Long Baseline Neutrino Oscillation Results (T2K and NOvA)

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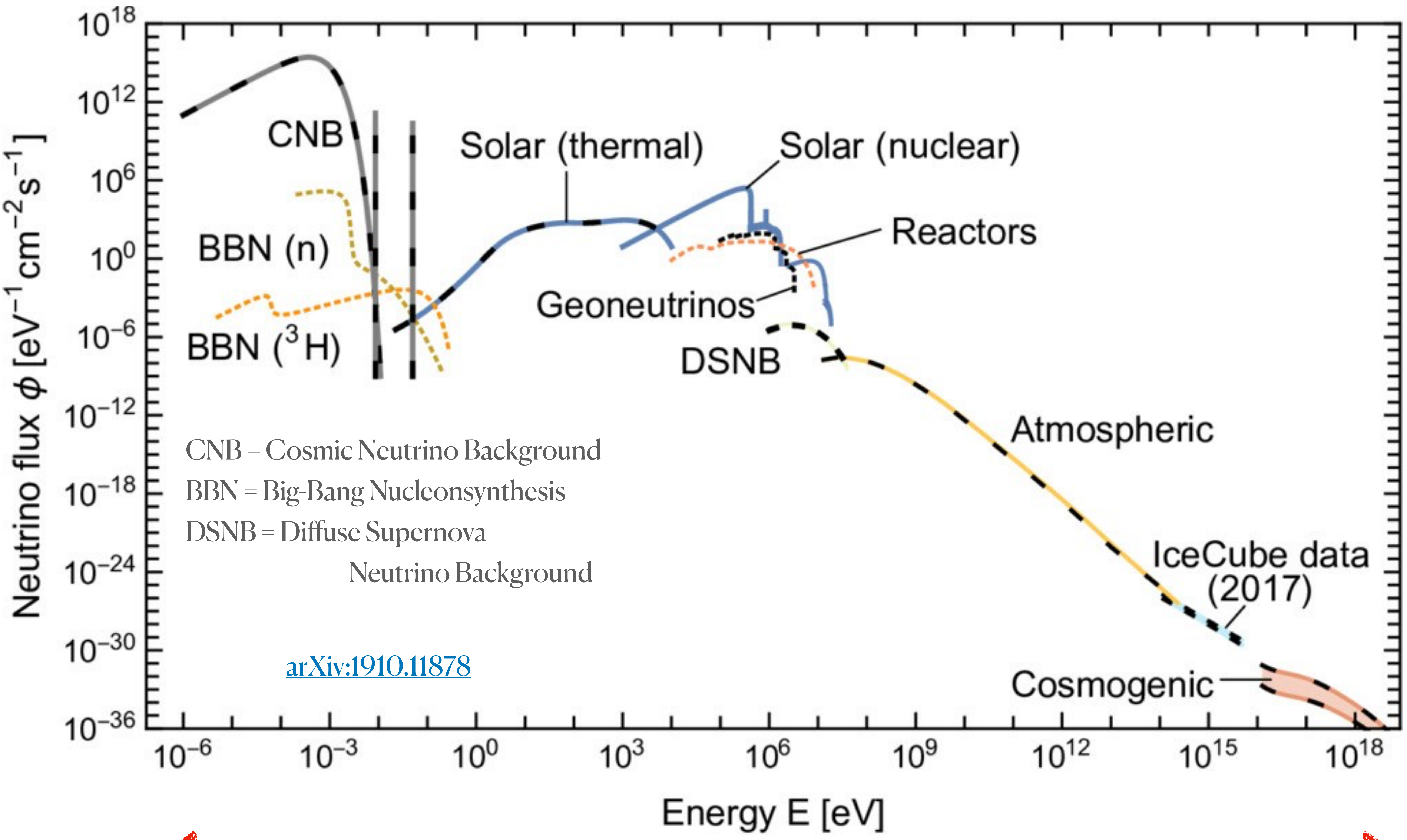
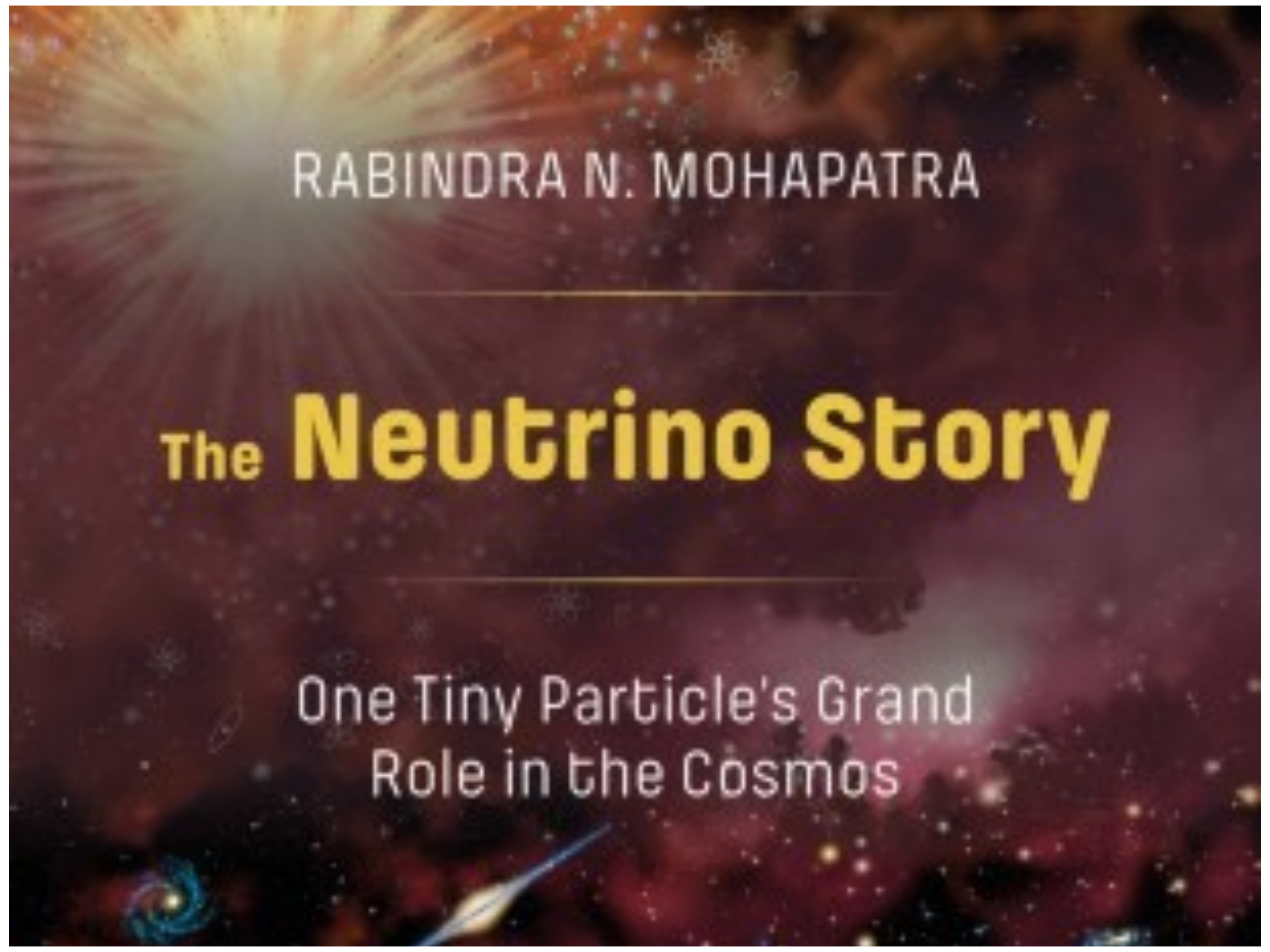
Based on recent T2K works arXiv:2303.03222, arXiv:2305.09916
and NOvA works PRD 106, 032004 (2022)

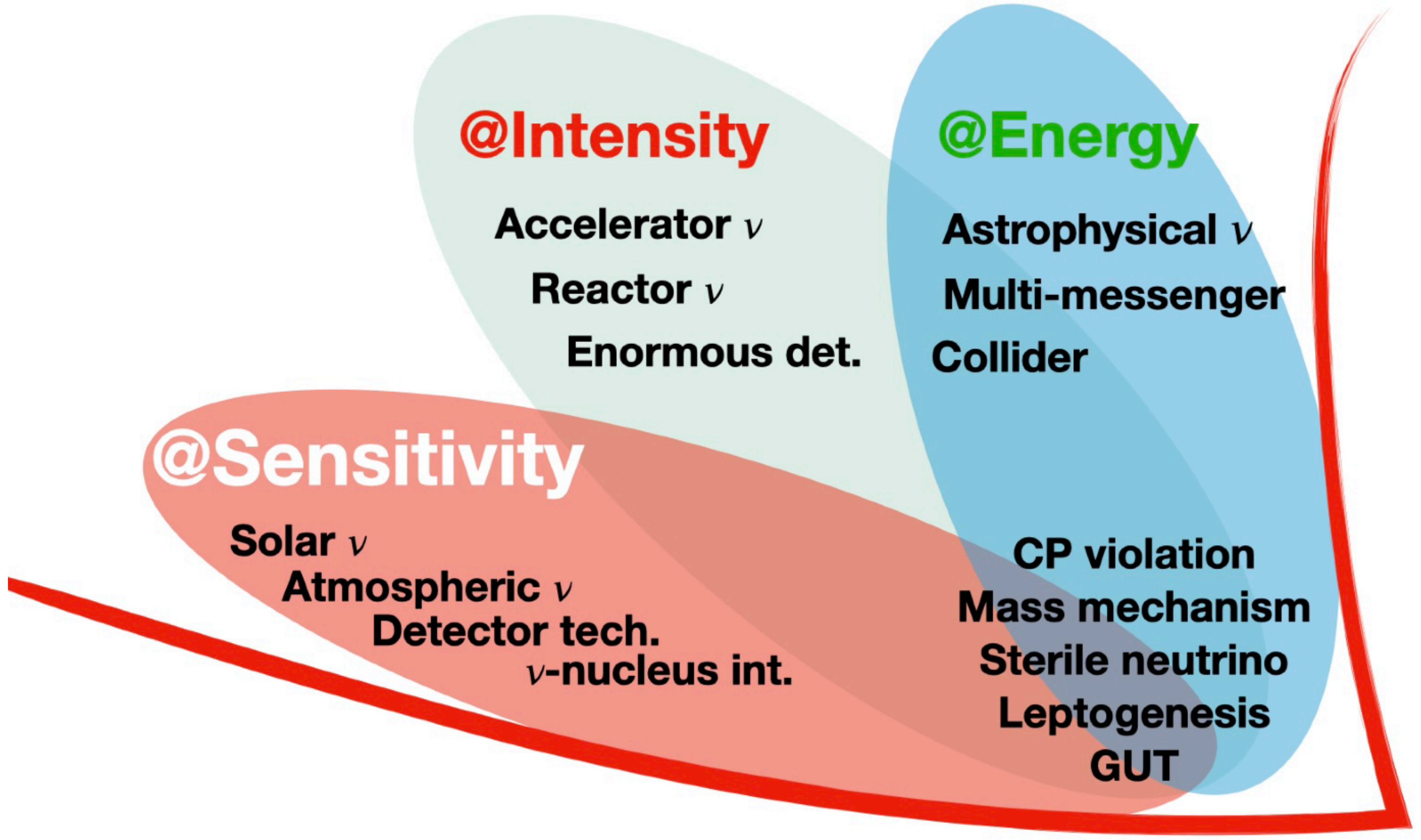
2023 August 10, 30th Anniversary of Rencontres du Vietnam — Windows on the Universe

Neutrino as a window on the Universe



Span ~ 24 orders of magnitude in energy





Ref. J. Kopp, Y. Wong, A. Ishihara's talks

Neutrino—the most abundant massive particle— plays essential roles in the sensitivity, intensity, and energy frontiers

Adapted "The Growing Excitement of Neutrino Physics" by APS

- ★ 1930: On-paper appearance as "desperate" remedy by W. Pauli
- ★ 1956: Anti-ν_e first experimentally discovered by Reines & Cowan
- ★ 1962: ν_μ existence confirmed by Lederman *et al*
- ★ 1986: Existence of ν_τ was established
- ★ 1998: Atmospheric ν oscillations discovered by Super-K
- ★ 2001: Solar ν oscillations detected by SNO (KamLAND 2002)
- ★ 2011: $\nu_\mu \to \nu_\tau$ transitions observed by OPERA
- ★ 2011-13: $\nu_\mu \to \nu_e$ observed by T2K and *anti*-$\nu_e \nrightarrow$ *anti*-ν_e by Daya Bay
- ★ 2015: Nobel prize for ν oscillations, Breakthrough prize (2016)
- ★ 2018: T2K hints on leptonic CP violation

T2K hints on leptonic CP violation

IceCUBE observes extragalactic ν

Nobel prize & Breakthrough prize for ν oscillation

T2K observe ν_e appeared from ν_μ

Daya Bay observe anti-ν_e disappeared

K2K confirm atmospheric ν oscillation

KamLAND confirms solar ν oscillation

Nobel prize for ν astrophysics

SNO observe solar ν oscillation to active flavor

Super-K confirms solar ν deficit and images the sun

Super-K observes ν oscillation

Nobel Prize for ν discovery

SAGE/Gallex observe the solar ν deficit

LEP shows 3 active flavors

Kamioka-II confirms solar deficit

Nobel Prize for neutrino beam & ν_μ discovery

Supernova neutrino observed

Pauli predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrino

muon neutrinos discovery

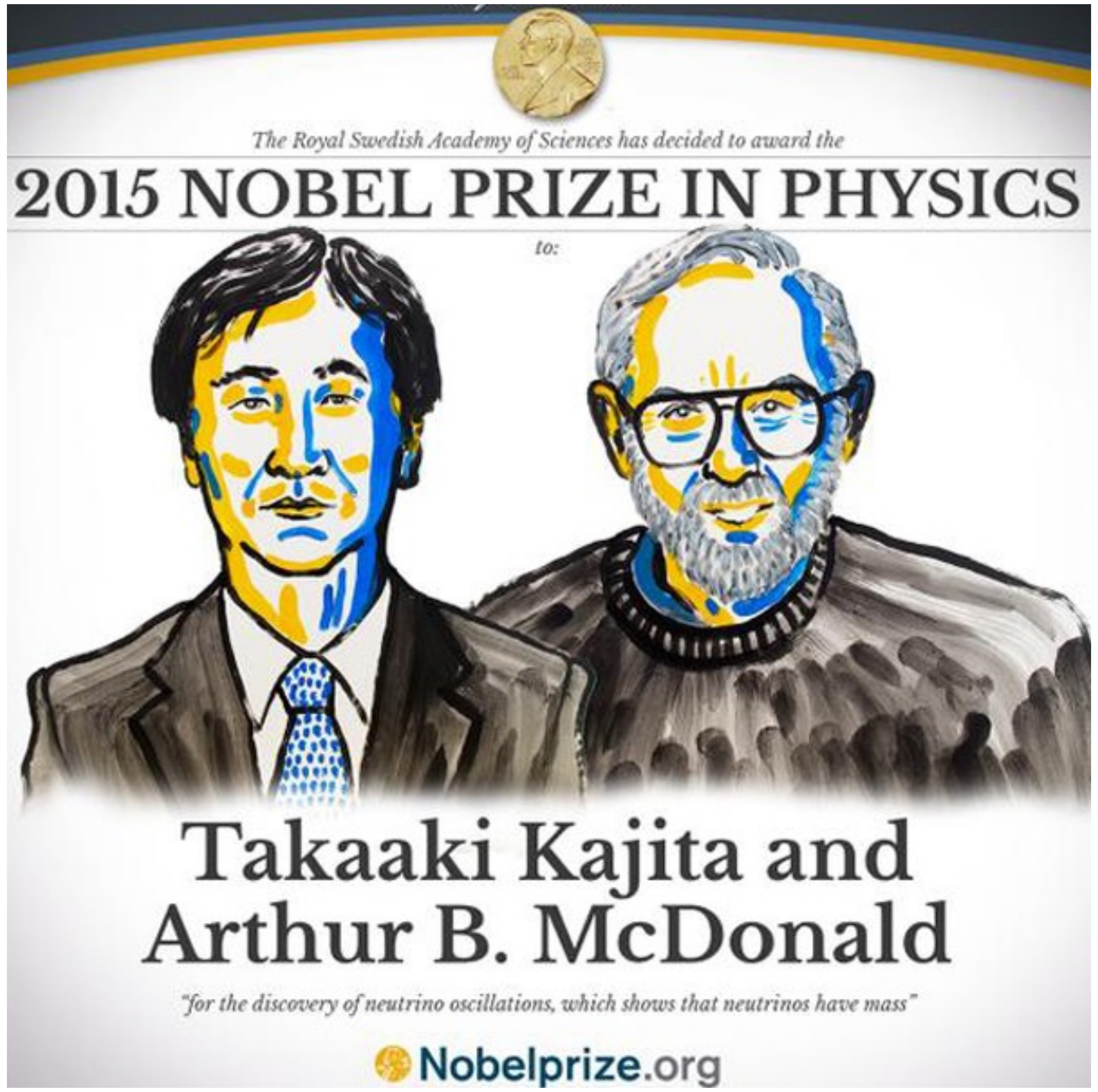
Solar neutrino anomaly

1930 1956 1962 1964 1980 1998 2018

~25 years

More details: https://neutrino-history.in2p3.fr/neutrinos-milestones-and-historical-events/

One of the most striking discoveries in the last 25 years is that neutrinos have mass and the leptons are mixed



Still neutrino is the most mysterious

Known unknowns (*at observable level*) in neutrino physics

- Neutrino mass ordering
- CP-violation in the lepton sector
- How close is leptonic mixing angle θ_{23} to $\pi/4$?
- Absolute mass of neutrinos
- Origin of neutrino mass: Dirac vs Majorana?
- Sterile neutrino ?
- ...

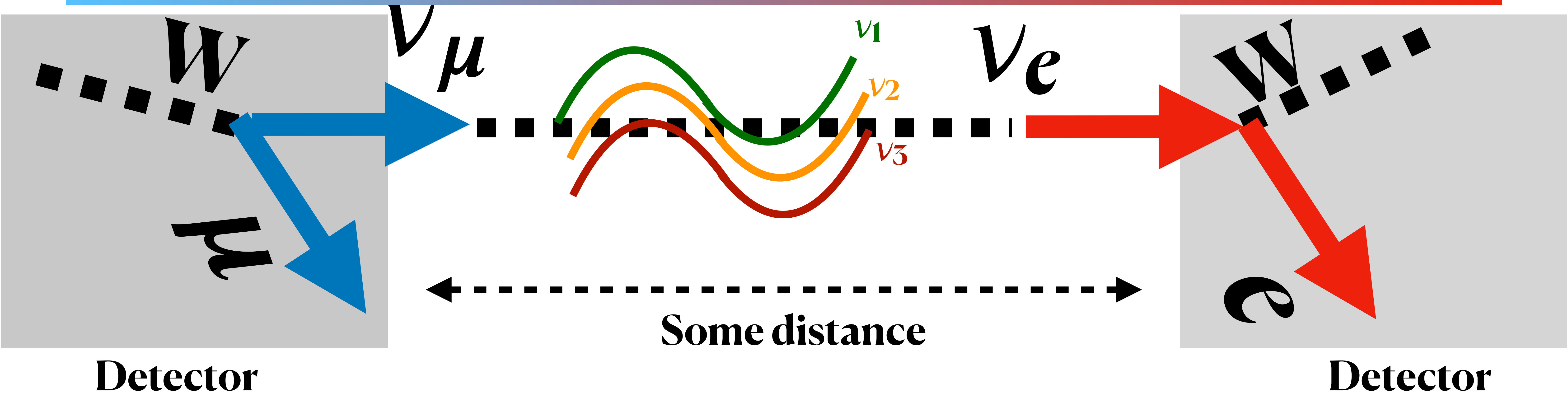
Ref. R.Saakyan's talk ←

Ref. M. Danilov's talk ←

The first three unknowns can be addressed directly with neutrino oscillation experiments

Neutrino oscillations *in short*

Neutrino can change its flavor when give it time to propagate



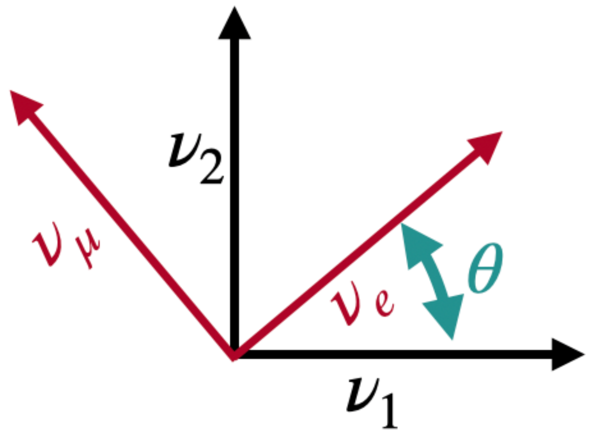
- **Neutrino oscillations** require the existence of a **neutrino mass spectrum**, i.e mass eigenstate ν_i with definite mass m_i (where i is 1, 2, 3* at least)
- It requires flavor eigenstate with definite flavor, ν_α (where α is e, μ, τ) must be **superpositions** of the mass eigenstates, *a fundamental quantum mechanic phenomenon*

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

flavor eigenstate

PMNS** leptonic mixing matrix

mass eigenstate

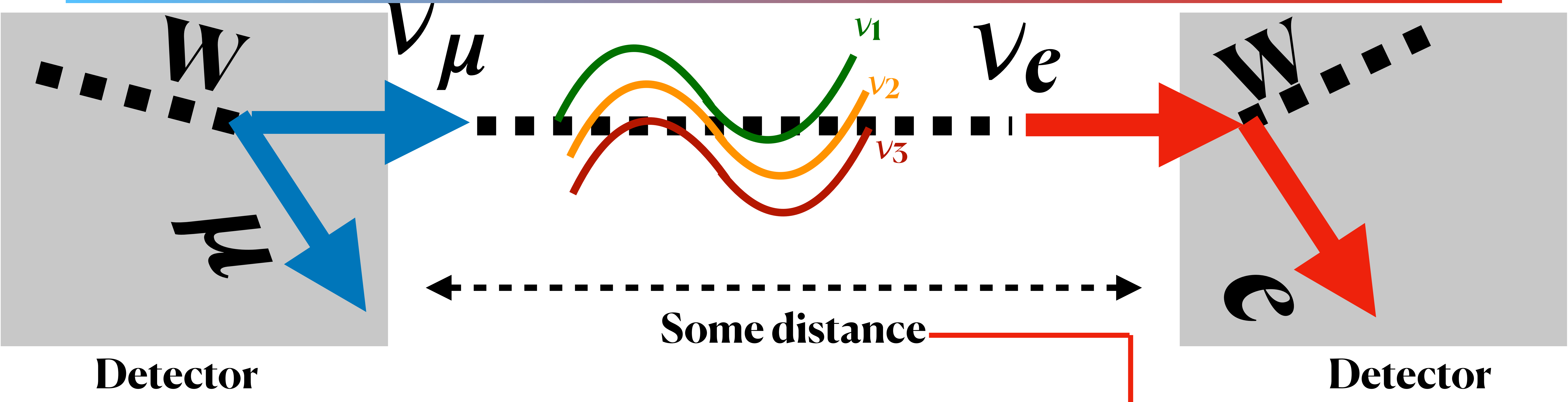


**It's still possible that there are more than 3 mass eigenstates*

***PMNS is shorted for Pontecorvo-Maki-Nakagawa- Sakata*

Neutrino oscillations *in short*

Neutrino can change its flavor when give it time to propagate



$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

$$+2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

for anti-neutrino, this changes to (—)

where $\Delta m^2_{ij} = m^2_i - m^2_j$

neutrino energy

By measuring the oscillation pattern/probability, *typically as function of neutrino energy*, it is possible to extract all oscillation parameters

Oscillation parameters

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

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \mathrm{Diag}(e^{i\rho_1}, e^{i\rho_2}, 0)$$

$\theta_{12} \approx \pi/6$

$\theta_{13} \approx \pi/20$

$\theta_{23} \approx \pi/4$

δ_{CP}?

- U_{PMNS} is 3x3 unitary matrix parameterized with **3 mixing angles (θ_{12}, θ_{13}, θ_{23})** and **one irreducible Dirac CP-violation phase (δ_{CP})**, *similar to CKM matrix of quark mixing*
  - If neutrino is a **Majorana particle**, there are **two additional CP-violation phases** (ρ_1, ρ_2), *which play no role in neutrino oscillations*
- Oscillation wavelengths are driven by **two mass-squared splittings**

$$\Delta m^2_{21} = m^2_2 - m^2_1 \approx 7.5 \times 10^{-5} (eV^2/c^4)$$

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| \approx 2.5 \times 10^{-3} (eV^2/c^4)$$

Mass ordering

$m_3 > m_2 > m_1$ *or* $m_2 > m_1 > m_3$ **is unknown**

Neutrino oscillation measurements

Far detector measurement

Constrained by external data and Near Det.

Det. mass

Det. efficiency

Det. response to ν energy

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \boxed{\Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true})} \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \vec{o})$$

Oscillation probability

where

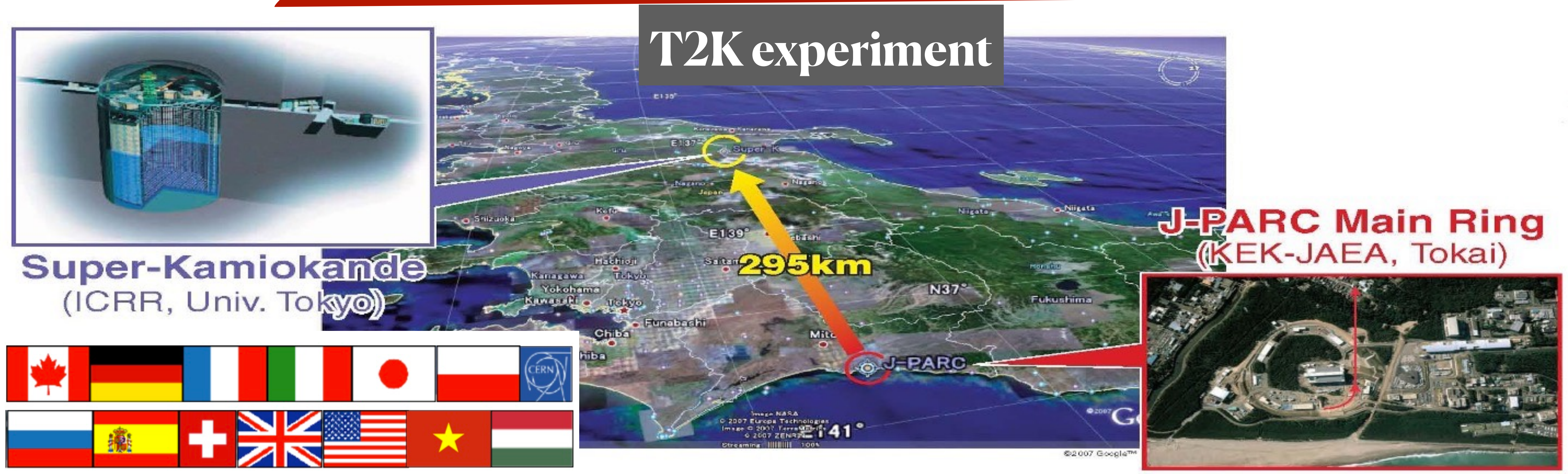
$$\vec{o} = (\Delta m^2_{21}, \Delta m^2_{31}; \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}; \rho_{mat.}, L)$$

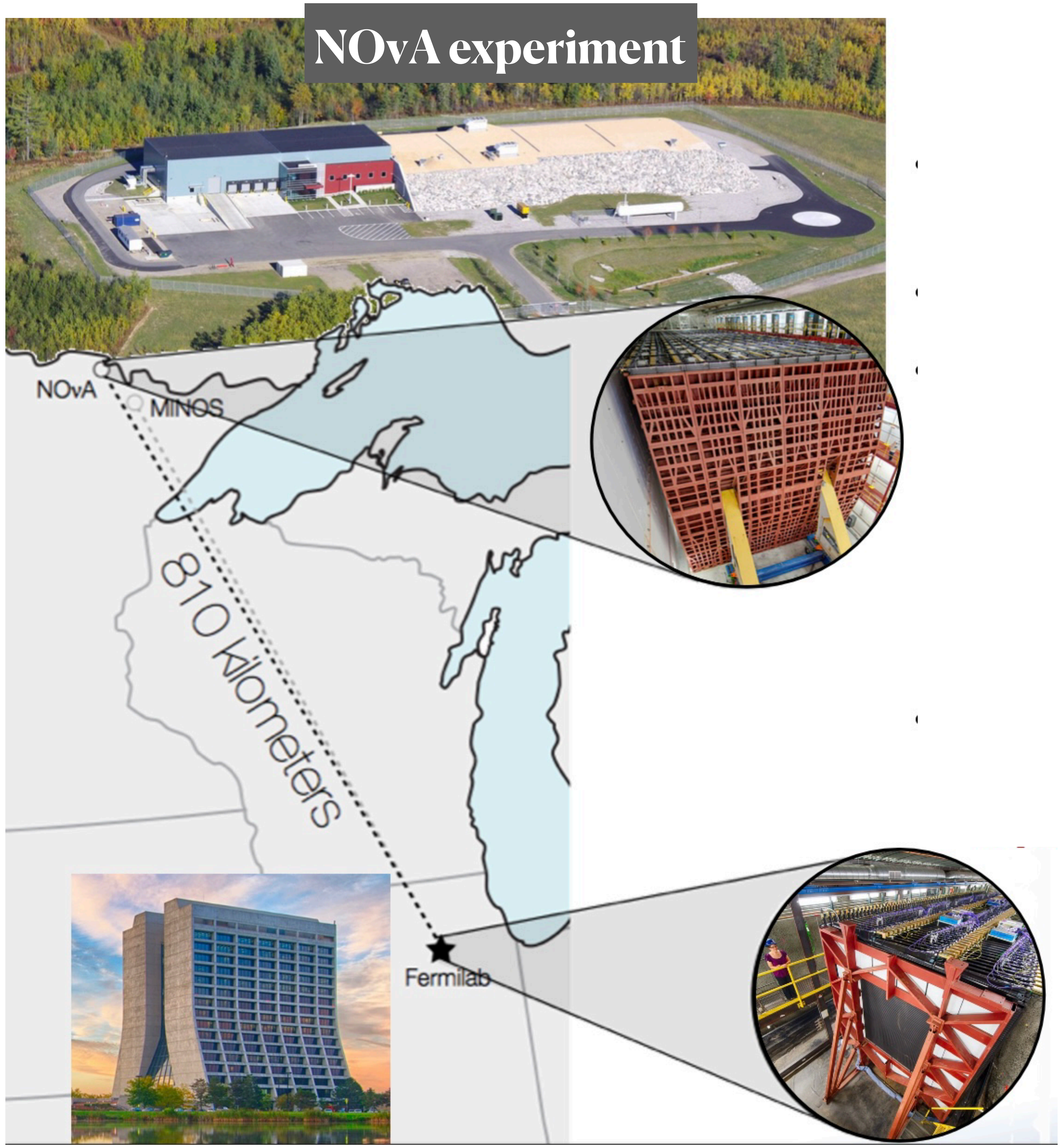
For precise measurement of neutrino oscillations:

- Powerful and well-controlled sources of (anti-)neutrinos
- Big detectors with flavor-tagging and energy-reconstruction capabilities
- Well-modeled $\nu/\bar{\nu}$ interactions with nucleons/nuclei and detector's $\nu/\bar{\nu}$ energy resolution
- Capability to resolve the parameter degeneracies , particularly among $\delta_{CP},\ \theta_{13}, \theta_{23}, sign(\Delta m^2_{31})$ ➔ Motivation for joint analyses

Three generations of long-baseline accelerator-based neutrino experiments

T2K & NOvA experimental specifications



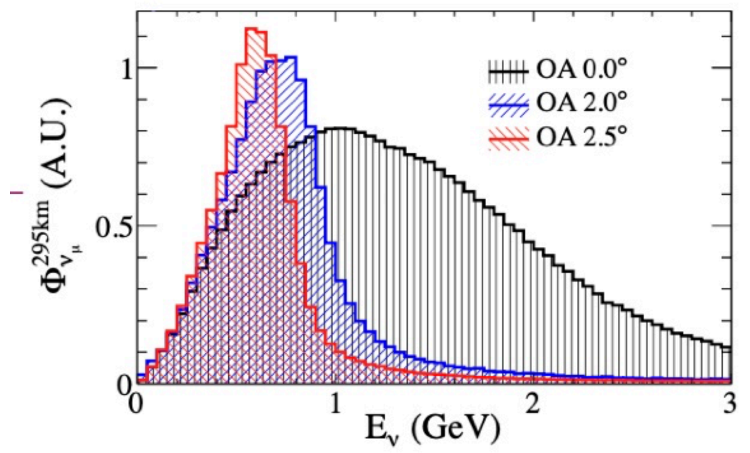


	T2K	NOvA
Proton energy & power	30 GeV / ~500 kW	120 GeV / ~700 kW
Peak neutrino energy	0.6 GeV	1.8 GeV
Baseline	295 km	810 km
Far detector mass	50 kton	14 kton
Detector technique	Water Cherenkov	Segmented liquid scintillator bar
Run period	2010 – (~2027)	2014 – (~2026)

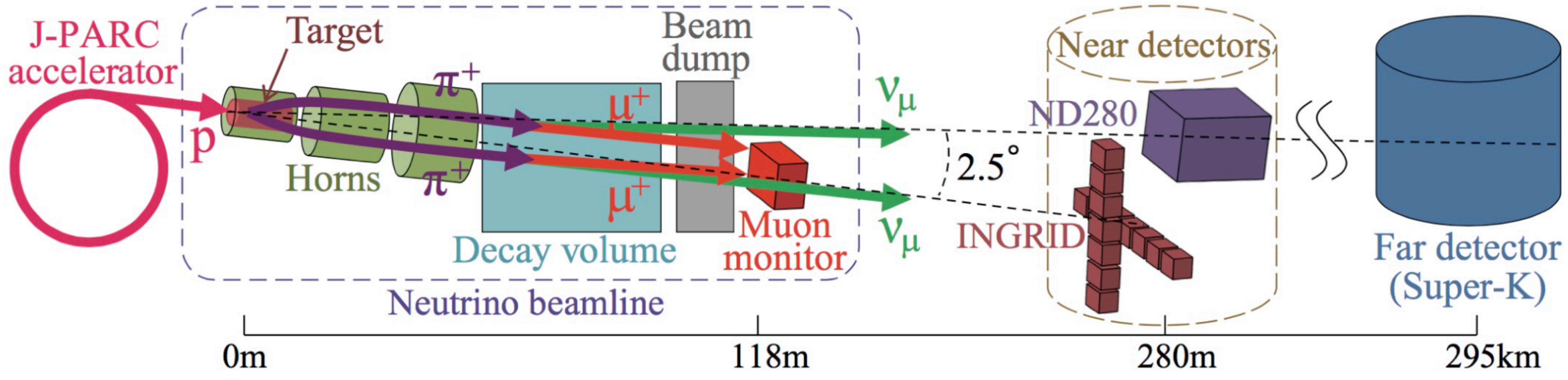
The two exp. with different baseline/energy and detection technique are complementary to study neutrino oscillations

Neutrino beam with accelerator-based exp.

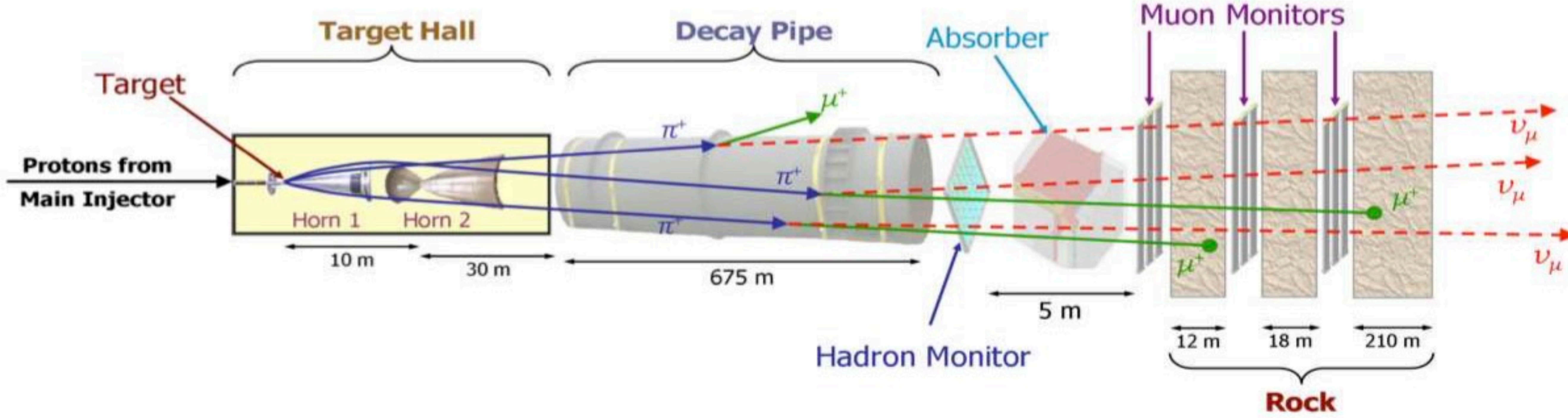
- Proton from accelerator is extracted, guided, and bombarded onto a graphite target (90—100 cm in length)
- Produced hadrons (π, K) are focused by a magnetic horn system
- Positive or negative hadrons can be focused/ defocused by switching the horn polarity to produce mainly ν_μ or $\overline{\nu}_\mu$ beam respectively
- Both T2K and NOvA far detectors are placed off-axis to receive a narrow-band beam



J-PARC beam to T2K exp.

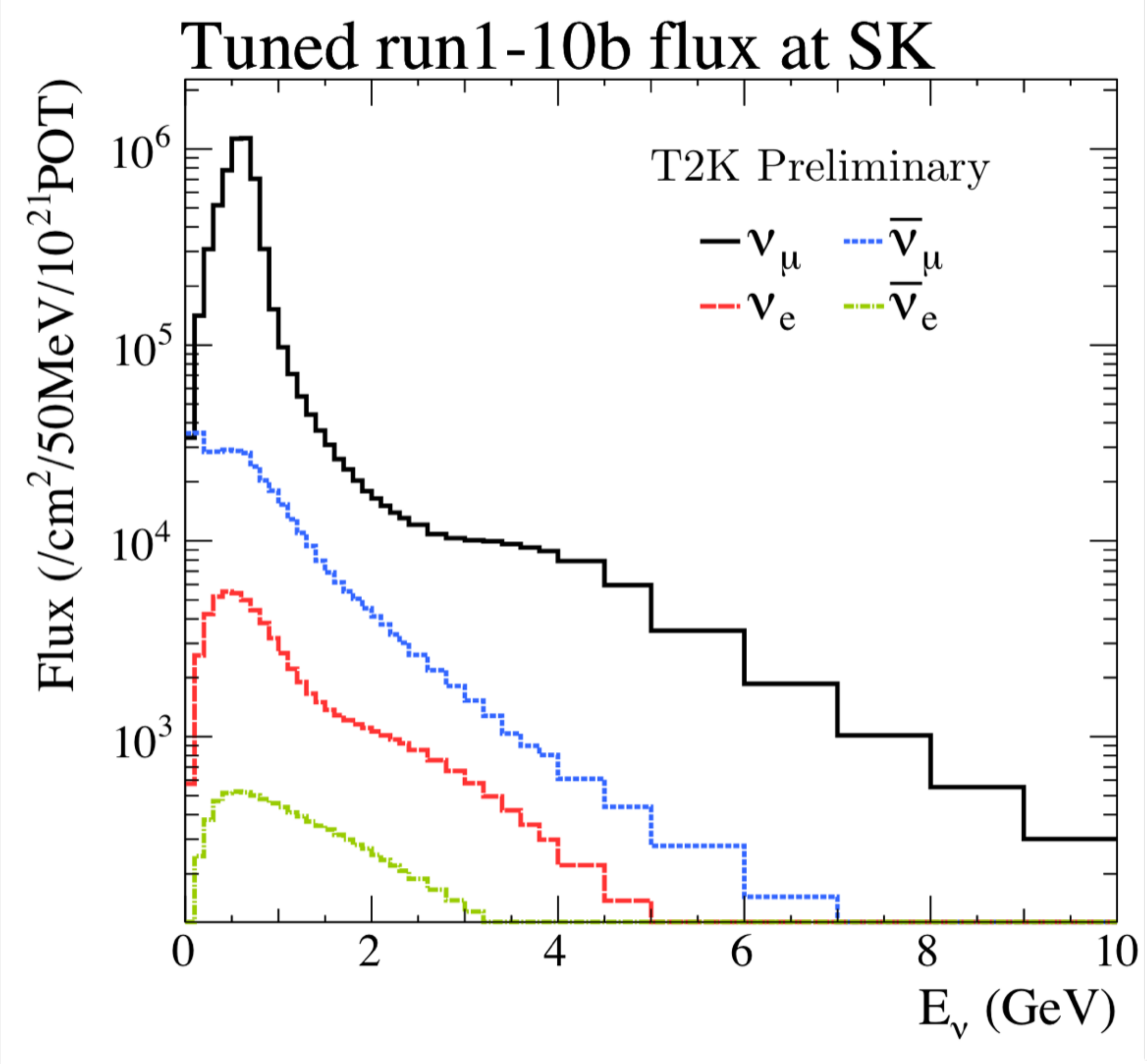


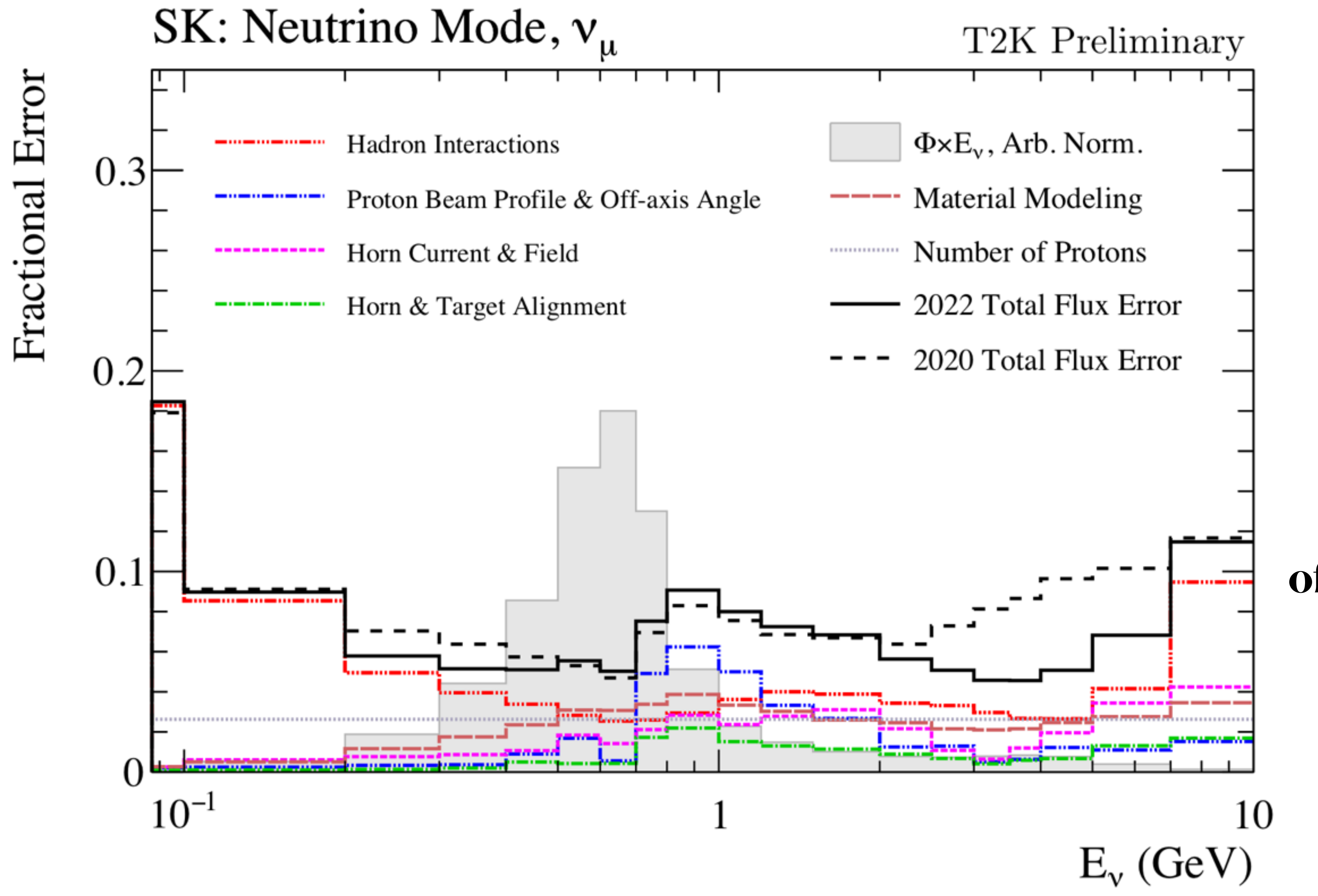
NuMI beam to NOvA exp.



Powerful and well-controlled neutrino beam

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \boxed{\Phi_{flux}^{\nu_\alpha}(E_\nu^{true})} \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times M_{det.} \times \epsilon_{det.}^{\nu_\beta}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$
$$\times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true}, \vec{o})$$





Thanks to NA61/SHINE

Replica target data

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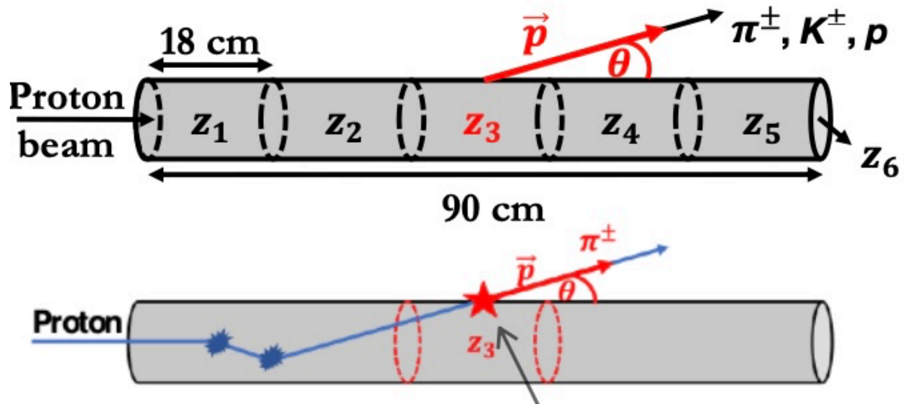


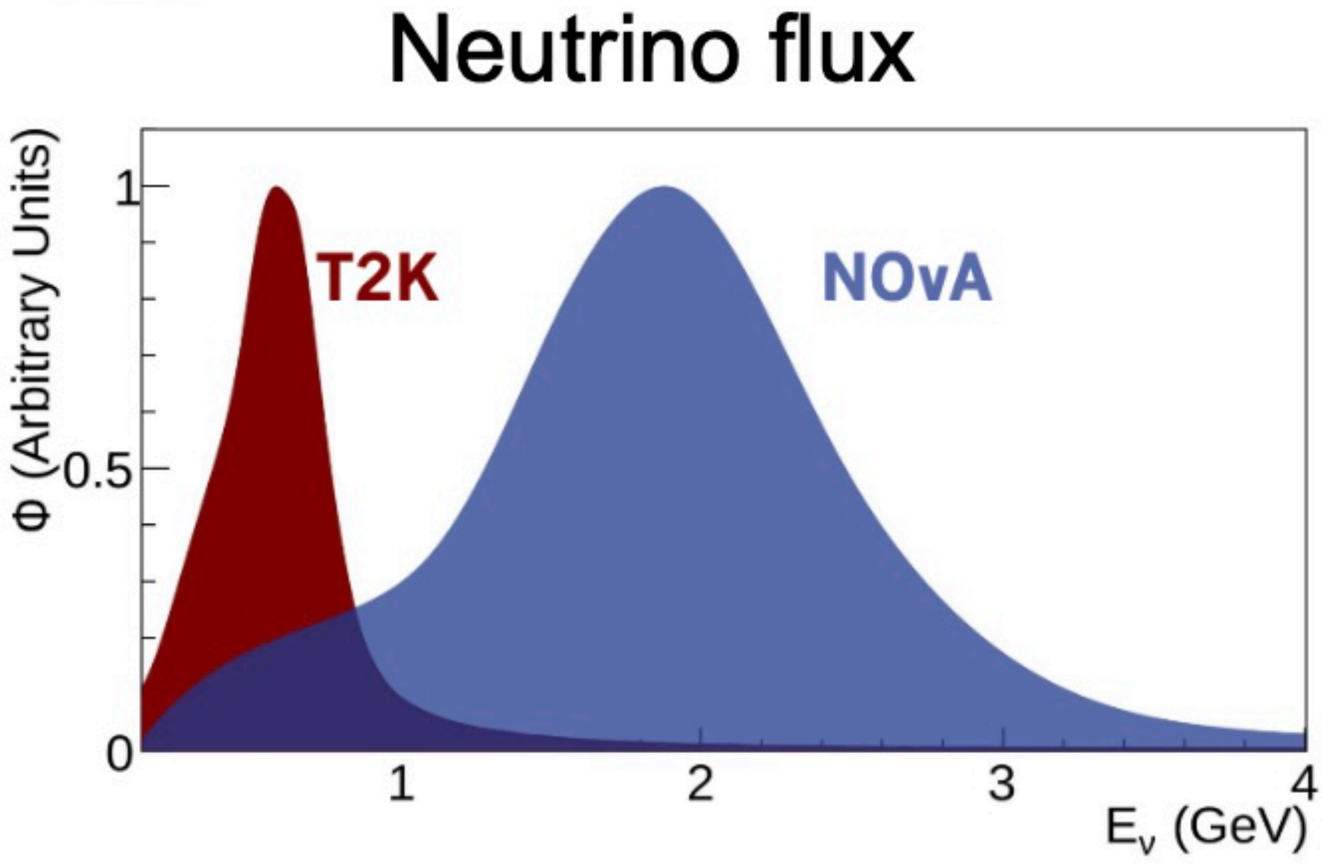
And more realistic modeling of cooling water in the magnetic horns

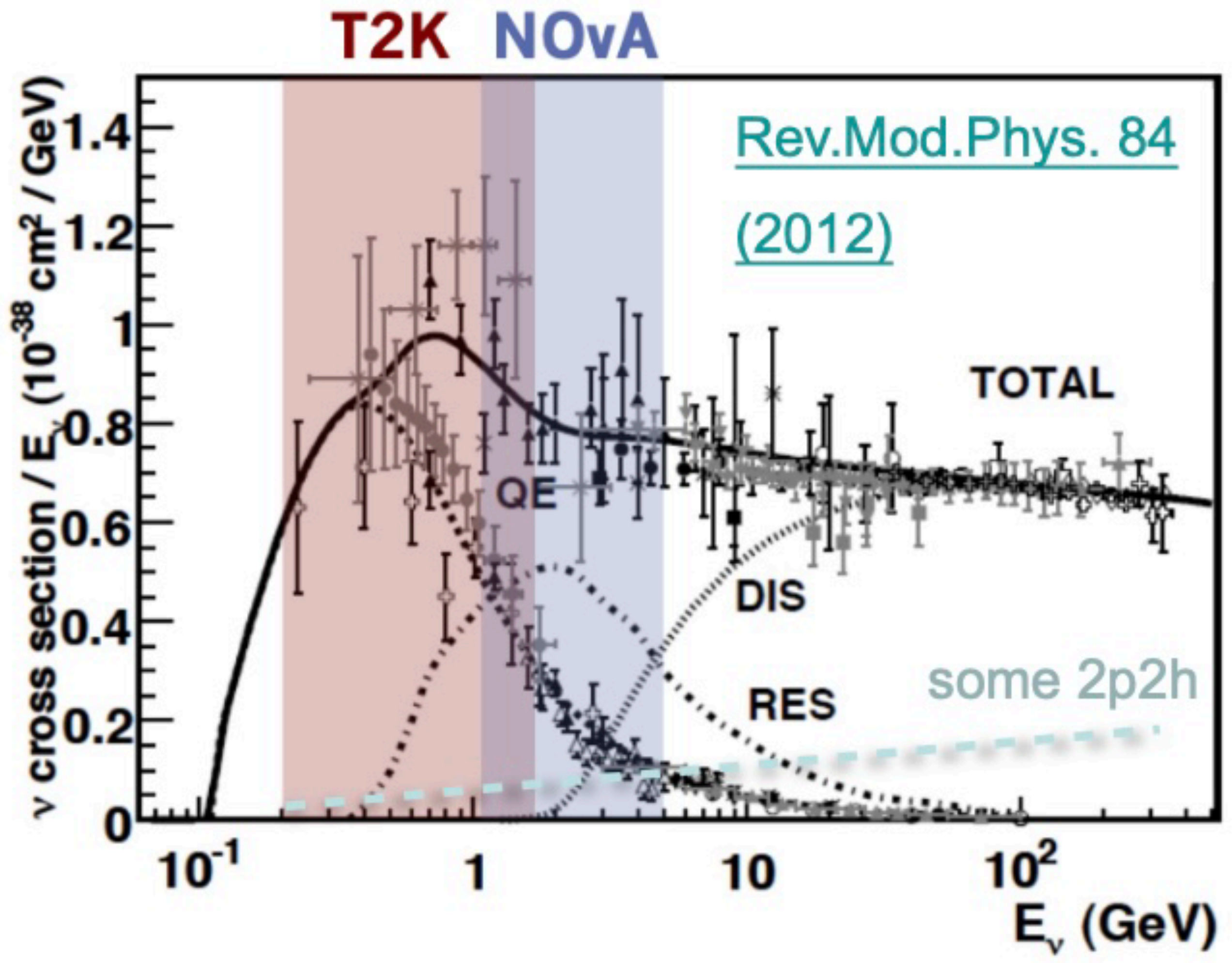
Highly pure $\nu_\mu/\bar{\nu}_\mu$ beam with <1% of intrinsic $\nu_e/\bar{\nu}_e$ with ~6%/~8% uncertainty at the peak for T2K/NOvA before constraints with near detector data. Hadron production is a dominant source of uncertainty

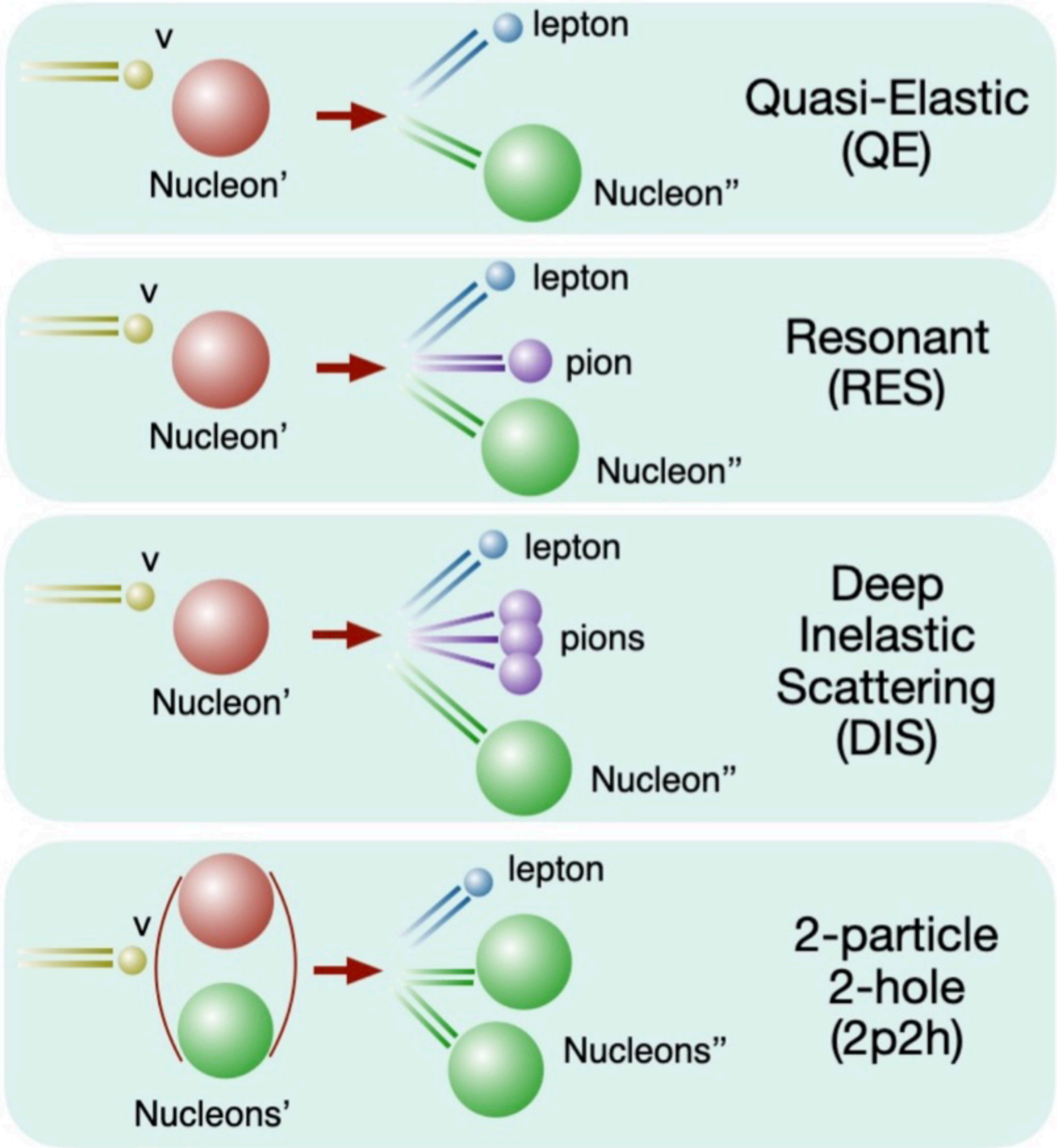
Neutrino-nucleon interaction

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi_{flux}^{\nu_\alpha}(E_\nu^{true}) \times \boxed{\sigma_{int.}^{\nu_\beta}(E_\nu^{true})} \times M_{det.} \times \epsilon_{det.}^{\nu_\beta}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$

$$\times P(\nu_\alpha \rightarrow \nu_\beta | E_\nu^{true}, \vec{o})$$



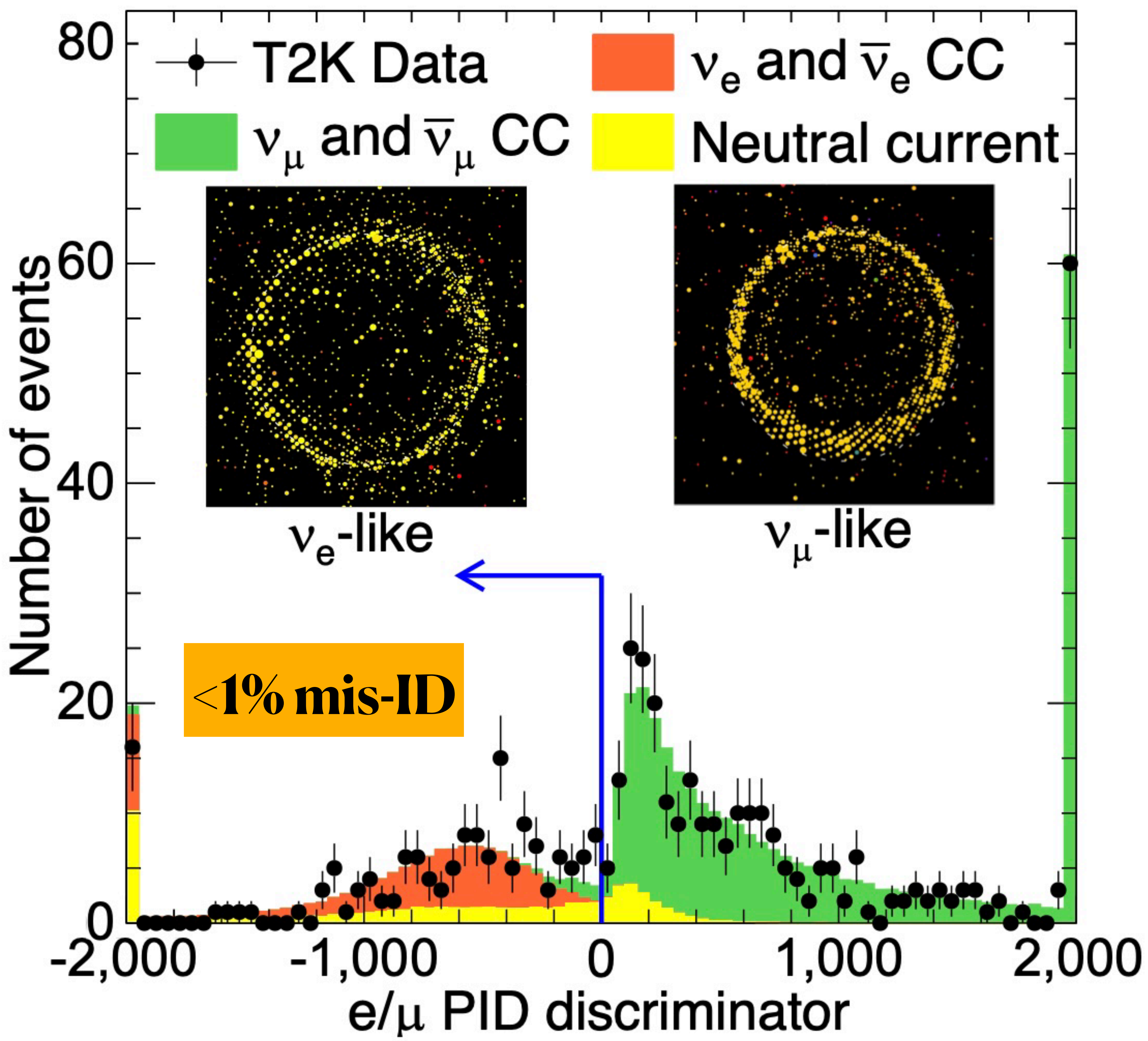




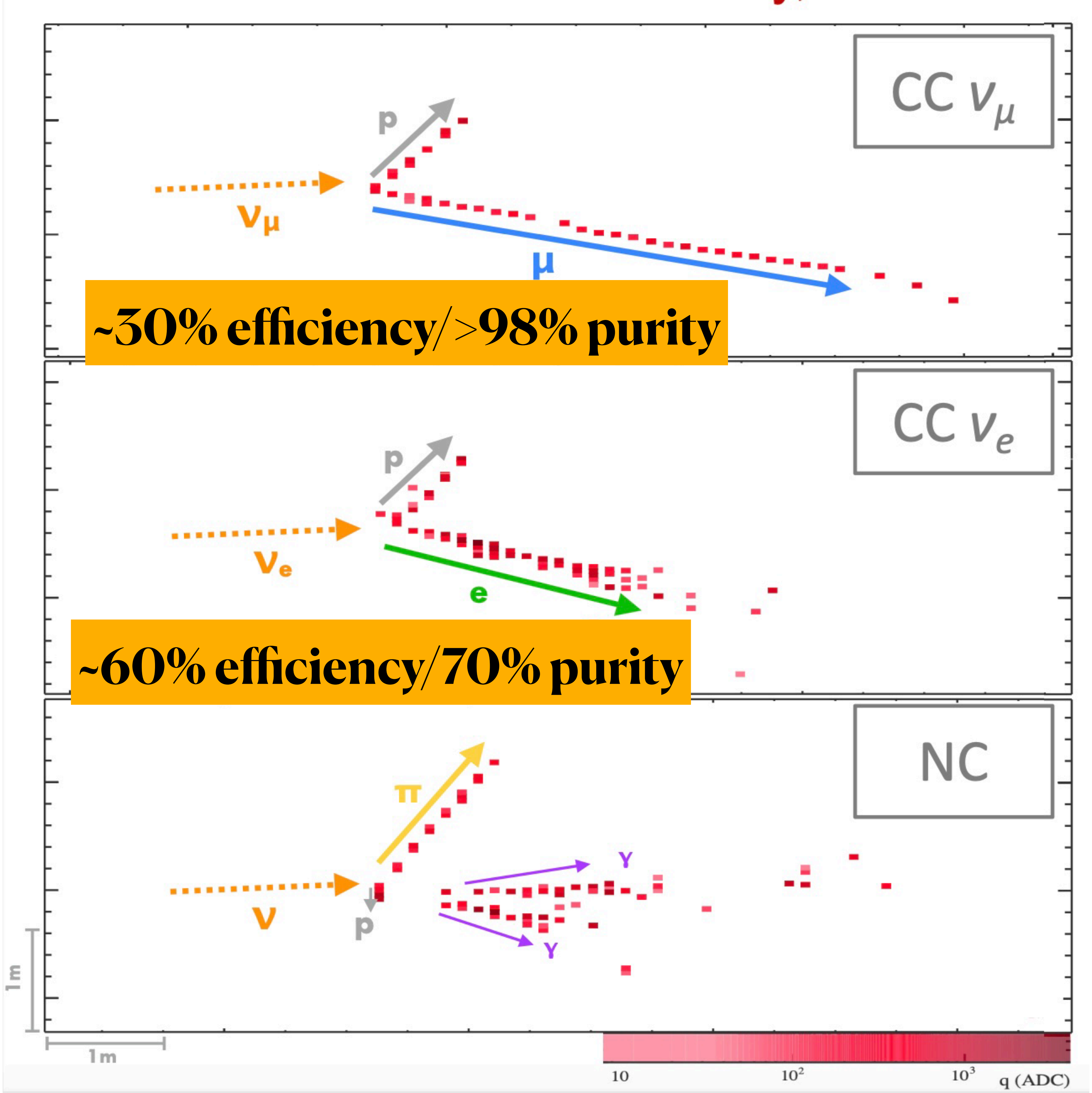
- T2K is dominated by the CCQE interaction and considerable 2p2h and CC resonance
- NOvA has large contribution from CC resonance and DIS at higher energy
- Each experiment utilizes Near Detector to tune and constrain interaction model (and flux) and makes prediction at Far Detector
  - T2K: ~13% ➔ ~3% uncertainty
  - NOvA: ~13% ➔ 3-6% uncertainty
- Two exp. use notably different interaction models with independent neutrino event generators as nominal MC

T2K & NOvA: Event classification

T2K experiment



NOvA experiment

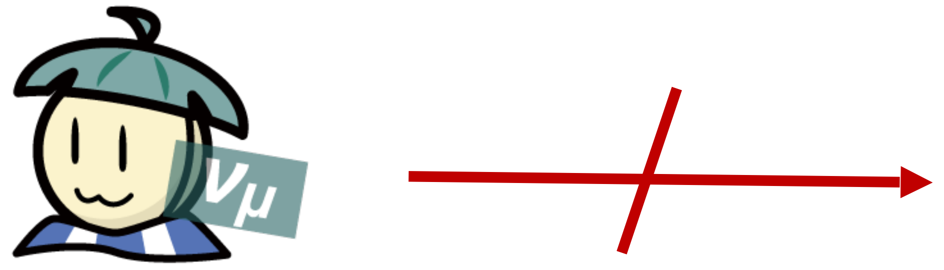


Caveat: NOvA far detector is on surface and suffers from high cosmic ray rate

Both detectors provide excellent capability to identify and classify the ν_μ, ν_e interactions

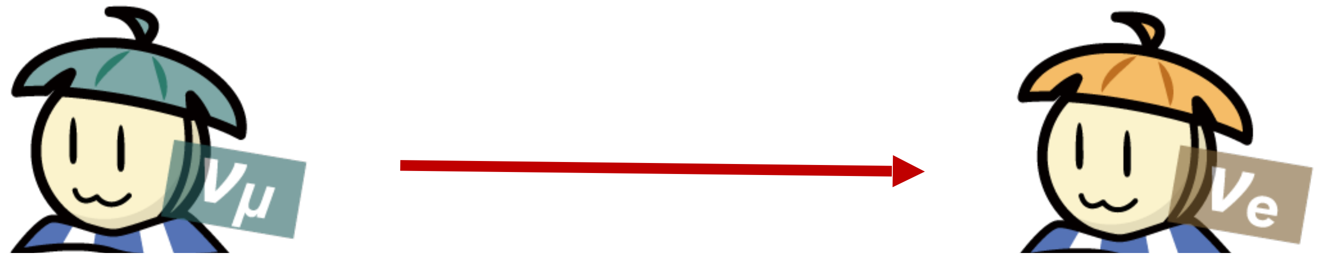
Main oscillation channels to measure

Muon (anti-)neutrino disappearance



$$P(\nu_\mu \to \nu_\mu) \sim 1 - \Big(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading-term}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\Big)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$

Electron (anti-)neutrino appearance



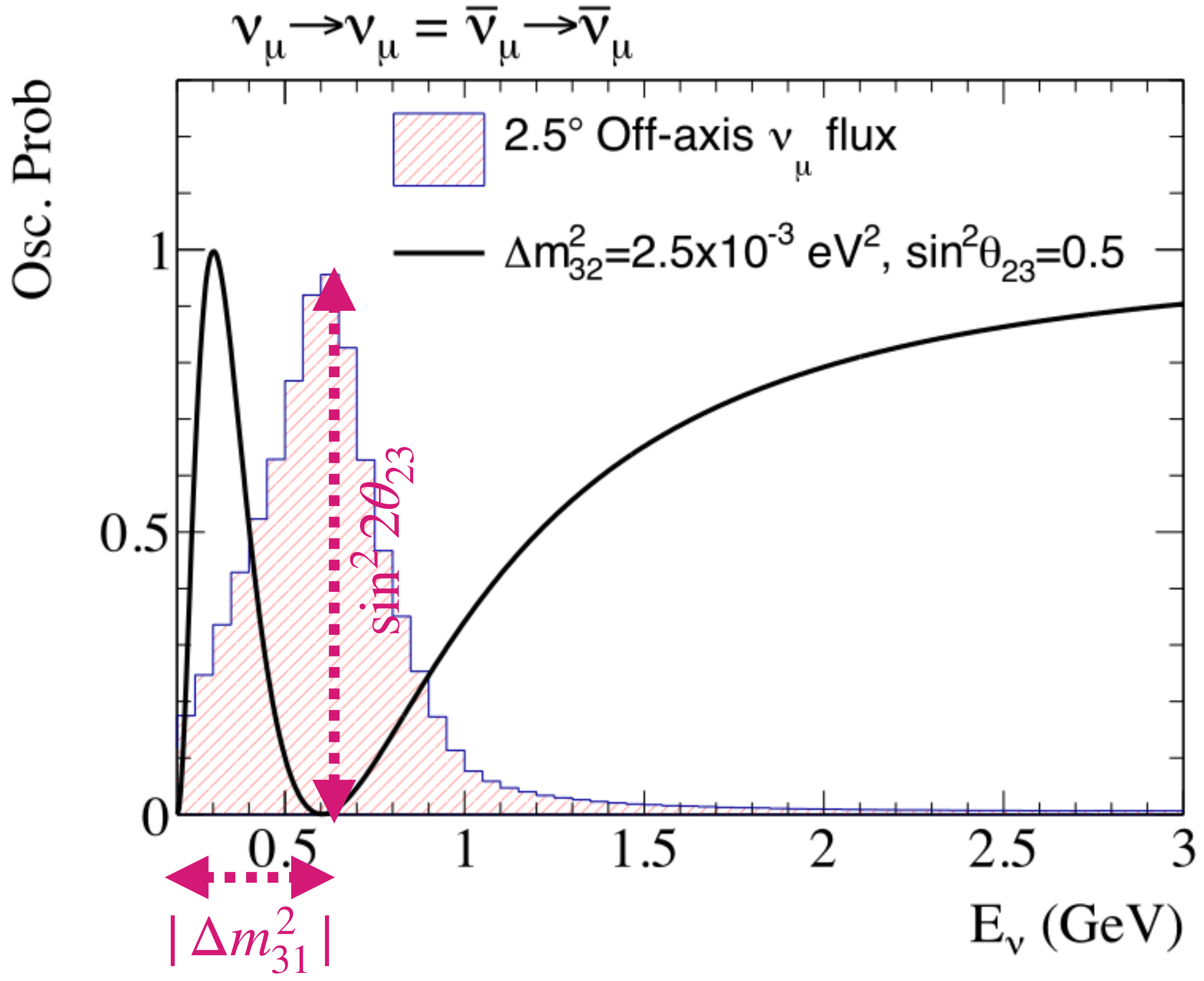
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = & \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}} && \text{Leading term} \quad \theta_{13}\\
& + 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} && \text{CPC}\\
& \boxed{-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}} && \text{CPV}\\
& + 4s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21} && \text{Solar}
\end{aligned}
$$

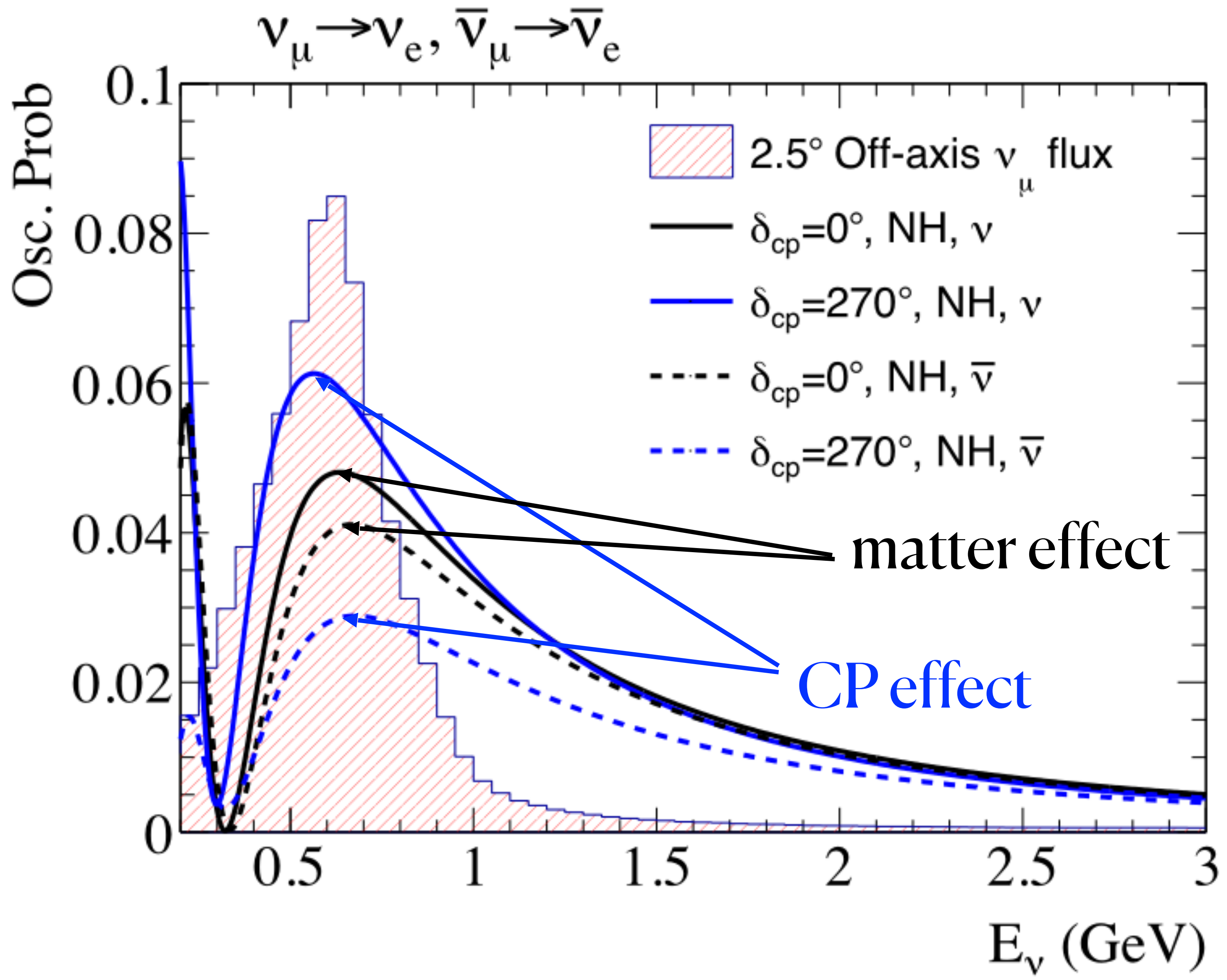
$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

$\Delta_{ij} = \Delta m^2_{ij}\dfrac{L}{4E_\nu}$

replace δ by $-\delta$ for $P(\overline{\nu}_\mu \to \overline{\nu}_e)$

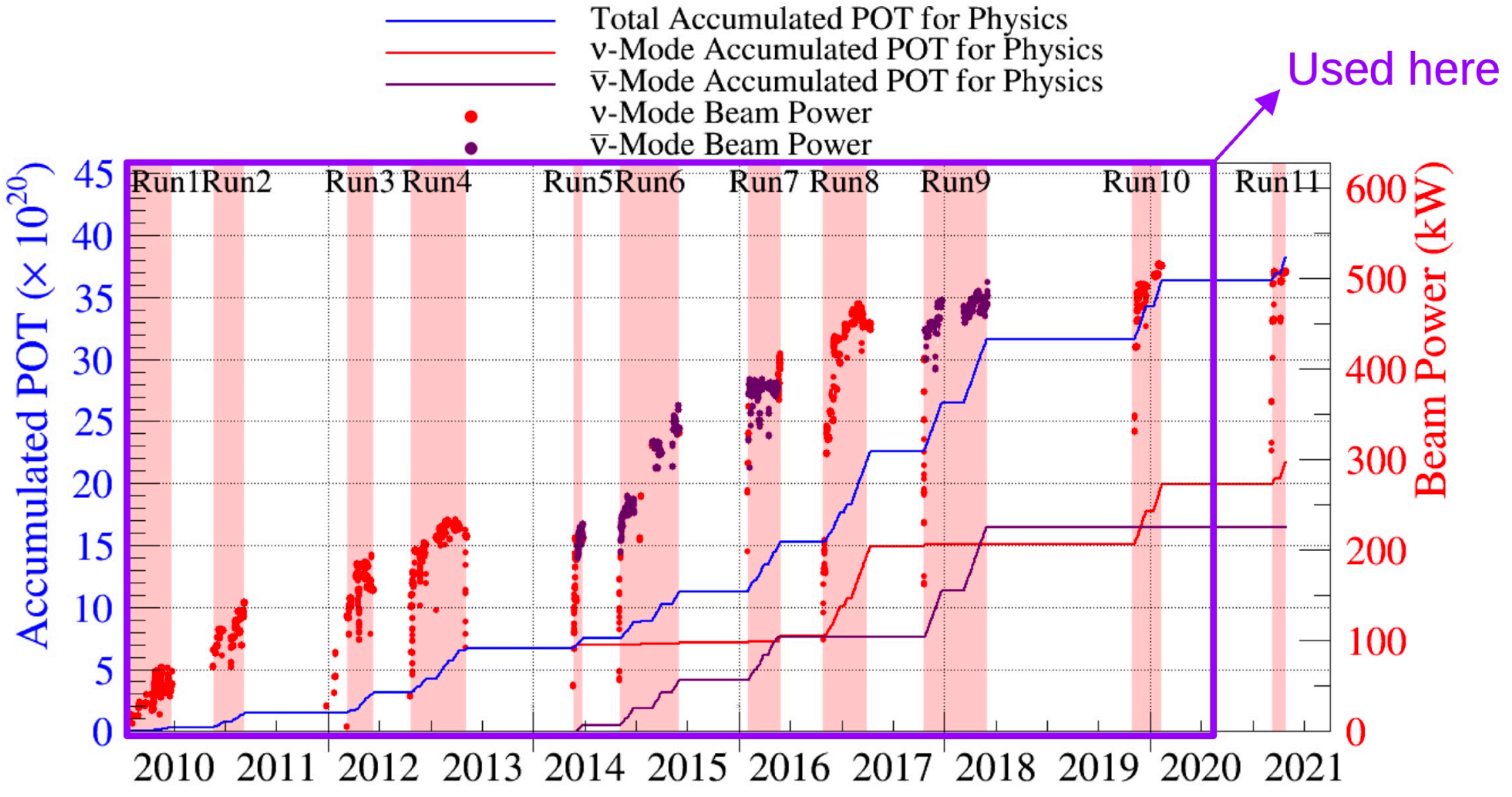
CP violating term introduced by interference among three-flavor mixing

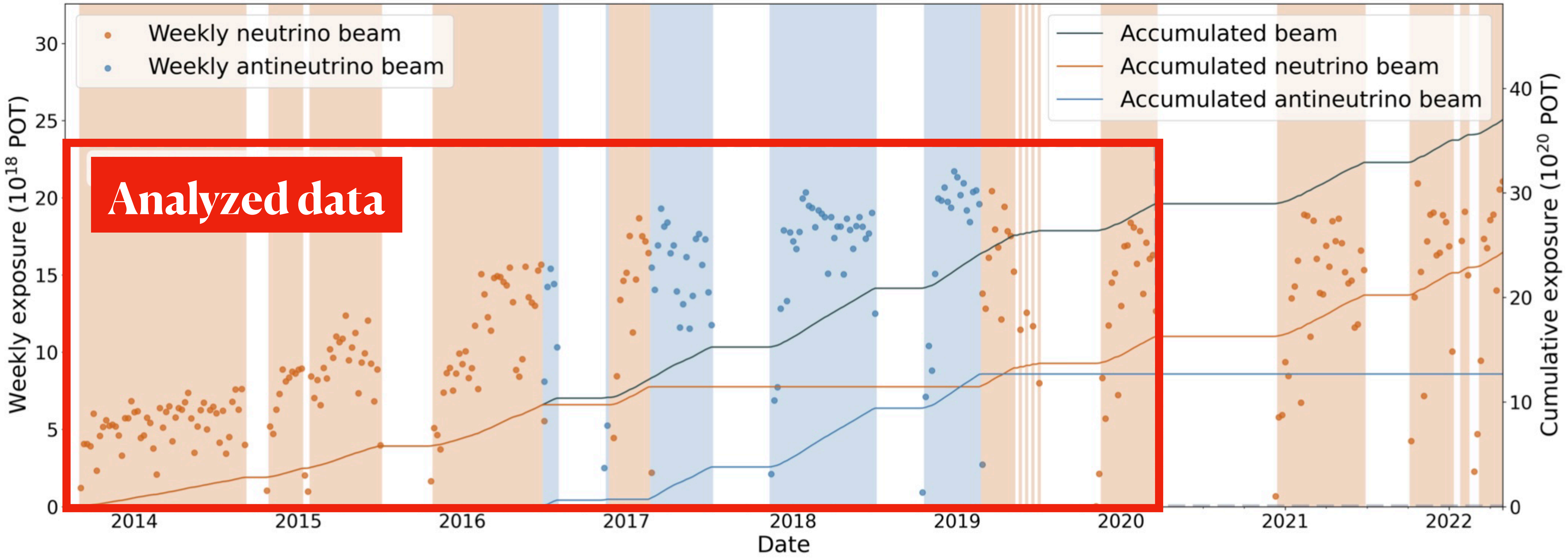




Data collection

Data [POT]	T2K	NOvA
Neutrino-mode	1.97E+21	1.36E+21
Anti-neutrino mode	1.63E+21	1.25E+21
Total analyzed data	3.60E+21	2.61E+21
Expectation by the operation end	10.E+21	7.2E+21





- ~30% data collected and analyzed
- Neutrino beamline upgrades will allow the two to obtain data considerably faster.

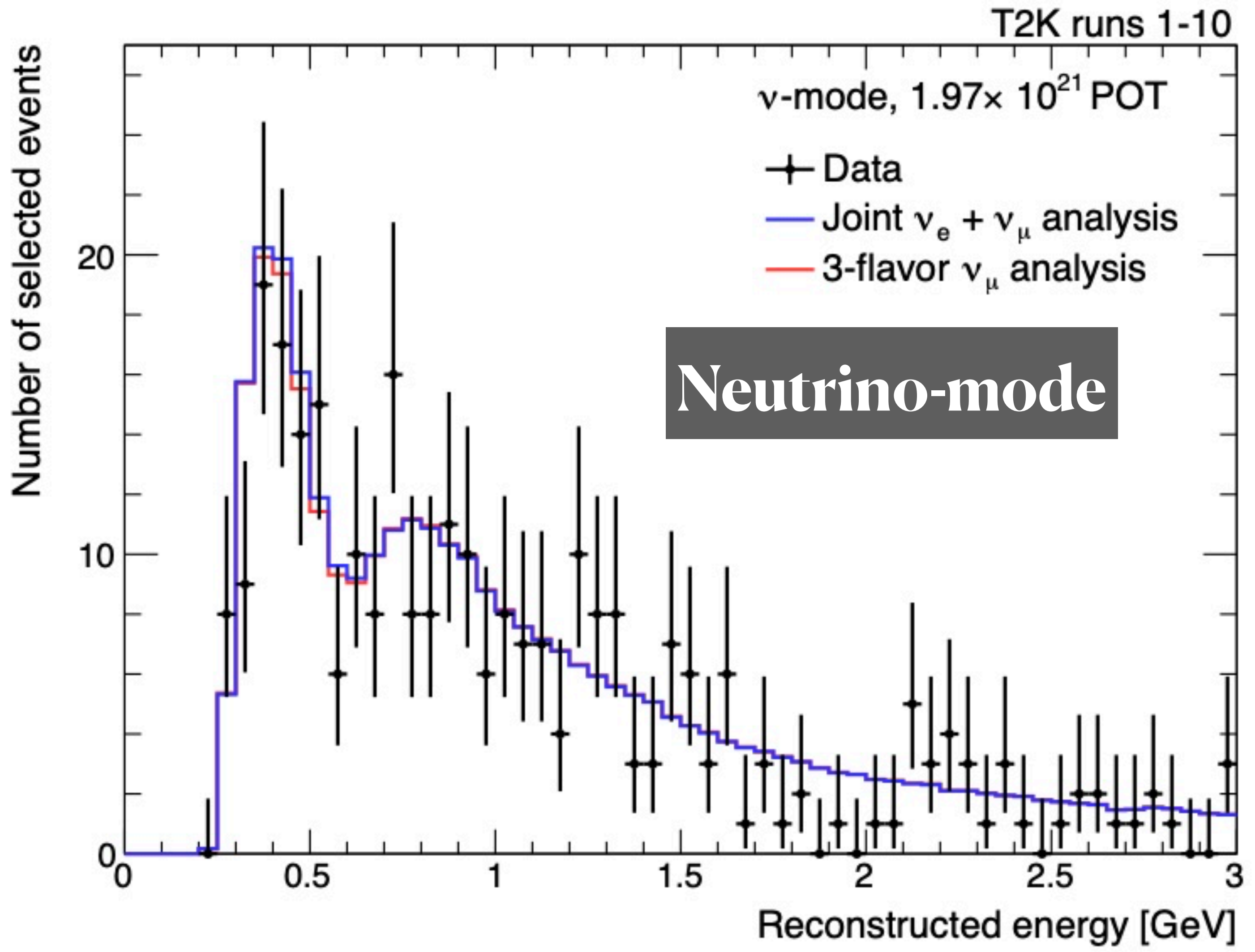
Latest results on leptonic CP violation, neutrino mass ordering, and others

Disappearance of ν_μ vs. $\bar{\nu}_\mu$

Consider two independent parameter sets driving disappearances of ν_μ and $\bar{\nu}_\mu$ (e.g. caused by CPT violation or NSI)

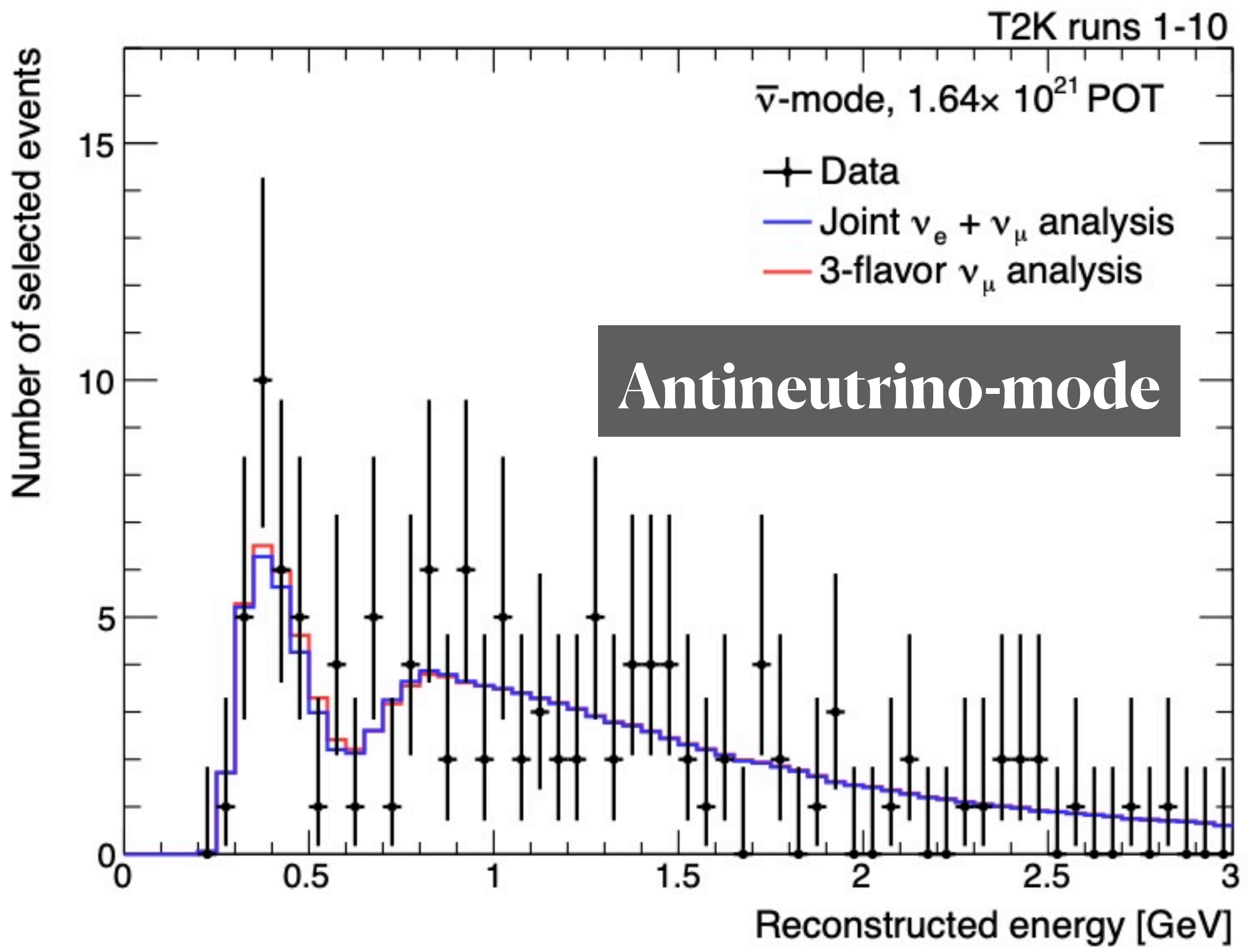
ν parameters

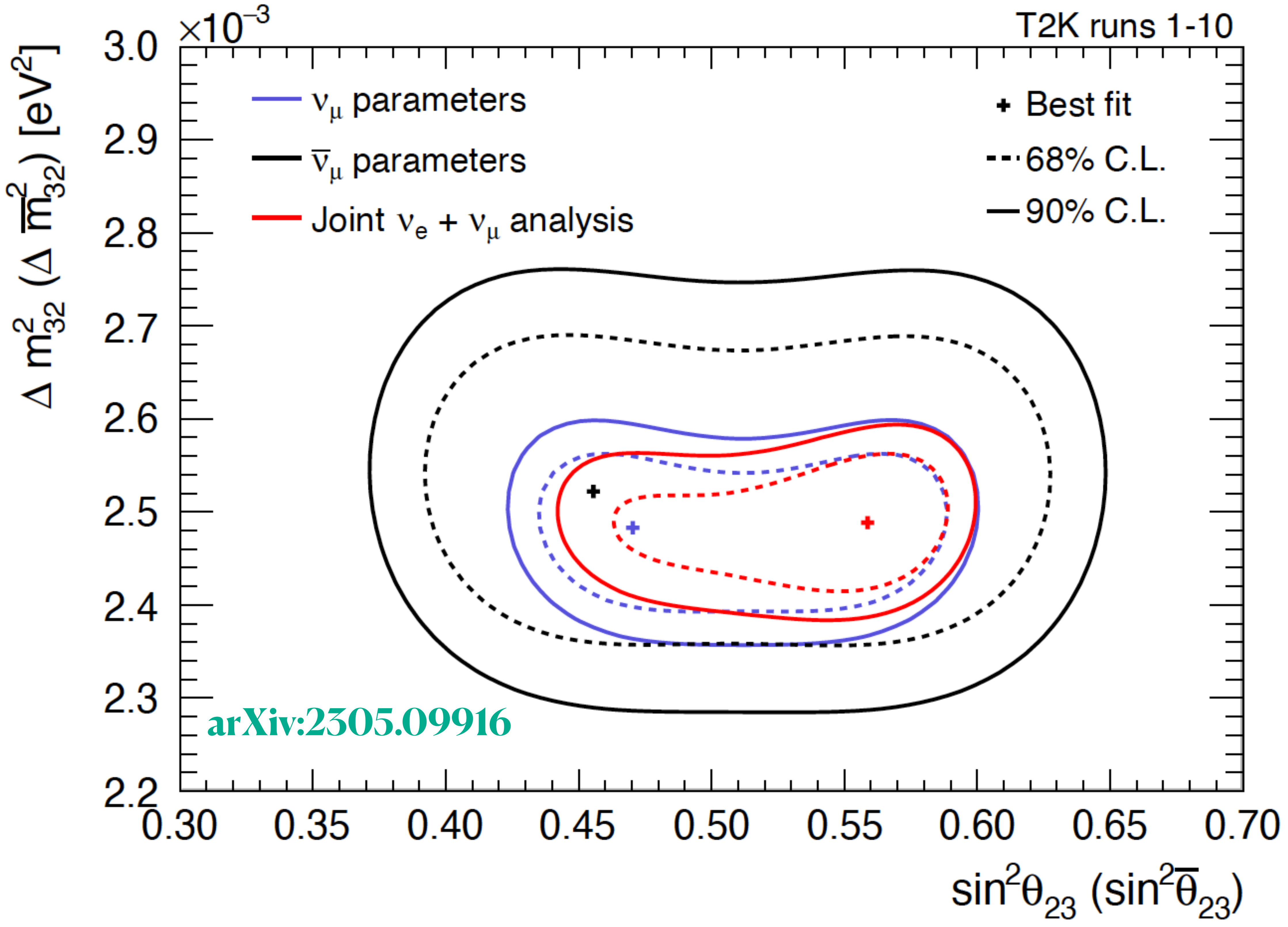
$(\Delta m^2_{31}, \sin^2\theta_{23})$



$\bar{\nu}$ parameters

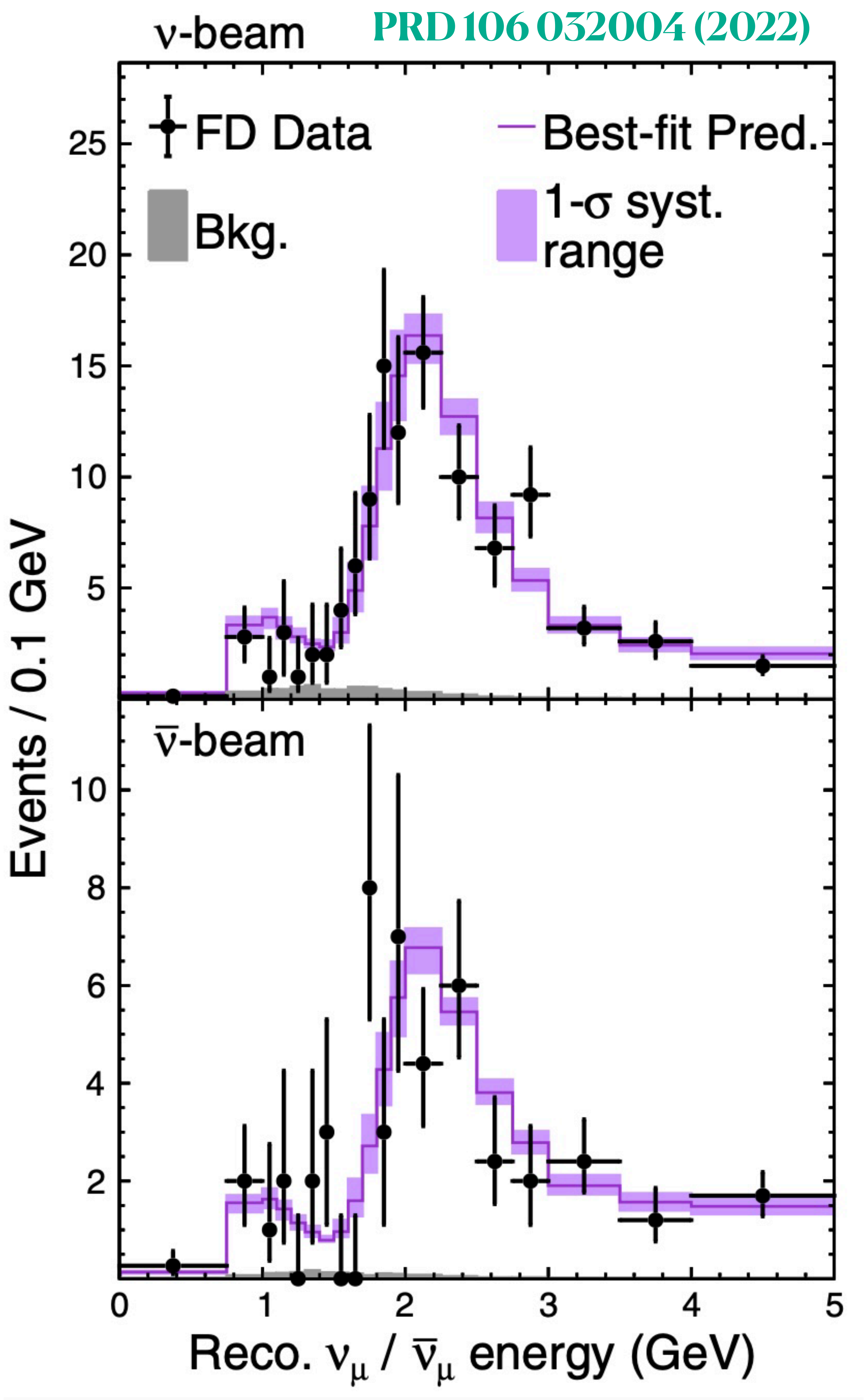
$(\Delta \bar{m}^2_{31}, \sin^2\bar{\theta}_{23})$

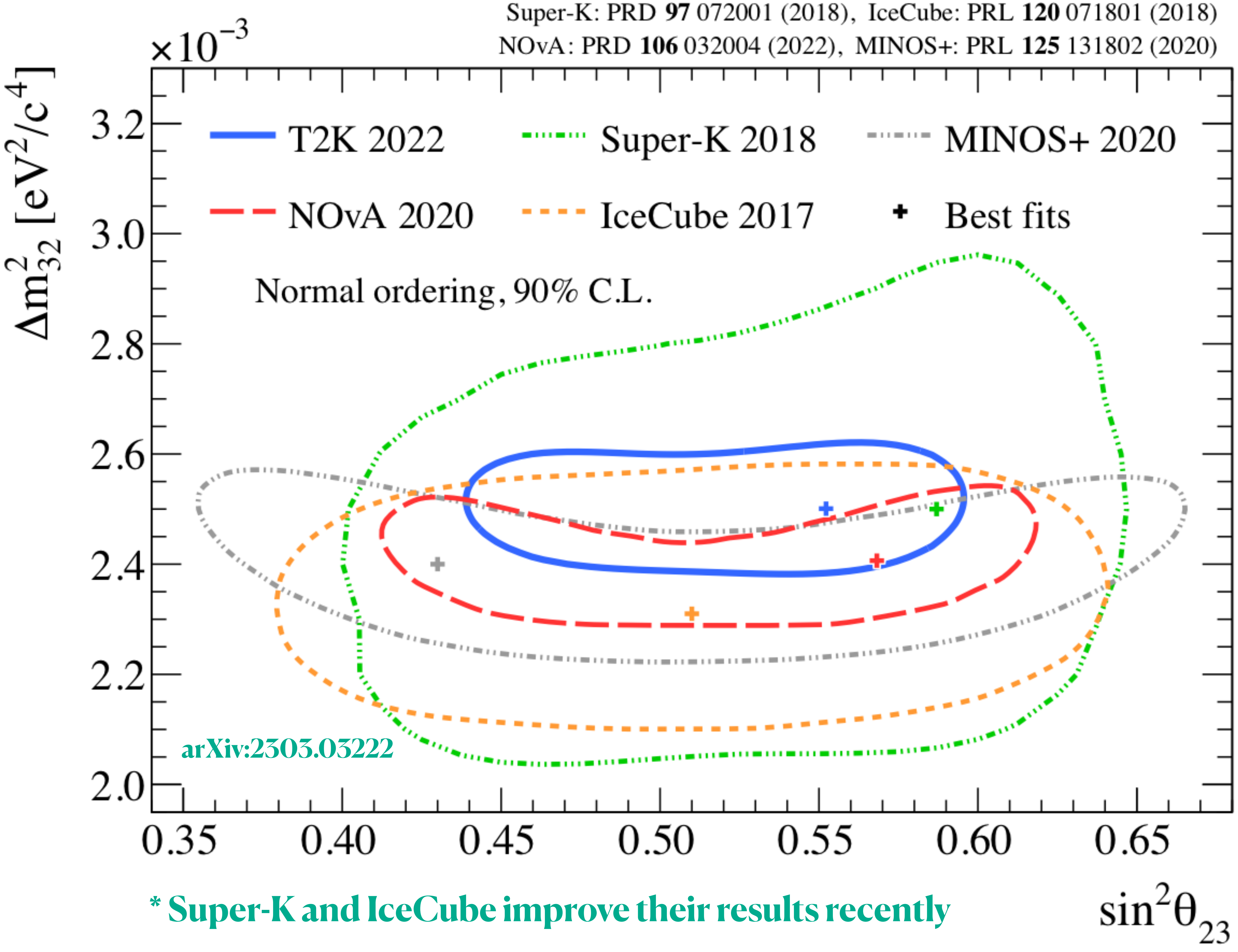




No significant difference btw. ν_μ and $\bar{\nu}_\mu$ disappearance

Consistent picture of atmospheric parameters

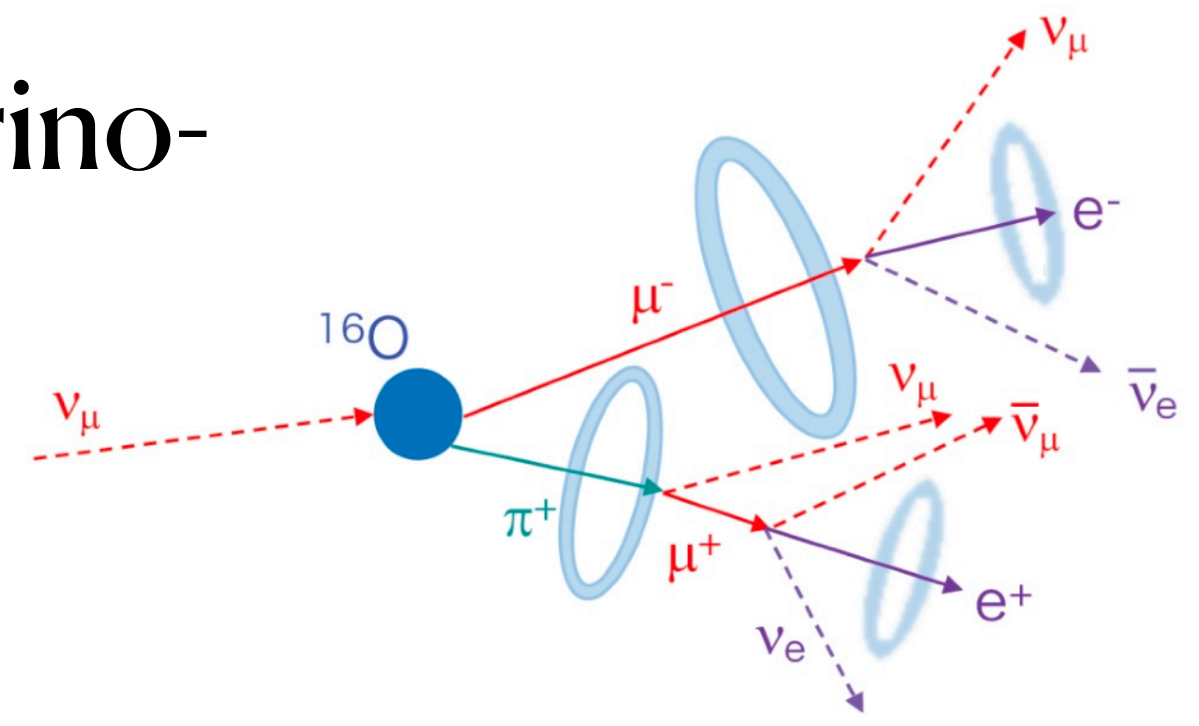


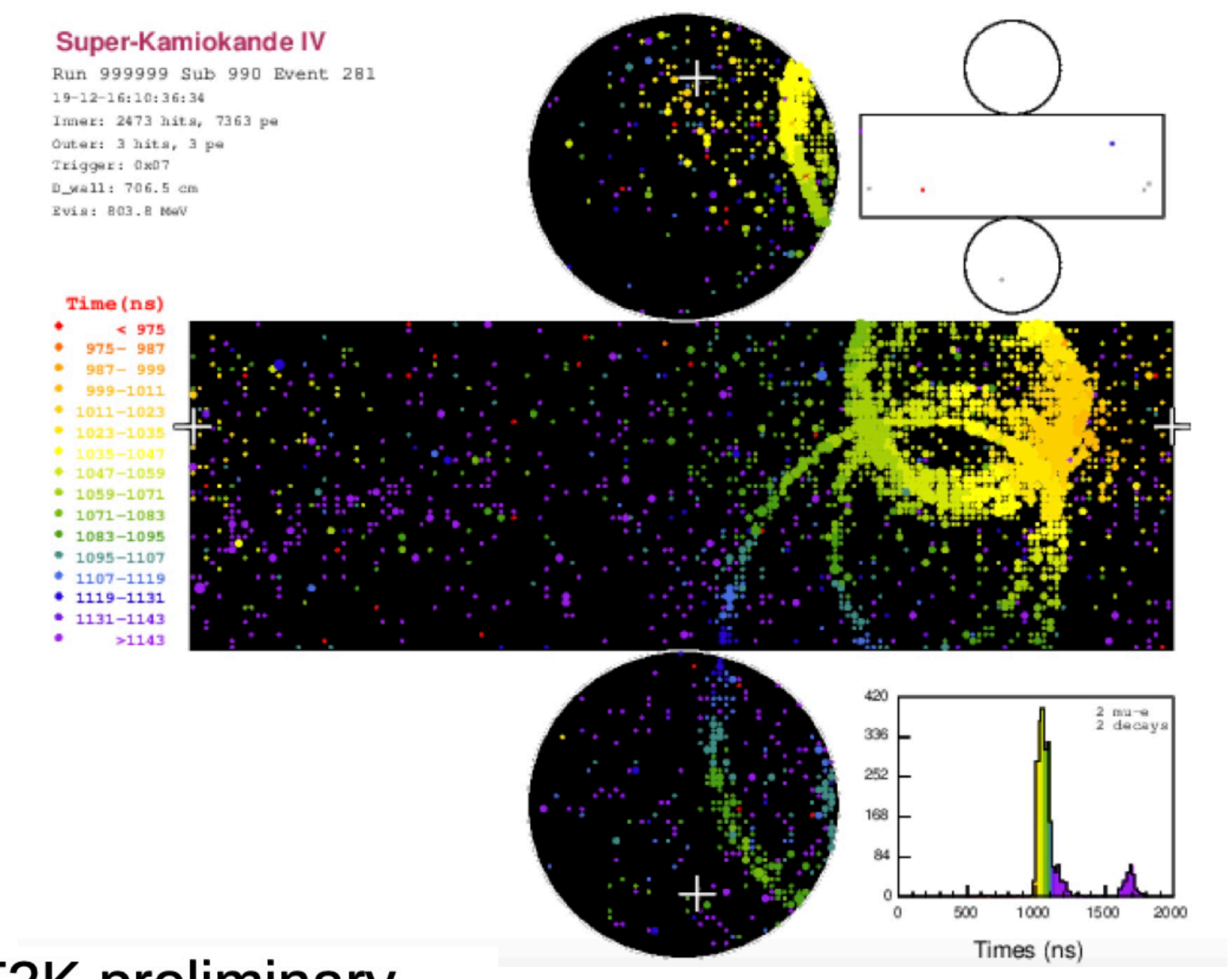


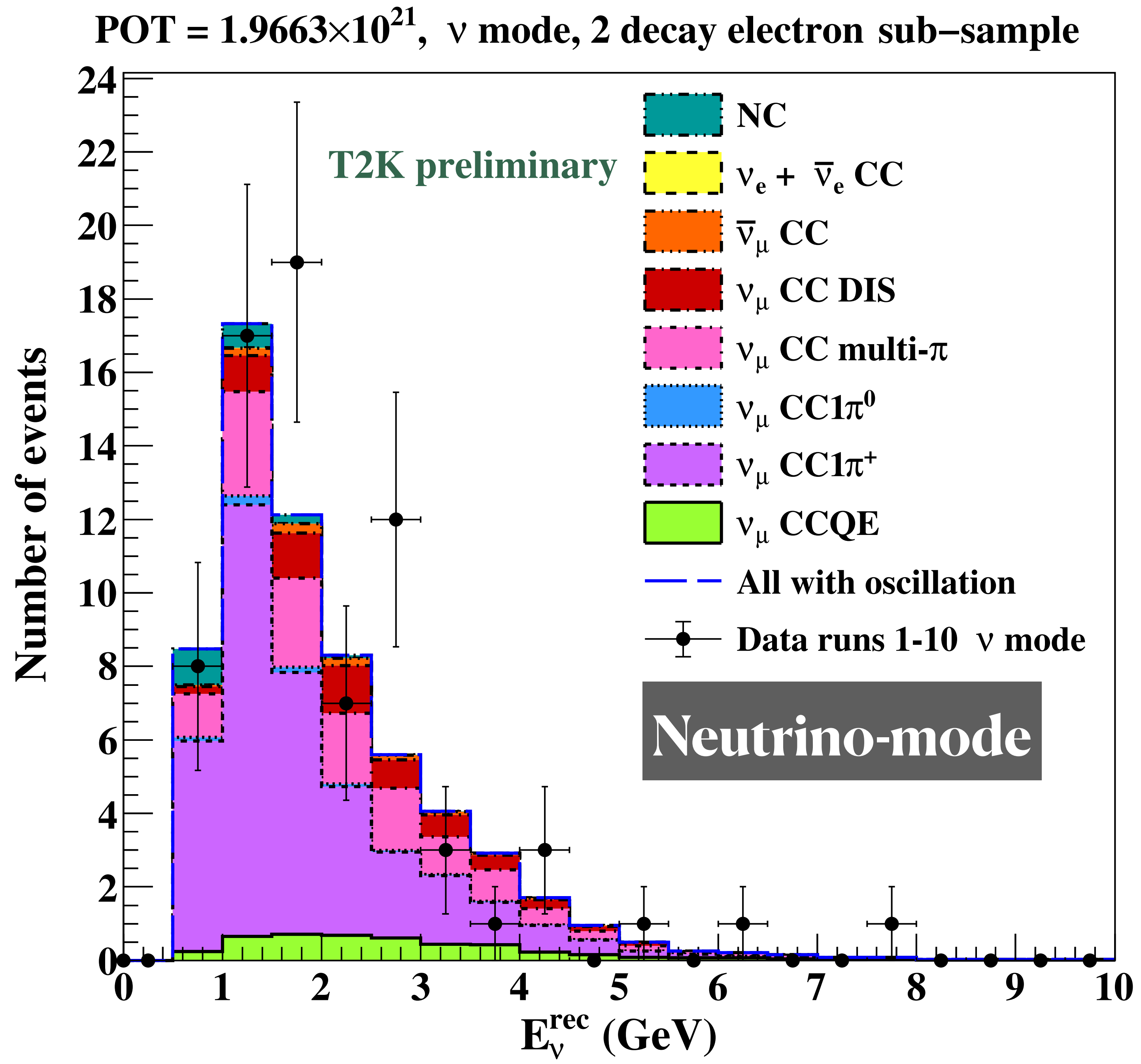
* Super-K and IceCube improve their results recently

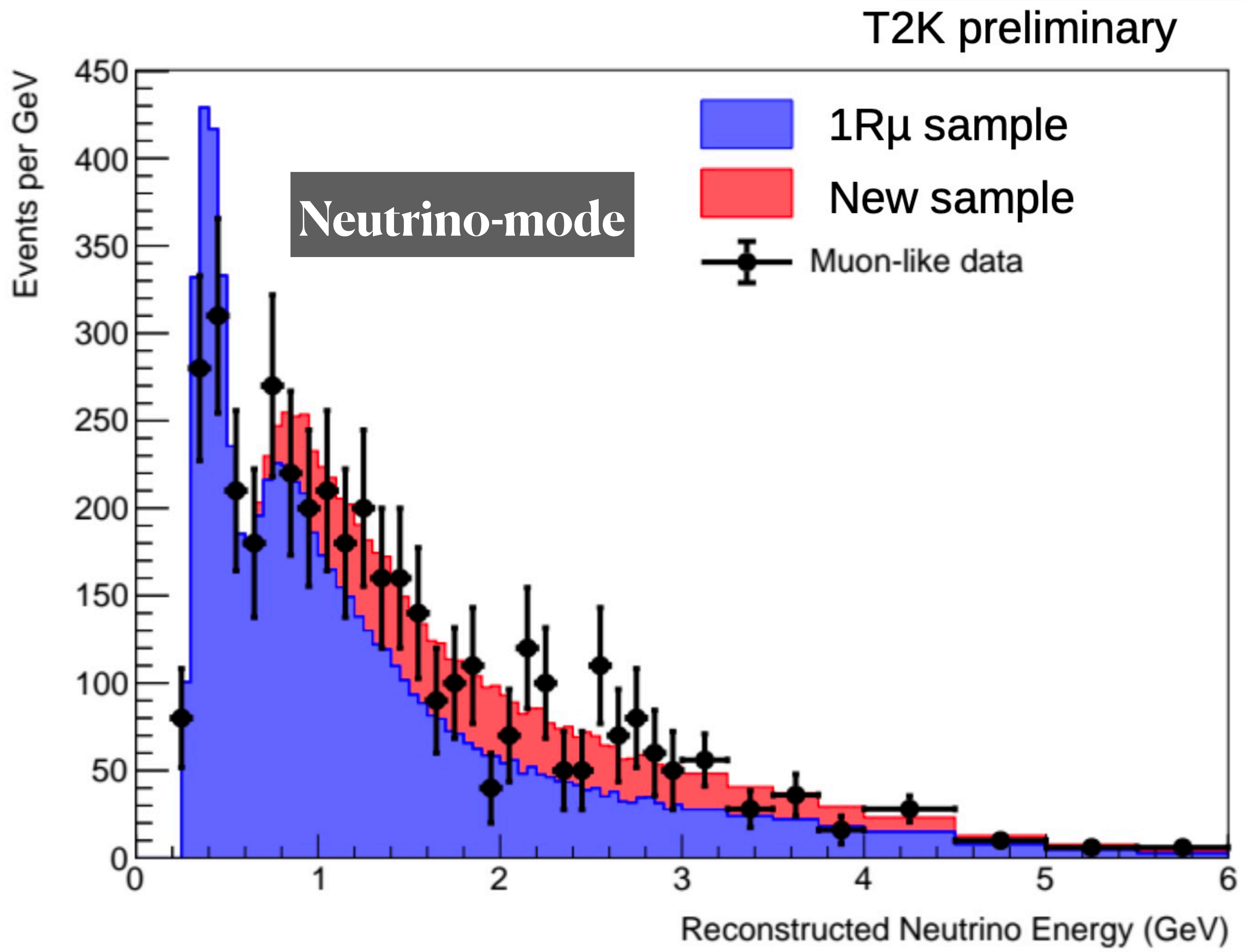
T2K data: new ν_μ disappearance sample

- First use of the multi-ring sample in neutrino-mode, dominated by CC1π
- 30% increase in statistics
- Higher energy and thus less sensitive to oscillation parameters than the single ring sample

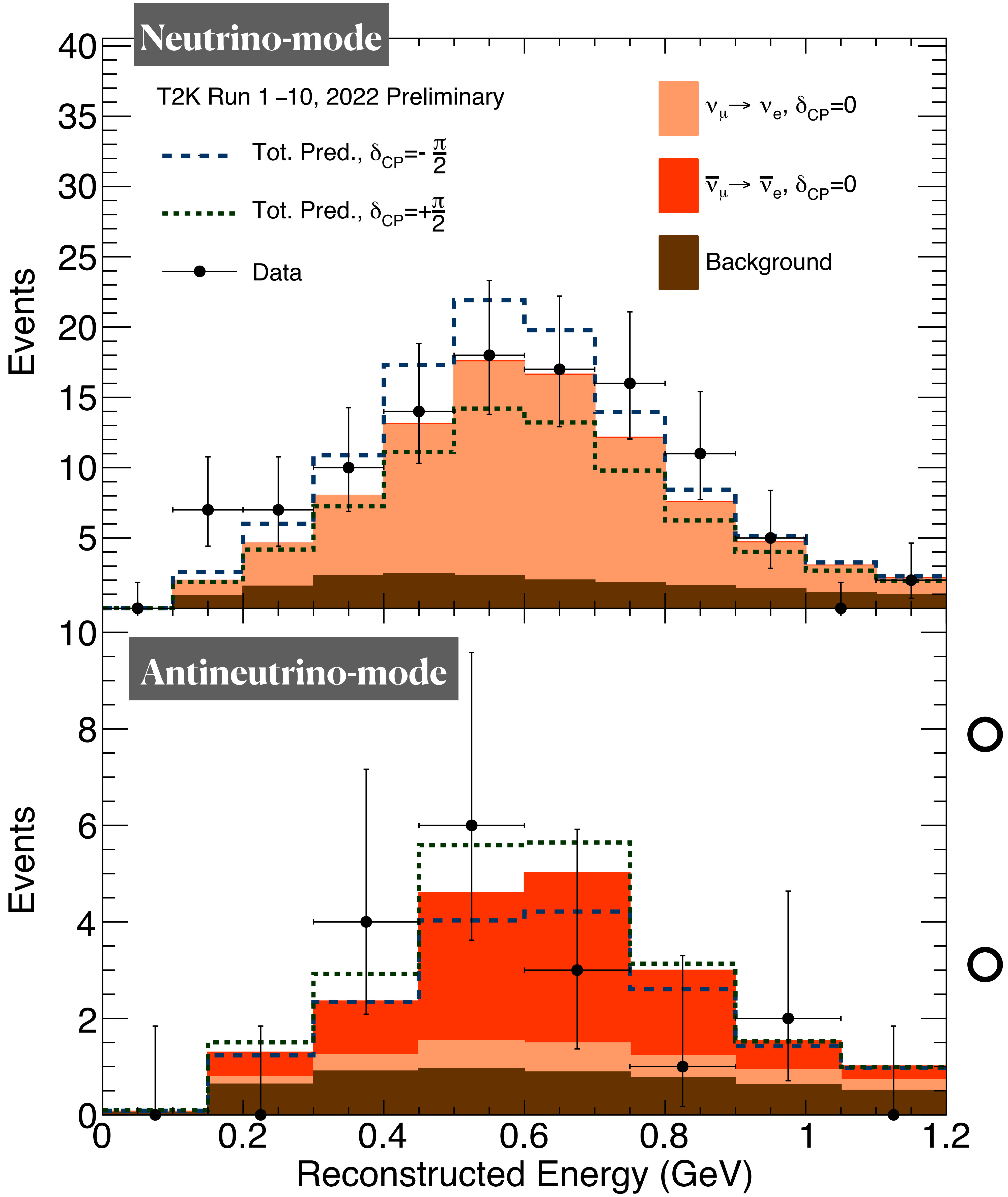


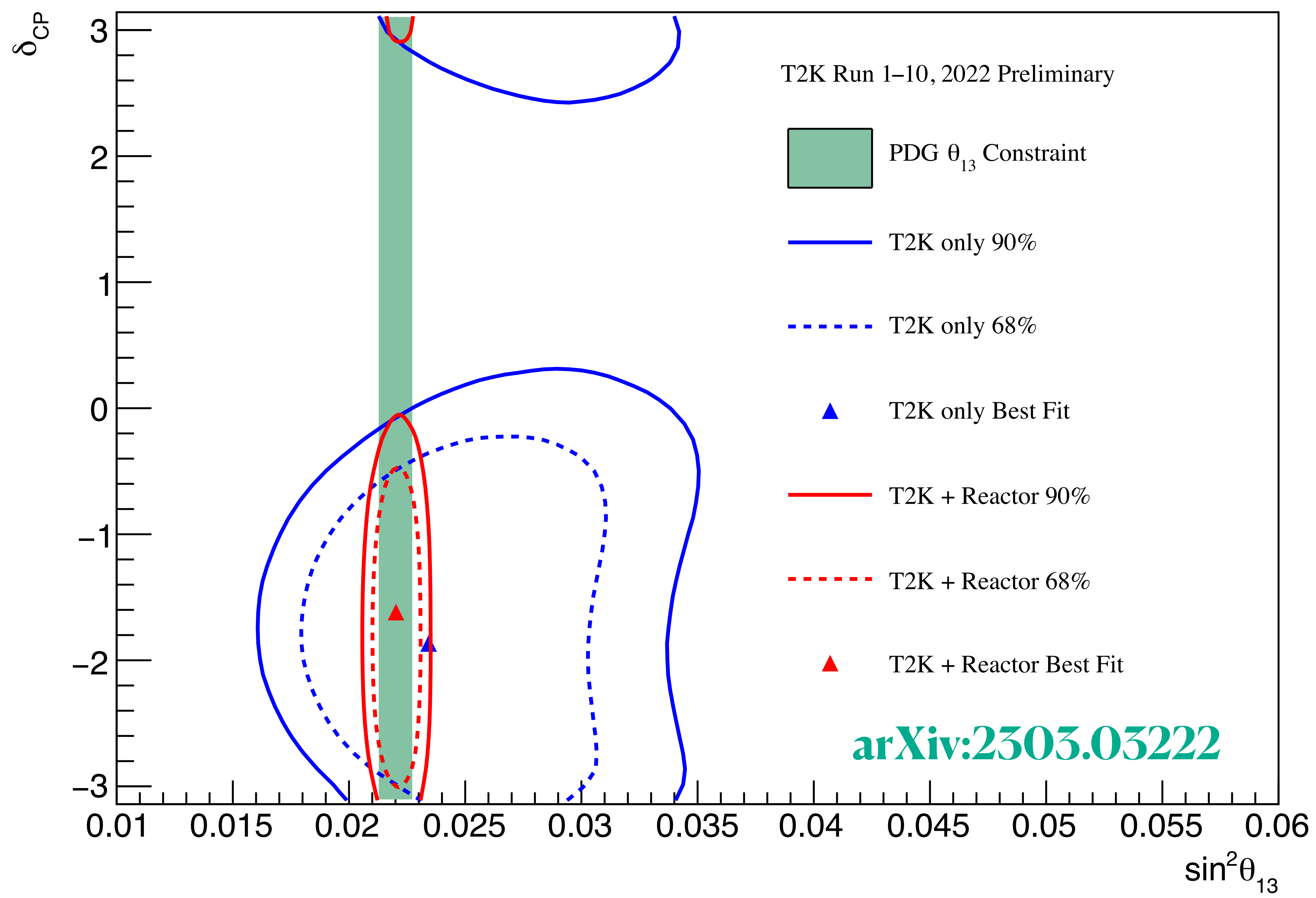






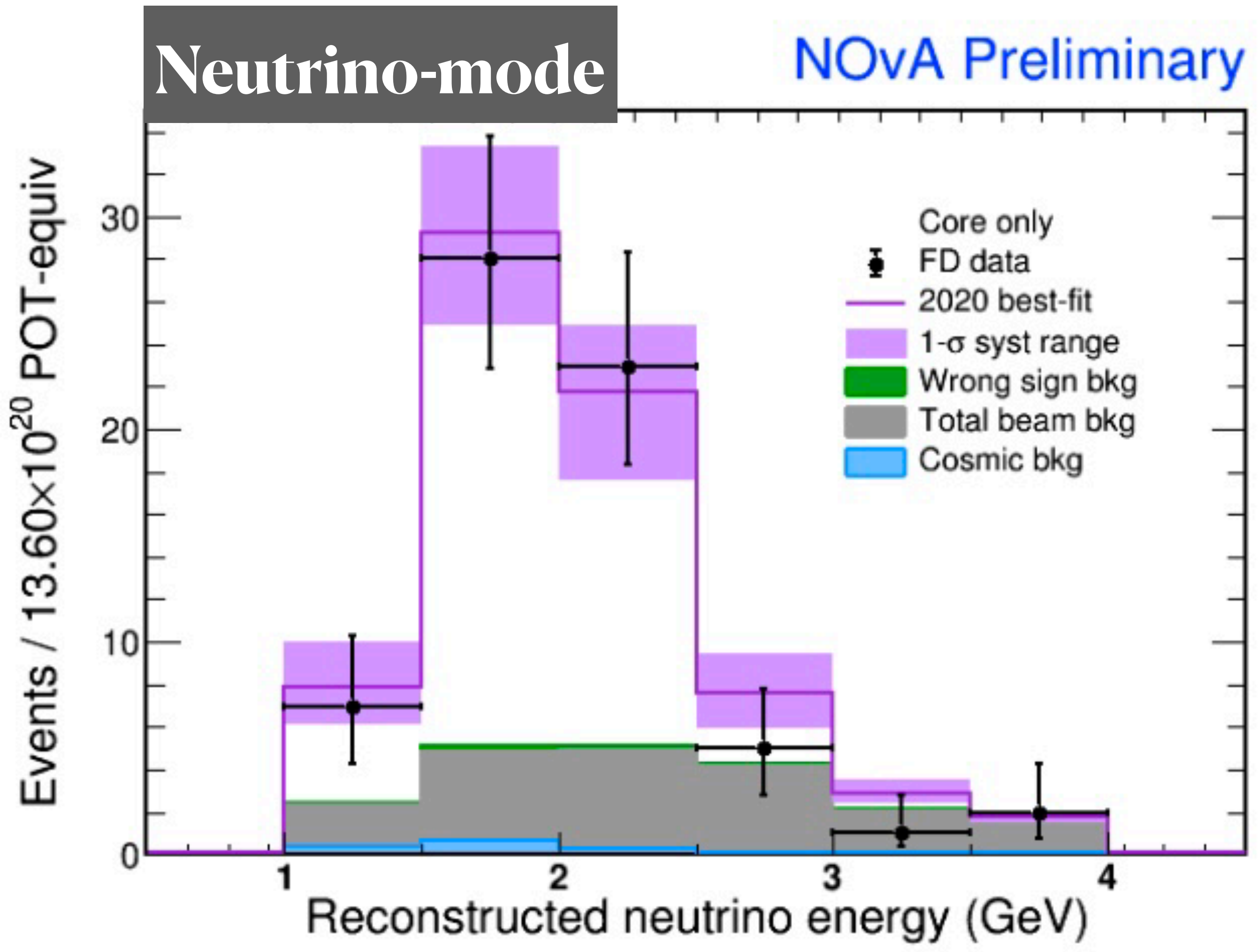
T2K data: $\nu_\mu \rightarrow \nu_e$ appearance channels

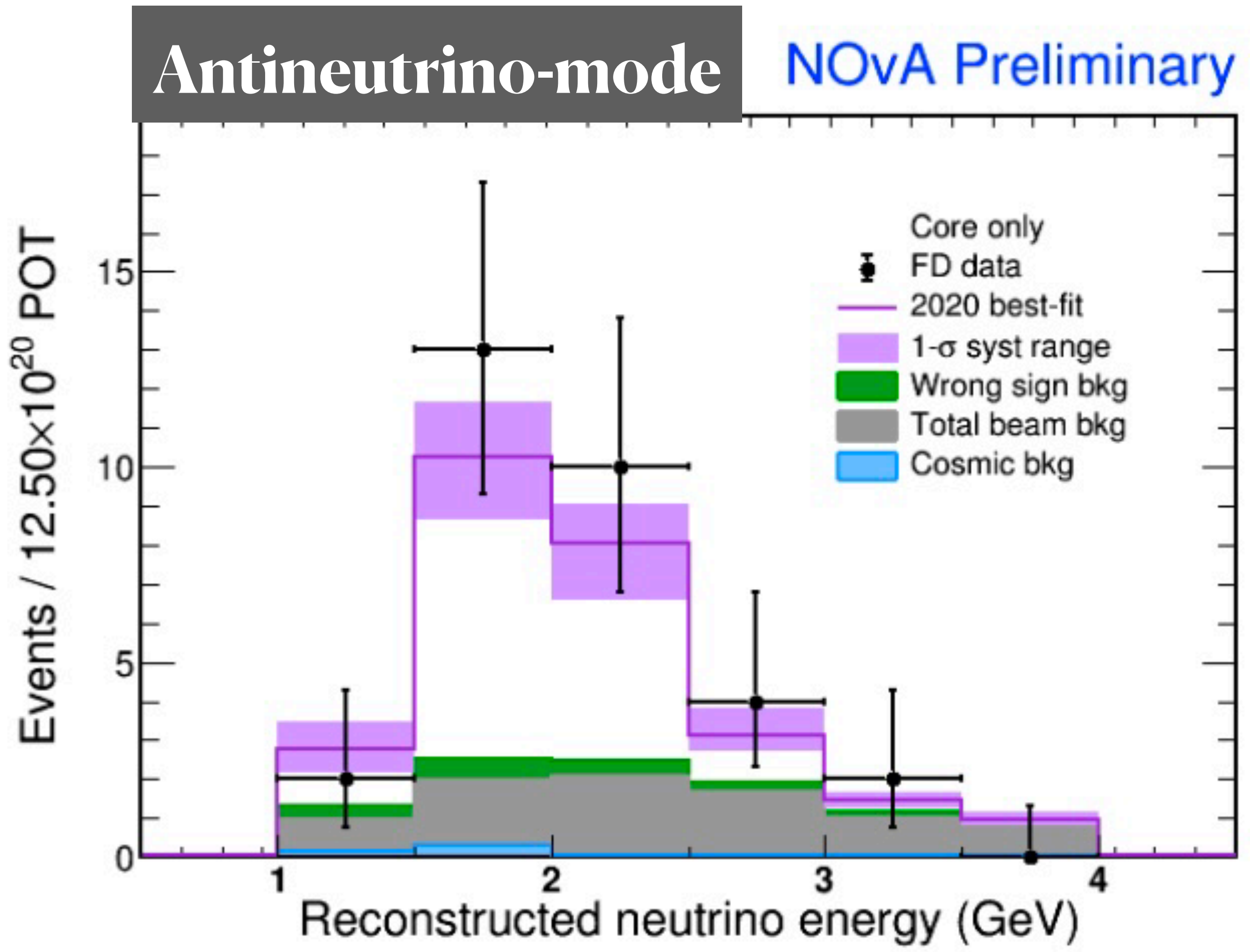




- T2K self-measurement of θ_{13} is consistent with the much stringent constraint of this parameter fr. reactor-based exp.
- T2K then implements the external constraint on θ_{13} to gain a better sensitivity to the other parameter measurements

NOvA data: $\nu_\mu \rightarrow \nu_e$ appearance channels





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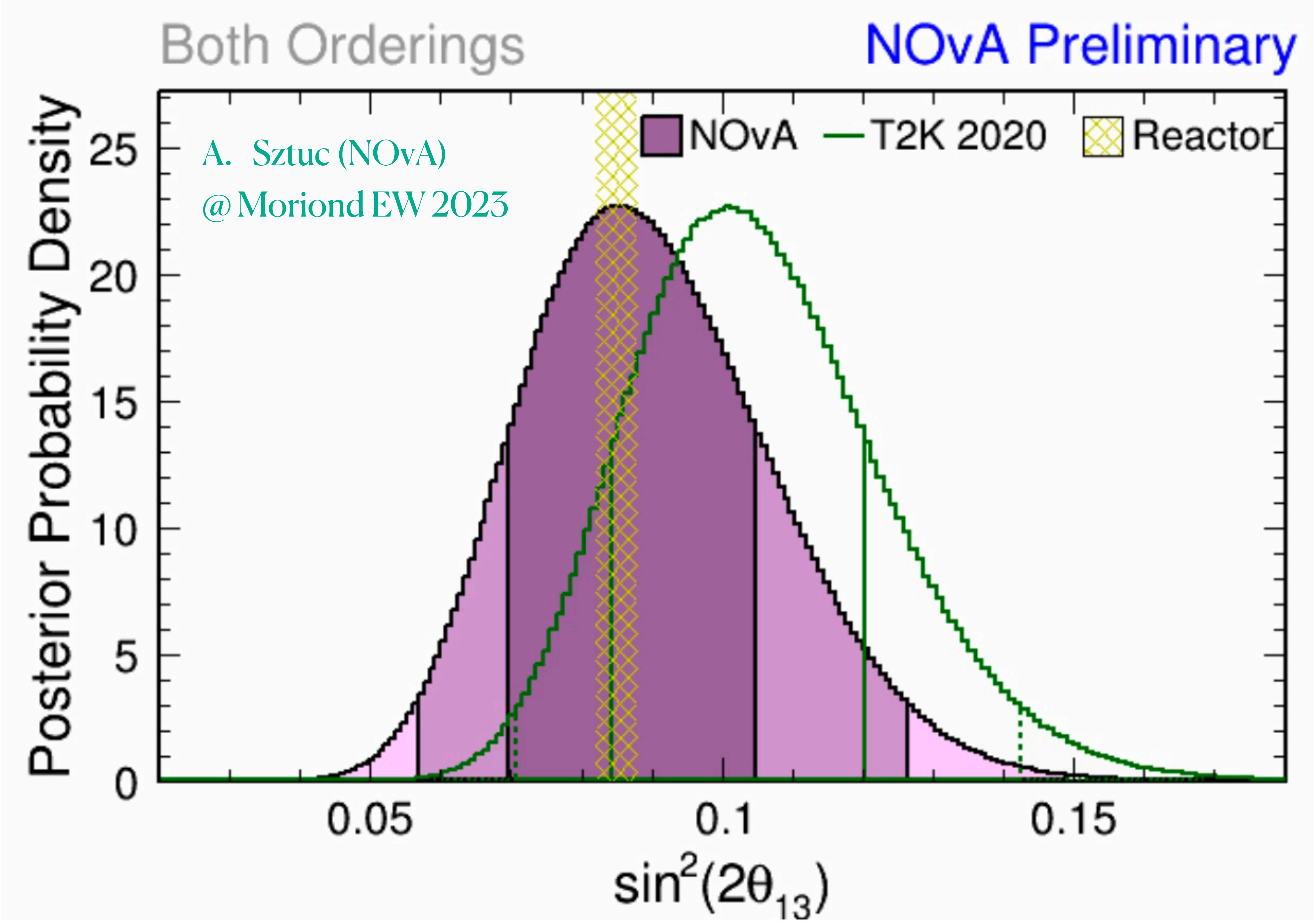
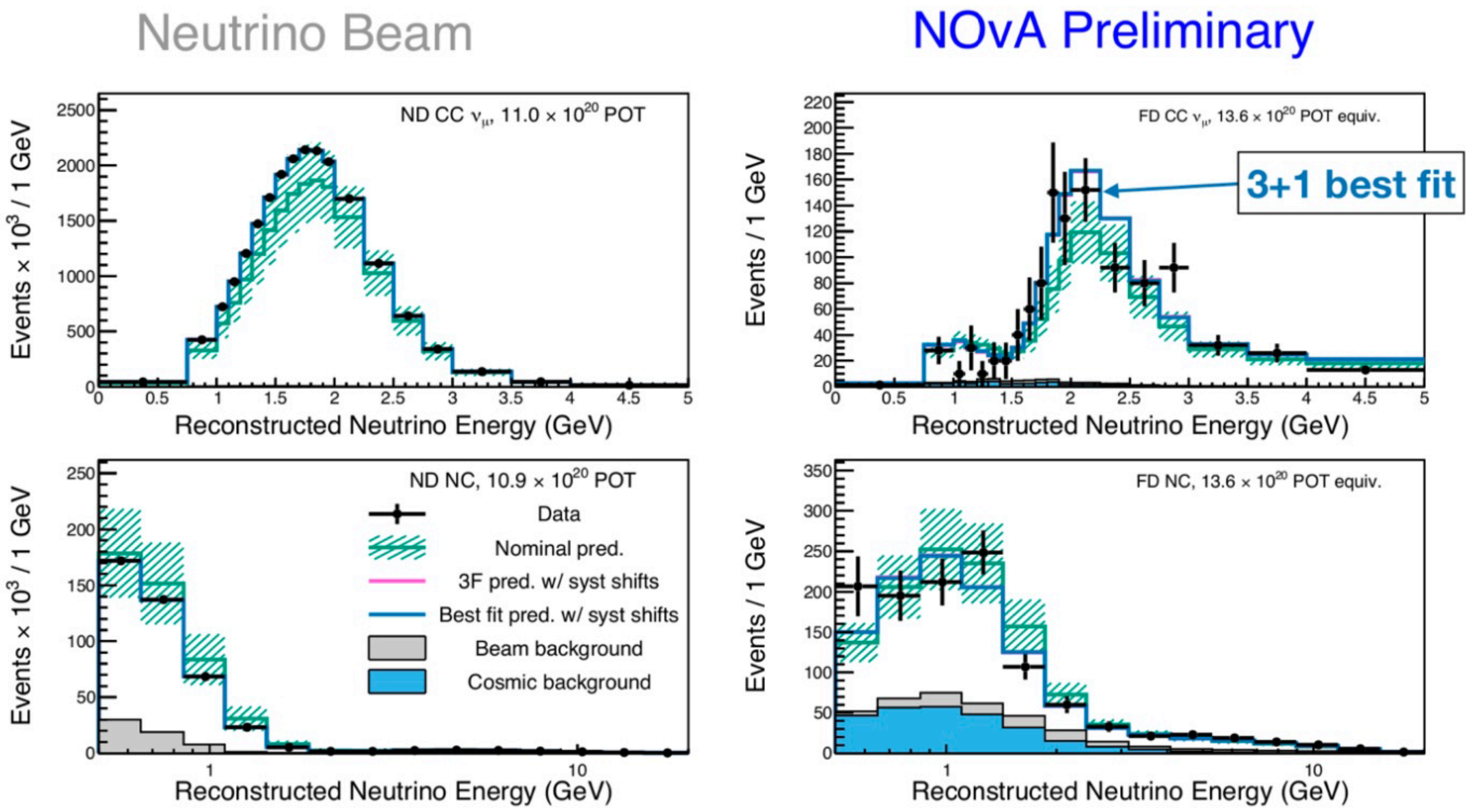


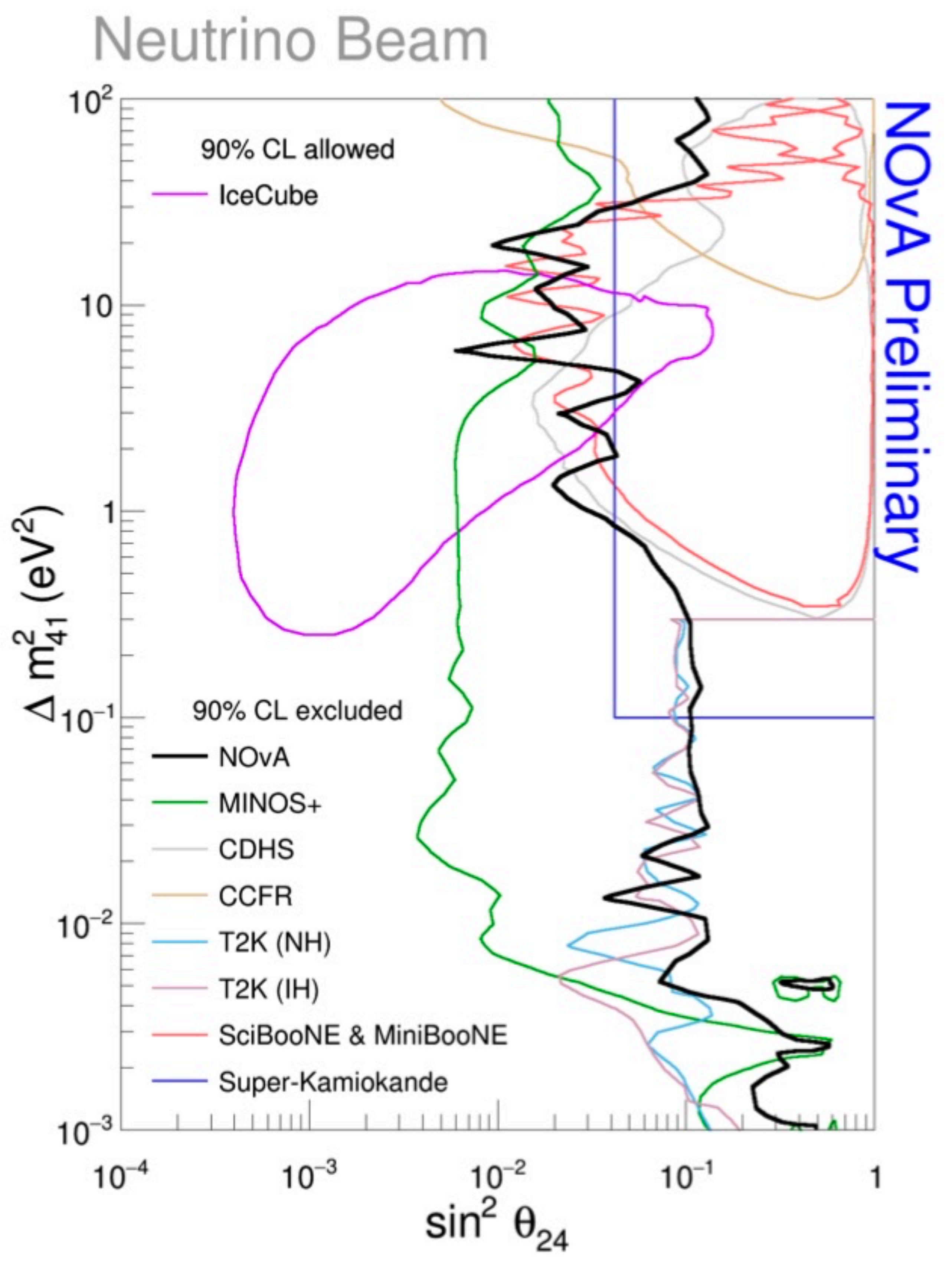
NOvA data is also consistent with constraint on θ_{13} from reactor-based experiments

Also, there is no significant indication of sterile neutrinos in both T2K and NOvA data. The two data sets are well-described with 3x3 *standard* PMNS mixing.

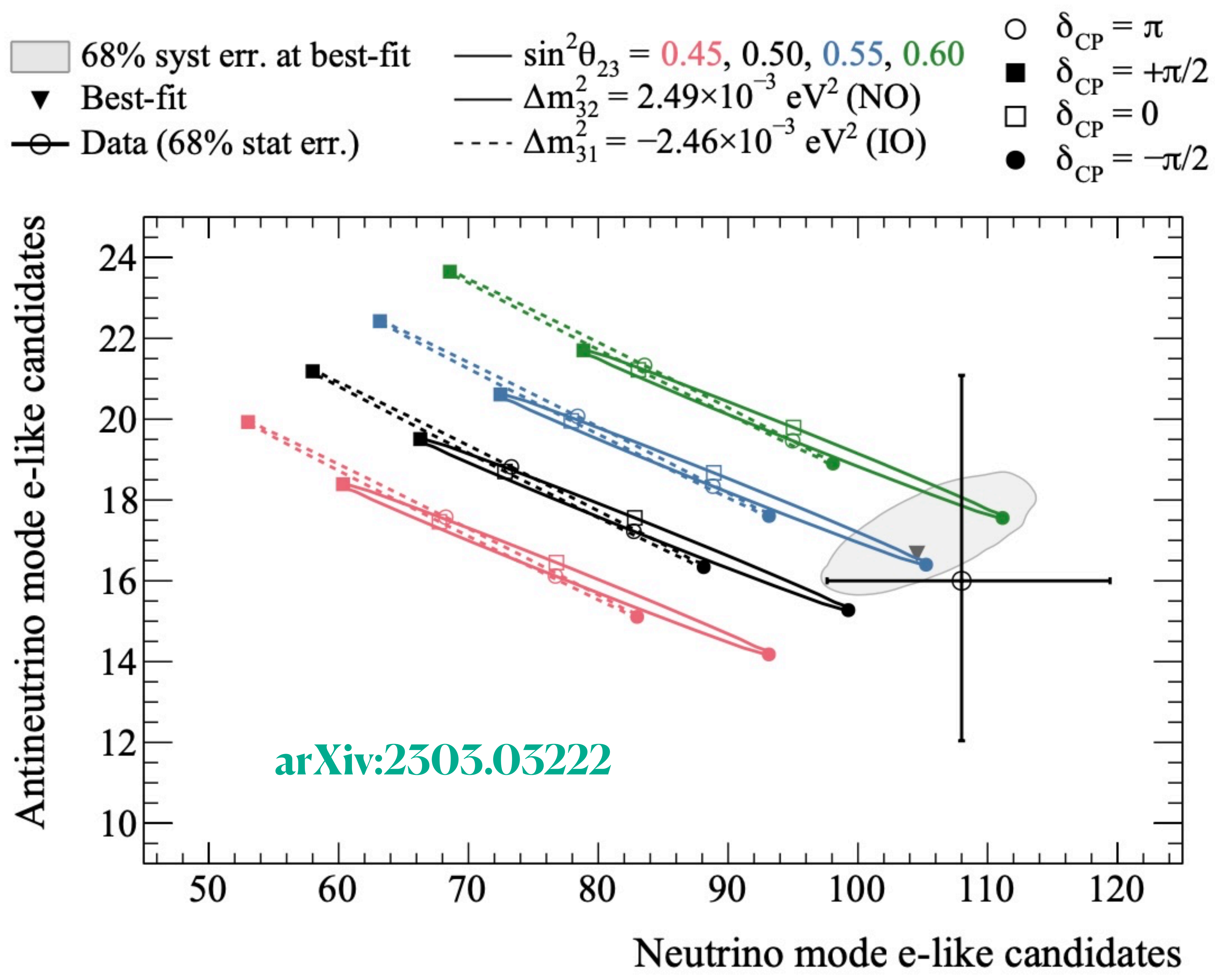


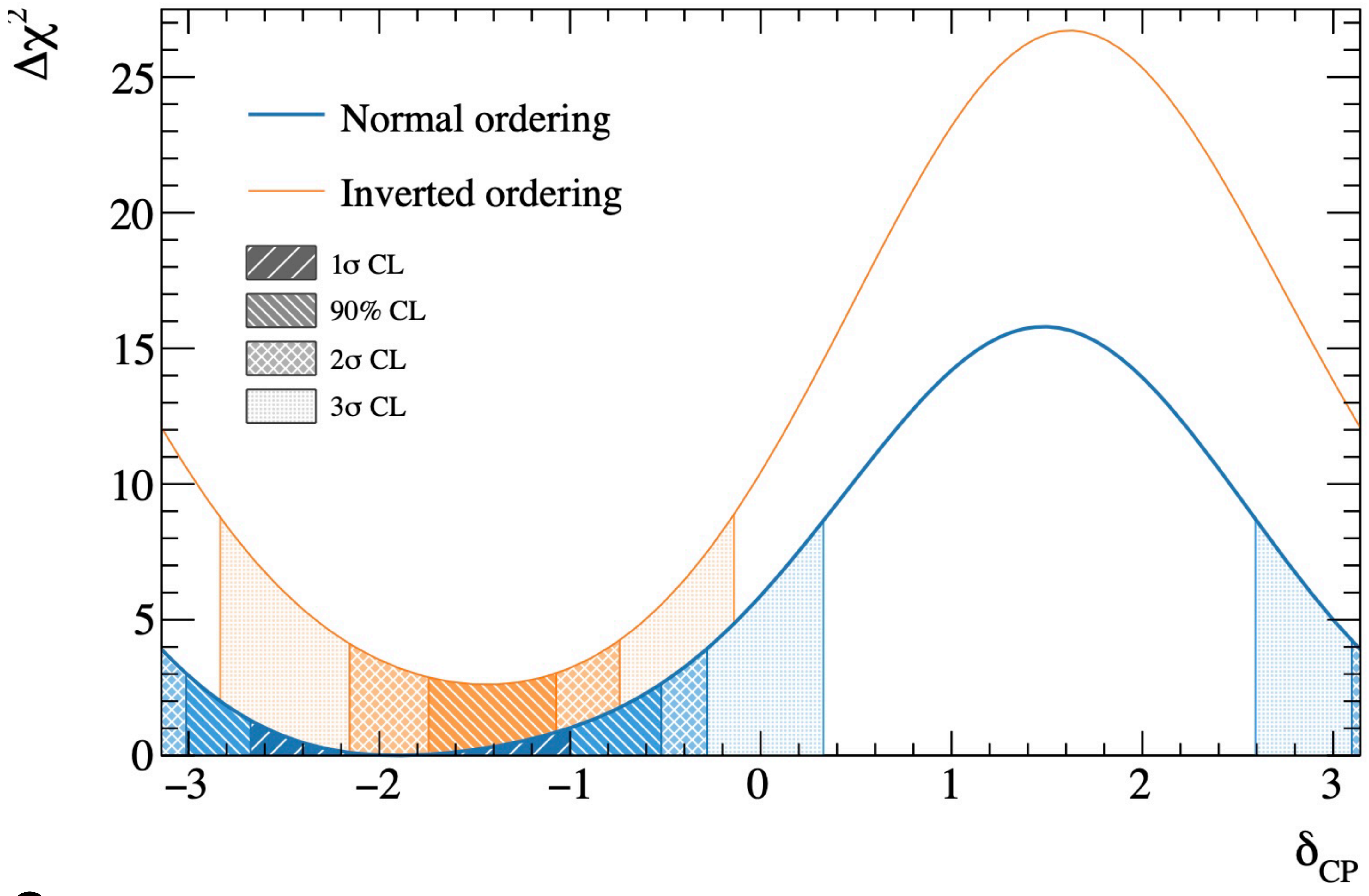
A. Aurisano @ NOW2022

3 and 3+1 flavor best fits ~ identical
Goodness of fit: χ^2/DOF = 56.4/66



T2K: CP violation, mass ordering...





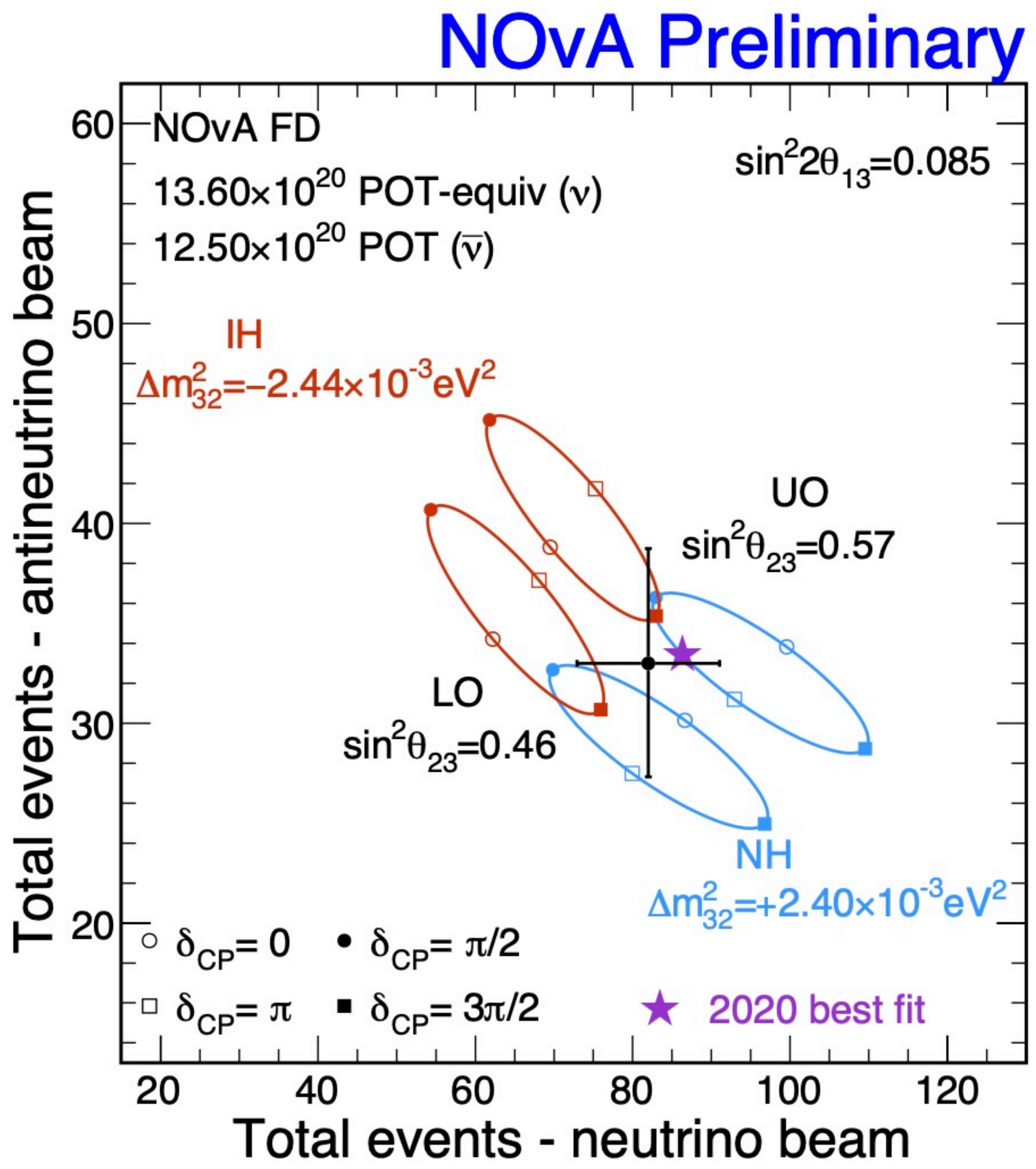
T2K preliminary	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO $(\Delta m^2_{32} > 0)$	0.20	0.54	0.74
IO $(\Delta m^2_{32} < 0)$	0.05	0.21	0.26
Sum	0.25	0.75	**1.00**

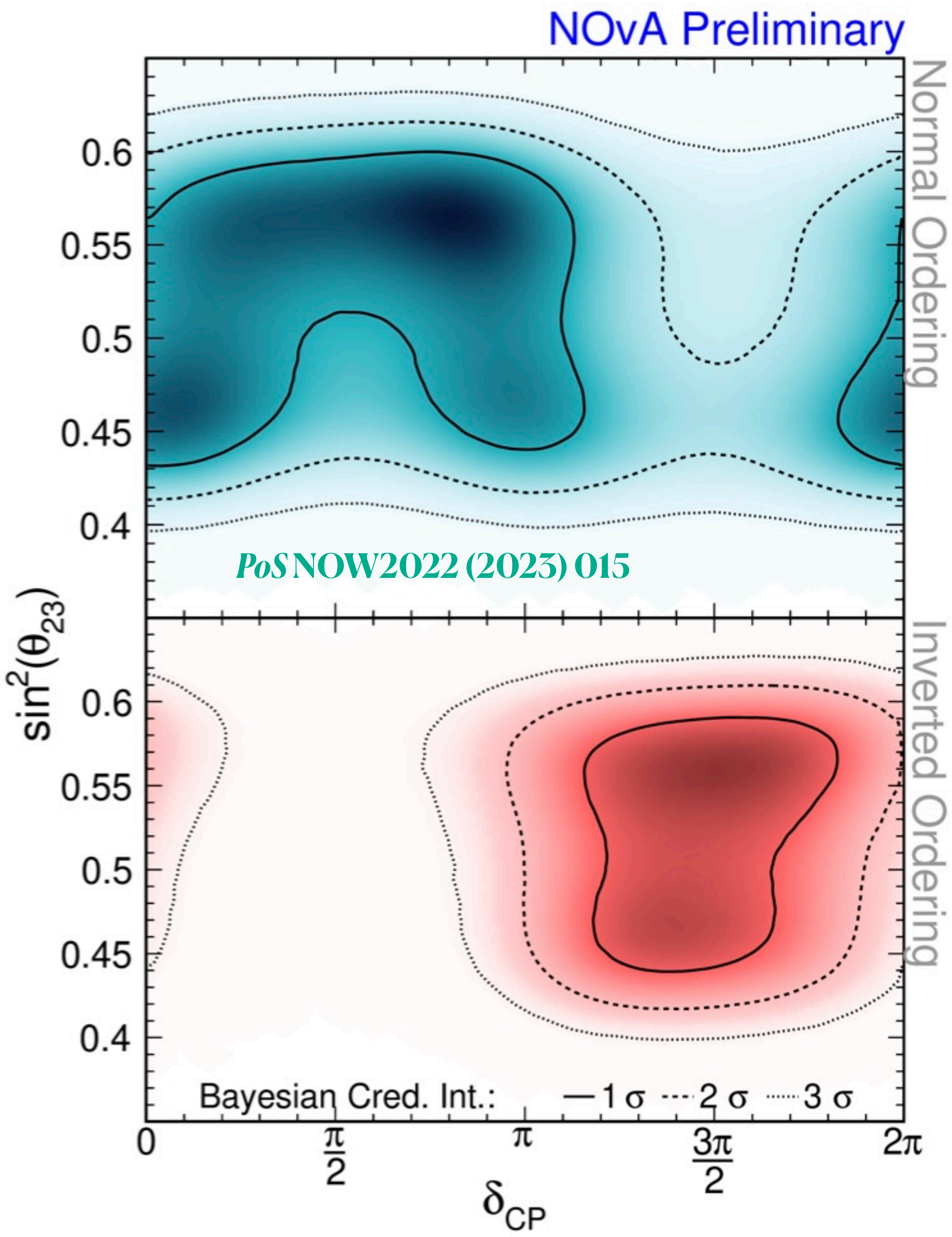
- T2K excludes CP conservation ($\delta_{CP} = 0,\ \pi$) with more than 90% C.L. but less than 2σ C.L. Wide range of δ_{CP} in the inverted ordering is excluded with more than 3σ C.L.
- T2K weakly favors normal mass ordering and higher octant with Bayes factor of 2.8 and 3.0 respectively

Use reactor constraint $\sin^2\theta_{13} = (2.18 \pm 0.07) \times 10^{-2}$

NOvA: CP violation, mass ordering…

- NOvA data is more consistent with the CP-conservation than $\delta_{CP} \sim -\pi/2$ $(or\ 3\pi/2)$ values as T2K's indication if neutrino mass ordering is normal
- Both T2K and NOvA indicate $\delta_{CP} \sim -\pi/2$ $(or\ 3\pi/2)$ in the inverted ordering option
- NOvA weakly favors normal mass ordering and higher octant





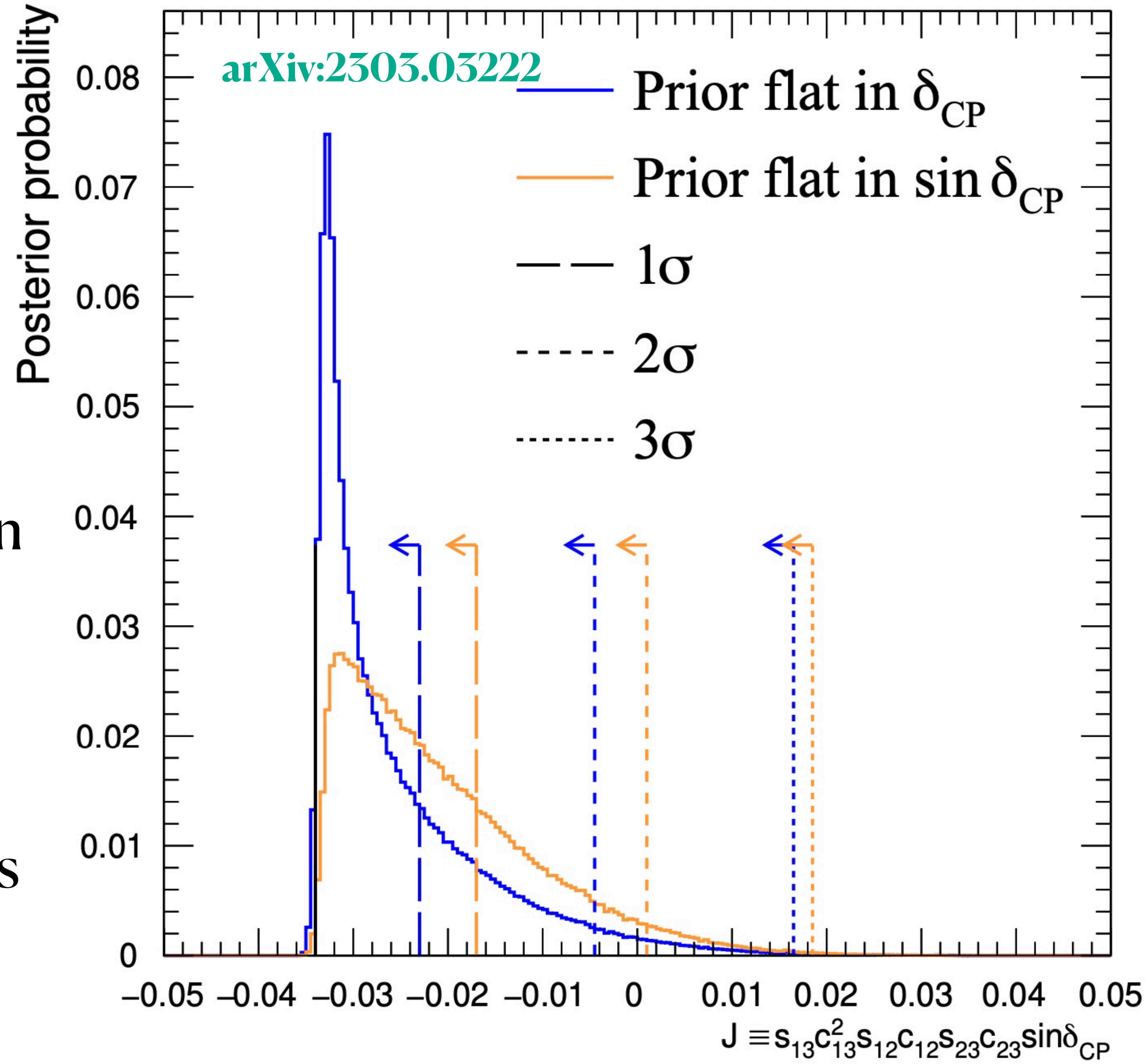
	N. Ordering	I. Ordering	
U. Octant	41.7%	20.9%	62.6%
L. Octant	25.8%	11.5%	37.4%
	67.5%	32.5%	

Jarlskog invariant

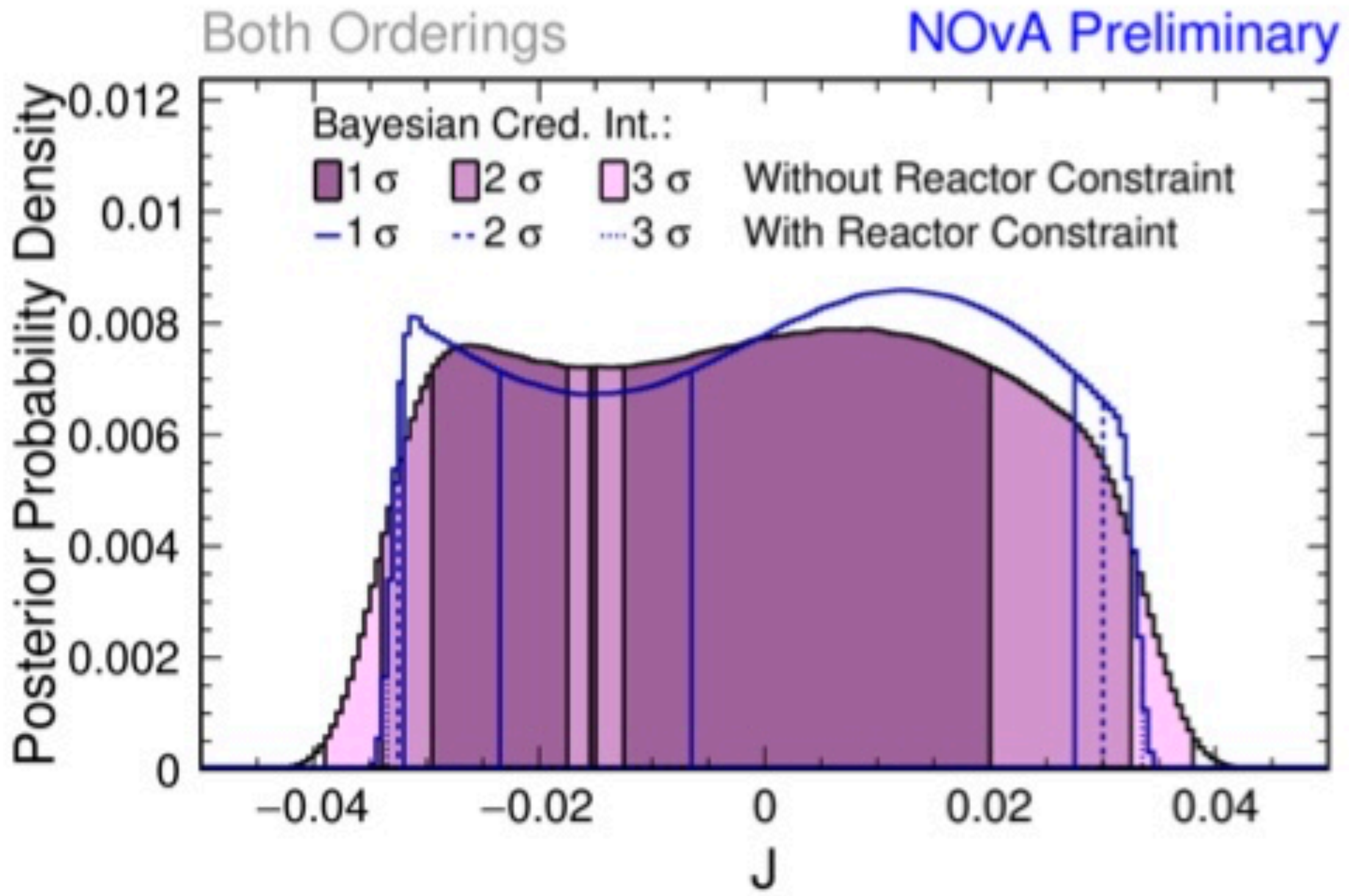
$$J_{CP}^{Lepton} = Im[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}]$$

$$= \frac{1}{8}\sin 2\theta_{12}\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{23}\sin\delta_{CP}$$

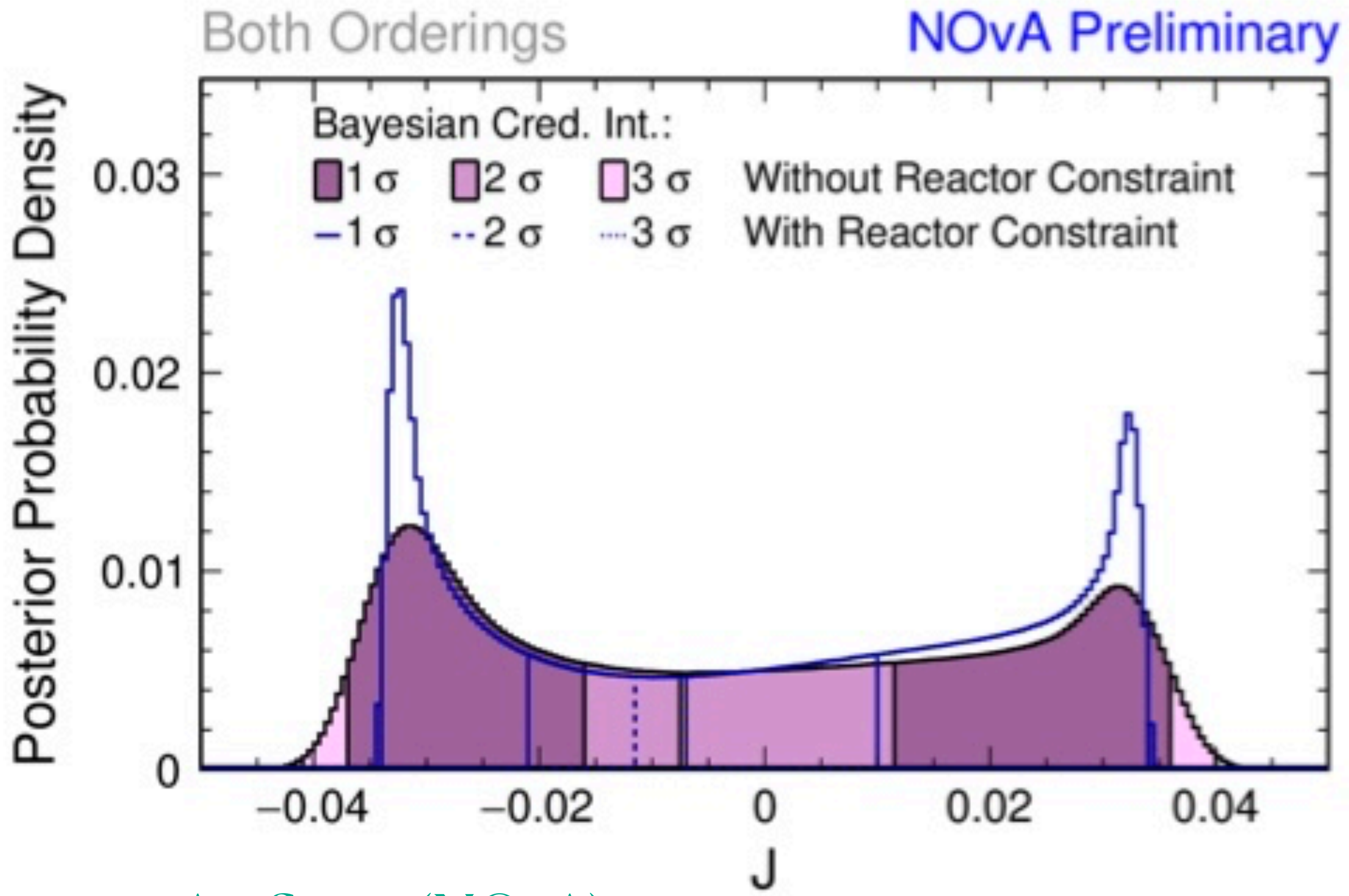
- Jarlskog invariant characterizes the amplitude of CPV and do not depend on parameterization
- $J_{CP} \neq 0$: CP is violated
- T2K can exclude zero J_{CP} at more than 2σ (or just below 2σ) credible level if a flat prior of δ_{CP} ($\sin\delta_{CP}$) is assumed
- With a flat prior of δ_{CP}, NOvA also has majority of probability at $|J_{CP}| \approx 0.03$



Prior uniform in $\sin(\delta_{CP})$:



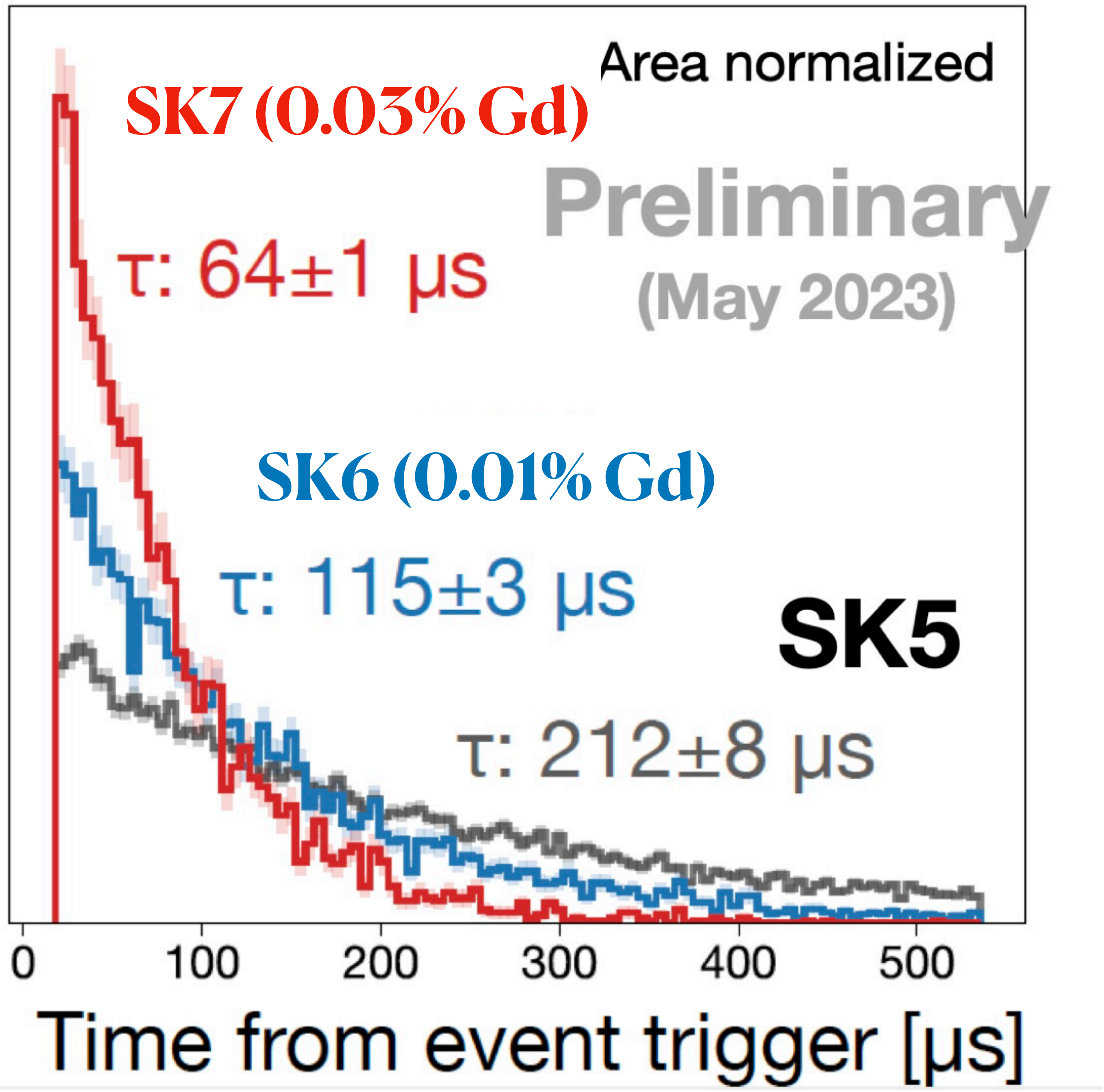
Prior uniform in δ_{CP}:



A. Sztuc (NOvA)
@ Moriond EW 2023

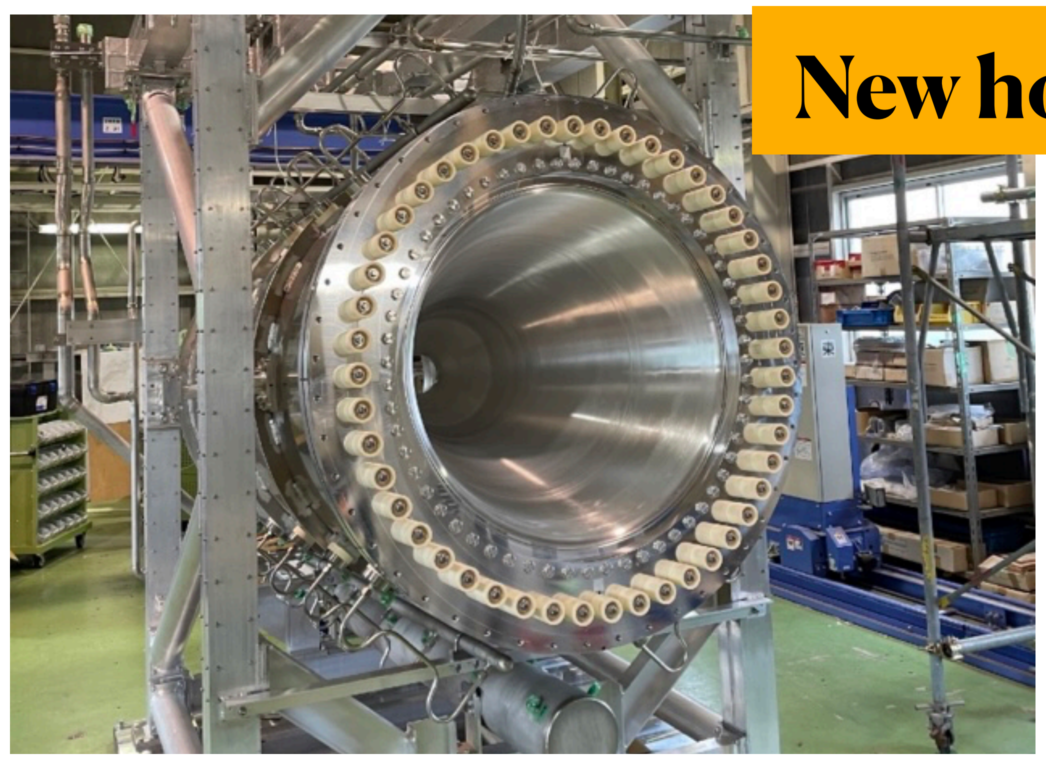
Prospects: Coming data with T2K and J-PARC upgrades

(1) Super-K as T2K far detector has been successful in loading Gd (0.03%), ~ 75% neutron capture efficiency



Neutron-capture time w/ atmospheric ν events

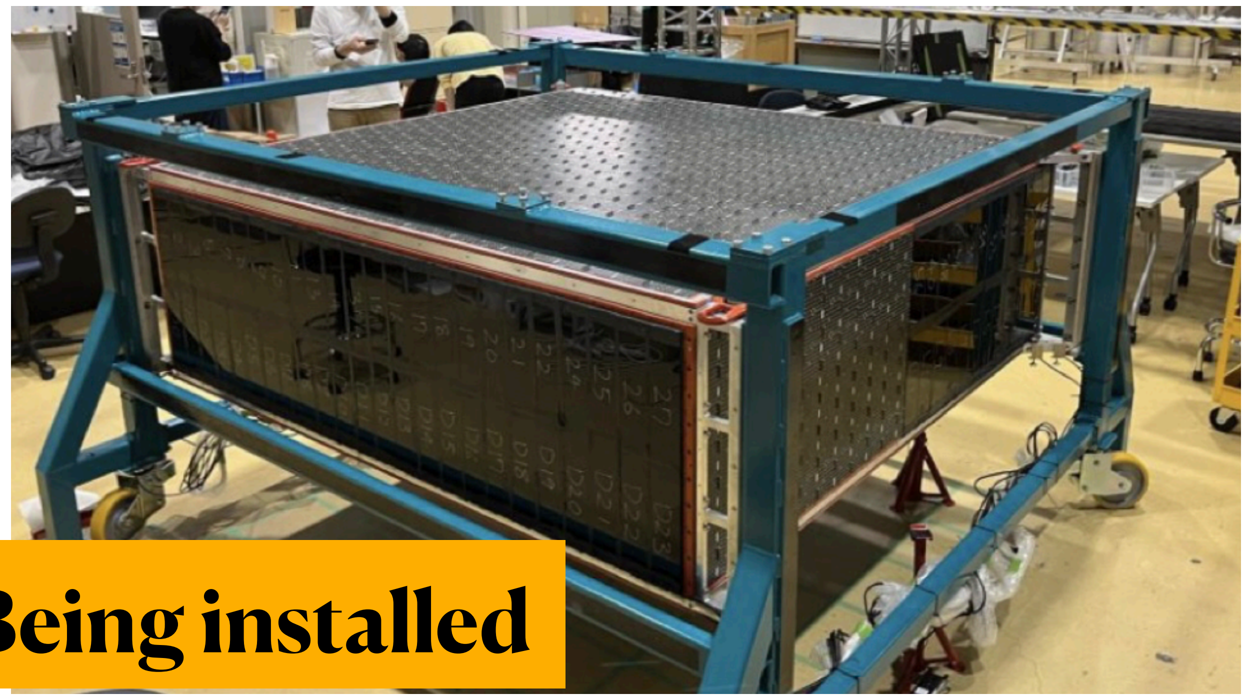
(2) J-PARC accelerator upgrade to faster proton delivery 2.48 s ➔ 1.32 s. Horn operation with 250kA ➔ 320kA, effectively 10% statistics increase and wrong-signed background suppression



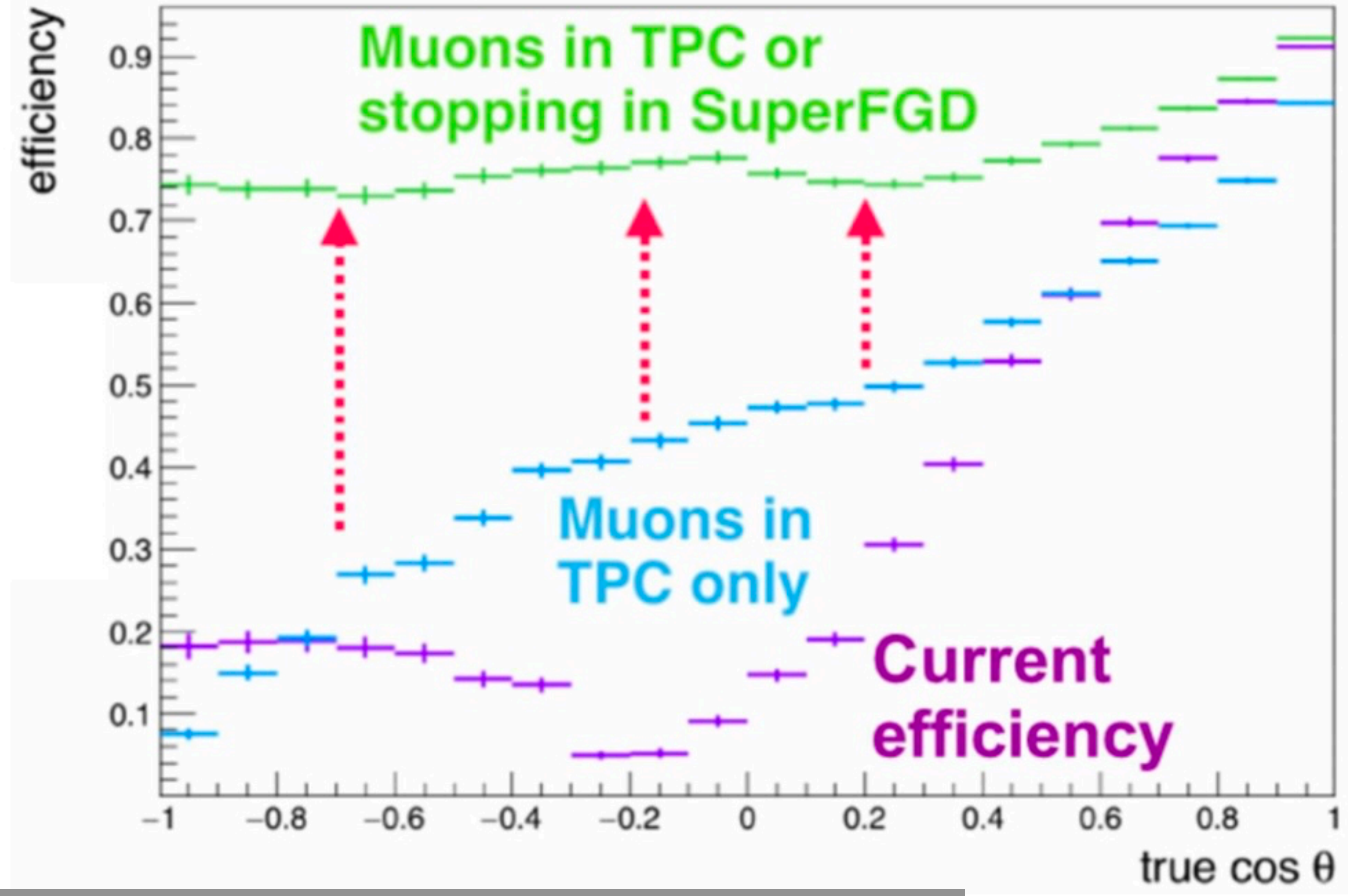
New horn

New MR magnet PS

(3) New near detector, Super-FGD, with ~2 millions 1cm^3 scintillation cube and 56k readout channels, and high-angle TPC for tracking charged particles with lower energy threshold and close to 4π angular acceptance

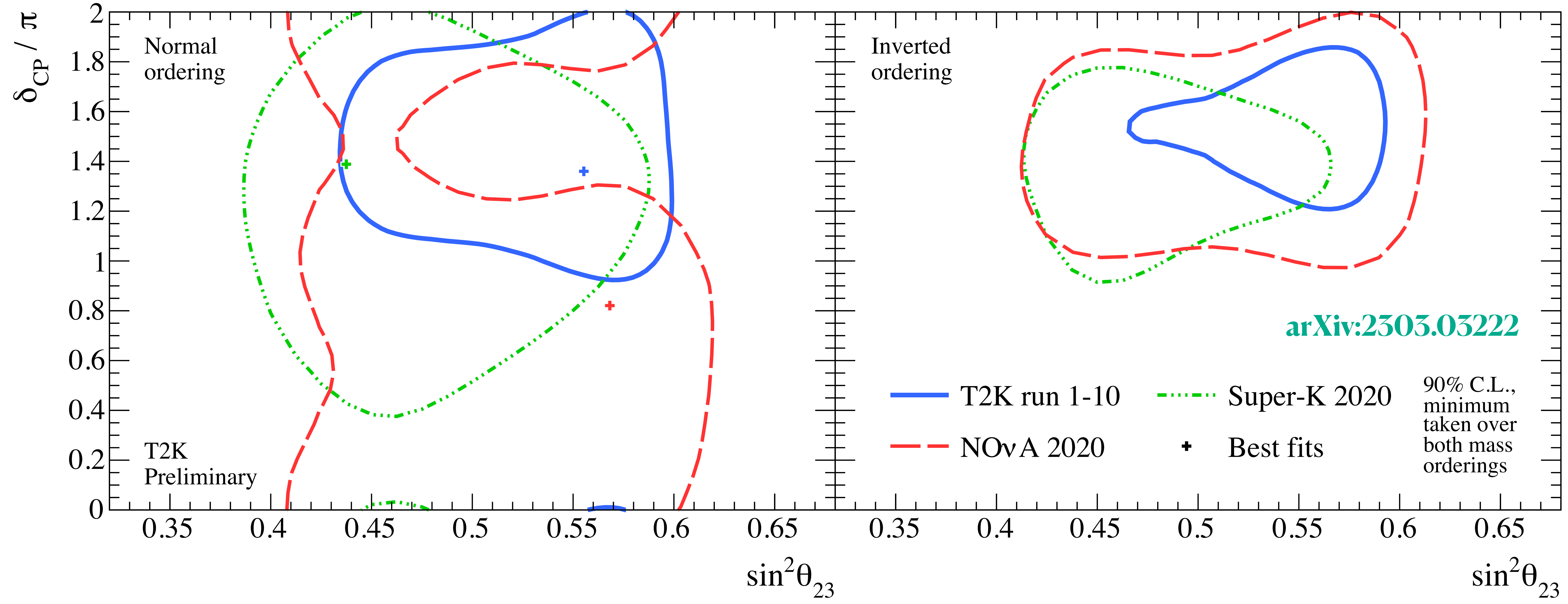


Being installed



Ref: N. Q. Viet's talk on Aug. 8th

Prospects: T2K-NOvA joint analysis



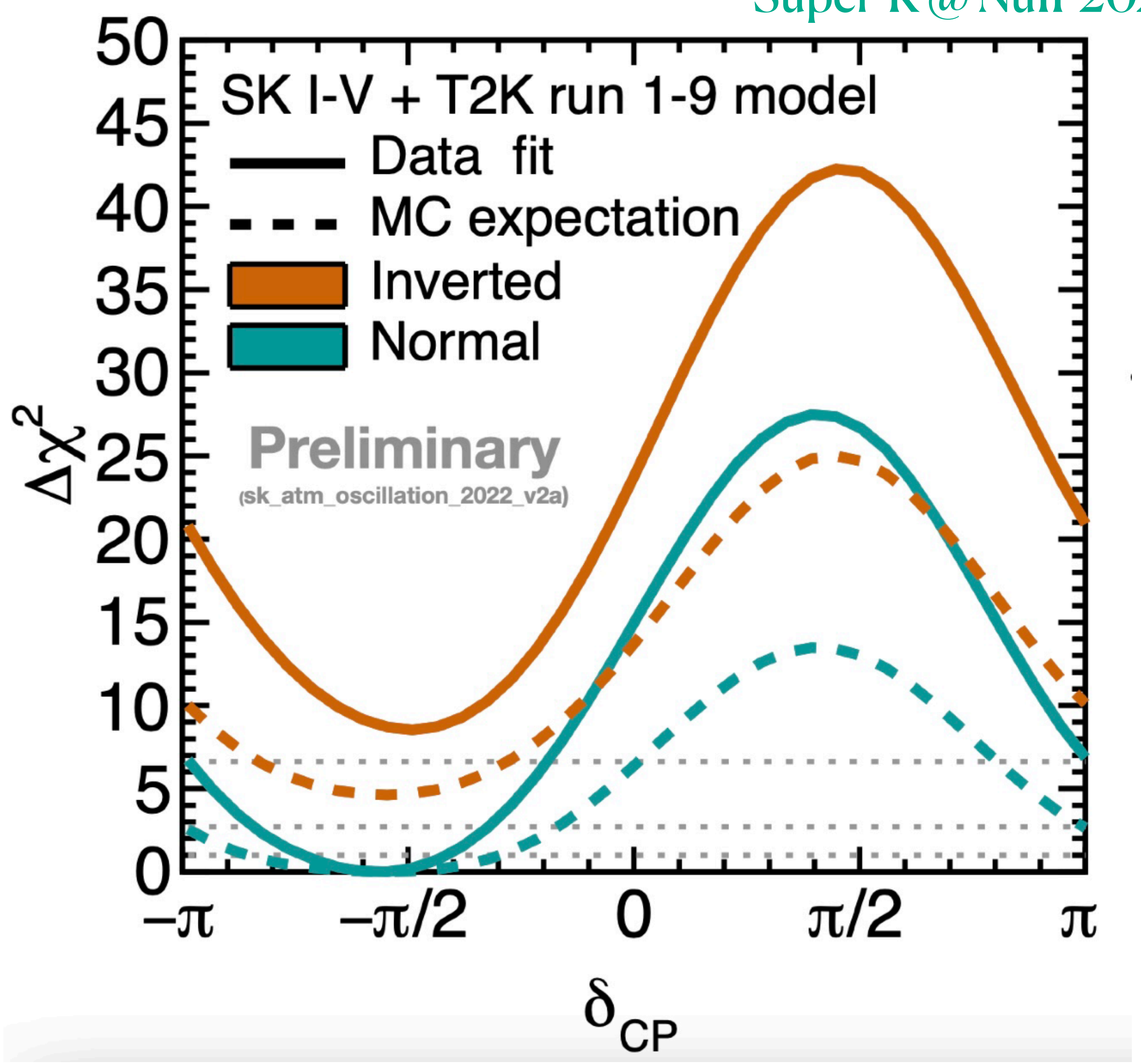
Official joint analysis btw. T2K and NOvA formulated and now under review process. Expected benefits:

- Complementarity (baseline/energy) to explore wider range of oscillation parameter space, particularly for CP violation, mass ordering, and precise mixing angle θ_{23}
- To use full likelihood maps for both experiments
- Study and examine neutrino interaction models currently used and tuned in each experiment
- Correlate the systematic uncertainties where appropriate

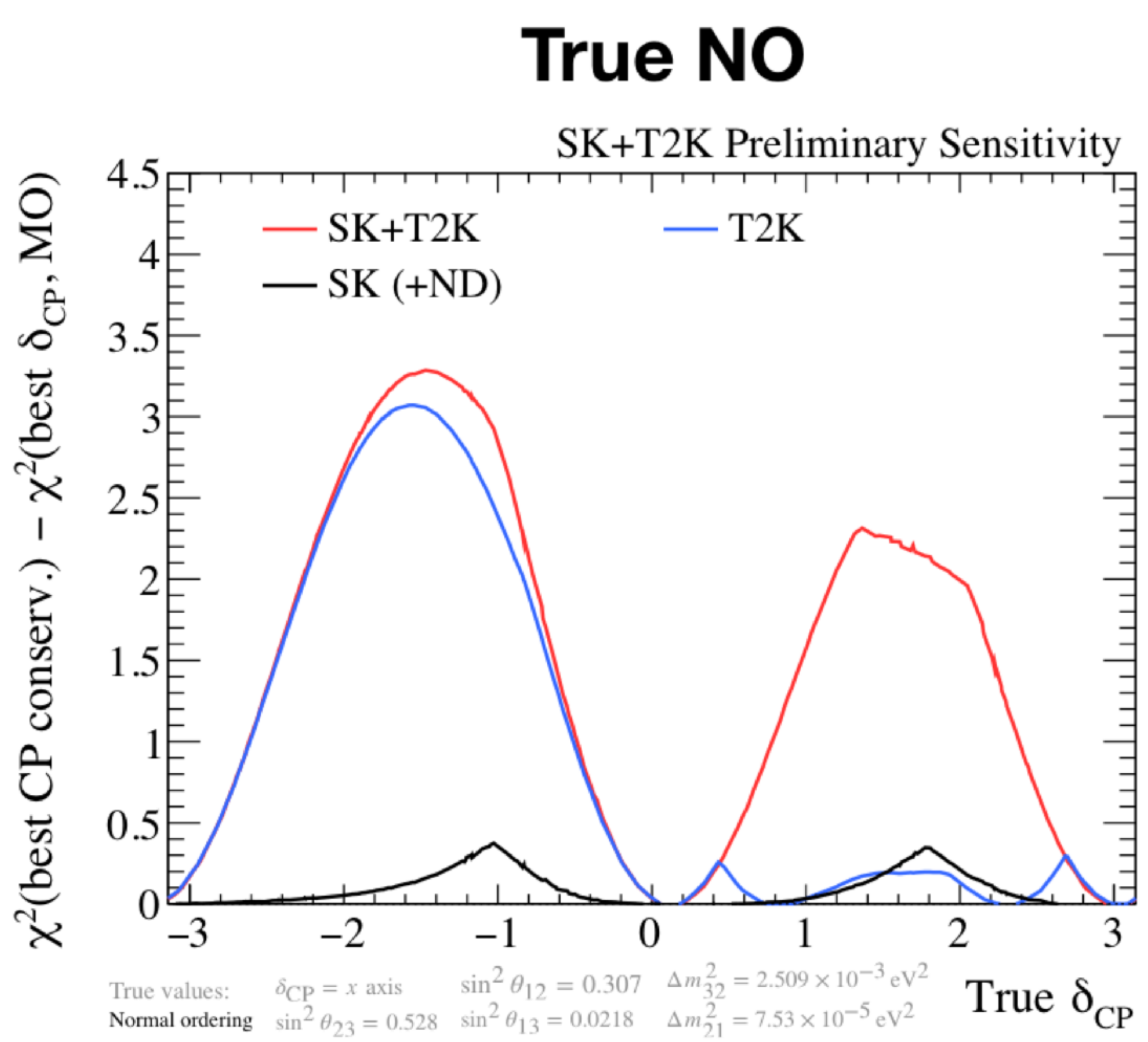
Prospects: T2K & Super-K atmospheric joint analysis

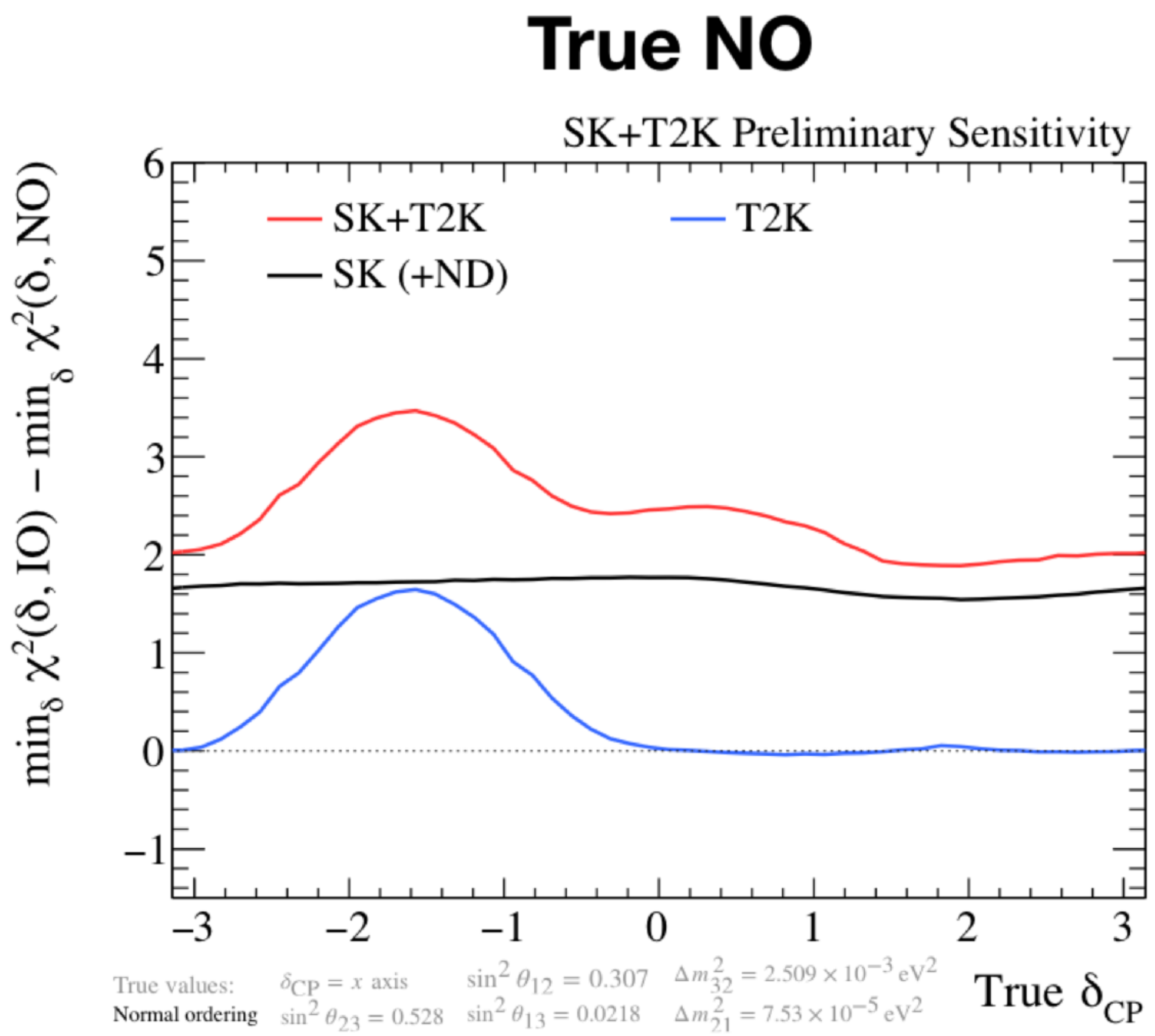
- Common detector ➔ strong correlated detector systematics and neutrino interaction models
- Complementarity to explore wider range of parameter space
- Enhance the sensitivity to mass ordering and potential break the δ_{CP}-mass ordering degeneracy

Super-K @ NuIF2023



From SK collaboration, not official joint T2K-SK





Summary

- T2K provides significant hints on CP violation but NOvA shows dissimilar tendency if mass ordering is normal. If mass ordering is inverted, the two consistently favor maximal CP violation.
- Normal mass ordering and higher octant of θ_{23} are weakly preferred for both exp.
- For non-standard physics
  - No significant deviation from the CPT (and Lorentz) conservation
  - No indication of sterile neutrino
- More data is coming and being acquired faster thanks to the beamline upgrade
- Incoming joint T2K-NOvA analysis; and joint T2K-Super-K analysis

We are getting close to the answers to the remaining unknowns in the νStandard Model. Stay tuned!