From T2K to HyperK

The search for Charge-Parity violation in neutrino oscillations

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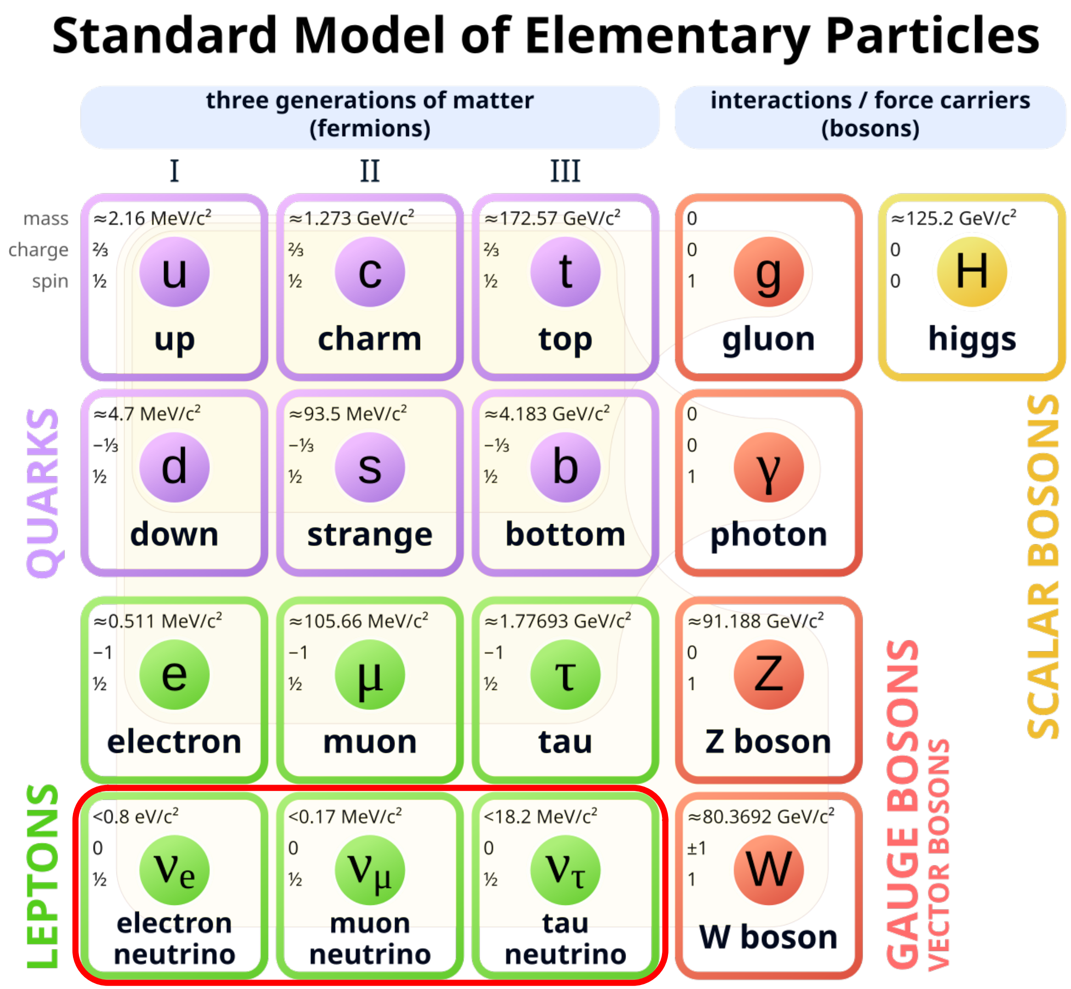
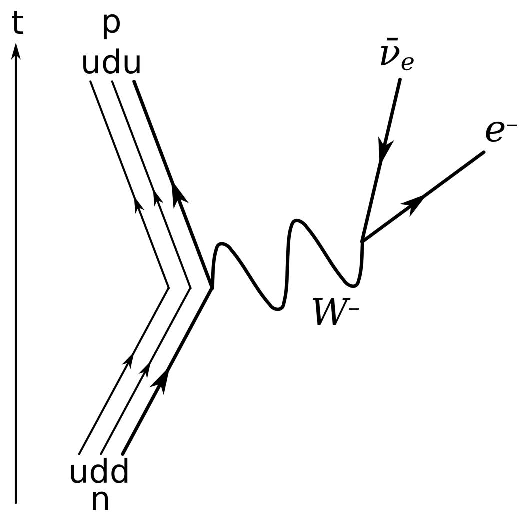
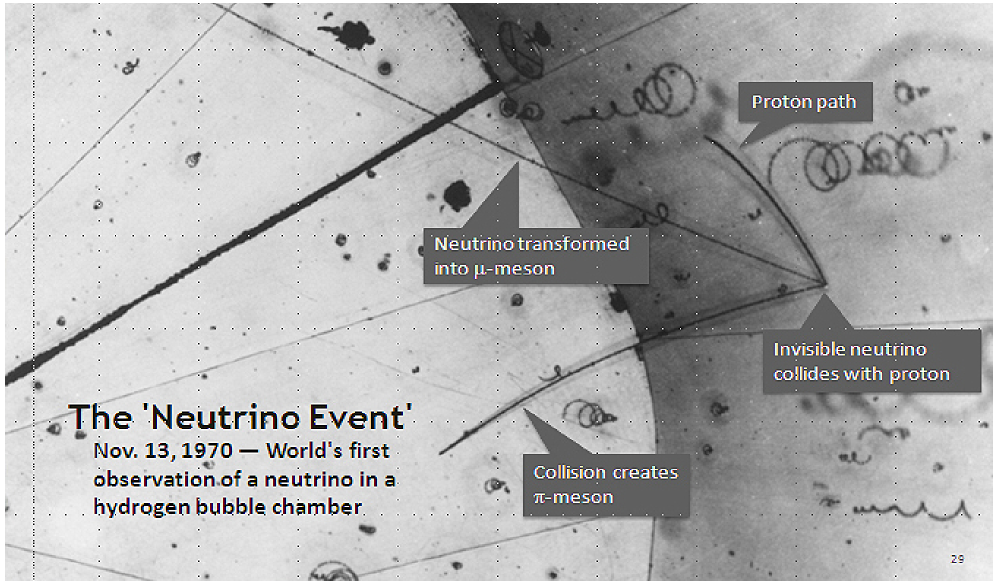
1. Introduction

Brief introduction to neutrinos



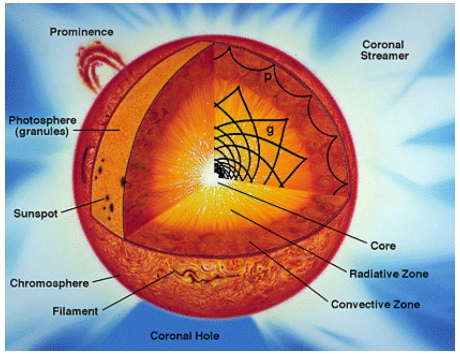


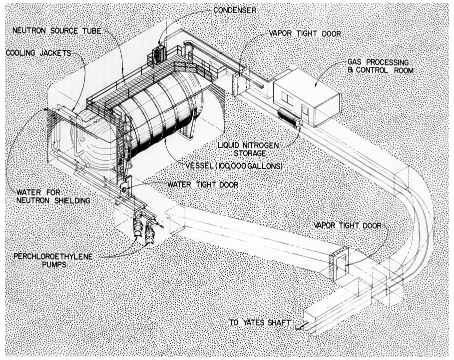


In the Standard Model: **no charge, no mass**

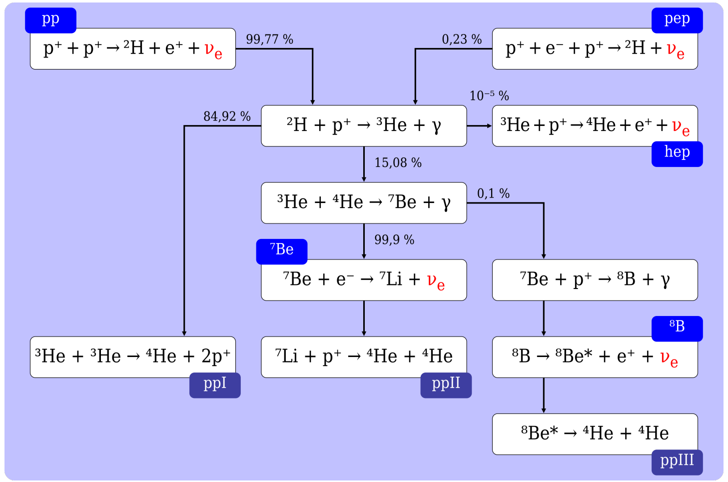
→ *ghost particles…*

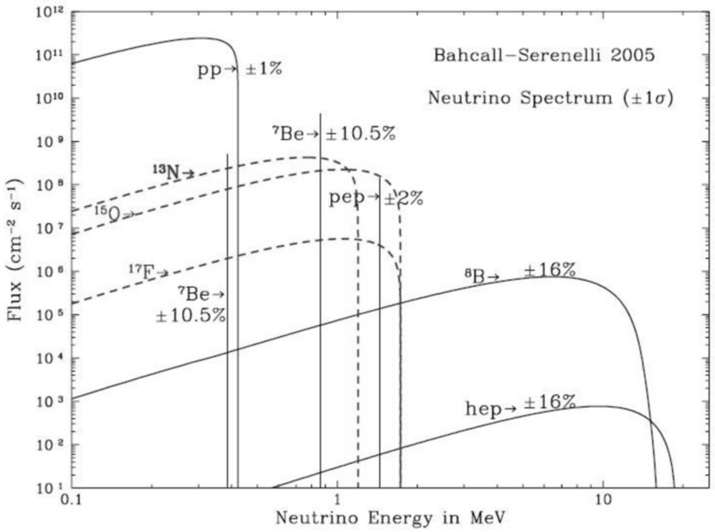
Solar Neutrino Problem

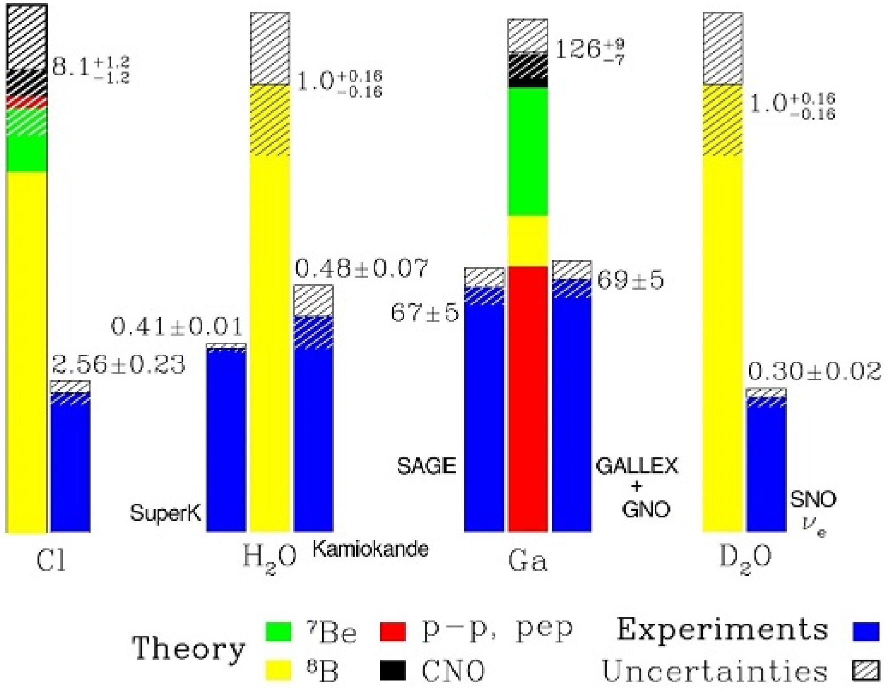




Homestake experiment (Bahcall and Davis)







→ very good knowledge of the Standard Solar Model

→ prediction of the Solar neutrino fluxes

→ on Earth, **deficit in neutrinos**, there must be something going on…

Parametrisation of the oscillation

For having oscillation, one needs :

- **massive** neutrinos, of 3 different masses ;
- a non-alignement : **mass** eigenstates ≠ **flavor** eigenstates ;

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\,\mathrm{e}^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\,\mathrm{e}^{i\delta_{\mathrm{CP}}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atm. and Accelerators	Reactors	Accelerators	Solar and Reactors
θ_{23} et $\lvert\Delta m^2_{32}\rvert$	θ_{13}	θ_{13} et δ_{CP}	θ_{12} et $\lvert\Delta m^2_{21}\rvert$

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CP symmetry

To explain matter-antimatter asymmetry in the Universe, three necessary conditions (Sakharov):

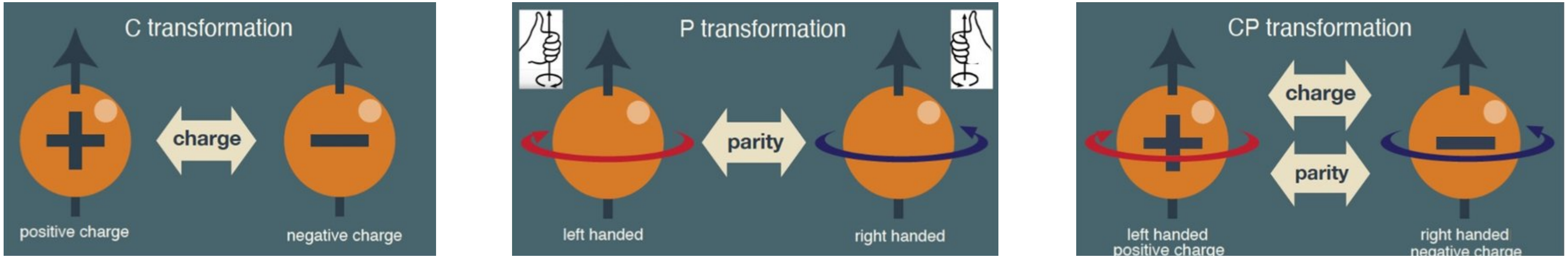
→ baryon number ***B*** **violation**

→ *C*-symmetry and ***CP*-symmetry violation**

→ interaction out of **thermal equilibrium**

CP symmetry violation means the laws of physics do not apply the same for **particles and antiparticles**

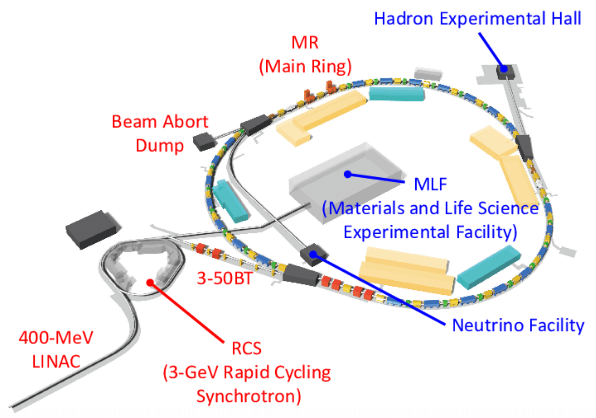
$$\mathcal{A}_{\rm CP} \equiv \frac{\mathcal{P}^{\nu}_{\mu\to e} - \mathcal{P}^{\overline{\nu}}_{\mu\to e}}{\mathcal{P}^{\nu}_{\mu\to e} + \mathcal{P}^{\overline{\nu}}_{\mu\to e}} \propto \sin\delta_{\rm CP}$$

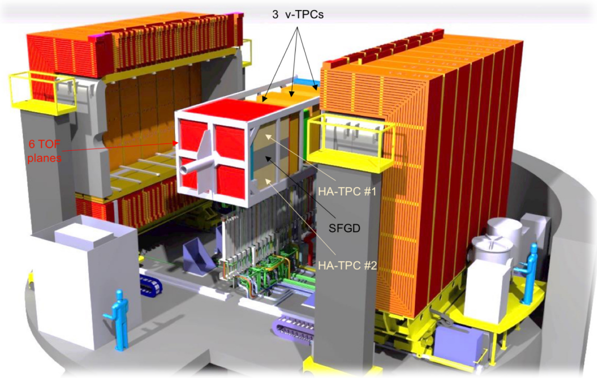


2. The T2K experiment

The T2K experiment

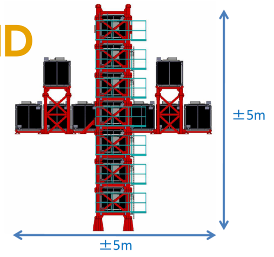
J-PARC

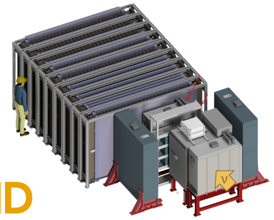




ND280

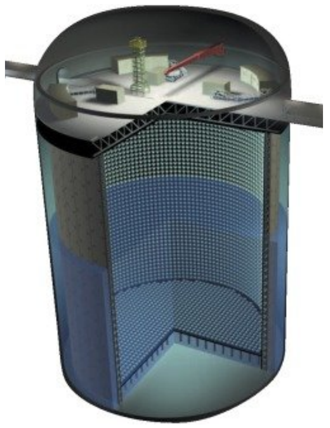
INGRID

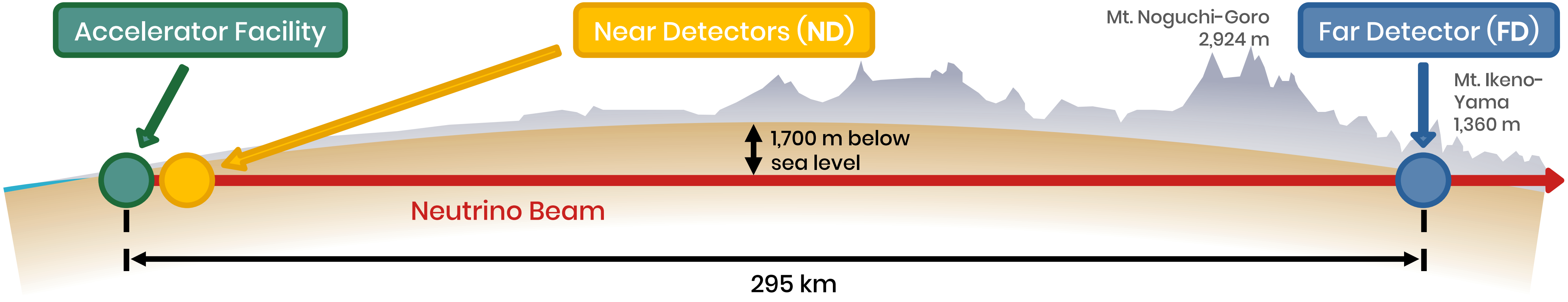




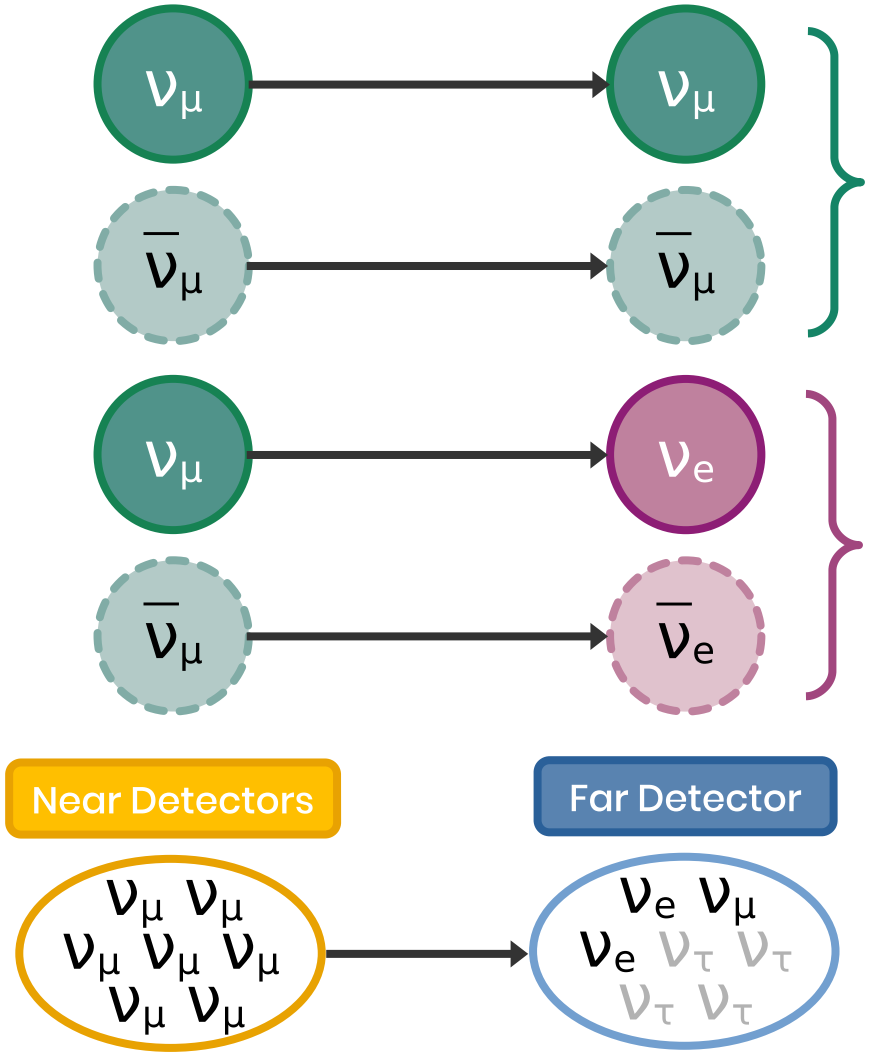
WAGASCI/
BabyMIND

Super-K





Oscillation channels at T2K



Disappearance channels
at first order:
Δm^2_{32} and θ_{23}

Appearance channels
at first order:
δ_{CP} and θ_{13}

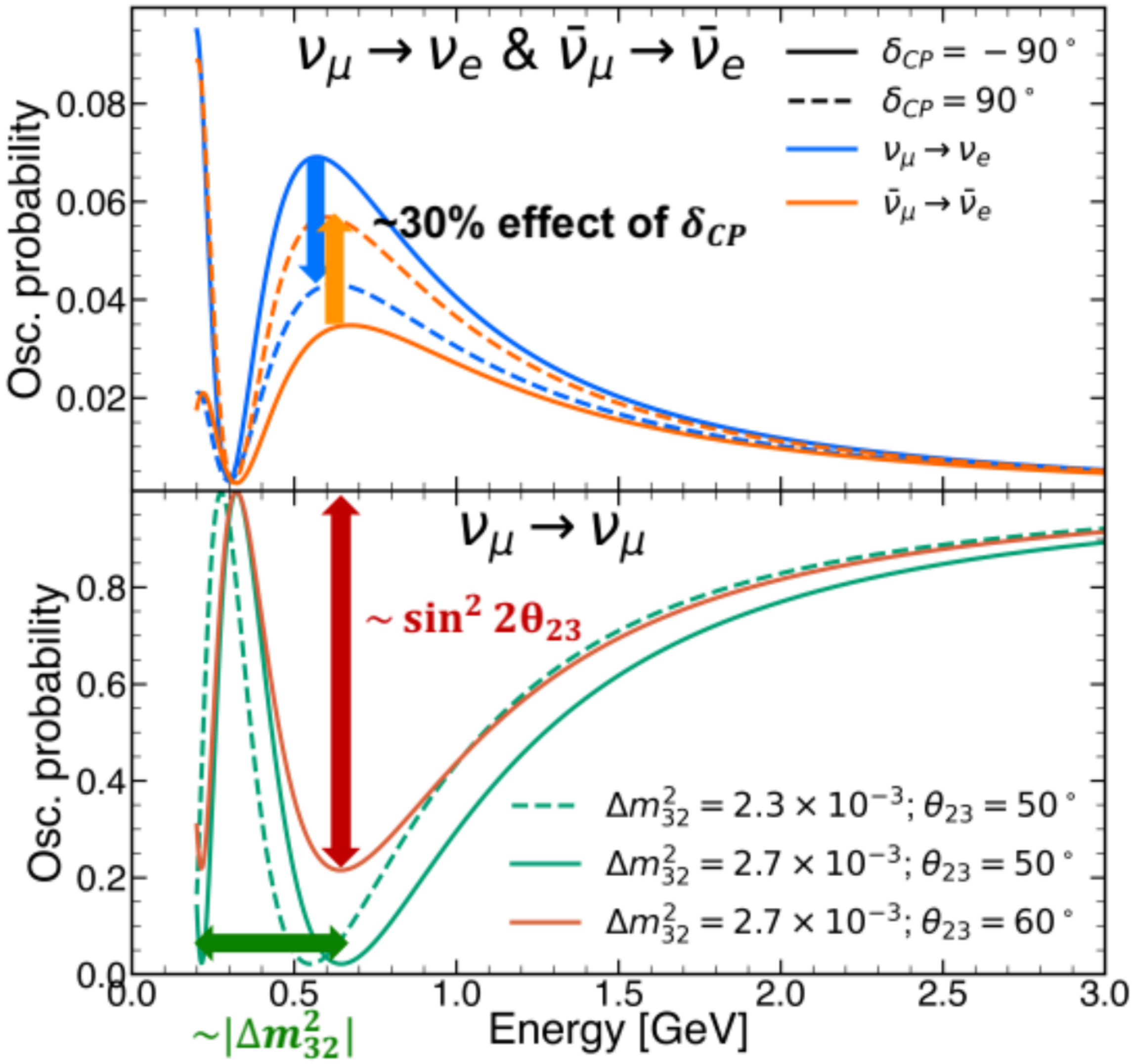
Combination of the 4 channels to resolve degeneracies between different oscillation parameters

→ **Especially the $\nu/\bar{\nu}$ ratio**

T2K oscillation physics:

- CP violation;
- Δm^2_{32} (NO) / $|\Delta m^2_{31}|$ (IO)
- θ_{23} octant
- oscillation interpretation beyond PMNS (unitarity tests…)
- *Mass Ordering* ; θ_{13}

Oscillation parameters at T2K



Example for the T2K configuration:

- $E = [0.2;\ 3]$ GeV
- $L = 295$ km

- $\boldsymbol{\delta_{CP}}$ modulates electron appearance probability (asymmetrically for ν_e and $\bar{\nu}_e$)

- The disappearance ($\nu_\mu \to \nu_\mu$) depth depends on $\mathbf{\sin^2 2\theta_{23}}$
- The oscillation frequency depends on $|\Delta \boldsymbol{m^2_{32}}|$

2. Strategy of the study

How to measure the oscillation probability

- Models + **ND** constraints
- **FD** data

Probability for neutrino ν_α to oscillate into ν_β, with energy E_{true} and after travelling L

Neutrino interaction **cross-section**

Neutrino **energy reconstruction**

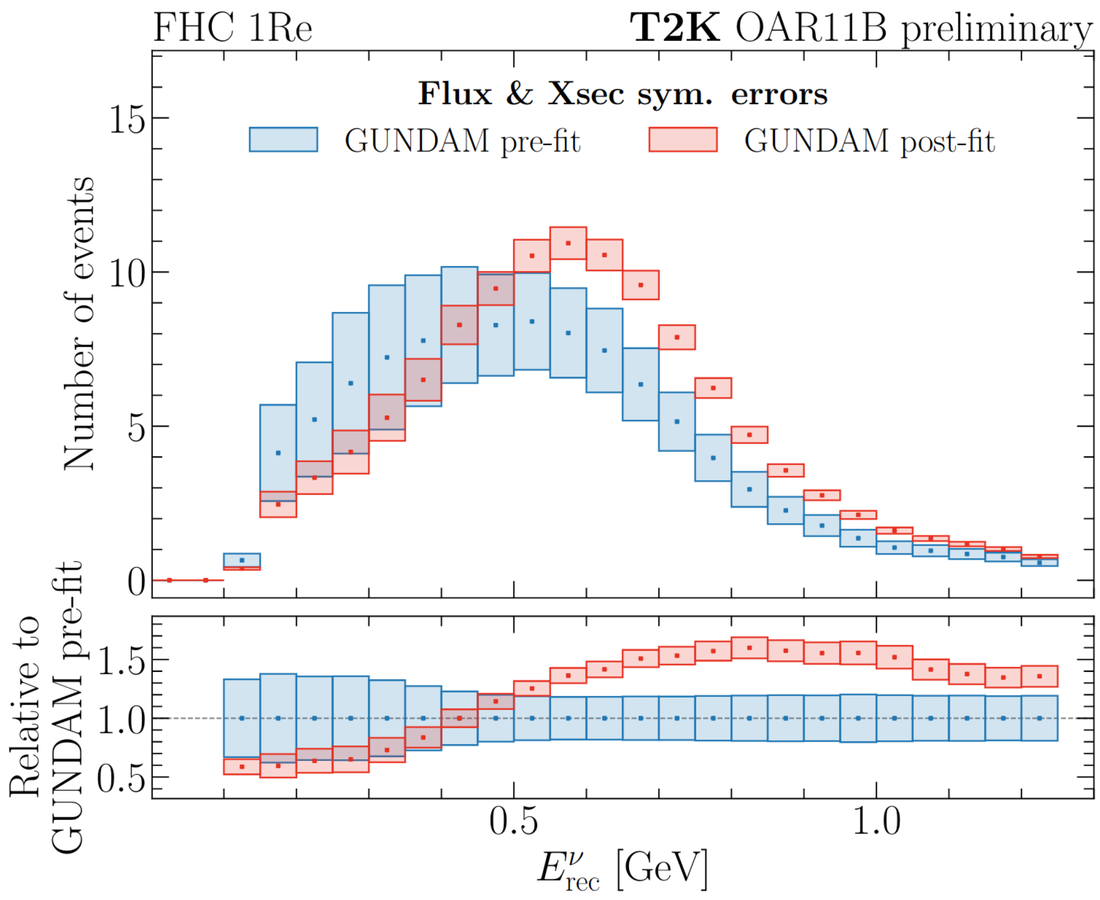
$$N_\beta\left(E_{\text{rec}}\right) \simeq \int \mathrm{d}E_{\text{true}} \left[\mathcal{P}_{\alpha\to\beta}(E_{\text{true}}, L) \times \Phi_\alpha(E_{\text{true}}) \times \sigma_\beta(E_{\text{true}}) \times \varepsilon_{\text{det}} \times d\left(E_{\text{true}}, E_{\text{rec}}\right)\right]$$

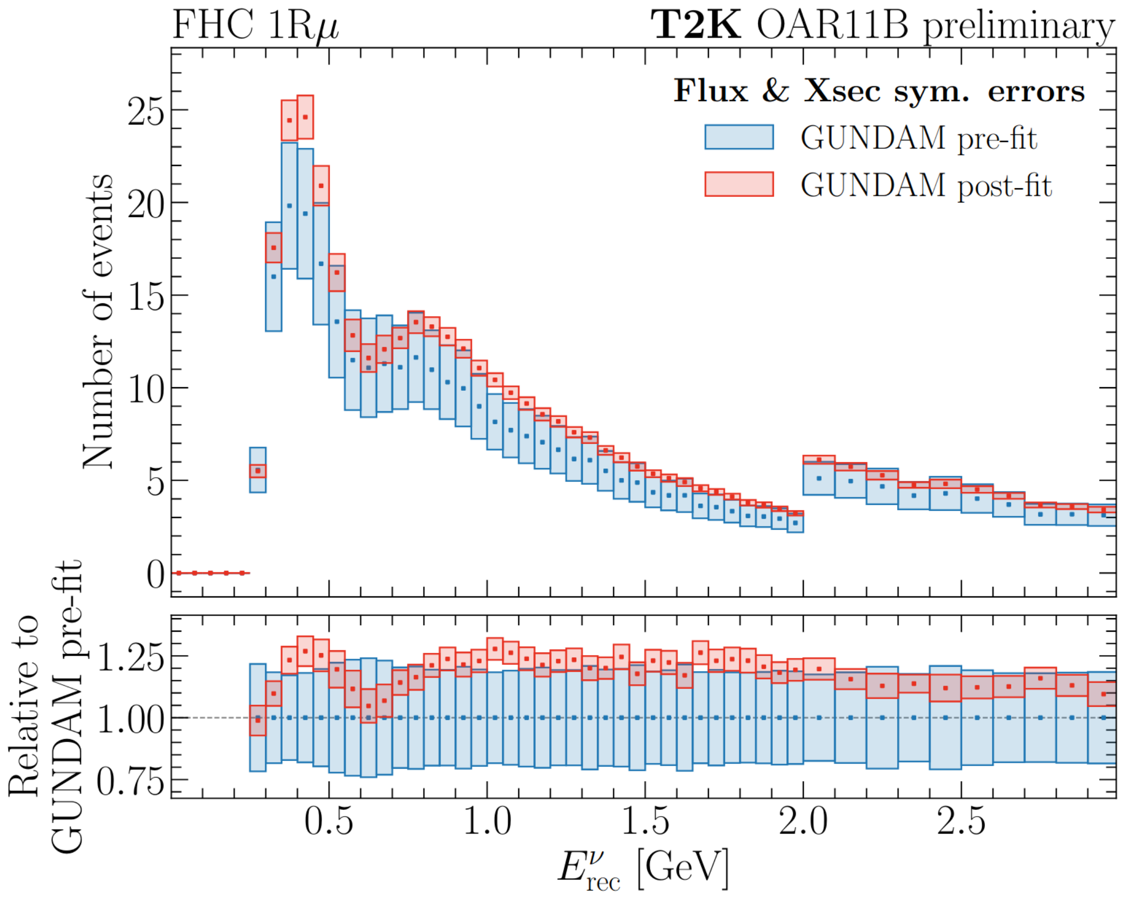
Number of oscillated ν_β

Unoscillated **flux** of ν_α

Detectors efficiency

Importance of the ND fit





3. CP violation sensitivities

CPV search : appearance channel

At T2K, the 3 leading terms are:

$$P_{\mu e} = 4s_{23}^2 s_{13}^2 c_{13}^2 \sin^2 \Delta_{31}$$ 1 Leading term

$$\mp J_{\mathrm{CP}} \sin \Delta_{32} \sin \Delta_{31} \sin \Delta_{21}$$ 2 CP violating term

$$\pm 8a(1 - 2s_{13}^2) s_{23}^2 s_{13}^2 c_{13}^2 \frac{\sin \Delta_{31}}{\Delta m_{31}^2} (\sin \Delta_{31} - \Delta_{31} \cos \Delta_{32})$$ 3 Matter effects

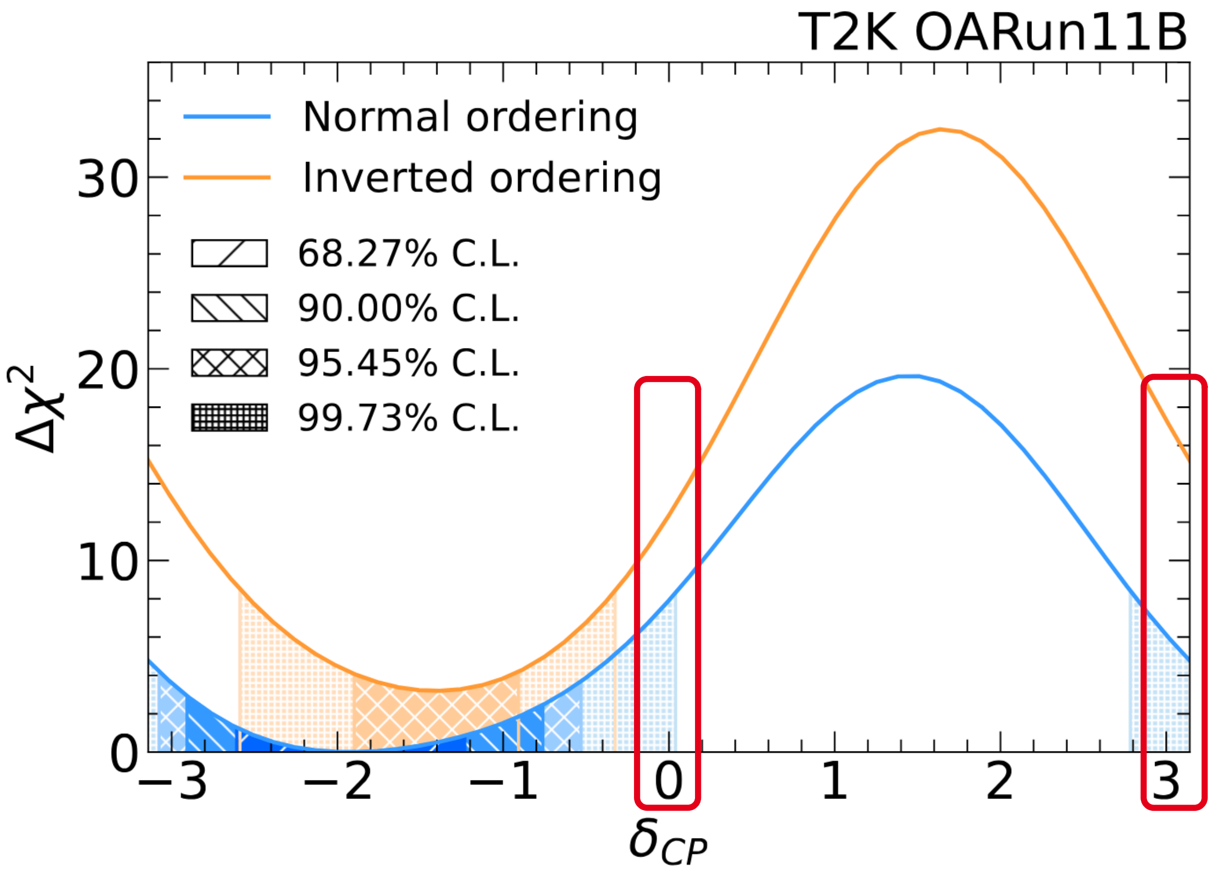
$$+ \cdots ,$$

with the Jarlskog invariant:

$$J_{\mathrm{CP}} = s_{13} c_{13}^2 s_{12} c_{12} s_{23} c_{23} \sin \delta_{\mathrm{CP}}$$

$$c_{ij} = \cos \theta_{ij}$$
$$s_{ij} = \sin \theta_{ij}$$
$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$
$$a = 2\sqrt{2} G_F n_e E$$

CPC exclusion: latest constraint from T2K



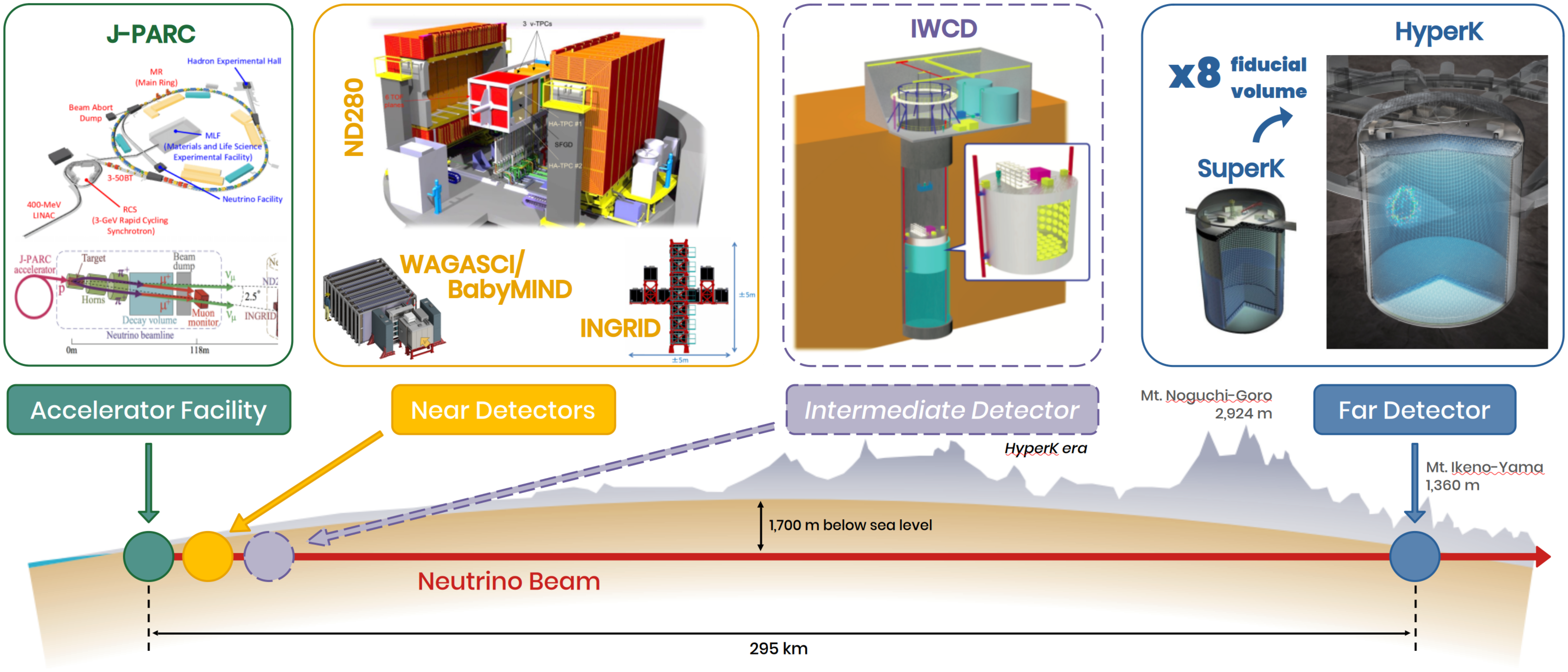
CP conservation exclusion

=> **min $\Delta\chi^2$ to exclude $\sin \delta_{CP} = 0$**

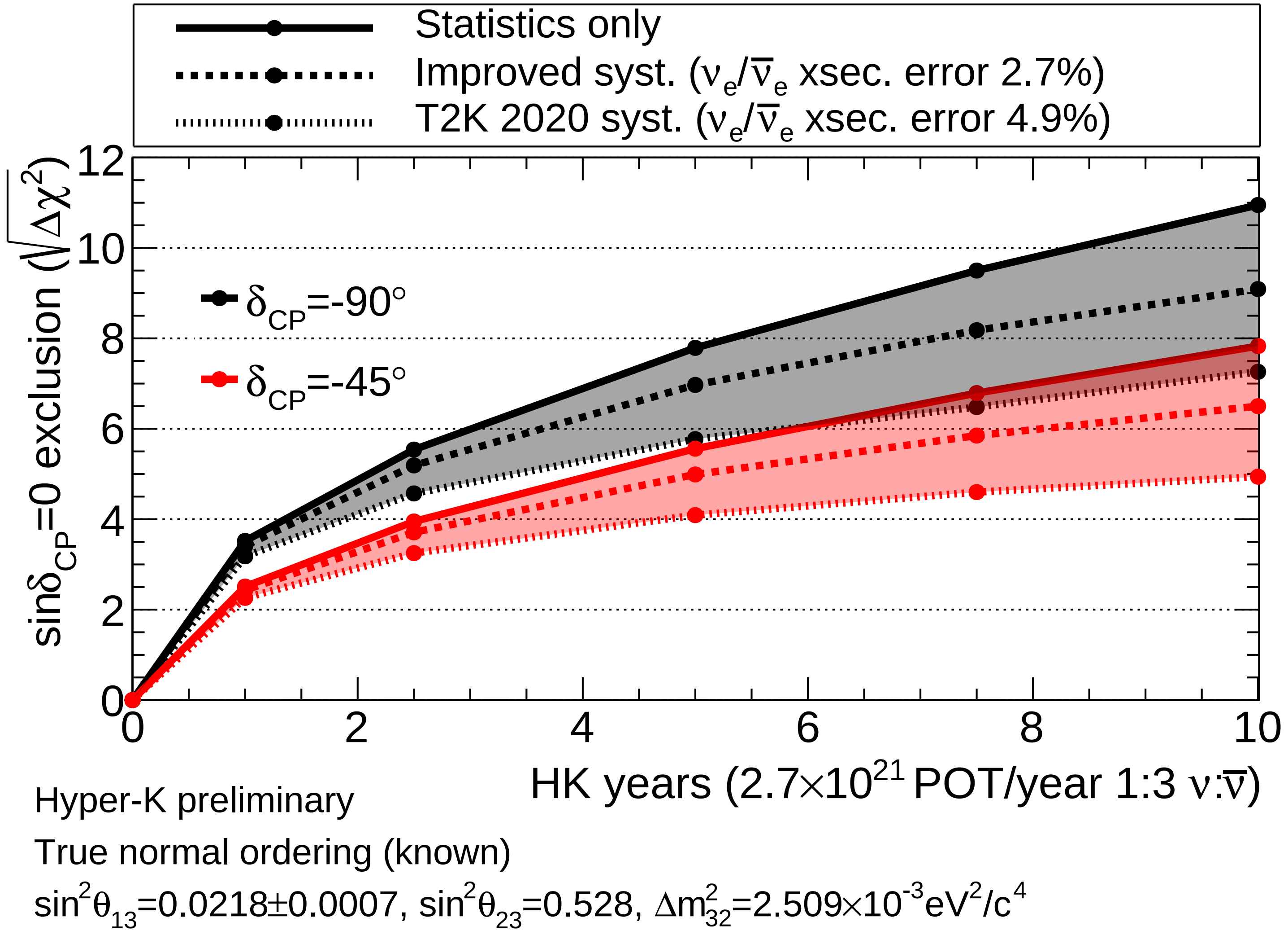
- latest T2K constraint (2026): close to **99% CL exclusion of CP conservation** for the frequentist analysis (around **2σ** for the bayesian analysis)

4. HyperK era

The HyperK experiment



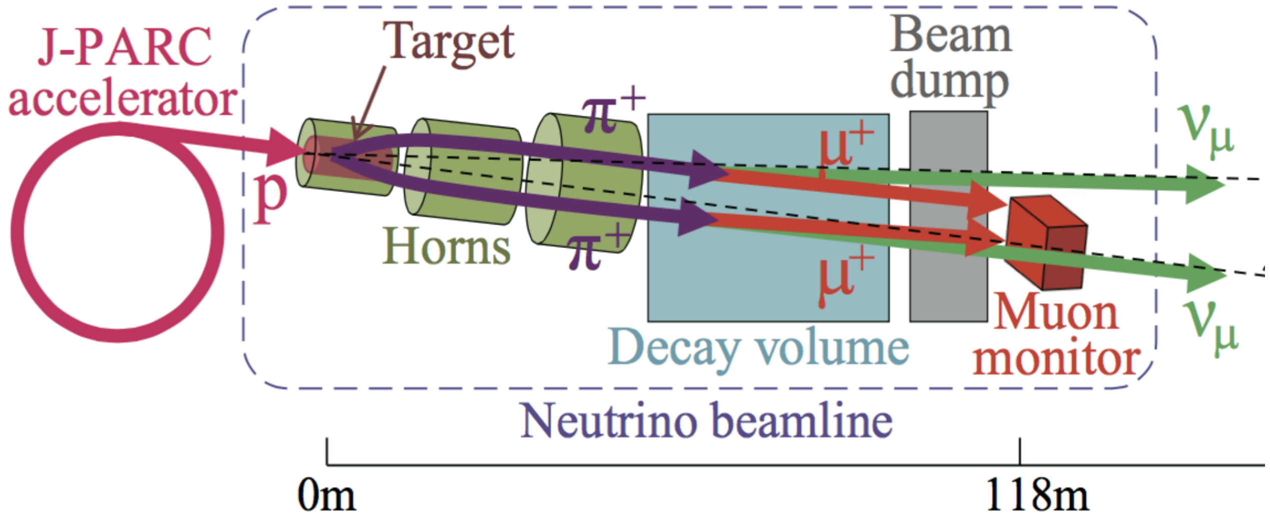
HyperK sensitivity to CPC exclusion



- we expect to reach the **5σ level** in **~3 years** if CP is maximally violated

Thanks for listening!

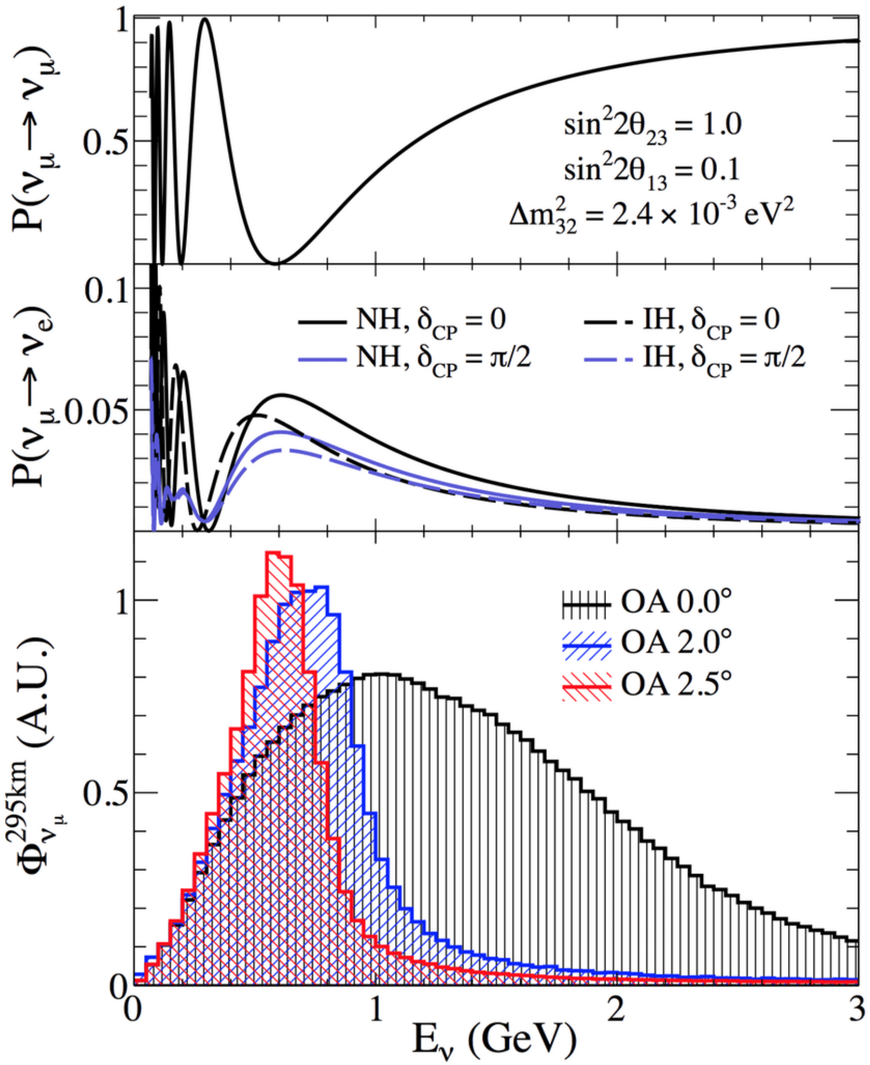
Producing neutrinos at T2K



Mesons focused/defocused by 3 electromagnetic horns

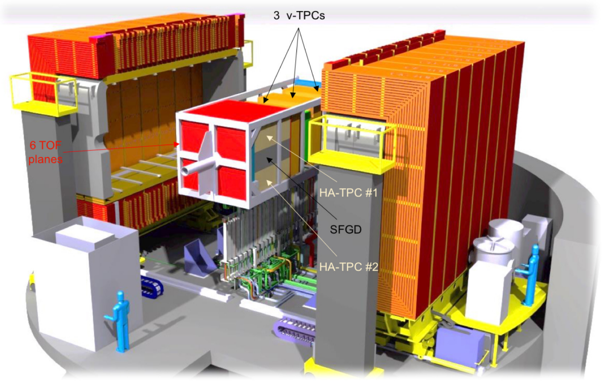
→ **neutrino mode** ("Forward Horn Current", **FHC**)

→ **antineutrino mode** ("Reversed Horn Current", **RHC**)

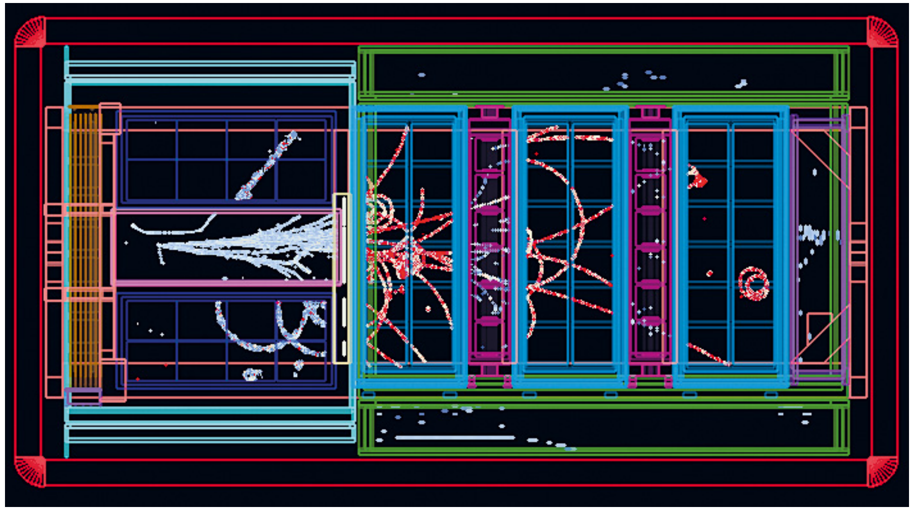


Detecting neutrinos at T2K

ND280

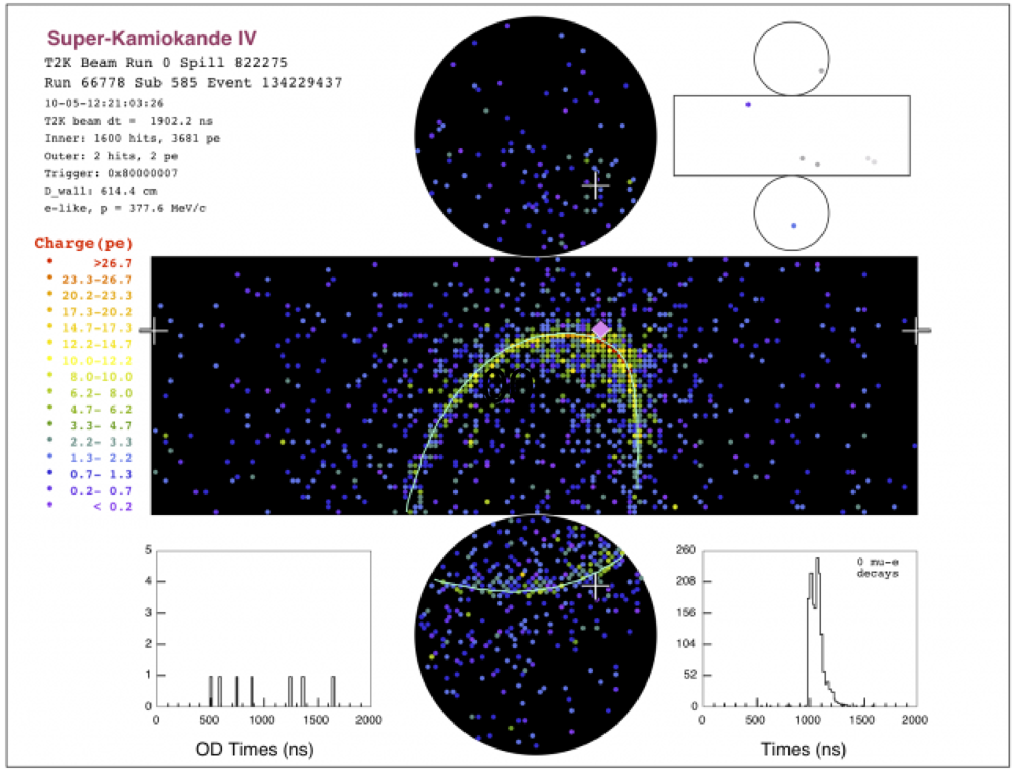


- **ND280** uses FGDs (scintillator and water layers) and TPCs (gas detector) to reconstruct particle tracks.

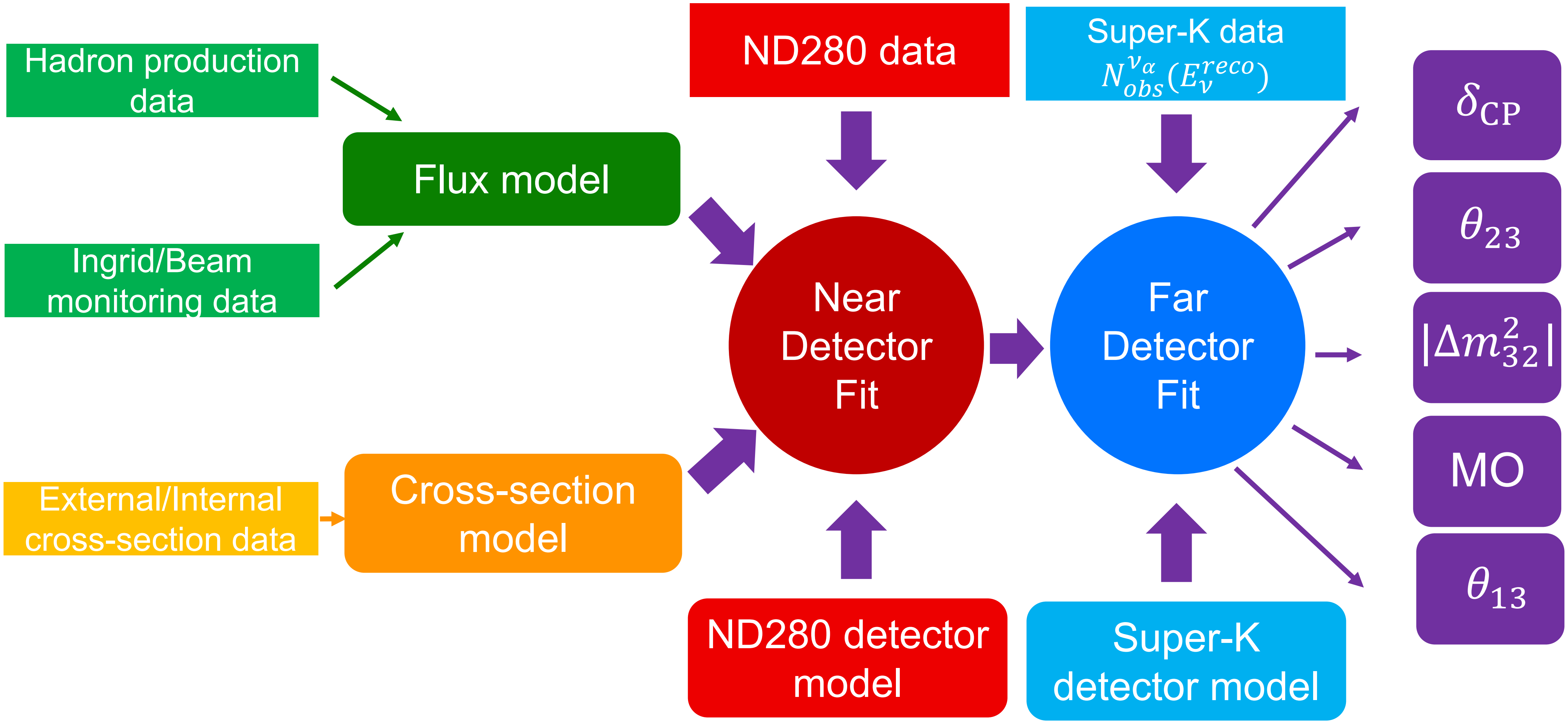


Super-K

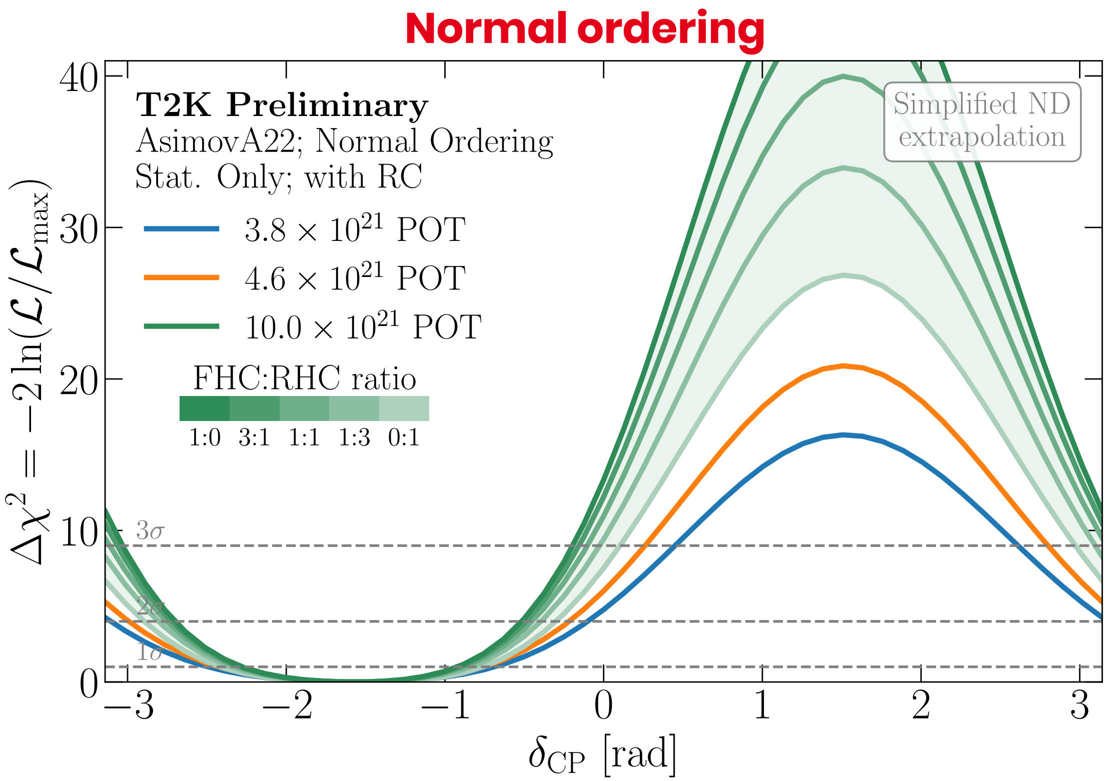
- **SuperK** uses PMTs to reconstruct the light-cone emitted by charged particles via Cherenkov effect in water.

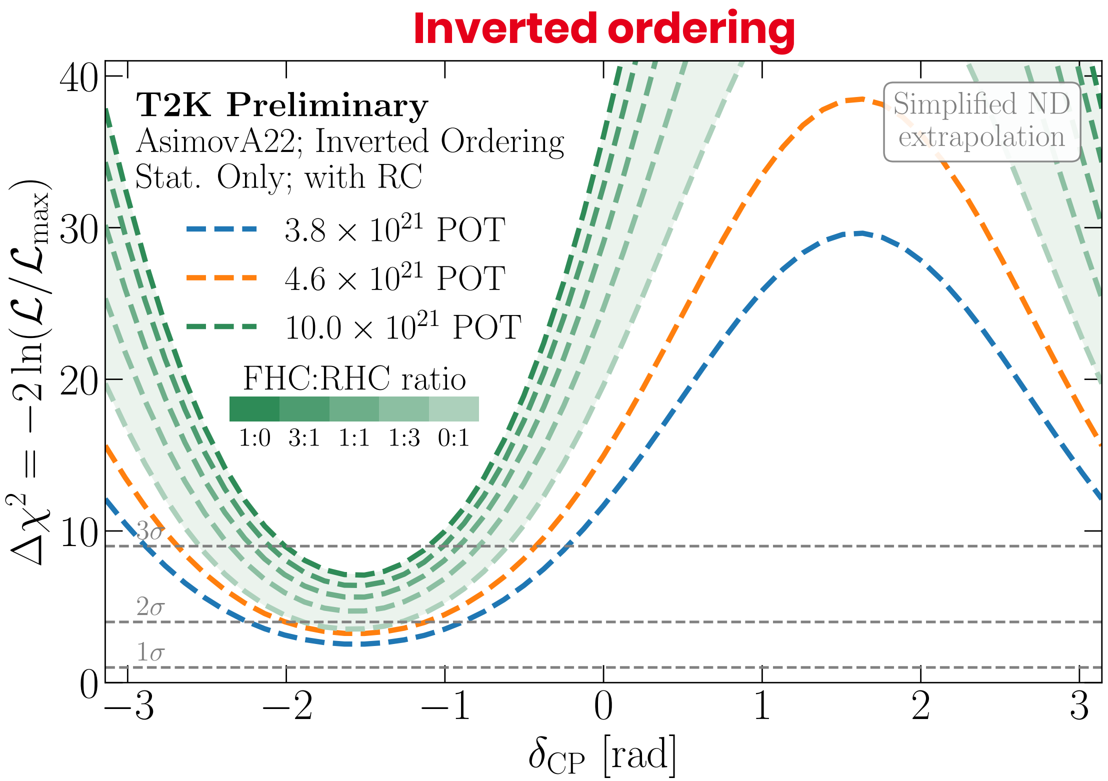


Strategy for T2K oscillation analysis



CPV search : δ_{CP} likelihood scan

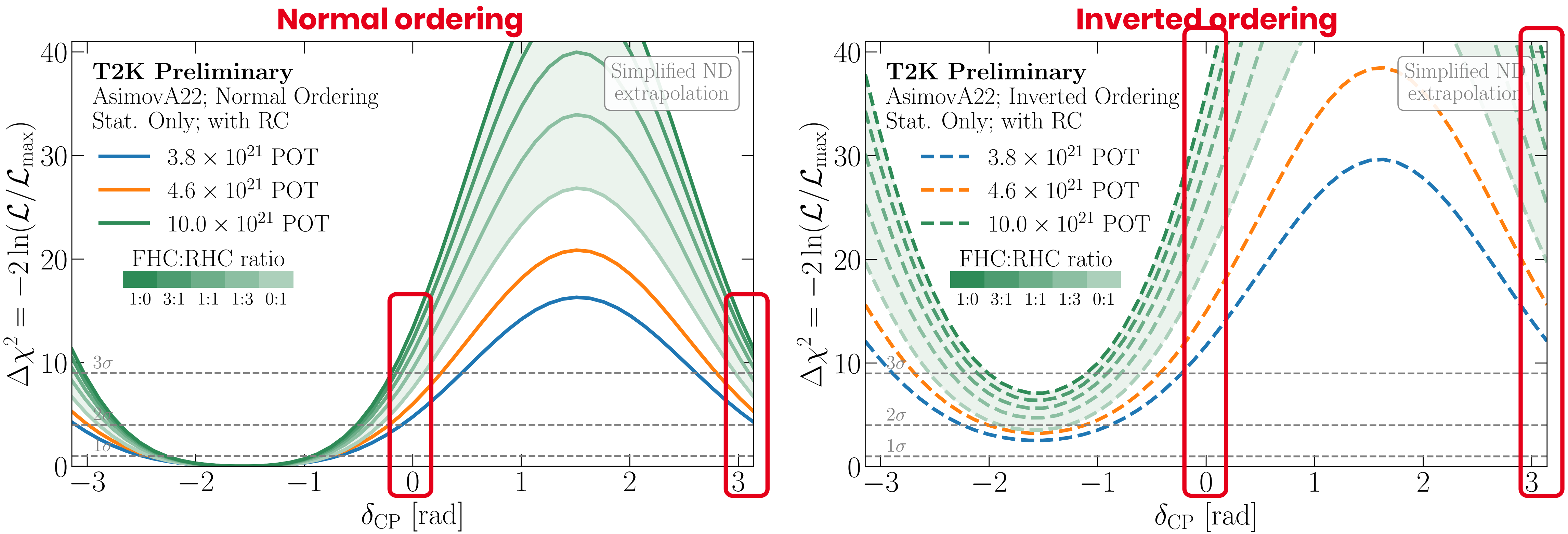




- good exclusion of the **sin δ_{CP} > 0** region;
- some sensitivity to excluding the **wrong hierarchy**;

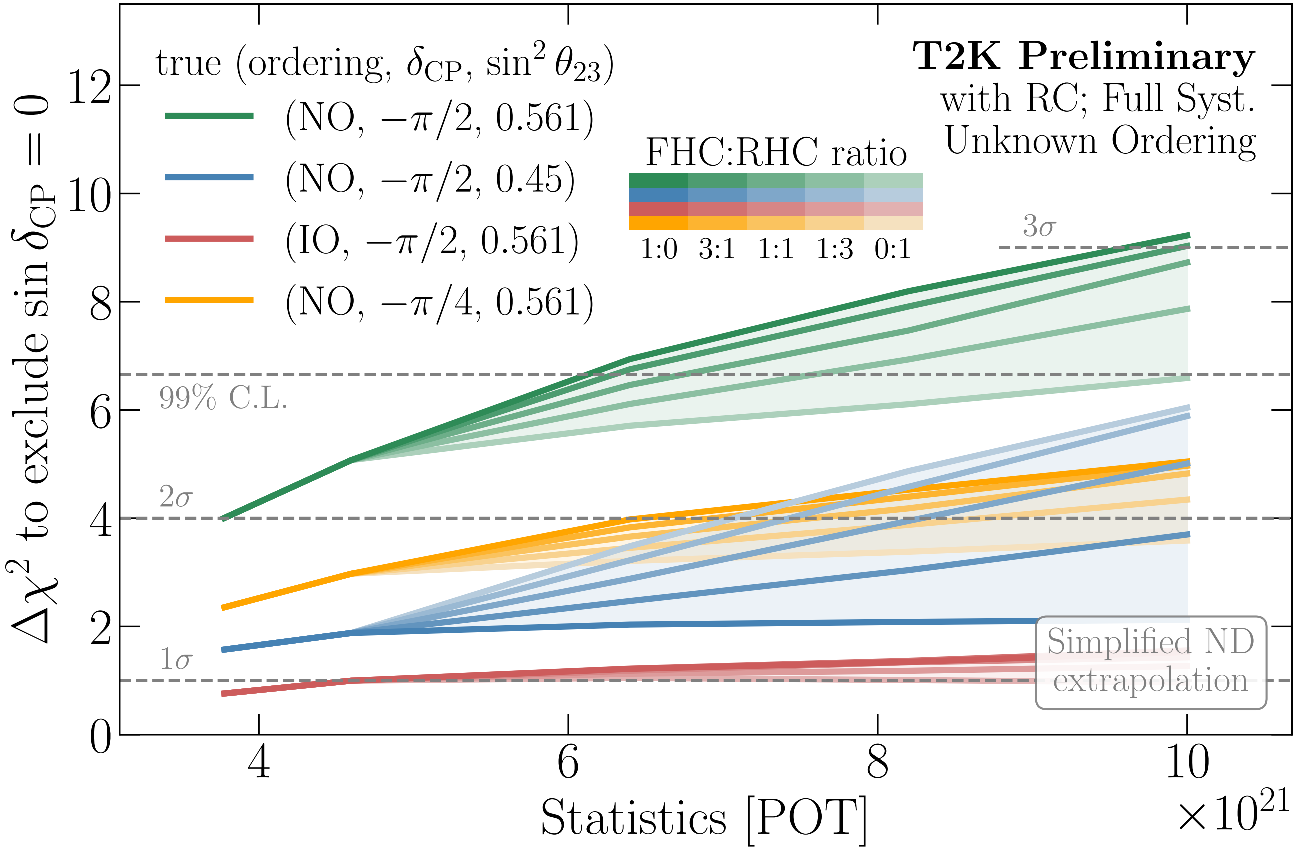
- **full neutrino mode** is preferred since neutrino cross-section with matter about ~3 times higher than antineutrinos;

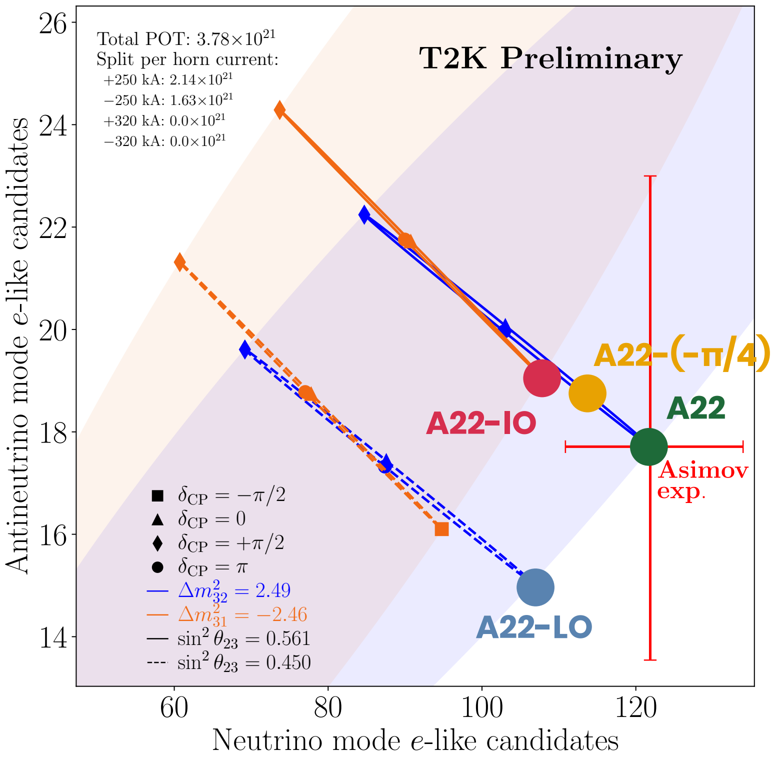
CPV search : CP conservation exclusion



CP conservation exclusion => **min $\Delta\chi^2$ to exclude $\sin \delta_{CP} = 0$**

CPC exclusion: summary plot





- the further away from degeneracies ➡ the better the sensitivity;
- the further away from degeneracies ➡ **full neutrino mode** is preferred (in upper octant);