Latest neutrino oscillation measurements from T2K

Masaki Ishitsuka (Tokyo University of Science)
for the T2K collaboration

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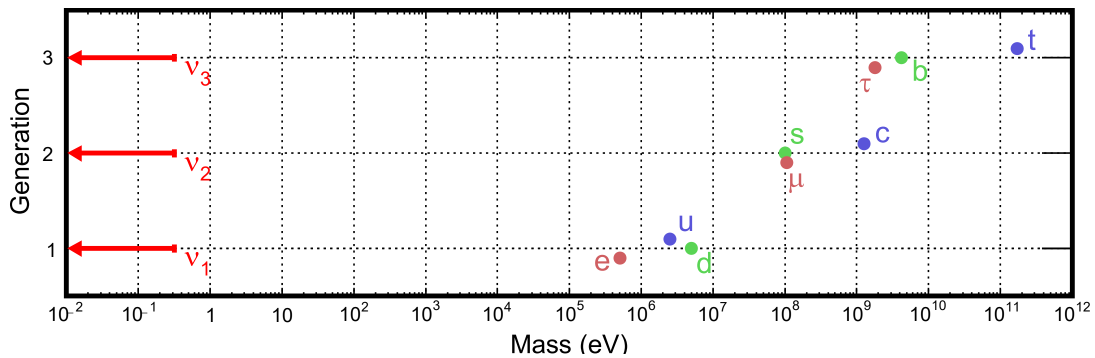
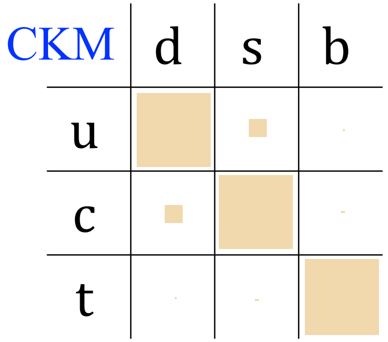
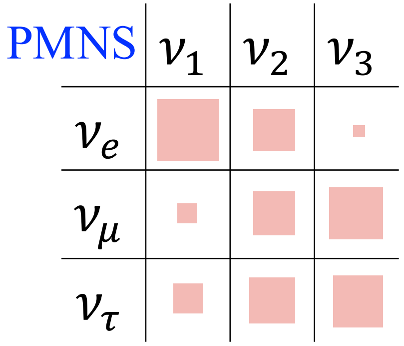
Neutrino mass and mixing

According to the discovery of neutrino oscillations and the following measurements

- **Neutrinos have finite mass, but they are extremely small**
  - Indicate existence of unknown mechanism beyond the Standard Model (i.e. Seesaw)
- **Three-flavor neutrinos are largely mixing w.r.t. quark sector**
  - This opened door to measure CP violation (δ_{CP}) in neutrino sector and explore the origin of matter through neutrinos (i.e. leptogenesis)







Next goals:

- Precision measurement of **neutrino mixing, including θ_{23} octant (i.e. $\theta_{23} < 45°$ or $\theta_{23} > 45°$)**
- Search for ***CP*** **violation (δ_{CP})** in neutrino sector
- Determination of **mass ordering: $m_3 \gg m_2 > m_1$ (normal) or $m_2 > m_1 \gg m_3$ (inverted)**

T2K (Tokai-to-Kamioka) experiment

- High intensity **ν_μ and $\bar{\nu}_\mu$ beam produced at J-PARC**
- Neutrino beam flux and cross section measured by the **near detector (ND280)**
- Neutrinos are observed by the **far detector (Super-Kamiokande)** at 295 km distance

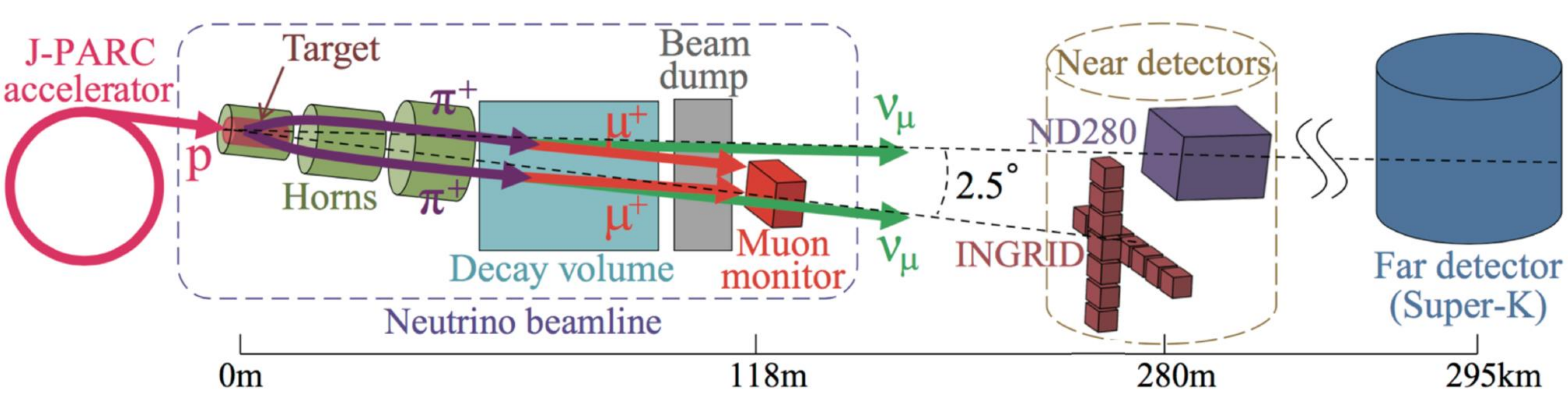
→ **Study of neutrino oscillations** (**$\nu_e/\bar{\nu}_e$ appearance** and **$\nu_\mu/\bar{\nu}_\mu$ disappearance**)

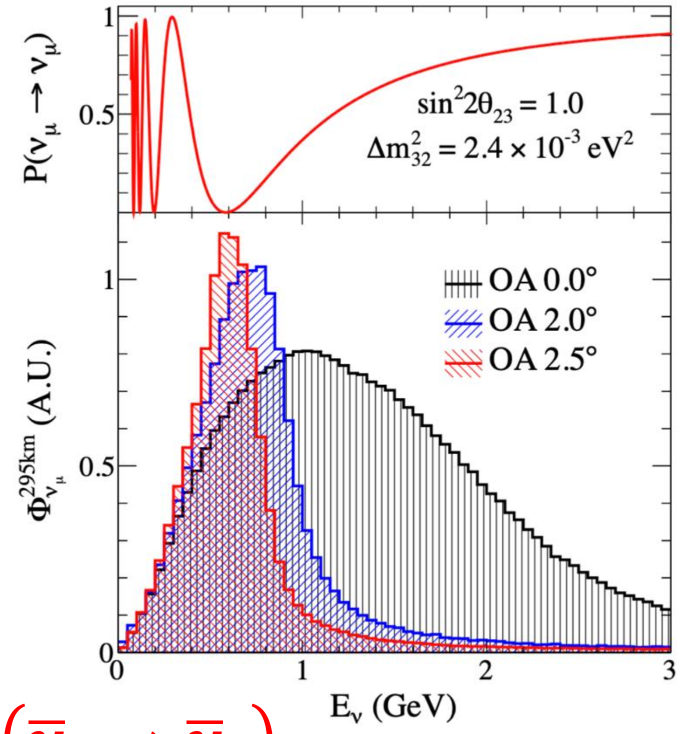
- First indication of $\nu_\mu \rightarrow \nu_e$ oscillation in 2011 [1], followed by the observation in 2014 [2]

[1] PRL107, 041801 (2011), [2] PRL112, 061802 (2014)

J-PARC neutrino beam

- High intensity neutrino beam produced from 30 GeV proton accelerator at J-PARC
  - 4.6×10^{21} POT in total for T2K (peak power: 829 kW)
- **$2.5°$ off-axis neutrino beam** for Super-K peaked at 0.6 GeV (oscillation maximum)
- Neutrino beam direction/intensity monitored by INGRID (by ν) and MUMON (indirectly by μ)





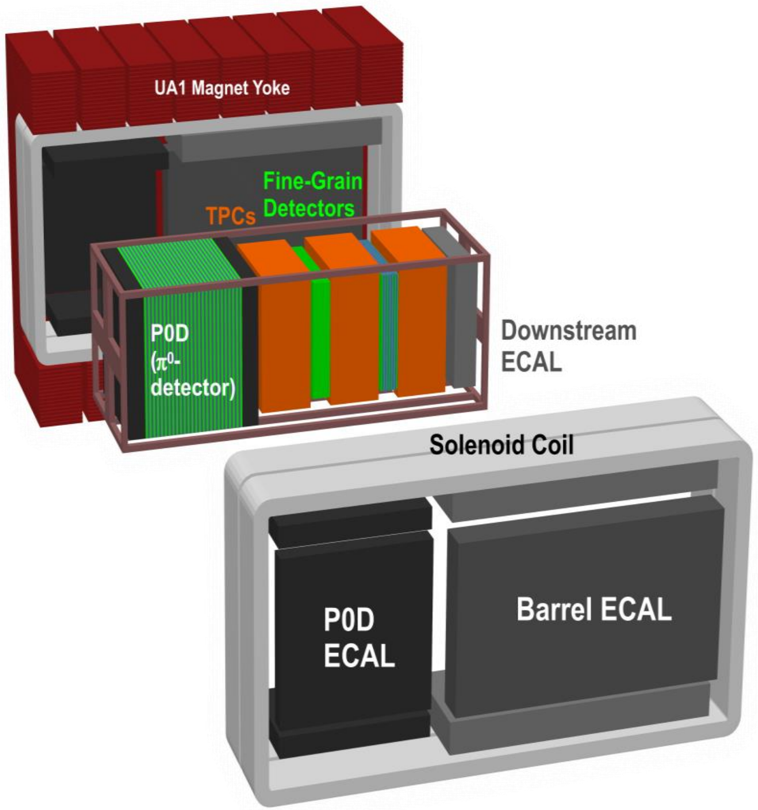
Neutrino mode: ν_μ beam produced by focusing π^+

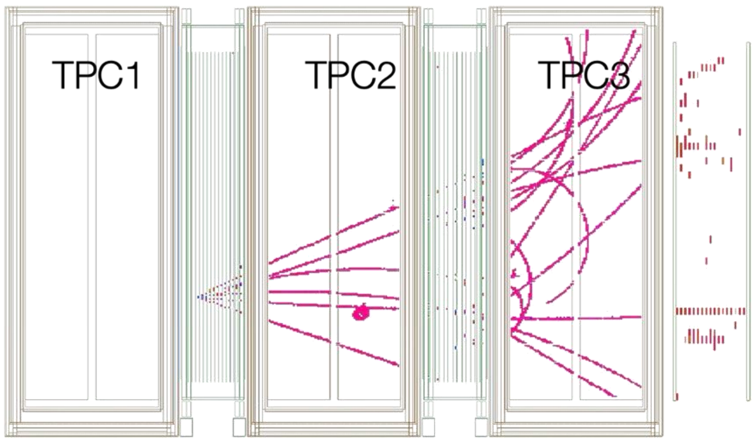
Antineutrino mode: $\bar{\nu}_\mu$ beam produced by focusing π^-

→ Search for CP violation from comparison of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

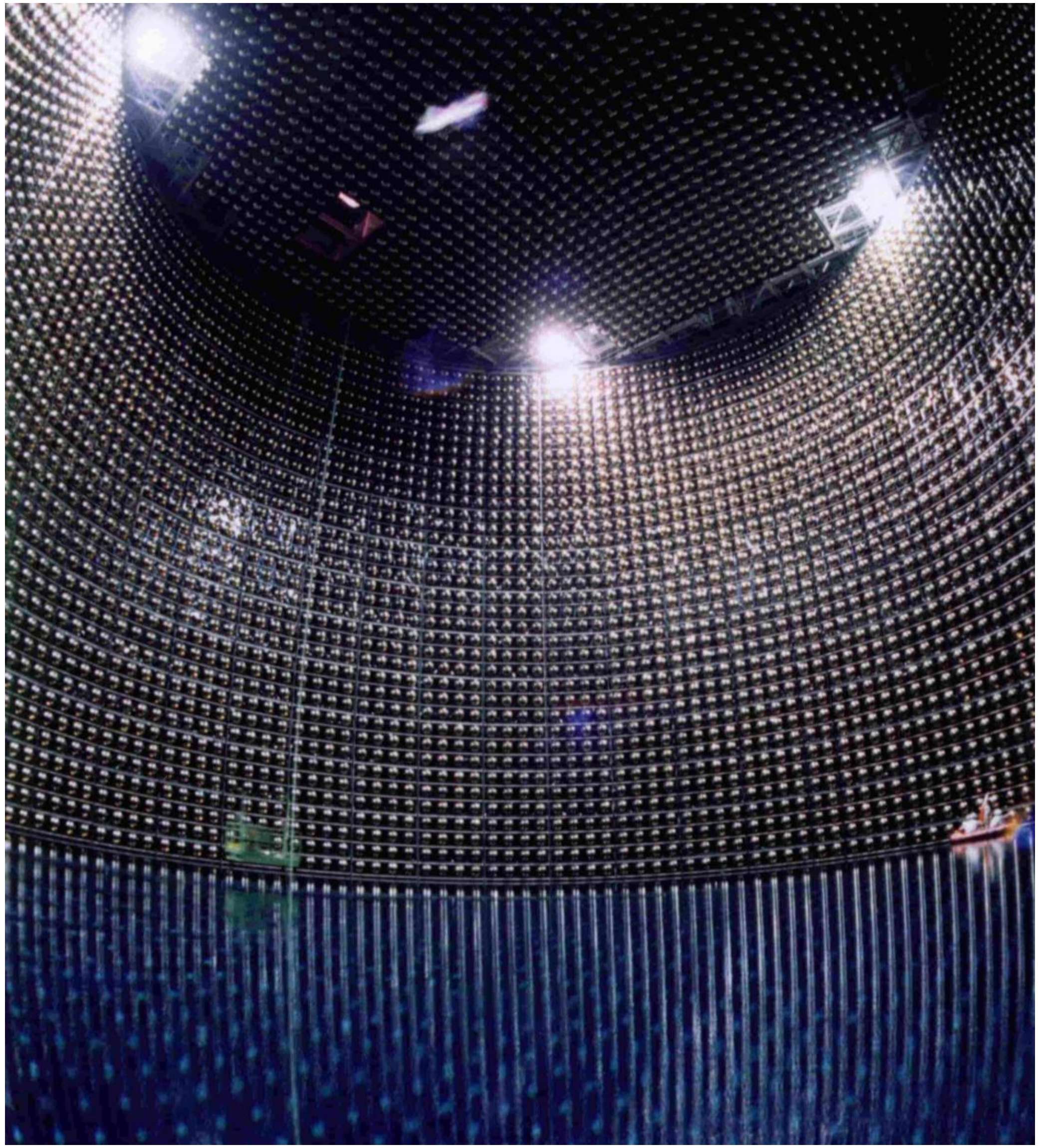
ND280 detector (before upgrade in 2024)

- Near detector located at 280m downstream and 2.5° off-axis
- ND280 detector consists of
  - Upstream π^0 detector (**POD**)
  - Fine Grain Detector (**FGD**) as target of neutrino interaction and tracking
  - Time Projection Chambers (**TPC**) for tracking
  - Electromagnetic calorimeter (**ECal**) and muon detector surrounding inner trackers
- Charge and momentum of the tracks can be measured with 0.2 T B-field provided by **UA1 magnet**
  → Measurement of wrong sign component (e.g. ν_μ in $\bar{\nu}_\mu$ beam)

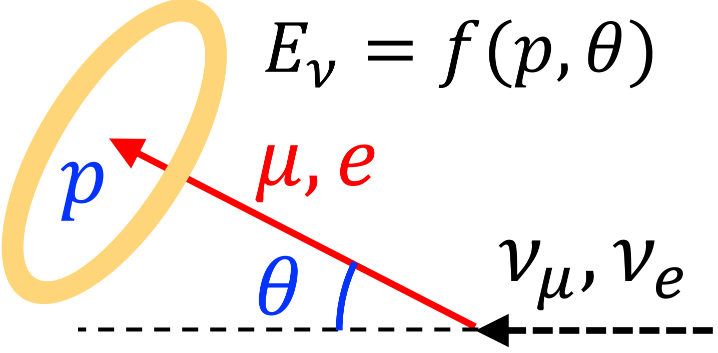


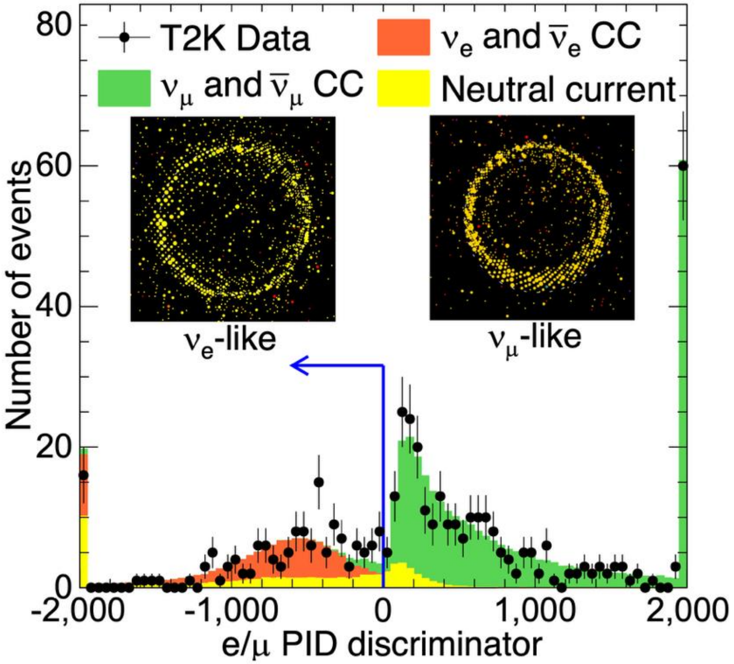


Super-Kamiokande detector



Quasi-Elastic (QE)





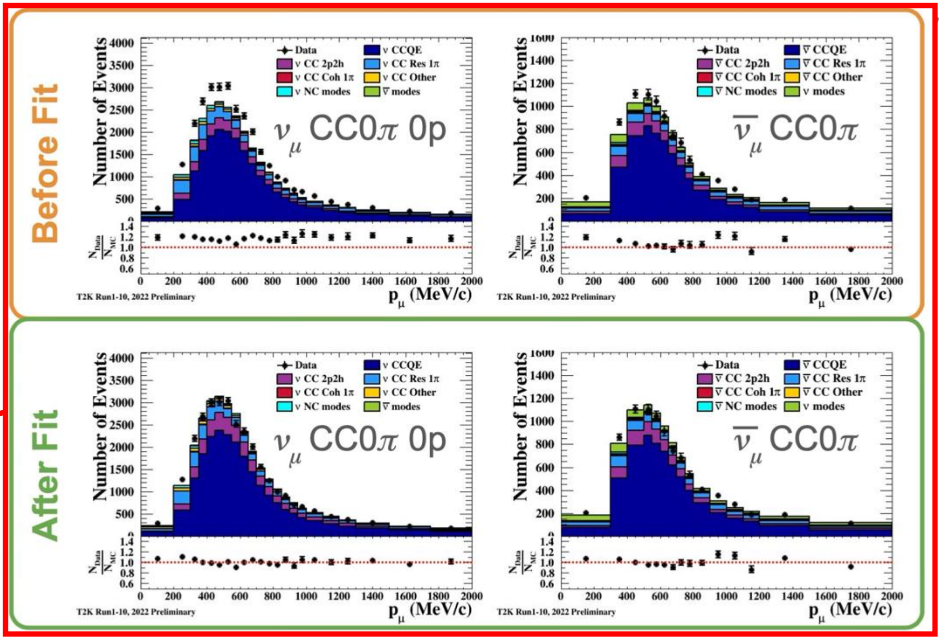
- 50 kton water Cherenkov detector
  - ~11,000 PMT for detection of Cherenkov ring
  - Gd loaded since 2020 for neutron tagging
- Major component in T2K data is QE scattering:
  - Neutrino flavor identified by μ/e separation
  - E_ν determined from (p, θ) of outgoing lepton
  - Non-QE and NC contamination suppressed by selecting single-ring event

T2K oscillation analysis

Neutrino flux prediction
Hadron production model constrained by NA61/SHINE replica target data

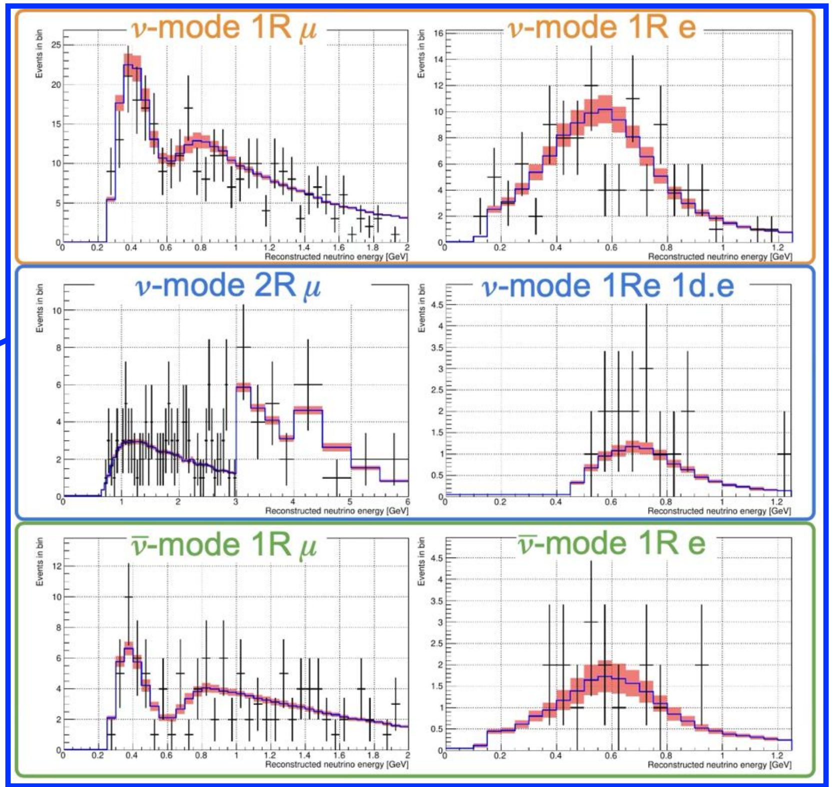
Neutrino interactions
Interaction models constrained by external data

ND280 measurements
Uncertainties on flux and cross sections constrained by ND280 data



Measurement of oscillation parameters by SK data

- Combine flux, cross section and ND280 measurement to predict expected events at SK → comparison with SK data



Two analyses:

- Frequentist: Sequential ND280 and SK fits
- Bayesian: Simultaneous ND280 and SK fit

4 samples in neutrino mode:

- 1-ring e-like w/ and w/o decay-e
- 1-ring μ-like w/ and w/o π

2 samples in antineutrino mode

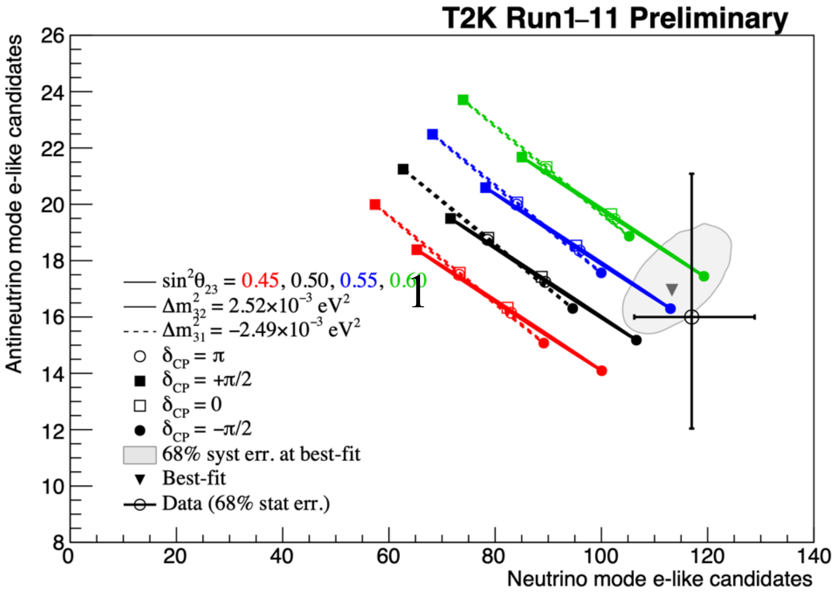
- 1-ring e-like and 1-ring μ-like

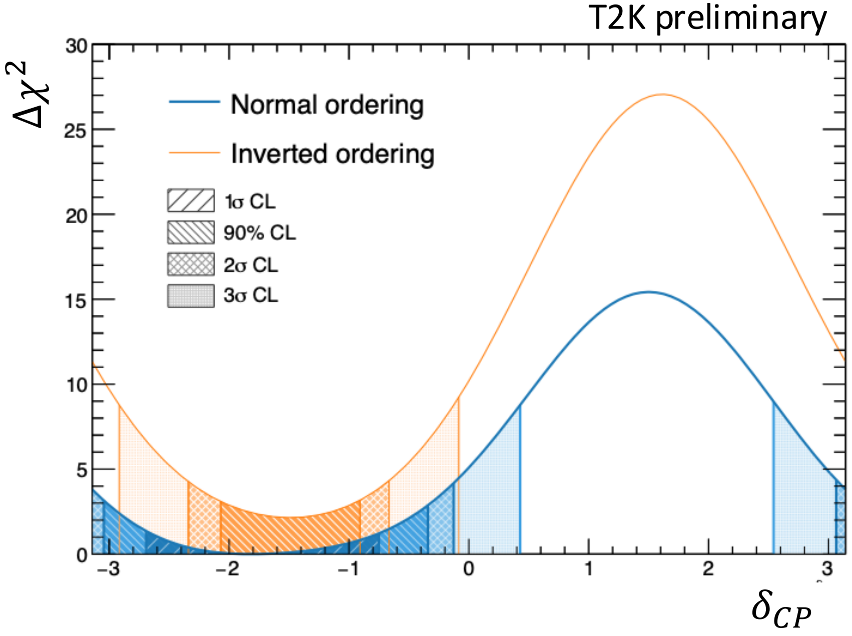
Results of T2K oscillation analysis

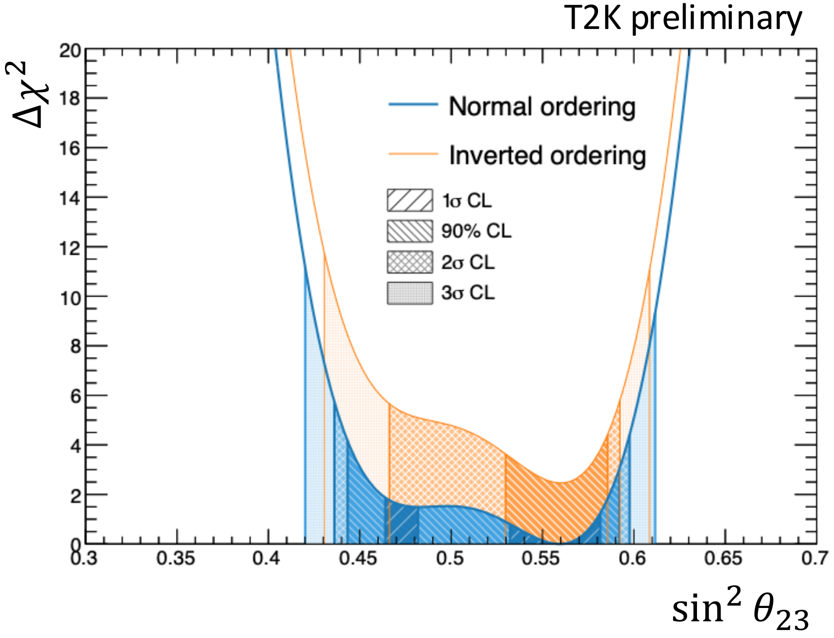
- Neutrino mode: 2.17×10^{21} POT (~10% increase from the previous analysis[1])
- Antineutrino mode: 1.65×10^{21} POT

[1] PRD108, 072011 (2023)

- Improvements for estimation of SK detector systematics and decay-e selection







- Best fit value close to maximal CP-violation ($\delta_{CP} = -90°$)
  - CP conservation hypothesis is excluded with 90% CL
- Slight preference for upper octant θ_{23} and normal mass ordering

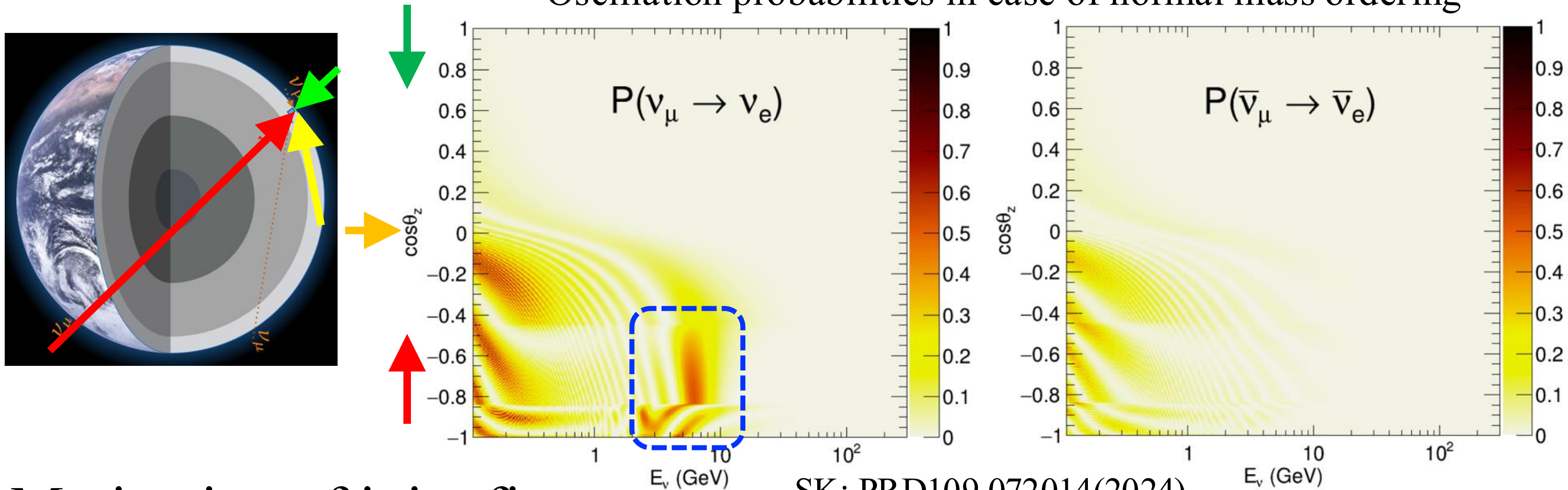
Joint analysis of T2K and Super-Kamiokande

T2K+SK: PRL134, 011801 (2025)

Atmospheric neutrino observation by Super-Kamioande

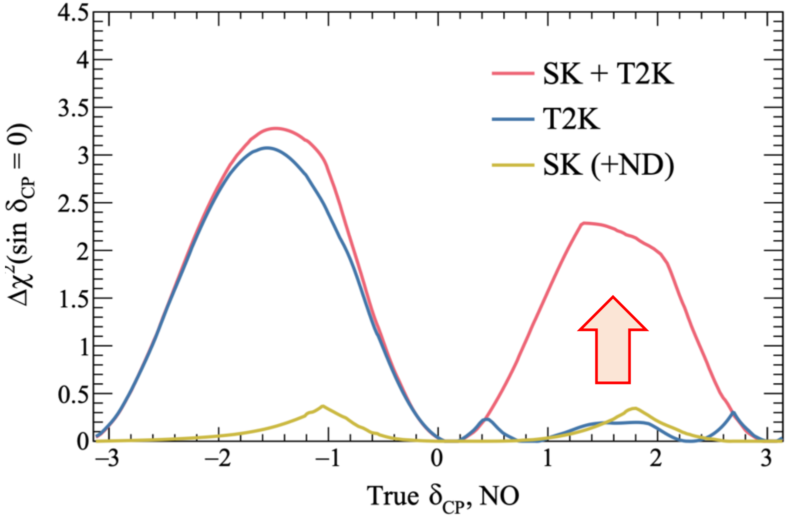
- A few to 10 GeV neutrinos are sensitive to mass ordering by the Earth's matter effects
  - $\nu_\mu \rightarrow \nu_e$ oscillation is enhanced in case of normal mass ordering
  - $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation is enhanced in case of inverted mass ordering

Oscillation probabilities in case of normal mass ordering



SK: PRD109,072014(2024)

Sensitivity to reject CP-conserving hypothesis



Motivation of joint fit

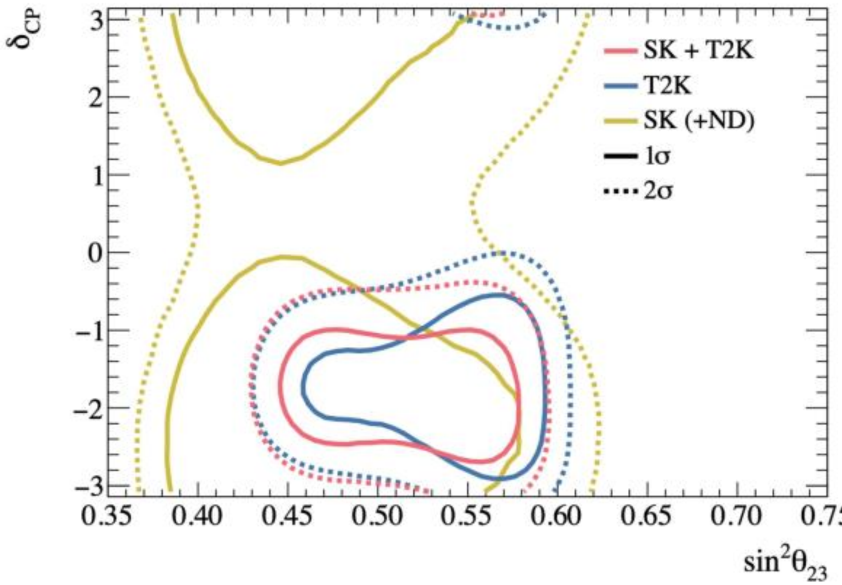
- Combination of T2K and SK data work to break degeneracies of δ_{CP} and mass ordering
- T2K and SK share the same detector (SK) and have overlapping energy spectrum
  → common interaction model for overlapped region and correlated detector systematics in fit

Results of T2K and SK joint oscillation analysis

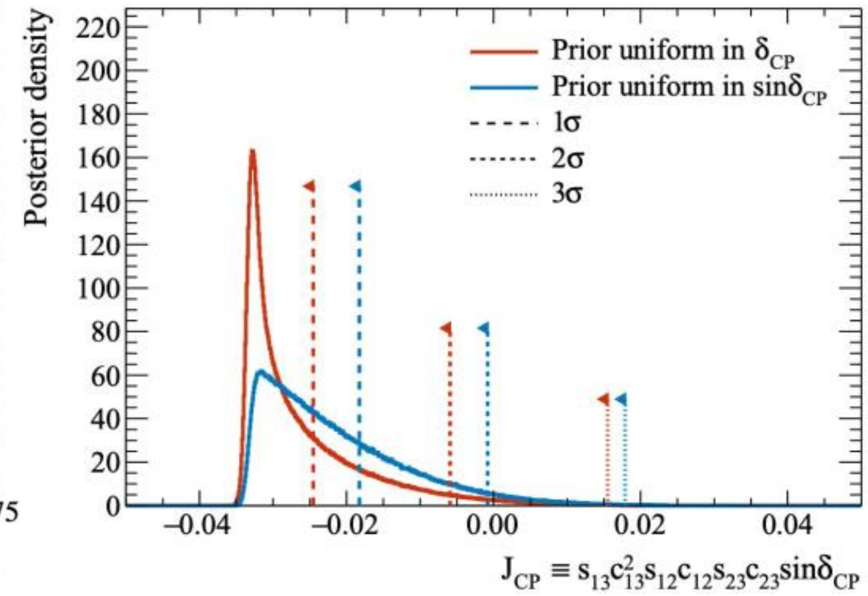
T2K+SK: PRL134, 011801 (2025)

- T2K and Super-K data have different preferences for θ_{23}
  → No strong preference for θ_{23} octant by the joint fit
- Jarlskog invariant CP conserving value (J_{CP}=0) is excluded at 1.9-2.0σ
- Limited preference for normal mass ordering (rejecting inverted ordering at 1.2σ)

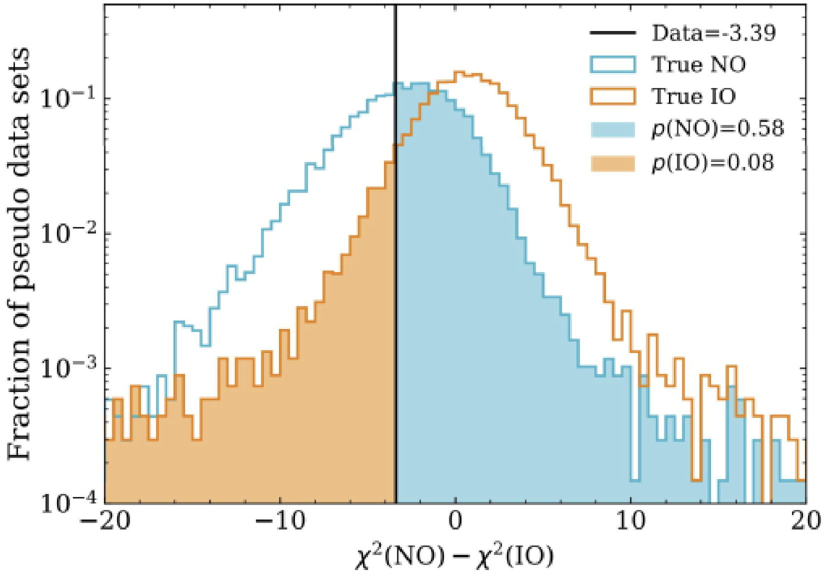
δ_{CP} vs. $\sin^2\theta_{23}$



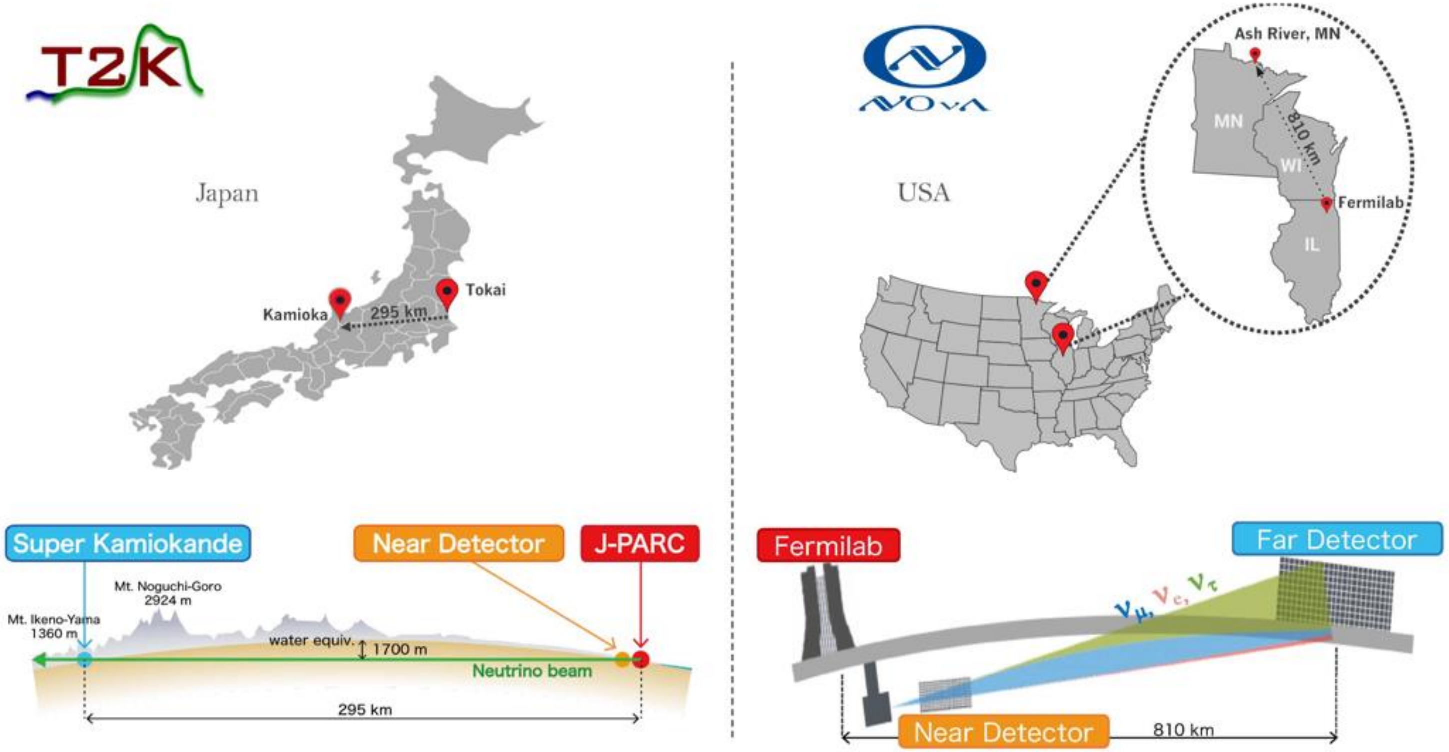
CP violation

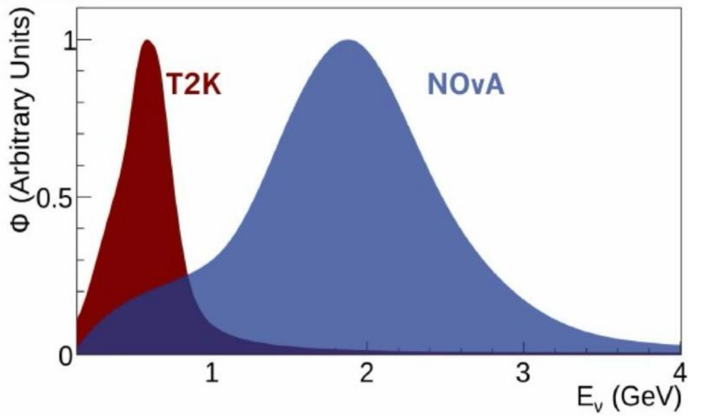


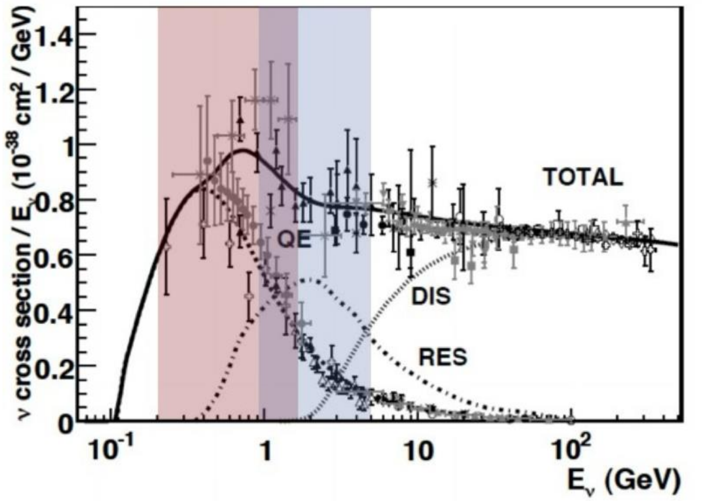
Mass ordering



Joint analysis of T2K and NOvA







295 km	Baseline	810 km
2.5°	Off-axis angle	0.84°
0.6 GeV	Peak energy	2 GeV
QE with 2p2h (peak) RES, DIS (tail)	Major interactions	QE, RES, DIS

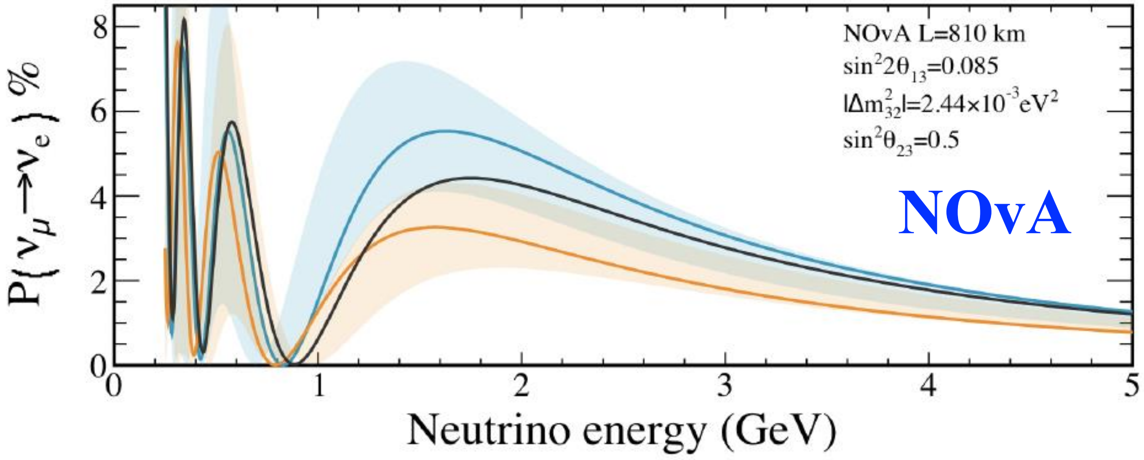
- Different energies and baselines
  - NOvA has larger E_ν and L than T2K
- Different detectors
  - T2K: water Cherenkov (FD) and tracking detector (ND)
  - NOvA: scintillator tracker (FD and ND)

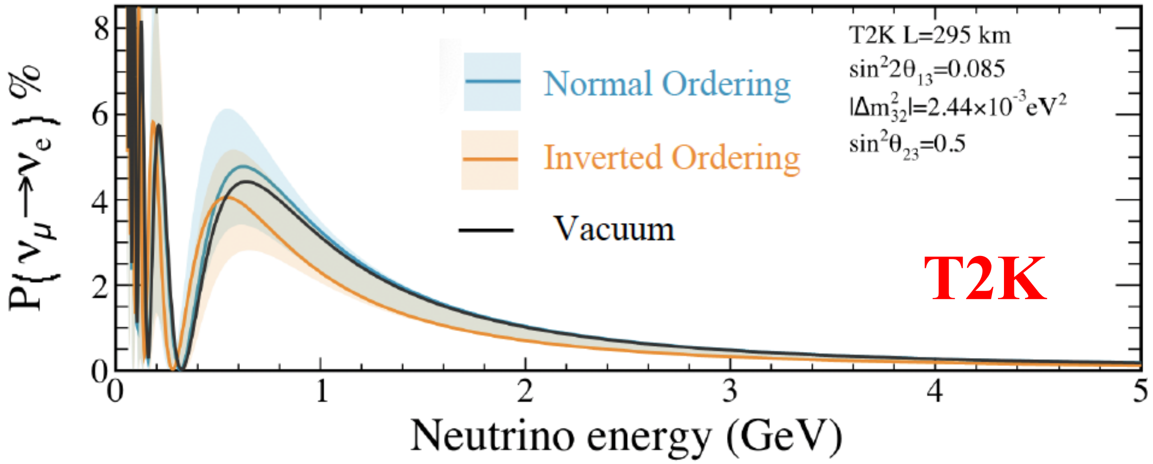
Joint analysis of T2K and NOvA (motivation)

- Different energies and baselines provide different oscillation probabilities for the same parameters (different degeneracies between mass ordering and δ_{CP})

- **NOvA (810 km)**
  - Better sensitivity to mass ordering due to longer baseline
  - Degeneracy for $\delta_{CP} = \pm 90°$ (CP violation hypothesis)

- **T2K (295 km)**
  - Better sensitivity to δ_{CP}
  - Degeneracy for $\delta_{CP} = 0°, 180°$ (CP conservation hypothesis)





→ Resolve the degeneracy by the T2K and NOvA joint fit

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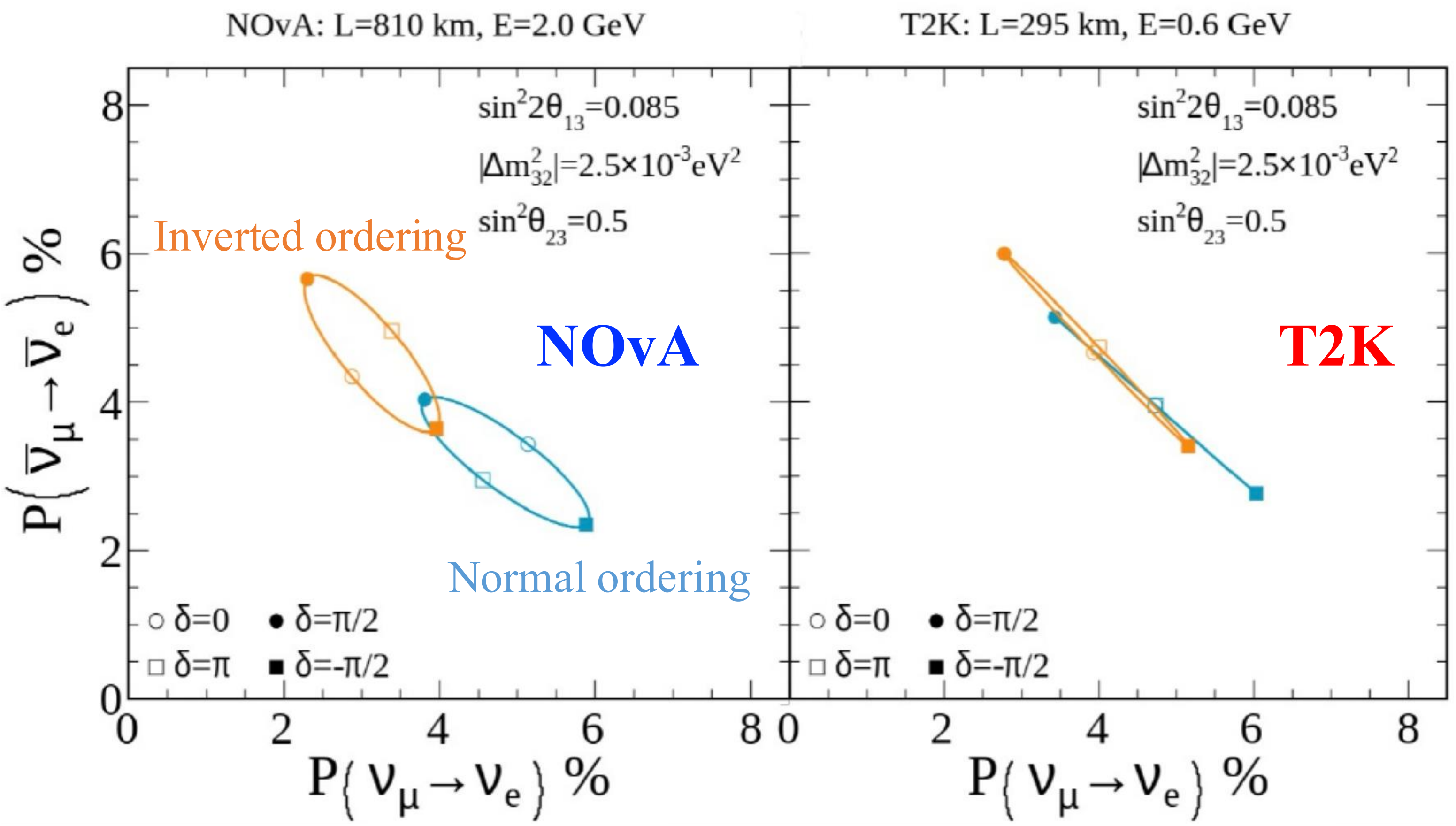
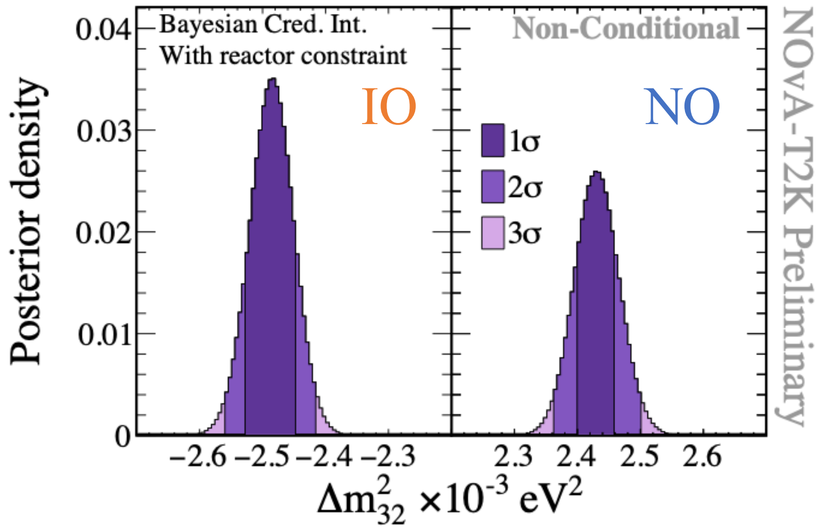


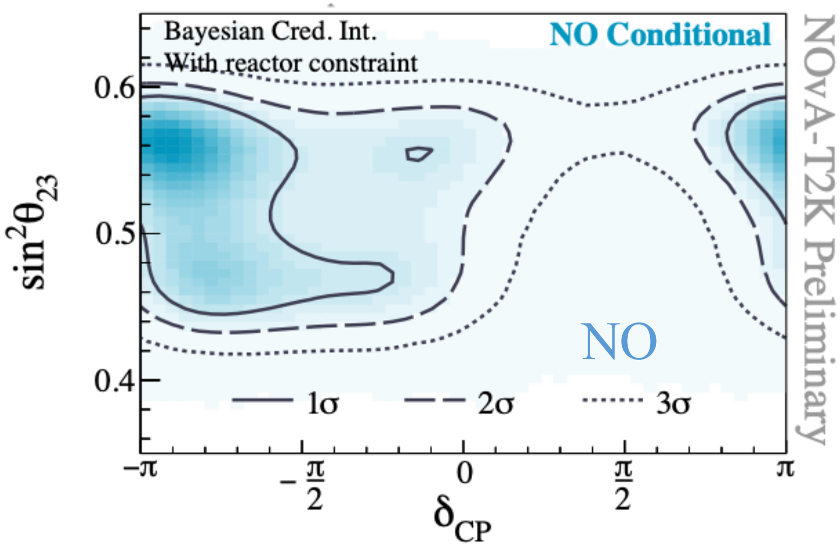
→ Resolve the degeneracy by the T2K and NOvA joint fit

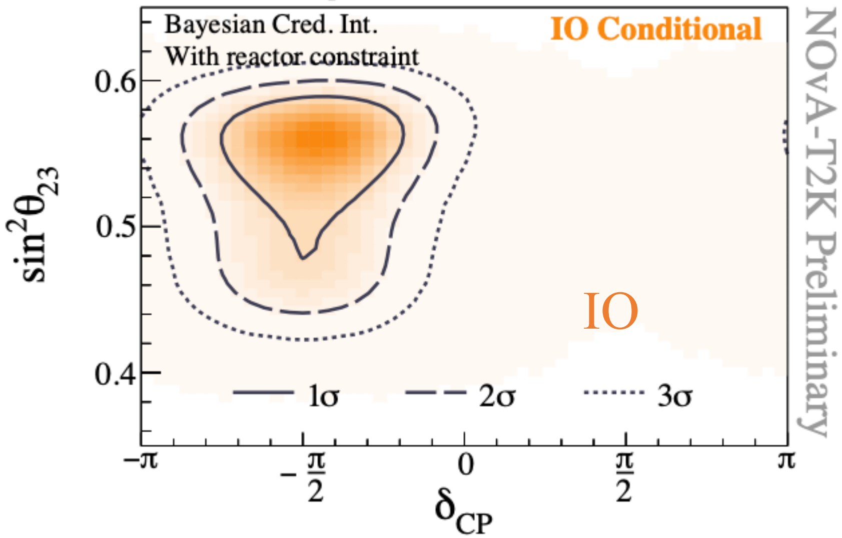
Results of T2K and NOvA joint oscillation analysis

- High precision for $|\Delta m^2_{32}|$
- No statistically significant preference for mass ordering
  - NO: Broad range of δ_{CP} allowed
  - IO: CP conserving values ($\delta_{CP} = 0°, 180°$) excluded at 3σ
- Joint fit agrees with individual fits from T2K and NOvA

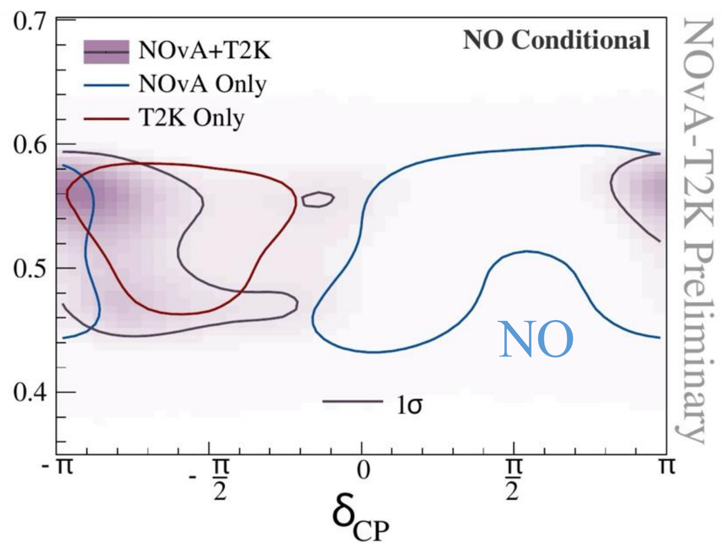


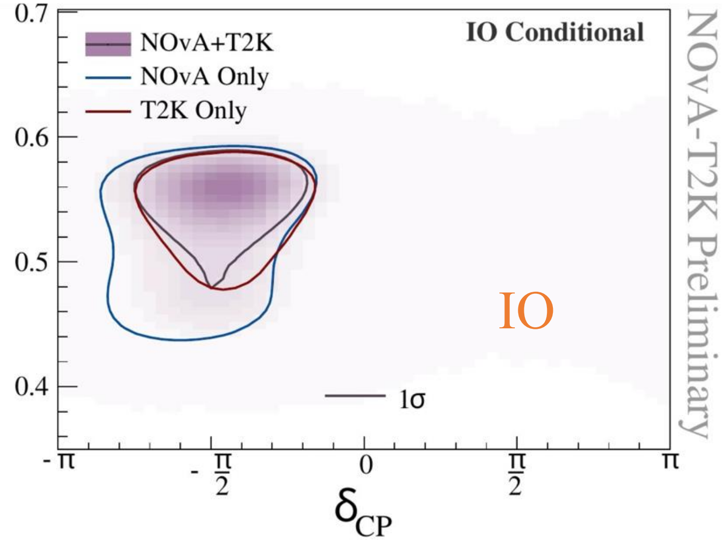
Results of T2K+NOvA joint fit





Consistency with each experiment

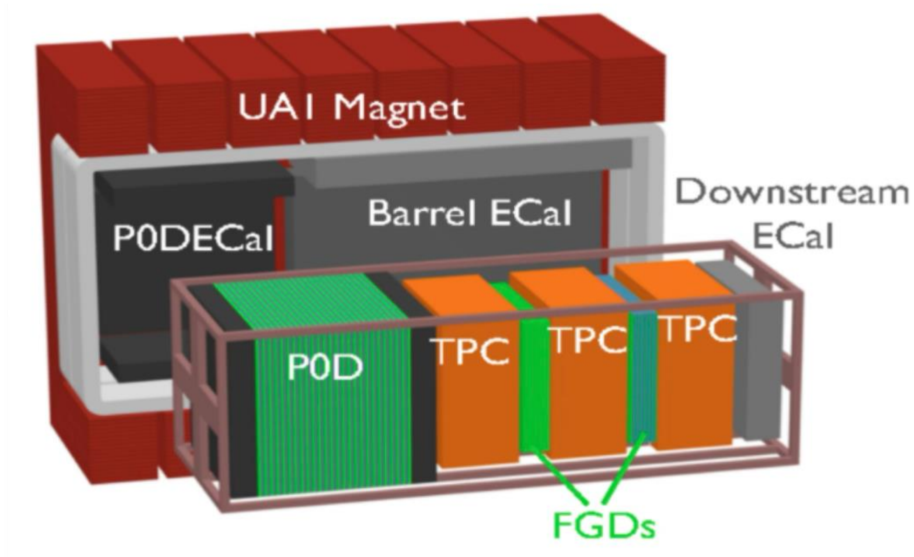




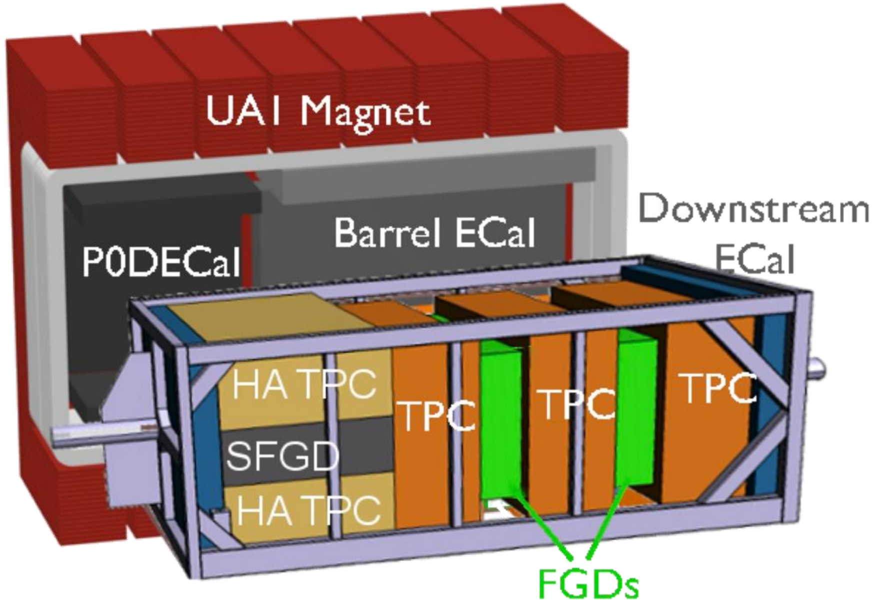
ND280 Near Detector Upgrade: Overview

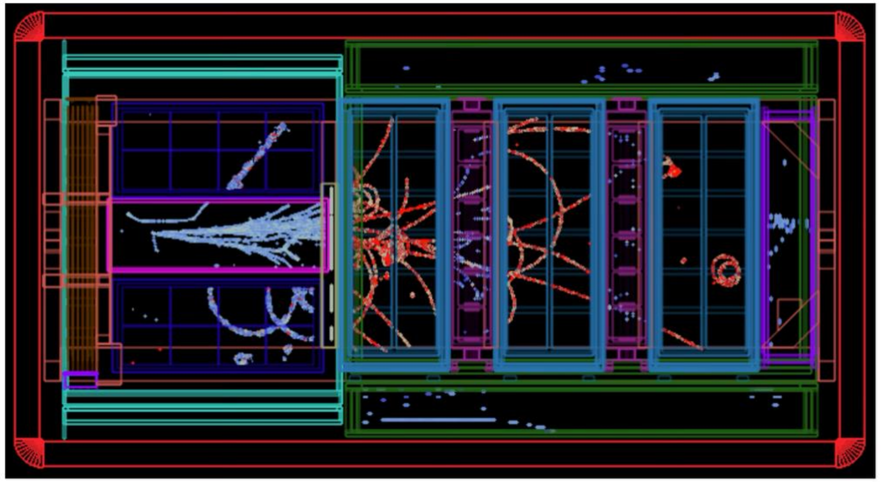
"T2K ND280 Upgrade - Technical Design Report" arXiv:1901.03750

2010-2022



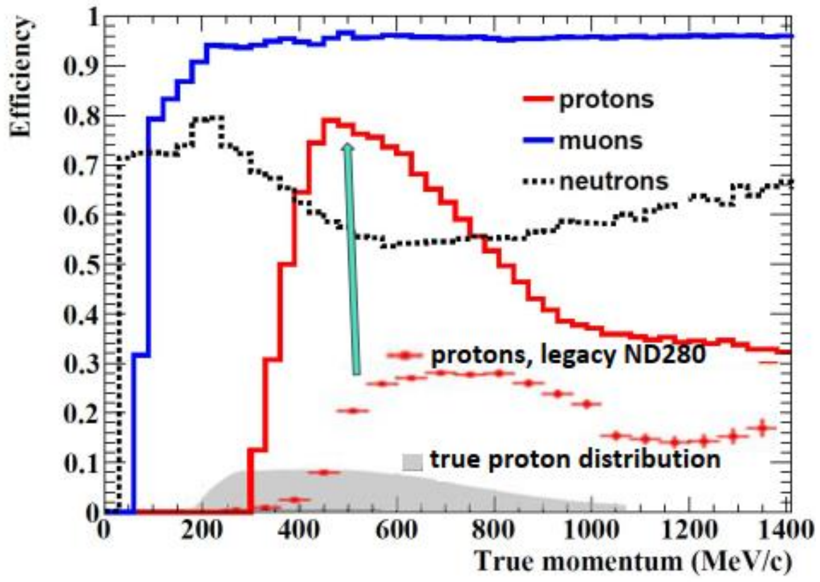
Completed in 2024



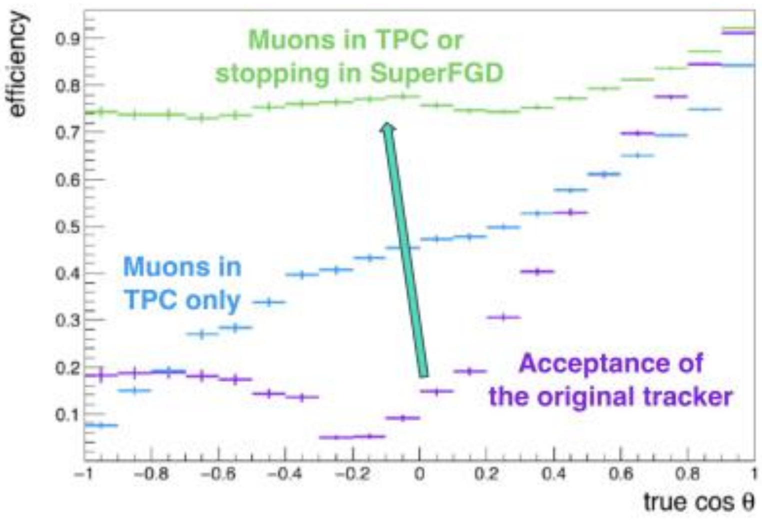


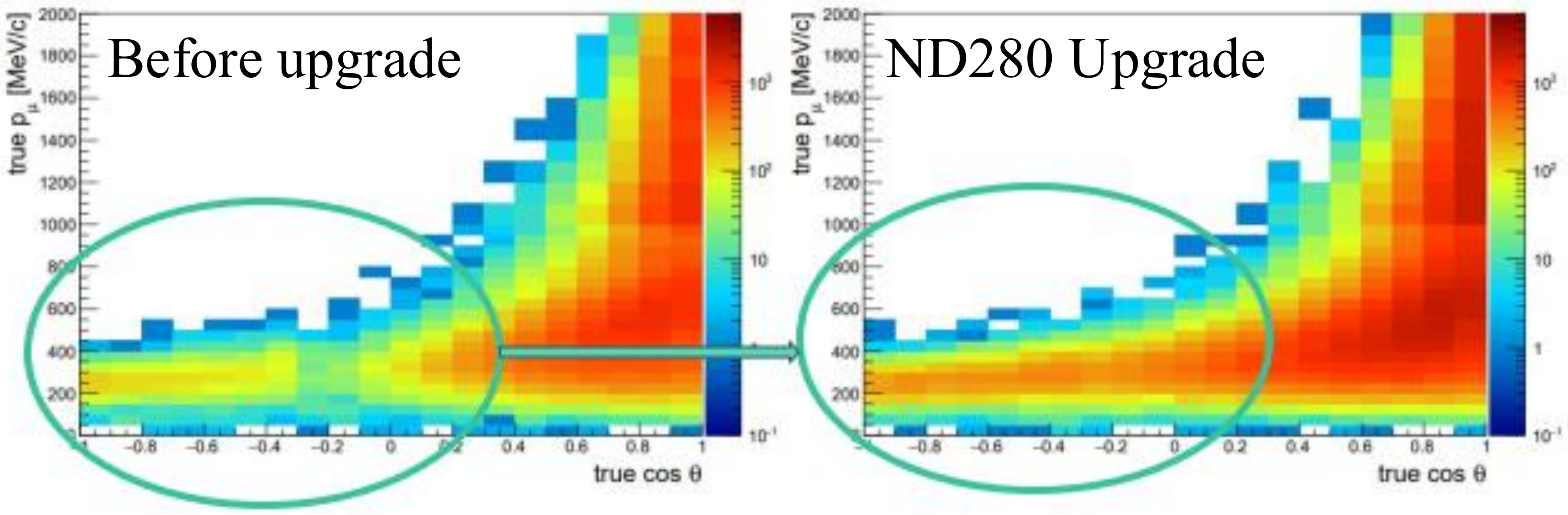
- POD detector replaced with Super FGD, 2 High Angle TPCs and Time of Flight
  - Improved acceptance and efficiency
  - Lower detection thresholds
  - Better sensitivity to neutrons
  - Larger neutrino target mass

ND280 Near Detector Upgrade: Performance



- Major improvements
  - Doubles the target mass for neutrinos with a much better granularity than FGD (Super FGD)
  - Detection of low momentum protons (Super FGD)
  - Acceptance for high angle muons (Super FGD, HA TPC) → Acceptance closer to SK (4π acceptance)
  - Measurement of neutrons kinematics (time of flight)





Summary

- **Beam power reached 830 kW, further upgrade for 1.3 MW beam is planned**
- **Updated T2K oscillation analysis with 10% more data in neutrino mode**
  - CP conserving values excluded at 90% CL
  - Preference for normal mass ordering and upper octant of θ_{23}
- **Joint analysis of T2K and Super-Kamiokande**
  - CP conserving value of the Jarlskog invariant is excluded at 1.9σ - 2.0σ
  - Preference for normal mass ordering
- **Joint analysis of T2K and NOvA**
  - No clear preference for mass ordering
  - Broad range of δ_{CP} allowed for NO while CP conserving values outside of 3σ for IO
  - Improved precision for $\left|\Delta m^2_{32}\right|$ (better than 2%)
- **ND280 upgrade has been completed in 2024**
  - T2K analysis will be updated with new near and far detector data
  - Improvement of the cross-section measurement is expected