21ST RECONTRES DU VIETNAM FLAVOUR PHYSICS

Recent results of the T2K experiment

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T2K

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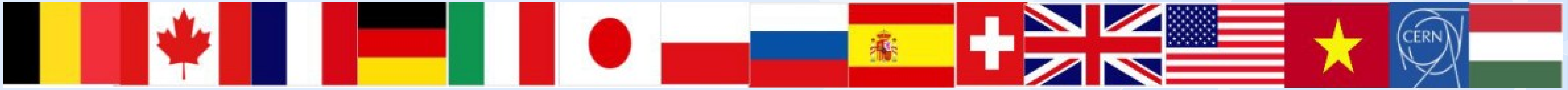
THE T2K COLLABORATION



- International collaboration of 560 members from 74 institutes
- Long-baseline neutrino oscillation experiment in Japan which started its operation in 2010
- Provides world leading measurements of oscillation parameters … also measures cross-sections of neutrino interactions

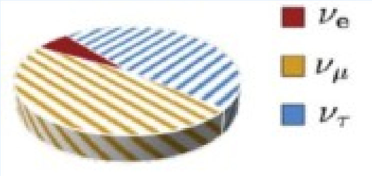
WHAT WE KNOW ABOUT NEUTRINOS

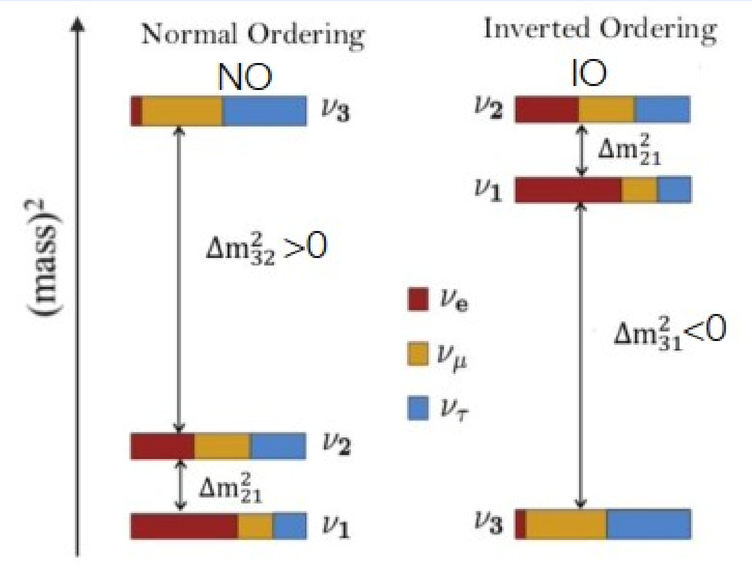
LBL experiments sensitive to these parameters

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics and LBL	Reactors	Solar and Reactors
$\theta_{23} \sim 45^\circ$	$\theta_{13} \sim 10^\circ$	$\theta_{12} \sim 35^\circ$
$\lvert\Delta m^2_{32}\rvert \sim 2.5\times10^{-3}\,eV^2$	δ_{CP} unknown	$\Delta m^2_{21} \sim 7.5\times10^{-5}\,eV^2$

- What is the value of δ_{CP} 0, π or in-between?
- What is mass ordering NO or IO? $\Delta m^2_{32}>0$?
- What is the octant of θ_{23}?
- Precise measurement of mixing parameters.

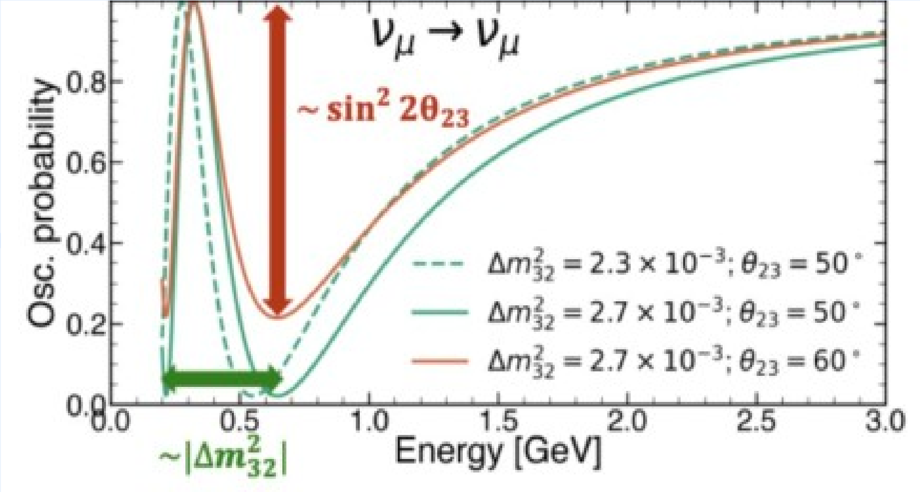


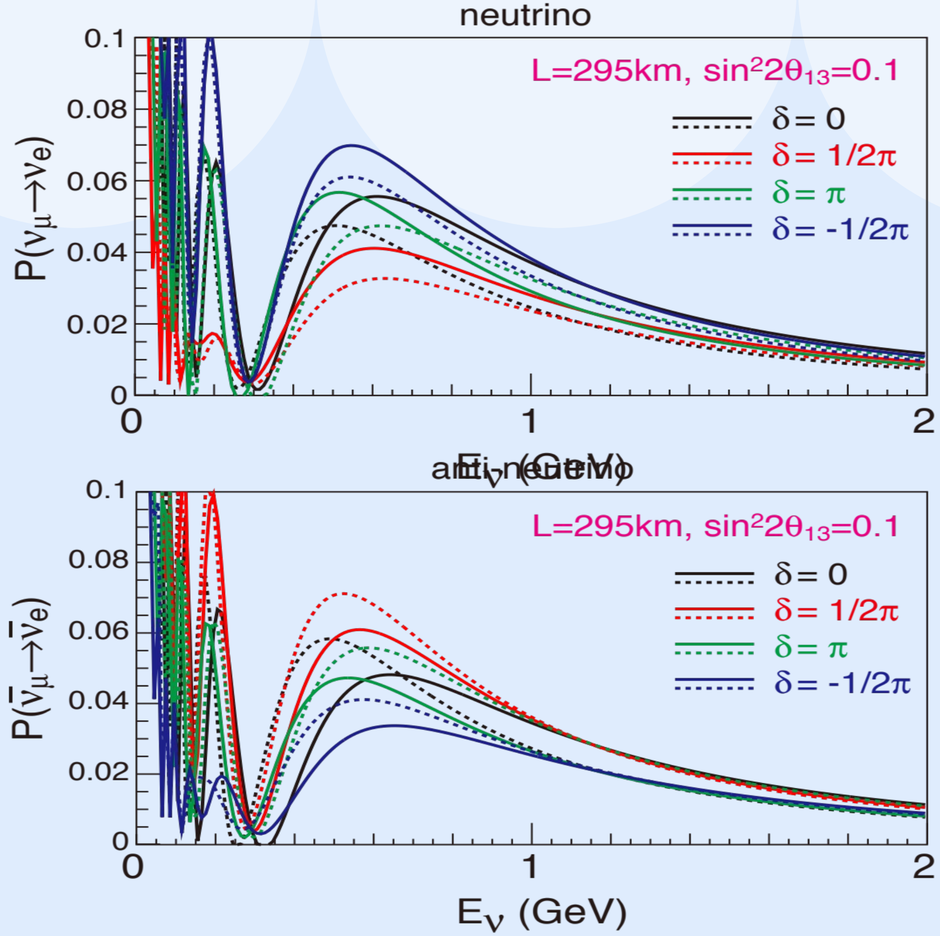


OSCILLATION PROBABILITY

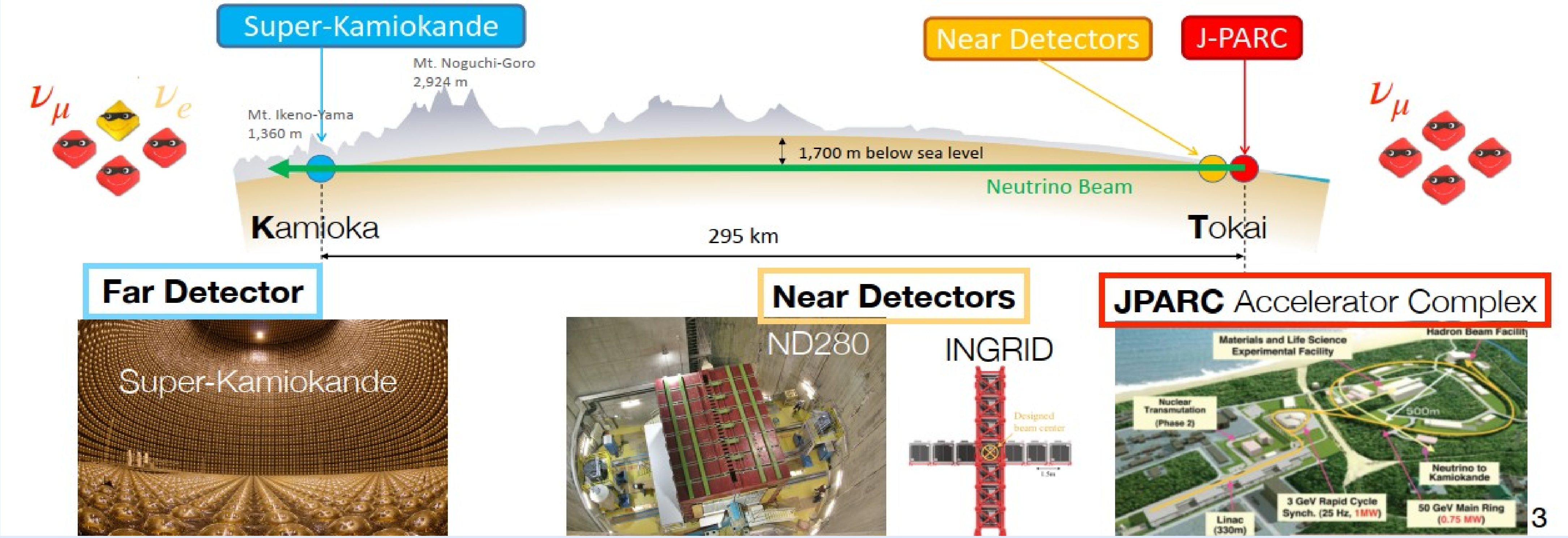
- **Disappearance** $P(\nu_\mu \rightarrow \nu_\mu)$
  - same for ν and $\bar{\nu}$
  - $\sin^2 2\theta_{23}$ modules amplitude
  - position of "dip" modelled by Δm^2_{23}

- **Appearance** $P(\nu_\mu \rightarrow \nu_e)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - sensitive to δ_{CP} with opposite effect for ν and $\bar{\nu}$
  - sensitive to mass ordering ~10% effect (NO - continuous line, IO - dashed line)
  - degeneracy δ_{CP} and mass ordering





THE T2K EXPERIMENT



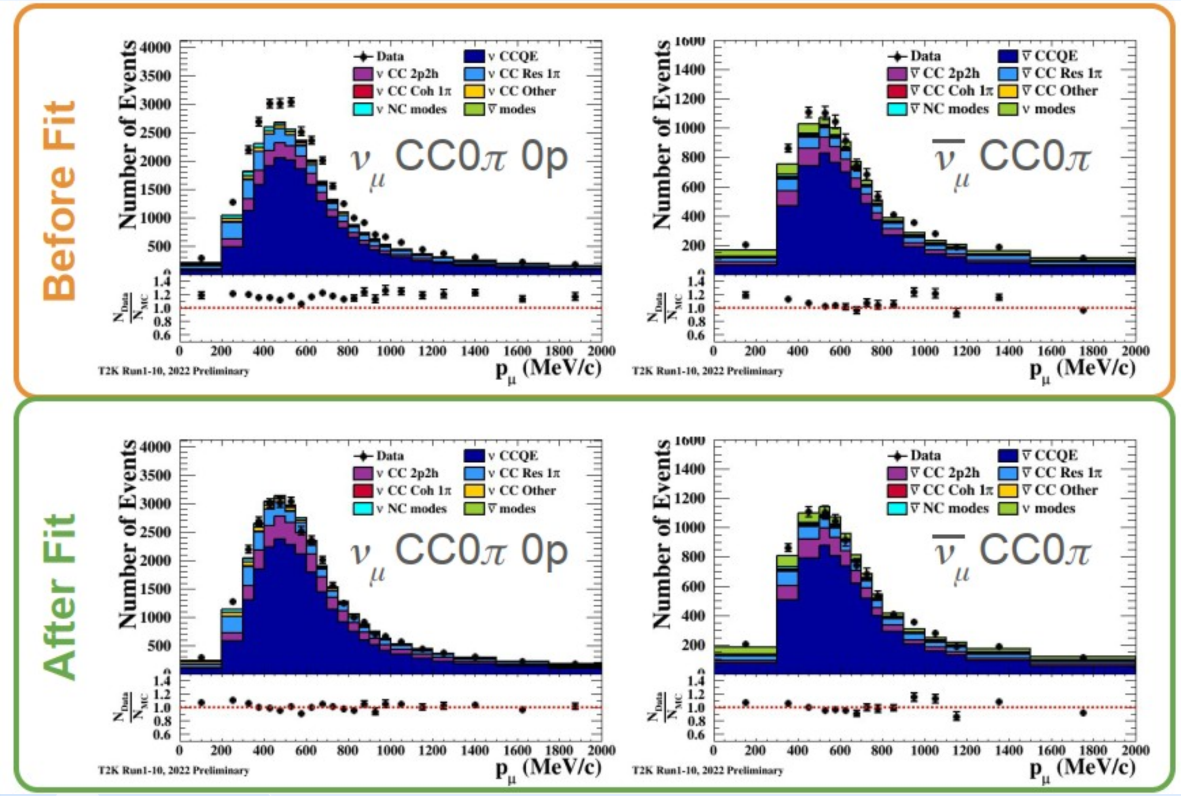
- 50kt water Cherenkov detector with Gd added since 2020
- Distinguish interactions of ν_μ and ν_e based on ring shape
- 11k 20″ PMTs inner detector,
- 2k 8″ PMTs outer detector

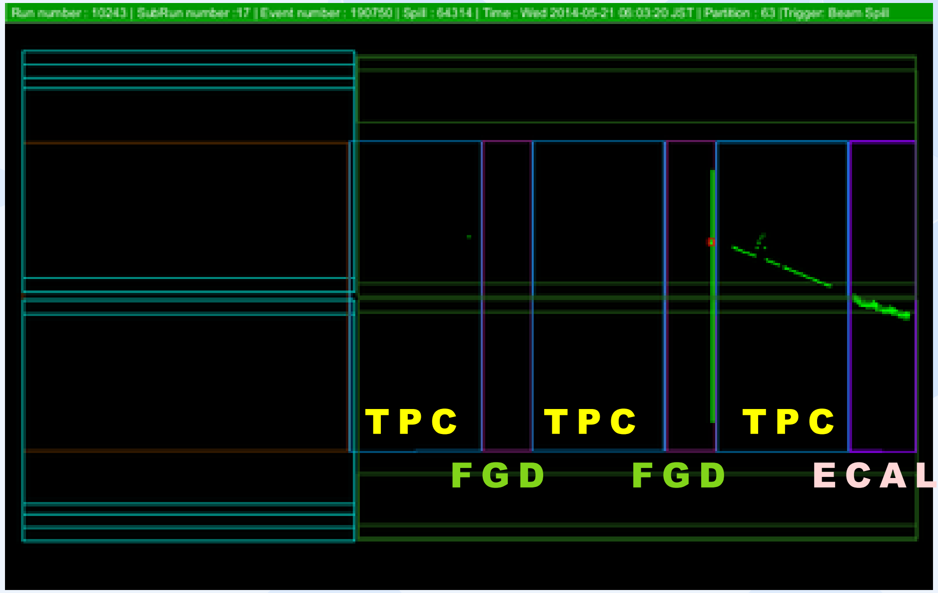
- Scintillator tracker and TPC
- Constraint un-oscillated neutrino flux
- Measures cross-sections of neutrino interactions

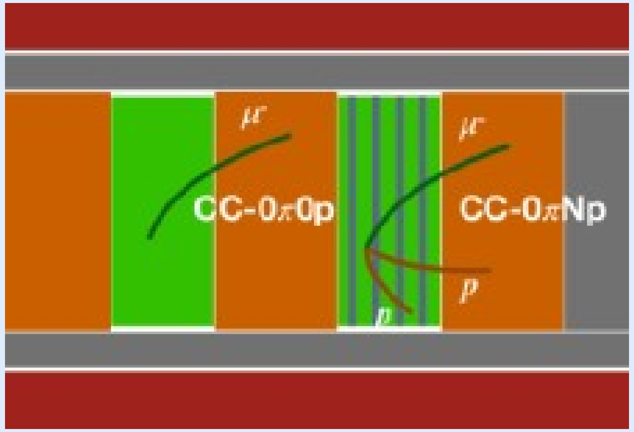
- 30GeV p send on graphite target
- producing $\pi^{+/-}$,$K^{+/-}$ decaying into flight producing ν_μ and $\bar{\nu}_\mu$ beam
- Beam power reached 830kW
- 2.5° off-axis, with peak energy 600MeV

NEAR DETECTOR DATA

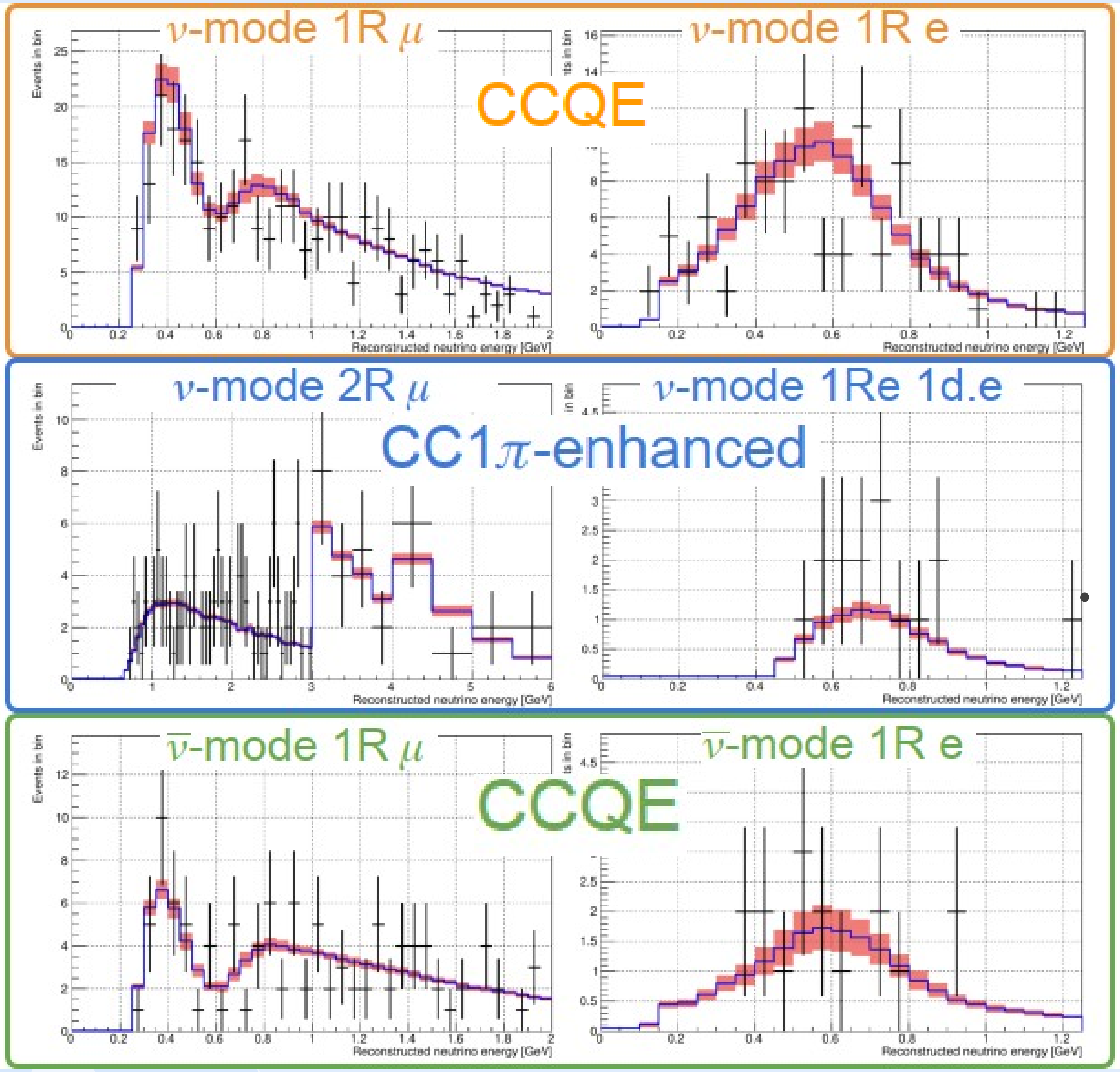
- 22 samples based on:
  - beam configuration
  - target CH/$H_2$0
  - number of pions, protons, photons

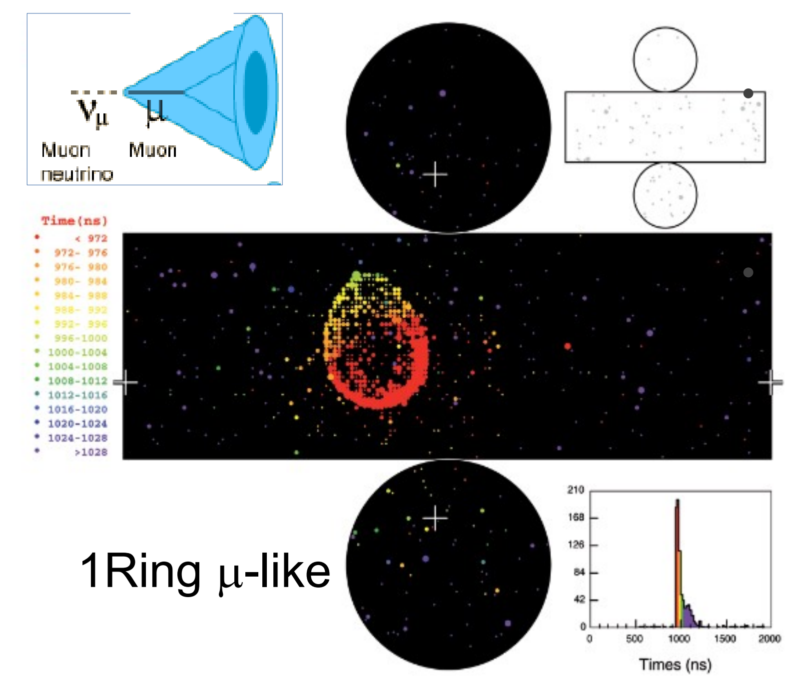






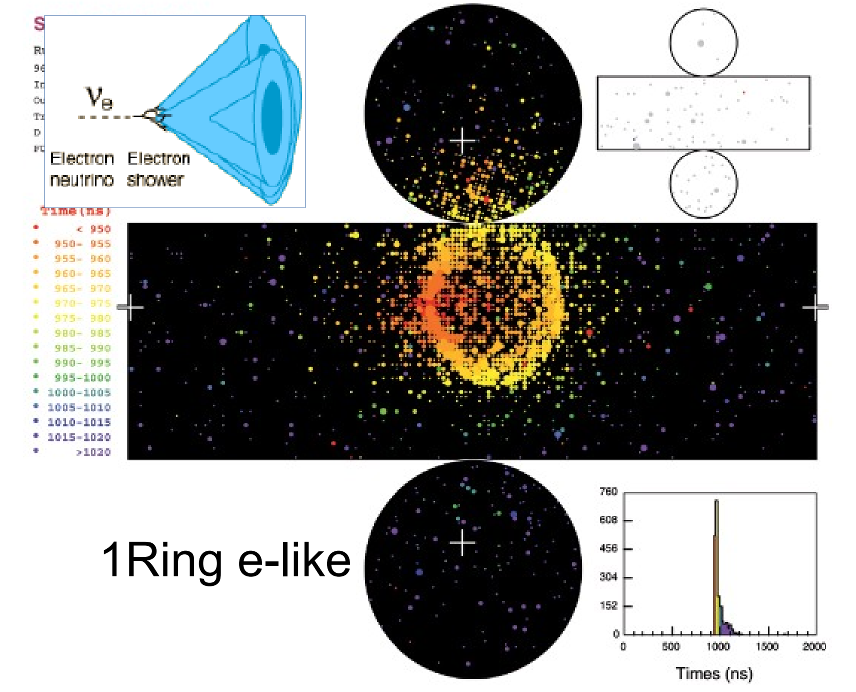
FAR DETECTOR DATA





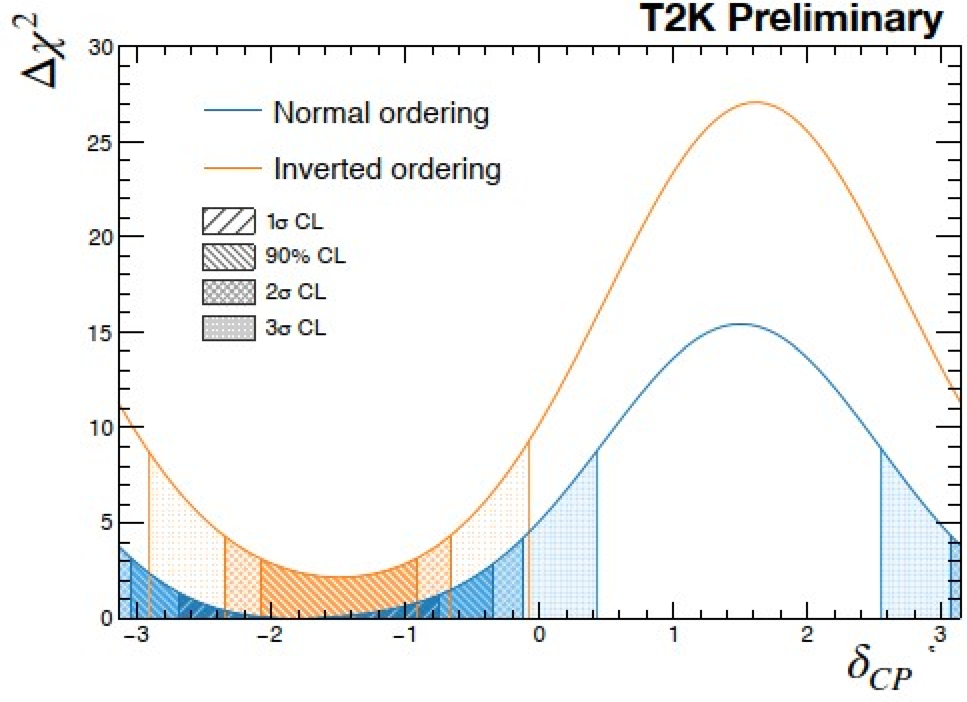
We can determine whether interaction is ν_μ or ν_e, based on shape of the ring

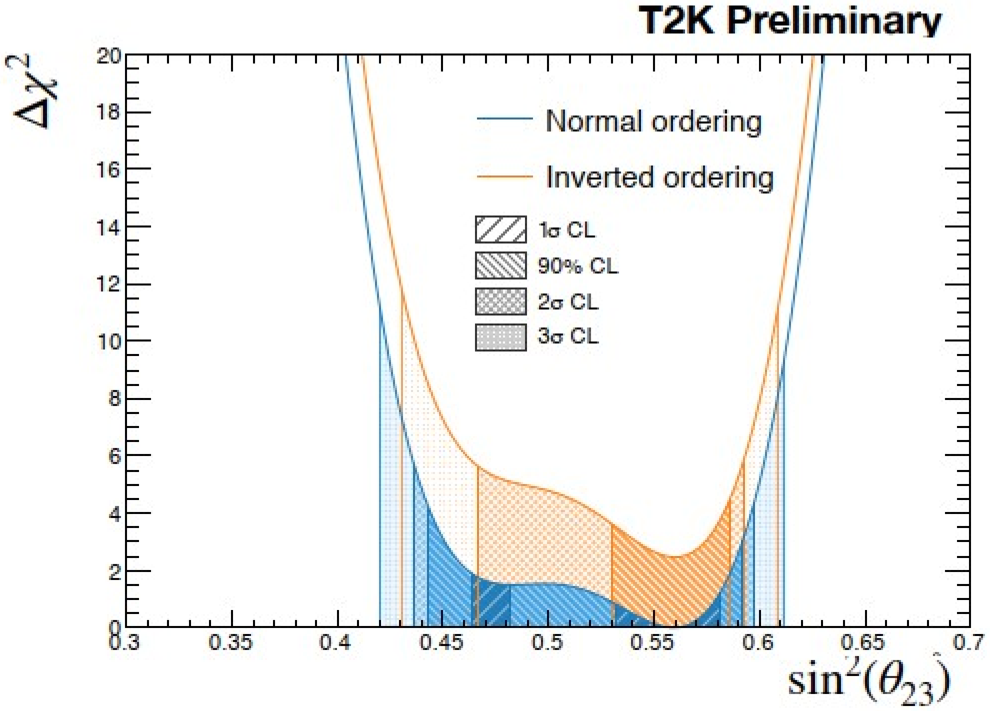
Detected amount of Cherenkov light and its timing allows to reconstruct particle energy, vertex and direction



RESULTS OF OSCILLATION ANALYSIS

- 10% more ν data
- Improved treatment of SK systematics
- Additional cuts to distinguish decay-e and neutron





Total :

ν: 2.17 x 10^{21} POT

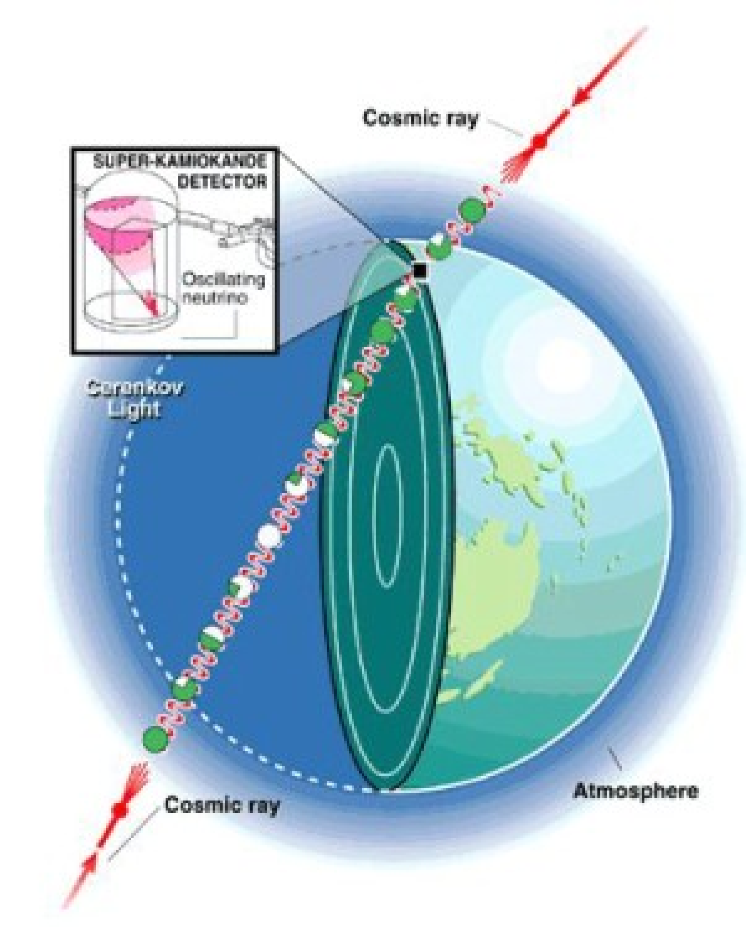
$\bar{\nu}$: 1.65 x 10^{21} POT

Confidence level	Interval NO	Interval IO
1σ	[-2.69,-0.75]	
90%	[-3.04,-0.34]	[-2.07,-0.91]
2σ	$[-\pi,-0.13] \cup [3.06,\pi]$	[-2.34,-0.67]
3σ	$[-\pi,0.43] \cup [2.54,\pi]$	[-2.92,-0.08]

Feldman-Cousins confidence intervals for δ_{CP}

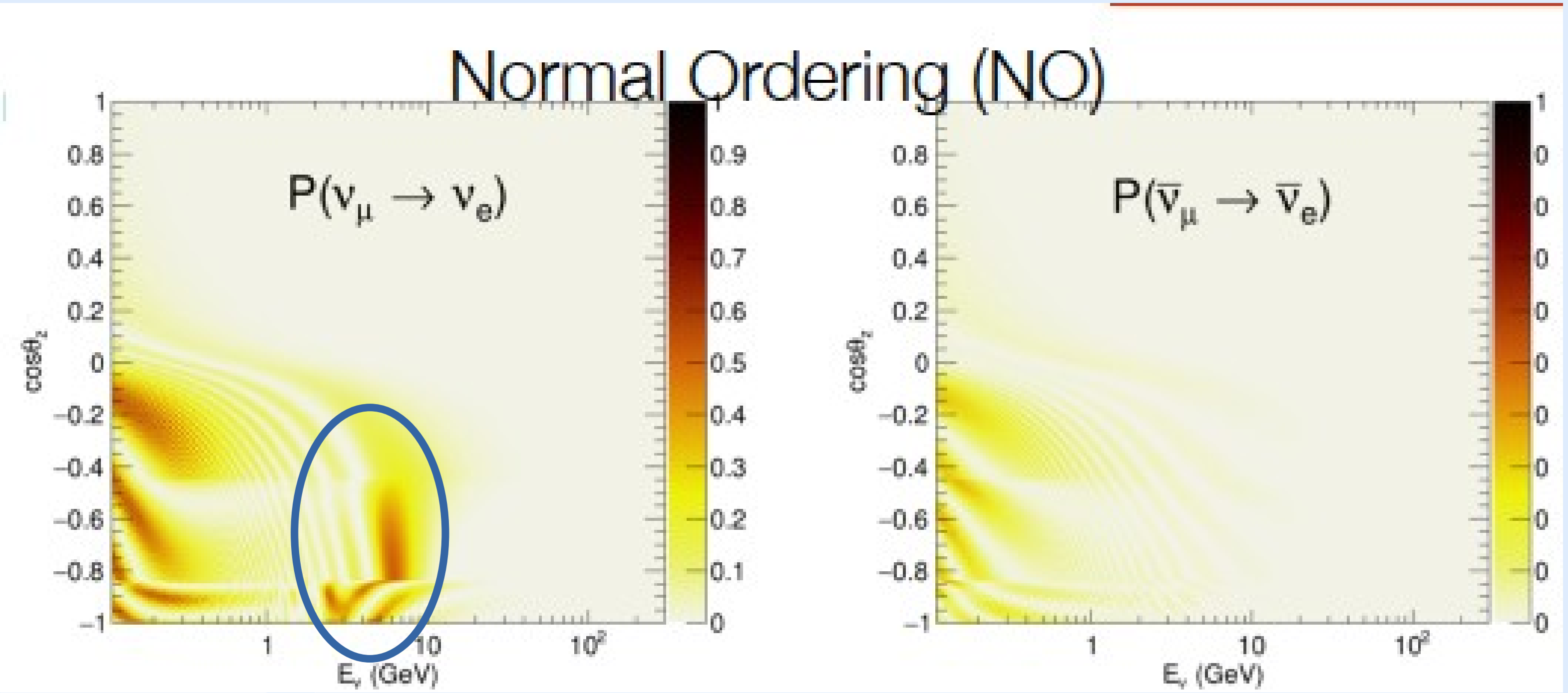
- Best fit value close to $\delta_{CP}=-\pi/2$
- CP conserving values outside of 90% C.L.
- Weak preference of upper octant of θ_{23} and NO

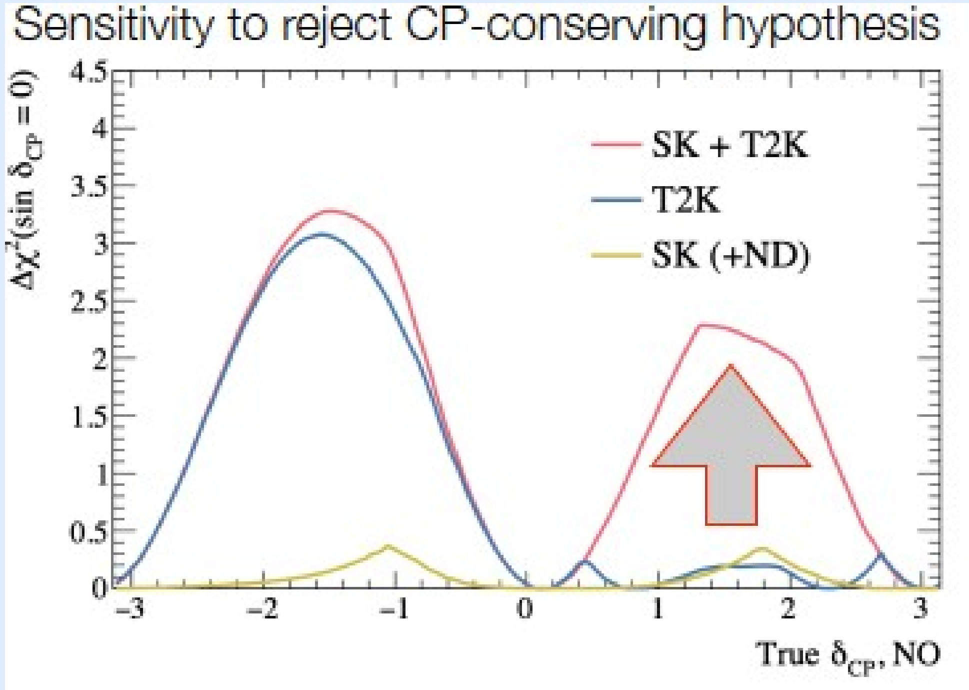
Joint analysis of T2K and Super-Kamiokande



OSCILLATIONS OF ATMOSPHERIC NEUTRINOS AT SUPER-K

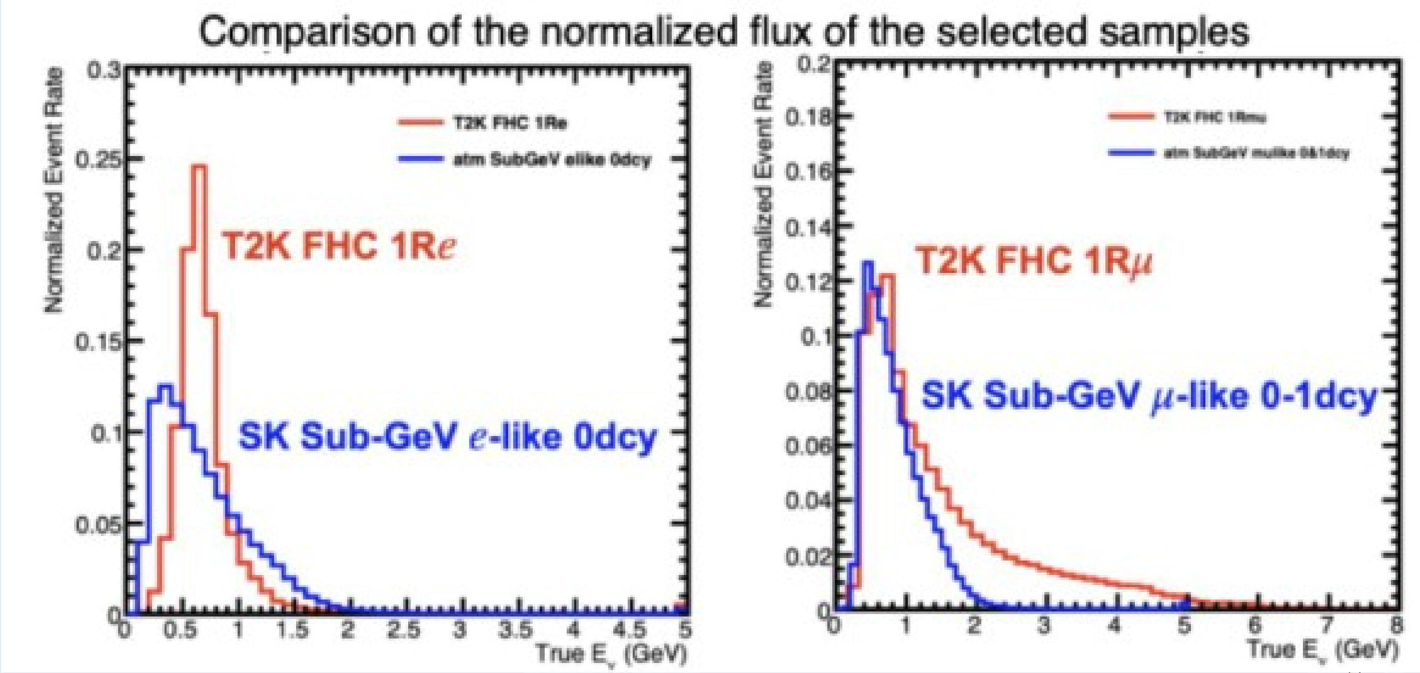
- Atmospheric neutrinos are produced in the atmosphere and travel between 15-13000km. They have energy range from MeV to TeV.
- They give sensitivity to MO through matter effects, which is particular a resonance driven by the θ_{13} between 2 and 10MeV energy. **For NO enhancement of ν_e appearance, while no effect for $\bar{\nu}_e$.** In case of IO effect is opposite. Size of the effect depends on $\sin^2\theta_{23}$, so sensitive to θ_{23} octant.
- **Help to break degeneracies between δ_{CP} and mass ordering**: **T2K** has good sensitivity to δ_{CP}, but no mass ordering while **SK** has good constraint on mass ordering, but not δ_{CP}.



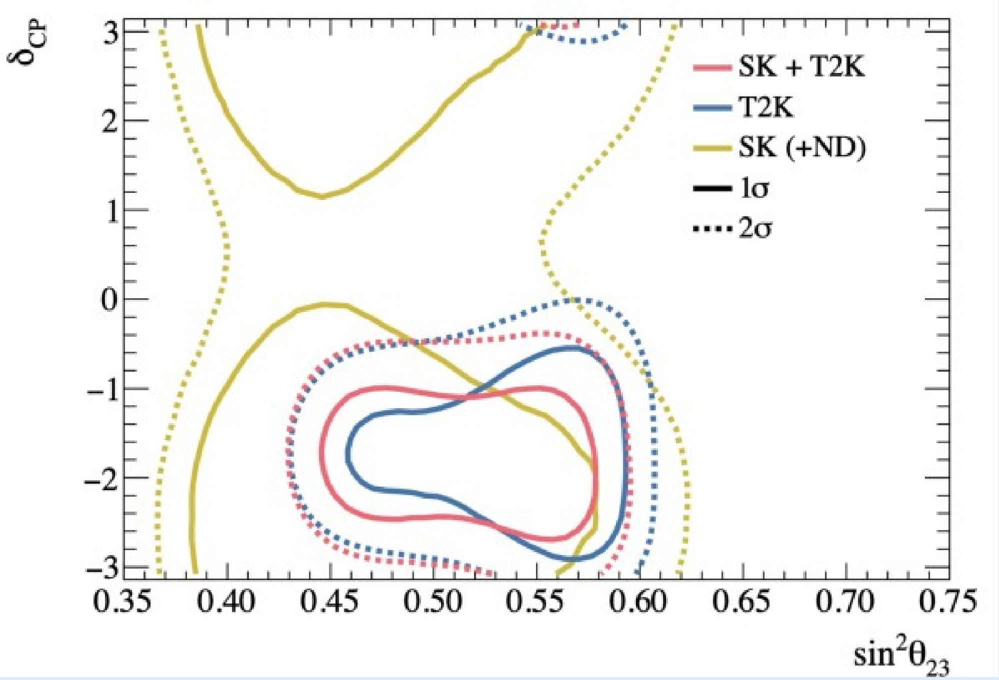


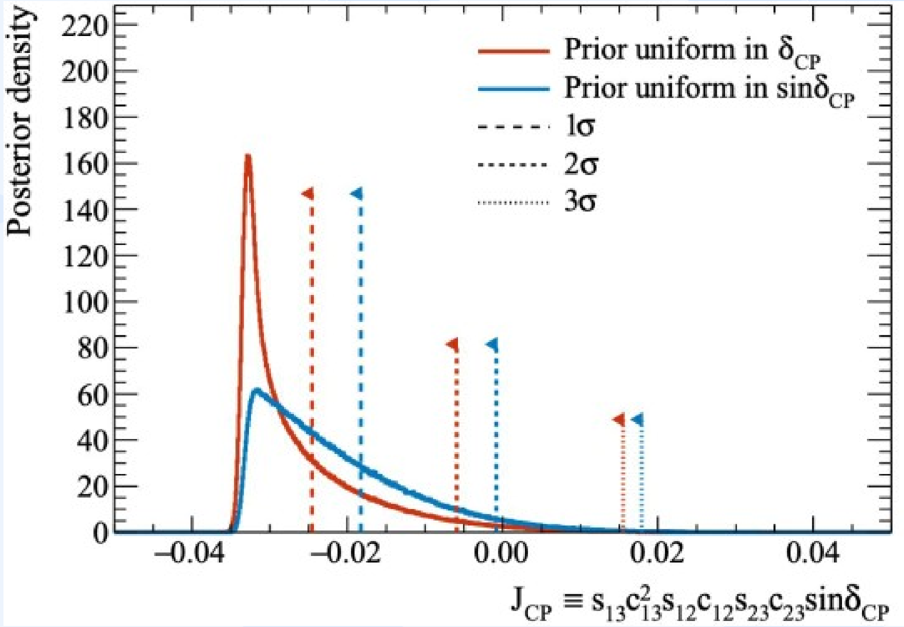
MOTIVATION OF T2K+SK JOINT FIT ANALYSIS

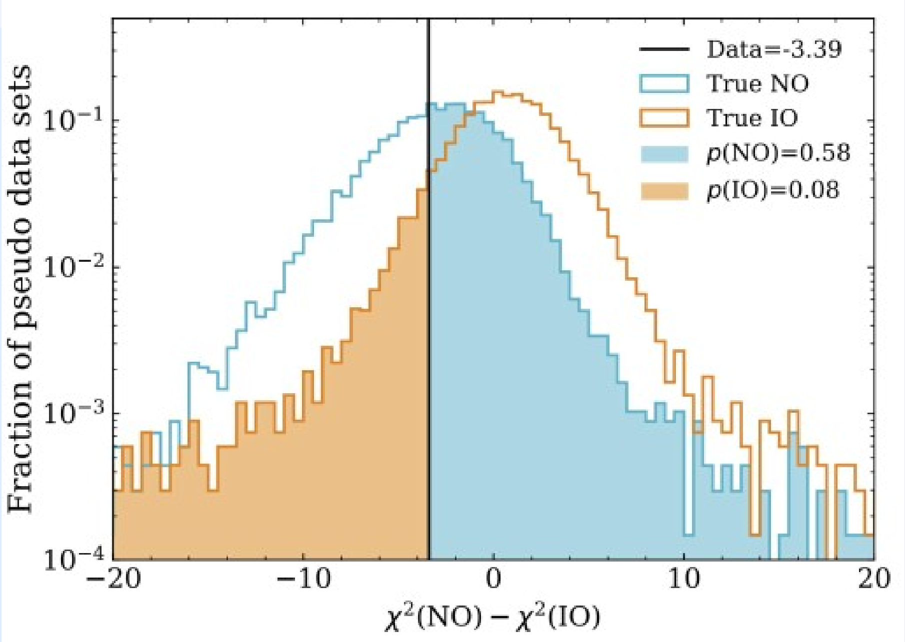
- Combining SK and T2K data will **increase statistics**
- Due to sensitivity to matter effects **SK helps to break degeneracies in T2K between δ_{CP} and mass ordering** since MO sensitivity is mostly independent on the value of δ_{CP} in SK contrary to T2K
- Both samples share the same detector and overlapping energy spectrum
  - Developed common interaction model for T2K-beam and SK low-energy sample
  - Common detector model with correlated systematics



RESULTS T2K+SK JOINT FIT



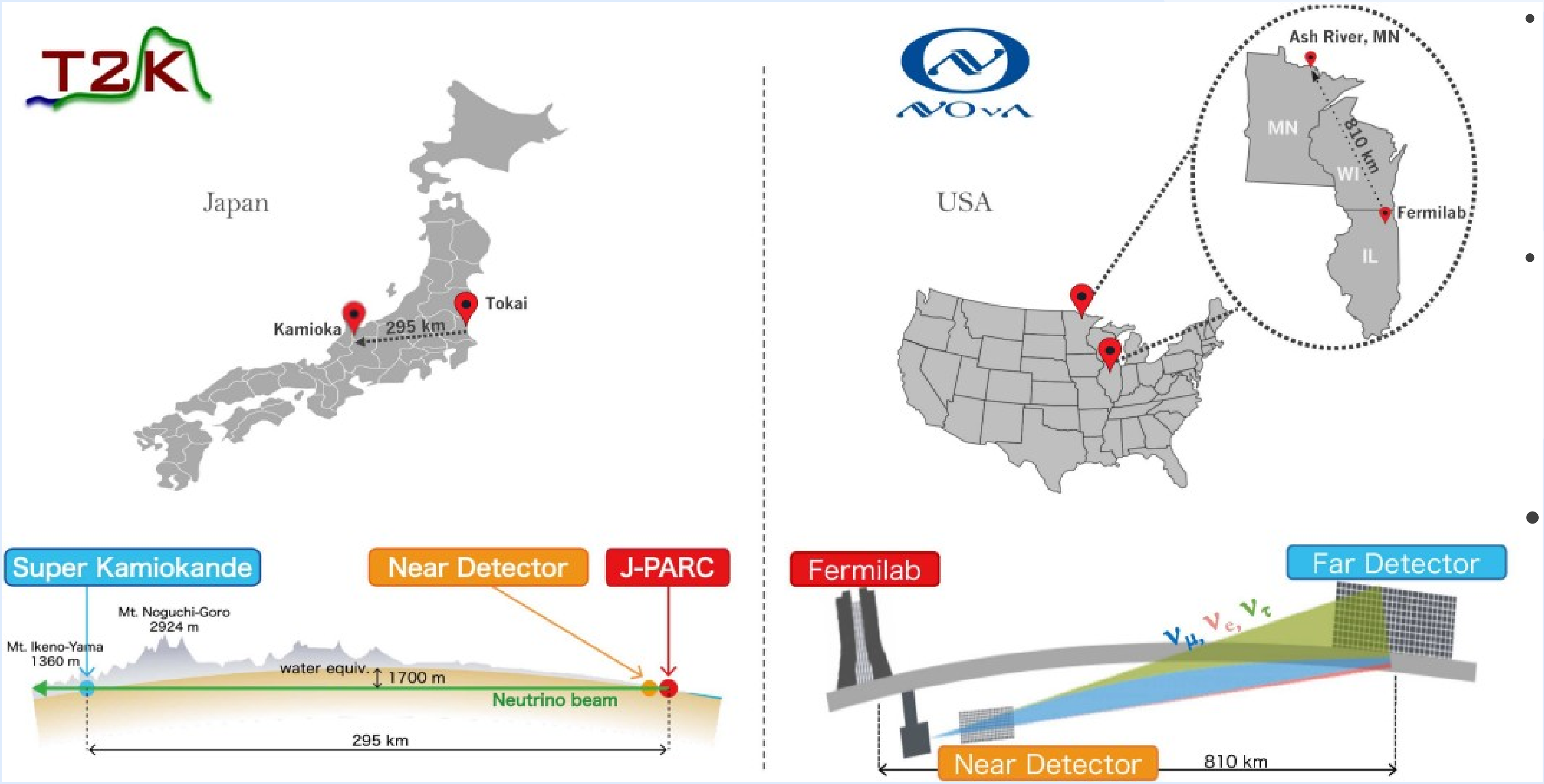




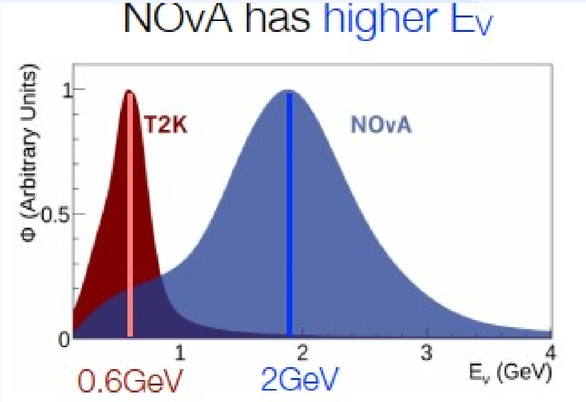
- T2K and SK has different preference for octant of θ_{23} → no preference for octant θ_{23} for joint fit
- Jarlskog invariant CP conserving value (J_{CP}=0) excluded at 1.9-2.0 σ
- Limited preference for NO; IO rejected at 1.2 σ

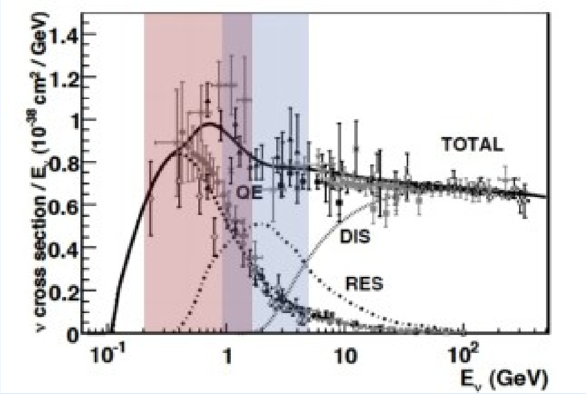
Joint analysis of T2K and Nova

COMPARISON OF T2K AND NOVA EXPERIMENTS



- Different detector techniques:
- T2K FD different than ND – shared uncertainties fitted and constrained via model
- Nova FD and ND active scintillator tracker (cancellation of uncertainties)





- Long baseline 295km 810km
- Off-axis beam 2.5° 0.84°
- Energy 0.6 GeV 2 GeV
- Interactions mainly QE with 2p2h mixture of QE, 2p2h, RES π
- RES, DIS in tail production and DIS

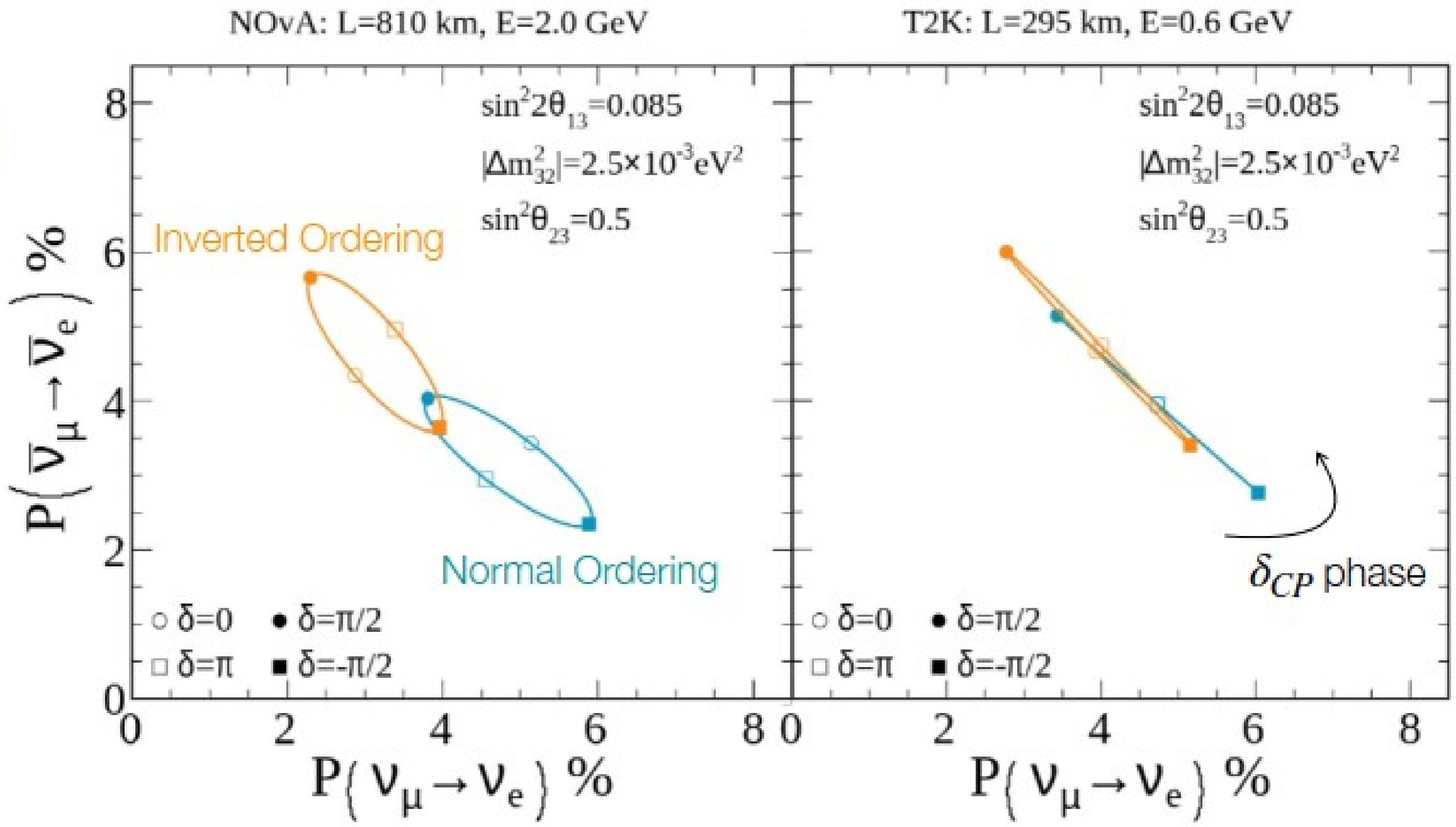
MOTIVATION TO T2K+NOVA JOINT FIT ANALYSIS

- Different energies and baselines provide different oscillation probabilities and sensitivity to oscillation parameters

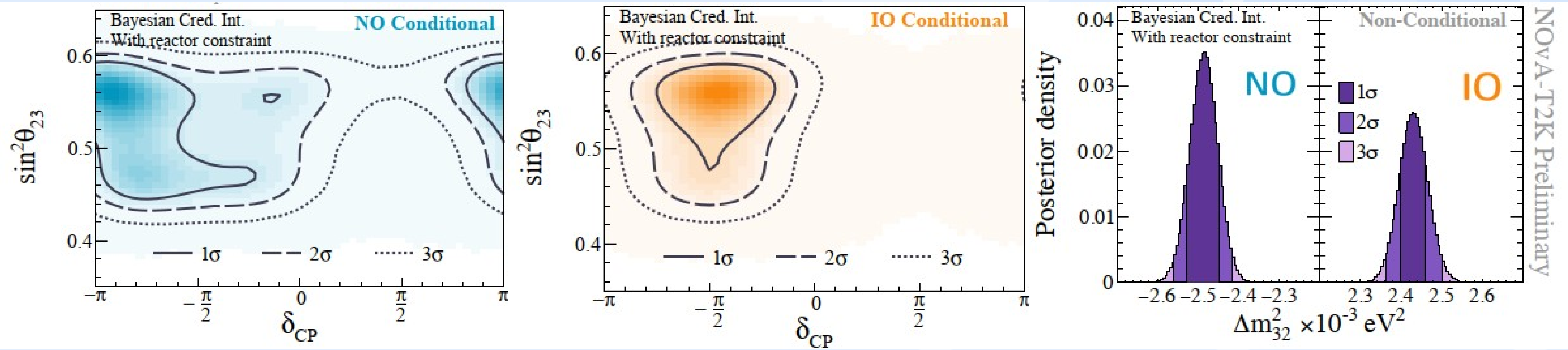
- Lifting degeneracies in each experiment between δ_{CP} and mass ordering

- NOvA has better mass ordering sensitivity due to longer baseline
- Degeneracy around $\delta_{CP} = \pm\pi/2$ CPV

- T2K more sensitivity to δ_{CP}
- Degeneracy around $\delta_{CP} = 0,\pi$ no-CPV



RESULTS OF T2K+NOVA JOINT FIT ANALYSIS



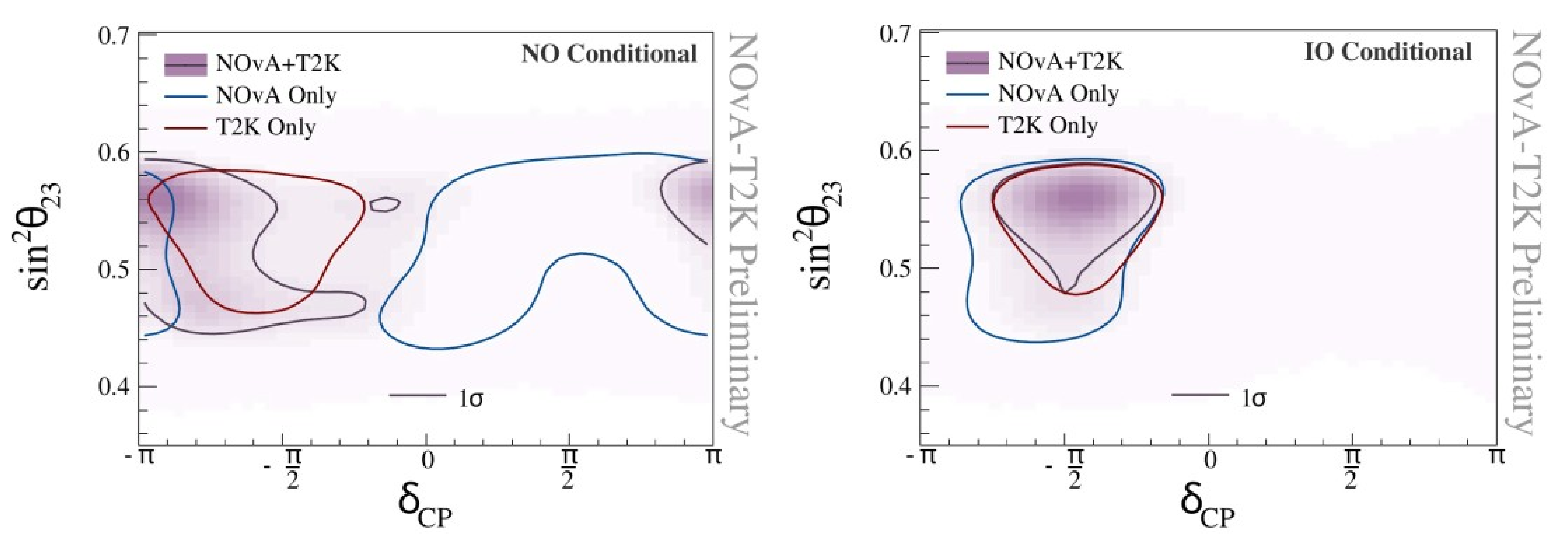
- Neither ordering has preference for $\delta_{CP} \sim +\pi/2$
- NO allows for broad range of δ_{CP}
- IO CP conserving values are excluded at 3σ
- Slight preference IO (θ_{13} dependent) but statistically insignificant (separate first prefer NO)

- High precision for $|\Delta m^2_{32}| < 2\%$

$$\Delta m^2_{32}\big|_{NO} = 2.43^{+0.04}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$$

$$\Delta m^2_{32}\big|_{IO} = -2.48^{+0.03}_{-0.04} \times 10^{-3}\ \mathrm{eV}^2$$

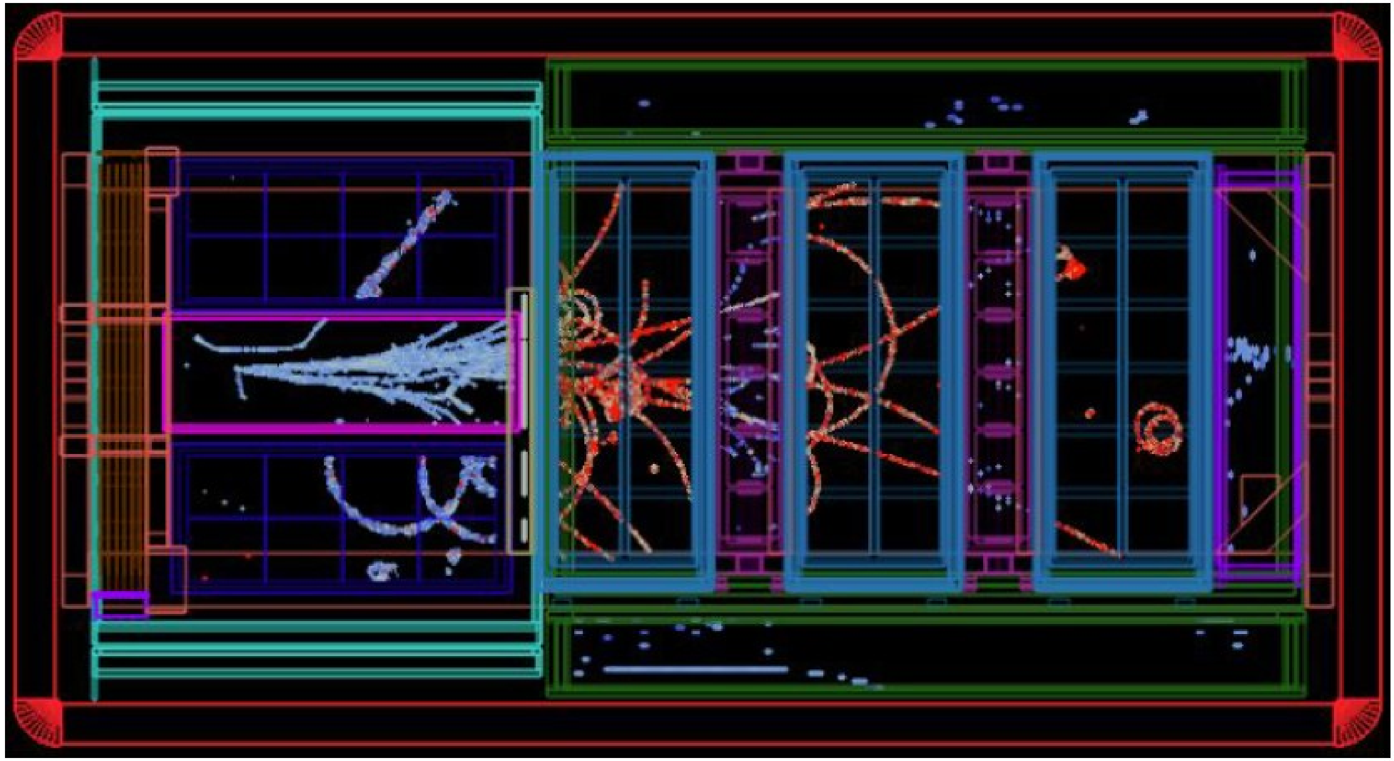
COMPARISON TO NOVA-ONLY AND T2K-ONLY RESULTS



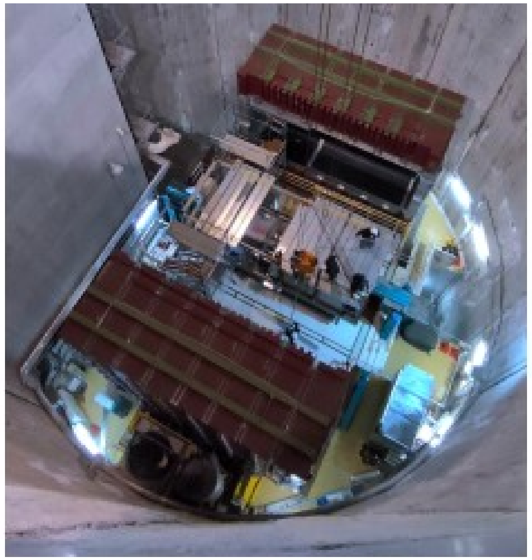
The joint fit is in agreement with both individual fits and improves constraints for IO

T2K Near Detector Upgrade

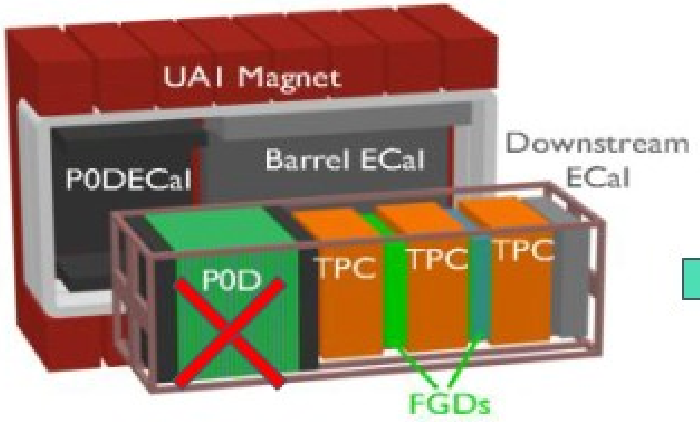
Upgrade installed: June 2024



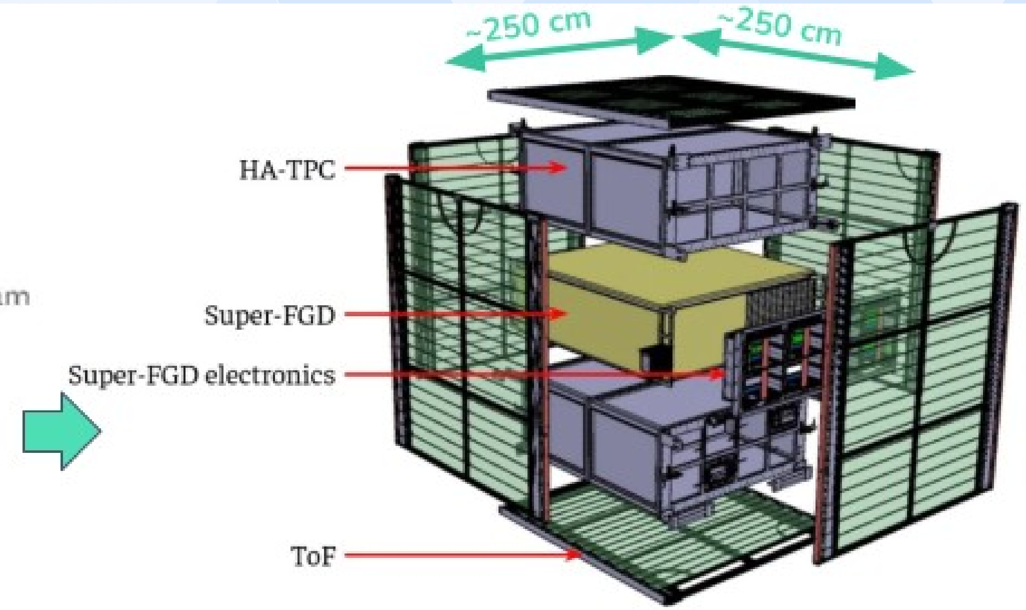
THE UPGRADED NEAR DETECTORS



ND280 pit @J-PARC



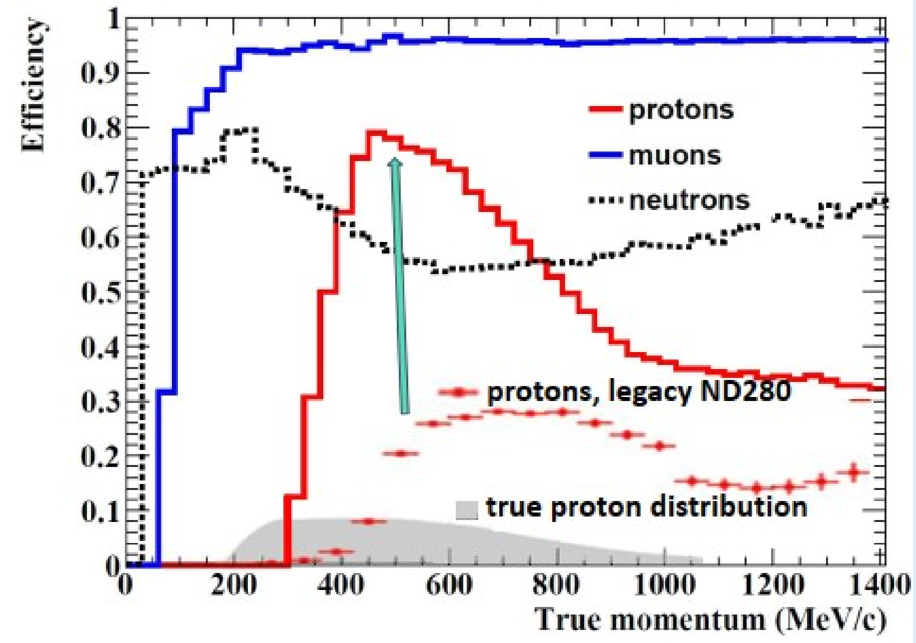
Legacy ND280



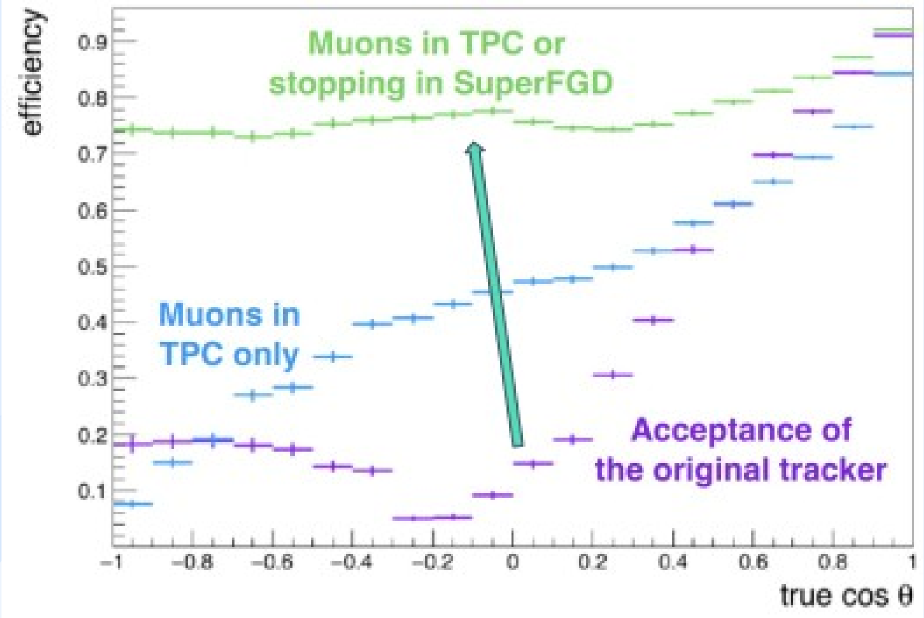
The ND280 Upgrade

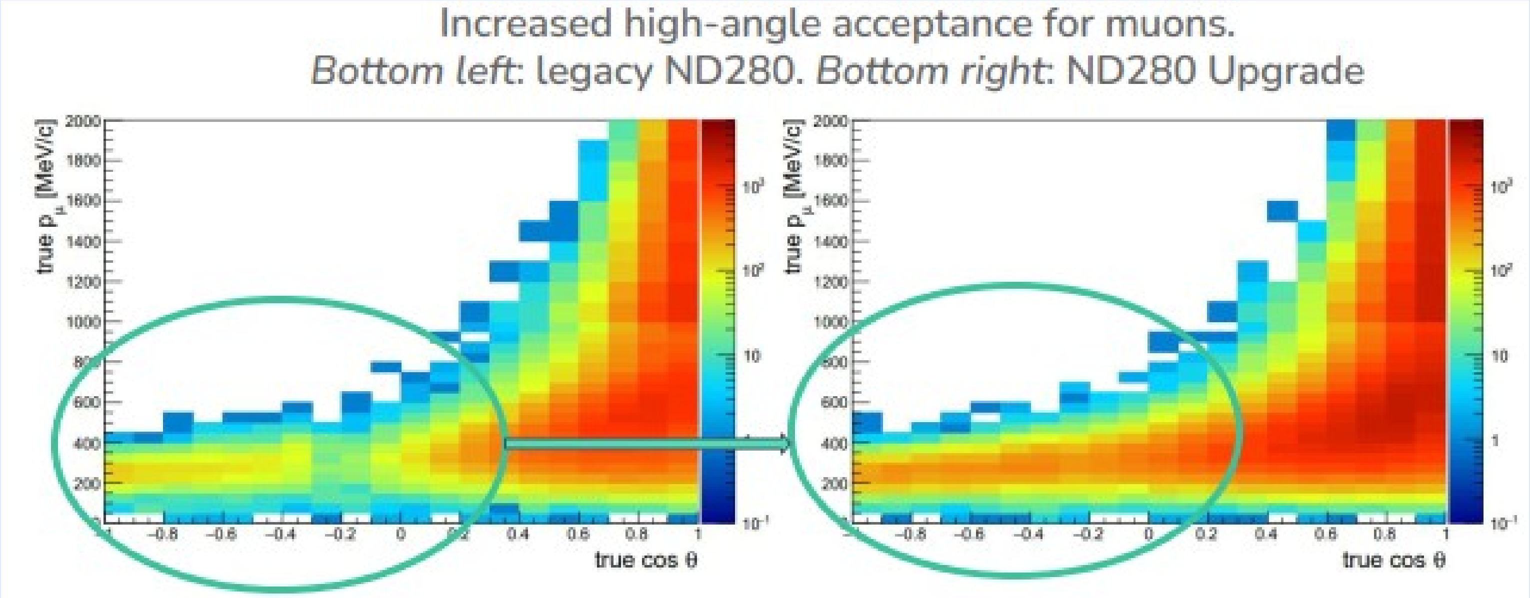
- **Super Fine Grained Detector (Super-FGD)** - ~2million 1cm^3 scintillator cubes readout by 3 optical fibres – improve final state identification
- **2 High-Angle Time Progection Chambers (HA-TPC)** – argon-based TPCs with central cathode and two 1m drift volumes; readout by ERAMs (Encapsulated Resistive Anode Micromegas) – measures high angle tracks
- **Time-of-Flight Detector (ToF)** – plastic scintillator read out by SiPM – time reference background rejection

PERFORMANCE OF THE UPGRADED NEAR DETECTORS



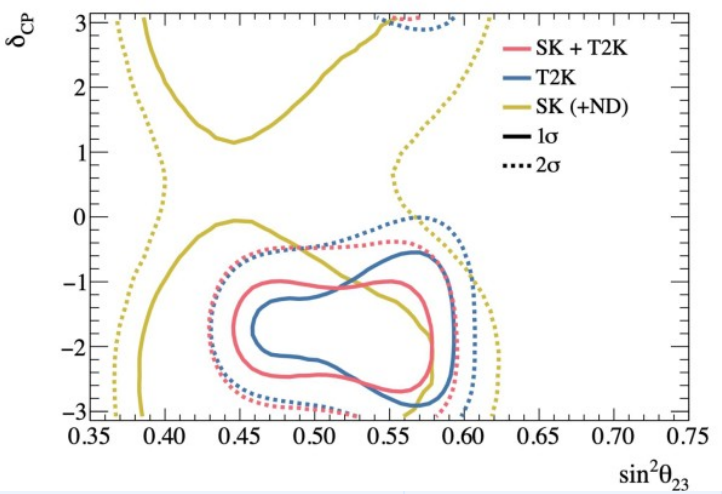
- Lower proton detection threshold
- Higher detection efficiency
- Higher angular acceptance
- Neutrons kinematics from time of flight





SUMMARY

- **Updated T2K oscillation** analysis with 10% more ν data
  - CP conserving values excluded at 90% CL
  - Preference for NO and upper octant of θ_{23}
- **Joint analysis T2K + SK**
  - CP conserving value of Jarlskog invariant excluded at 1.9-2.0σ
  - Preference for NO
- **Joint analysis T2K + Nova**
  - CP conserving values outside of 3σ for IO
  - No clear preference for mass ordering
  - High precision for $|\Delta m^2_{32}| < 2\%$
- T2K analysis will be updated with new near and far detector samples
- For upgraded detector samples will be developed and systematics assigned
- The near detector ND280 will be used by Hyper-K (from 2028)



Upgrade installed: June 2024

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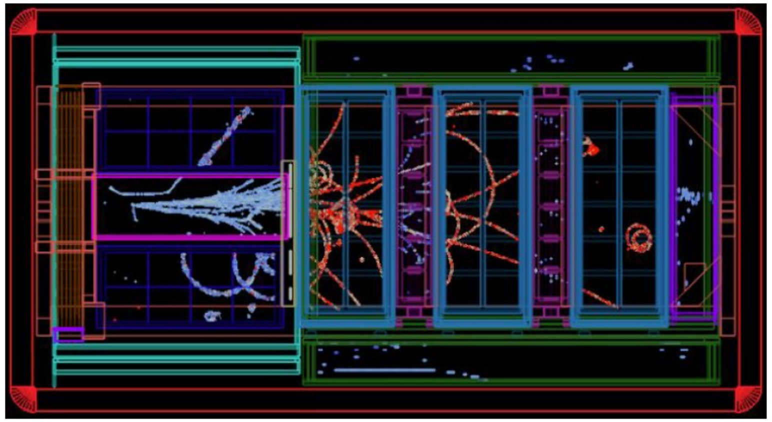


Backup

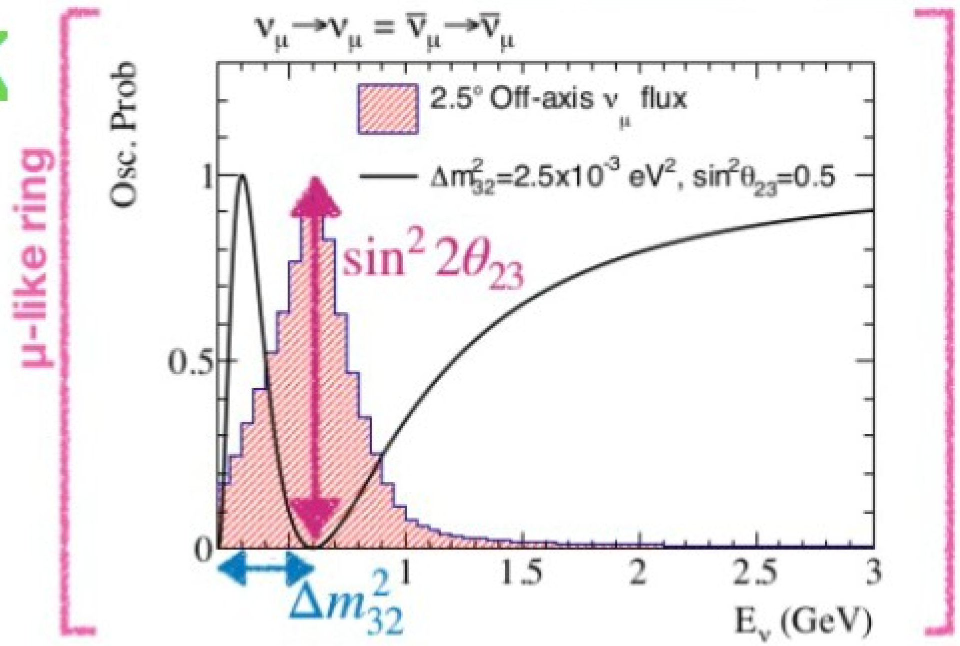
LAYOUT OF PRESENTATION

- Introduction to T2K:
  - what we probe
  - experiment layout
- Update of T2K oscillation analysis
- Joint fit oscillation analysis of Super-Kammiokande atmospheric data and T2K data
- Joint fit of T2K and Nova accelerator experiments data
- Upgrade of the T2K Near Detector - ND280

Neutrino oscillations in T2K

ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$



ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

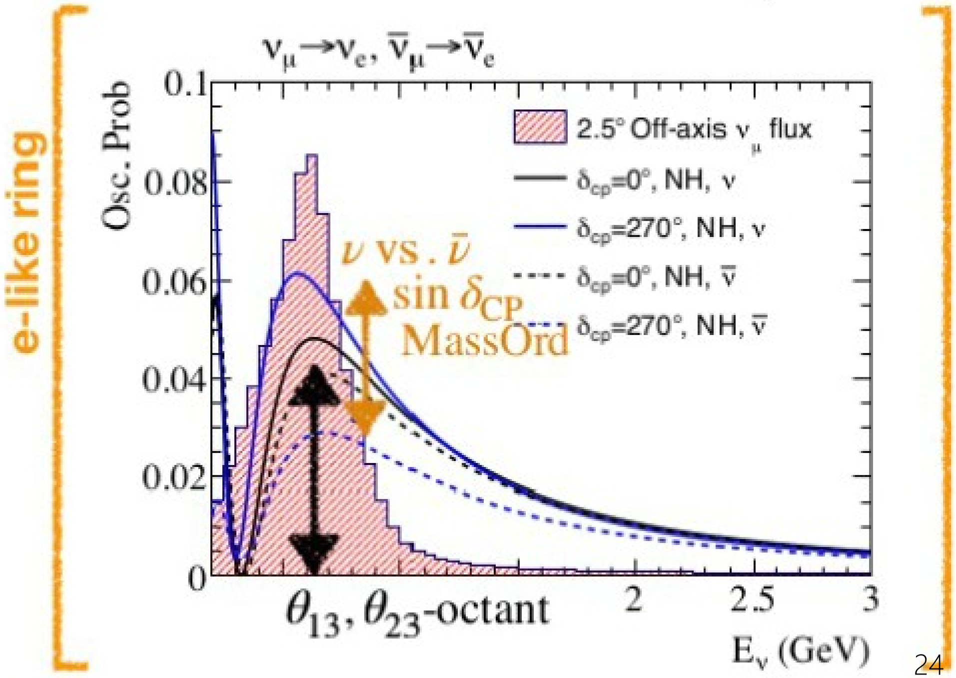
"-" for ν

"+" for $\bar{\nu}$

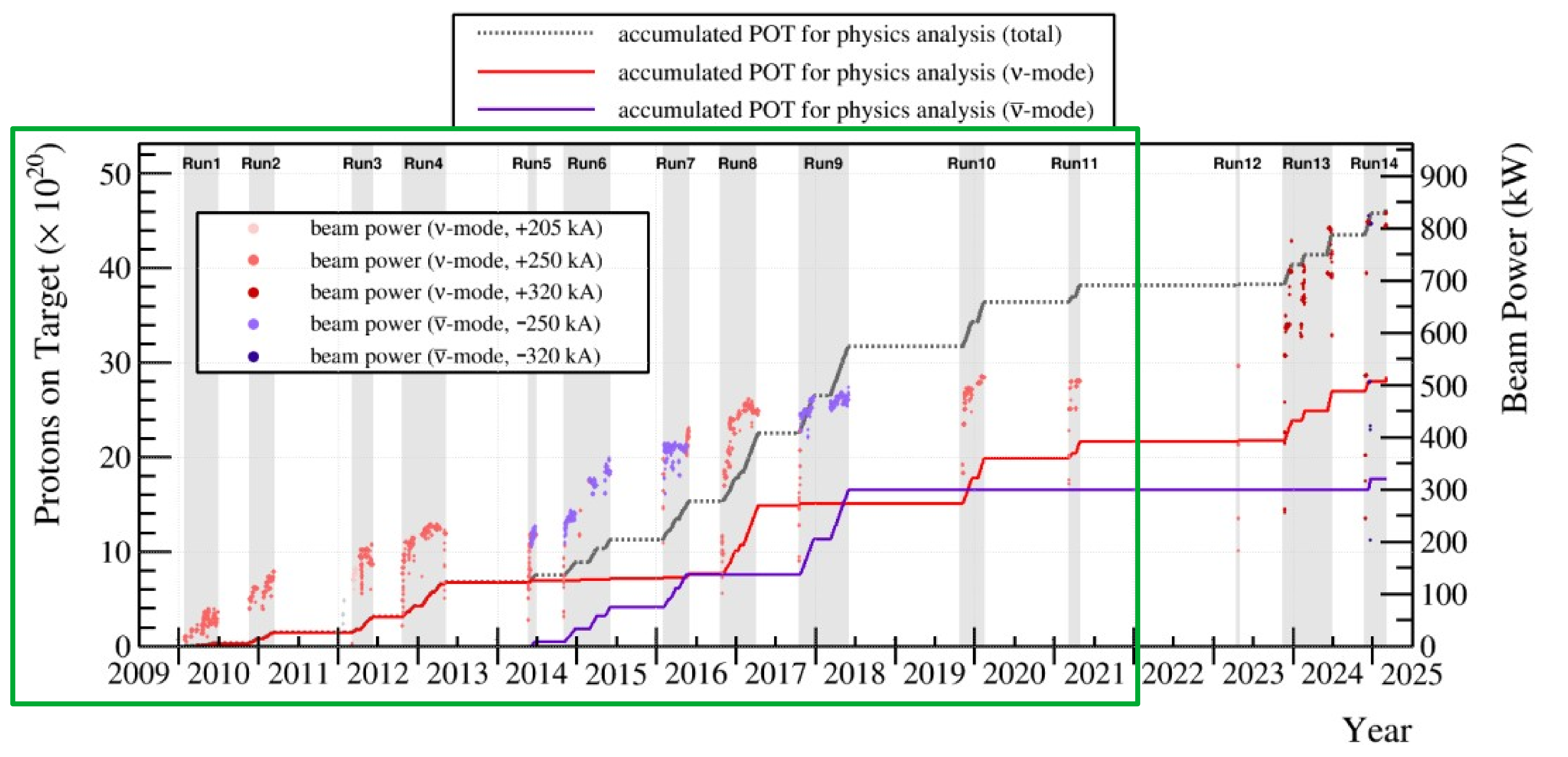
$$\mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

$$J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP} = 0.033\sin\delta_{CP}$$

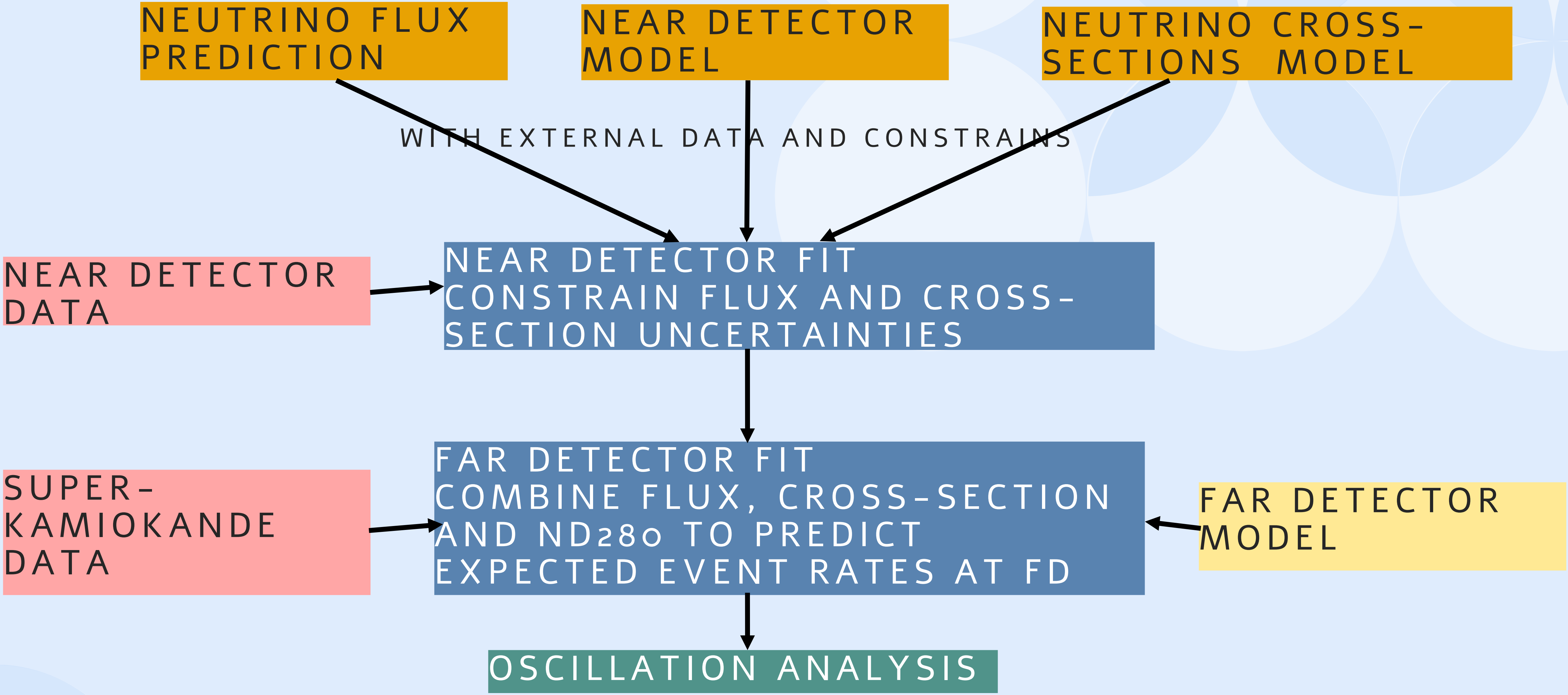
Equations w/o matter effect



PROTONS ON TARGET ACCUMULATED BY T2K

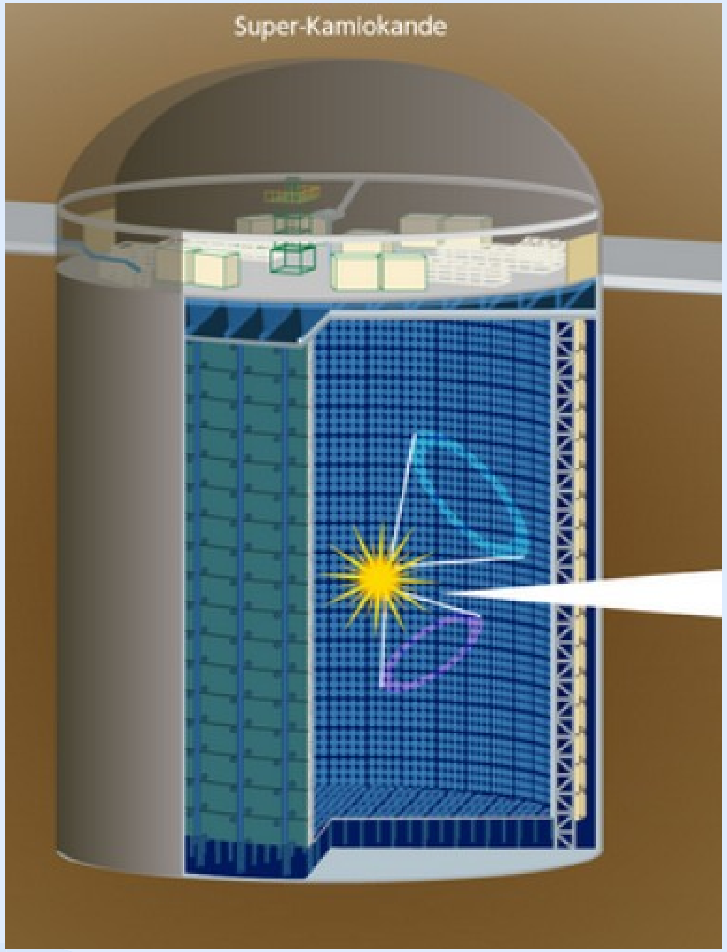


STRATEGY OF THE OSCILLATION ANALYSIS



NEAR AND FAR DETECTOR ARE EITHER FITTED SEQUENTIALLY- FREQUENTIST OR SIMULTANEOUSLY - BAYESIAN

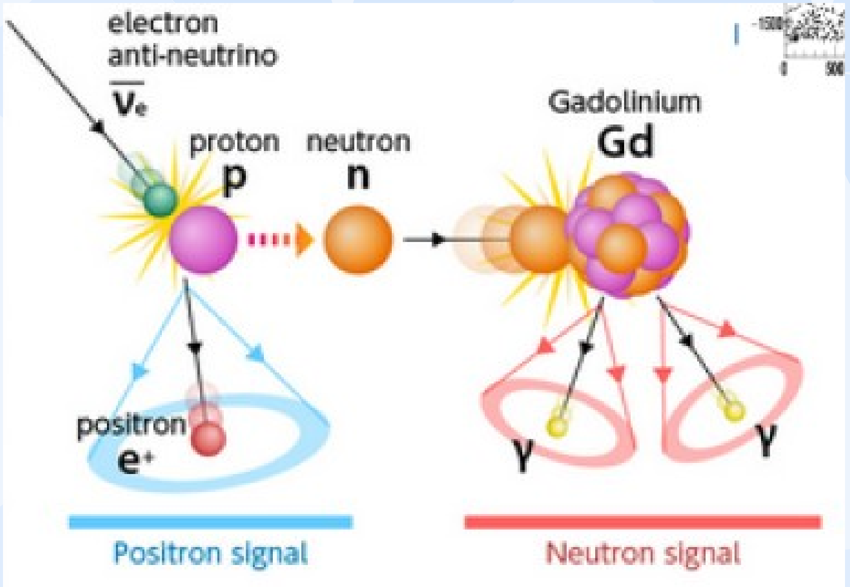
SUPER-KAMIOKANDE WITH GADOLINIUM



CHARGED CURRENT QUASI-ELASTIC INTERACTIONS

$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$



- First Gd salt loading happened in 2020 reaching Gd concentration of 0.01%, Recently added T2K ν beam data corresponds to this Gd concentration

- Second Gd salt loading happened in 2022 with Gd concetntaion 0.03% till now