Recent results and future prospects from the T2K experiment

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International Conference on the Physics of the Two Infinities

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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 $\Delta m^2_{21}, \Delta m^2_{32}$, and CP phase δ_{CP}.

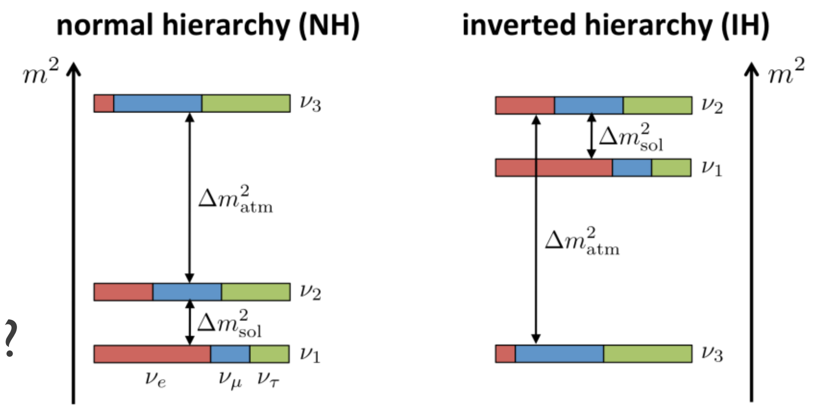
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13} e^{i\delta_{CP}} & 0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

Flavor eigenstates

Pontecorvo–Maki–Nakagawa–Sakata matrix

Mass eigenstates

- Remaining questions.
  - Is $\sin\delta_{CP}$ non-zero? (CP violation in lepton?)
  - Is θ_{23} 45°? (maximal mixing? octant?)
  - Normal hierarchy ($m_3 > m_2 > m_1$) or inverted hierarchy ($m_2 > m_1 > m_3$)?



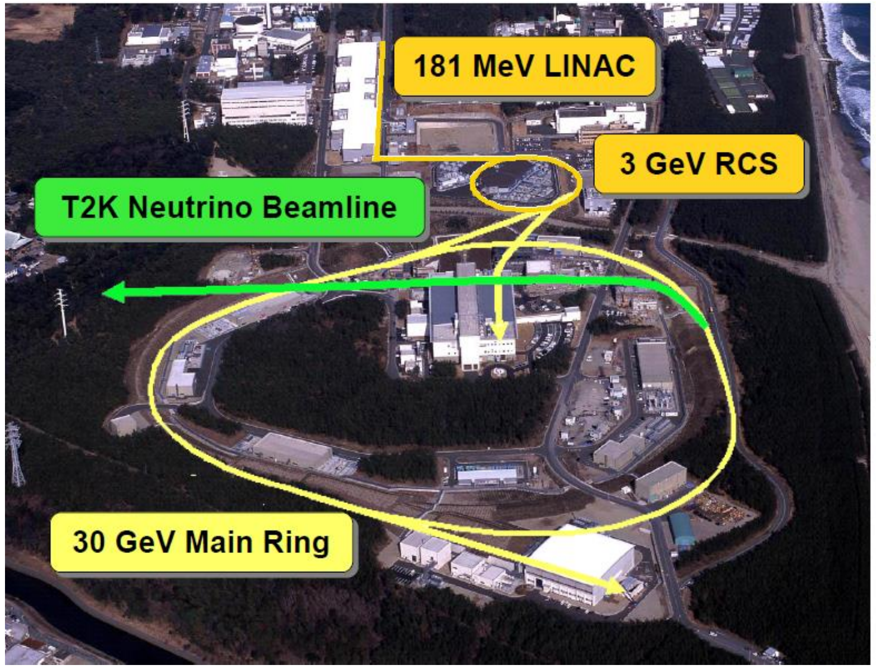
The T2K experiment

- Long-baseline neutrino oscillation experiment in Japan.
- Produce ν_μ or $\bar{\nu}_\mu$ beam at J-PARC.
- Measure the neutrinos at near detector and Super-Kamiokande away from 295km.

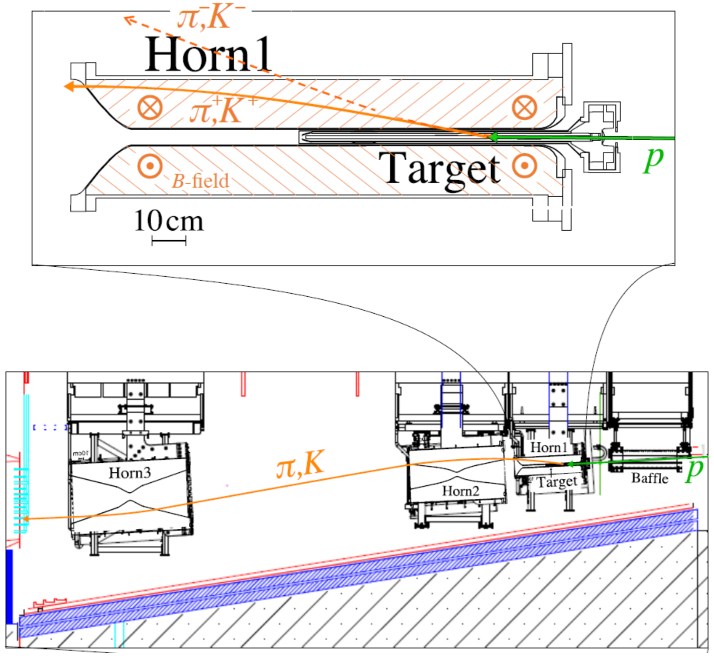
Neutrino beam

- 30 GeV proton beam from J-PARC accelerators on graphite target produces pions.
- Magnetic horns focus π^+ or π^- to produce ν_μ or $\bar{\nu}_\mu$ beam.
- Off-axis method to produce narrowband neutrino beam and maximize oscillation.

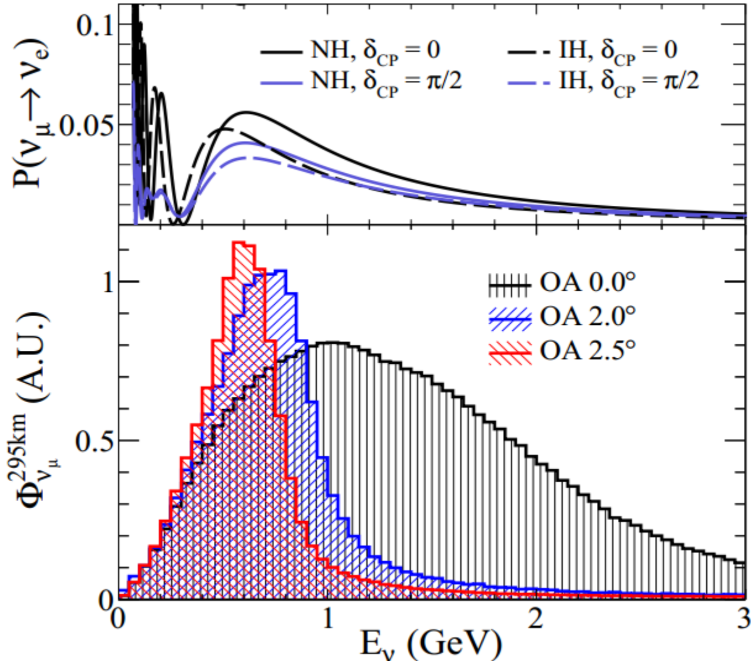
J-PARC accelerators



Target and magnetic horns



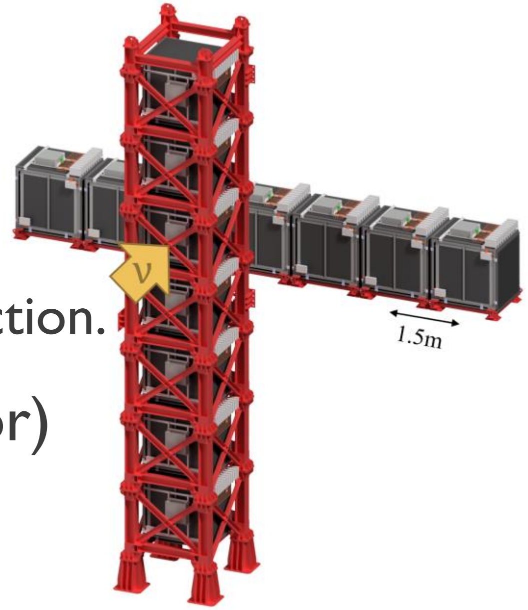
Neutrino beam spectra on and off axis



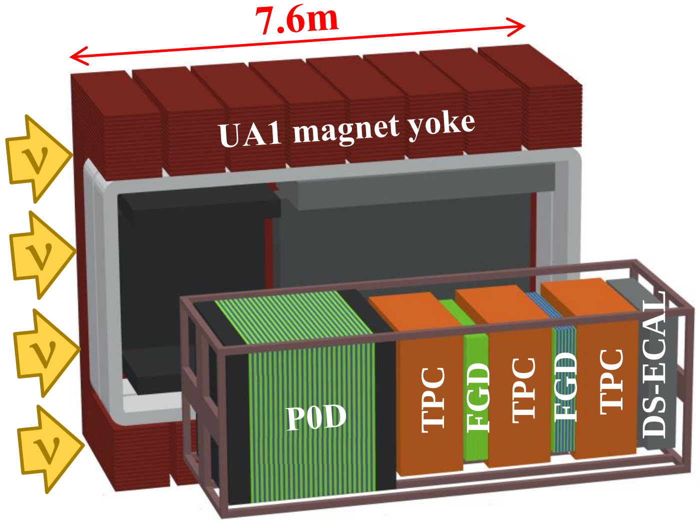
Near detector

- INGRID (on-axis detector)
  - 14 identical detectors arranged in a cross shape.
  - Monitor beam direction and neutrino event rate.
- ND280 (2.5° off-axis detector)
  - Magnetized (0.2T) complex detector.
    (Scintillator tracker, TPC, EM calorimeter etc.)
  - Measure neutrino flux to Super-K and cross section.
- WAGASCI-BabyMIND (1.5° off-axis detector)
  - New detector installed in 2019.
  - Located at different off-axis angle from ND280
    to measure cross section for higher-energy neutrinos.

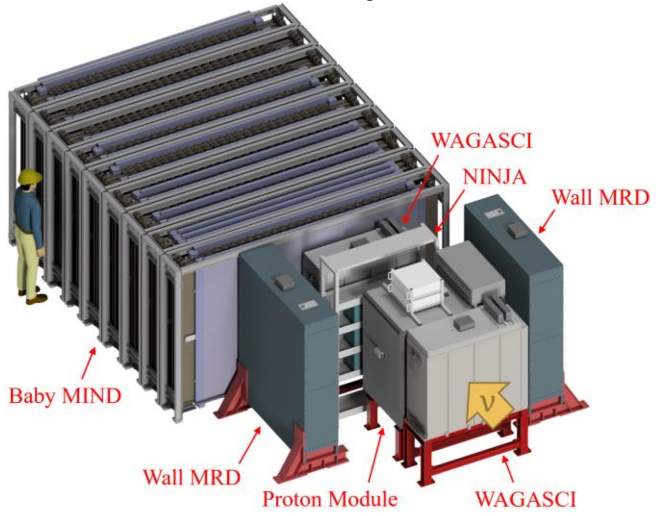
INGRID



ND280



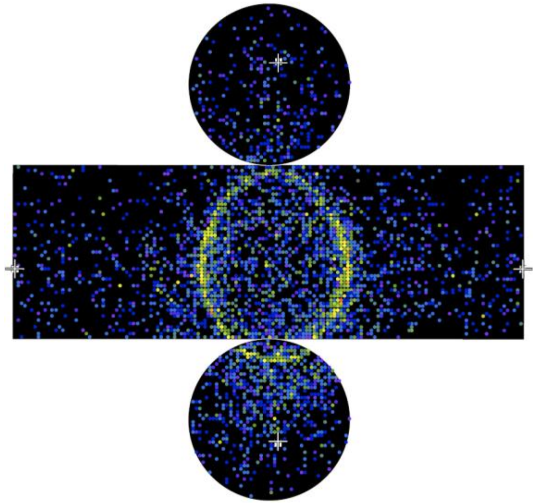
WAGASCI-BabyMIND



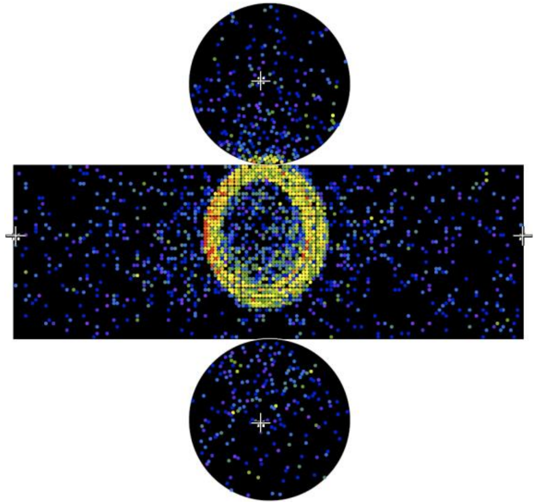
Super-Kamiokande

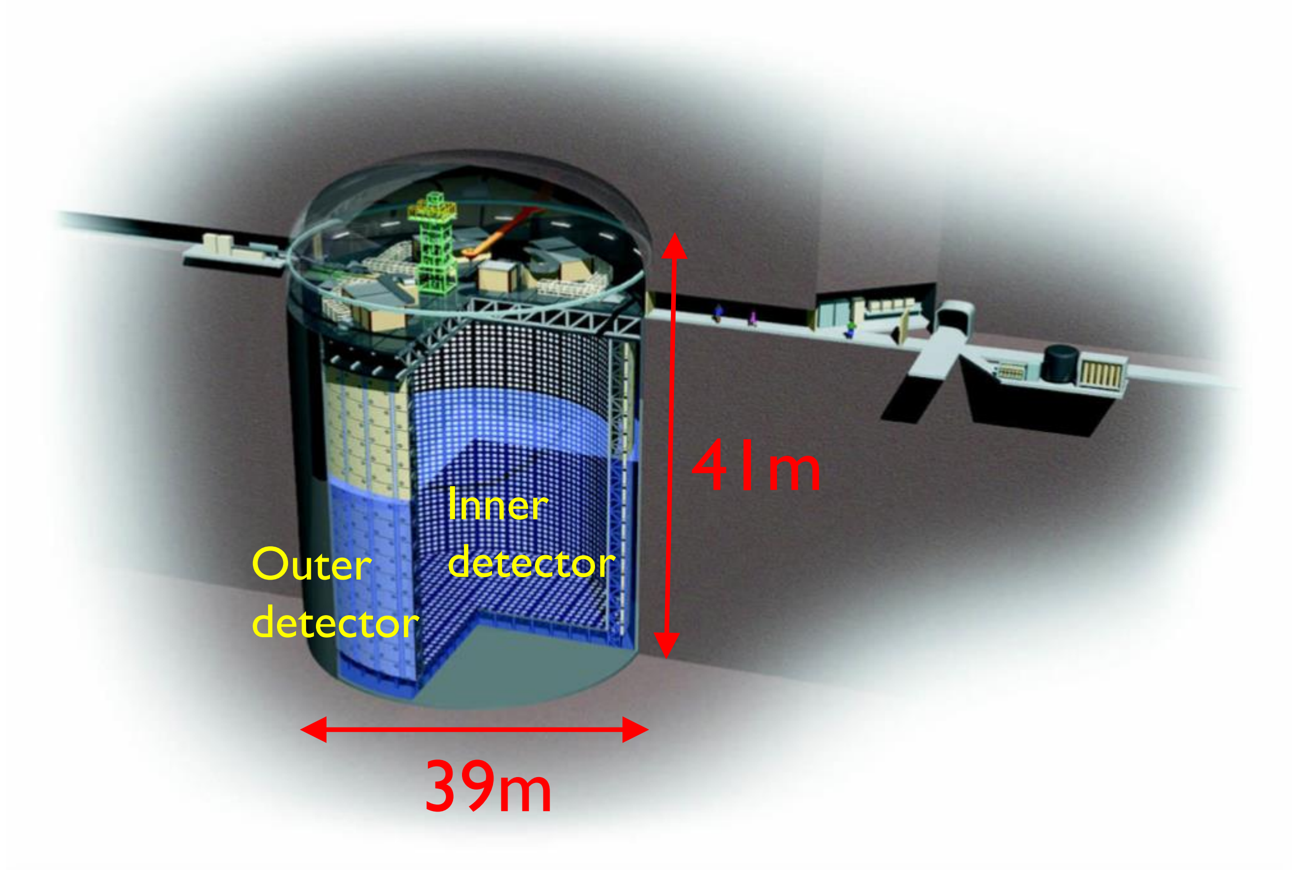
- 50kt water Cherenkov detector having ~11,000 20 inch PMTs.
- Good separation of electrons and muons. → Separate ν_e and ν_μ CC interactions.
- Gd loaded for enhanced neutron detection in 2020.

ν_e candidate event
(fuzzy Cherenkov ring)



ν_μ candidate event
(sharp Cherenkov ring)

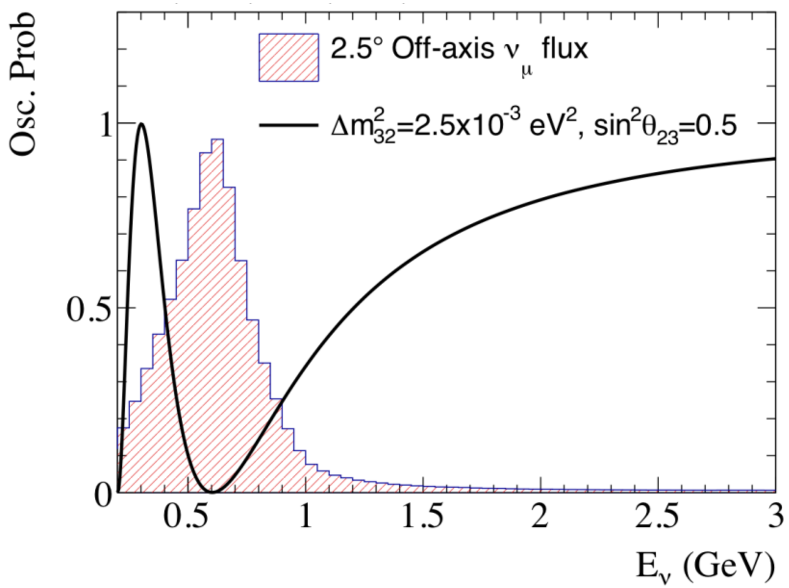




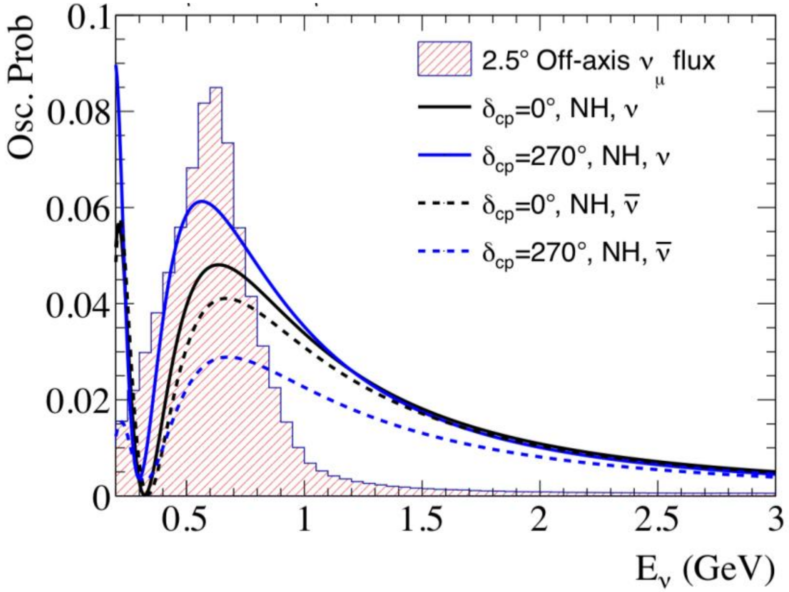
Oscillations in T2K

- ν_μ or $\bar{\nu}_\mu$ disappearance
  - Sensitive to $\sin^2 2\theta_{23}$. But hard to distinguish octant ($\theta_{23} < 45°$ or $\theta_{23} > 45°$).
  - Sensitive to $|\Delta m^2_{32}|$. But does not depend on mass hierarchy ($m_3 > m_2 > m_1$ or $m_2 > m_1 > m_3$).
- $\nu_\mu \rightarrow \nu_e$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
  - Sensitive to $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$. Can distinguish octant.
  - Dependent on δ_{CP}. Can search for CP violation.
  - Affected by matter effect. Sensitive to mass hierarchy.

ν_μ or $\bar{\nu}_\mu$ disappearance

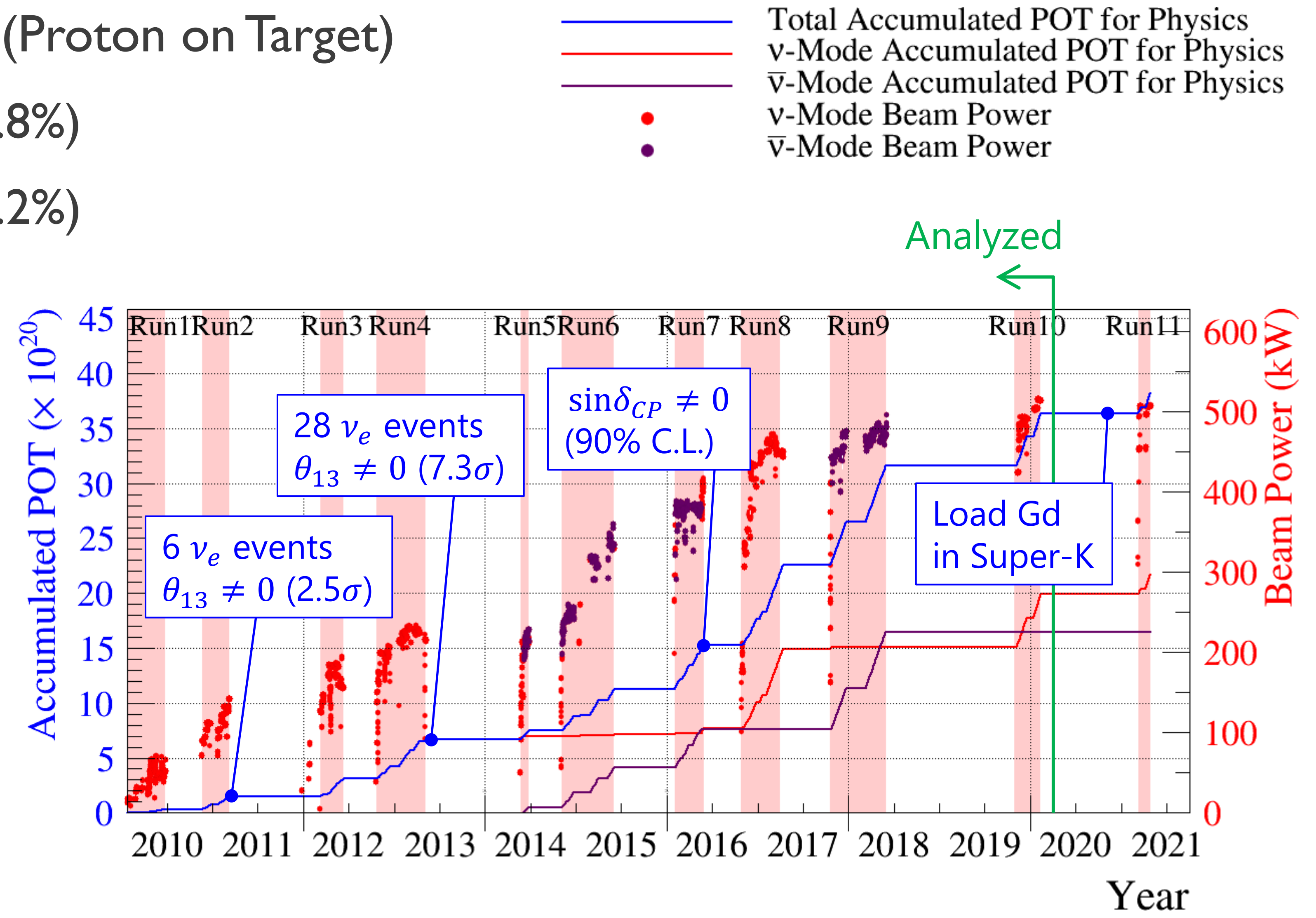


$\nu_\mu \rightarrow \nu_e$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance



Data acquisition

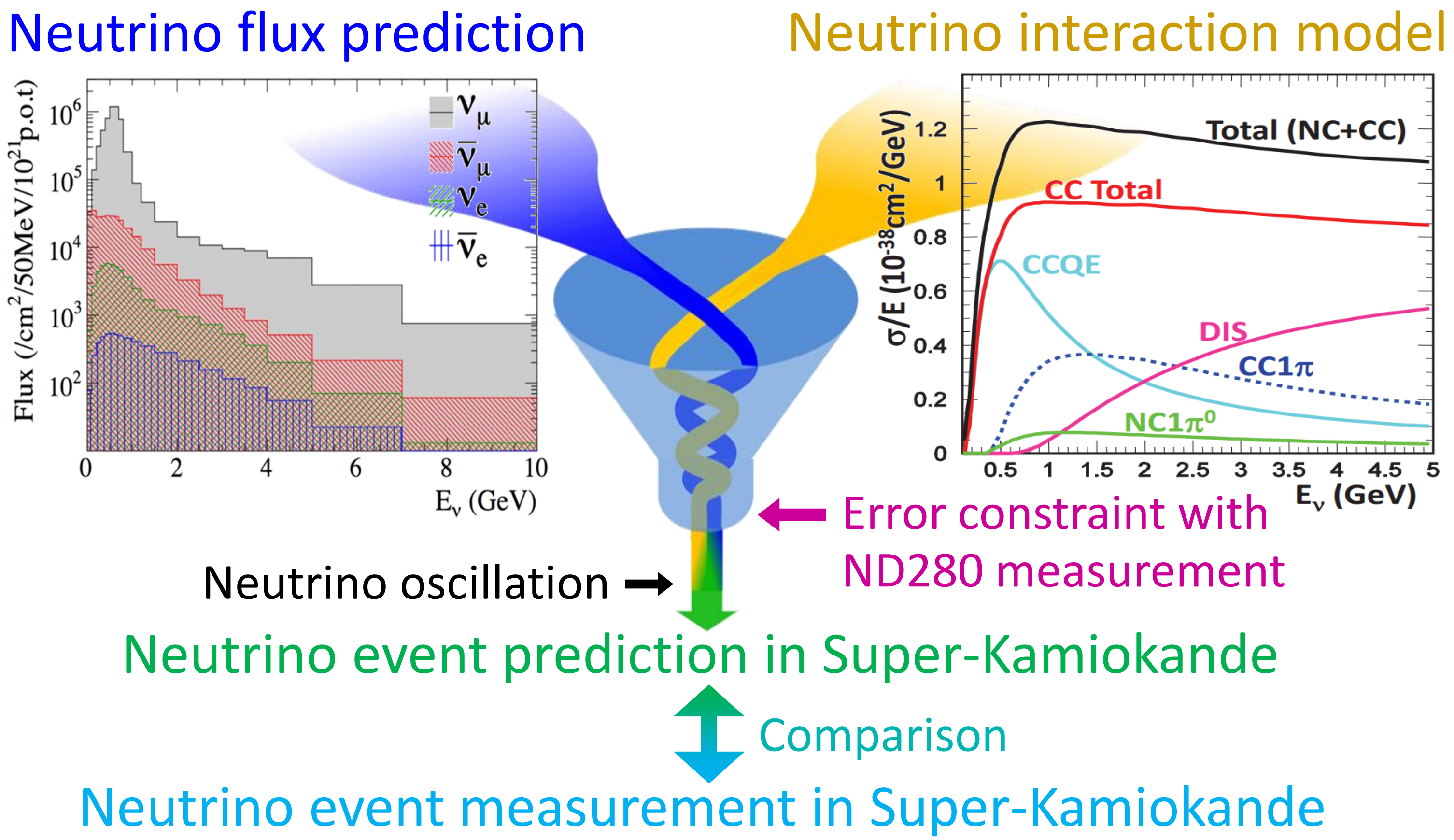
- Accumulated 3.82×10^{21} POT (Proton on Target)
  - ν mode: 2.17×10^{21} POT (56.8%)
  - $\bar{\nu}$ mode: 1.65×10^{21} POT (43.2%)
- Achieved ~515 kW stable beam operation. (522.6kW at maximum)
- Data until 2020 (3.64×10^{21} POT) was analyzed.



Analysis strategy and improvements in 2022

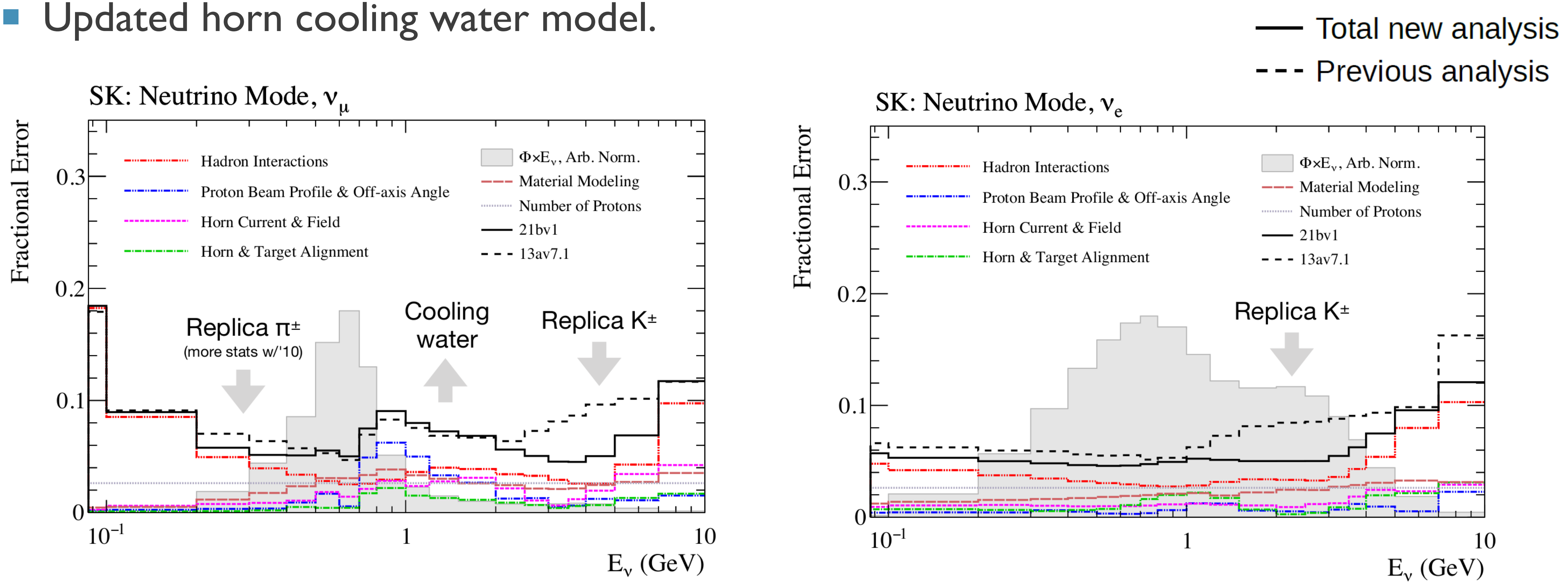
- Significant analysis improvements in 2022.
  - Neutrino flux prediction
  - Neutrino interaction model
  - Near detector analysis
  - Far detector analysis
- Highlight these improvements.

Flow of frequentist oscillation analysis



Neutrino flux prediction

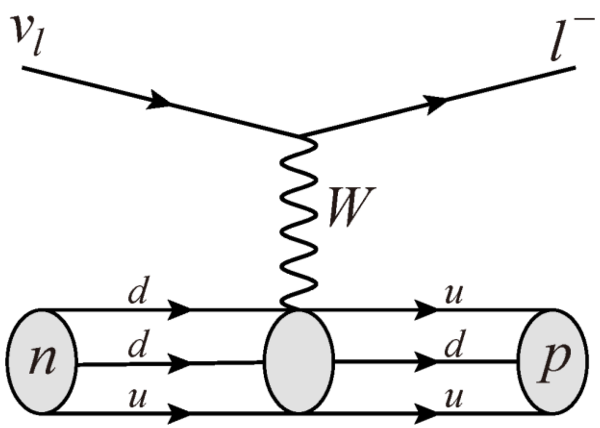
- Simulation with hadron production tuning based on measurements by NA61/SHINE.
- Improved by higher-statics NA61/SHINE data including kaons from T2K replica target.
- Updated horn cooling water model.



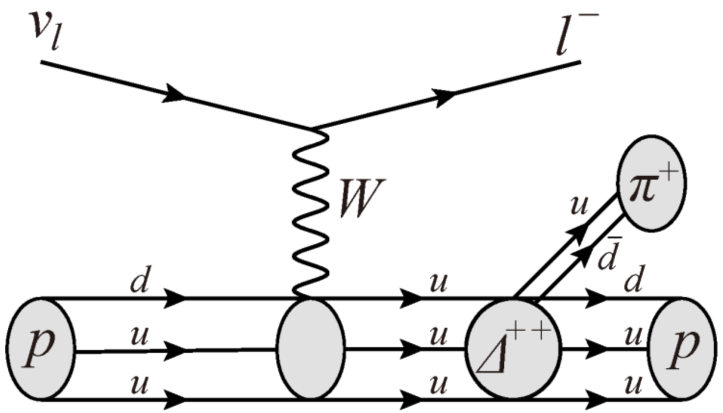
Neutrino interaction model

- Charged-current quasi-elastic
  - Based on spectral function tuned to electron scattering data.
  - New uncertainties on nuclear shell structure, nuclear potential and Pauli Blocking.
  - Nucleon removal energy has a parameterized dependence on momentum transfer.
- Charged-current resonant pion production
  - Based on Rein-Sehgal model with RFG nuclear model.
  - New tuning with bubble chamber data.
  - Effective inclusion of binding energy.
  - New uncertainty for resonance decay.

Charged-current quasi-elastic



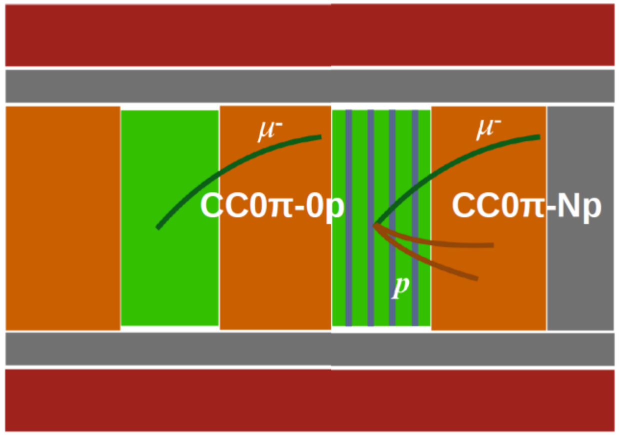
Charged-current resonant pion production



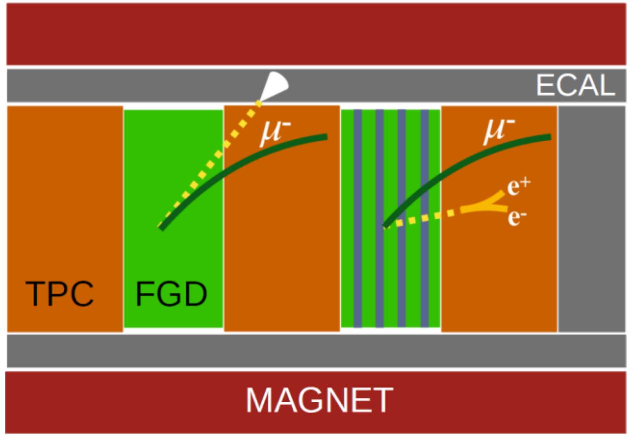
Near detector analysis

- Select ν_μ or $\bar{\nu}_\mu$ CC interactions and separate by target and observed particles.
- Fitting gives tuned nominal values and constrained uncertainties for flux and interaction.
- Changed sample separation.
  - Split CC0π sample based on proton.
  - Separate events with tagged photons.

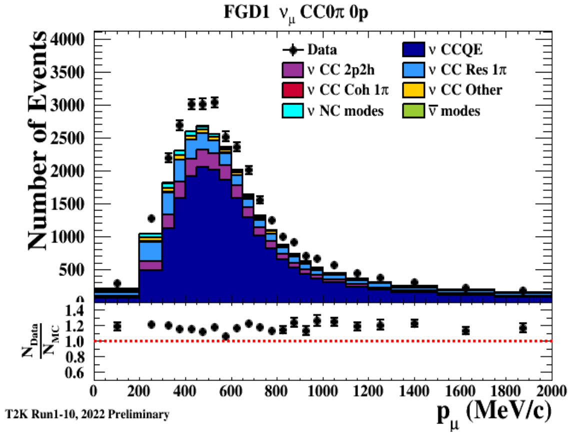
Sample separation by proton



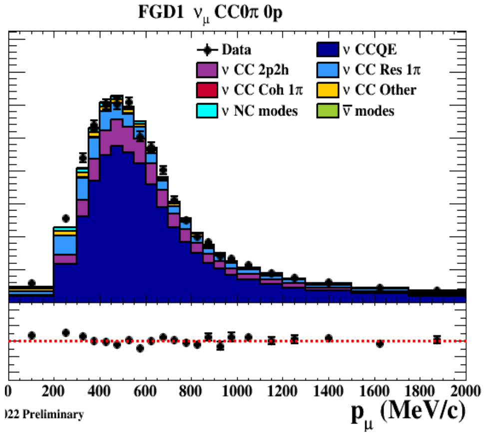
Sample separation by photon tagging



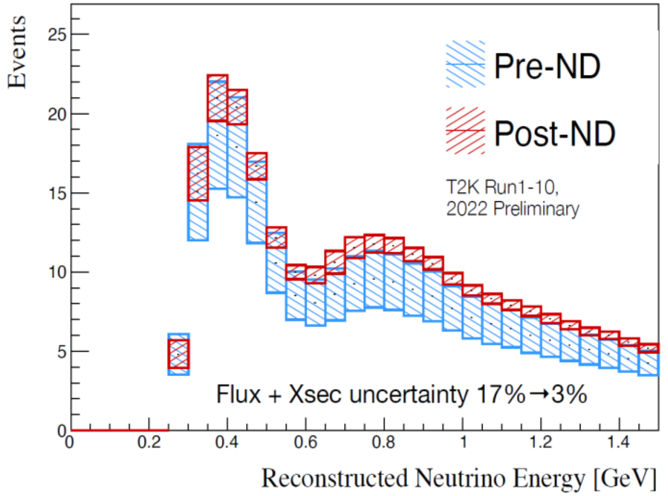
Before fitting



After fitting



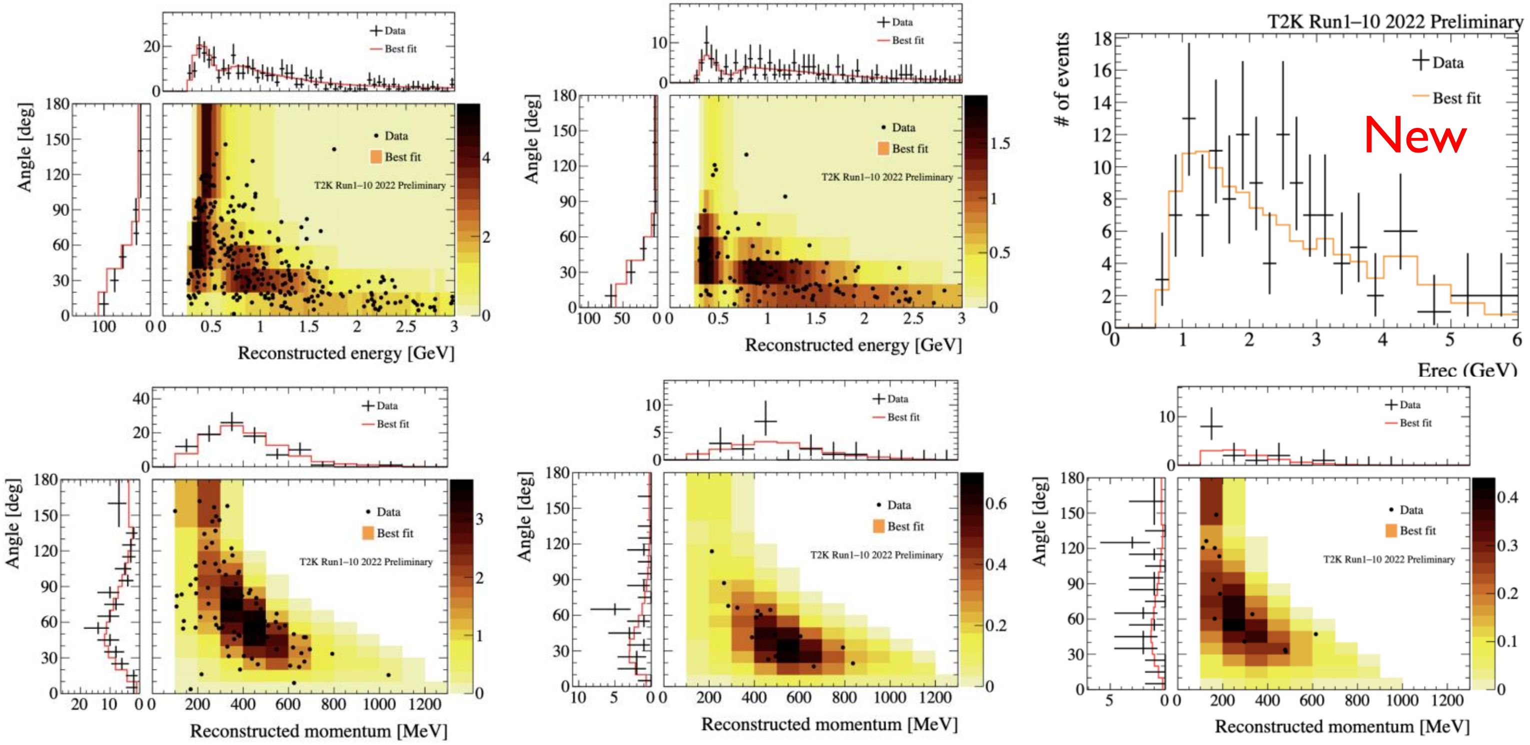
Systematic error for Super-K events



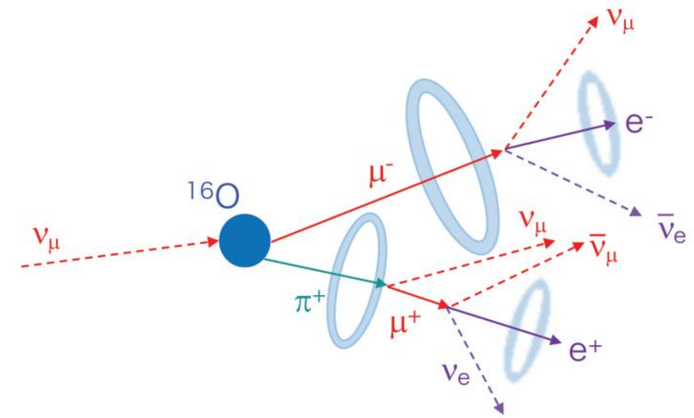
Far detector analysis

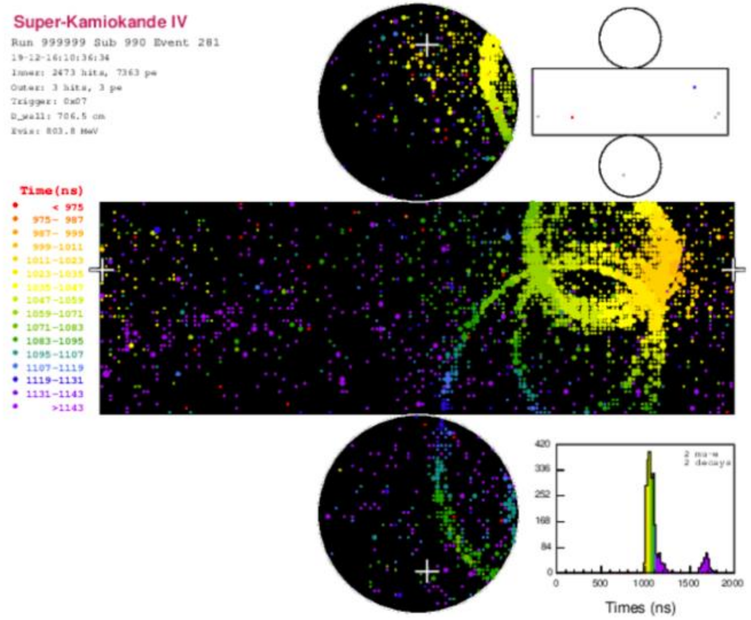
- 6 samples at Super-K for ν_μ / $\bar{\nu}_\mu$ disappearance and $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance.
- Multi-ring sample added for the first time.

6 samples at Super-Kamiokande



Multi-ring sample event at Super-K

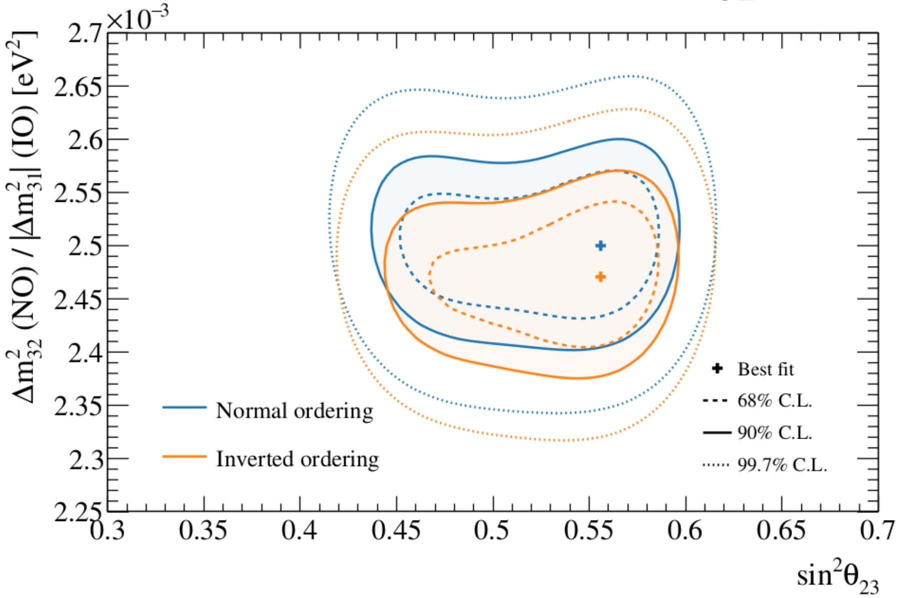




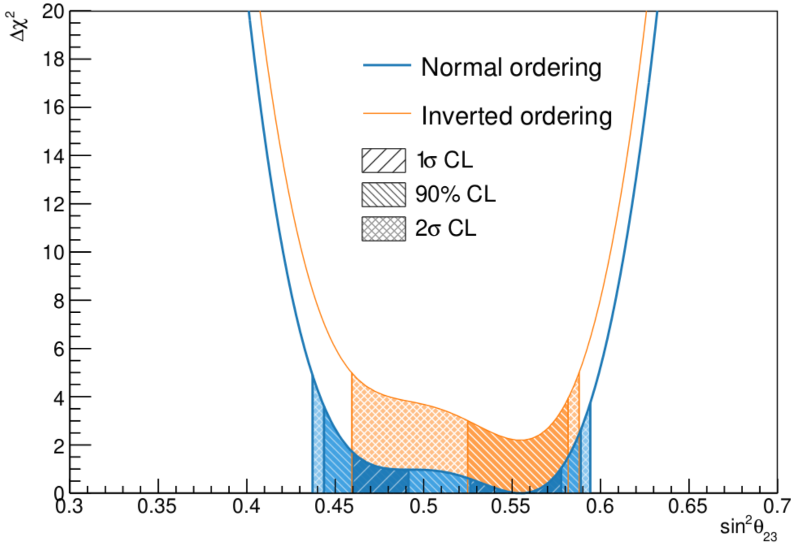
Results for atmospheric mixing parameters

- Best fit in upper octant ($\sin^2\theta_{23} > 0.5$).
- But still compatible with both octants.
- World-leading measurements.

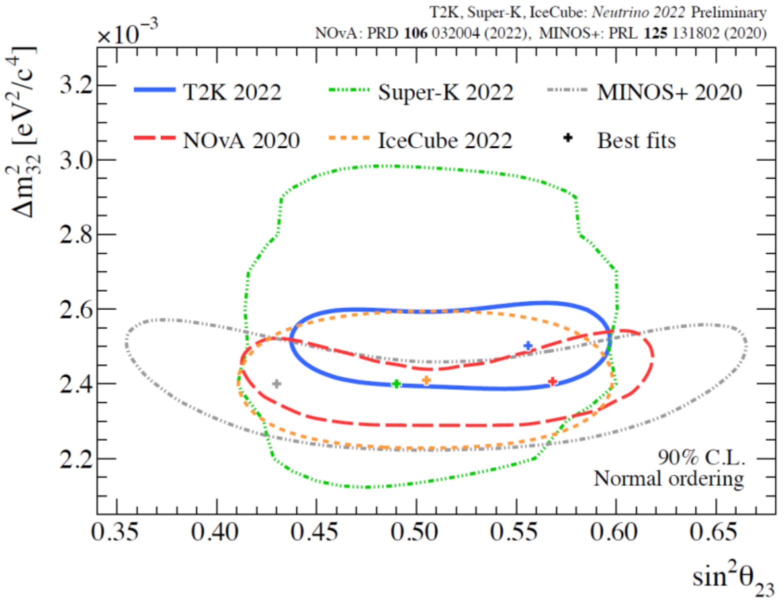
Result on $\sin^2\theta_{23}$ and Δm^2_{32}



Result on $\sin^2\theta_{23}$



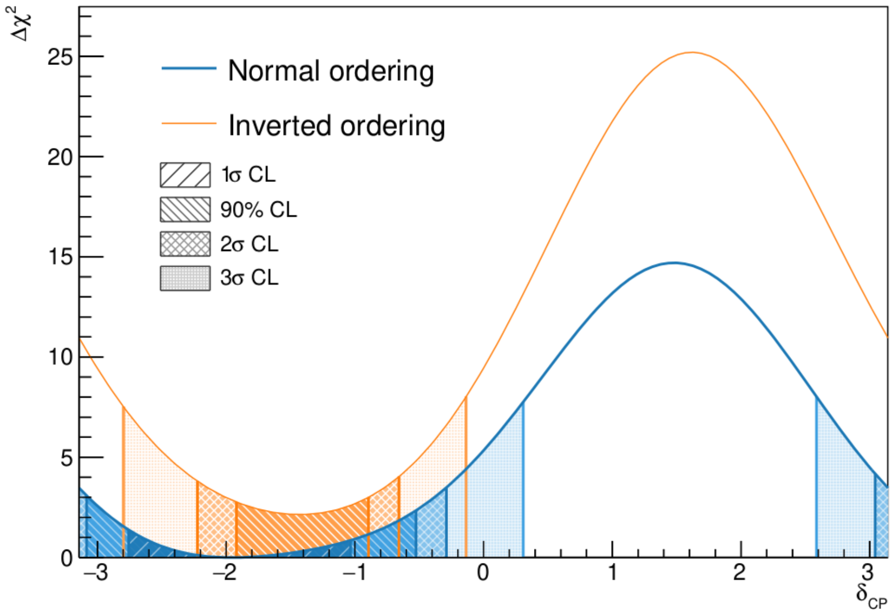
Comparison with other experiments for normal hierarchy



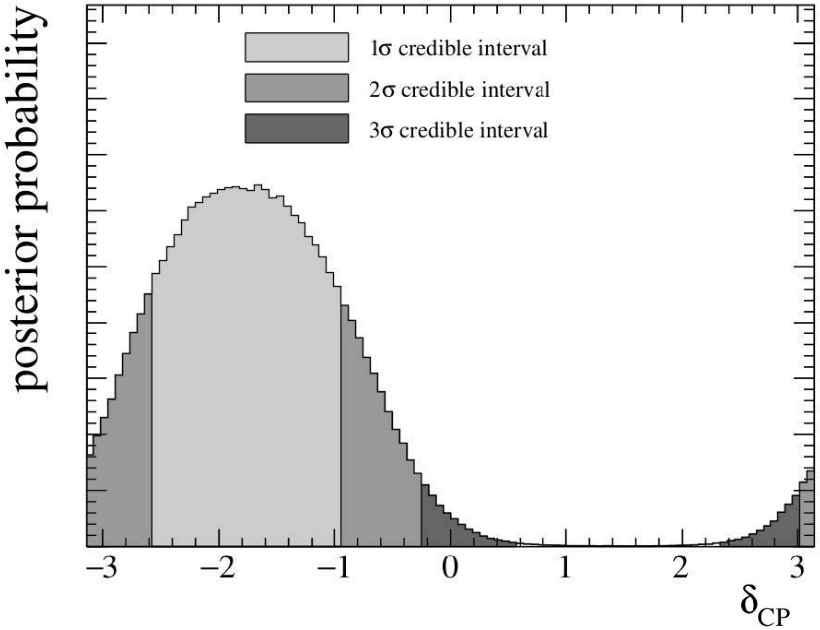
Results for CP violation search

- Large region of δ_{CP} excluded at 3σ.
- CP conservation ($\sin\delta_{CP} = 0$) excluded at 90%.
- Weekly prefer normal hierarchy.
- Jarlskog invariant result depends on prior δ_{CP} and $\sin^2\theta_{23}$

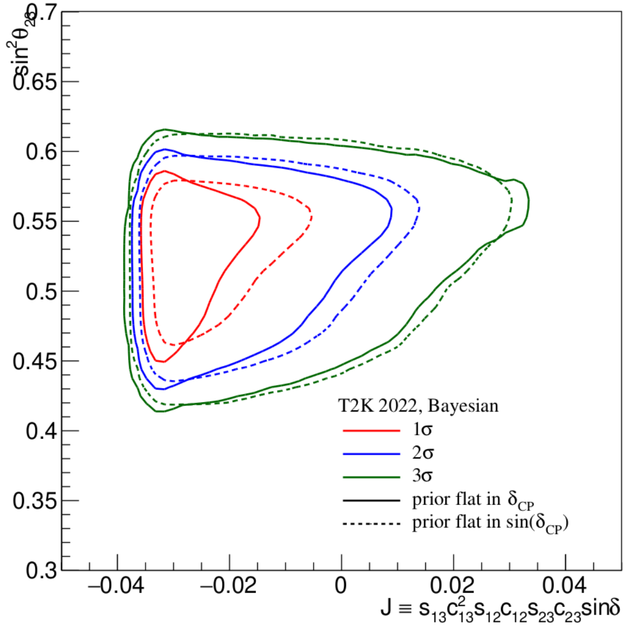
Frequentist result on δ_{CP}



Bayesian result on δ_{CP}



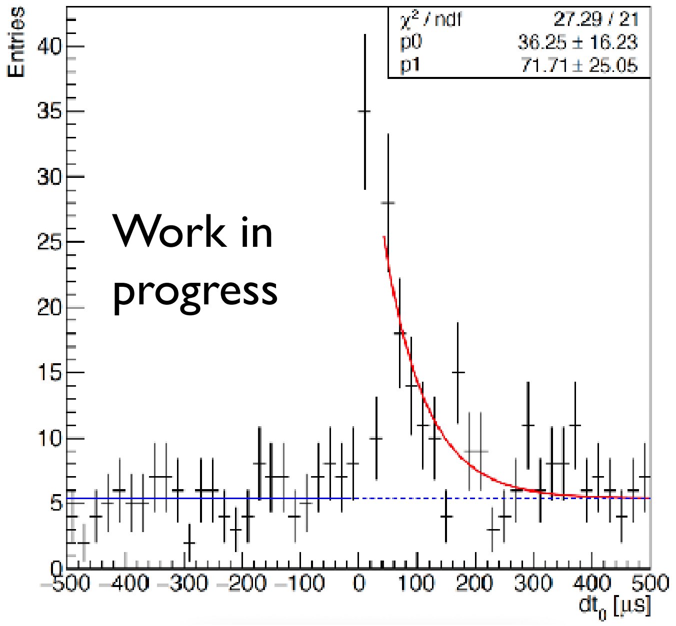
Result on Jarlskog invariant

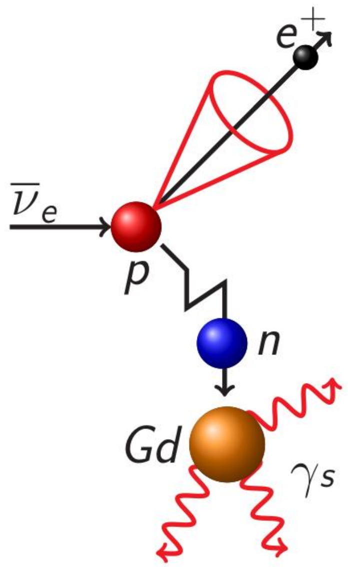


Future prospect

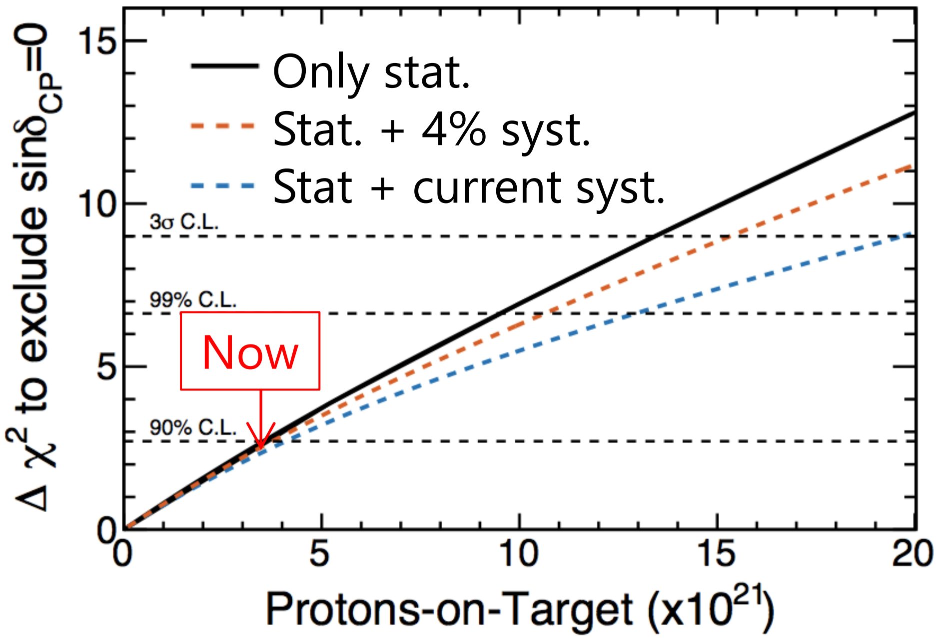
- Recorded beam data with Gd-loaded Super-Kamiokande, but not yet used in analysis.
  → Potential for better neutron measurement.
- Statistical error is still dominant. → Accelerator and beamline upgrade.
- Neutrino interaction model uncertainty is large. → Near detector upgrade.

Gd neutron capture event candidates in Gd-loaded Super-K





Expected sensitivity to CP violation when $\delta_{CP} = -\pi/2$

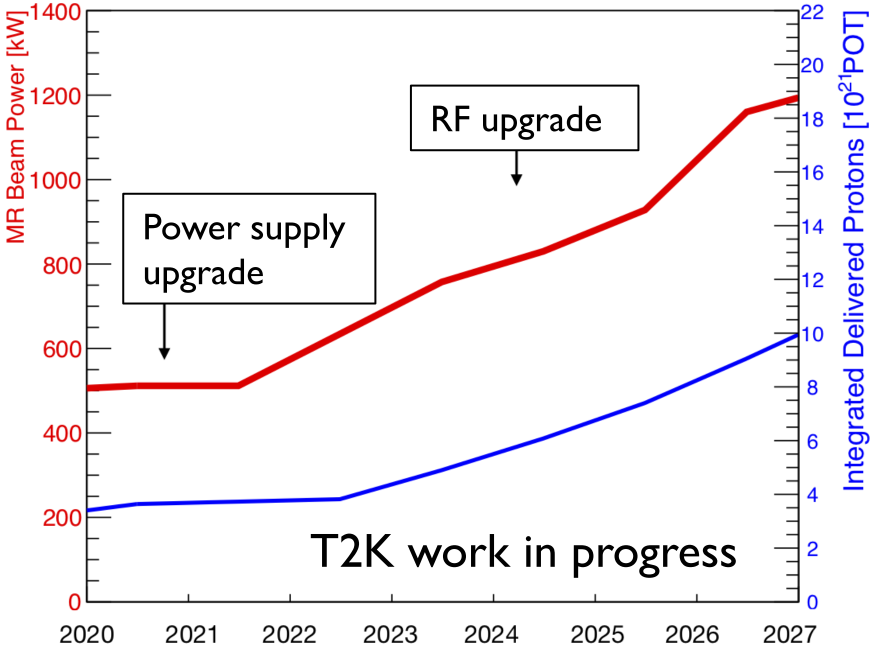


Accelerator and beamline upgrade

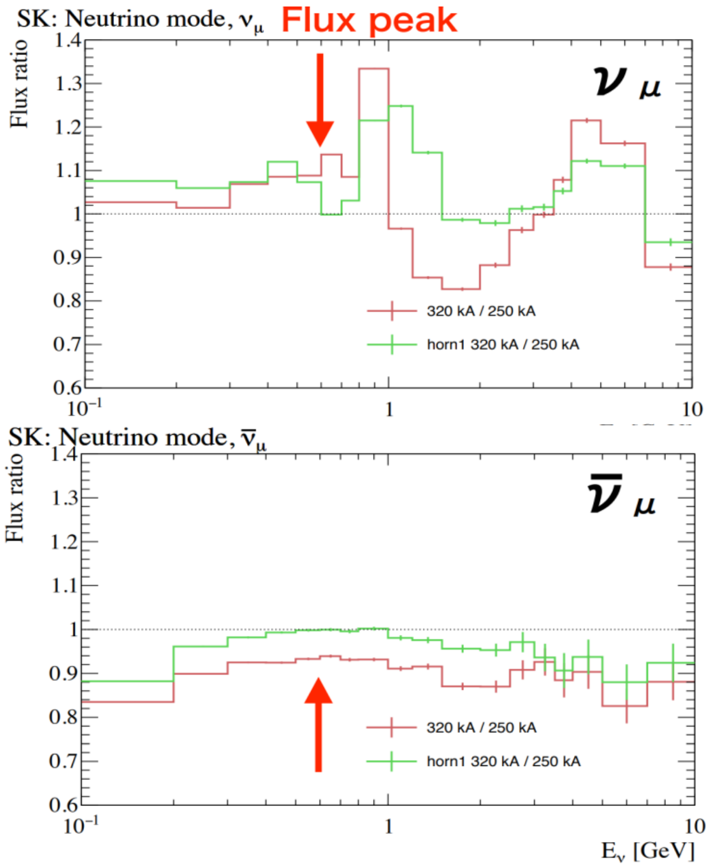
- Increase beam power ~500kW→1.3MW by J-PARC main ring power supply and RF.
- Increase horn current 250kA→320kA to increase neutrino beam power (~10%) and reduce wrong-sign background.

New main ring power supply

T2K projected POT



Expected change of ν_μ and $\bar{\nu}_\mu$ fluxes by horn current 250kA→320kA

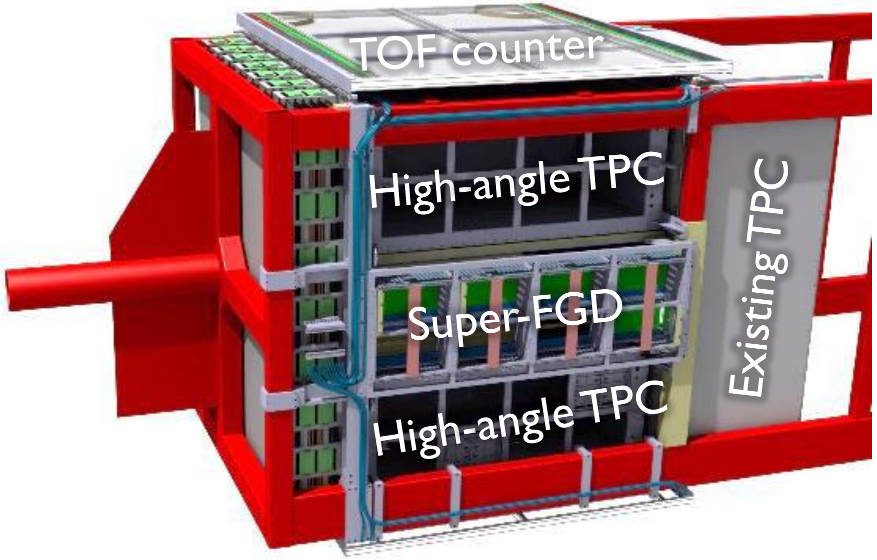


Near detector upgrade

- Upstream part of ND280 (P0D) will be replaced to new detectors.
- Super-FGD: 2 million 1cm^3 cubic scintillators readout by fibers in 3 directions.
- High-angle TPCs: Precisely measure high-angle particles from neutrino interactions.
- TOF counters: Provide 150 ps time resolution.

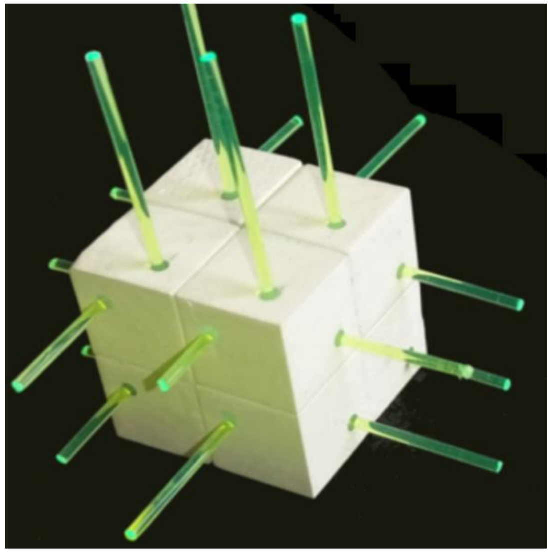
Talk by César Jesús-Valls on Mar. 29th

ND280 upgrade



Super-FGD under construction

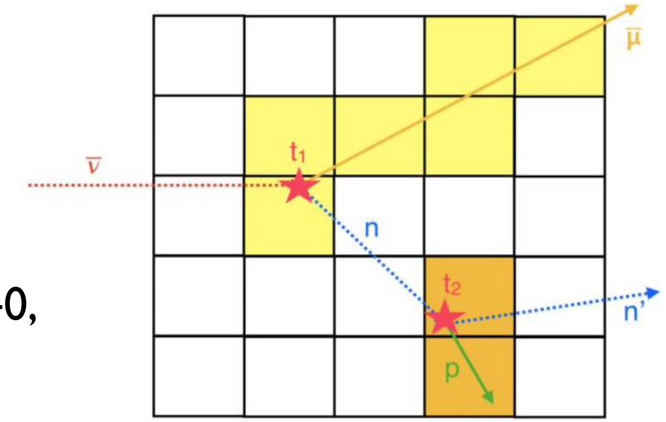
Super-FGD structure



Near detector upgrade

- 4π acceptance like Super-Kamiokande.
- Low momentum threshold for hadrons (especially protons).
- Better separation of electron / γ-ray.
- Neutron kinematics measurement using ToF.

Neutron measurement using ToF



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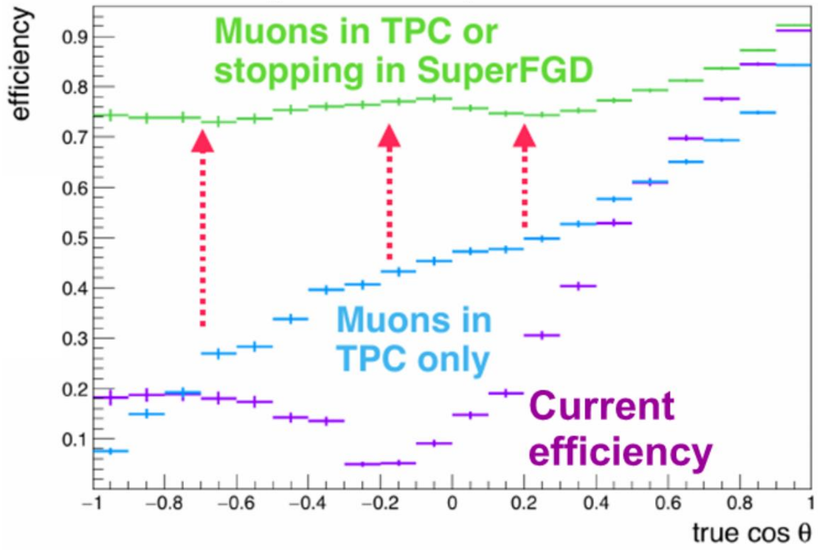
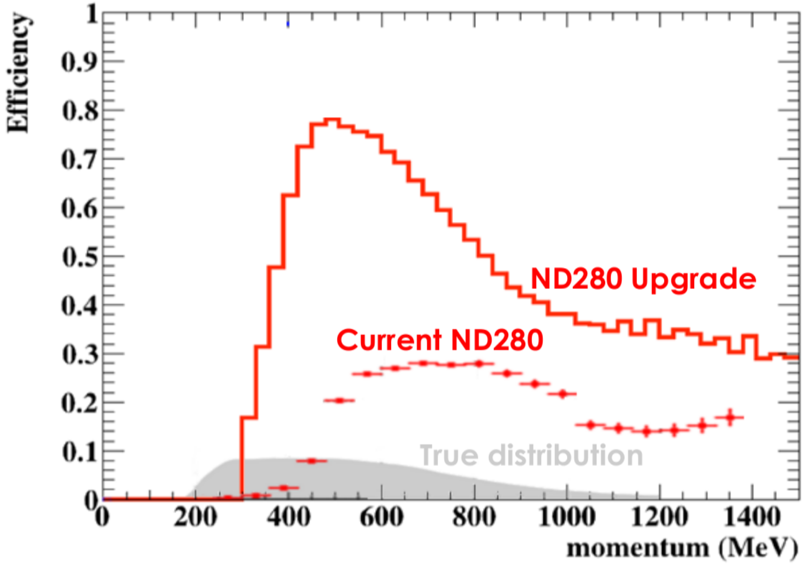
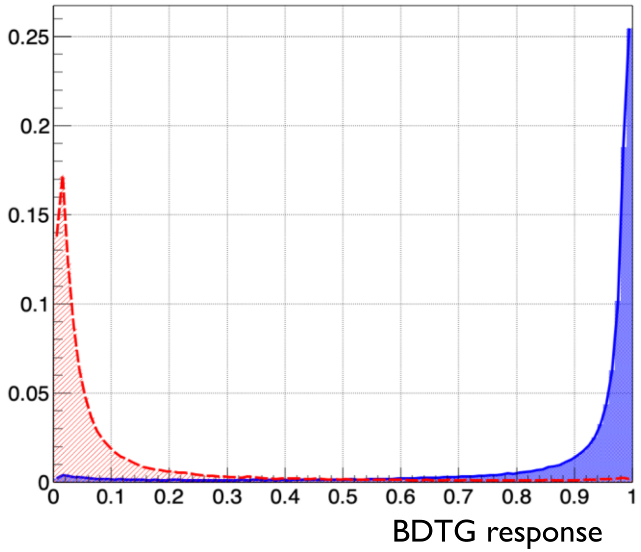
Muon detection efficiency vs angle



Proton detection efficiency vs momentum



Electron / γ-ray separation



Summary

- T2K aims for precise measurement of neutrino oscillations and search for CP violation.
- Oscillation analysis using 3.64×10^{21} POT data with many improvements.
- World-leading measurement of atmospheric mixing parameters.
- Large region of δ_{CP} excluded at 3σ. CP conservation ($\sin\delta_{CP} = 0$) excluded at 90%.
- Upgrade of accelerator, beamline and near detector ongoing for more precise measurement of neutrino oscillations.