Latest Neutrino Oscillation Results from T2K and NOvA

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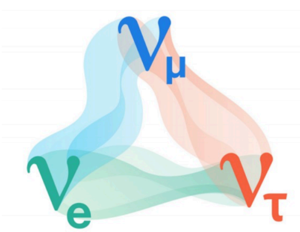
Neutrino Oscillation

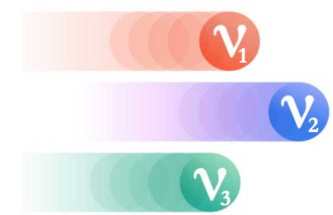
- Flavor of neutrino $(\nu_e, \nu_\mu, \nu_\tau)$ changes periodically as it propagates.
- Described by mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$, mass squared differences $(\Delta M^2_{32}, \Delta M^2_{21})$, and CP phase δ_{CP}.



Flavor Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix



Mass Eigenstates

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

Measurement: $\theta_{12} \sim 34^\circ$ $\theta_{13} \sim 8.5^\circ$ $\theta_{23} \sim 45^\circ$

Precision: $\sin^2\theta_{12} \sim 4\,\%$ $\sin^2\theta_{13} \sim 3\,\%$ $\sin^2\theta_{23} \sim 5\,\%$

Neutrino Oscillation

- The goal of Long Baseline neutrino experiments:

✓ Remaining problems: CP symmetry, Mass ordering, Octant of θ_{23}

✓ Precise measurements of θ_{23}, $|\Delta m^2{}_{31}|$ ($\sim |\Delta m^2{}_{32}|$)

Muon neutrino disappearance ($\nu_\mu \to \nu_\mu$) :

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

Sensitive to:

θ_{23}, $\left|\Delta m^2{}_{31}\right| \left(\sim \left|\Delta m^2{}_{32}\right|\right)$

Electron neutrino appearance ($\nu_\mu \to \nu_e$) :

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1 + \frac{2a}{\Delta m^2_{31}}\left(1 - 2\sin^2\theta_{13}\right)\right)$$

$$- \sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

Sensitive to:

θ_{13}, δ_{CP}, θ_{23}, and

Mass ordering $\Delta m^2{}_{31}$

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$: δ turns into – δ and a to -a ("a" matter effect term)

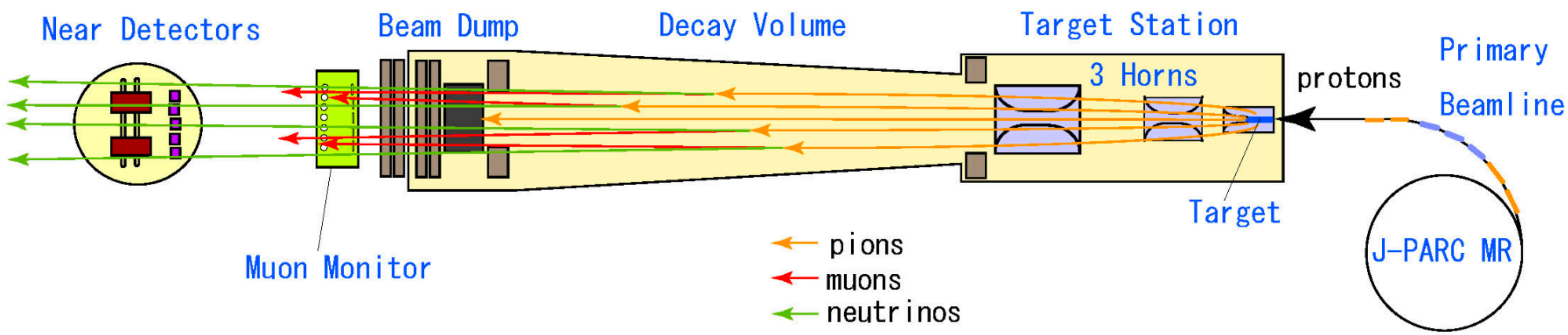
T2K and NOvA

Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak ν energy	0.6 GeV	2 GeV
Matter effect	9%	29%
CP effect*	32%	22%

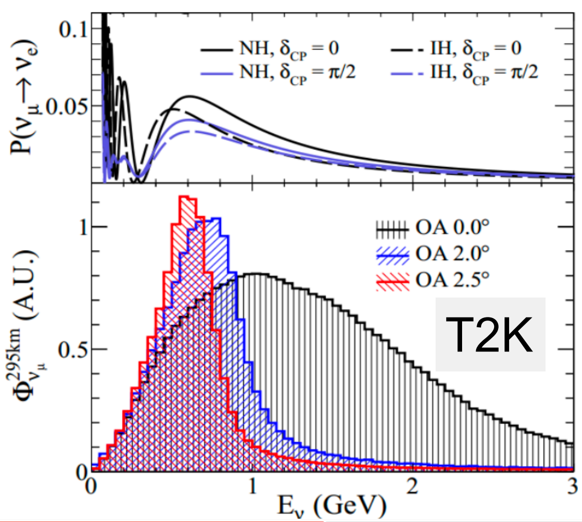
*Minimum difference of $\sin(\delta_{CP}) = 0$ and ± 1, for $[P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)]_{\text{CP}}$

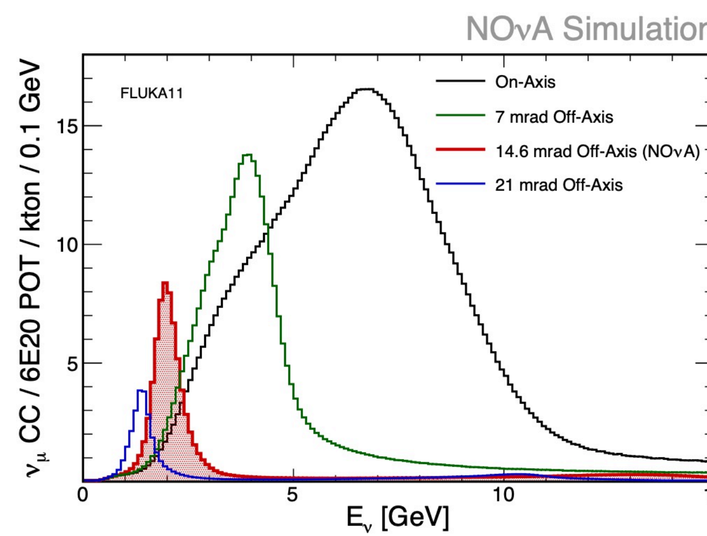
Neutrino Beam

- Proton beam from accelerators on graphite target produces pions.
- Can switch from ν_μ beam to $\bar{\nu}_\mu$ beam by inverting the horn polarities



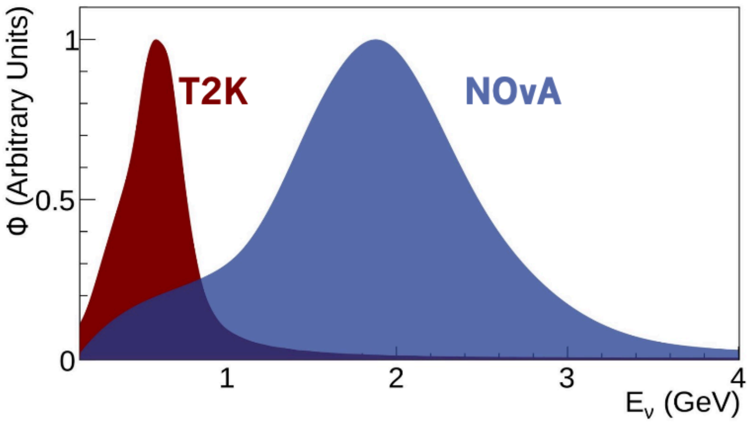
- Off-axis method to produce narrowband neutrino beam and maximize oscillation.

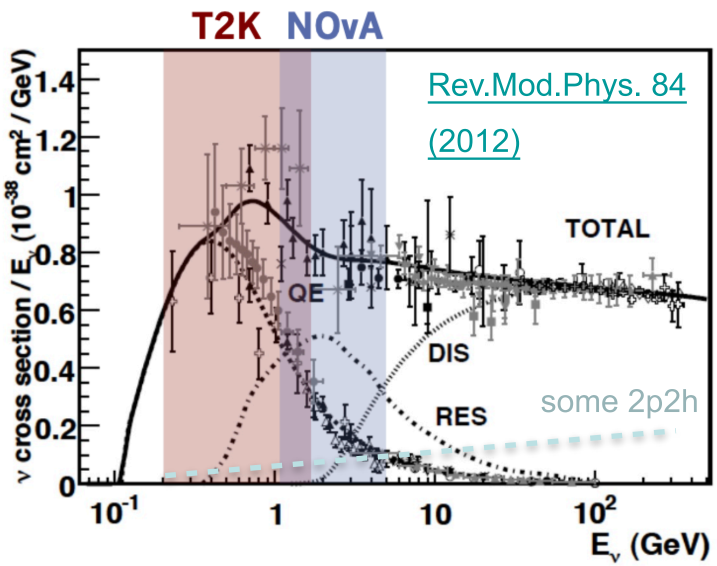


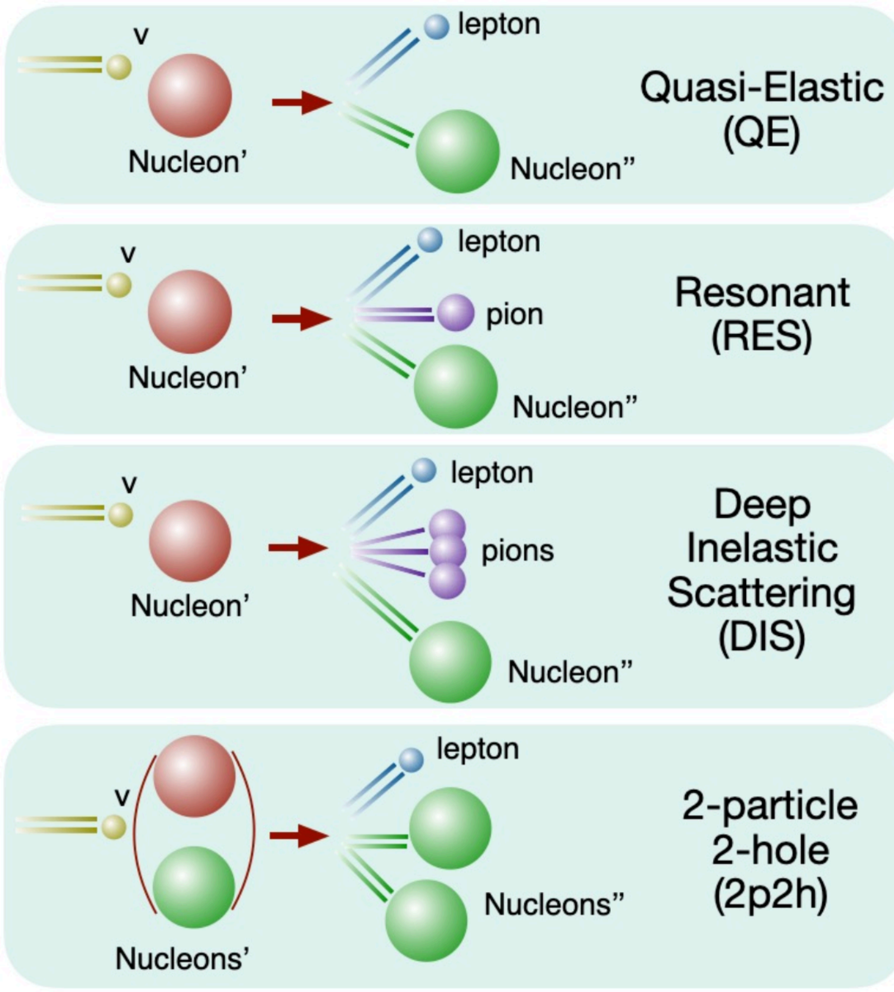


T2K and NOvA

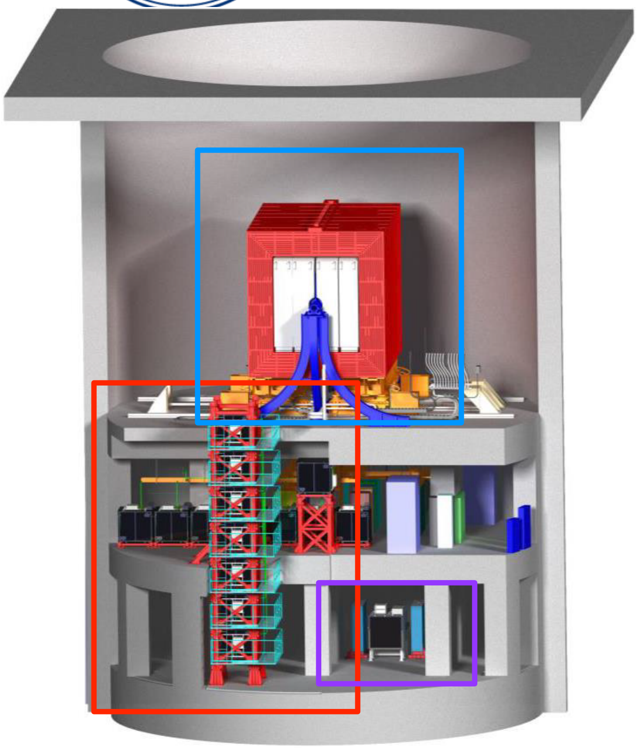
Neutrino flux

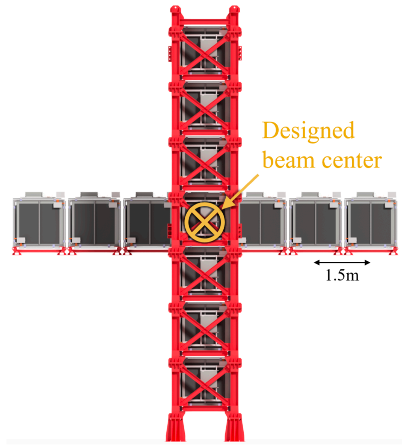




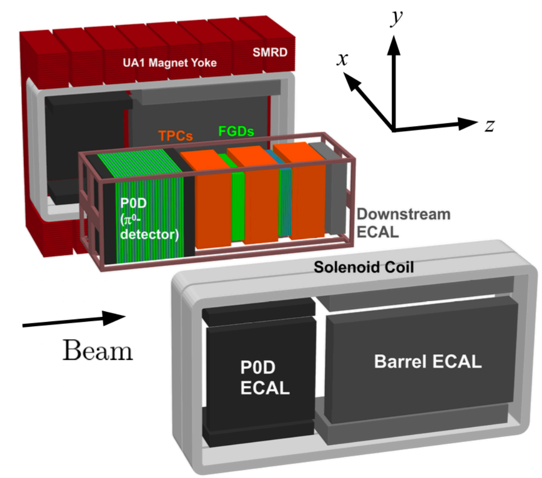


Near Detector in T2K

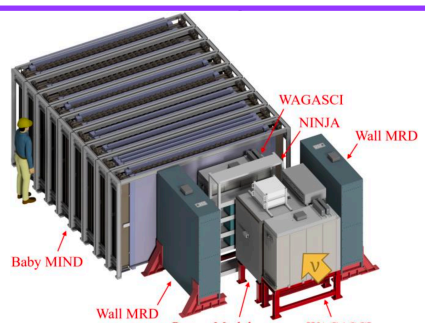




- INGRID (on-axis detector)
- 14 identical detectors arranged in a cross shape.
- Monitor beam direction and intensity



- ND280 (2.5° off-axis detector, same as SuperK)
- Magnetized (0.2T) complex detector
- Water and CH targets (2000 kg mass)
- Constrain cross-section and flux uncertainty model



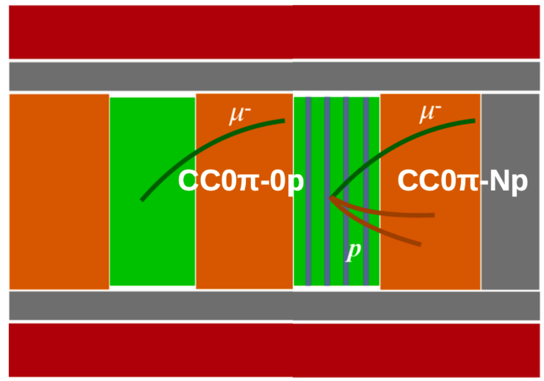
- WAGASCI-BabyMIND (1.5° off-axis detector)
- New detector installed in 2019
- Measure cross section for higher-energy neutrinos

Near Detector in T2K

- Select ν_μ or $\bar{\nu}_\mu$ CC interactions from FGDs.
- Separate events by target and observed particles ($\pi^\pm, \gamma$, p).
- Fitting gives tuned nominal values and constrained uncertainties for flux and interaction.

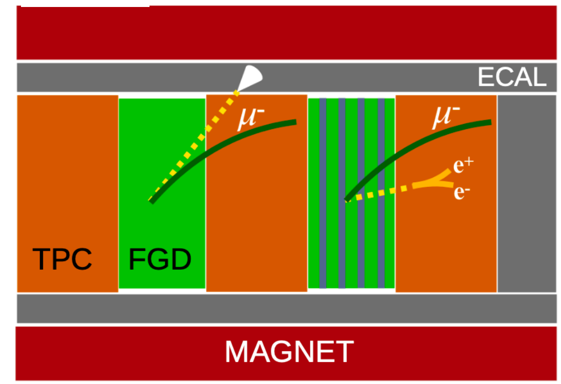
Sample separation by proton

Constrain CCQE and 2p2h models

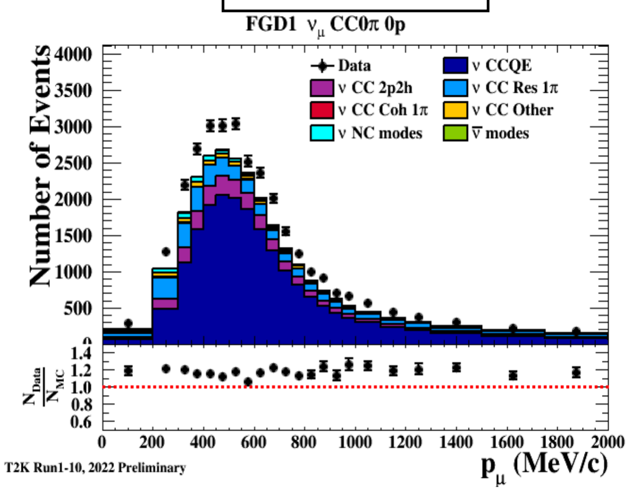


Sample separation by photon

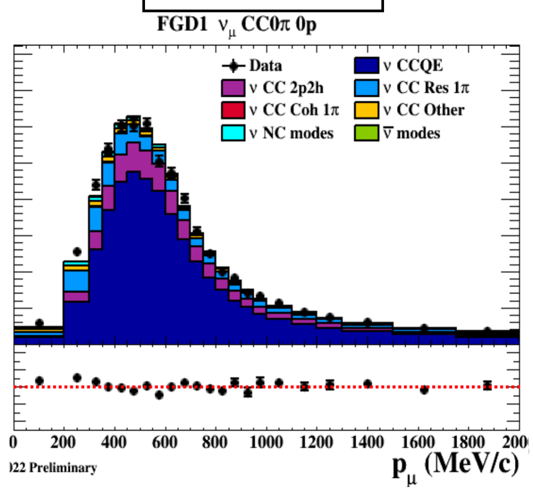
Creates new samples dominated by DIS and CCπ^0



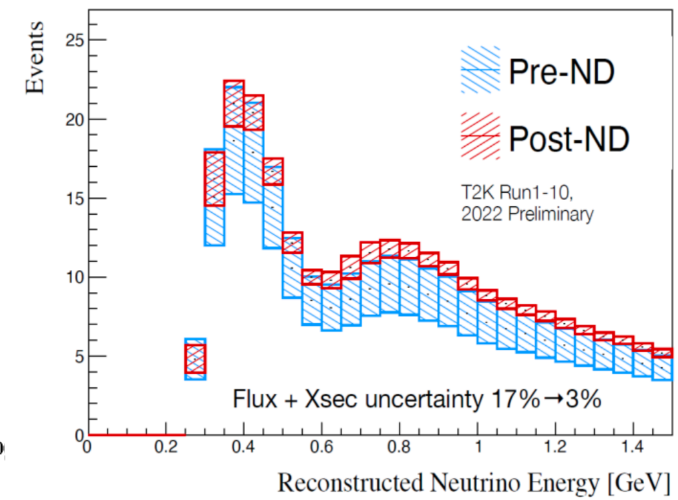
Before Fitting



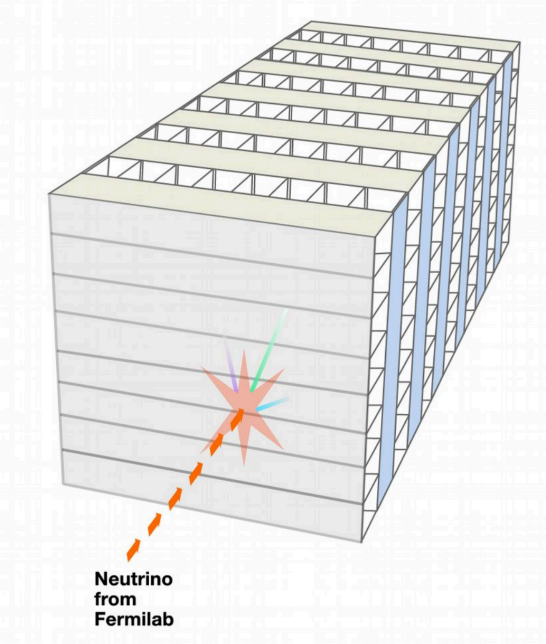
After Fitting

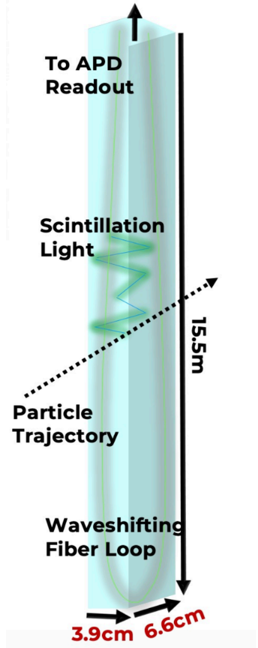


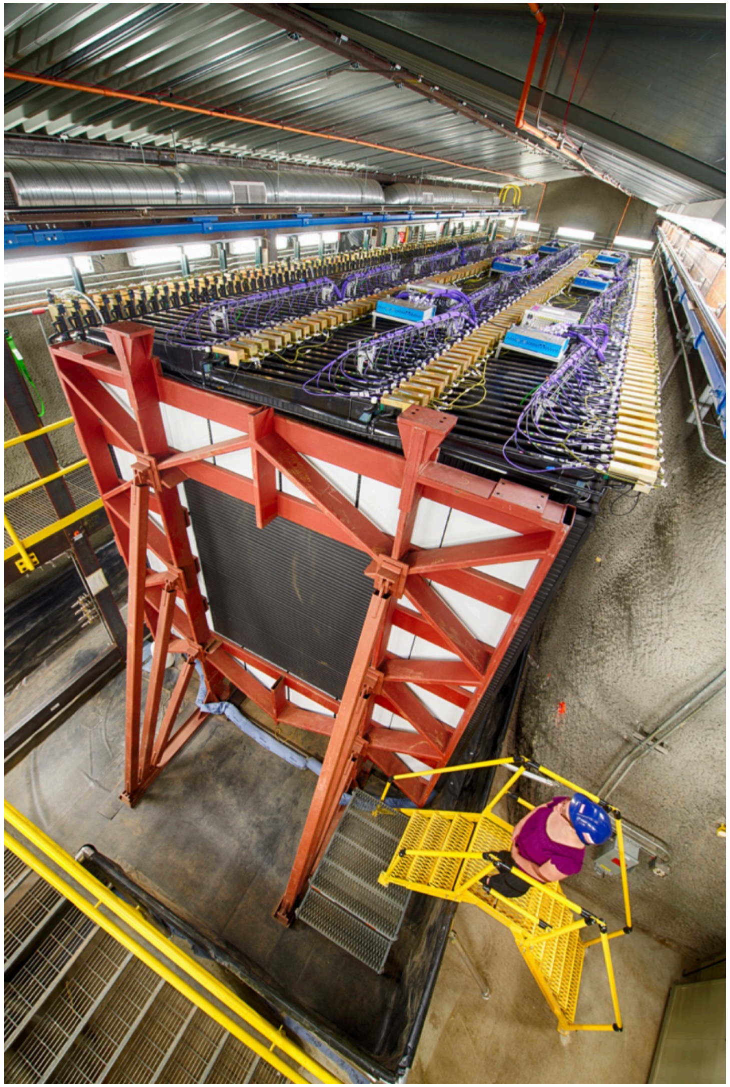
Systematic error for Super-K events



Near Detector in NOvA



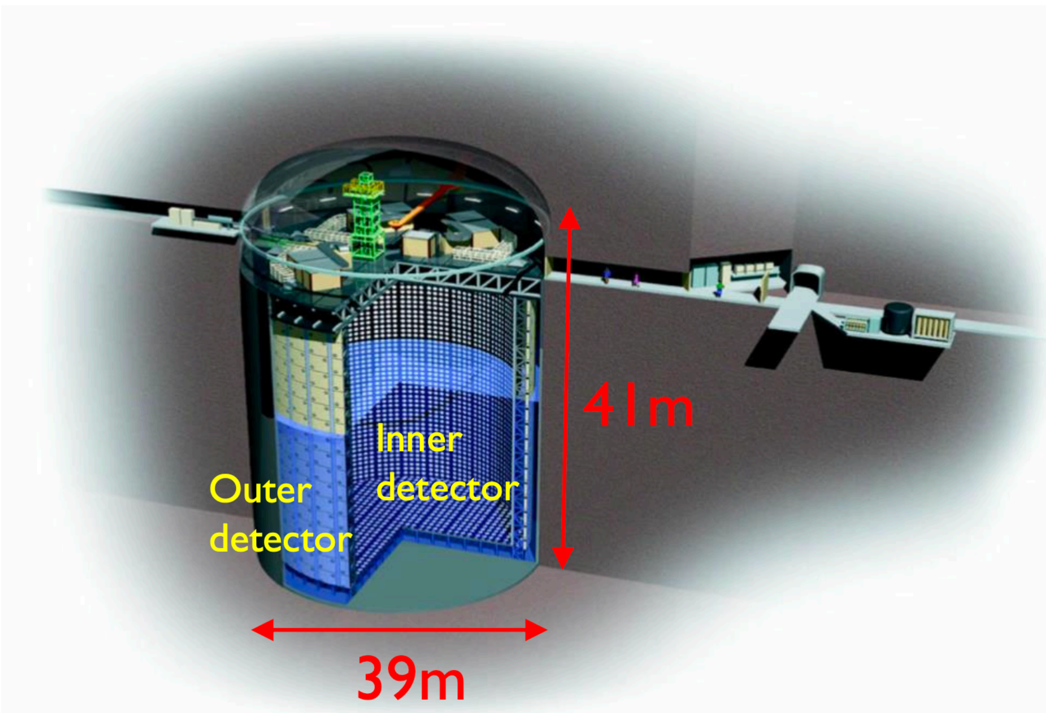


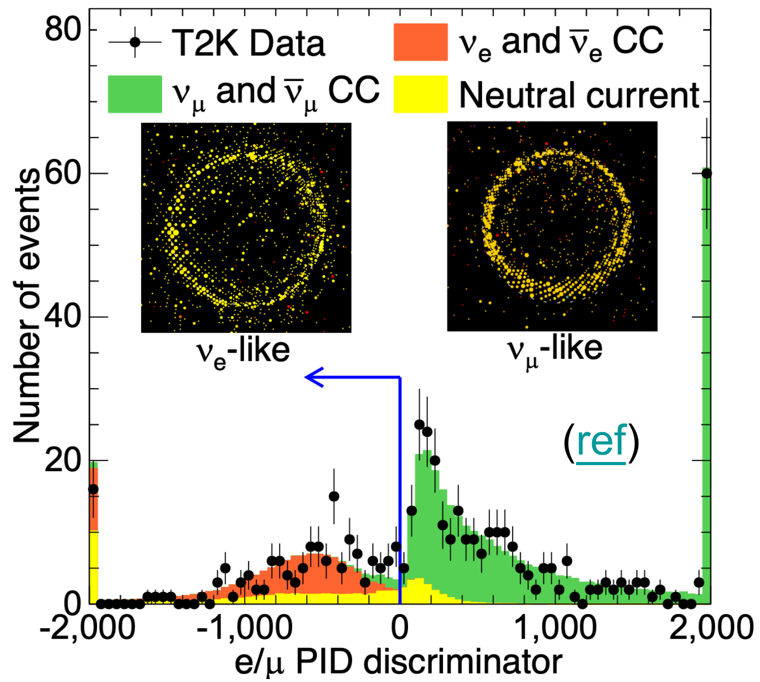


- Segmented liquid scintillator detectors
  - Tracking calorimeter
- Functionally identical to far detector
- 300 tons, 1 km from target
- Huge statistics: >1M ν_μ CC selected events

Far Detector in T2K

- 50kt water Cherenkov detector having ~11,000 20 inch PMTs.
- Good separation of $e^{\pm}$ and $\mu^{\pm}$ → Separate ν_e and ν_μ CC interactions.
- Only sees photons and charge particle above Cerenkov threshold



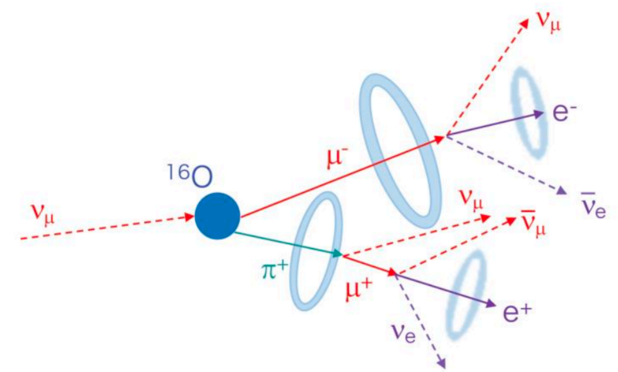


Less than 1% mis-PID at 1 GeV for single ring events

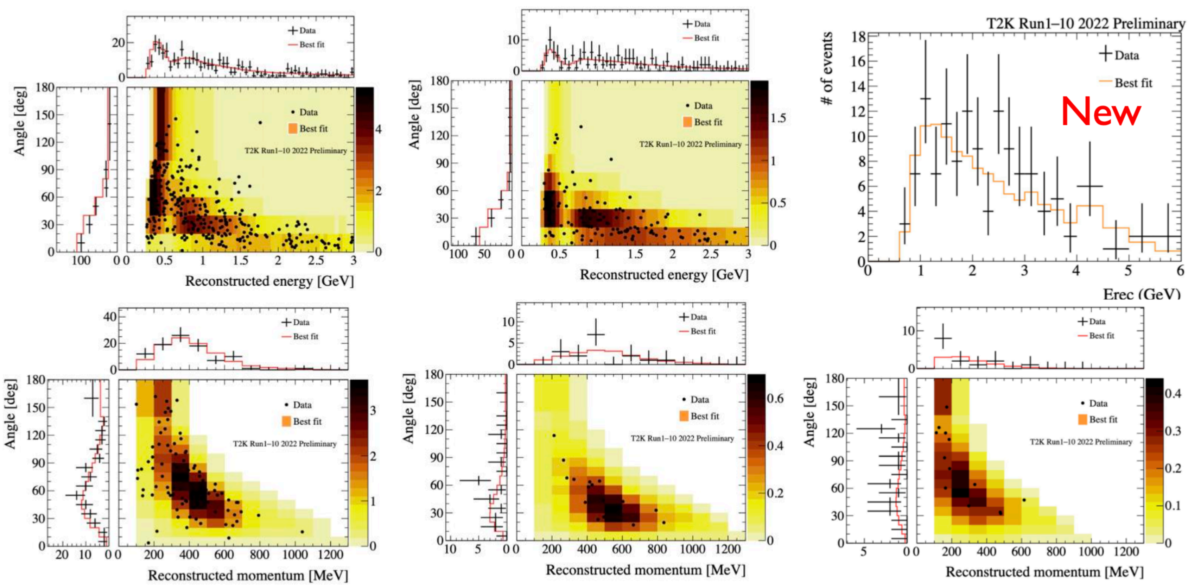
Far Detector Data in T2K

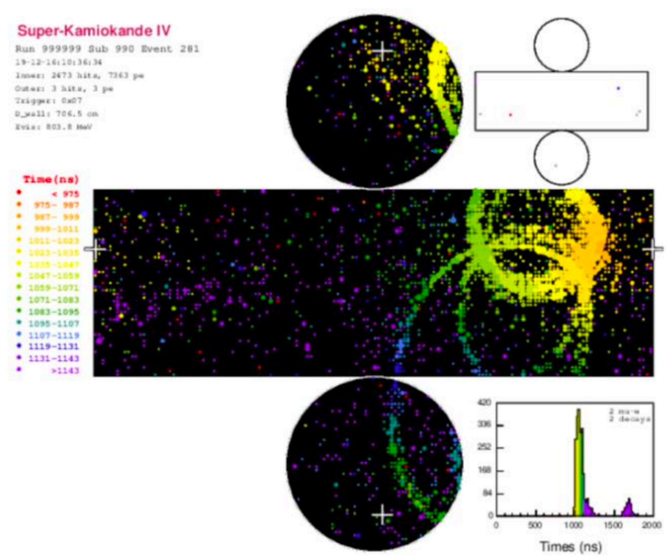
- New analysis adds a far detector sample targeting ν_μ CC1π^+ interactions in ν-mode
- Increase ν-mode μ-like statistics by ~30%
- Sensitive to oscillations, but higher energy than nominal μ-like sample

New samples: Combination of 1Rμ + 2 M.e and 2 rings events



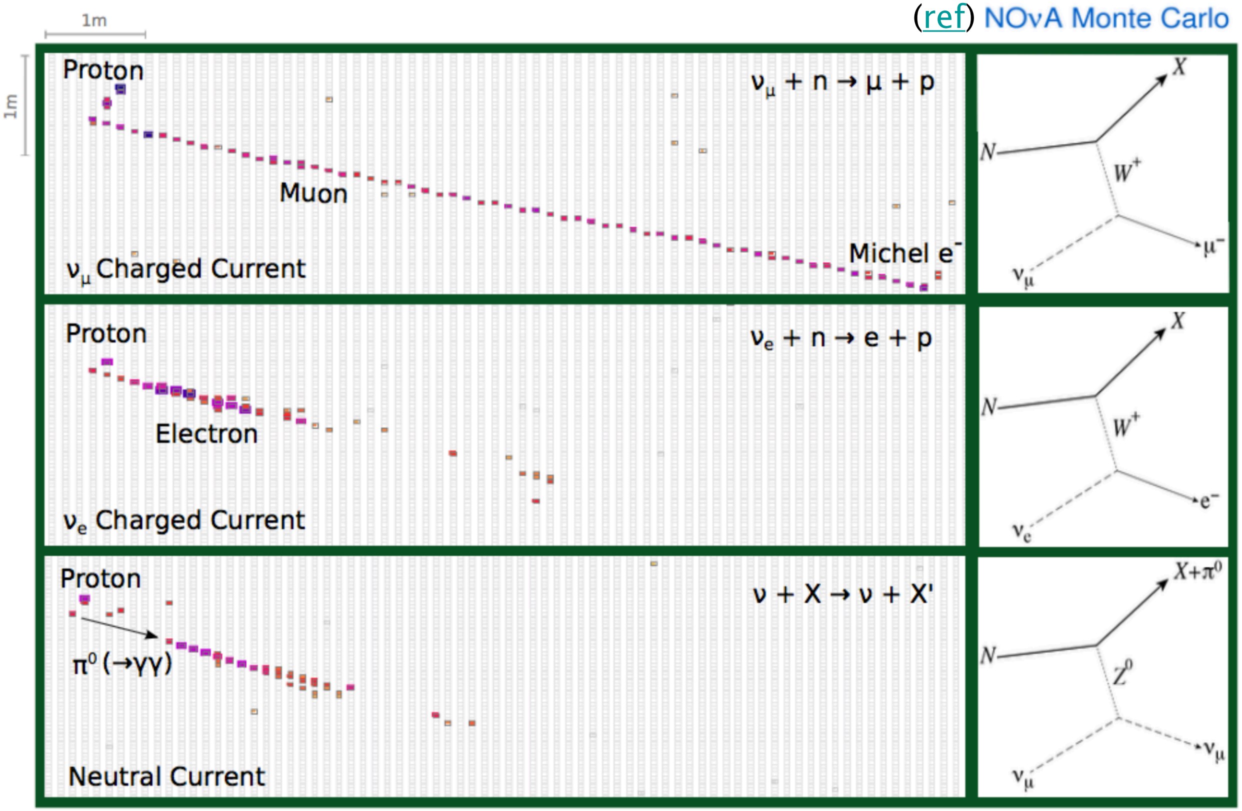
6 samples at Super-Kamiokande selected based on beam mode and PID





Far Detector in NOvA

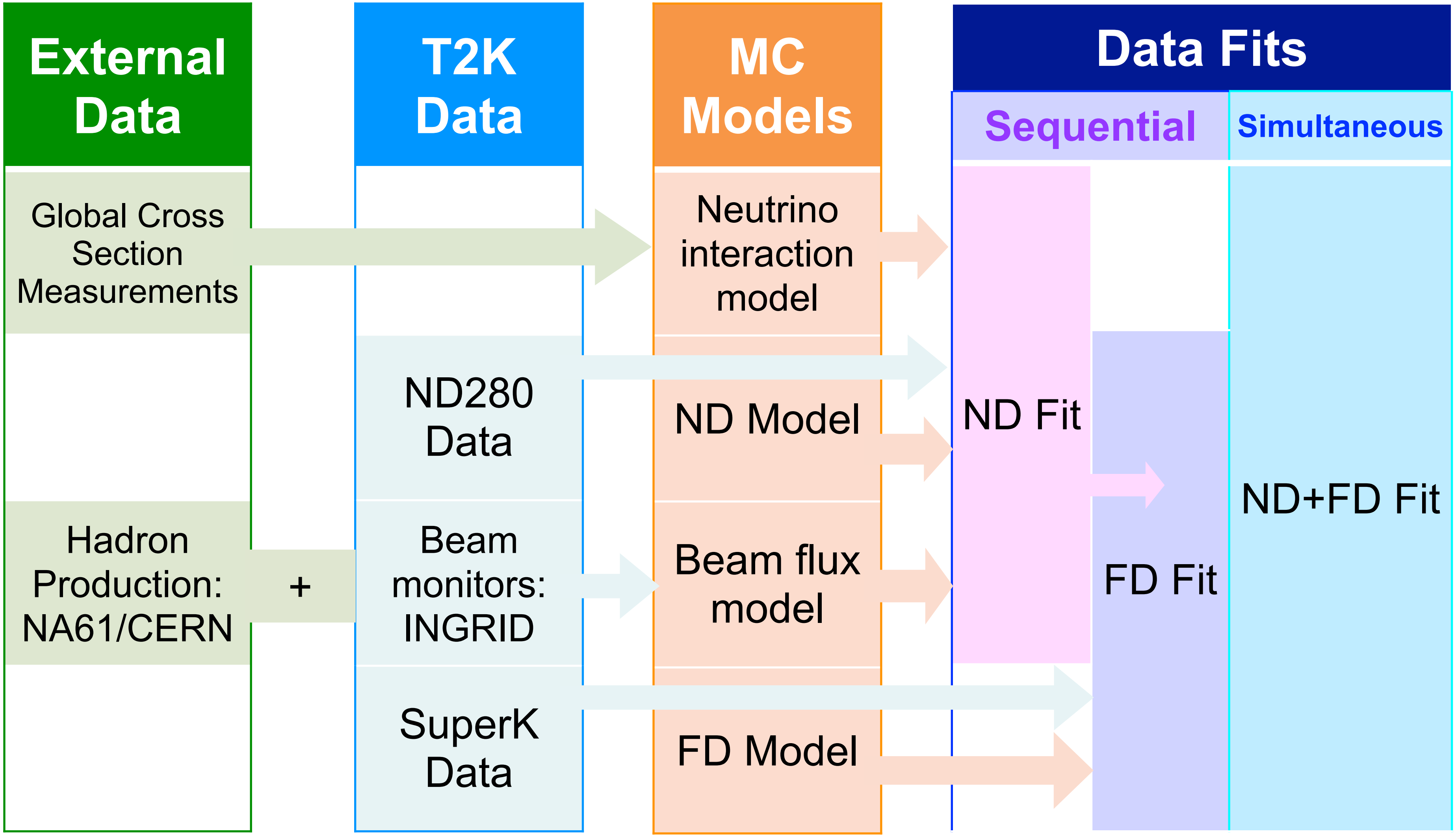
(ref) NOvA Monte Carlo



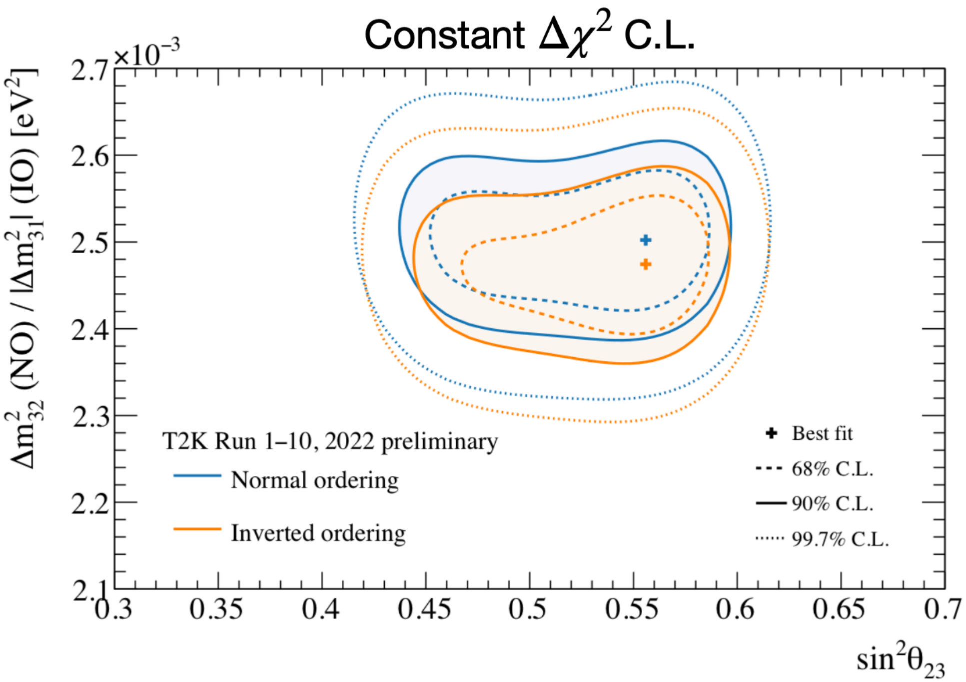
- Far detector: 14 kton, with 344k cells
- Event features:
1. ν_μ CC events: long, low dE/dx track indicative of a minimally ionizing muon
2. ν_e CC events: shorter, broader electromagnetic shower
3. NC events: the hadronic component is the only signature

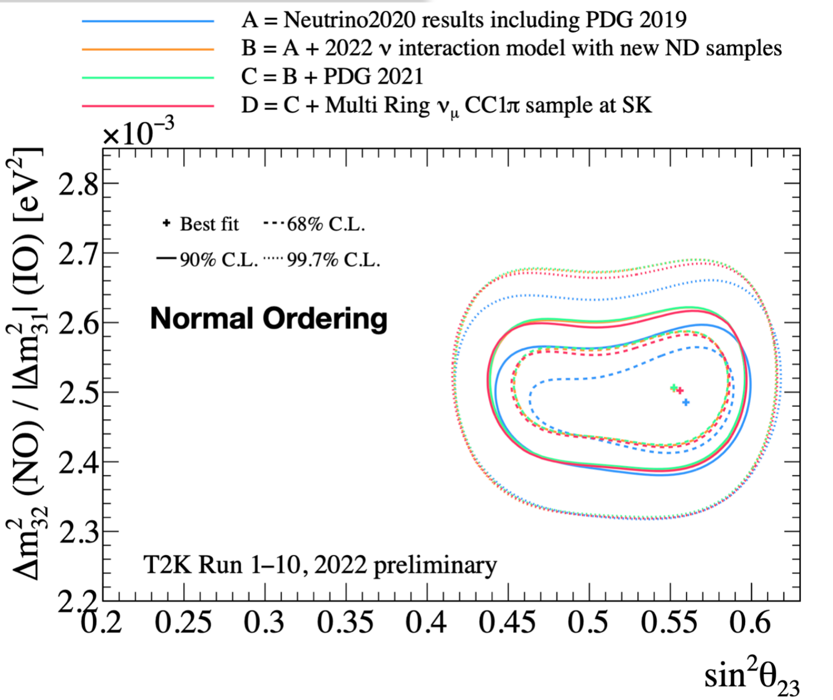
- Neutrino flavor Identification: using a convolutional neural network in the image recognition style.
- Performance relative to preselection: ν_μ: ~90% efficiency, 99% bkg. rejection
  ν_e: ~80% efficiency, 80% bkg. rejection

Oscillation Analysis Strategy



Atmospheric Mixing Parameters (T2K)

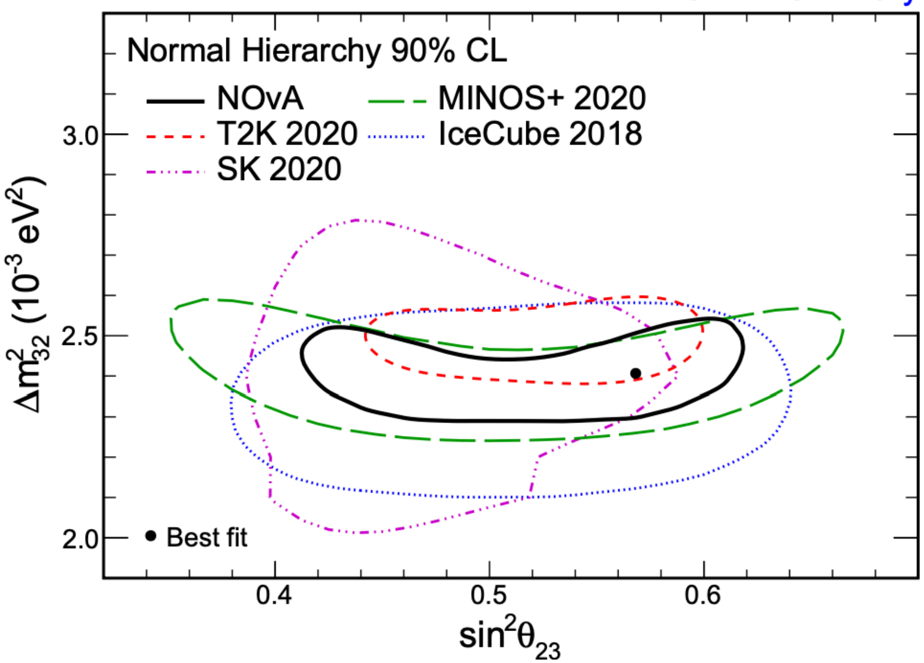




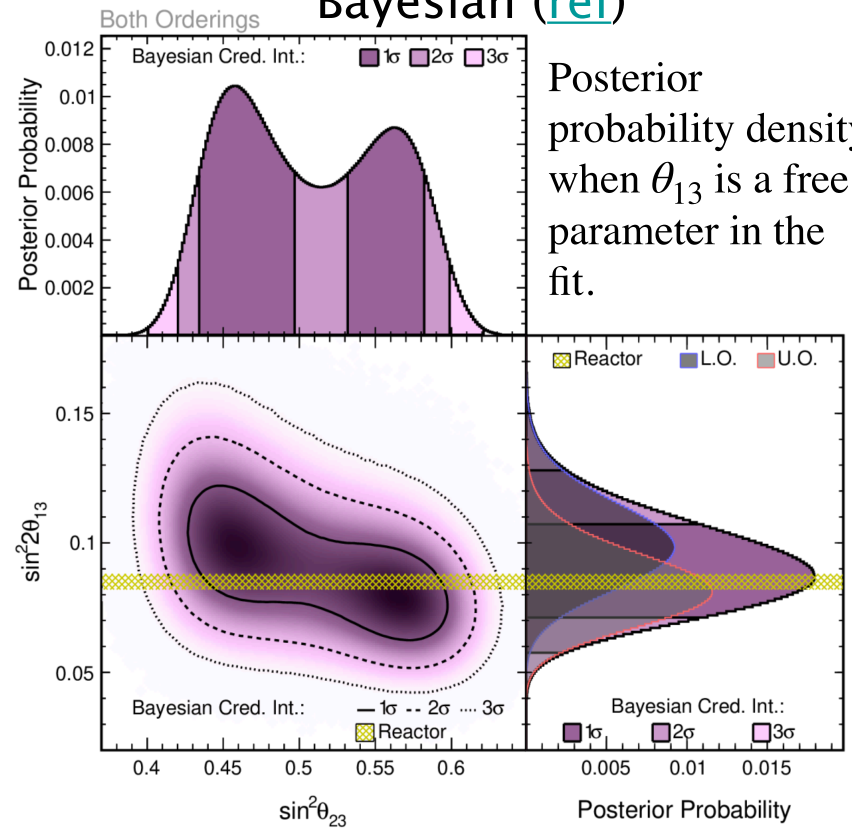
- Prefer upper octant ($\sin^2\theta_{23} > 0.5$), while the lower octant included within 68% C.L.
- Difference from Neutrino2020 results mainly comes from the updated interaction model and new ND samples
  - Improved uncertainties for SF model
  - Additional uncertainty for resonance and muti-pion events, as well as FSI.
- New multi-ring μ-like CC1π sample in SK has a marginal impact due to its relatively higher energy above the oscillation maximum

Atmospheric Mixing Parameters (NOvA)

Frequentist (ref)



Bayesian (ref)

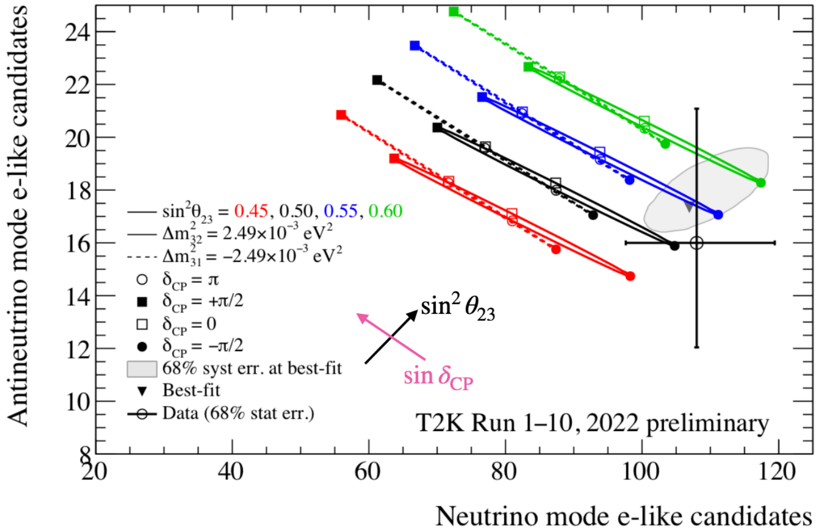


Posterior probability density when θ_{13} is a free parameter in the fit.

- The $\Delta m^2_{32} \times \sin^2\theta_{23}$ contours show consistency among atmospheric and accelerator neutrino oscillation experiments.

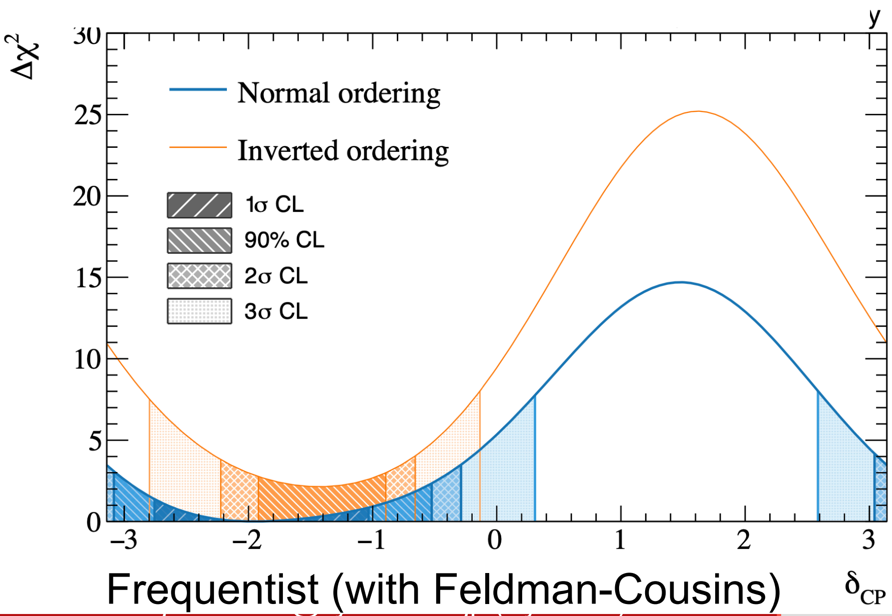
- Prefer lower octant if θ_{13} is larger
- Higher preference for the upper octant with the reactor constraint

Constraint on δ_{CP} (T2K)

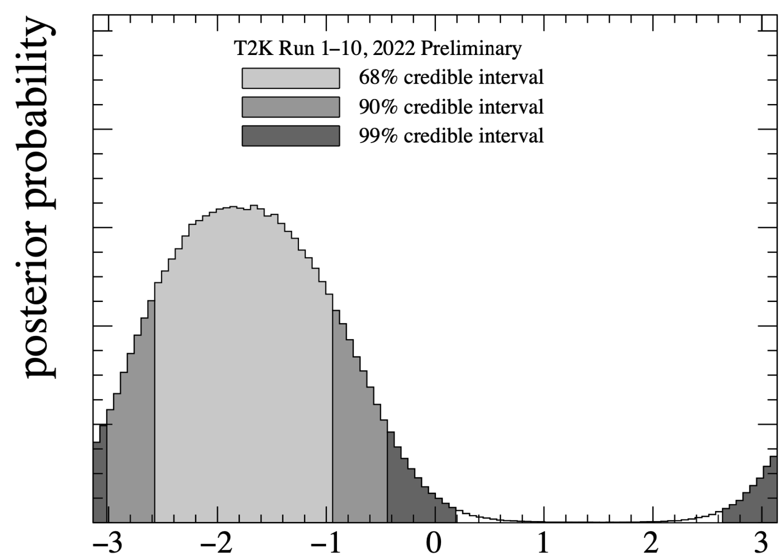


- Asymmetry from oscillation for appearance of ν_e and $\bar{\nu}_e$
- Weak preference of normal ordering
- Large region around $\delta_{CP} = \pi/2$ excluded at 3σ
- CP-conservation (δ_{CP} = 0 or π) excluded at 90%

Using θ_{13} constraint from reactor experiments: $\sin^2(2\theta_{13}) = 0.0861 \pm 0.0027$



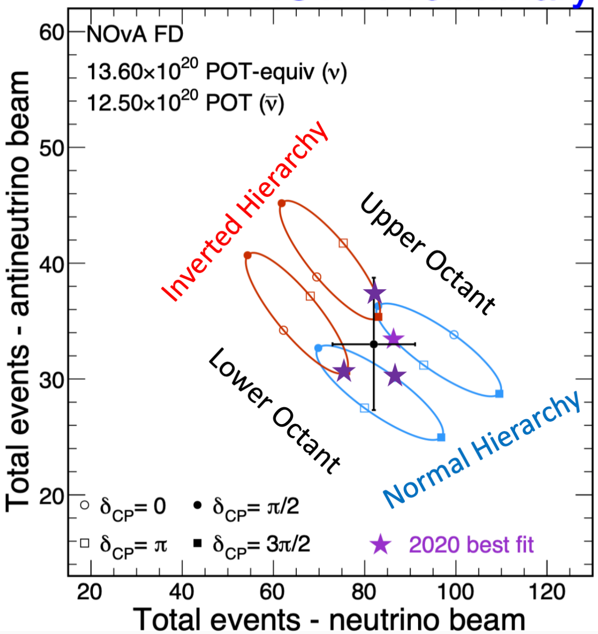
Frequentist (with Feldman-Cousins)



Bayesian (Marginalized over MO)

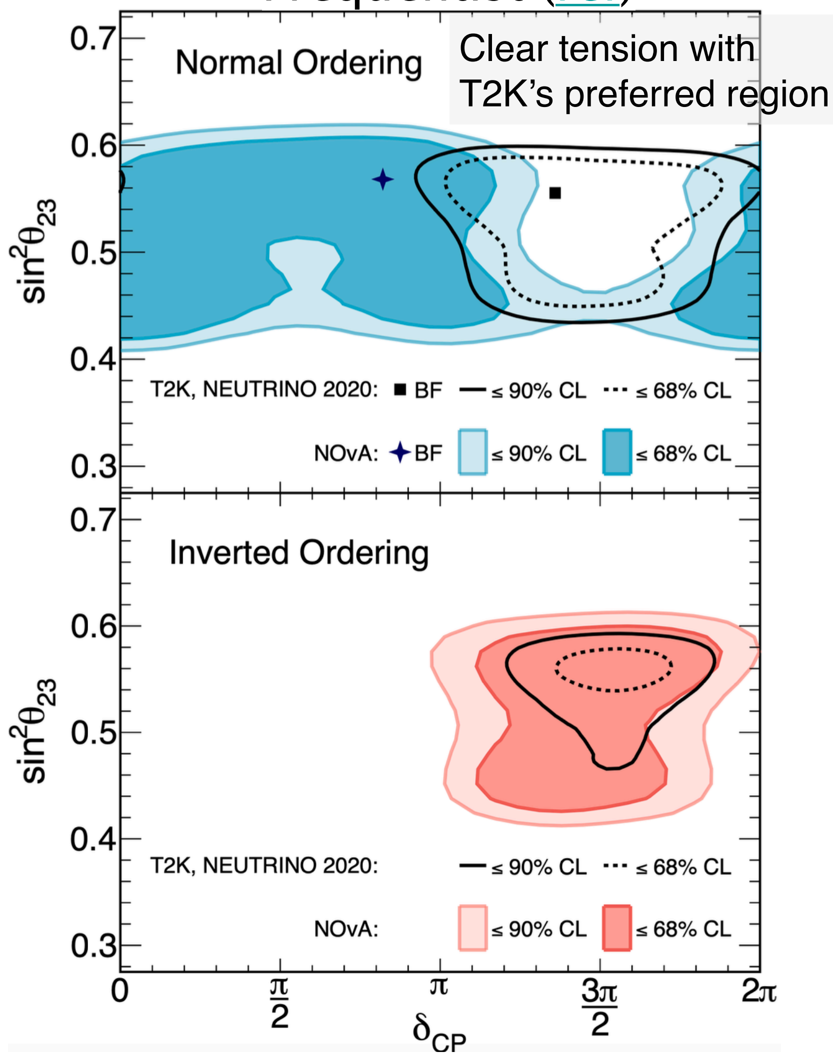
Constraint on δ_{CP} (NOvA)

NOvA Preliminary



- No strong asymmetry from oscillation for appearance of ν_e and $\bar{\nu}_e$
- Clear tension with T2K's preferred region

Frequentist (ref)

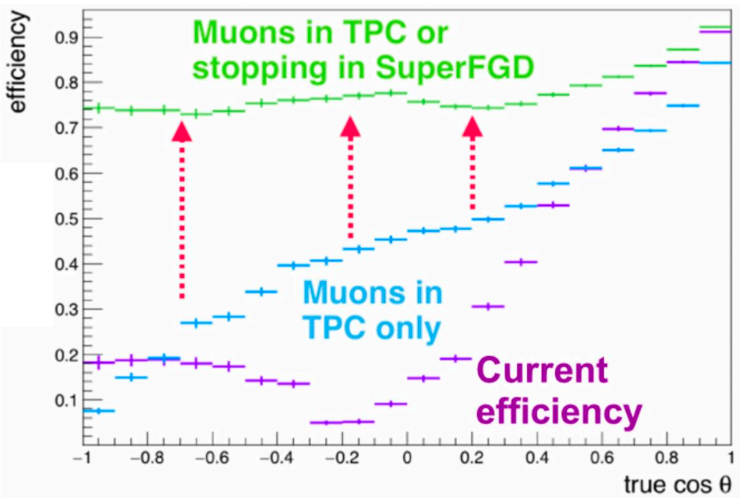


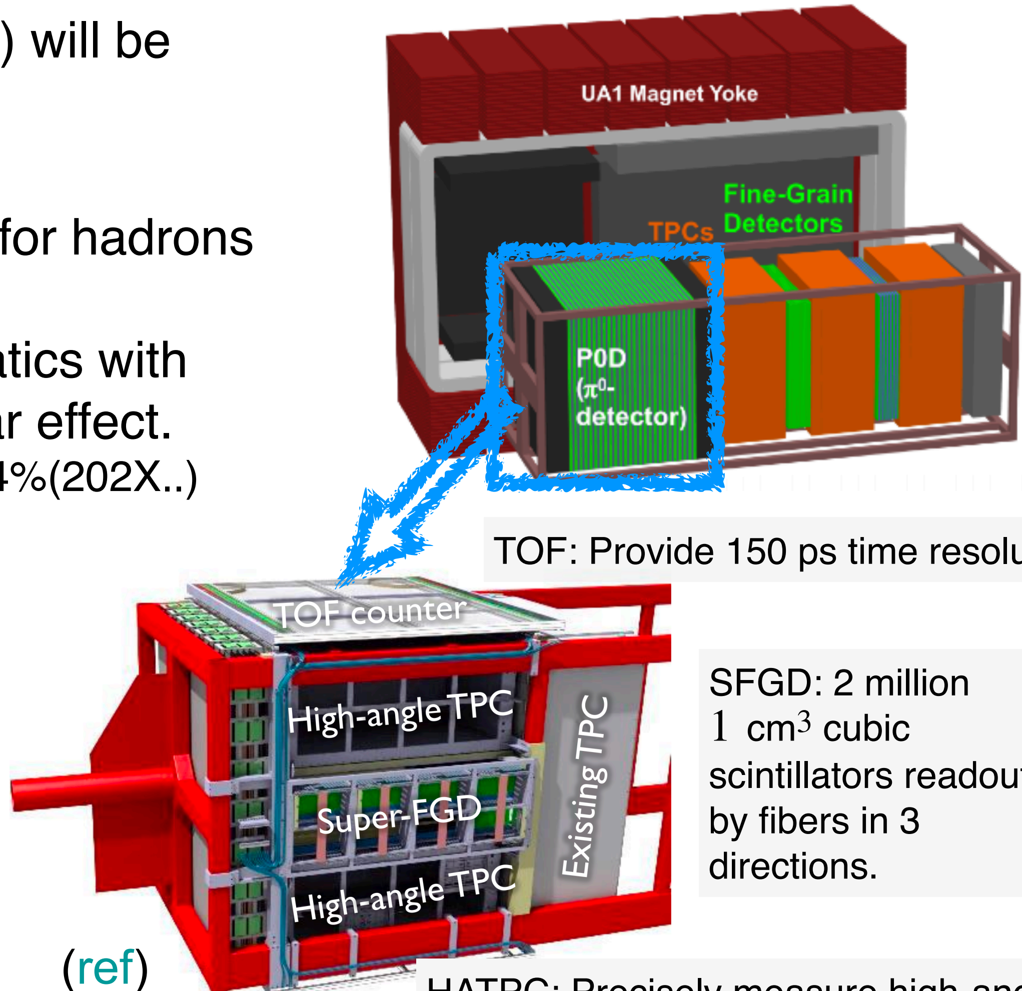
Best-fit result:

- $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3} \mathrm{eV}^2$
- $\sin^2\theta_{23} = 0.57^{+0.04}{}_{-0.03}$
- exclude IH, $\delta = \pi/2$ at $> 3\sigma$
- disfavor NH, $\delta = 3\pi/2$ at $\sim 2\sigma$

Outlook

- Upstream part of ND280 (P0D) will be replaced to new detectors.
  - 4π acceptance like SK.
  - Low momentum threshold for hadrons (protons).
- Reduce cross section systematics with better understanding of nuclear effect.
  - 18% (2011) → 5-7% (2022) → 4%(202X..)





TOF: Provide 150 ps time resolution.

SFGD: 2 million 1 cm^3 cubic scintillators readout by fibers in 3 directions.

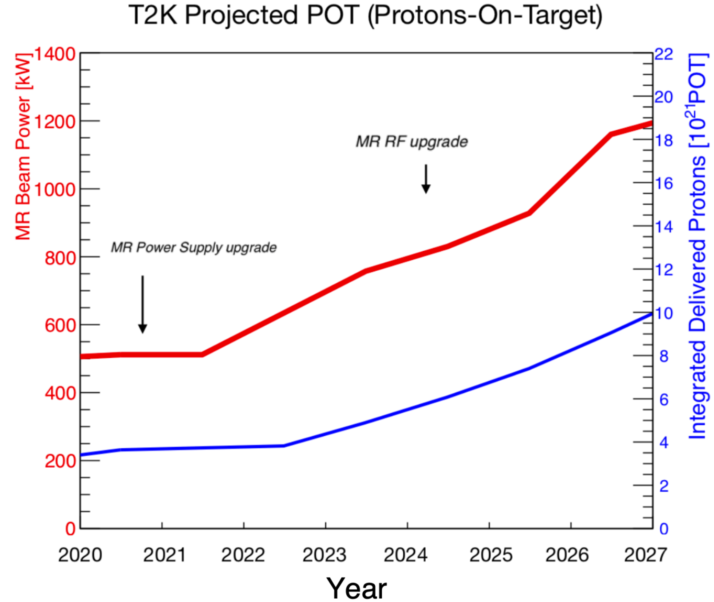
(ref)

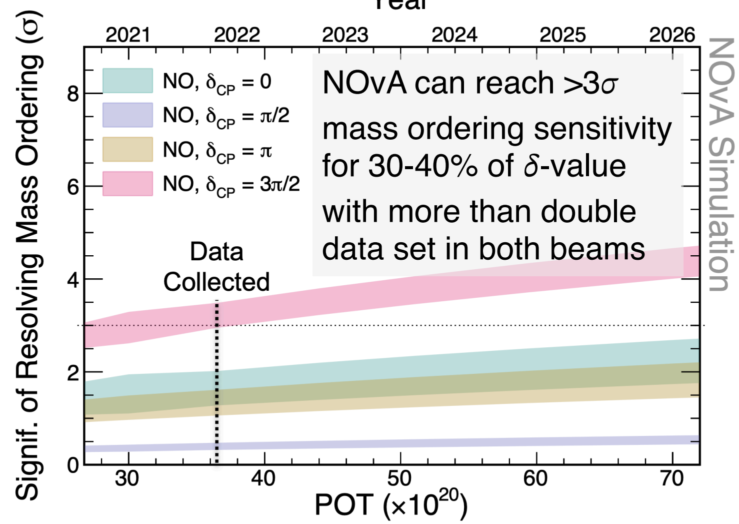
HATPC: Precisely measure high-angle particles from neutrino interactions.

Outlook

- Beam power upgrade:
- T2K: Reaching ~1.3 MW beam power by 2027 (currently ~500 kW)
  - Upgrading the main ring power supply and RF
  - Goal of the next run: Increase horn current and reduce wrong-sign background
- NOvA: Working towards 900+ kW by upgrading the NuMI beamline components

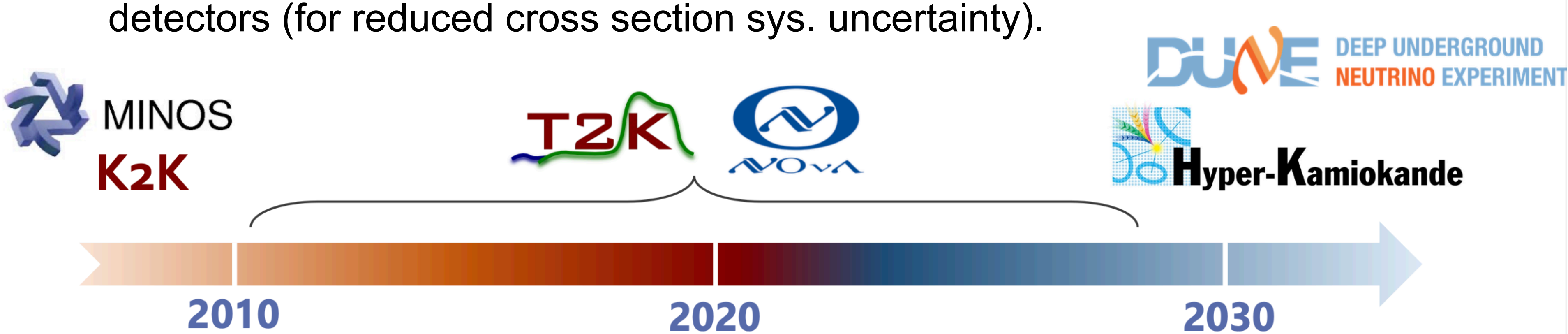
- Physics goal:
- T2K: Reduced cross-section systematic errors and more statistics to search for a possible evidence of CP violation at 3σ level
- NOvA: Reach 3σ hierarchy sensitivity for 30-50% of δ_{CP} values, with the full dataset and an upgraded beam.
- A joint fit of the data from the two experiments is ongoing to quantify the consistency and improve the precision.





Summary

- T2K and NOvA are long baseline experiments studying neutrino oscillations using accelerator neutrinos.
- CP-conservation (δ_{CP} = 0 or π) excluded at 90% in T2K, while NOvA has no preference on CP violation.
- T2K and NOvA both prefer for normal ordering and upper octant.
- Ongoing joint analyses between T2K and NOvA.
- On-going upgrade of the accelerator (for higher beam intensity) and near detectors (for reduced cross section sys. uncertainty).



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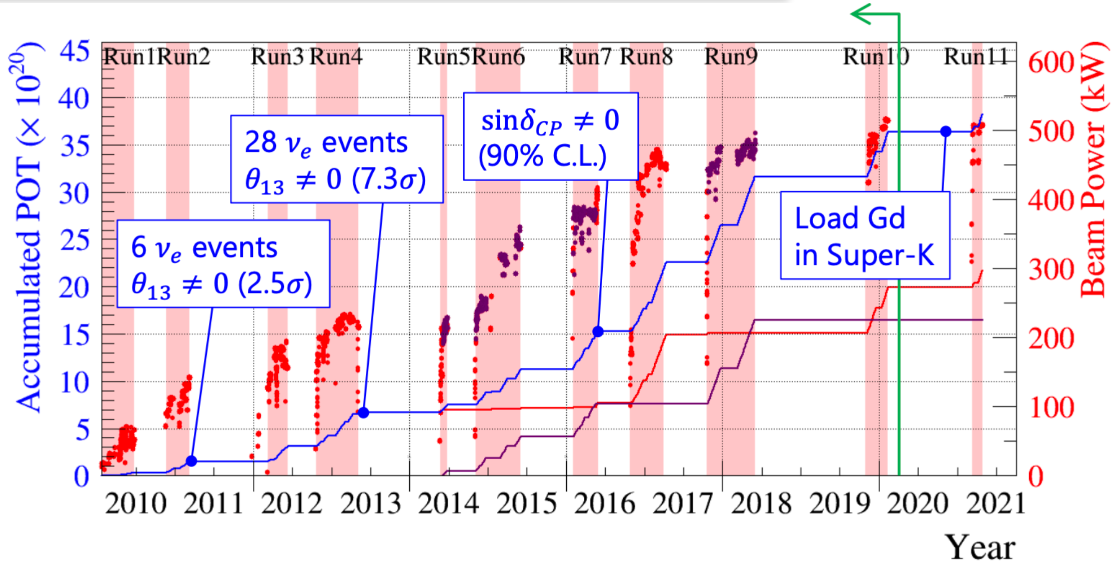
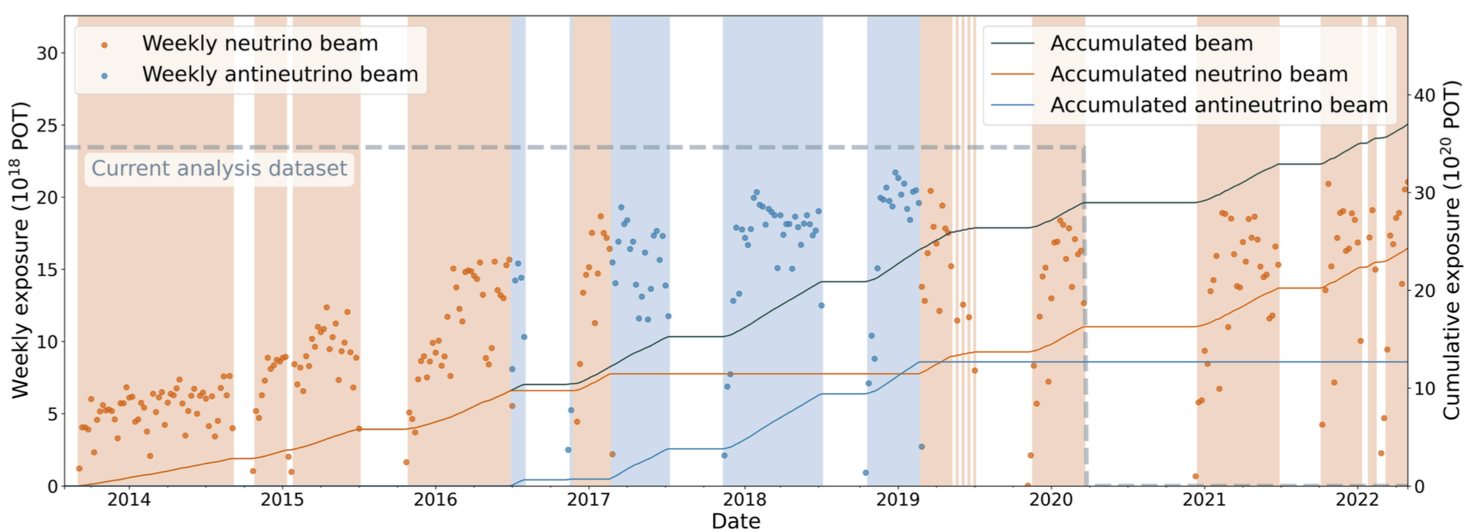
Back up

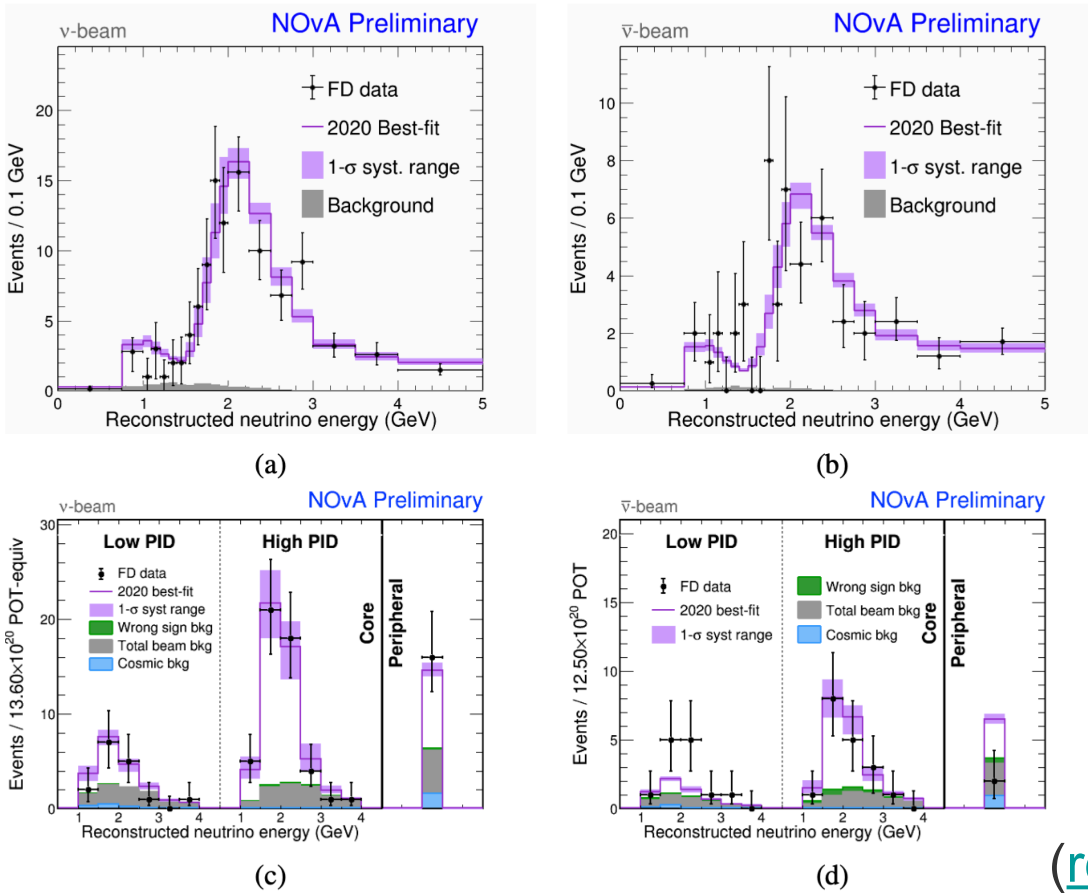
Data acquisition



- T2K has accumulated 3.82×10^{21} POT
  - ν mode: 2.17×10^{21}(56.8%)
  - $\bar{\nu}$ mode: 1.65×10^{21}(43.2%)
- NOvA:
  - ν mode: 1.36×10^{21}
  - $\bar{\nu}$ mode: 1.25×10^{21}



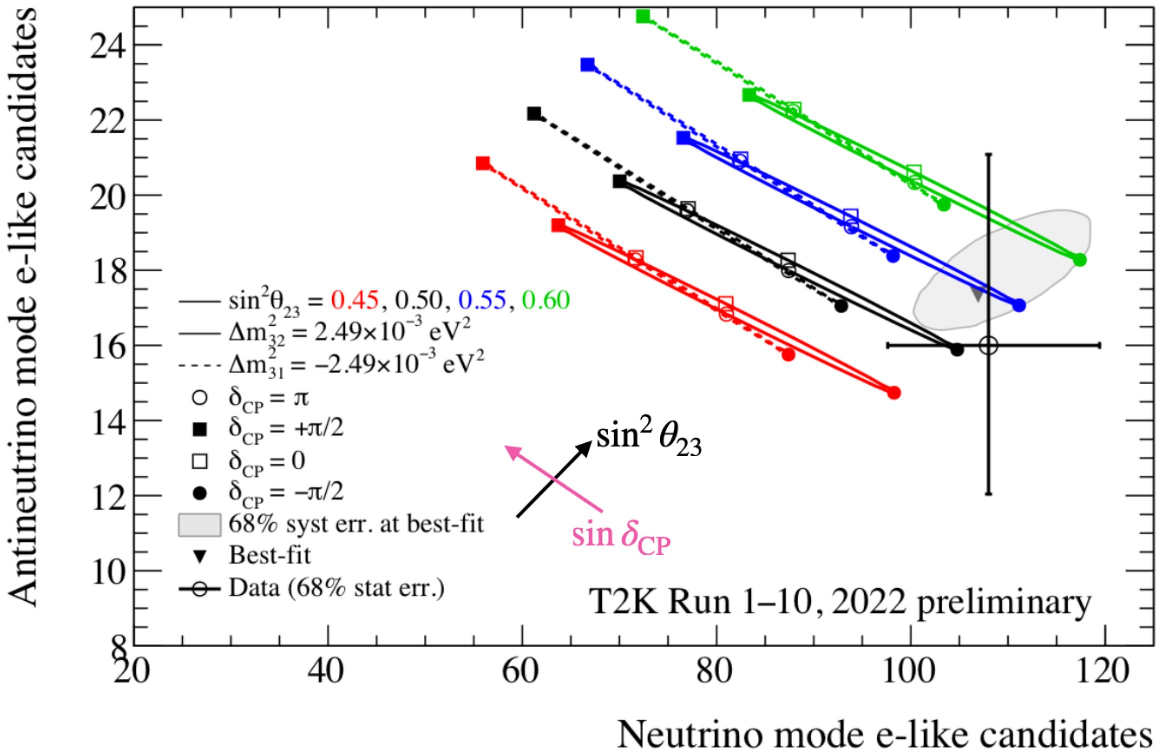
Far Detector Data in NOvA



(ref)

Figure 2: Energy spectra of selected (a) muon neutrino, (b) muon antineutrino, (c) electron neutrino, and (d) electron antineutrino events in the Far Detector. Data is in black and simulation in purple, drawn with a 1σ systematic range. Total background in (a) and (b) is gray; backgrounds in (c) and (d) are factored into wrong sign contamination (green), beam backgrounds (gray), and cosmics (blue).

Oscillation Results in T2K

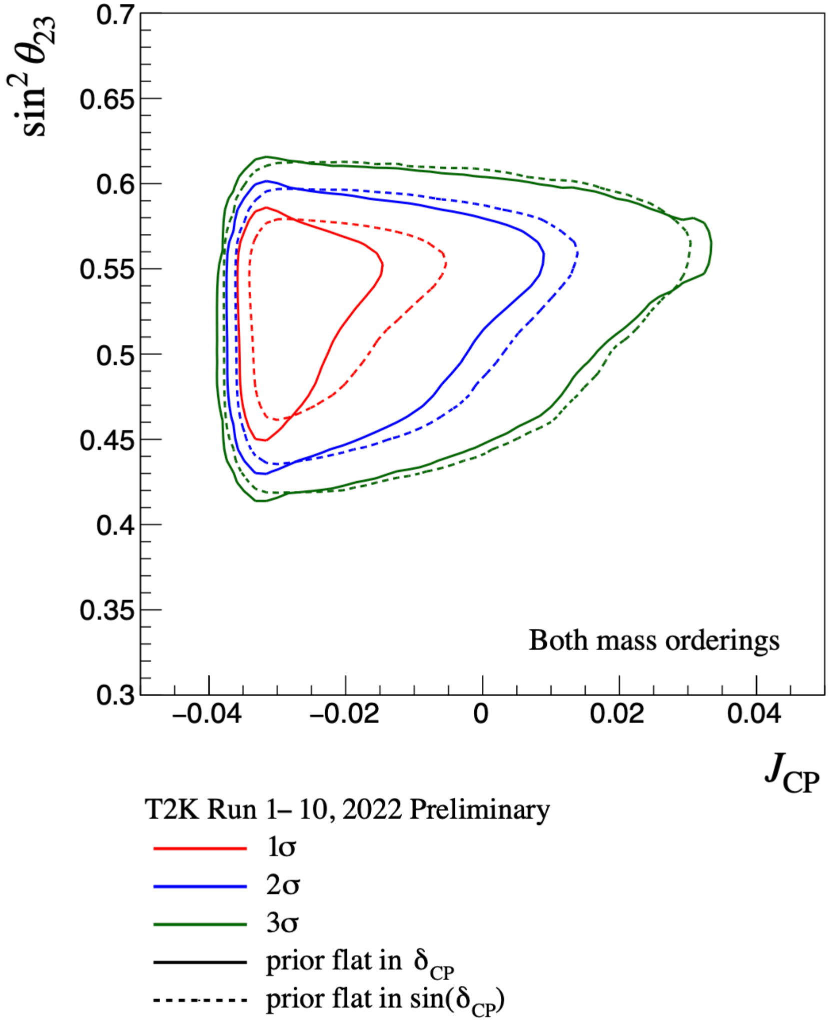


Best-fit δ_{CP} close to $-\pi/2$

Weak preference of NO with Bayes factor (P_{NO}/P_{IO}) = 2.8

Weak preference of the upper octant with Bayes factor (P_{UO}/P_{LO}) = 3.0

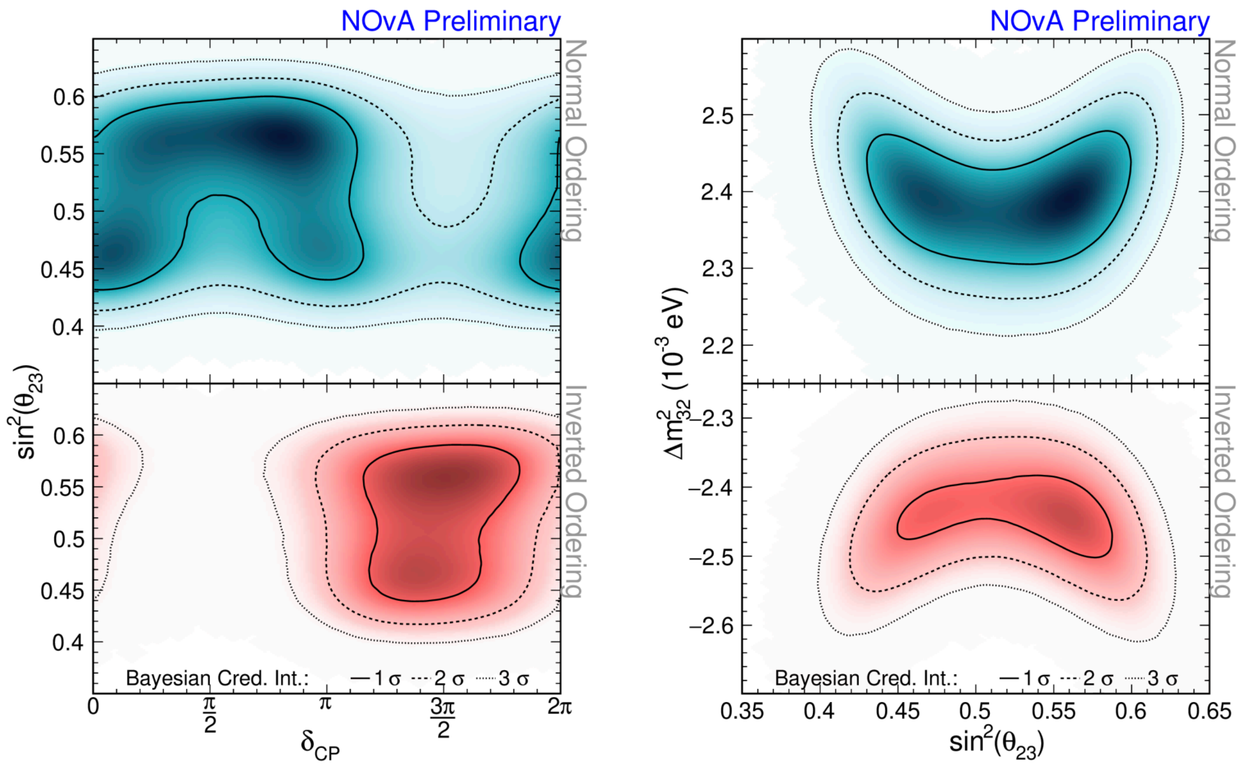
Jarlskog Invariant (T2K)



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

- Independent of PMNS parameterization
- Stable CPV-preference for different priors

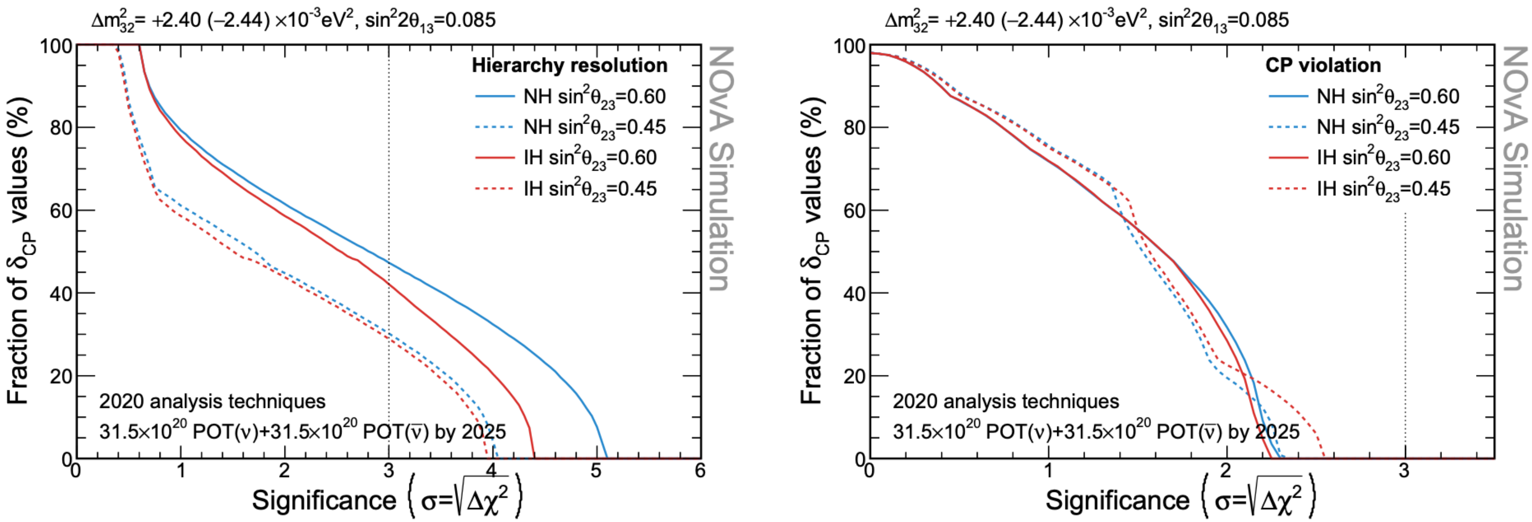
Results in NOvA



Left: $\sin^2(\theta_{23})$ as a function of δ_{CP} for the normal (top) and inverted (bottom) ordering. Right: Δm^2_{32} as a function of $\sin^2(\theta_{23})$ for the normal (top) and inverted (bottom) ordering. (ref)

- Examine results in new ways: Markov Chain MC Bayesian analysis
- The conclusions are not changed with respect to the 2020 analysis:
  - $\delta_{CP} = \frac{3\pi}{2}$ is not preferred at the 2σ level with normal ordering
  - $\delta_{CP} = \frac{\pi}{2}$ is excluded at 3σ with inverted ordering
  - Upper octant of θ_{23} is preferred.

Outlook for NOvA



(ref)

Figure 6 – Fraction of δ_{CP} values in the range $[0, 2\pi)$ for which the neutrino mass ordering (left) or CP non-conservation (right) could be resolved by NOvA at a given sensitivity σ by the year 2025, assuming an accumulated exposure of 63×10^{20} protons-on-target. The lines correspond to different true values of $\sin^2\theta_{23}$ and true normal ordering (blue) or inverted ordering (red).

NOvA is expected to take data through 2026, and the current projection for the ultimate exposure is 60-70$\times 10^{20}$ protons-on-target, approximately doubling the data analyzed so far [11]. Figure 6 shows some projections for the resolution of the neutrino mass ordering and CP violation. NOvA could reach 2σ determination of CP violation, 3σ sensitivity to the ordering for 30-50% of δ_{CP} values, and up to $\sim 5\sigma$ in the most favorable case.