Latest Results and Plans from T2K

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- Come in three different flavours e, μ & τ

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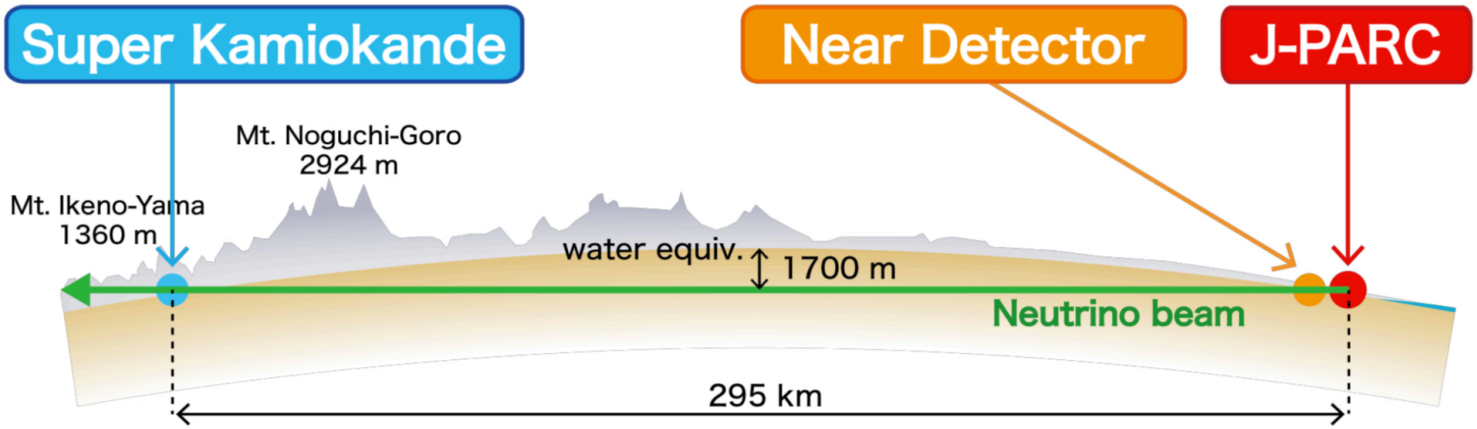
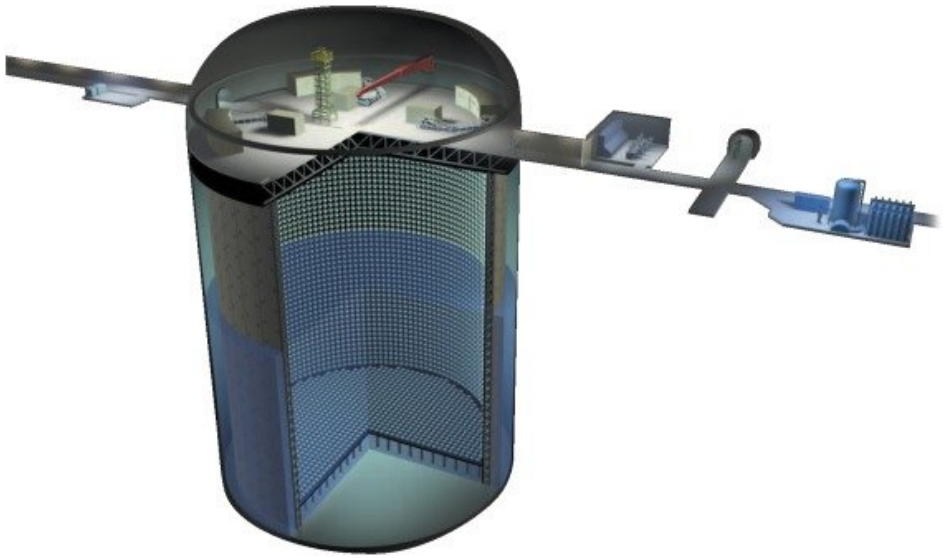
- What are ν mixing angles? $\theta_{12} \sim 33^\circ$, $\theta_{23} \sim 45^\circ$, $\theta_{13} \sim 9^\circ$
- What are masses of ν? $\Delta m^2_{21} \sim 7.5 \times 10^{-5}\,\text{eV}^2$, $\Delta m^2_{32} \sim 2.4 \times 10^{-3}\,\text{eV}^2$
- Dirac or Majorana masses? ? $\nu = \bar{\nu}$
- What is the mass hierarchy? ? $\nu_3 > \nu_2 > \nu_1$
- Is there CP violation for νs? ? $P_{\mu e} = P_{\bar{\mu}\bar{e}}$

T2K Experiment



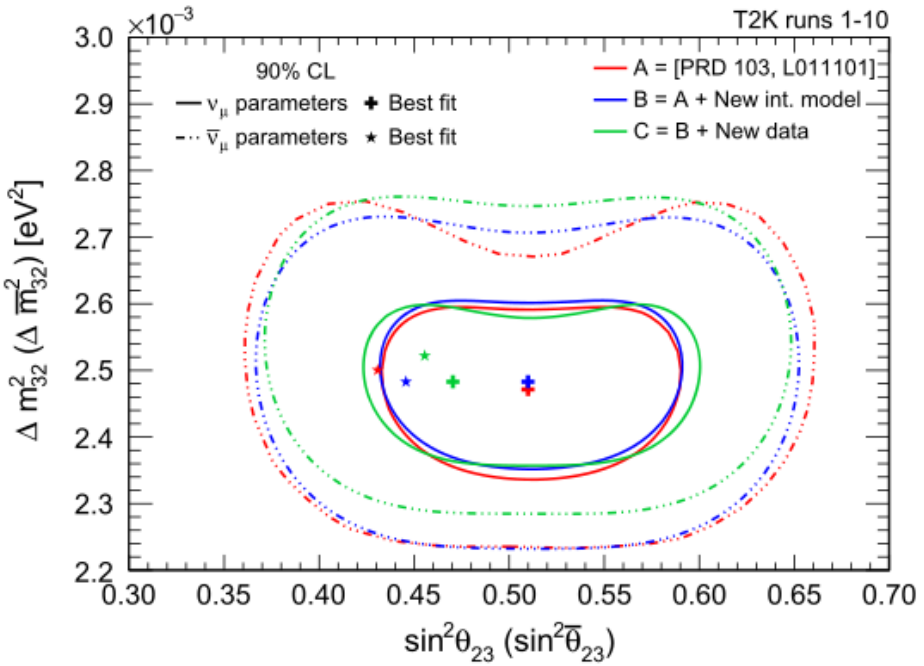
- J-PARC facility produces an intense 2.5° off-axis beam of ν_μ
- $<$1% of flux is ν_e
- Neutrino flux peaks at 0.6 GeV
- Both ν & $\bar{\nu}$ mode
- Super-Kamiokande detector, 295 km away. Main goal is to measure the oscillation parameters



Updated T2K measurements of ν_μ & $\bar{\nu}_\mu$ disappearance using 3.6×10^{21} POT [1]

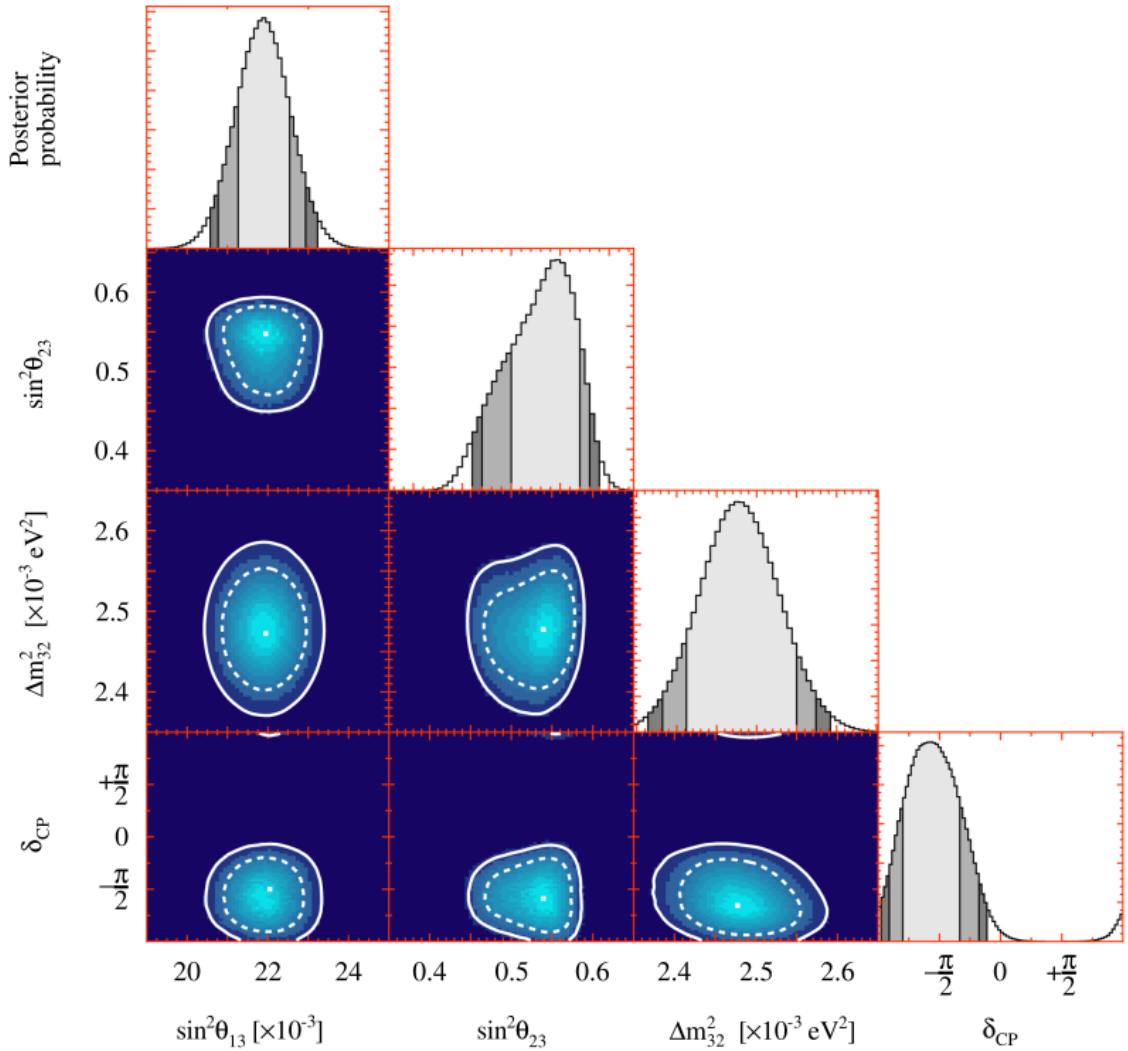
- 2 μlike FD samples (FHC/RHC mode is 90%/60% $\nu/\bar{\nu}$)
- $\sigma_{\bar{\nu}}$ typically $\sigma_\nu/2$
- Combined fit for ν & $\bar{\nu}$ done in RHC mode & ν and $\bar{\nu}$ parameters are varied separately
- Fitted in log-likelihood scheme

- $\bar{\nu}_\mu$ selection improved, data set doubled
- New flux model from NA61/SHINE 2009 replica target $\pi^\pm$ yield data
- Improved FSI uncertainties
- Syst. error reduced by 45%/9% for 1Rμ ν-mode/$\bar{\nu}$-mode



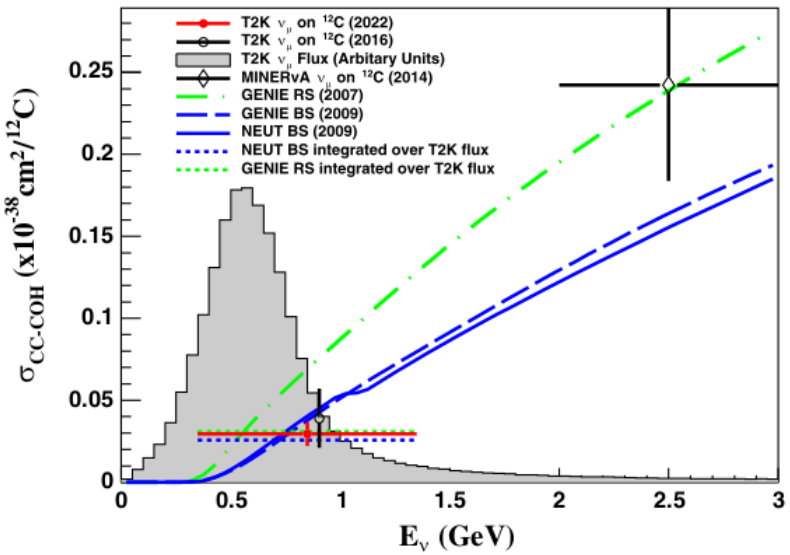
Measurements of neutrino oscillation parameters from the T2K experiment using 3.6×10^{21} protons on target [2]

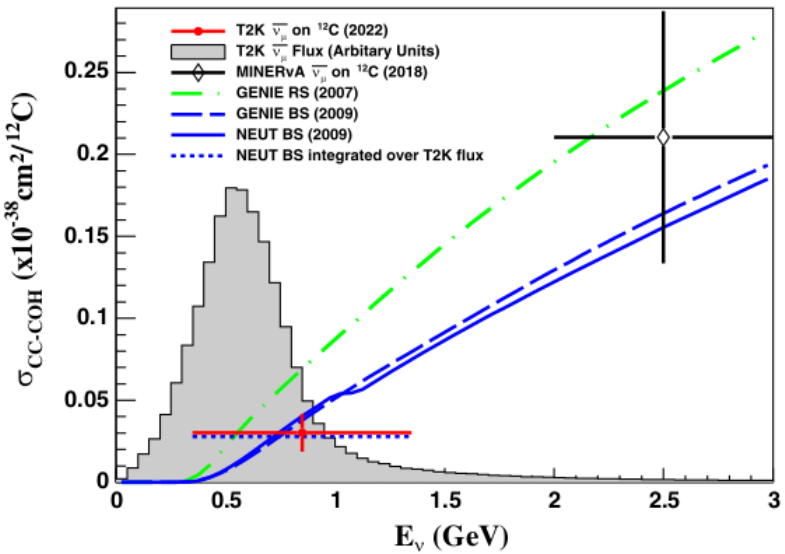
- New neutrino nucleus interaction model: spectral function
- 2D probability of nucleon $|p|$ & removal energy, E_{rmv}
- Marginalised posterior prob. ρ data fit including reactor constraint
- Exclude CP-conserving values of δ_{CP} at between 90% and 2σ
- Weak preference for the upper octant and normal mass ordering



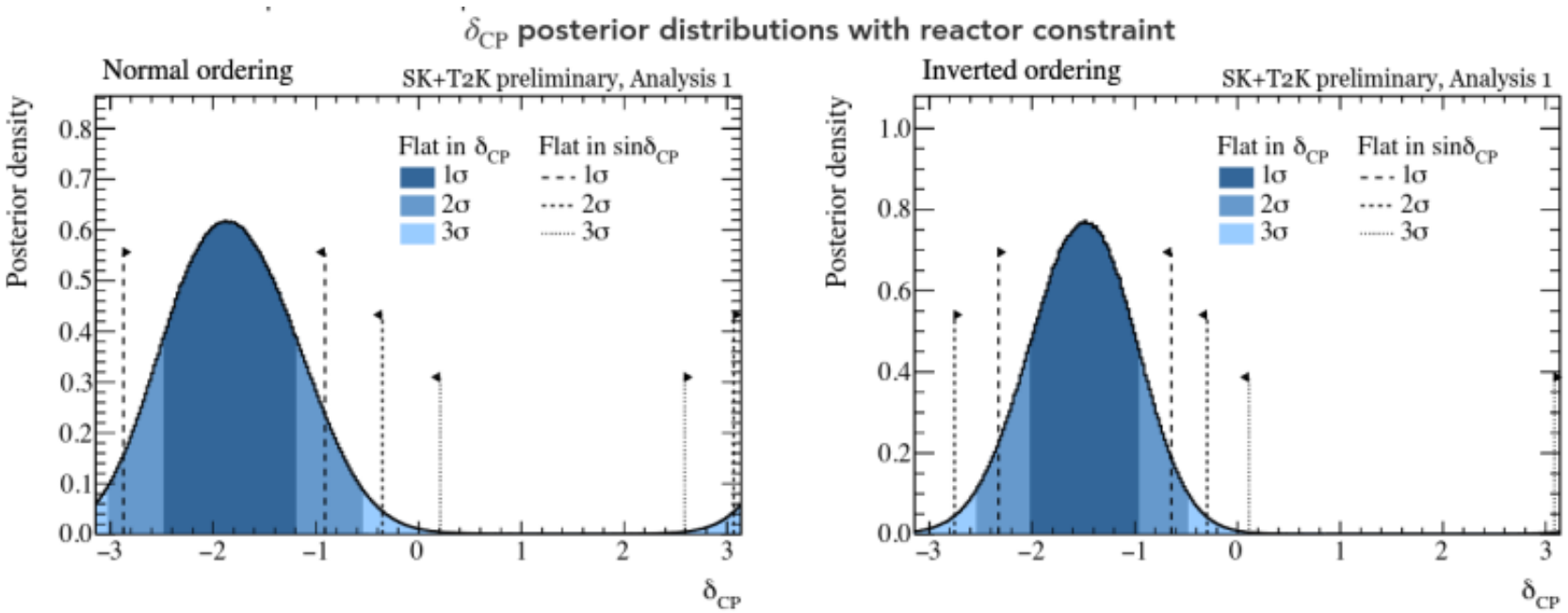
Measurements of the ν_μ and $\bar{\nu}_\mu$-induced coherent charged π production xsec on ^{12}C by the T2K experiment [3]

- Rare interaction mode that is not well modelled theoretically
- 11.54×10^{20} POT FHC & 8.15×10^{20} POT RHC
- Cuts on VA and $|t|$ then fitted with binned Log-likelihood fitter
- Main uncertainty is statistical & low Q^2 CC-RES suppresion uncertainty
- Results agree with NEUT Berger-Sehgal and GENIE Rein-Sehgal models within errors



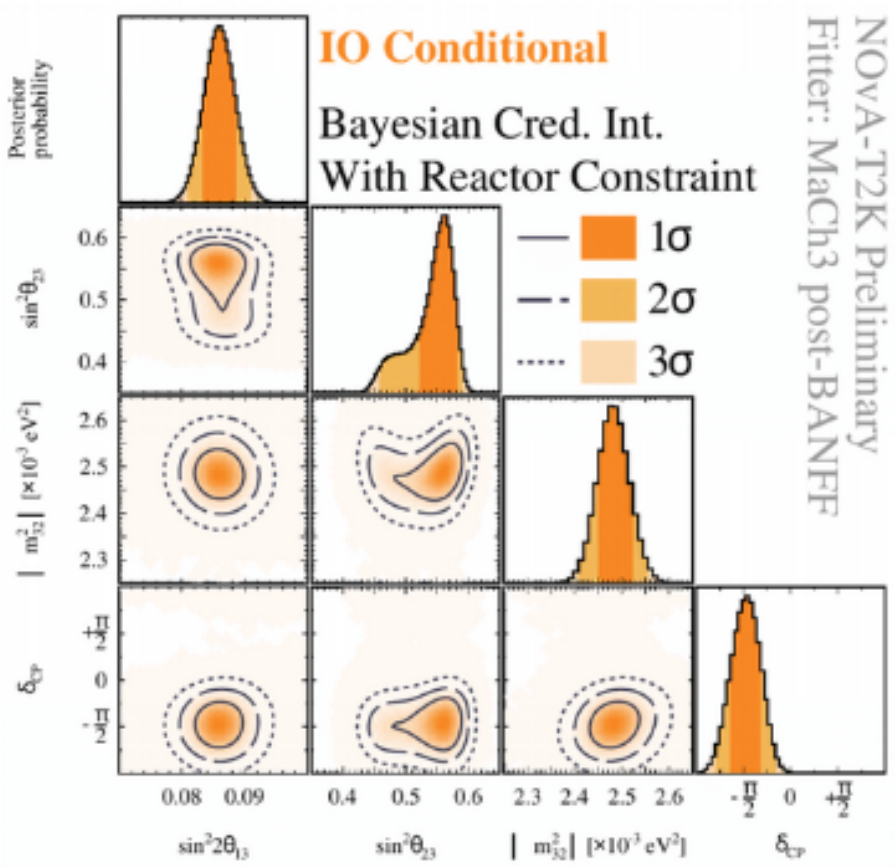


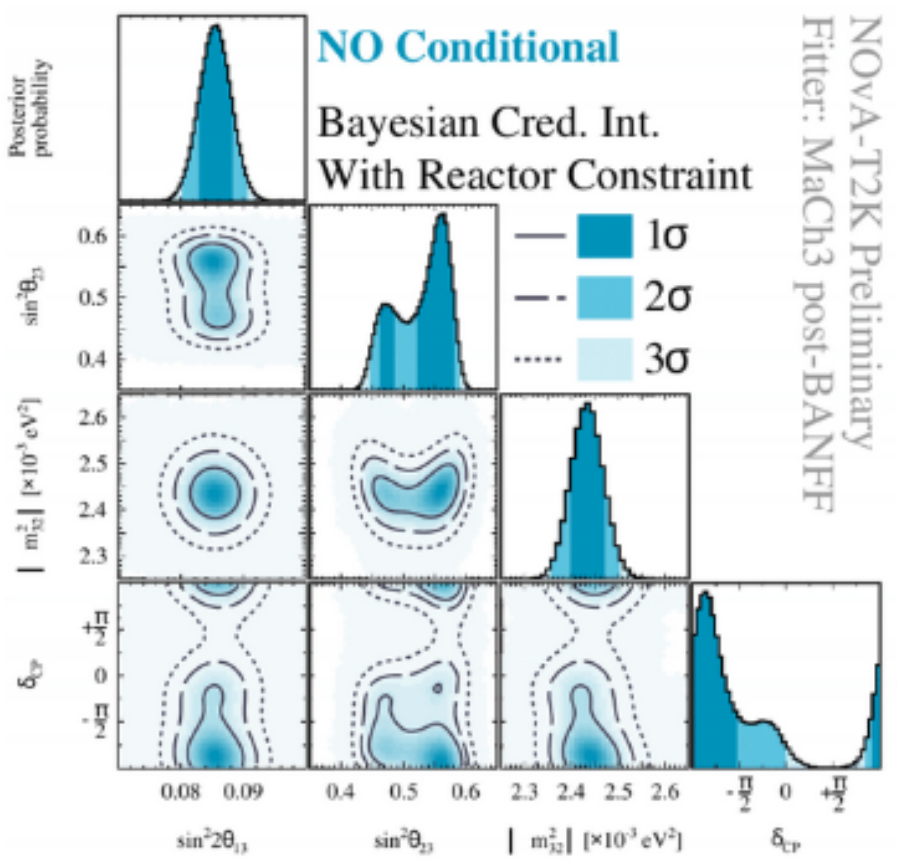
T2K+SK joint fit



- Gains can be made by combining with the atmospheric samples from SK, recently presented at NNN conference
- CP conserving values are excluded at 2σ when the flat prior in δ_{CP} is applied

T2K+NOνA joint fit

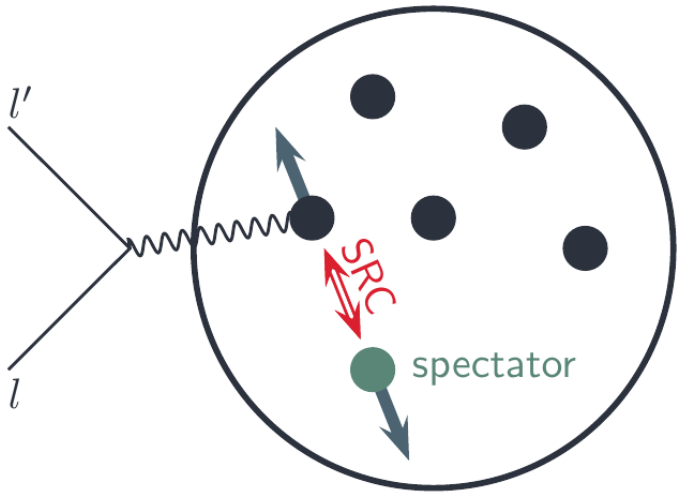


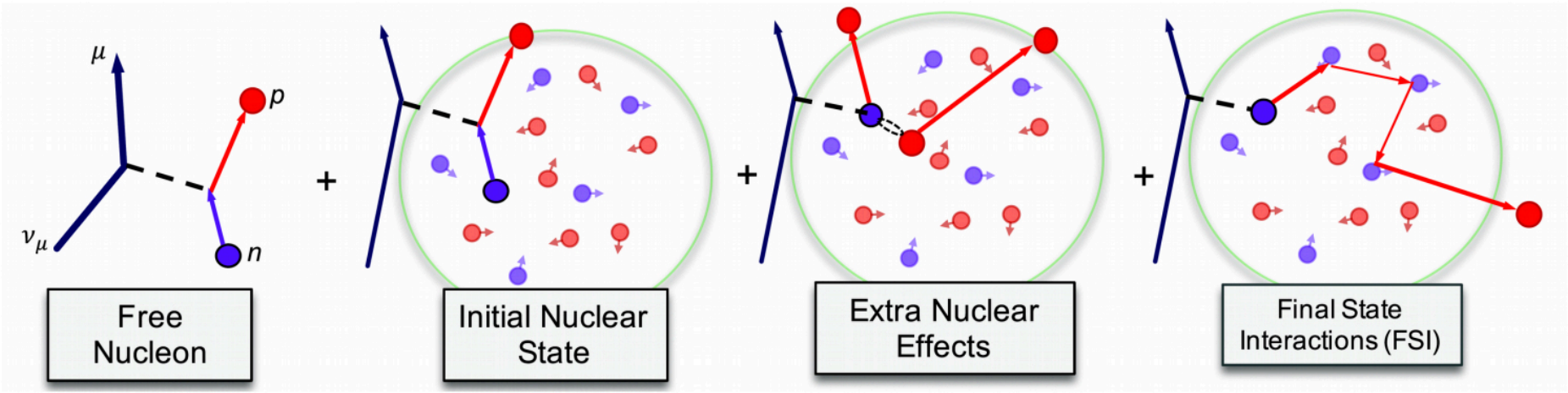


- Very exciting result shown at seminar last week: `https://kds.kek.jp/event/49811/`
- Combines the distinctive power of both experiments for most stringent result yet

ND280 Upgrade: physics goals

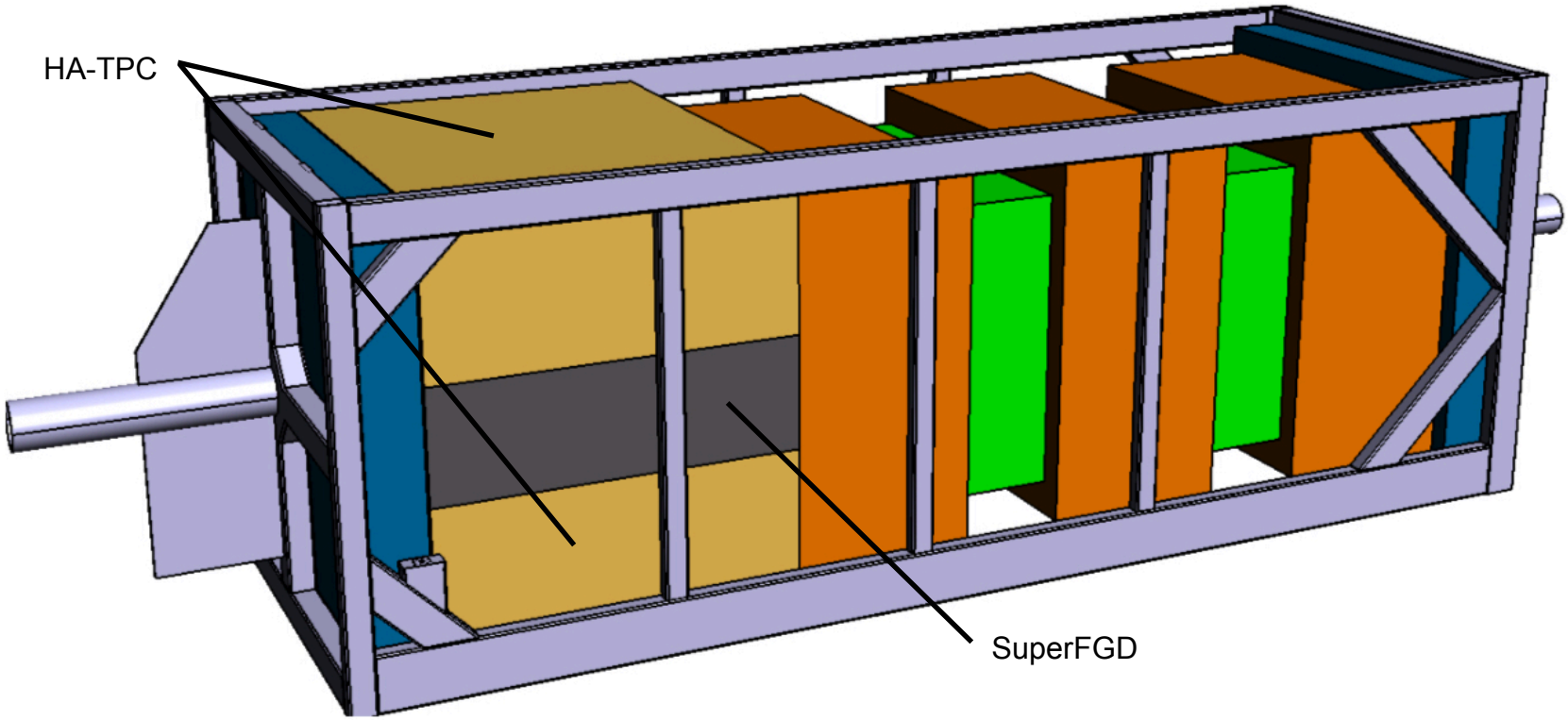
- Reduce systematic errors on flux and cross-section necessary for oscillation analysis to the 3-4% level
  - Uncertainties from CCMN modelling
    - ★ Measure kinematic imbalance (transverse variables) improve models for background processes
  - Uncertainties from FSI
    - ★ Distinguish between different final state topologies & have lower momentum threshold - FSI can modify the multiplicity and kinematics of secondary particles
    - ★ 4π coverage - match SK





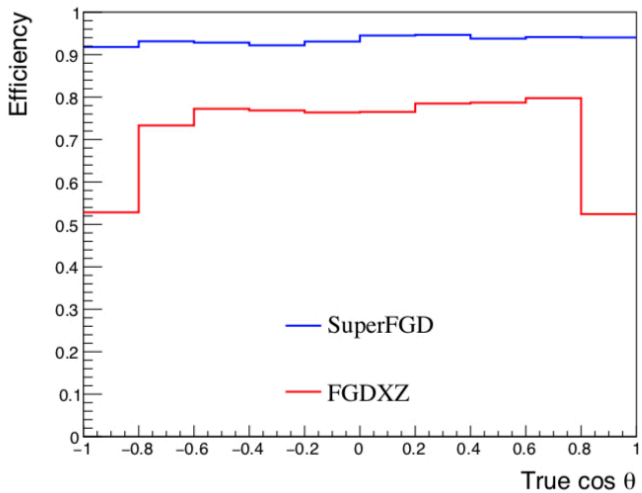
ND280 Upgrade design

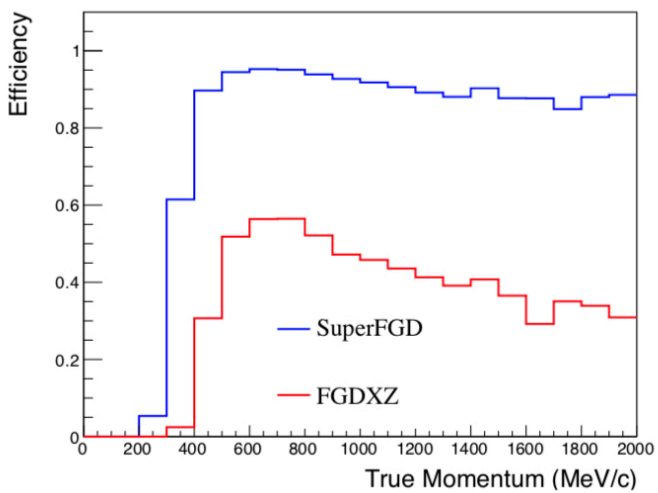
- **SuperFGD:** novel fully active 3D fine-grained scintillator detector
- **HA-TPC:** used for 3D track reconstruction, p measurement and PID
- **TOF:** 6 planes with $\sim$5 m^2 surface area surrounding the SuperFGD and the TPCs



ND280 Upgrade design

- **SuperFGD:** 2 million fully active scintillator cubes allows high fidelity image reconstruction
- **HA-TPC:** Capture high angle tracks leaving the SuperFGD, increases the acceptance of the ND matching FD
- **TOF:** High resolution timing allows OOFV background events to be distinguished and rejected

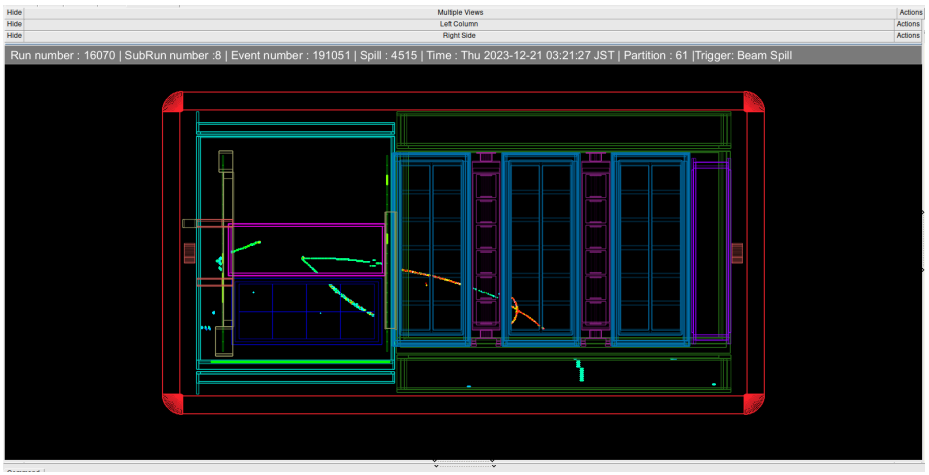


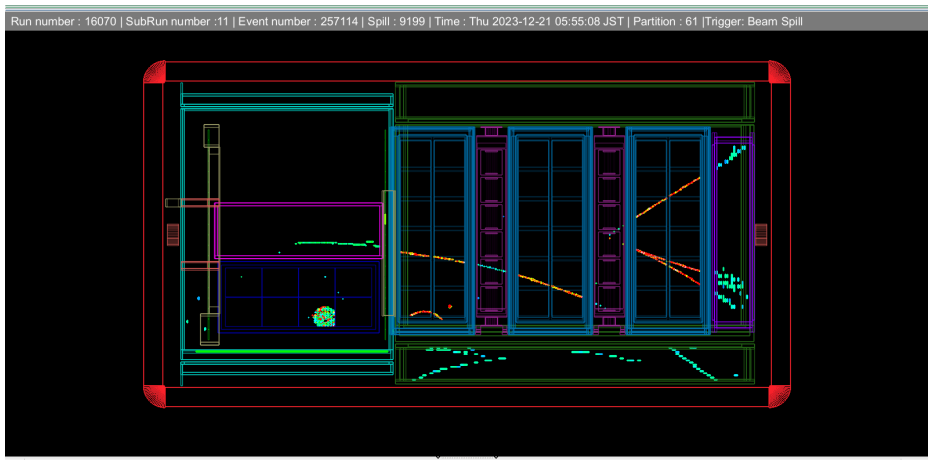


- Events in extended phase space can be reconstructed and studied
- **Can access new physics measurements with upgraded detector**

ND280 Upgrade in action

- Throughout September/October 2023 upgrade installed at J-PARC
- In November/December 2023 commission run in the J-PARC
- During this first run event displays of through going events for the full upgrade were made!
- Detectors performing as expected - many further refinements to come
- Looking forward to first physics measurements in 2024!





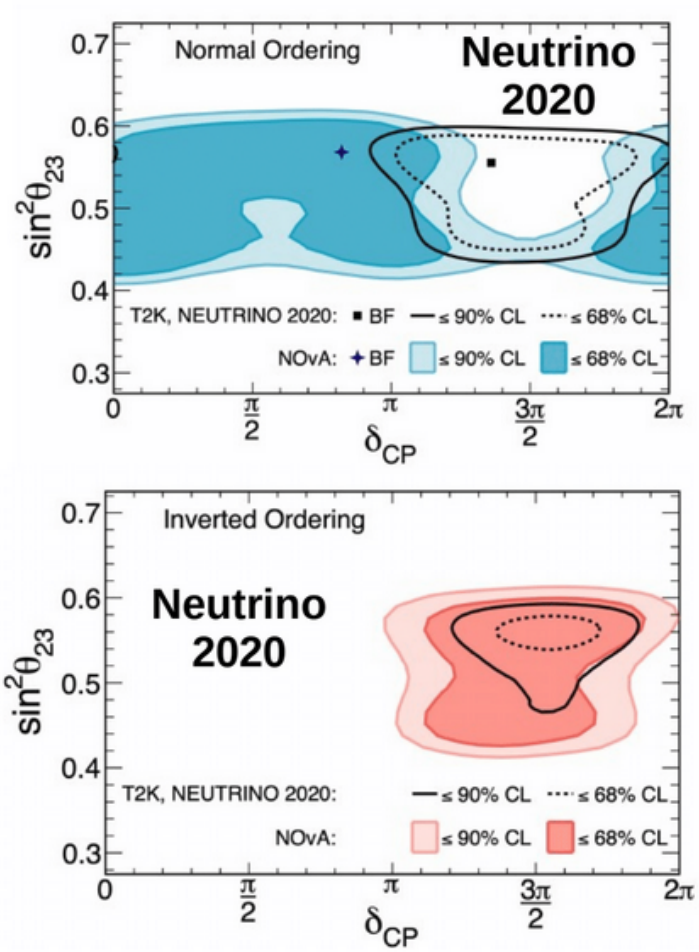
Conclusions

- T2K continues to make exciting progress
- The plans of T2K phase II are now being realised
  - stable beam operation with horns at 320 kA
  - stable beam operation with beam power maintained at 760 kW
  - ND280 upgrade installed and taking data
  - Additional off-axis detector (WAGASCI) analysis mature
  - updated neutrino oscillation analysis
  - new and unique cross-section measurements
- First results from joint analyses T2K+SK & T2K+NOνA
- First public conference display of events in ND280 upgrade!
- First public conference display of events with beam upgrades!
- Latest neutrino oscillation results confirm validity of PMNS oscillation formalism
- New and improved measurements of ν & $\bar{\nu}$ coherent scattering in agreement with GENIE and NEUT models
- Exciting new measurements with ND280 upgrade to come shortly!

T2K+NOvA

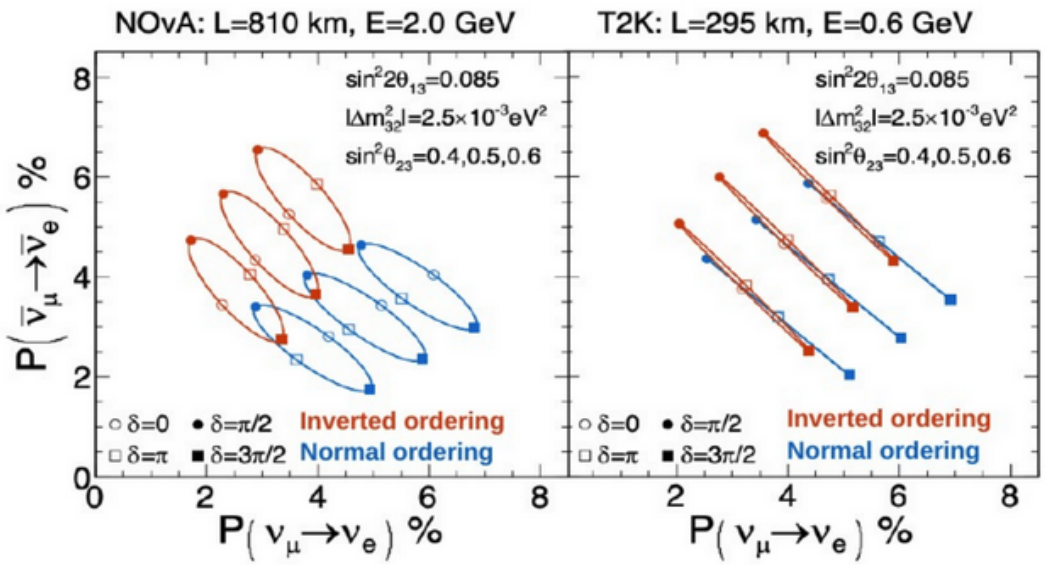
Why combine NOvA and T2K?

- ☆ Different baselines and energies **lift degeneracies**
- ☆ **Consistent statistical inference** across full dimensions of phase space
- ☆ **Proper combination of full detailed likelihood**
- ☆ Full implementation of **energy reconstruction and detector effects of both experiments**
- ☆ Review of each experiments' **models, systematic uncertainties and possible correlations**
- ☆ In-depth examination of **different analysis approaches** driven by contrasting detector design



Combining T2K and NOvA

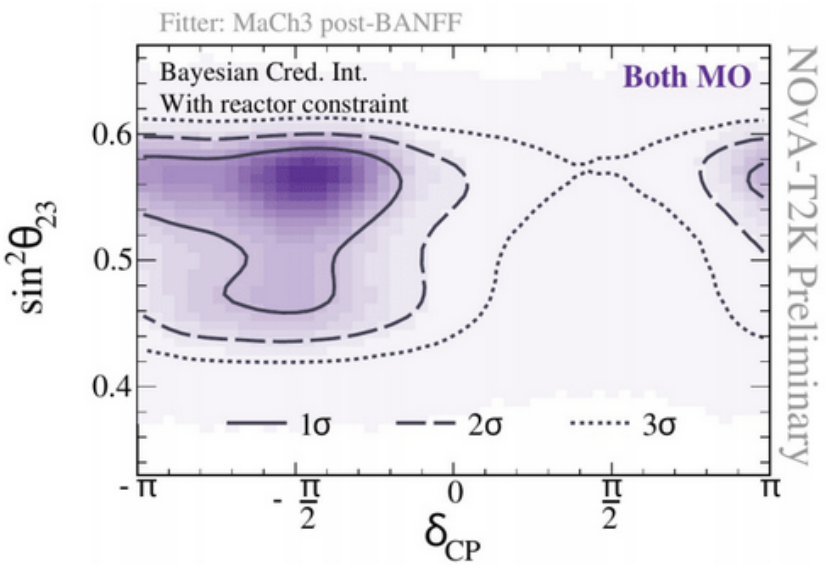
- **Energies** and **baselines** mean different oscillation probabilities
- **NOvA**:
  - Better Mass Ordering sensitivity
  - Degenerate values around $\delta_{CP}=+\pi/2$ and $\delta_{CP}=-\pi/2$
- **T2K**:
  - Better δ_{CP} sensitivity
  - Degenerate values around $\delta_{CP}=0$ and $\delta_{CP}=\pi$
- **Joint Analysis** probes both spaces **lifting degeneracies of individual experiments**

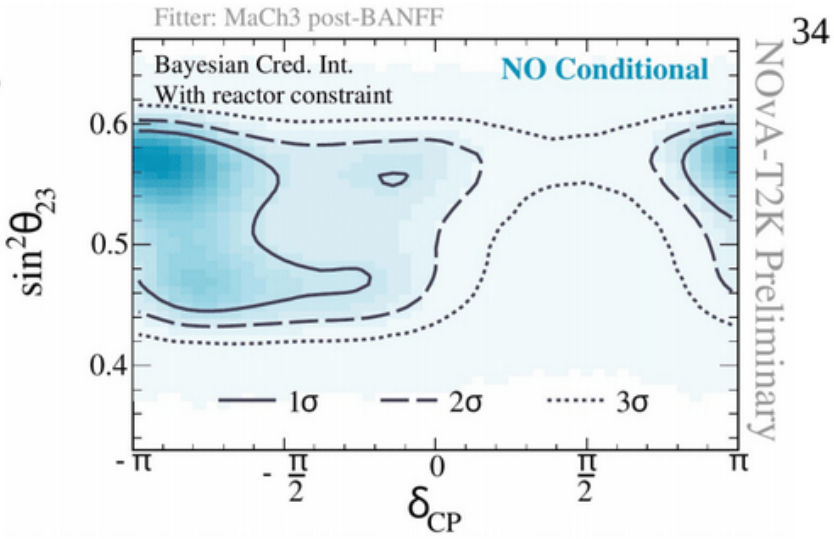


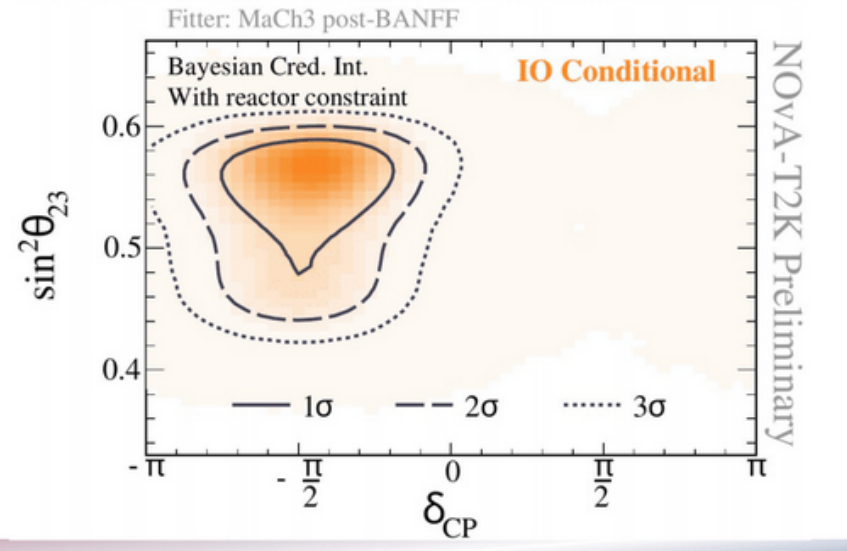
T2K+NOvA

Joint Analysis Results: δ_{CP}

- **Both mass orderings:** higher posterior density around δ_{CP}=-π/2
- **Normal**: a wider range of values with higher posterior density closer to δ_{CP}=±π
- **Inverted**: enhanced preference for δ_{CP}=-π/2

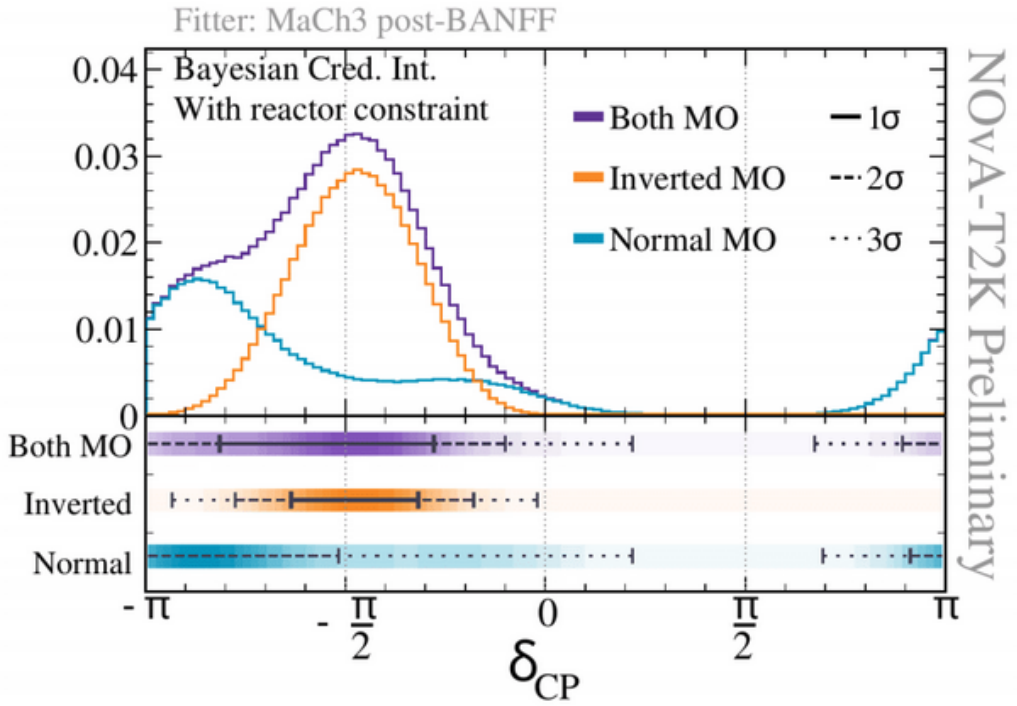




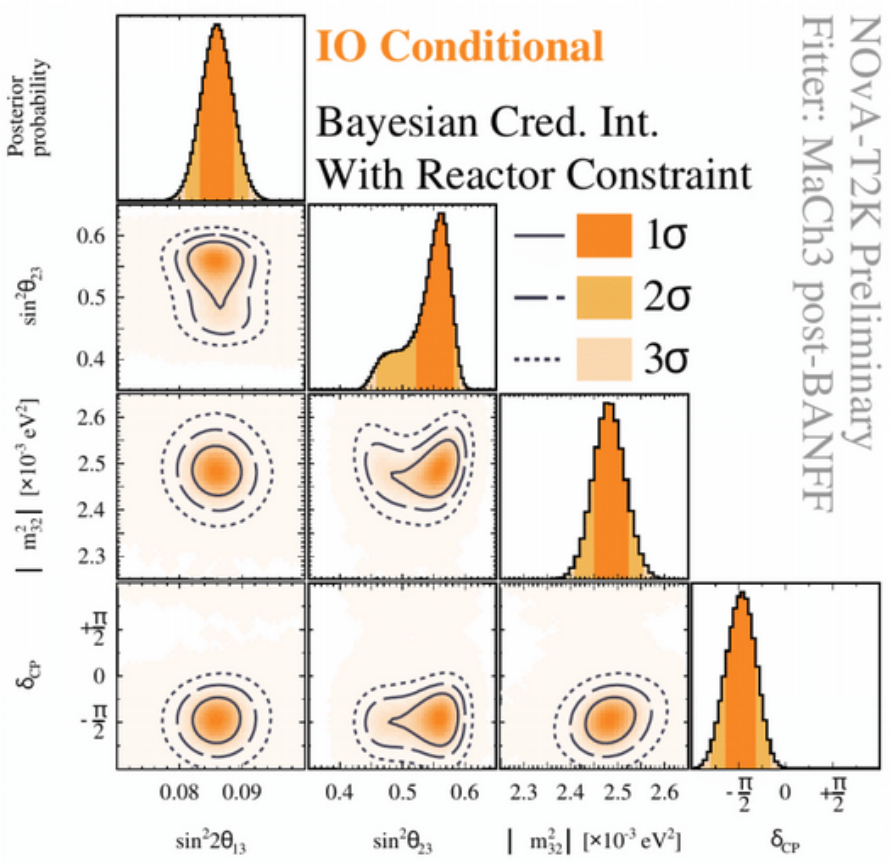


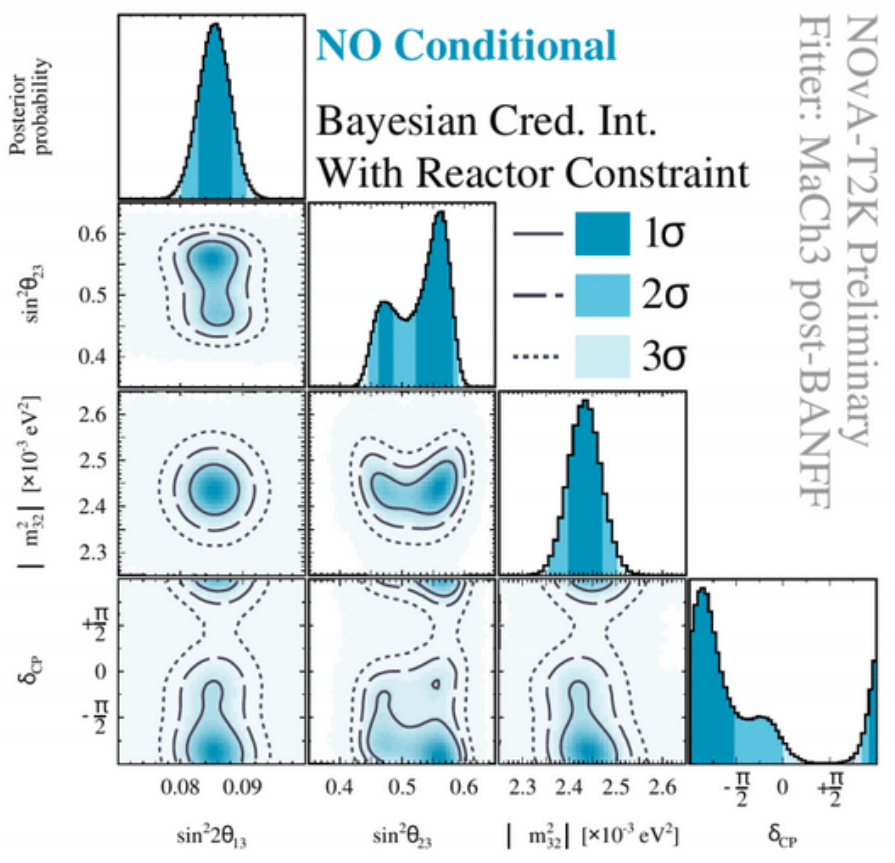
Joint Analysis Results: δ_{CP}

- When marginalised onto **1D** the change in the preference is clearer
- Normal Ordering allows for a **broad range** of possible δ_{CP} values
- Clearly a tighter constraint in Inverted Ordering with $\delta_{CP}=0$ and $\delta_{CP}=\pm\pi$ **outside of the 3σ credible interval**
- **Neither ordering** has a preference for δ_{CP} values around $+\pi/2$



Summary of 1D and 2D results



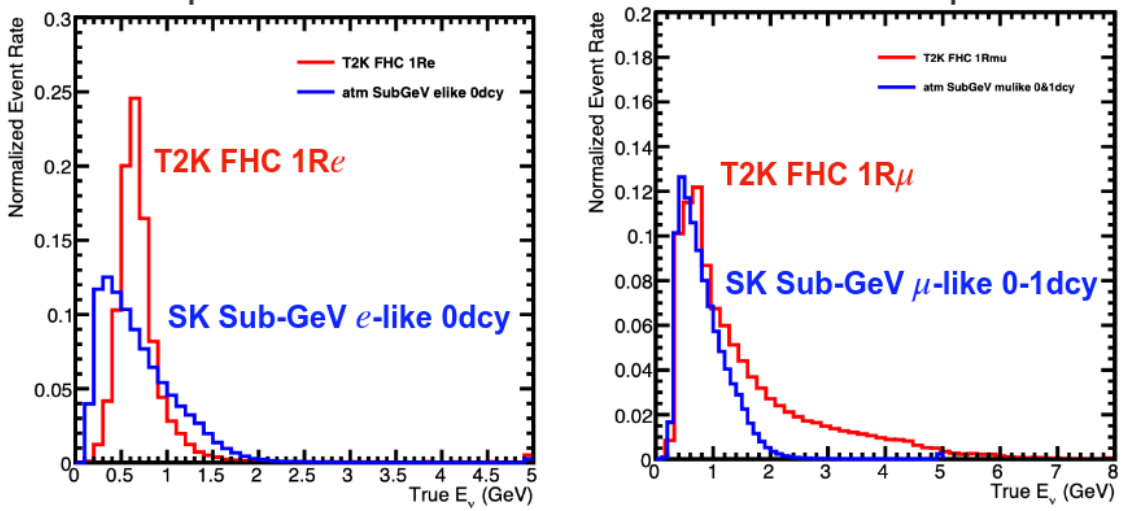


Motivation of the Joint Analysis

- We expect to have **several benefits beyond the increased statistics**.

- T2K and SK use the same detector and have samples with similar energy ranges and similar selections.
  - We can take into account the **correlations of the systematic uncertainties**.
  - **T2K near detector** can be used to constrain the cross-section uncertainties for the low-energy atmospheric samples as well.

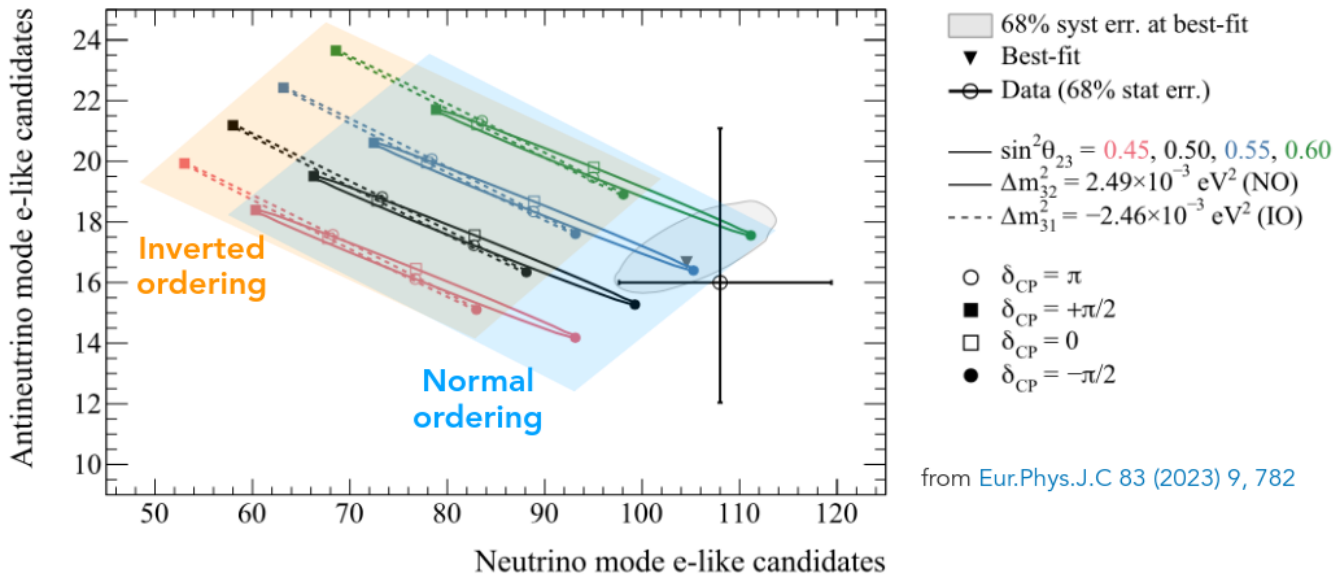
Comparison of the normalized flux of the selected samples



Motivation of the Joint Analysis

- The additional benefit of the joint fit
  - The event rate of $\nu_e/\bar{\nu}_e$ depends on the value of δ_{CP}.
  - However, δ_{CP} and **neutrino mass ordering** have a similar effect to the $\nu_e/\bar{\nu}_e$ event rates we observe in T2K (we call this "**degeneracy**" of the oscillation parameter).

Number of T2K beam $\nu_e/\bar{\nu}_e$ events with different sets of oscillation parameter values



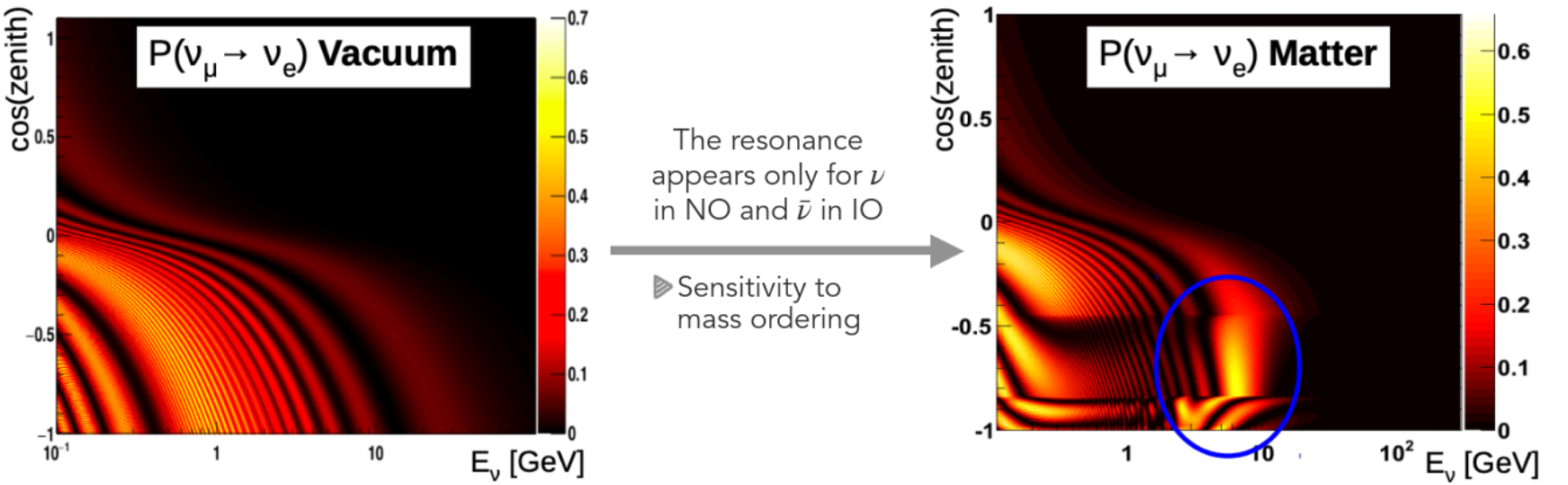
from Eur.Phys.J.C 83 (2023) 9, 782

Motivation of the Joint Analysis

- The additional benefit of the joint fit
  - SK has **stronger discrimination of the mass ordering** thanks to the **matter effect** at the few GeV regions, which is not degenerate with δ_{CP}.

Atmospheric neutrino oscillation probability (normal ordering)

from C. Bronner @ PANE 2018

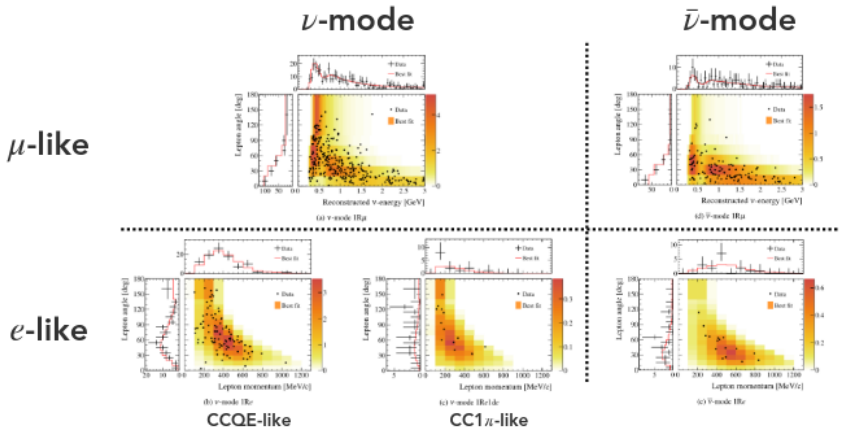


Data Set and Samples

- **5 T2K beam samples** and **18 SK atmospheric samples** are fitted simultaneously.
  - **T2K near detector** is used to constrain the beam flux and low-energy cross-section parameters.
  - Data set before Gd loading is used.

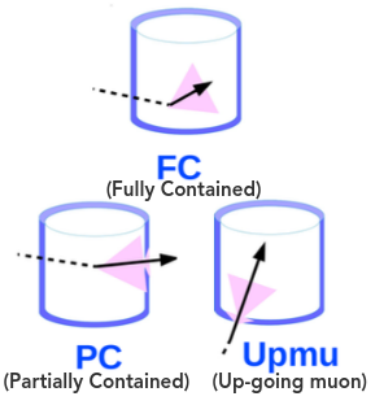
T2K Run 1-10 (not the latest analysis)
[Eur.Phys.J.C 83 (2023) 9, 782]

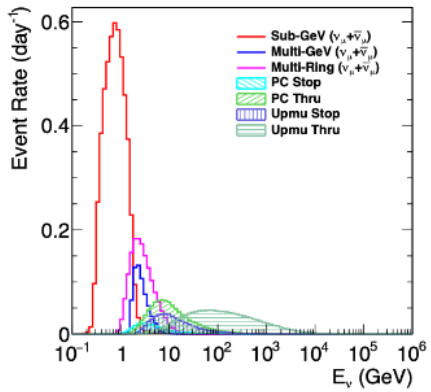
- Neutrino mode: 19.7×10^{20} POT
- Antineutrino mode: 16.3×10^{20} POT
- Mean neutrino energy ~ 0.6 GeV



SK IV atmospheric neutrinos
[PTEP 2019 (2019) 5, 053F01]

- 3244.4 days of data taking
- 18 samples depending on the event topologies and neutrino energies
- **Wider energy ranges** than T2K



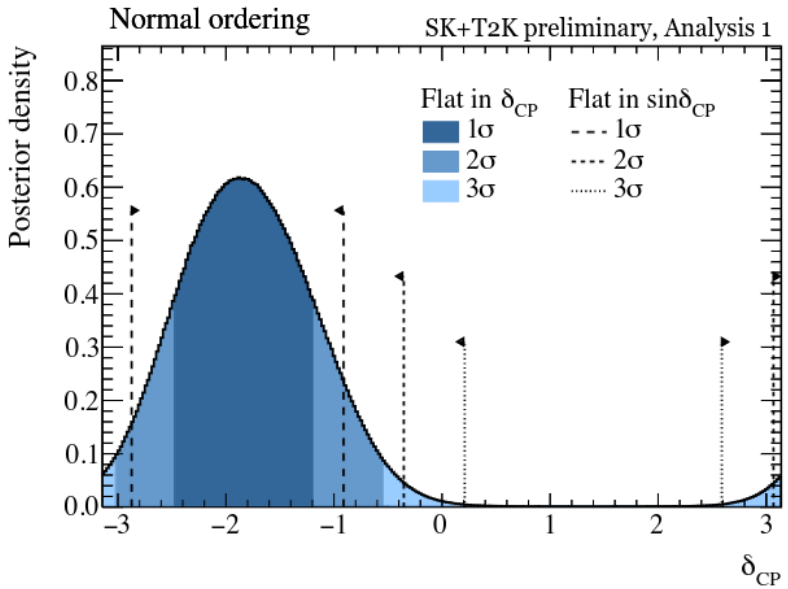


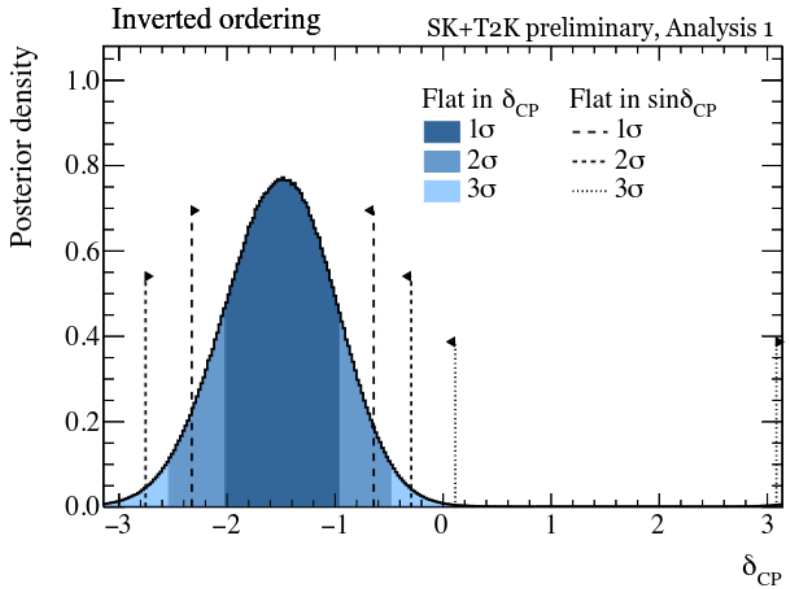
Data Fit δ_{CP} Credible Intervals

- δ_{CP} credible intervals
  - CP conserving values ($\delta_{CP} = 0, \pi$) are **excluded at** 2σ when the flat prior in δ_{CP} is applied.
  - However, $\delta_{CP} = \pi$ **is not excluded in normal ordering** when the flat $\sin \delta_{CP}$ prior is applied.

  [see backup for these prior choices]

δ_{CP} posterior distributions with reactor constraint

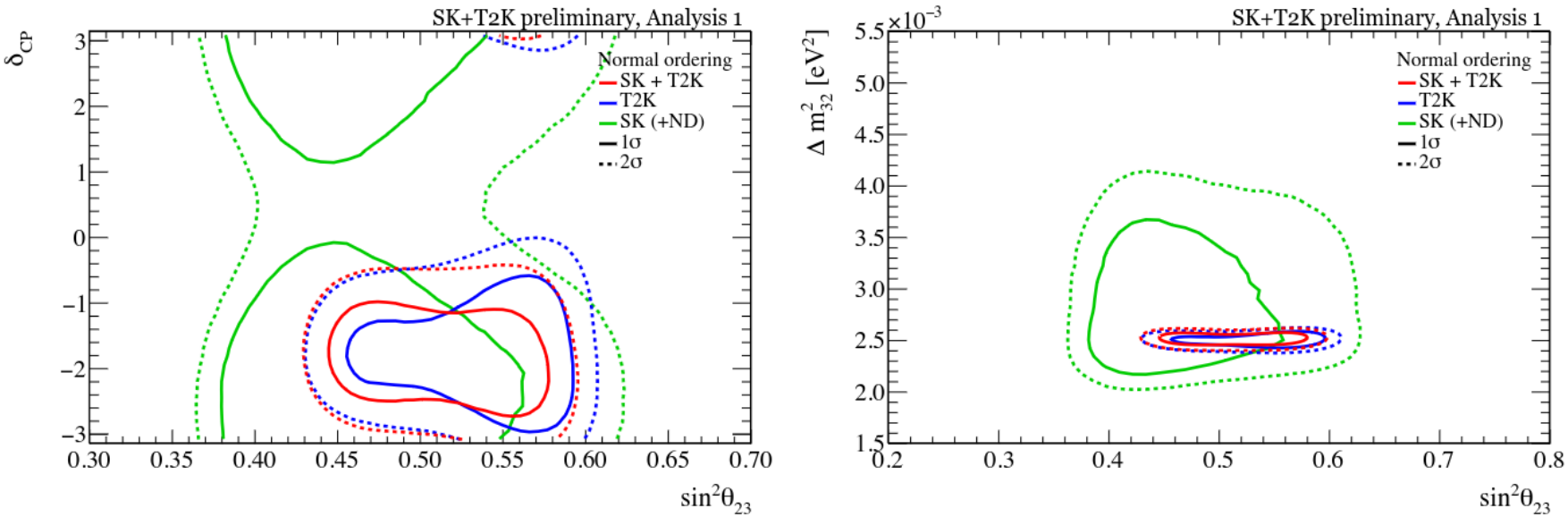




Data Fit SK+T2K/T2K/SK Comparison

- 2D posterior distributions for T2K-only and SK-only (with T2K near detector constraint) fits compared to the joint SK+T2K fit.
  - The constraints are largely dominated by T2K but SK also has a significant contribution on the octant.

Comparison of the 2D posterior distribution for the fit with different sets of samples



[1] K. Abe et al. Updated T2K measurements of muon neutrino and antineutrino disappearance using 3.6×10^{21} protons on target. *Phys. Rev. D*, 108(7):072011, 2023.

[2] K. Abe et al. Measurements of neutrino oscillation parameters from the T2K experiment using 3.6×10^{21} protons on target. *Eur. Phys. J. C*, 83(9):782, 2023.

[3] K. Abe et al. Measurements of the ν_μ and ν_μ-induced coherent charged pion production cross sections on C^{12} by the T2K experiment. *Phys. Rev. D*, 108(9):092009, 2023.