T2K experiment

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ICRR Young Researchers' Workshop

Contents

Neutrino Mixing

- Neutrino flavor (weak) eigenstates and mass eigenstates are mixed

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

Weak eigenstate (α = e, μ, τ)

Mass eigenstate (i = 1, 2, 3)

PMNS mixing matrix

- Neutrinos change their flavor as they travel (neutrino oscillation)
- Natural interferometer to explore fundamental nature of neutrinos

Two neutrino case: $P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 = \sin^2 2\theta \sin^2 \left(\Delta m^2 \frac{L}{4E} \right)$

Amplitude ($\sin^2 2\theta$)

Frequency (Δm^2)

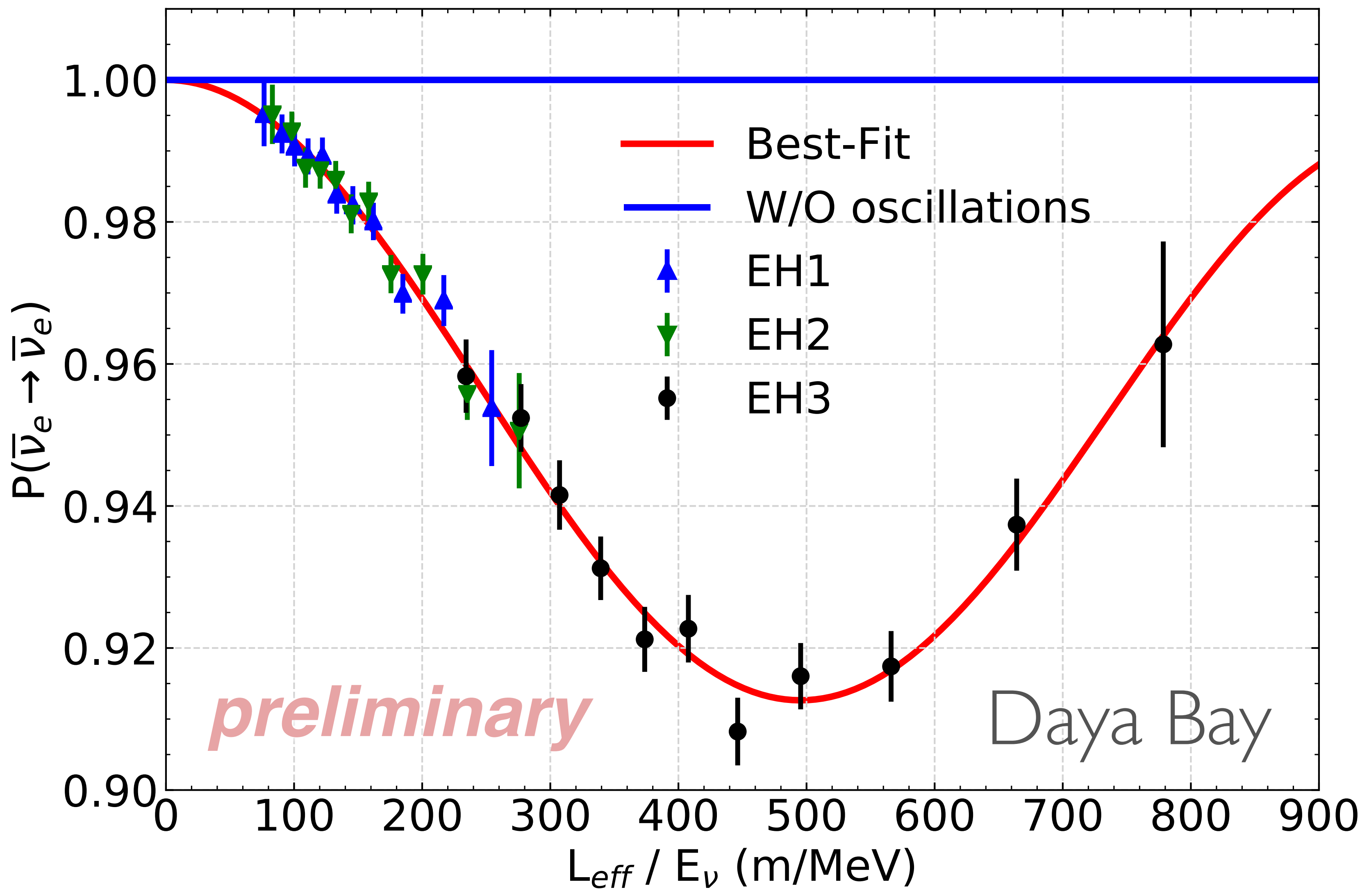


Figure taken from J. P. Ochoa's presentation at Neutrino2018

θ	**: mixing angle**
Δm^2	**: mass squared difference**
L	: the distance traveled
E	: the energy of neutrino

Neutrino Mixing

All the three angles are finally observed!

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

$\theta_{23} \approx 45^o$
Atmospheric ν
Accelerator ν

$\theta_{13} \sim 9^o$
Reactor ν

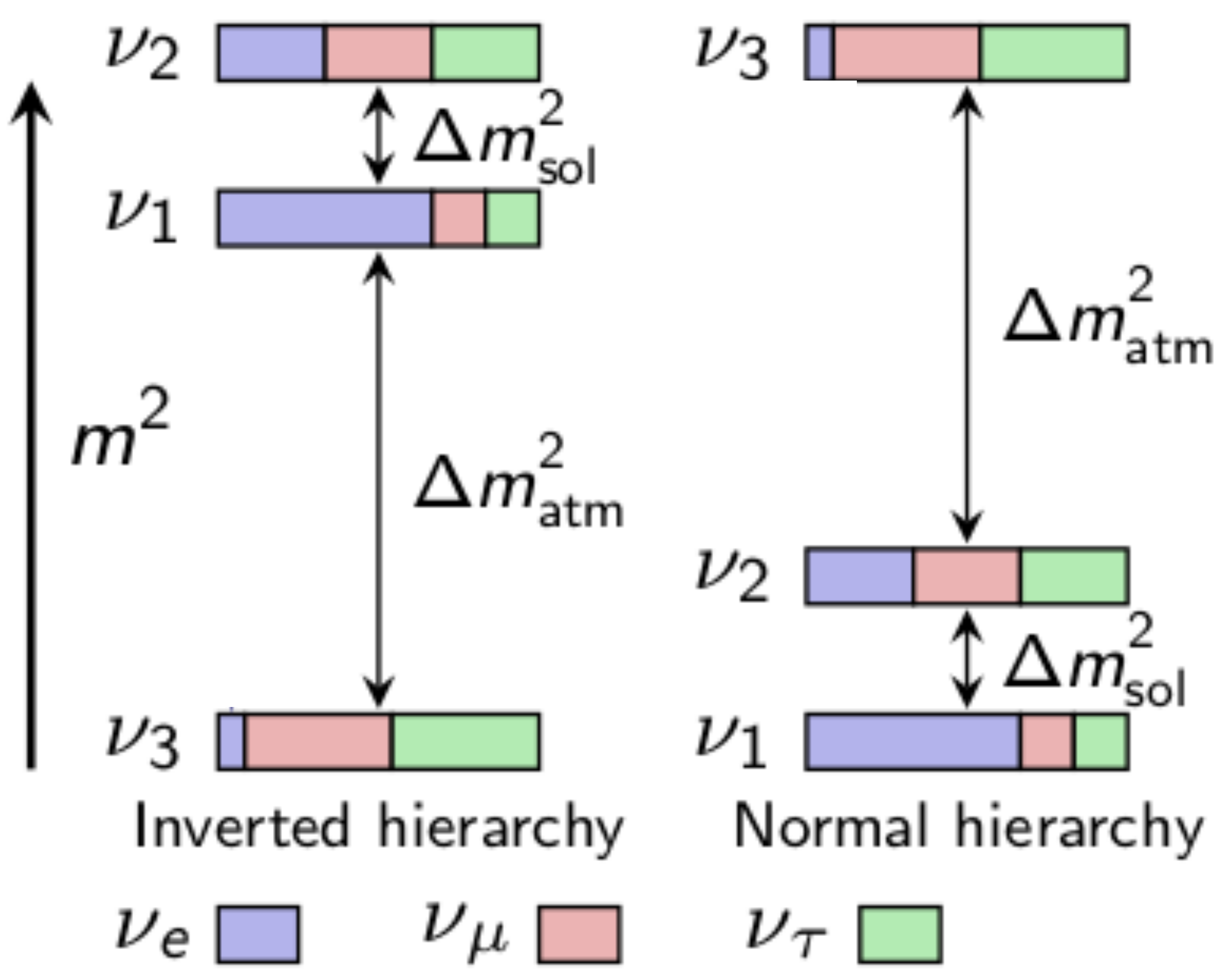
$\theta_{12} \approx 35^o$
Solar ν
Reactor ν

$\Delta m^2_{32} \sim \Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2

$\Delta m^2_{21} \sim 7.5 \times 10^{-5}$ eV^2

Still many open questions:

- **What is the CP-violation phase, δ_{CP} ?**
- What is the absolute mass scale/ordering?
- What is the origin of neutrino mass?
- Are there any extra spices?

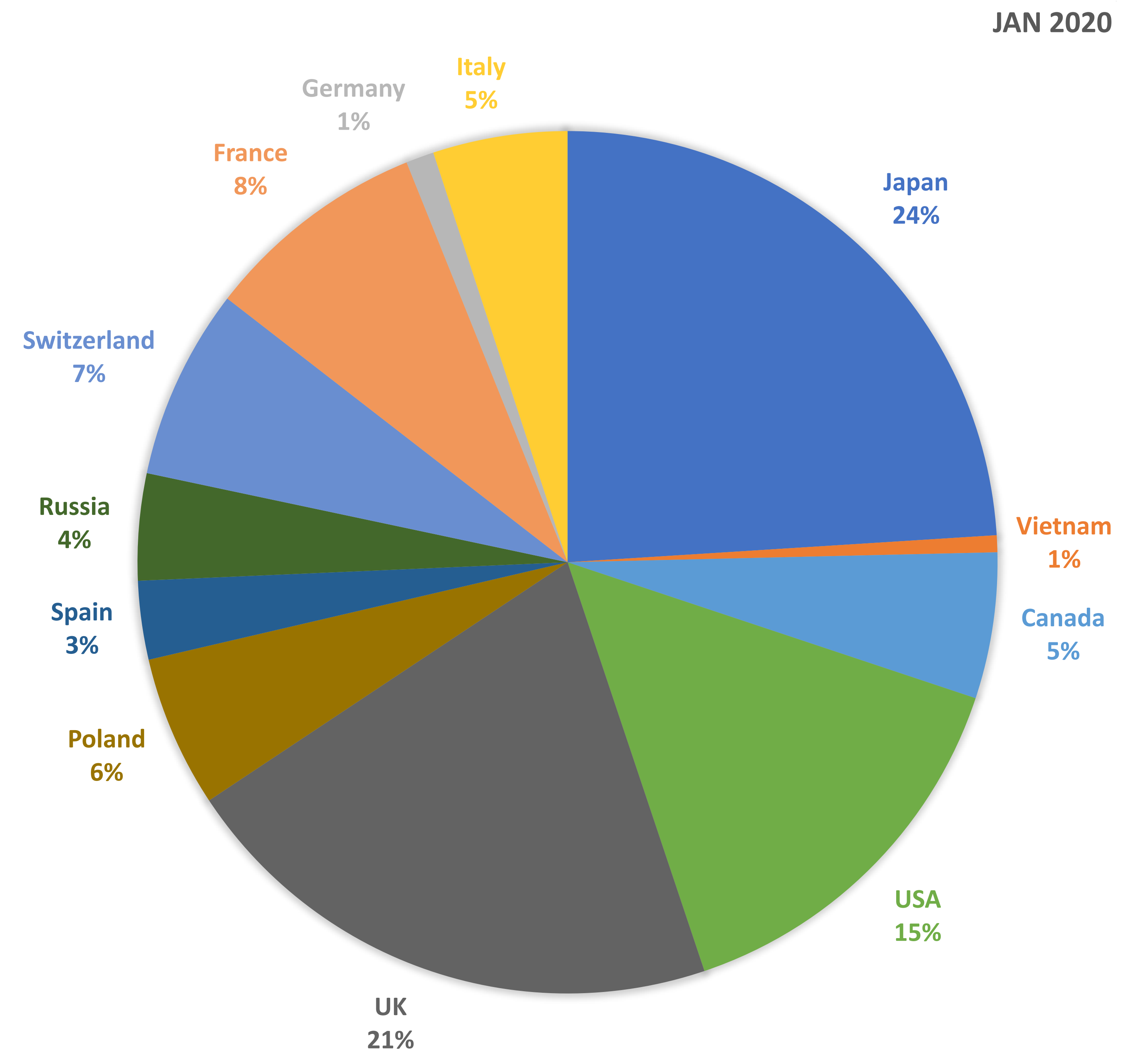


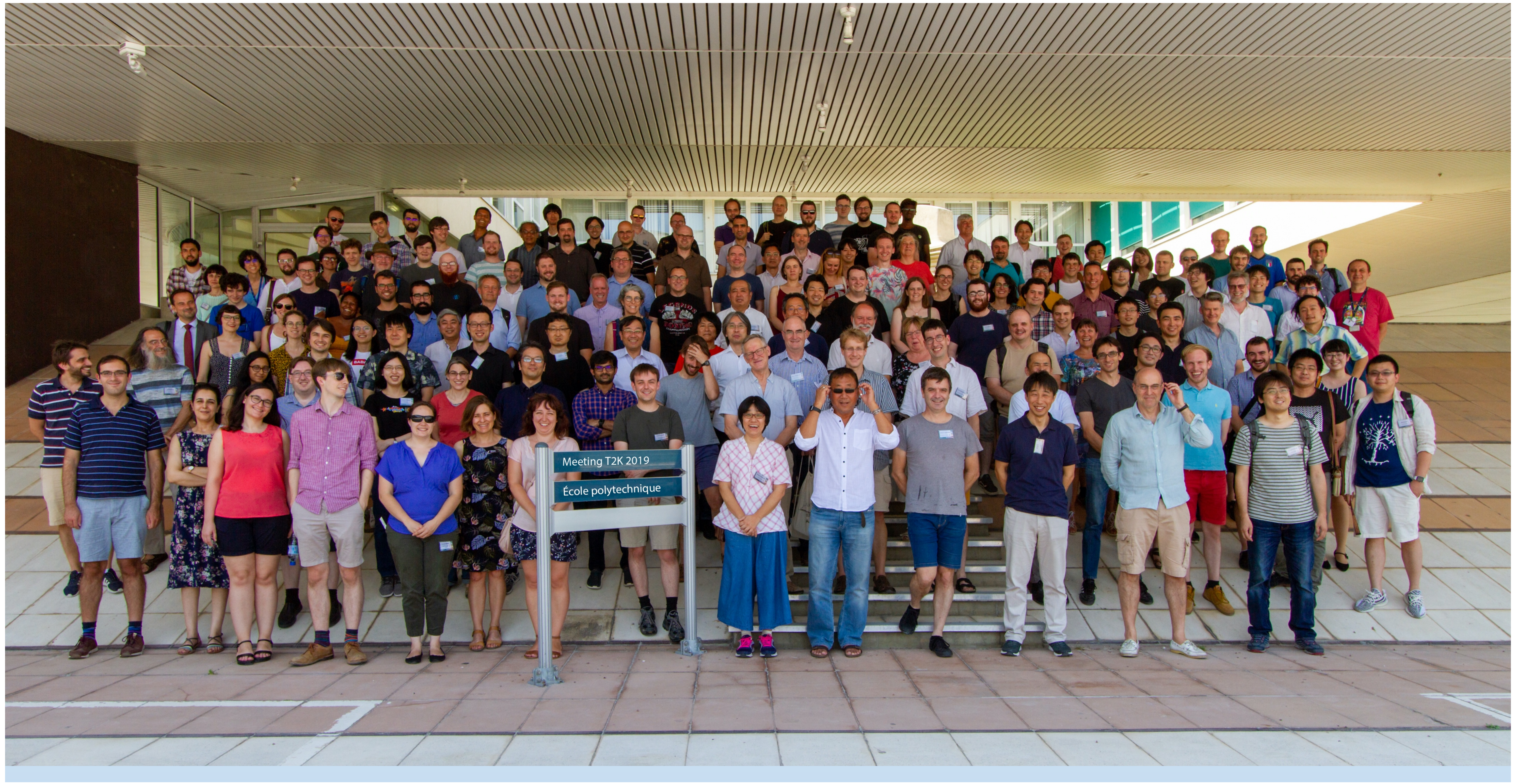
T2K experiment

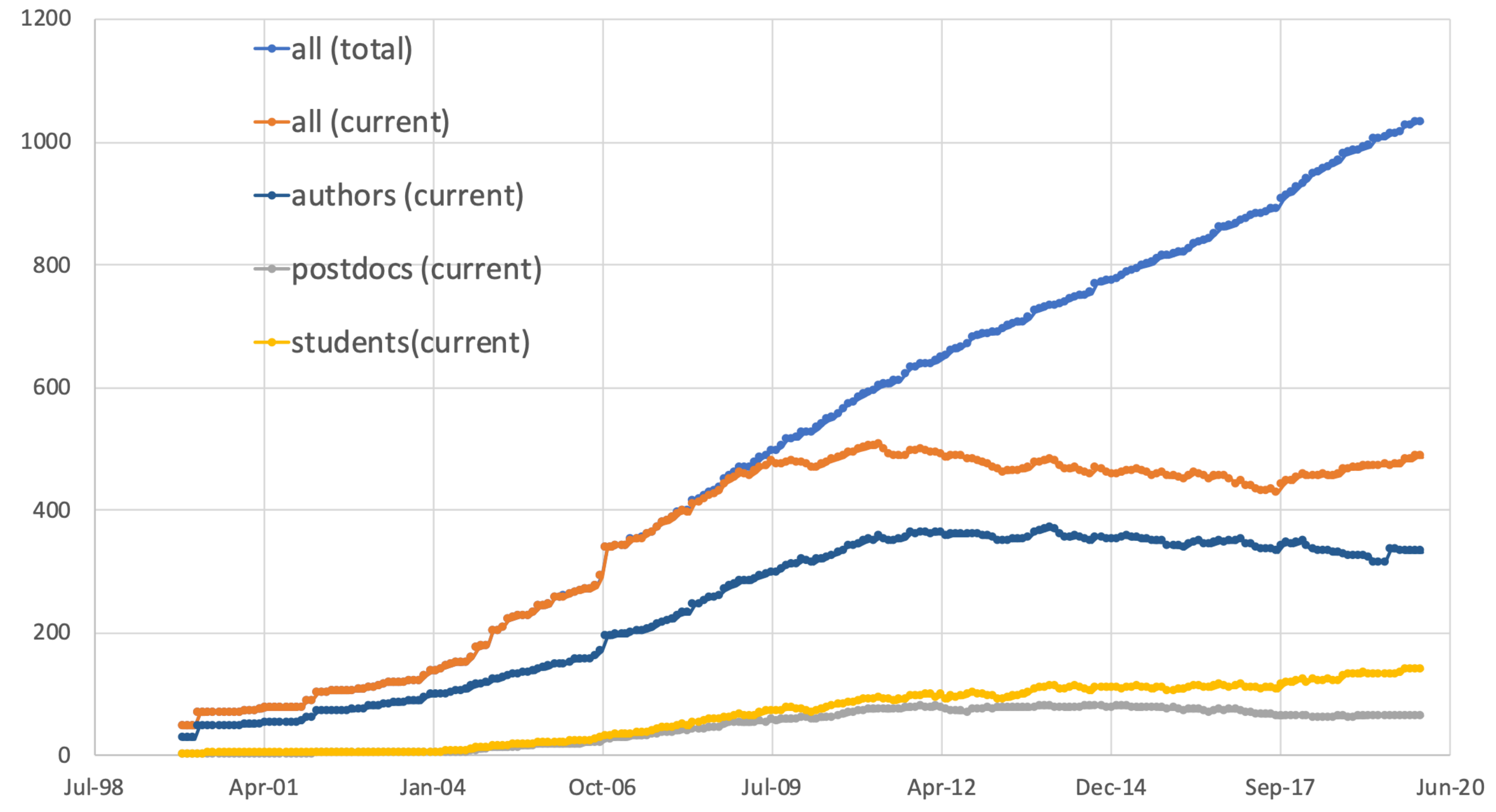
Tokai-to(2)-Kamioka long-baseline neutrino oscillation experiment

T2K collaboration

- ~500 members, 69 institutes, 12 countries







ICRR members of T2K

- Kamioka Observatory: 17 members
  - K. Abe, C. Bronner, Y. Hayato, M. Ikeda, J. Kameda, Y. Kataoka, M. Miura, S. Moriyama, M. Nakahata, Y. Nakajima, S. Nakayama, H. Sekiya, M. Shiozawa, Y. Sonoda, A. Takeda, H. Tanaka, T. Yano
- RCCN (Kashiwa): 5 members
  - T. Kajita, G. Megias, K. Okumura, H. Seungho, J. Xia

Blue: (Project) Assistant professors and Postdocs
Green : Graduate students

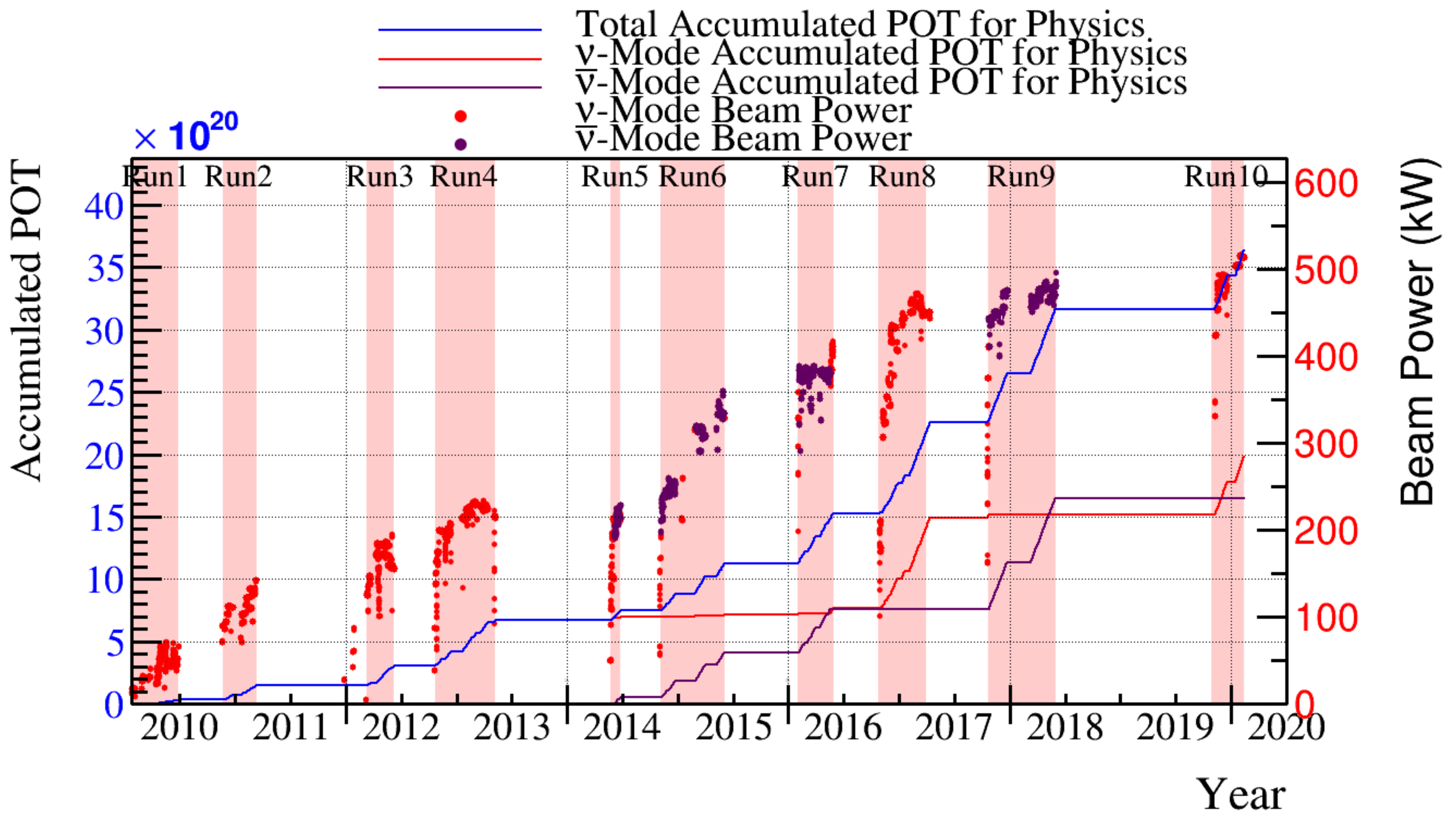
Latest neutrino oscillation analysis results

Nature **580**, no.7803, 339-344 (2020)
Updated results in Neutrino 2020

C. Bronner (ICRR): one of the oscillation analysis conveners
Y. Nakajima (ICRR): one of the T2K-SK working group conveners

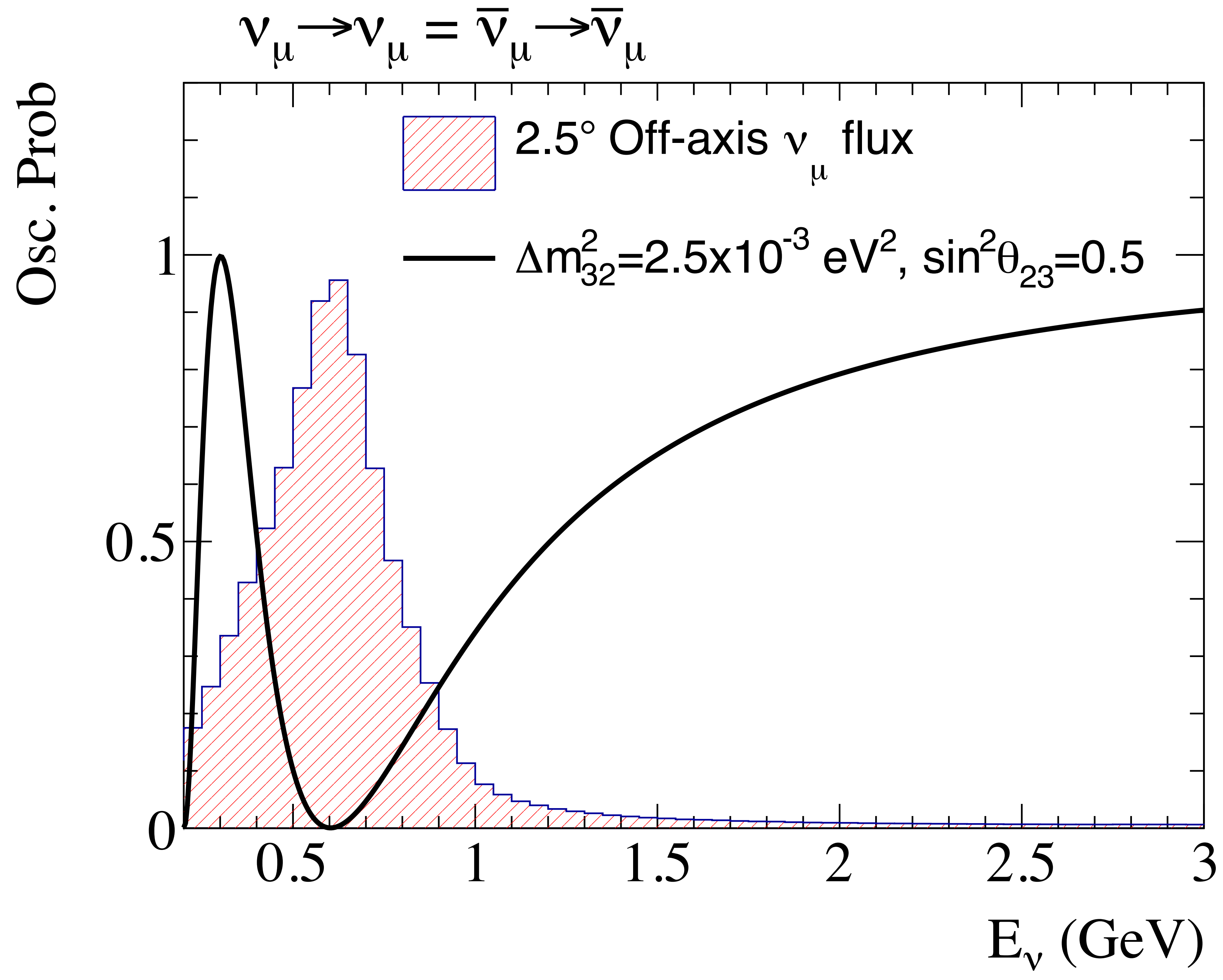
T2K operation history

- Data taking started in 2009
- 515 kW stable operation achieved in 2020
- Total collected protons-on-target (POT):
  - 1.97 x 10^{21} (ν-mode)
  - 1.63 x 10^{21} ($\bar{\nu}$-mode)



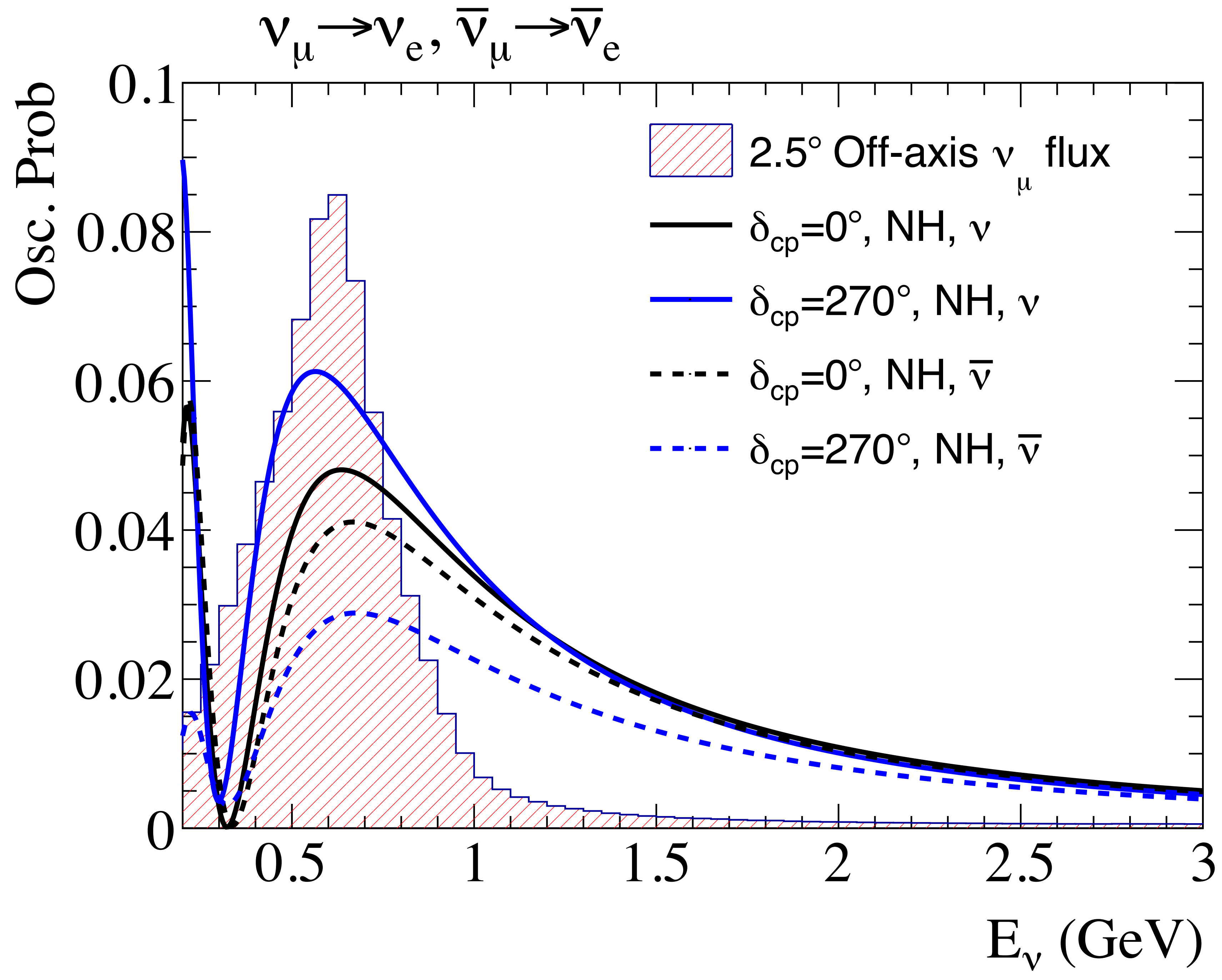
Oscillation signatures

ν_μ disappearance



- Precision measurement of **$\sin^2 2\theta_{23}$** and **$|\Delta m^2_{32}|$**

ν_e appearance



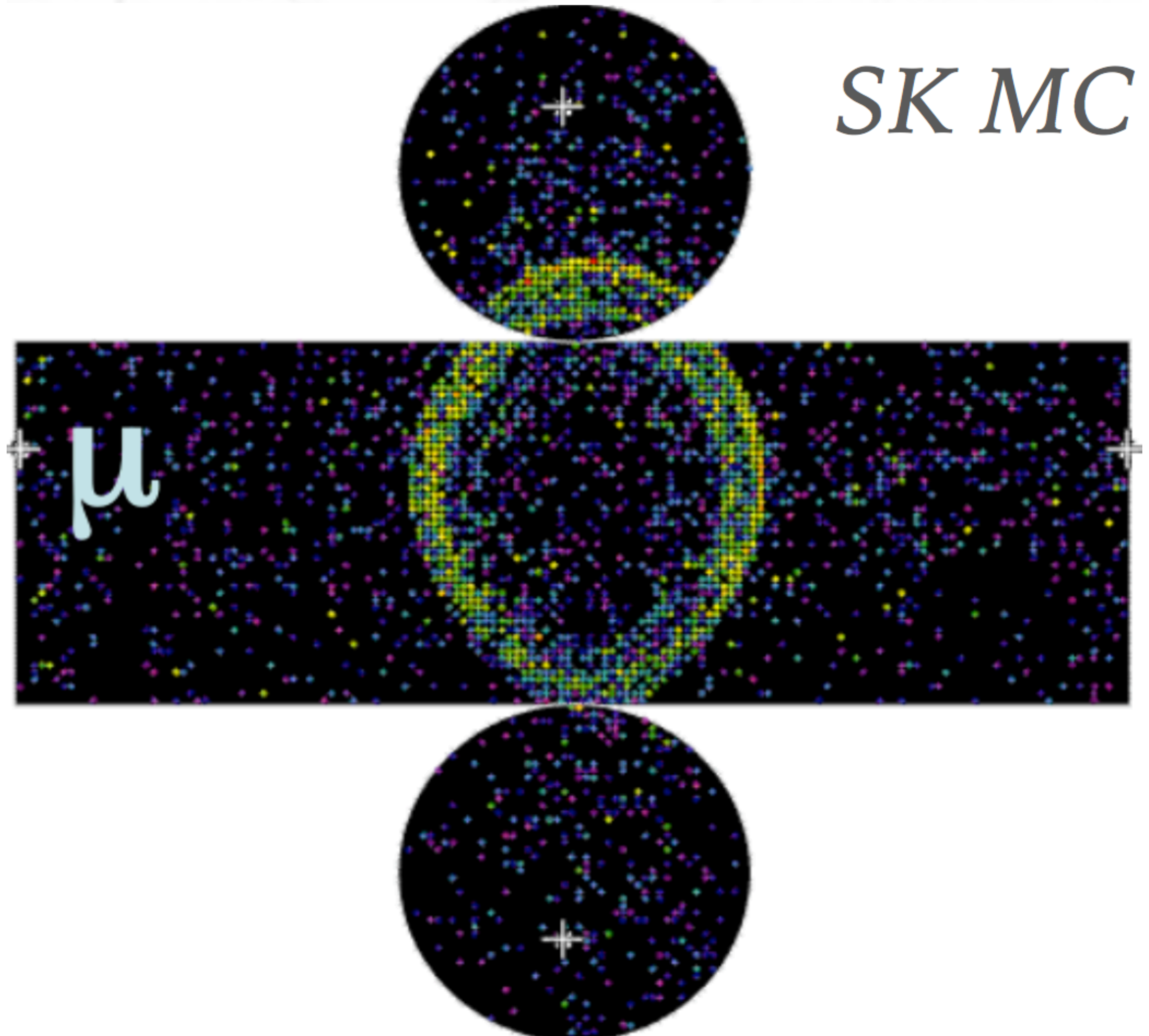
- Sensitivity to **$\sin^2 2\theta_{13}$**, CP violating phase **δ**, **θ_{23} octant**, and **mass ordering** through the matter effect

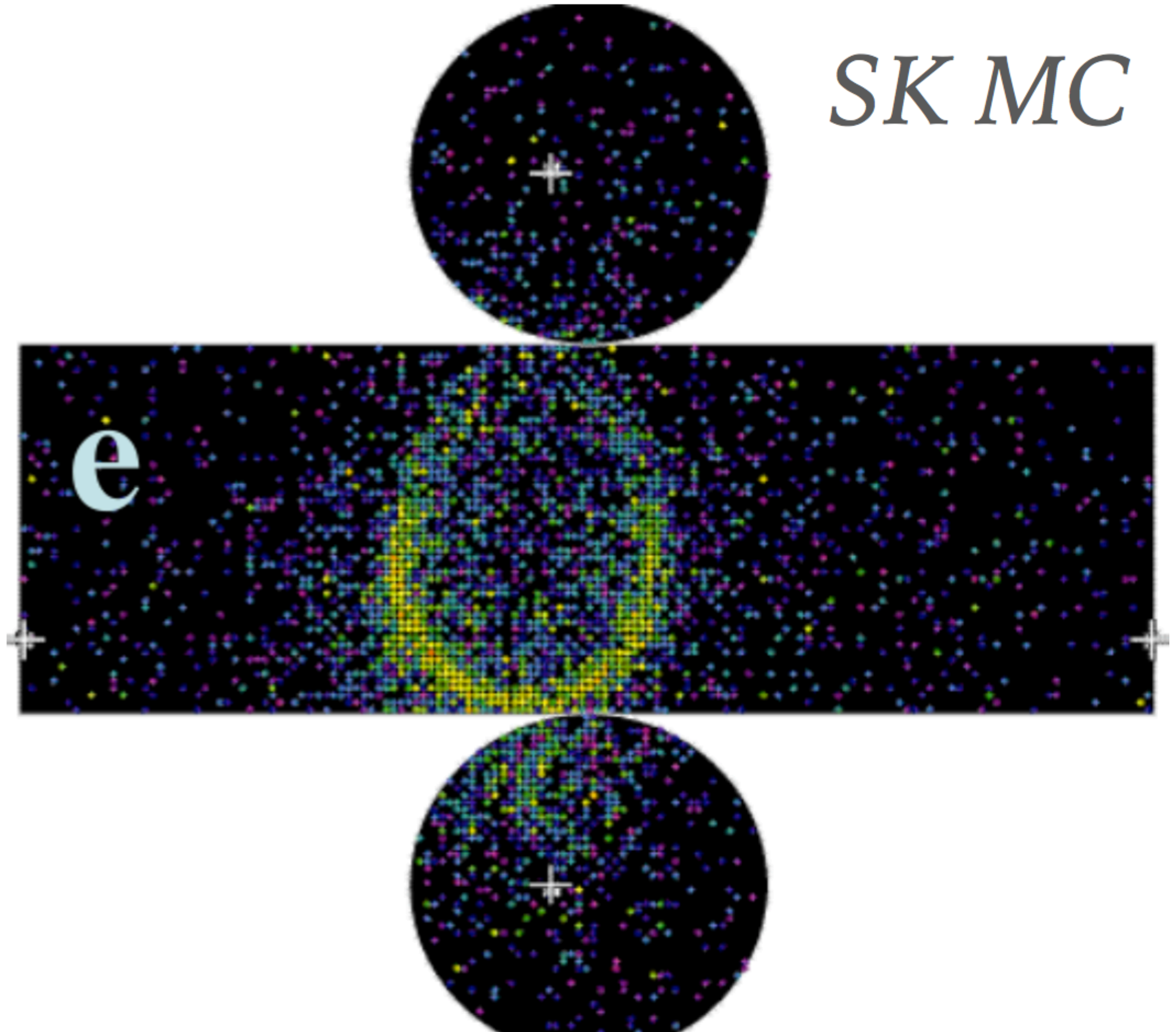
Signal at Super-Kamiokande

- Primary signal: Charged-Current Quasi-Elastic scattering
- Identify neutrino flavor by outgoing leptons
- Reconstruct neutrino energy with lepton kinematics

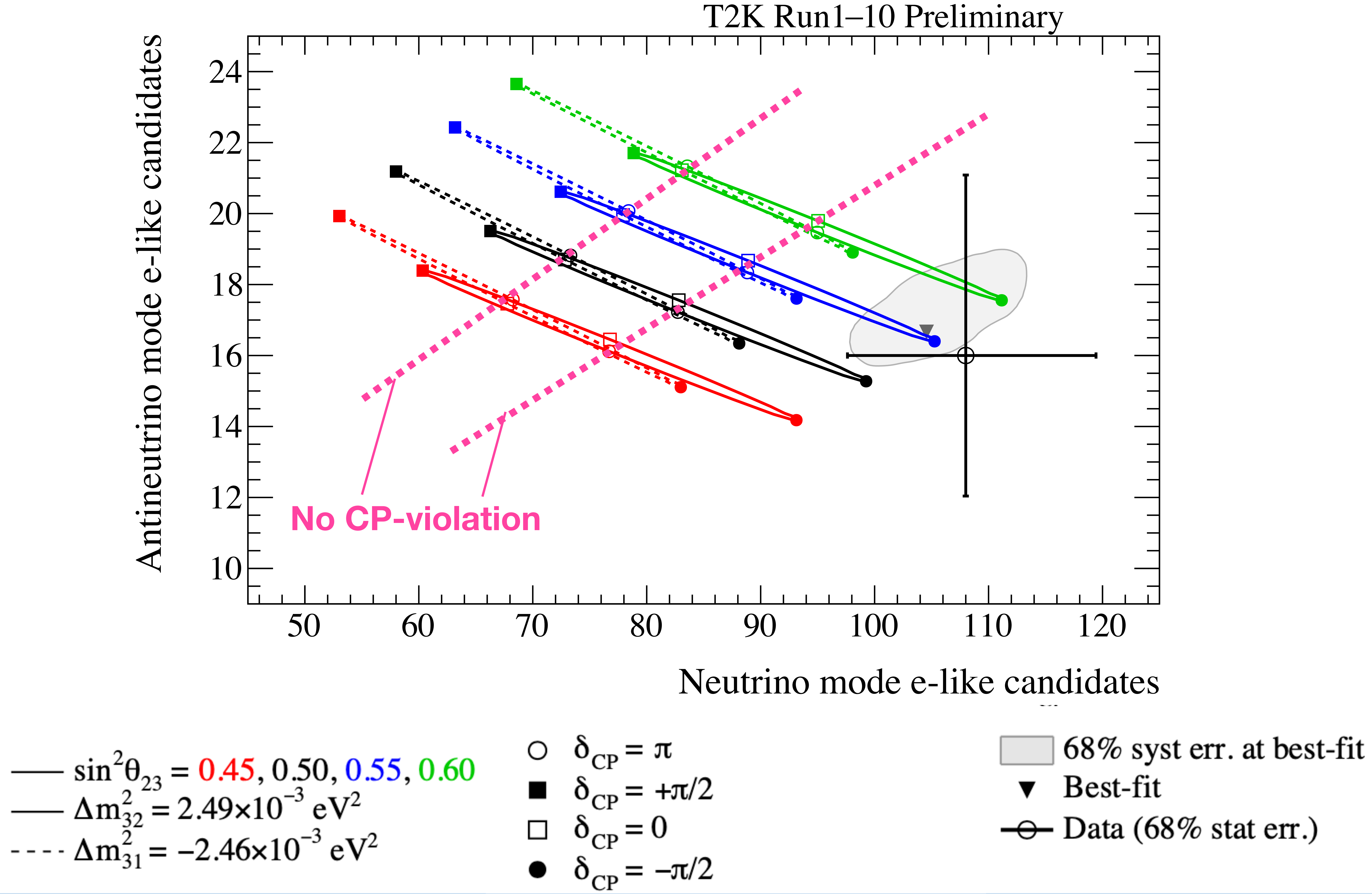
$$\overset{(-)}{\nu}_{\mu} + n(p) \rightarrow \mu^{-(+)} + p(n)$$

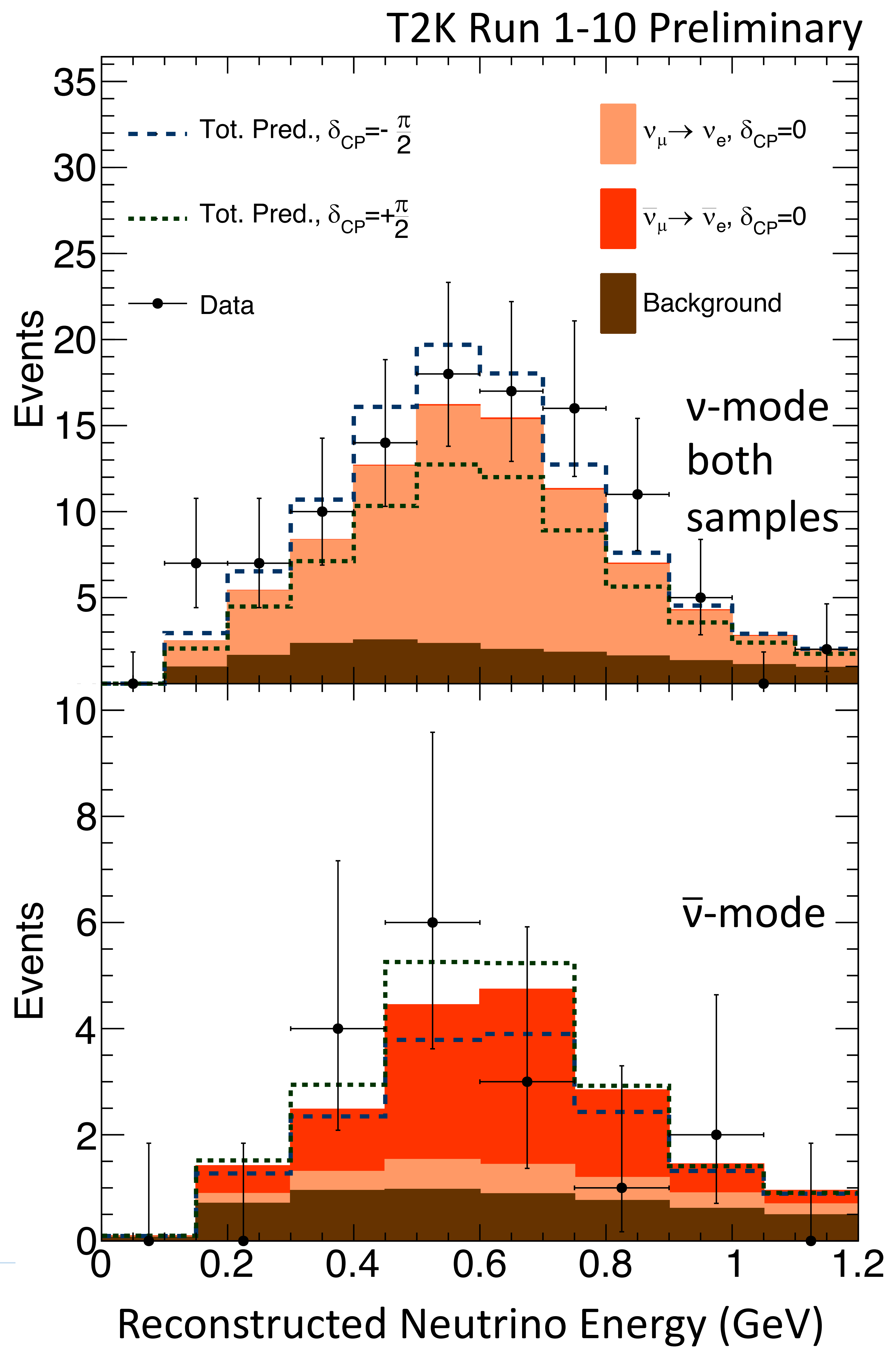
$$\overset{(-)}{\nu}_{e} + n(p) \rightarrow e^{-(+)} + p(n)$$





Observed electron neutrino candidates

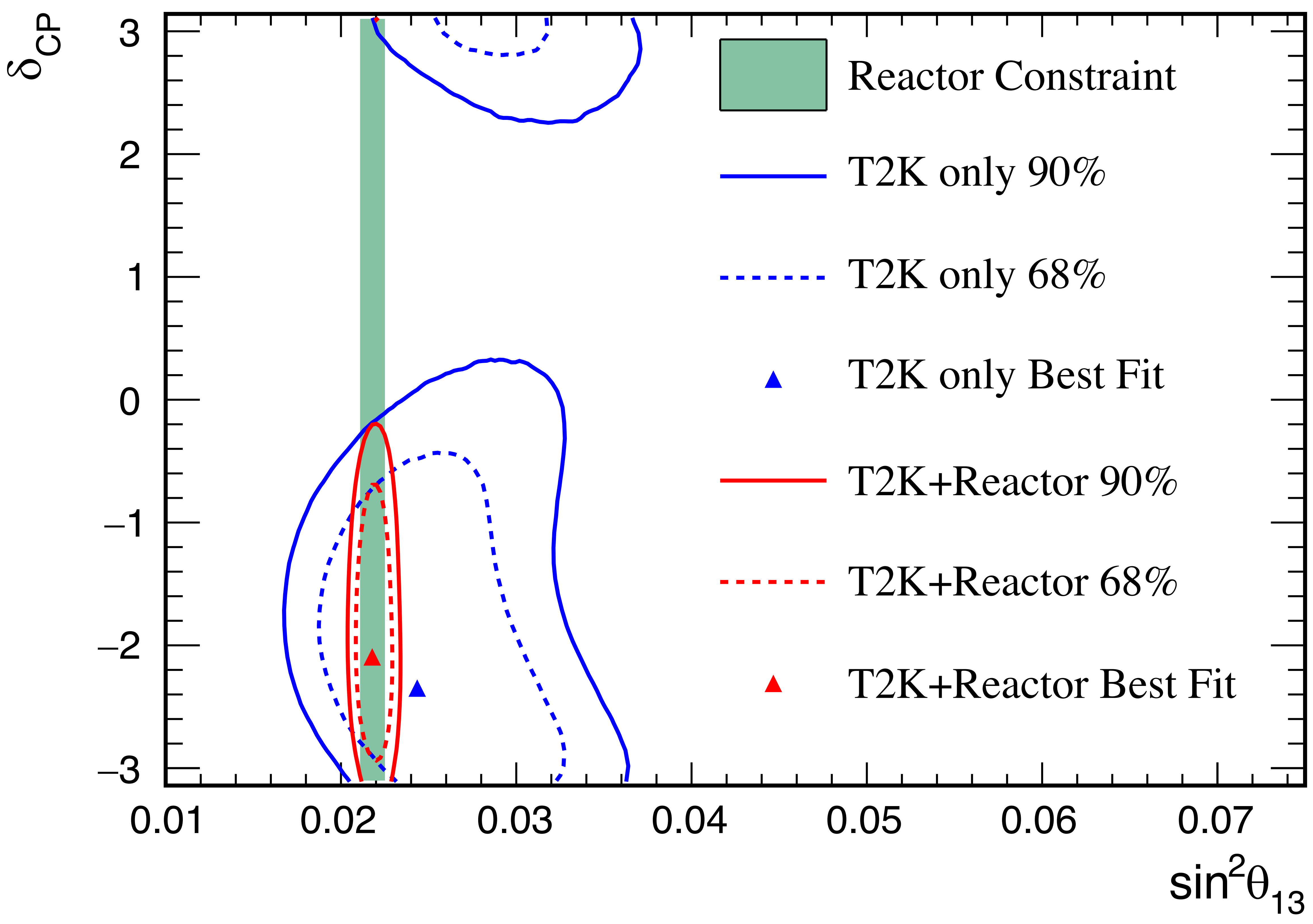


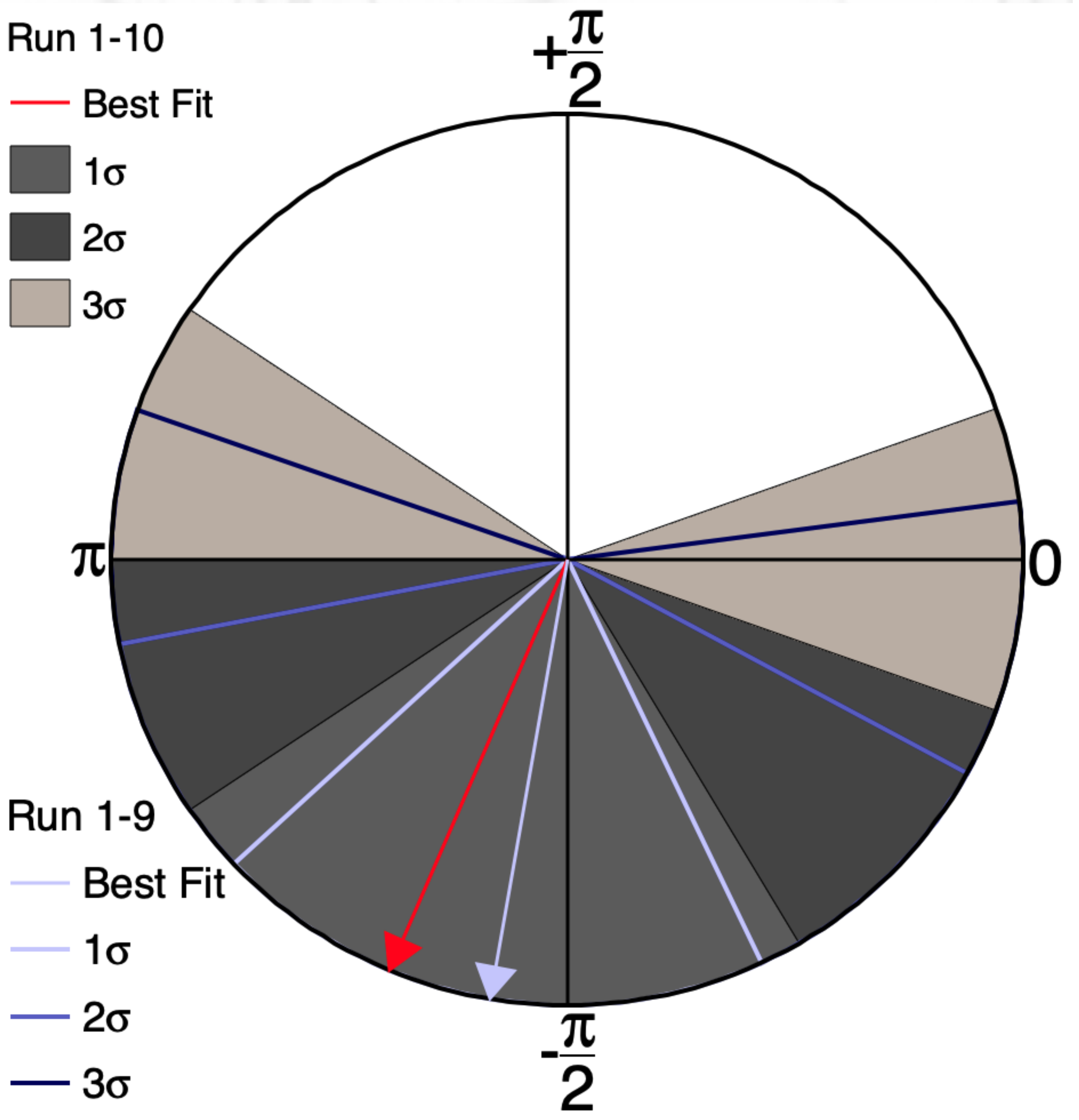


More neutrinos events and less antineutrino events than the no CP-violation case

Constraints on δ_{CP} and θ_{13}

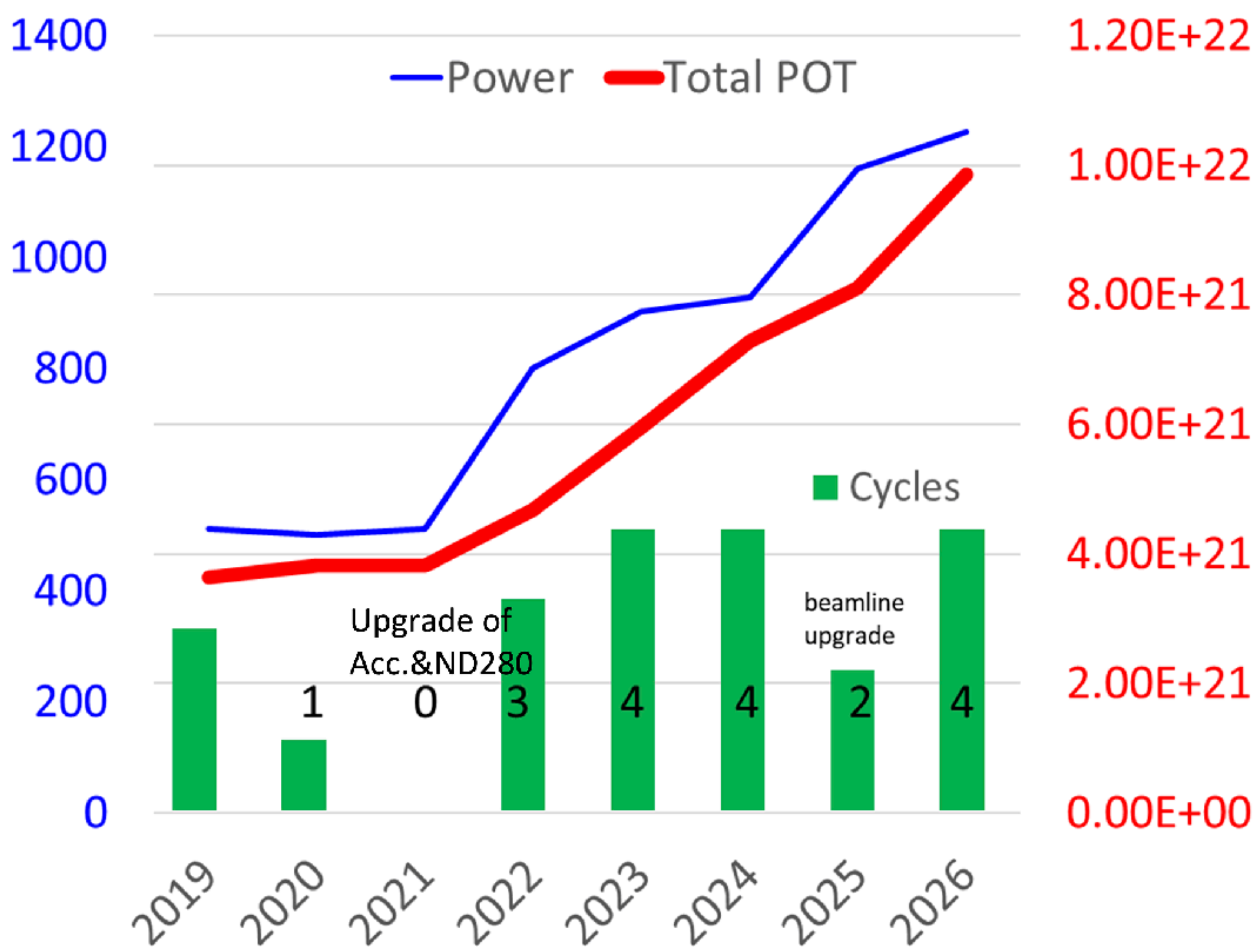
T2K Run 1-10 Preliminary

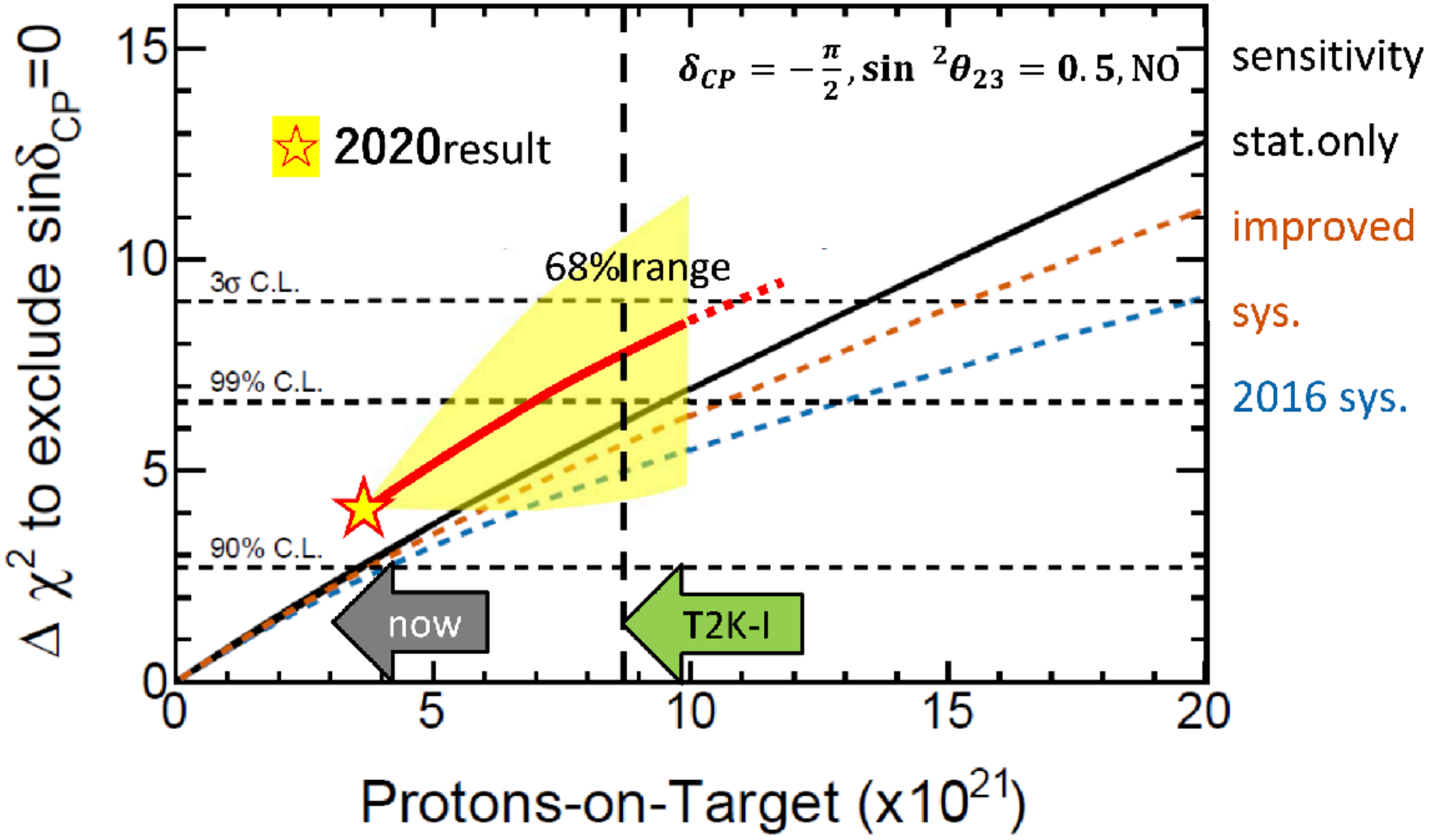




Large part of δ_{CP} phase excluded by more than 3 σ

Prospects





Sensitivity will be further improved by near-detector upgrades etc.
If CP is maximally violated, we have a good chance to reach 3σ exclusion of non-CPV

More (future) T2K(-related) results

Neutron yield

- Made the first measurement of neutron yield from neutrino and antineutrino CC interactions

  Work done by the former ICRR graduate student, R. Akutsu

- Important input for utilizing neutrons for neutrino/ antineutrino separation etc (GeV neutrinos)

- Constrains atmospheric neutrino backgrounds for supernova relic neutrino searches at SK(-Gd).

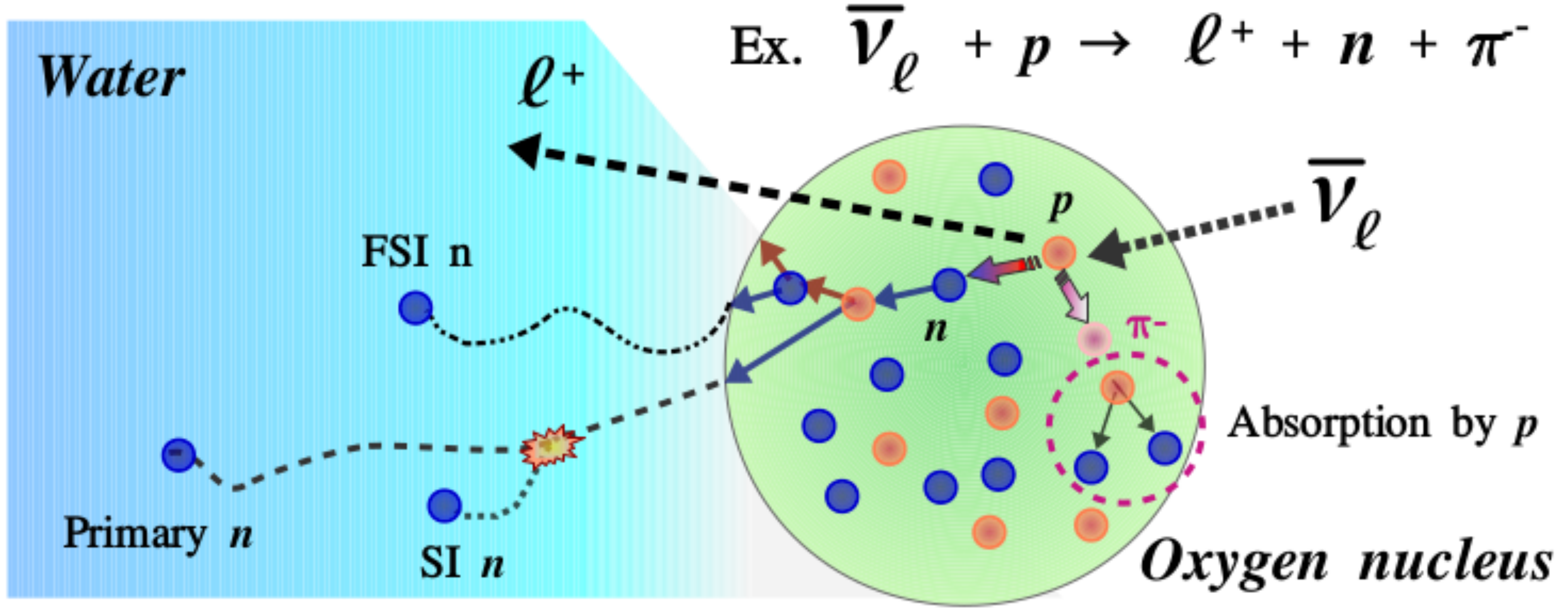
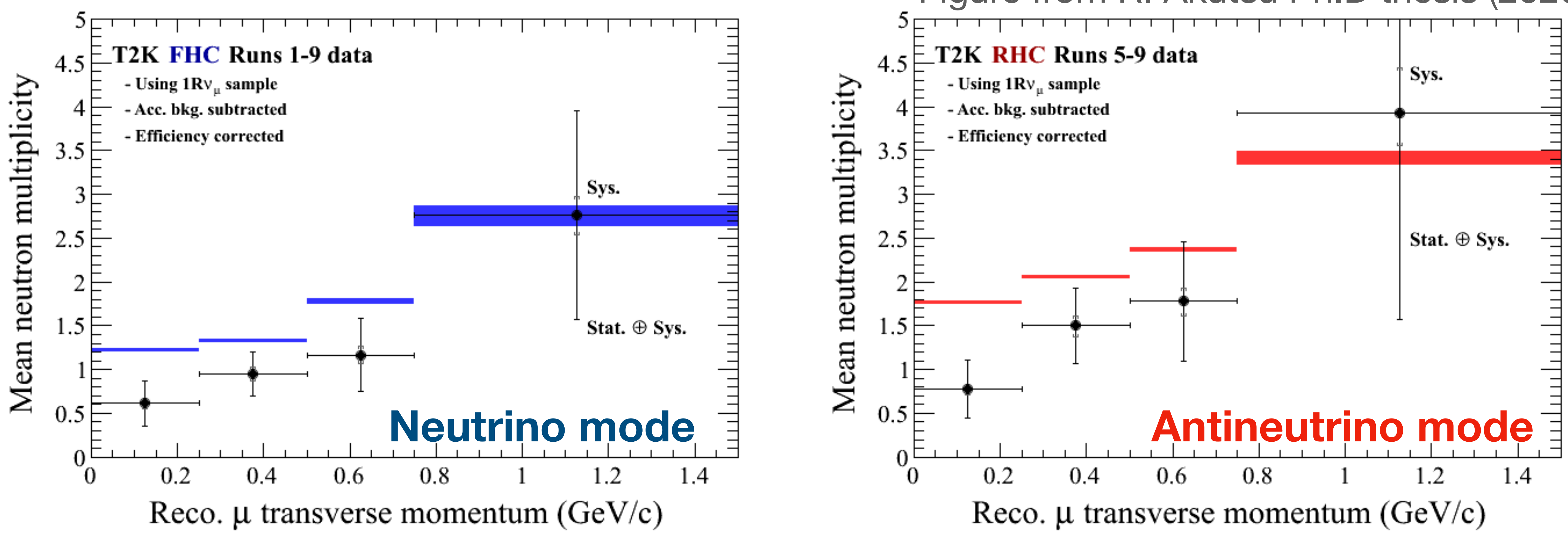
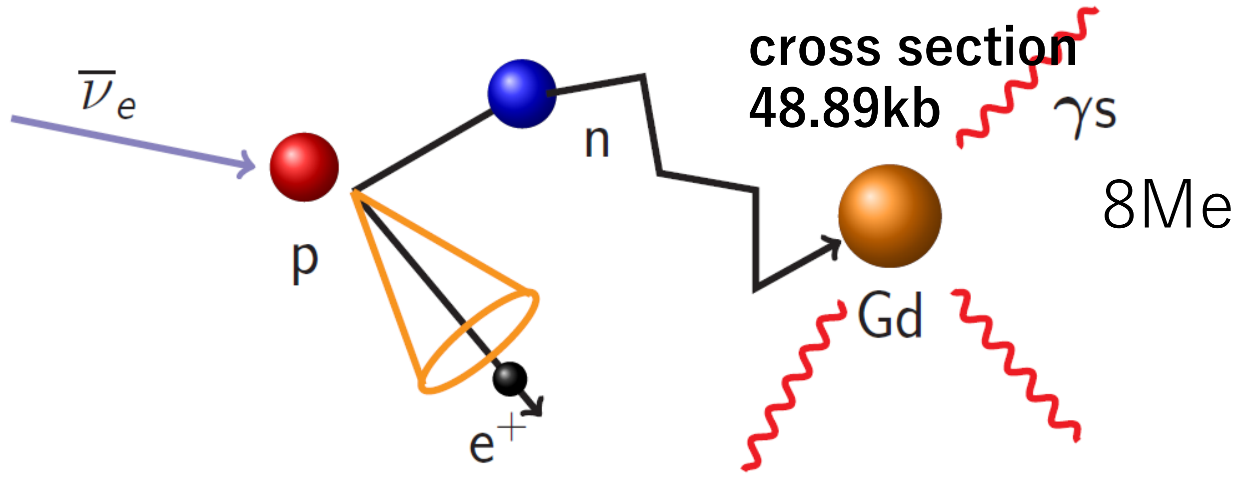


Figure from R. Akutsu Ph.D thesis (2020)

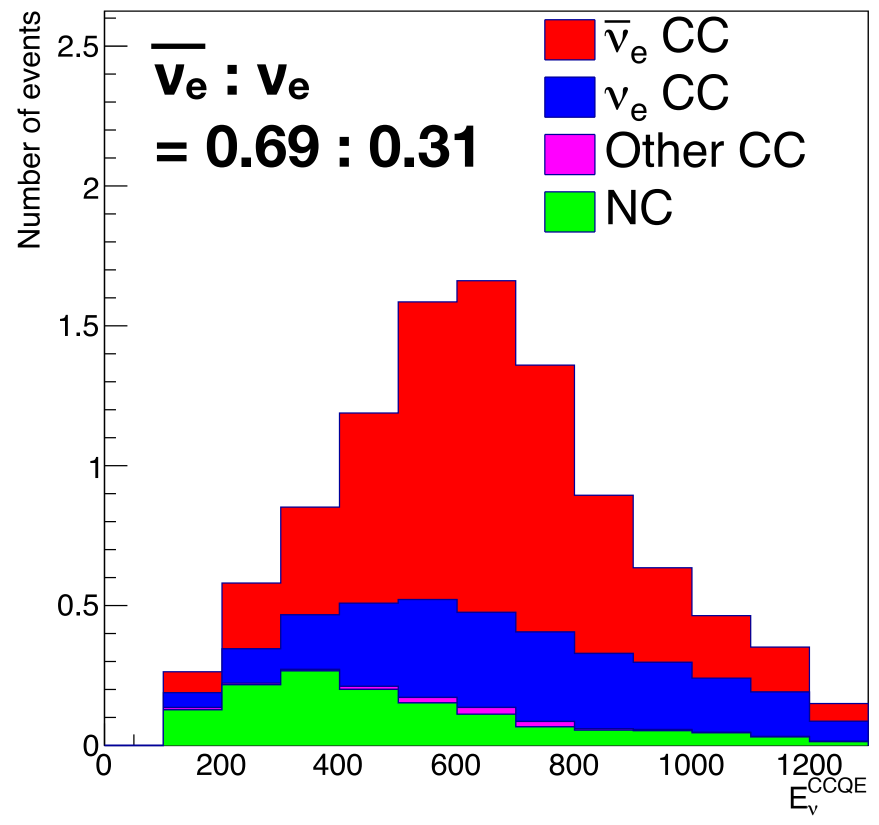


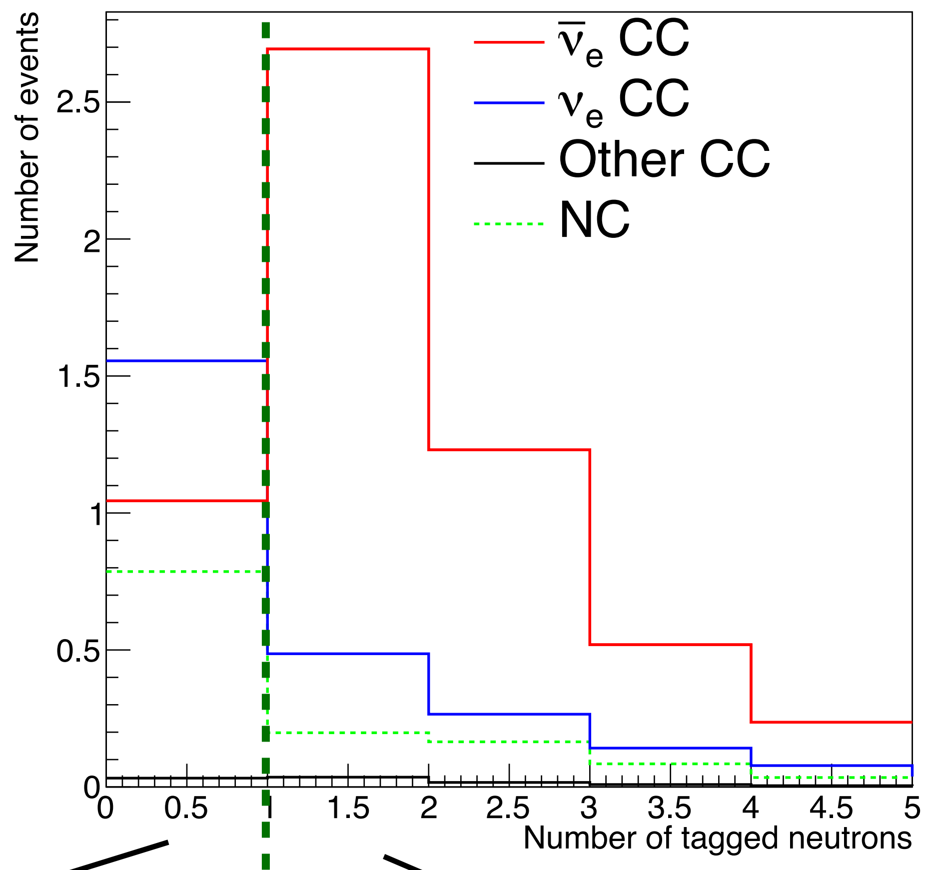
Oscillation analysis with neutron tag

- Super-K introduced Gadolinium to significantly enhance neutron detection efficiency (See Ikeda-san's talk for Super-K)
- New neutron tagging algorithm being developed by H. Seungho (ICRR grad student) and many other SK and T2K collaborators.
- Neutron tagging can improve T2K measurements



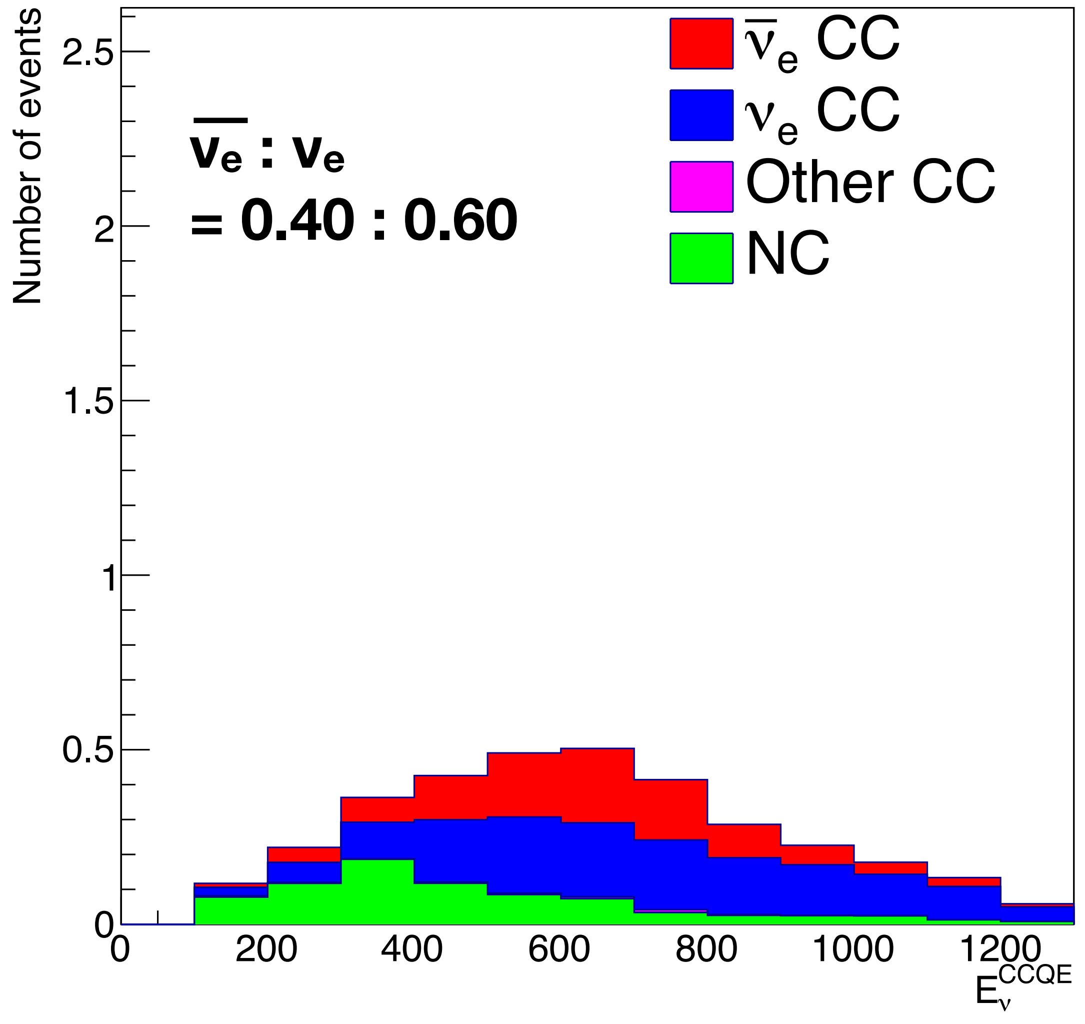
Expected electron (anti-)neutrino candidates in anti-neutrino mode beam

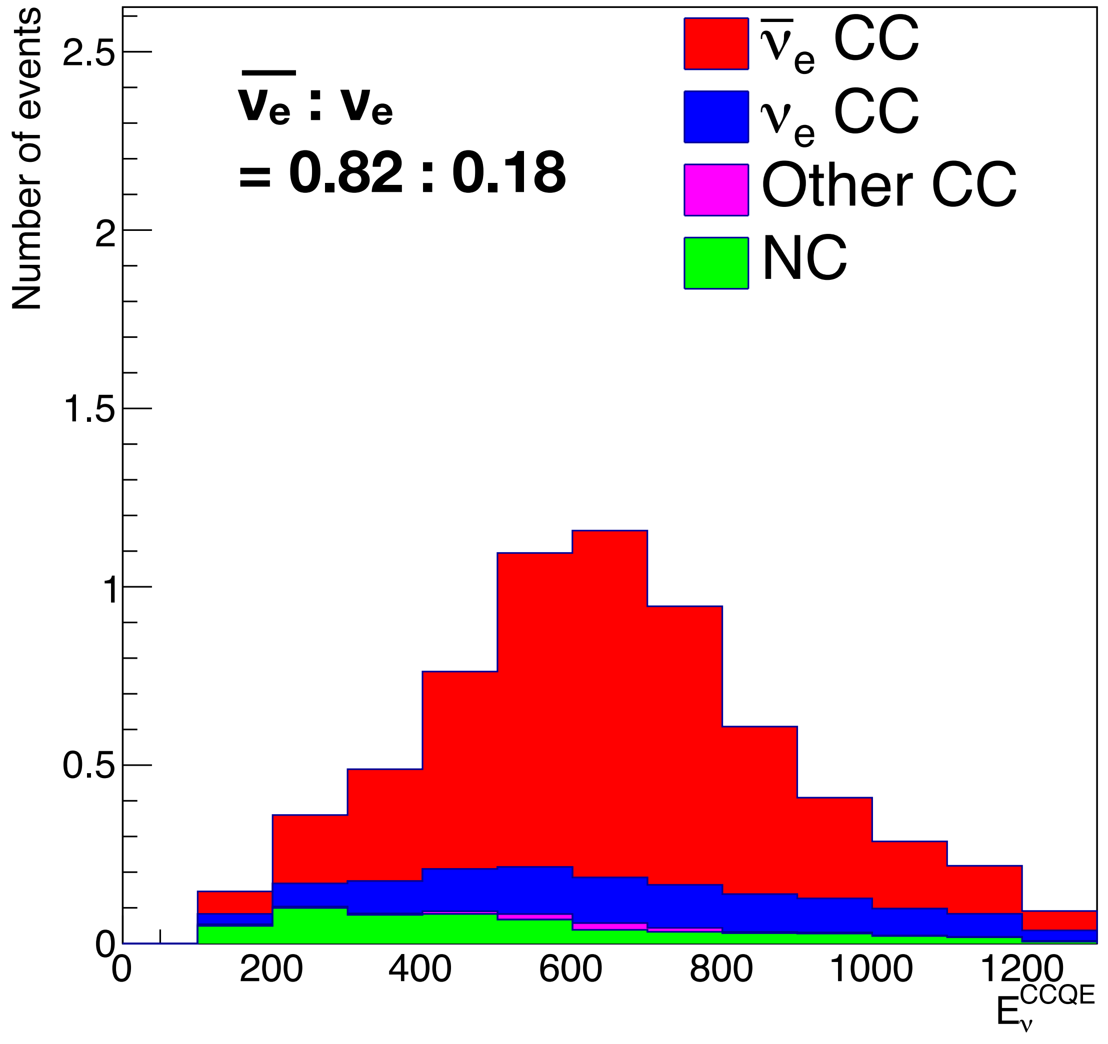




Can separate "wrong-sign" neutrinos and NC interactions

Work in progress





T2K + SK joint fit

J. Xia (Grad student at ICRR)

Current Status of SK and T2K

- Despite the fact that these 2 experiments share the same detector (SK tank is the far detector in T2K), neutrino oscillation analyses are done by independent working groups.
  - T2K **so far** has focused on sub-GeV events, while SK also cares about multi-GeV.
  - T2K neutrino beam is >99% ν_μ at generation, while SK atmospheric neutrino source has different flavors at origin.
- Given the differences in neutrino data, the 2 experiments have developed different event selection schemes and strategies of uncertainty estimation.

So Why A Joint Analysis?

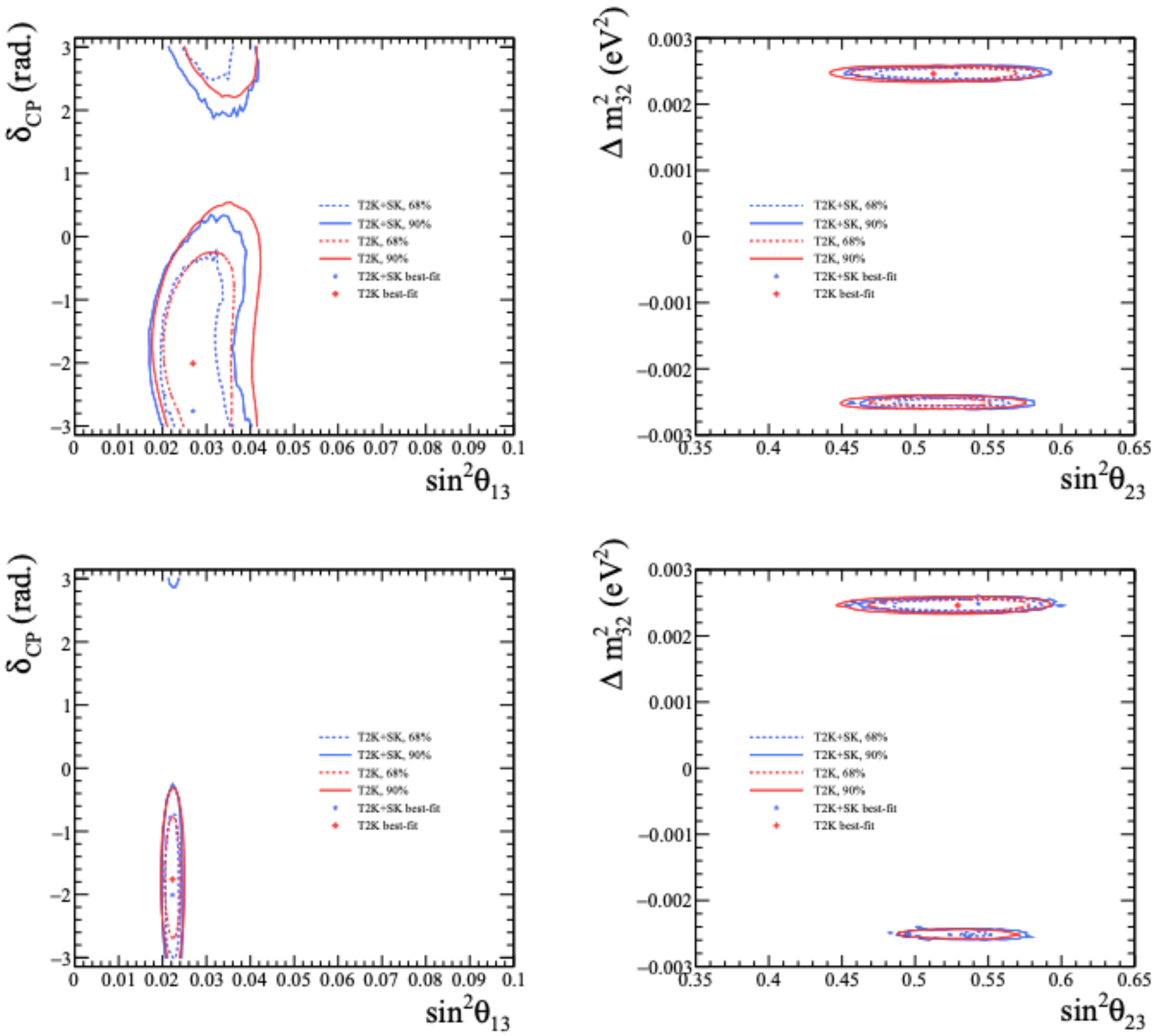
- **T2K**: Precise measurements of neutrino oscillation parameters thanks to its artificial neutrino source, but the result is still limited by statistics.
- **SK**: Observes atmospheric neutrinos that are abundant and free, but it has relatively larger systematic uncertainties. On the other hand the oscillation resonance region to determine mass hierarchy from neutrinos traversing through the earth is 2~10 GeV, in which T2K is not so sensitive.

A joint analysis that treats the data simultaneously can help to strengthen both experiments and push forward the frontier of neutrino physics.

T2K + SK joint fit (cont'd)

J. Xia (Grad student at ICRR)

- Back in 2018, the first SK-T2K joint analysis was attempted by X. Li (https://www.stonybrook.edu/commcms/grad-physics-astronomy/_theses/li-xiaoyue-august-2018.pdf).



- Even with only sub-GeV 1-ring neutrino events, a substantial improvement in the measurement of δ_{CP} was still achieved by the joint analysis compared to T2K-only results.

- Currently we are working to include the multi-GeV multi-ring events in the joint analysis, which are expected to improve the measurements of δ_{CP} and Δm^2_{32}.

Summary

- T2K: Long-baseline neutrino oscillation experiment between J-PARC (Tokai) and Super-K (Kamioka)
- Testing CP-violation in neutrino (lepton) sector at world-leading sensitivity
- Many ICRR involvements in the current and future activities:
    - Super-K detector operation and data processing (of course)
    - Oscillation analysis
    - Neutron yield measurement
    - Oscillation analysis w/ Gd
    - T2K+SK joint fit
    - And many more…

Enjoy discussions with the T2K members at ICRR!

An SK-T2K Joint Neutrino Oscillation Analysis

Junjie Xia
11.11.2020

Current Status of SK and T2K

- Despite the fact that these 2 experiments share the same detector (SK tank is the far detector in T2K), neutrino oscillation analyses are done by independent working groups.
  - T2K neutrino beam peaks at 0.6 GeV and tails to ~30 GeV, while the SK atmospheric neutrino data has a broader energy spectrum from ~O(100) MeV to ~O(1TeV).
  - T2K **so far** has focused on sub-GeV events, while SK also cares about multi-GeV.
  - T2K neutrino beam is >99% numu at generation, while SK atmospheric neutrino source has different flavors at origin.
- Given the differences in neutrino data, the 2 experiments have developed different event selection schemes and strategies of uncertainty estimation.

So Why A Joint Analysis?

- T2K is powerful in precise measurements of neutrino oscillation parameters thanks to its artificial neutrino source. However the strength becomes a disadvantage in the case of achieving rich data samples. For example, T2K leads the world measurement of neutrino CP-violating phase δ_{CP}, but the result is still limited by statistics.
- SK observes atmospheric neutrinos that are abundant and **free**, but it has relatively larger systematic uncertainties compared to T2K in some key parameters such as neutrino flux, cross-sections, etc. On the other hand the oscillation resonance region to determine mass hierarchy from neutrinos traversing through the earth is 2~10 GeV, in which T2K is not so sensitive.
- So T2K and SK have their own advantages and can be complementary. A joint analysis that treats the data simultaneously can help to strengthen both experiments and push forward the frontier of neutrino physics.

An Earlier Effort to The Joint Analysis

- Back in 2018, the first SK-T2K joint analysis was attempted by X. Li (https://www.stonybrook.edu/commcms/grad-physics-astronomy/_theses/li-xiaoyue-august-2018.pdf).

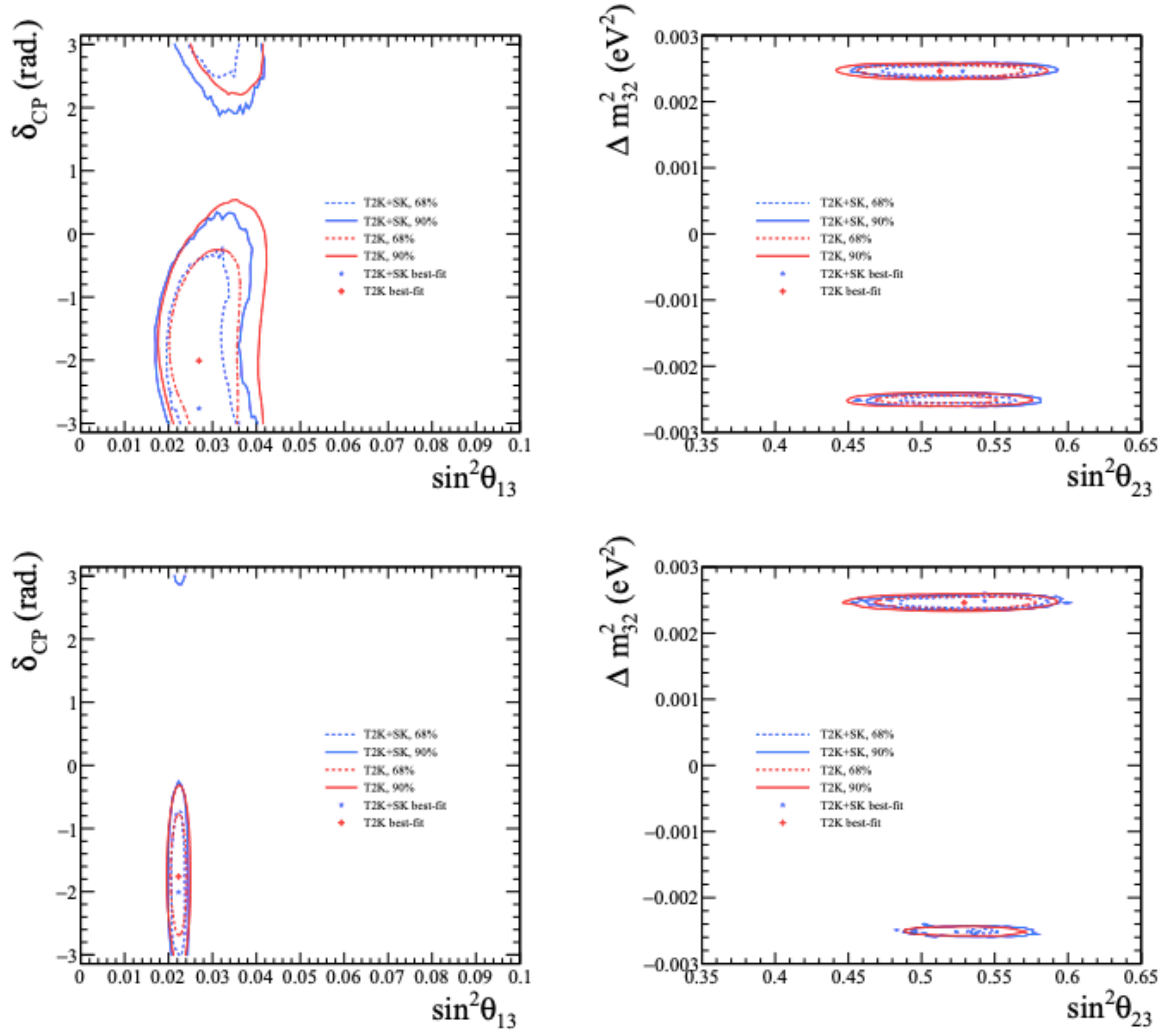


Figure 6.30: A comparison between the T2K+SK data fit with the T2K-only data fit. Top left: δ_{CP} v.s. $\sin^2\theta_{13}$ without reactor constraint; top right: Δm^2_{32} v.s. $\sin^2\theta_{23}$ without reactor constraint; bottom left: δ_{CP} v.s. $\sin^2\theta_{13}$ with reactor constraint $\sin^2 2\theta_{13} = 0.0857 \pm 0.0046$; bottom right: Δm^2_{32} v.s. $\sin^2\theta_{23}$ with reactor constraint $\sin^2 2\theta_{13} = 0.0857 \pm 0.0046$. The T2K-only sensitivities are taken from [147]. Note that the T2K-only fit uses five T2K samples (four CCQE-like samples and the ν_e CC1π^+ sample), whereas the T2K+SK joint fit only uses the four CCQE-like samples from T2K.

- Even with only sub-GeV 1-ring neutrino events, a substantial improvement in the measurement of δ_{CP} was still achieved by the joint analysis compared to T2K-only results.

- In this second iteration we are working to include the multi-GeV multi-ring events in the joint analysis, which are expected to improve the measurements of δ_{CP} and Δm^2_{32}.

Challenges in This Work

1. Since T2K has mainly been focusing on the sub-GeV neutrino interactions, its implementation of the multi-GeV counterpart has shown some tension to the SK results. To solve this additional studies of cross-section at T2K Near Detector is needed, as well as model development.

2. Due to their very differences in nature, the correlation between atmospheric and beam neutrino fluxes needs more study.

3. An improvement is also needed for the current implementation of detector systematic uncertainties. Directions of study includes introducing another control sample, better strategies to estimate systematic errors, and the correlation among different detector systematics.

4. The previous joint analysis was tailored to a specific framework. But it is preferred to have the process run in a more general way that can be self-validated. Multiple frameworks for the joint analysis are now under construction.

For the moment I have been working on 1&4, and a preliminary joint analysis framework with systematic uncertainties on atmospheric fluxes and T2K neutrino cross-sections implemented has been set up.