KEK-TRIUMF Symposium
@December 14, 2017

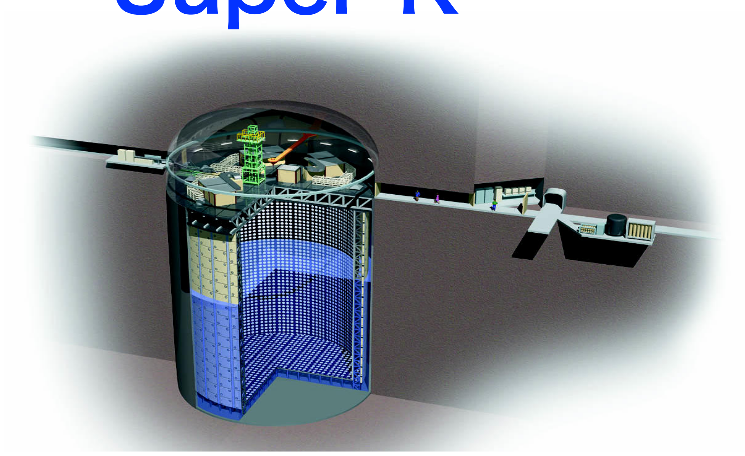
T2K Status and Plan
— Canada and Japan —

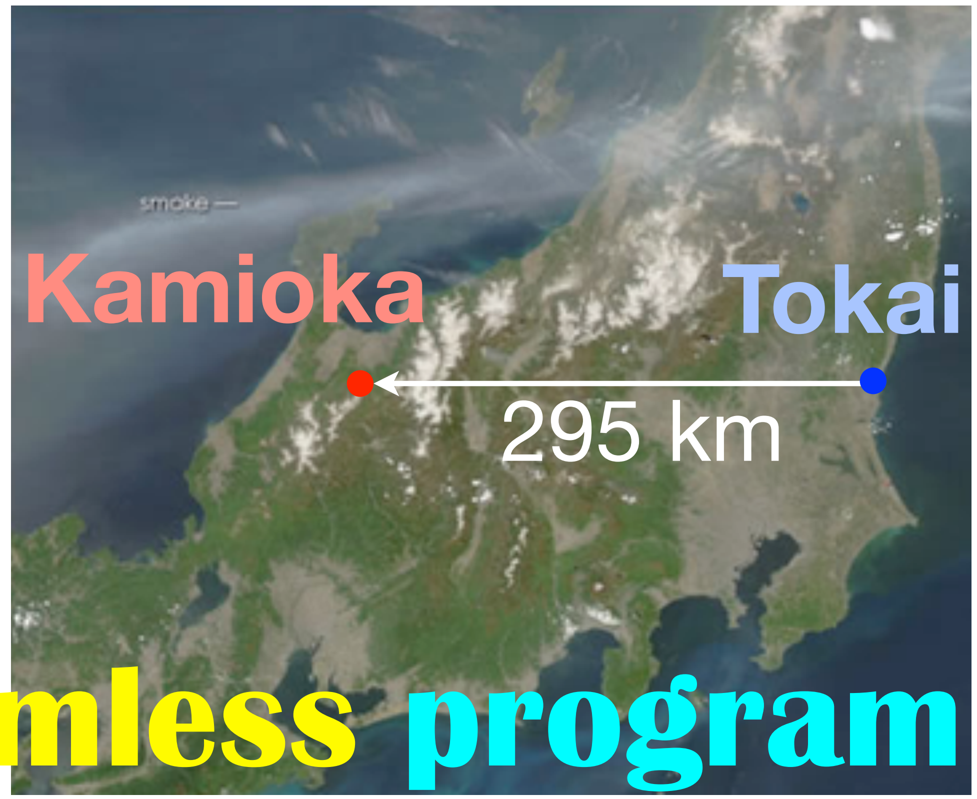
T. Nakaya (Kyoto University)

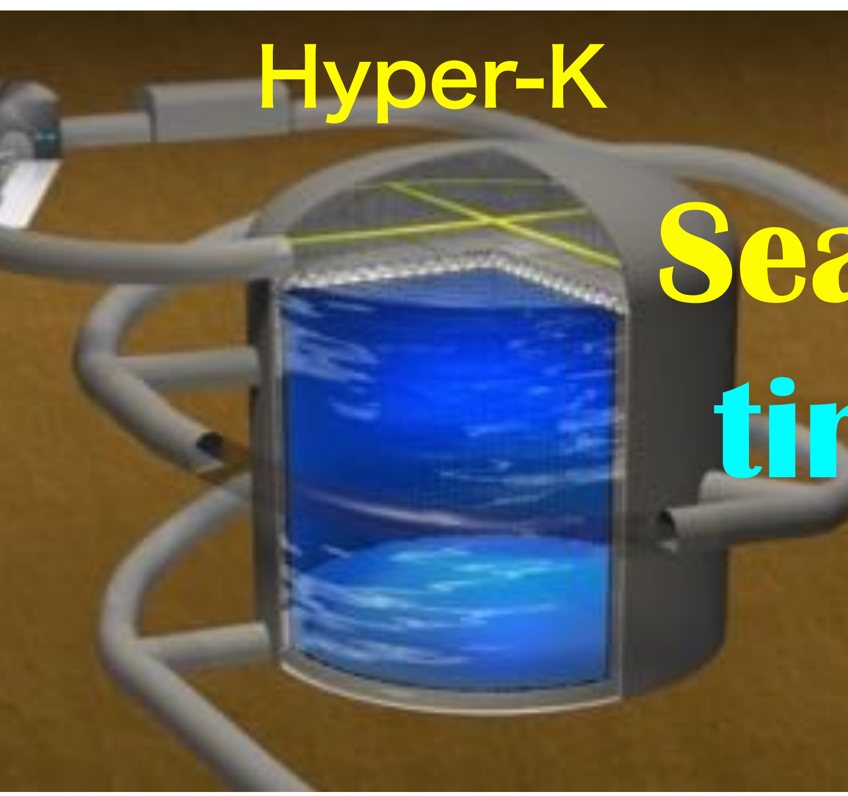
Neutrino oscillation experiments in Japan

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

Super-K

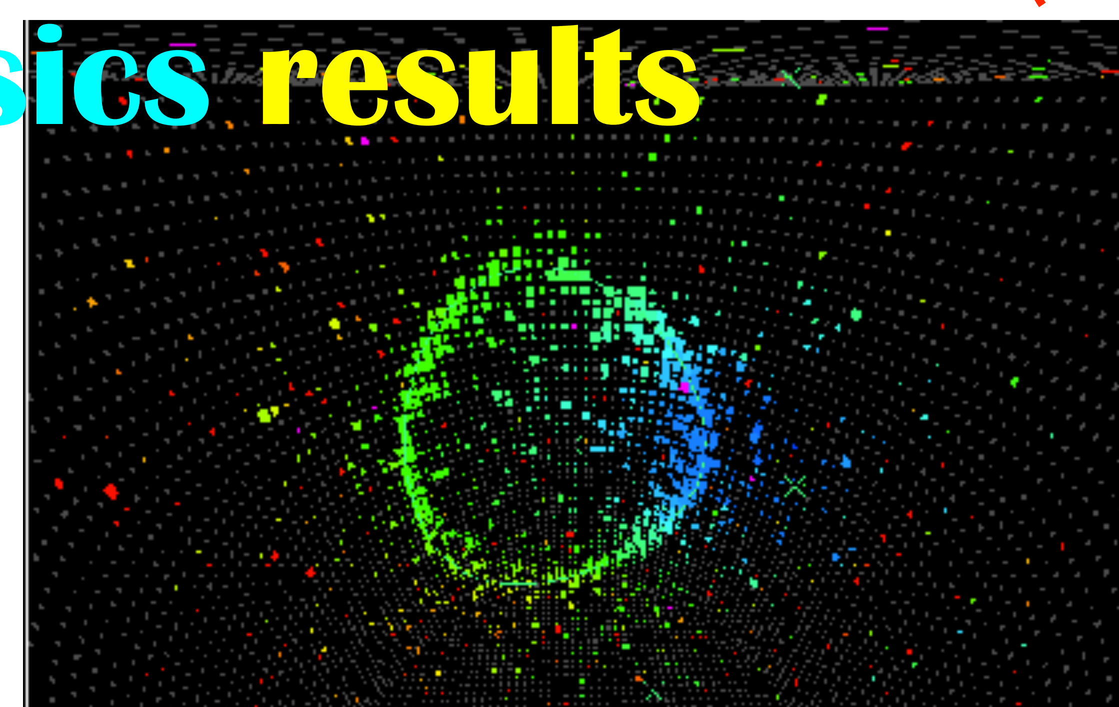






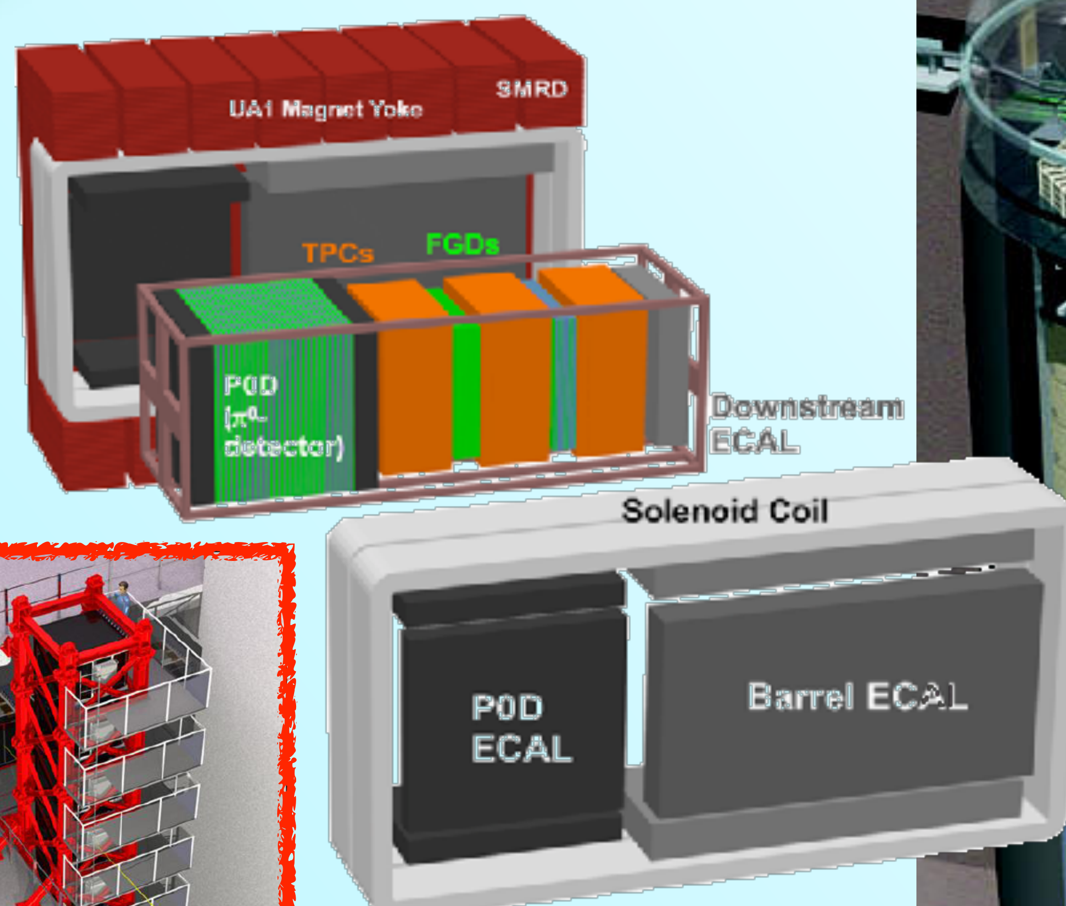
- 470 kW (today)
- ~1MW (2020)
- 1.3 MW (2025)

Seamless program with timely physics results

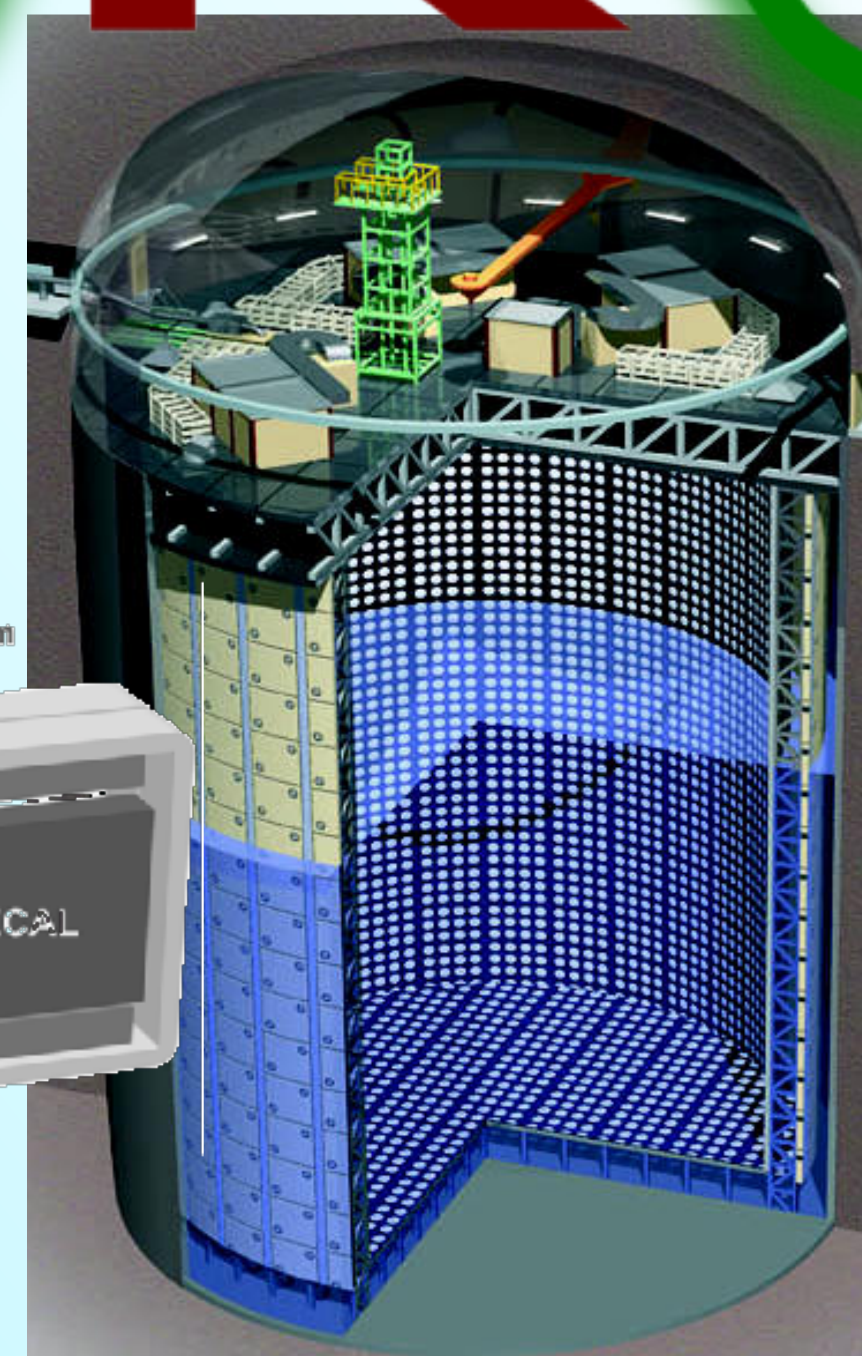


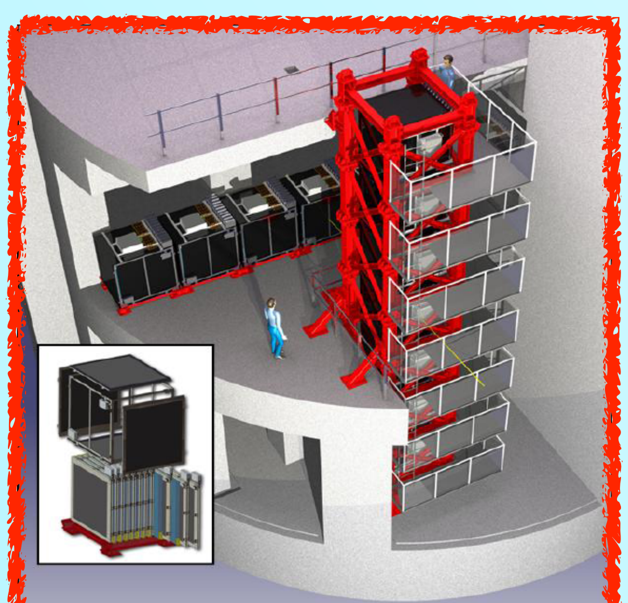
- 22.5 kton (Super-K, ~2026)
- 190 kton (Hyper-K, 2026~)

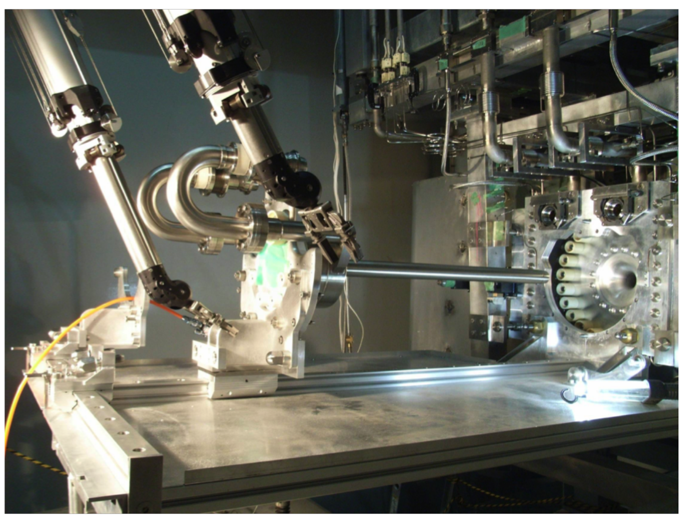
T2K



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

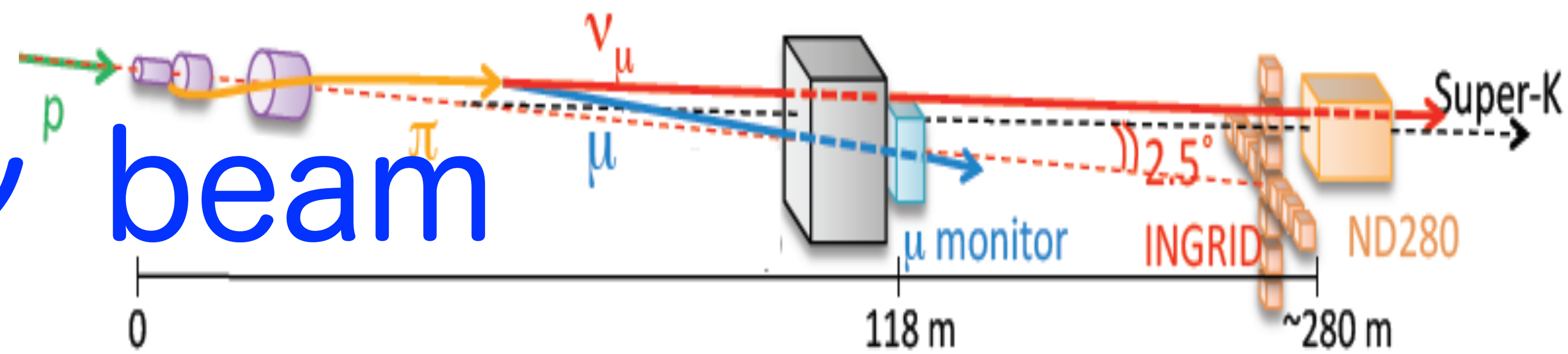




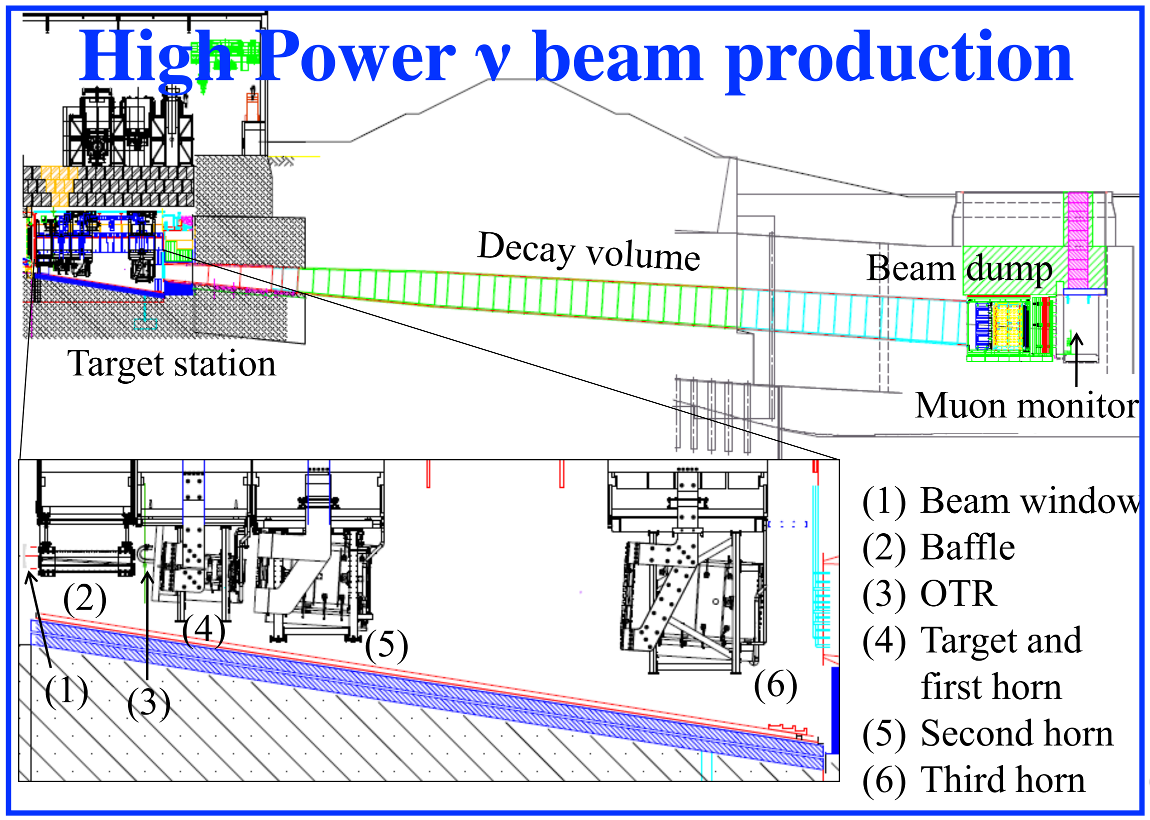


Target + remote handling system

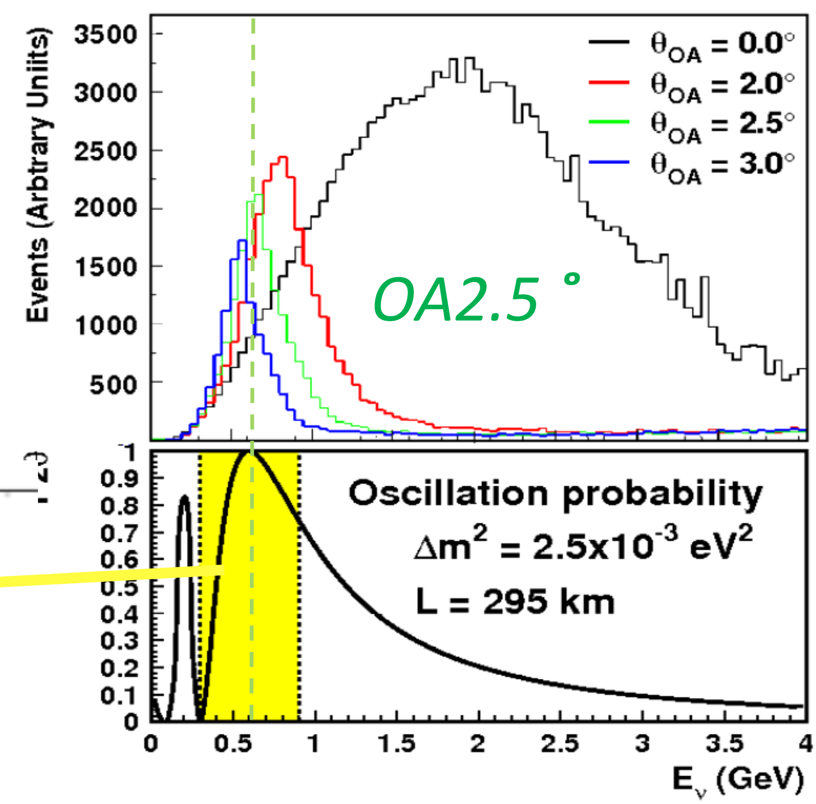
T2K ν beam



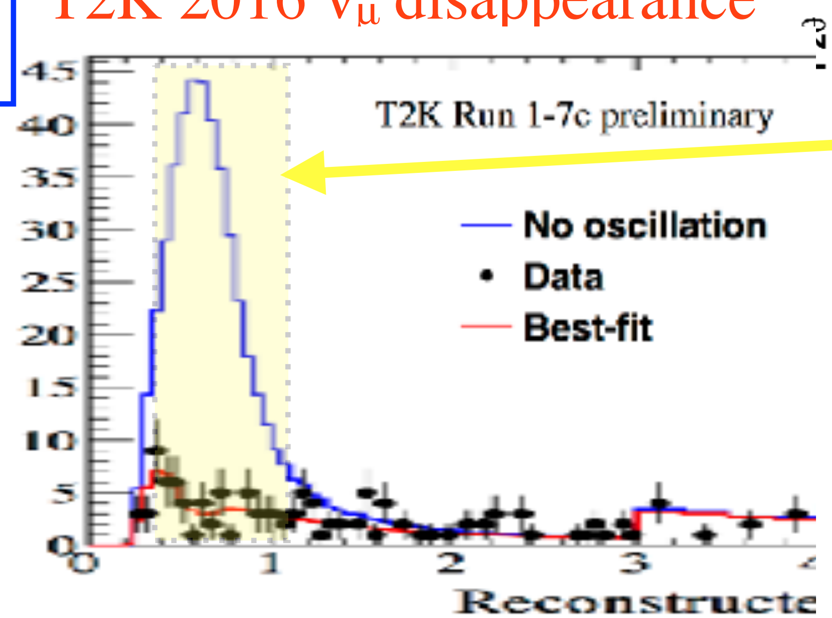
- **Off-axis (2.5 °) ν_μ beam**
  - Intense, low energy narrow-band
  - Peak E_ν tuned for oscillation max. (~0.6 GeV)
  - Reduce BG from high energy tail
  - 1mrad direction shift => ~2% energy shift at peak
  - Small ν_e fraction (~1%)



- 30 GeV **~2×10^14** 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

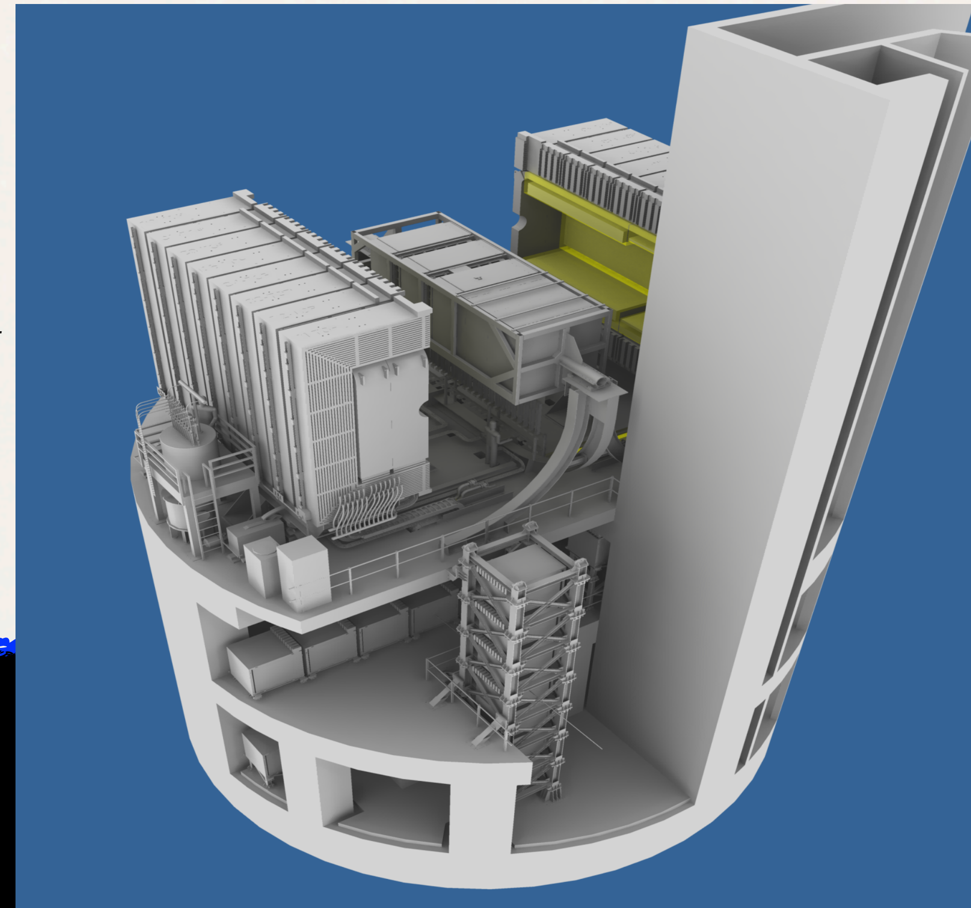


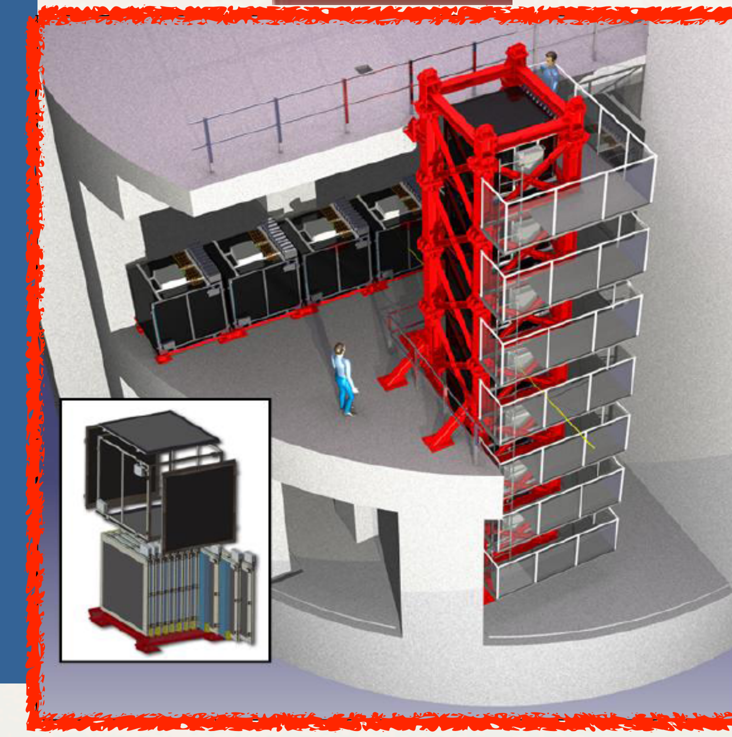
T2K 2016 ν_μ disappearance

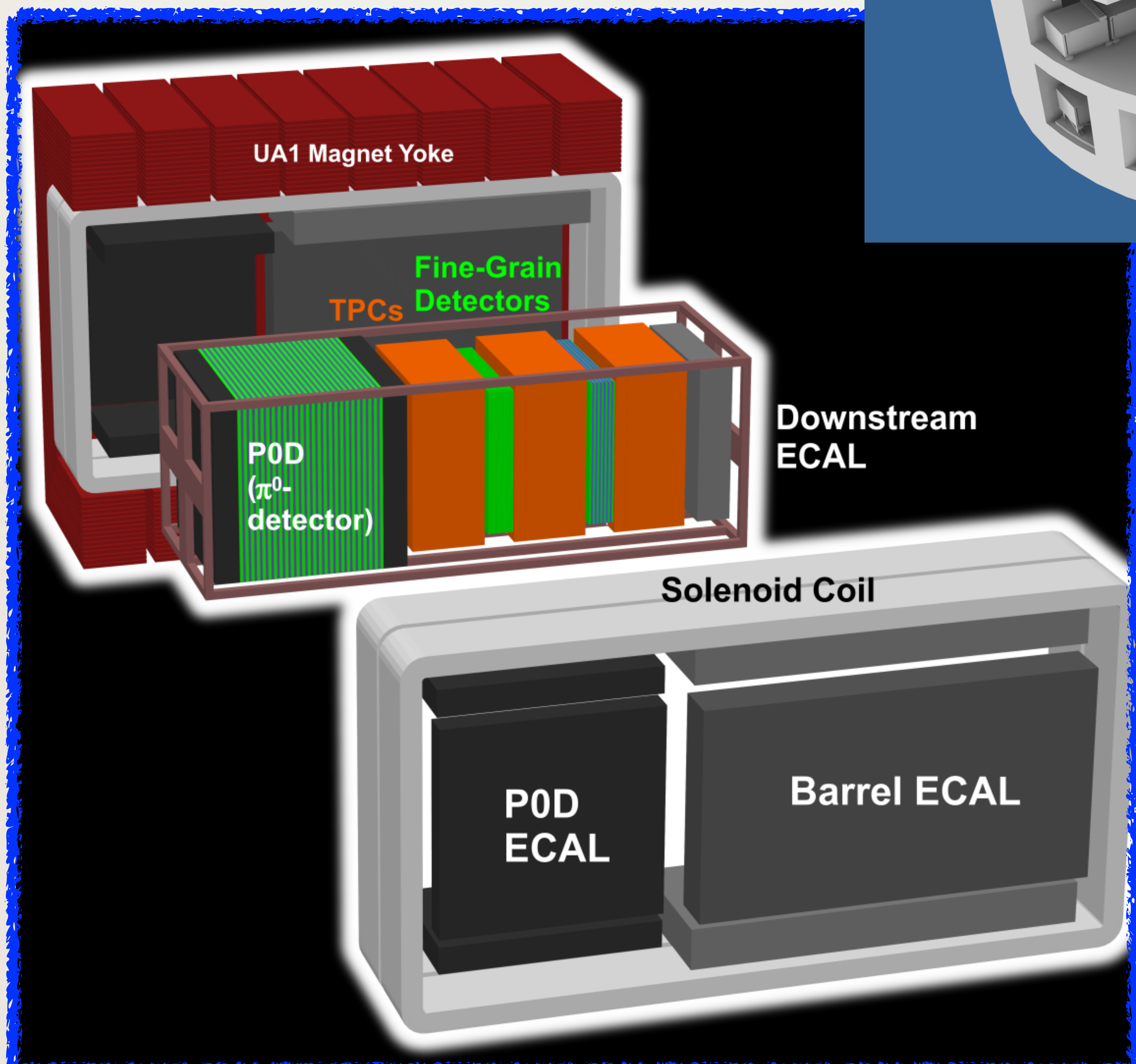


ND280

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**

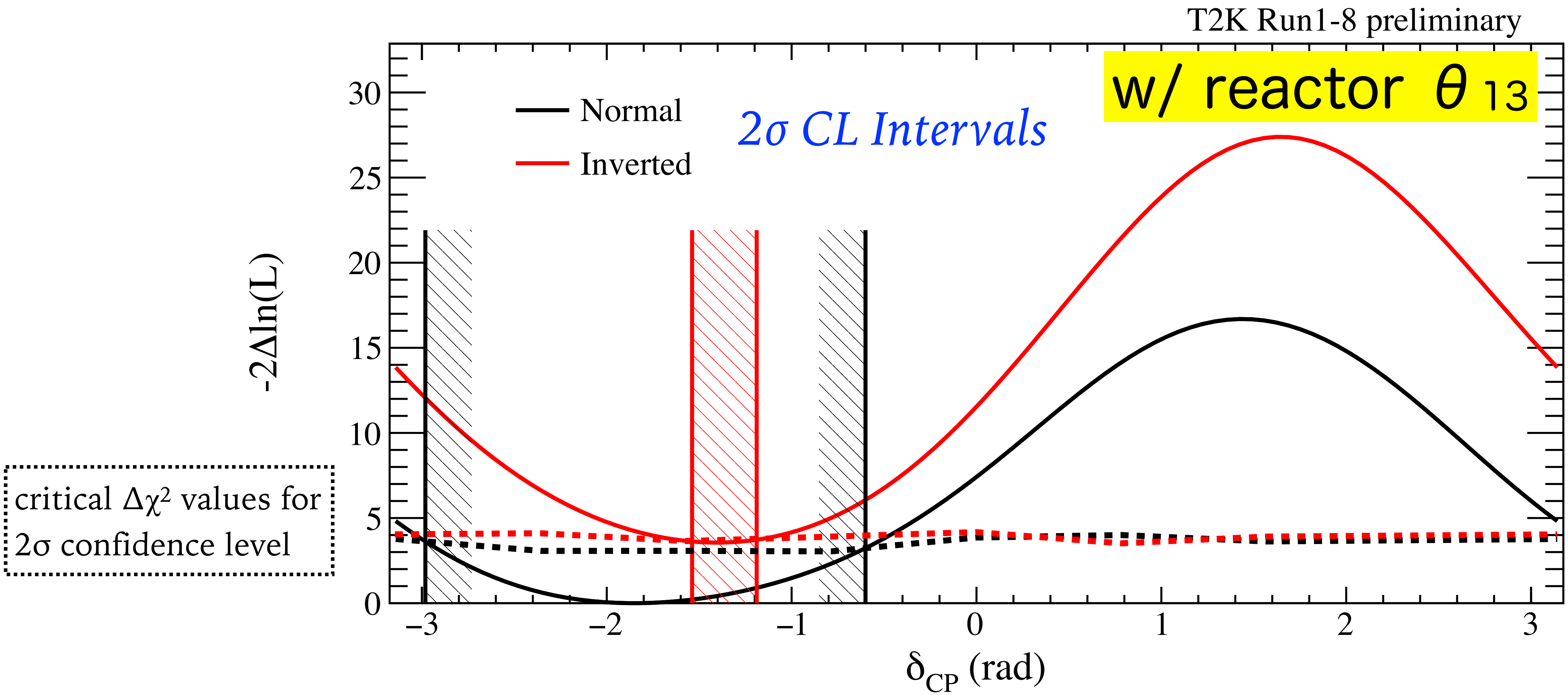
The Canadian group has led T2K

- An idea of off-axis beam and the beam line design
  - OTR beam monitor
  - Remote handling
  - Beam flux estimation
- ND280
  - FGD (Fine-Grained-Detector)
    - Proposal of SiPM (MPPC), MPPC developments, Electronics,
  - TPC
  - Network
  - Computing (and software) with data storage and MC production
  - Common Infrastructure (Dry air, cooling, crane, clean tent, etc..)
- Super-K
  - New algorithm (fiTQun)
  - Hybrid-pi0 BG estimation
- Pion cross section measurements and tuning
- T2K web page
- **Analysis**

New T2K results (summer 2017)

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

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



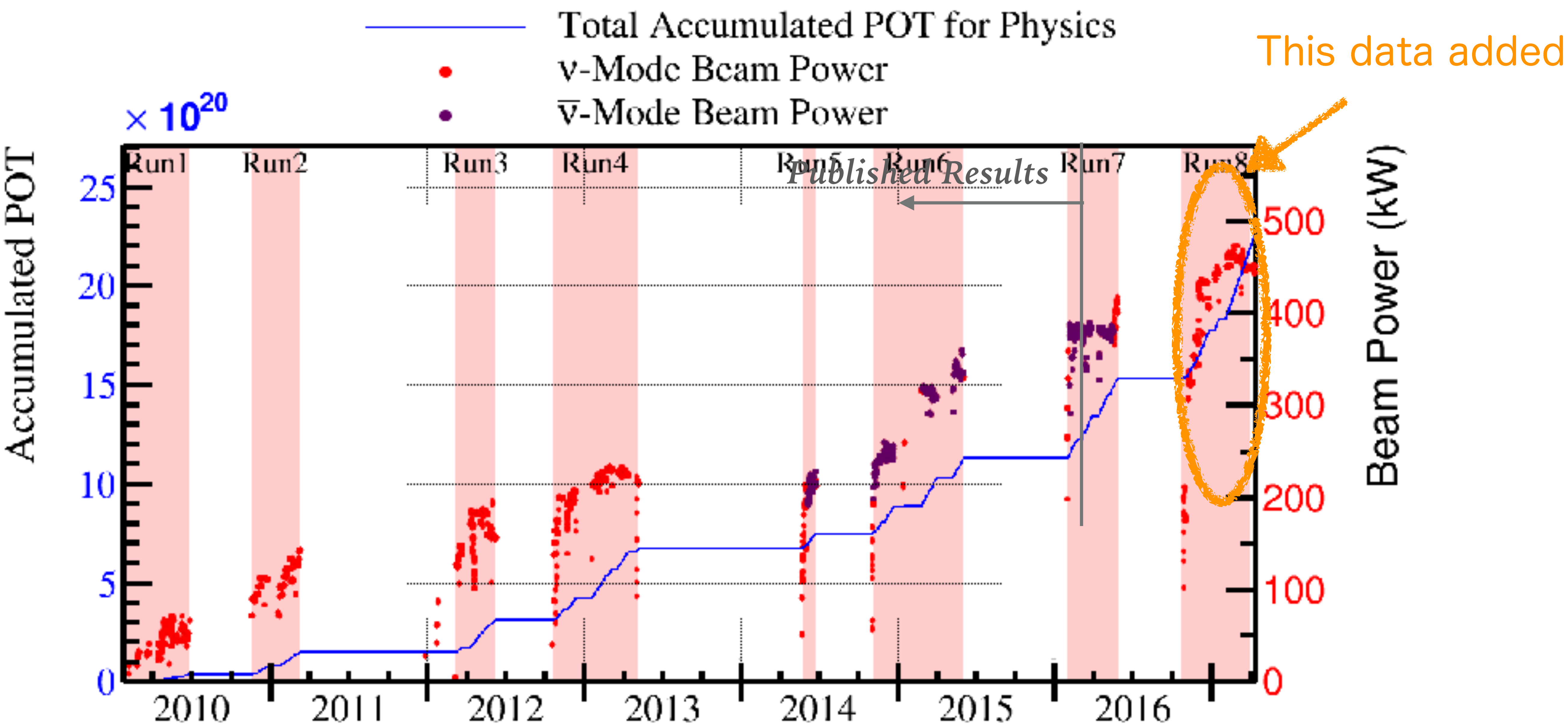
Best fit: $\delta_{CP}=-1.83^{+0.60}_{-0.66}$ in Normal Hierarchy

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

What's new this year!

- Double neutrino beam data in one year!
  - 7.48×10^{20} POT → 14.7×10^{20} POT
  - We are collecting anti-neutrino beam data to be doubled before the next summer. Additional ~3.5×10^{20} POT data collected now.
- Increase the far detector fiducial volume!
  - ~20% more events (w/ fiTQun)
- Adding a new event sample (CC-1π) on ν_e
  - ~10% more events

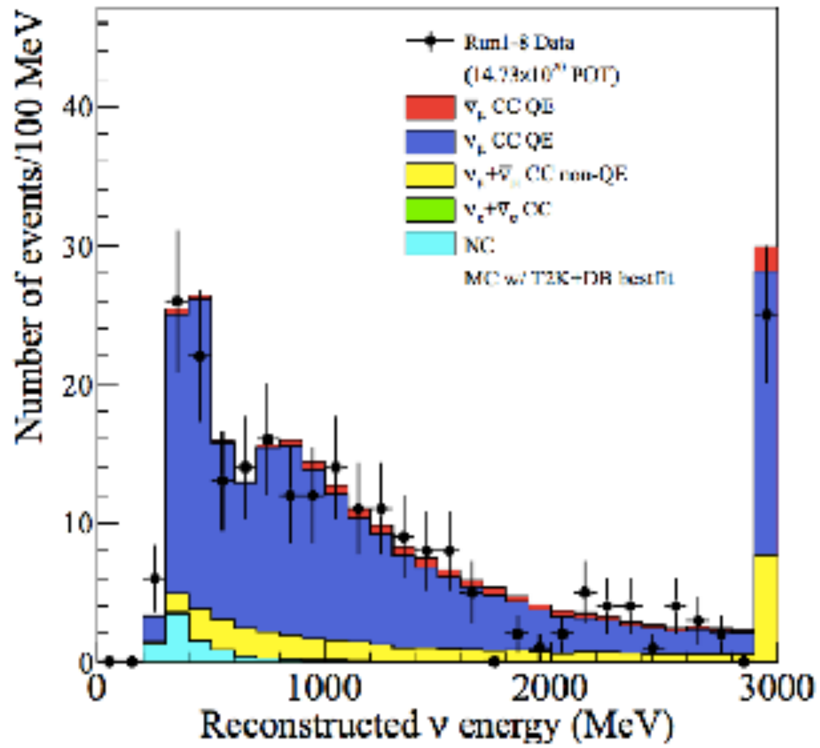
T2K Data before summer 2017



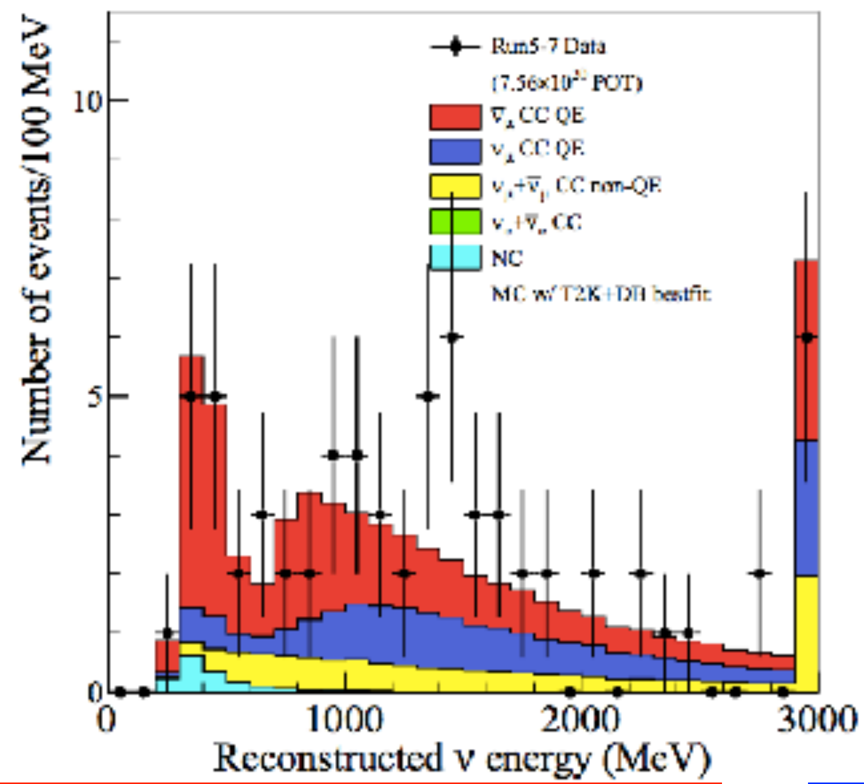
- Accelerator has achieved stable operation with 470 kW beam power
- 14.7×10^{20} protons-on-target (POT) in neutrino mode and 7.6×10^{20} POT in antineutrino mode

Observation at Super-K

Neutrino 1 μ-like ring

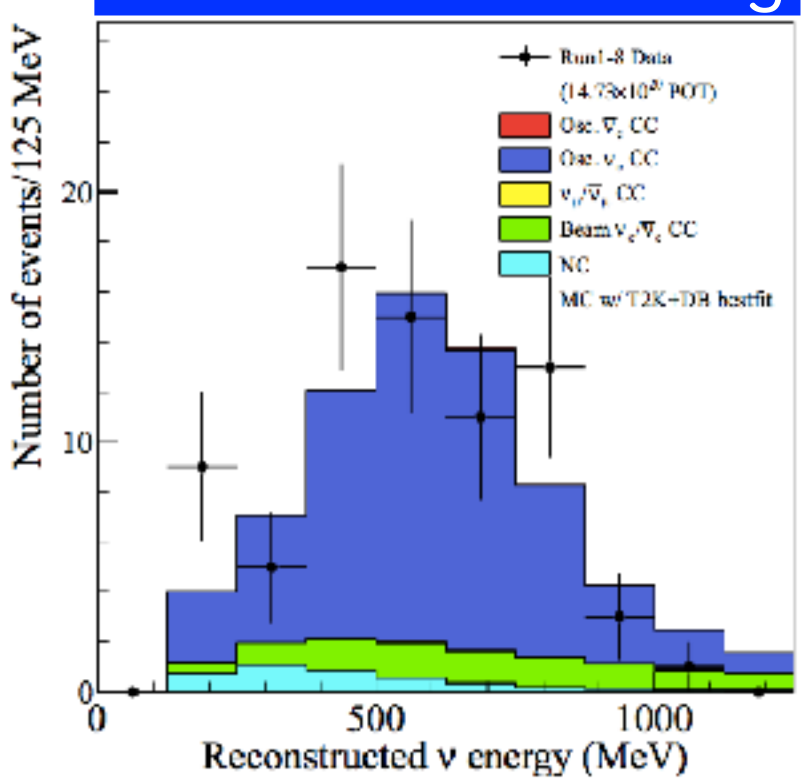


Antineutrino 1 μ-like ring

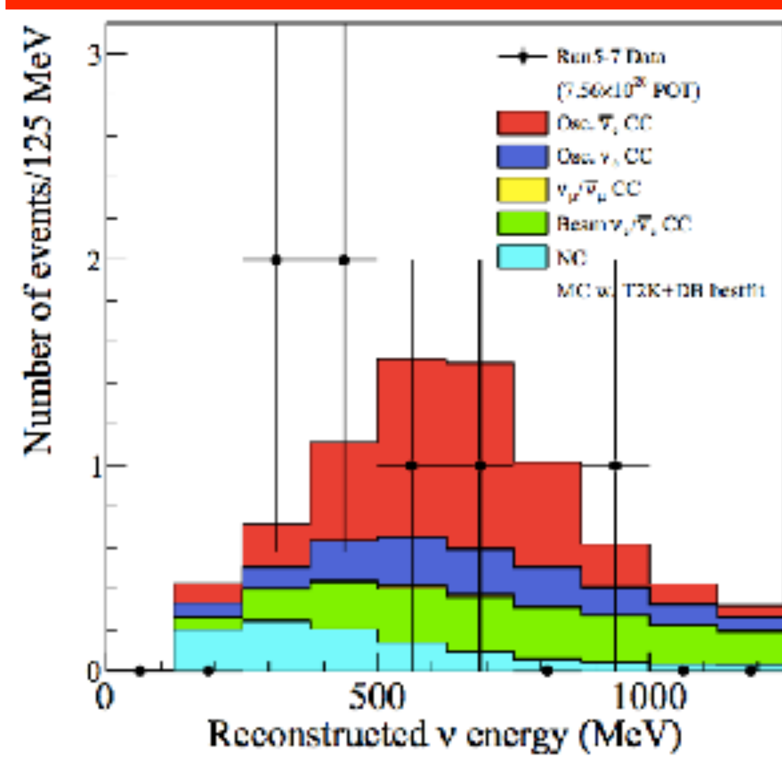


T2K Preliminary

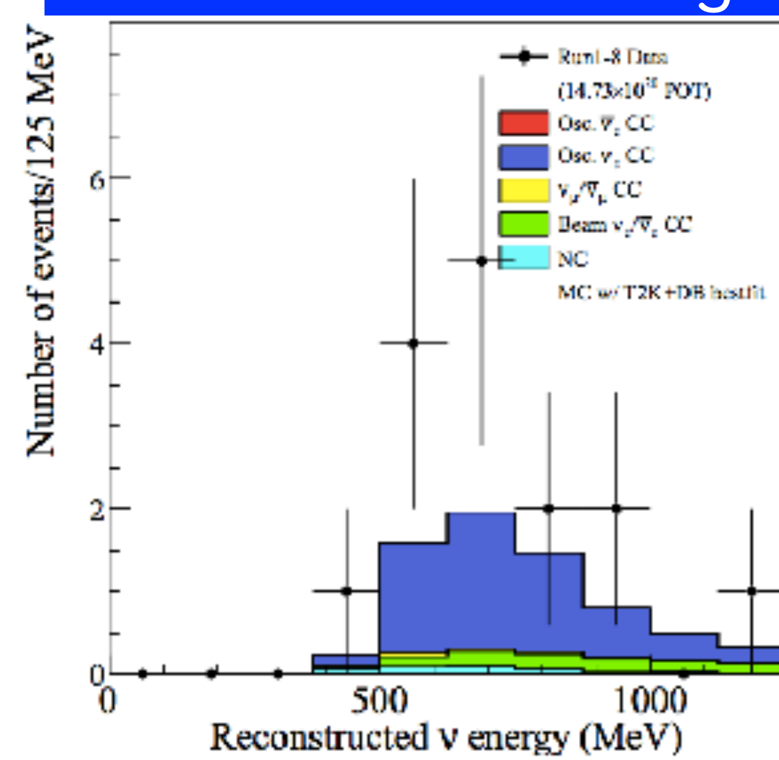
Neutrino 1e-like ring



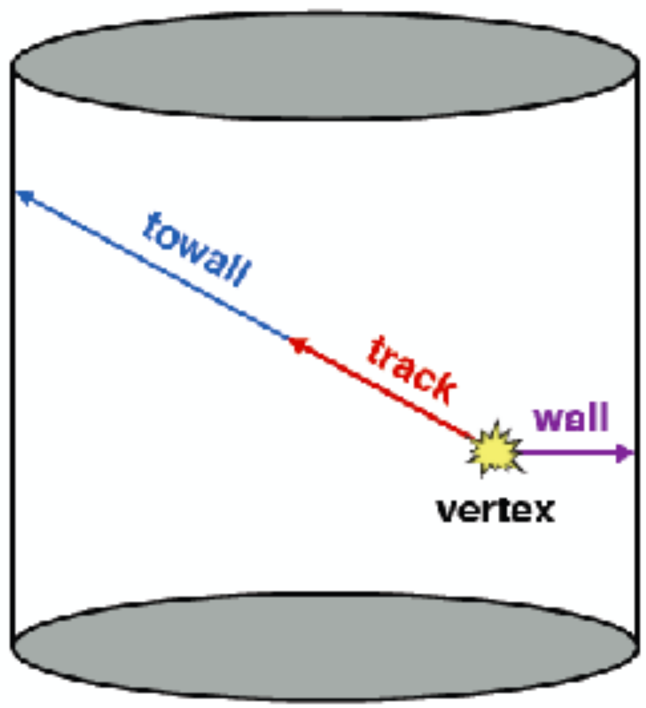
Antineutrino 1e-like ring

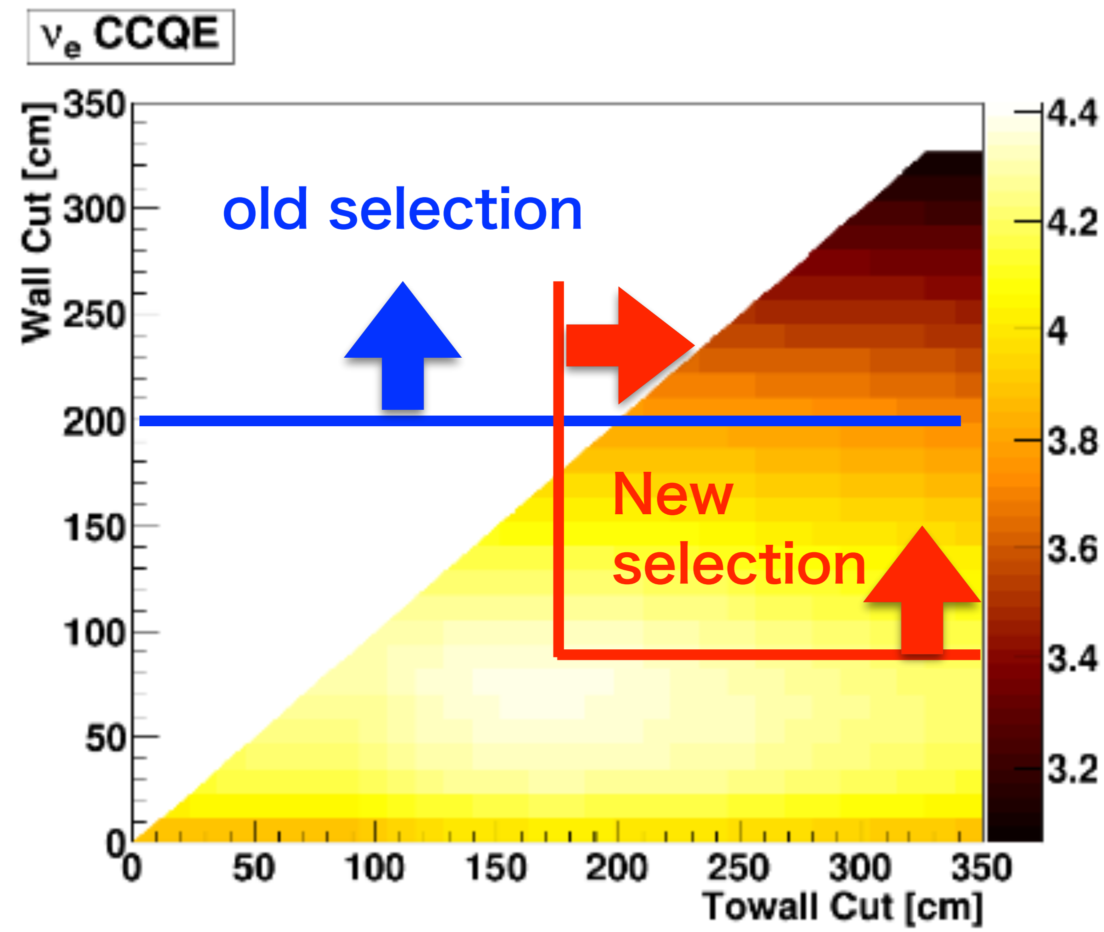


Neutrino 1e-like ring + π



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

	Predicted Rates				Observed
Sample	$\delta_{cp}=-\pi/2$	$\delta_{cp}=0$	$\delta_{cp}=\pi/2$	$\delta_{cp}=\pi$	Rates
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

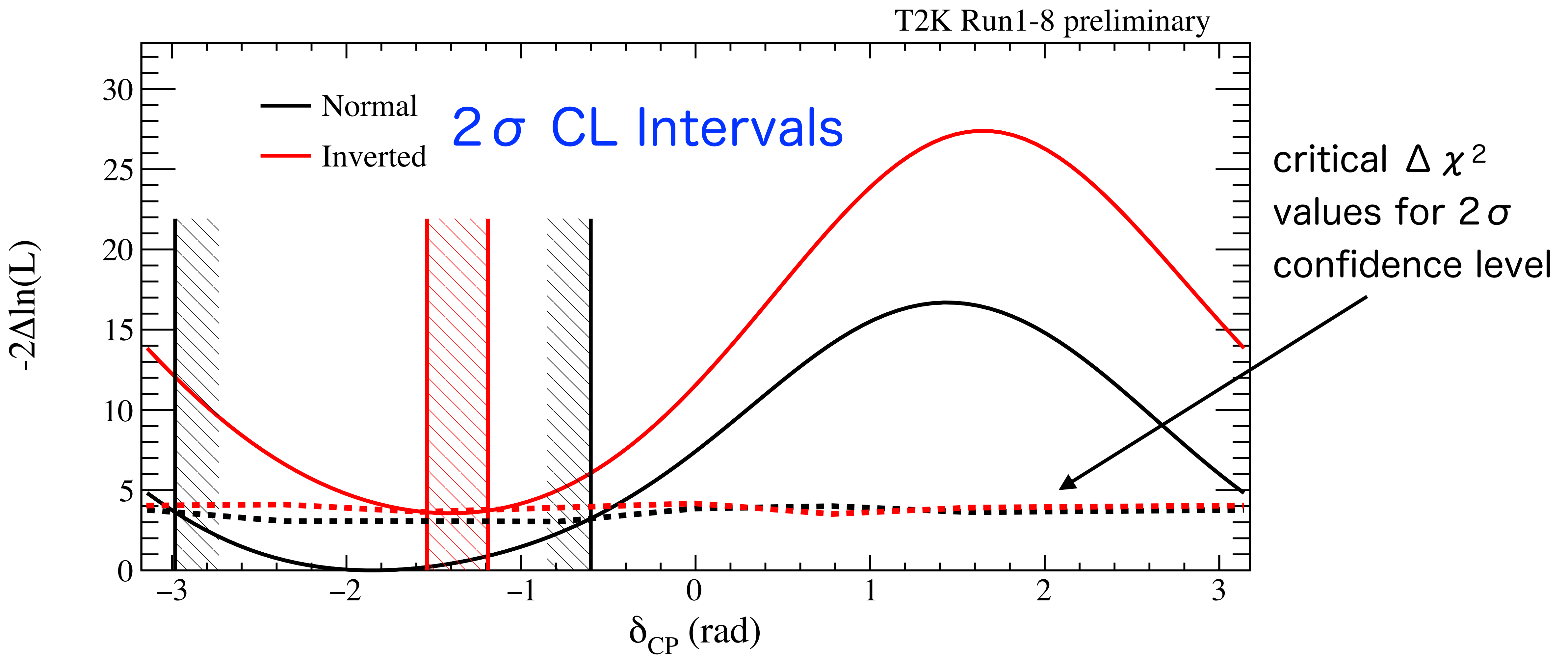
- The number of observed events are largely in line with the predictions after oscillations
  - The e-like samples have rates most consistent with the $\delta_{cp}=-\pi/2$ hypothesis
- The observed μ-like rate in neutrino mode is lower than prediction
  - consistent within statistical and systematic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

Systematic Errors

	% Errors on Predicted Event Rates (Osc. Para. A)					
	1R μ-like		1R e-like			
Error Source	FHC	RHC	FHC	RHC	FHC CC1π	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
NC1γ	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

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



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

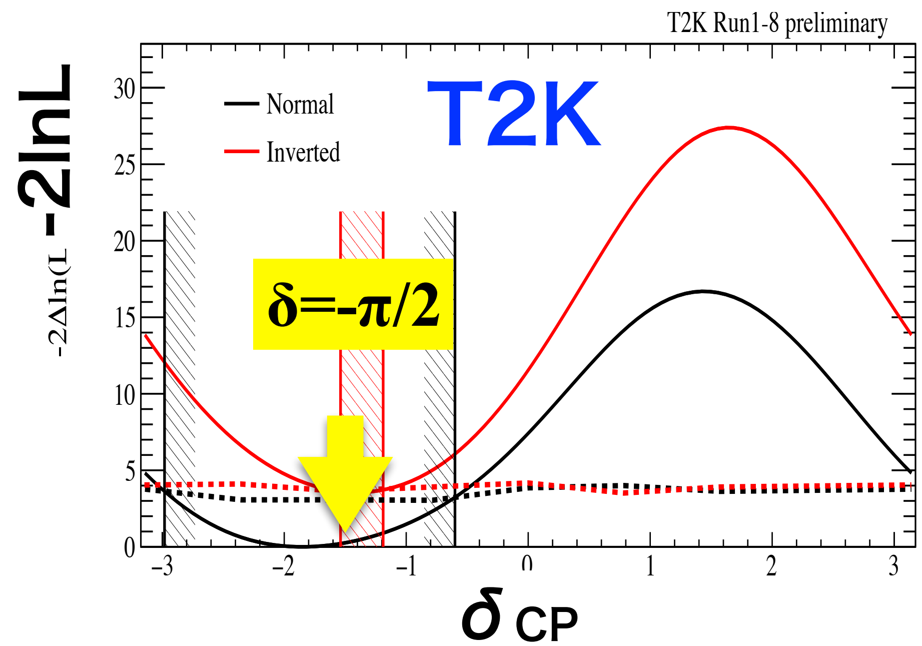
Posterior probabilities (with reactor constraint)

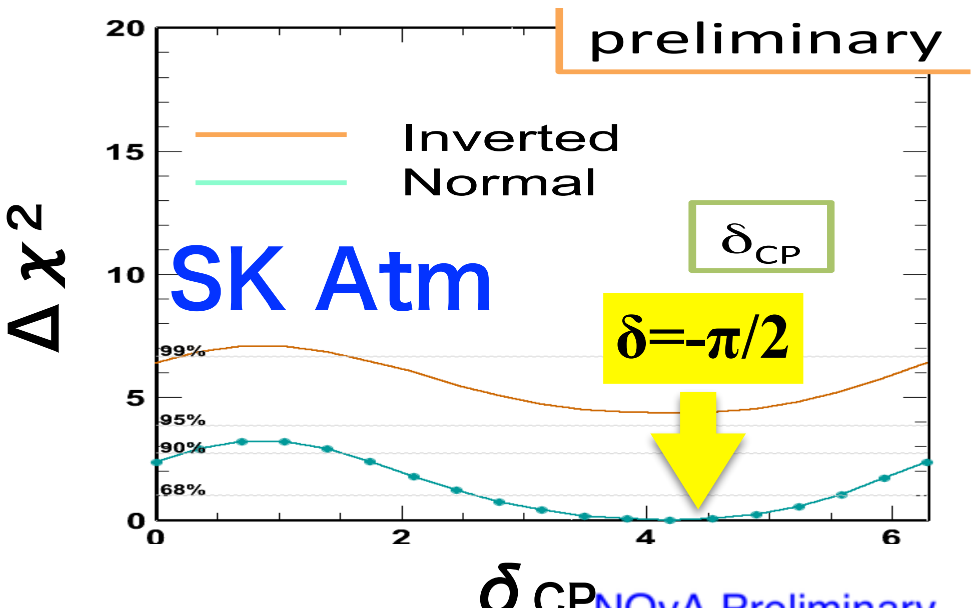
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	

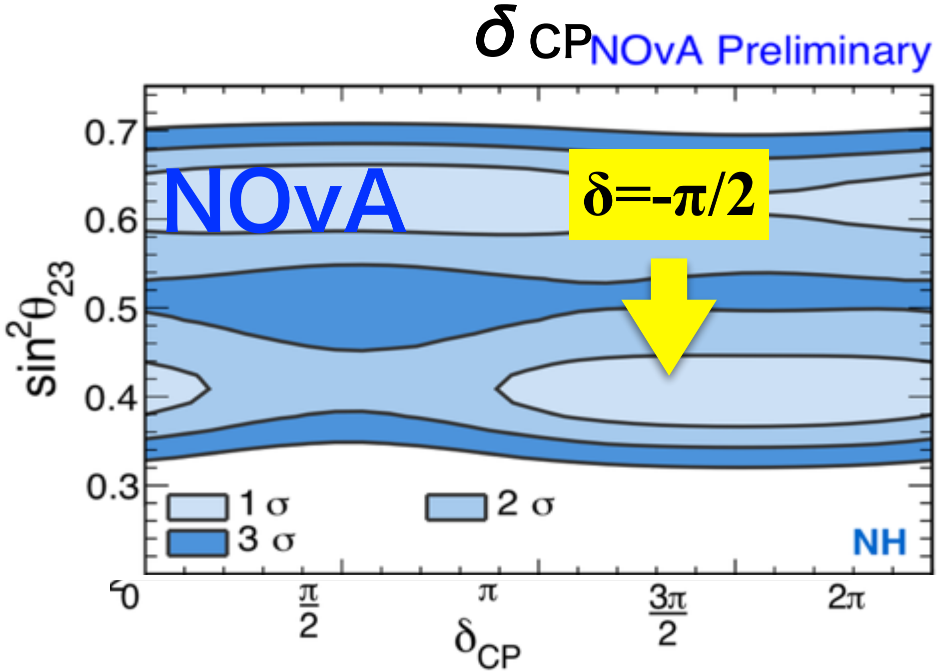
T2K-II (and Hyper-K)

CP Violation

Today

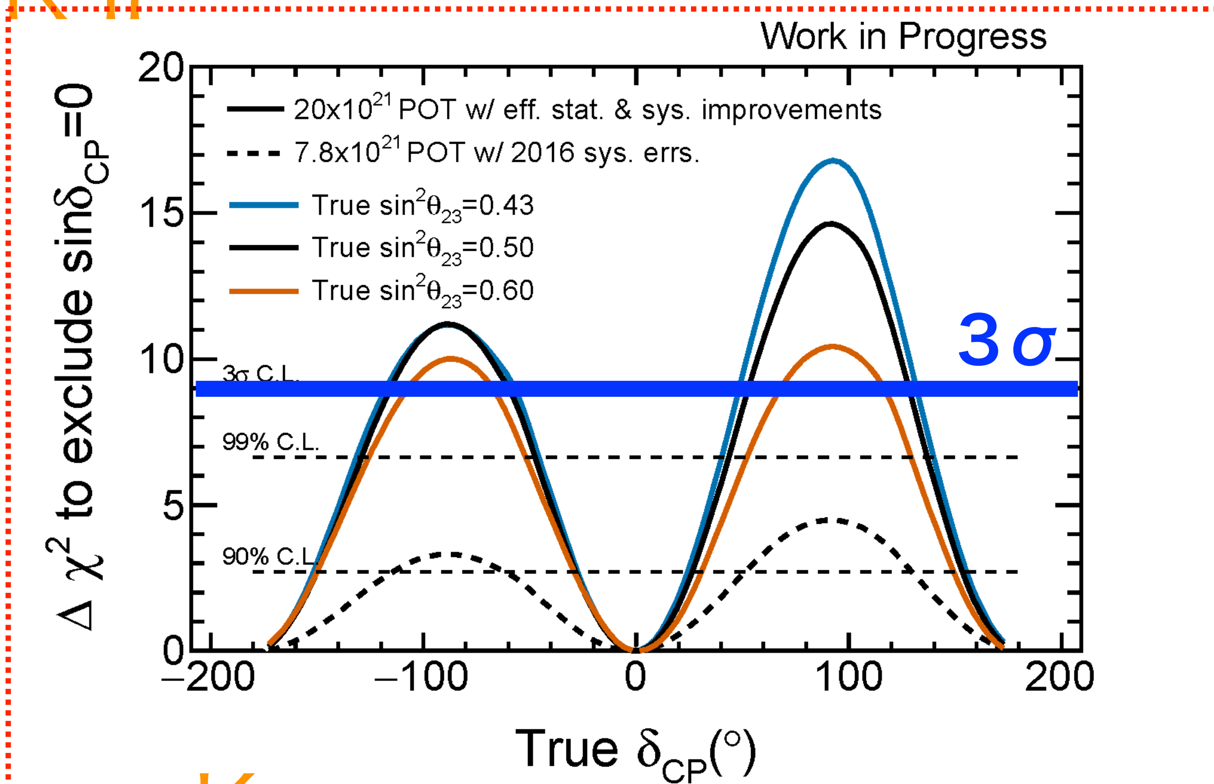




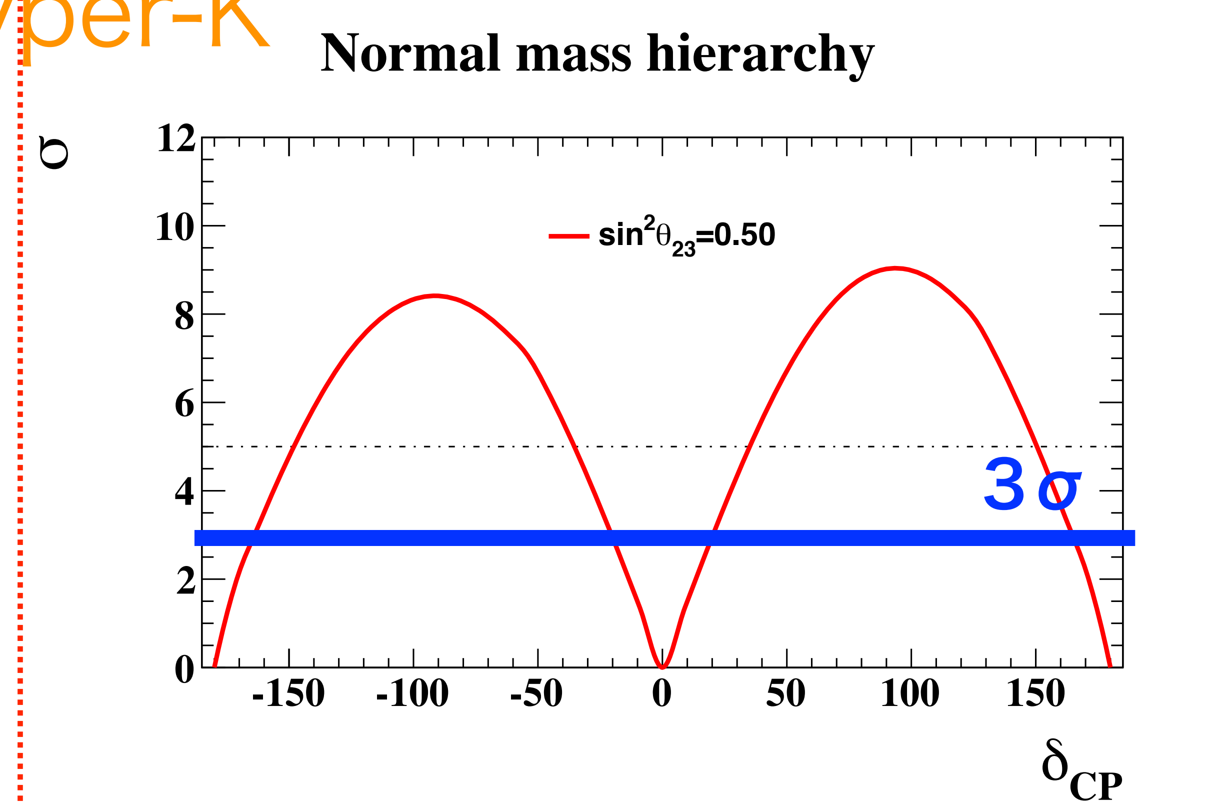


T2K-II

Mass hierarchy is assumed to be known.



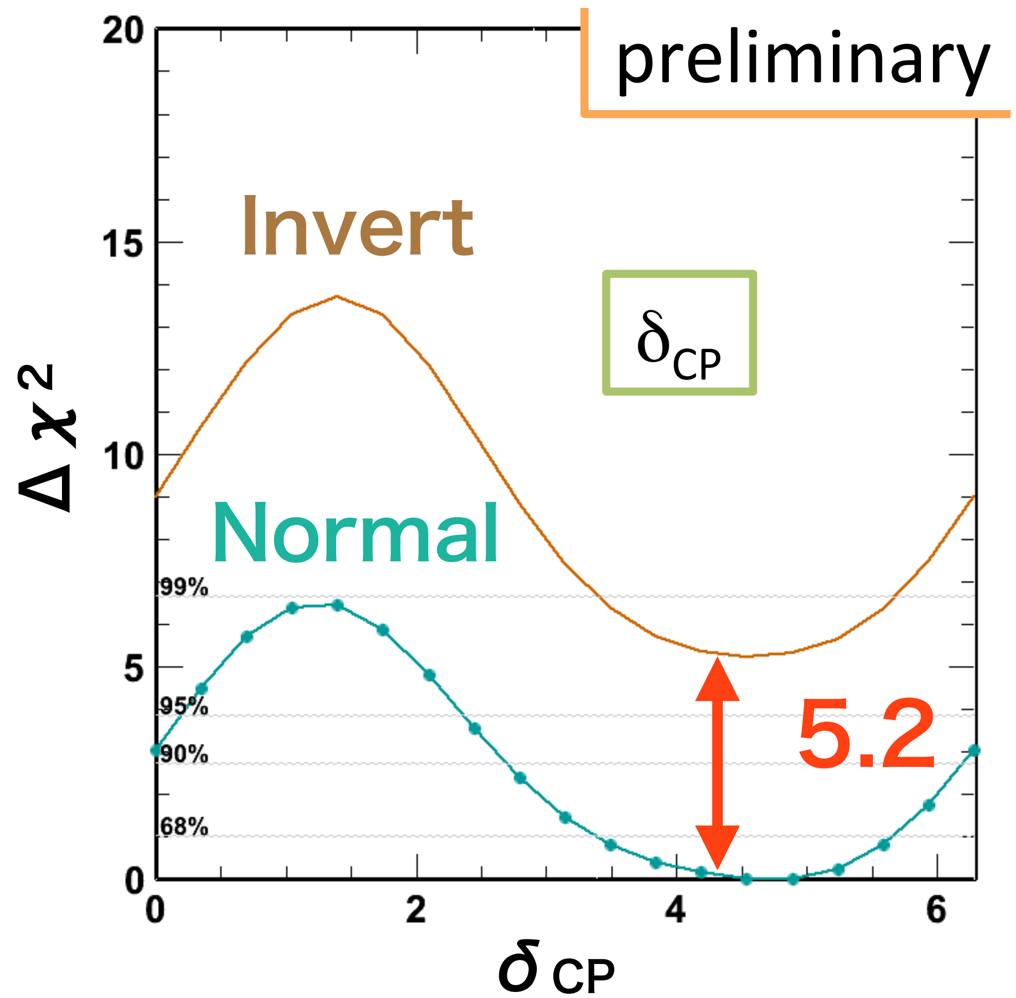
Hyper-K



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.

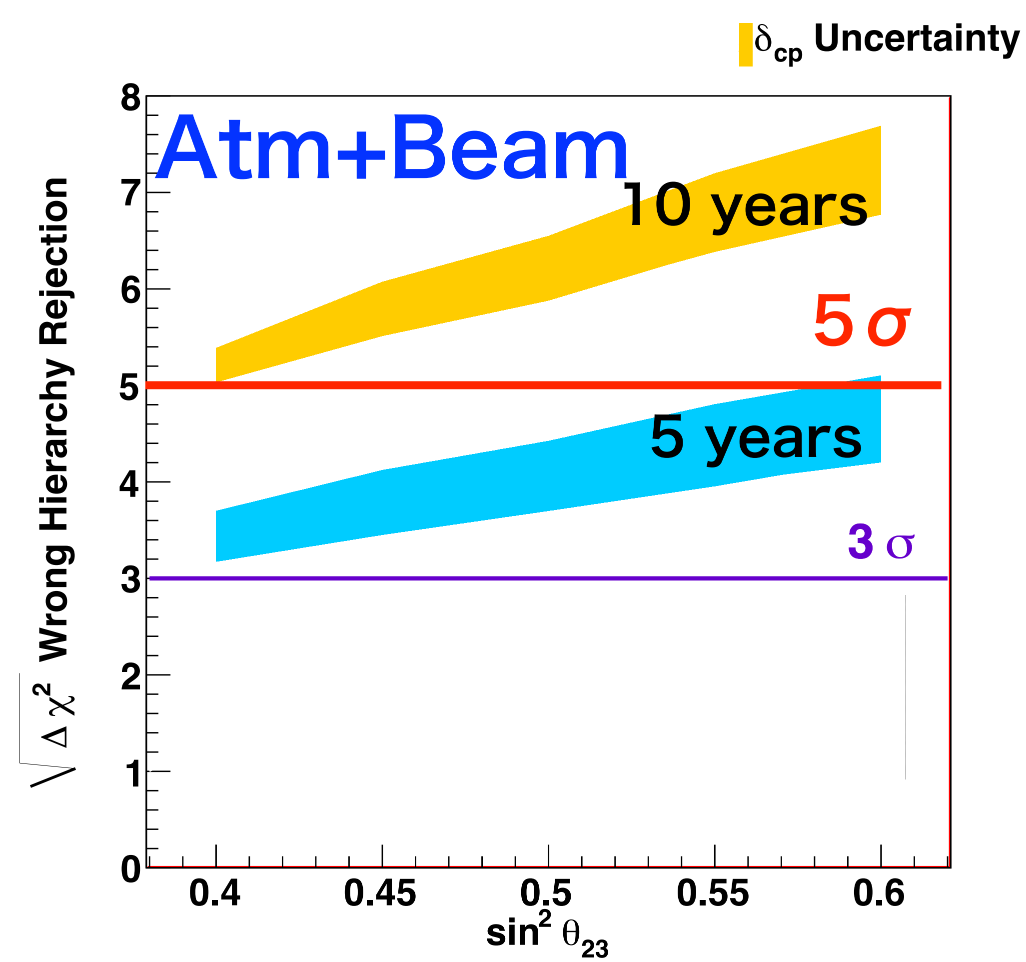
Today **SK Atm+T2K**



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

Hyper-K (Design Report)

Wrong Hierarchy Rejection



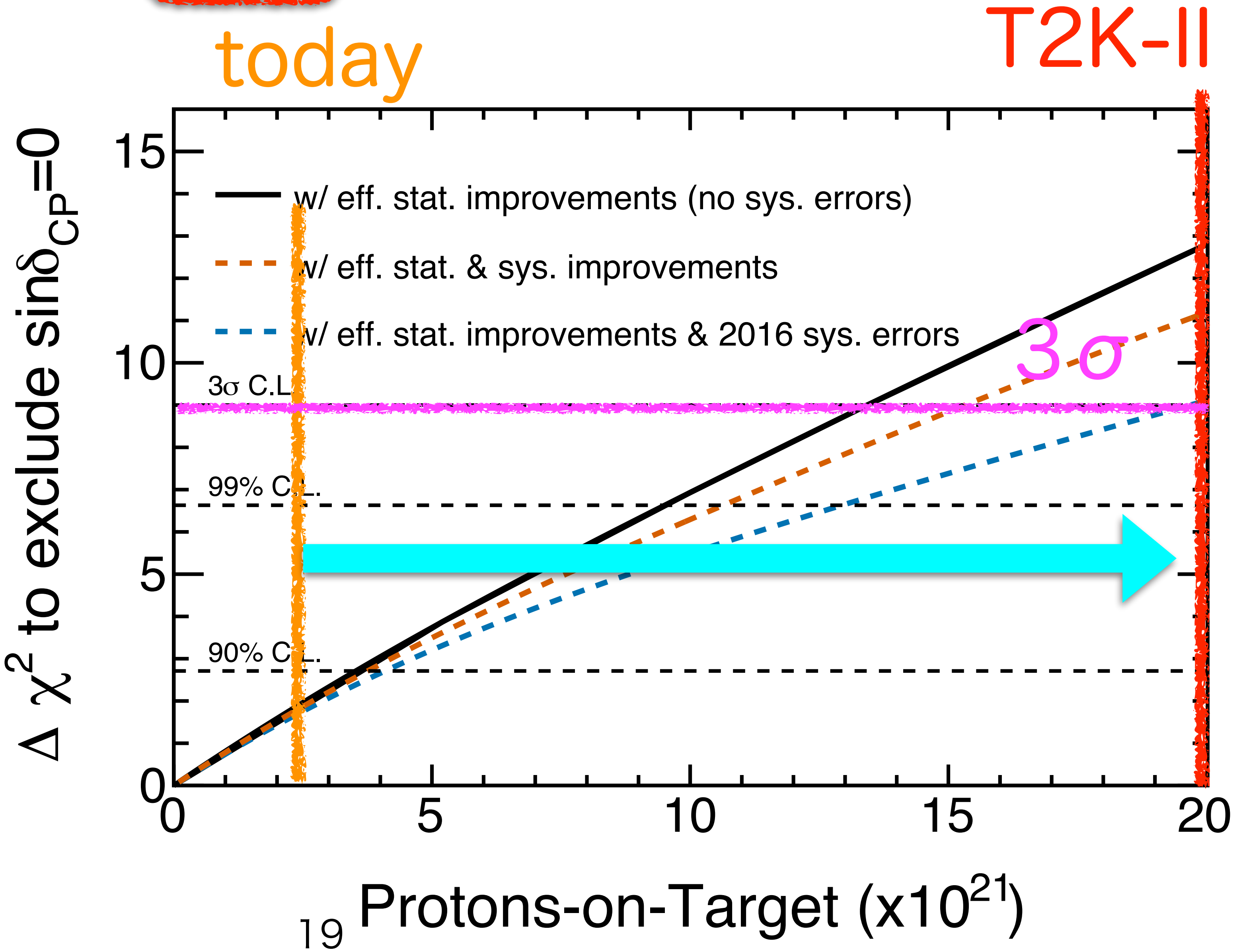
T2K-II with J-PARC Upgrade

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.

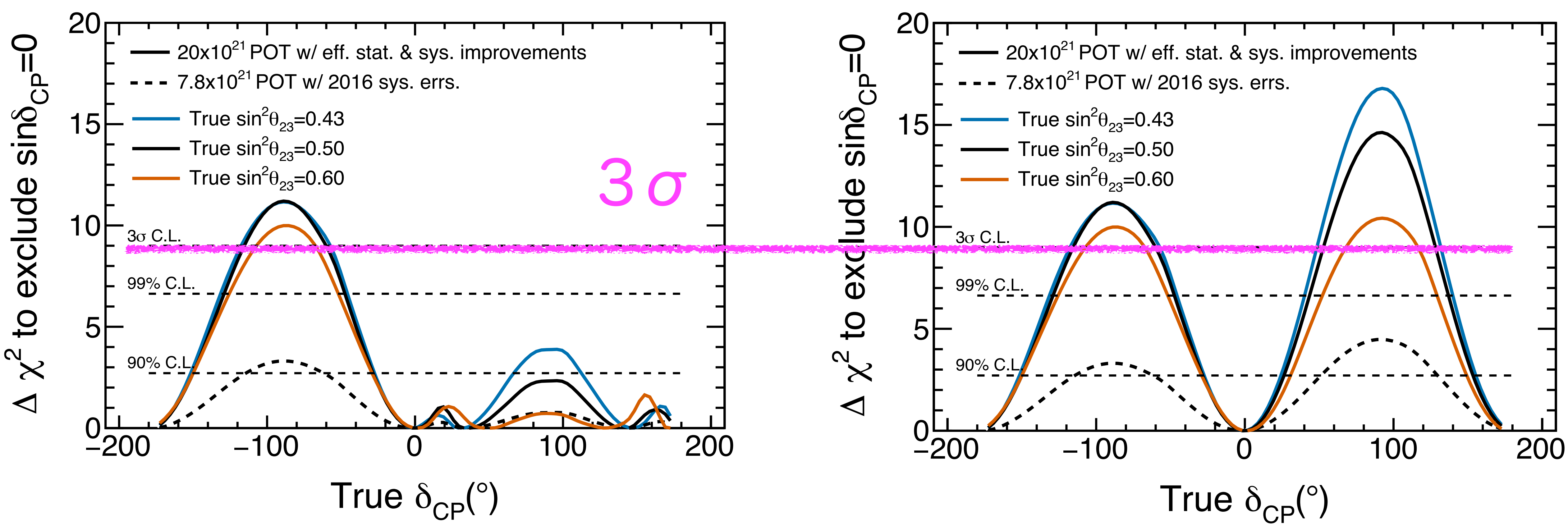
J-PARC PAC gives Stage 1 approval. We are preparing the Technical Design Report.



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.

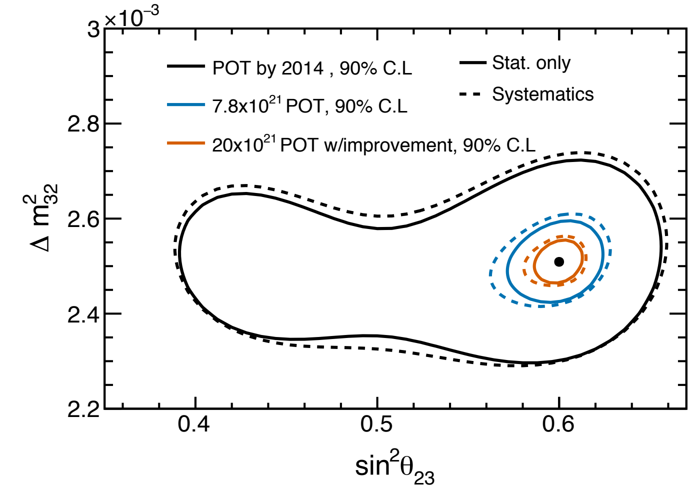
assuming MH unknown　　　　　　　　assuming MH known



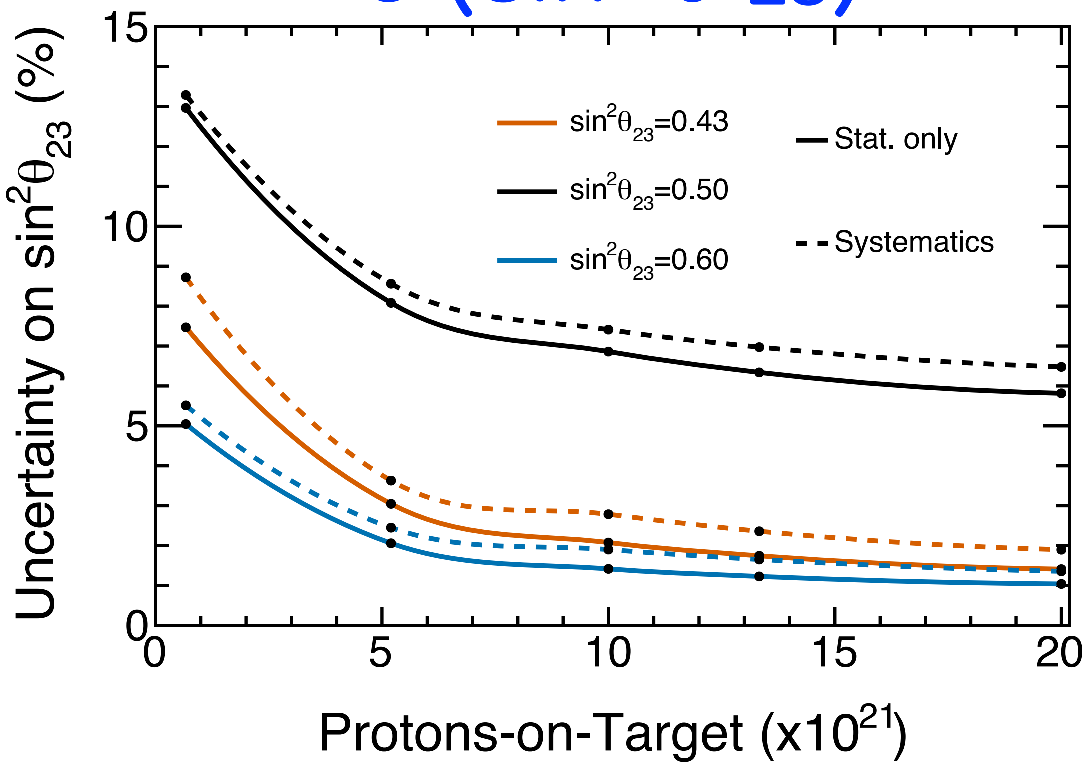
(Note) Although T2K alone can't measure MH, we can help with the MH measurement by, ie, combining T2K + NOVA

T2K-II Physics Sensitivity

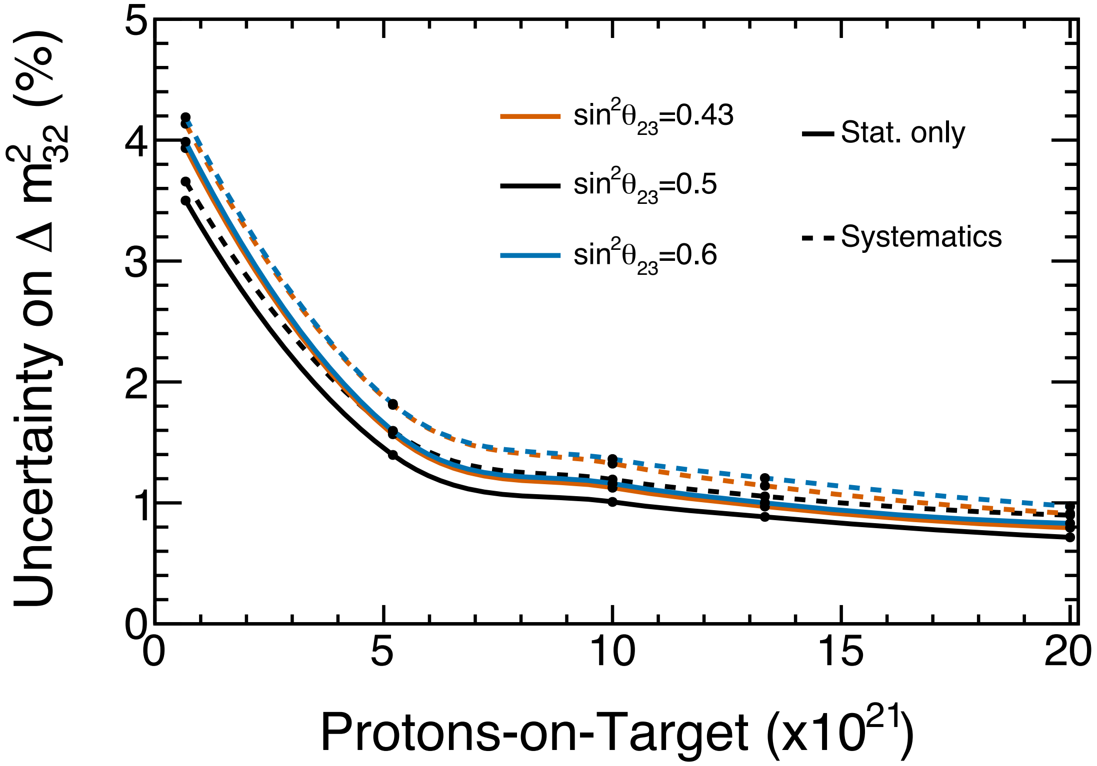
- Precisions of $\sin^2\theta_{23}$ and Δm_{32}^2



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



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



- More physics for Neutrino Interactions and non-standard models

Conclusion

- The Canadian and Japanese groups work in good collaboration, that makes a great discovery in T2K.
- 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 conduct the neutrino experiments for a discovery in particle physics.