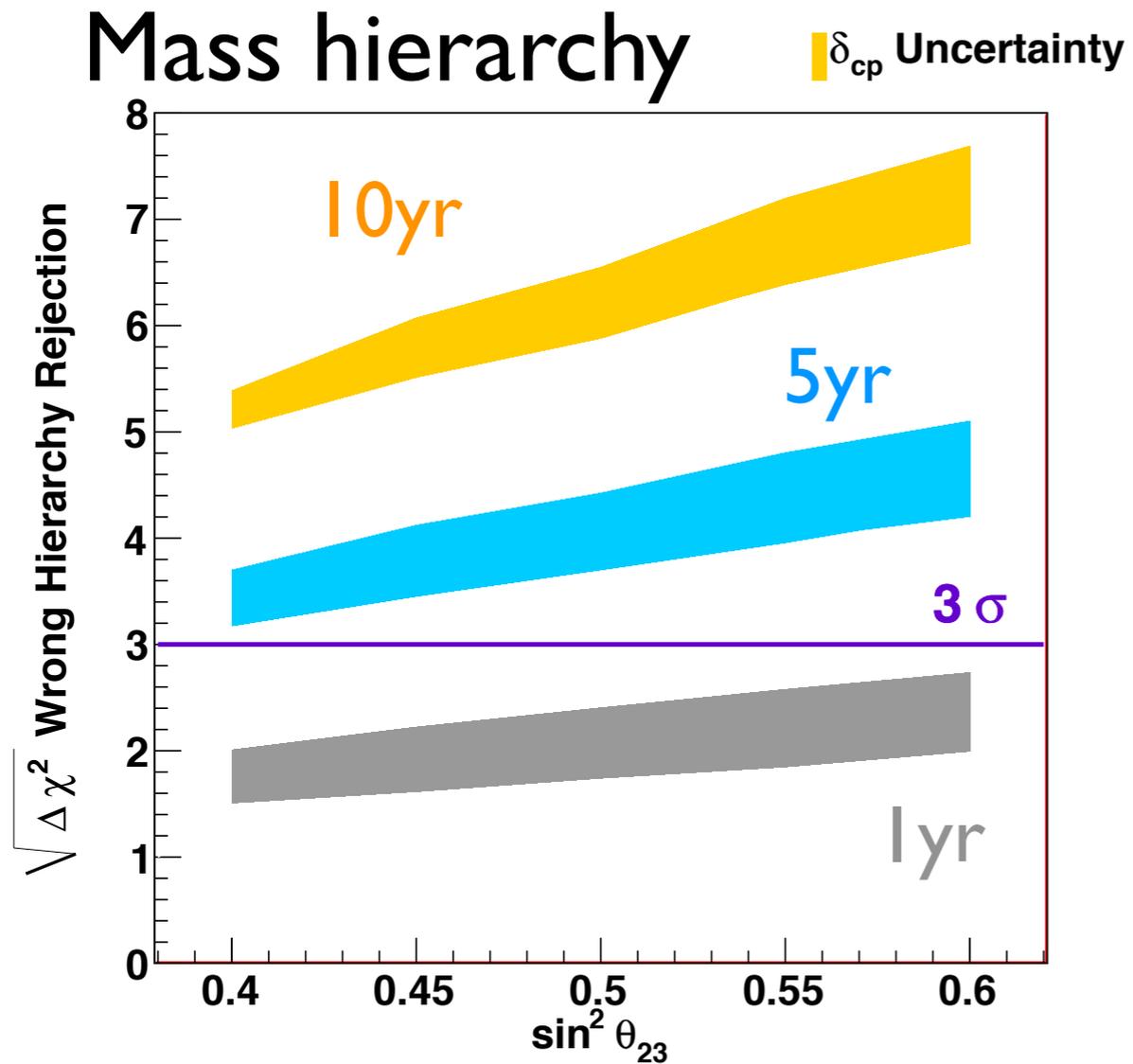
Normal mass hierarchy



Normal mass hierarchy



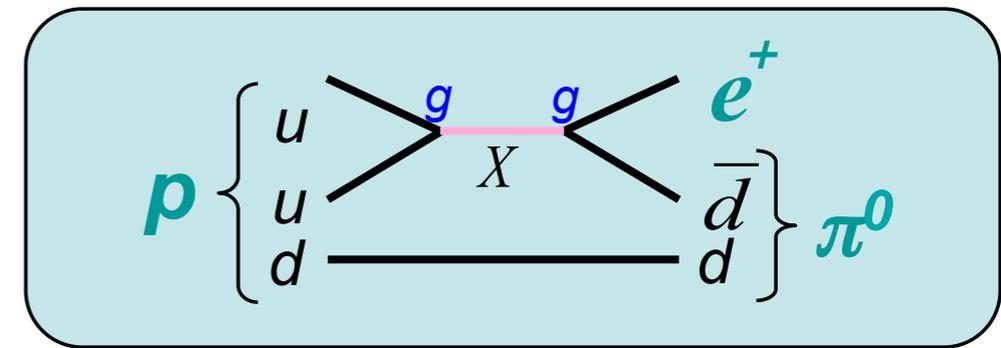
Beam + Atm ν combination



- Complementary information from beam and atm ν
- Sensitivity enhanced by combining two sources!

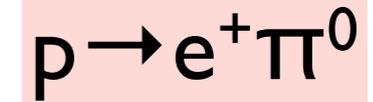
Proton Decay

Mediated by gauge bosons



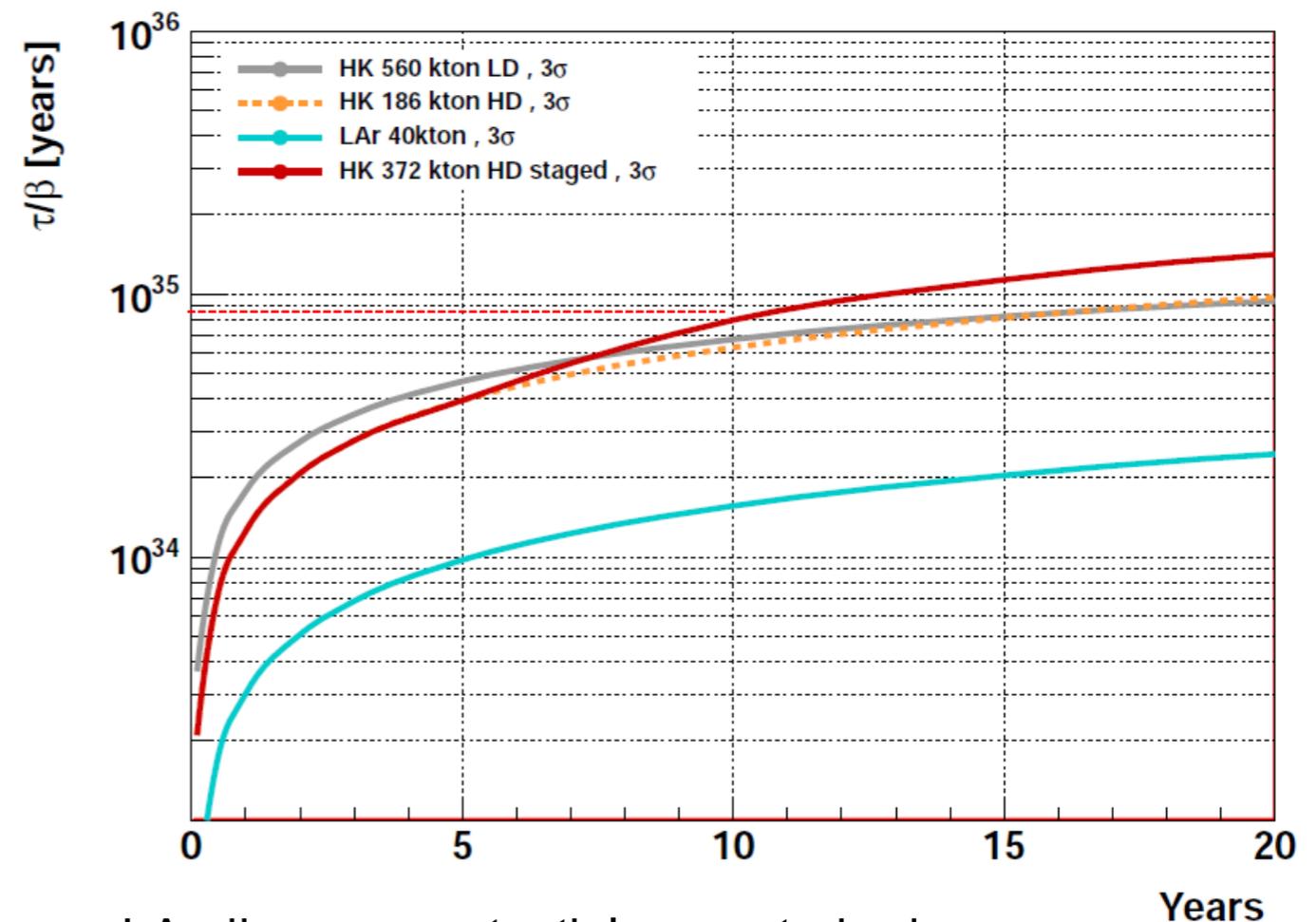
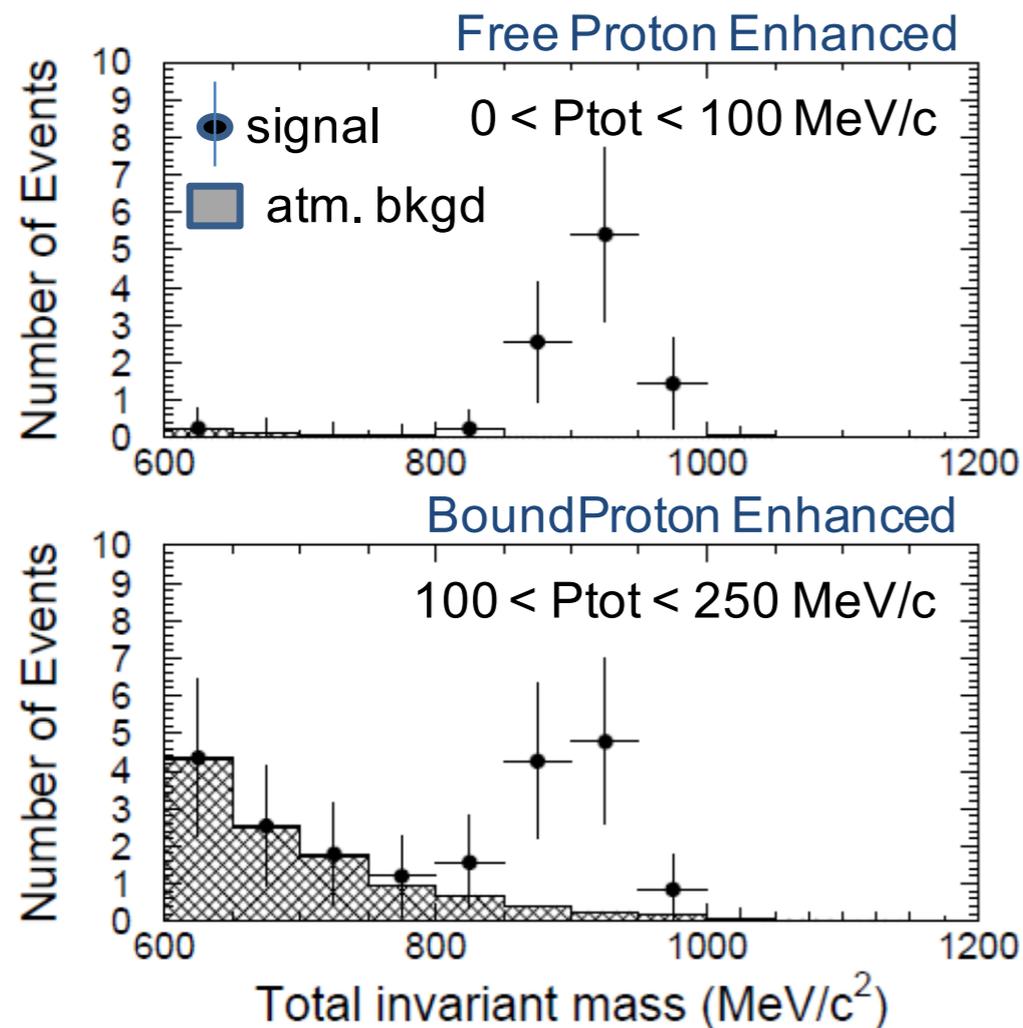
- **Keep looking for GUT with neutrinos.**

- Example: $p \rightarrow e^+ \pi^0$ in Hyper-K



$$\Gamma(p \rightarrow e^+ \pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

$\tau_{\text{proton}} = 1.4 \times 10^{34}$ years (SK 90% CL limit)



Hyper-K Status

(2016.3) 日本学術会議「マスタープラン2017」に提案提出

- ✓ 水槽1基の早期実現(2018年着工、2026年観測開始)を提案
- ✓ (2017.2) 重点大型研究計画28件に選定

推進体制、国際協力体制に関する取り組み

- ✓ (2017.3) 宇宙線研究所将来計画検討委員会: ICRRの次期主要プロジェクト
- ✓ (2017.10) 連携研究機構(ICRR, IPMU, 理学部)の東大内設置
- ✓ (2016.6) KEKプロジェクト実施計画(KEK-PIP): 将来計画の中で、「ハイパーカミオカンデのためのJ-PARC加速器高強度化」を最優先課題
- ✓ (2017.3) 海外分担の合意形成(PMTの約半分などを海外分担で実現)

文科省による予算措置に係るロードマップ2017

- ロードマップ2017(案)に選定された
- 評価結果
 - 「a」 研究者コミュニティの合意、実施主体、共同利用体制、妥当性
 - 「a」 緊急性、戦略性、社会国民の支持
- 文科省による概算要求の基盤ができた
 - 着工に向けた準備が急務
 - 設計、人員計画、予算計画のさらなる具体化

分野	分類	計画名称	計画概要	実施主体	所要経費(億円)	計画期間														評価①	評価②	主な優れている点等	主な課題・留意点等	備考
						H28	H29	H30	H31	H32	H33	H34	H35	H36	H37	H38	H39	H40	H41					
臨床医学	大規模研究計画	ゲノム医学研究視点の形成	「ゲノム医学研究拠点」を整備し、大規模ゲノム解析により、遺伝性疾患、多因子疾患、がんなど、多くの疾患の発症機構を解明し、疾患の分子病態に介入する革新的な治療法の開発を推進する。	東京大学(ゲノム医学研究機構)、国立遺伝学研究所、国立成育医療研究センター、横浜市立大学、国立国際医療研究センター、国立がん研究センター	総額193 次世代シーケンサー20、コンピュータ50、運営費123	H28: 大規模ゲノム解析拠点の整備 H29: 大規模ゲノム解析データベース構築を開始 H30-H34: 本格運用	H28 H29 H30 H31 H32 H33 H34 H35 H36 H37 H38 H39 H40 H41 H42	b	a	<ul style="list-style-type: none"> ●多因子性疾患等に係るゲノム要因を究明する計画であり、社会的意義が高い。 ●実施主体においてゲノム医学研究機構を設置し、3年間の実績を上げるなど、体制整備が進んでいる。 ●同様の研究が先行する海外との関係において、先方が持つ研究データへのアクセス権利を確保するなど、協議を図る上で、日本における体制整備が重要である。 	<ul style="list-style-type: none"> ●オールジャパンによる共同利用体制(ネットワーク)の構築に向けた戦略や、全国の医療機関から持続的に協力を得る仕組みを更に明確化する必要がある。 ●巨額の研究経費の具体性が不明瞭であるなど、大型研究計画として推進するためには、更なる検討が必要である。 	●強厚・医療戦略(平成28年7月閣議決定)等を踏まえ、ゲノム医療を実現するための取組を関係府省・関係機関が連携して推進している。本計画においては、こうした国全体の動きと整合性をもって取組られることが望まれる。												
		高エネルギー大型ハドロン衝突型加速器(HL-LHC)による素粒子実験	欧州合同原子核研究機関の大型ハドロン衝突型加速器(HC)を2024年頃に高輝度化(HL-LHC)し、LHCよりも広い質量領域で新粒子を探査する。また、ヒッグス粒子などの詳細測定から新物理の兆候を探る。	LHC加速器に対する寄与は高エネルギー加速器研究機構が中心となる。ATLAS実験は国際共同実験で、国内組織は高エネルギー加速器研究機構や東京大学など17の研究機関からなる。	総額104 加速器: ビーム分離用電磁石33、建設分担保25 検出器: シリコン24、ミュオントリガー14、トリガー用計算機など8	H28-H33: 開発および試作品製造 H31-H35: 建設 H36-H37: 検出器搬入設置調整 H38-H47: 本格運用	H28 H29 H30 H31 H32 H33 H34 H35 H36 H37 H38 H39 H40 H41 H42	a	a	<ul style="list-style-type: none"> ●日本の科学技術レベルの発展とともに国際協力の促進につながると期待できる。 ●日本の分担機器に係る開発研究は、若手研究者を中心に進められており、計画着手に向けた準備状況も良好である。 	<ul style="list-style-type: none"> ●日本の参加が計画どおりとならなかった場合(例えば、分担費用の確保がかなわない場合)における代替案(バックアッププラン)を検討する必要がある。 ●実施主体の中心となる高エネルギー加速器研究機構が、将来プロジェクトに係る優先順位として公表している「KEK Project Implementation Plan」(KEK-PIP)において、本計画が2位に位置付けられていることから、本計画の着手に向けては、1位に位置付けられている「大型先端検出器による様子崩壊・ニュートリノ振動実験」にかかわる研究者コミュニティの調整を行うことが必要である。 													
物理学	大型施設計画	大型先端検出器による様子崩壊・ニュートリノ振動実験	スーパーカミオカンデに代わる超大型水チエレンコフ検出器ハイパーカミオカンデを建設し、J-PARC加速器ニュートリノと組み合わせて世界最先端のニュートリノ研究を行う。また最高感度での様子崩壊探索を行う。	東京大学宇宙線研究所と高エネルギー加速器研究機構素粒子原子核研究所が中心となり推進し、国内外の大学・研究機関の参加も予定。	総額1547(うち日本担当分: 1393) ハイパーカミオカンデ: 建設費675(551)、運転経費400/20年 J-PARC: 運転経費400/10年 他、加速器増強費等72(42)	H30-H57: ハイパーカミオカンデ地質調査及び建設、運転 H38-H47: J-PARC JMW大規模運転	H30 H31 H32 H33 H34 H35 H36 H37 H38 H39 H40 H41 H42	a	a	<ul style="list-style-type: none"> ●日本の独創的発想にはじまり、これまで国際的にも大きな実績をあげており、日本のフラッグシップとして、世界に対する優位性を維持、発展する重要な計画である。 ●実施主体内外から300人を超える研究者が参画する体制を構築するなど、計画着手に向けた準備が進んでいる。 	<ul style="list-style-type: none"> ●本計画は規模・経費ともに巨大であるため、国際連携の更なる深化、拡大を図り、多方面にわたる国際協力体制の構築を検討する必要がある。 ●実施主体における現行の大型研究計画との関係を整理し、予算面、人員面におけるより実行的かつ総合的な計画を検討する必要がある。(スーパーカミオカンデとの関係においては、特に整理が望まれる。) 													

分野	分類	計画名称	計画概要	実施主体	所要経費(億円)	計画期間	評価														主な課題・留意点等	備考		
							①	②	108	109	110	111	112	113	114	115	116	117	118	119			120	
物理学	大型施設計画	次世代赤外線天文衛星 SPICA	宇宙が重元素と星間塵により多様で豊かな世界になり、生命が存在可能な惑星世界がもたらされた過程を解明することを目指す。日欧共同で大口径の極低温冷却望遠鏡を製作し、前例のない高感度の赤外線観測を実現する。	国内：宇宙航空研究開発機構 (JAXA)、大阪大学、国立天文台、東京大学、名古屋大学、東北大学、関西学院大学、京都大学等 国外：欧州宇宙機関 (ESA)、遠赤外線観測装置コンソーシアム (代表：オランダ)	総額1000程度 日本担当分は戦略的に実施する中型計画 (300程度を想定) 規模で、ESA担当分はCosmic Vision M-class (550Mユーロ) 規模で、精査中	H28-H34：設計 H35-H39：製作・試験 H39-H43：打上げ H40-H42(44)：観測運用	108	109	110	111	112	113	114	115	116	117	118	119	120	○	○	●赤外線望遠鏡計画として諸外国からも注目される、日本が主導してきた国際計画であり、学術的意義が高く、多くの成果が期待できる。 ●国際的な分担金の負担など、前回から計画が見直され、より現実的になっている。 ●観測データの多様性あり、天文学をはじめとする物理学全体の発展に寄与すると考えられる。	●大きな経費を欧州の機関が分担する計画になり、欧州側において採択されることが期待される一方、欧州側において採択されれば、日本も対応する義務が生じることに留意が必要である。 ●計画に着手する際は、スケジュールや人材育成などについて、相乗効果も見込まれる他の大型望遠鏡計画との関係を踏まえた対応が望まれる。	●本計画は国立研究開発法人が実施主体となるものであり、本ロードマップを参考として、科学技術・学術審議会の関係会議や、内閣府宇宙政策委員会などにおける更なる検討が必要である。
		LiteBIRD	宇宙はどのように始まったのだろうか？熱いビッグバン以前の宇宙を記述する最も有力な仮説がインフレーション宇宙理論である。本計画では宇宙背景放射の偏光を全天で観測し、この理論が予測する原始重力波を検出する。	国内：宇宙航空研究開発機構 (JAXA) 宇宙科学研究所、東京大学国際高等研究所 国外：アメリカ航空宇宙局 (NASA)、カリフォルニア大学	総額約300 (日本担当分として) ミッション部 (観測装置) 開発費約100、衛星開発費約125、ロケット約50、打ち上げ・運用約25	H28-H33：準備期間 H31-H37：設計・製造・打上げ H38-H43：観測 H41-H44：成果発表	108	109	110	111	112	113	114	115	116	117	118	119	120	○	○	●宇宙論と素粒子論の融合分野であり、国際的にも独自性と学術的価値の高い計画である。このため、多くの研究者の参画や協力を得た体制構築が図られている。 ●実験装置において、実施主体と民間企業との共同研究成果が活用されていることなどから、技術的な実現性は確保されていると考えられる。	●原始重力波を検出できるかどうか鍵だが、検出できなかった場合、宇宙初期の解明にいかなる利点が付されるのか検討する必要がある。	●本計画は国立研究開発法人が実施主体となるものであり、本ロードマップを参考として、科学技術・学術審議会の関係会議や、内閣府宇宙政策委員会などにおける更なる検討が必要である。
		アト秒レーザー科学研究施設	軟X線アト秒ビームラインを4本整備し、アト秒分解能での時間分解分光装置、顕微鏡を整備する。更に、レーザープラズマ加速とアト秒レーザー技術を融合して、次世代アト秒光源技術の開発を行う。	東京大学を中核機関とし、理化学研究所をはじめとする日本全国の大学、研究機関、民間企業の研究者が参加。実行組織として「設備整備委員会」、「利用推進委員会」、「解析支援委員会」を設置。	総額96 中核施設「アト秒レーザー科学研究施設」整備費74、計測装置設備費14、運営費8	H29-H33：建設期間 H31-H34：部分運用 H35-H38：本格運用	108	109	110	111	112	113	114	115	116	117	118	119	120	○	○	●物質・生命科学、電子工学、創薬・医療など、幅広い分野への応用や、次世代顕微鏡への展開など、レーザー研究の新たな領域の開拓が期待される。 ●国際的にも高い実績と優位性を有する実施主体であり、実現可能性は高いと考えられる。	●実施主体を中心に最先端技術の研究開発を進め、専門家の育成やコミュニティの拡大を図りつつ、共同利用体制を構築していく必要がある。 ●学術分野のみならず技術開発と産業振興の観点からも計画を検討し、全学連携の仕組みを明確化する必要がある。	
2分野以上に関わる融合領域	大型施設計画	新しい時代の科学を支える放射光科学の高度化計画	物質・生命科学の更なる発展を目指し、低コスト建設、省エネルギー運転を設け、基本思想に取り入れた低エミッタンス運転と挿入光源を基本とした3GeVクラス高輝度放射光施設の早急な建設・運転開始を行う。	理化学研究所、高エネルギー加速器研究機構を中心とした全日本の協力体制で施設建設・運営を行う。上記組織に学術界、産業界から志願した組織を加えた組織でビームライン建設を実施する。	総額300 中型放射光施設建設250、ビームライン施設整備30、運営費20 (※土地取得経費は含まず)	H28：デザインコンセプトの決定 H29-H32：放射光施設・ビームライン建設 H33：供用試験開始	108	109	110	111	112	113	114	115	116	117	118	119	120	○	○	●世界的に整備が進む一方、日本においては既存施設間の格差となる高輝度光源を整備する計画であり、化学、生命科学、物理学、物質科学など、幅広い分野による利用が期待される。 ●産業界の技術開発においても重要であり、産学官の共同事業として進められる計画になっている。	●施設の建設候補地、安定的な運用を図るための産業界の協力、幅広い利用者ニーズの把握など、計画の着手に向けては更に検討を進める必要がある。 ●既存の放射光施設との関係(役割分担)を整理の上、総合的な研究計画を検討する必要がある。	●本計画は国立研究開発法人量子科学技術研究開発機構が実施主体となる予定であり、本ロードマップを参考として、科学技術・学術審議会の関係会議における更なる検討が必要である。

まとめ

- T2K provides the world best measurement of neutrino CP violation.
 - The new results on neutrino CP violation will be released on Friday, August 4th.
- Super-K atm. ν provides the world best measurement of neutrino mass hierarchy.
- Hyper-Kamikande is selected as one of seven highest-priority large-scale projects. The roadmap in Japanese can be found here:
 - http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/1388523.htm or
 - http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/_icsFiles/afieldfile/2017/07/31/1388523_001_1_1.pdf (Hyper-K is the third project from the top in the table of the page 15)