14: The Future of Long Baseline Neutrino Physics

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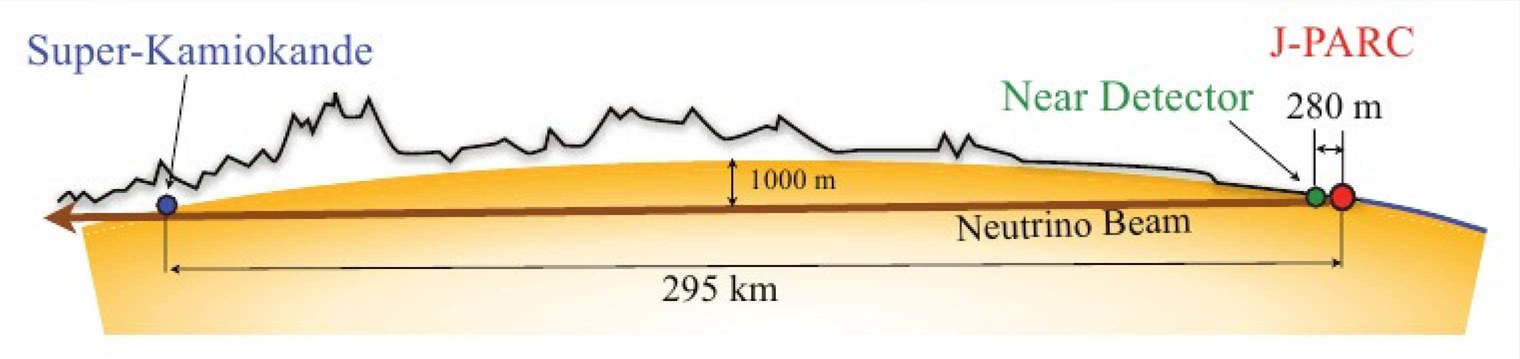
Introduction: T2K

- **T2K** is a long baseline accelerator experiment with a water Cherenkov far detector (Super-Kamiokande)
- We estimated expected events in T2K assuming the **planned goal of $20*10^{21}$ protons-on-target** (POT)
- We used these estimations to predict the T2K potential in probing **CP violation** and **mass ordering**



Introduction: expected number of events

$$N_\nu = \int \Phi_\nu(E) \sum_T N_T \sigma_T(E) dE \times \epsilon_\nu$$

Flux at FD

Targets:
H1 and O16

# of targets in FV
of T2K 22.5 kt

Cross sections
calculated with
GENIE

Efficiency:
0.7~0.85

Parameter	Value
$\sin^2\theta_{12}$	0.307 ± 0.013
$\sin^2\theta_{13}$	0.0210 ± 0.0011
$\sin^2\theta_{23}$	0.51 ± 0.04
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\mathrm{eV}^2$
$\lvert\Delta m^2_{31}\rvert$	$(2.45 \pm 0.05) \times 10^{-3}\mathrm{eV}^2$

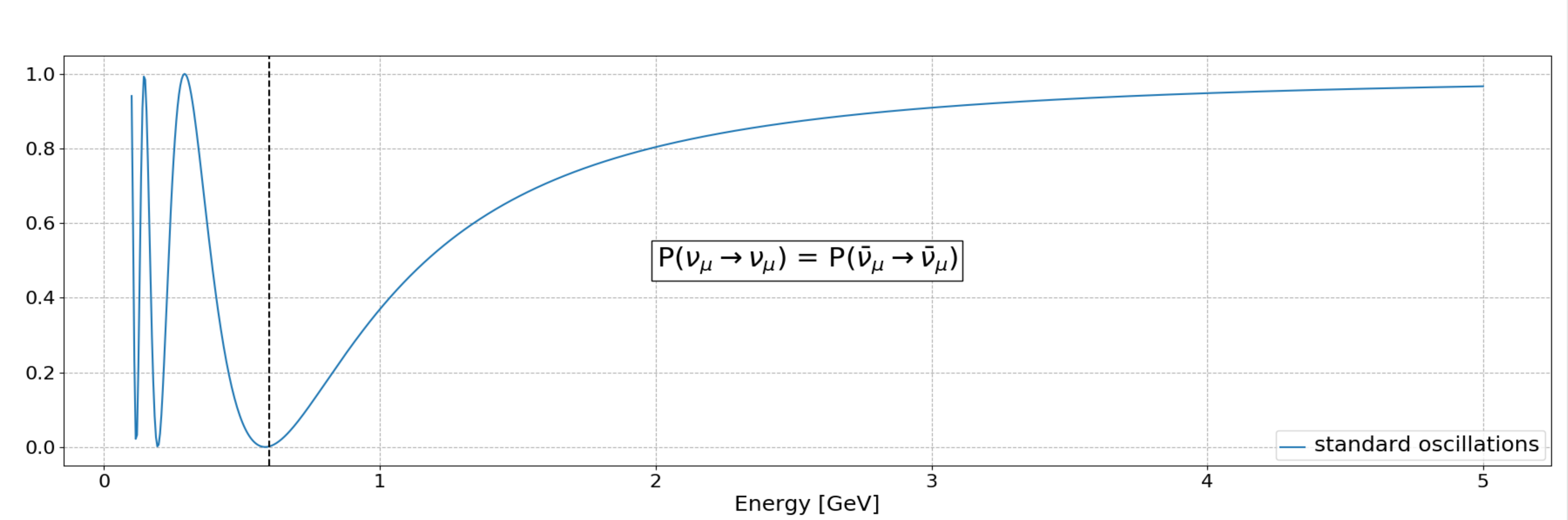
Table 1: Neutrino oscillation parameters in PDG2017

Introduction: oscillations

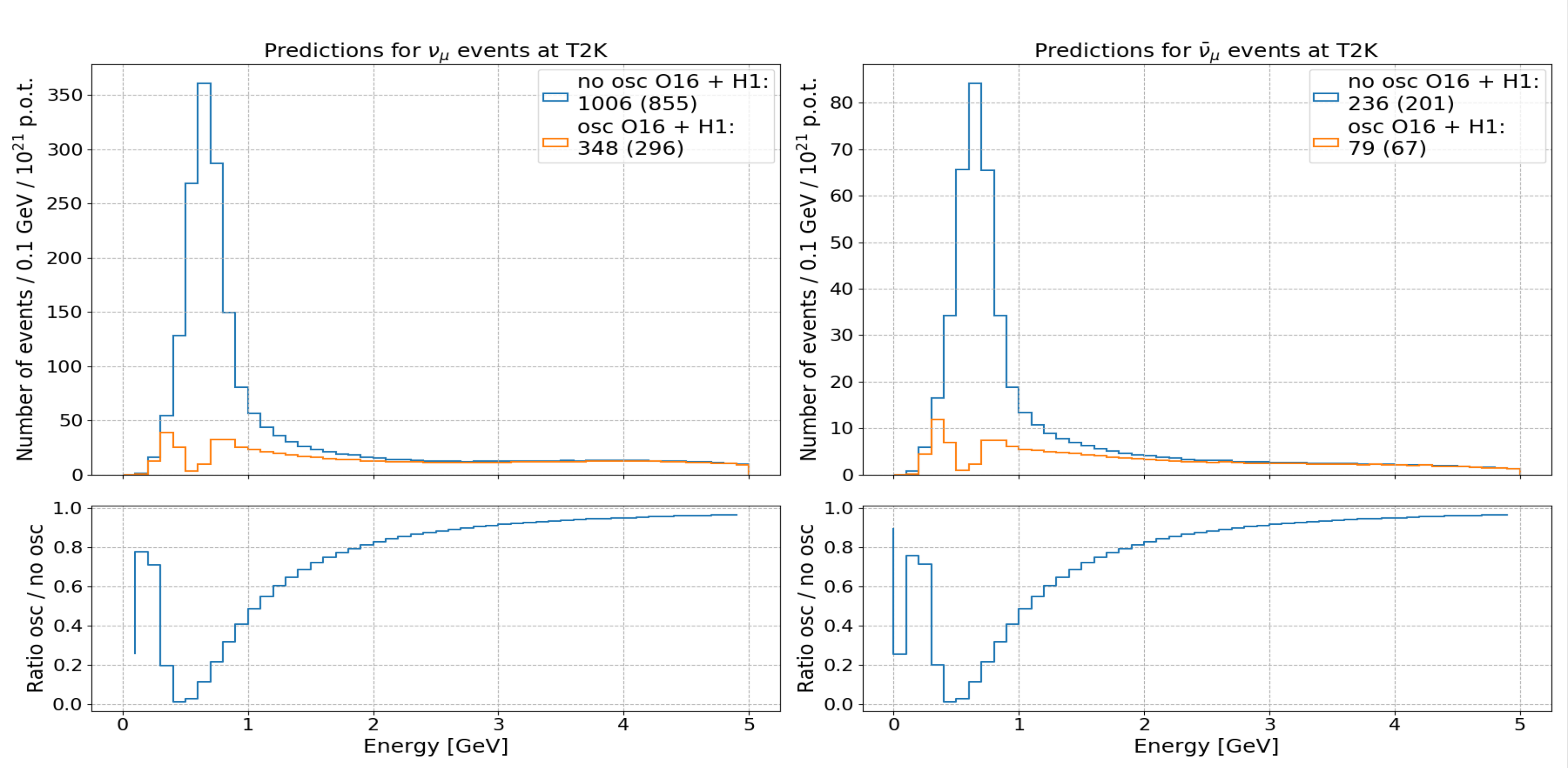
- In our calculations we focused on
  - The muon (anti)neutrino disappearance mode
  - The electron (anti)neutrino appearance mode

Muon (anti)neutrino disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - [\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}]\sin^2\Delta m^2_{31}\frac{L}{4E}$$



Muon (anti)neutrino disappearance



Analysis: $\sin^2 \theta_{23}$

- The muon (anti)neutrino disappearance probability depends on $\sin^2 \theta_{23}$, which in principal is sensitive to the "octant" of θ_{23}, namely whether it is greater than or less than $\pi/4$ radians (assuming it isn't exactly $\pi/4$ radians). Is it possible to extract the octant of θ_{23}, assuming it has a non-maximal value using just this channel?

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- No!

Analysis: $\sin^2 \theta_{23}$

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$$\Rightarrow \cos 2\theta_{23} = \frac{\frac{-s^2_{13}}{2} \pm \sqrt{(\frac{-s^4_{13}}{2})^2 - 4(P - 1 + c^4_{13} + \frac{s^2_{13}}{2})}}{2c^4_{13}}$$

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two answers! cannot extract!

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  Is the same for neutrino and anti neutrino channels. Is there is a simple reason why this is the case?

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  Is the same for neutrino and anti neutrino channels. Is there is a simple reason why this is the case?

  - Yes, ν_μ is unaffected by matter effects, so when you change from the neutrino to antineutrino channel the only term that would change is δ_{CP} which this probability does not depend on.

Electron (anti)neutrino appearance

It's more complicated......

$$\boxed{P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2},$$

$$T_2 = \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)},$$

$$T_3 = \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)},$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\boxed{\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2}$$

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$$\alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$$

$$x \equiv 2\sqrt{2} G_F N_e \frac{E}{\Delta m^2_{31}}$$

$$\Delta \equiv \Delta m^2_{31} \frac{L}{4E}$$

for antineutrino $x \rightarrow -x, \delta \rightarrow -\delta$

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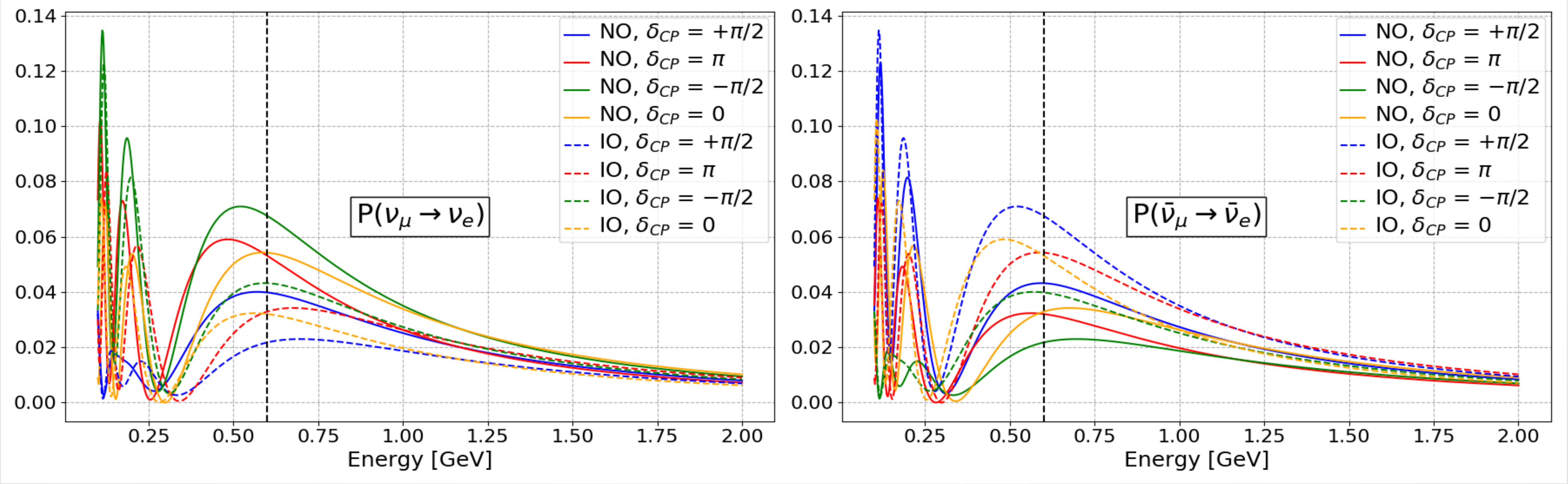

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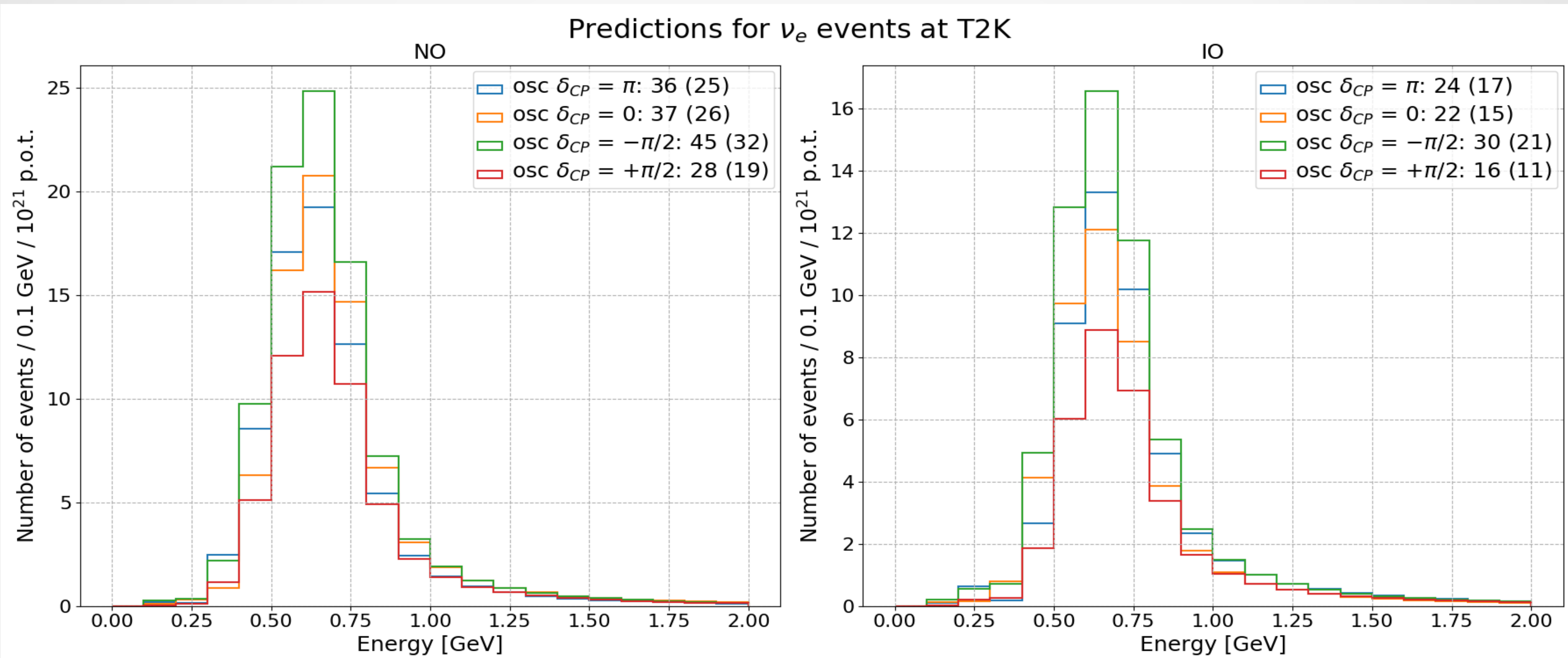

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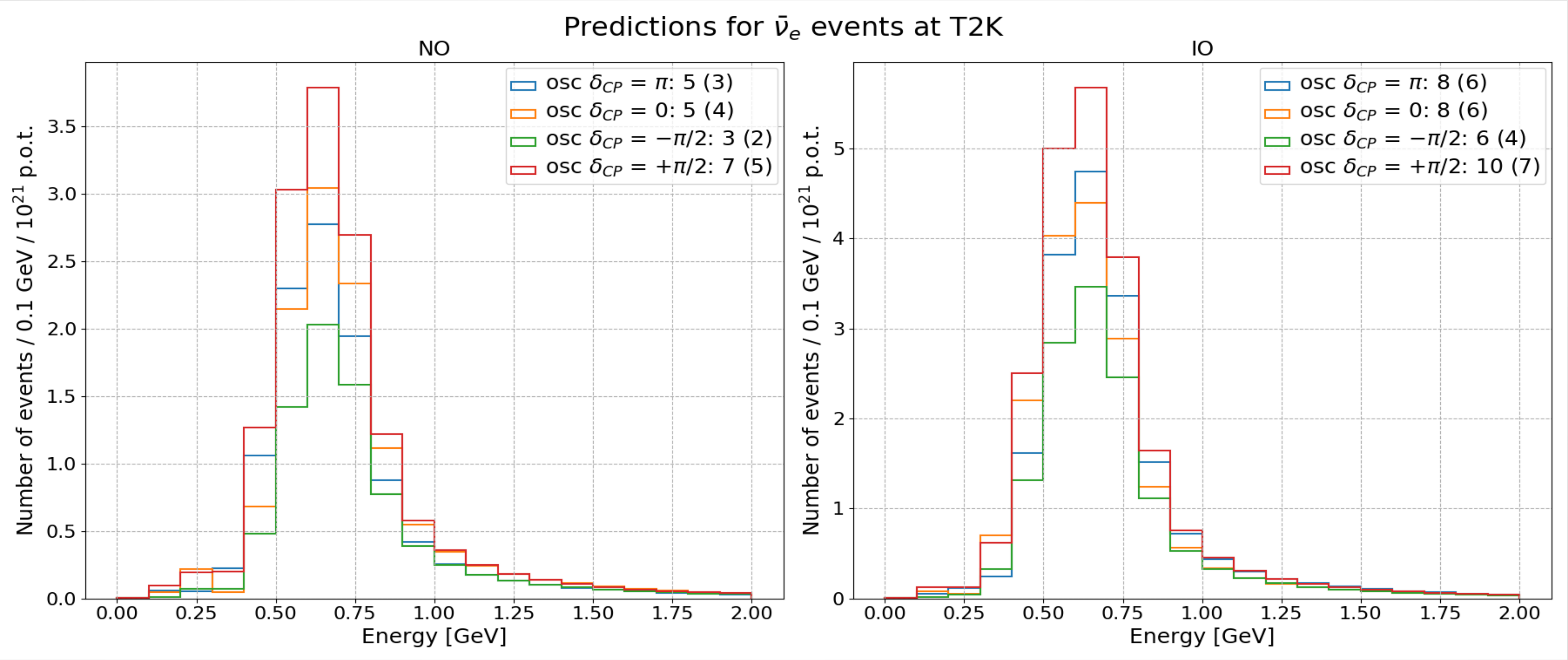
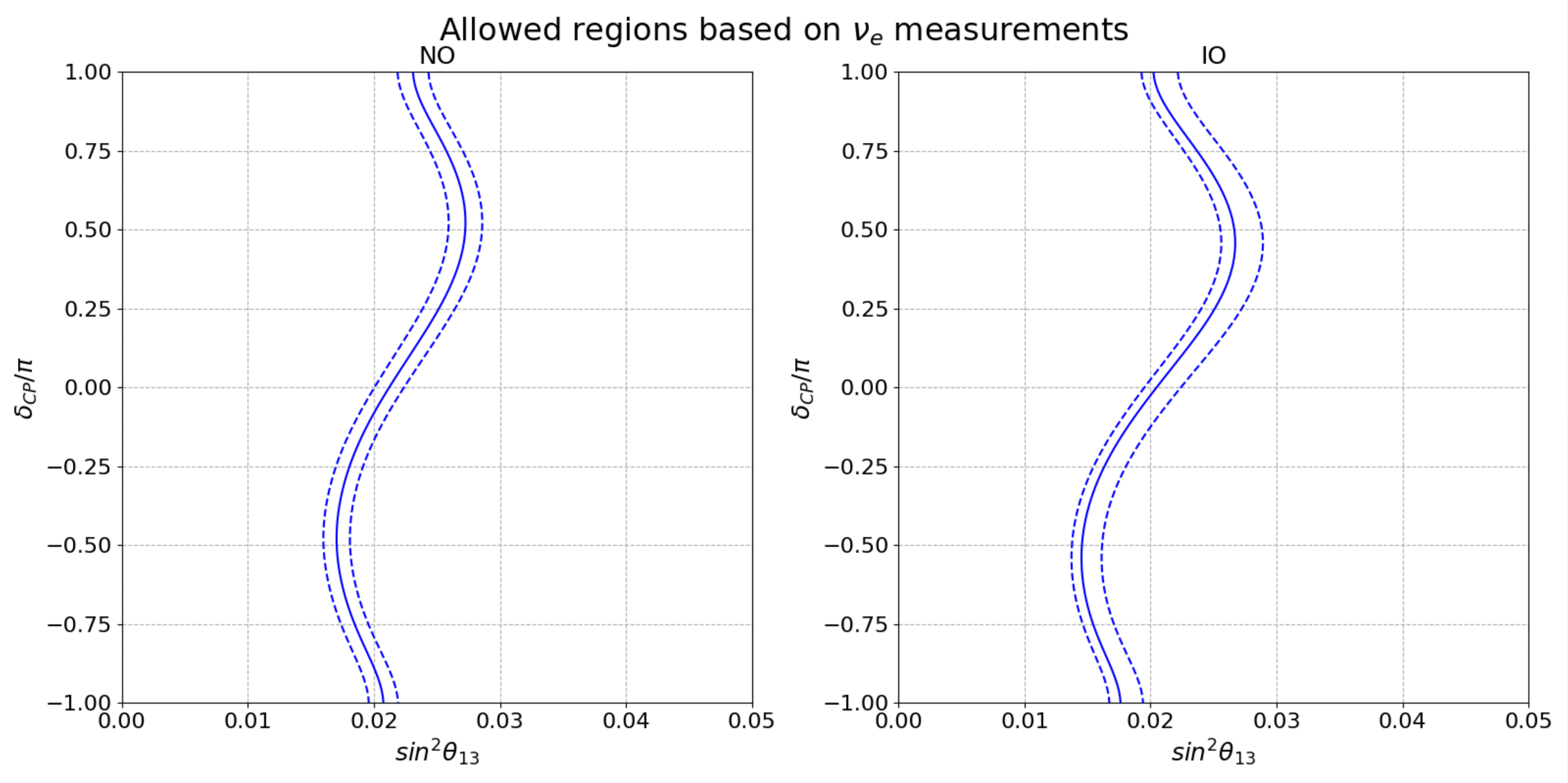


Allowed regions



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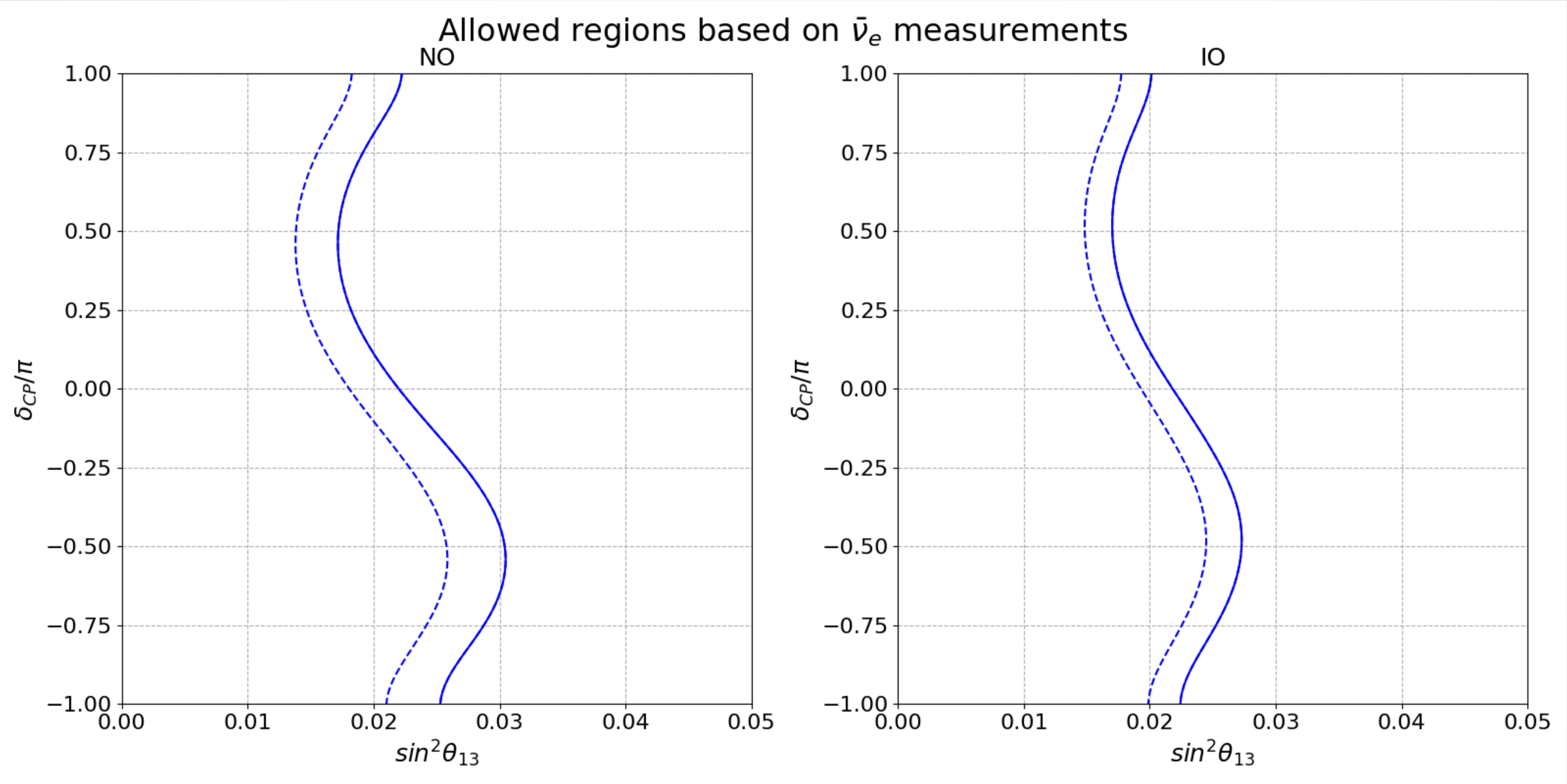
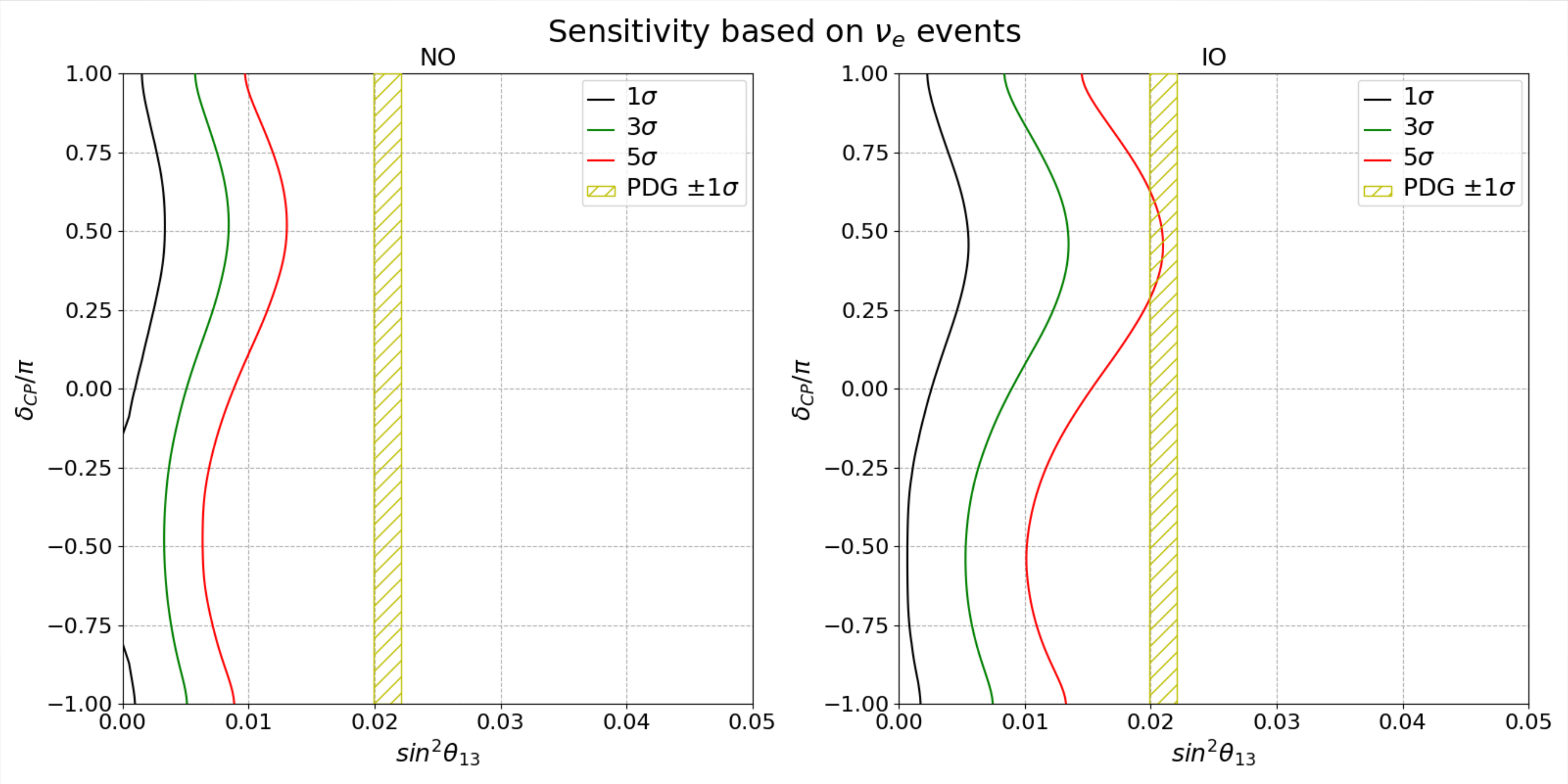


Current T2K Statistics: ~1*10^{21} POT



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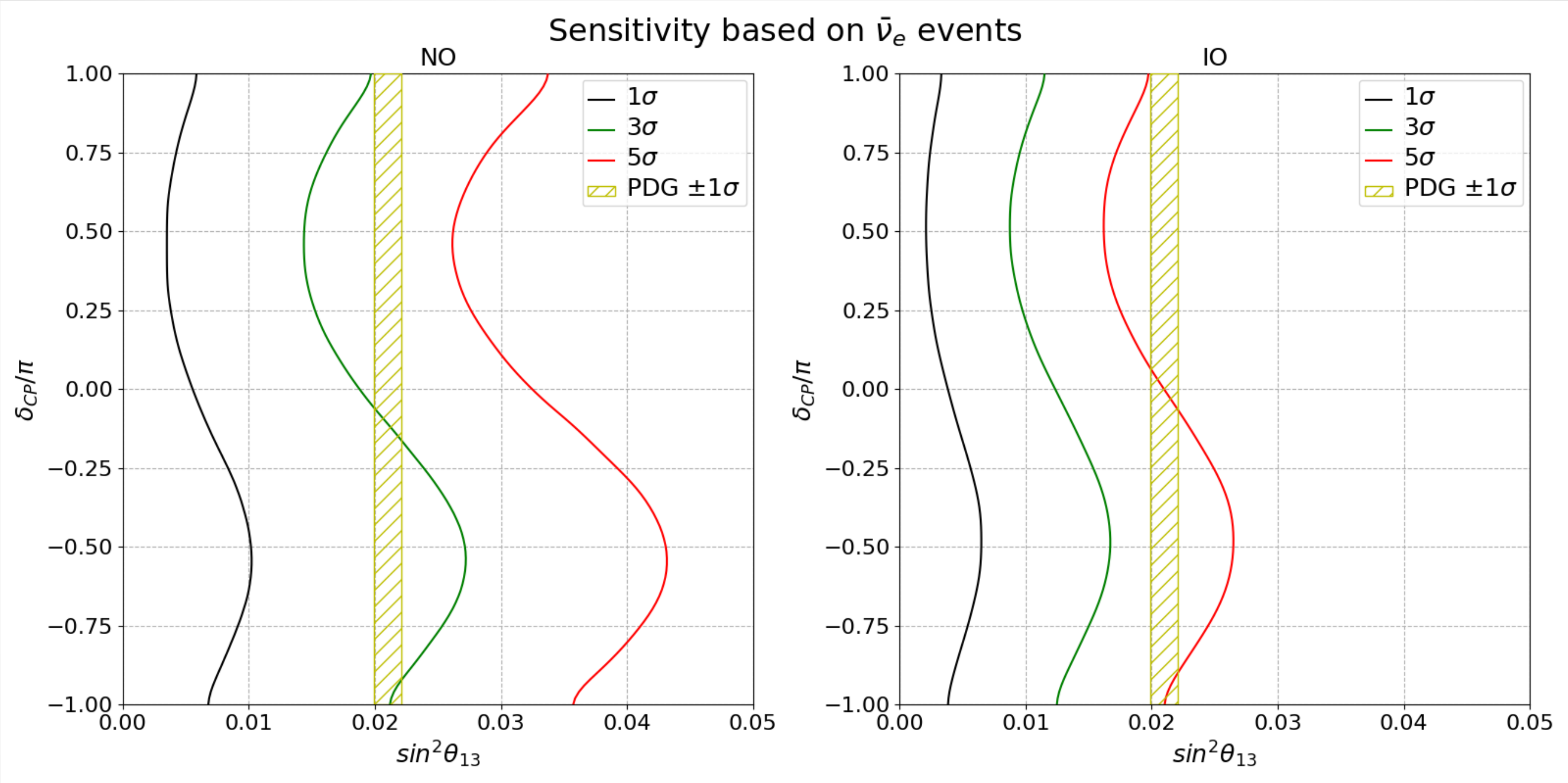
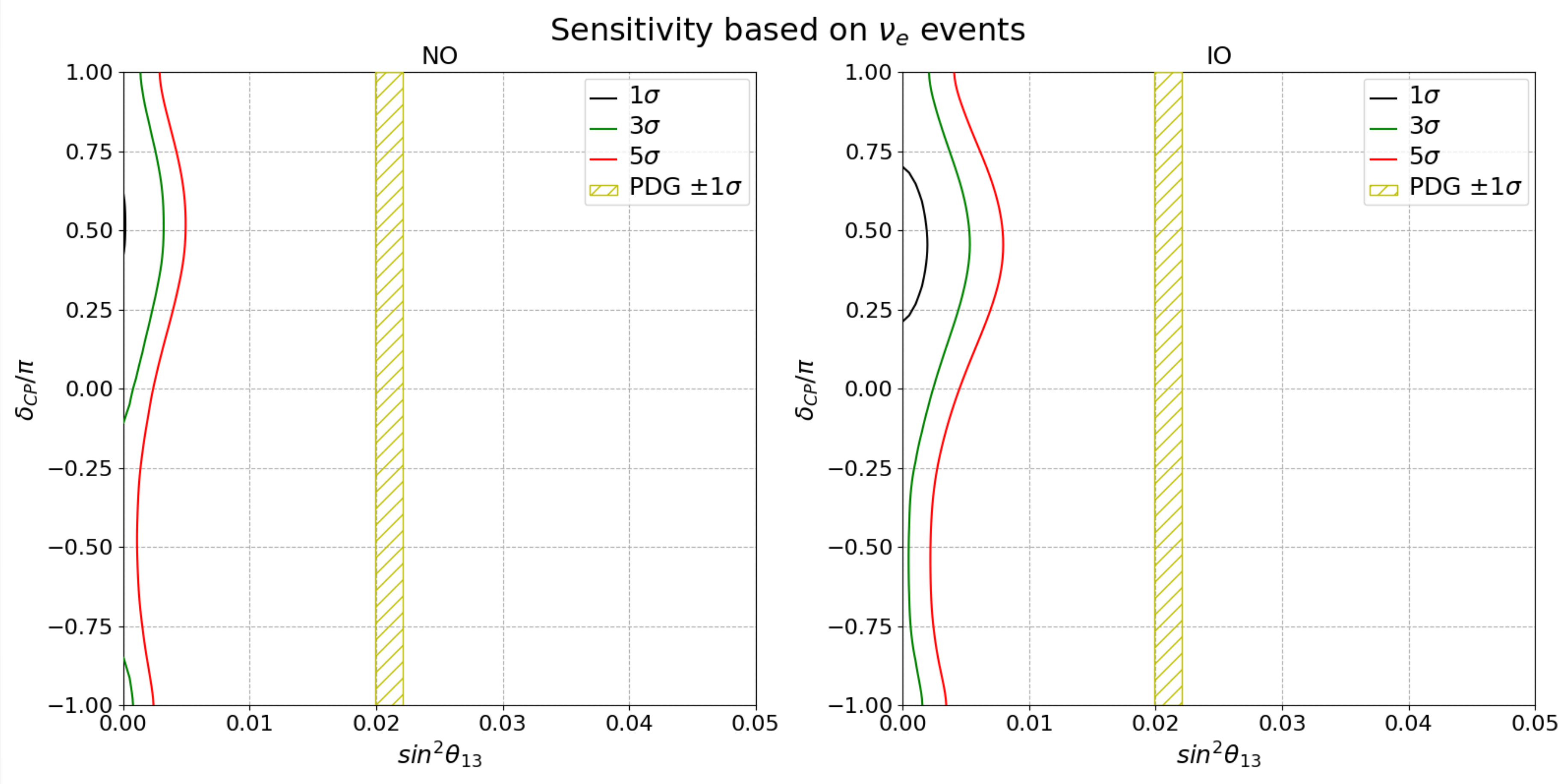


Predicted T2K Statistics: ~10*10^{21} POT



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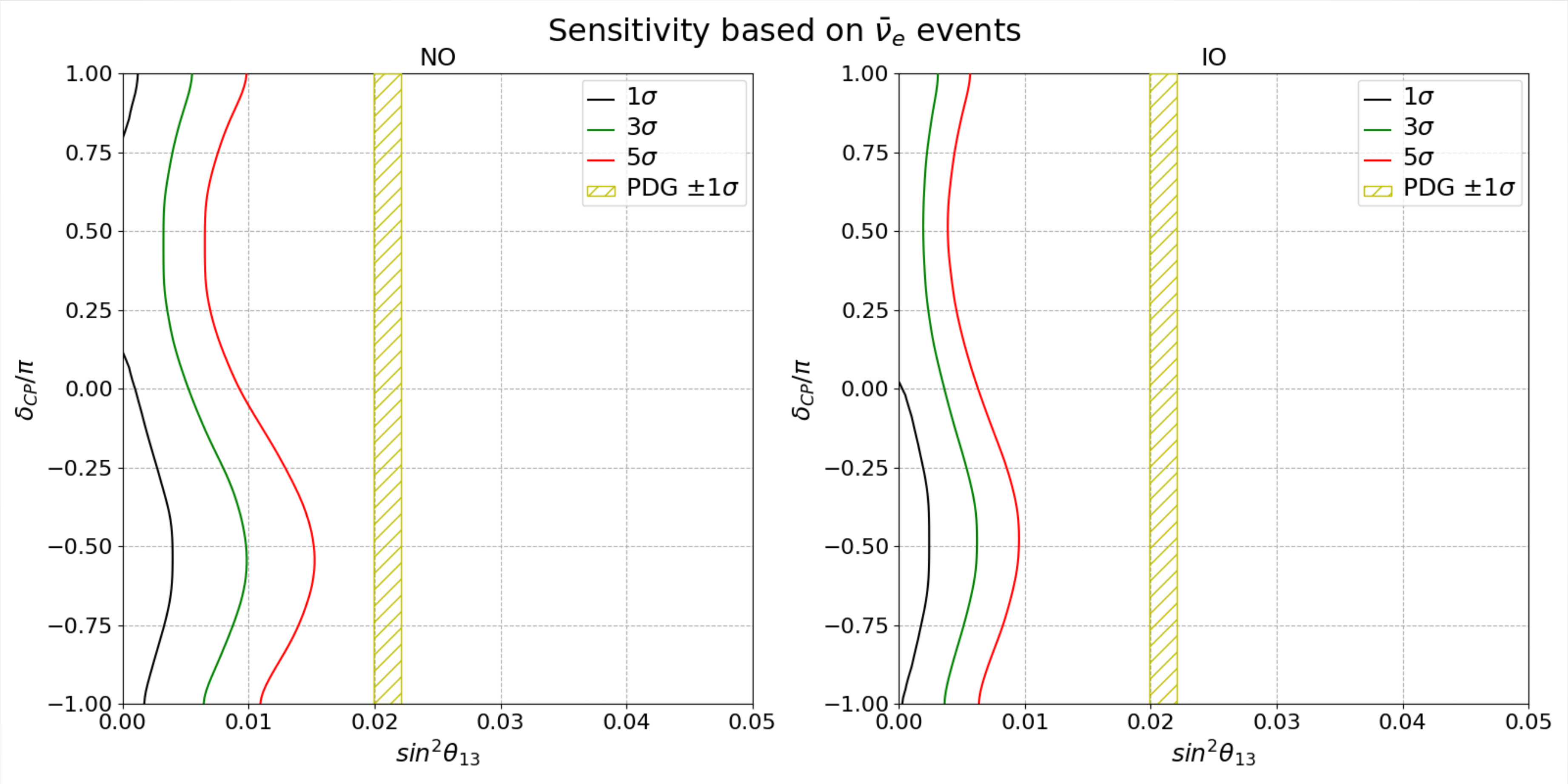
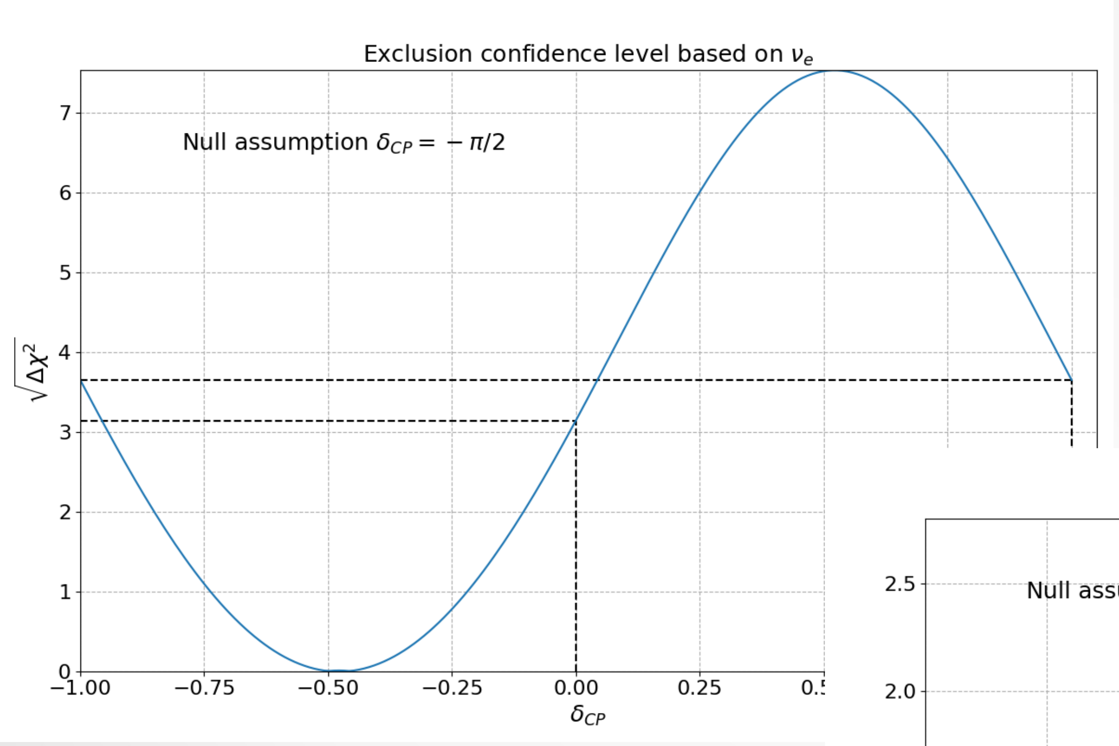
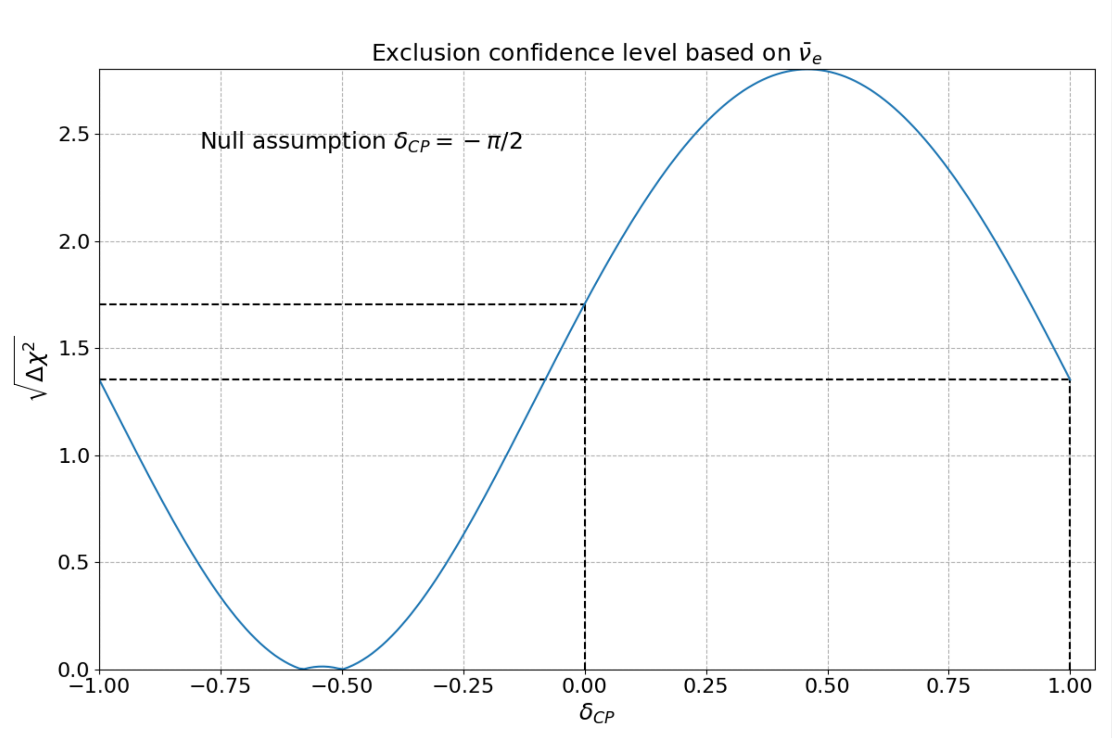


Can we exclude CP-conserving values?

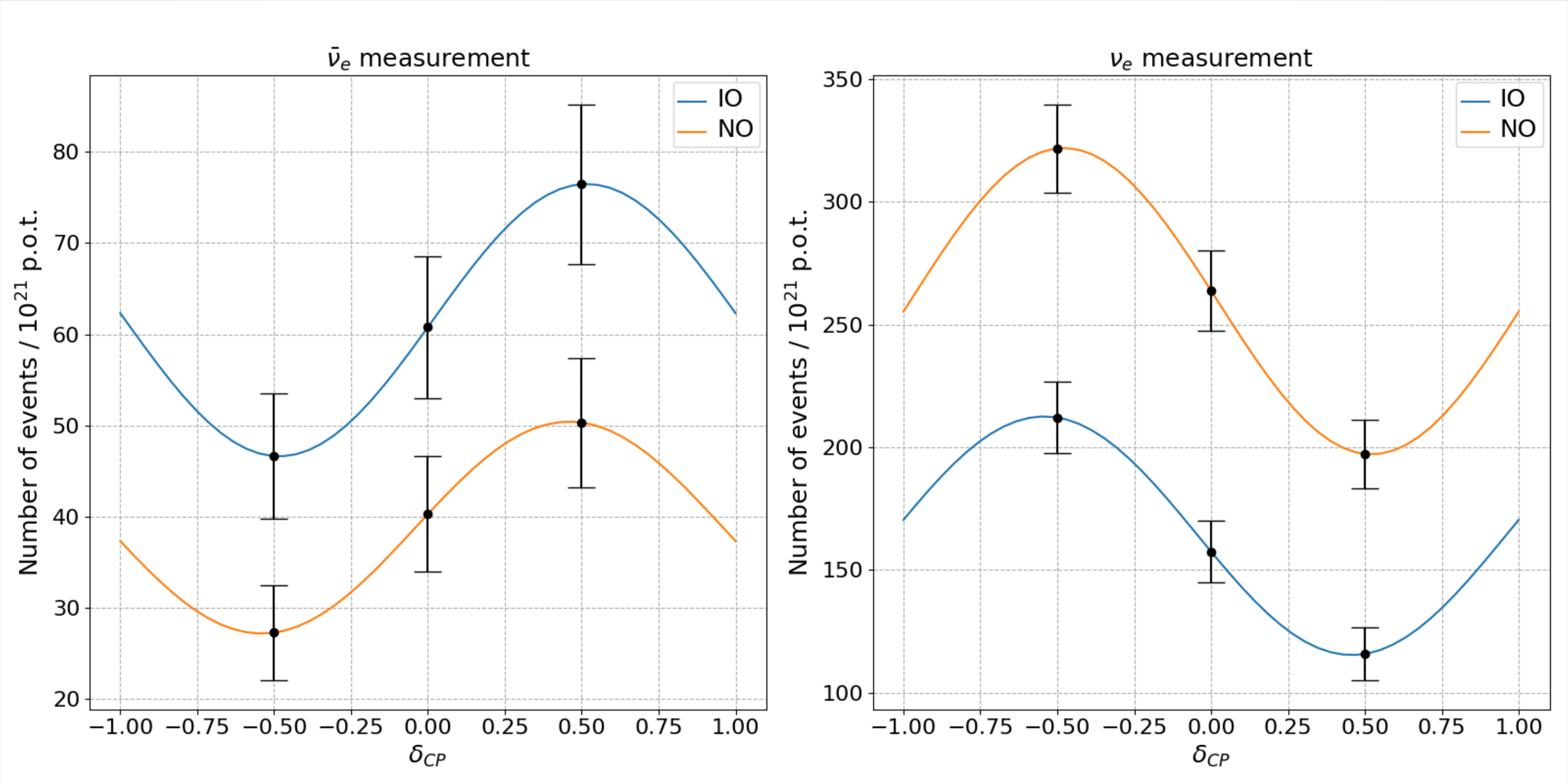


Assuming NO and that the true value of δ_{CP} is $-\pi/2$, can we exclude $\delta_{CP} = 0$ or π?



With the expected POT, Combining electron neutrino and antineutrino appearance, we can exclude $\delta_{CP} = 0$ with 3.6σ and $\delta_{CP} = \pi$ with 3.9σ CL

Can we disentangle the mass ordering?



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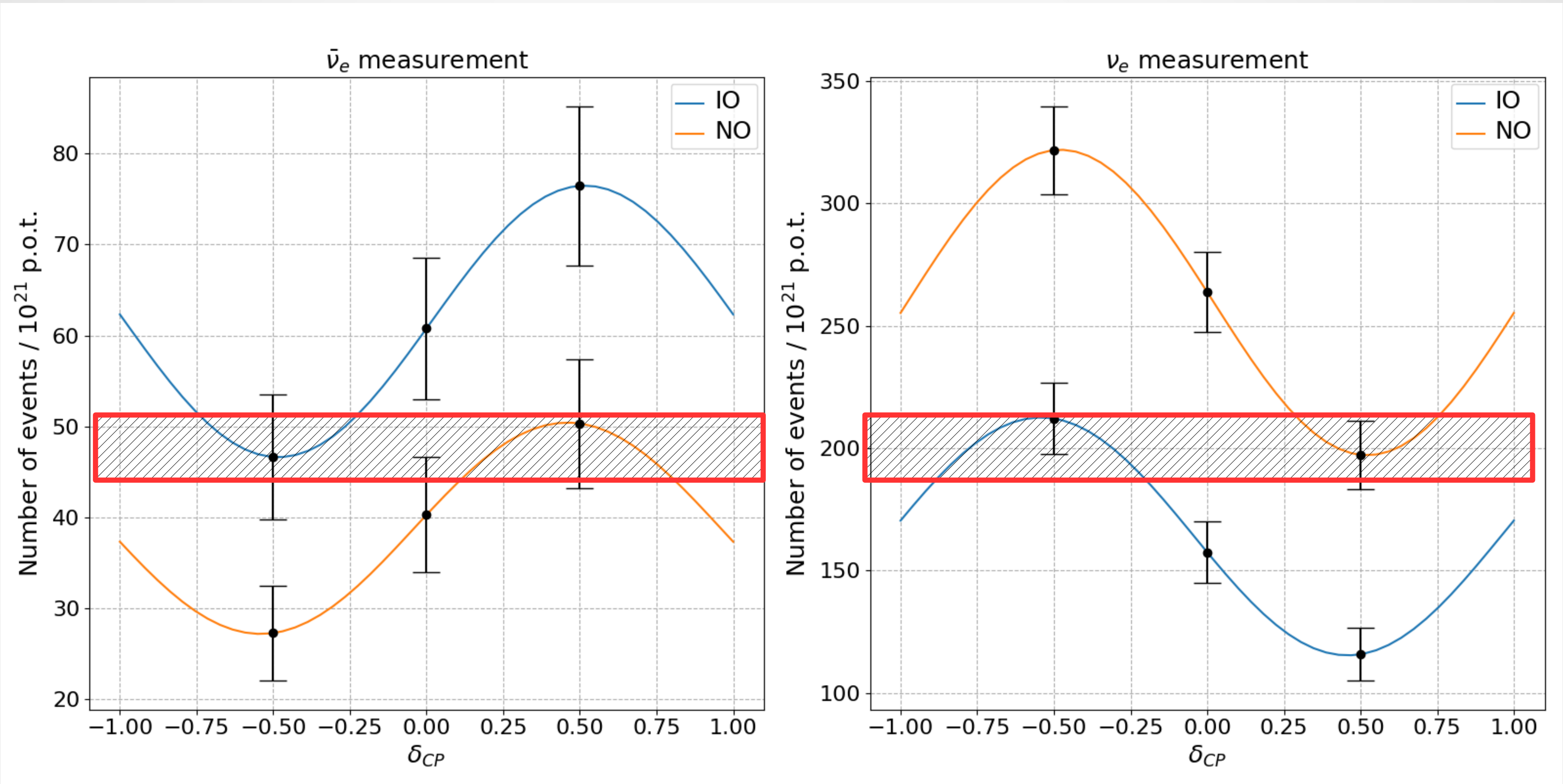
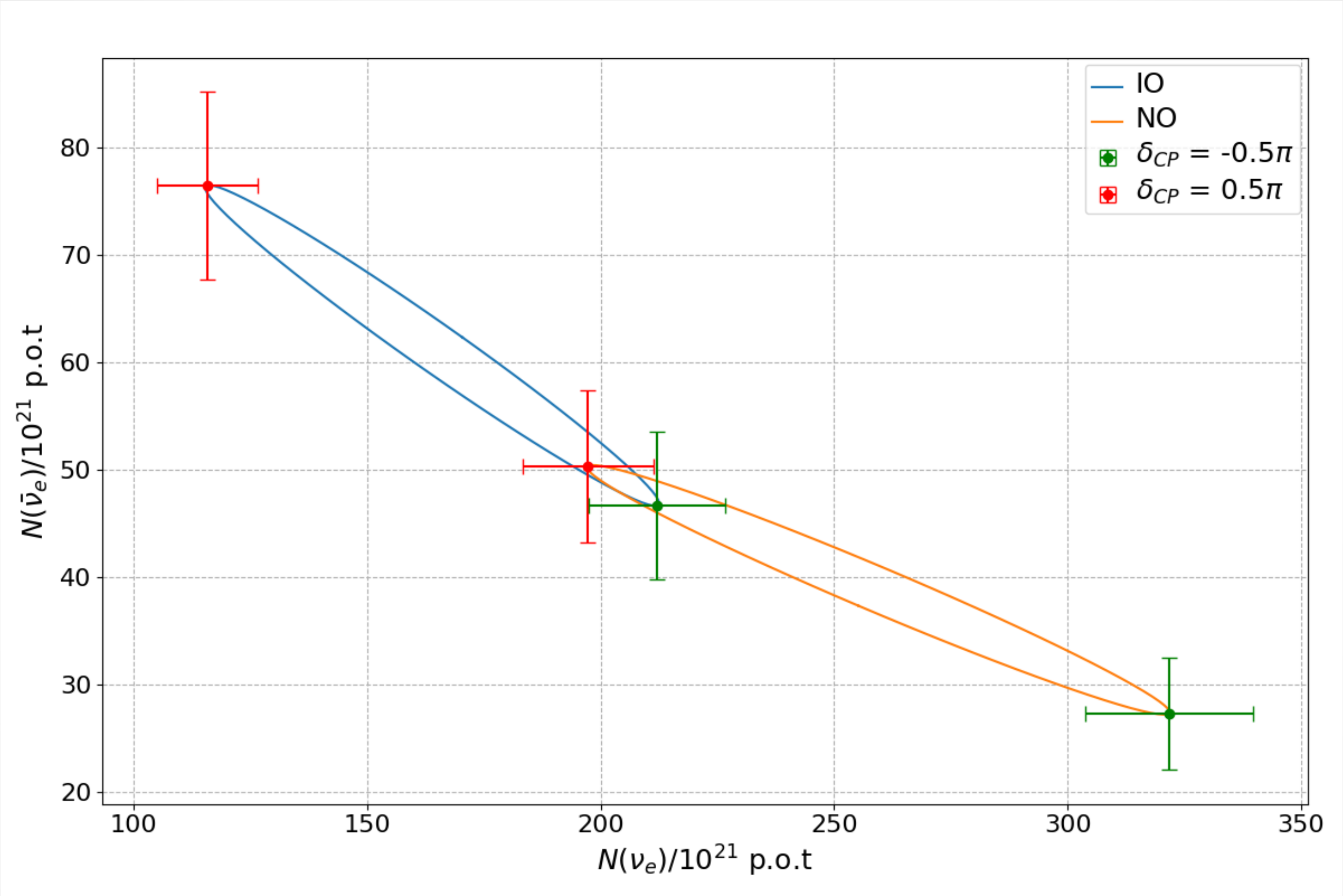


In which cases can T2K determine the mass ordering? If we knew δ_{CP}, in any case! Since we don't know it, we cannot distinguish IO with $\delta_{CP} = -\pi/2$ and NO with $\delta_{CP} = \pi/2$

Combined analysis with neutrino and antineutrino



The same analysis combining both plots from before: at maximal CP violation IO and NO are not distinguishable

Conclusions

- We made **a lot** of plots!
- With the planned high exposure ($20*10^{21}$ POT) T2K has **high sensitivity**. Within our approximation, T2K can **give a hint** towards mass ordering.
- However, in some states regardless of δ_{CP} mass ordering cannot be disentangled
- Uncertainties and inefficiencies we did not account for: uncertainties on the mixing parameters and cross section, detection efficiency and resolution etc.
- Similar analysis can be done with **NOva**