Recent Results and Future Prospects of Neutrino Oscillation Experiments

Roger Wendell
Kyoto University
2017.01.06
KMI Symposium 2017, Nagoya

Introduction

- Recently there has been a lot of progress in understanding neutrino mixing in oscillation experiments using a variety of sources
  - Atmospheric
  - Accelerator: both long- and short-baseline
  - Reactor neutrinos
- In this talk I will discuss the most recent results and prospects for the near- and mid-term future
- N.B. There is a worldwide program dedicated to resolving questions in neutrino oscillation physics
  - I will touch briefly on the whole, but emphasis will be placed on the Japanese program
- *Apologies* to those projects that I don't cover in detail!
  - INO, JUNO, ORCA – to name a few

Status of Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Solar

- Three mixing angles, two independent mass differences (Δm^2_{21} , Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain

Esteban, I et al: 1611.01514

	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$

Status of Neutrino Oscillations

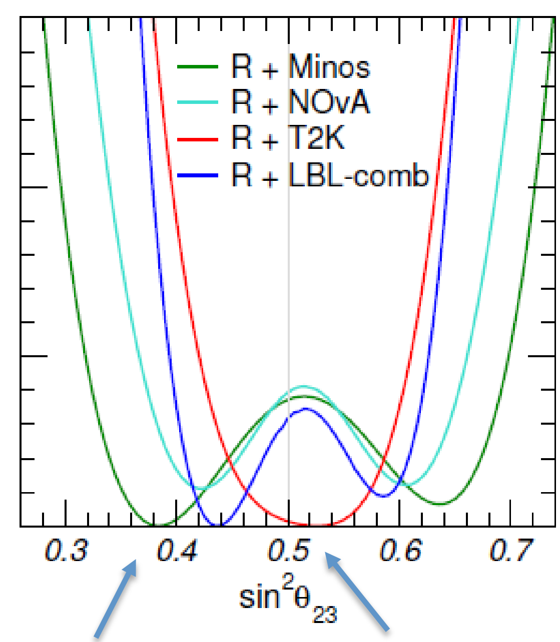
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

Solar

- Three mixing angles, two independent mass differences (Δm^2_{21}, Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - Maximal Mixing?

Is Atmospheric Mixing Maximal



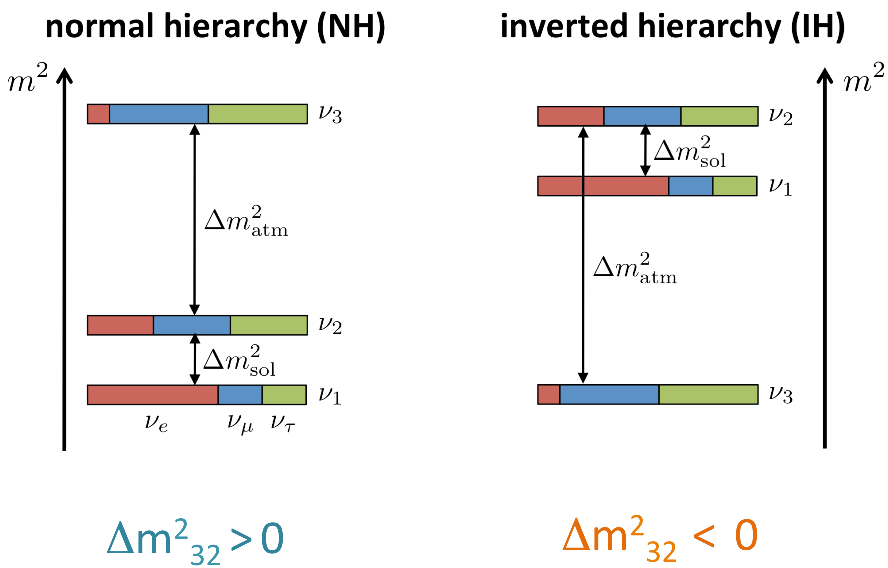
Status of Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric Solar

- Three mixing angles, two independent mass differences (Δm^2_{21}, Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - Neutrino Mass hierarchy?

Mass Ordering is Unknown



Status of Neutrino Oscillations

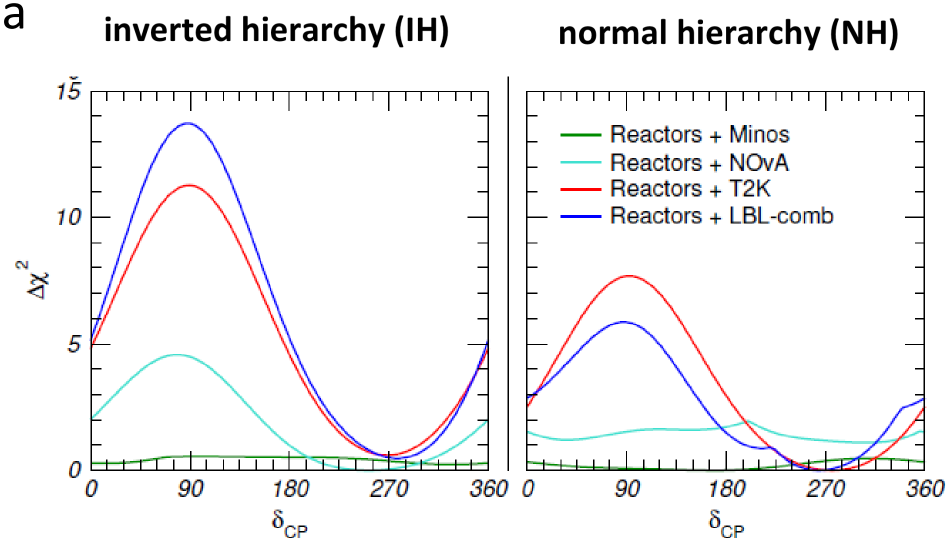
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric

Solar

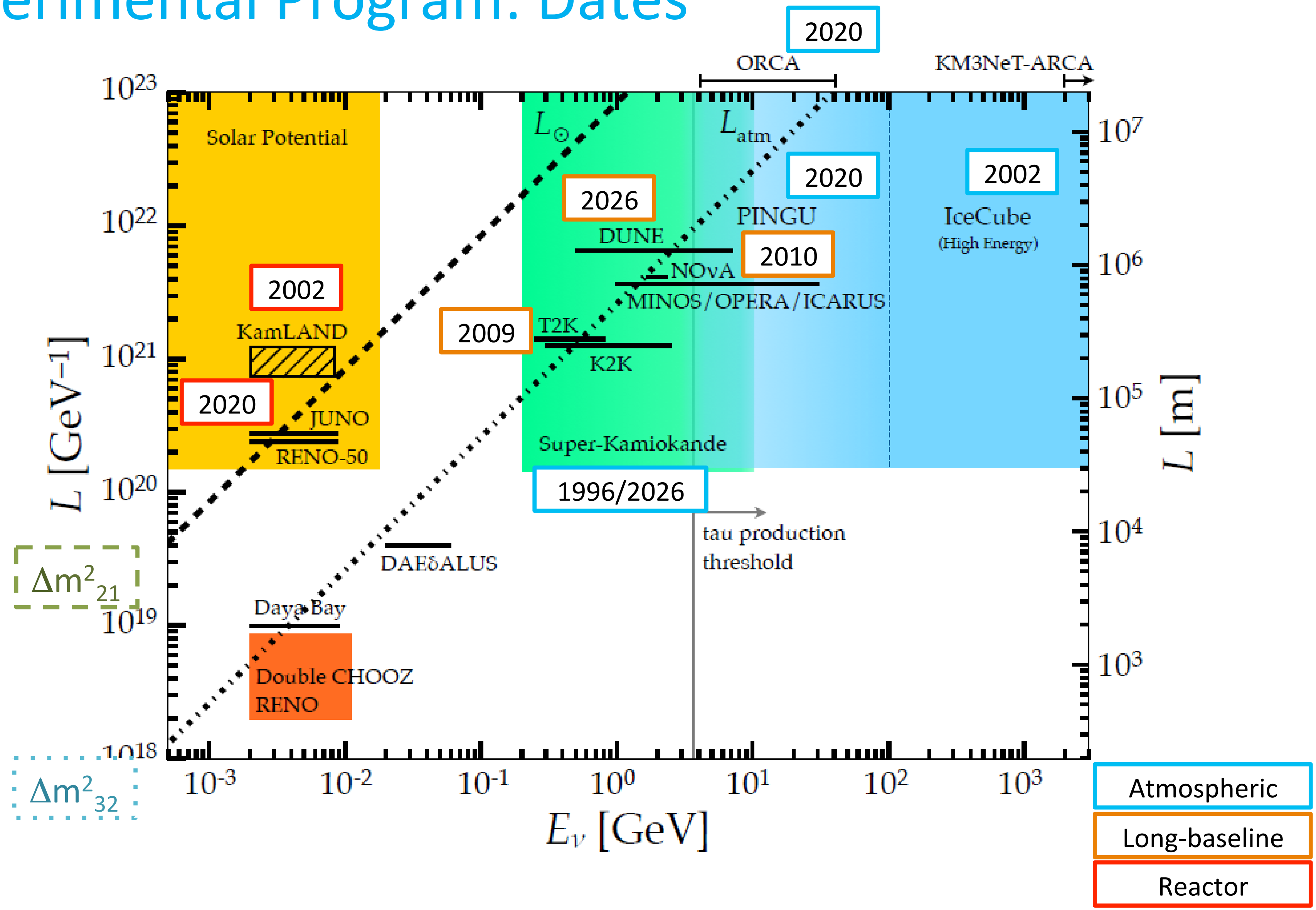
- Three mixing angles, two independent mass differences (Δm^2_{21} , Δm^2_{32}), and a CP violating phase δ_{cp}
- Currently, ***all*** parameters have been measured, though δ_{cp} is the least well constrained and the topic of much interest
- However, several open questions remain
  - Neutrino Mass hierarchy

Is CP Violated in Neutrino Mixing?



Esteban, I et al: 1611.01514

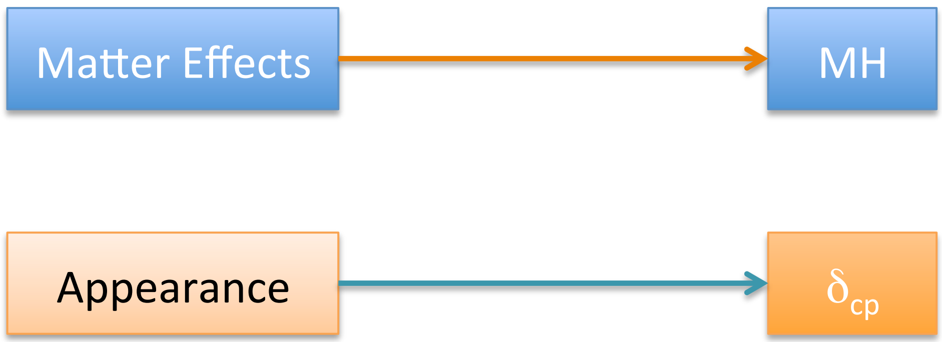
Experimental Program: Dates



- Many experiments ongoing and planned
- Mass hierarchy and δ_{cp} measurements rely on the similar techniques, for the most part

Determination of The MH and δ_{cp}

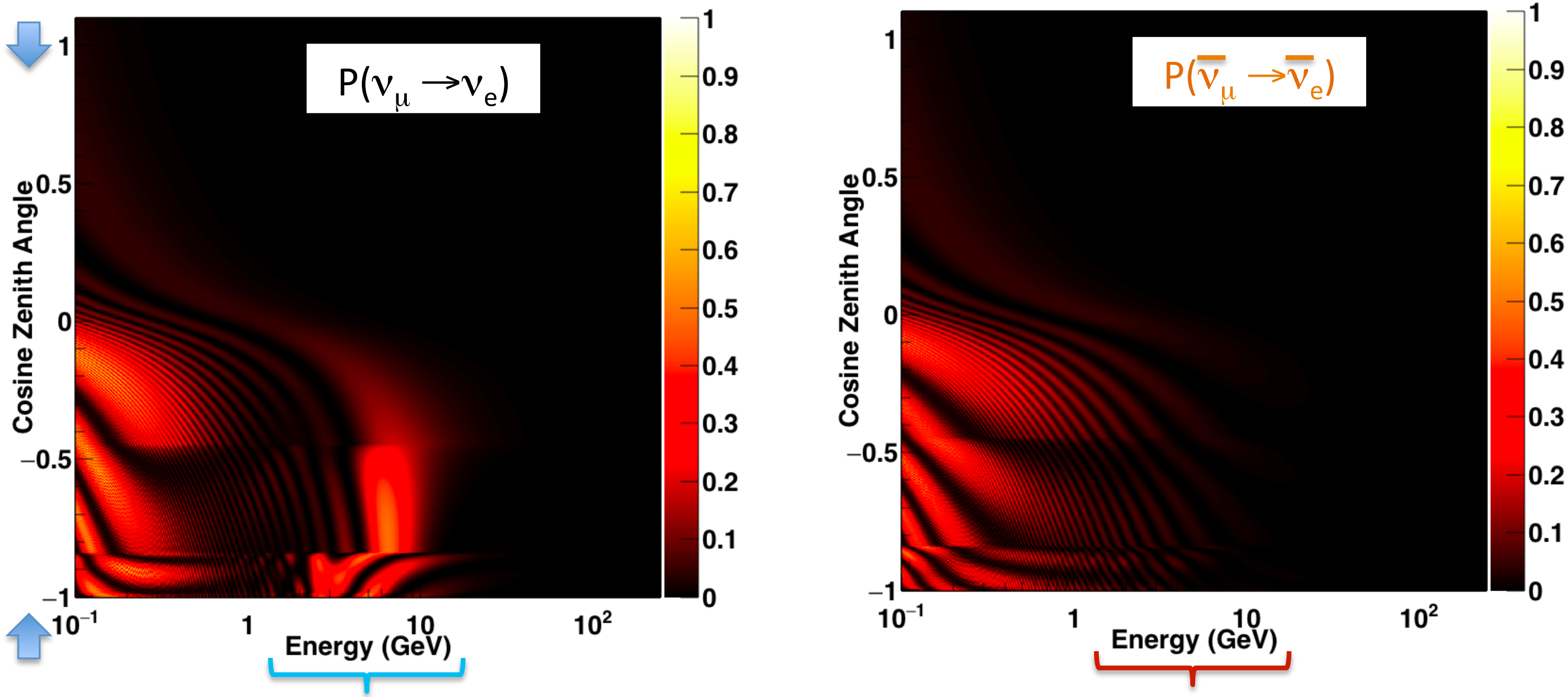
For the purposes of today's Talk:



- Dominant oscillation mode for measurements is the *appearance* channel
  - $\nu_{\mu} \rightarrow \nu_{e}$
  - This mode was established in 2012 by T2K and confirmed with NOνA
  - Notable exception is the JUNO experiment (backup)
- Additional sensitivity from *disappearance* mode $\nu_{\mu} \rightarrow \nu_{\mu}$

Mass Hierarchy Determination: Matter-Effects

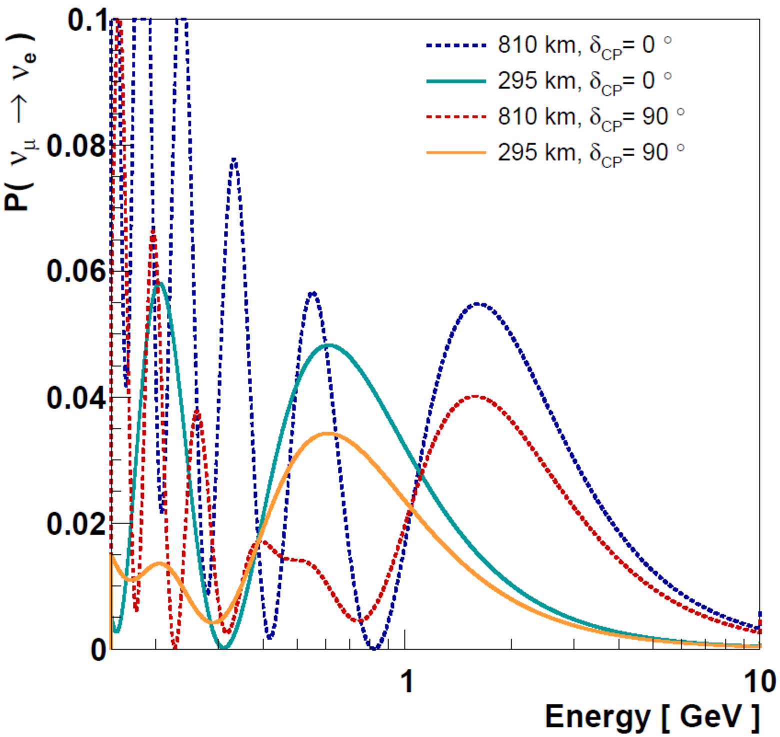
Normal Hierarchy

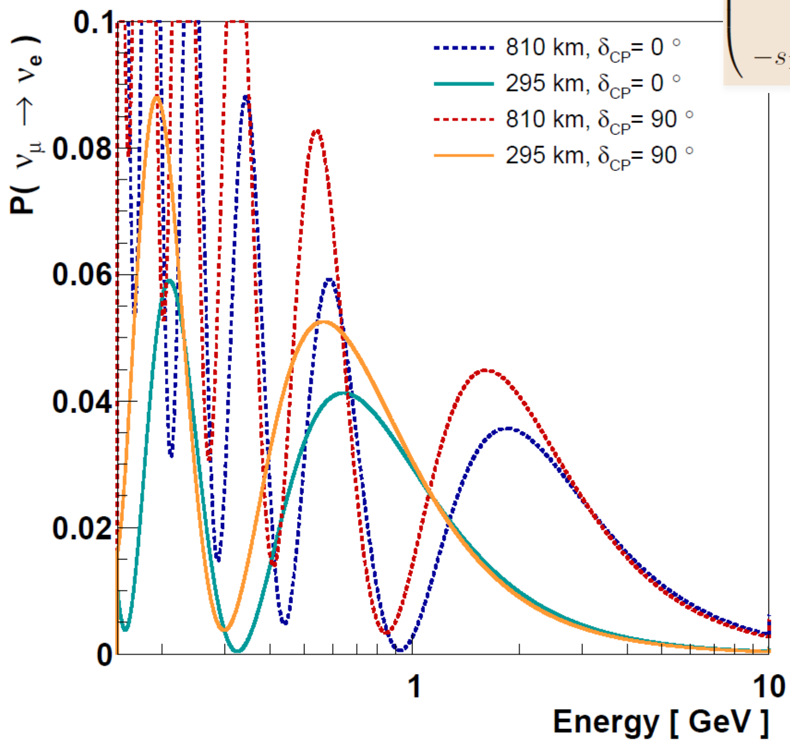


- Mattter induces asymmetric oscillations between electron-type neutrinos and antineutrinos
  - *If the baseline is long enough the asymmetry can be large (NOvA, DUNE, HKK)*
- For atmospheric neutrinos: enhanced oscillations for *either* neutrinos or antineutrinos (not both), depending upon the mass hierarchy
  - *Muon nuetrinos also sensitive (ICAL-INO)*

Measuring δ_{cp} Parameter : Long-baseline

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}$$



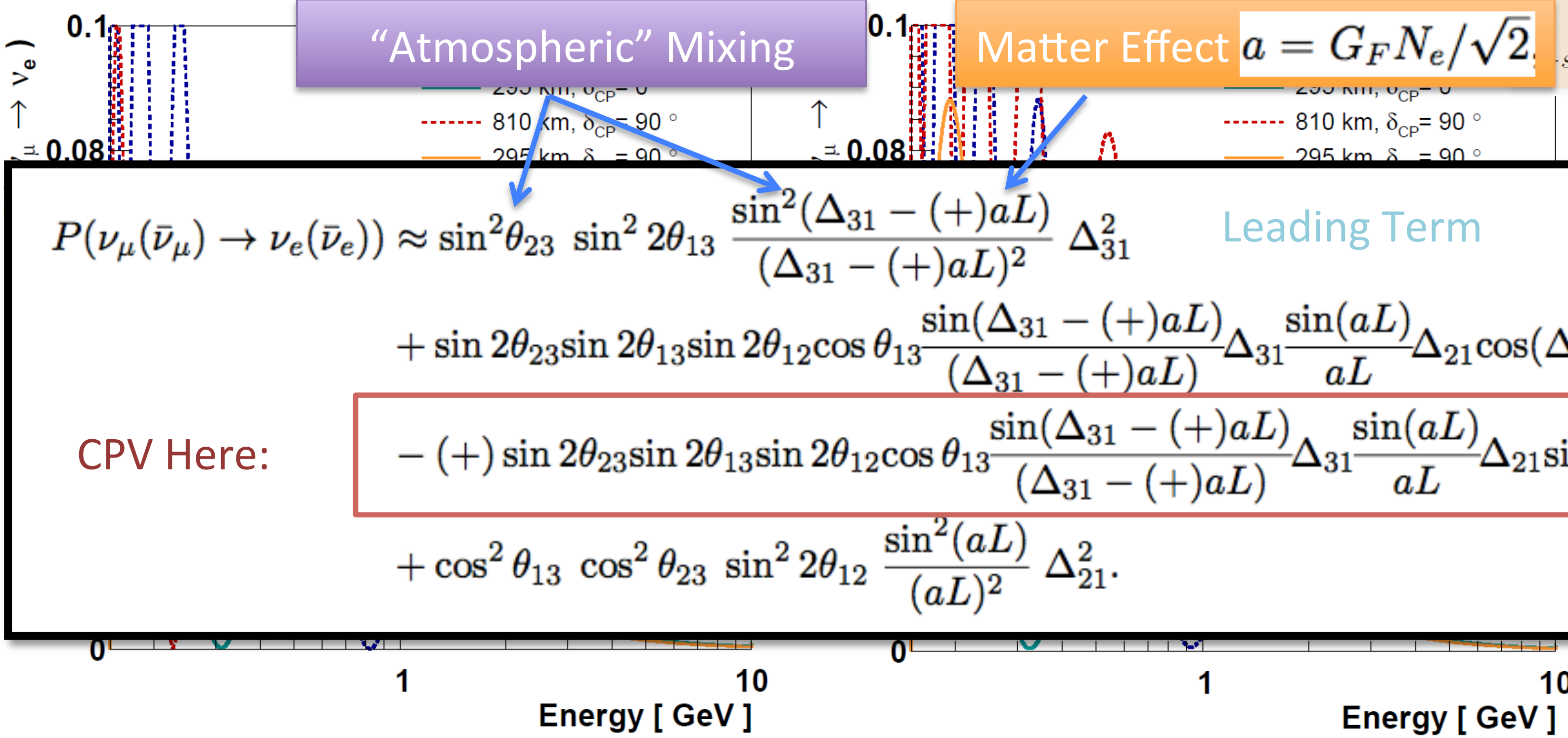


- Modulation of the electron neutrino appearance probability is the *dominant* channel with sensitivity to δ_{cp}
- Neutrino/antineutrino sign selection provides direct probe

- T2K baseline : 295 km
- NOνA baseline : 810 km

Measuring θ_{23} and δ_{cp} Parameter : Long-baseline

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}$$



"Atmospheric" Mixing

Matter Effect $a = G_F N_e/\sqrt{2}$

Leading Term

$$P(\nu_\mu(\bar{\nu}_\mu) \to \nu_e(\bar{\nu}_e)) \approx \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \frac{\sin^2(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)^2}\ \Delta_{31}^2$$

$$+ \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \cos(\Delta_{32}) \cos\delta$$

CPV Here:

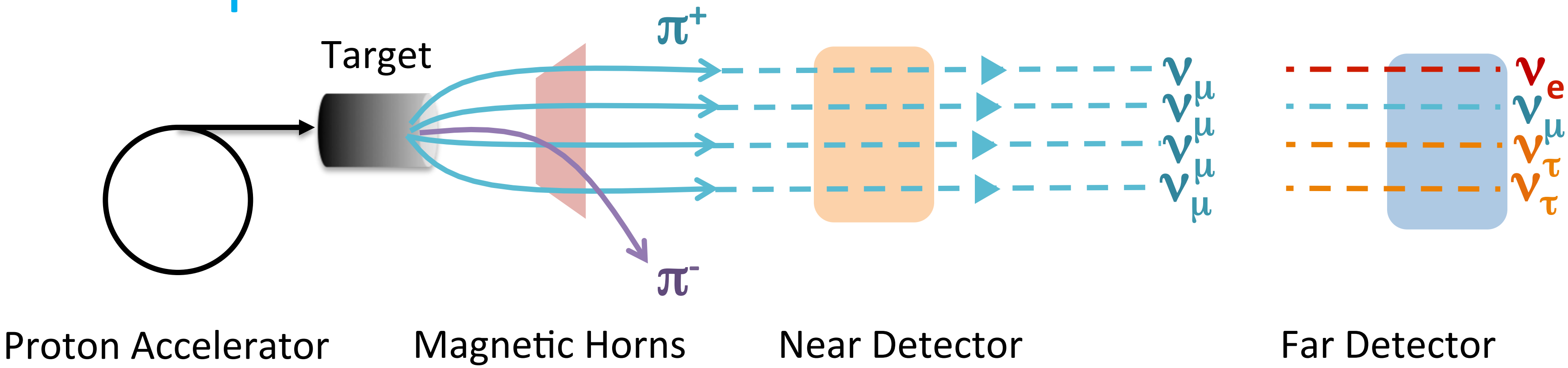
$$- (+) \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\theta_{13} \frac{\sin(\Delta_{31} - (+)aL)}{(\Delta_{31} - (+)aL)} \Delta_{31} \frac{\sin(aL)}{aL} \Delta_{21} \sin(\Delta_{32}) \sin\delta$$

$$+ \cos^2\theta_{13}\ \cos^2\theta_{23}\ \sin^2 2\theta_{12}\ \frac{\sin^2(aL)}{(aL)^2}\ \Delta_{21}^2.$$

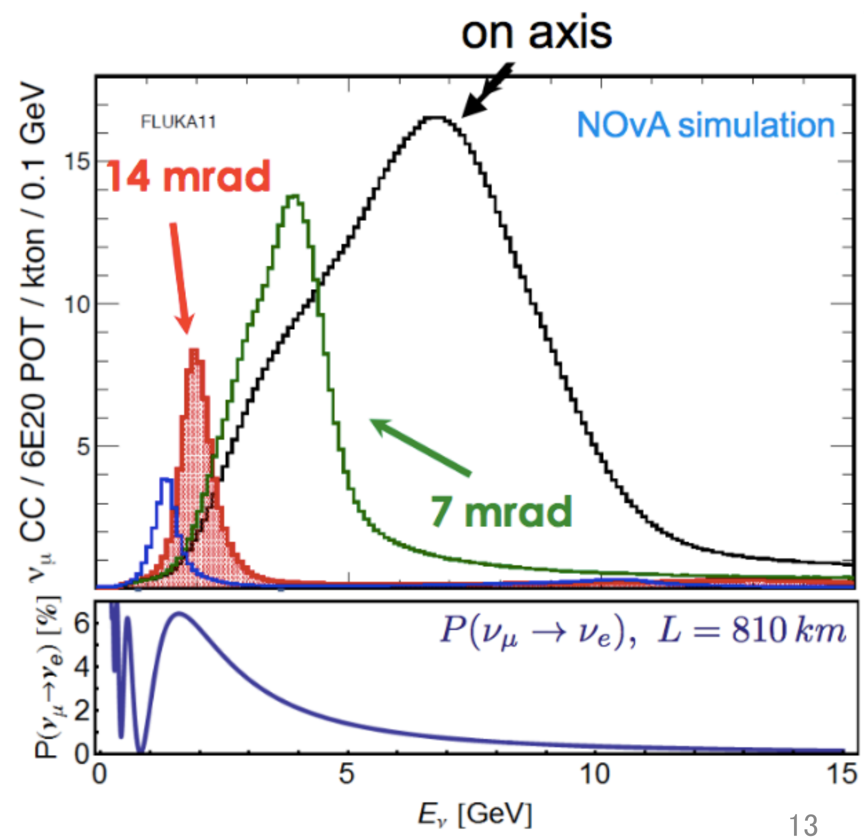
- It is *not sufficient* to just search for electron neutrino appearance to study neutrino CP
- Experiments utilize constraints (in-situ measurements) from the disappearance channel to improve sensitivity to
  - Equally relevant for atmospheric neutrinos!

Current Experiments

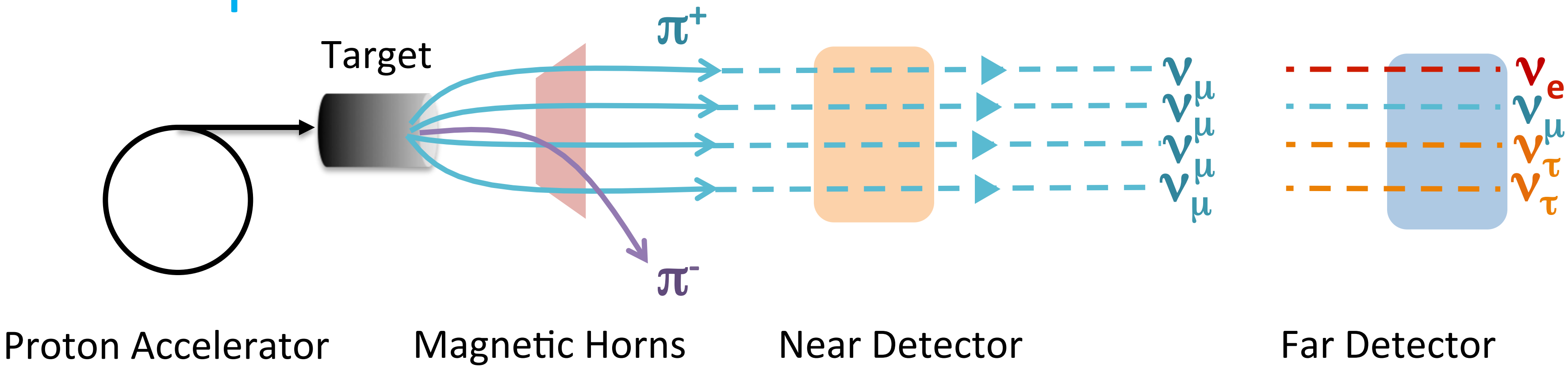
Beam Experiments:

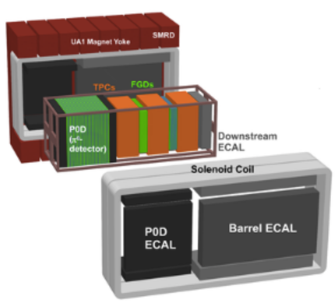


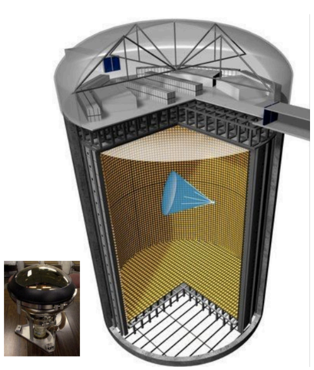
- Off-axis beam used to create a narrow neutrino energy
  - Baseline optimized for maximum oscillation effect
- Near detectors are used to constrain flux and interaction model at the far detector
- Changing magnetic horn polarity allows one to create either a neutrino or antineutrino enhanced beam



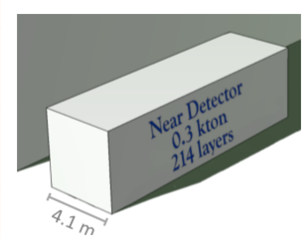
Beam Experiments:



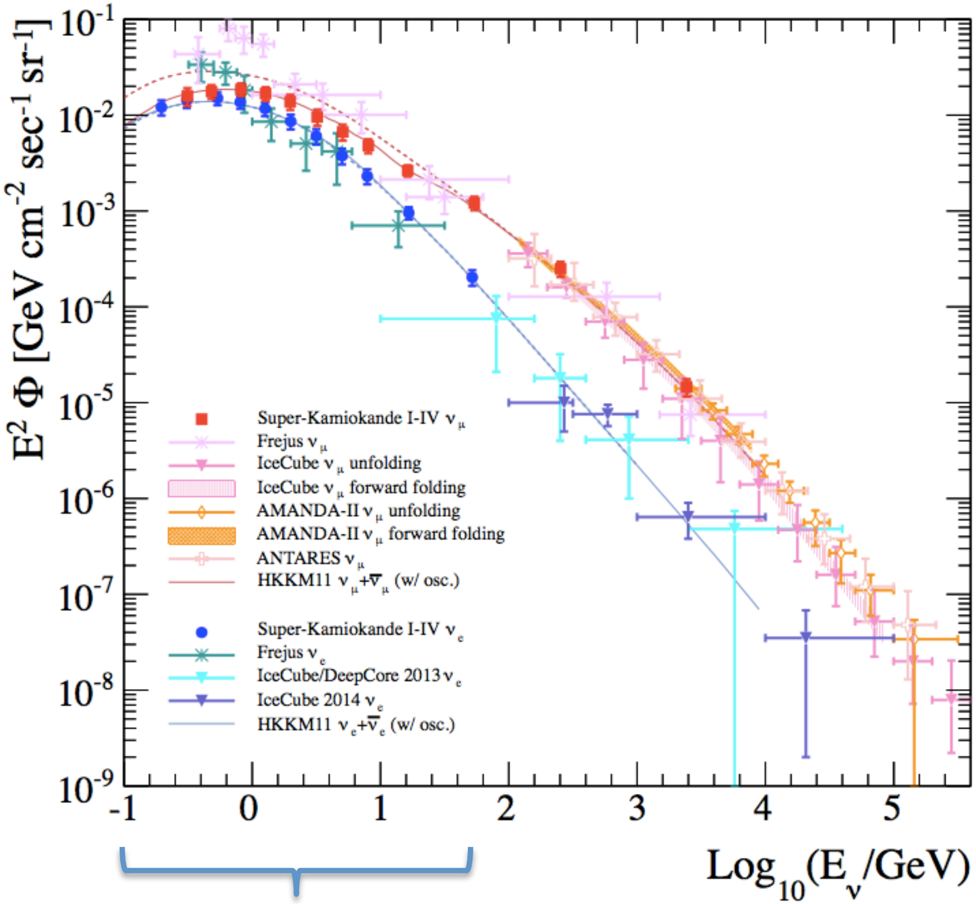




	T2K	NOνA
Location	Japan / J-Parc	U.S.A. / FNAL
Beam Power	400 kW	560 kW
Proton Energy	30 GeV	120 GeV
Baseline Length	295 km	810 km
Near Detector	Tracker: FGD, TPC	Lq. Scintillator
Target	Carbon	Carbon
Far Detector	Super-K 50kton	Lq. Scintillator
Target	Water	Carbon
Off-axis Angle	2.5 deg / 44 mrad	0.8 deg / 14 mrad
Peak ν Energy	~600 MeV	~2 GeV



Atmospheric Neutrino Experiments:



Oscillations

Super-Kamiokande

IceCube/DeepCore

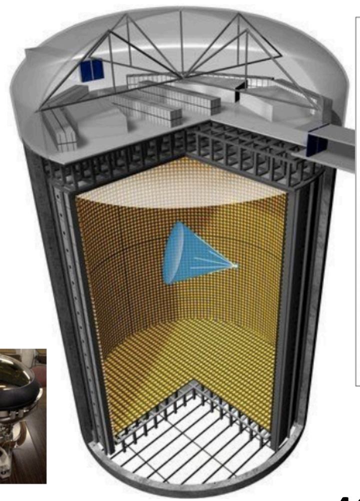
$$p^+ + N \rightarrow \pi^+ + hadrons$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

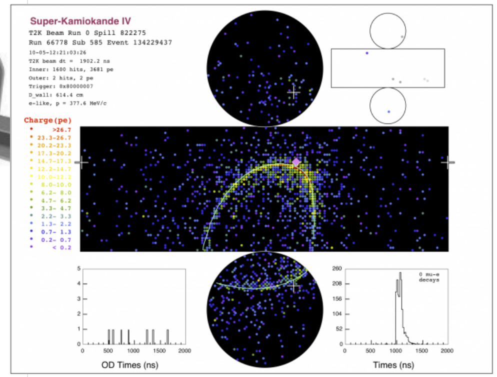
- Diverse range of energies
- Produced nearly isotropically about the Earth

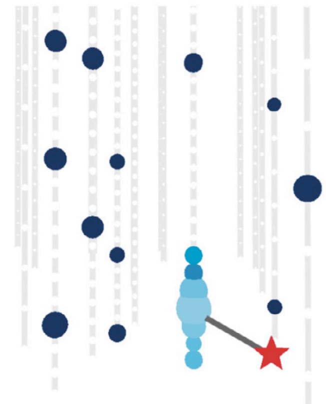
- Both electron and muon neutrinos
- Both neutrinos and antineutrinos
  - No “Horn” to focus one or the other

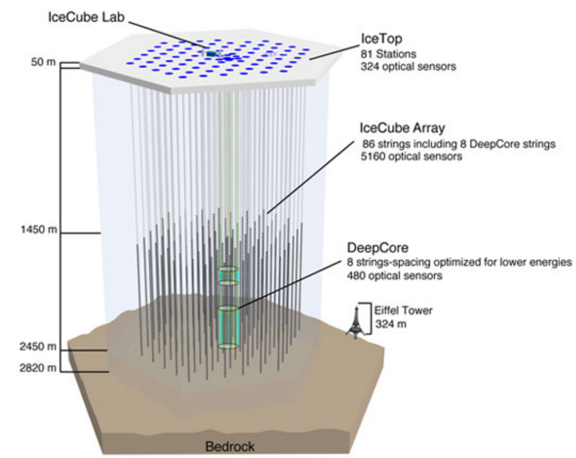
- No knowledge of neutrino production point or precise direction
- No near detector to control interaction systematics

Atmospheric Neutrino Experiments:









40m

ICECUBE

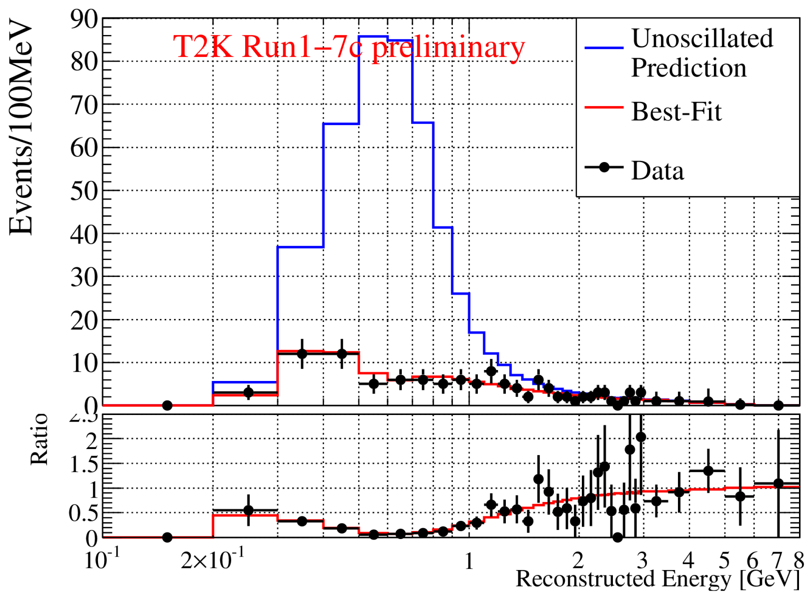
1 km

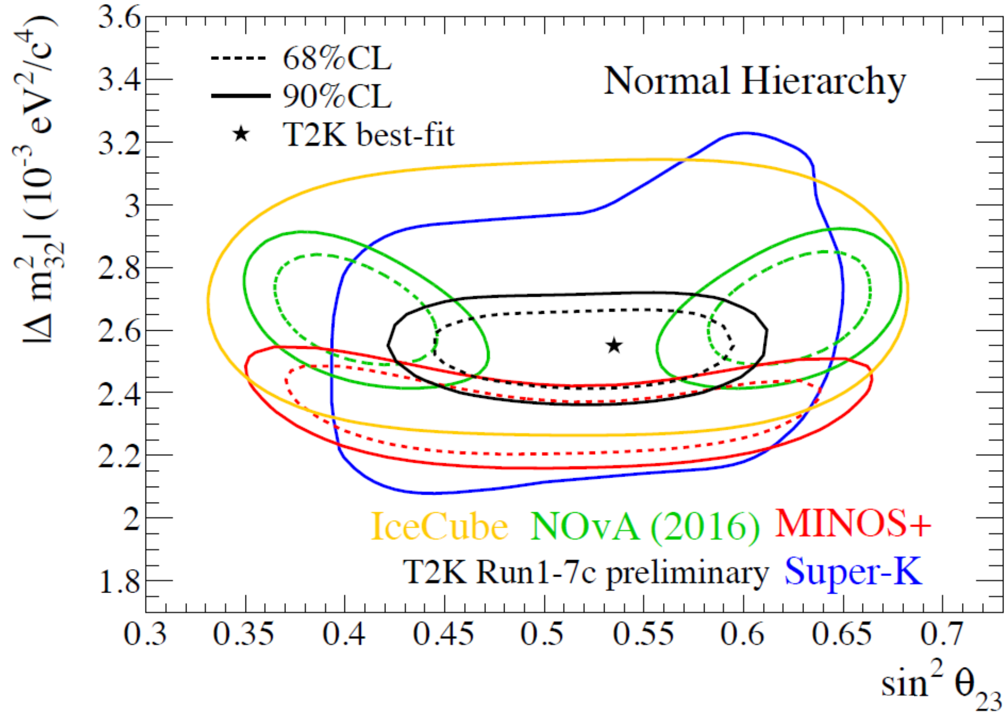
Super-Kamiokande	IceCube
50,000 Ton Ultrapure Water	1 km^3 of Antarctic *Ice*
11,000 20" PMTs (ID) 1885 8" (OD)	5100 Digital Optical Modules (DOM)
Ring-Imaging	"String" Imaging
40% Cathode Coverage	86 Strings, 17m / 7m DOM Spacing
0.1 ~ 10^3 GeV	10 ~ 10^5 GeV
Excellent e/μ PID, MIS PID 1%	Cascade (e/NC) and Track (μ)

Both are Cherenkov detectors without event-by-event $\nu/\bar{\nu}$ separation

Atmospheric Mixing

Atmospheric Mixing: Muon Neutrino Disappearance

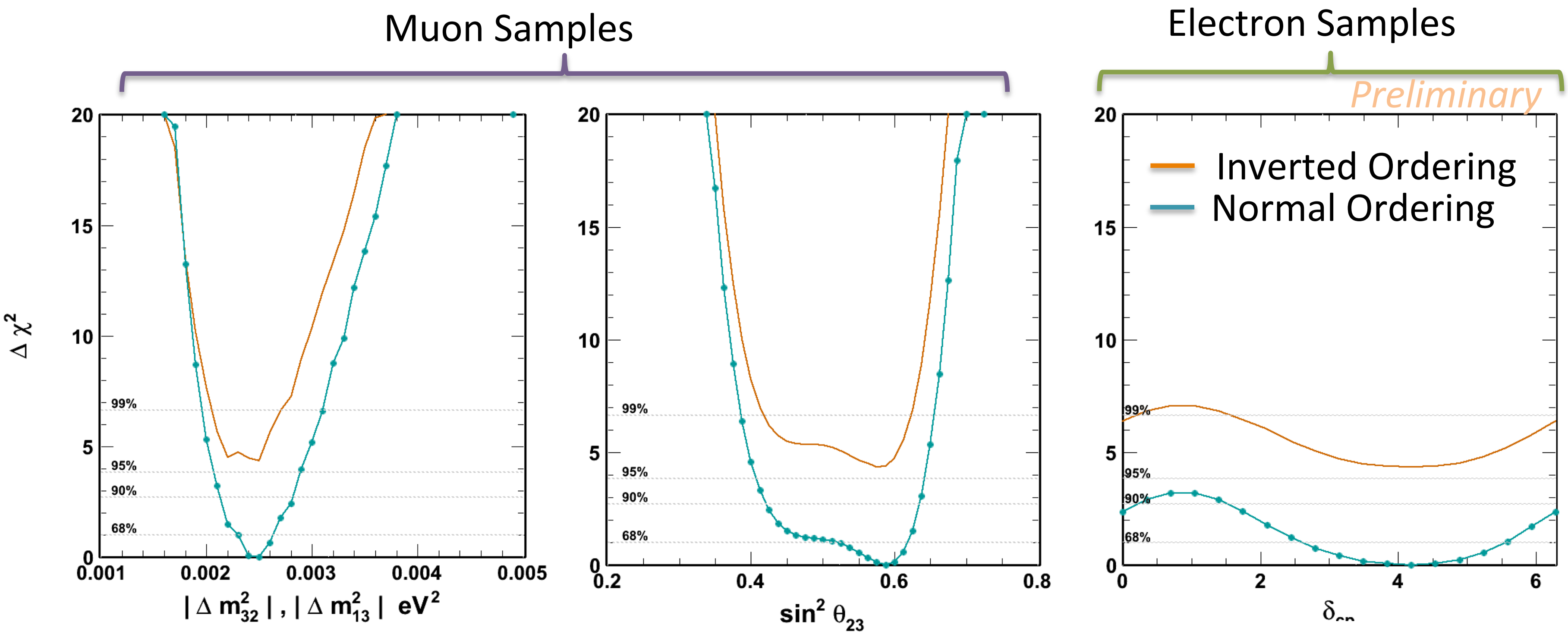




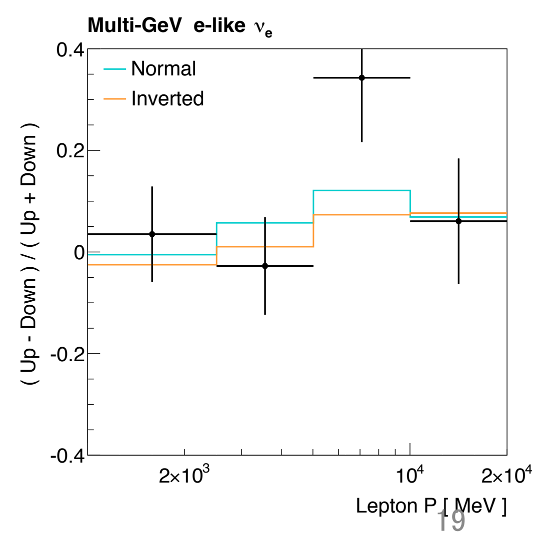
Experiment	Null Osc.	Observed	Best Fit	Comment
T2K (ν-mode)	522	135	135.3	7.5e20 POT
T2K (ν-mode)	185	66	64.1	7.5e20 POT
NOνA	437	78	82	6.05e20 POT
IceCube	6830	5174	---	Atmospheric

- NOνA currently rejecting maximal mixing at 2.5σ

Atmospheric Mixing + δ_{cp}: Super-Kamiokande



- Comparatively weak constraint on atmospheric mixing
- Observe an excess of upward-going electron neutrino events weakly favoring the *normal hierarchy*
  - $\Delta\chi^2$ (NH − IH) = -4.3
  - P(NH|IH) : 3.1%



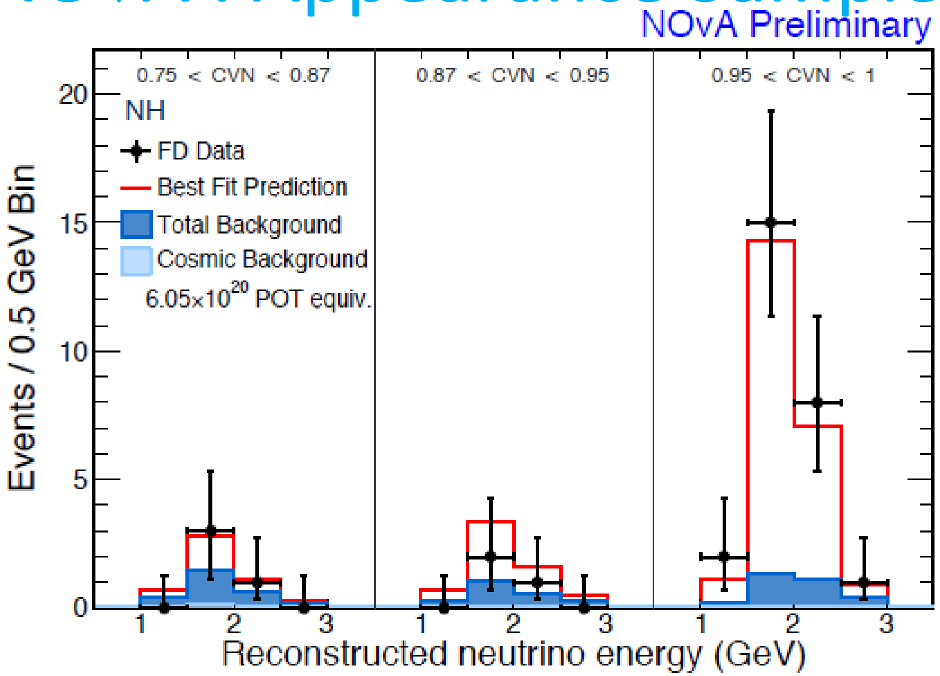
- Weak hint for δ_{cp} ~1.33π

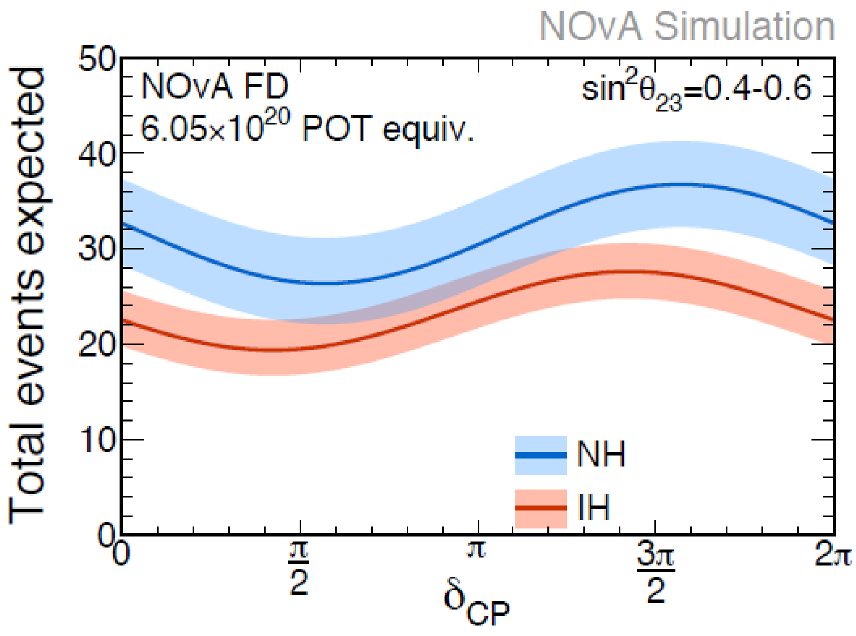
Electron Appearance And δ_{cp}

Recall: ν_μ -> ν_e oscillations are mode with dominant sensitivity

However: oscillation dependence on atmospheric mixing necessitates use of disappearance sample as an in-situ constraint

NOνA : Appearance Sample





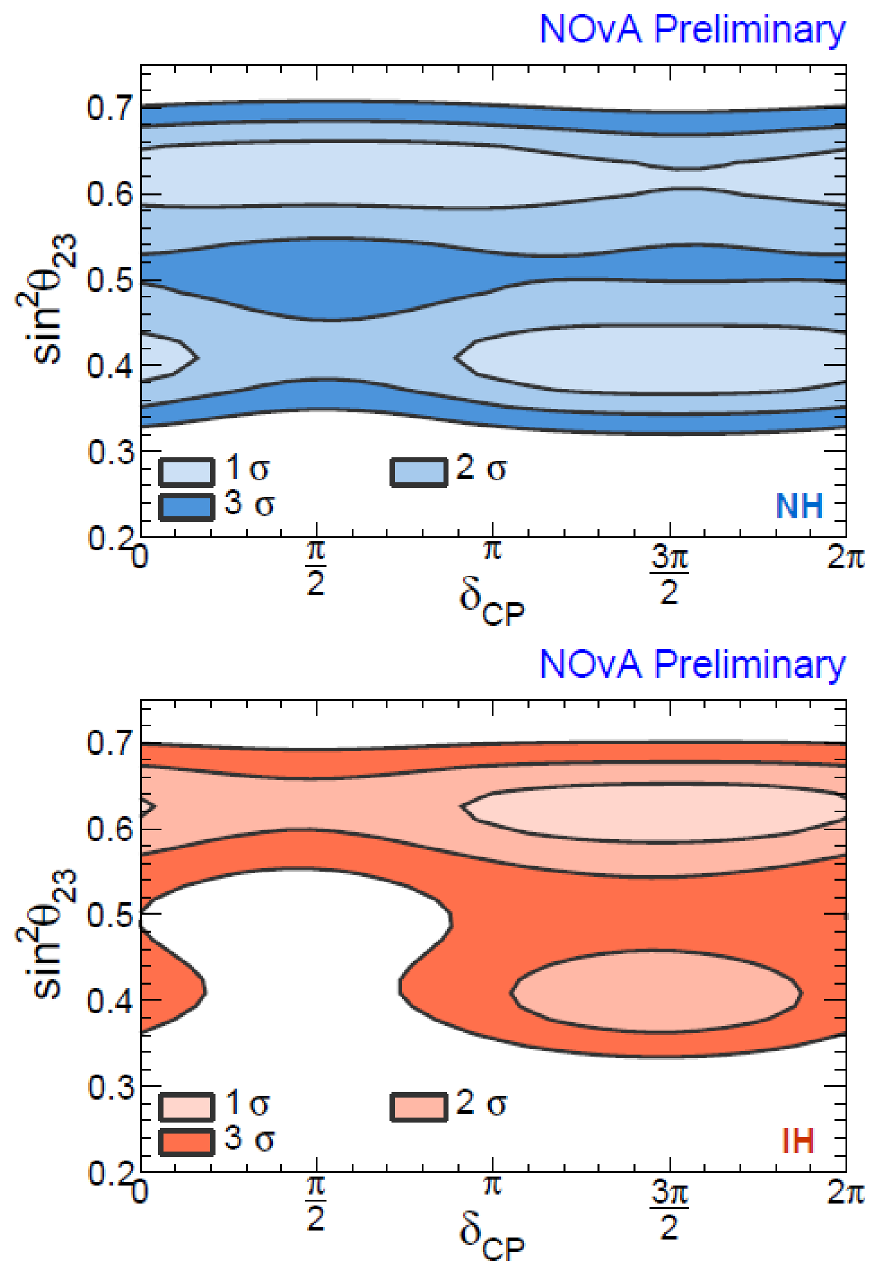
J.Hartnell NOW2016

- With 6.1e20 POT observe 33 events in the far detector
  - BG: 8.2 +- 0.8 expected (3.7 NC, 3.1 Intrinsic)
  - Signal systematic uncertainty is 5%

- Expect 28.2 events for NH, $\delta_{cp} = 3\pi/2$
- Expect 11.2 events for IH, $\delta_{cp} = \pi/2$

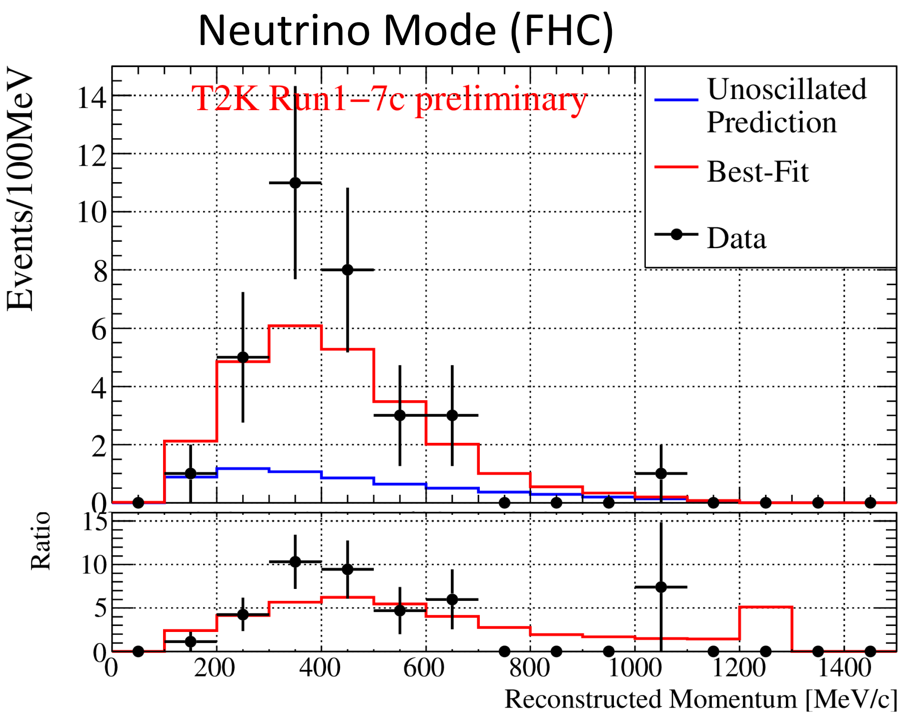
NOνA : Full Analaysis

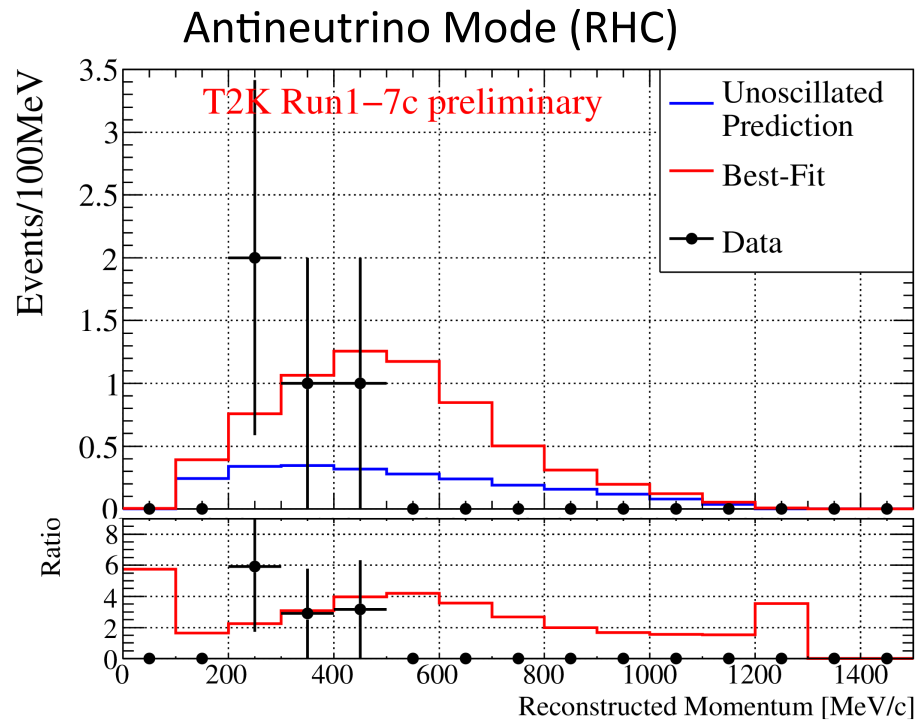
- Combined analysis of appearance and disappearance samples
- So far neutrino mode only
- Preference for Normal hierarchy
  - $\Delta\chi^2 = 0.47$
  - $\delta_{cp} = 1.49\pi$
  - $\sin^2(\theta_{23}) = 0.40$
- 3σ exclusion of IH with $\delta_{cp} = 0.5\pi$



J.Hartnell NOW2016

T2K : Appearance Samples

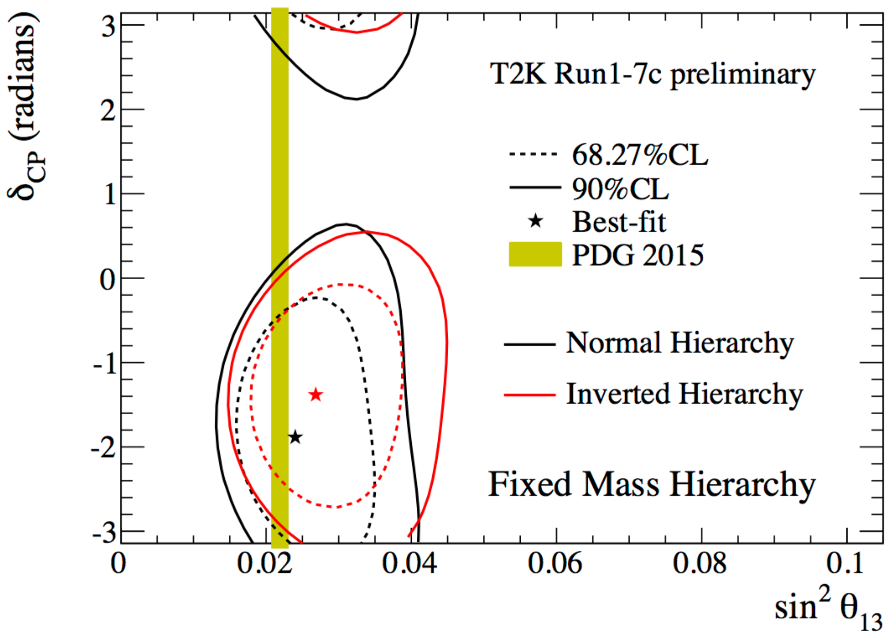


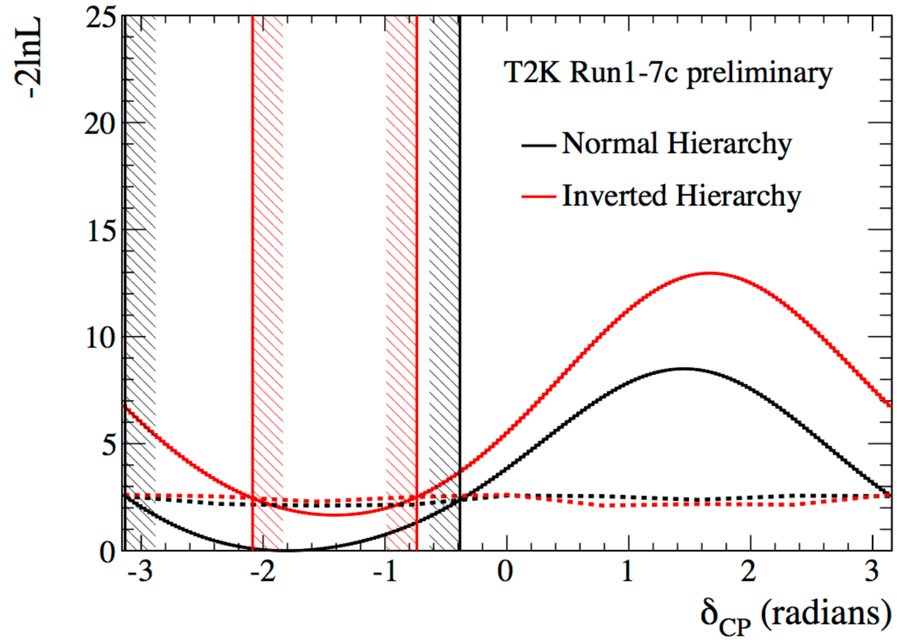


- With 7.5e20 POT for both neutrino mode (FHC) and antineutrino mode (RHC)
  - FHC : 33 events
  - RHC: 4 events

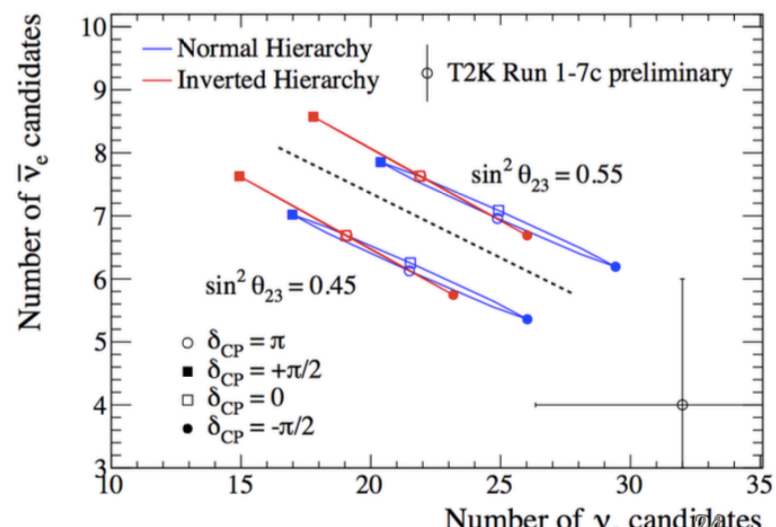
Expectation	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν_e	28.7	24.2	19.6	24.1
$\bar{\nu}_e$	6.0	6.9	7.7	6.8

T2K: First Hints of Leptonic CP-Violation?



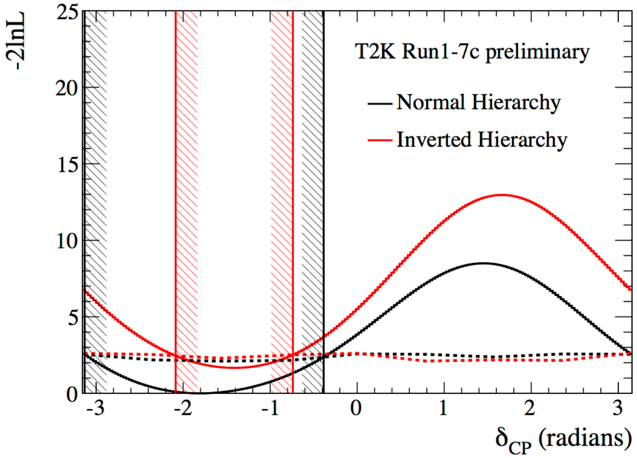


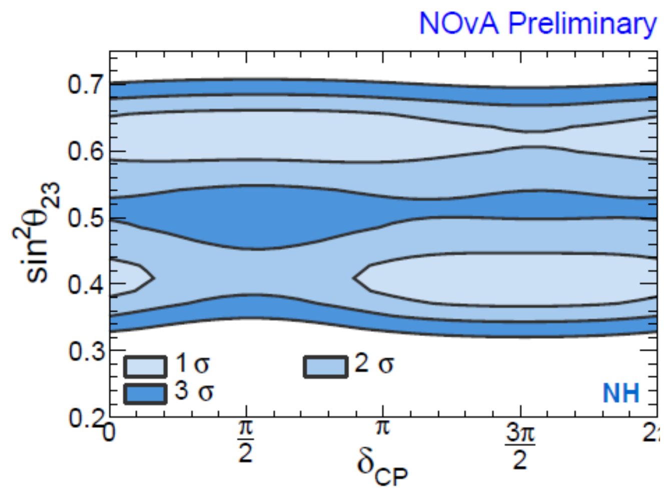
- Allowed region for δ_{cp} at 90% C.L.
  - NH: [-3.13 , 0.39]
  - IH : [-2.09 , -0.74]
- CP-conserving values 0, π are (just) outside of this range!

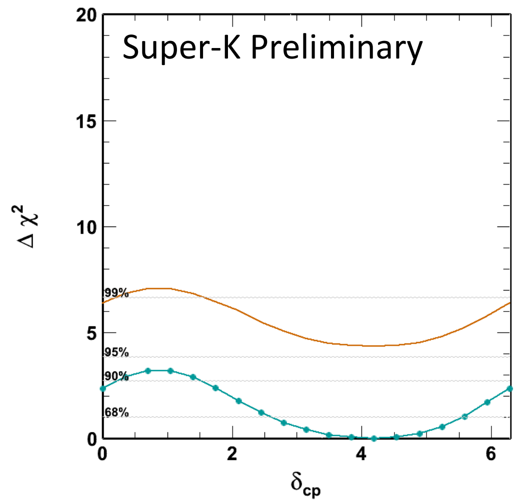


Into the Future

Into the Future



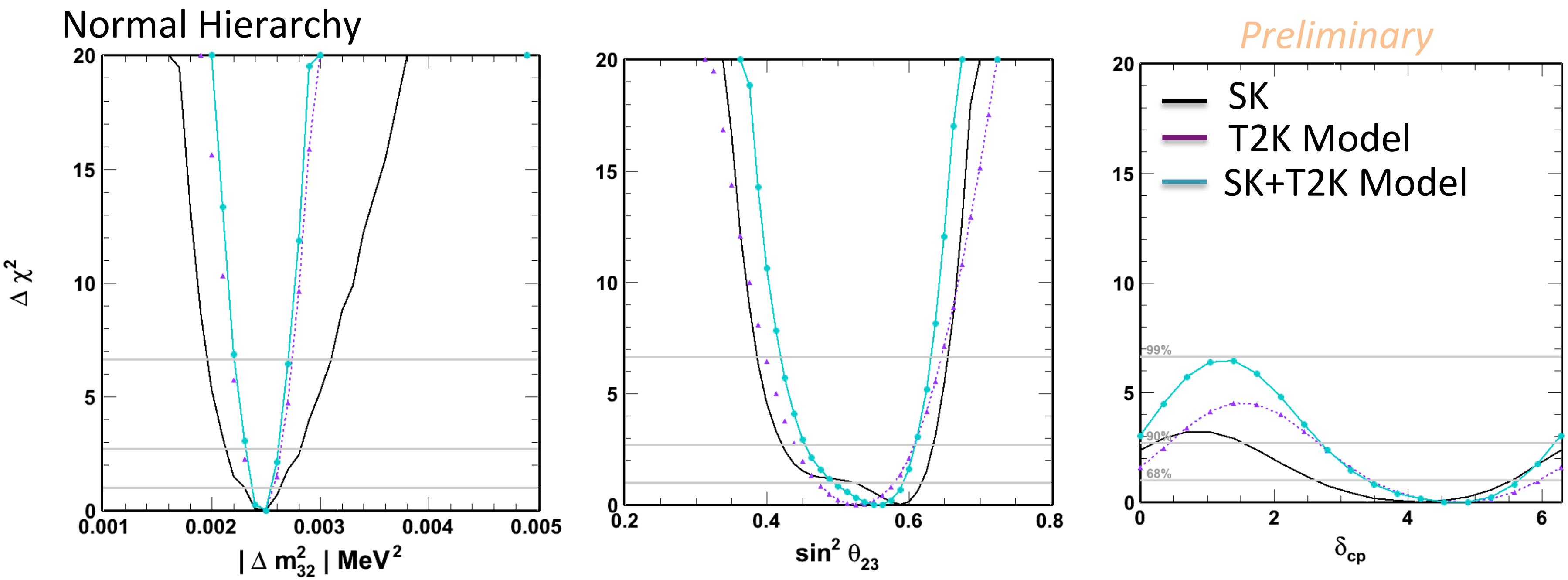




- T2K, NOvA, and Super-K show consistent preferences for normal hierarchy and $\delta_{cp} = 3\pi/2$

As of 2016	Hierarchy $\Delta\chi^2$ (NH-IH)	δ_{cp} / π
Super-K	-4.30	1.33
T2K	-1.40	1.50
NOνA	-0.47	1.49

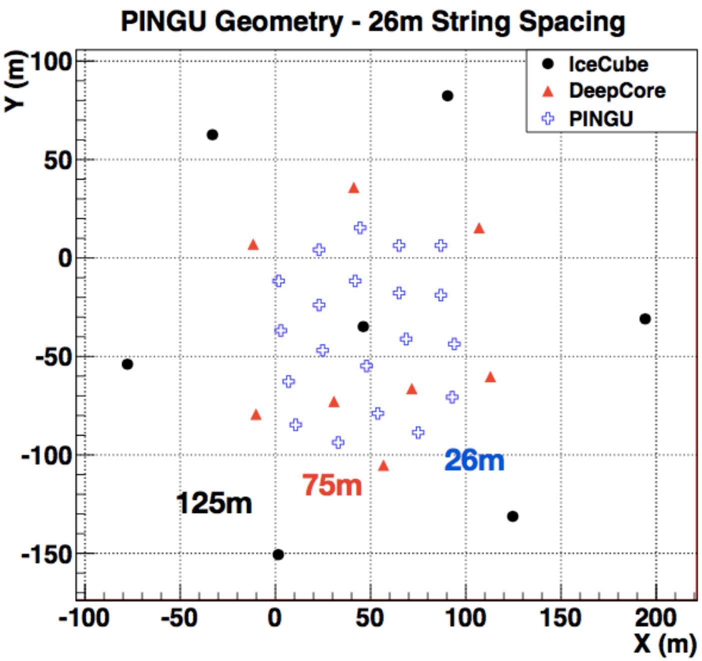
Into the Future: Combining T2K-SK?

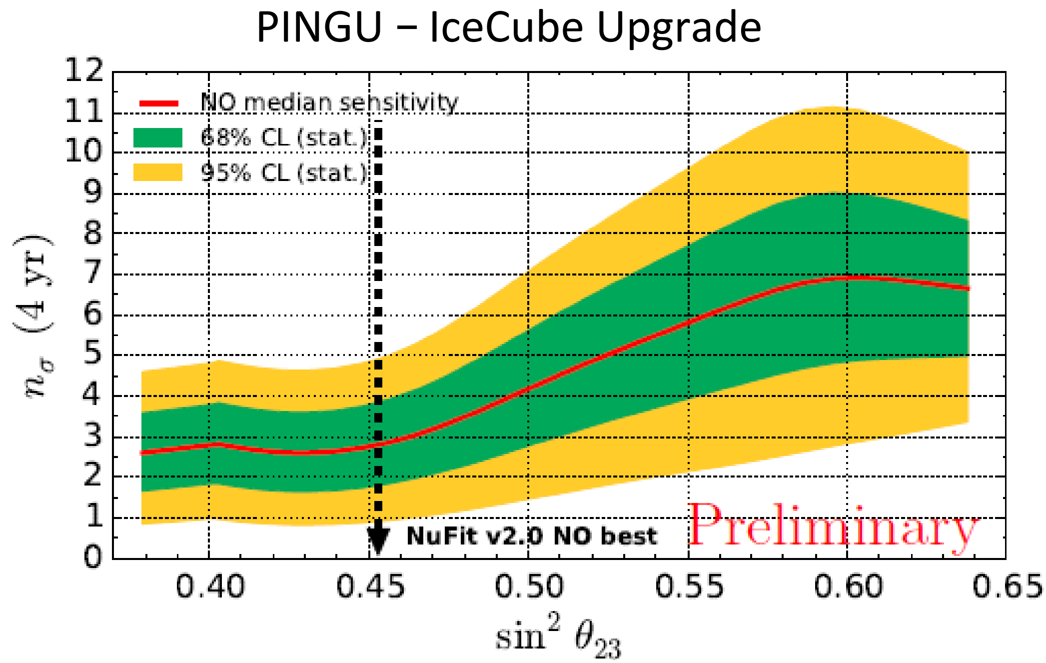


- Super-K collaboration has used *publicly available* information to model and fit the T2K experiment together with atmospheric neutrinos
- Atmospheric mixing constraint improves NH preference
  - $\Delta\chi^2$ (NH − IH) = -5.1 (-4.3 SK Only)
  - P(NH|IH) : 2.7%

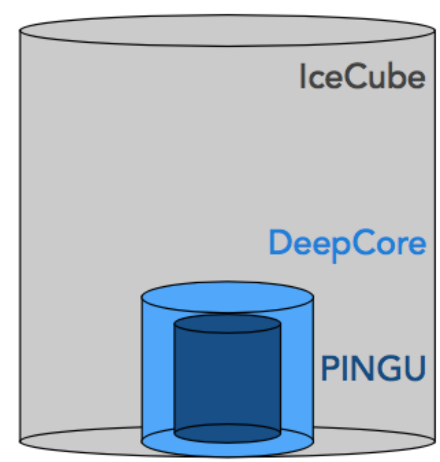
- Better constraint with correlated systematics between experiments: future?!
- T2K + NOνA combination also in discussion

Near Future : Hierarchy with Atmospheric Neutrinos





PINGU
Lower energy threshold of DeepCore/IceCube to ~5 GeV, by addition of densely instrumented strings
Improved resolution, PID and sensitivity to electron component of flux
If funded begin data taking with full detector in 2020+



* N.B. : Similar project in mediteranean sear, ORCA, also expects 4σ sensitivity (backup)

Mass Hierarchy Sensitivity Summary

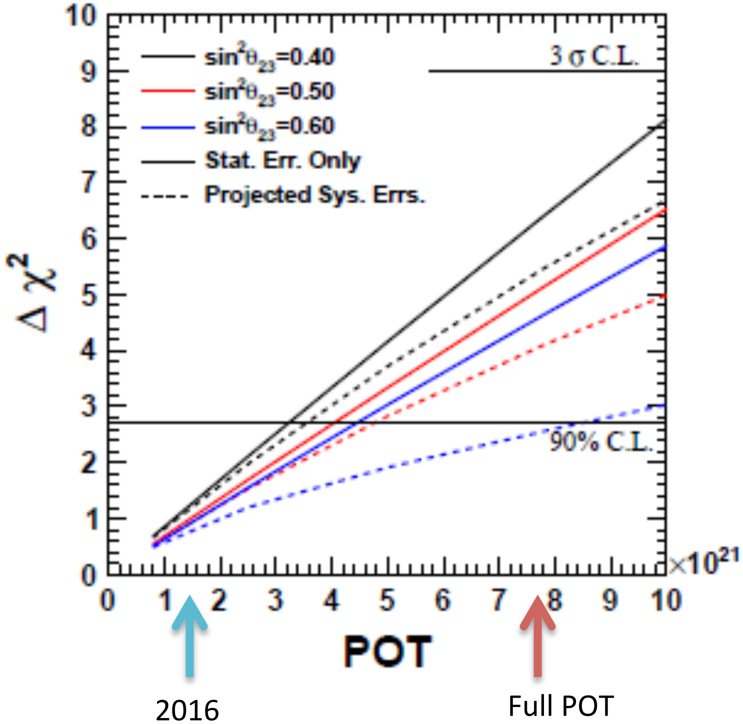
- Assuming 2nd octant of θ_{23}

Experiment	2020	2025-6	2030	2035
Super-K	2.5σ	3.0σ		
T2K /-II				
NOvA	3.4σ	4.4σ		
KM3NeT	0.5σ	4.0σ		
IceCube (Pingu)		$>4.0\sigma$		
JUNO *		4.0σ		
ICAL-INO		2.0σ	3.0σ	$\sim 4\sigma$
DUNE		3.0σ	5.0σ	$\sim 7\sigma$
Hyper-K			4.0σ	$\sim 6\sigma$

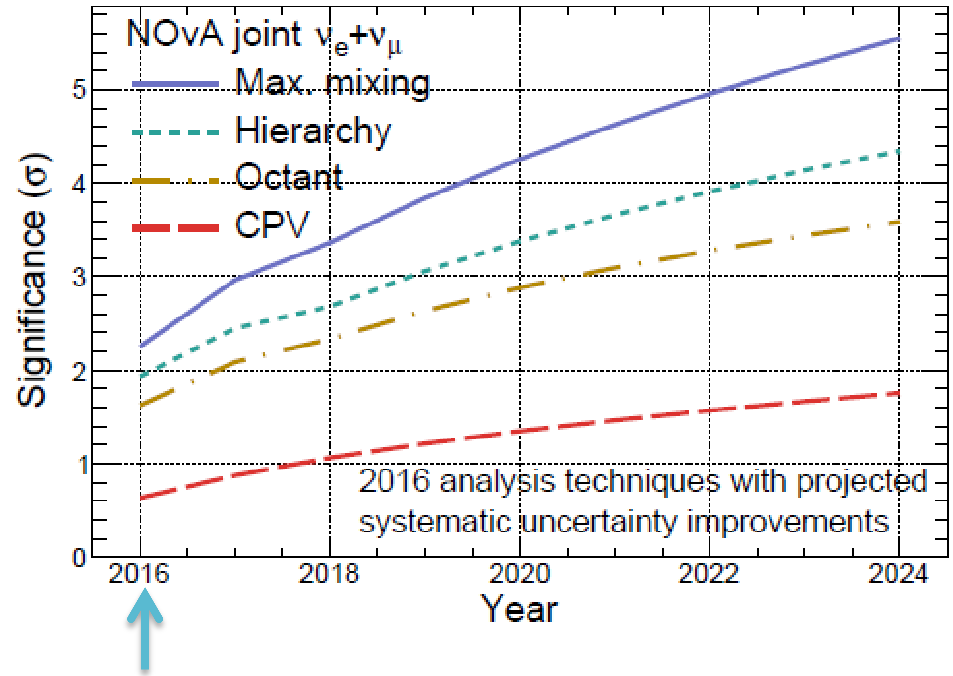
- Currently , not all are funded but good chance for a determination in 10 years

Near Future : CP Violation

T2K – CPV Sensitivity



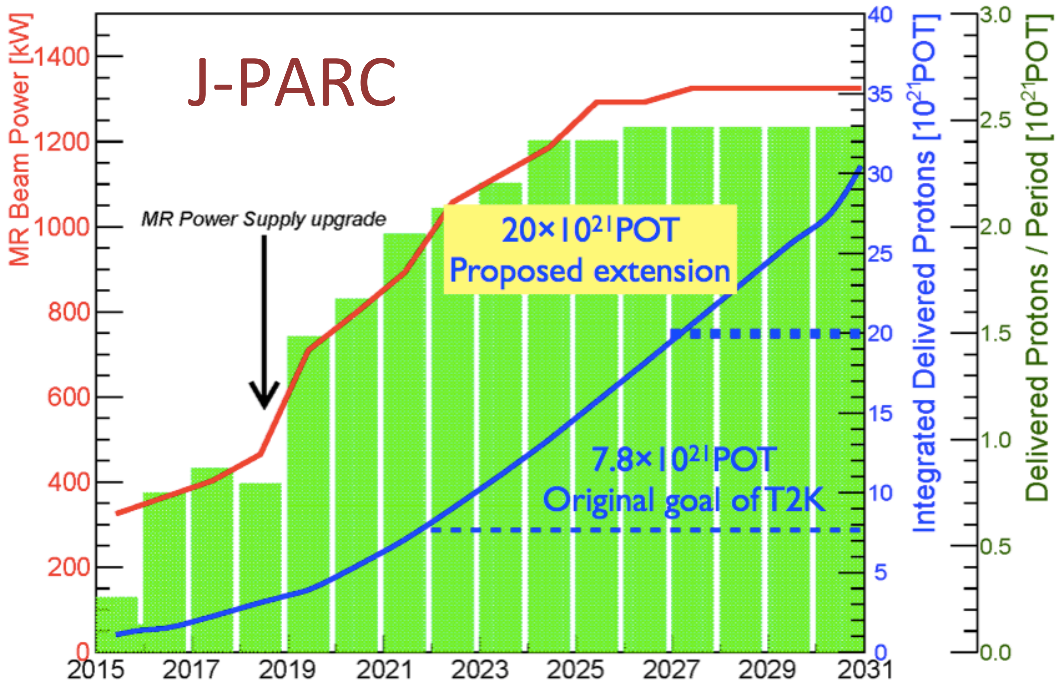
NOvA Sensitivity, $\sin^2\theta_{23} = 0.6$



- As of 2016:
  - T2K : 7.5×10^{20} P.O.T. ν and 7.5×10^{20} P.O.T. $\bar{\nu}$
  - NOvA : 6.1×10^{20} P.O.T. ν
- For 2017
  - T2K : Plan to double ν P.O.T.
  - NOvA : Additional 3.0×10^{20} P.O.T. ν and 3.0×10^{20} P.O.T. $\bar{\nu}$

The Future of T2K : T2K-II

- Hints for CP-violation can be probed early on with more P.O.T.
- *T2K-II Proposal*
  - Accumulate 20×10^{21} P.O.T by ~2026
  - Bridge the gap between T2K and Hyper-K
  - Stage-1 approval with J-PARC PAC
- More than just an extended run!
  - Upgrade *all* parts of the experiment
  - Accelerator, and neutrinno beamline



The Future of T2K : T2K-II

- Hints for CP-violation can be probed early on with more P.O.T.
- *T2K-II Proposal*
  - Accumulate 20×10^{21} P.O.T by 2025-2026
  - Bridge the gap between T2K and Hyper-K
  - Stage-1 approval with J-PARC PAC
- More than just an extended run!
  - Upgrade *all* parts of the experiment
  - Reduce systematic errors to 4% : Upgrade near detector

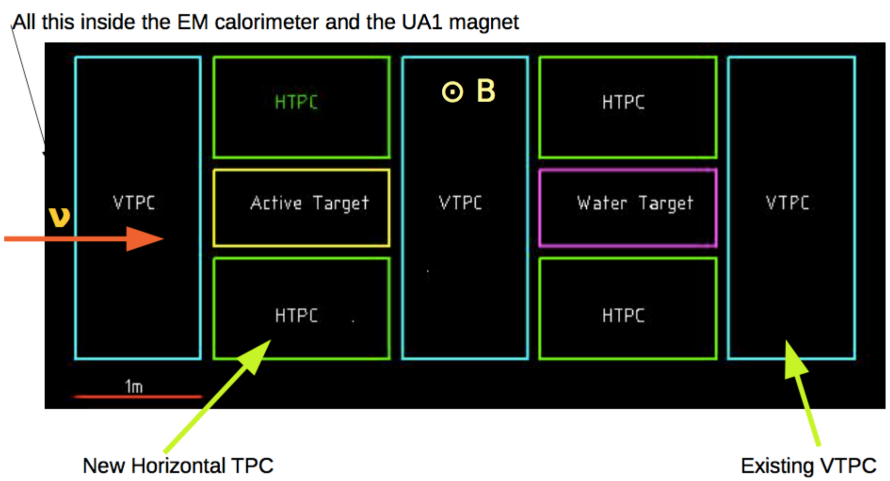
2016

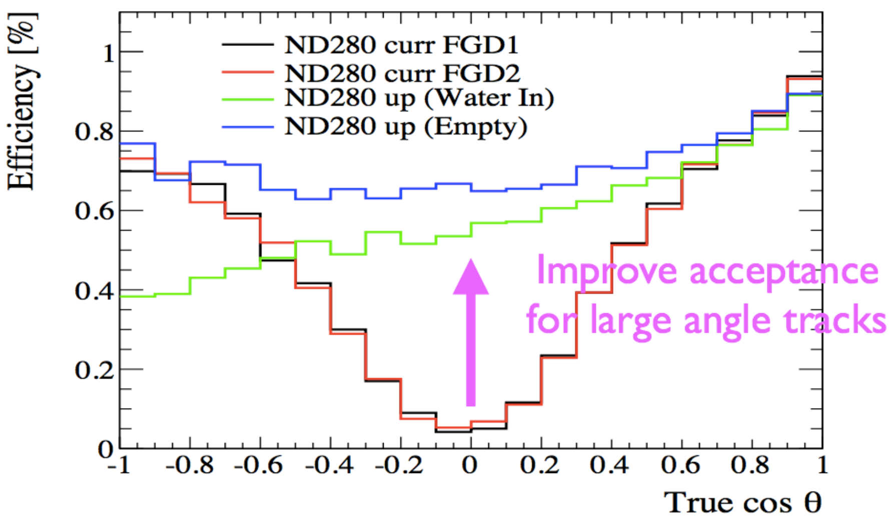
Source	ν e-like	$\bar{\nu}$ e-like	$\frac{\nu \text{ e-like}}{\bar{\nu} \text{ e-like}}$
SK Detector	2.4%	3.1%	1.6%
SK Final State/Secondary Interactions	2.5%	2.5%	3.6%
Flux and Cross Sections Constrained by ND280	2.9%	3.2%	2.2%
NC 1γ	1.4%	3.0%	1.5%
ν_e and $\bar{\nu}_e$	2.7%	1.5%	3.1%
NC Other	0.2%	0.3%	0.2%
Total	5.4%	6.2%	5.8%

The Future of T2K : T2K-II

- Hints for CP-violation can be probed early on with more P.O.T.
- *T2K-II Proposal*
  - Accumulate 20×10^{21} P.O.T by 2025-2026
  - Bridge the gap between T2K and Hyper-K
  - Stage-1 approval with J-PARC PAC
- More than just an extended run!
  - Upgrade *all* parts of the experiment
  - Reduce systematic errors to 4% : Upgrade near detector

Current Concept:

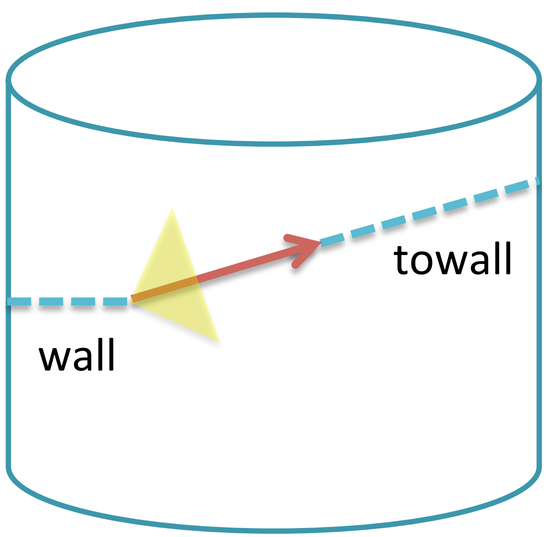


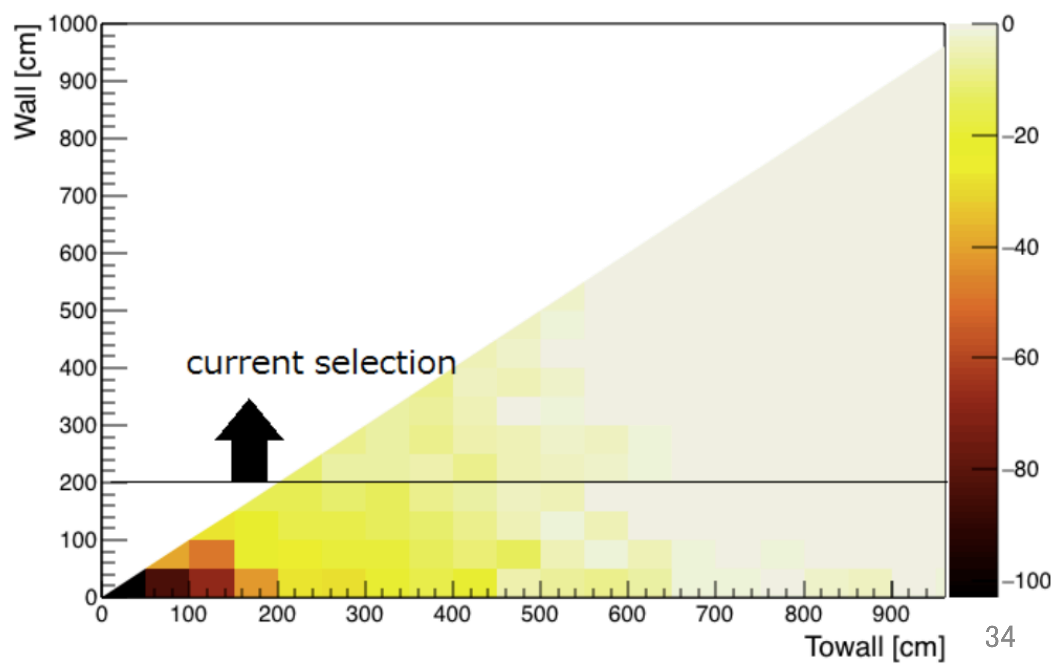


Installation goal 2020

The Future of T2K : T2K-II

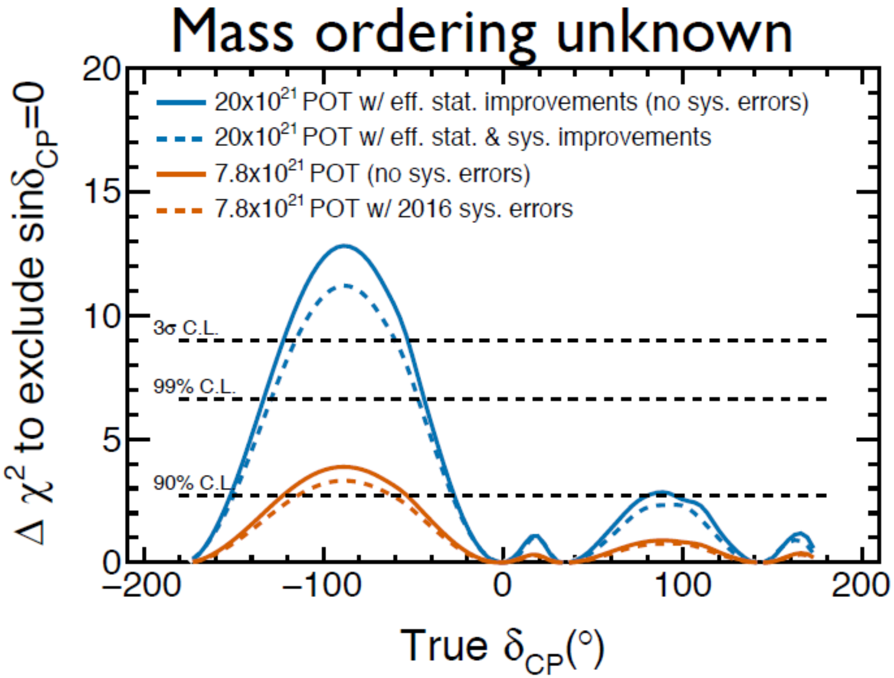
- Hints for CP-violation can be probed early on with more P.O.T.
- *T2K-II Proposal*
  - Accumulate 20×10^{21} P.O.T by 2025-2026
  - Bridge the gap between T2K and Hyper-K
  - Stage-1 approval with J-PARC PAC
- More than just an extended run!
  - Upgrade *all* parts of the experiment
  - Effective statistical increases (+50%) with FD reconstruction upgrades, and the introduction of new analysis samples (multiple-rings, invisible decays)

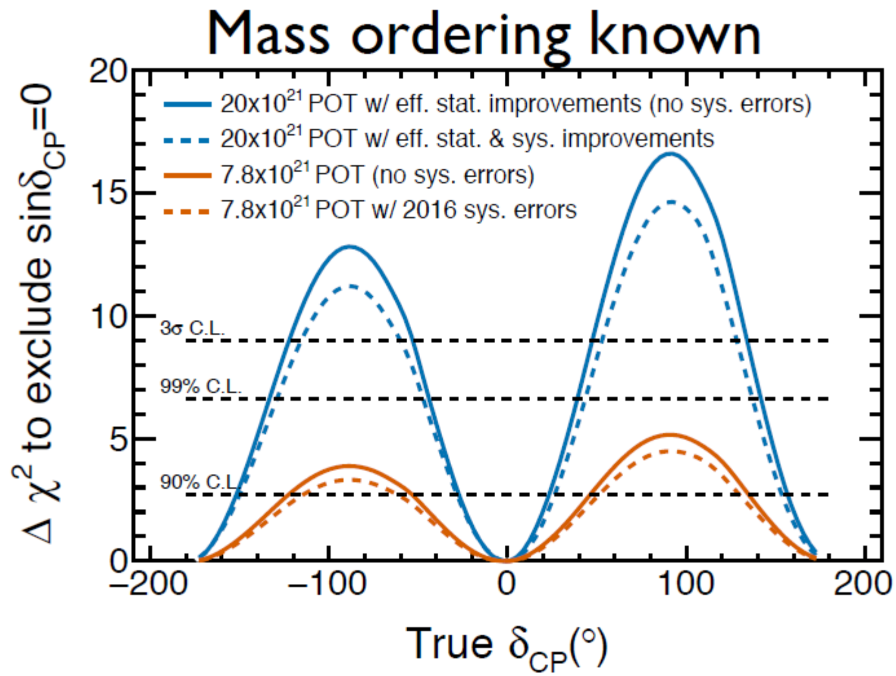




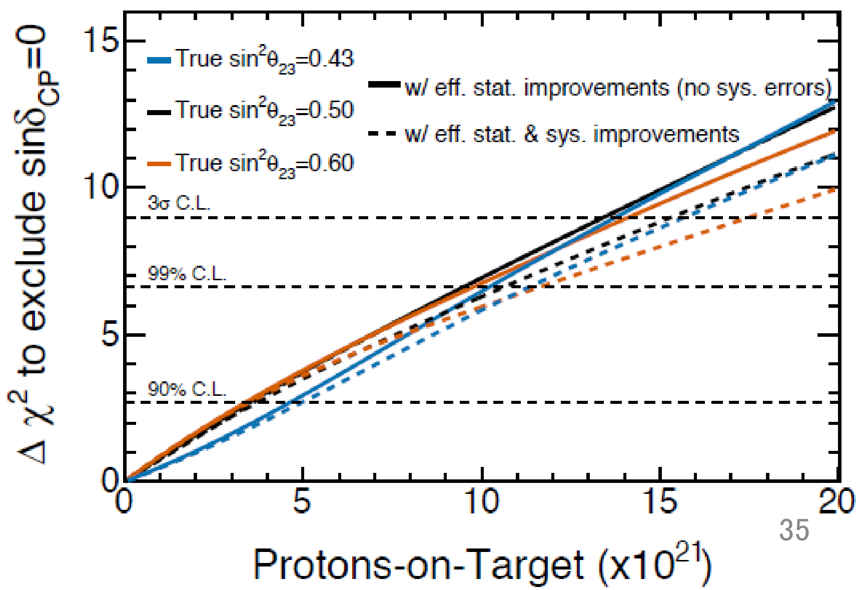
T2K-II

By external experiment!





- 3σ measurement of CPV possible !
- Odds improve greatly with if the hierarchy is known



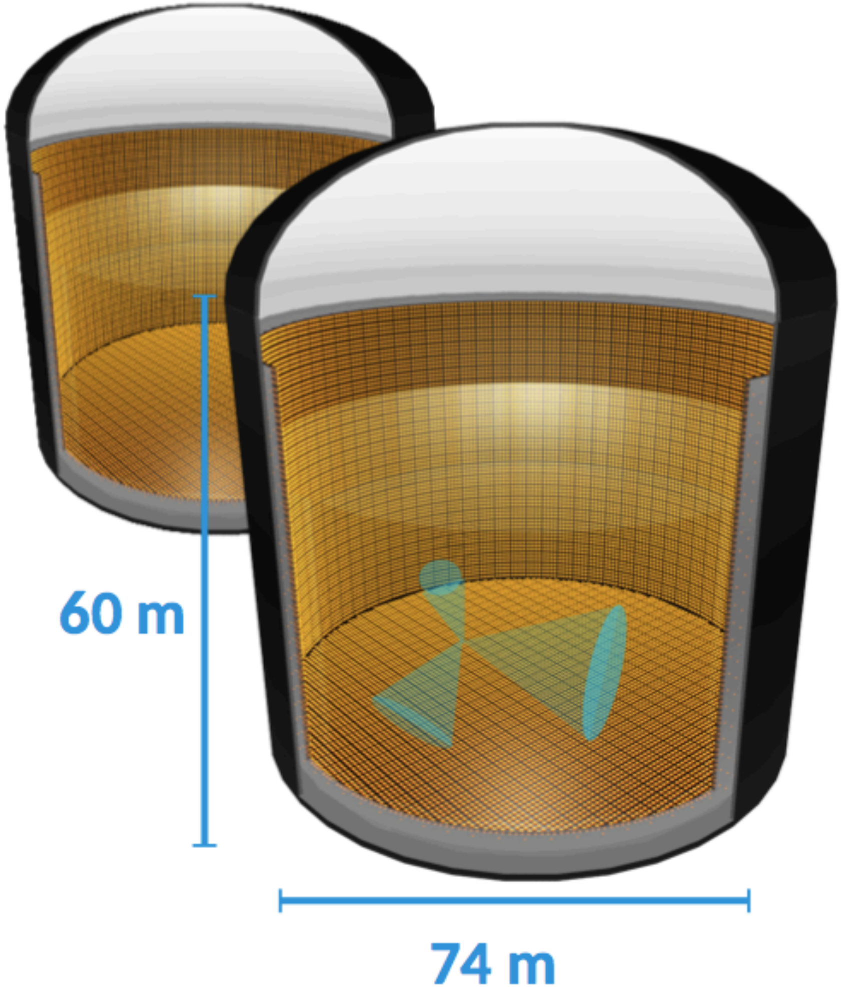
Farther Future: Next Generation Experiments

	Hyper-K	DUNE
Location	Japan / J-PARC	U.S.A. / FNAL
Proton Energy	30 GeV	120 GeV
Beam Power	1.2 MW	1.2MW
Baseline Length	295 km	1300 km
Near Detector	Tracker: FGD, TPC	FGT, STT, Pl. Sci.
Target	Carbon, Water	Ar, C, Fe
Far Detector	360 kton WC	40 kton Lq. Ar TPC
Target	Water	Argon
Off-axis Angle	2.5 deg / 44 mrad	0 deg (on-axis)
Peak ν Energy	~600 MeV	2.5 GeV
Neutrino Data	2025~26	2025~26

- N.B. Both projects are more than oscillation experiments
  - Nucleon Decay, Astrophysical neutrinos, precision cross section

Hyper-Kamiokande

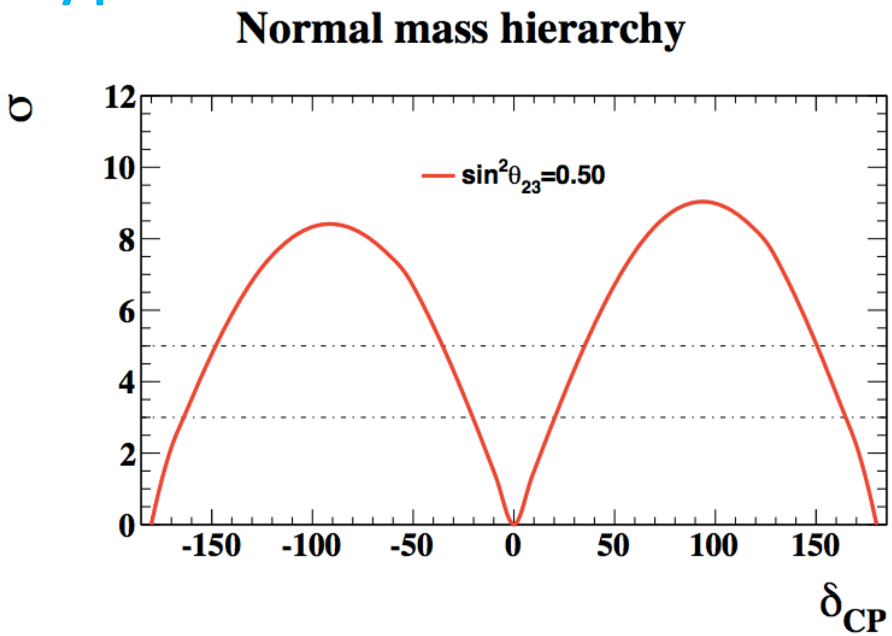
Hyper-Kamiokande

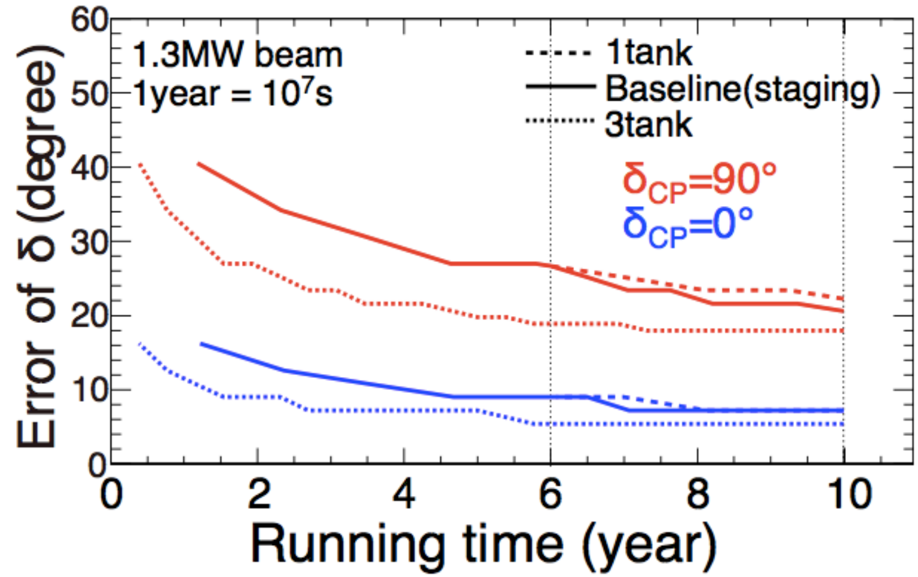


Staged design:
186 kton 6 years,372 kton thereafter

- 186 (×2) kton fiducial volume (2 × 8.3 × SK)
- Optically separated into
  - Inner Detector 40,000 (×2) PMTs (2×4×SK)
    - 40% Coverage (same as SK)
  - Outer Detector 12,000 (×2) PMTs (2×6×SK)
- ID Photosensors will be high QE
  - Single photon detection : 24% (2 × SK)
- Receive 1.3 MW beam from J-PARC
  - Accumulate 2.7×10^{22} POT (3 × T2K)
- Multipurpose machine
  - All of the physics of Super-K and T2K
  - Plus more! Geophysics
    - Accessible only with very large detectors
- Not just a larger version of Super-K
  - Improved performance: photosensors, tank materials

Hyper-Kamiokande: Oscillations

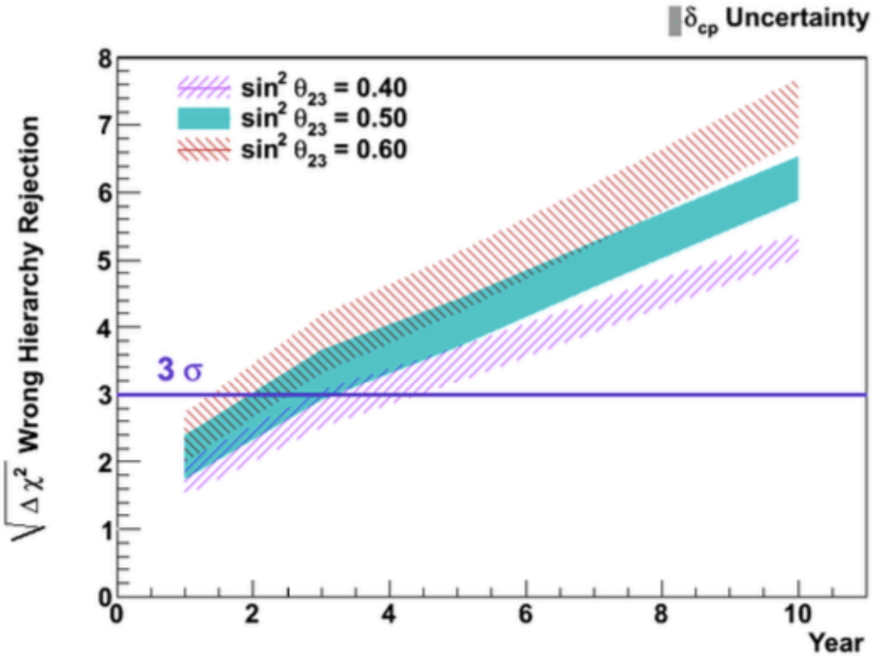


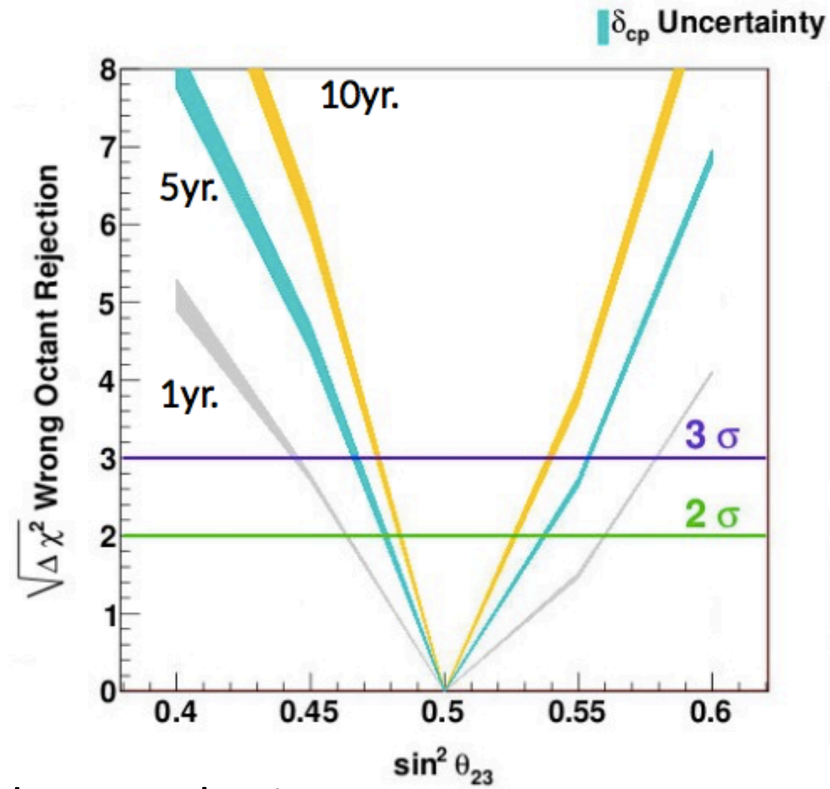


		signal		BG						Total
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	ν_μ CC	$\overline{\nu}_\mu$ CC	ν_e CC	$\overline{\nu}_e$ CC	NC	BG Total	
ν mode	Events	2300	21	10	0	347	15	188	560	2880
	Eff.(%)	63.6	47.3	0.1	0.0	24.5	12.6	1.4	1.6	—
$\overline{\nu}$ mode	Events	289	1656	3	3	142	302	274	724	2669
	Eff. (%)	45.0	70.8	0.03	0.02	13.5	30.8	1.6	1.6	—

- Observation of CPV at 5σ for 60% of phase space
- Measure atmospheric mass splitting to less than 1%
- Atmospheric mixing angle, $\sin^2\theta_{23}$, to less than 3%

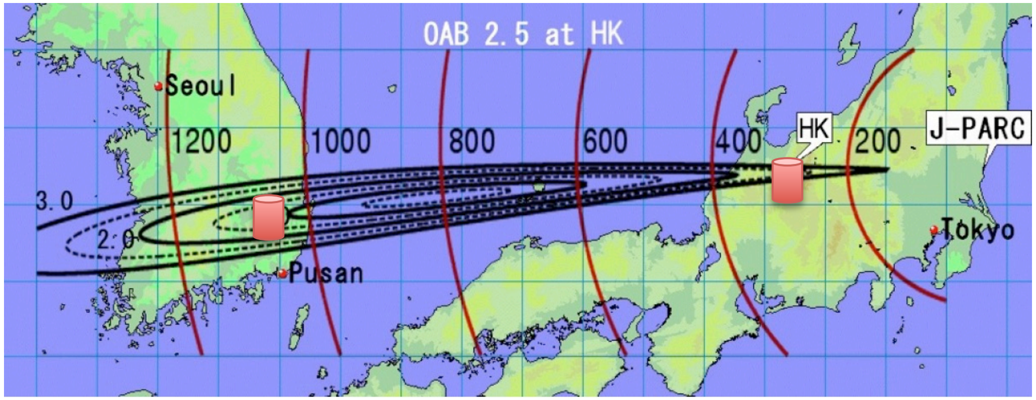
Combination with Beam Neutrinos : Hierarchy and Octant



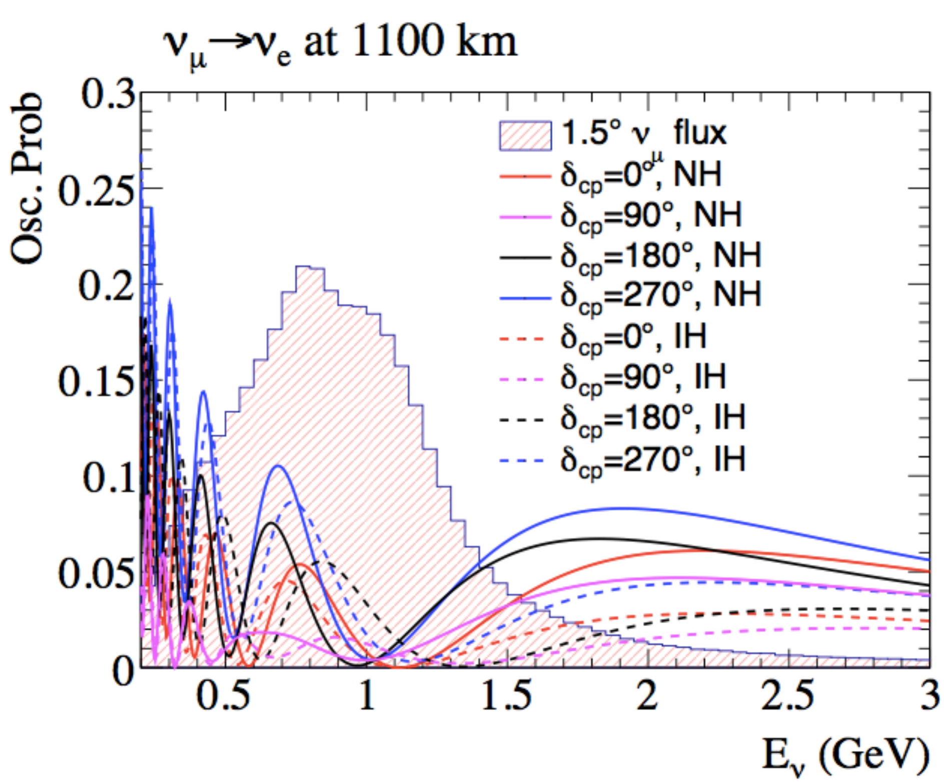


- Unique in its ability to study but beam and atmospheric neutrinos due to its size
- Combination with beam neutrinos allows mass hierarchy determination in 1~4 years if not already known
- 3s determination of the q23 octant if $|\theta_{23} - 45°| > 3°$

Hyper-K: Second Detector in Korea?

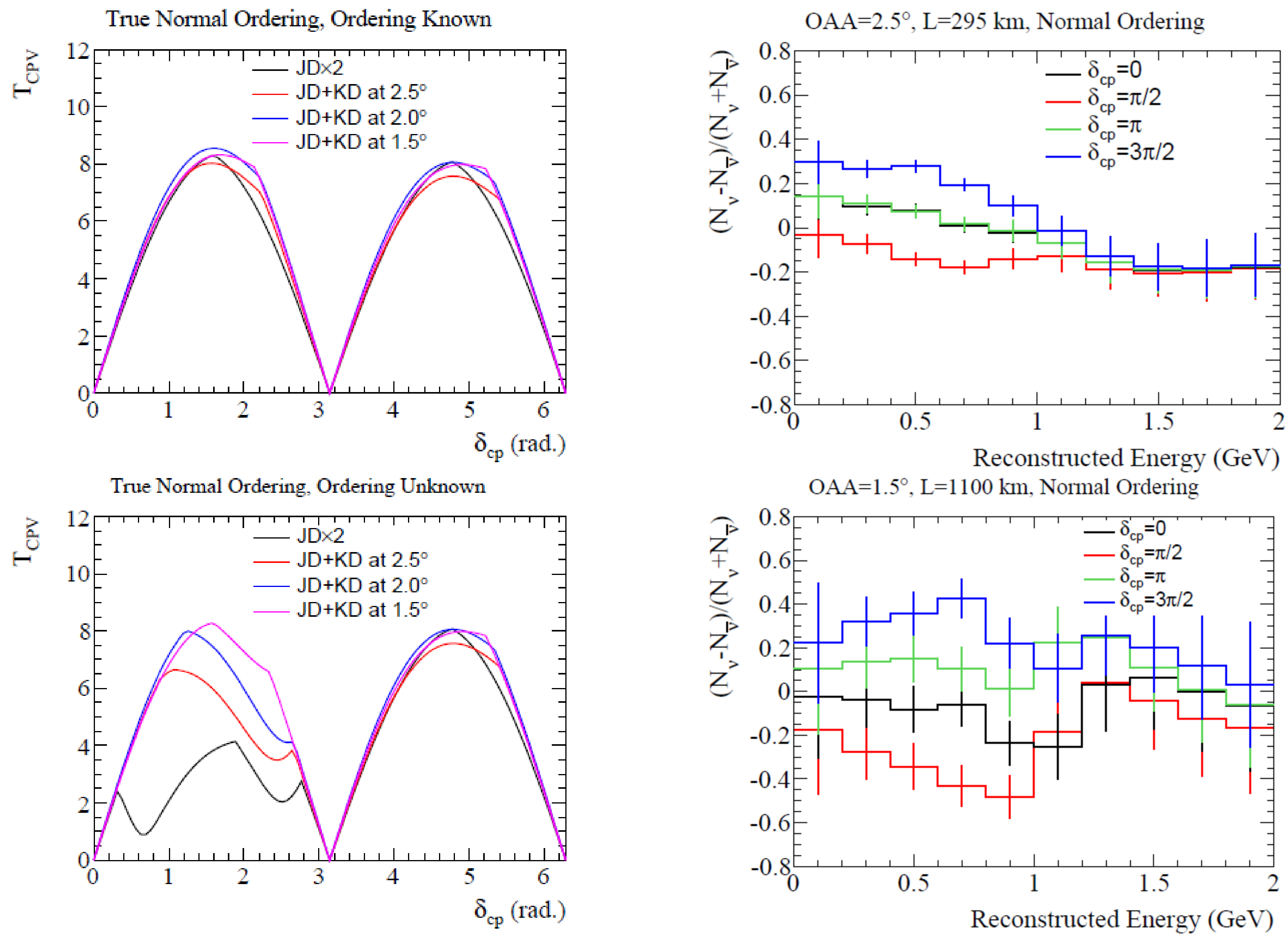


- With the staged design it is possible to place second detector outside of Kamioka,
  - Korea is an option under serious consideration (Mt. Bisul ~ 1100 km baseline)



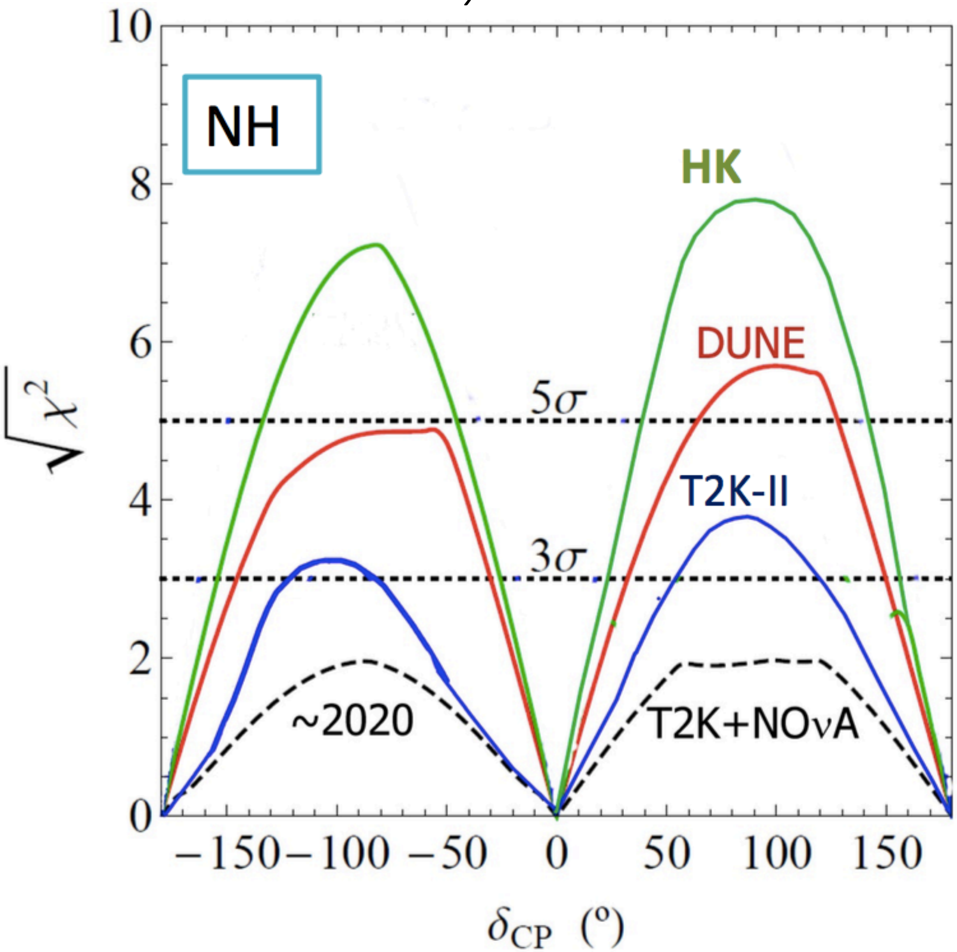
- Improved CP asymmetry a longer baselines via 2nd oscillation maximum
- Larger matter effects for hierarchy sensitivity
- Optimize second detector as necessary
- Truly *international* experiment

Hyper-K, Korea – Beam



CP Violation Sensitivity Summary

T.Nakaya NuFact2016



2035: HK 10 years, staged

2033: Dune 7 years full configuration

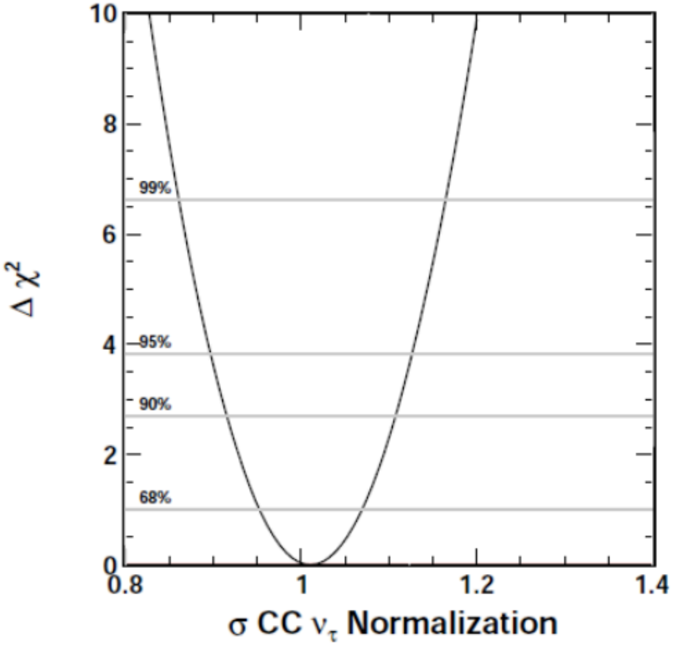
2027: T2K-II, 20e20 POT w/ improvements

2020: T2K + NOvA full stats

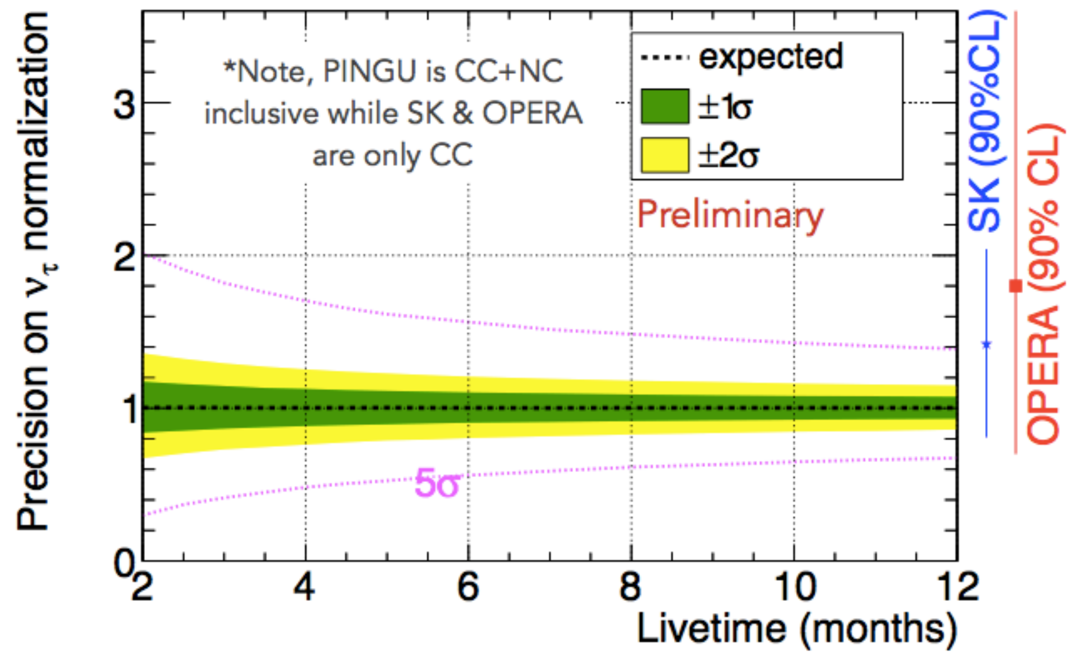
- Several complementary measurements planned in the years ahead
- Definitive δ_{cp} measurement 10~20 years?

A Word about Tau Neutrinos

Hyper-Kamiokande



PINGU



per/ 100 kton yr.	Hyper-K	LAr
Signal CC ντ	40.2	28.5
Background	448.7	44.8
S /√B , 10 years	9.6	8.5

- HK Numbers are upward-going event rate
- LAr numbers based on PRD82, 093012

- Achieve 7% uncertainty on tau cross section normalization with 560 Mton-year exposure of Hyper-K
- PINGU is similar, but faster
- These samples will be useful for testing cross section modeling as well as providing direct probe of $|U_{\tau 3}|^2$

Summary and Prospects:

- The race is on for the neutrino mass hierarchy
  - Several competing ideas
  - Expect a 3~4σ determination within 10 years

- CP violation measurements are similarly drawing a lot of interest
  - Require large detectors and more beam power
  - A precise determination will likely take another 10 or 20 years, but is in the cards

- Many projects on-going or planned to address these issues!
  - Its an exciting time for neutrino physics, with a lot of activity
  - Apologies I could not give each sufficient detail in this talk