«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE
TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

39th Course: NEUTRINOS IN COSMOLOGY, IN ASTRO-, PARTICLE- AND NUCLEAR PHYSICS

ERICE–SICILY: 16 – 24 SEPTEMBER 2017

Sponsored by the: • European Physical Society • Extreme Matter Institute EMMI
• GSI Helmholtzzentrum für Schwerionenforschung • KCETA Karlsruhe Institute of Technology
• Italian Ministry of University and Research • Sicilian Regional Government

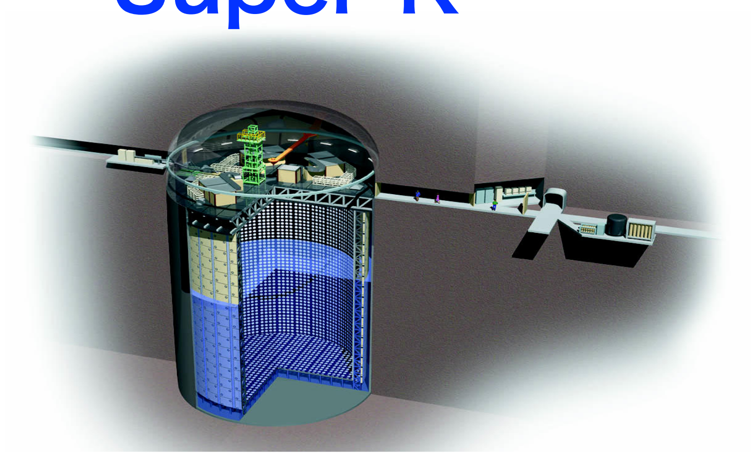
Present status of long baseline experiments in Japan (mainly the T2K experiment)

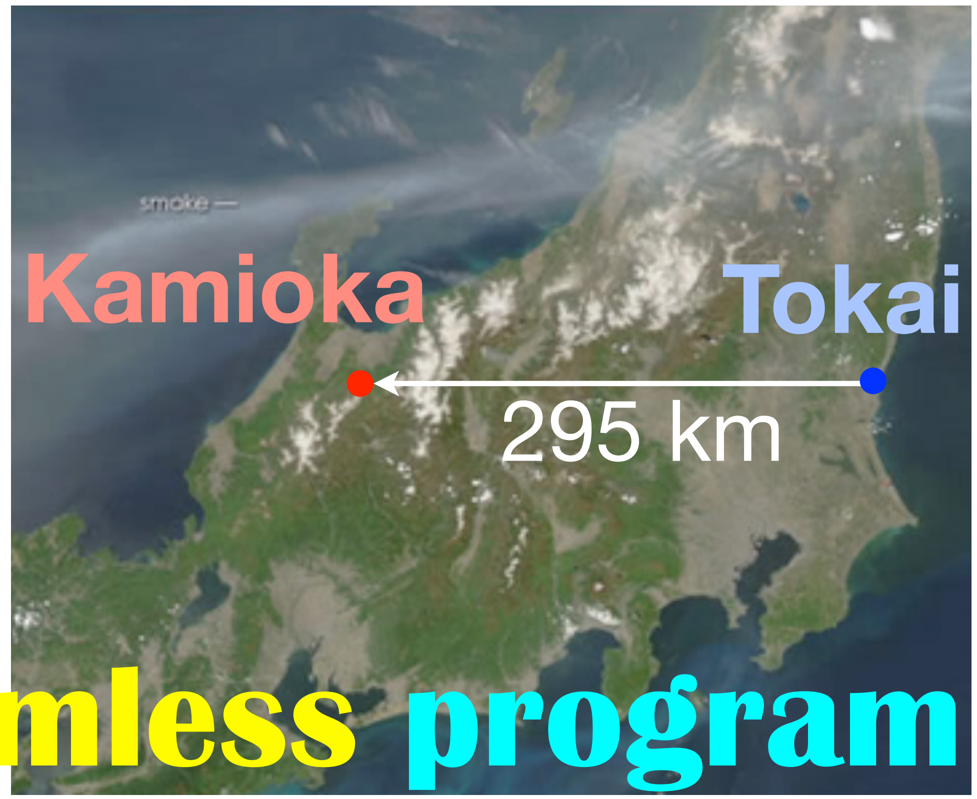
T. Nakaya (Kyoto University)

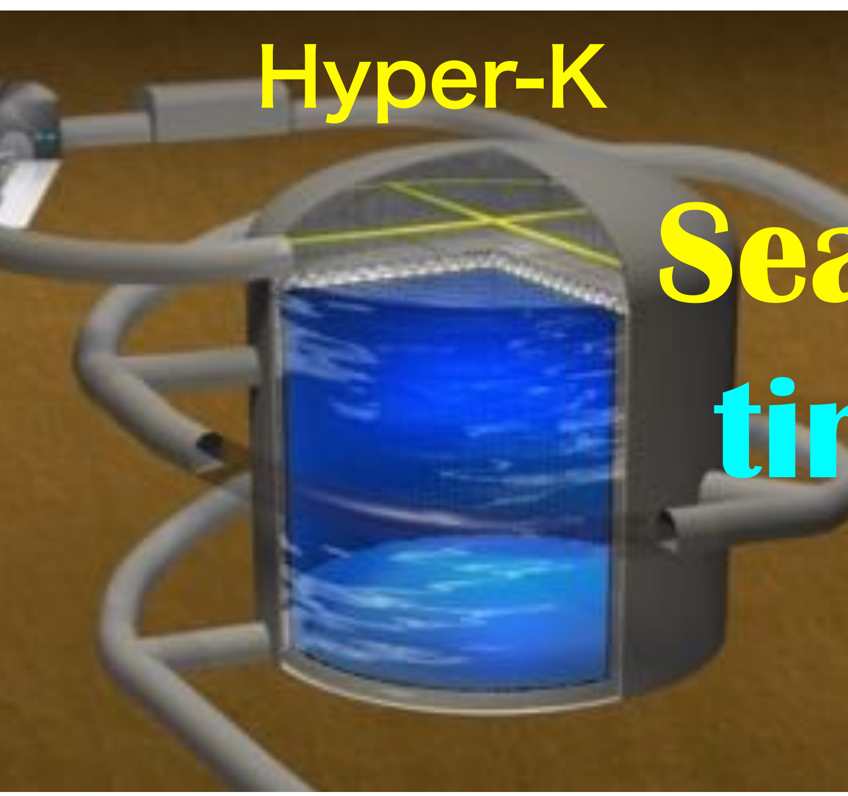
Neutrino oscillation experiments in Japan

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

Super-K

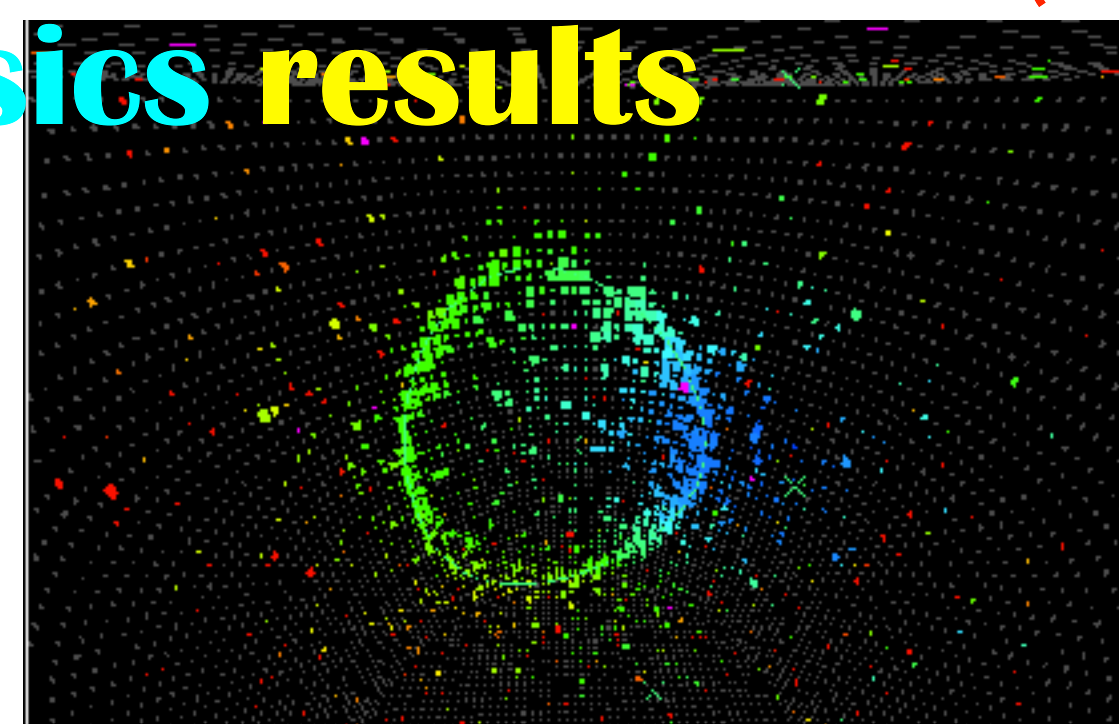






- 470 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)

Seamless program with timely physics results

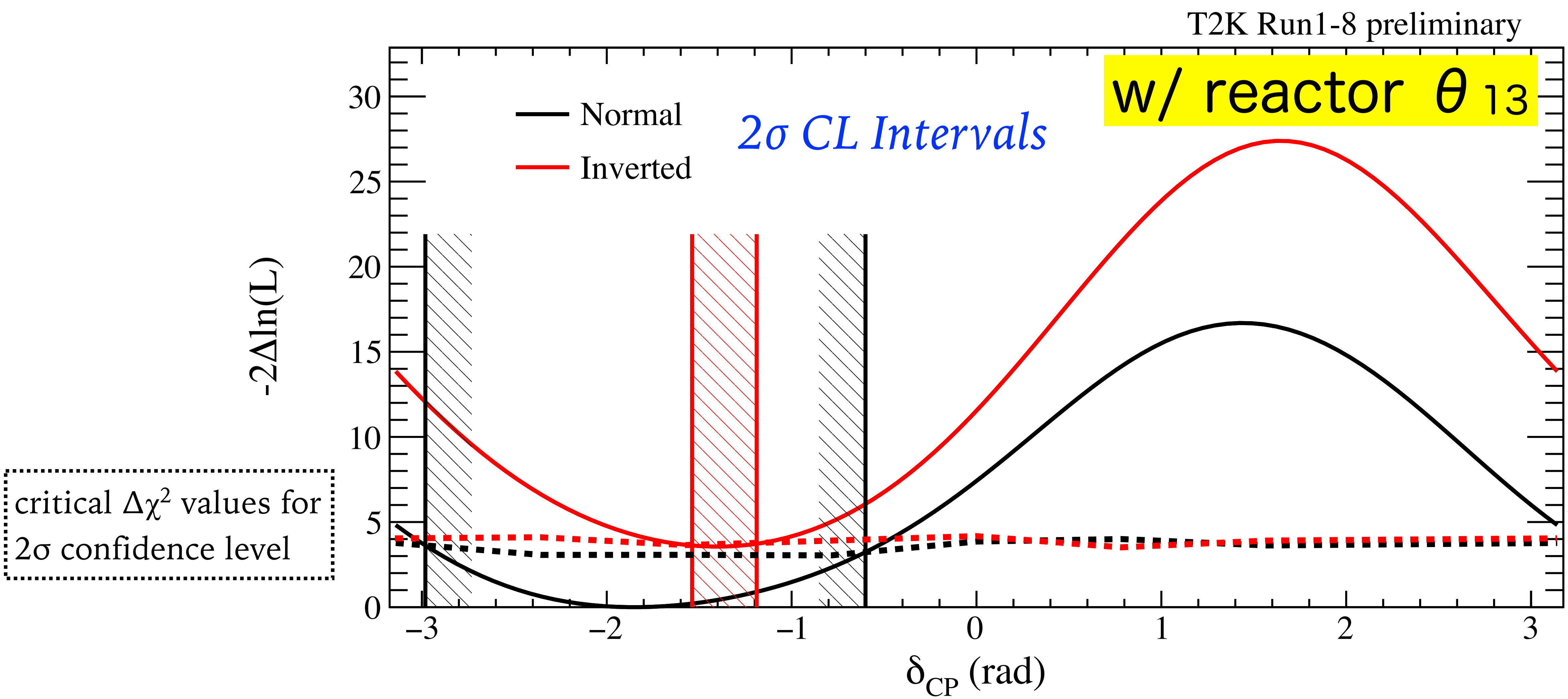


- 22.5 kton (Super-K, ~2026)
- 190 kton (Hyper-K, 2026~)

New T2K results (in August 4, 2017)

Seminar at KEK: https://www.t2k.org/docs/talk/282

Based on 89 ν_e and 7 $\overline{\nu}_e$ events



Best fit: $\delta_{CP}=-1.83^{+0.60}_{-0.66}$ in Normal Hierarchy

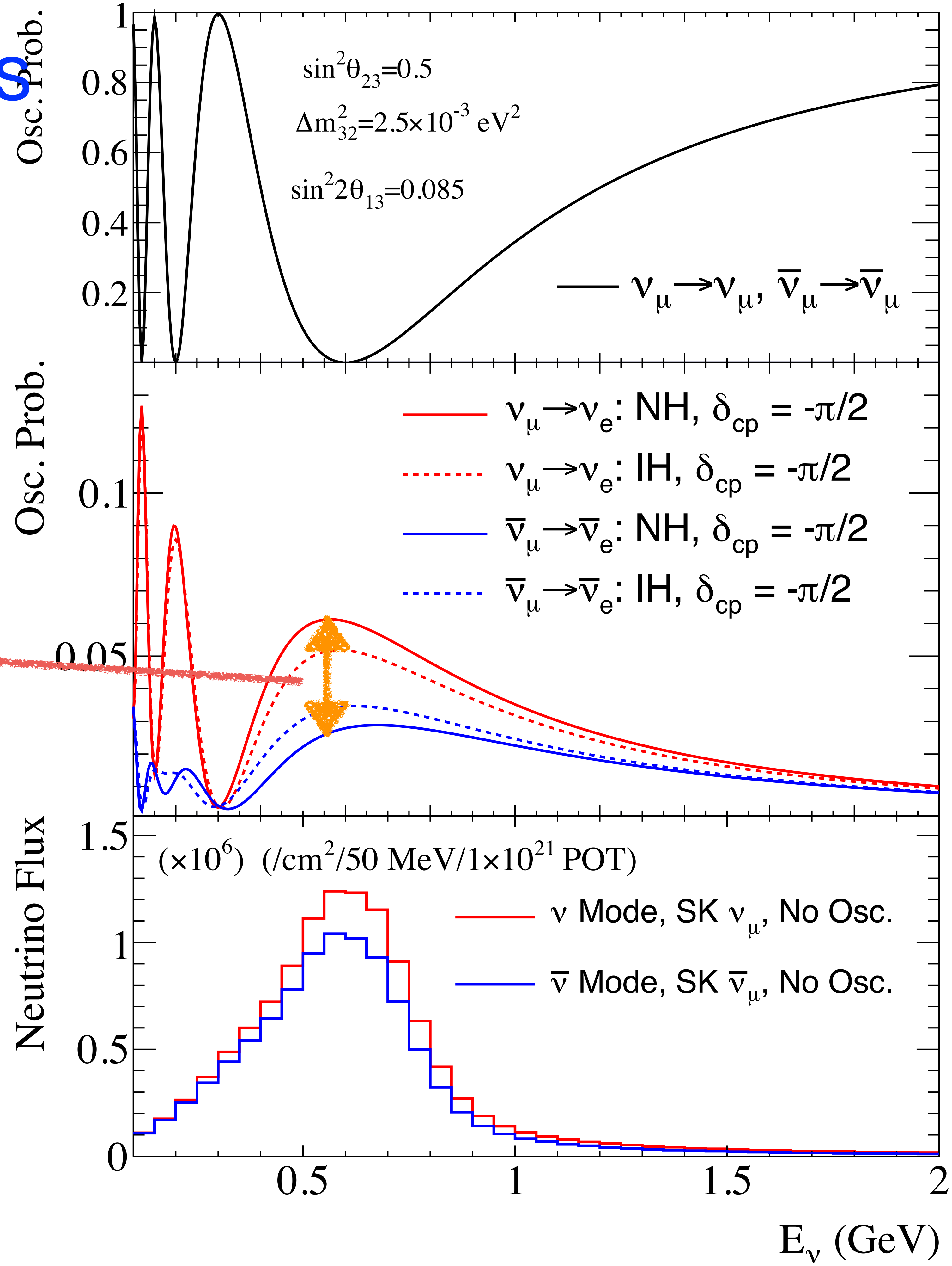
CP conserving values (0,π) fall outside of the 2σ CL intervals

What's new?

- Double neutrino beam data in one year!
  - 7.48×10^{20} POT → 14.7×10^{20} POT
- Increase the far detector fiducial volume!
  - ~20% more events
- Adding a new event sample (CC-1π) on ν_e
  - ~10% more events

Neutrino Oscillations in T2K

- ν_μ disappearance
  - $\sin^2 2\theta_{23}$, $|\Delta m^2_{32}|$
- ν_e appearance
  - $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}, Δm^2_{31}
- CP Violation in T2K
  - ~±20% effects in $\#\nu_e$
  - ~100 $\nu_e \to \delta N/N$~10% : ~2σ sensitivity for maximum CP Violation without systematic errors
  - $\Delta(\sin^2\theta_{23})$~10%
  - ~8% effect by matter
  - Systematic error ~ 5% (including cross section uncertainties)



Formula of Oscillation Probability with CP violation

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{132}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu}(1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2}(1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

Leading

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

CPV

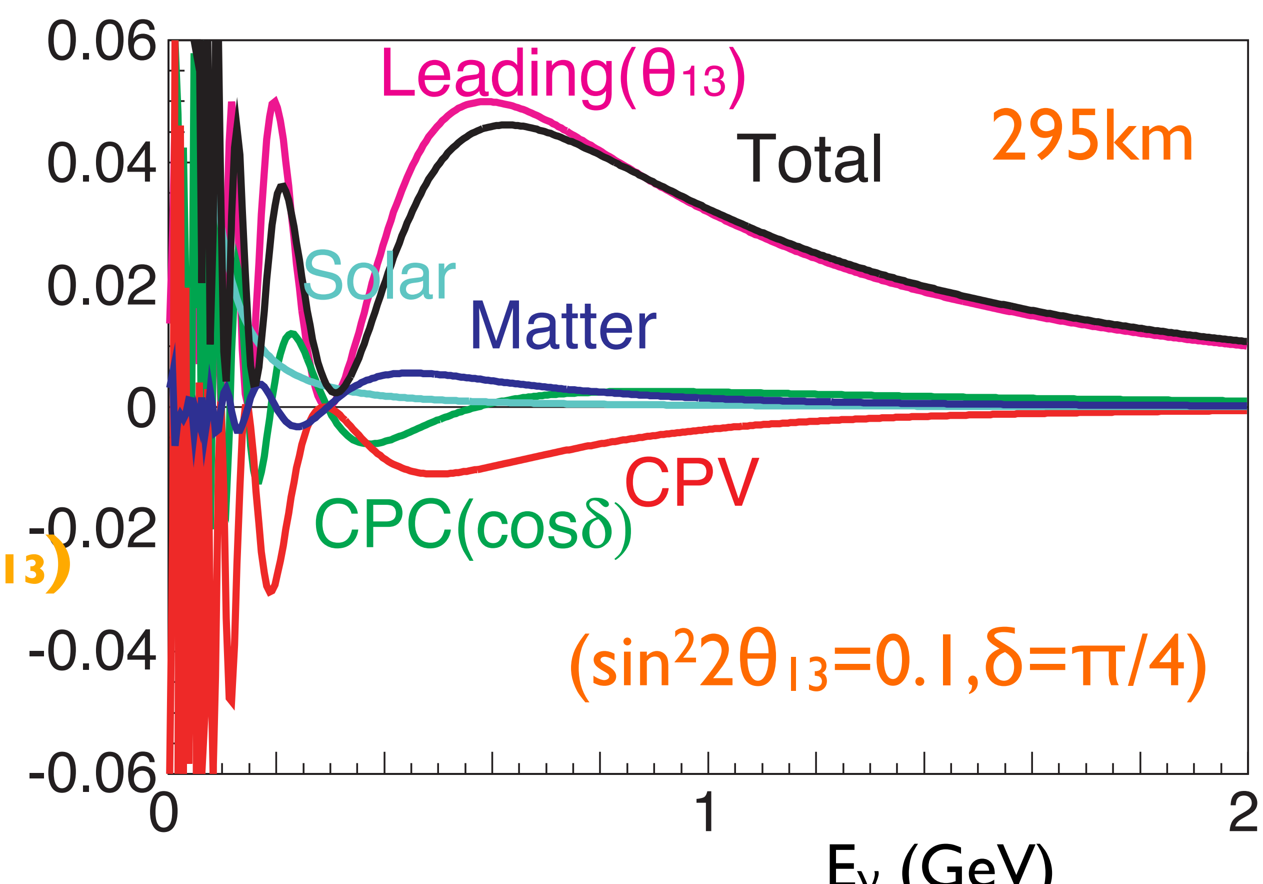
$$\frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \sin\delta$$

~0.03 ~11.8 (6.4 from $1/\sin\theta_{13}$)

$$\sim \frac{\pi}{4} \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{\sin^2\theta_{23} \sin\theta_{13}} \frac{E_{1st\max}}{E} [leading] \sin\delta$$

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

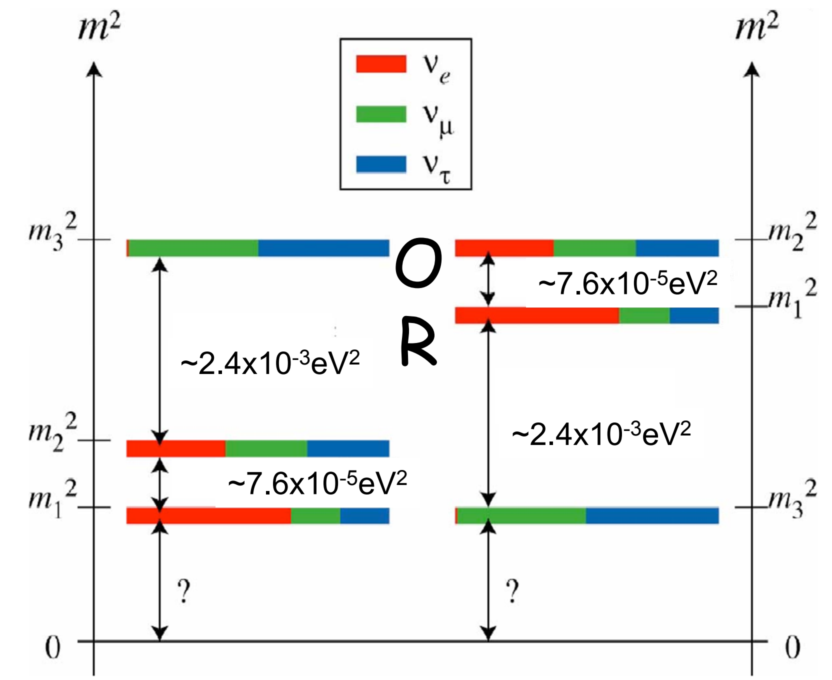
27%



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

Status of Neutrino Oscillations

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 (ν_1, ν_2)

Atmospheric, Accelerator (ν_2, ν_3)

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

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

Atmospheric
Accelerator

Accelerator
Reactor
Atmospheric

Solar
Reactor

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

$\delta \sim -\pi/2$?

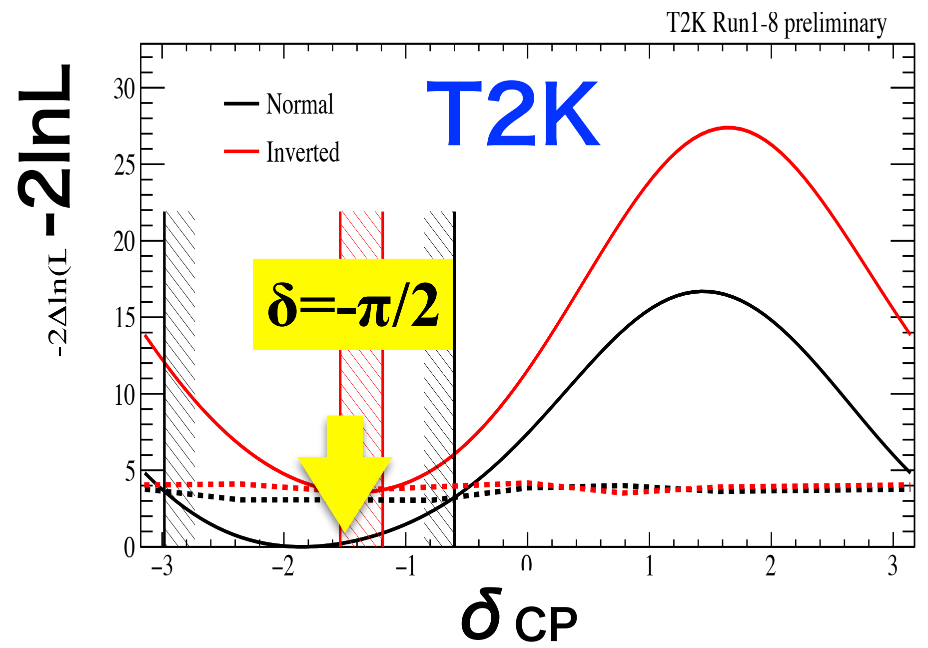
$$U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & \sim 1 \end{pmatrix}$$

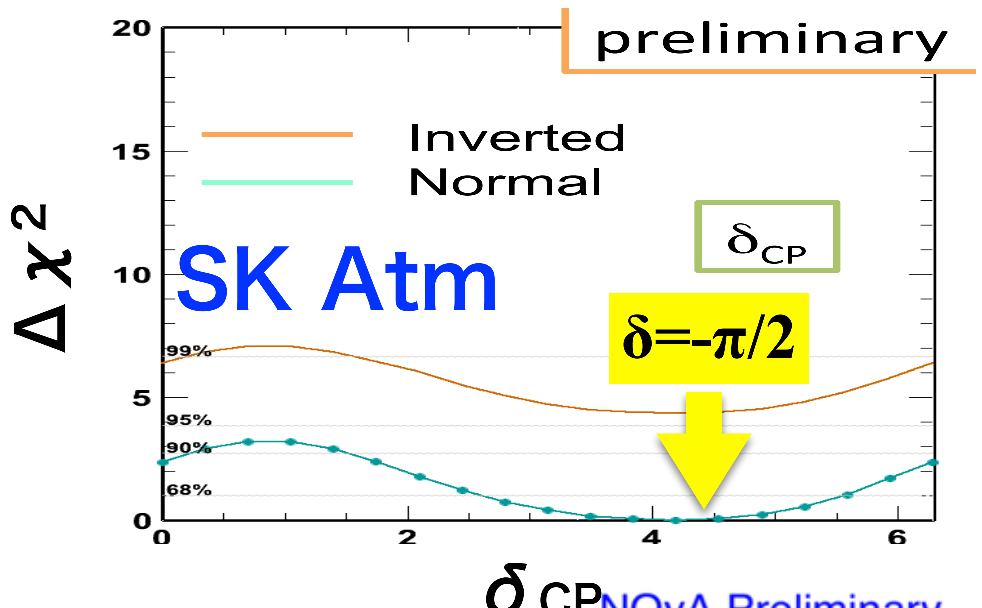
$\delta = 60°$

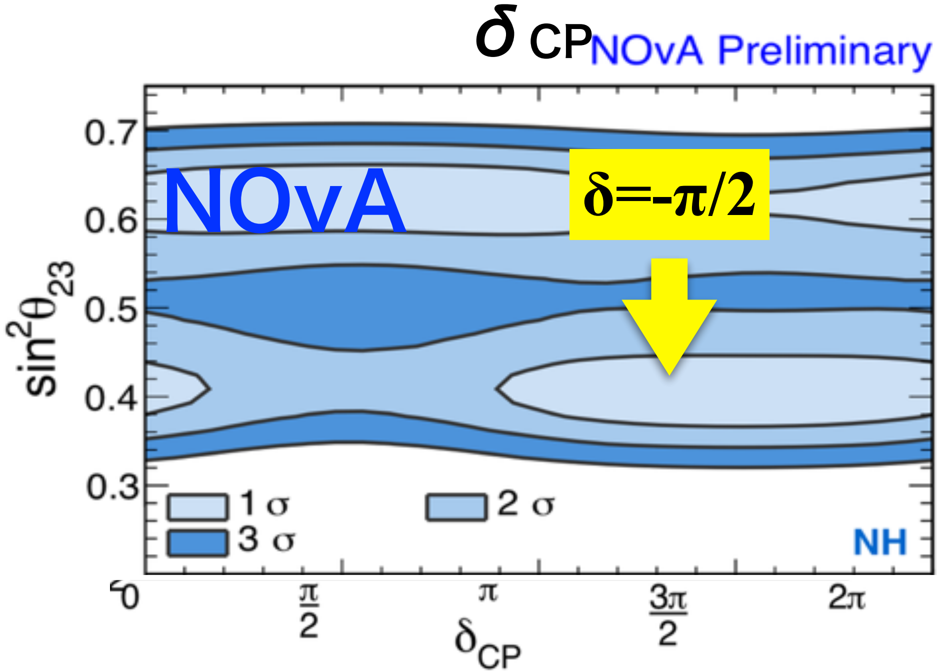
- In the framework of 3 neutrinos, the unknowns are
  - mass ordering
  - CP violation parameter: δ_{CP}

Today @LP2017

CP Violation

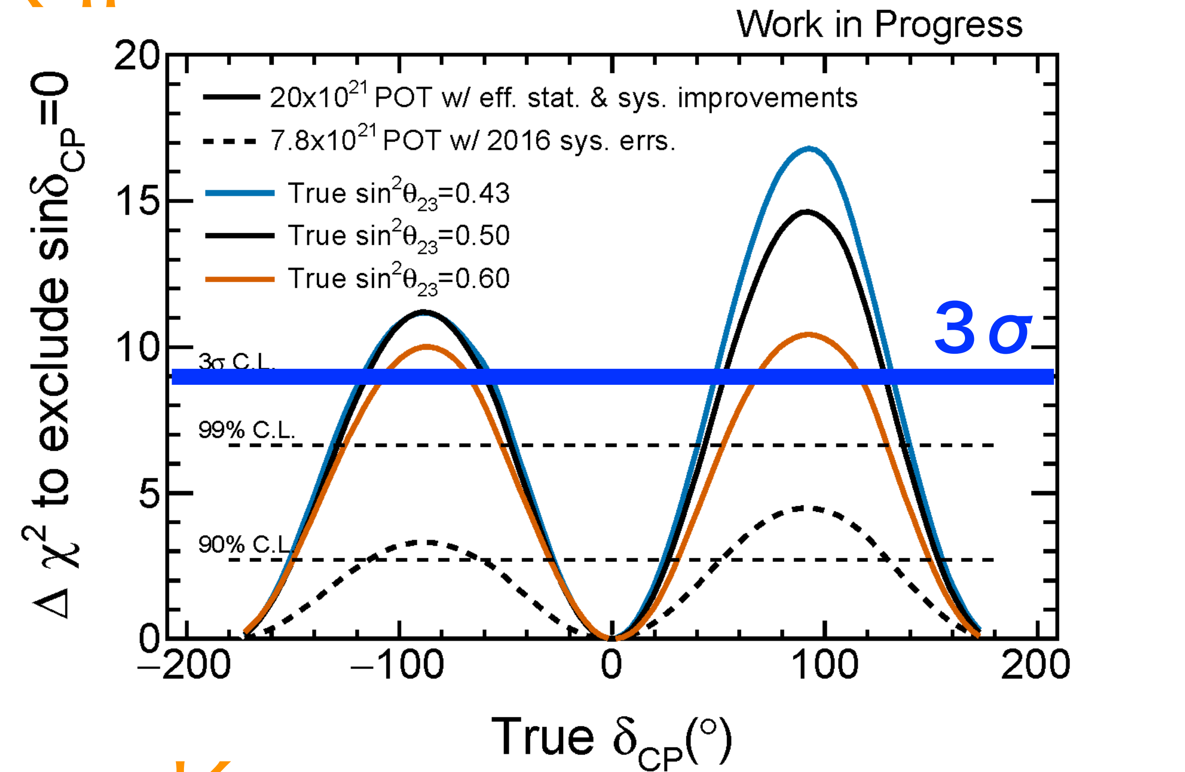




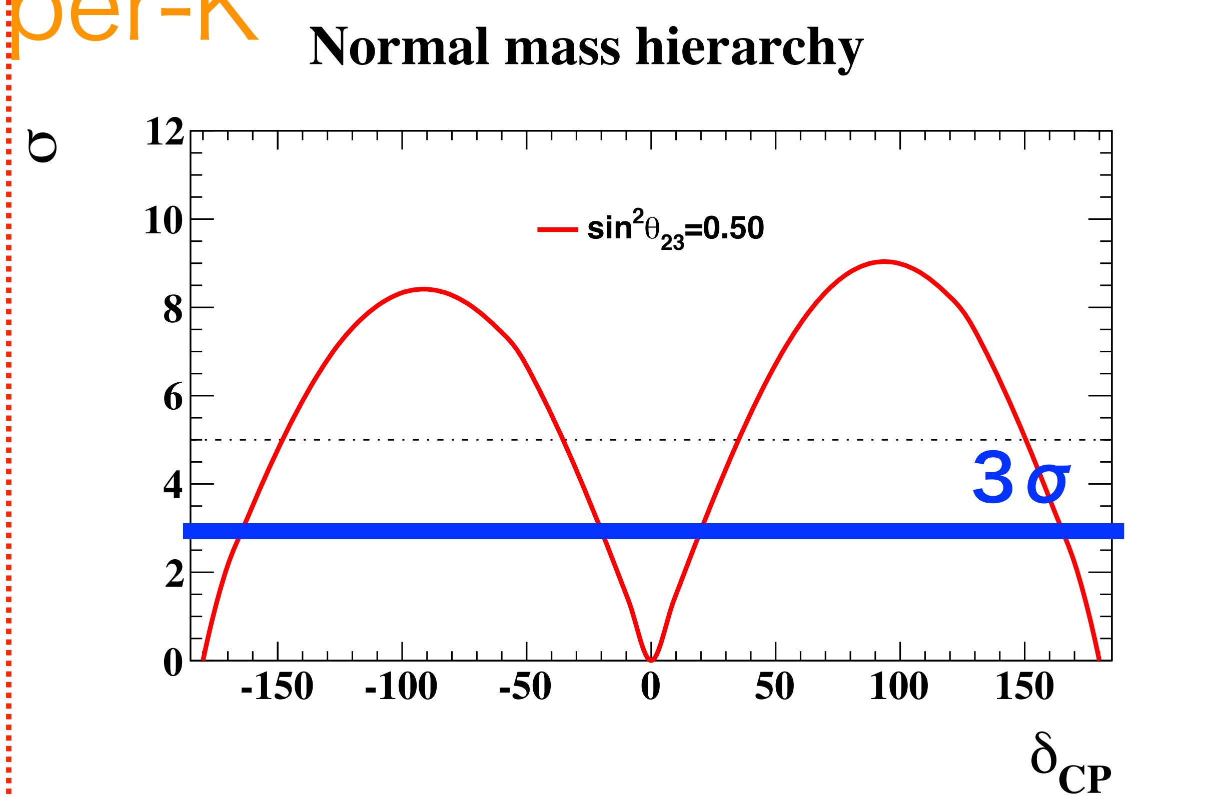


T2K-II

Mass hierarchy is assumed to be known.



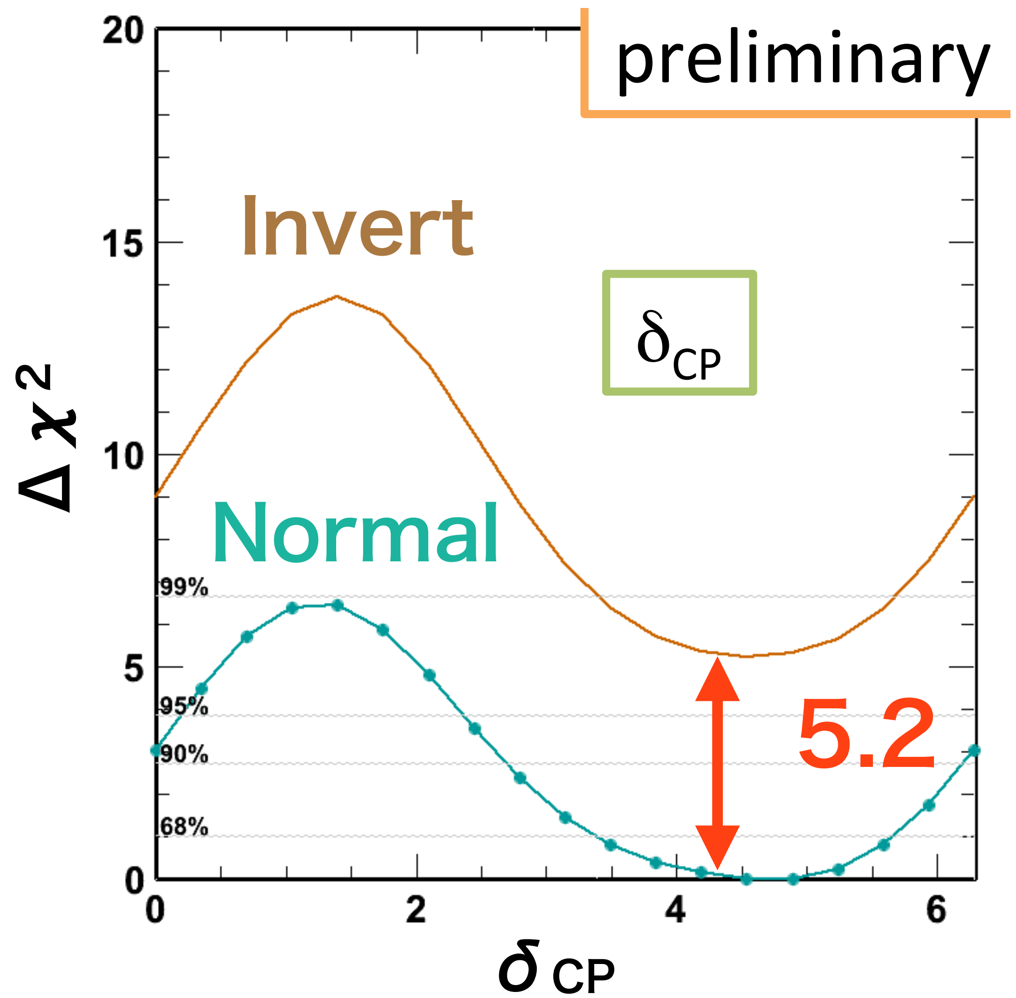
Hyper-K



Mass Hierarchy

- A hint of mass hierarchy may be seen. Within 5~10 years, we expect more information on mass hierarchy from SK atmospheric neutrinos, NOvA (+T2K), IceCube, ORCA and JUNO.

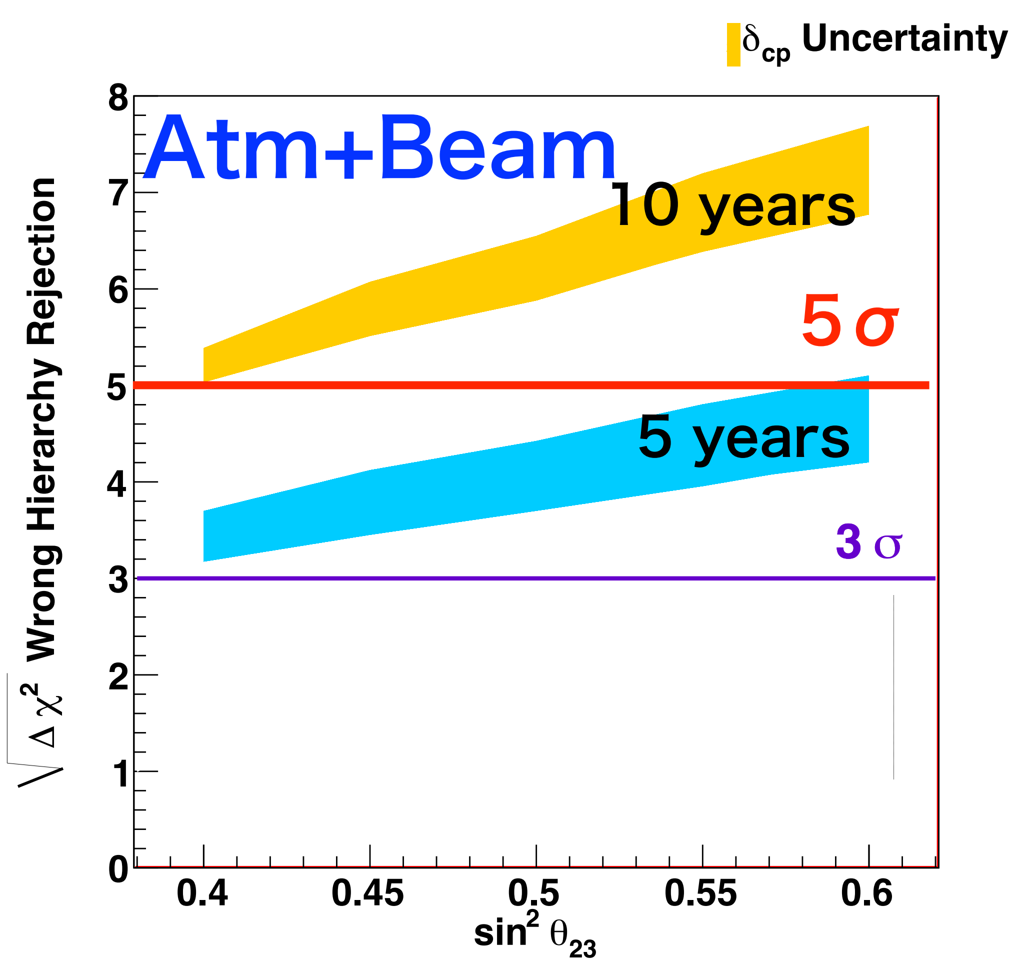
Today **SK Atm+T2K**



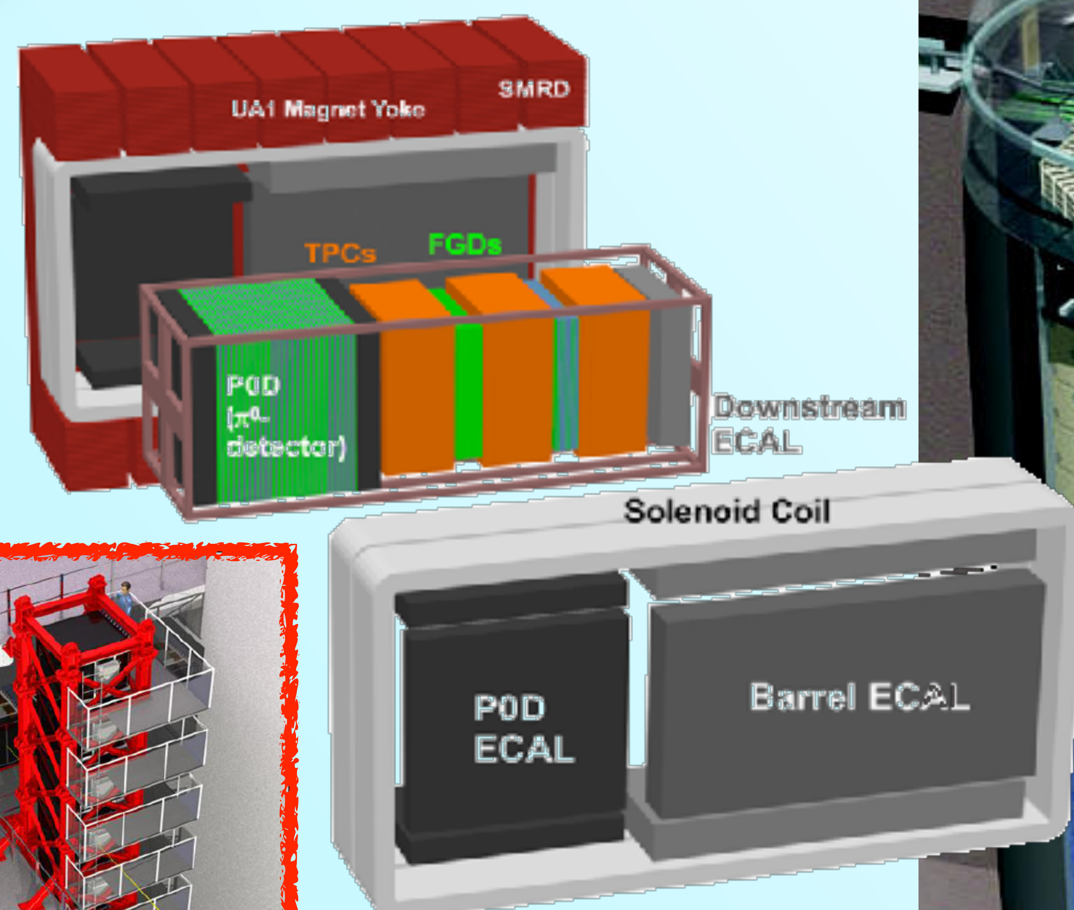
SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$

Hyper-K (Design Report)

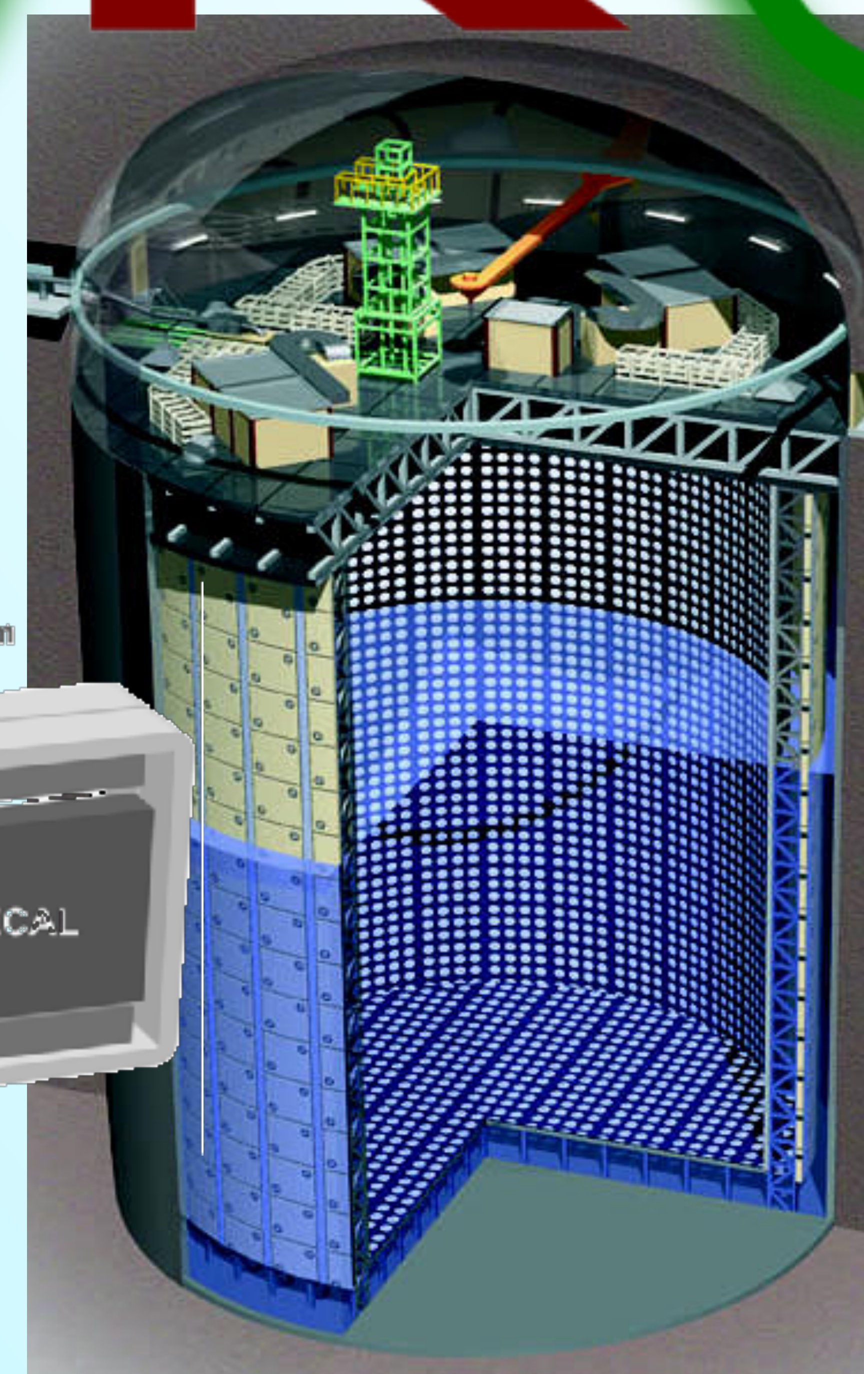
Wrong Hierarchy Rejection

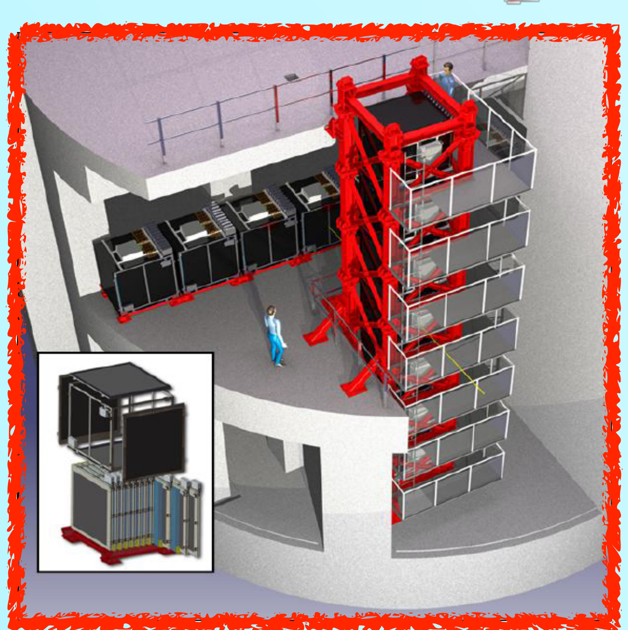


T2K

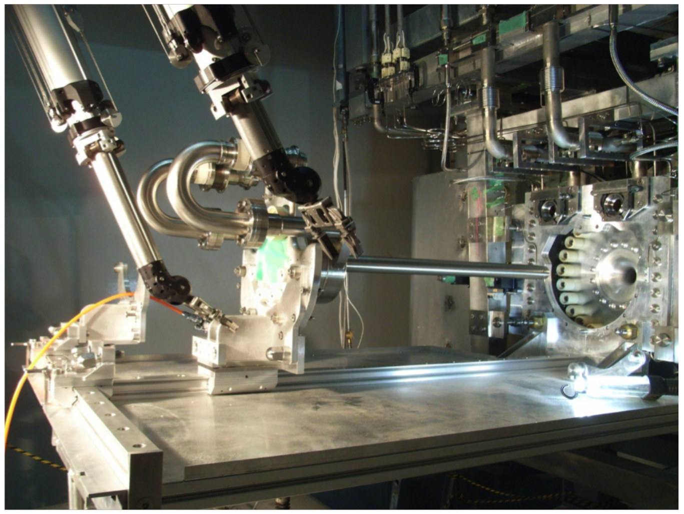


UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π^0 detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL

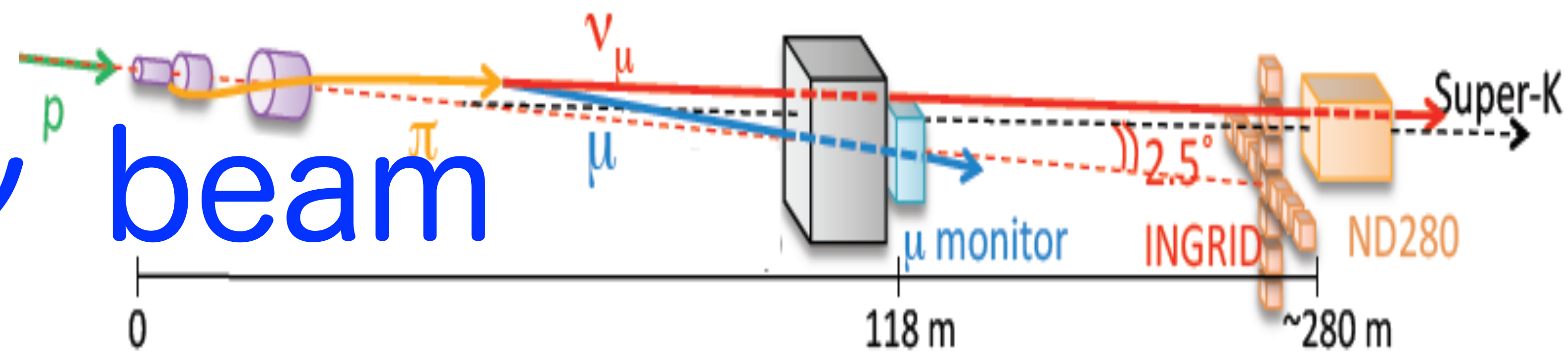




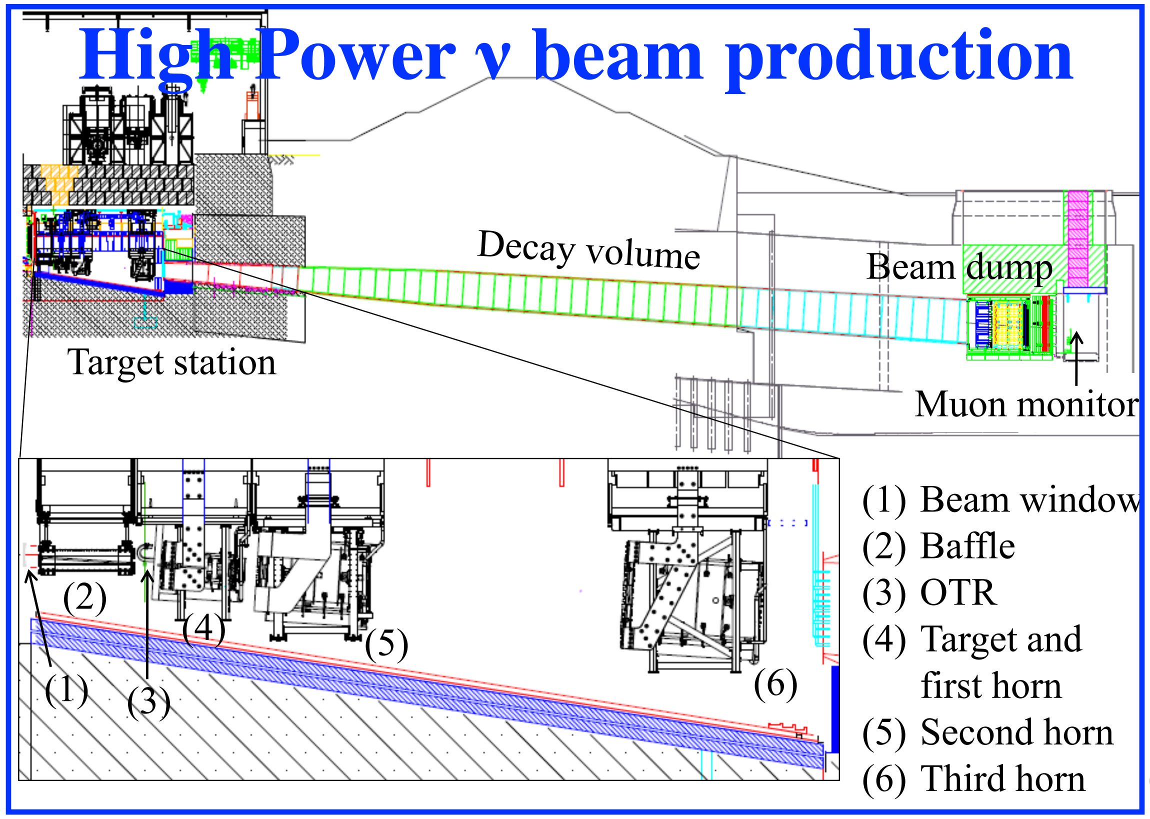
T2K ν beam

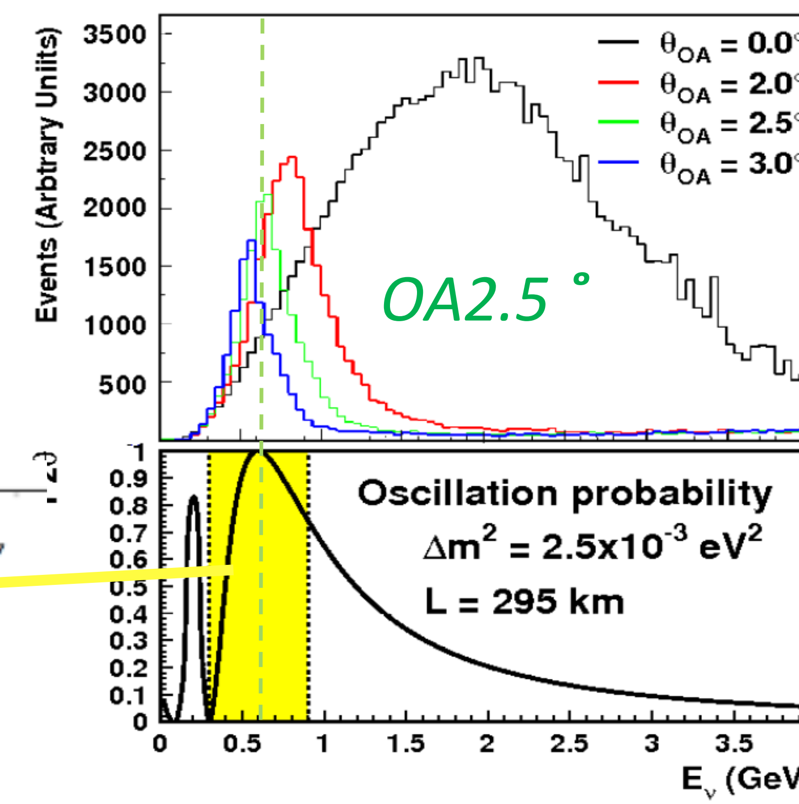


Target + remote handling system

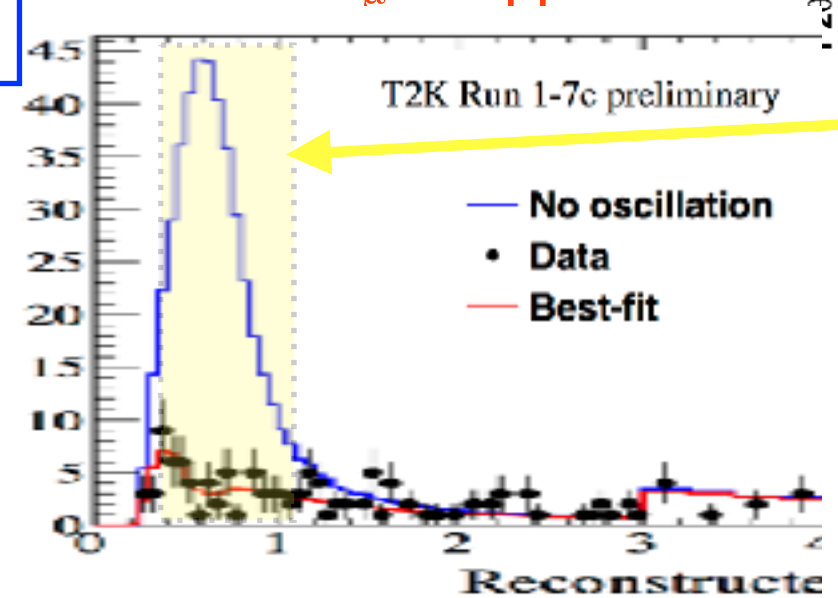


- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - 1mrad direction shift => ~2% energy shift at peak
  - Small ν_e fraction (~1%)





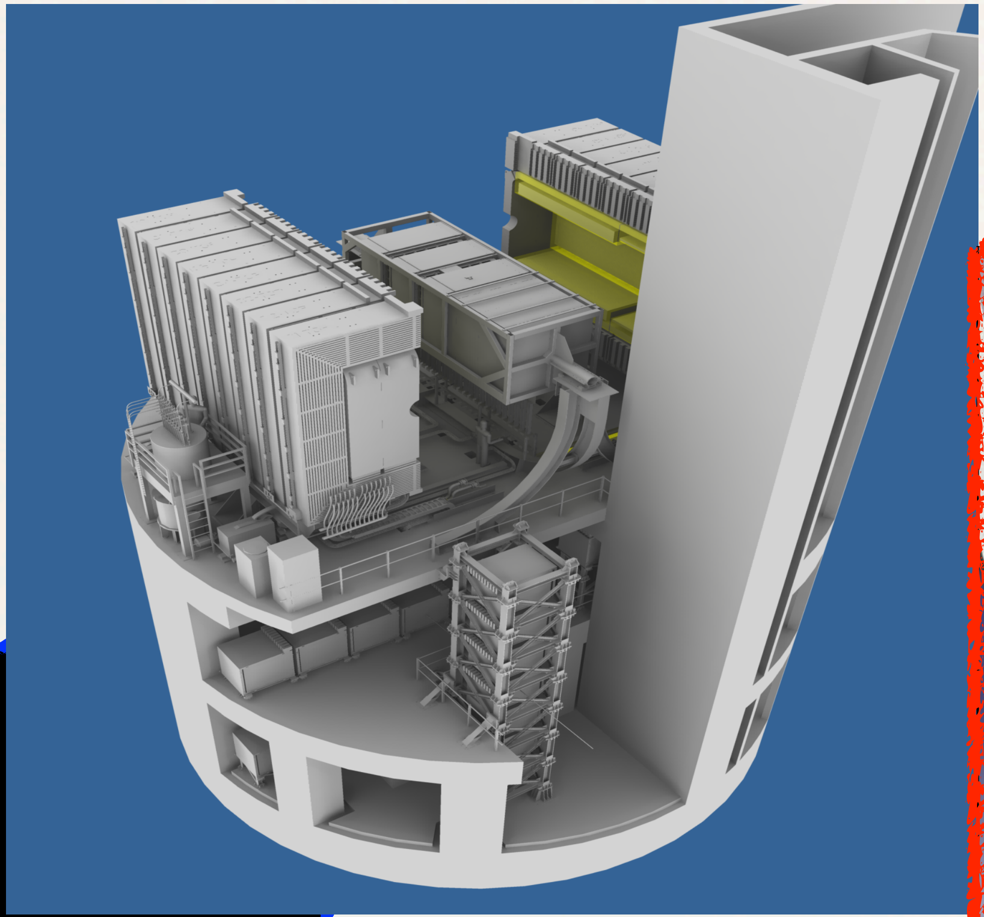
T2K 2016 ν_μ disappearance

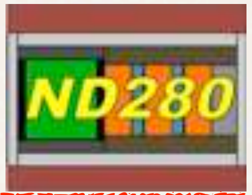


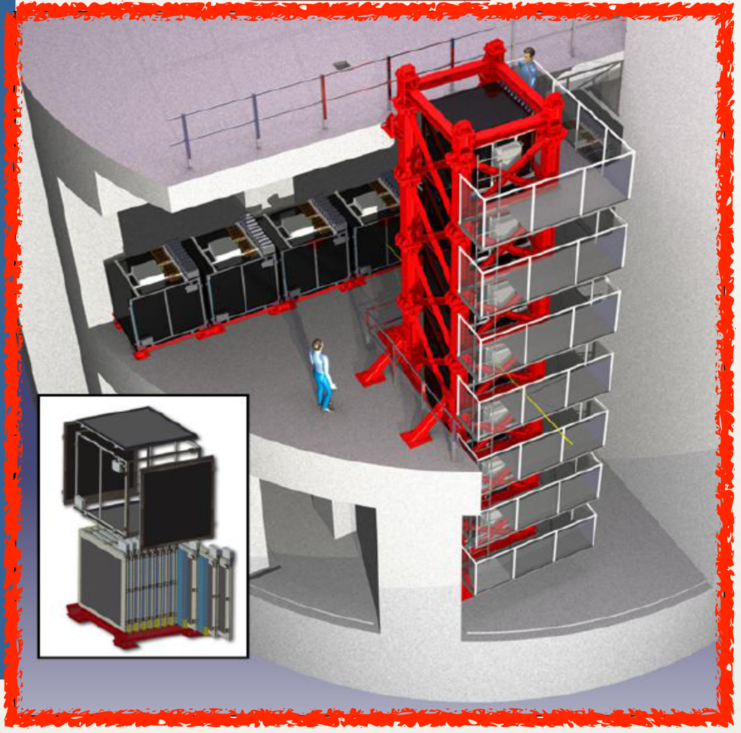
- 30 GeV **~1×10^{14}** protons extracted every 2.5/1.3 sec. directed to the carbon target.
- Secondary π^+(and K^+) focused by three electromagnetic horns (**250kA/320kA**)
- ν_μ from mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - ν_e in the beam come from K and μ decays

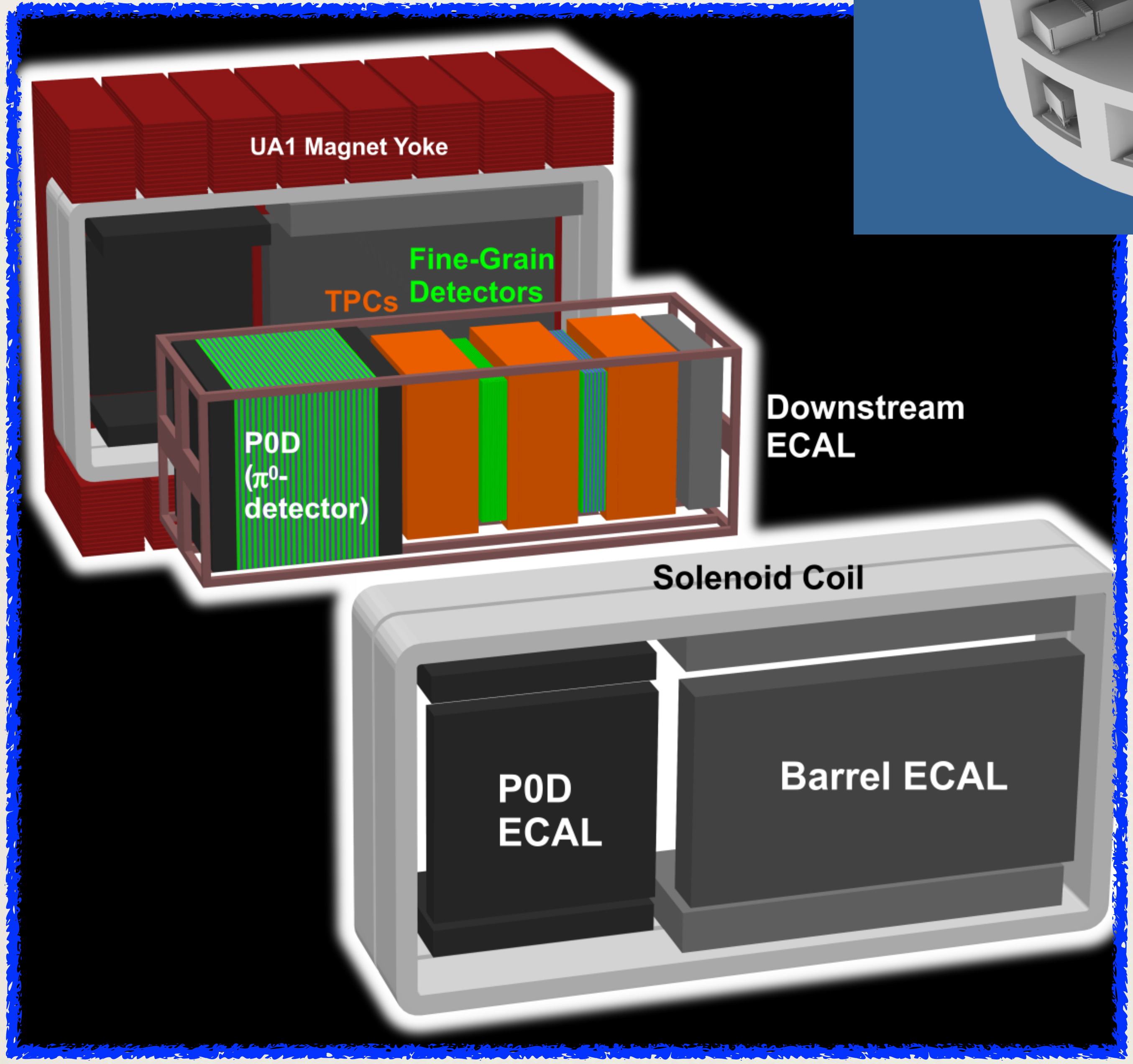
ND280

Near Detector @ 280m from the target





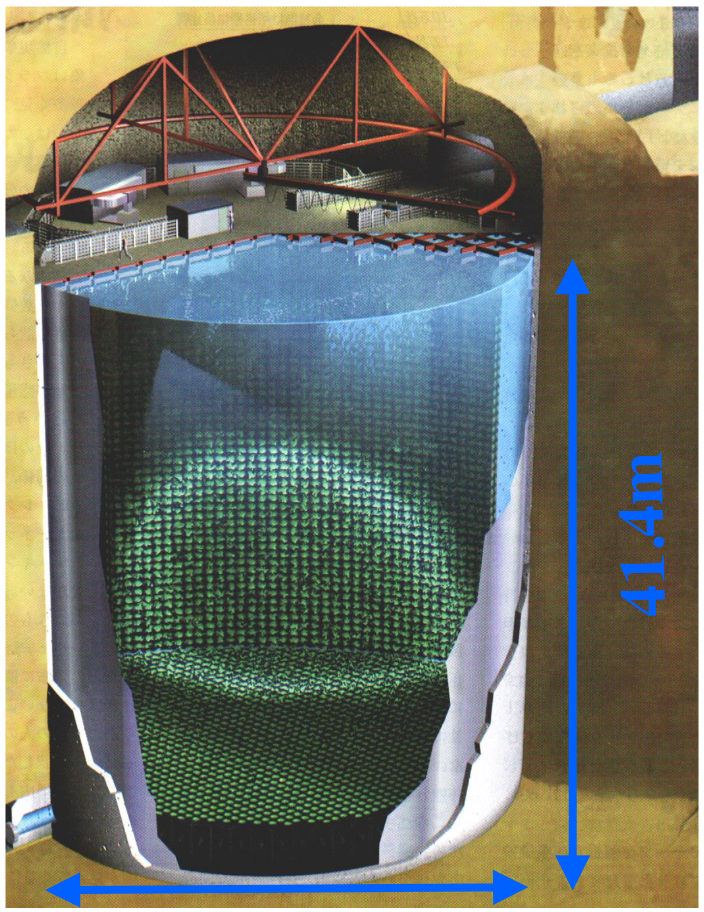




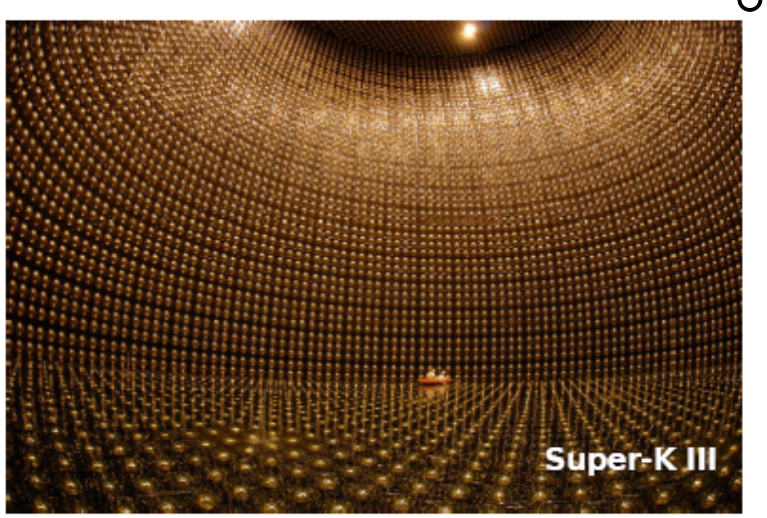
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, and stability]

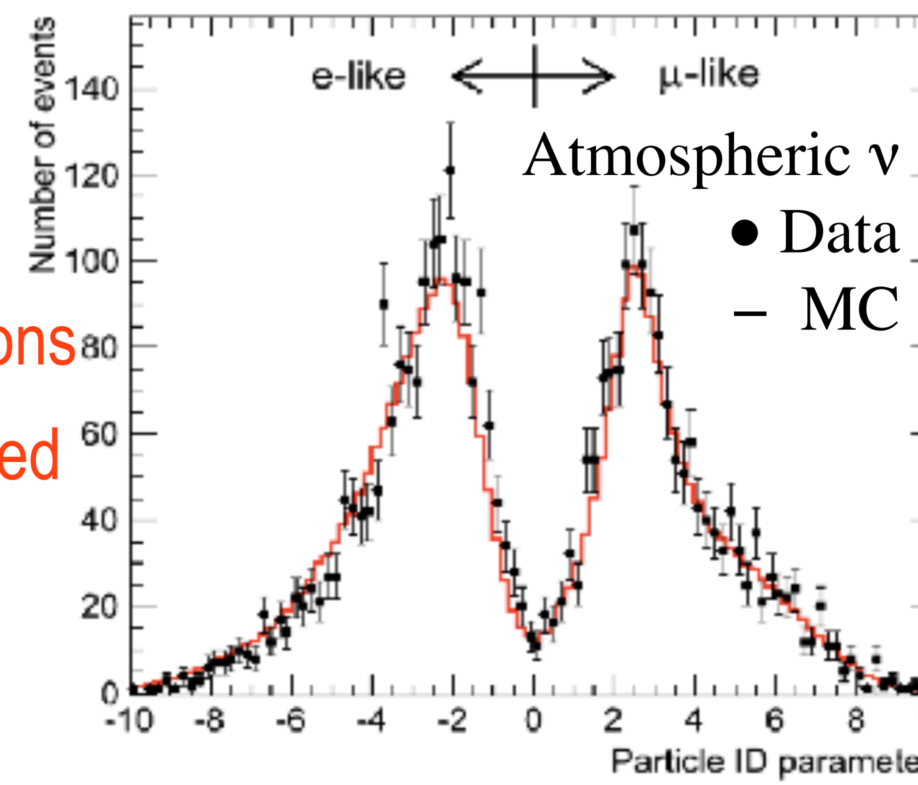
- **ND280** @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D:** π^0 Detector
    - **FGD+TPC:** Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

T2K-Far Detector: Super-Kamiokande



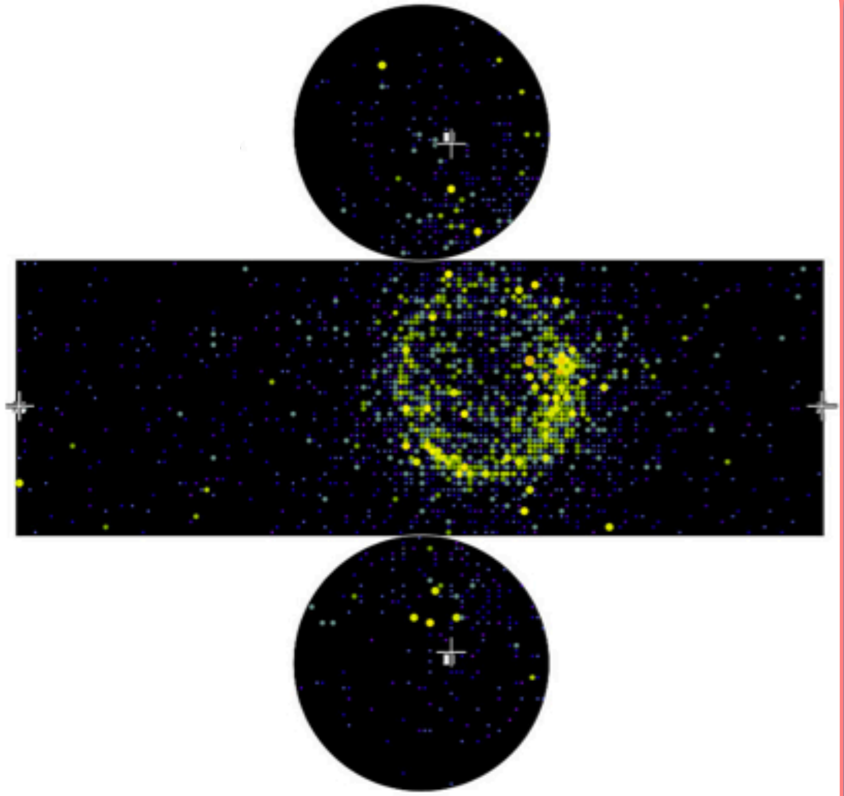
- Water Cherenkov detector with 50 kton mass (22.5 kton Fiducial volume) located at 1km underground
  - Good performance (momentum and position resolution, PID, charged particle counting) for sub-GeV neutrinos.
  - [Typical] 61% efficiency for T2K signal ν_e with 95% NC-$1\pi^0$ rejection
    - Inner 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 ±500μsec window centered on the the neutrino arrival time.



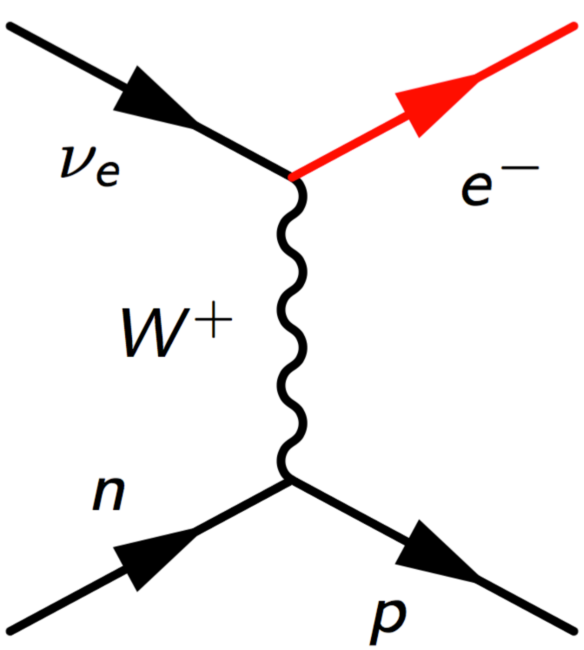


Neutrino Detection at SK Far Detector

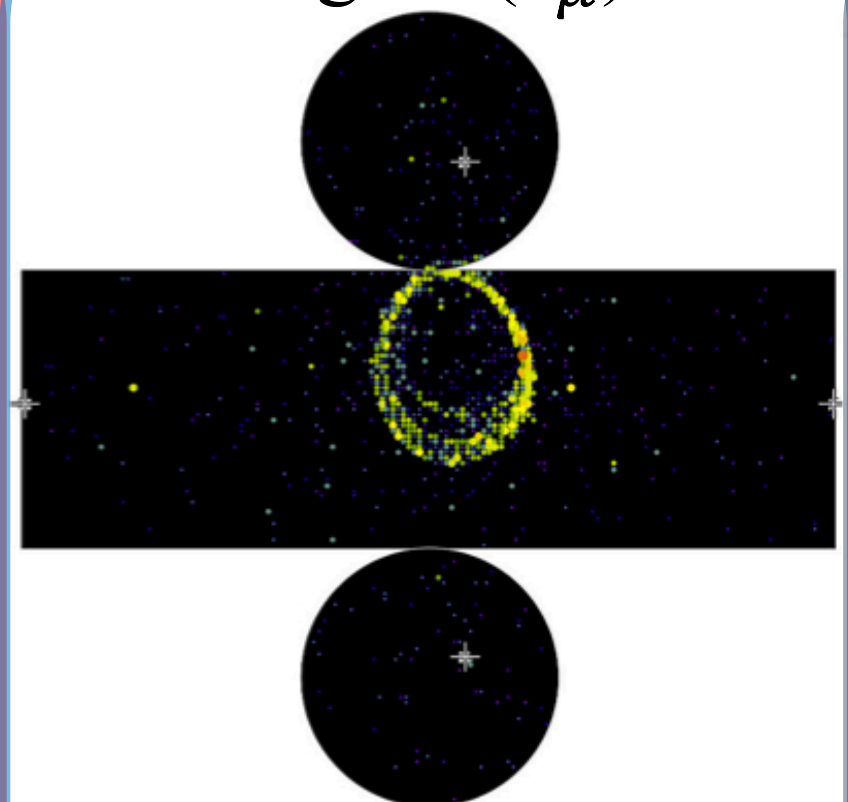
Signal (ν_e)



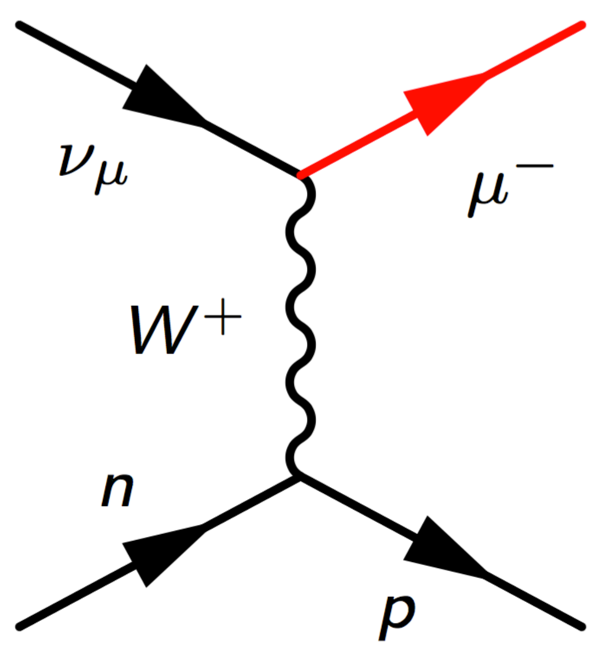
ν_e CCQE



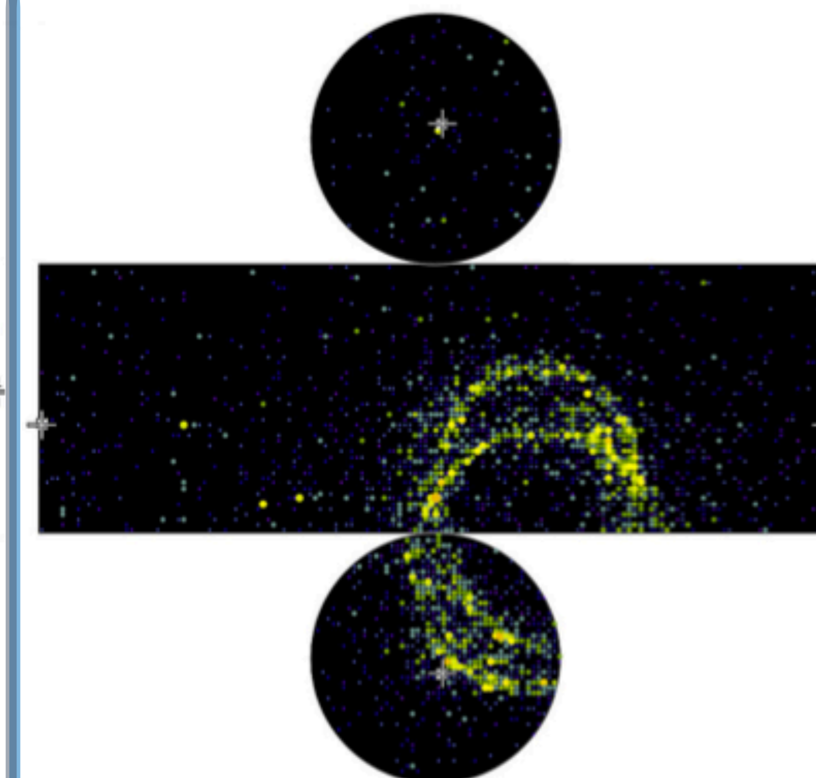
Signal (ν_μ)



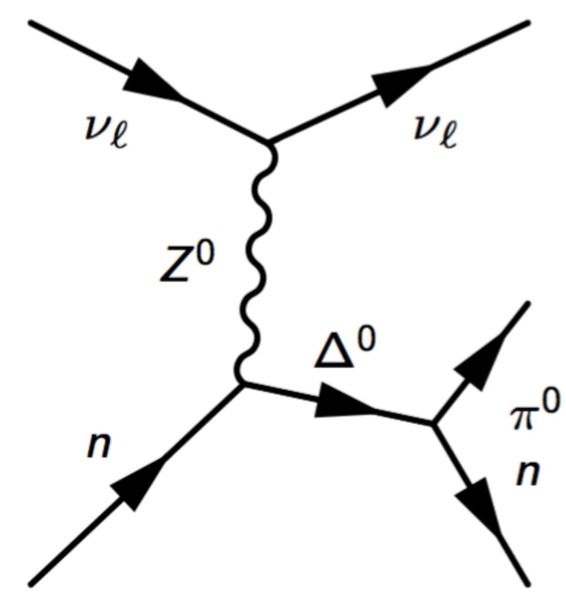
ν_μ CCQE



Background



ν_ℓ NC1π^0



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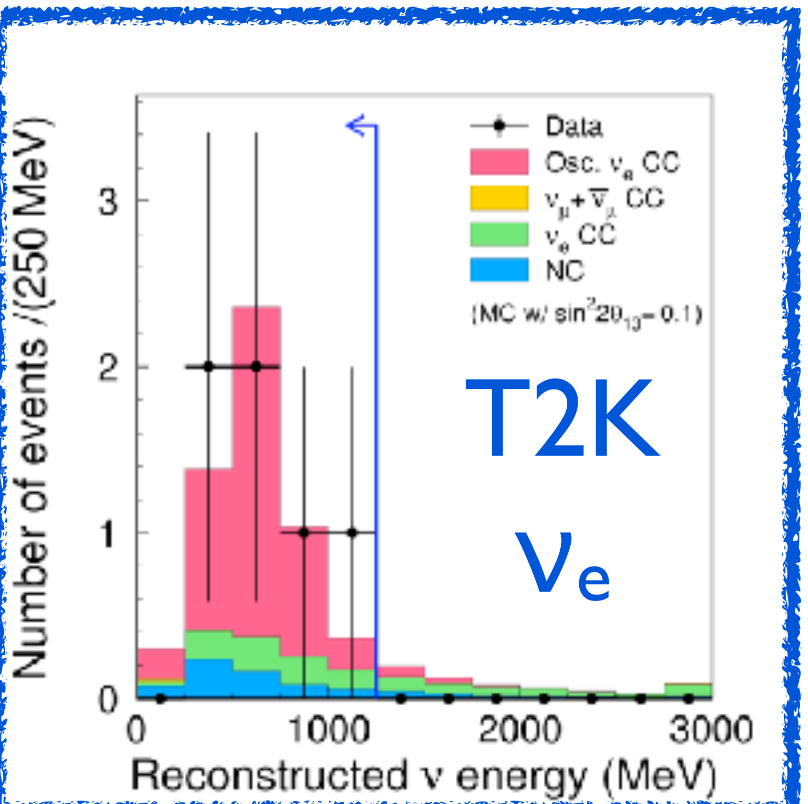
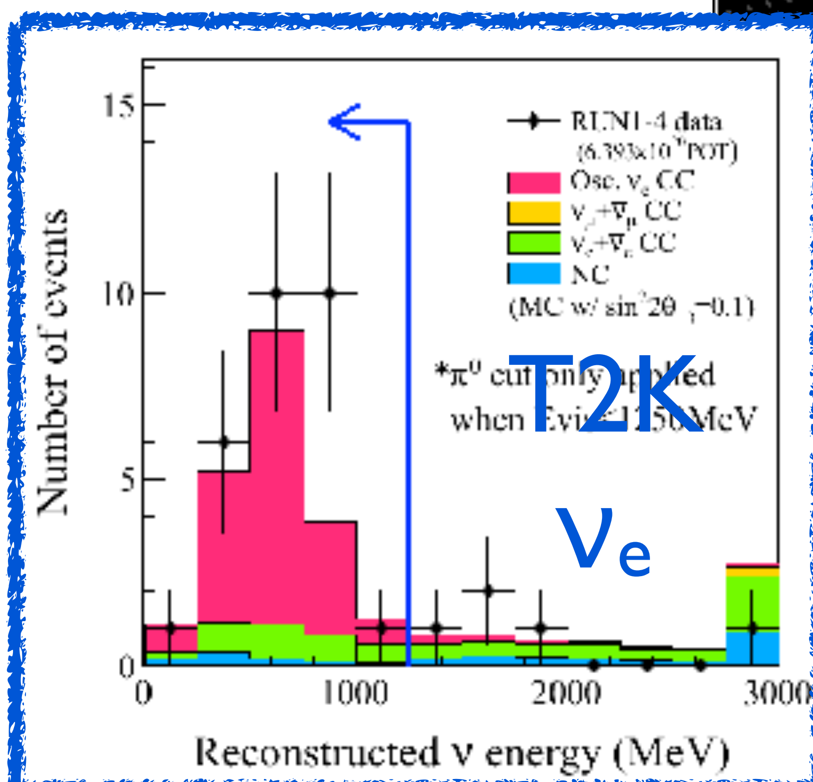
A door to Neutrino CP violation is opened

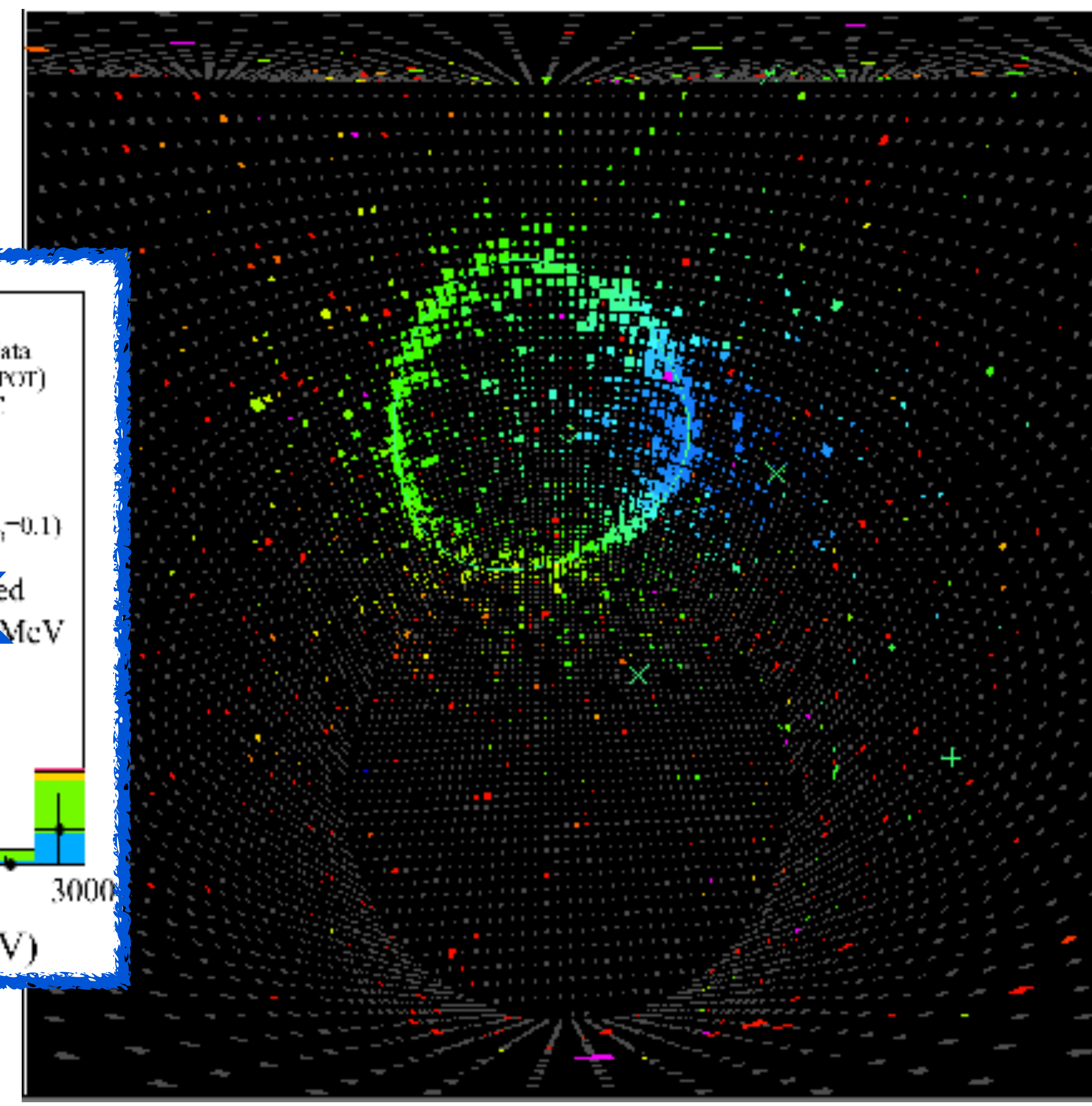
- $\nu_\mu \rightarrow \nu_e$ oscillation w/ Δm_{atm}^2 discovered by the T2K experiment
  - Indication in 2011 [PRL 107, 041801 (2011)]
  - Observation in 2013 [PRL 112, 061802 (2014)]

2011



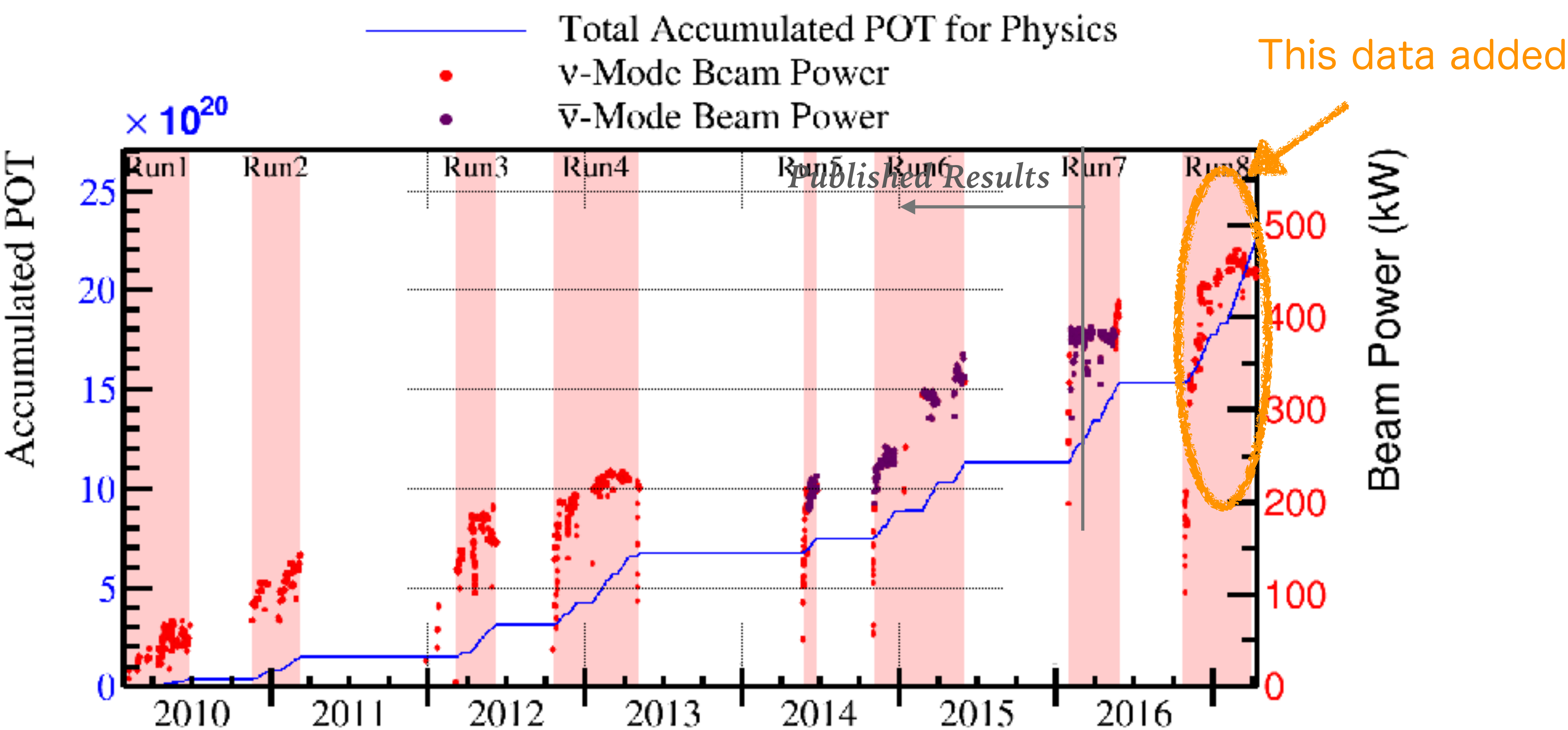
2013





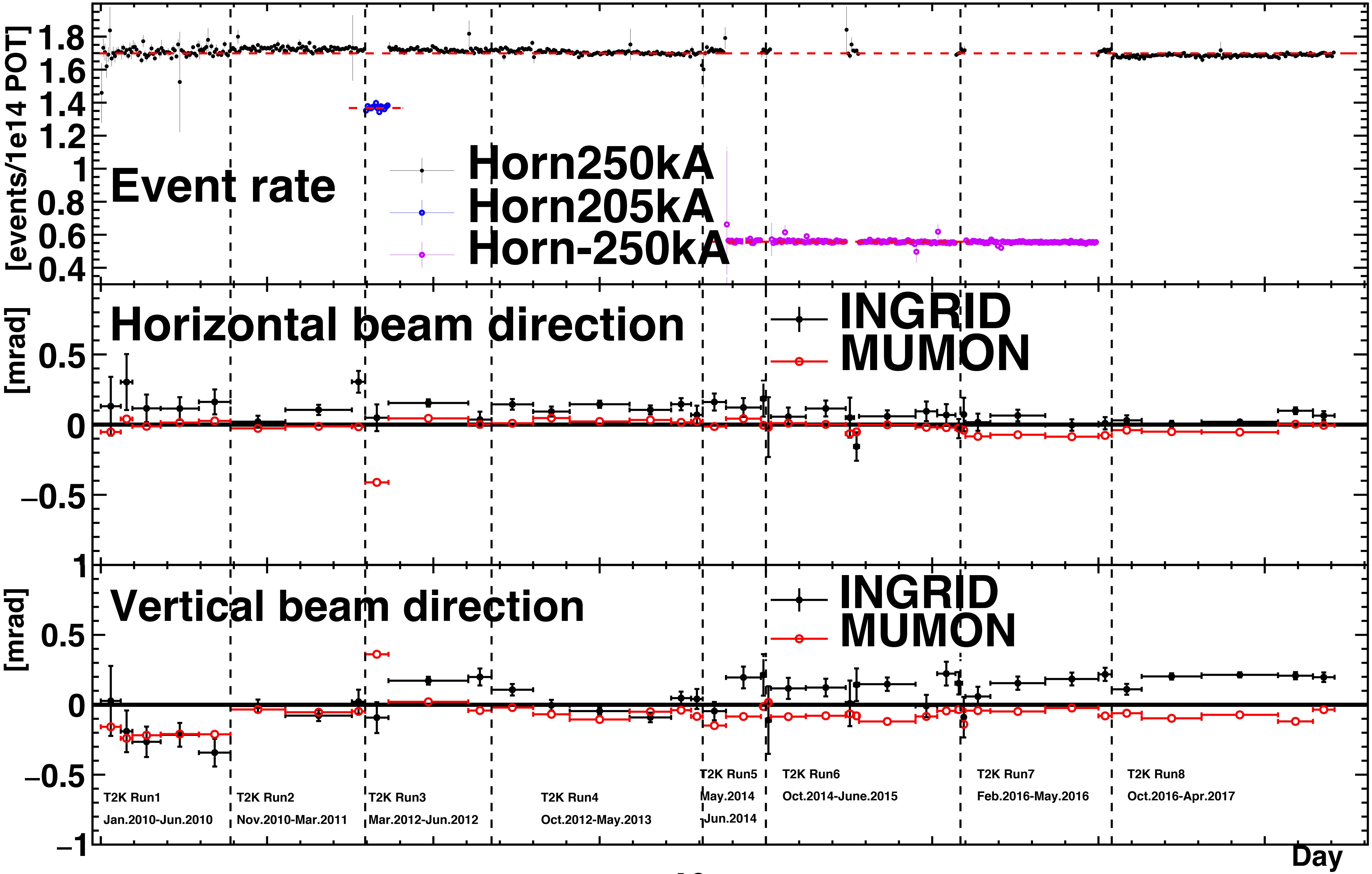
New Results
in summer 2017

T2K Data



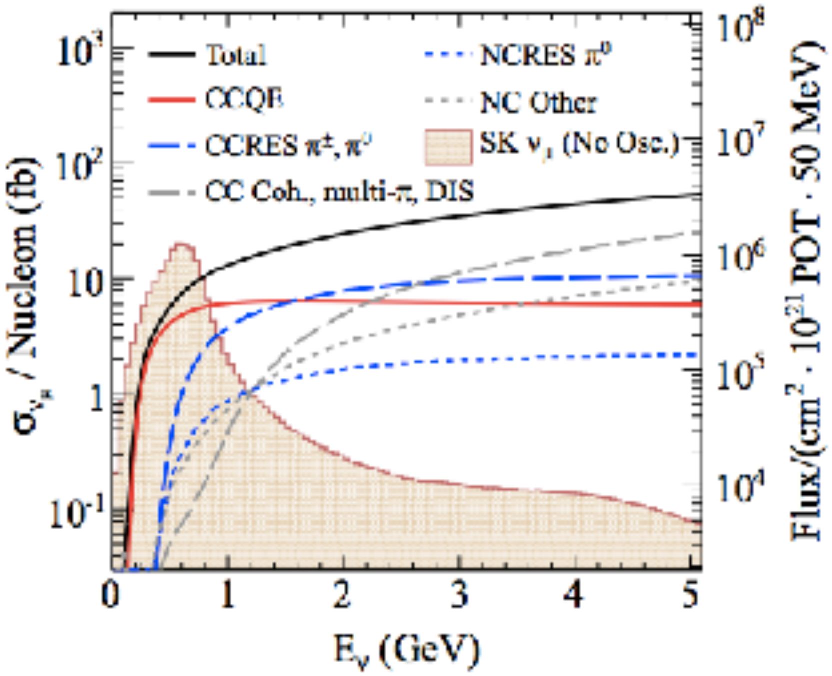
- Accelerator has achieved stable operation with 470 kW beam power
- 14.7×10^{20} protons-on-target (POT) in neutrino mode and 7.6×10^{20} POT in antineutrino mode

T2K Beam monitoring

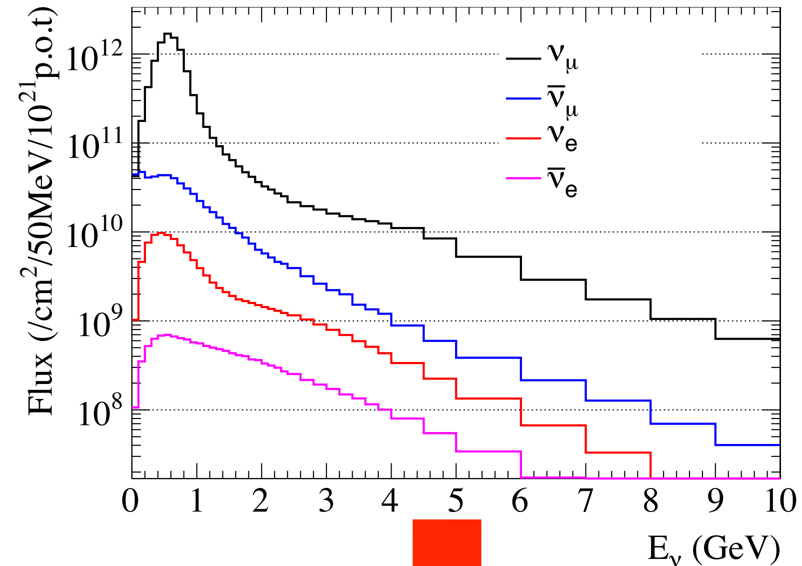


Oscillation Analysis: Step 1

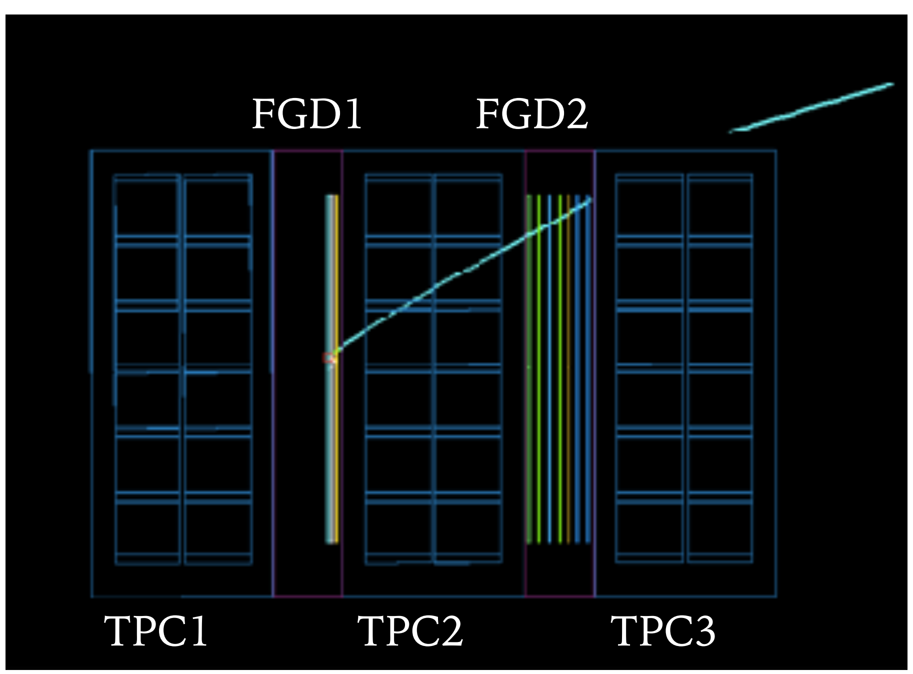
Neutrino-nucleus Interaction Model



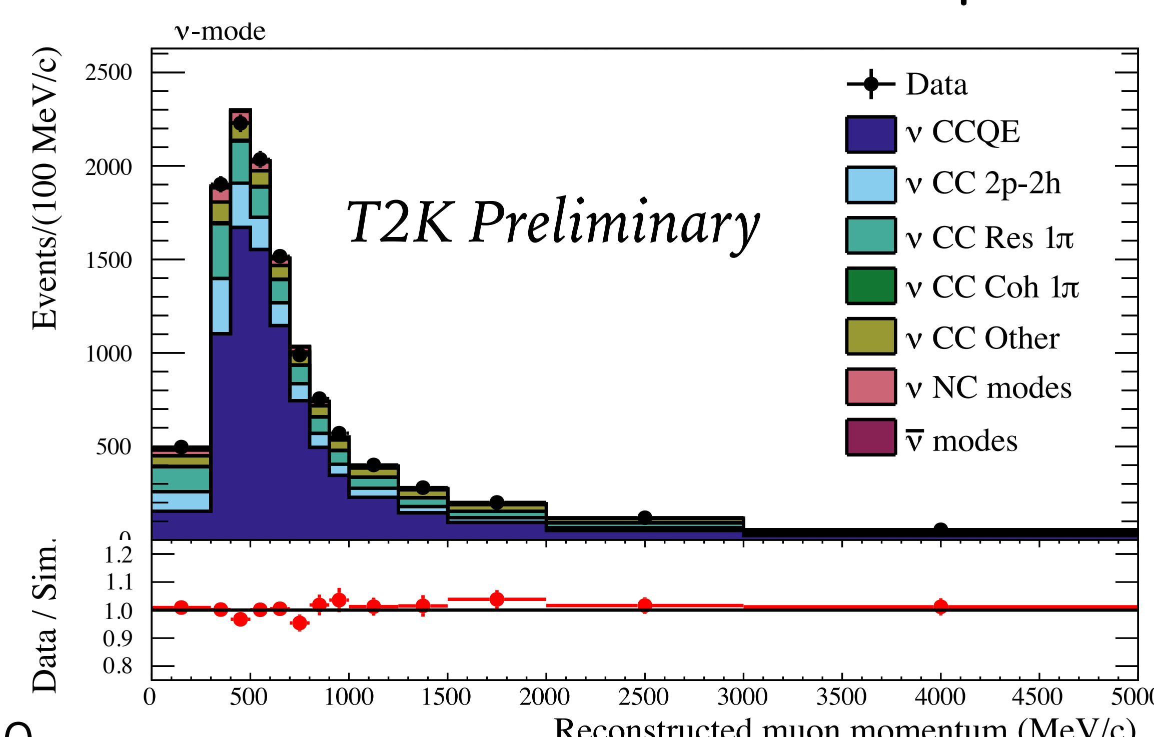
Neutrino Flux Model



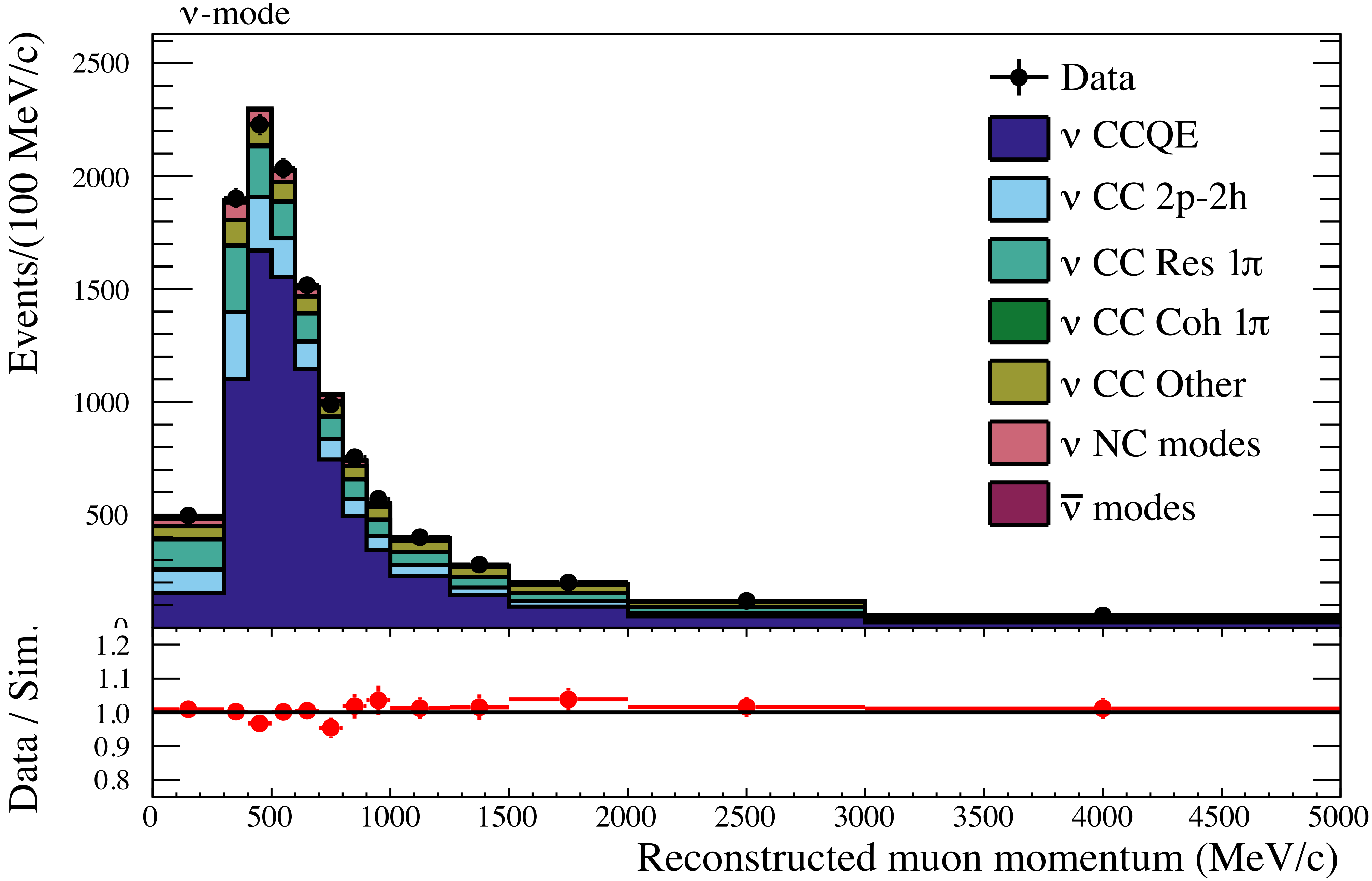
ND280 Data



Fit to ND280 data constrains neutrino flux parameters and interaction model parameters



Fitting ND280 Data



- Example fitted FGD2 (water) CC-0π muon momentum
- The fit reproduces the data well with a p-value of 0.47

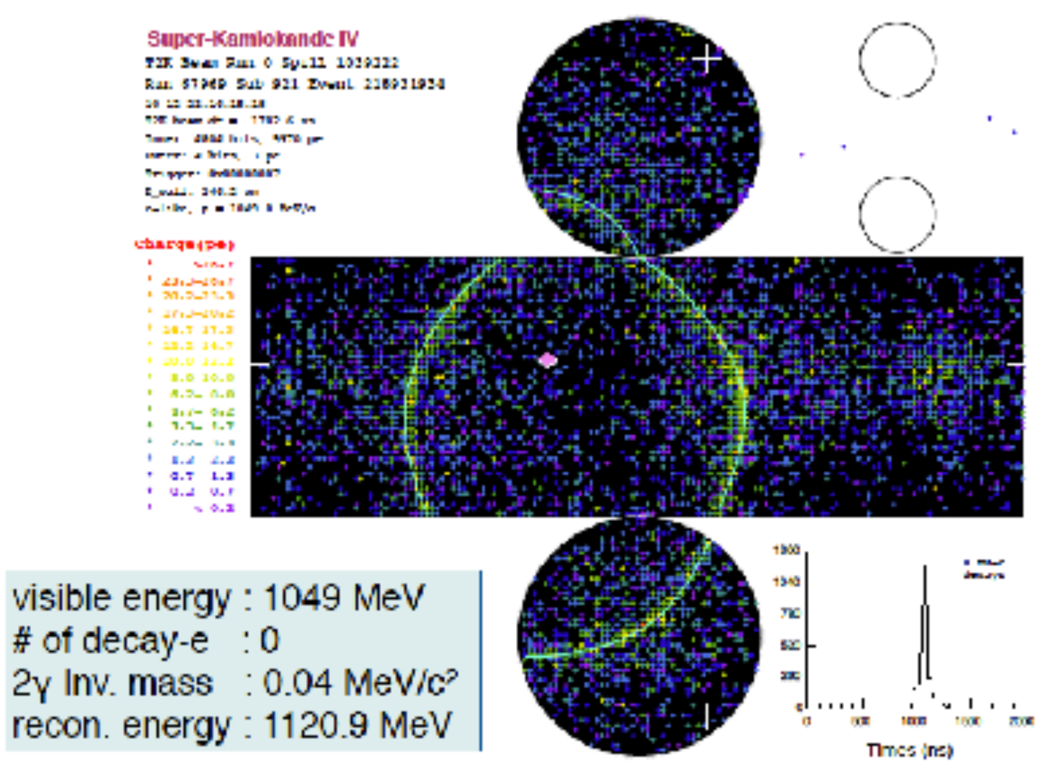
Oscillation Analysis: Step 2

Prediction at Super-K

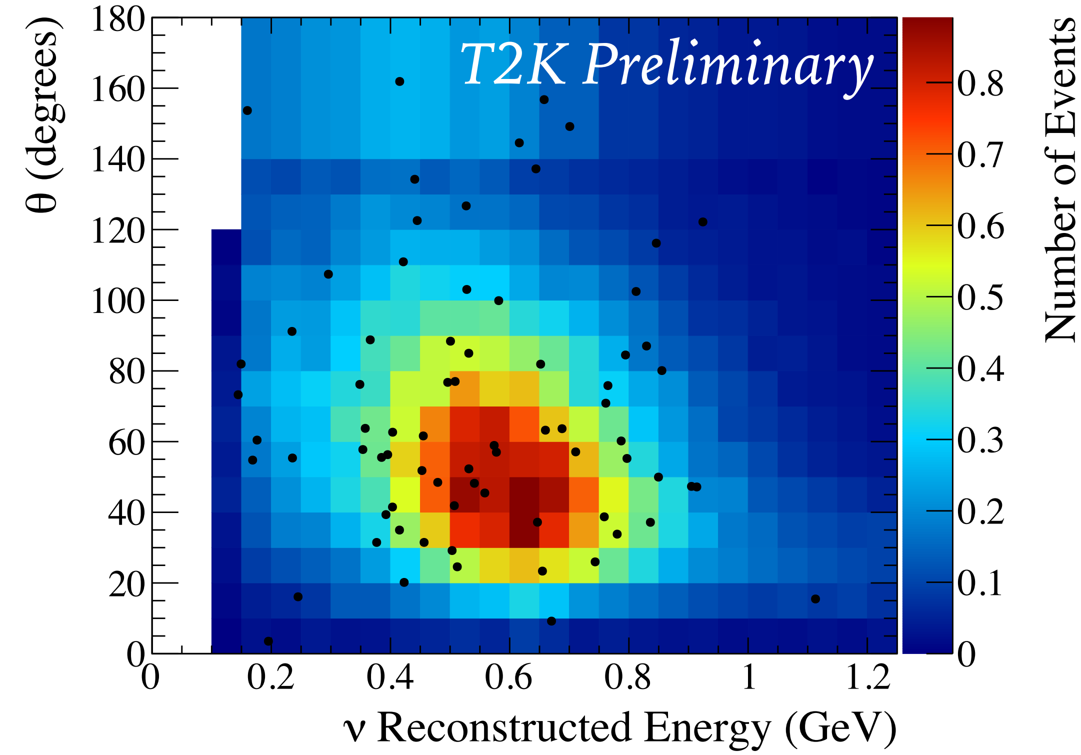
Oscillation Probability — Constrained by near detector

$$N(p_k,\theta_k;\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)=\sum_i^{E_\nu\text{ bins}}\sum_j^{flavors}\boxed{P_{\nu_j\to\nu_k}(E_{\nu,i};\theta_{23},\Delta m^2_{32},\delta_{CP}\ldots)}\boxed{\Phi_j^{far}(E_{\nu,i})\sigma_k(E_{\nu,i},p_k,\theta_k)}\epsilon(p_k,\theta_k)M_{det}$$

T2K Super-K Data



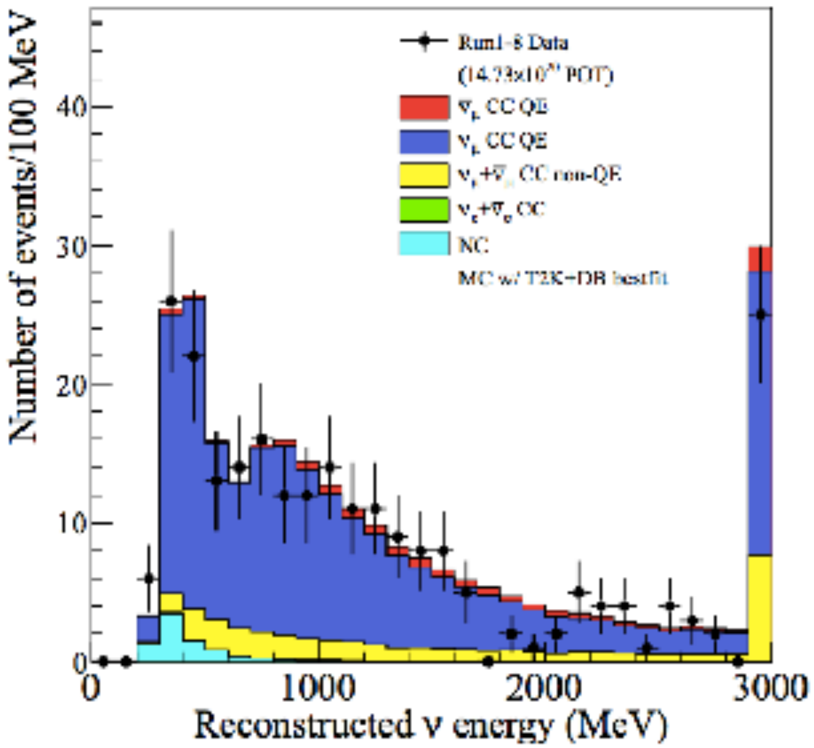
Fit to SK data to extract oscillation parameter intervals



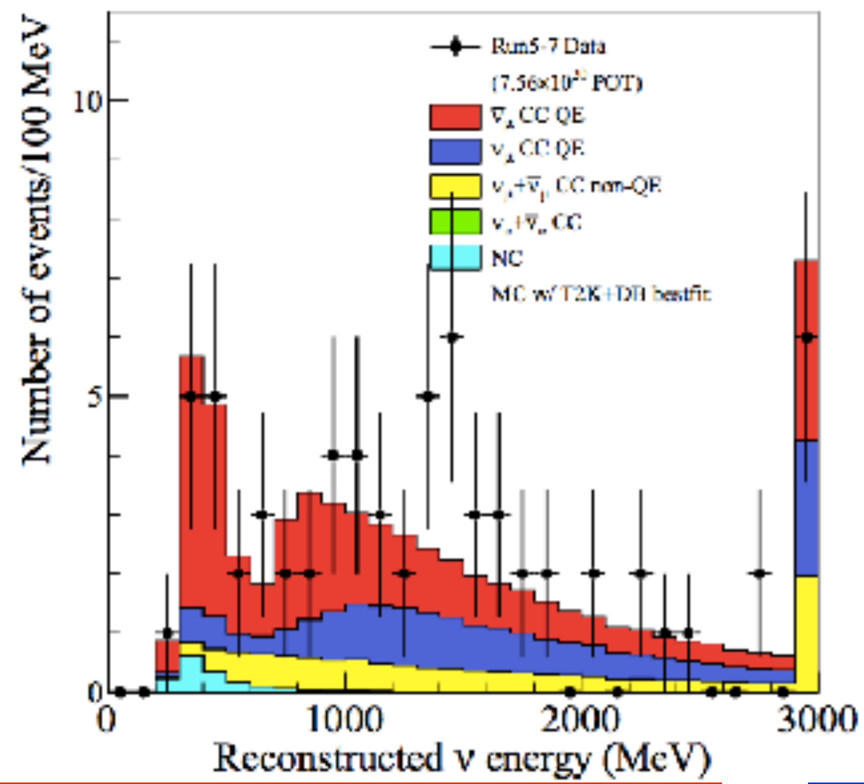
ν Mode ν_e Candidates

Observation at Super-K

Neutrino 1 μ-like ring

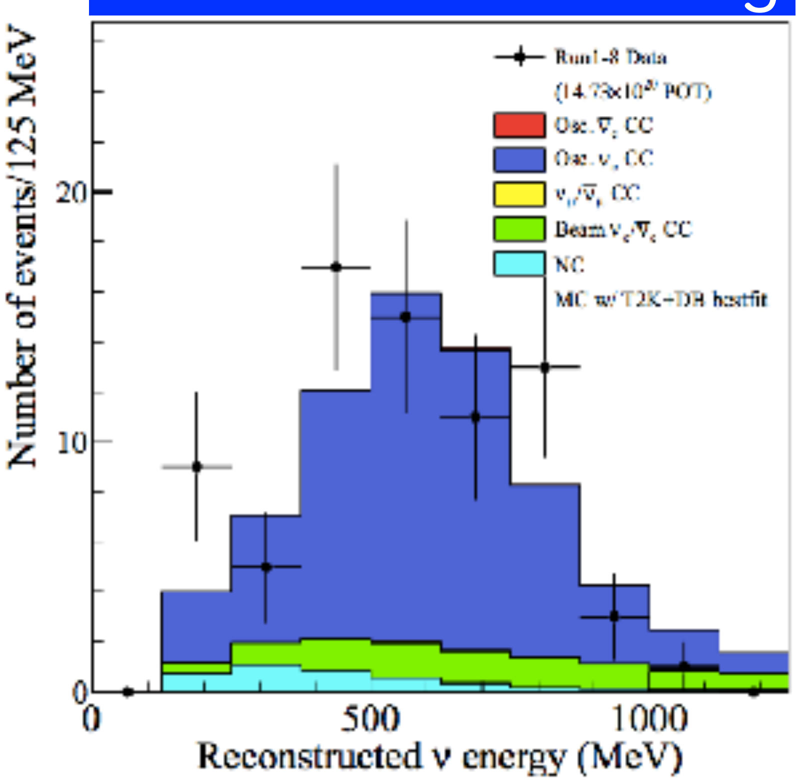


Antineutrino 1 μ-like ring

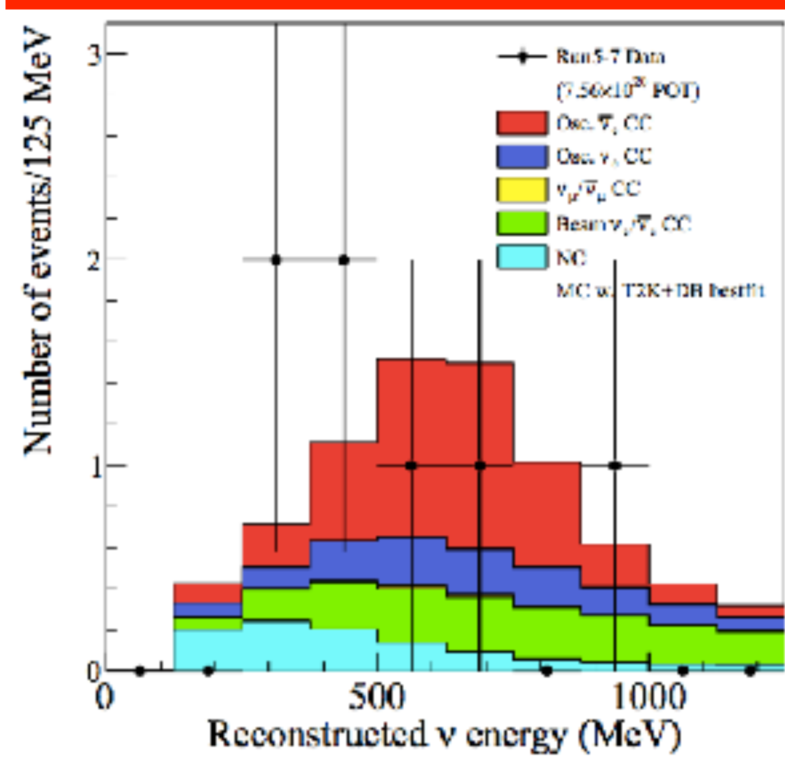


T2K Preliminary

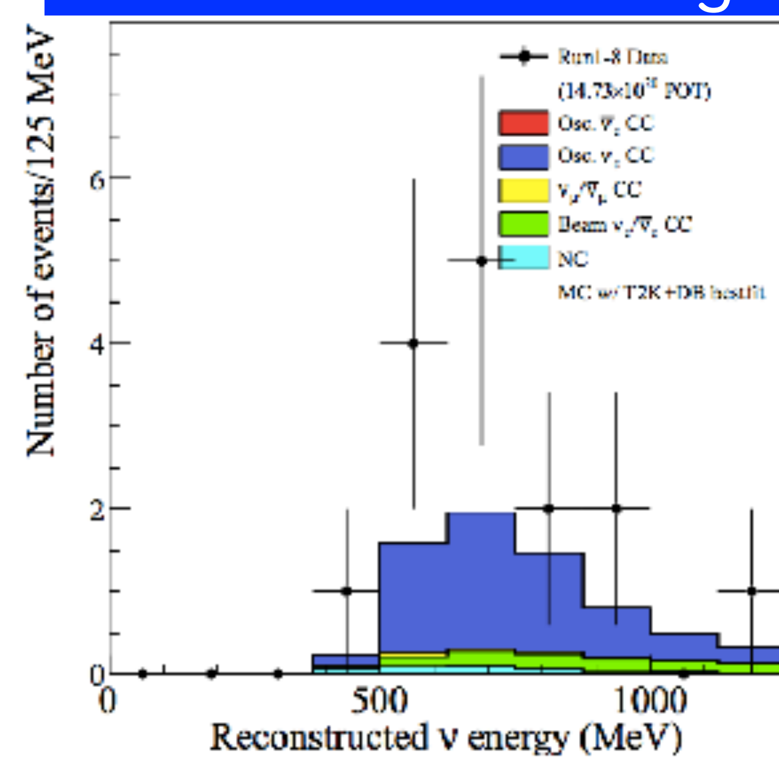
Neutrino 1e-like ring



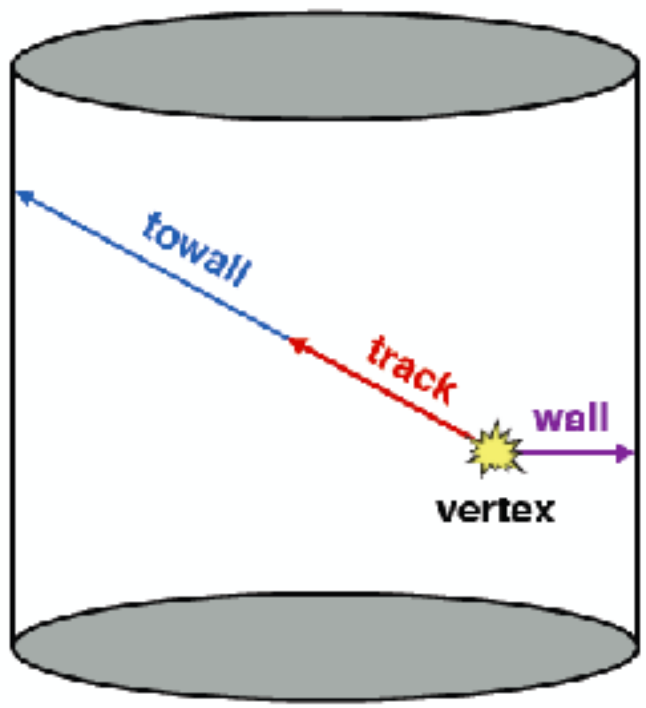
Antineutrino 1e-like ring

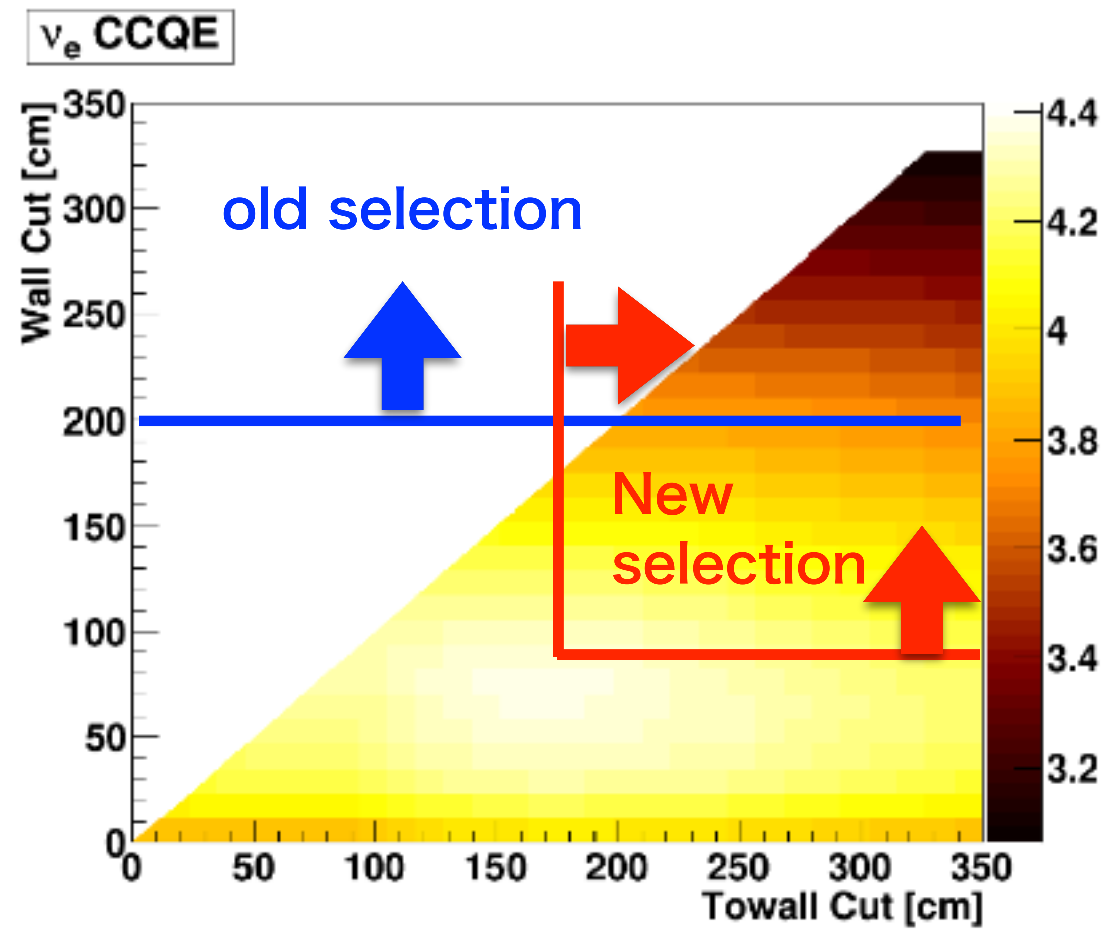


Neutrino 1e-like ring + π



Expansion of the Fiducial Volume





Sample	Towall Cut	Wall Cut
CCQE 1-Ring e-like FHC	170 cm	80 cm
CCQE 1-Ring μ-like FHC	250 cm	50 cm
CC1π 1-Ring e-like FHC	270 cm	50 cm
CCQE 1-Ring e-like RHC	170 cm	80 cm
CCQE 1-Ring μ-like RHC	250 cm	50 cm

Predictions and Observation

Sample	Predicted Rates				Observed Rates
	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	
e-like FHC	73.5	61.5	49.9	62.0	74
e-like+π FHC	6.92	6.01	4.87	5.78	15
e-like RHC	7.93	9.04	10.04	8.93	7
μ-like FHC	267.8	267.4	267.7	268.2	240
μ-like RHC	63.1	62.9	63.1	63.1	68

- The number of observed events are largely in line with the predictions after oscillations
  - The e-like samples have rates most consistent with the $\delta_{cp}=-\pi/2$ hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
  - consistent within statistical and systematic errors

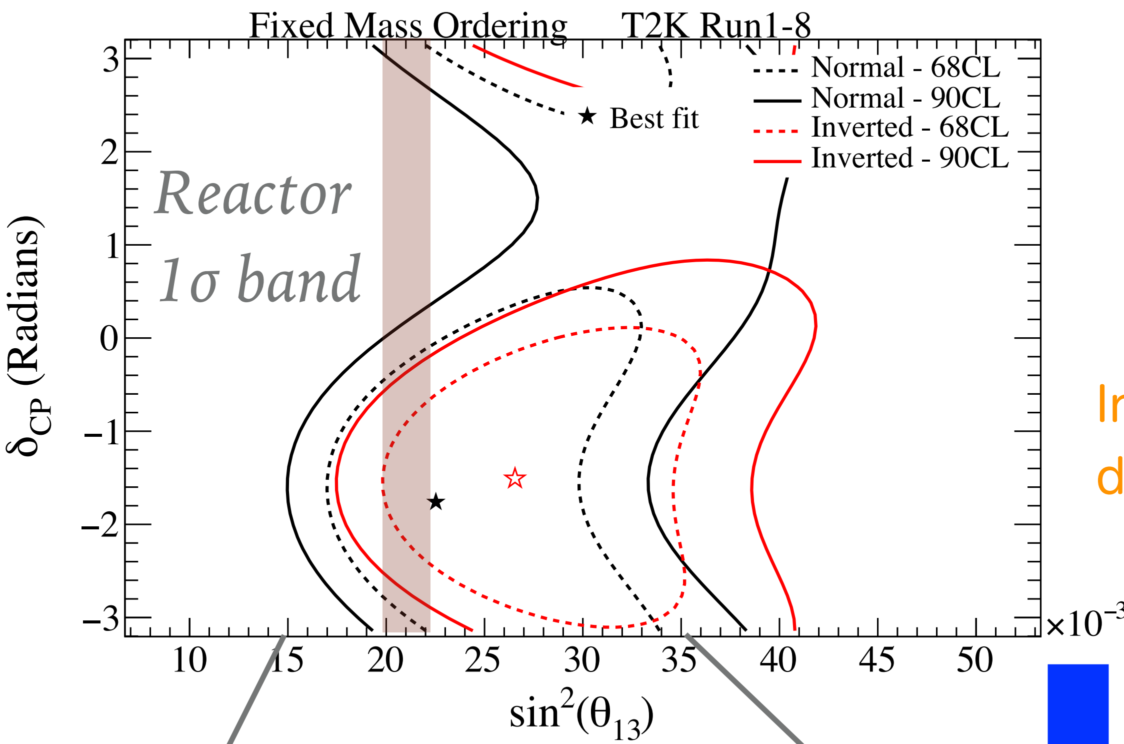
Systematic Errors

	% Errors on Predicted Event Rates (Osc. Para. A)					
	1R μ-like		1R e-like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1 π	FHC/RHC
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1 γ	0.00	0.00	1.08	2.59	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	**4.40**	**3.76**	**6.10**	**6.51**	**20.94**	**4.77**

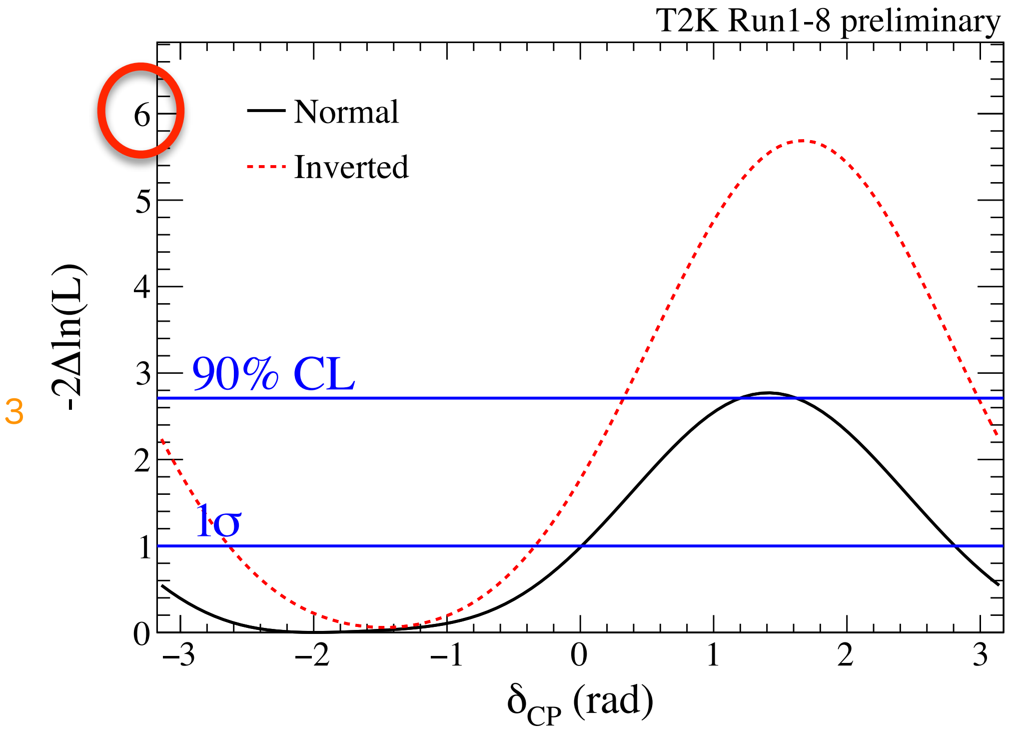
- Total error is in the 4-7% range. 4.8% error on the relative rate for neutrino mode and antineutrino mode samples

Oscillation Parameter Sensitivities

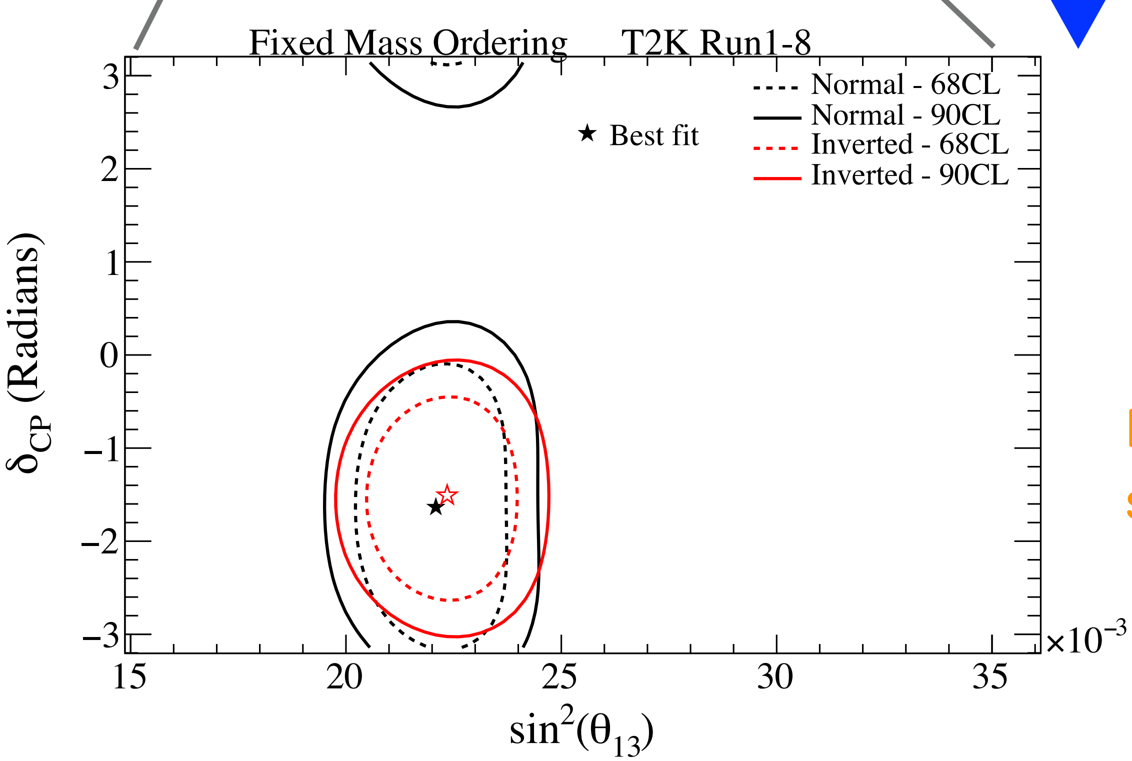
Without the reactor experiment constraint on $\sin^2 2\theta_{13}$



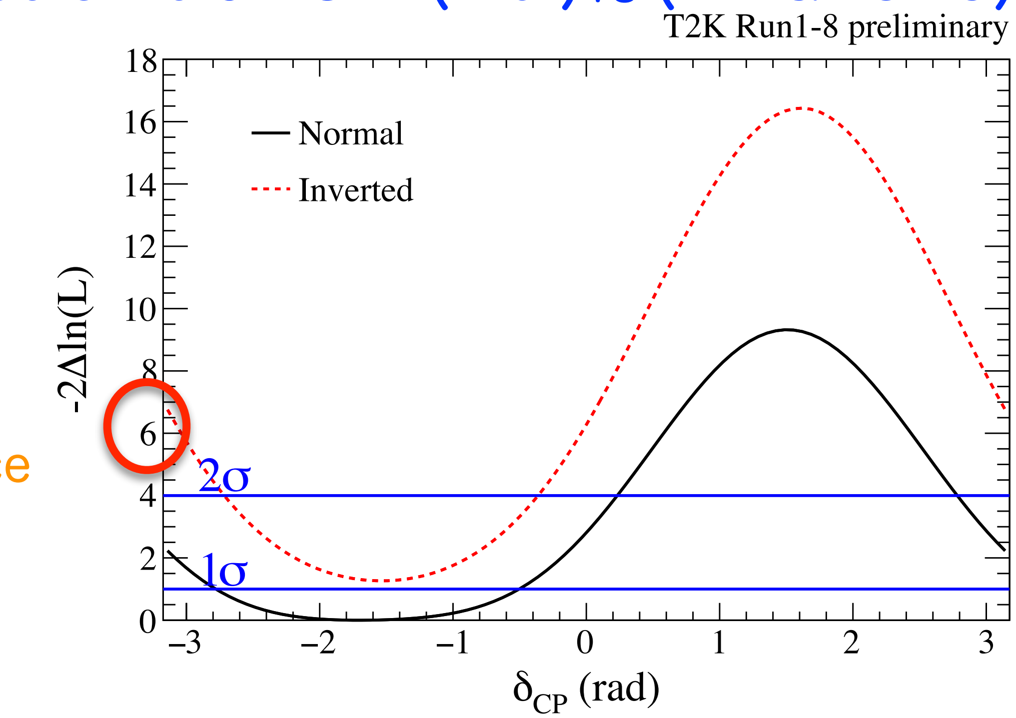
Integrate out $\sin^2\theta_{13}$ dependence



Reactor constraint on $\sin^2(2\theta)_{13}$ (PDG2016)

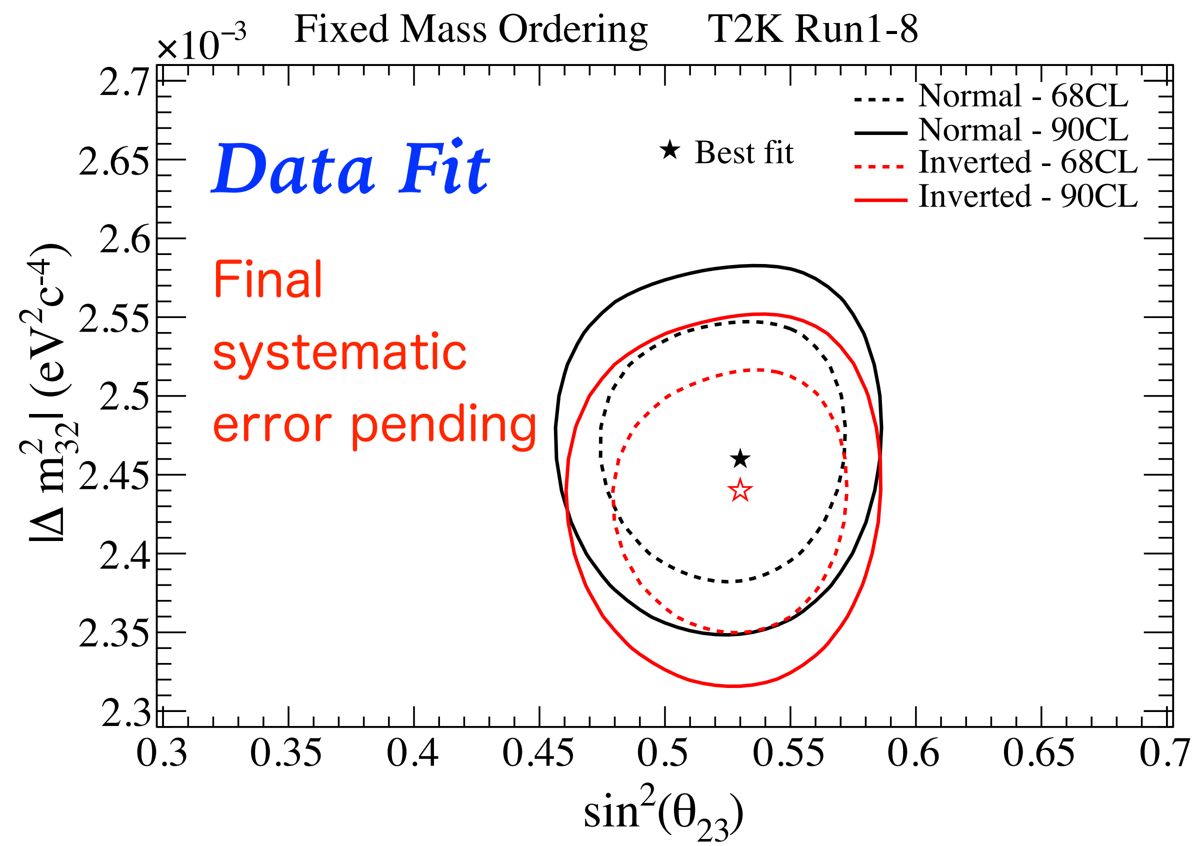


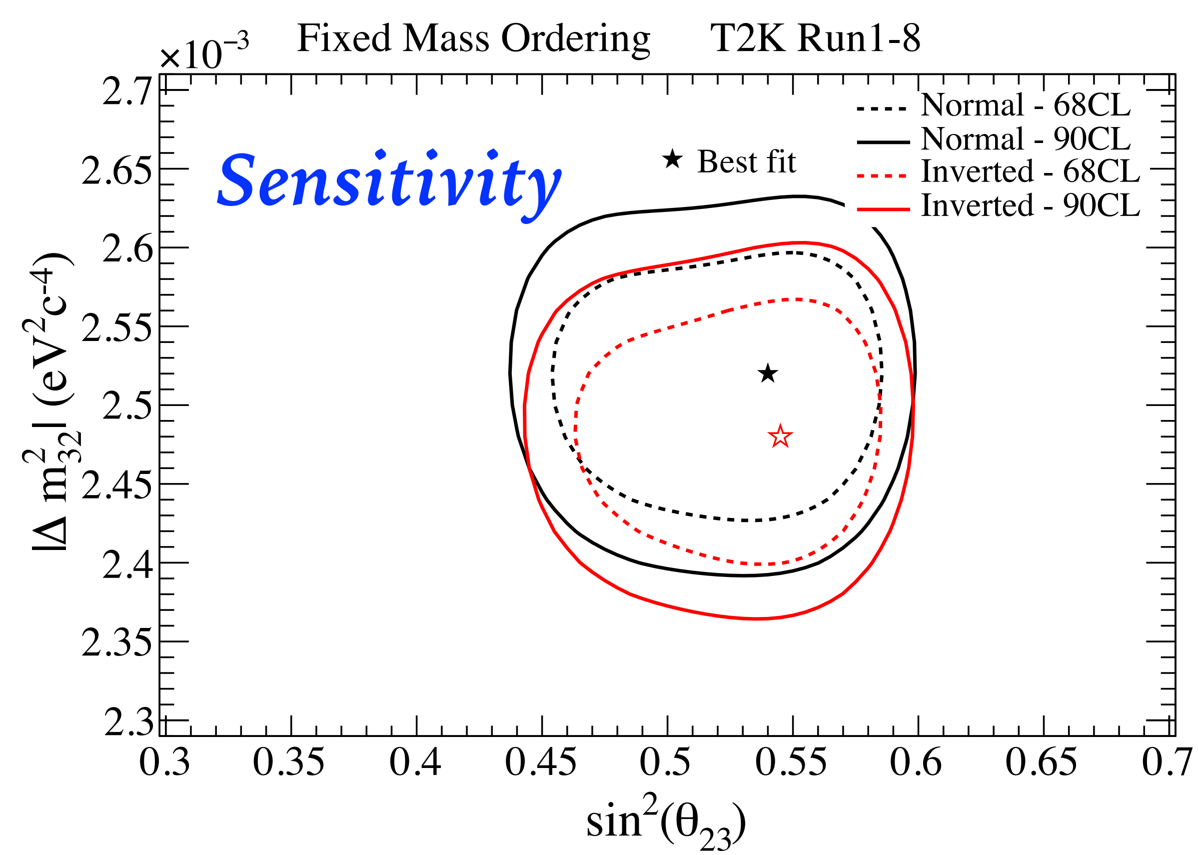
Integrate out $\sin^2\theta_{13}$ dependence



$\sin^2\theta_{23}$ status

- Fit the normal and inverted hierarchies separately
- Results with the reactor constraint on $\sin^2 2\theta_{13}$
- Constraint on $\sin^2\theta_{23}$ is slightly stronger than the sensitivity





θ_{13} and δ_{CP}

- Fit without the reactor constraint: closed contours in δ_{cp} at 90% CL
- The T2K value for $\sin^2\theta_{13}$ is consistent with the PDG 2016

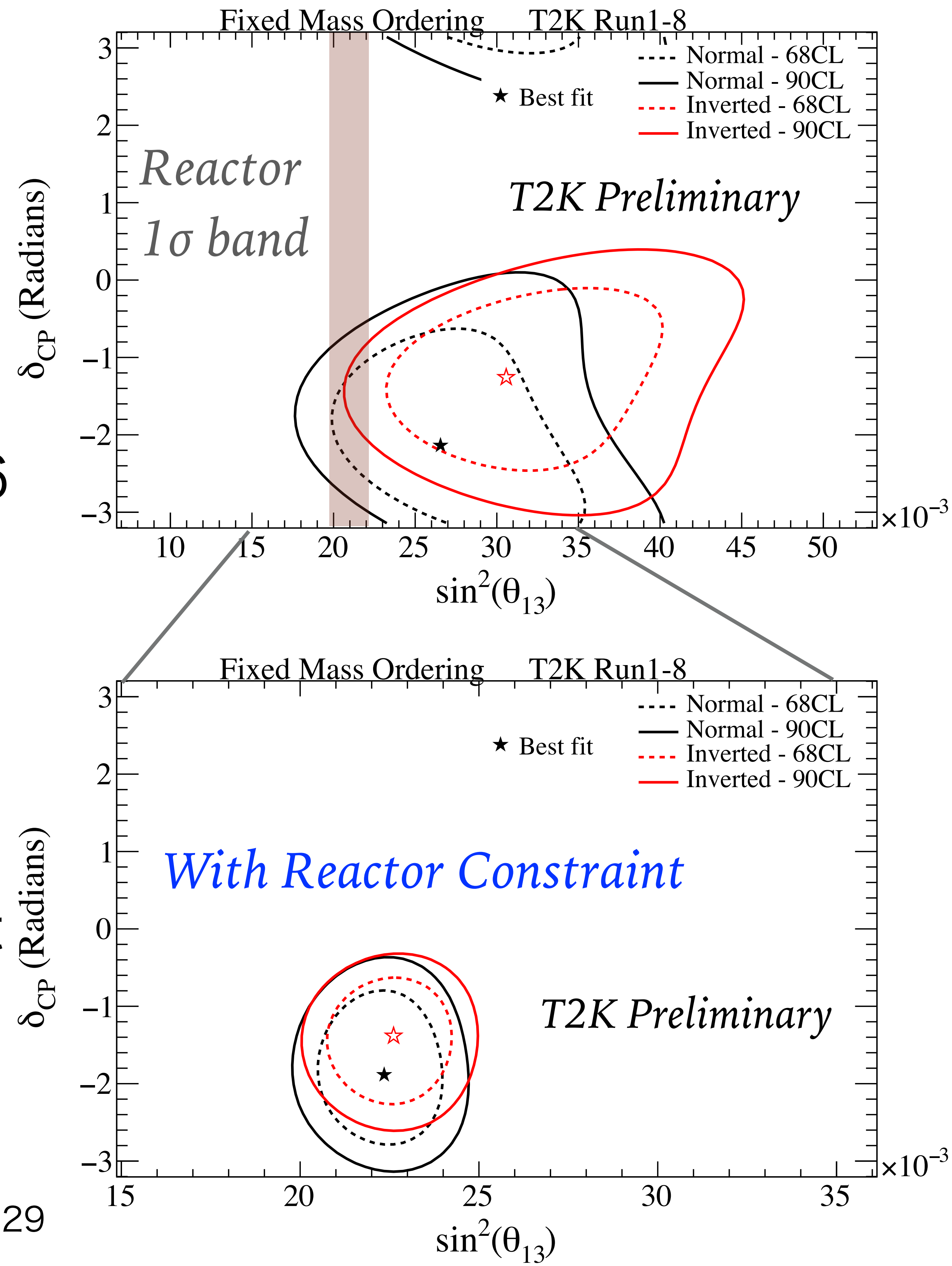
T2K Best Fit:

$$\sin^2\theta_{13} = 0.0277^{+0.0054}_{-0.0047} \text{ (NH)}$$

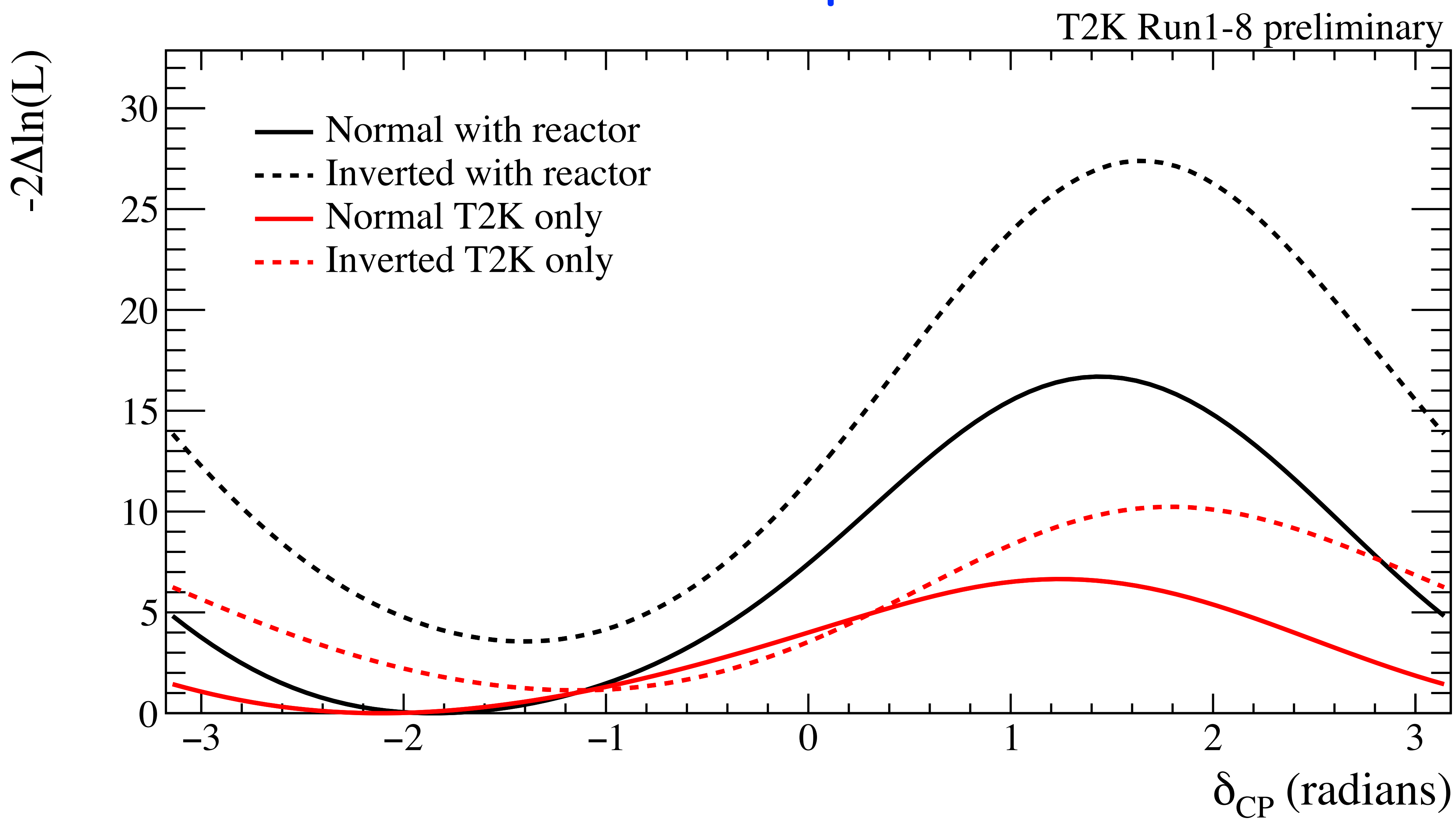
PDG 2016:

$$\sin^2\theta_{13} = 0.0210 \pm 0.0011$$

- Adding the reactor constraint improves the constraint on δ_{cp} average:

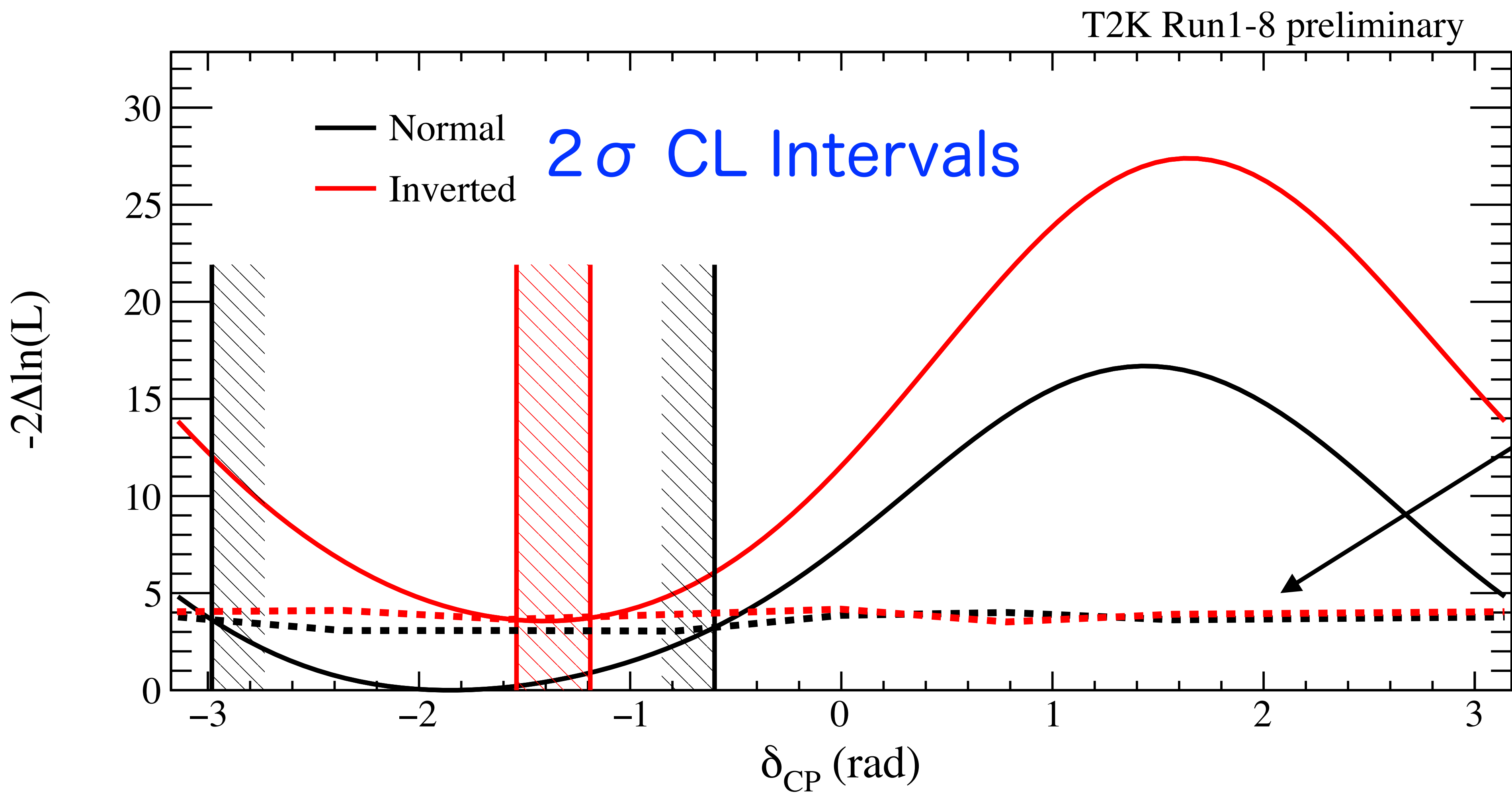


δ_{cp}



- T2K data with (black) and without (red) the reactor constraint on $\sin^2\theta_{13}$ show consistent preference for value near -2 radians
- The confidence intervals for the results with the reactor constraint are produced using the critical $\Delta\chi^2$ values calculated in the Feldman Cousins construction (next slide)

Measurement of δ_{cp} with reactor θ_{13}



critical $\Delta\chi^2$ values for 2σ confidence level

Best fit point: **-1.83 radians in Normal Hierarchy**

The 1σ CL confidence interval: **Normal hierarchy: [-2.49, -1.23] radians**

The 2σ CL confidence interval: **Normal hierarchy: [-2.98, -0.60] radians**
Inverted hierarchy: [-1.54, -1.19] radians

- CP conserving values $(0, \pi)$ fall outside of the 2σ CL intervals

θ_{23} octant and mass hierarchy

- Bayesian analysis: natural way to infer data preference for **θ_{23} octant** or **mass hierarchy**
- Assume equal prior probability for both octant and hierarchy hypotheses
- Fraction of steps from Markov Chain in each octant/hierarchy is posterior probability for the octant/hierarchy hypothesis
- T2K data prefers the normal hierarchy and upper octant

Posterior probabilities (with reactor constraint)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	

Future prospect
T2K-II

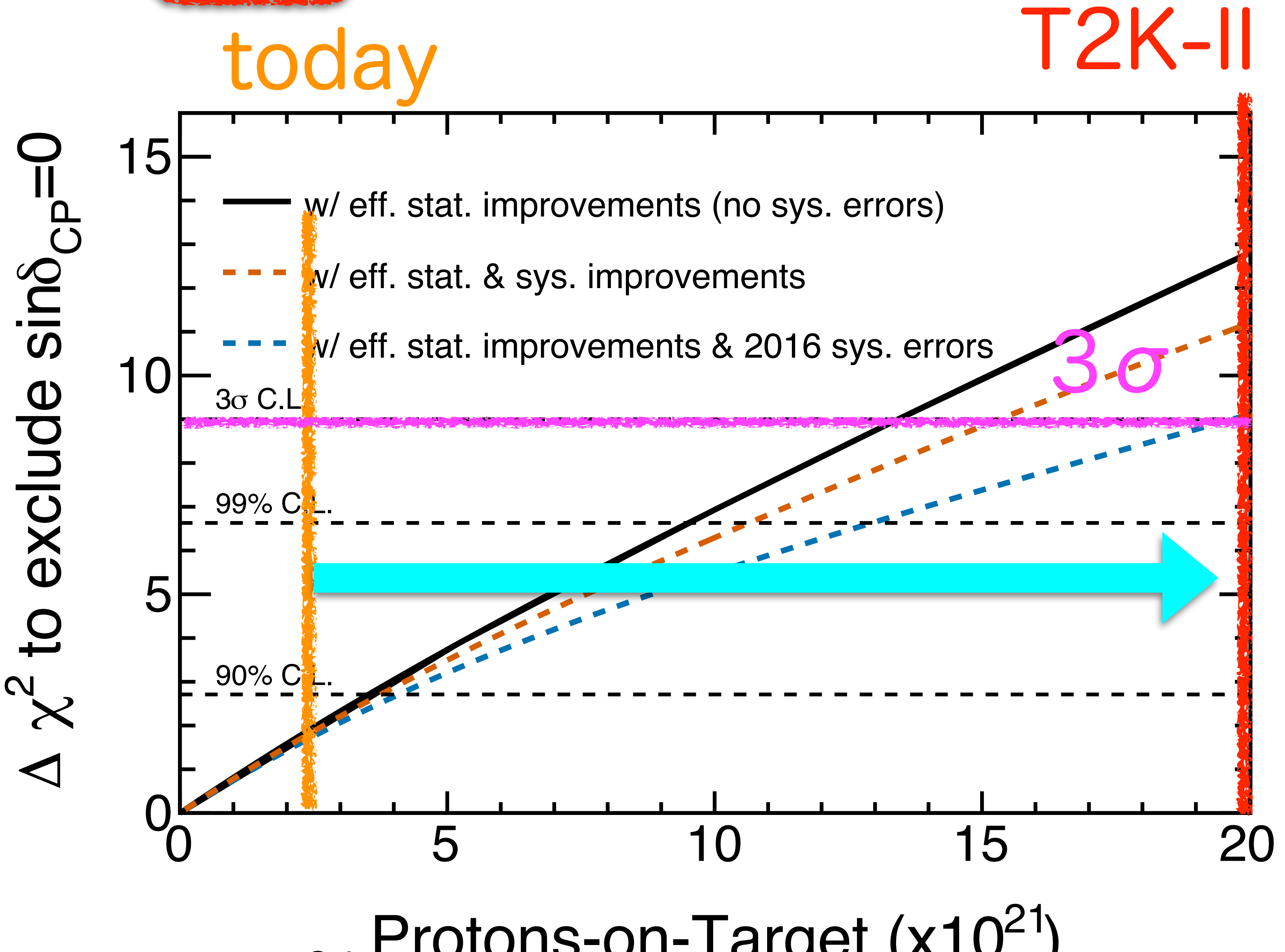
T2K-II with J-PARC Upgrade

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

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	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

- 3σ sensitivity to CP violation for favorable parameters with
  - 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.

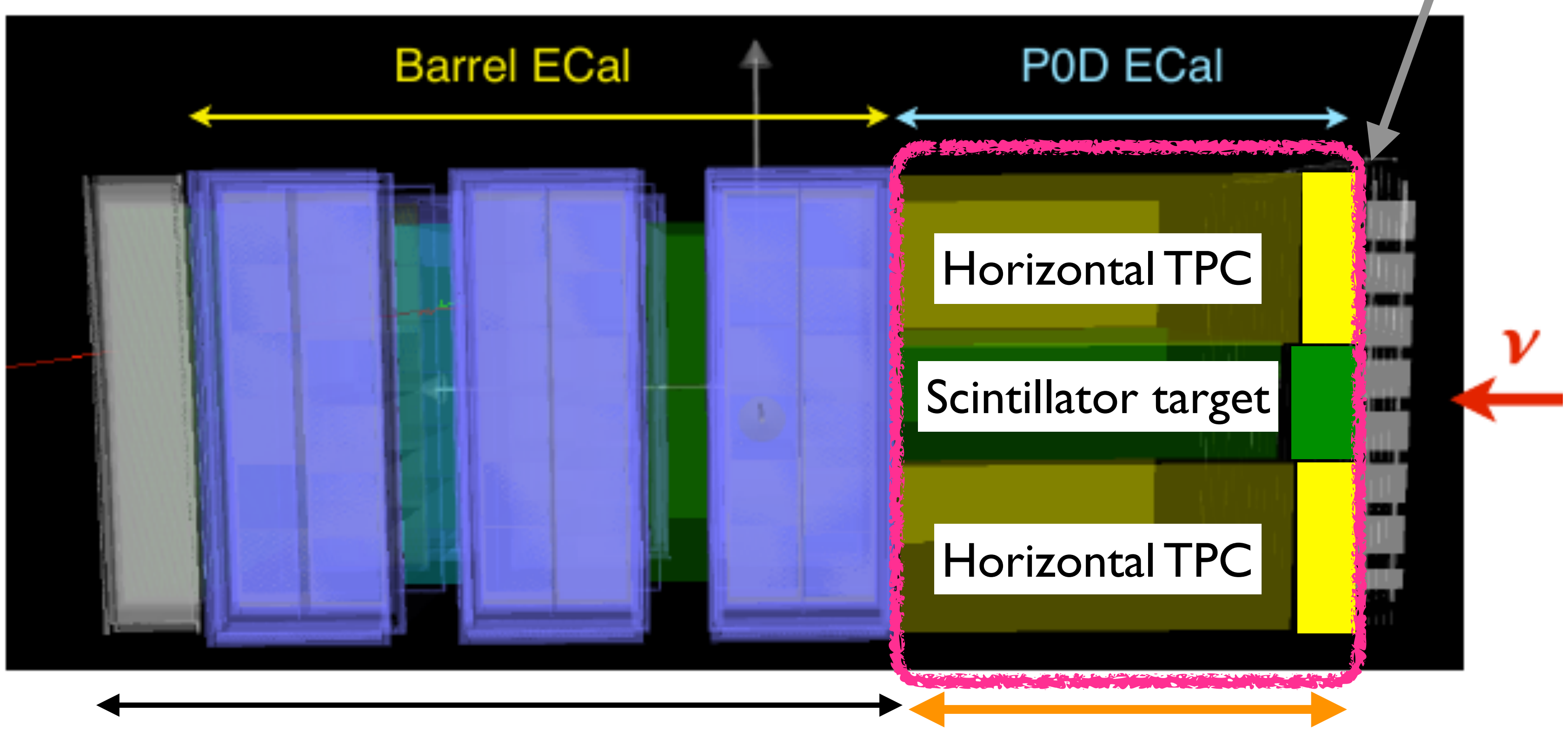


Near Detector Upgrade

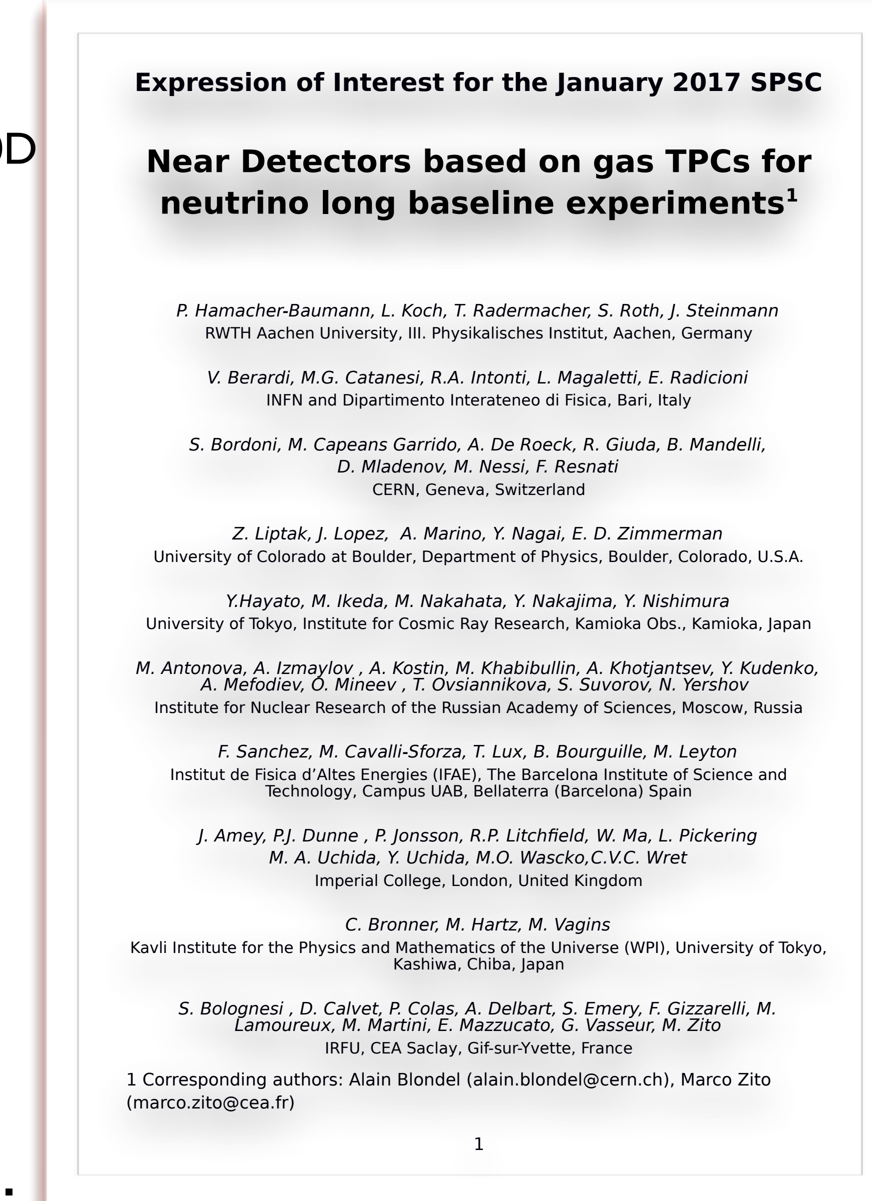
CERN SPSC-EOI-015

Baseline configuration

Plan to retain upstream Ecal-P0D



Keep current tracker + DS Ecal   New detectors


Expression of Interest for the January 2017 SPSC

Near Detectors based on gas TPCs for neutrino long baseline experiments[1]

P. Hamacher-Baumann, L. Koch, T. Radermacher, S. Roth, J. Steinmann
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Z. Liptak, J. Lopez, A. Marino, Y. Nagai, E. D. Zimmerman
University of Colorado at Boulder, Department of Physics, Boulder, Colorado, U.S.A.

Y.Hayato, M. Ikeda, M. Nakahata, Y. Nakajima, Y. Nishimura
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S. Bolognesi , D. Calvet, P. Colas, A. Delbart, S. Emery, F. Gizzarelli, M. Lamoureux, M. Martini, E. Mazzucato, G. Vasseur, M. Zito
IRFU, CEA Saclay, Gif-sur-Yvette, France

1 Corresponding authors: Alain Blondel (alain.blondel@cern.ch), Marco Zito (marco.zito@cea.fr)

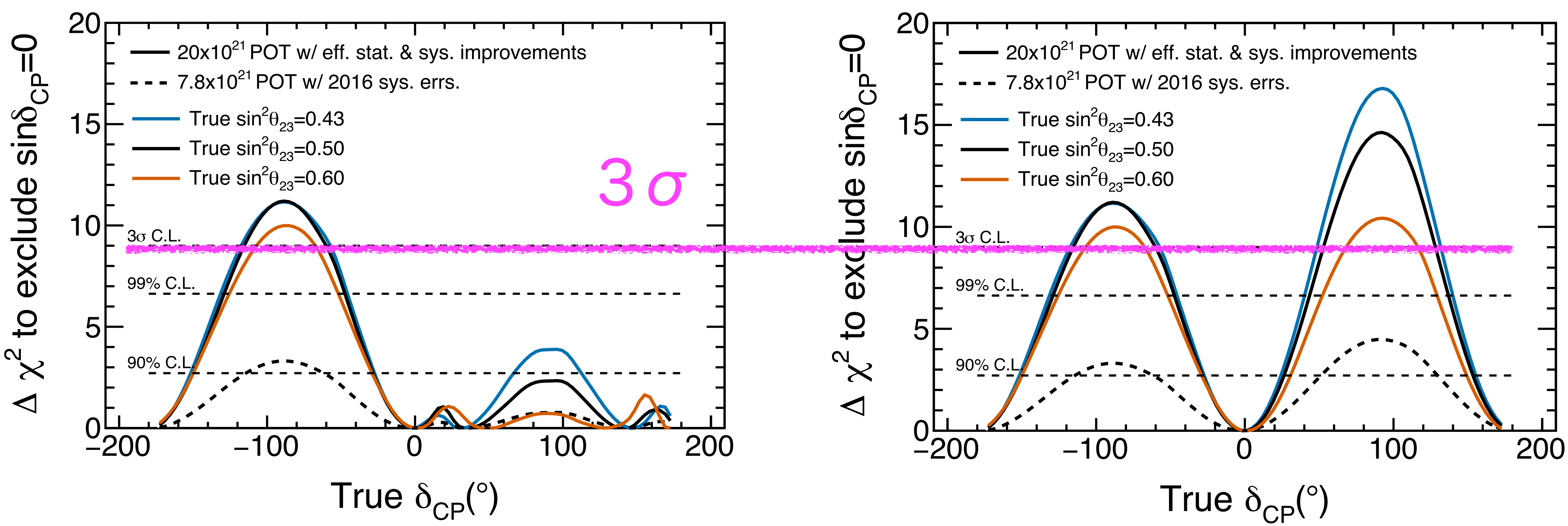
1

- T2K steadily improves the systematic uncertainty.
  - ~18% (2011) → ~9% (2014) → ~5% (2017)   [→ ~3% (2020)]
- Near Detector upgrade to understand the neutrino-nucleus interactions to improve the systematic.

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.

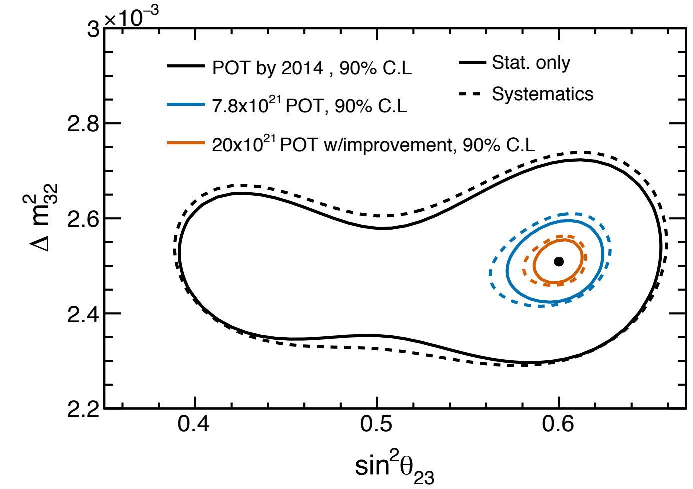
assuming MH unknown — assuming MH known



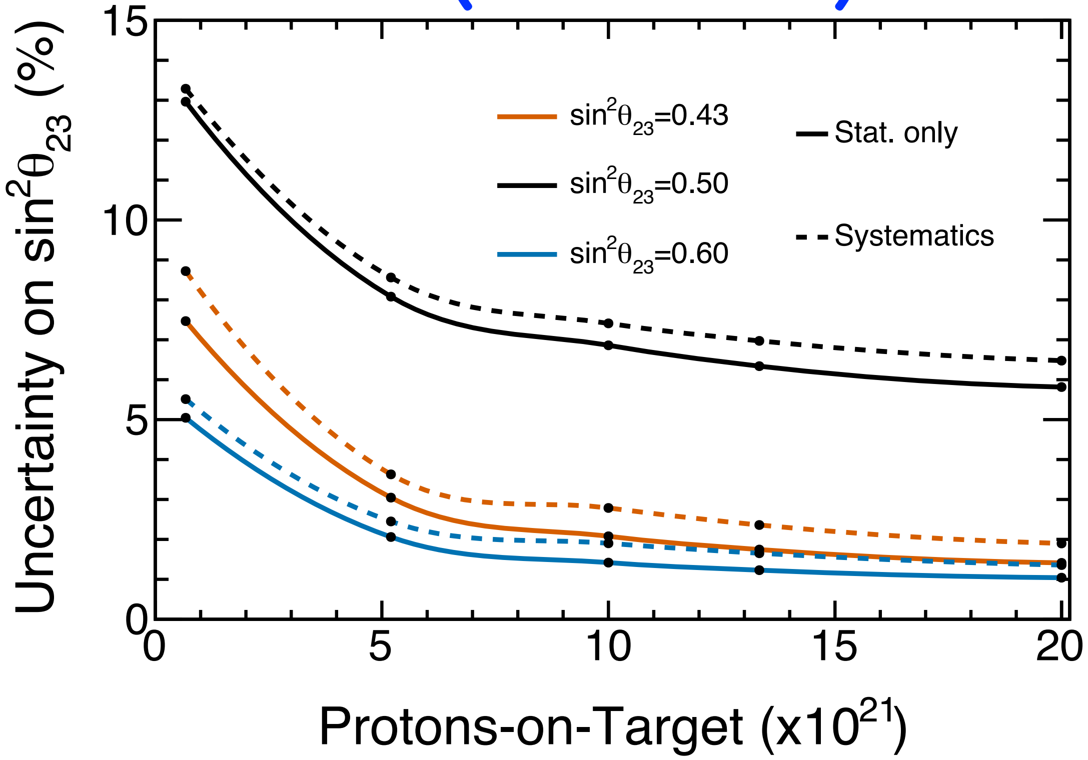
(Note) Although T2K alone can't measure MH, we can help with the MH measurement by, ie, combining T2K + NOVA

T2K-II Physics Sensitivity

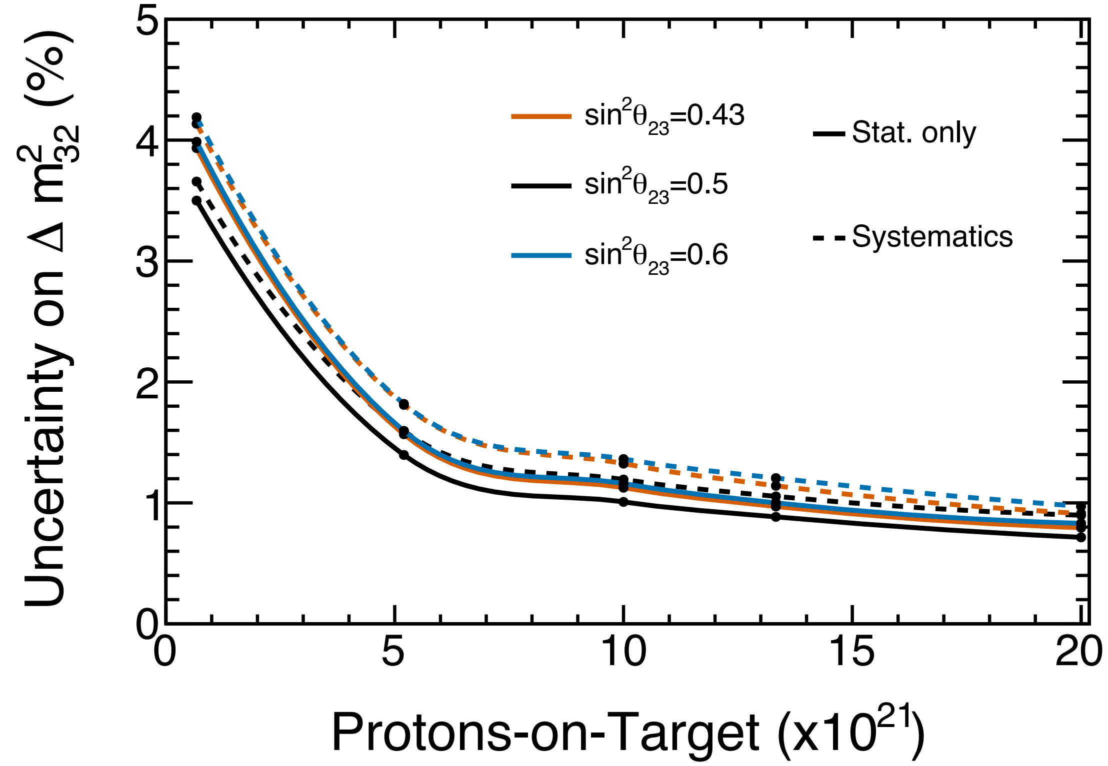
- Precisions of $\sin^2\theta_{23}$ and Δm_{32}^2



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



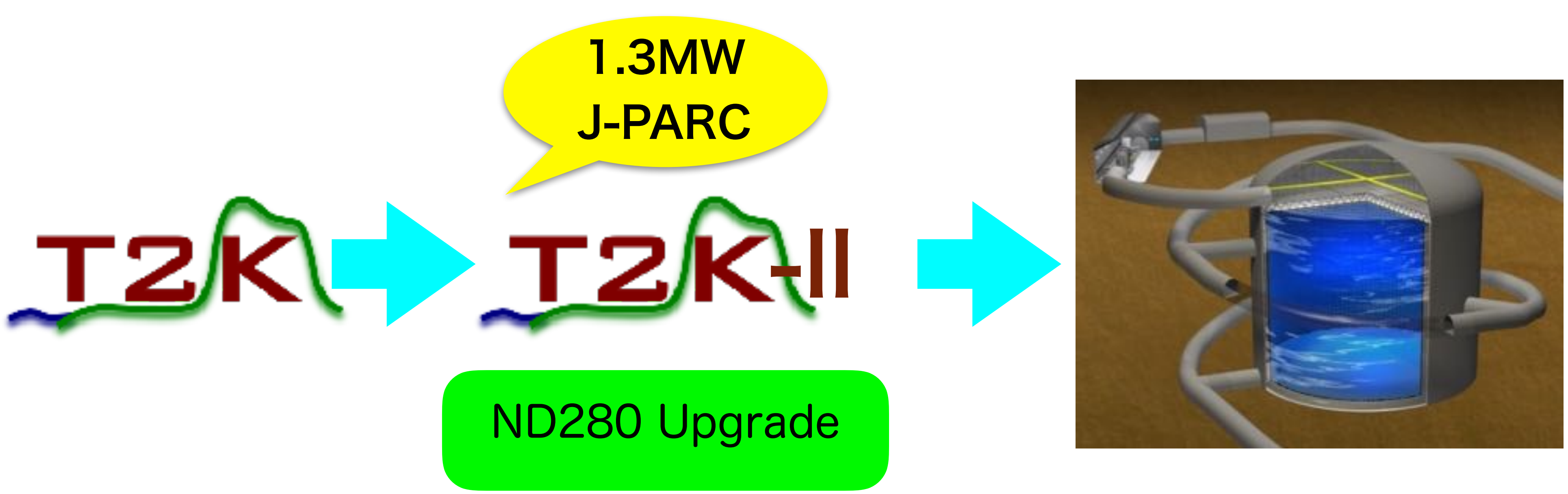
$\delta(\Delta m_{32}^2)$



- More physics for Neutrino Interactions and non-standard models

Conclusion

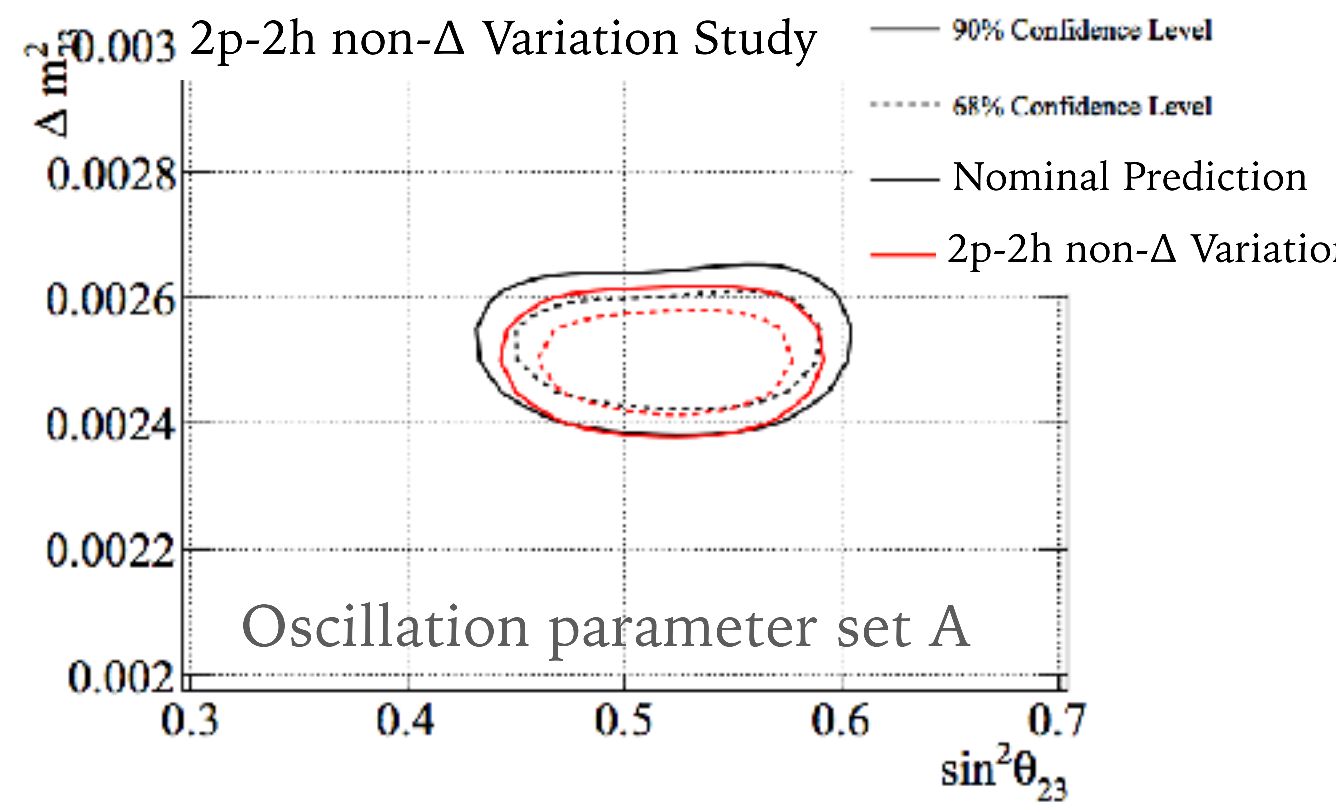
- CP violation in lepton sector is within the reach. In addition, there are rich physics programs in front of us.
  - Let's utilize the current facilities to explore new physics in neutrinos.
  - Let's work together to build a new facility for a discovery in particle physics.

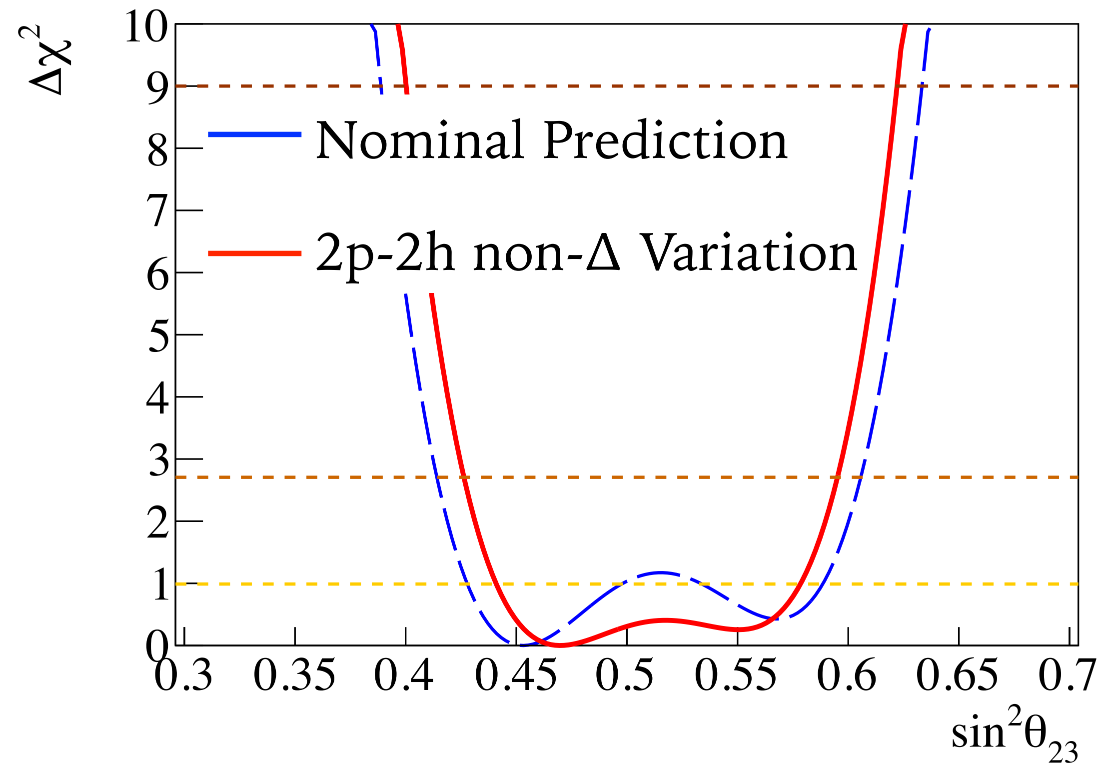


Backup

IMPACT ON ATMOSPHERIC PARAMETERS

- In this study, Δm^2_{32} is biased to lower values
- $\sin^2\theta_{23}$ is biased towards maximal disappearance
  - Leads to narrower contour than fit to nominal prediction
- Shift towards maximal also seen in 1-D contour for oscillation parameter set B (bottom)

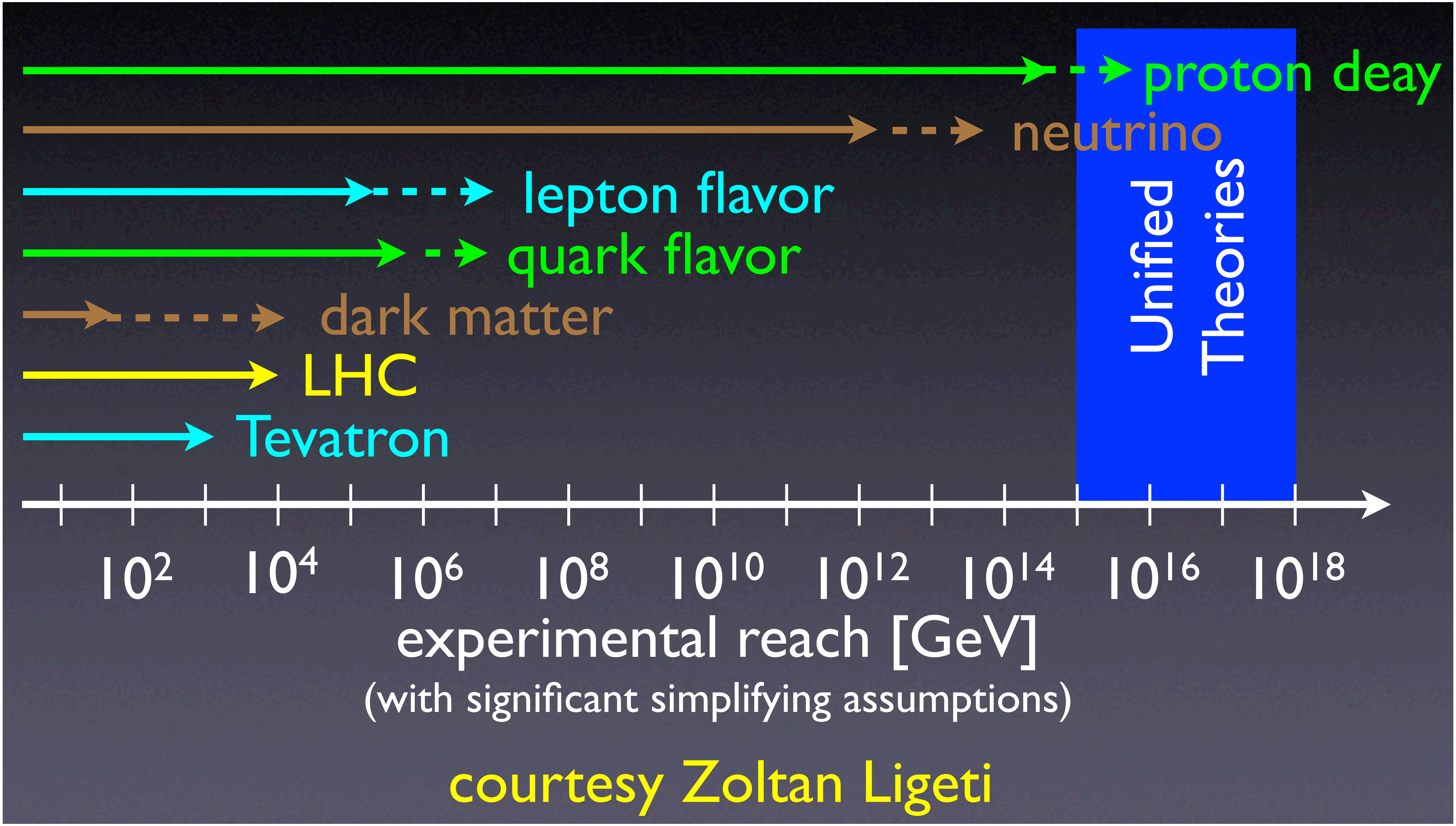




STUDY DISCUSSION

- We are investigating if this type of variation represents a physical effect that should be included as a systematic uncertainty
- We present Δm^2_{32} vs. $\sin^2\theta_{23}$ contours with caveat that the systematic error model may be updated in the future
- In the future 1p-1h vs. 2p-2h systematic effects will be addressed by:
  - The use of 4π samples in the fit to ND280 data
  - Study of the hadronic recoil system with proton reconstruction
  - Near detector upgrades designed to target interaction modeling issues

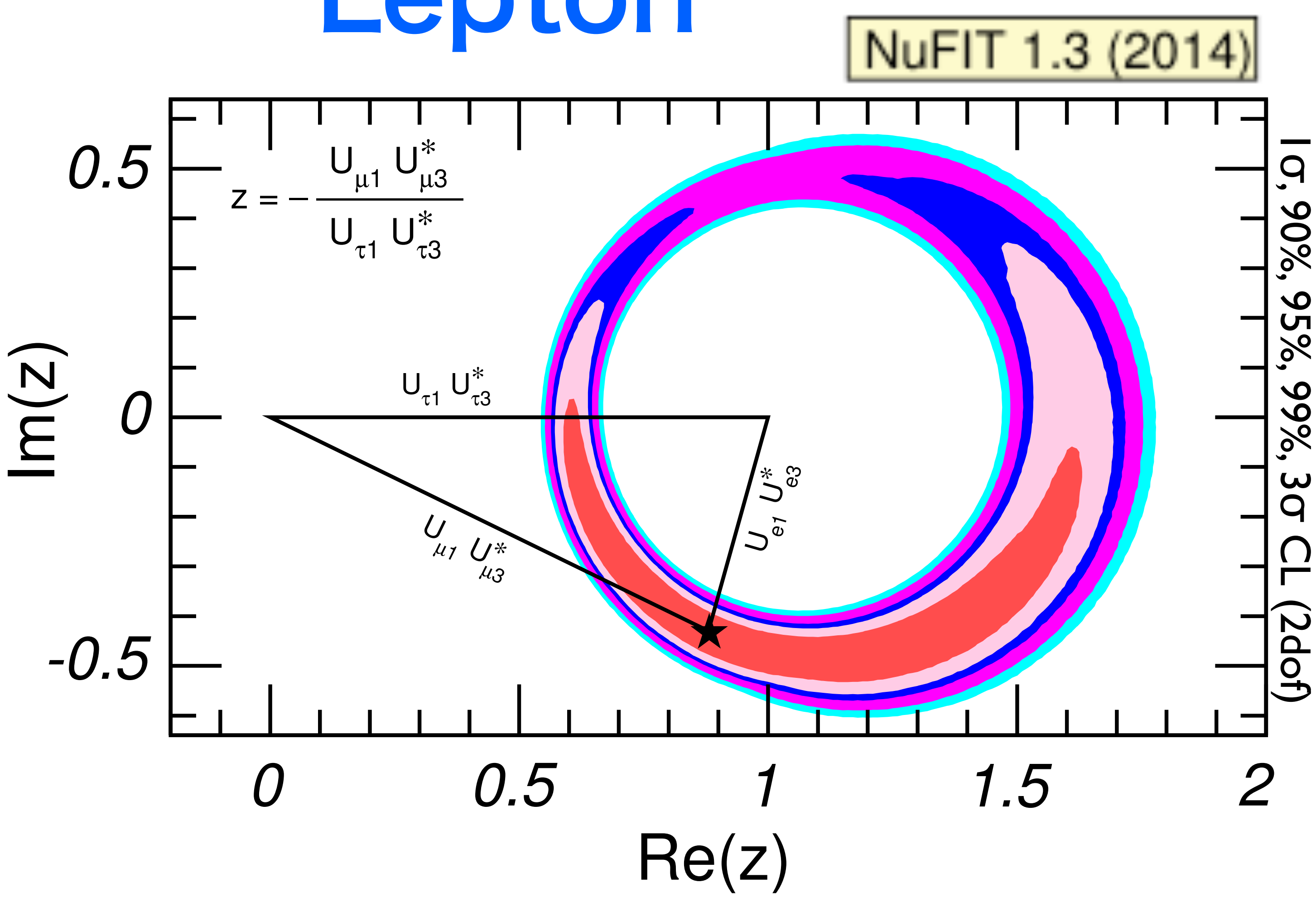
A window to Ultra High Energy



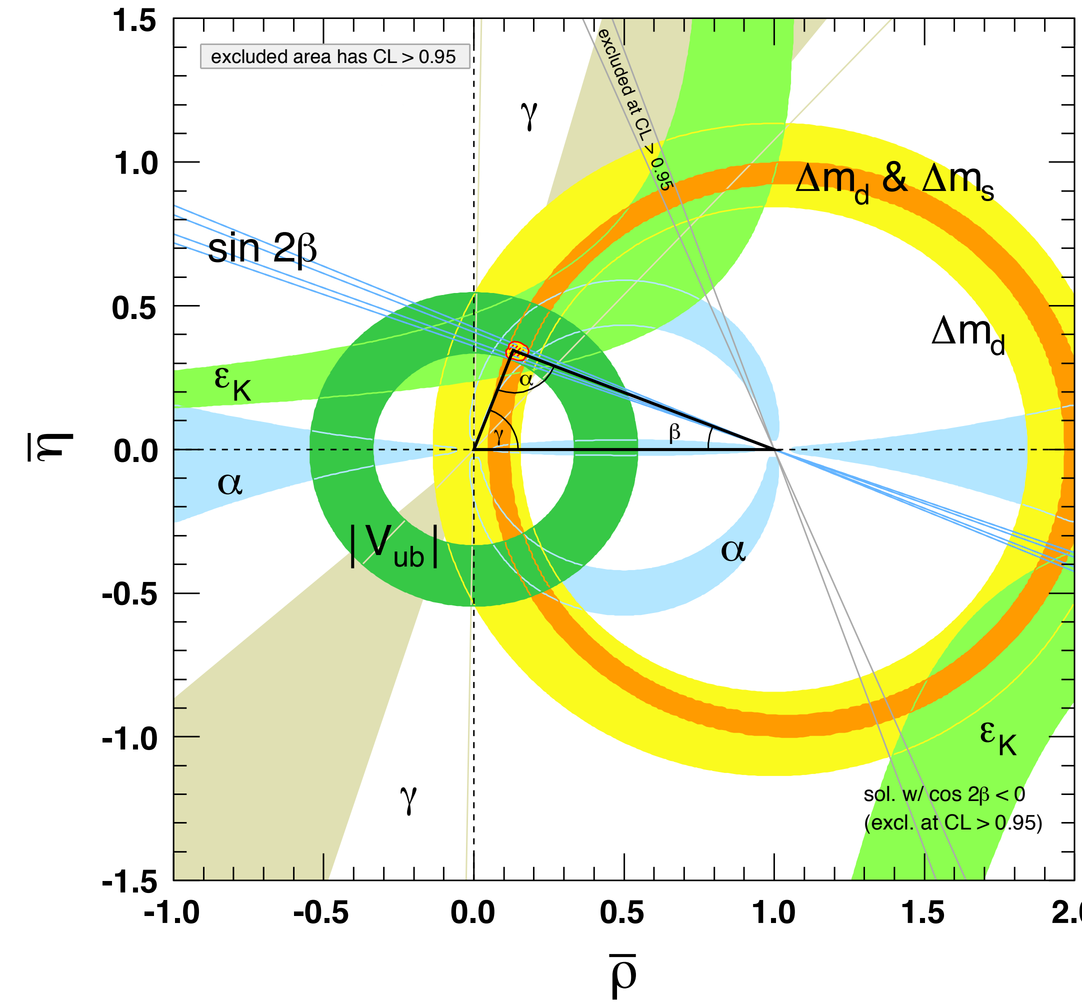
Three neutrinos and Beyond

Leptonic unitarity triangle

Lepton



Quark



Assuming unitarity (3 neutrinos)

by T. Schwetz @ NuFact2014

Neutrino Physics in Japan

ν astro

ν osc.

- Supernova ν
- Solar ν

- Atmospheric ν
- Solar ν

- 6 quark

CP

- Atmospheric ν
- Accelerator ν

T2K II

Hyper-K

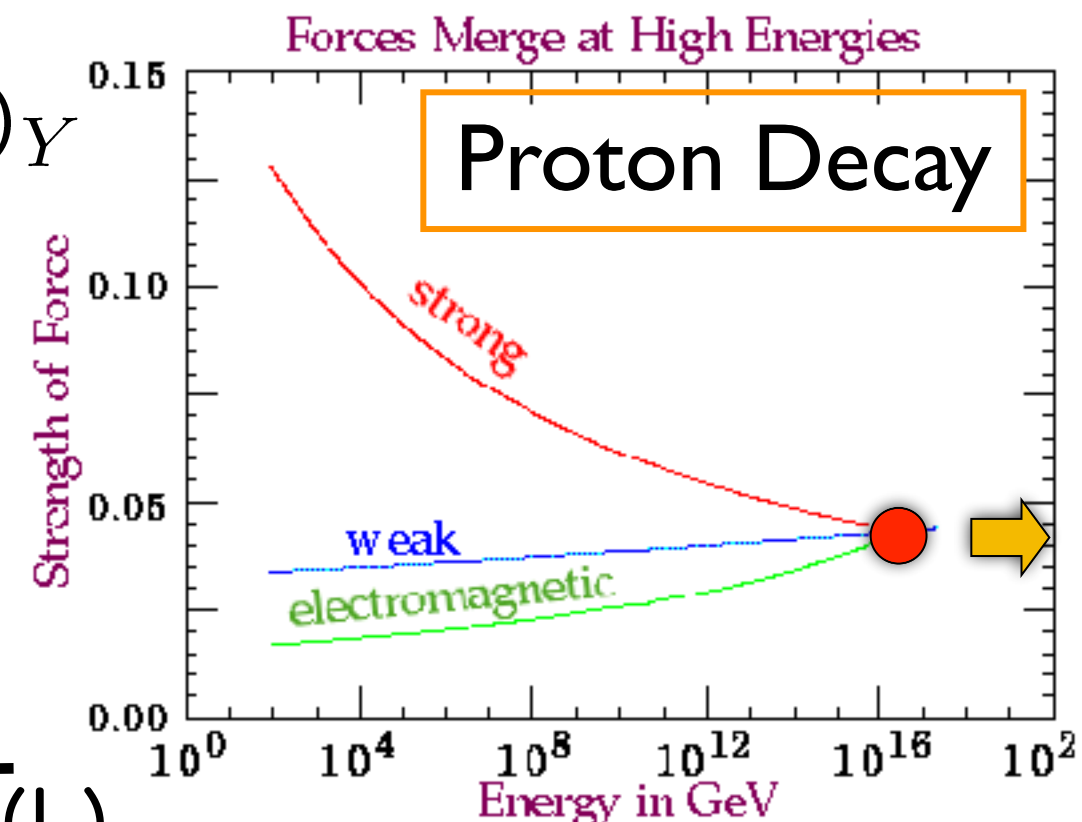
$E_6 \longrightarrow SO(10) \longrightarrow SU(5)$

Example *a GUT* by N. Maekawa

1. Unification
    1. Force (w/ SUSY)

    $SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$

    2. Quark and Leptons



$$\boxed{Q \quad U_R^c \quad E_R^c} \ \boxed{D_R^c \quad L} \ \boxed{N_R^c}$$

$$\mathbf{10} \quad + \quad \bar{\mathbf{5}} + \mathbf{1} \quad = \quad \mathbf{16}$$

- 10(Q_i) has more hierarchy than $\overline{5}$(L)

2. Hierarchy
    1. mixing: lepton (large) >> quark (small)
    2. mass: u-type quark >> d-type quark, charged lepton >> neutrino

Leptogenesis and Neutrino CPV

- Saharov conditions for Baryon Asymmetry
  - [B] Baryon Number Violation
  - [CP] C and CP violation
  - [T] Interactions out of thermal equilibrium

- Leptogenesis and Low Energy CP violation in Neutrinos
  - [B] Sphaleron process for $\Delta(B+L)\neq 0$
  - [CP] Heavy Majorana Neutrino decay and/or Neutrino oscillations
    - $|\sin\theta_{13}\sin\delta|>0.09$ is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix [Phys. Rev. D75, 083511 (2007)].
      - $\sin\theta_{13}\sim 0.15$ ➡ $|\sin\delta|>0.6$