

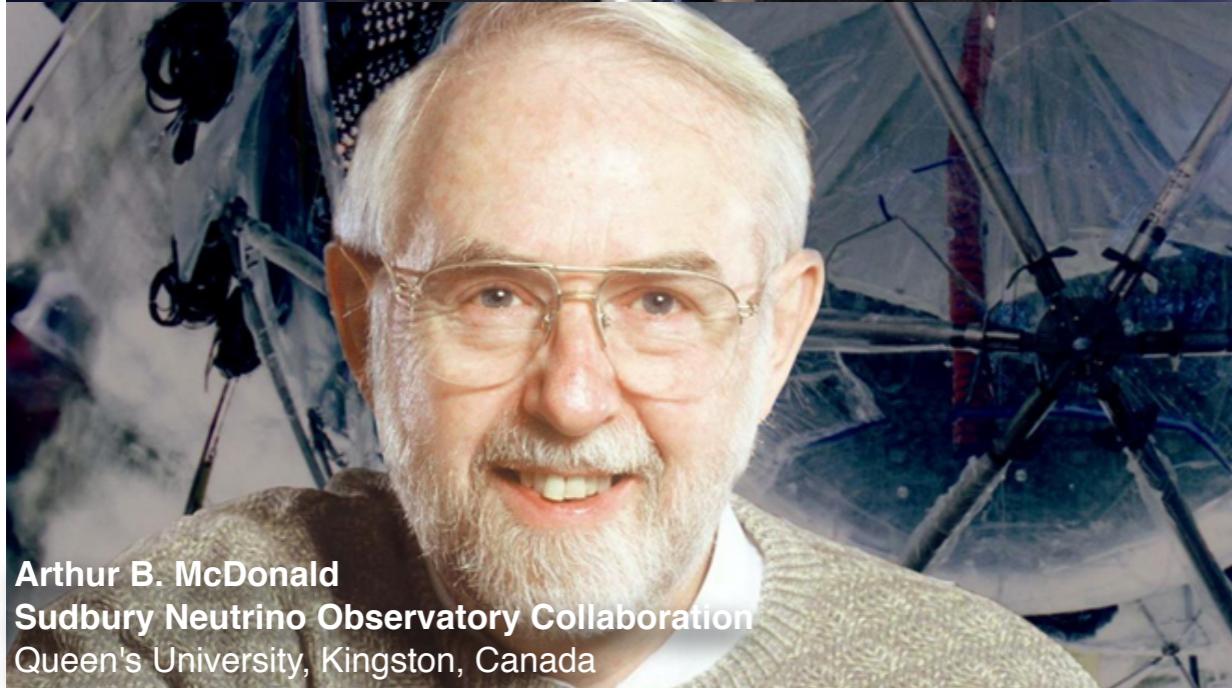
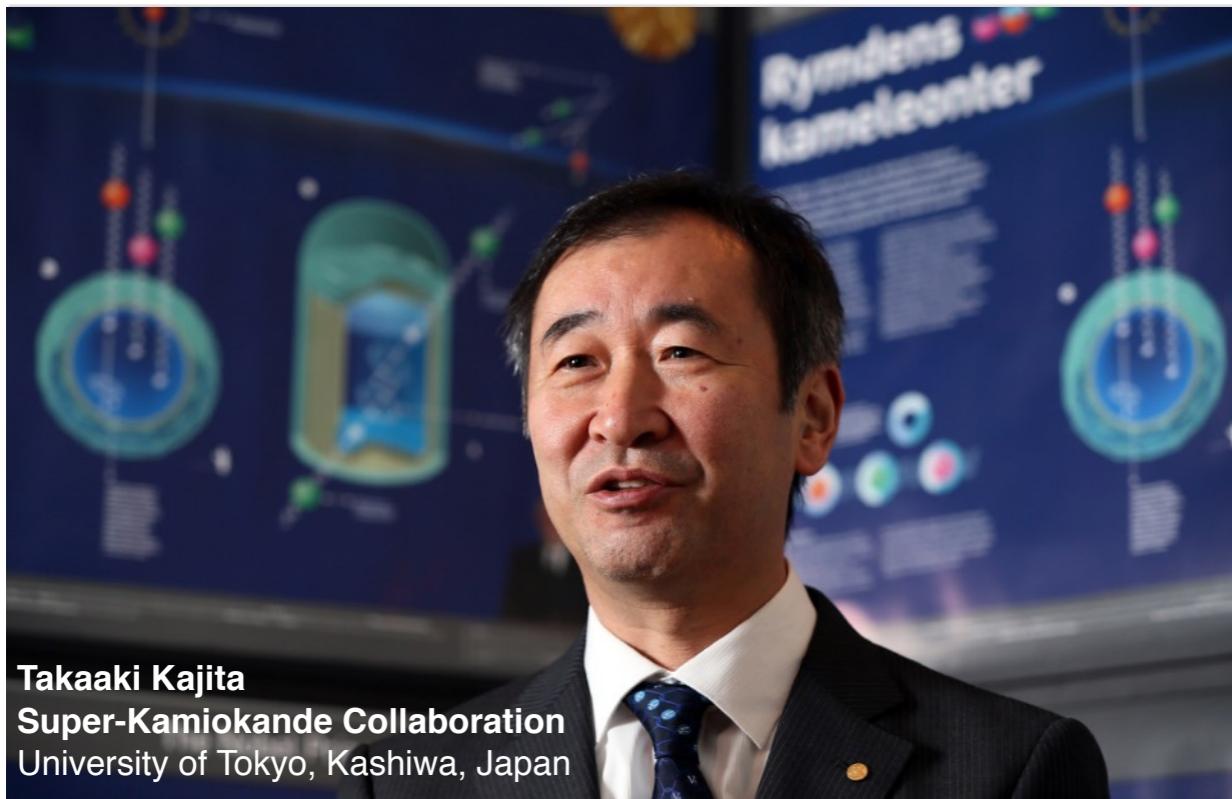
Long Baseline Neutrinos

Mark Messier
Indiana University

XXIX International Symposium on
Lepton Photon Interactions at High Energies

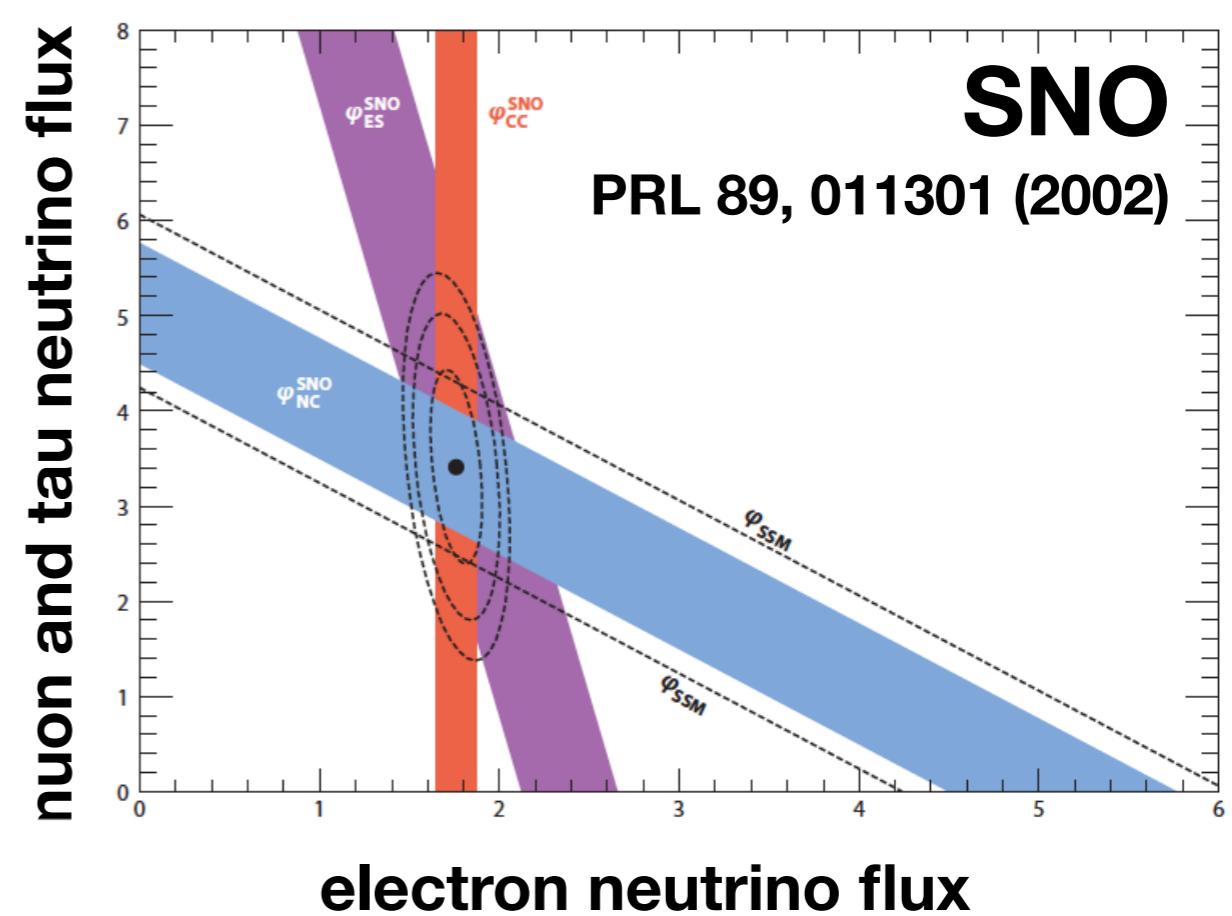
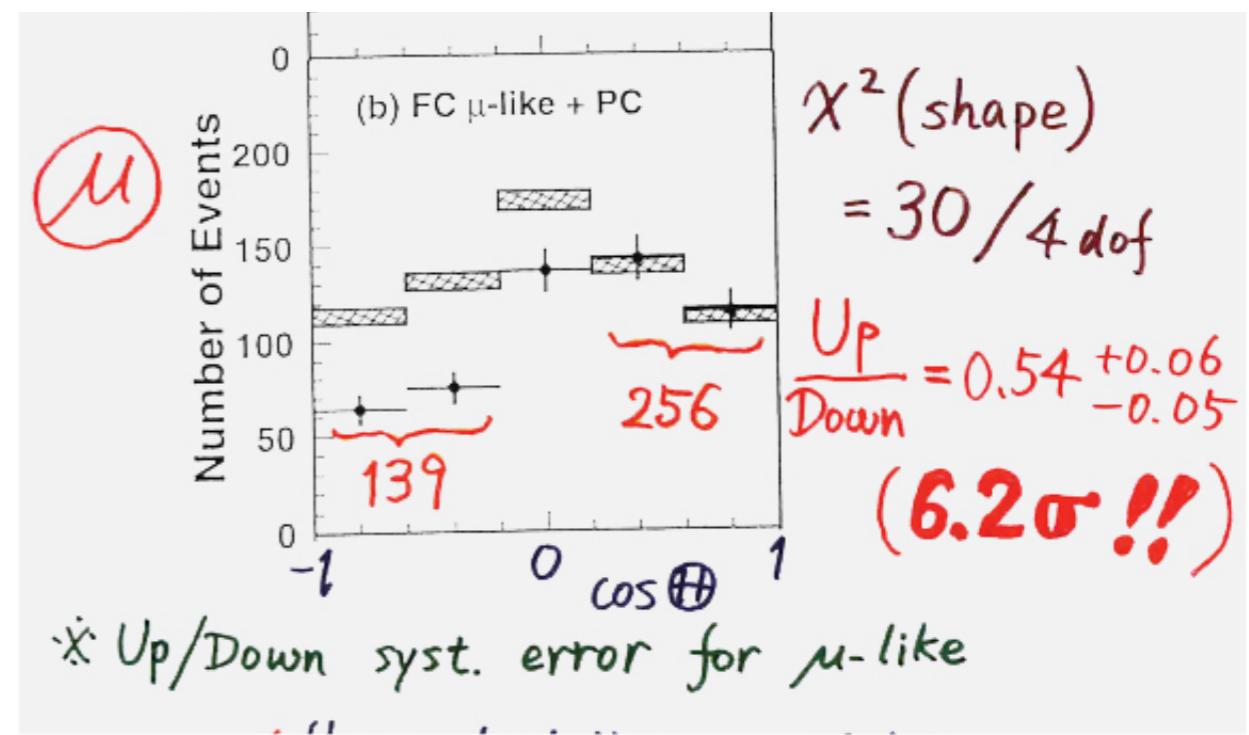
August 9, 2019





2015 Nobel Prize in physics “for the discovery of neutrino oscillations, which shows that neutrinos have mass”

T. Kajita June 5th, at Neutrino 1998



Neutrino oscillations

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ & -s_{13}e^{i\delta} & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & & s_{12} \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}$$

$$P_{\alpha\beta} = \sin^2(2\theta) \sin^2 \left(1.27 \Delta m^2 [\text{eV}^2] \frac{L [\text{km}]}{E [\text{GeV}]} \right)$$

$$\begin{aligned} |\Delta m_{32}^2| &\equiv |m_3^2 - m_2^2| \\ &\simeq 2 \times 10^{-3} \text{ eV}^2 \end{aligned}$$

$$\Delta m_{31}^2 \simeq \Delta m_{32}^2$$

$$\Delta m_{21}^2 \simeq 8 \times 10^{-5} \text{ eV}^2$$

$$\nu_\mu \rightarrow \nu_\mu$$

$$\nu_e \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_e$$

$$\nu_\mu \rightarrow \nu_\tau$$

$$\nu_\mu \rightarrow \nu_e$$

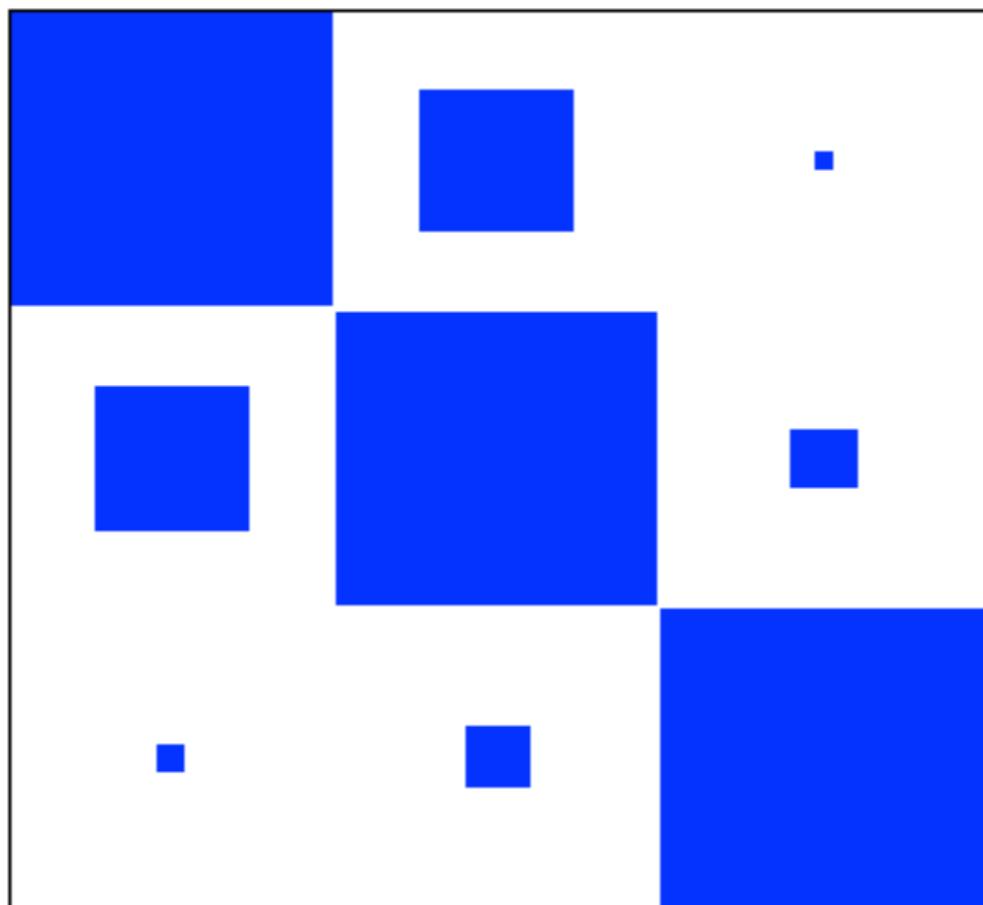
$$\nu_e \rightarrow \nu_\mu + \nu_\tau$$

atmospheric and
long baseline

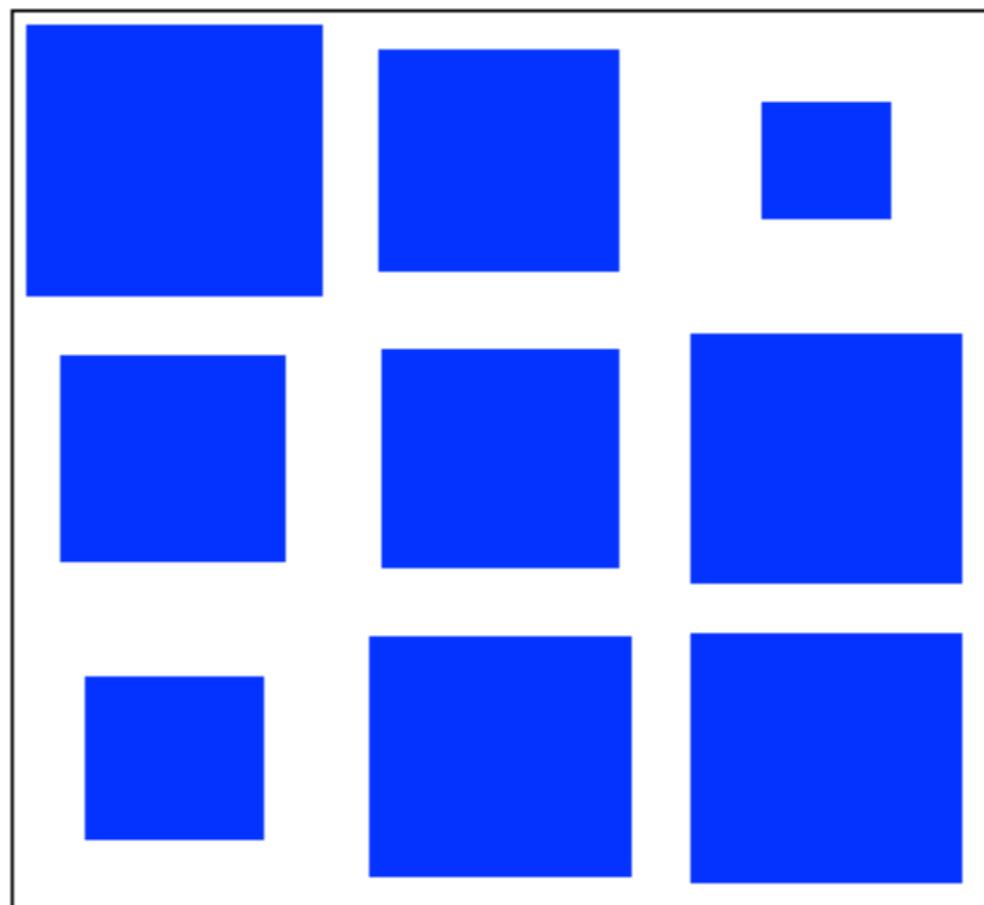
reactor and
long baseline

solar and
reactor

Quark mixing

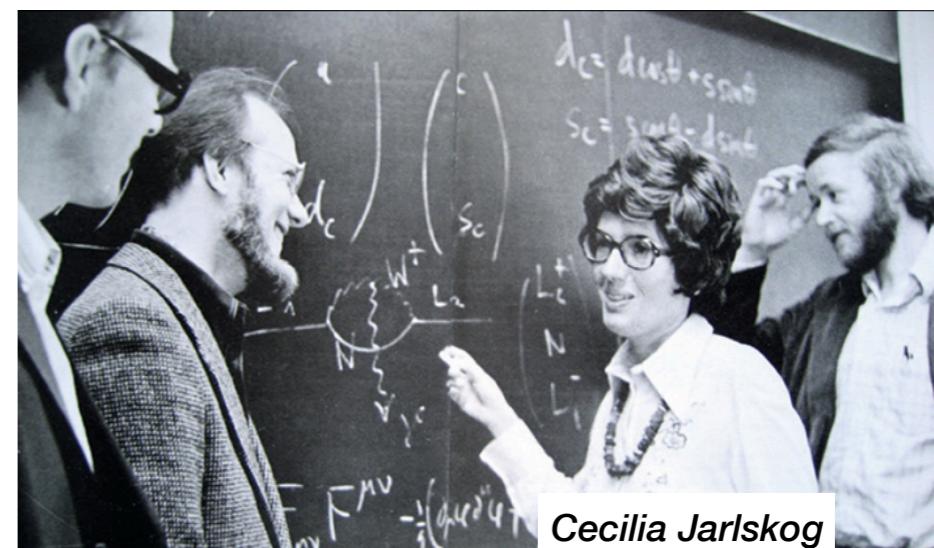


Neutrino mixing



$$\frac{J_{\text{PMNS}}}{J_{\text{CKM}}} = \frac{3 \times 10^{-2}}{3 \times 10^{-5}} \sin(\delta_{\text{PMNS}})$$

CP violation in leptons



Neutrino mass models

$$U_{e3} = \sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

normal mass ordering

$$U_{e3} = \frac{\Delta m_{12}^2}{\Delta m_{13}^2} \sqrt{\frac{\Delta m_{31}^2}{2}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$$
$$\sqrt{\frac{\Delta m_{31}^2}{2}} \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

inverted mass ordering

follows [hep-ph/0510213](#)

Measurements

- θ_{12}
- θ_{13}
- θ_{23}
- δ_{CP}
- Mass ordering
- Dirac/Majorana

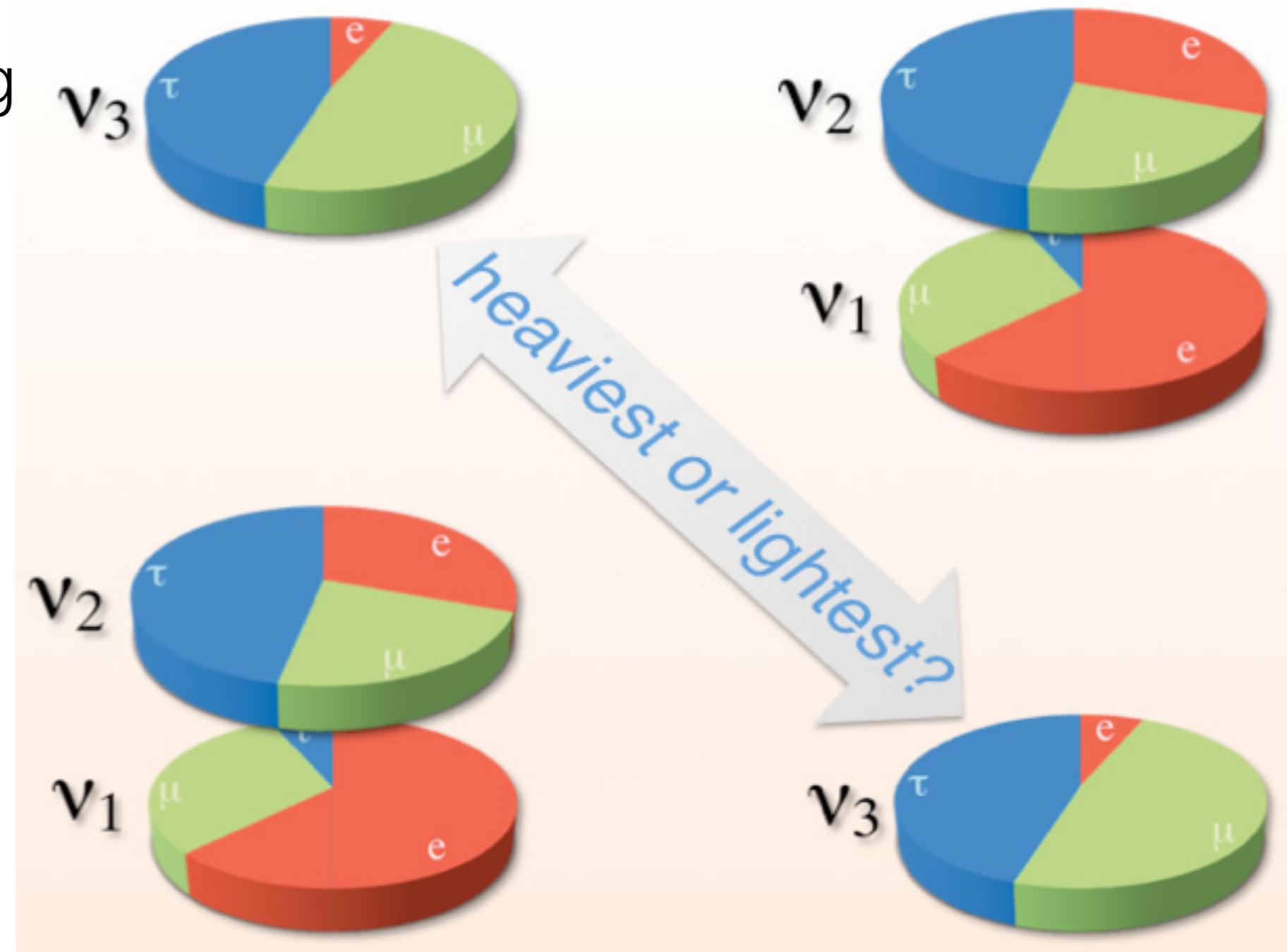
Extrapolate to GUT scale

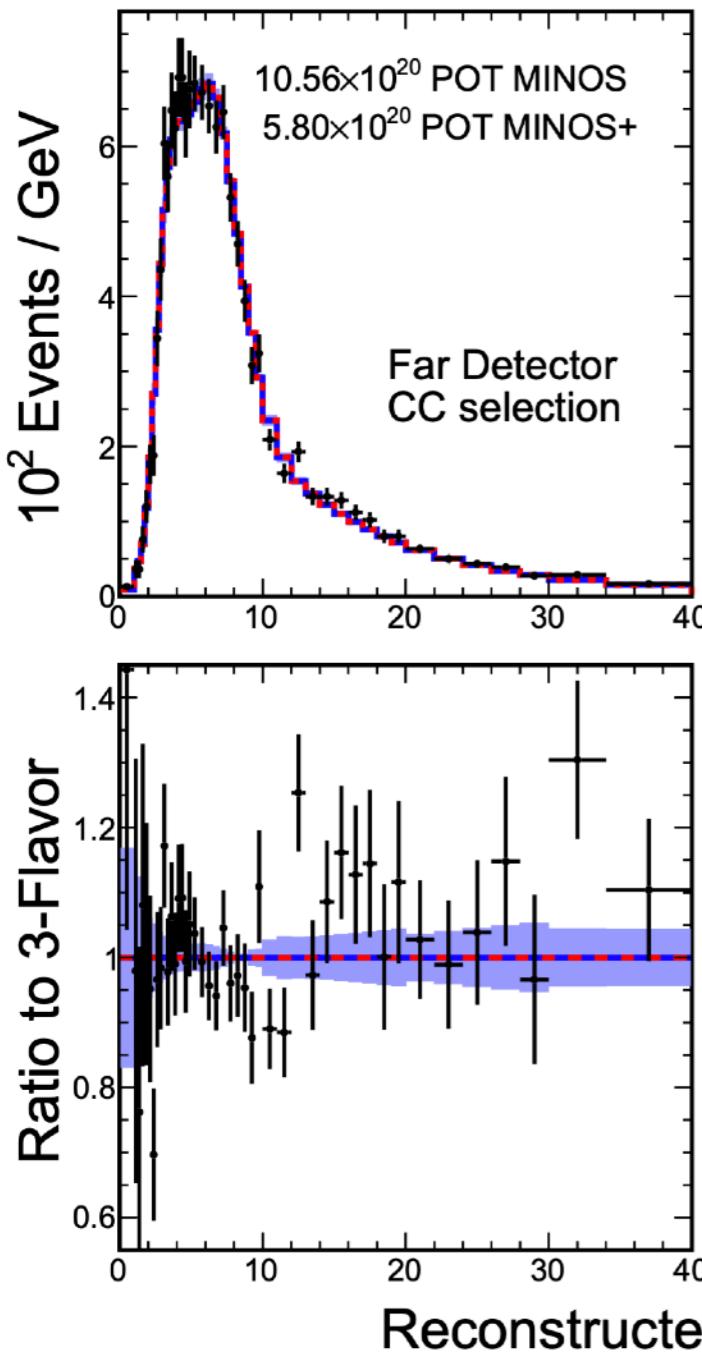
$$|Y_B| \simeq 2.4 \times 10^{-11} |\sin \delta| \left(\frac{\sin \theta_{13}}{0.15} \right) \left(\frac{M_1}{10^{11} \text{ GeV}} \right)$$

for example Pascoli, Petcov & Riotto PRD2007

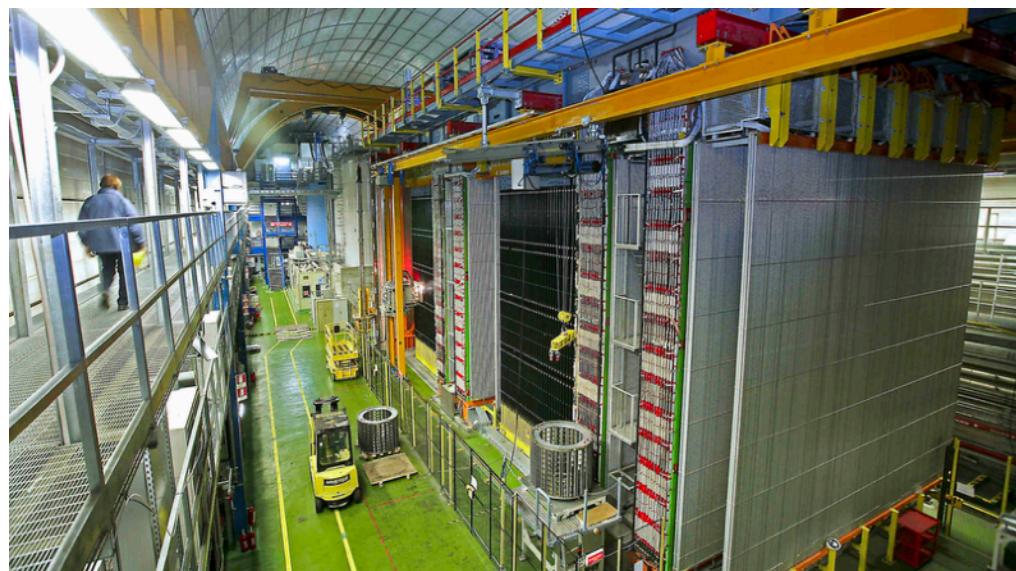
Next Questions In Neutrino Physics

- Mass ordering
- Nature of ν_3 - θ_{23} octant
- Is CP violated?
- Is there more to this picture?



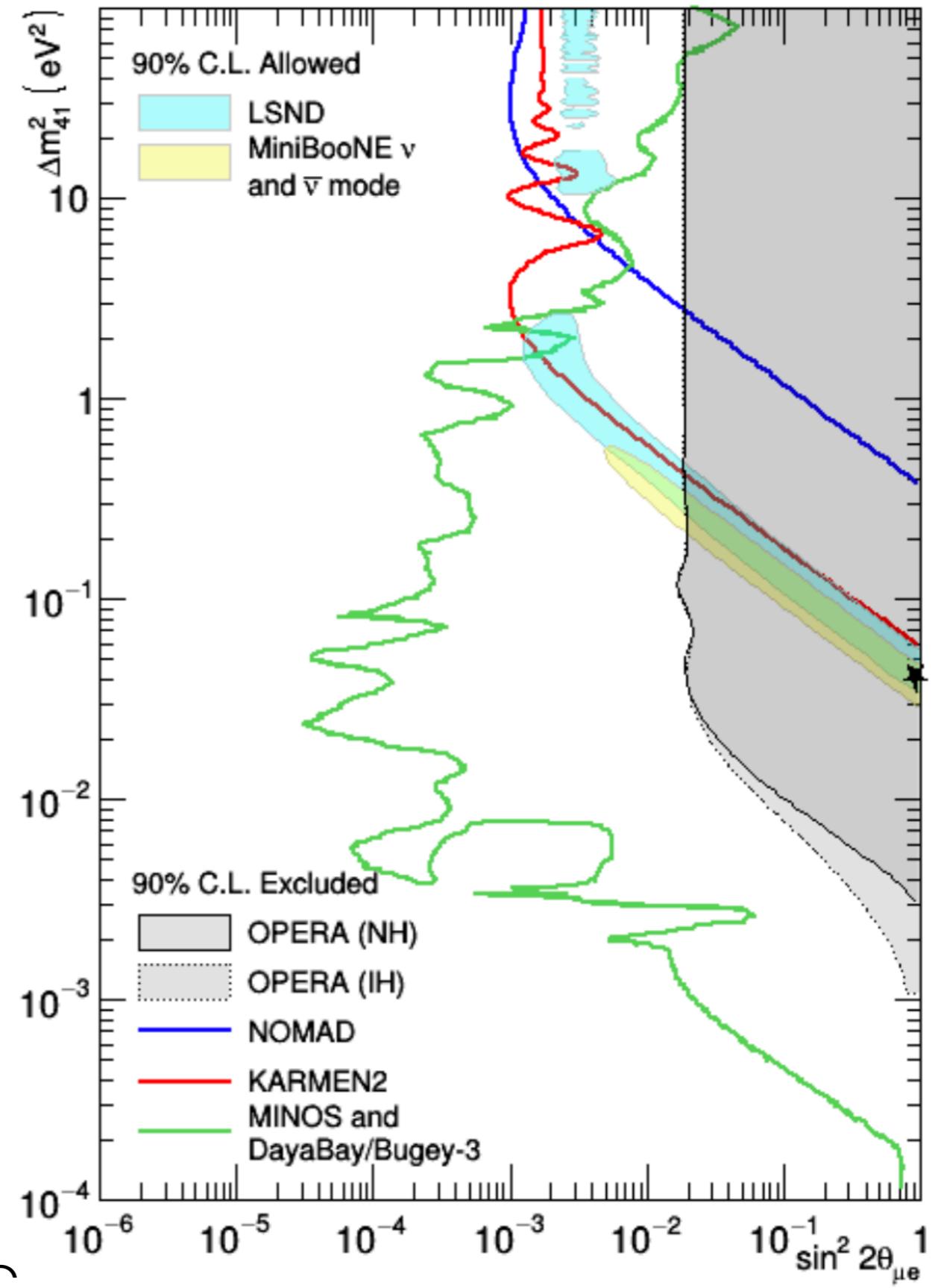


MINOS / MINOS+



OPERA

35 ν_e CC
5782 ν_μ CC
5 ν_τ CC
1724 NC



arXiv:1904.05686v1
Phys.Rev.Lett. 122 (2019)

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_\mu) &\simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i} \\ &\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i} \end{aligned}$$

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &\simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2 \\ &= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta) \end{aligned}$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \boxed{\sin^2 2\theta_{23}} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= \boxed{P_{\text{atm}}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\text{atm}}} = \boxed{\sin \theta_{23}} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}}P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

Neutrino oscillations at long baseline

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32} + \delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + P_{\text{sol}} + 2\sqrt{P_{\text{atm}} P_{\text{sol}}} (\cos \Delta_{32} \cos \delta \mp \sin \Delta_{32} \sin \delta)$$

$$\sqrt{P_{\text{atm}}} = \sin \theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{\Delta_{31} \mp aL} \Delta_{31}$$

$$\sqrt{P_{\text{sol}}} = \cos \theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{aL} \Delta_{21}$$

$$aL = 0.08 \text{ for } L = 295 \text{ km}$$

$$aL = 0.23 \text{ for } L = 810 \text{ km}$$

$$aL = 0.37 \text{ for } L = 1300 \text{ km}$$

Parameter

Channels

Question

$\sin^2 2\theta_{23}$: $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$:

Is θ_{23} maximal?

$\sin^2 \theta_{23} \sin^2 2\theta_{13}$: $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Octant of θ_{23}

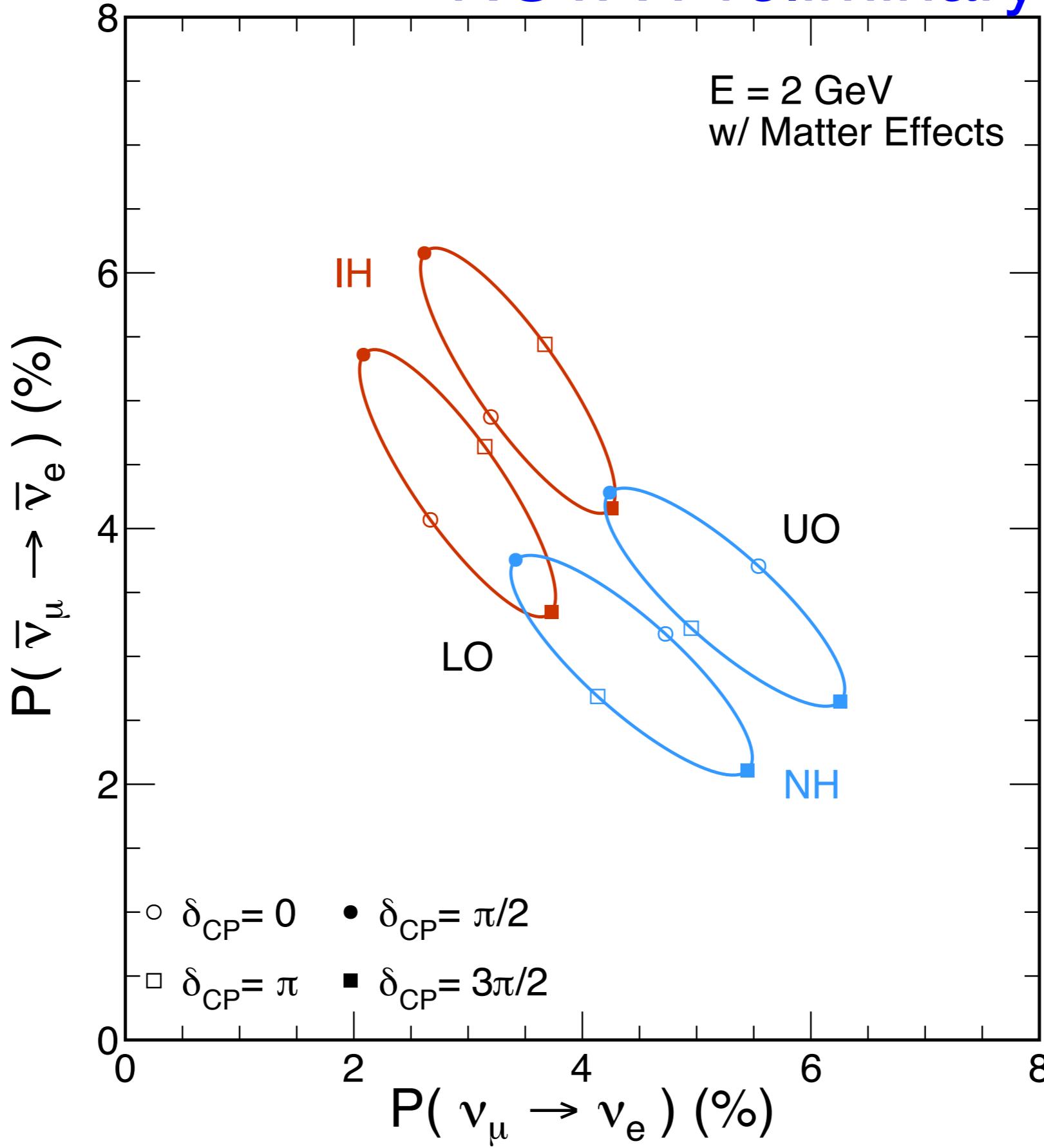
sign $[\Delta_{31}]$: $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Neutrino mass hierarchy

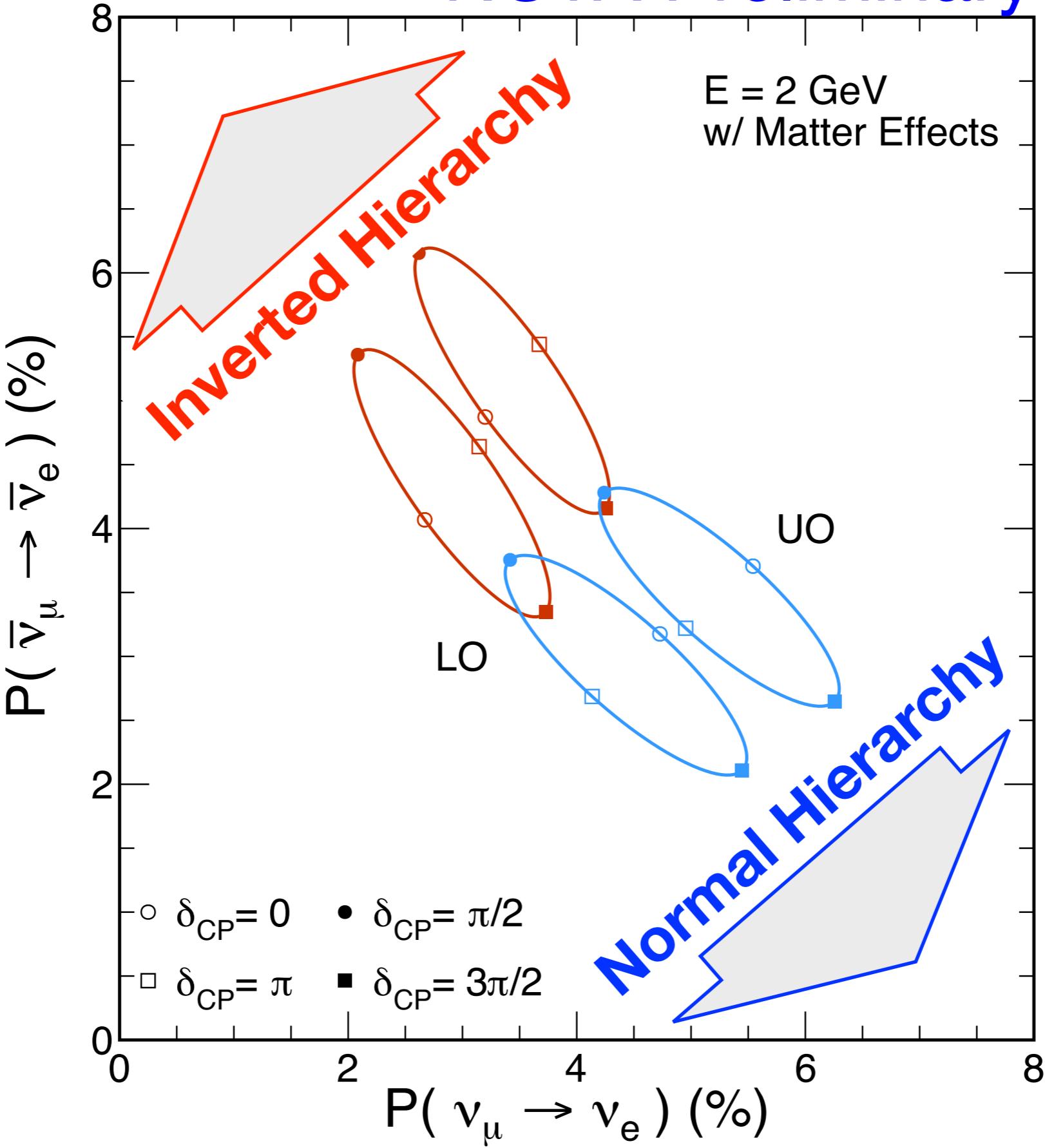
δ_{CP} : $\nu_\mu \rightarrow \nu_e$ vs. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$:

Is CP violated?

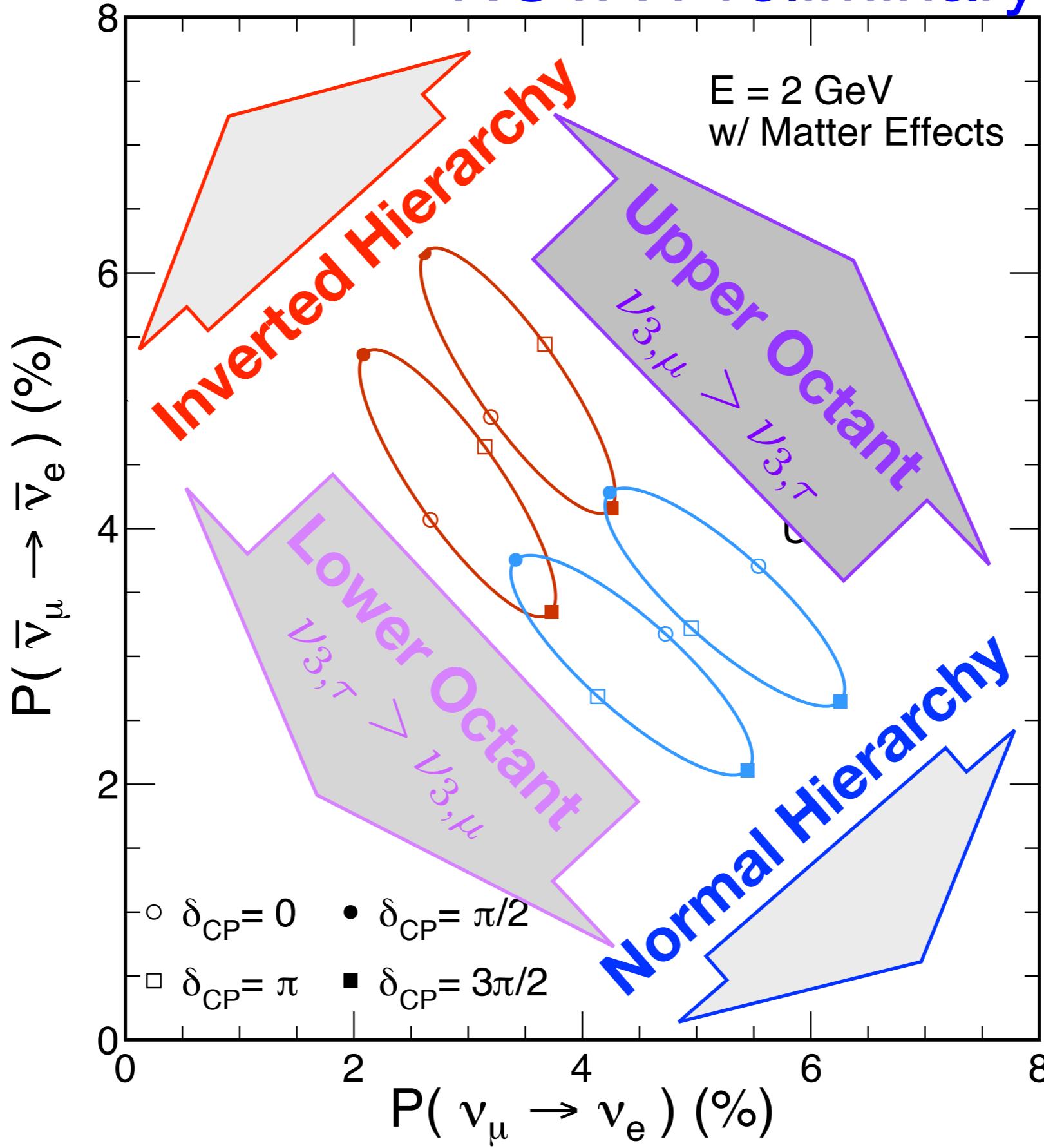
NOvA Preliminary



NOvA Preliminary



NOvA Preliminary

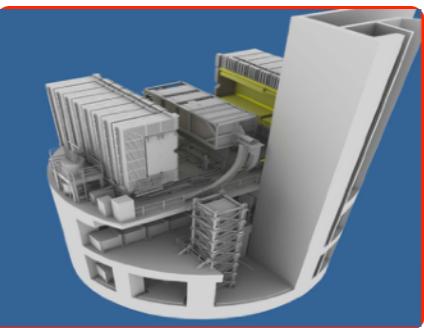
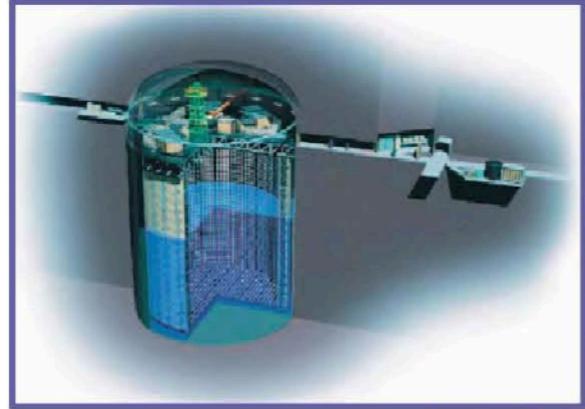


T2K

$E_\nu \simeq 0.7 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$

Super-Kamiokande
(ICRR, Univ. Tokyo)



INGRID +
ND280

J-PARC Main Ring
(KEK-JAEA, Tokai)

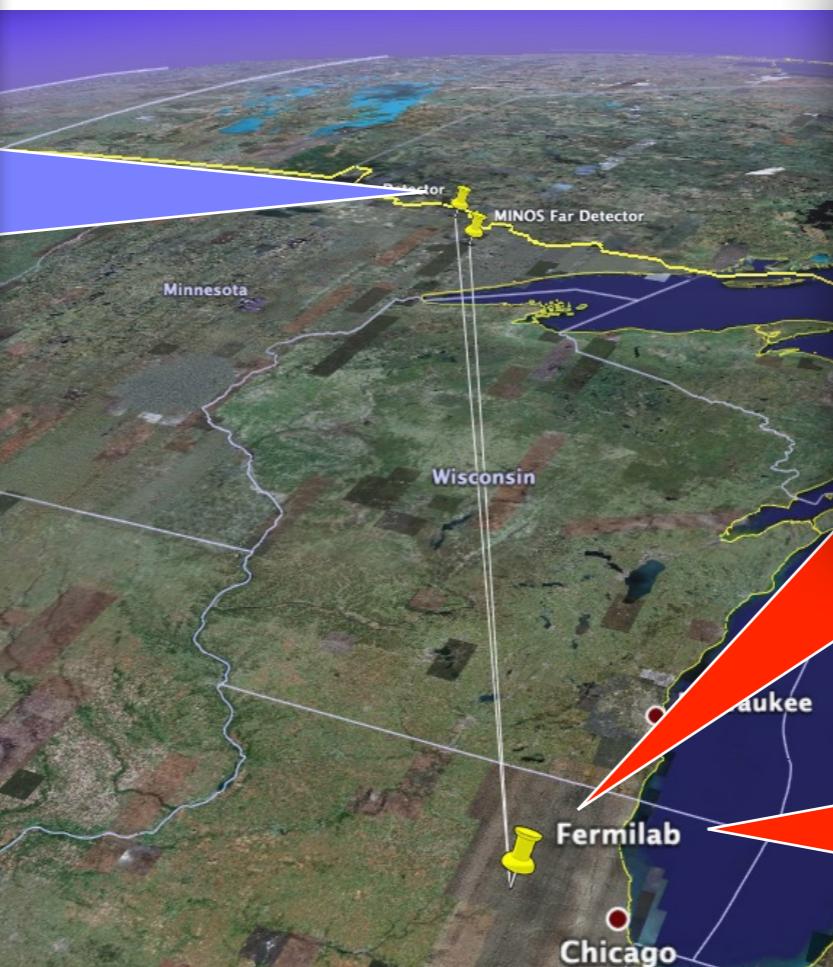


NOvA

$E_\nu \simeq 2 \text{ GeV}$,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA Far Detector



NOvA
Near
Detector

Fermilab Main Injector

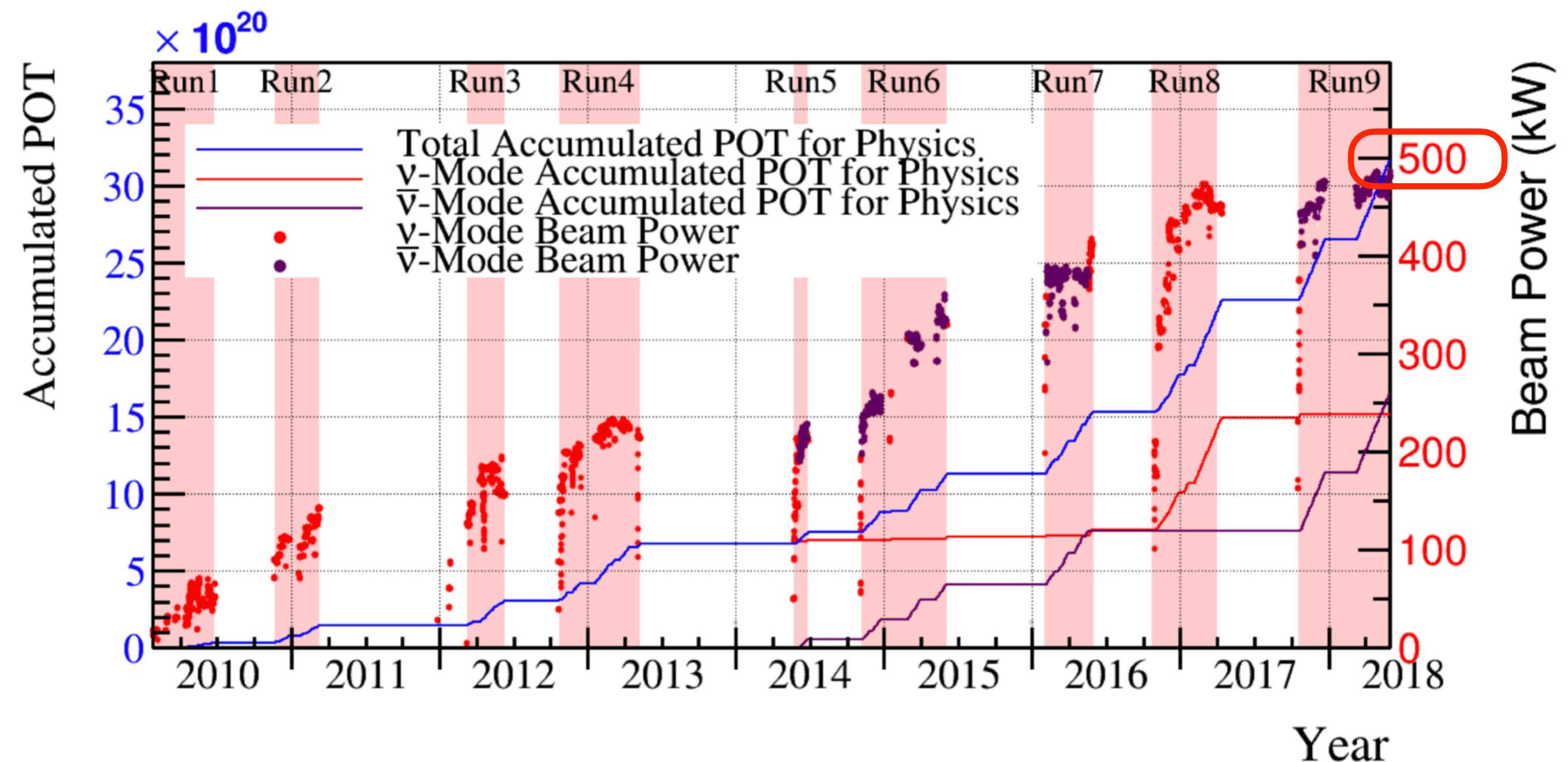


Summary of sensitivity of $\nu_\mu \rightarrow \nu_e$ rates to physics questions

Factor	Type	Inverts for $\bar{\nu}$?	NOvA	T2K
Matter effect (mass ordering)	Binary	Yes	$\pm 19\%$	$\pm 10\%$
CP violation	Bounded, continuous	Yes	$[-22...+22]\%$	$[-29...+29]\%$
θ_{23} octant	Unbounded, continuous	No	$[-22...+22]\%$	$[-22...+22]\%$

Nota bene:

- Calculations are for rate only; there is some additional information in the energy spectrum
- These estimates neglect non-linearities in combining different effects
- In the calculation of the matter effect and CP violation effects the calculated values account for the fact that T2K runs at an energy on the first oscillation maximum while NOvA runs at an energy slightly above the oscillation maximum
- θ_{23} was varied inside the $\pm 2\sigma$ range found by a recent global fit (PRD 90, 093006)



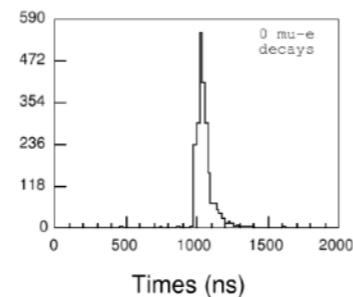
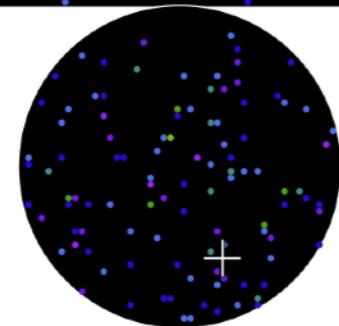
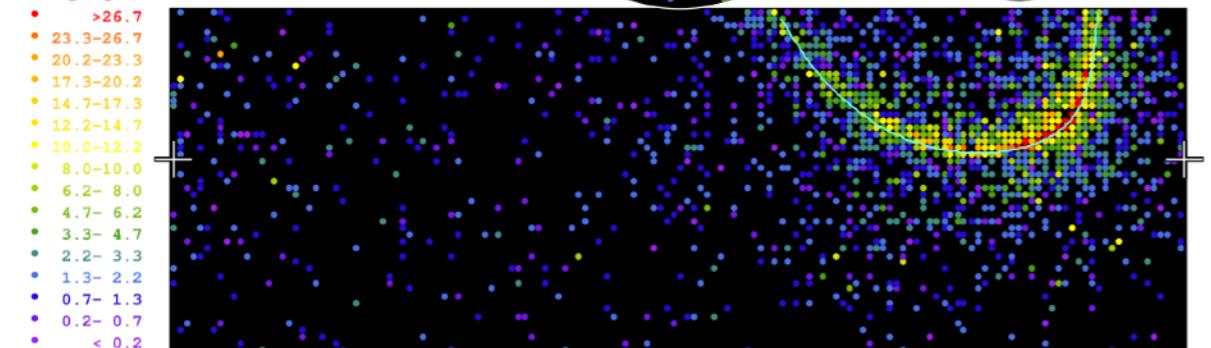
Latest results, January 2019, use
14.9E20 protons on target in neutrino mode
and
16.3E20 POT in antineutrino mode.
Represents 40% of total planned exposure.

**JPARC Beam
Delivery to T2K**

Super-Kamiokande IV

T2K Beam Run 430013 Spill 4033842
 Run 69739 Sub 201 Event 48168772
 12-05-30:05:03:02
 T2K beam dt = 2463.6 ns
 Inner: 2350 hits, 7009 pe
 Outer: 1 hits, 0 pe
 Trigger: 0x80000007
 D_wall: 644.8 cm
 e-like, p = 690.1 MeV/c

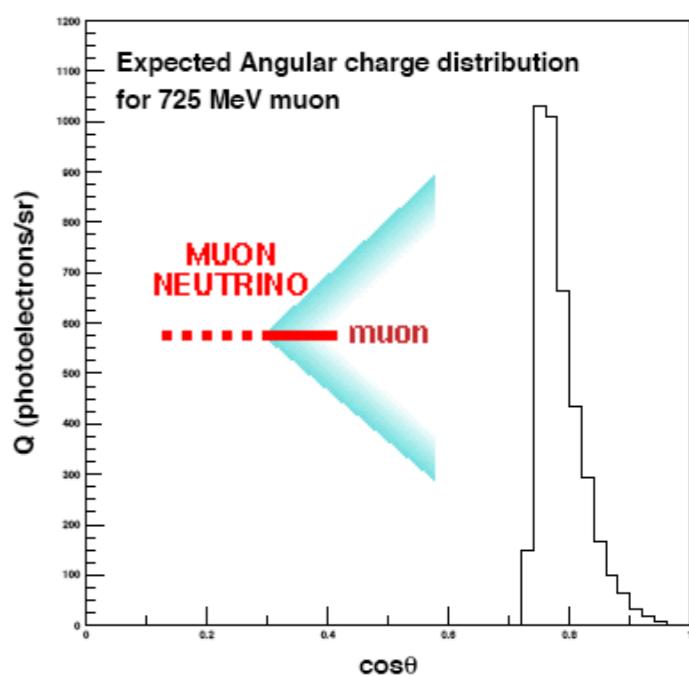
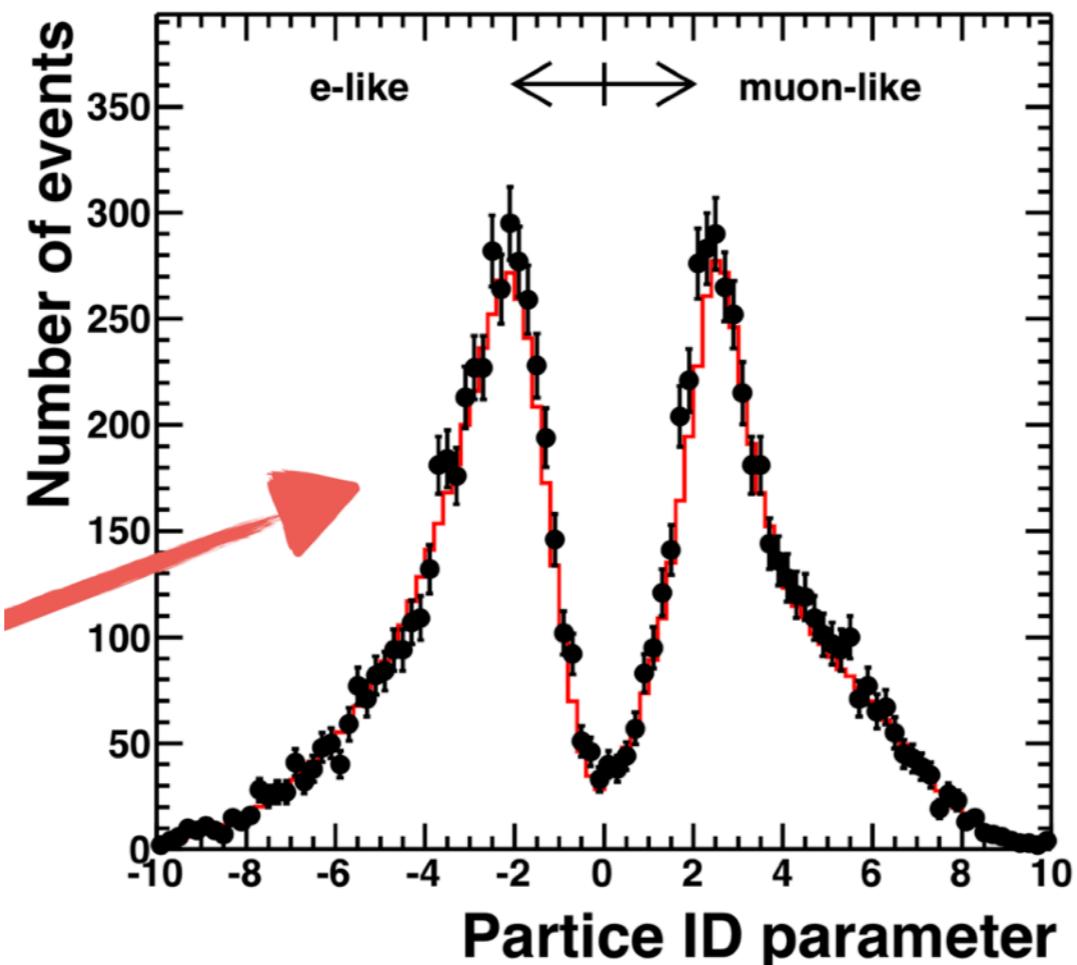
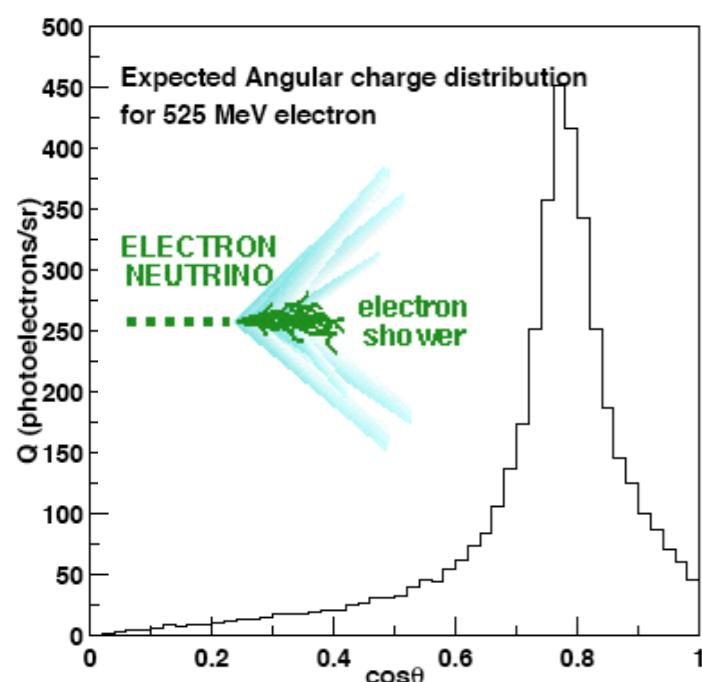
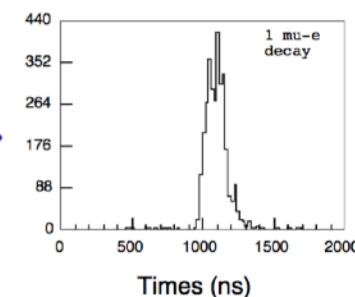
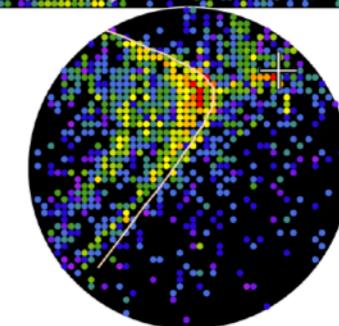
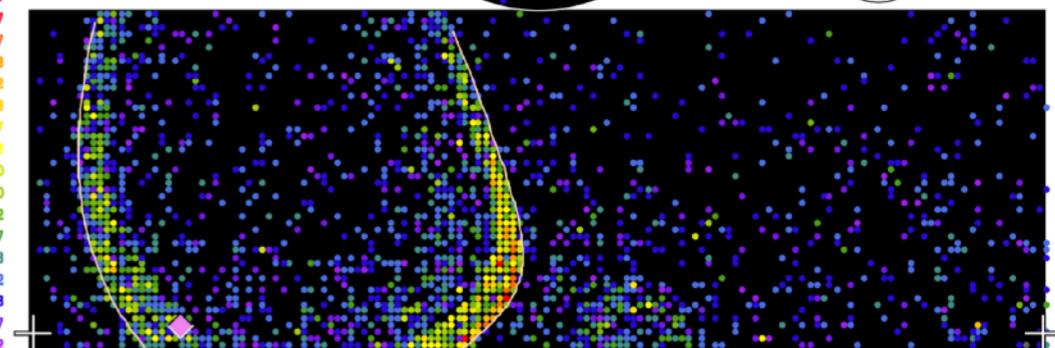
Charge (pe)

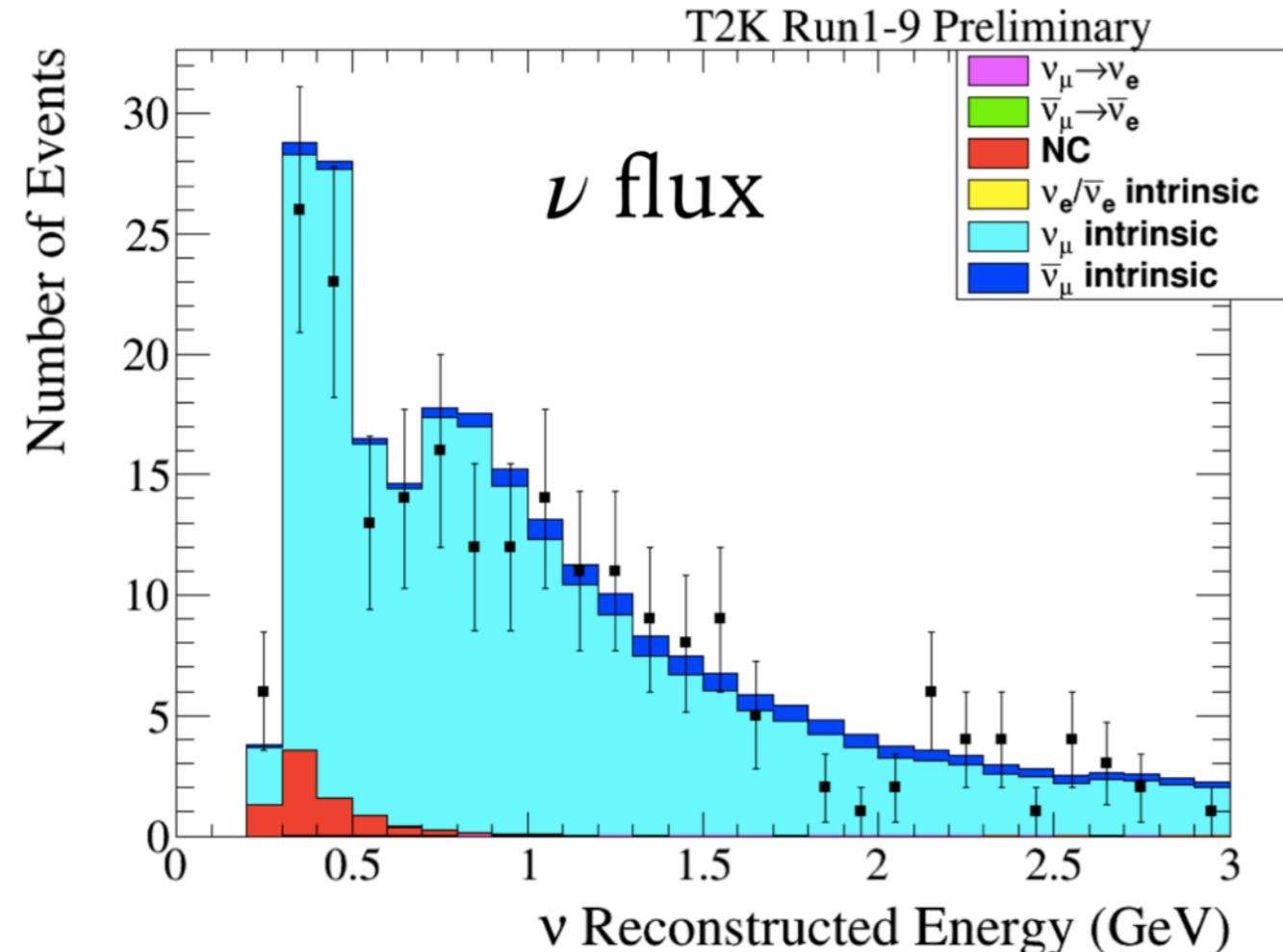
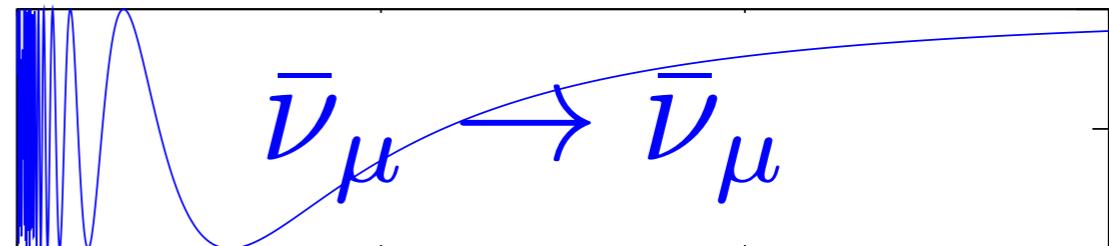
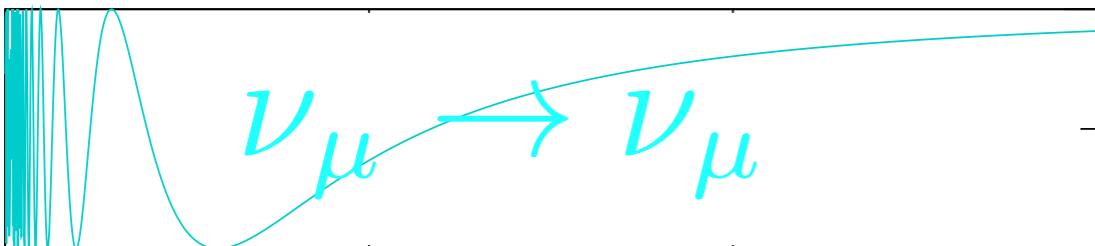


Super-Kamiokande IV

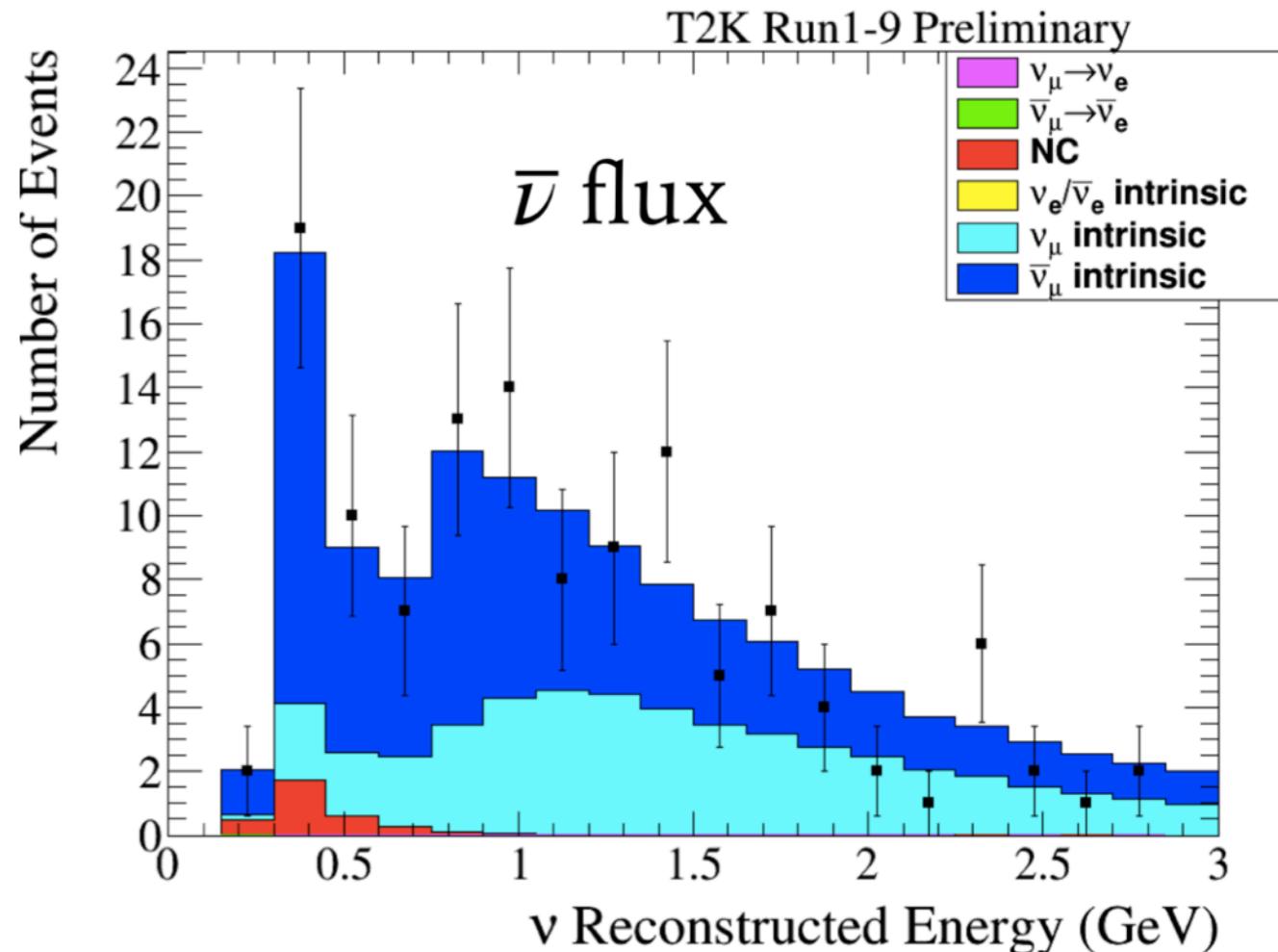
T2K Beam Run 0 Spill 1932249
 Run 72711 Sub 429 Event 96517853
 14-05-25:07:56:56
 T2K beam dt = 464.8 ns
 Inner: 3164 hits, 9525 pe
 Outer: 1 hits, 0 pe
 Trigger: 0x80000007
 D_wall: 236.5 cm
 Evis: 852.7 MeV
 mu-like, p = 953.0 MeV/c

Charge (pe)





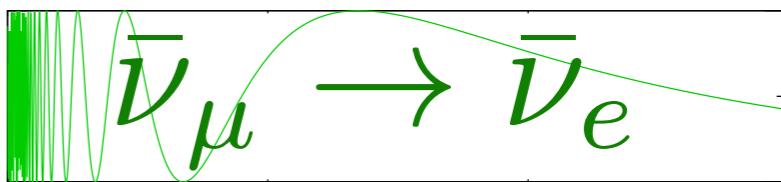
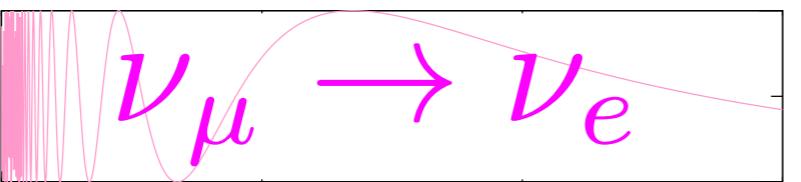
With $\sin^2(\theta) = 0.528$: 272.4 expected



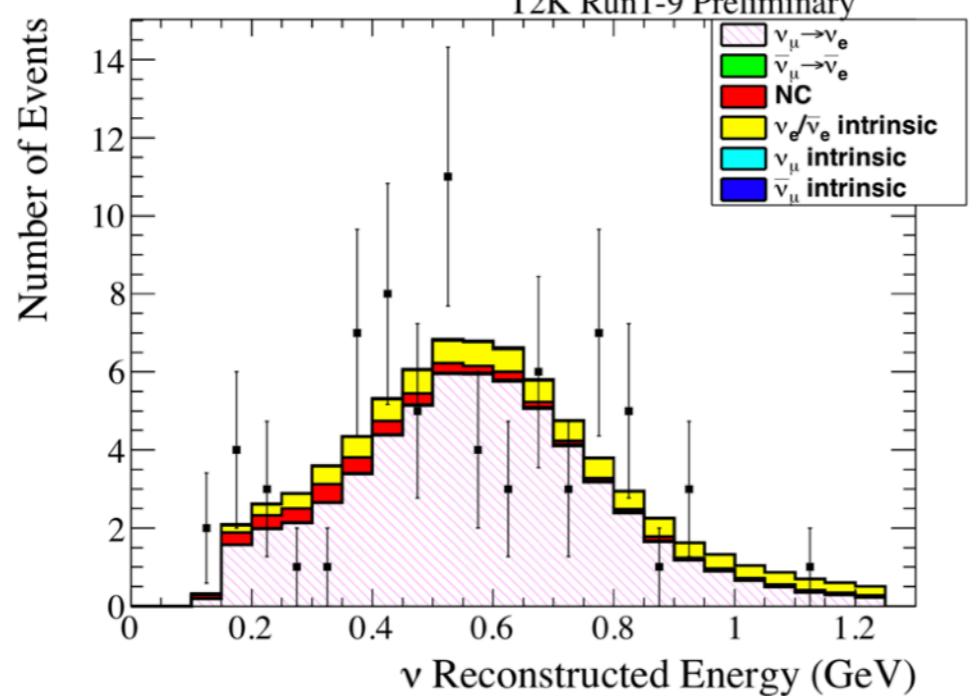
140 observed
139.5 expected

T2K muon neutrino and antineutrino disappearance

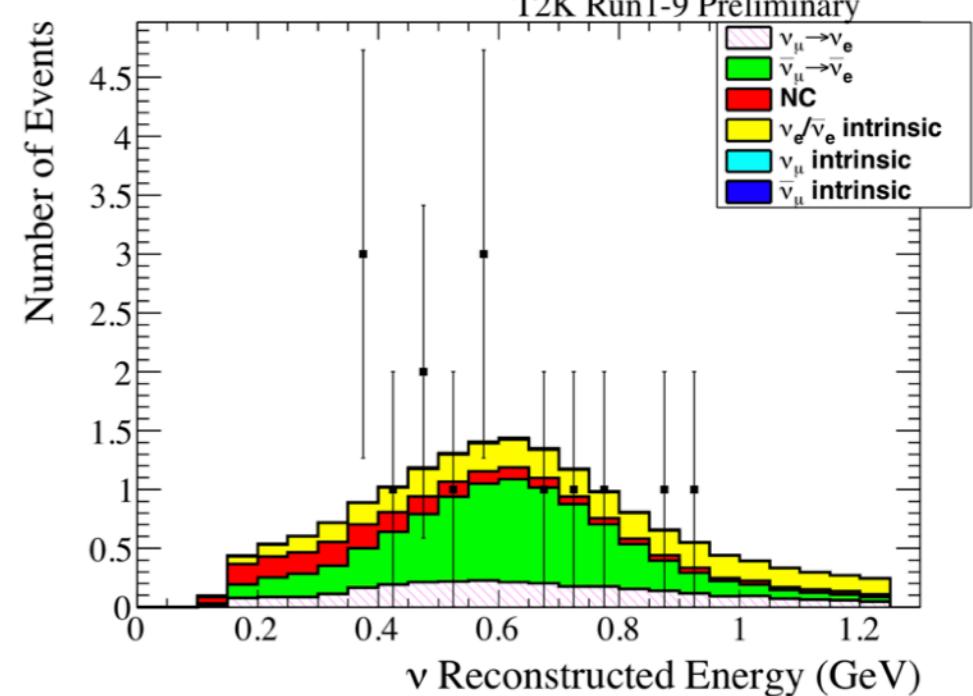
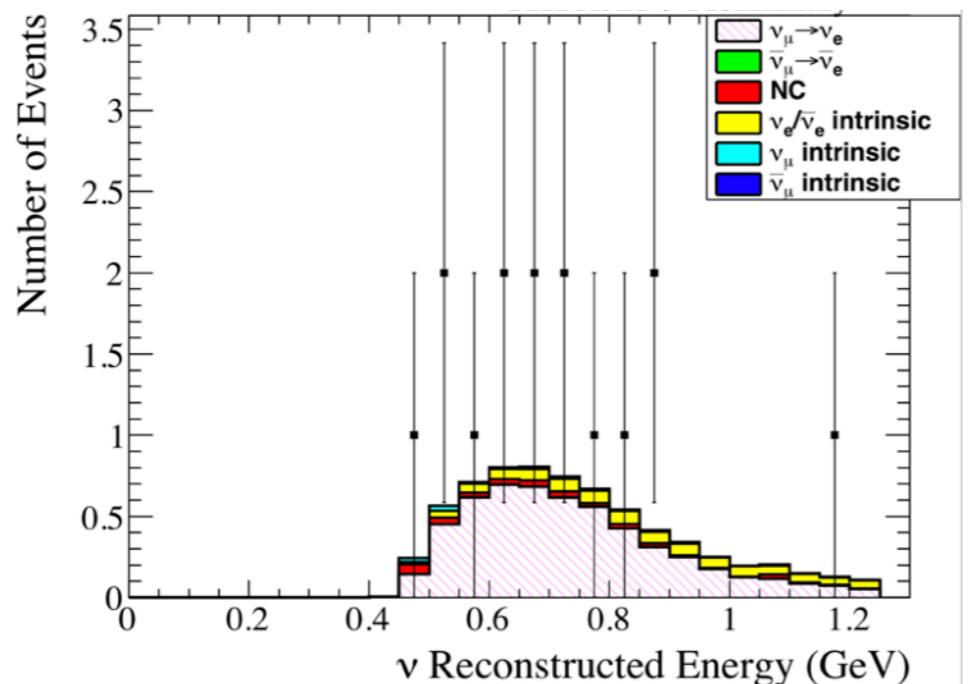
Rates consistent with maximal θ_{23} mixing



**single-ring
quasi-elastic
tag**



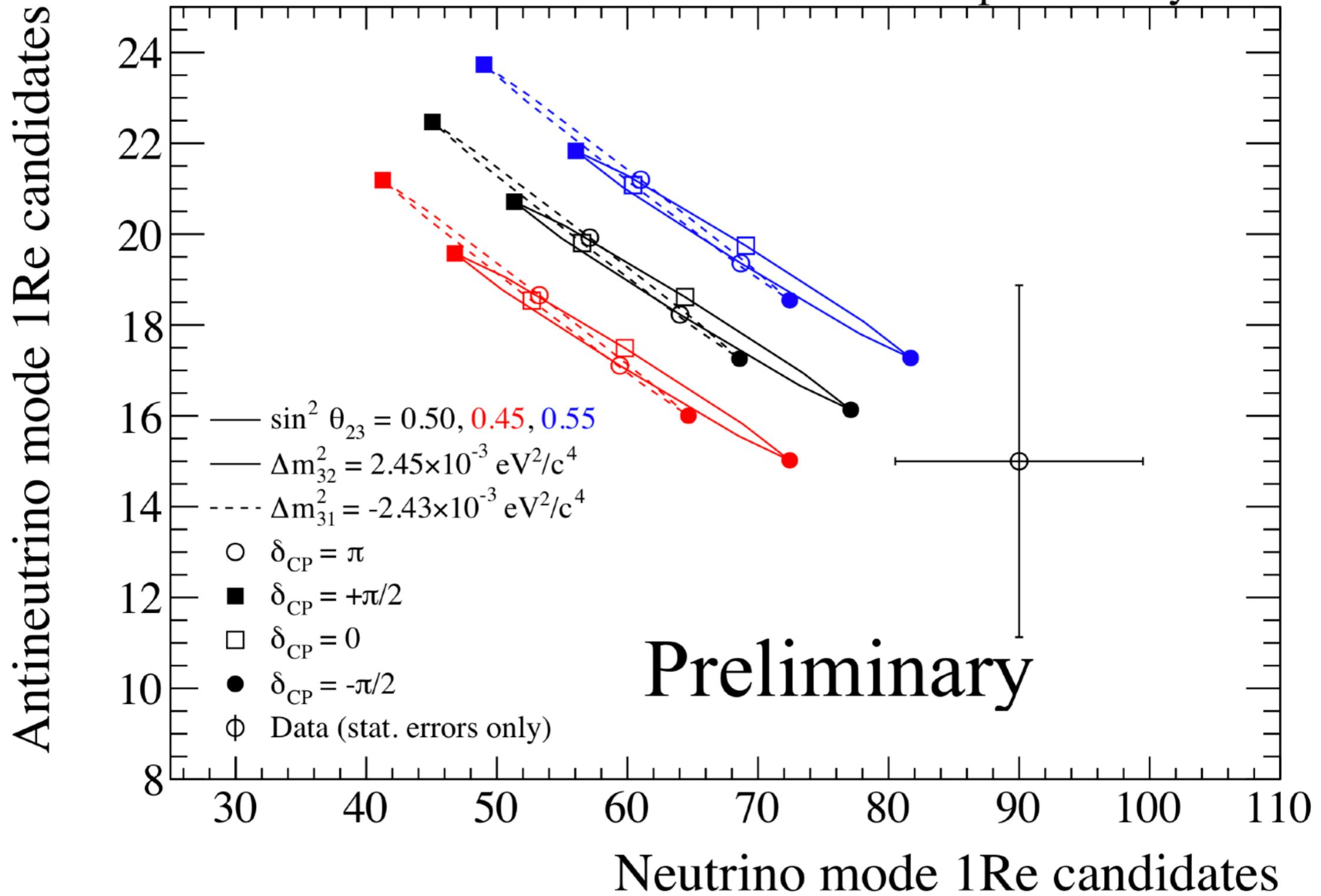
**single-ring
single-pion
tag**



	Observed	Expected $\delta_{CP}=-\pi/2$
$\nu_\mu \rightarrow \nu_e$ QE	75	74.4
1π	15	7.0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ QE	15	17.1

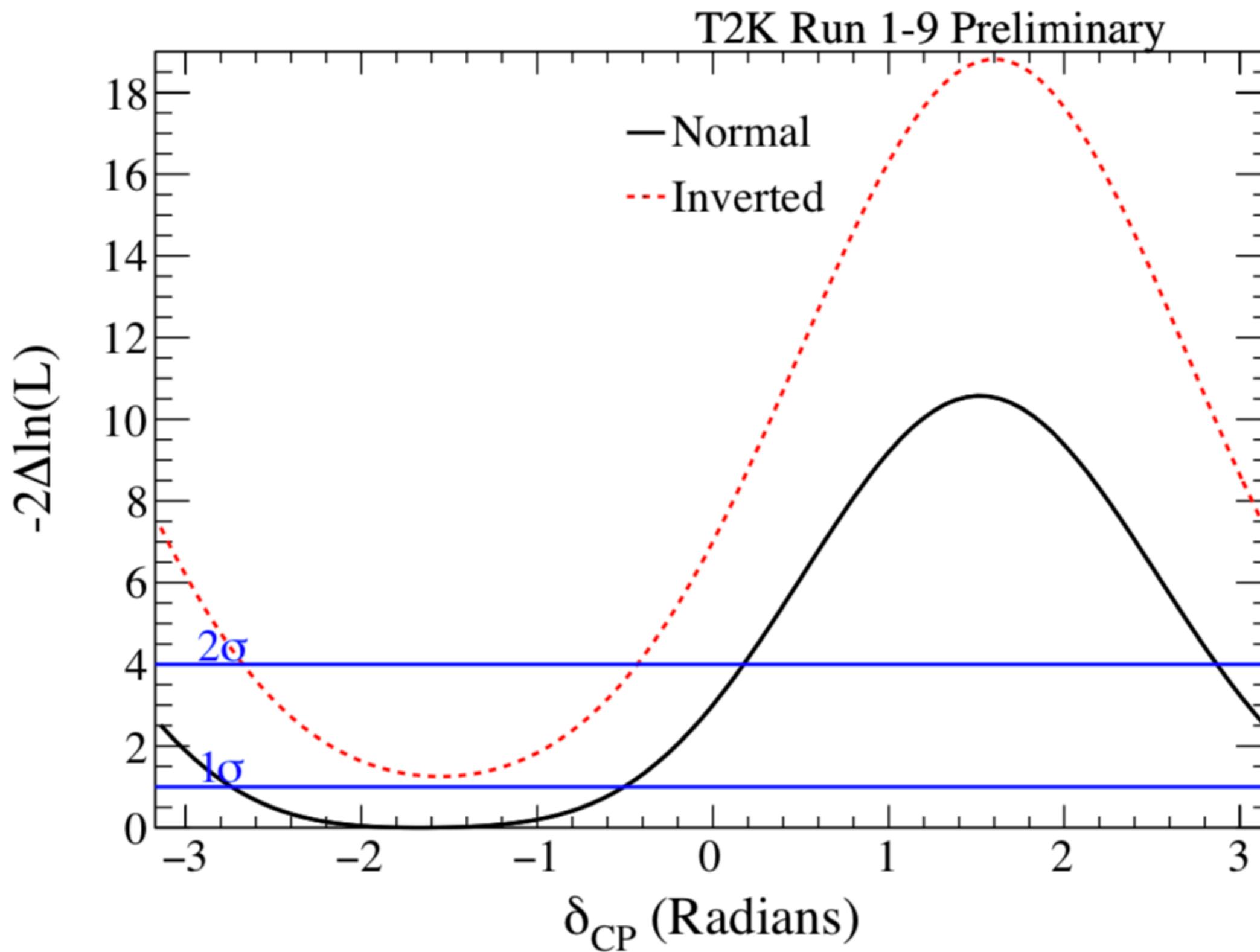
T2K Electron neutrino and antineutrino appearance

15 events observed in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ channel over a background of 9.4 events: 2.2σ significant observation.



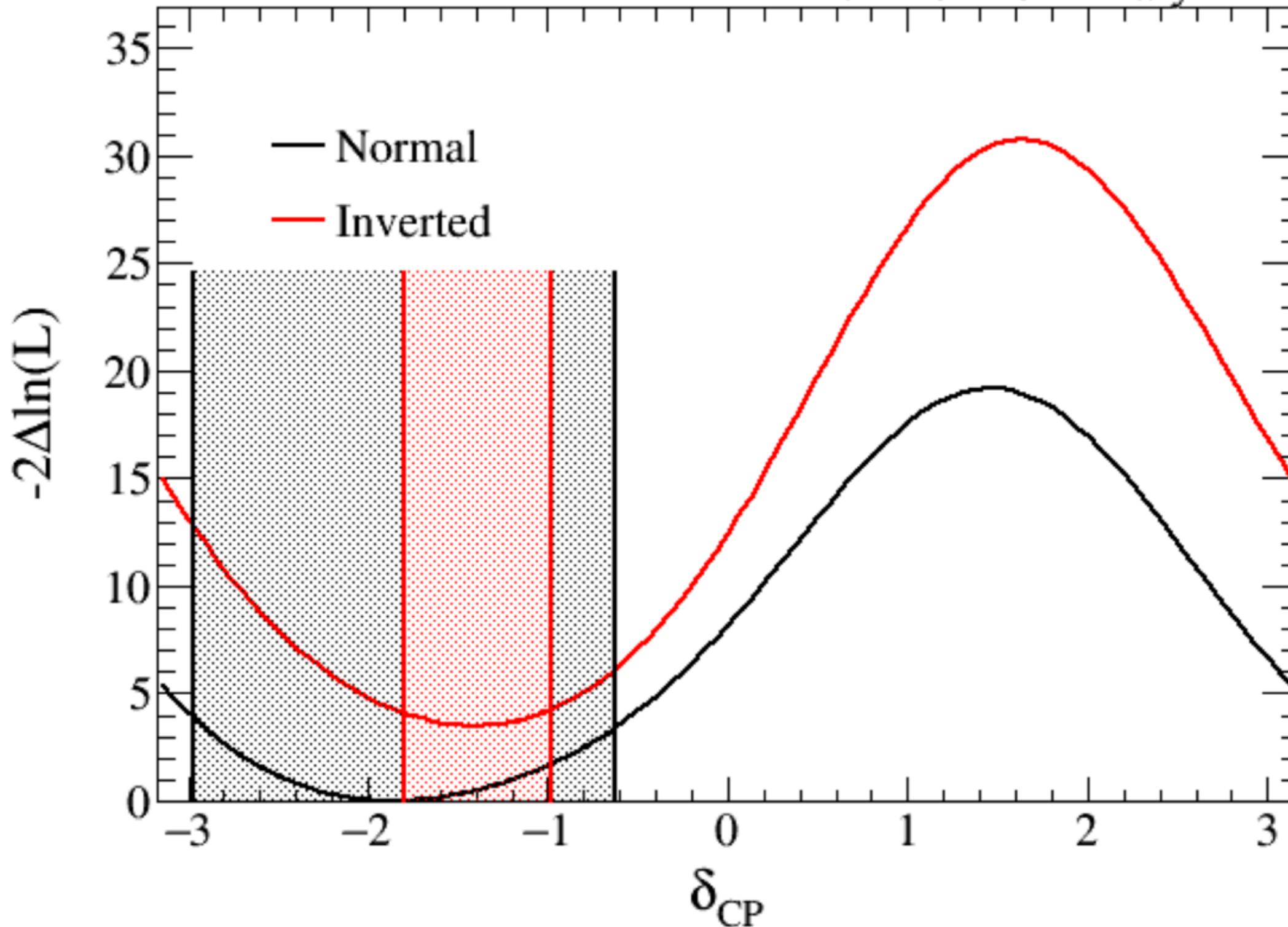
T2K Neutrino and Antineutrino Event Counts

Larger counts than expectations in neutrino mode favor solutions with normal hierarchy and large CP violation



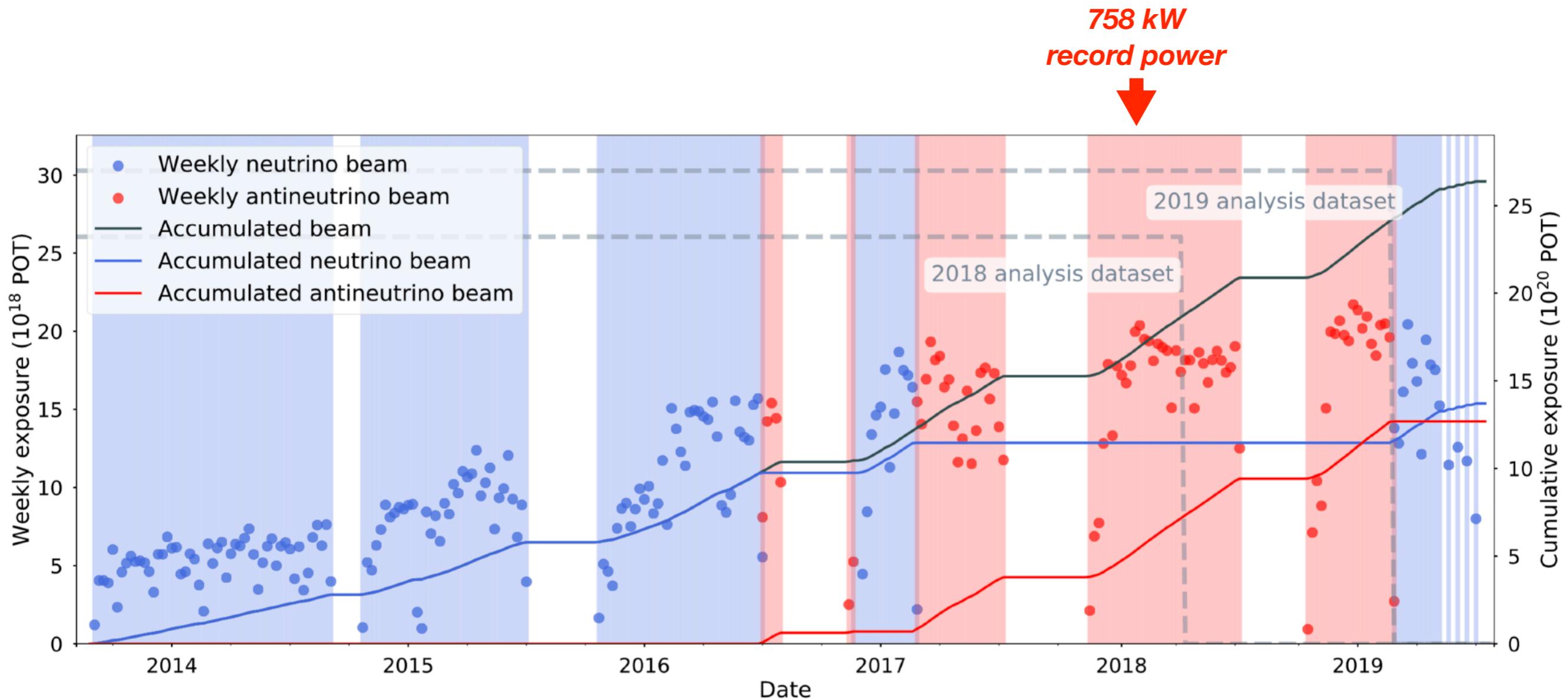
Sensitivity of T2K to CP violation

Current data sample is sensitive to CP violation at about 1.7σ and mass hierarchy at about 1.1σ .



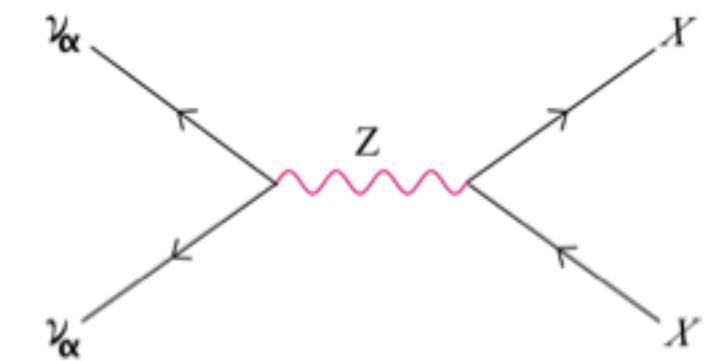
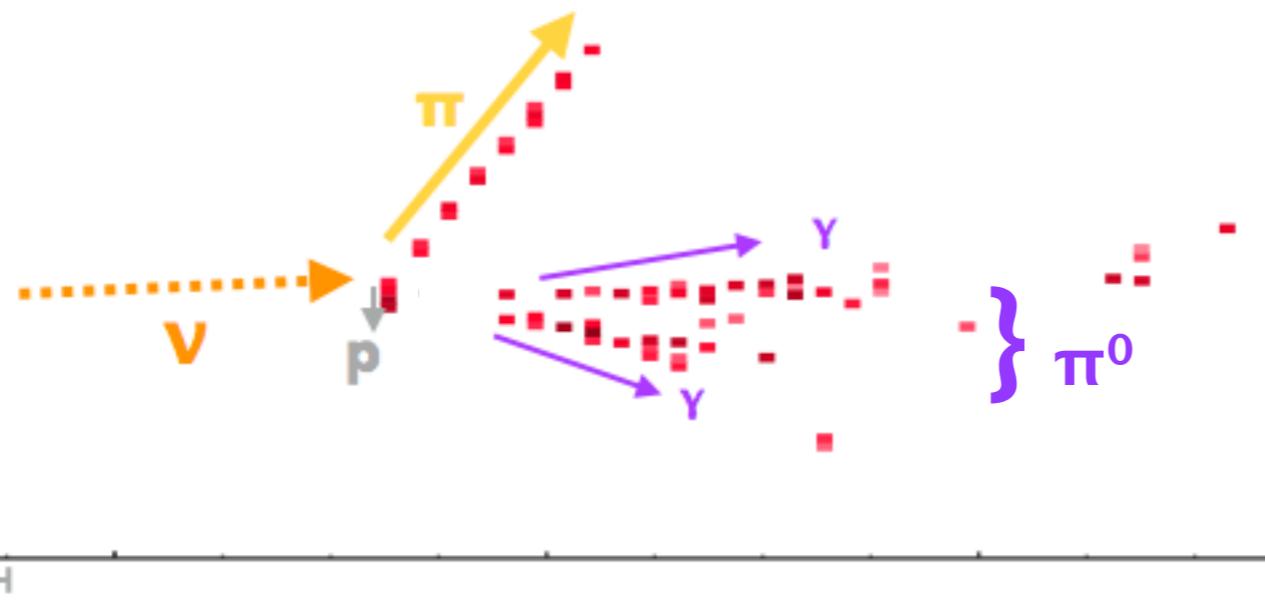
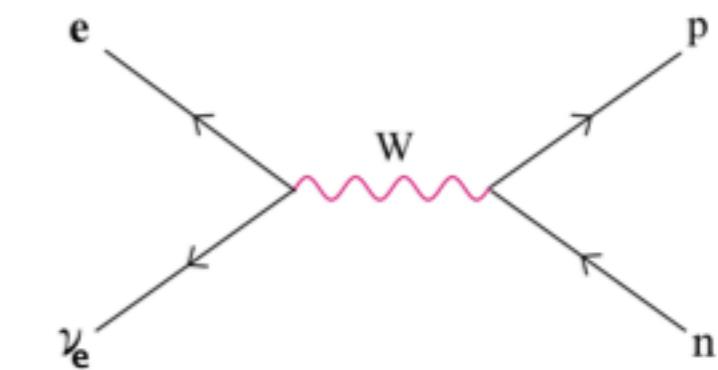
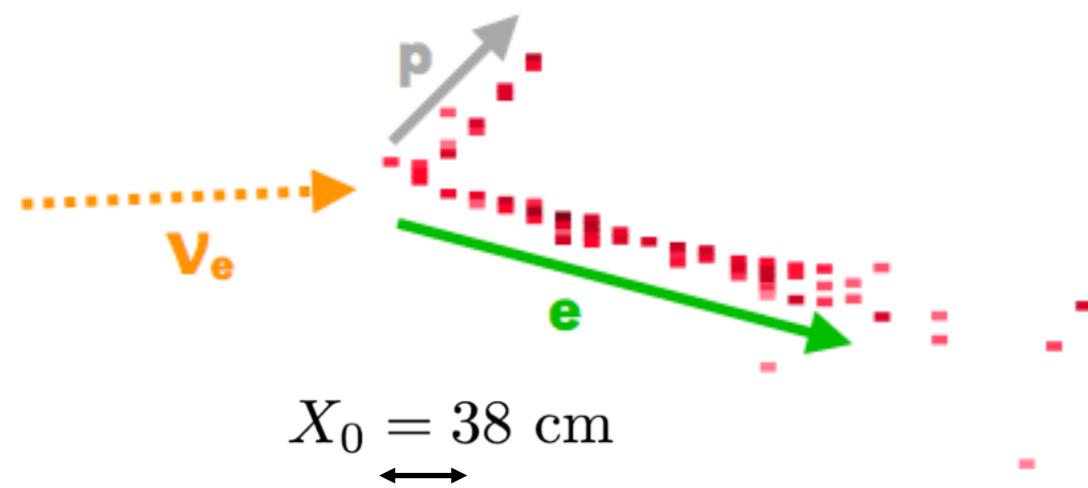
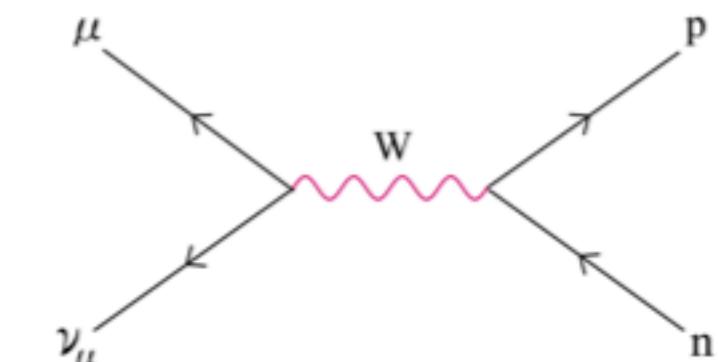
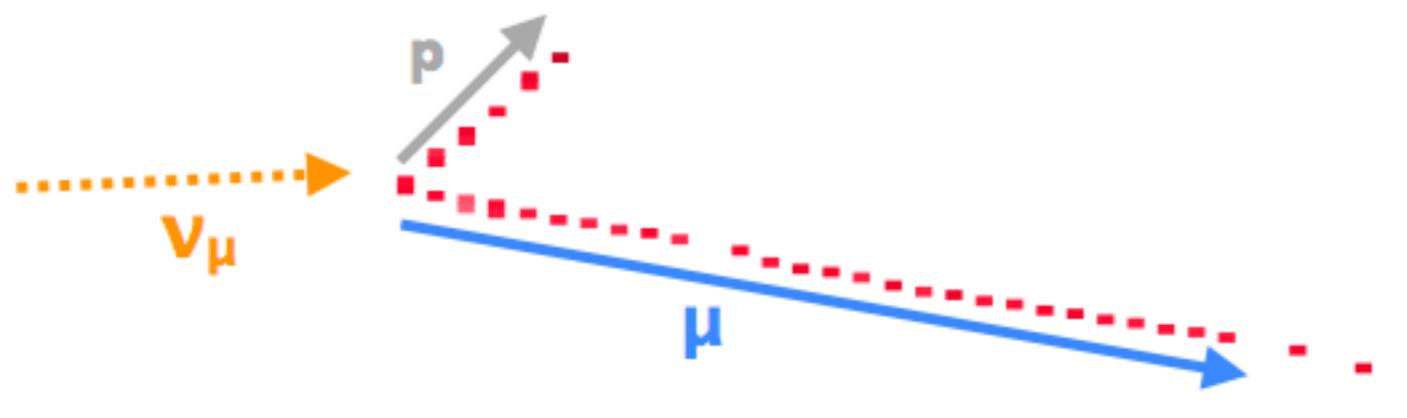
T2K CP violation result

The CP conserving values, 0, and $-\pi/2$ fall outside the 2σ confidence interval.



Latest results, July 2019, use
8.85E20 protons on target in neutrino mode
and
12.33E20 POT in antineutrino mode.
Represents ~40% of total planned exposure.

Fermilab beam delivery to NOvA



1m
1m

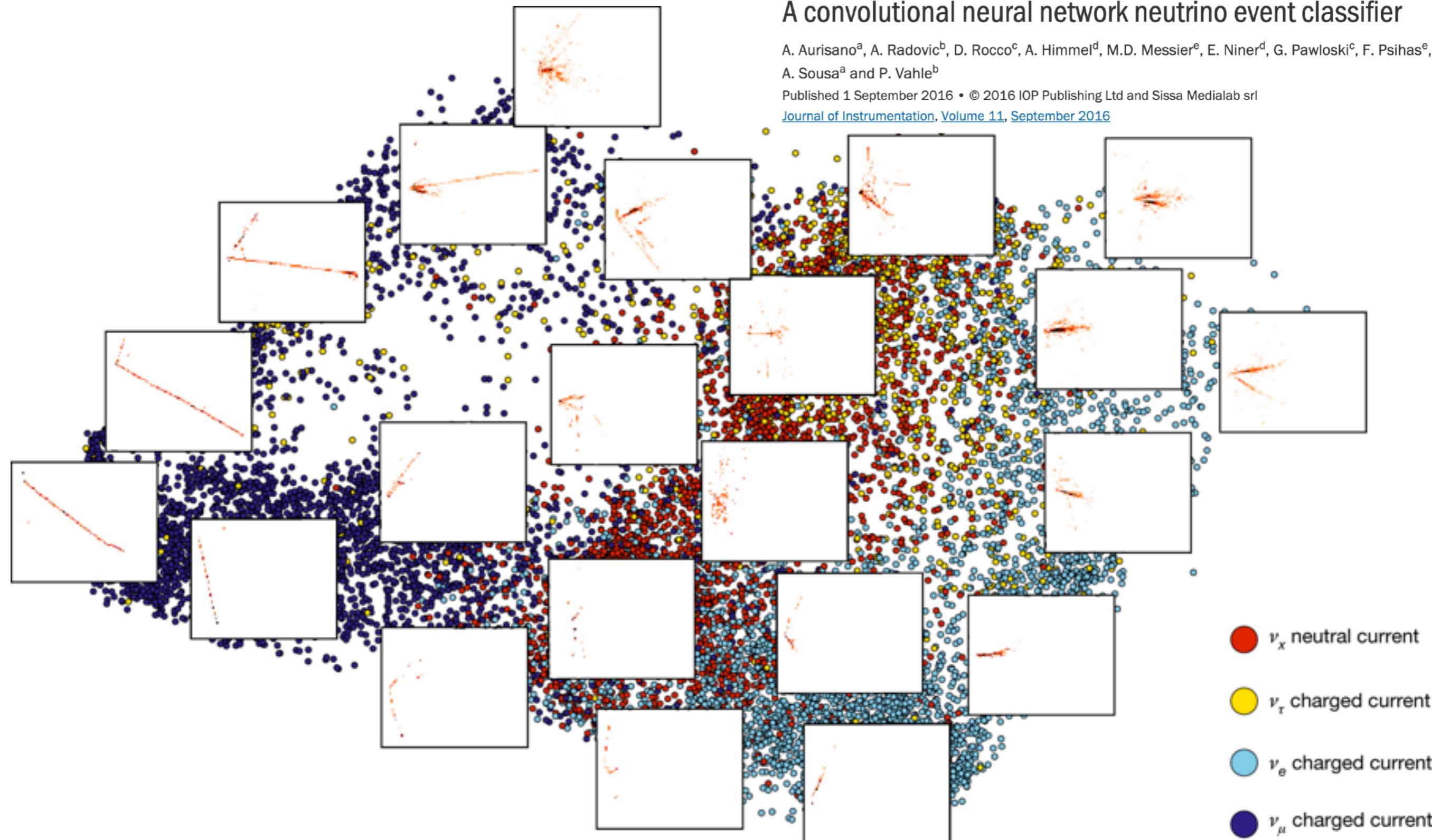
10 10² 10³ q (ADC) 20

A convolutional neural network neutrino event classifier

A. Aurisano^a, A. Radovic^b, D. Rocco^c, A. Himmel^d, M.D. Messier^e, E. Niner^d, G. Pawloski^c, F. Psihas^e, A. Sousa^a and P. Vahle^b

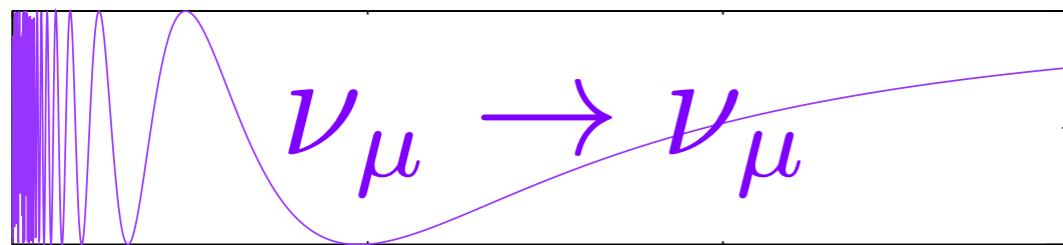
Published 1 September 2016 • © 2016 IOP Publishing Ltd and Sissa Medialab srl

[Journal of Instrumentation, Volume 11, September 2016](#)



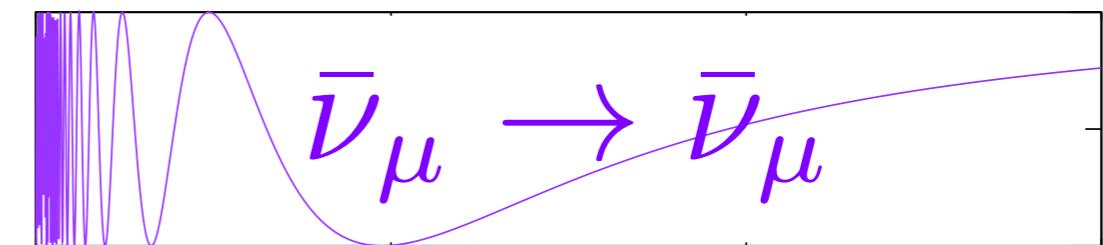
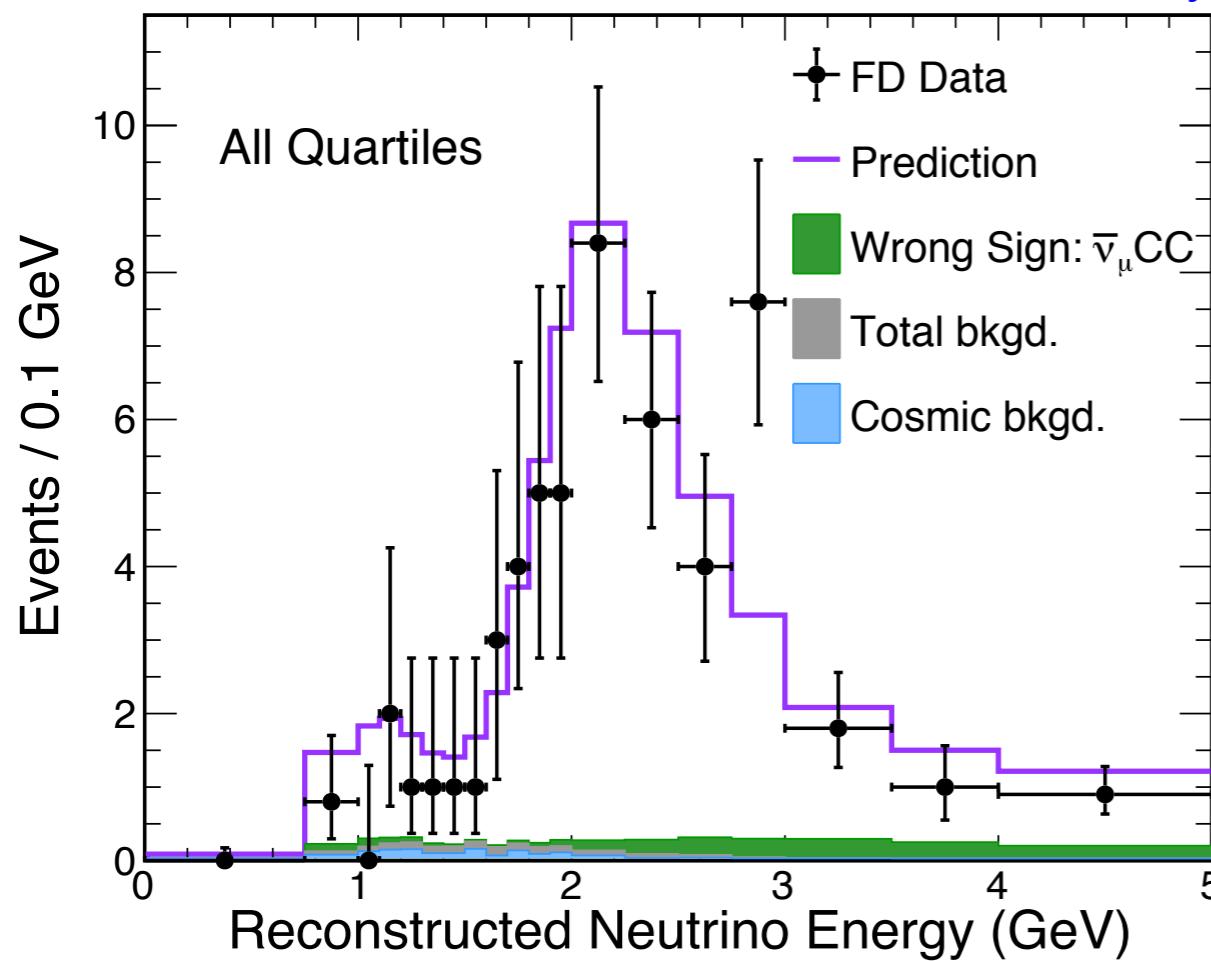
Machine learning at the energy and intensity frontiers of particle physics

Alexander Radovic^{1*}, Mike Williams^{2*}, David Rousseau³, Michael Kagan⁴, Daniele Bonacorsi^{5,6}, Alexander Himmel⁷, Adam Aurisano⁸, Kazuhiro Terao⁴ & Taritree Wongjirad⁹



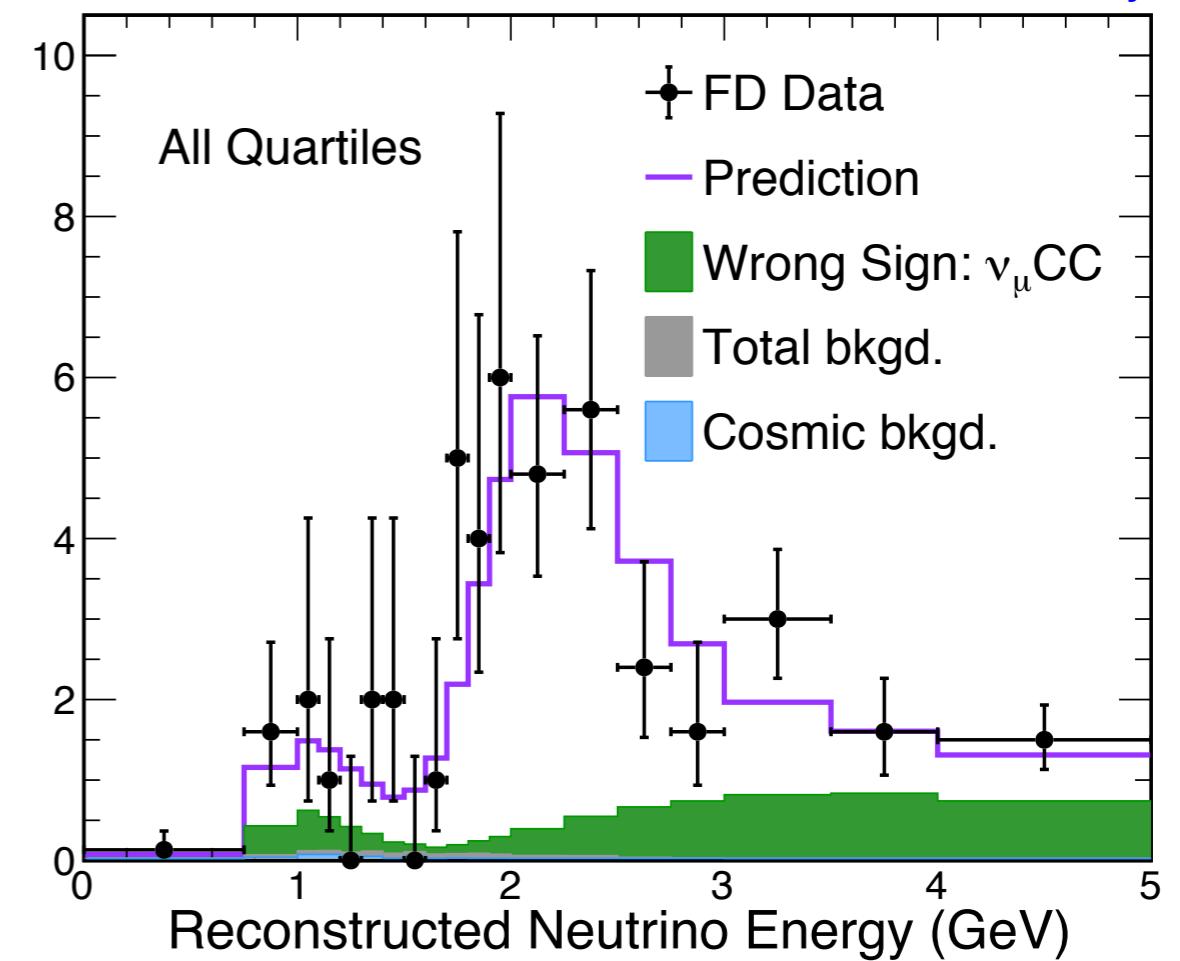
Neutrino beam

NOvA Preliminary



Antineutrino beam

NOvA Preliminary

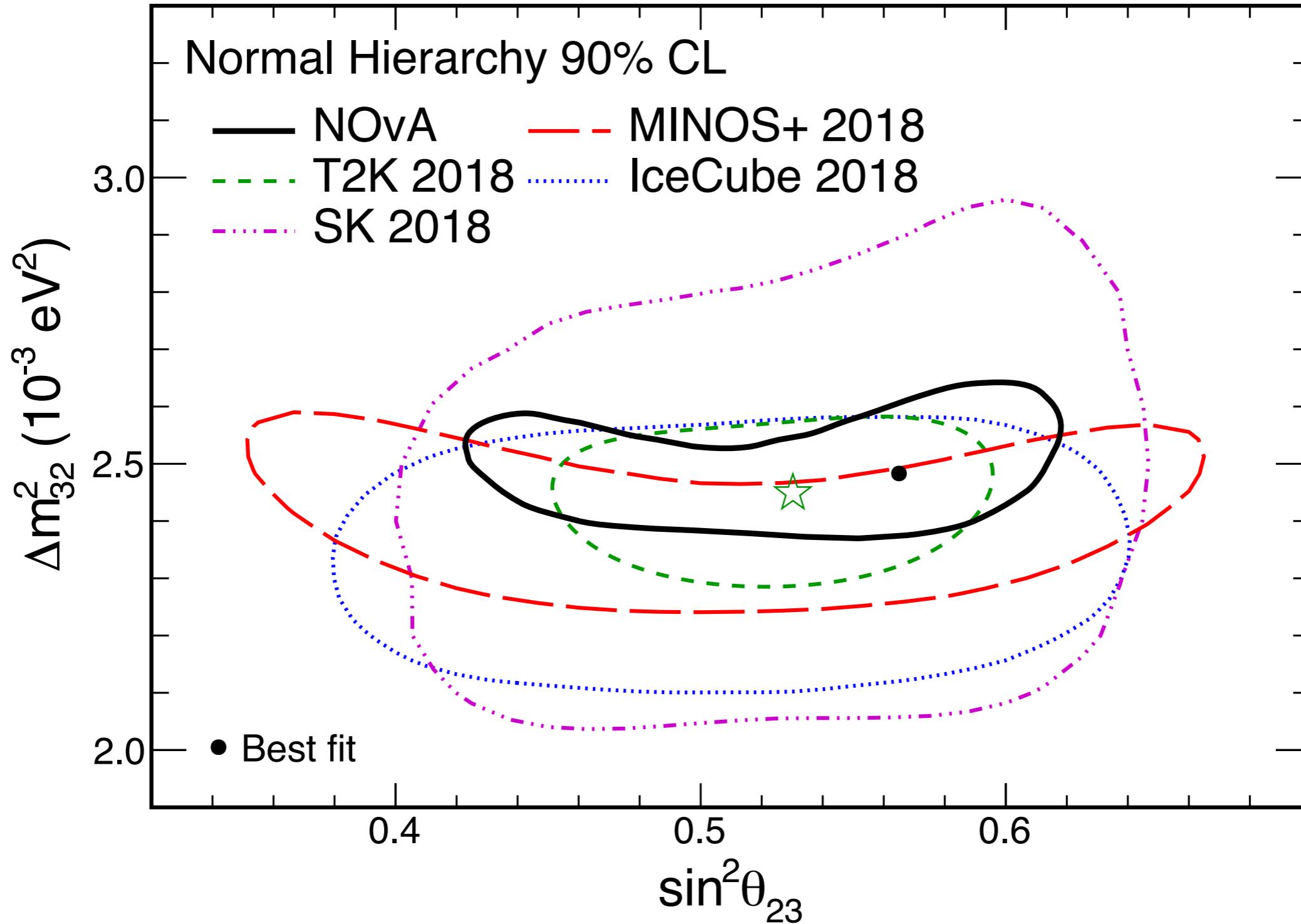


No oscillations	730
Best Fit	124
Cosmic bkg	2.1
Beam bkg	2.1
Observerd	113

No oscillations	476
Best Fit	96
Cosmic bkg	0.8
Beam bkg	1.4
Observerd	102

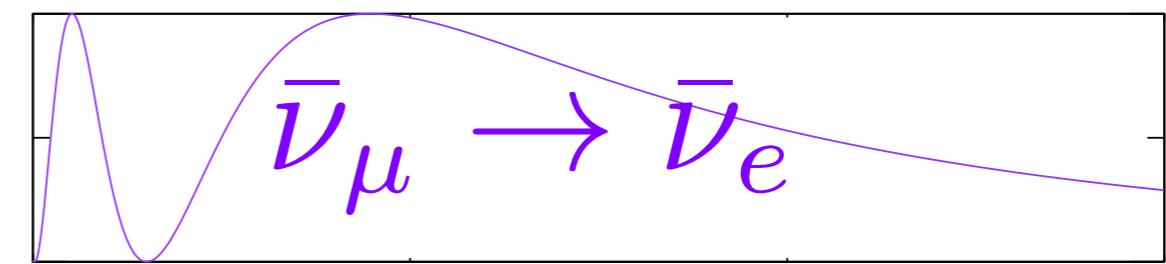
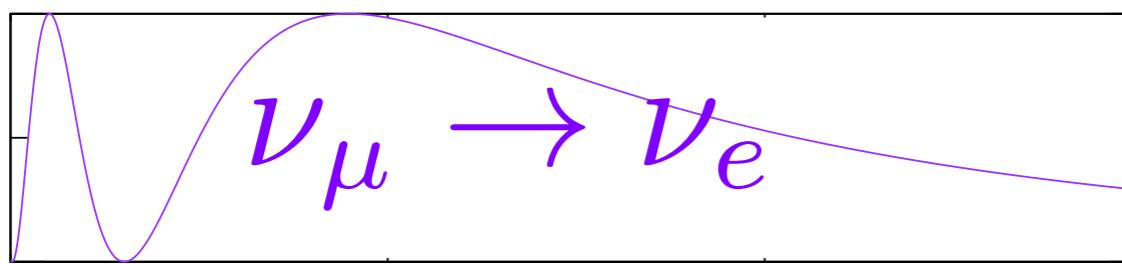
NOvA muon neutrino and antineutrino disappearance

arXiv:1906.04907



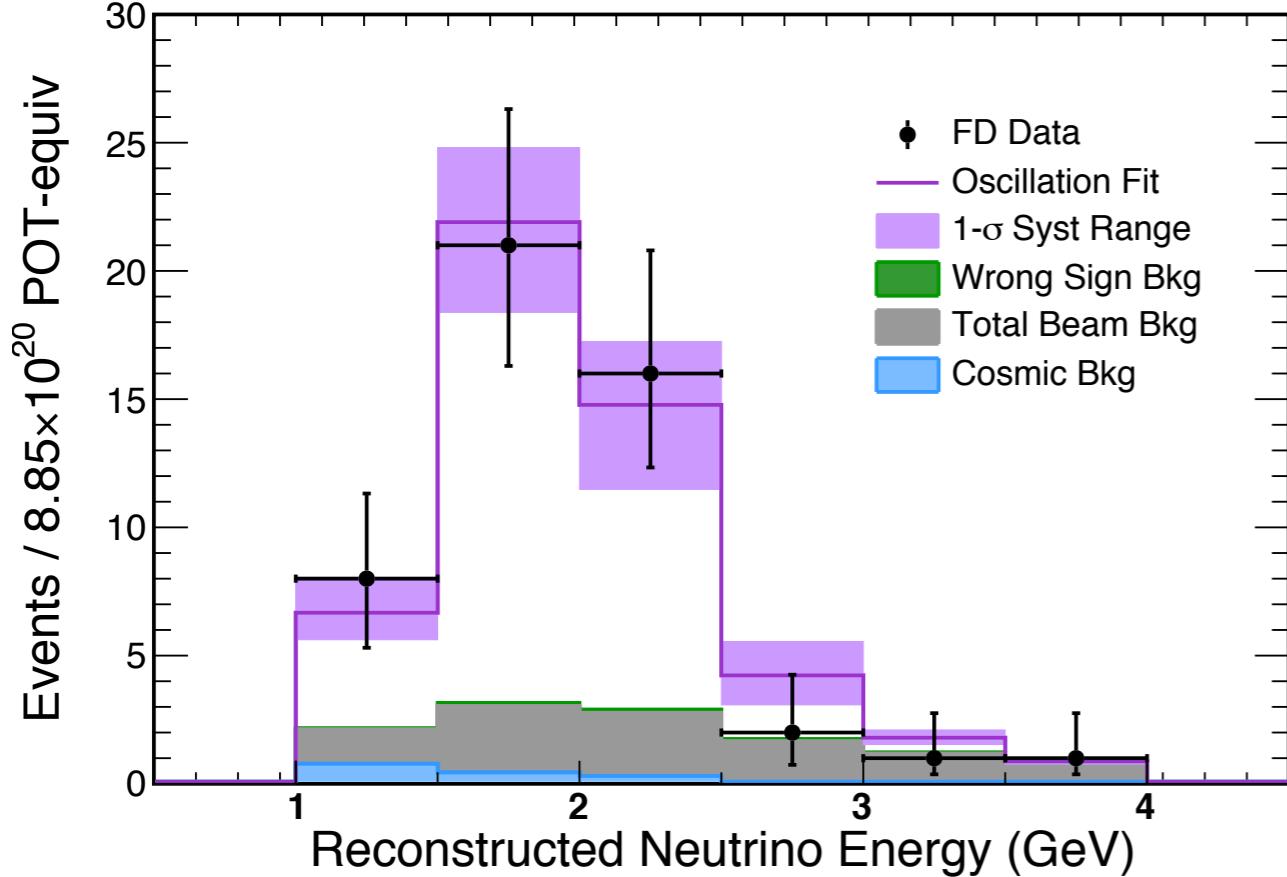
Δm²₂₃ & θ₂₃ Results

Both NOvA and T2K are consistent with maximal θ_{23} . NOvA has a slight (1.6σ) preference for the upper octant



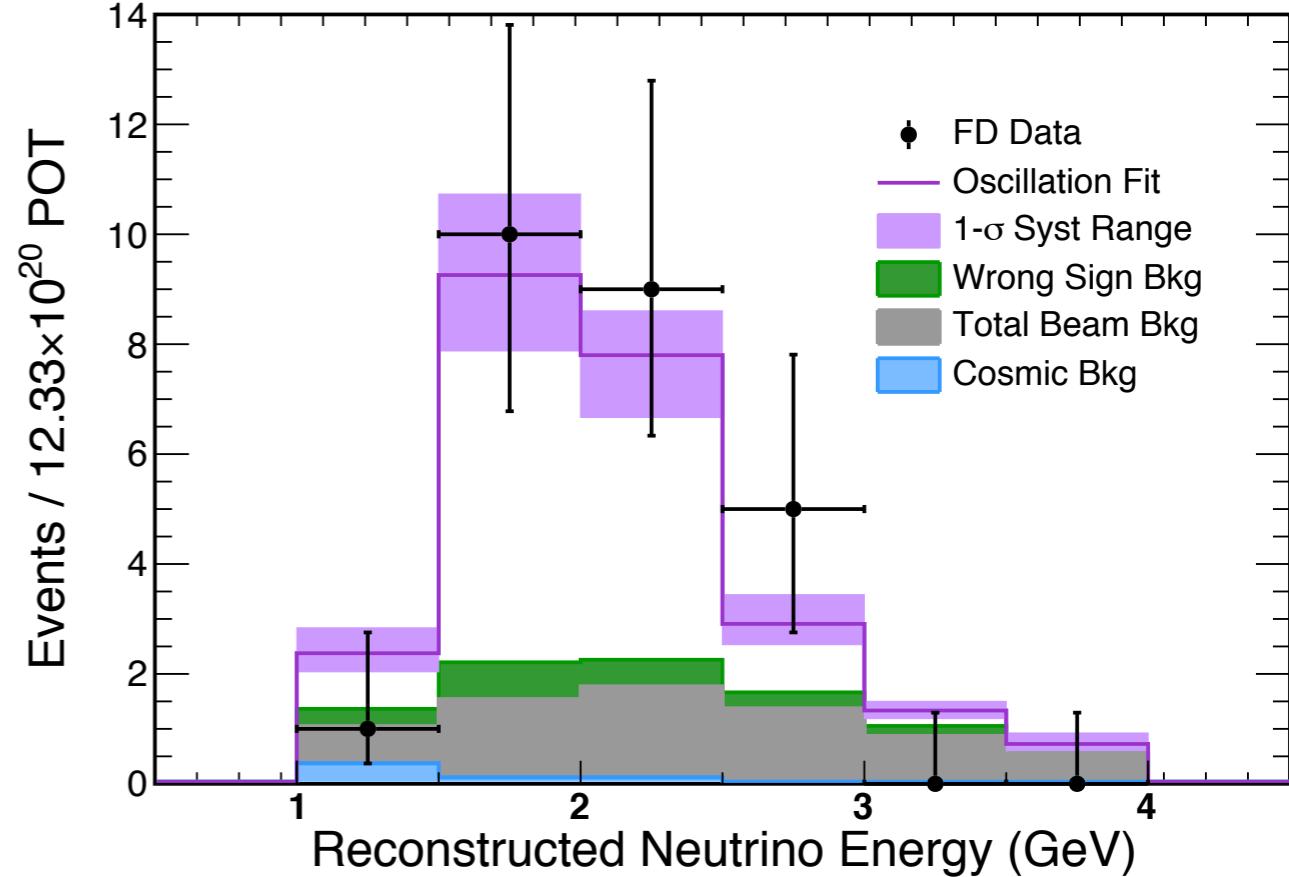
Neutrino Beam

NOvA Preliminary



Anti-Neutrino Beam

NOvA Preliminary



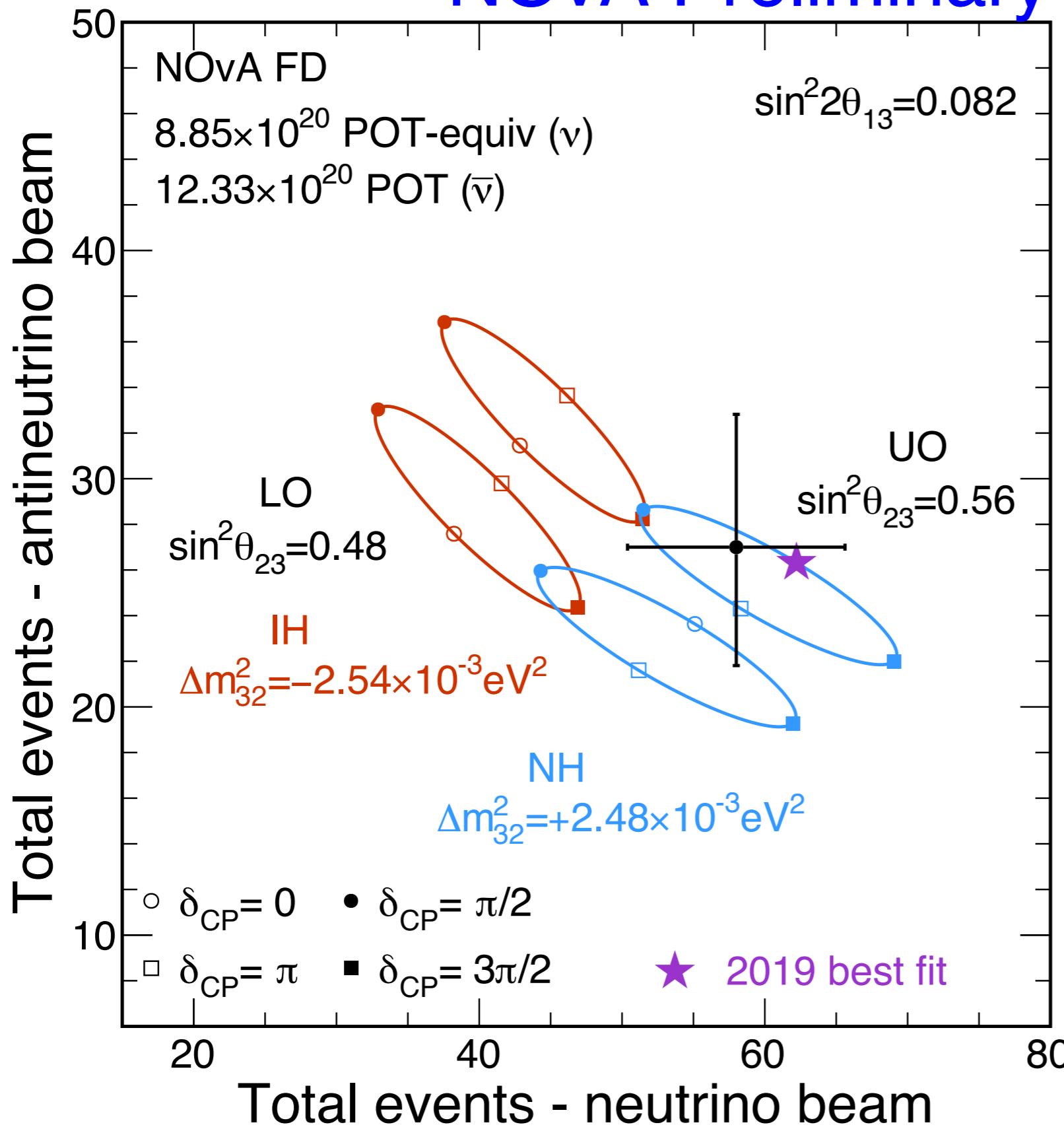
Best fit	59
Total bkg	15.0
Wrong-sign bkg	0.7
Beam bkg	11.1
Cosmic bkg	3.3
Observed	58

Best fit	27
Total bkg	10.3
Wrong-sign bkg	2.2
Beam bkg	7.0
Cosmic bkg	1.1
Observed	27

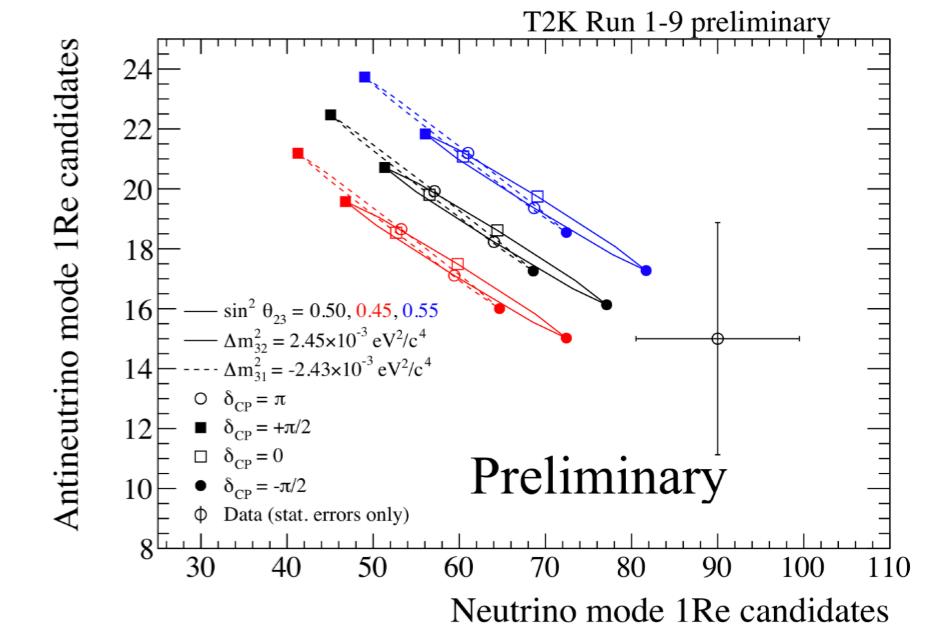
NOvA electron neutrino and antineutrino appearance

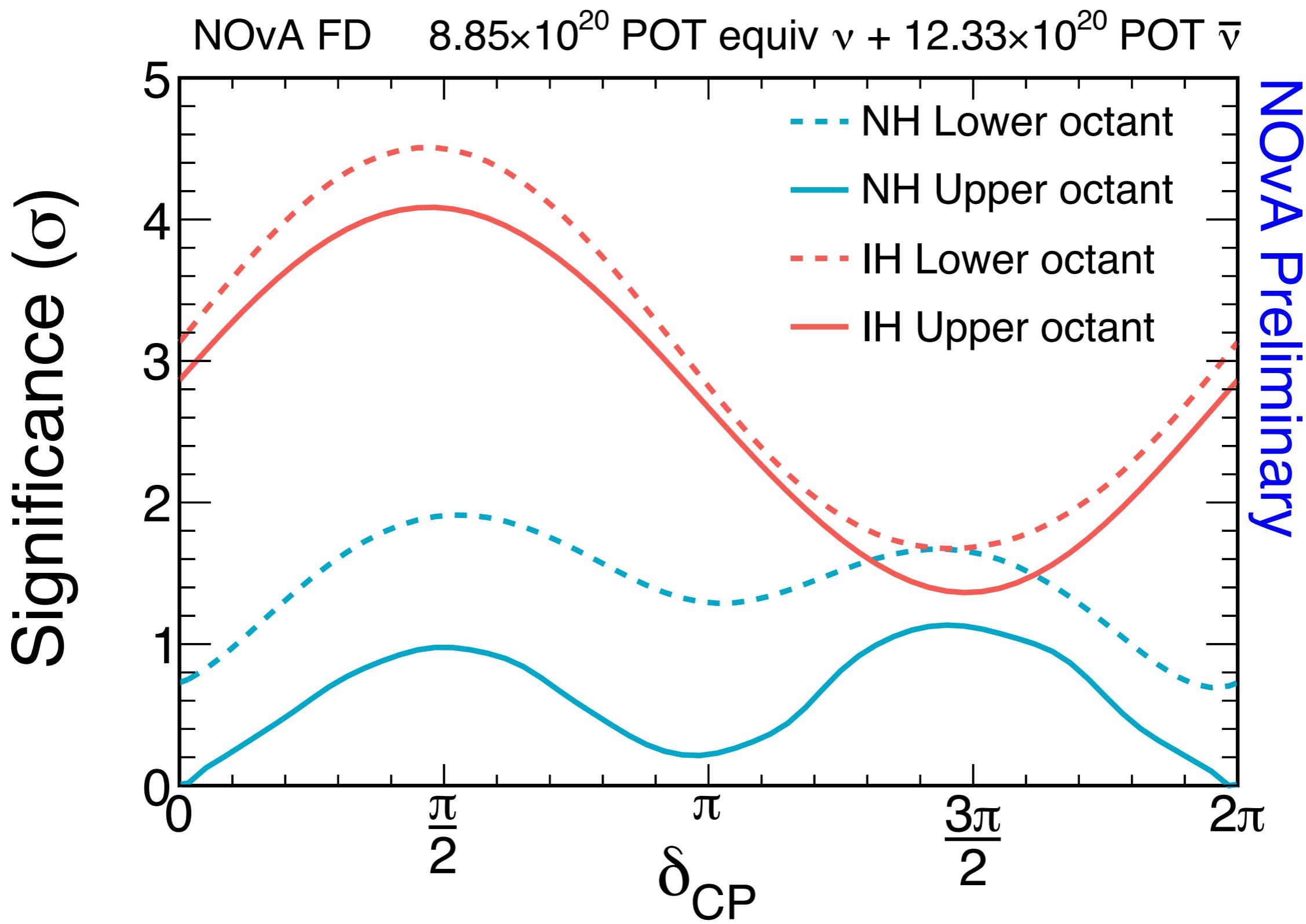
NOvA sees anti electron neutrino appearance with 4.4σ significance

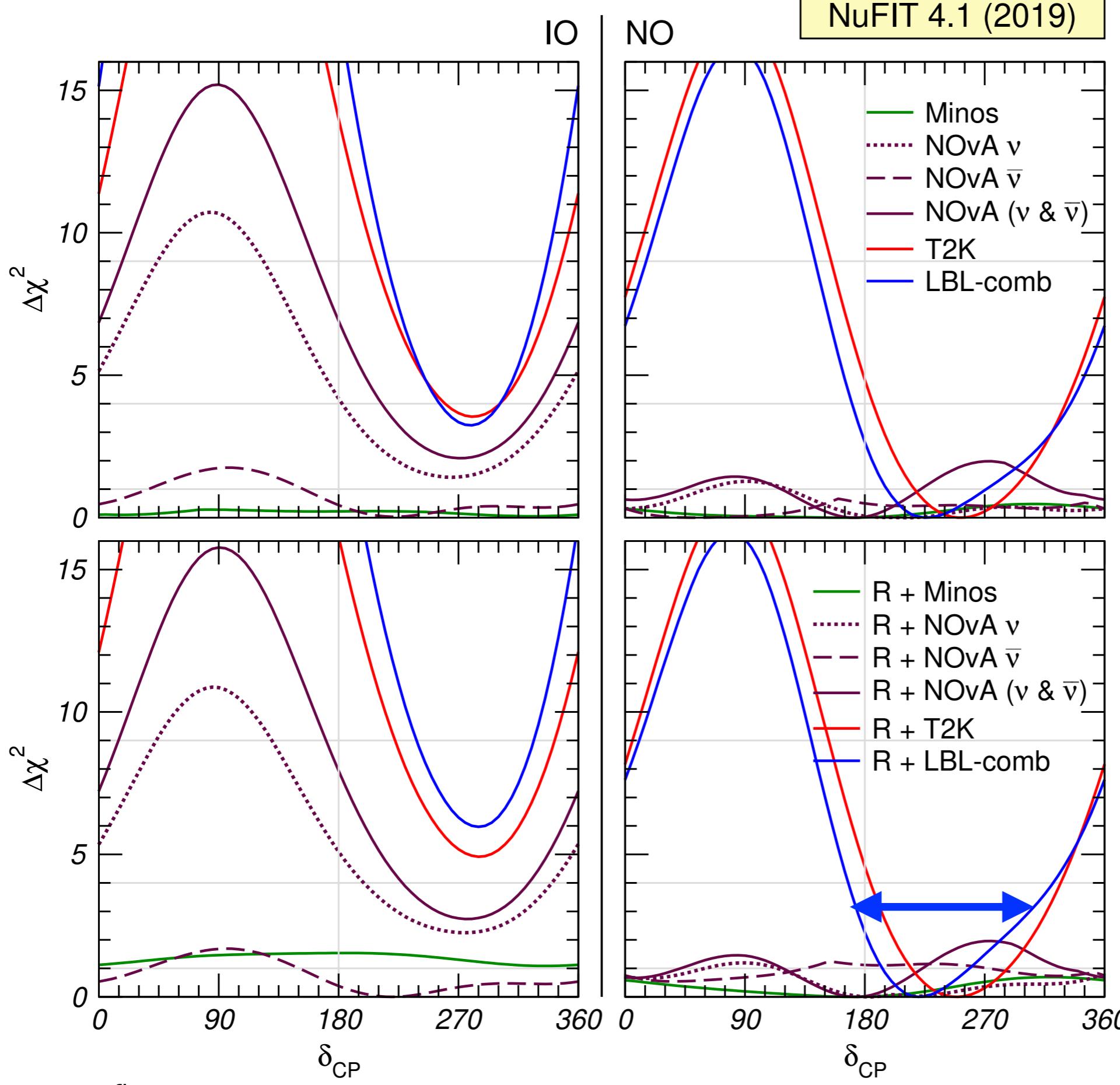
NOvA Preliminary



NOvA data prefers
upper θ_{23} octant by 1.6σ
and
Normal neutrino mass hierarchy by 1.9σ
but has
no preferred value of δ_{CP}



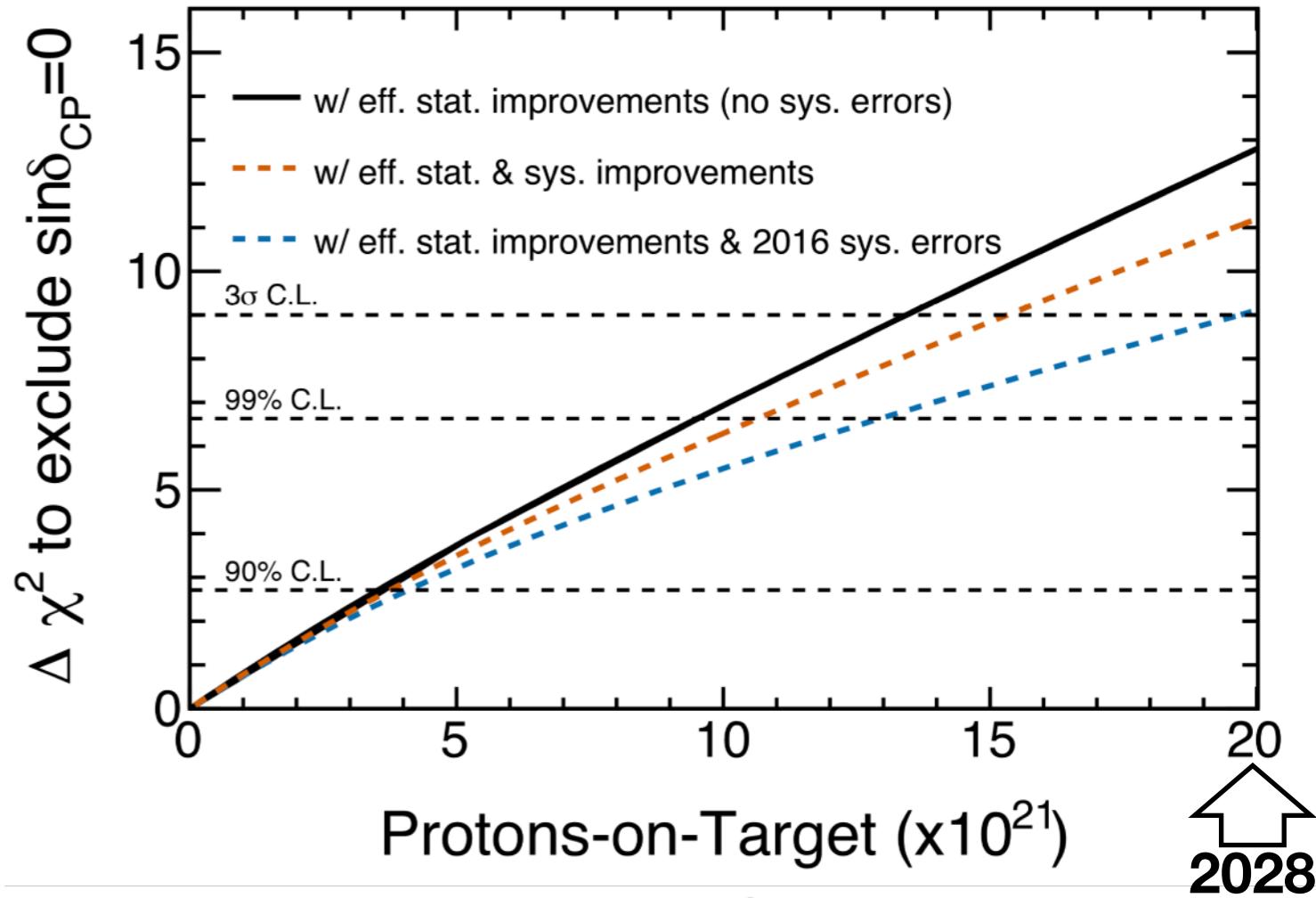




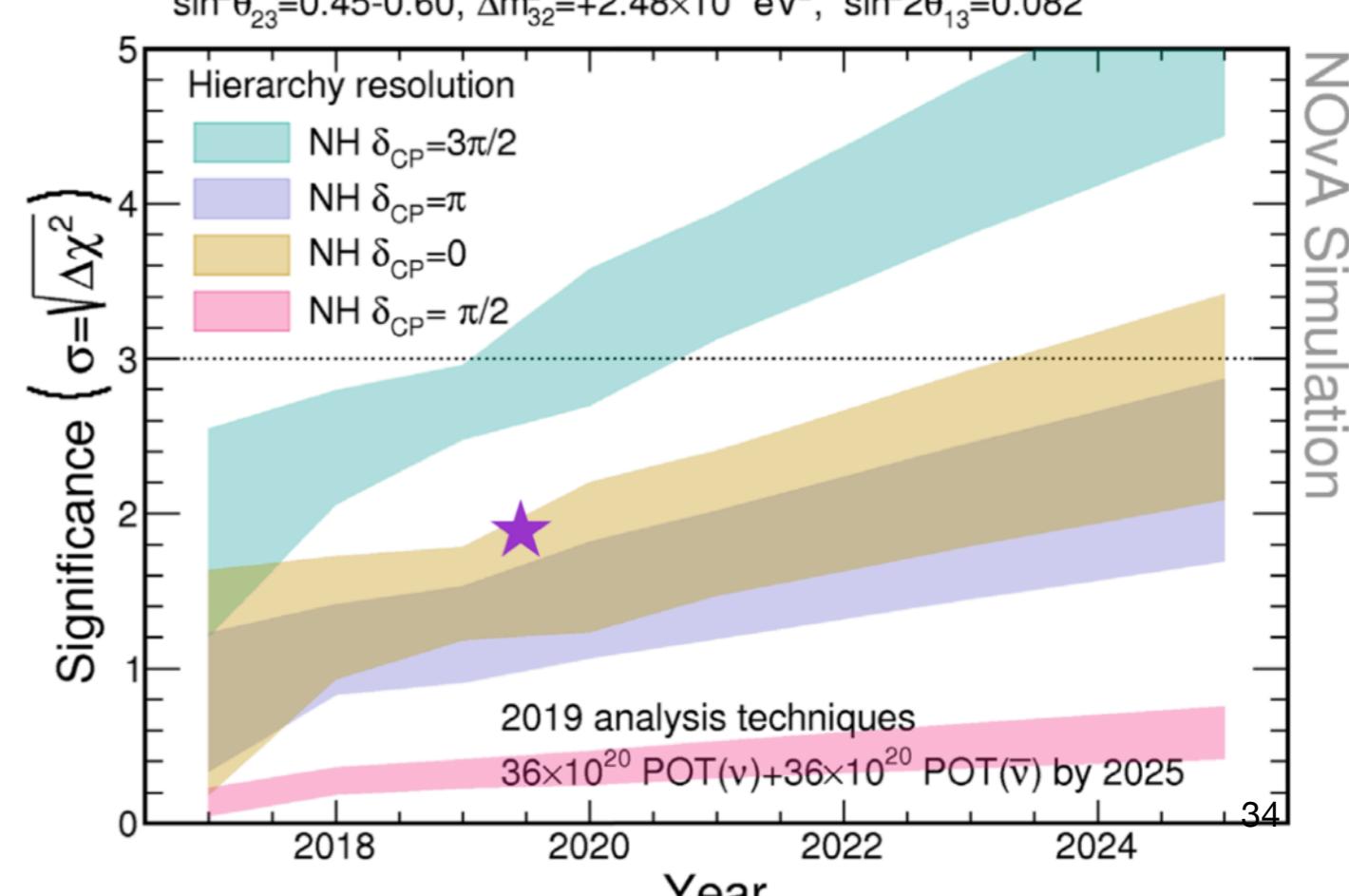
CPV hints driven by
T2K data
When combined with
other data, $\delta_{\text{CP}}=180^\circ$ is
allowed within 2σ

Significance of normal
hierarchy increases to
just over 3σ in
combination

T2K will run until 2028 with improvements to beam intensity up to 1.3 MW



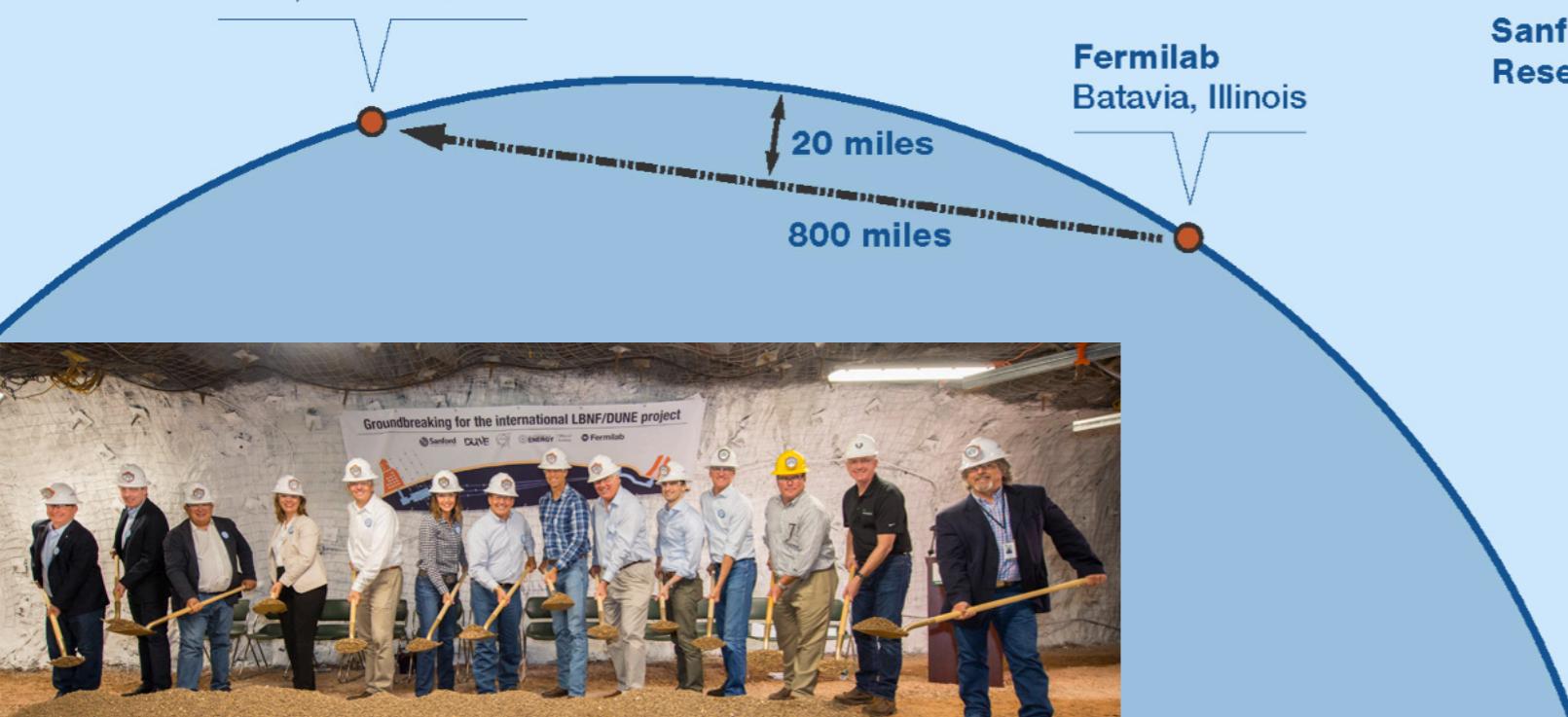
NOvA will run to 2025 with improvements to beam intensity up to 0.9 - 1 MW



Collaborations working toward a joint fit

Deep Underground Neutrino Experiment

Sanford Underground
Research Facility
Lead, South Dakota

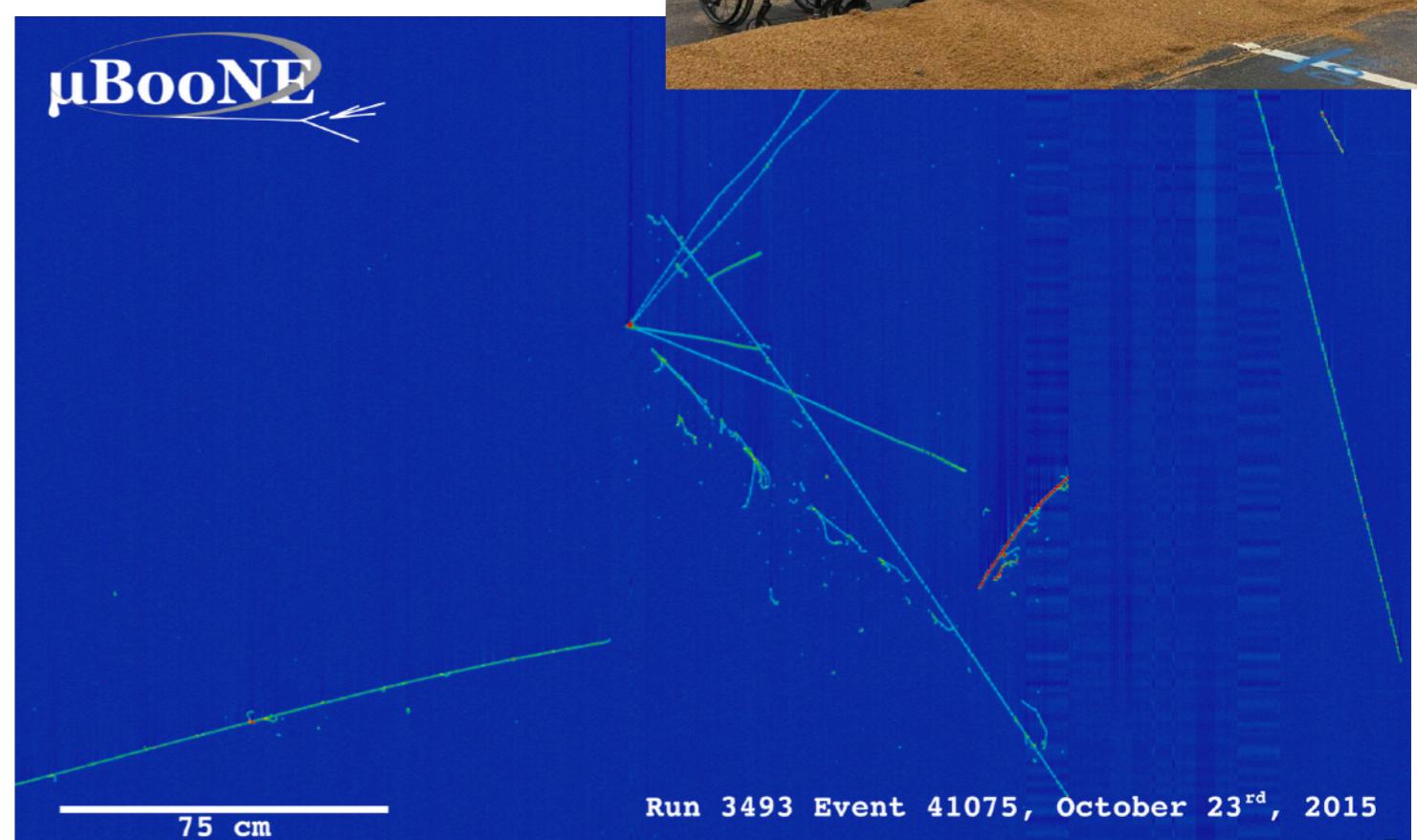


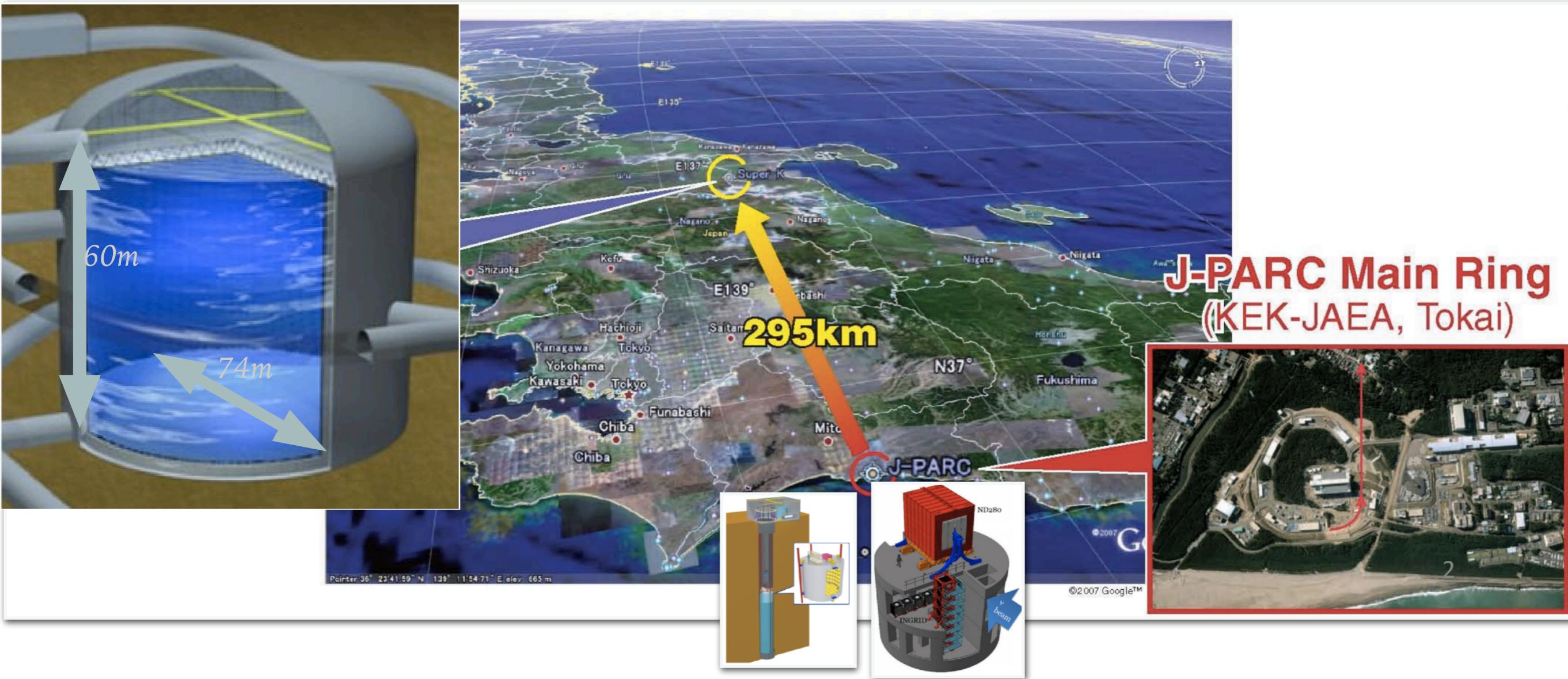
Groundbreaking, July 2017

DUNE Experiment

Upgrade beam to 1.2 then 2 MW
4x17 kt detector modules with millimeter resolution located 4850 feet underground
Successful prototype program at CERN
Data taking by ~2027

>5 σ resolution of mass hierarchy
>5 σ resolution of CP violation

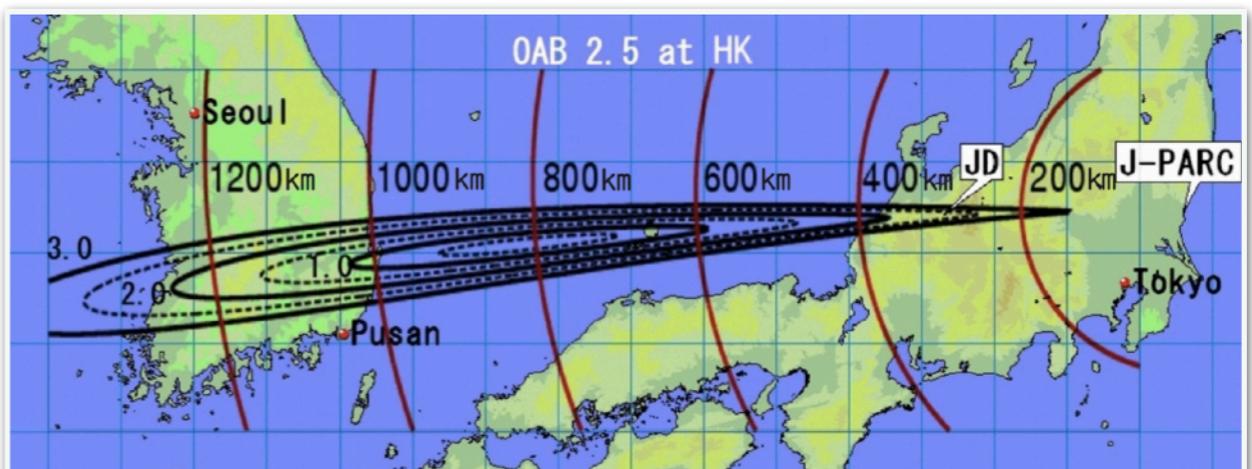




Hyper-Kamiokande Experiment

Upgrade beam to 1.3 MW
 260 kt far detector
 Expected data taking from 2027
 Exploring possibility of 2nd detector in Korea

>5 σ resolution of mass hierarchy
 >5 σ resolution of CP violation



Summary

- T2K and NOvA are measuring neutrino oscillations in all four channels required to address outstanding questions in neutrino mixing
 - θ_{23} is consistent with maximal; NOvA's pull into upper octant is 1.6σ significant
 - Both experiments prefer the normal neutrino mass hierarchy, NOvA at 1.9σ . Combinations of experiments increases this to 3σ
 - CP conserving values of δ_{CP} are outside the 2σ allowed T2K allowed region
 - Both programs have plans to continue to take data through mid-to-end of this decade when high precision experiments (DUNE and HyperK) are expected to turn on
- Results from long baseline experiments show no evidence of non-PMNS oscillations

Long baseline neutrinos at Lepton-Photon 2019

Tuesday	I	Neutrino Recent T2K Neutrino Oscillation Results	Helen O'Keeffe	Lancaster University
		Latest three-flavor neutrino oscillation results from NOvA	Gavin Davies	Indiana U. / U. of Mississippi
Tuesday	II	The upgrade of the T2K Near Detector ND280	Clark McGrew	Stony Brook University
		Near Detectors for the Hyper-K Experiment	Mark Hartz	TRIUMF & Kavli IPMU
		Capabilities of the DUNE Near Detector Complex	Kevin McFarland	University of Rochester
		Performance of the protoDUNE-SP liquid argon detector from a particle	Leigh Whitehead	University of Cambridge
Thursday	I	DUNE – Precision Neutrino Observatory of the Future	Alfons Weber	University of Oxford



29th International Symposium on Lepton Photon
Interactions at High Energies

5-10 August 2019
Westin Harbour Castle, Toronto Canada

Search...