T2K Status and Plans

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Neutrino oscillation

- Neutrino mixing is characterized by PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\textbf{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

3 mixing angles $(\theta_{23}, \theta_{13}, \theta_{12})$ and 1 CP phase δ_{CP}

Leading term of oscillation probabilities

$$P(\nu_\mu \to \nu_e) \sim \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(1.27 \frac{\Delta m^2_{13}[\mathrm{eV}^2] L[km]}{E_\nu[\mathrm{GeV}]} \right)$$

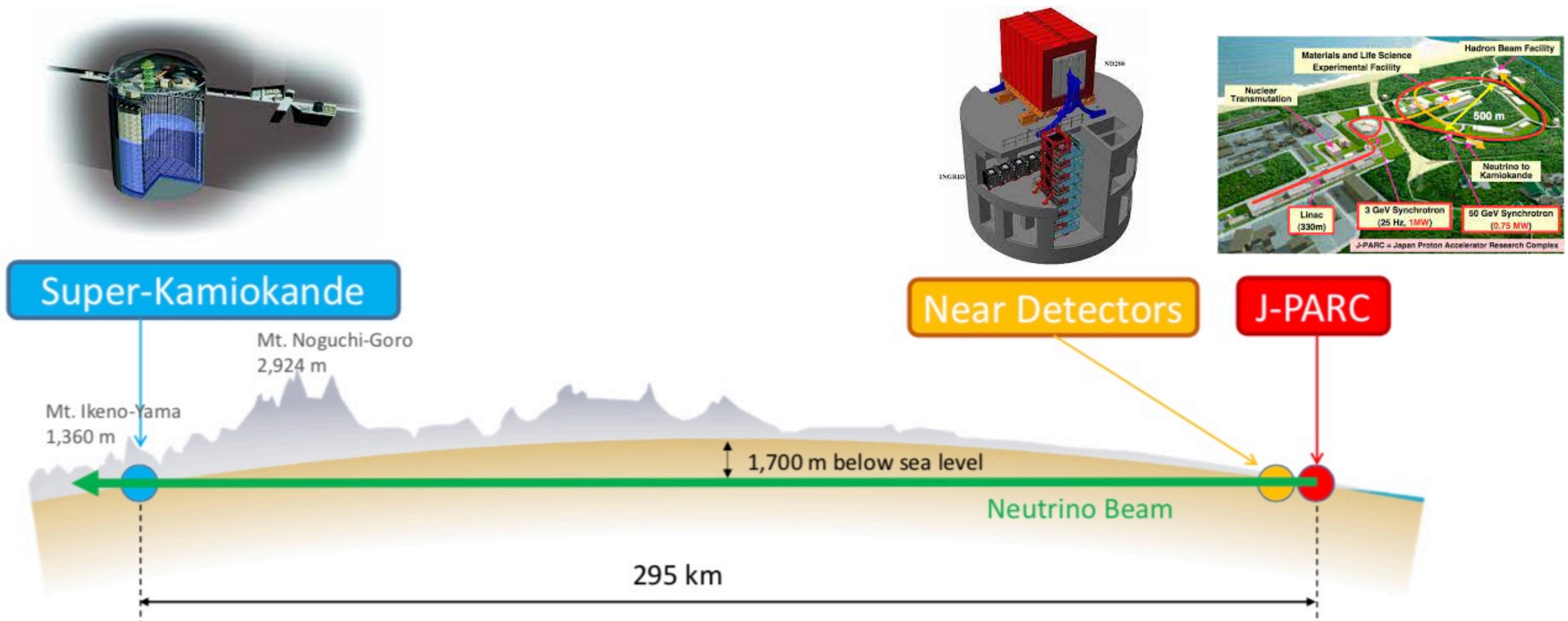
δ_{CP} appears at higher order

Open questions: δ_{CP}, θ_{23} octant, mass ordering ⋯

T2K experiment

- T2K is a long baseline neutrino oscillation experiment designed to measure neutrino oscillation parameters
- World leading of δ_{CP}, θ_{23}, Δm^2_{32}

  -> To find the evidence of CP violation,
  reduction of systematics uncertainty is important

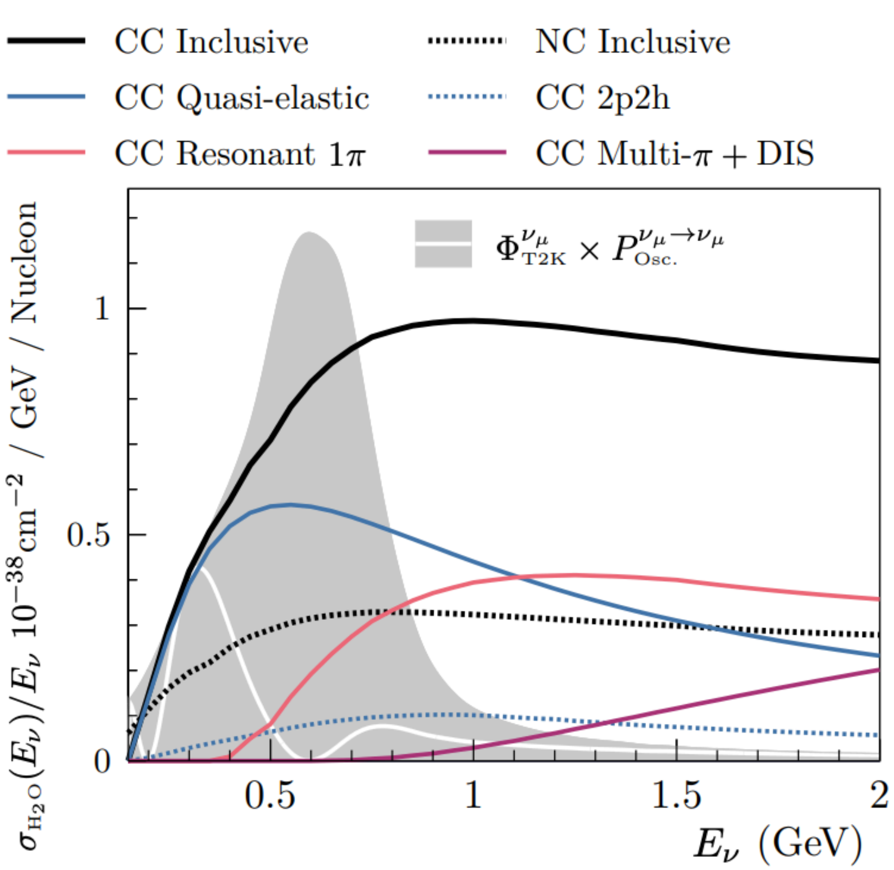


$$\nu_\mu,\ \nu_e \longleftarrow \nu_\mu$$

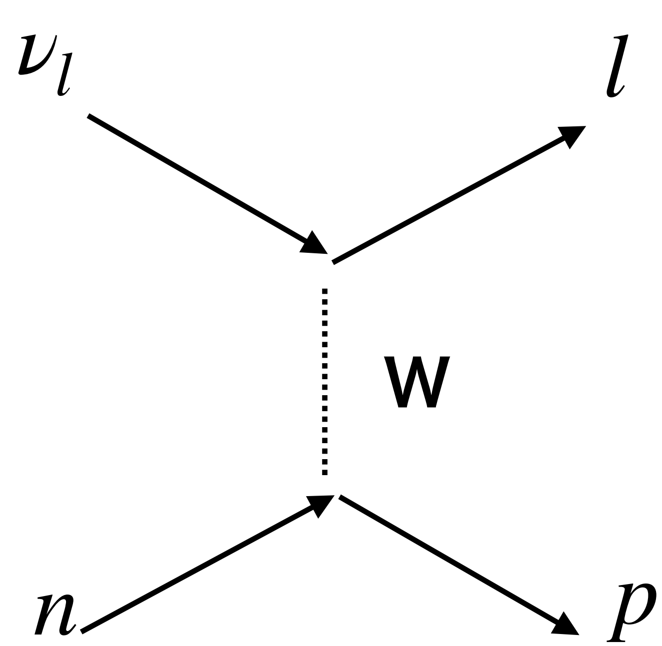
$$\bar{\nu}_\mu,\ \bar{\nu}_e \longleftarrow \bar{\nu}_\mu$$

Neutrino-nucleus interaction

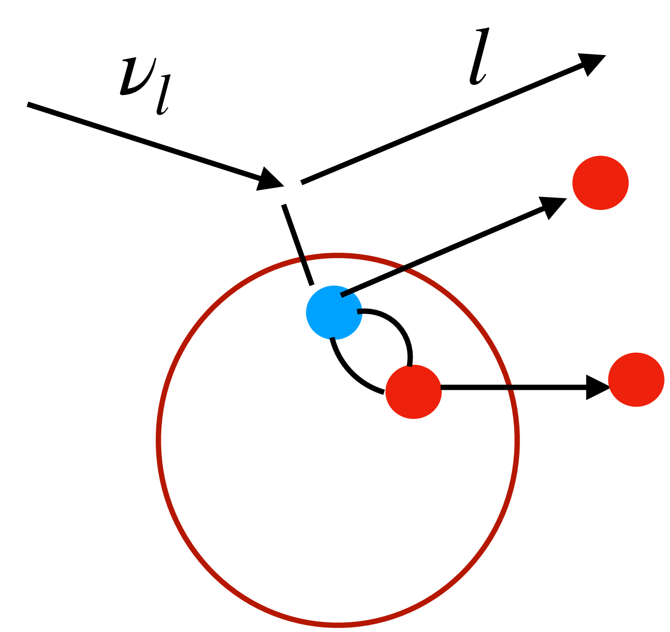
- One of the main sources of the systematic uncertainty in neutrino oscillation measurement
- CCQE dominates plus multi-nucleon ‘2p2h’ and resonant CC1π at neutrino energy of T2K
- It is difficult to understand these interaction models



CCQE



Nucleon correlations(2p2h)



Near detectors

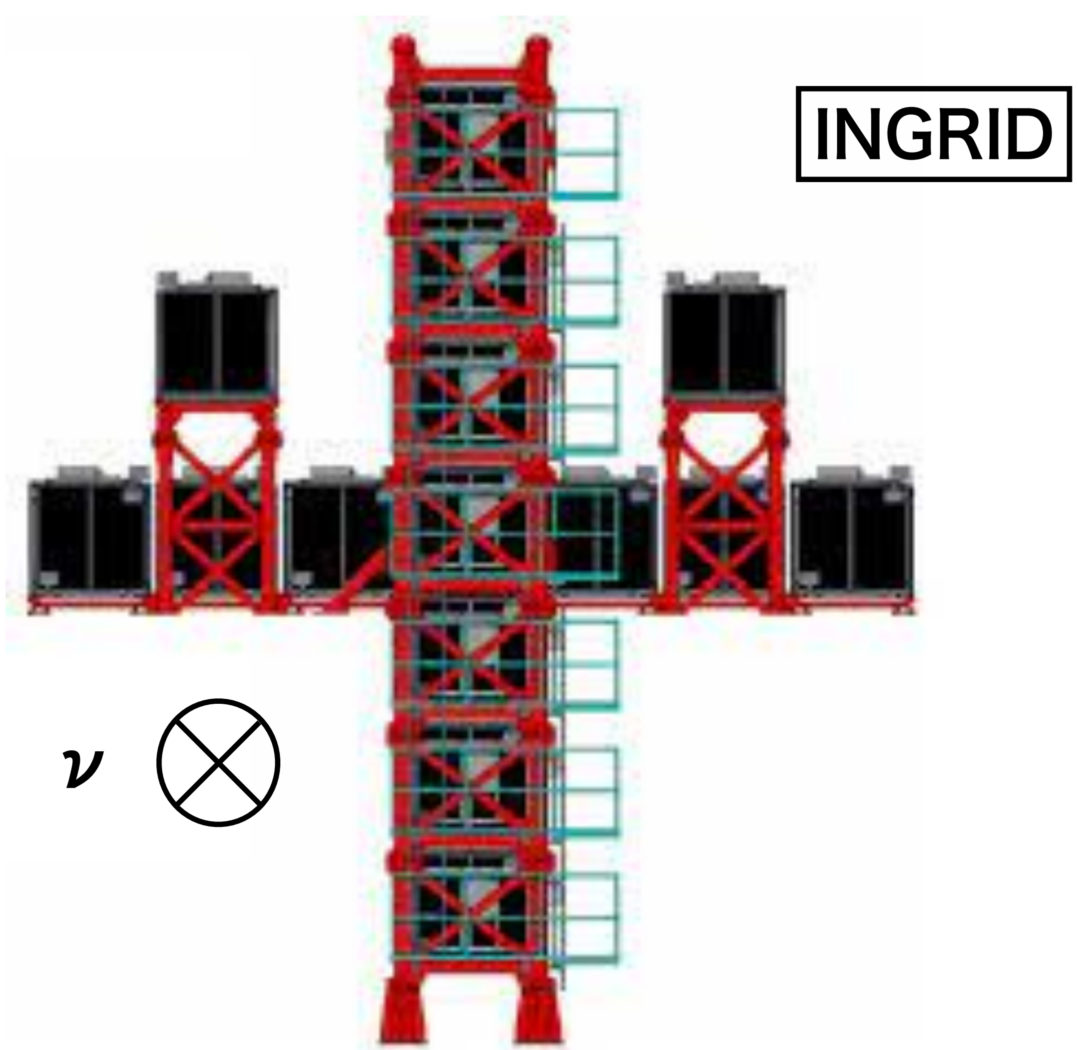
Located 280 m downstream of beam target

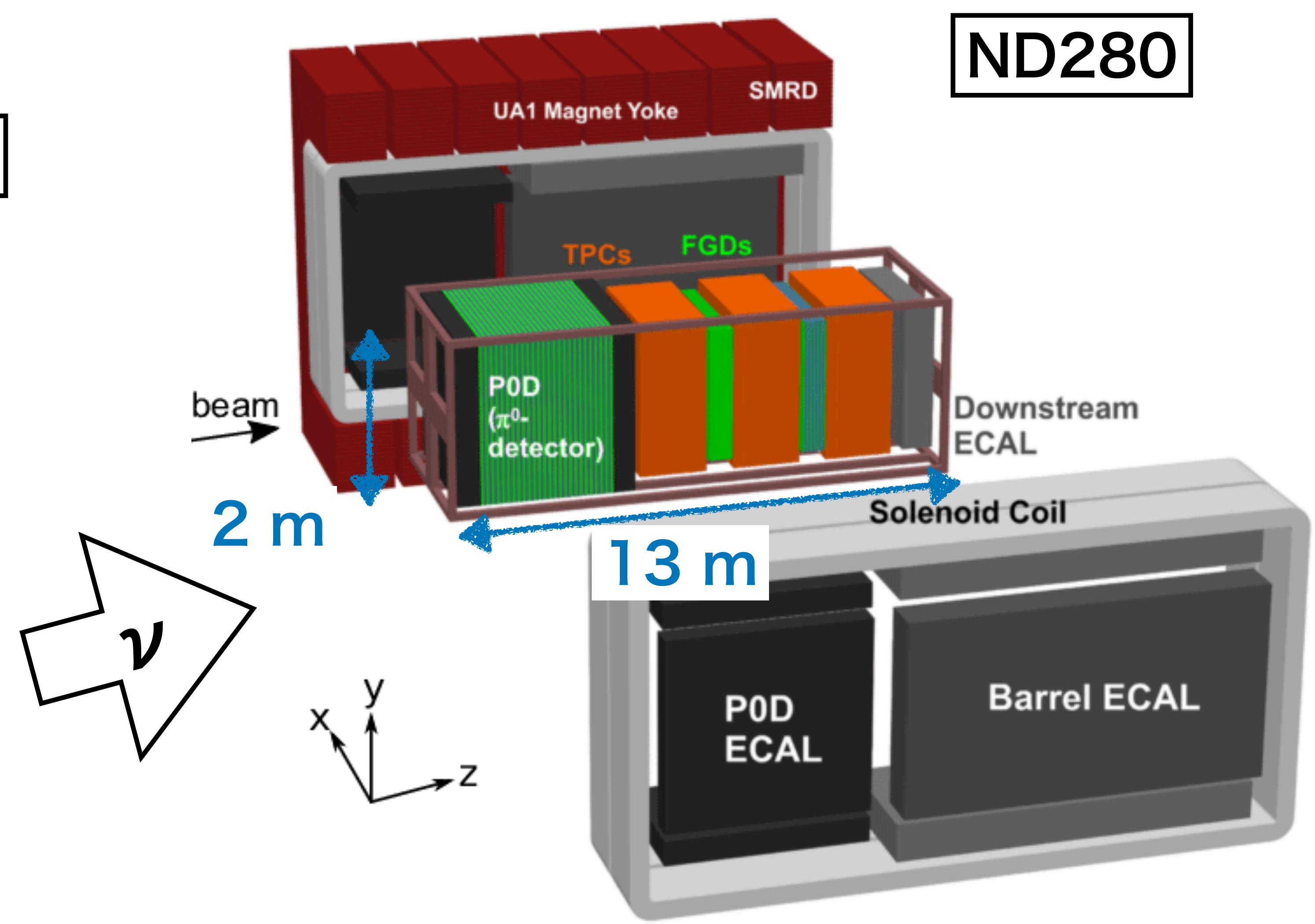
- INGRID ··· Monitoring neutrino beam direction and intensity
- ND280 ··· Consist of several detectors

  FGD ··· Active scintillator-bar targets

  TPC ··· Time projection chamber to track charged particles

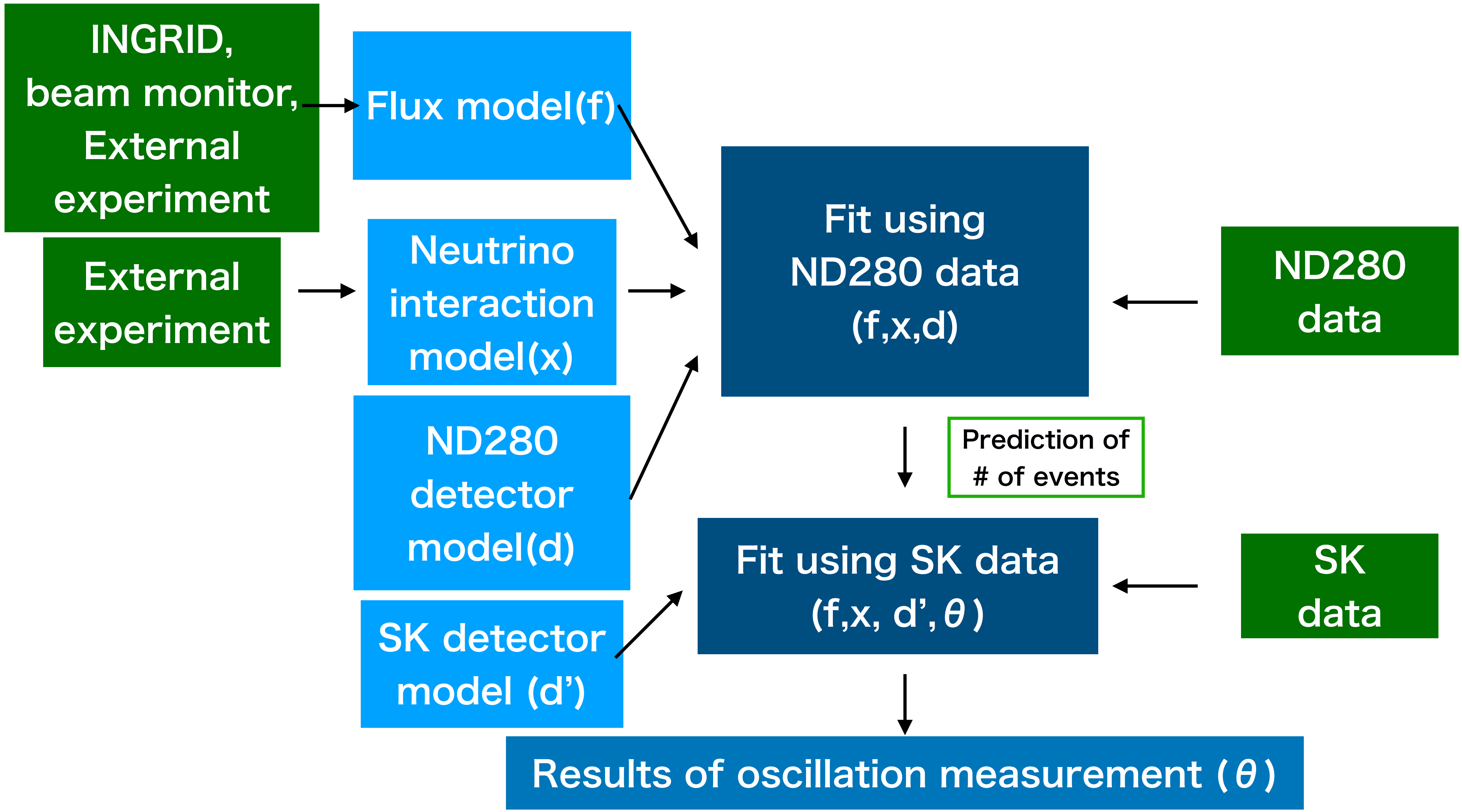
  -> Constrain neutrino interaction and neutrino flux models





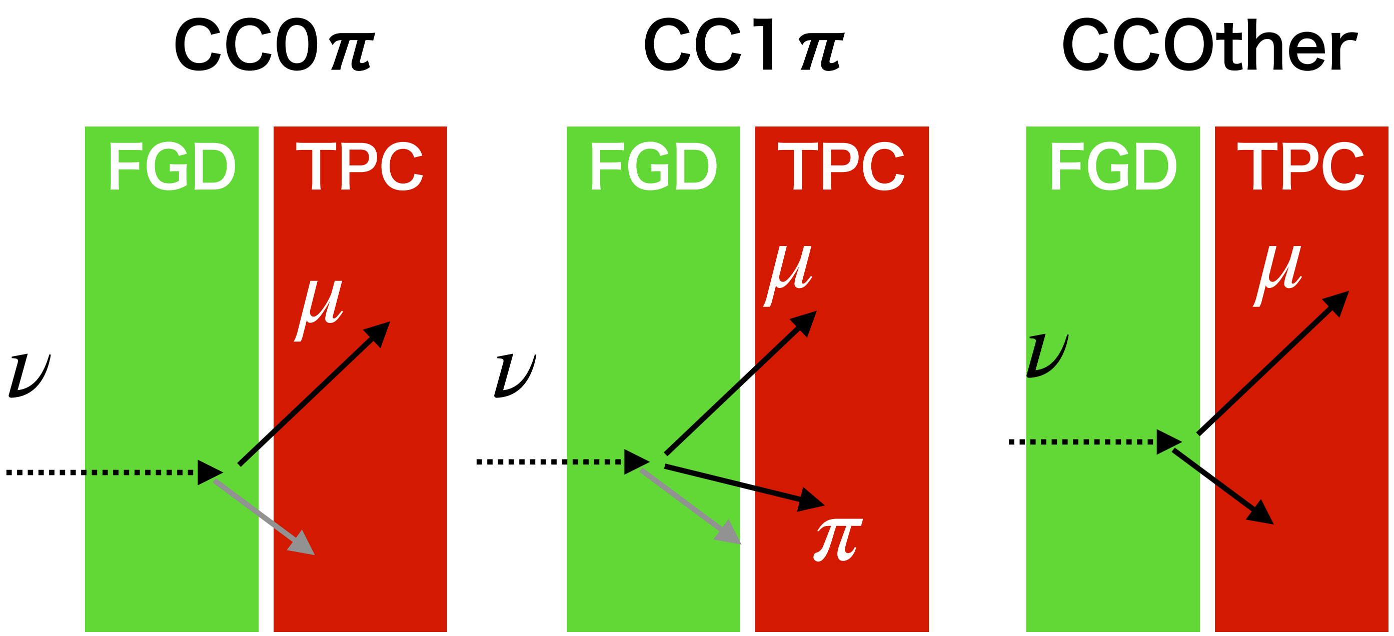
Oscillation analysis

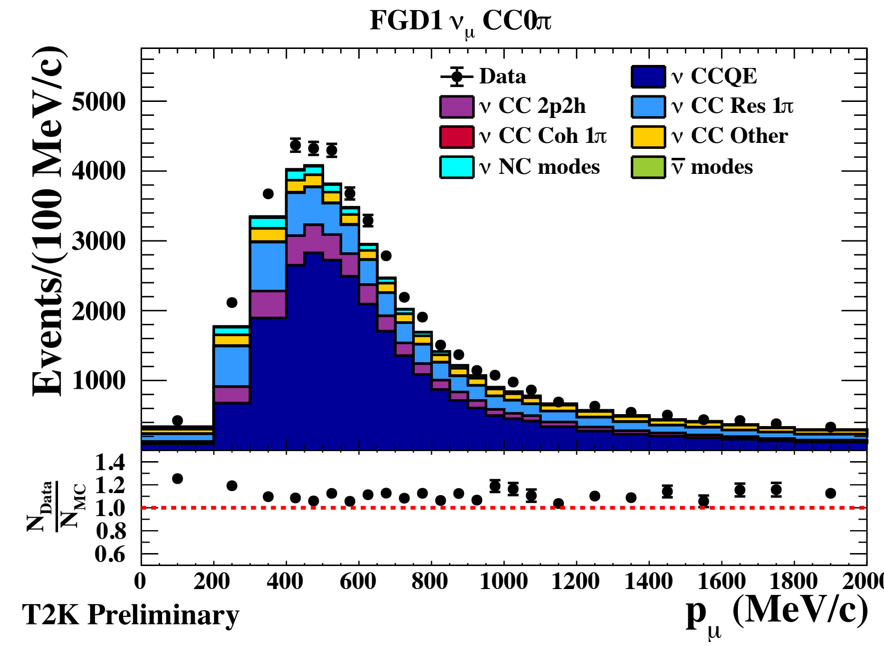
Oscillation analysis flow (frequentist way)



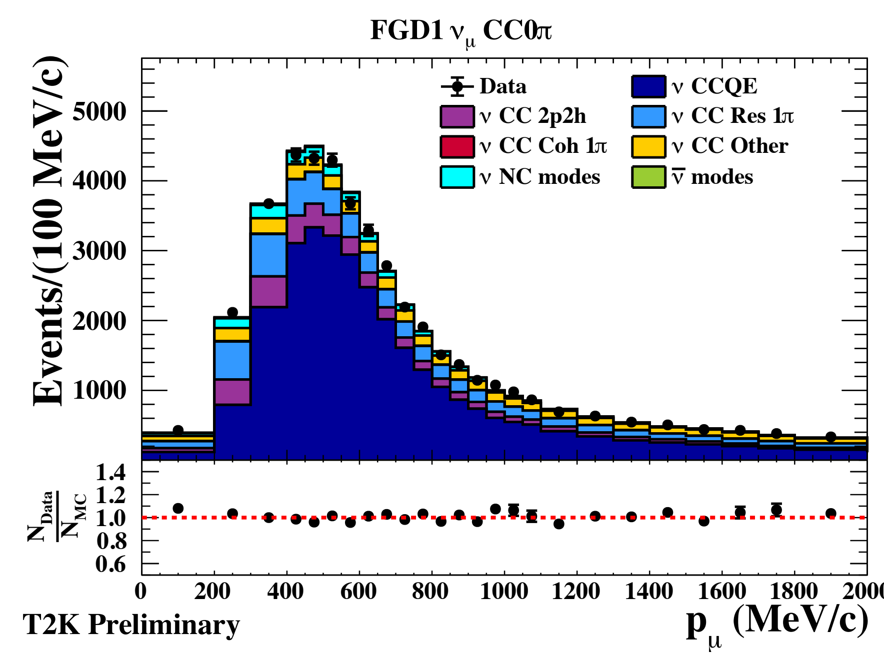
- First fit to near detector, and then fit to SK data (frequentist analysis)
- Bayesian analysis(joint fit with near detector and SK) is also performed and results of both approaches are consistent

Near detector fit





pre fit



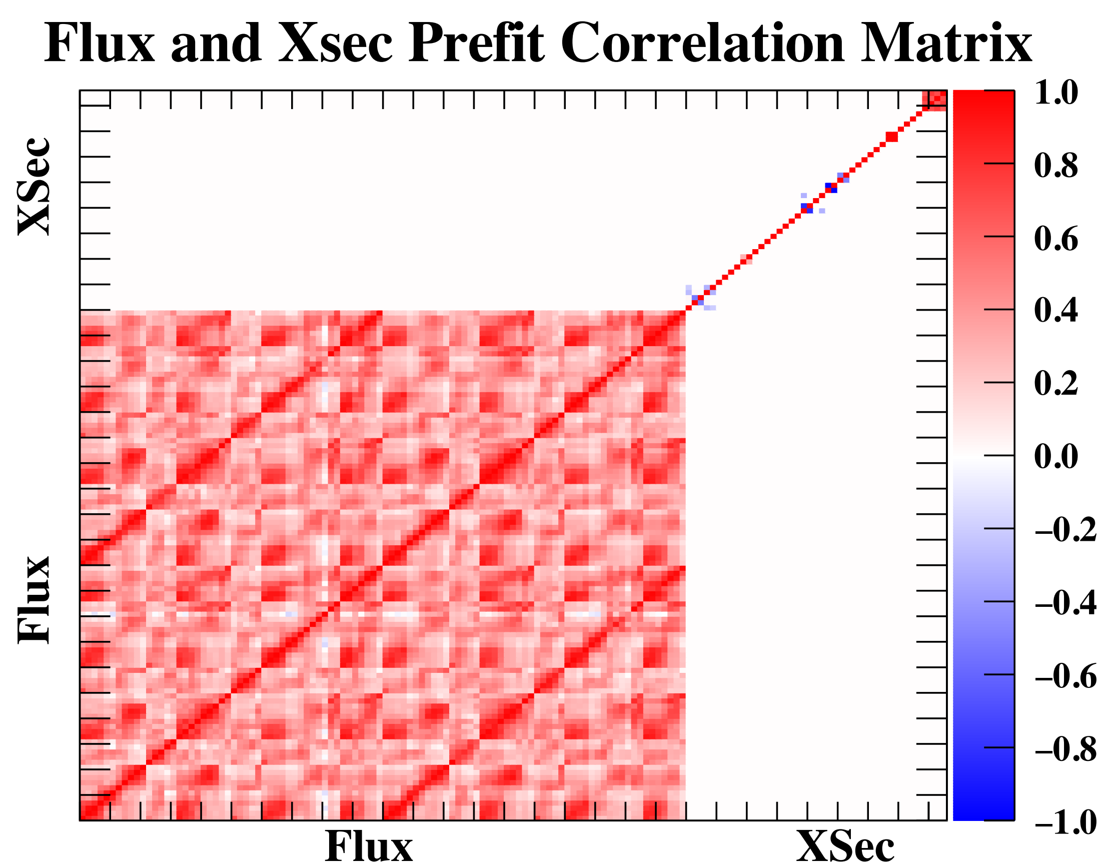
post fit

- Separate charged current interaction candidates into 3 samples based on the number of π in the ND280.
- Compare μ kinematics distribution of data and MC for each sample
  -> Constrain the parameters of neutrino interaction model and flux

Near detector fit

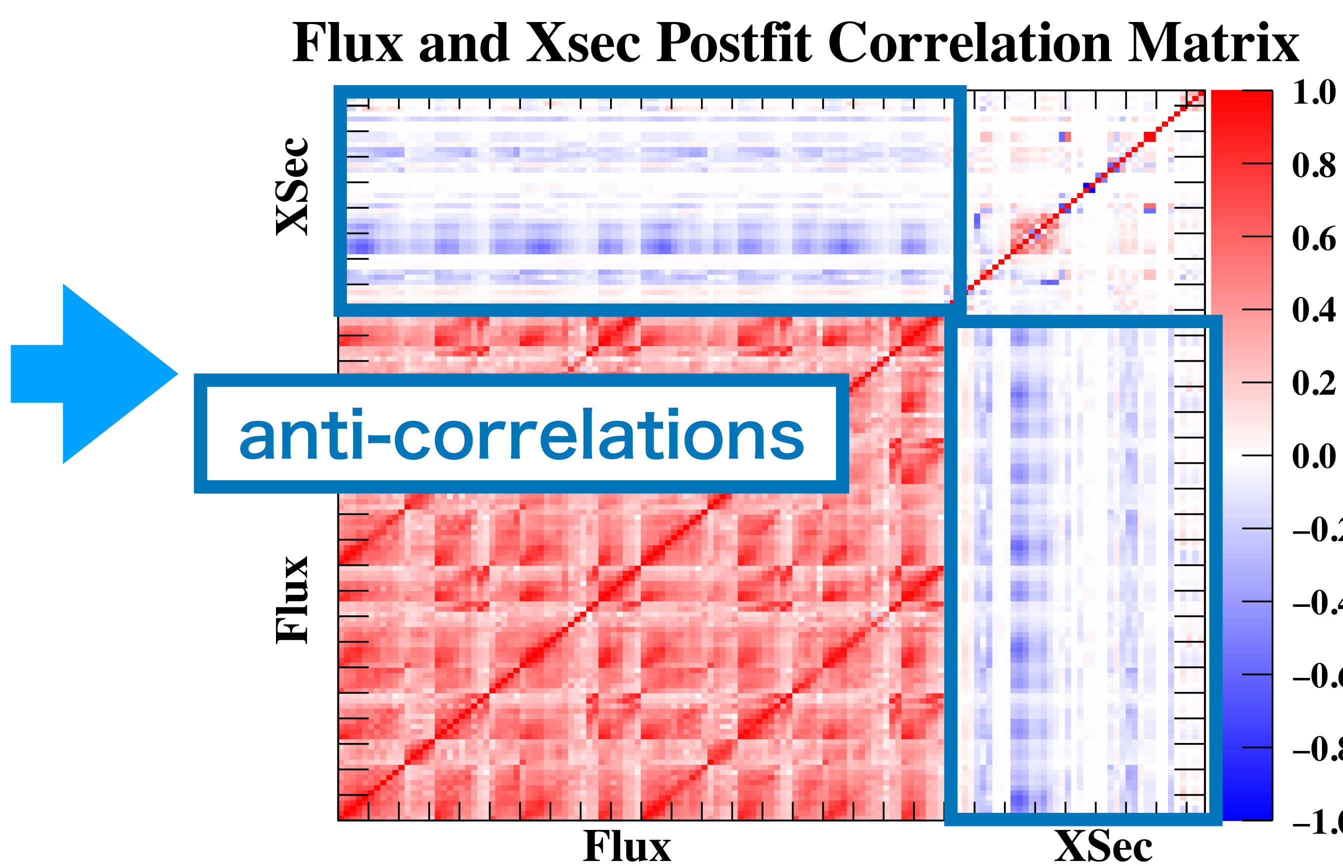
- Near detector fit introduce anti-correlations between flux and xsec (neutrino interaction) parameters

pre fit



T2K Preliminary Run 1-10

post fit

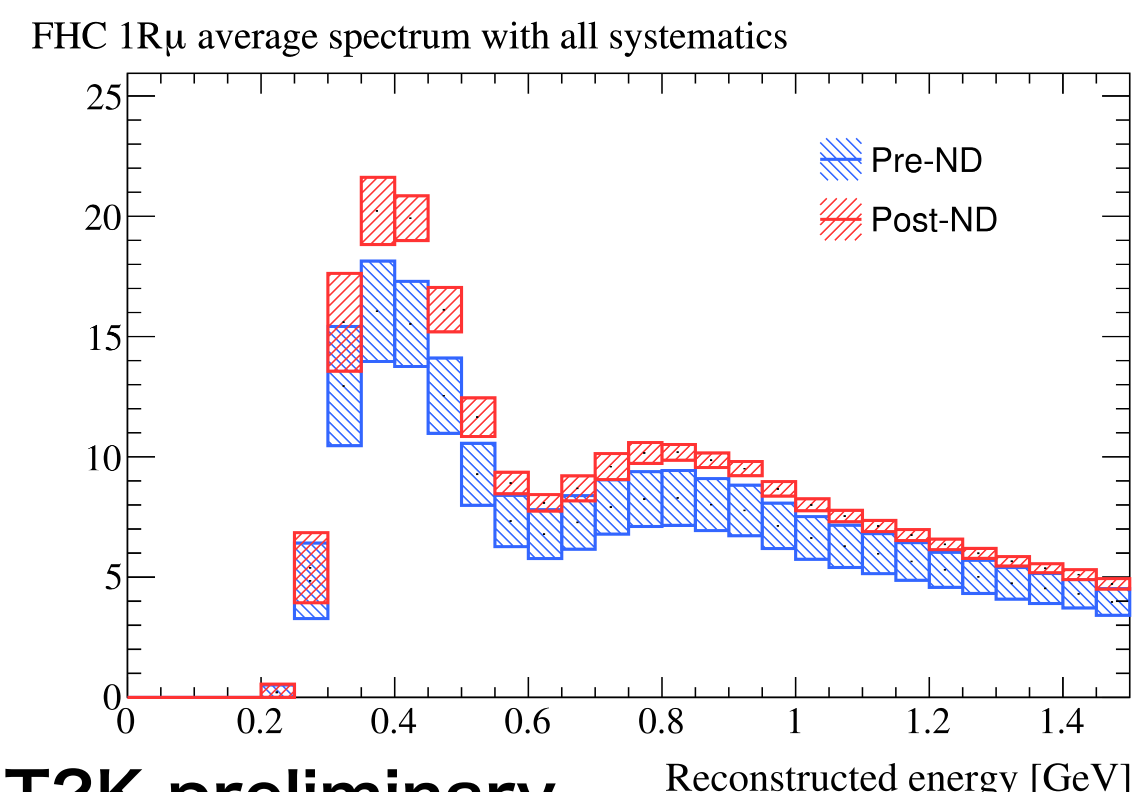


T2K Preliminary Run 1-10

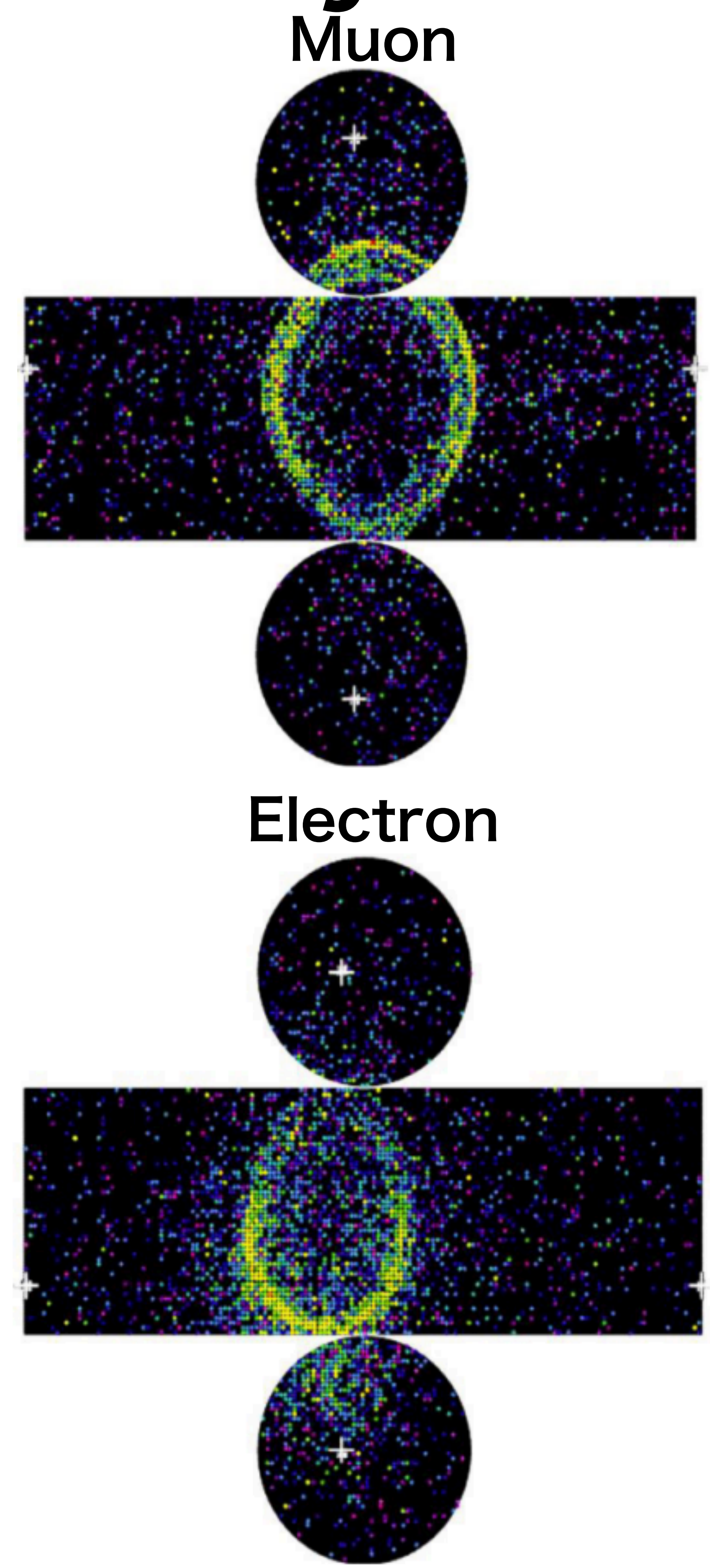
- Reduction of uncertainty of ν_e rate at SK from 13.0% to 4.7%

Far detector(SK) analysis

- 5 far detector samples
  - Two samples with μ-like rings (sharp) (one in ν-mode, one in $\bar{\nu}$ -mode)
  - Three samples with e-like rings (fuzzy) (Two with e-ring only in ν-mode and $\bar{\nu}$ -mode targeting CC0π events, One with Michel electron from decay targeting CC1π events)
- Systematic uncertainties are constrained by near detector fit

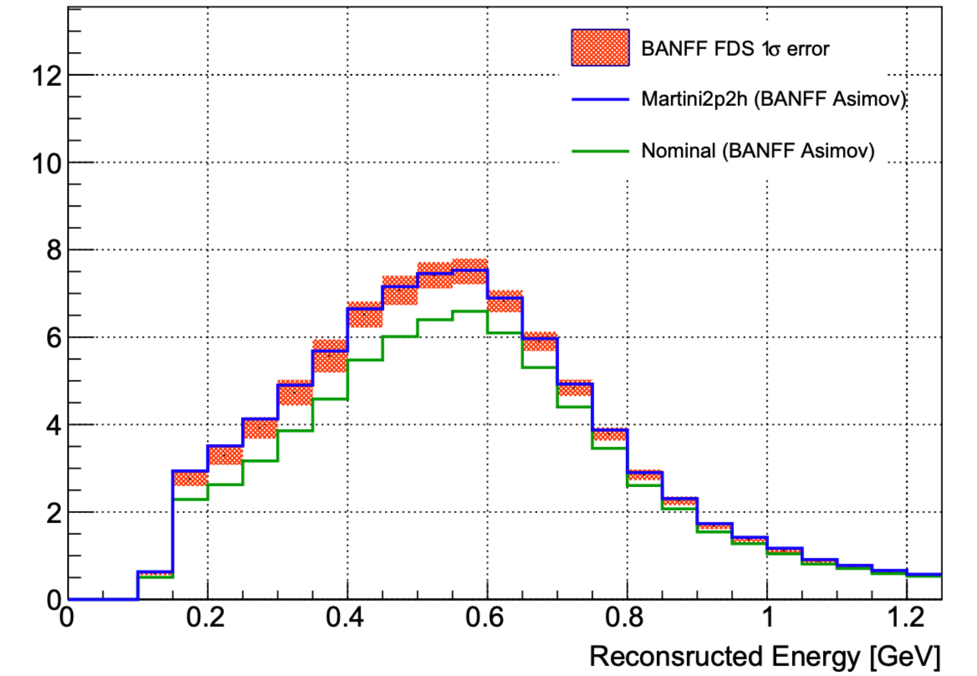


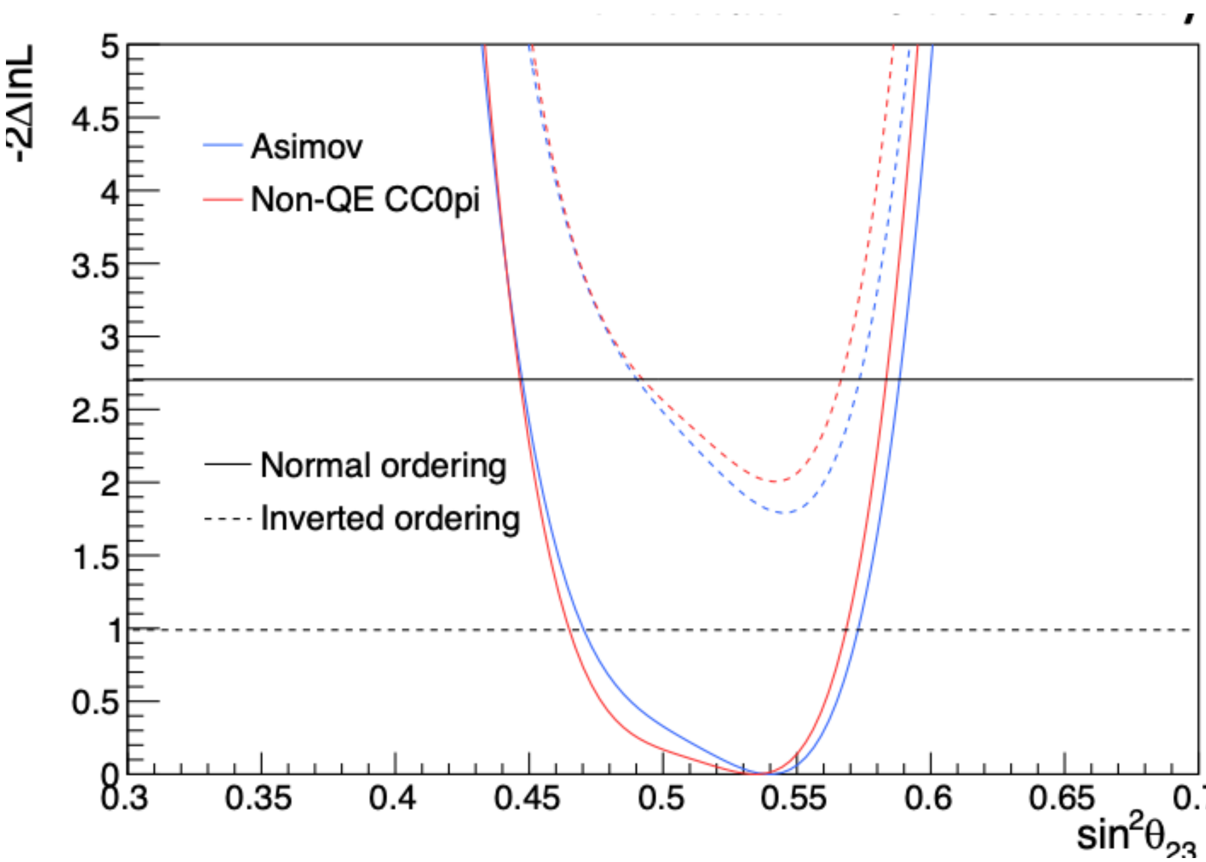
T2K preliminary

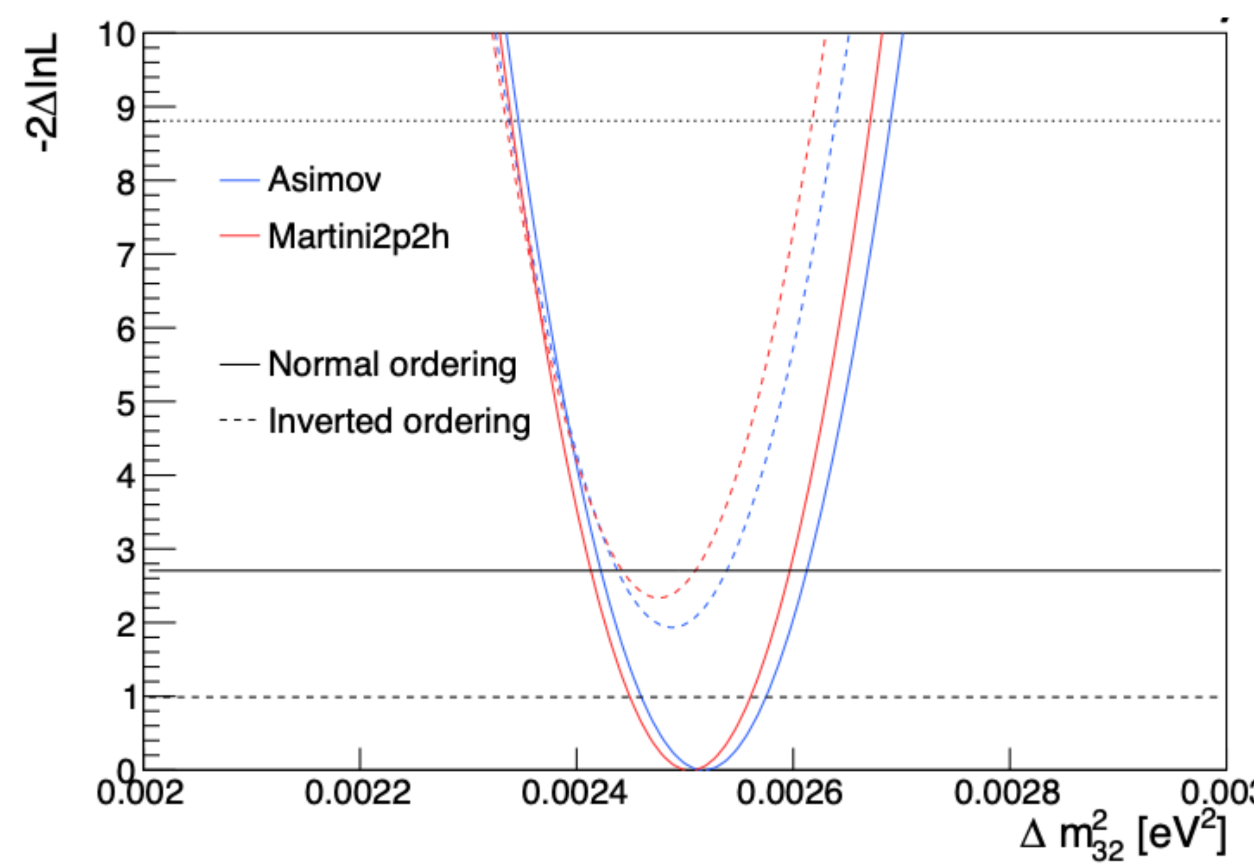


Robustness study

- Choice of the neutrino interaction model is susceptible to introducing a bias for the oscillation analysis
- To estimate the bias, we perform fitting data simulated with alternate interaction models
- No significant bias on θ_{23}
  Small bias seen on Δm^2_{32} and an additional uncertainty was added to account for this







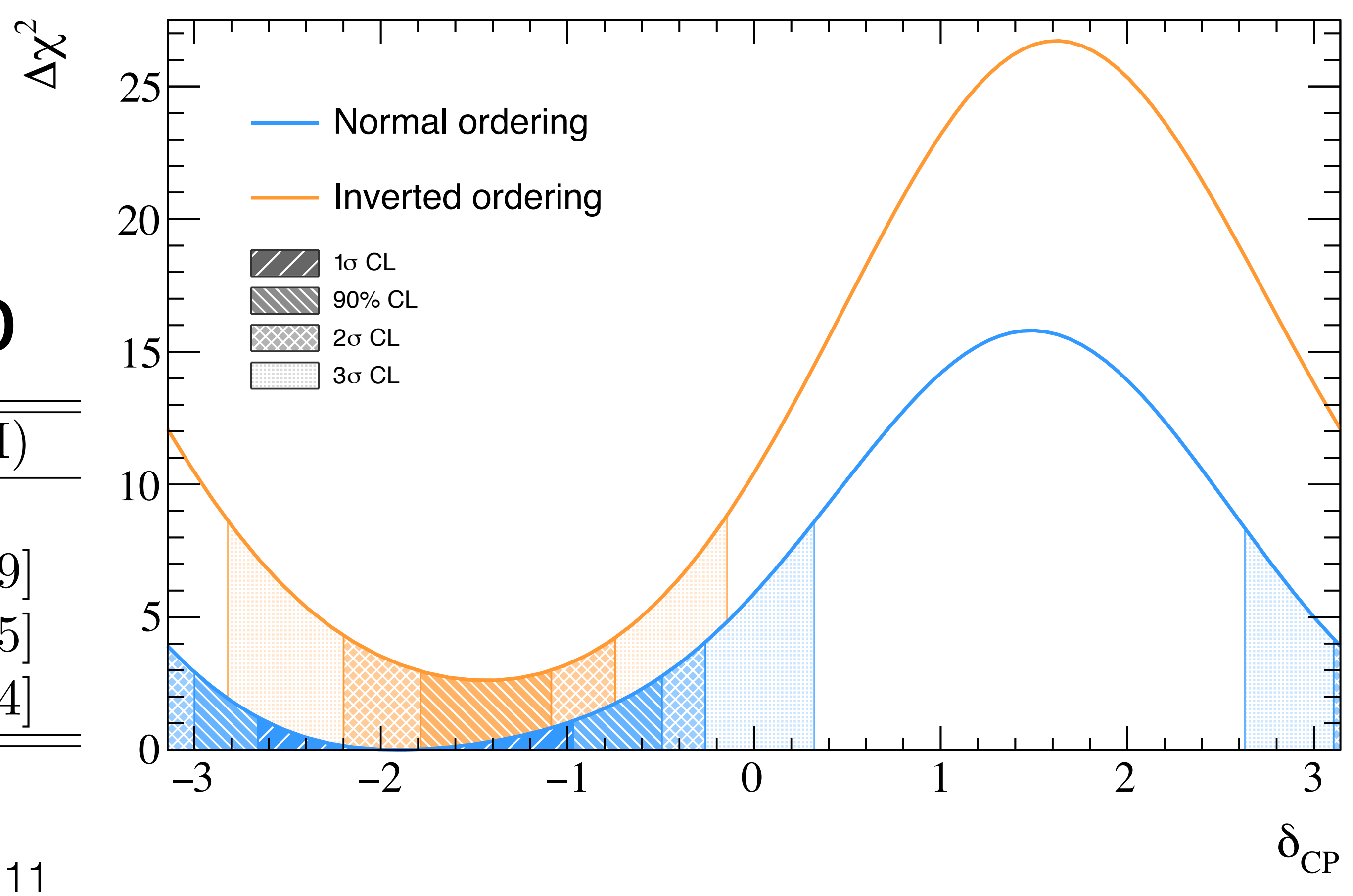
Results of CP violation in oscillation analysis 2020

- 35% of δ_{CP} excluded at 3σ
- CP-conserving values $(0, \pi)$ excluded at 90%
- There are no significant changes in any of our robustness studies (Largest $\Delta\chi^2$ changes seen would cause left (right) edge of 90% interval to move by 0.073 (0.080))

T2K preliminary Run1-10

Confidence level	Interval (NH)	Interval (IH)
1σ	$[-2.66, -0.97]$	
90%	$[-3.00, -0.49]$	$[-1.79, -1.09]$
2σ	$[-\pi, -0.26] \cup [3.11, \pi]$	$[-2.20, -0.75]$
3σ	$[-\pi, 0.32] \cup [2.63, \pi]$	$[-2.82, -0.14]$

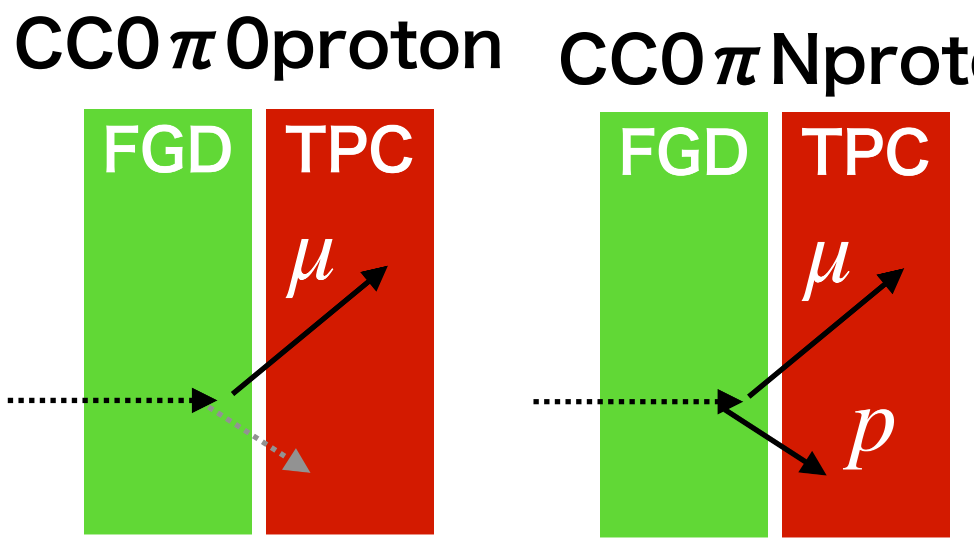
T2K preliminary Run1-10



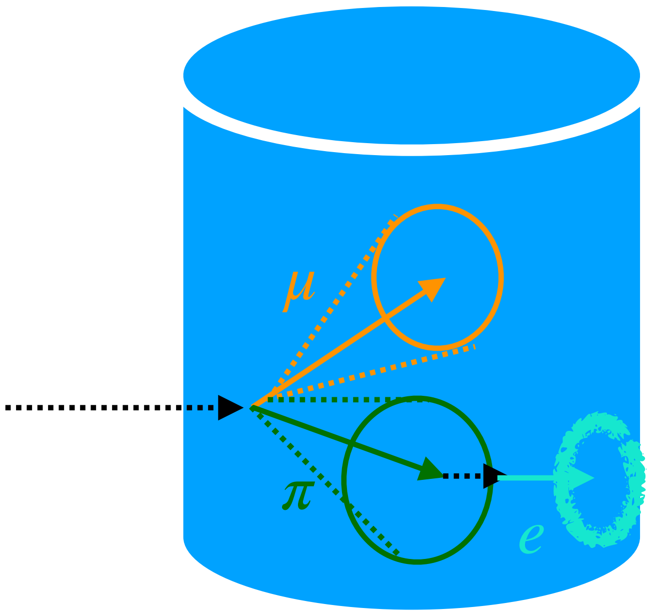
Beyond oscillation analysis 2020

- The latest analysis is being performed
  - New sample selection based on presence of proton(photon) in near detector fit -> Unique sensitivity to nuclear effects
  - New samples in SK fit (2 μ-like rings and 1 or 2 decay-e) -> Slight better sensitivity to θ_{23} and $|\Delta m^2_{32}|$

New sample selection in near detector



New sample in SK

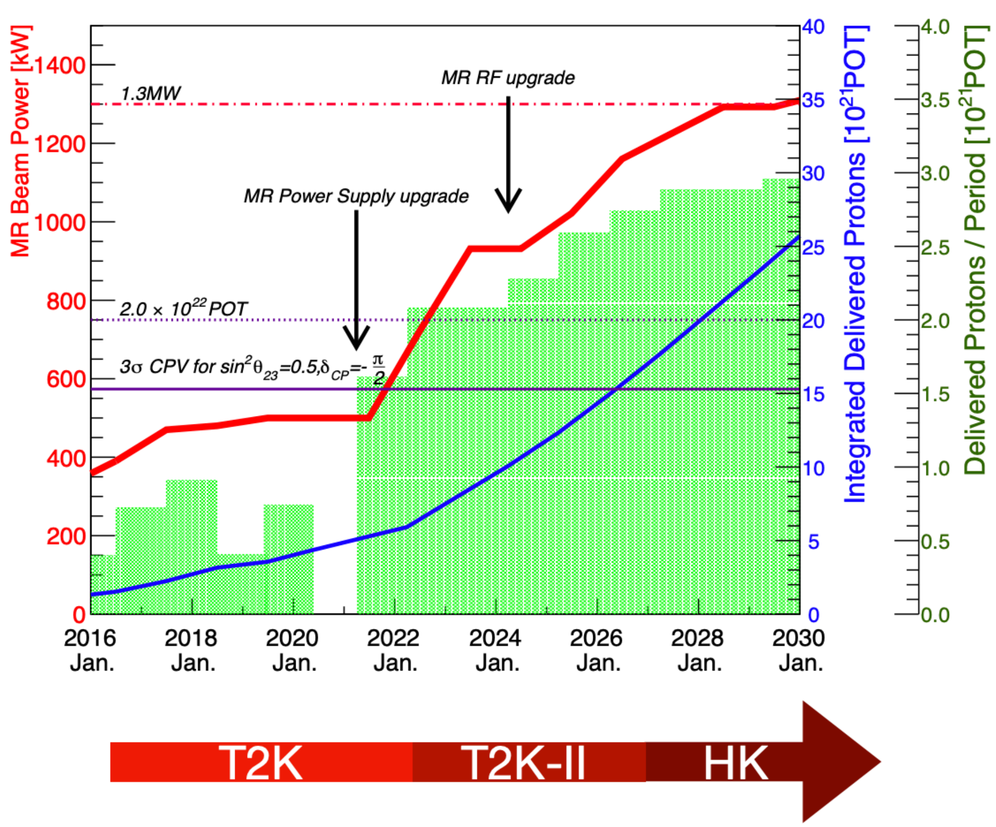


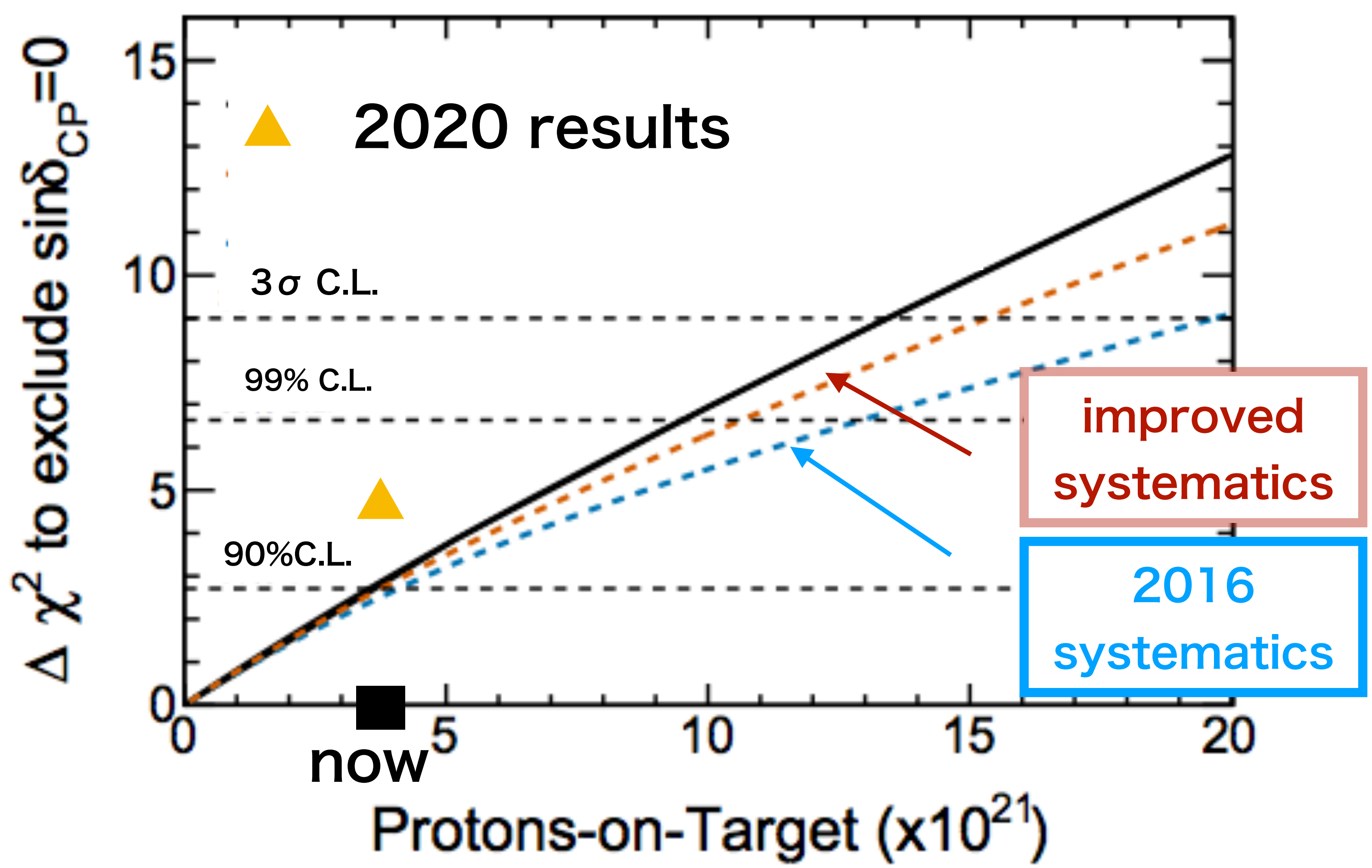
- Updated robustness study is ongoing
- T2K-SK, T2K-Noνa joint fits are ongoing -> important to break degeneracies and understanding systematics correlations between experiments

T2K-II

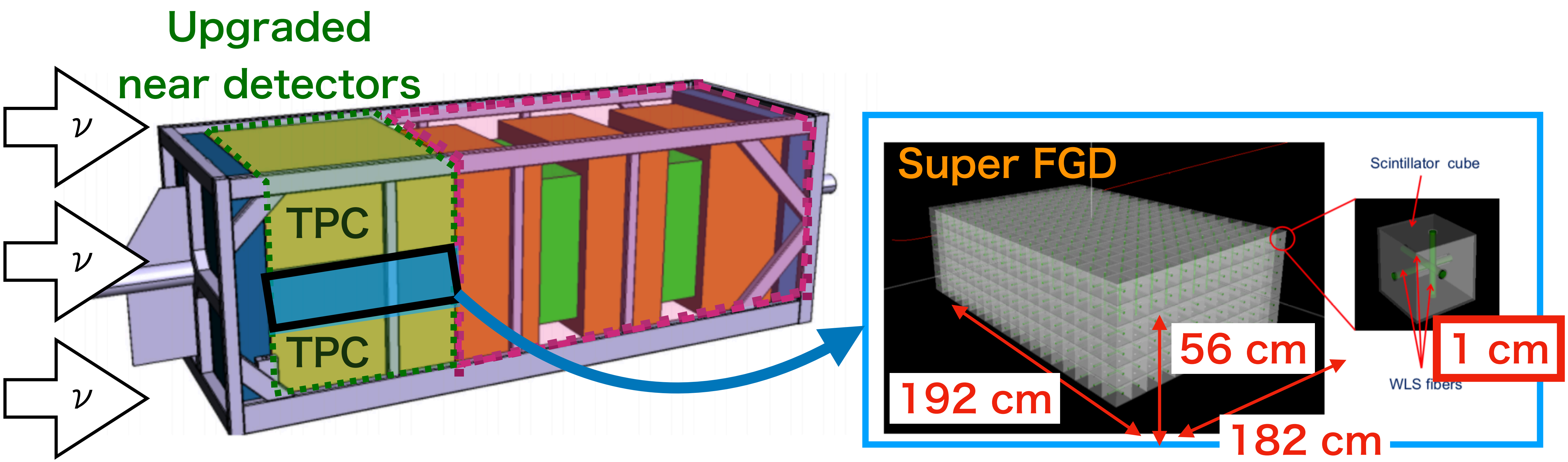
- Toward the more precise measurement especially to find evidence of CP violation in neutrino sector, increase of statistics and reduction of systematics error are needed
  -> T2K-II (2023 ~ 2026)
- T2K-II
  - Beam upgrade
  - Near Detector upgrade

T2K-II Target POT (Protons-On-Target)





ND280 upgrade



ND280 upgrade

- Super FGD - fine granulated plastic scintillator detector
  1 cm³ cubes x 2 million (~ 2 ton)
- 2 High-Angle TPCs
- 6 Time of flight detectors

→ **Low momentum threshold**
4π acceptance (same as SK)

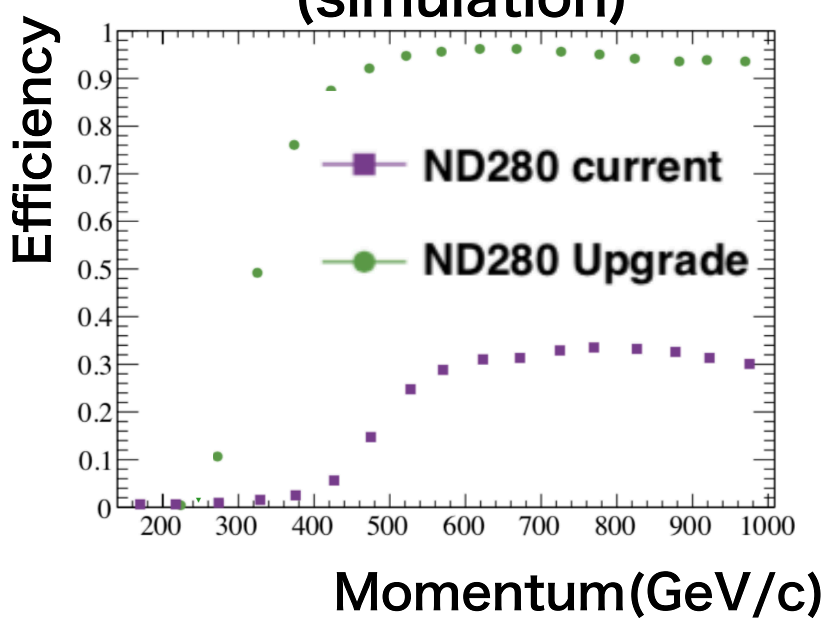
- Installation will be done by spring 2023

Impacts of ND280 upgrade on physics

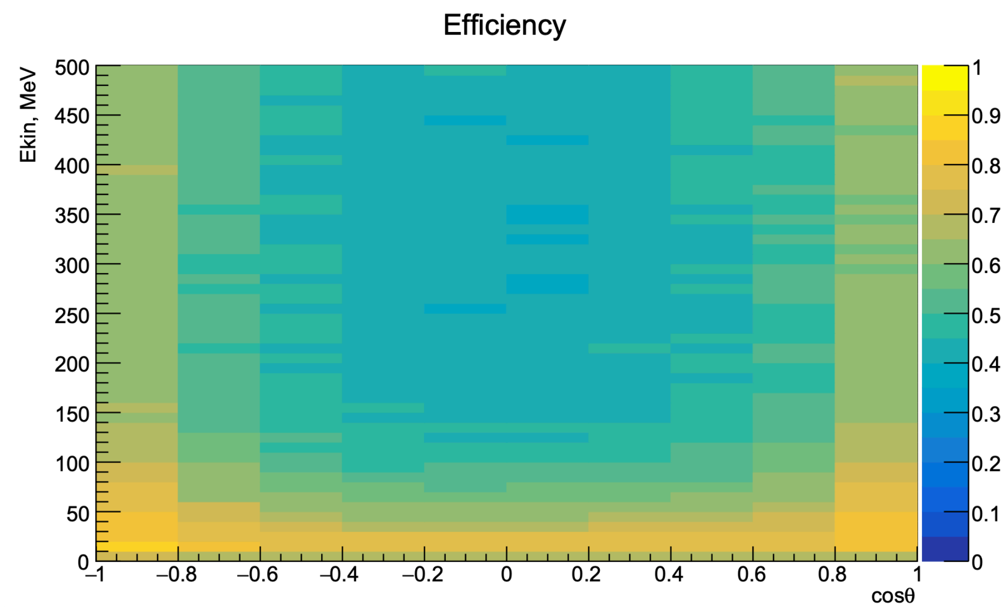
- New detectors have many impacts on neutrino physics
  - Detection of low momentum proton (600 MeV/c -> 300 MeV/c) -> More understanding nucleus effect of neutrino interaction
  - Neutron kinematics
  - e-γ separation -> precise measurement of ν_e cross section

  etc.

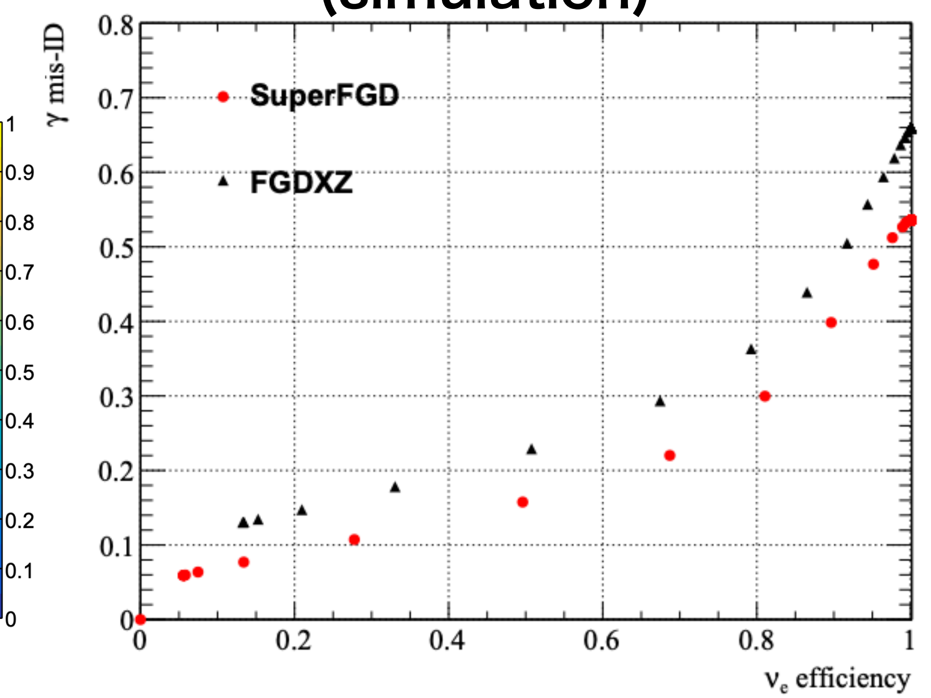
Proton detection efficiency (simulation)



Neutron detection efficiency in Super FGD(simulation)



e-γ misidentification probability (simulation)



"K. Abe et all, T2K ND280 Upgrade -- Technical Design Report"

Expected to give us new findings of neutrino interaction!

Summary

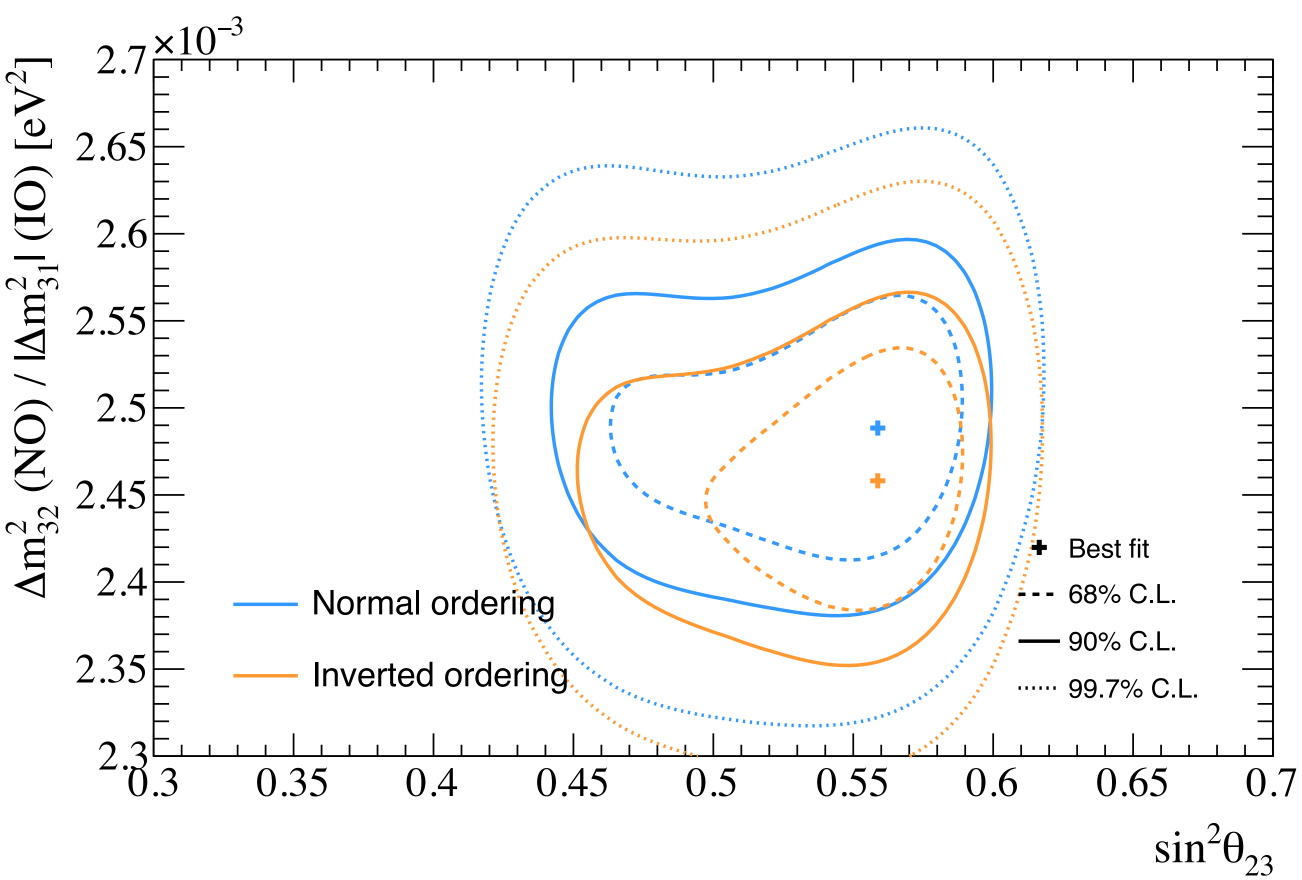
- T2K is performing world-leading measurements of neutrino oscillation parameters
- CP conservation of neutrino oscillation is excluded at 90%
- The oscillation analysis including new near and far detector samples is ongoing now
- We are planning T2K-II experiment
  -> Beam and ND280 upgrades are ongoing

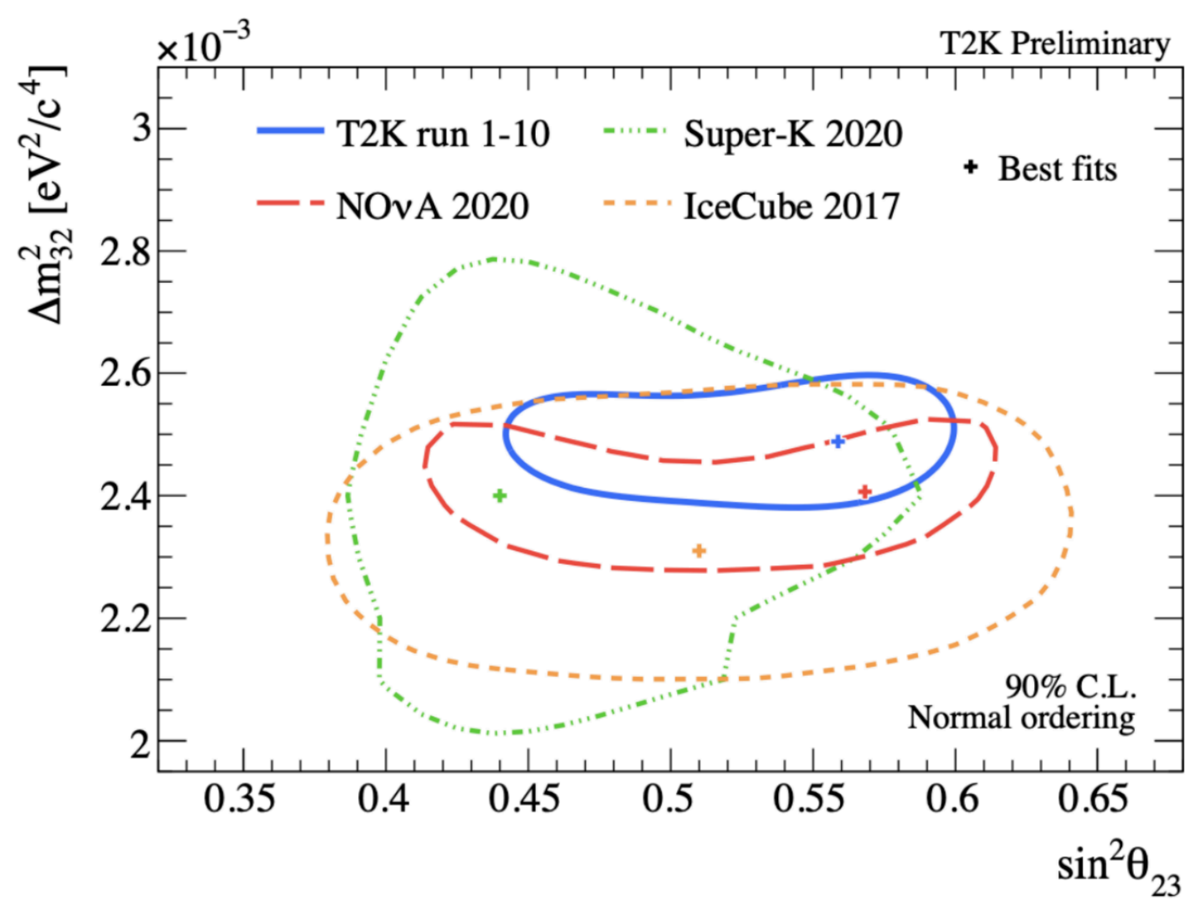
Back up

Results of θ_{23}, Δm^2_{23} in oscillation analysis 2020

- Slight preference for upper octant and normal ordering
- Small bias seen by the robustness studies

T2K preliminary

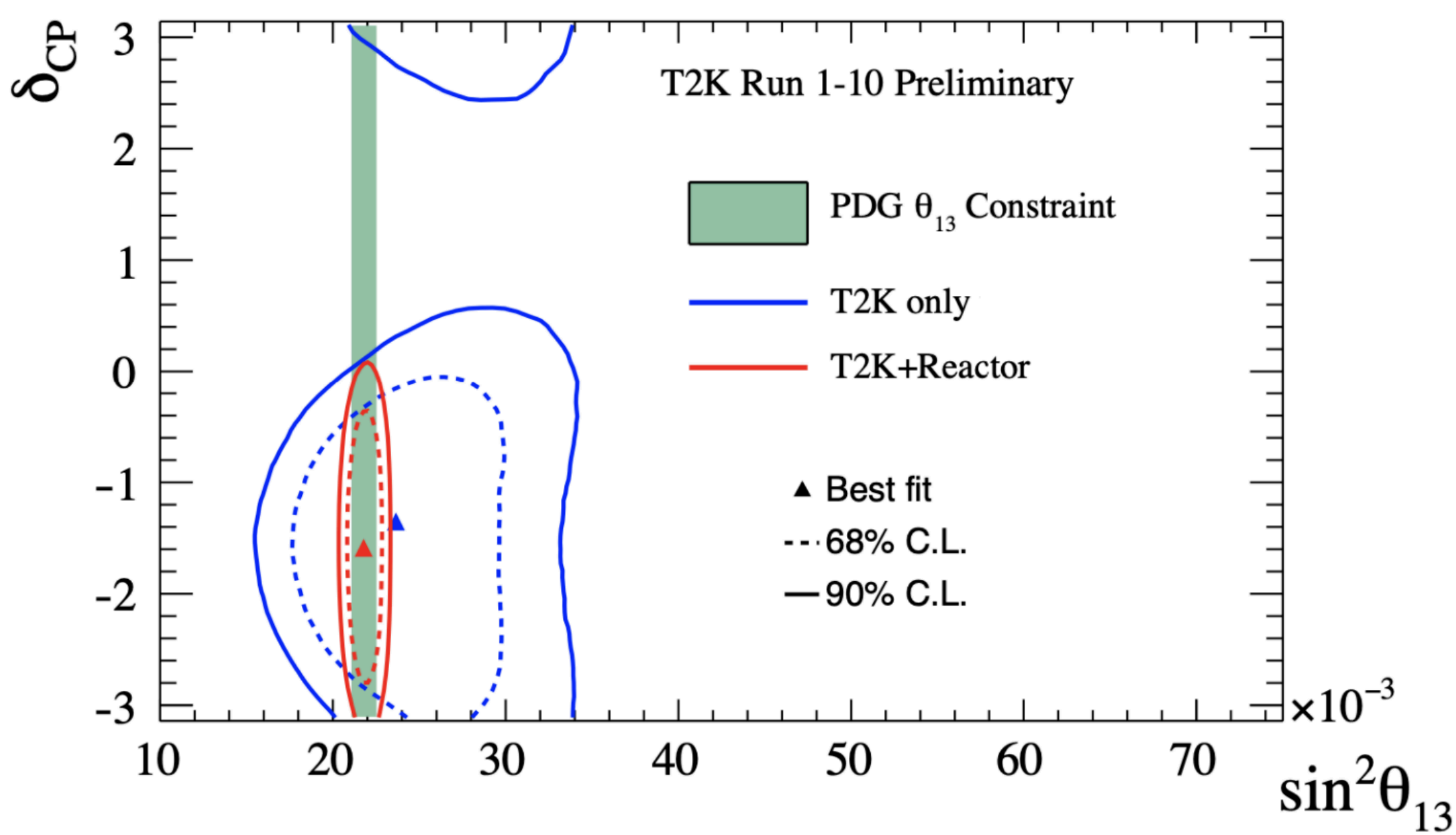




Results of θ_{13} in oscillation analysis 2020

- Measure with and w/o Reactor constraint
- Both of them are consistent with reactor data

T2K preliminary



WAGASCI, NINJA

- There are various approaches to understand neutrino interaction model
  - WAGASCI-BabyMIND experiment
    … water target, neutrino energy spectrum slightly different from ND280
  - NINJA experiment
    -> See next talk in detail

WAGASCI experiment