Recent results from T2K and joint analyses with Super-K and NOvA

~560 members, 74 institutes, 15 countries(incl. CERN)

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2024 July 8, 20th Rencontres du Vietnam— PASCOS

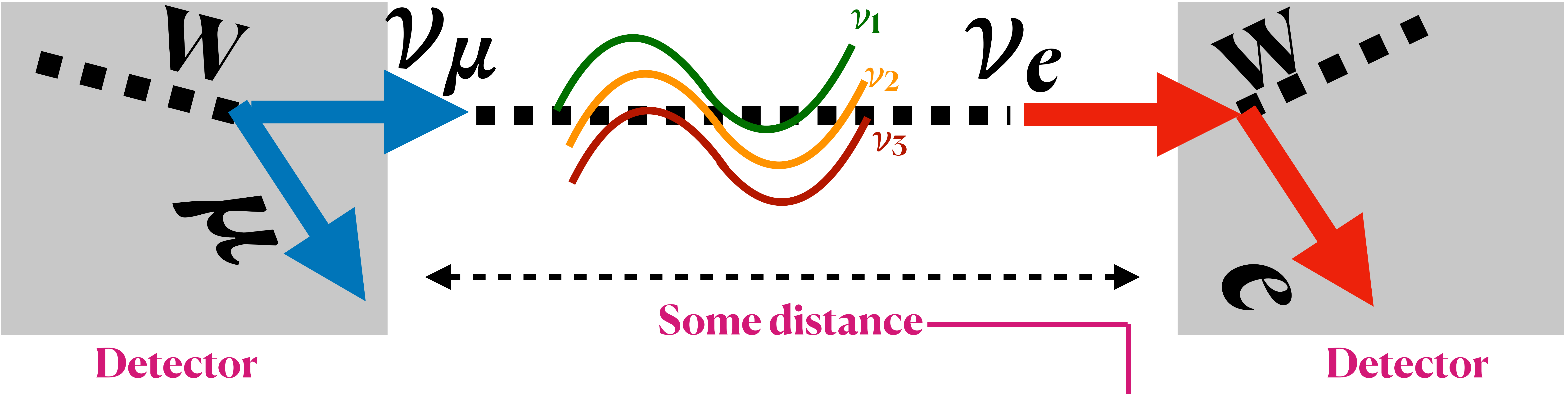
Outline

- Neutrino oscillation and measurements with T2K
- Latest neutrino oscillation results from T2K
- Results from first joint analyses with Super-Kamiokande and NOvA
- Future prospects

Neutrino oscillation & measurements

- Well-established neutrino oscillation phenomenon
- *QM explained*: Neutrinos with definite flavor (e, μ, τ) are not states with definite mass $|\nu_i; m_i>$ but linear superposition or mixed states
- Leptonic mixing amplitudes manifest themselves in flavor-change probabilities when $\Delta m^2_{ij} \neq 0$

Giving time to propagate, neutrinos materialize in a different flavor than their initial.



$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right)$$

$$\pm 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

(+) for ν

(-) for $\overline{\nu}$

where $\Delta m^2_{ij} = m^2_i - m^2_j$

ν energy

Measuring the oscillation pattern/probability, *typically as function of neutrino energy*, allows us to extract leptonic mixing parameters and mass-squared difference

Ref: "The legacy of neutrino oscillation experiments" by Jose W. F. Valle

Leptonic mixing: Present landscape T2K

- Global data is consistent with formulated 3x3 unitary matrix U_{PMNS}, parameterized with **3 mixing angles** $(\theta_{12}, \theta_{13}, \theta_{23})$ and **one irreducible Dirac CP-violation phase** δ_{CP}
  - If neutrino is a **Majorana particle,** two additional phases (ρ_1, ρ_2) included in U_{PMNS}, *which are inaccessible in neutrino oscillation measurements*
- Oscillation patterns are driven by **two mass-squared splittings**

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix} \text{Diag}(e^{i\rho_1}, e^{i\rho_2}, 1)$$

$\theta_{12} \approx \pi/6$

$\theta_{13} \approx \pi/20$ **$\neq$ CKM?**

$\theta_{23} \approx \pi/4$

δ_{CP}?

$c_{ij} = \cos\theta_{ij};\ \ s_{ij} = \sin\theta_{ij}$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \approx 7.5 \times 10^{-5}(eV^2/c^4)$$

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| \approx 2.5 \times 10^{-3}(eV^2/c^4)$$

Mass ordering is undisclosed

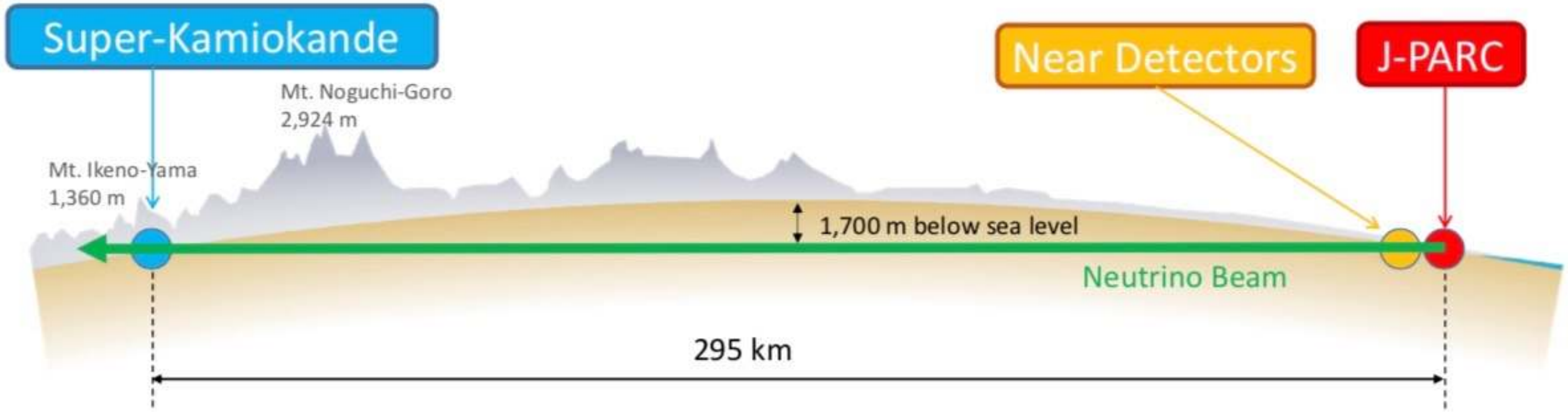
$m_3 > m_2 > m_1 \ or \ m_2 > m_1 > m_3$

Also, $m_{lightest} = ?$

Ref: "The legacy of neutrino oscillation experiments"/ NOvA and others

Dive into neutrino oscillation measurements

$\vec{o} = (\Delta m^2_{21}, \Delta m^2_{31};$
$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP};$
$\rho_{mat.}, L)$



$$N^{\nu_\beta}_{pred.}(E^{reco.}_\nu, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E^{true}_\nu)$$ ← Intense and well-controlled $\nu(\bar{\nu})$ sources

Prediction @ Far det.

$$\times P(\nu_\alpha \rightarrow \nu_\beta \,|\, E^{true}_\nu, \vec{o})$$ ← Optimized baseline/energy; parameter sensitivity enhanced by external constraints/ multi-exp. joint analysis

$$\times \sigma^{\nu_\beta}_{int.}(E^{true}_\nu)$$ ← Well-modeled $\nu/\bar{\nu}$ interactions with nucleons/nuclei

$$\times M_{det.} \times \epsilon^{\nu_\beta}_{det}(E^{true}_\nu) \times S_{det.}(E^{true.}_\nu, E^{reco.}_\nu)$$ Big detector w/ excellent flavor-identified & energy-reconstructed capabilities

$R_{det.}(E^{true.}_\nu, E^{reco.}_\nu)$ for brief

(Challenge for precision measurements is limited statistics rooted from extremely weak interaction of neutrinos. So much effort is required to overcome this.)

Dive into neutrino oscillation measurements

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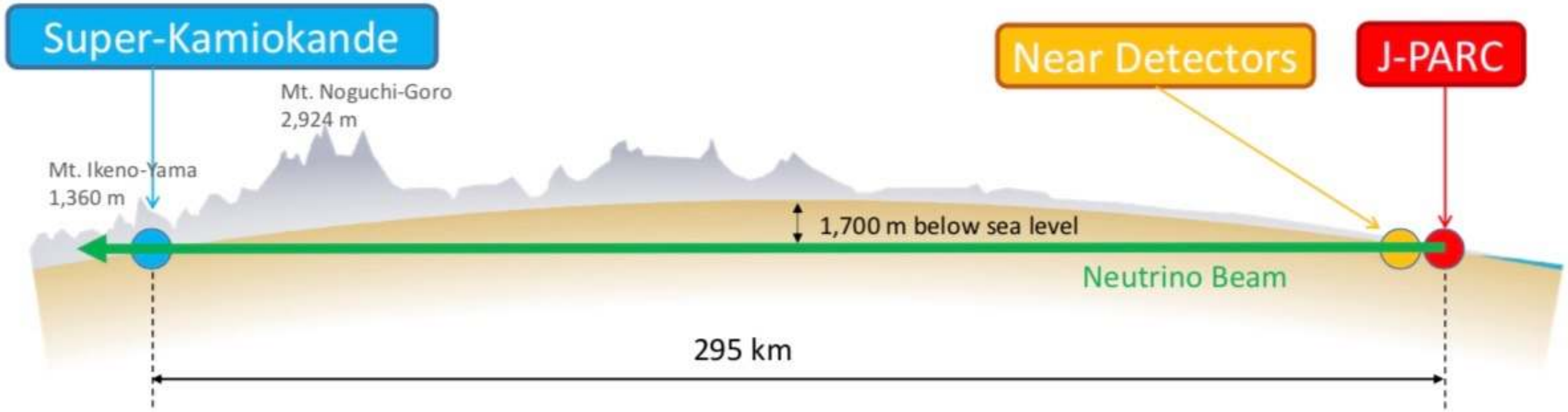


$$N^{\nu_\beta}_{pred.}(E^{reco.}_\nu, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E^{true}_\nu)$$ ← Intense and well-controlled $\nu(\bar{\nu})$ sources

Prediction @ Far det.

$$\times P(\nu_\alpha \to \nu_\beta | E^{true}_\nu, \vec{o})$$ ← Optimized baseline/energy; parameter sensitivity enhanced by external constraints/ multi-exp. joint analysis

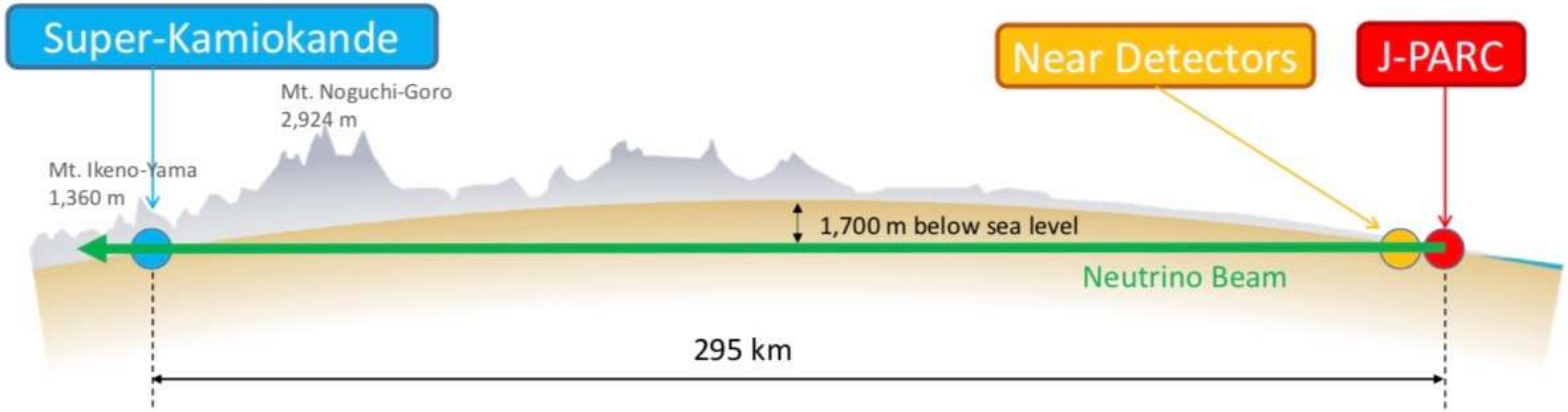
$$\times \sigma^{\nu_\beta}_{int.}(E^{true}_\nu)$$ ← Well-modeled $\nu/\bar{\nu}$ interactions with nucleons/nuclei

$$\times M_{det.} \times \epsilon^{\nu_\beta}_{det}(E^{true}_\nu) \times S_{det.}(E^{true.}_\nu, E^{reco.}_\nu)$$ Big detector w/ excellent flavor-identified & energy-reconstructed capabilities

$R_{det.}(E^{true.}_\nu, E^{reco.}_\nu)$ for brief

Largely constrained by Near detector

Dive into neutrino oscillation measurements



$\vec{o} = (\Delta m^2_{21}, \Delta m^2_{31};$
$\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP};$
$\rho_{mat.}, L)$

$N^{\nu_\beta}_{pred.}(E^{reco.}_\nu, \vec{o}) =$ $\Phi^{\nu_\alpha}_{flux}(E^{true}_\nu)$ ← Intense and well-controlled $\nu(\bar{\nu})$ sources

Prediction @ Far det.

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$R_{det.}(E^{true.}_\nu, E^{reco.}_\nu)$ for brief

Frequentist: $\chi^2\left(N_{obs.} | N_{pred.}(\vec{o})\right) + \chi^2_{ext.}$

Bayesian: $P\left(N_{pred.}(\vec{o}) | N_{obs.}, \vec{o}_{prior}\right)$

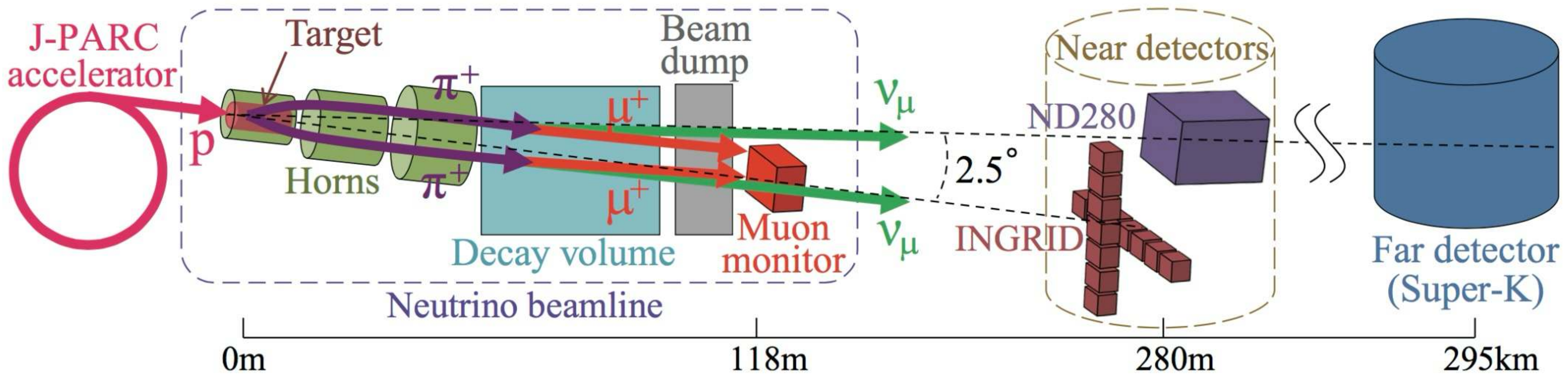
← Statistical inference for parameter estimation

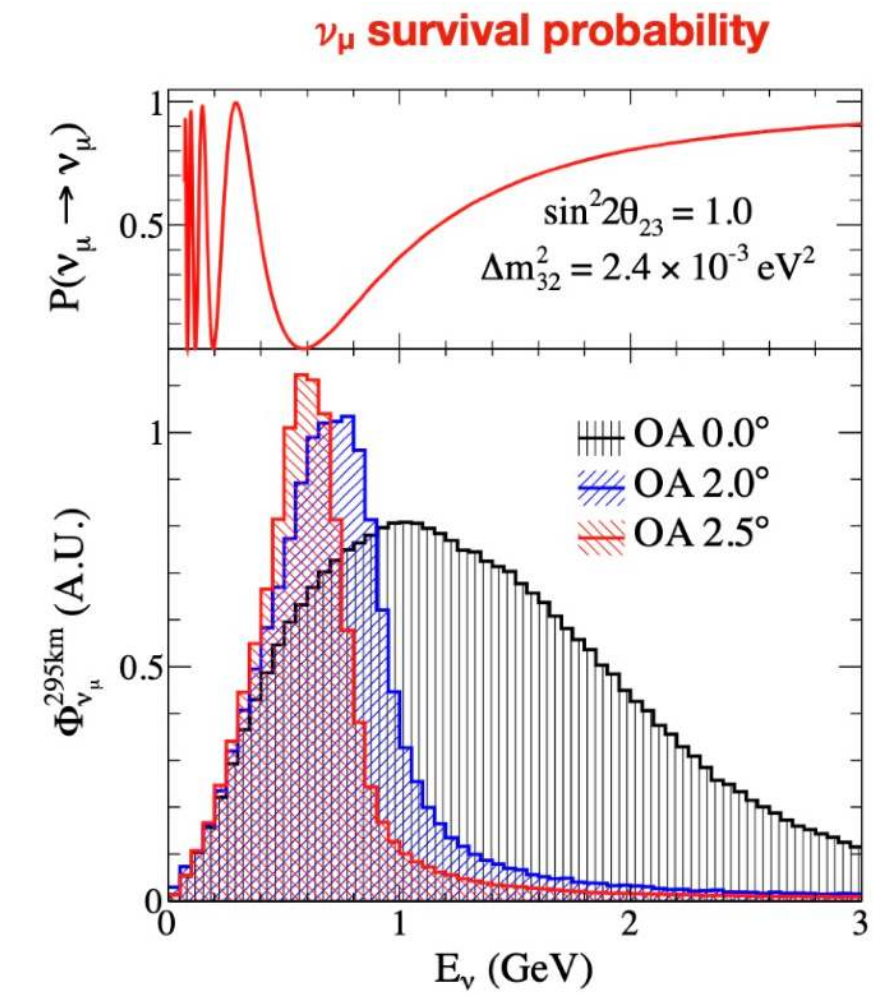
Data @ Far det.

$N_{obs.}$

T2K develops analyses to fit the data of near and far detectors either sequentially or concurrently.

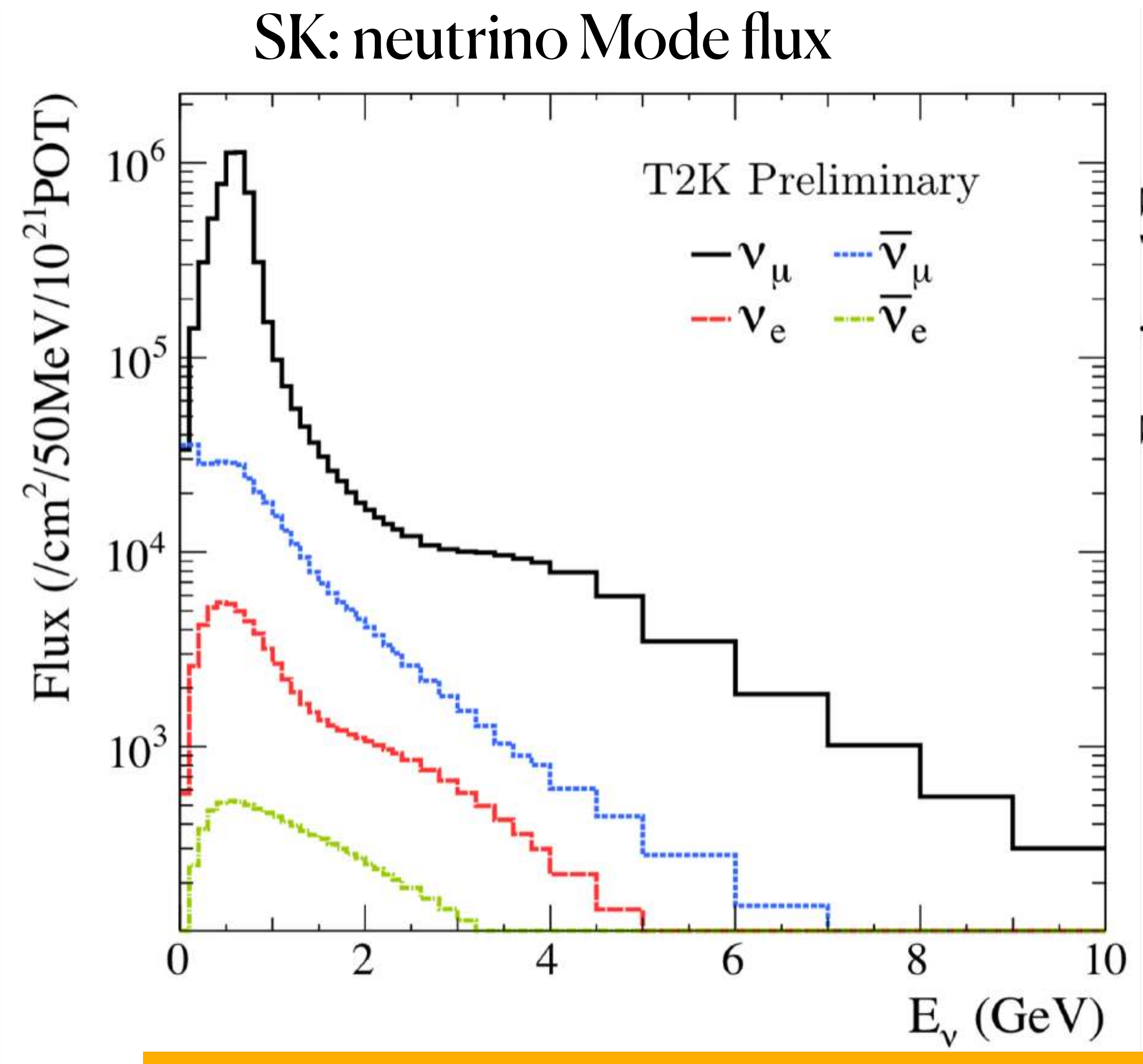
Intense and well-controlled neutrino beam

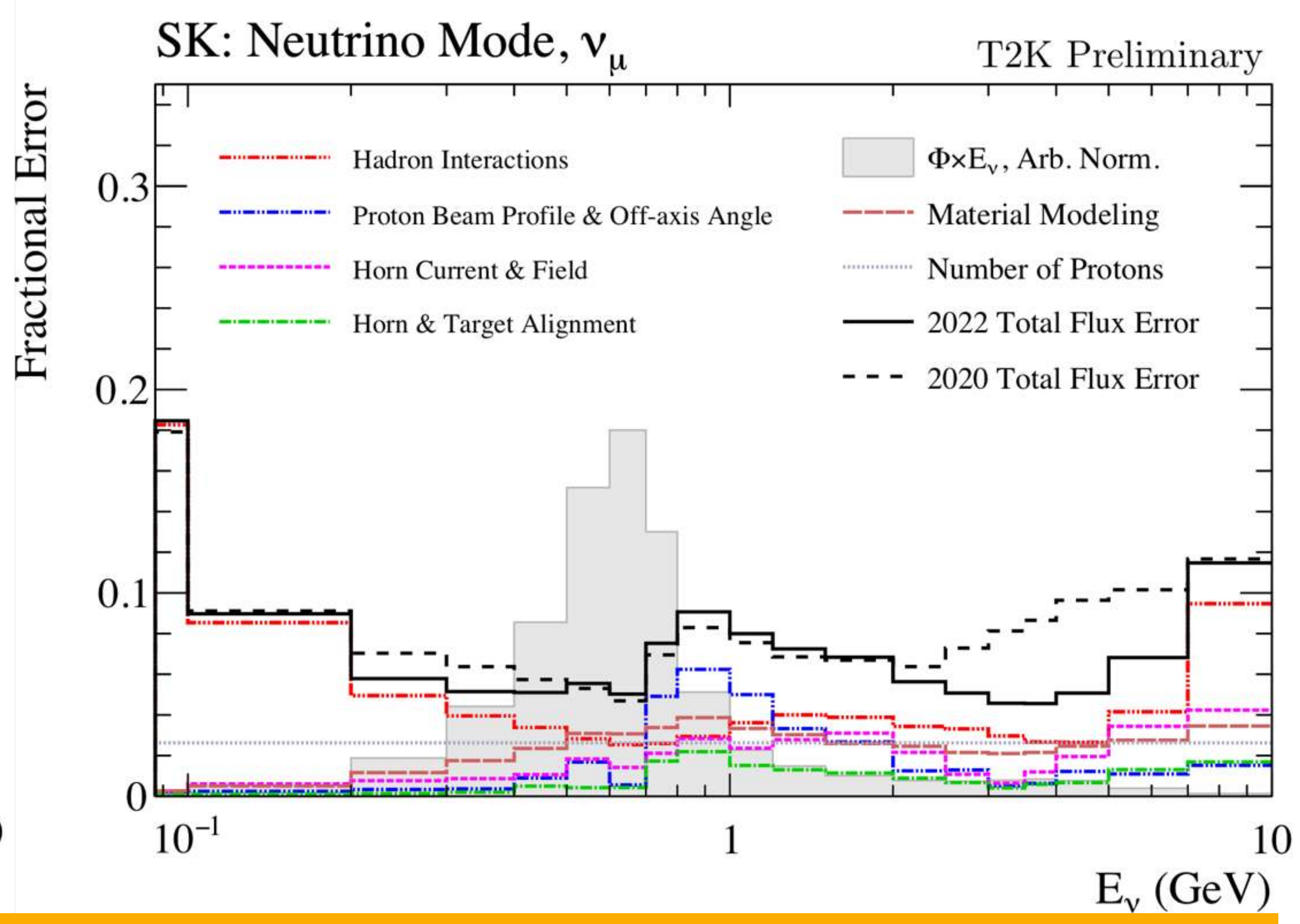




Far detector is placed off-axis to receive a narrow-band beam at 1st oscillation maximal $|\Delta m^2_{32}|L/4E \approx \pi/2$

- Accelerated 30 GeV protons are extracted, guided, and bombarded onto a graphite target
  - NA61/SHINE data to constrain hadron production
- Produced hadrons focused by magnetic horns
  - Select positive or negative hadrons by switching horn polarity, result in ν_μ or $\overline{\nu}_\mu$ beam respectively ➜ critical to CPV search
- Careful monitoring: track proton beam profiles and loss before hitting target; and observe the produced muon and neutrinos with MUMON and INGRID detectors



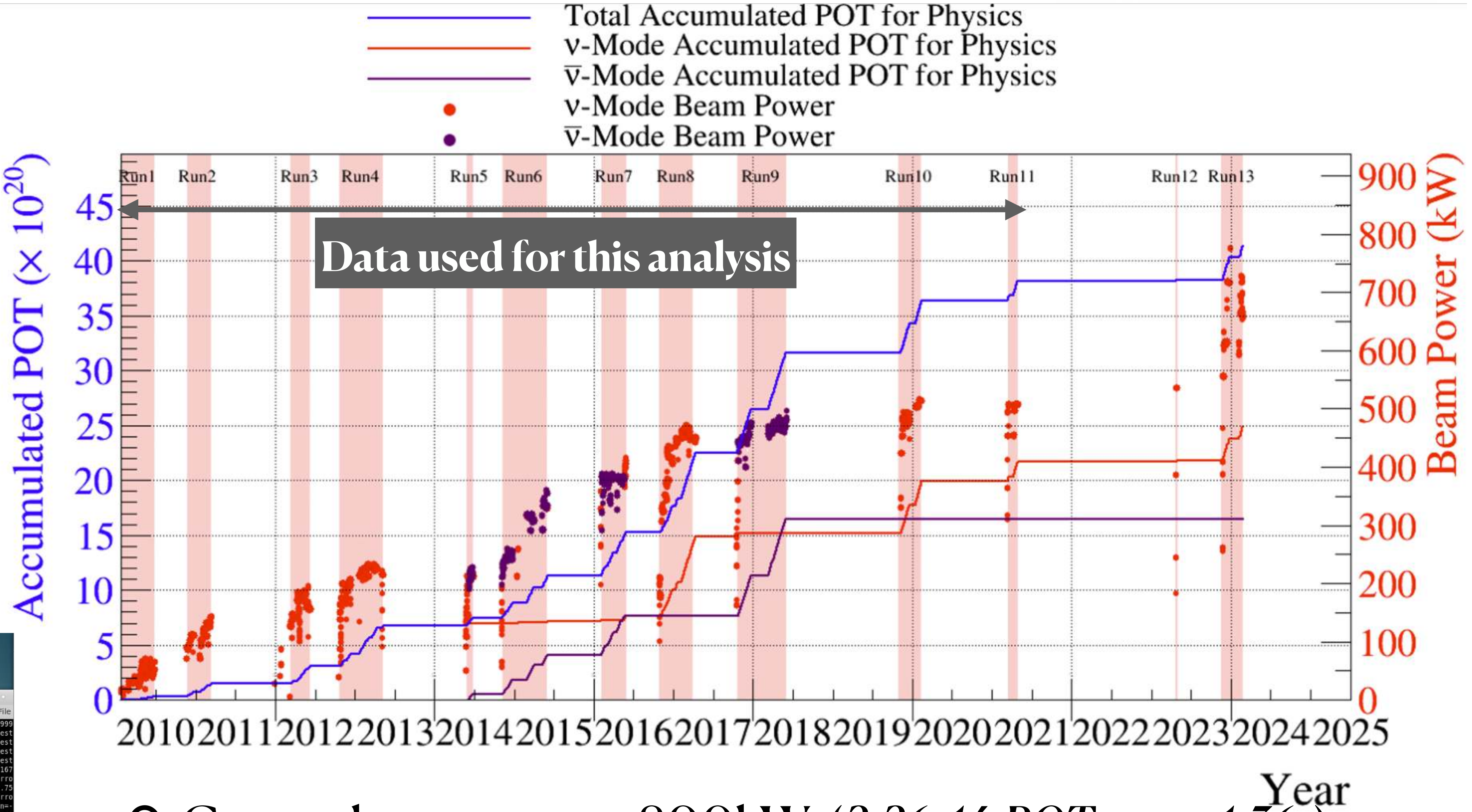


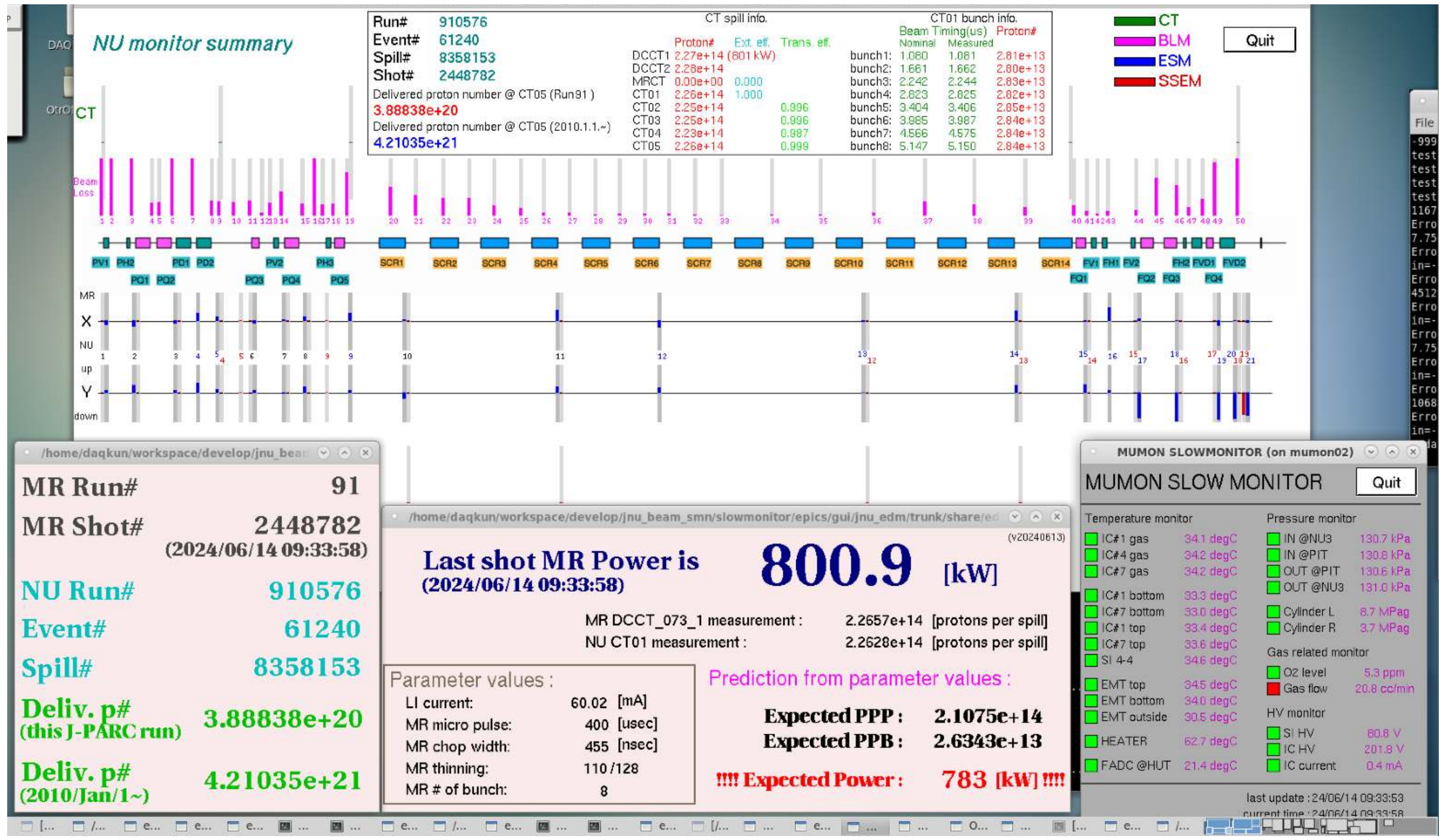
Highly pure $\nu_\mu/\overline{\nu}_\mu$ beam (<1% of intrinsic $\nu_e/\overline{\nu}_e$).
~6% uncertainty at the peak before constraints w/ near det. data.

Ref: "Monitor developments for MW-power proton beam at J-PARC extraction beamline" - SC

Data taking and analysis usage

- More than 43e20 Protons-on-target (POT) accumulated
- This analysis uses data up to T2K Run11, corresponding to 21.4e20 POT in ν-mode and 16.3e20 POT in $\overline{\nu}$-mode



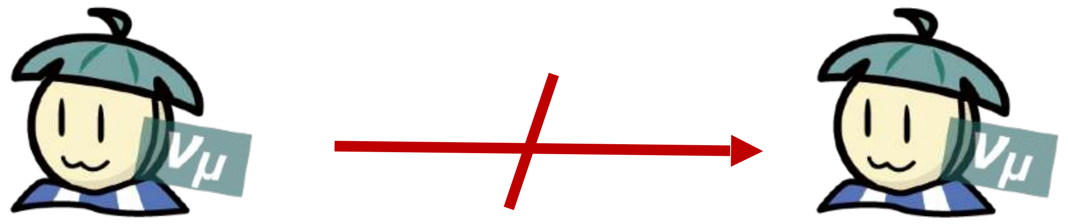


- Currently operate at 800kW (*2.26e14 POT every 1.36s*) proton beam (*was 500kW before upgrading*)
  - Intensified by 320kA-current horn operation, effectively gain ~10% more neutrino flux than previous 250kA-current

Oscillation channels to measure

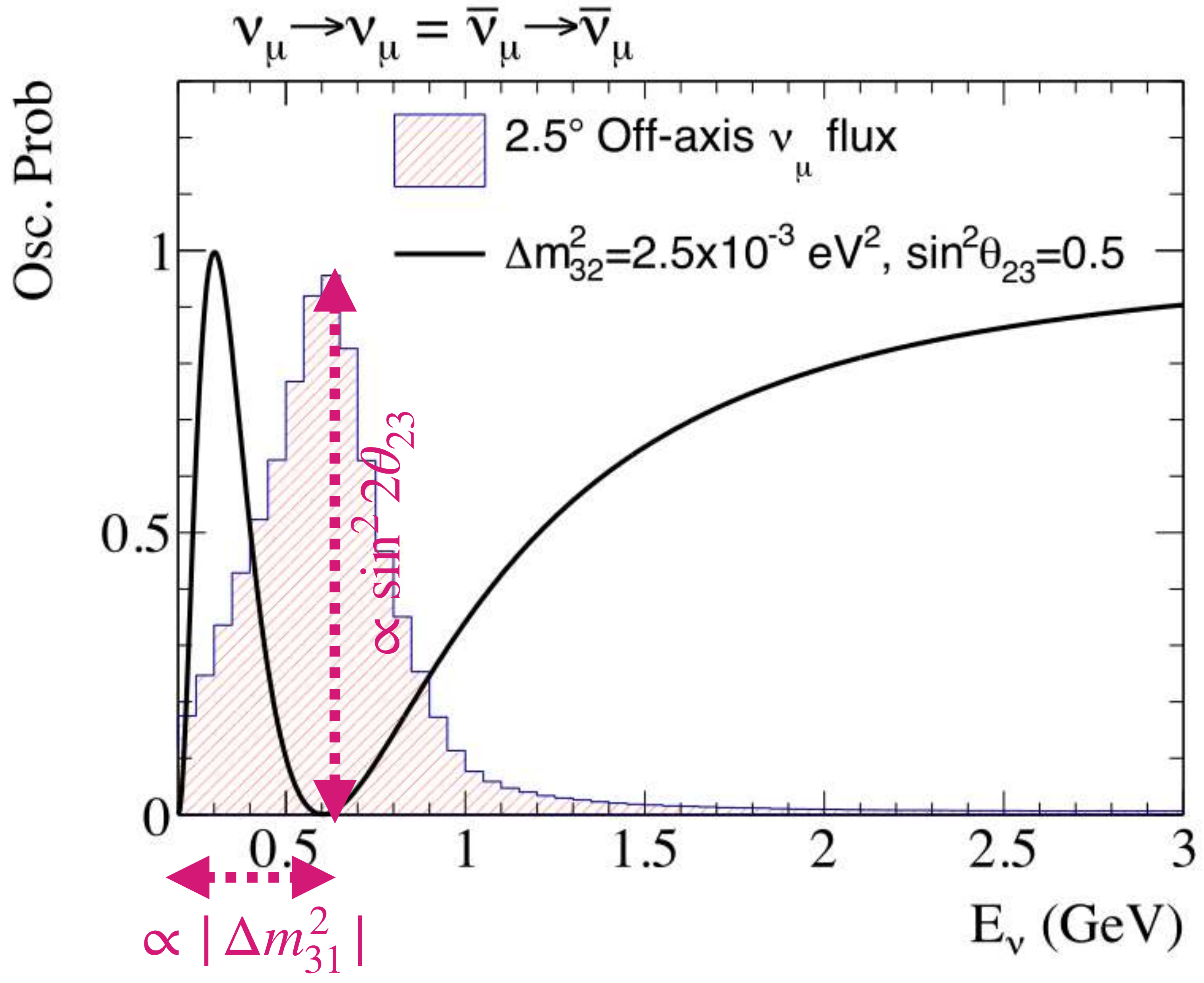
$$N^{\nu_\beta}(E_\nu^{reco.},\vec{o}) = \Phi_{flux}^{\nu_\alpha}(E_\nu^{true}) \times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true},\vec{o}) \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.},E_\nu^{reco.})$$

$\nu_\mu(\bar{\nu}_\mu)$ disappearance



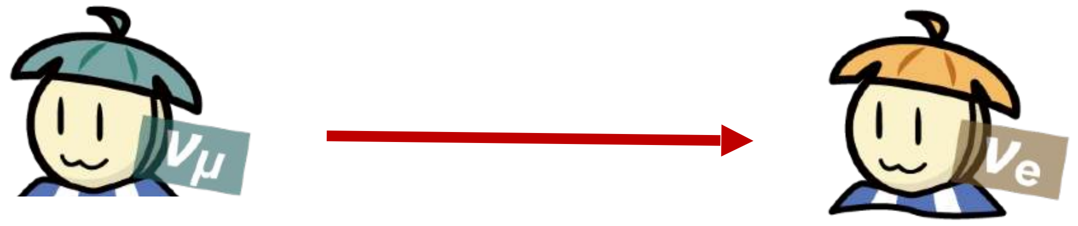
$$P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{31}^2\cdot L}{4E}$$

Leading-term — Next-to-leading



measure precisely $|\Delta m_{31}^2|$ and $\sin^2 2\theta_{23}$ and sensitive to CPT test $P_{\nu_\mu\to\nu_\mu}$ vs. $P_{\bar{\nu}_\mu\to\bar{\nu}_\mu}$

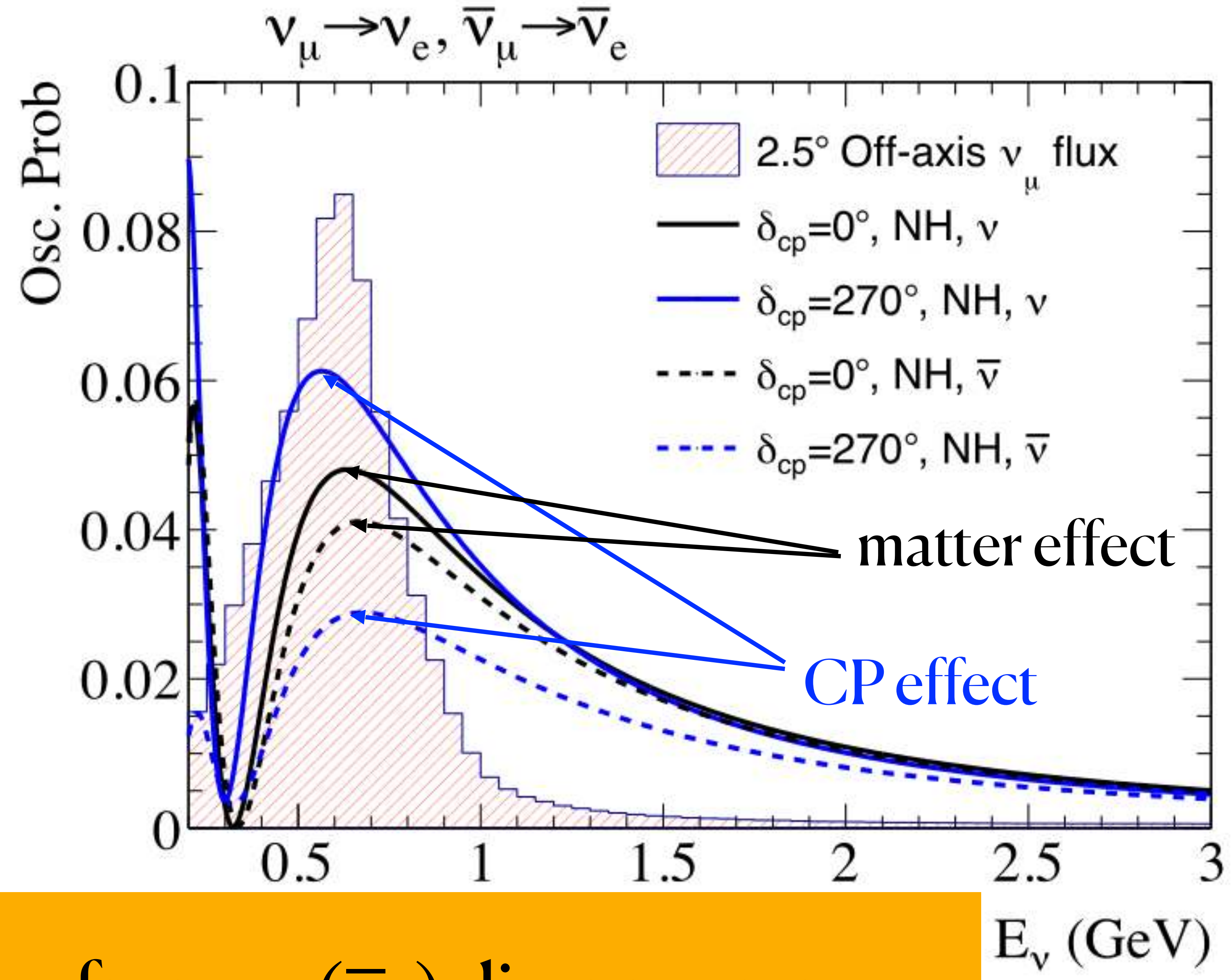
$\nu_e(\bar{\nu}_e)$ appearance



$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}]$$
$$\overset{(+)}{-}\ \alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}]$$
$$+\ \alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}]$$

$$\alpha = \Delta m_{21}^2/\Delta m_{31}^2$$
$$\Delta_{ij} = \Delta m_{ij}^2 L/4E$$
$$A = (-)2\sqrt{2}G_F n_e E/\Delta m_{31}^2$$
$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}.$$

Sensitive to $\sin^2\theta_{23}$, mass ordering (*sign of* Δ_{31} *and* A) through matter effect, and CPV phase manifested in difference btw. $P_{\nu_\mu\to\nu_e}$ and $P_{\bar{\nu}_\mu\to\bar{\nu}_e}$

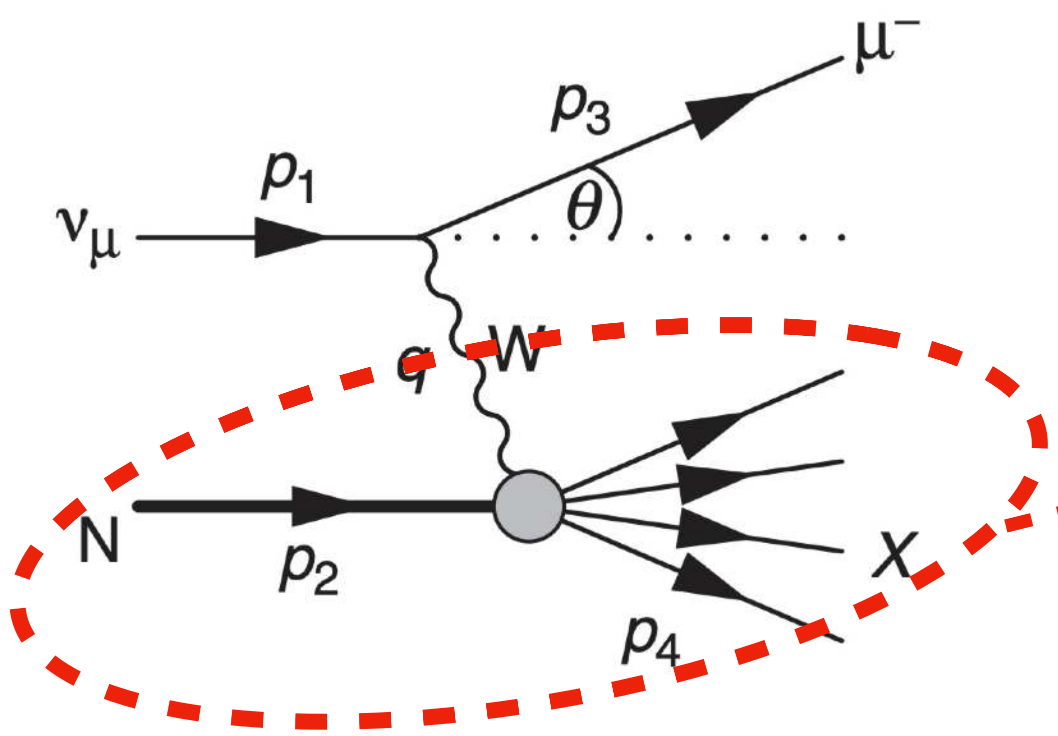


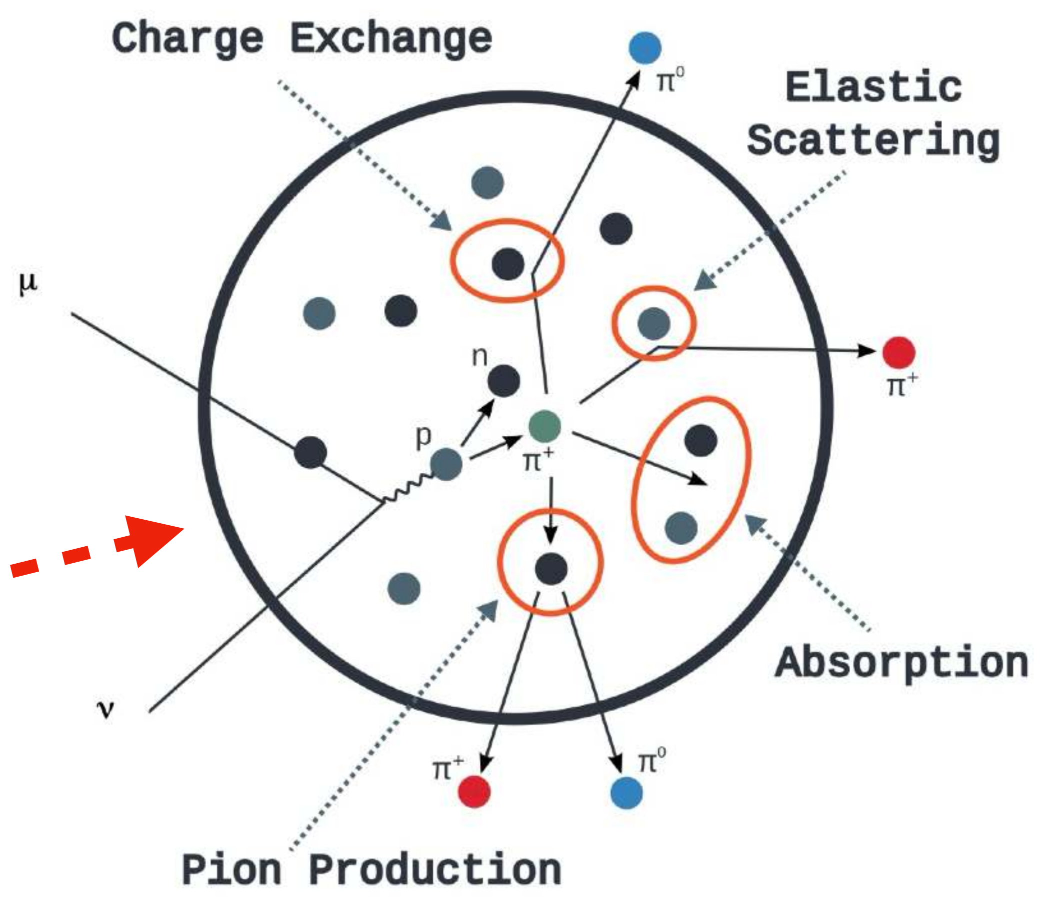
Unless stated, combined data samples from $\nu_\mu(\bar{\nu}_\mu)$ disappearance and $\nu_e(\bar{\nu}_e)$ appearance are utilised to extract all sensitive parameters

Neutrino-nucleon/nucleus interaction

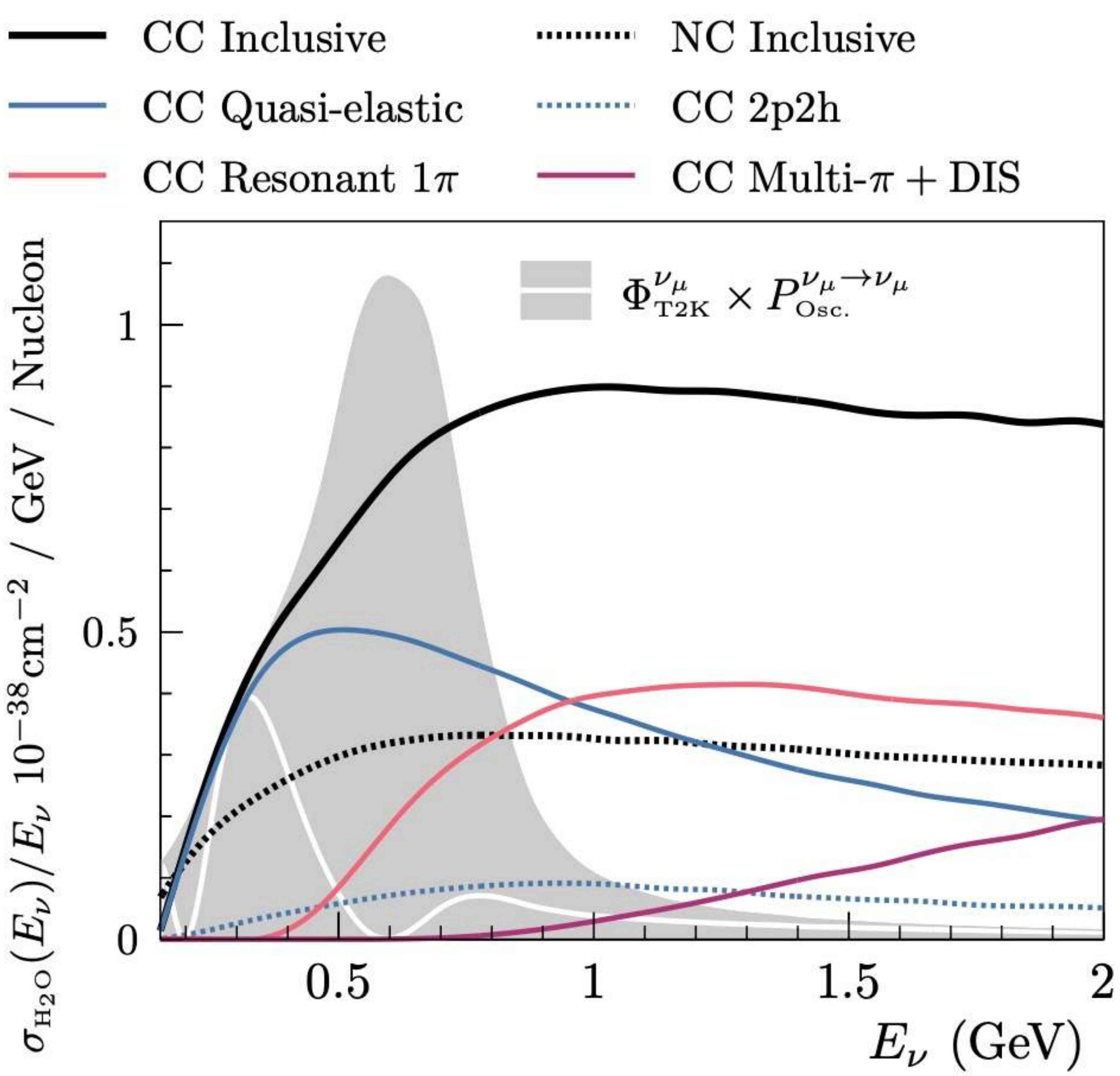
$$N^{\nu_\beta}(E_\nu^{reco.},\vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true},\vec{o}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$

- T2K's ν energy is not monochromatic but ranged from ~0.1 GeV to few GeV (*peak at 0.6 GeV*)
  - ν energy is reconstructed fr. lepton's kinematics and hadron's energy
- Dominated by the CCQE (*or 1p1h*) interaction and considerable 2p2h and CC resonance
- Usage of nuclear target (O, C) for higher interaction rate must take into account the nuclear effects
  - Initial nucleon bound in nucleus (*Fermi momentum, binding energy...*)
  - ν -induced hadrons undergo final-state interaction in nuclear medium





(CC= Charged Current)

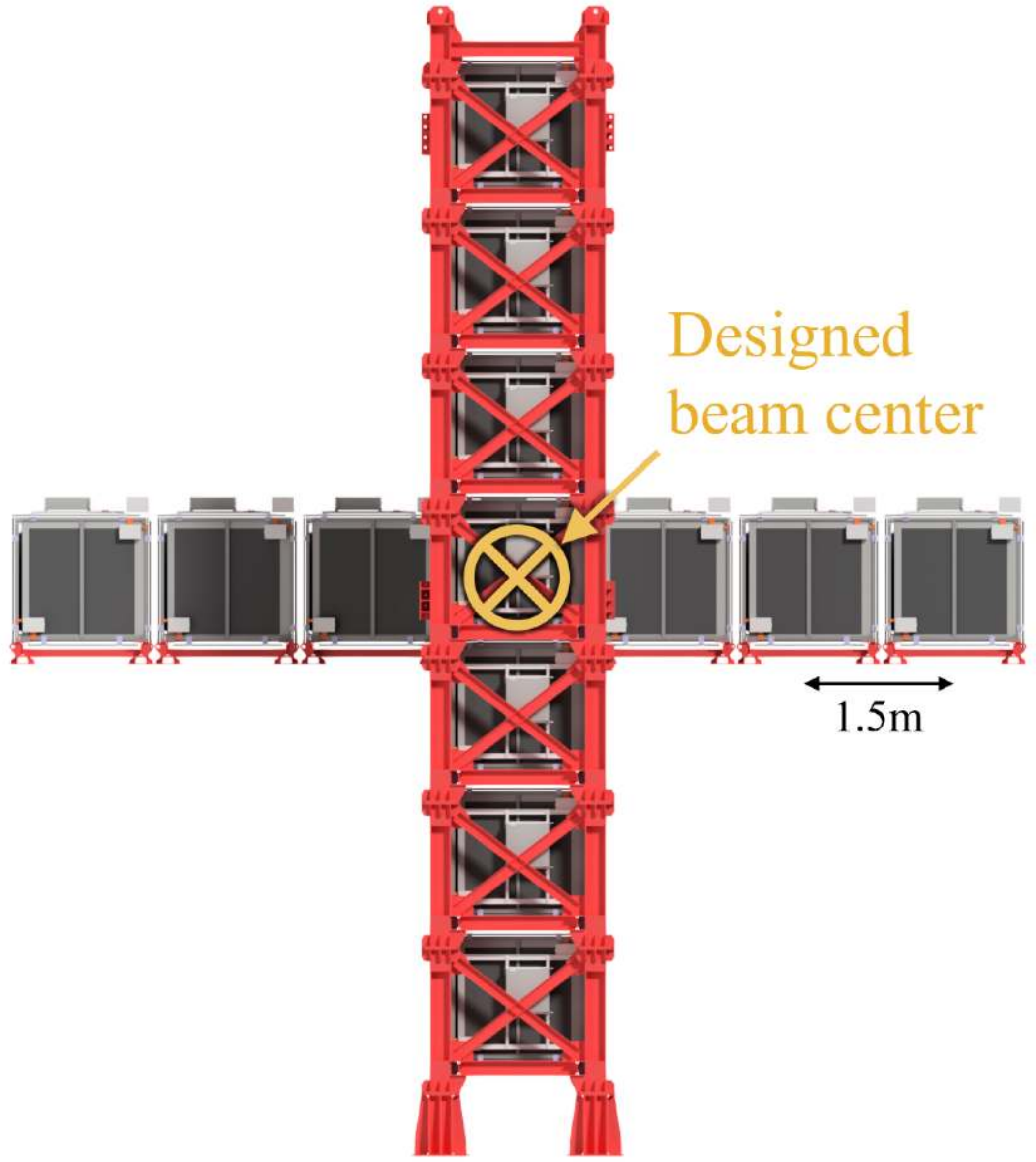


Ref: T2K other talks by A. Izmaylov and A. Ramírez

T2K Near Detector complex

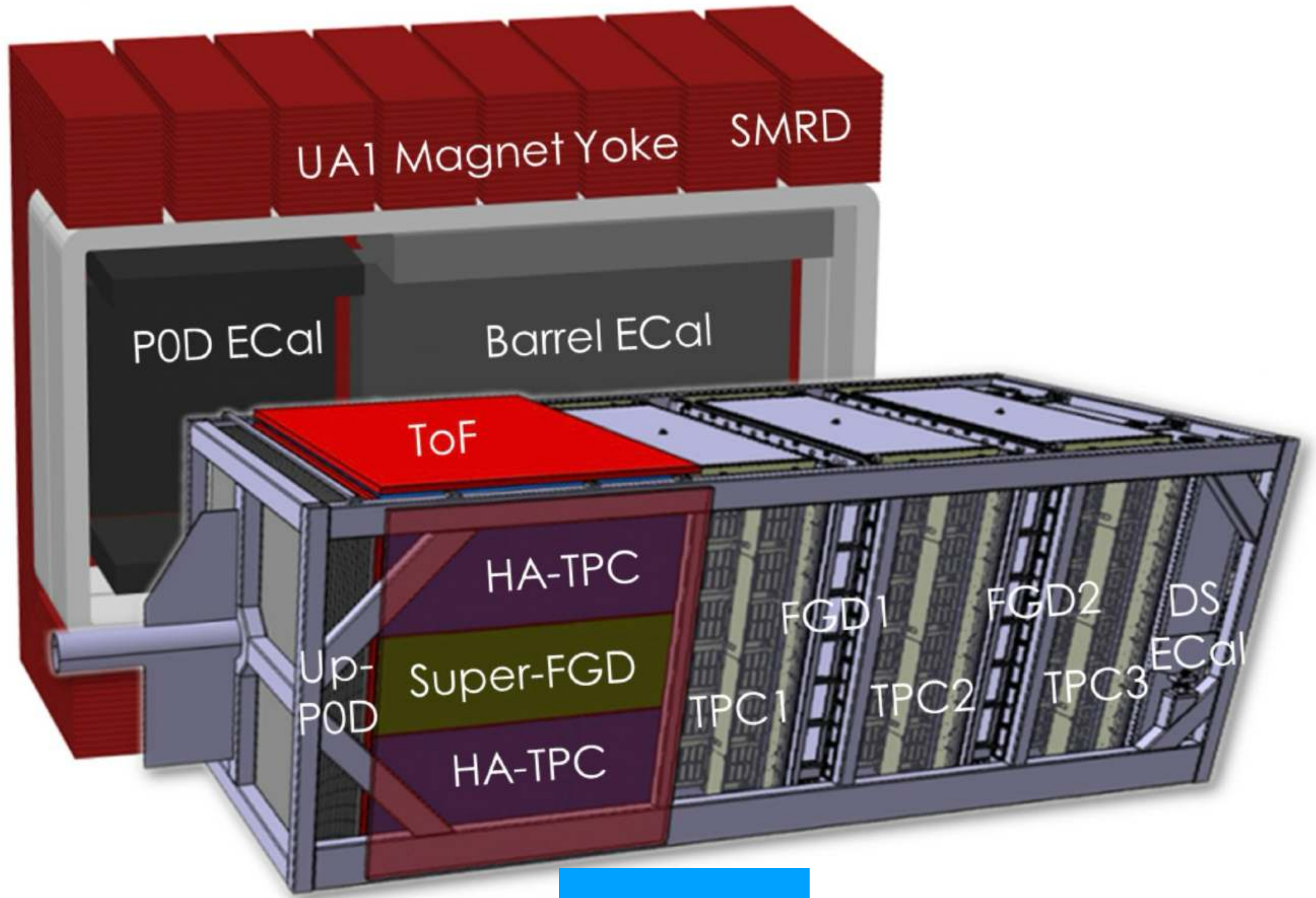
$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi_{flux}^{\nu_\alpha}(E_\nu^{true}) \times P(\nu_\alpha \rightarrow \nu_\beta | E_\nu^{true}, \vec{o}) \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$

Placed 280m fr. target to characterize neutrino flux before oscillating and to understand the (anti-)neutrino interaction with nuclear targets



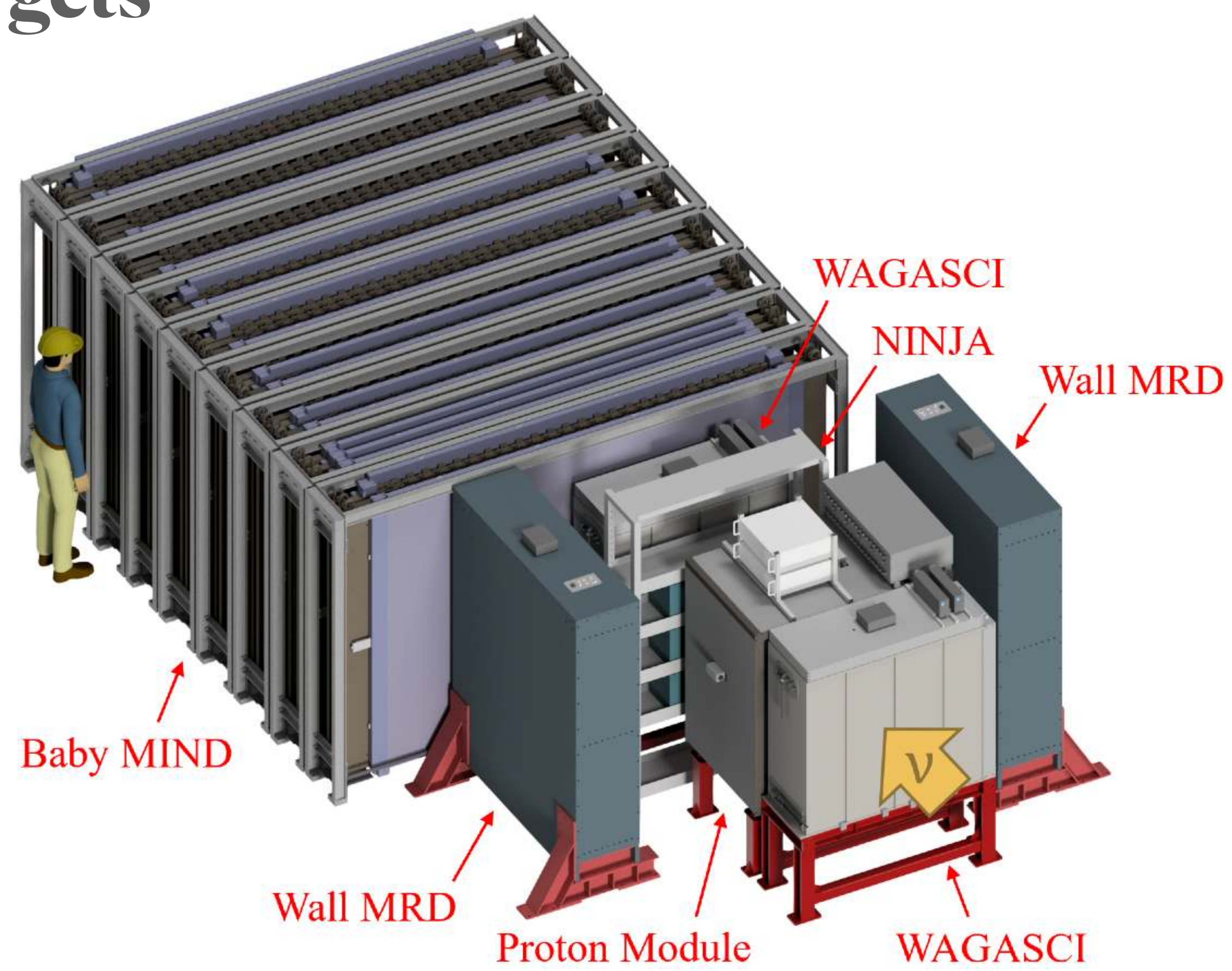
INGRID

- On-axis detector, 7.1 ton of iron & scintillator / each module (x14) ; operate since 2009
- Monitor the ν beam profile in daily basis
- Mean energy of 1.5 GeV cross section measurements



ND280

- 2.5° off-axis detector (*same direction as far detector*), few tons of scintillator /water; operated since 2010, **upgraded in 2024**
- ~0.6 GeV (peak) cross section measurement; constrain flux and interaction model on the T2K far detector's spectral prediction



WAGASCI/BabyMIND

- 1.5° off-axis detector ($E_\nu \approx 0.8$ GeV (peak), 2 tons of water/scintillator; operated since 2019
- Measure cross section of ν interaction on water, and water-to-scintillator ratio

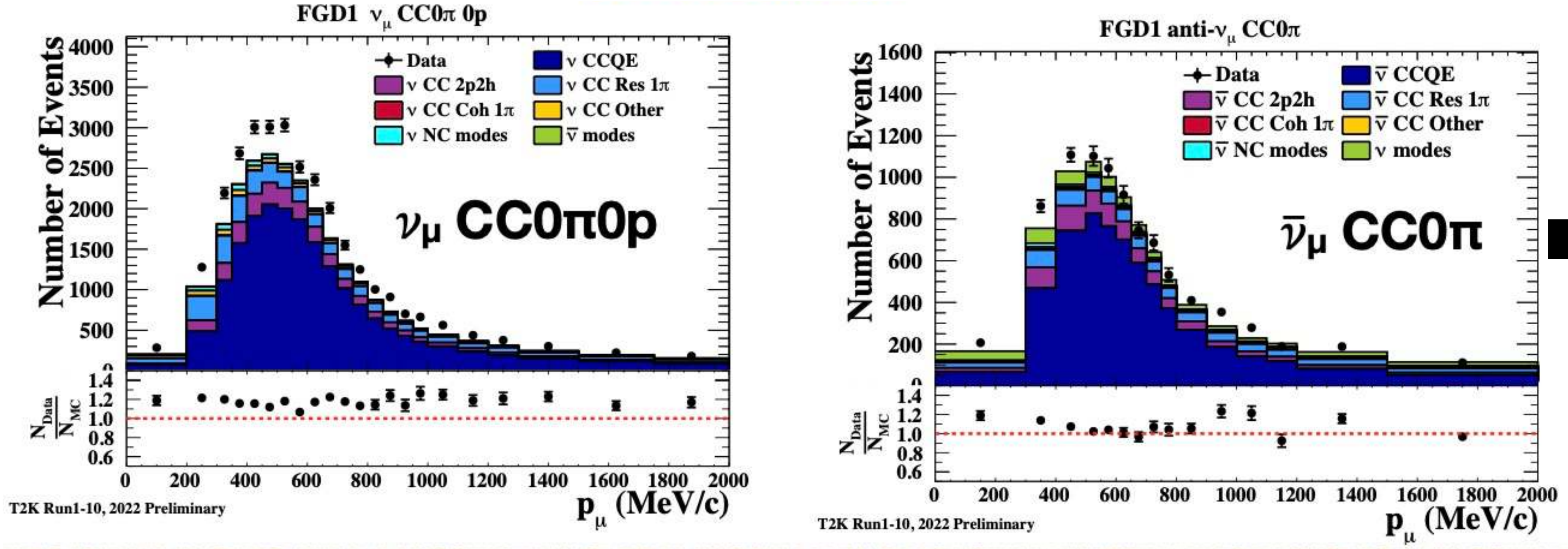
Ref: T2K other talks by A. Izmaylov and A. Ramírez

Constraint with Near Detector

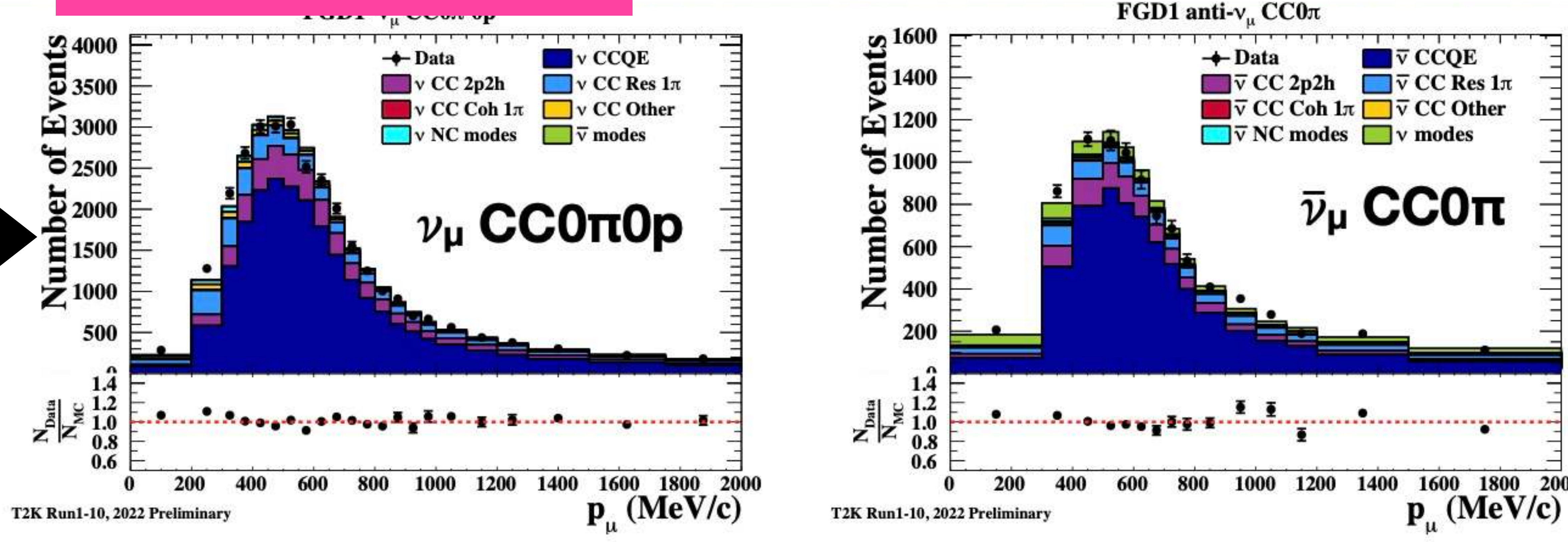
$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times P(\nu_\alpha \to \nu_\beta | E_\nu^{true}, \vec{o}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$

ND280 data, categorized into multiple samples based on their observable topology, are used to fit the underlying flux and interaction model's parameters

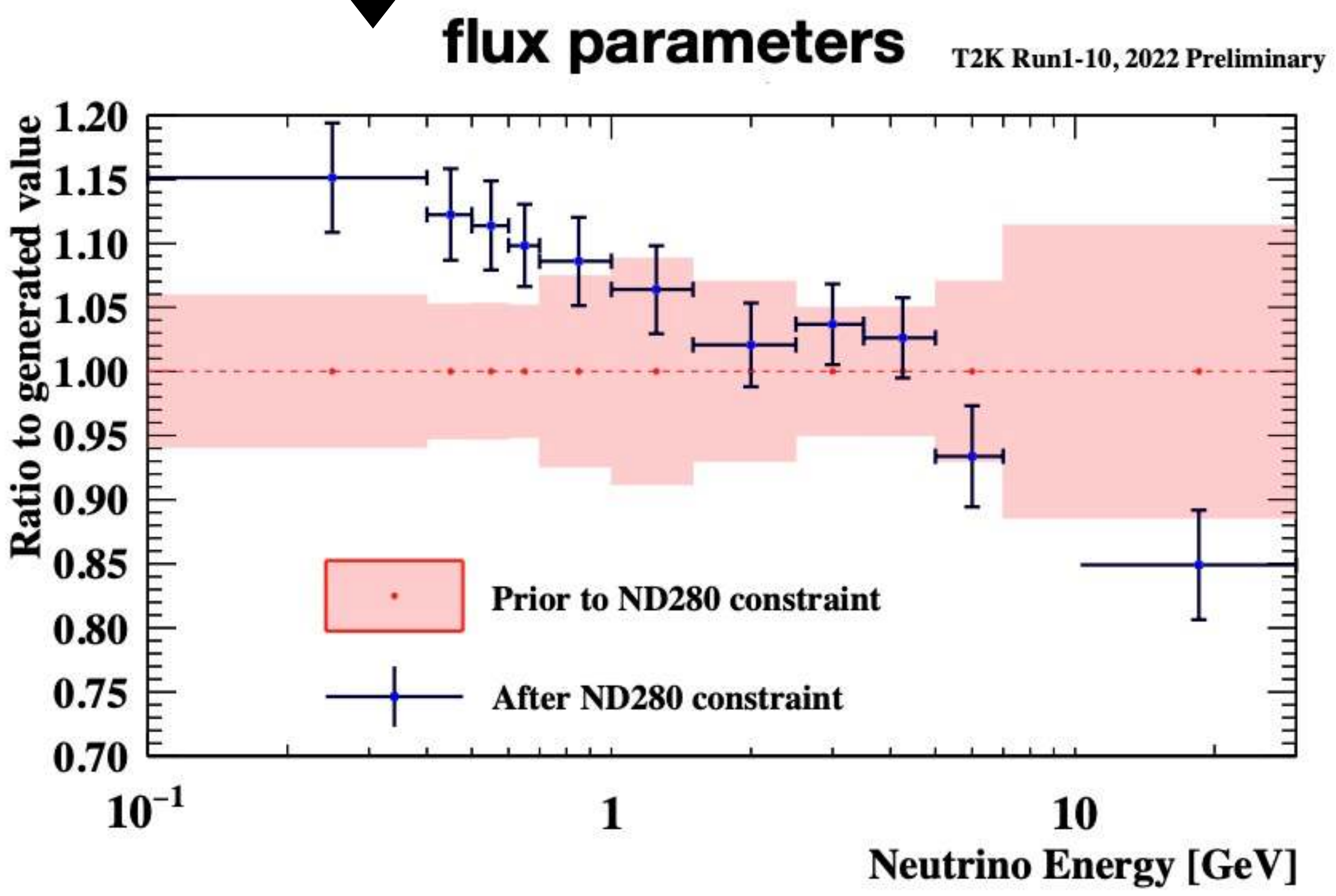
With nominal models of flux and cross-section

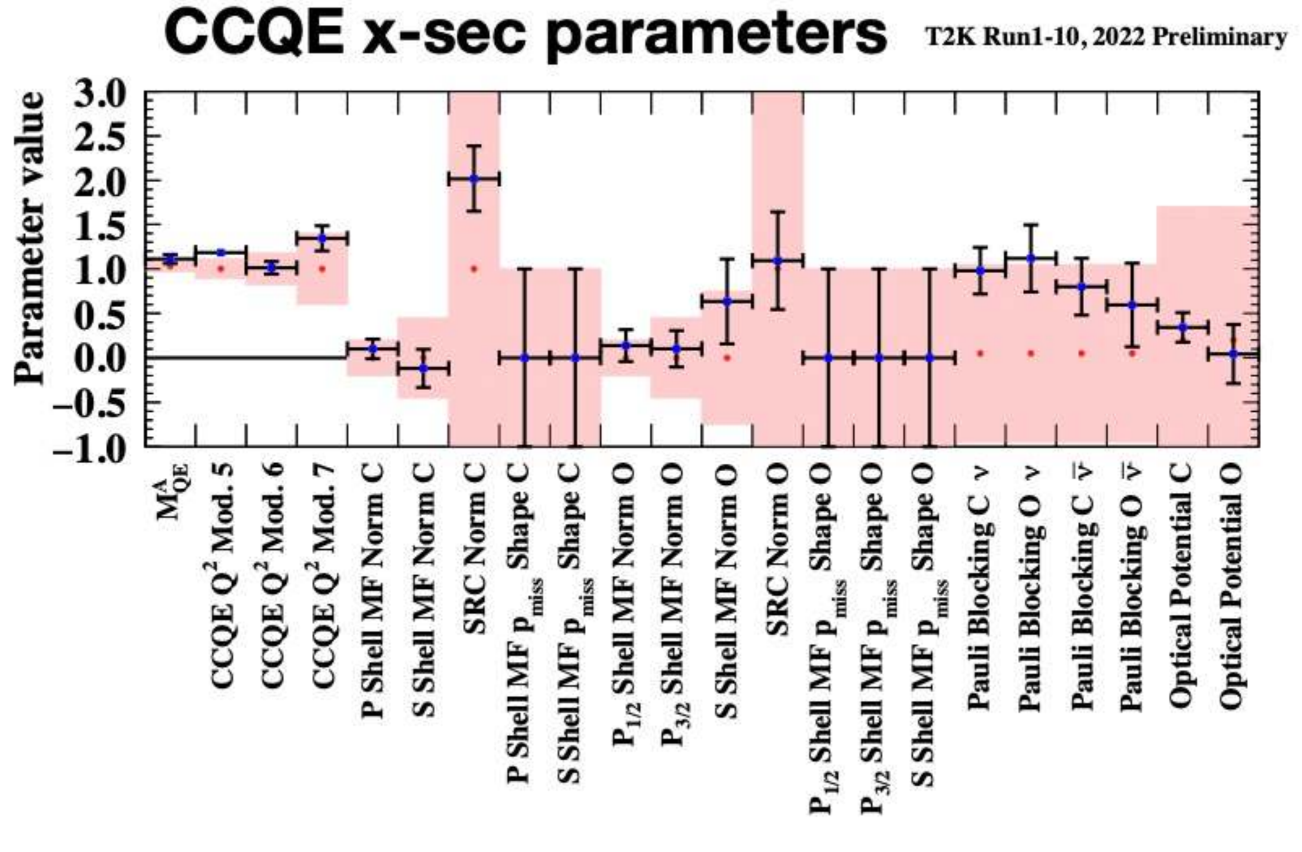


Post-fit with ND280 data



- Fit simultaneously flux parameters (*normalization factors at different E_ν bins*) and ν interaction model (*x-sec*) parameters
  - Pre-fit central values and its error are estimated from external data.
- Reduce significantly the systematic uncertainty characterized by flux and x-sec parameters ➜ impact largely onto predicted spectra at far detector





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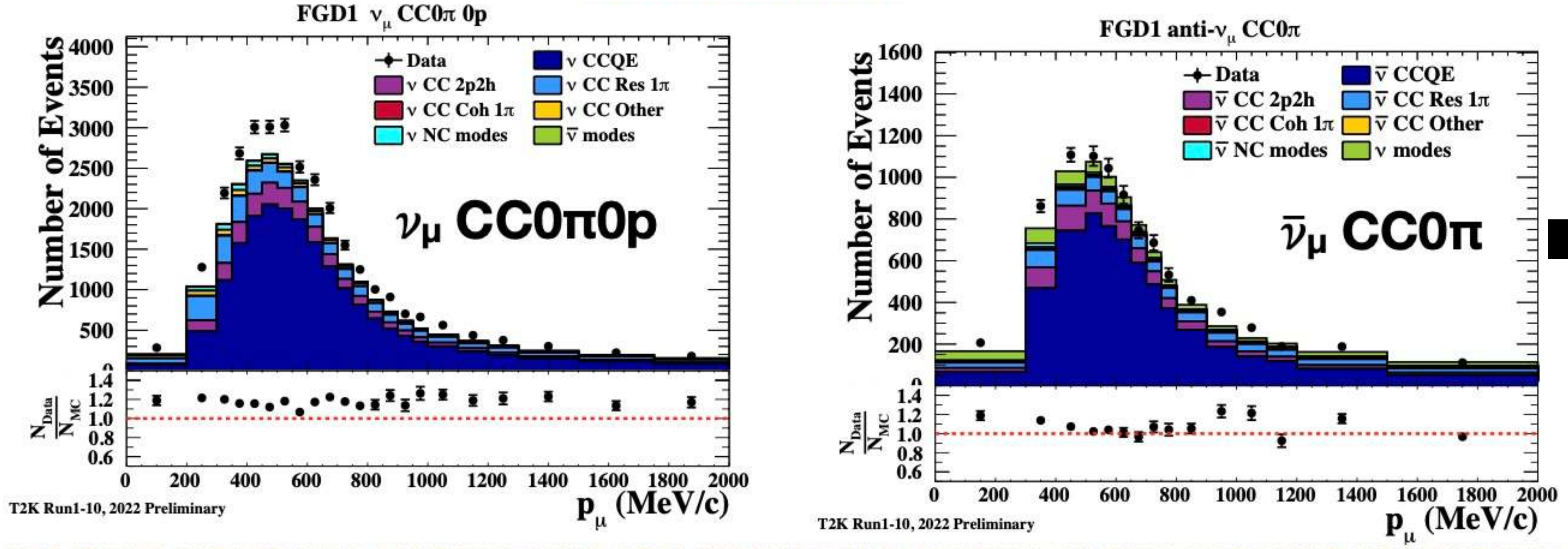

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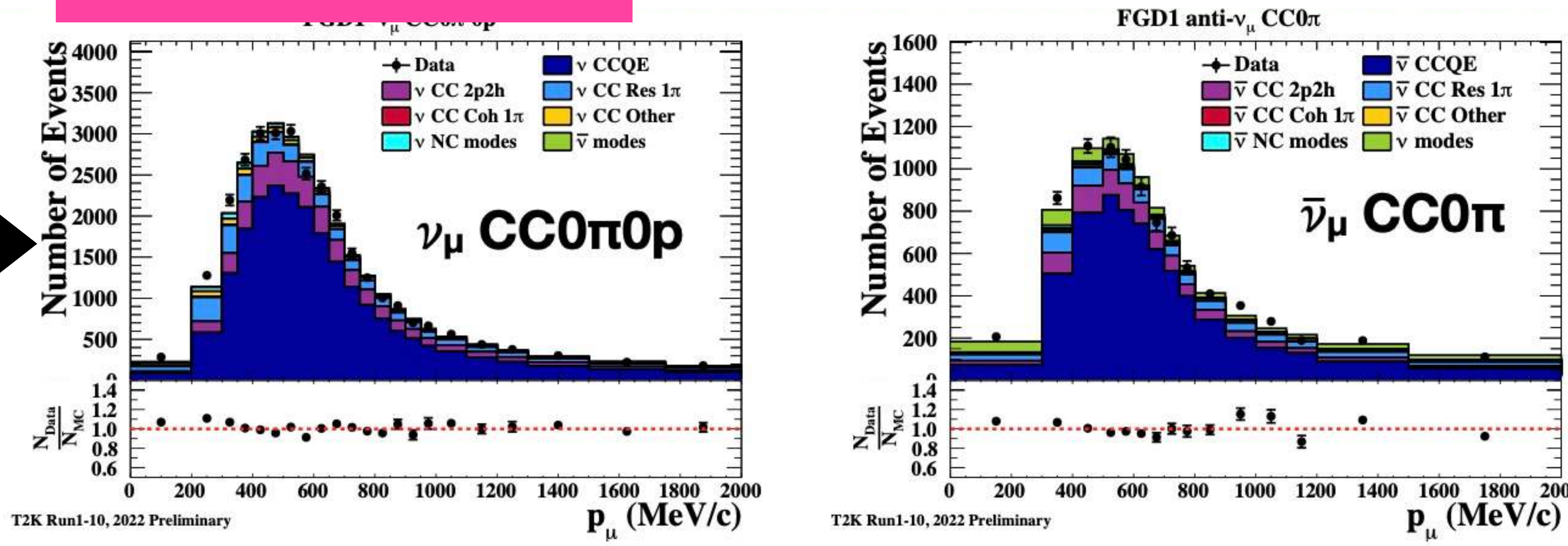

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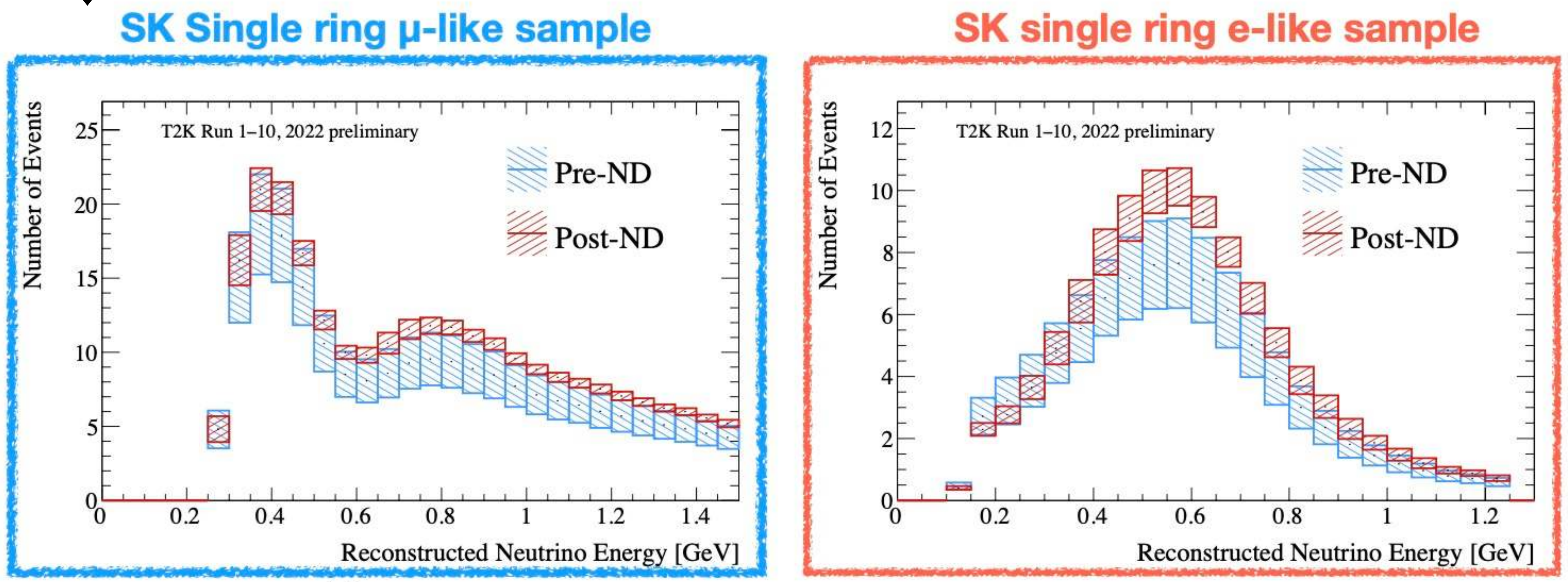
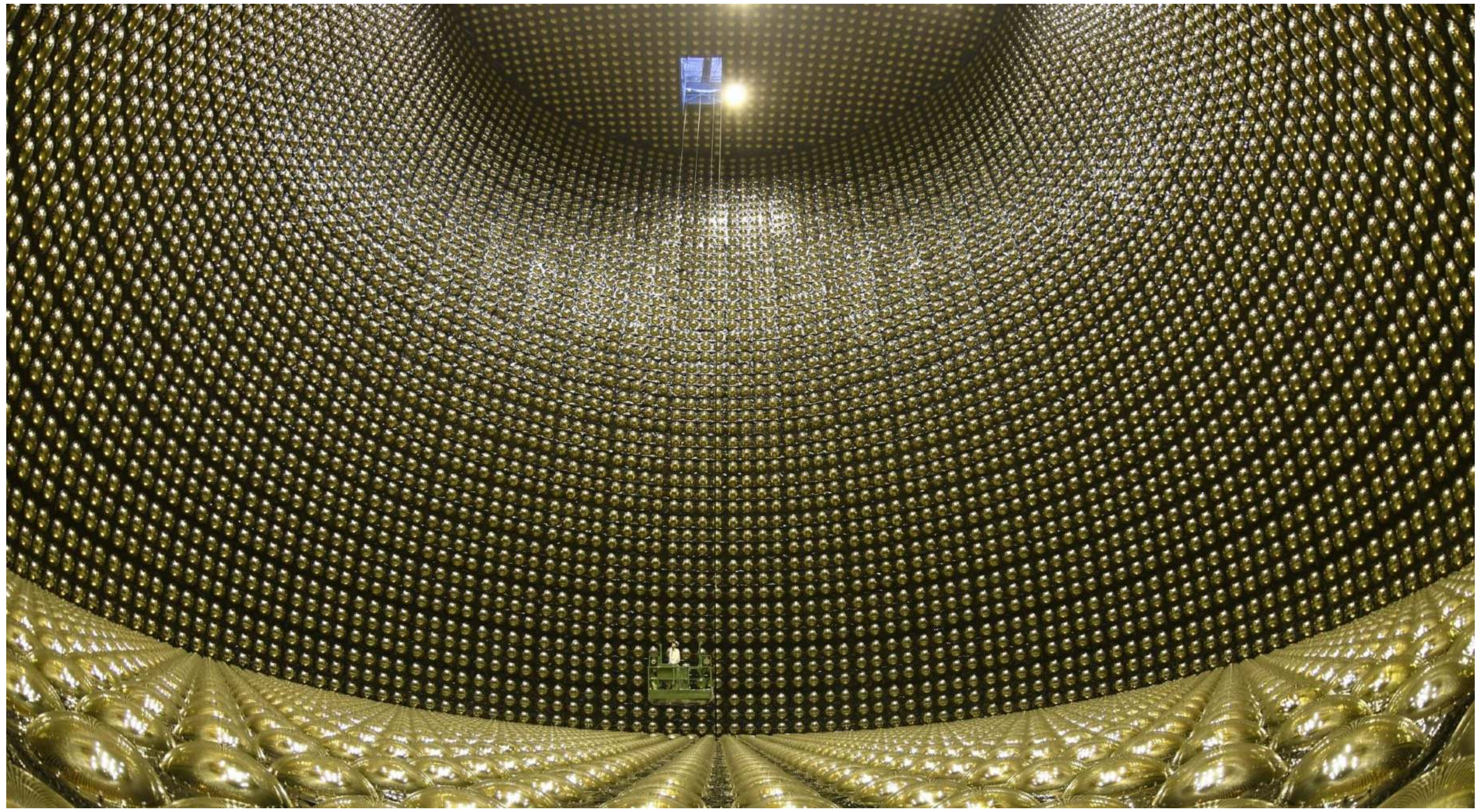
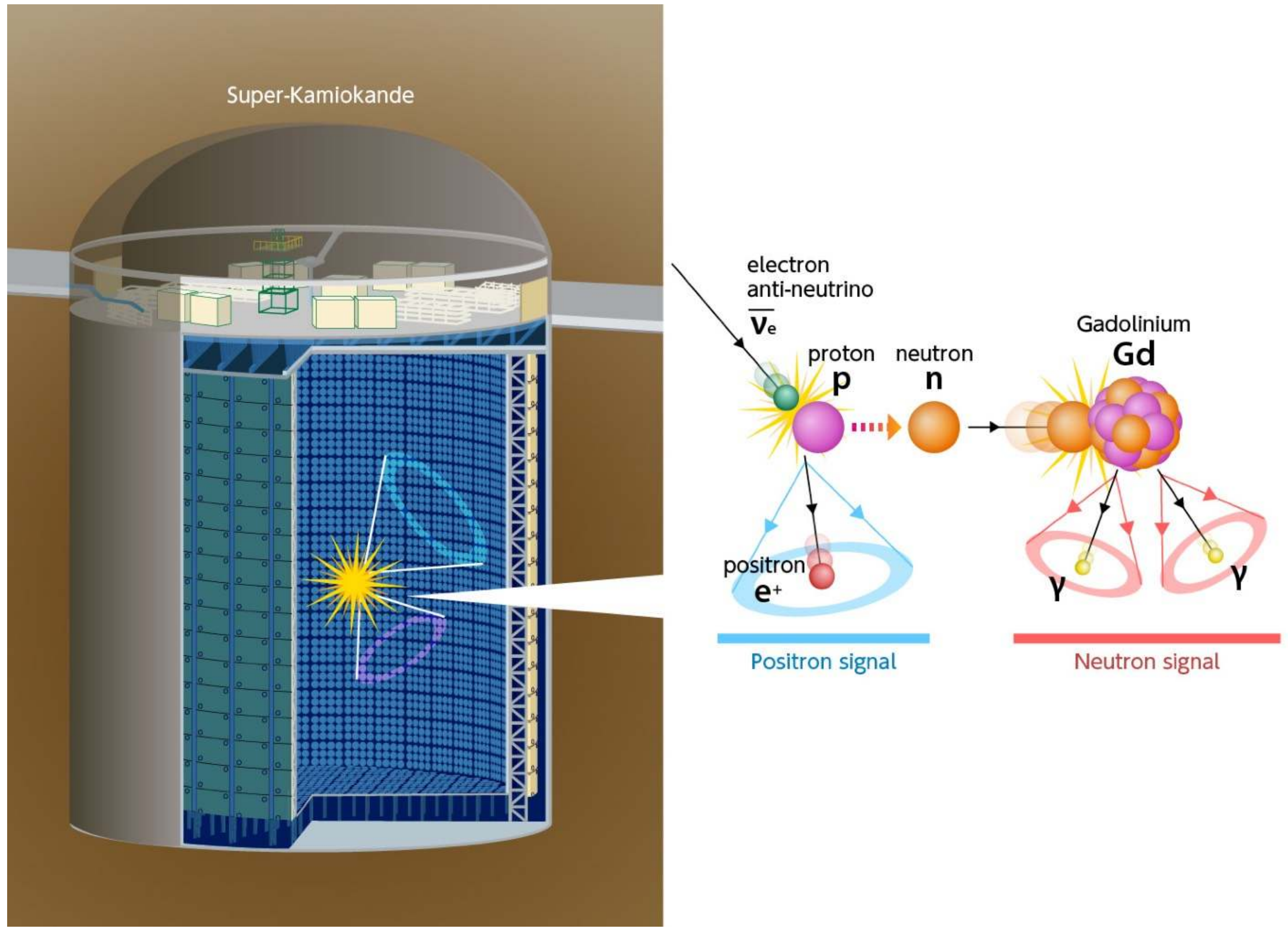


Super-K —T2K far detector

50 kton water Cherenkov observatory, equipped with/ 11000 of 20”- PMTs and 2000 of 8”-PMTs placed 1km underground





Operated since 1996, contributed to observation of atmospheric neutrino oscillation in 1998 and numerous world-leading proton-decay searches and other physics

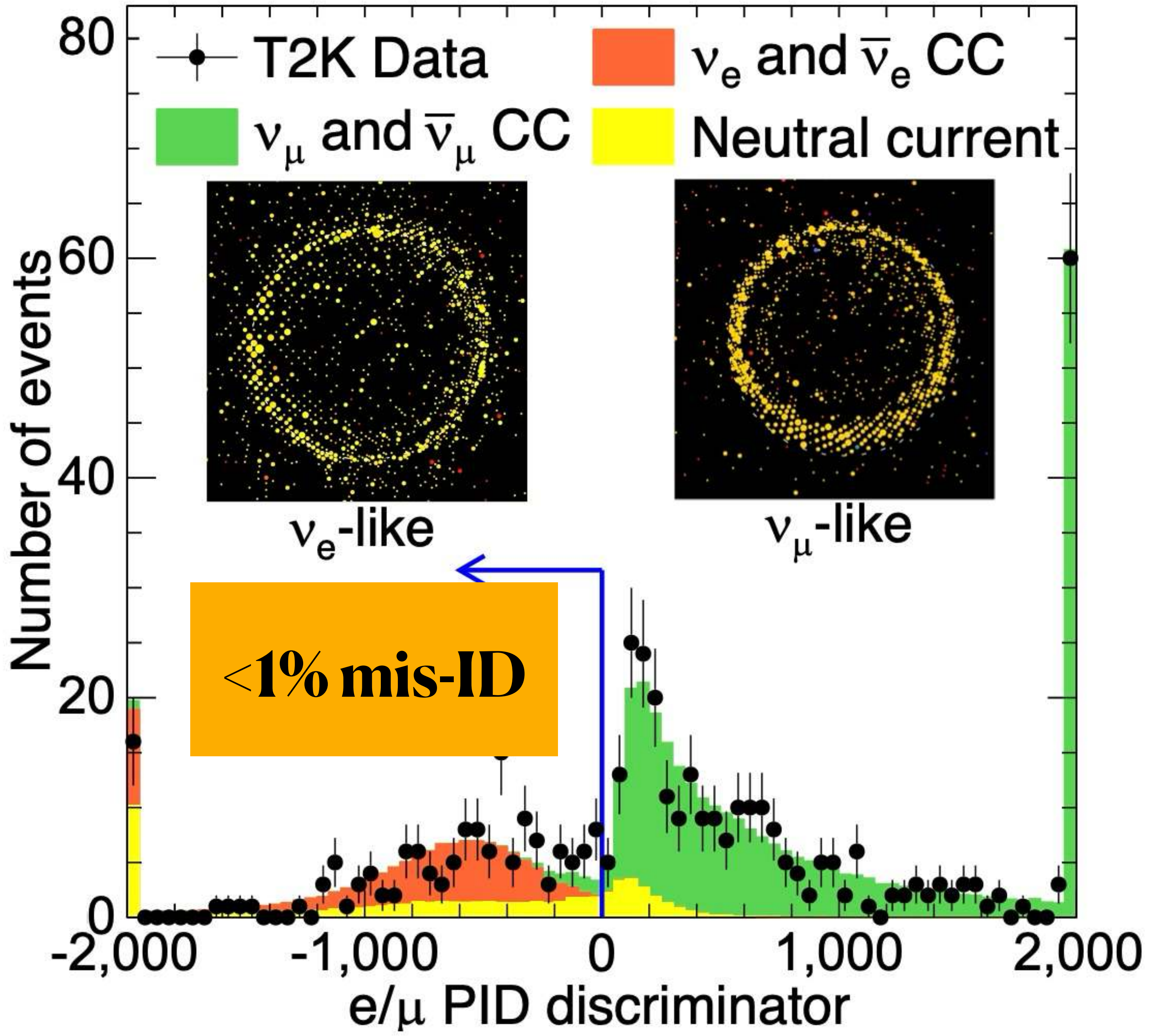
Entering a new period of observation by introducing Gd into detector (0.01% in 2020 ➔ 0.03% Gd in 2022)

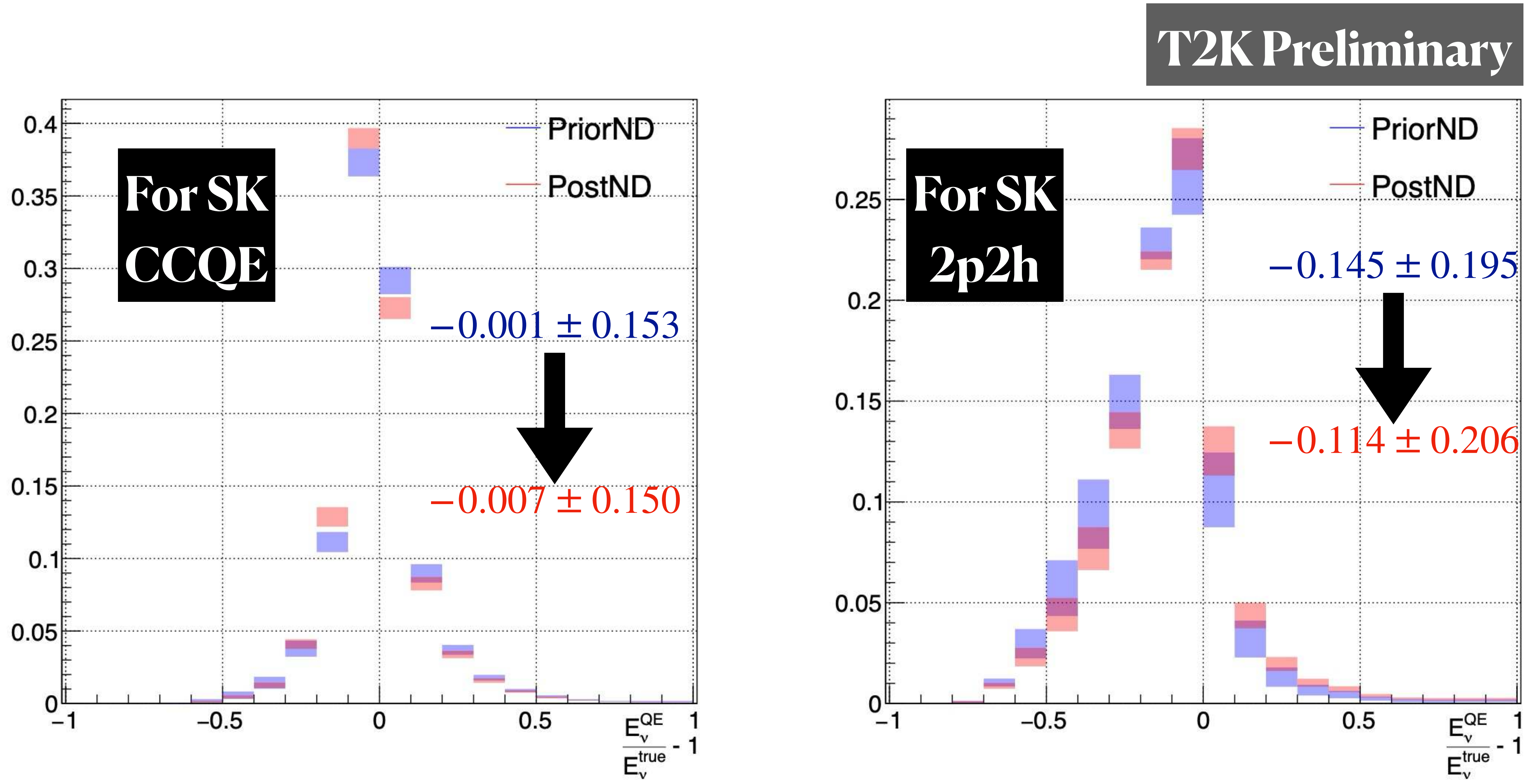
- Motivated by diffuse supernova background search
- Other improvements (*supernova direction pointing, energy reconstruction, ν and $\overline{\nu}$ separation, …*)

Ref: Super-K talks @ Neutrino 2024, Milano

Super-K — T2K far detector: Performance

$$N^{\nu_\beta}(E_\nu^{reco.}, \vec{o}) = \Phi_{flux}^{\nu_\alpha}(E_\nu^{true}) \times P(\nu_\alpha \to \nu_\beta \,|\, E_\nu^{true}, \vec{o}) \times \sigma_{int.}^{\nu_\beta}(E_\nu^{true}) \times R_{det.}(E_\nu^{true.}, E_\nu^{reco.})$$



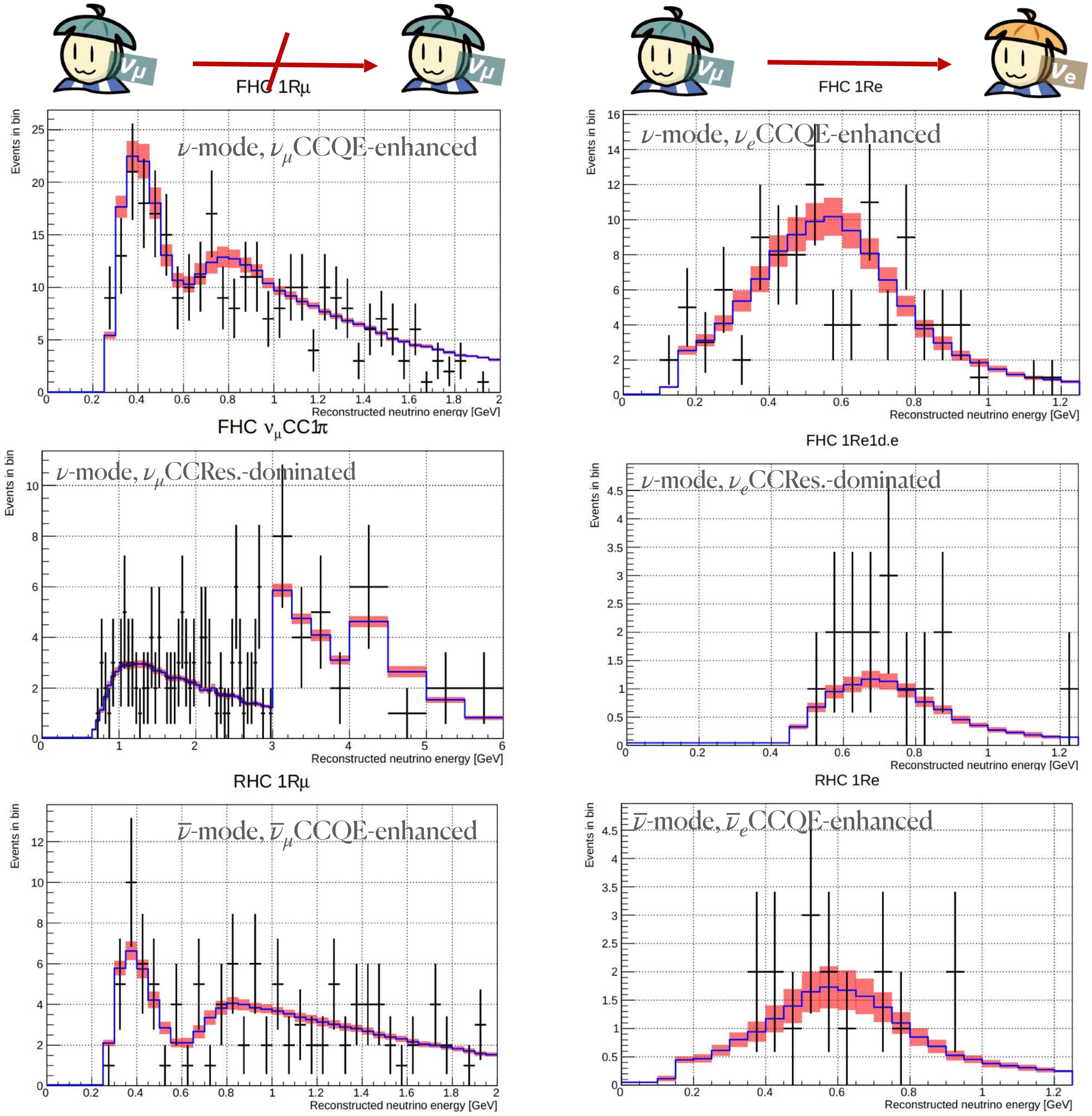


Provide excellent capability to identify and classify the ν_μ, ν_e interactions

Detector's neutrino energy reconstruction

- Outstanding for dominated CCQE interaction
- Potential bias for sub-dominated processes such as 2p2h, CC-resonance is thoroughly investigated and taken into account as systematic errors.

Super-K — T2K far detector: Data sample



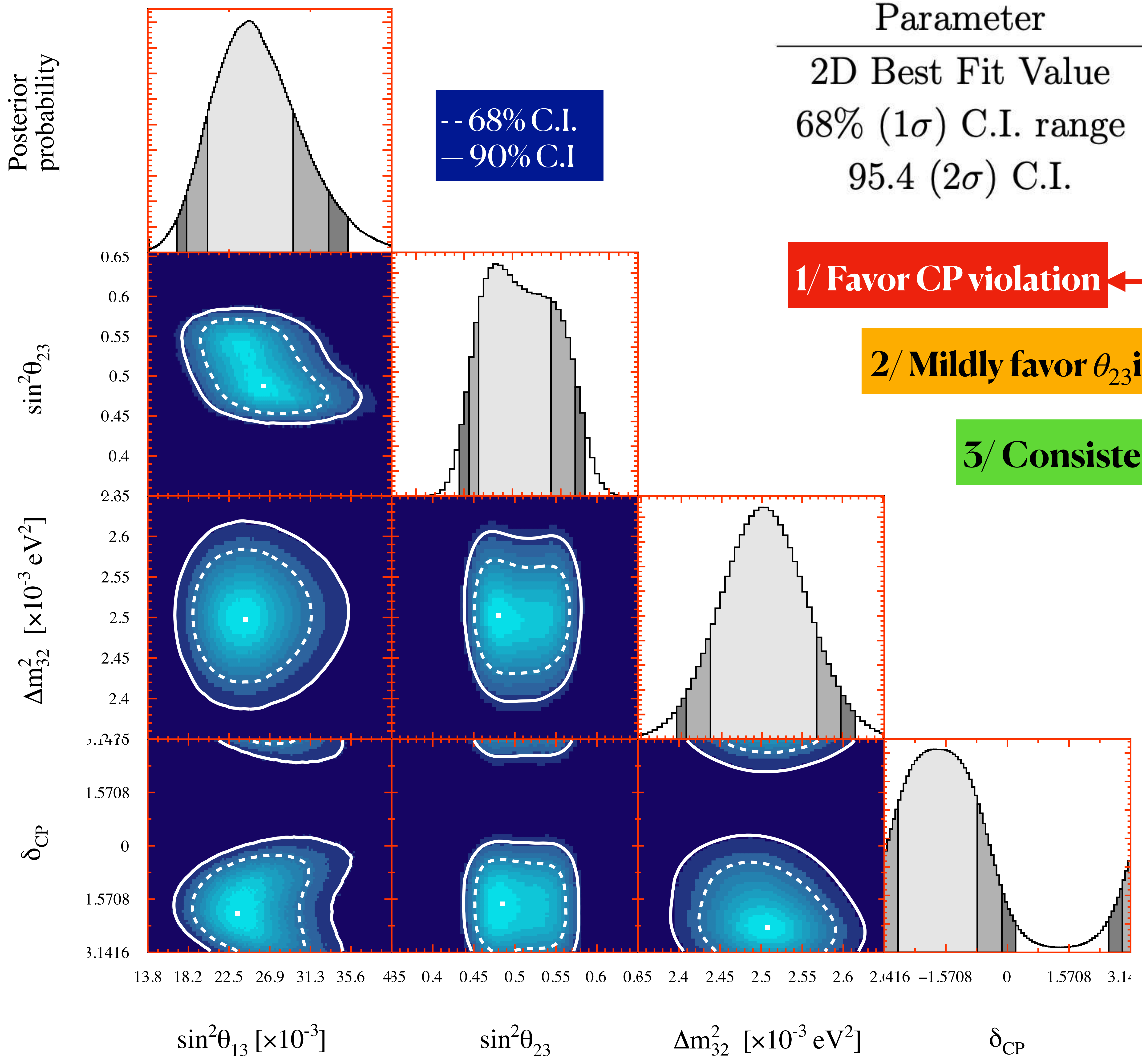
- Total 37.77e20 POT; ν-mode: $\bar{\nu}$-mode = 1.3:1.0
- 6 data samples are selected : 4 in ν-mode an 2 in $\bar{\nu}$-mode based on distinguishable topologies of events in Super-K
- Use 0.01% Gd-loaded data samples (~10% of ν-mode) for the first time
- Introduce new systematic covariance matrix for far detector to reduce uncertainty in $CC1\pi$ samples and low energy of other samples

Error source (units: %)	1R FHC e	1R FHC μ	1R RHC e	1R RHC μ	1R/MR CC1π e CC1π^+	1R/MR CC1π μ CC1π^+	ratio e FHC/RHC
Flux	2.8	2.8	3.0	2.9	2.9	2.9	2.2
Xsec (ND constr)	3.8	3.6	3.5	3.5	4.3	3.0	2.4
Xsec (all)	4.8	3.7	4.8	4.2	5.1	3.3	4.4
Flux+Xsec (ND constr)	2.9	2.8	2.7	2.6	3.7	2.2	2.3
2p2h Edep	0.2	0.5	0.2	0.5	0.0	0.1	0.2
IsoBkg low-p_π	0.1	0.3	2.1	2.3	0.1	0.9	1.9
$\sigma(\nu_\mu)/\sigma(\nu_e)$, $\sigma(\bar{\nu})/\sigma(\nu)$	2.6	0.0	1.5	0.0	2.6	0.0	3.1
NC γ	1.2	0.0	2.1	0.0	0.0	0.0	0.8
NC Other	0.2	0.2	0.4	0.2	0.9	1.0	0.2
Flux+Xsec (all)	4.1	2.8	4.3	3.5	4.6	2.6	4.4
SK	2.7	1.4	5.1	3.6	4.3	2.9	4.0
Total All	4.9	3.2	6.7	5.0	6.3	3.9	5.9

Latest results from T2K
(focused on leptonic mixing and ν mass ordering)

For latest cross section result , please come to A. Izmaylov's talk

Latest results from T2K



Parameter	δ_{cp} [rad.]	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	Δm^2_{32} [$\times 10^{-3}$ eV^2]
2D Best Fit Value	-2.01	0.48	0.024	2.51
68% (1σ) C.I. range	[-2.83,-0.75]	[0.47,0.55]	[0.021,0.030]	[-2.59,-2.51] $\cup$ [2.44,2.57]
95.4 (2σ) C.I.	[$-\pi$,0.25] $\cup$ [2.51,π]	[0.45,0.58]	[0.018,0.036]	[-2.65,-2.45] $\cup$ [2.39,2.62]

1/ Favor CP violation

2/ Mildly favor θ_{23} in lower octant

3/ Consistent w/ reactor-based measurements

4/ Slightly favor normal ν mass ordering

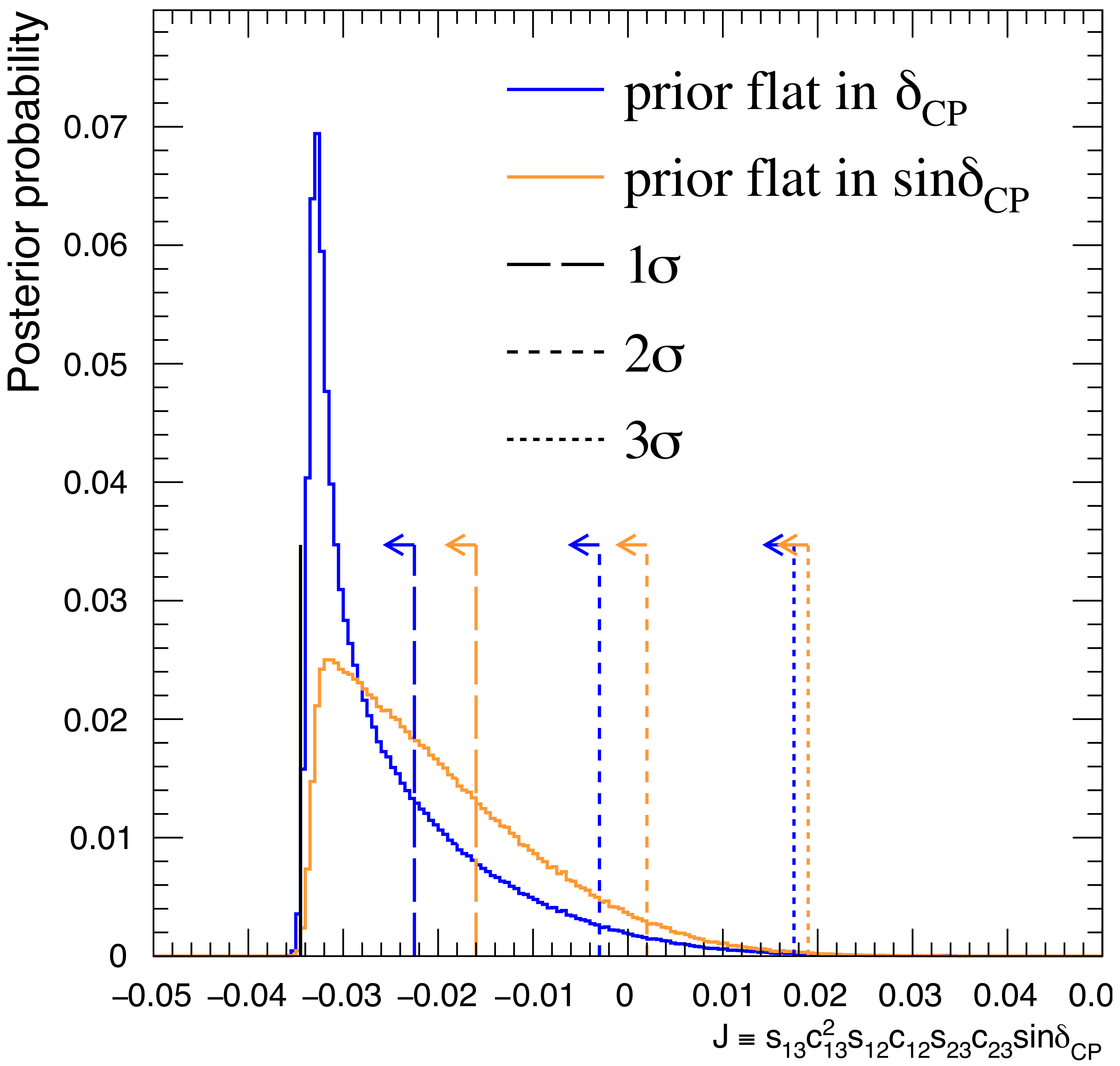
- 4 out of total 6 parameters constrained by **T2K data only**
- T2K measurement of θ_{13} is consistent but less stringent than constraint from reactor-based ν experiments, $\sin^2\theta_{13}^{\text{reactor}} = 0.0220 \pm 0.0007$
- This reactor constraint is used as external constraint or prior to enhance sensitivity to other parameters.

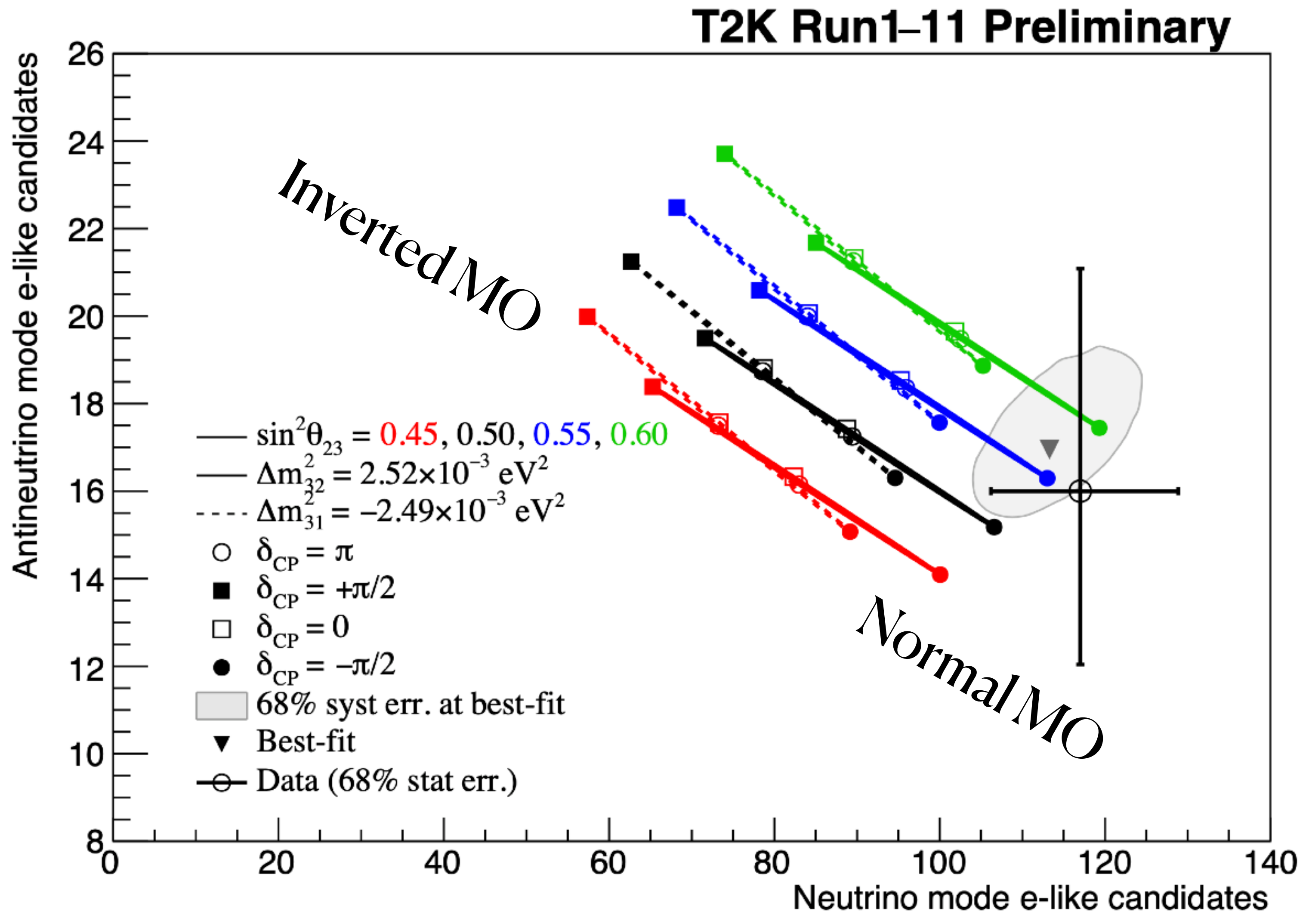
Latest results from T2K (cont'd)

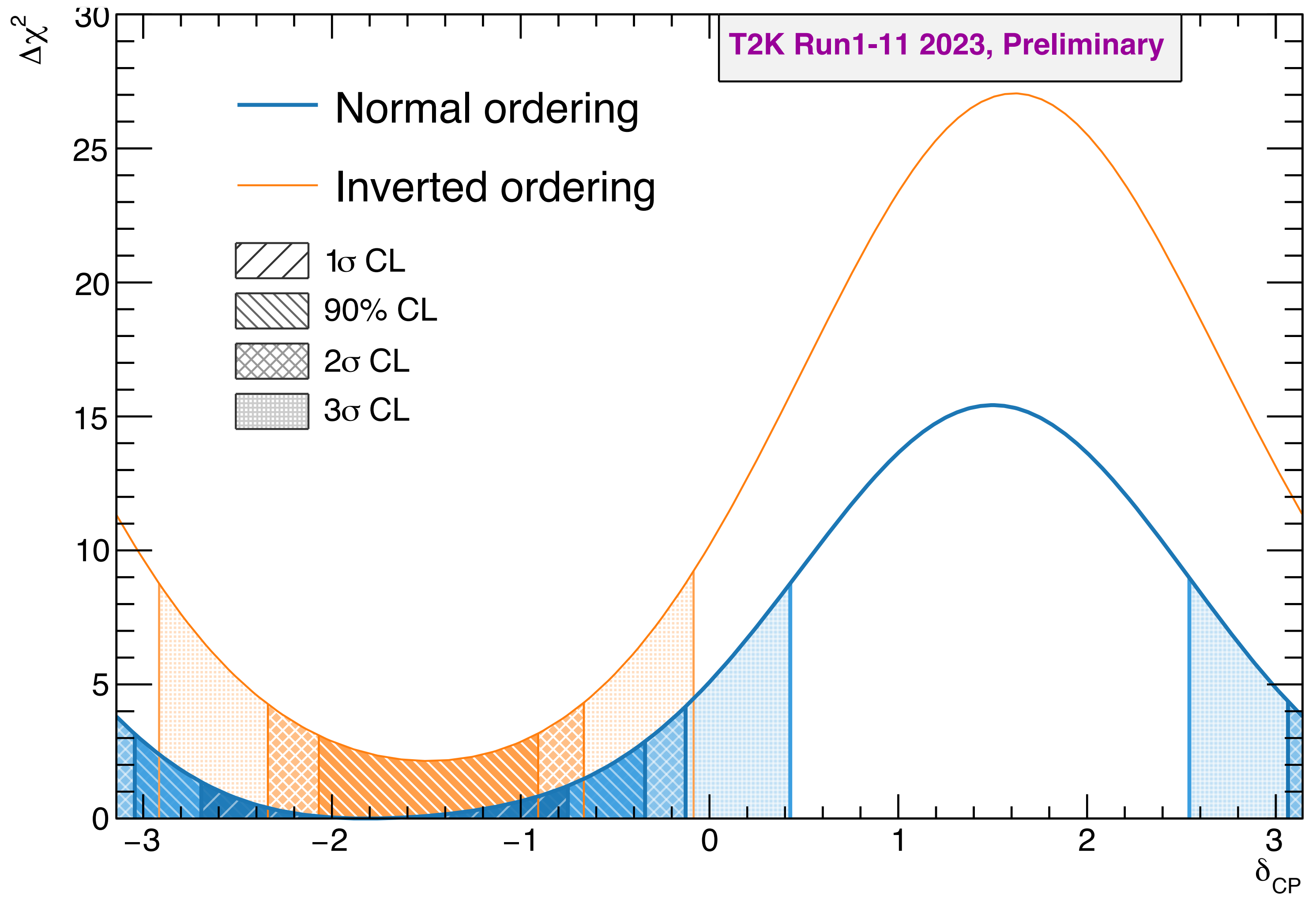
T2K data with constraint $\sin^2\theta_{13}^{\text{reactor}} = 0.0220 \pm 0.0007$

Parameter	δ_{cp} [rad.]	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	Δm^2_{32} [$\times 10^{-3}$ eV^2]
Central Value	-1.85	0.54	0.022	2.50
1σ C.I.	[-2.60,-1.01]	[0.49,0.56]	[0.021,0.023]	[2.42,2.59]
2σ C.I.	[$-\pi$, -0.34] ∪ [3.10, π]	[0.46,0.58]	[0.021,0.023]	[-2.63,-2.47] ∪ [2.38,2.62]

- Data are described best with $\sin\delta_{CP} \approx -1$, but be consistent with CP conservation ($\sin\delta_{CP} = 0$) within 2σ
- Jarlskog invariant, characterizes CP violation amplitude with parameterization-independence, is measured w/ majority of probability at $|J|_{lepton} \approx 3.2 \times 10^{-2}$
  - Results varied slightly depending on the δ_{CP} prior.
  - Ref. $|J|_{quark} \approx (3.18 \pm 0.15) \times 10^{-5}$







Latest results from T2K (cont'd)

T2K data with constraint $\sin^2\theta_{13}^{\text{reactor}} = 0.0220 \pm 0.0007$

Parameter	δ_{cp} [rad.]	$\sin^2\theta_{23}$	$\sin^2\theta_{13}$	Δm^2_{32} [$\times 10^{-3}$ eV^2]
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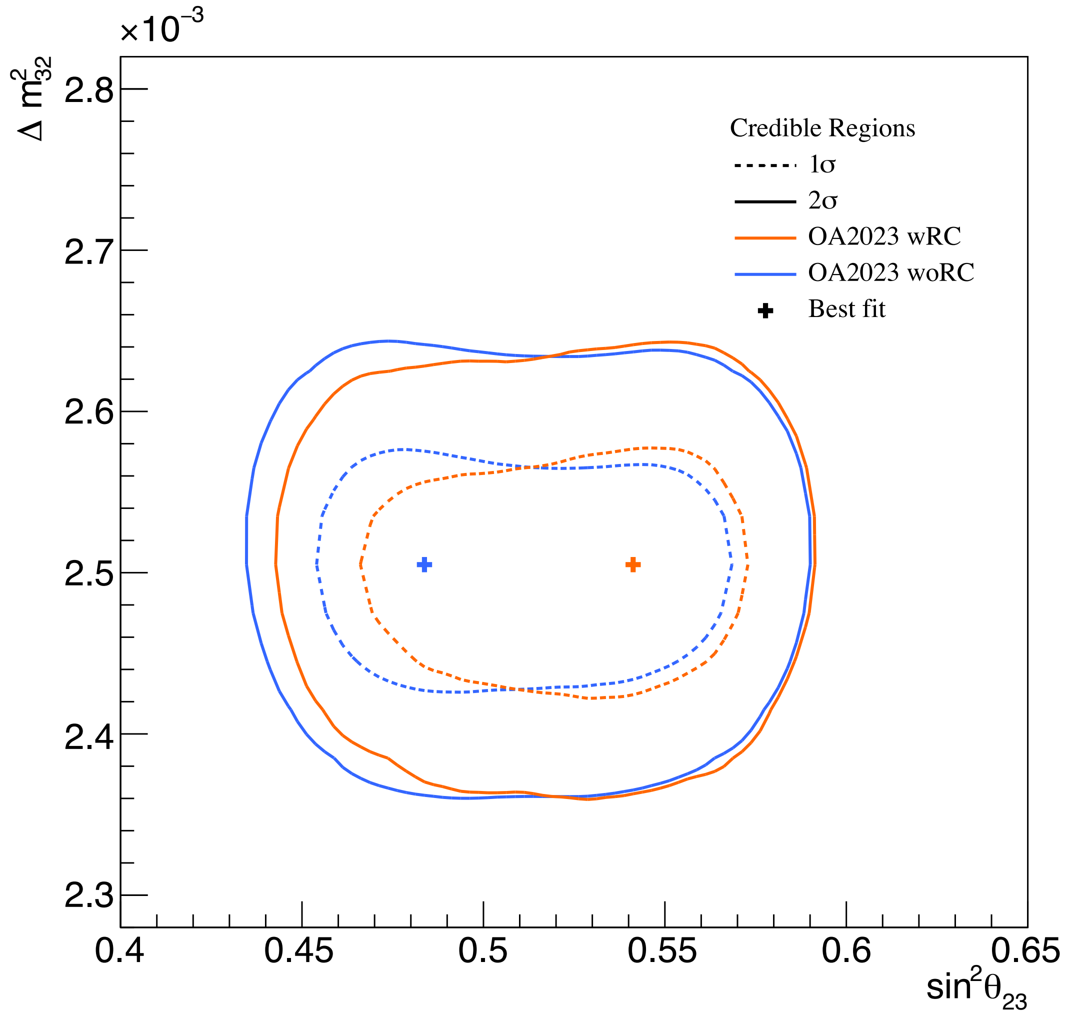
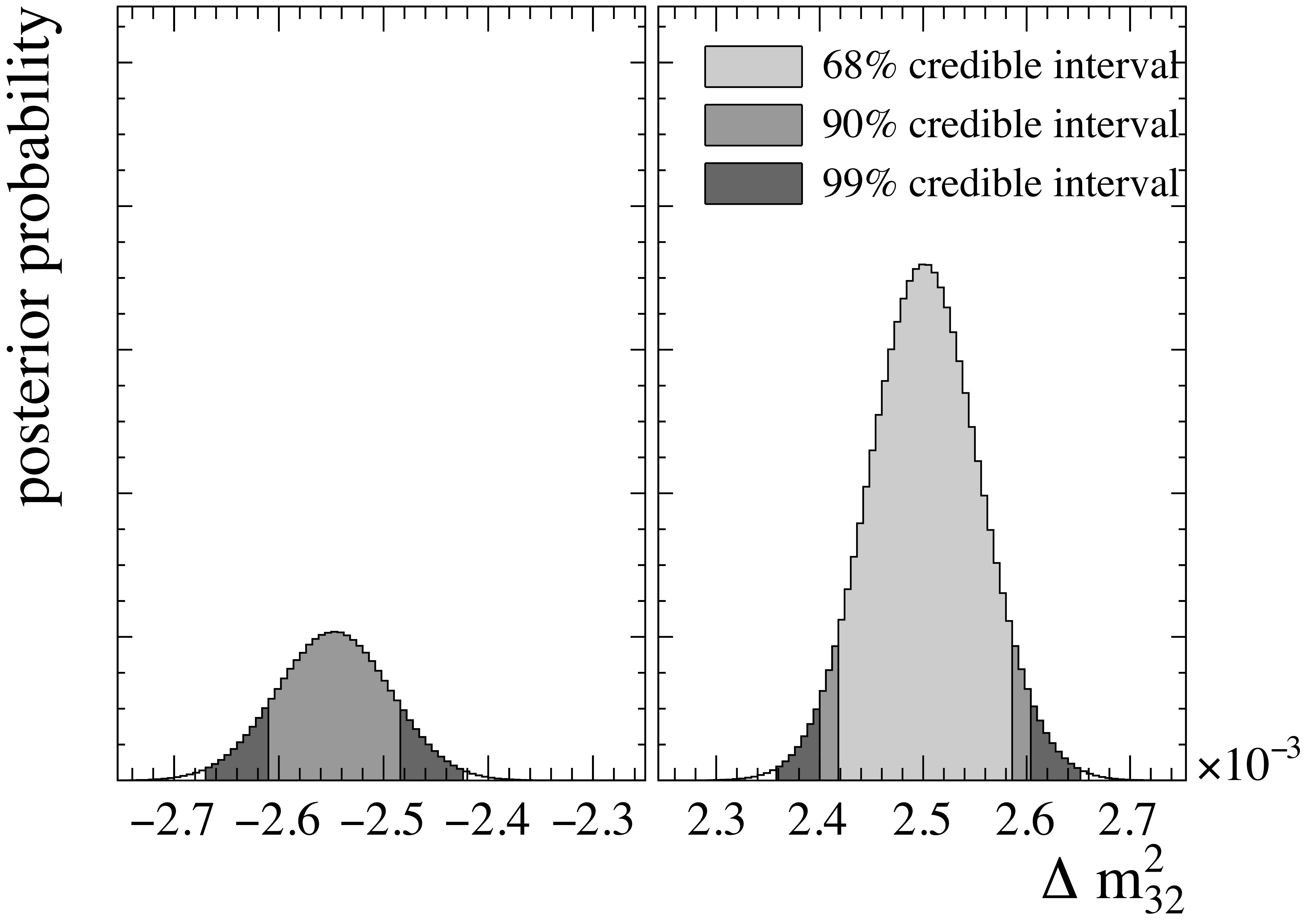


Applying reactor constraint results in a swap of octant preference

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.23	0.54	0.77
IH ($\Delta m^2_{32} < 0$)	0.05	0.18	0.23
Sum	0.28	0.72	1.00

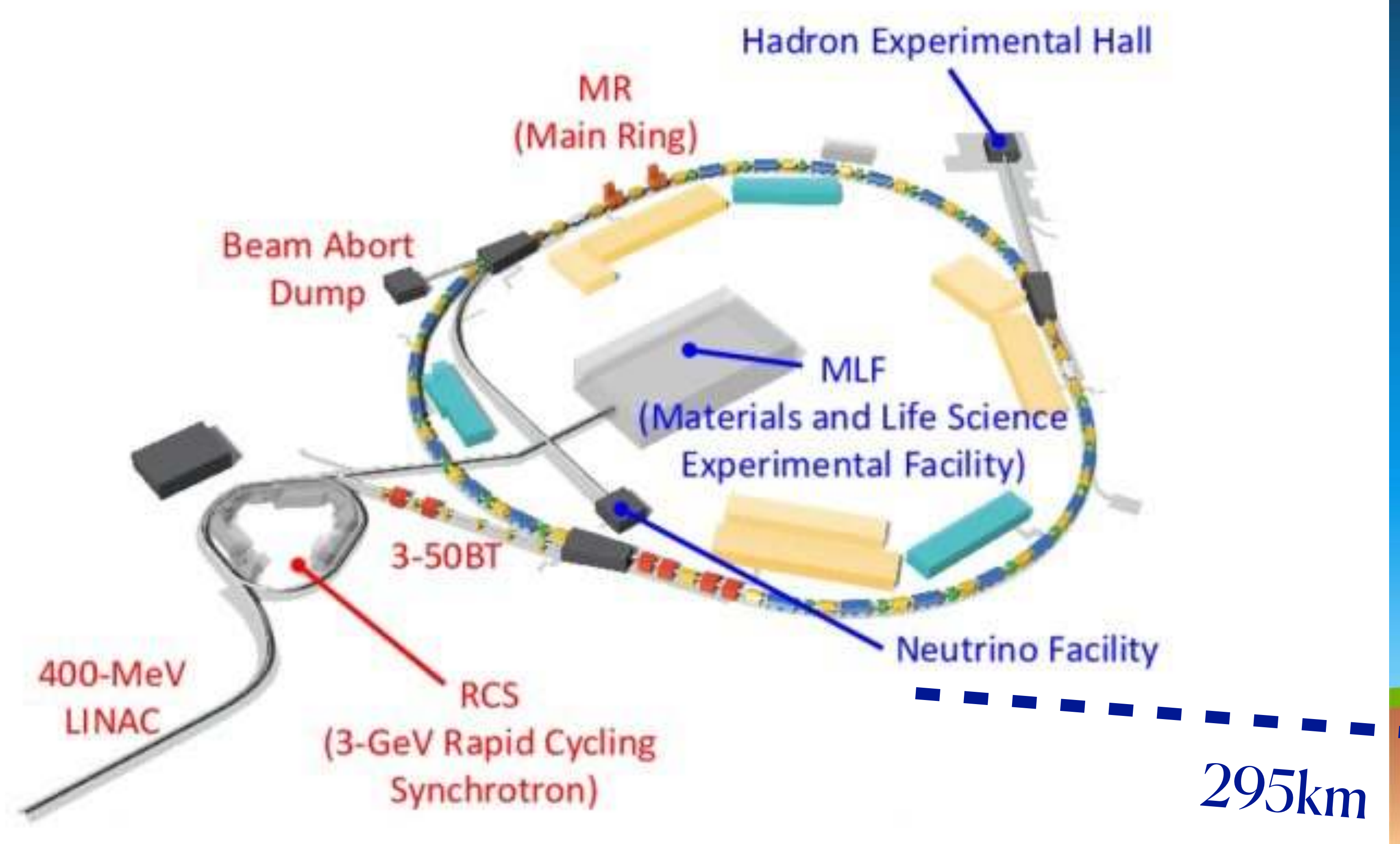


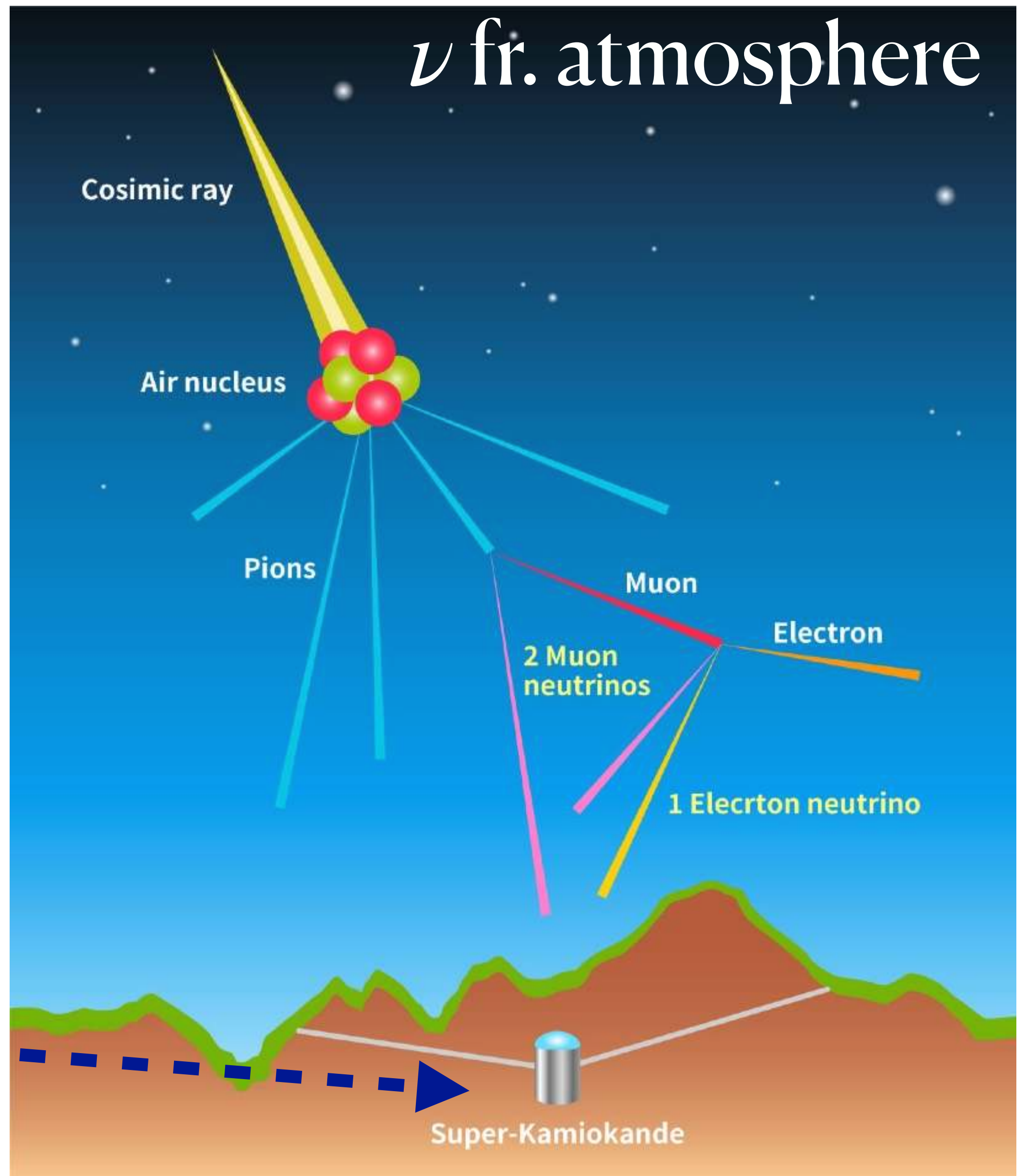
T2K weakly favors normal mass ordering and higher octant with Bayes factor of 3.2 and 2.6 respectively

Joint analysis with Super-K (SK)

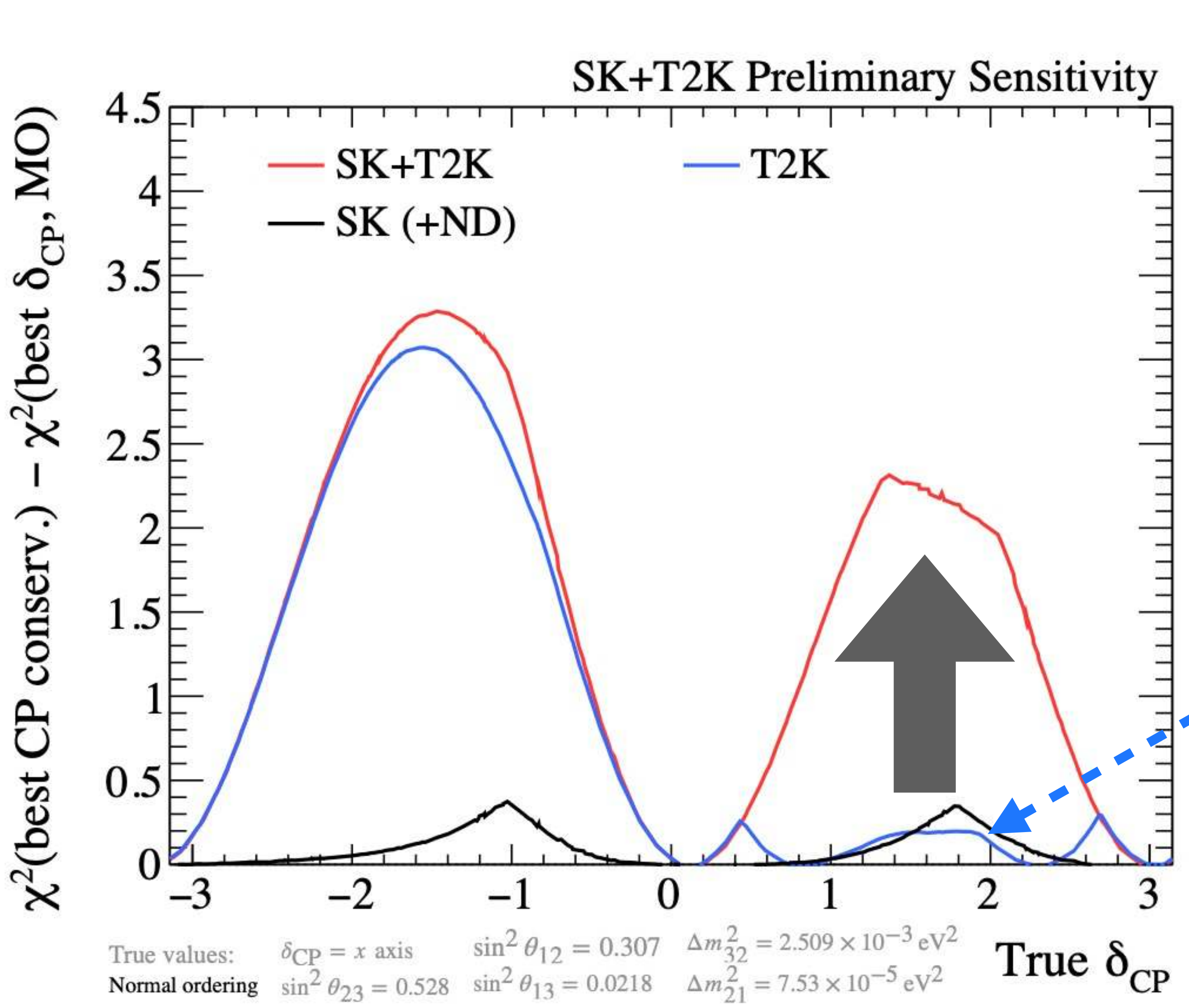
T2K & SK: motivation for joint analysis

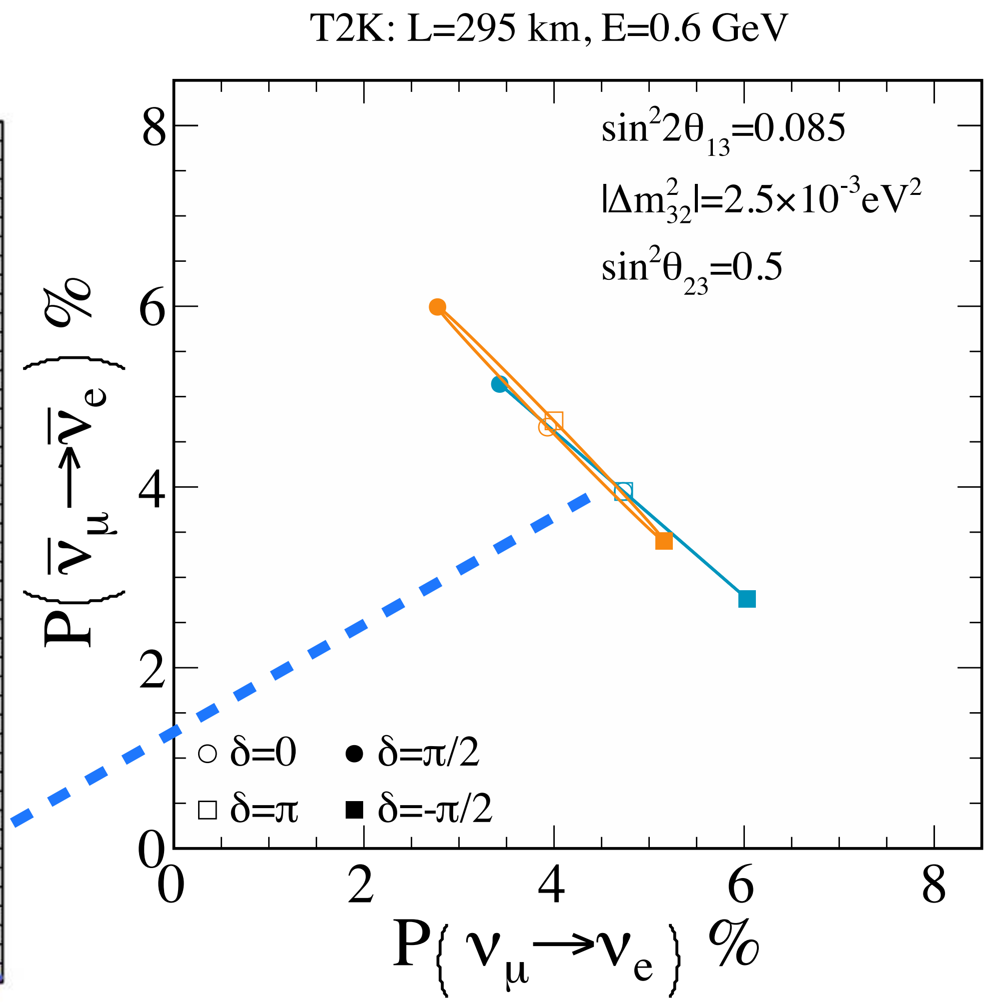
ν fr. accelerator





- **Complementary in measurements**: higher sensitivity of MO in Super-K and of CP violation in T2K

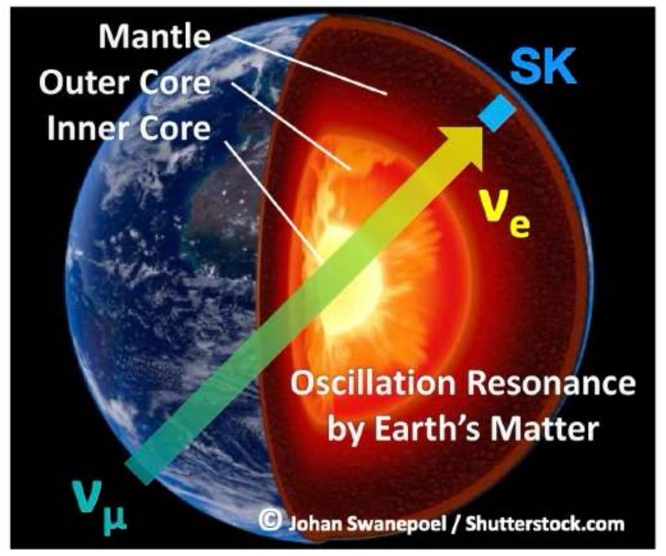


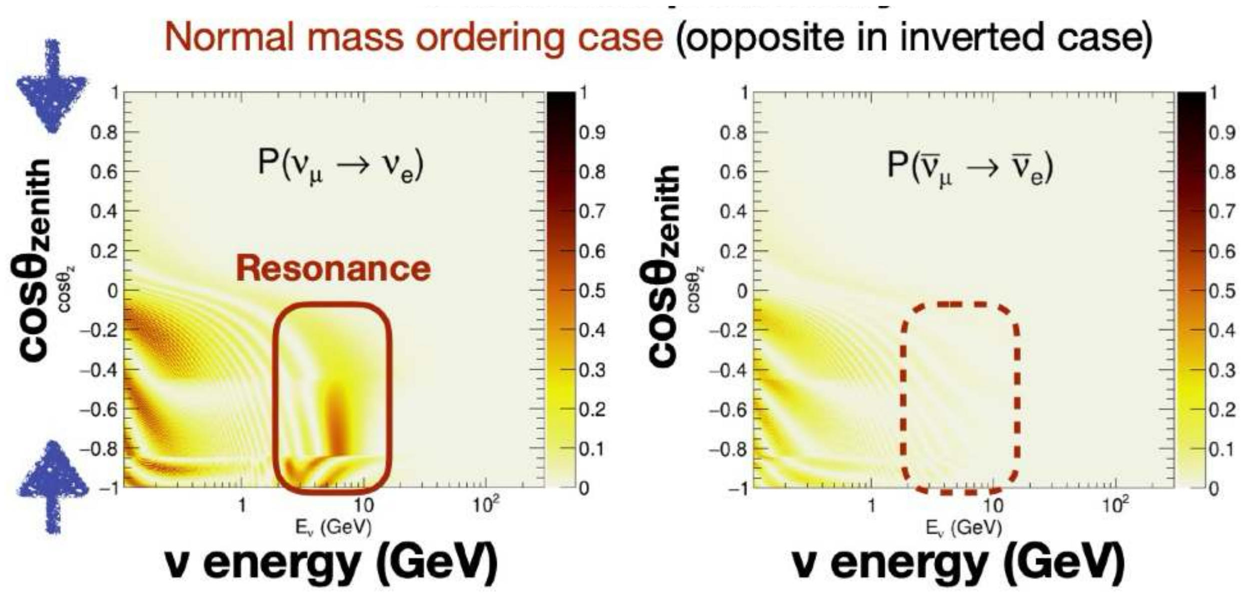


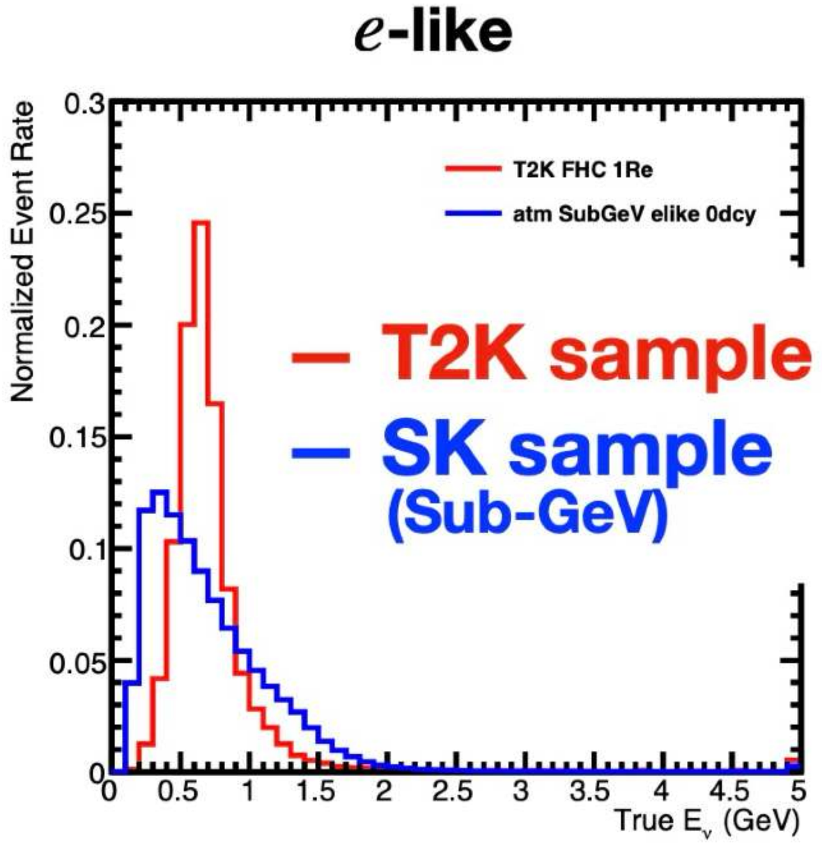
Degeneracy btw. δ_{CP} and MO in T2K

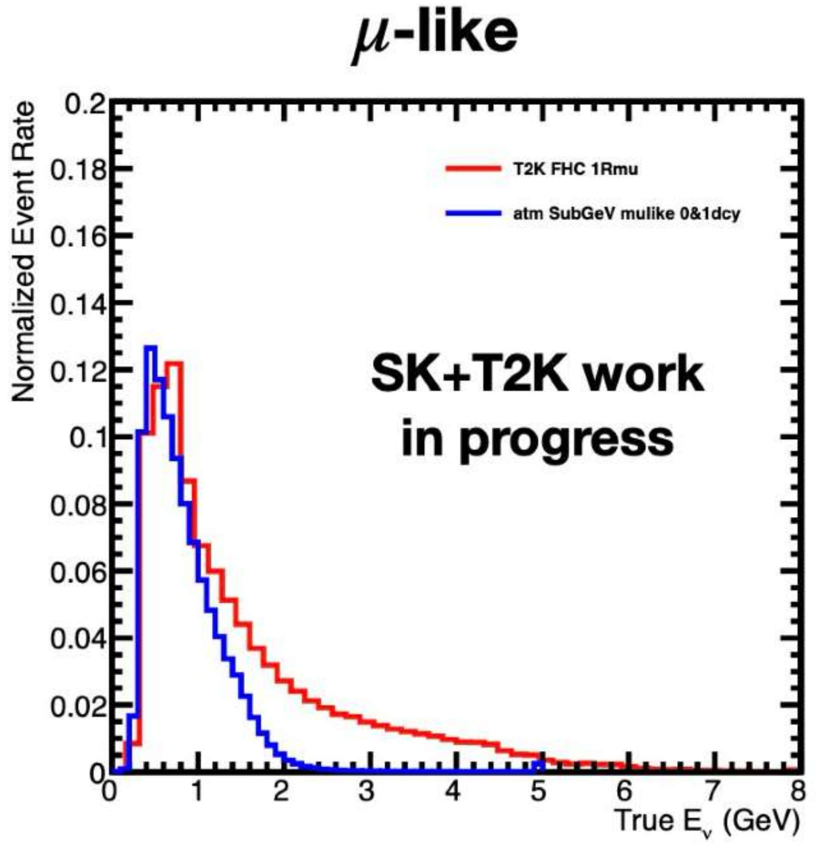
- Same detector, different neutrino sources but similar energy range ➜ strongly correlated in detector systematics; interaction models and nuclear effects

Matter effect in SK is sensitive to MO





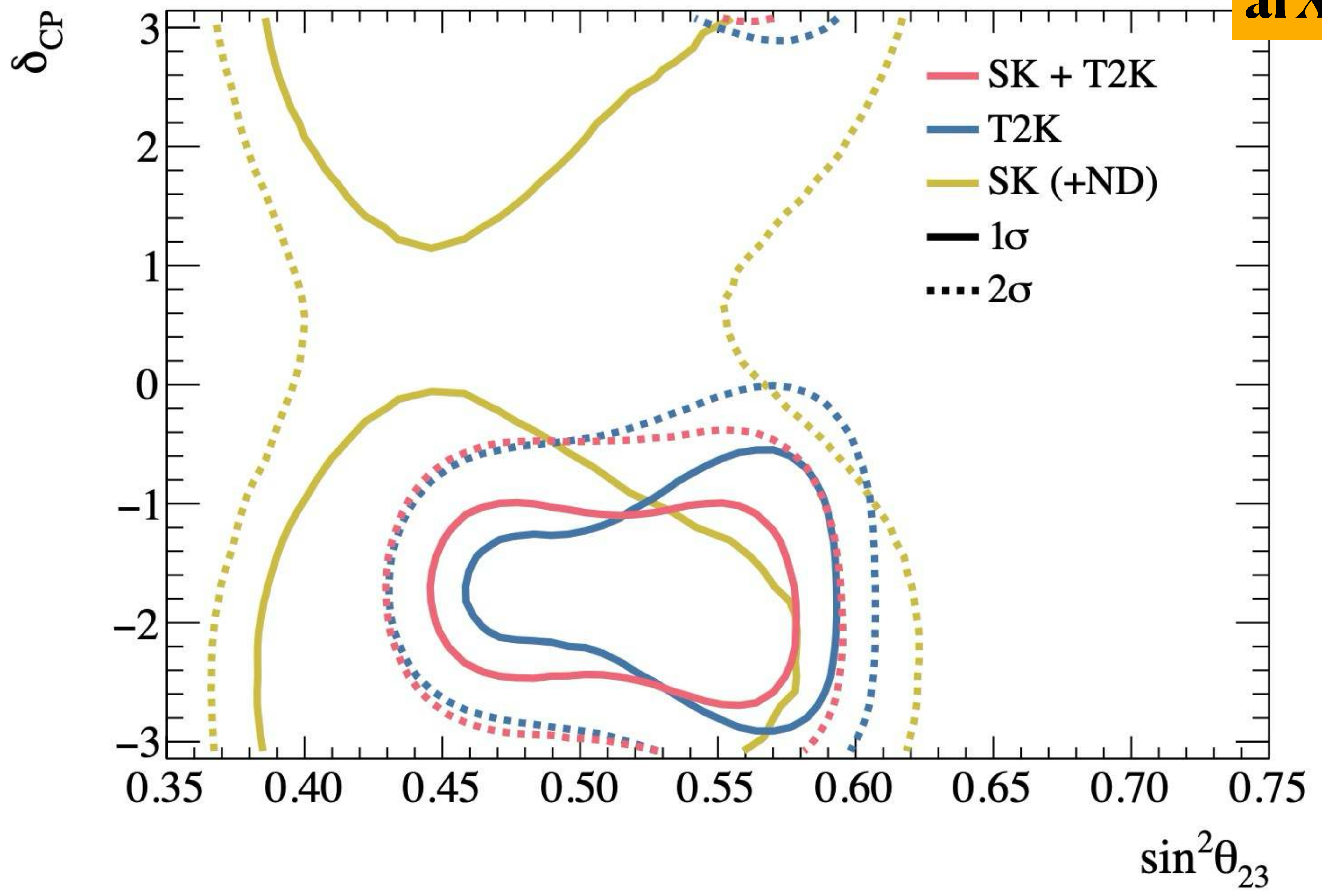


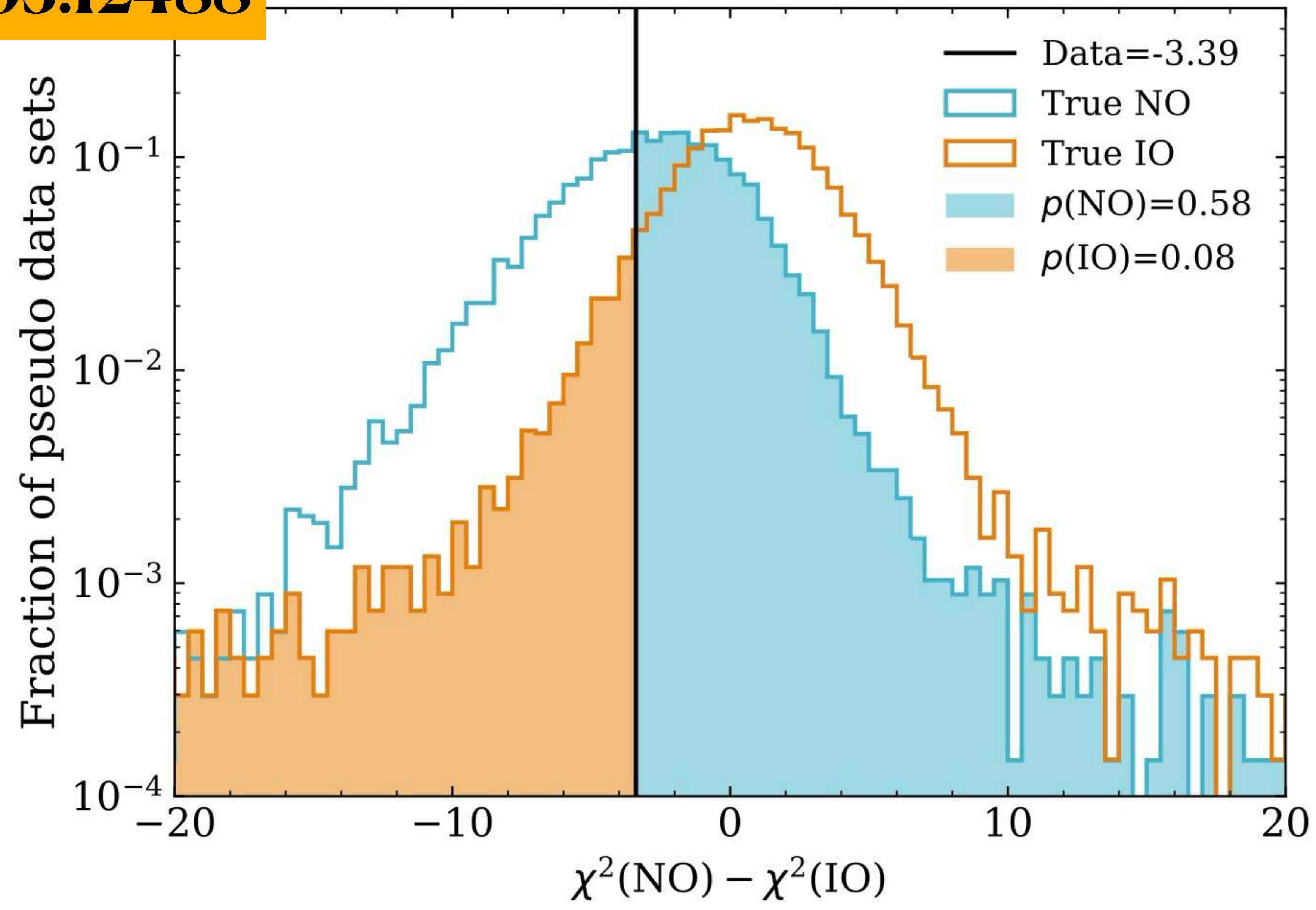


- Also, expect to improve precision on $\theta_{23},\ \theta_{13},\ |\Delta m^2_{32}|$

T2K & SK: Joint fit's results

arXiv:2405.12488





Use 36e20 POT exposure from accelerator and 3244.4 days of atmospheric neutrino data

Hypothesis test.	uniform prior in	
	δ_{CP}	$\sin \delta_{CP}$
$J_{CP} = 0$	2.2σ	1.9σ
$\delta_{CP} = 0$	2.5σ	2.2σ
$\delta_{CP} = \pi$	1.9σ	1.4σ

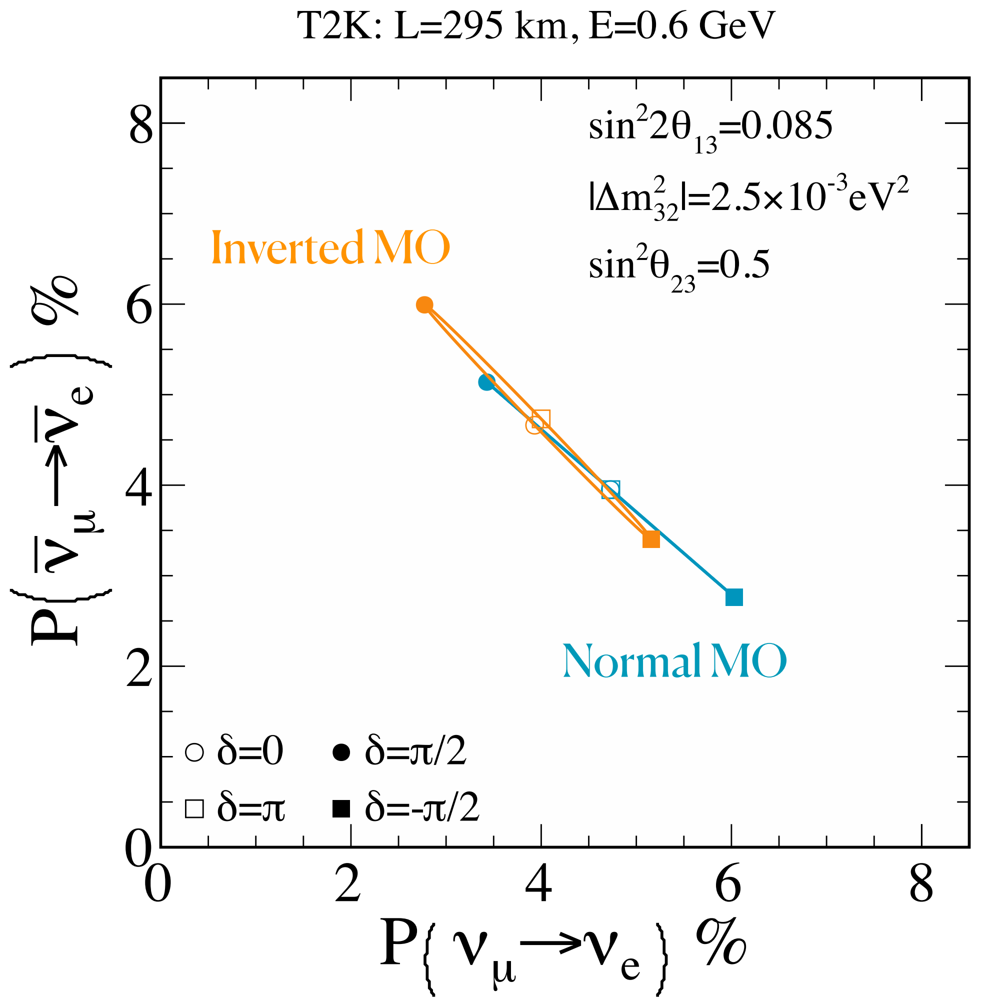
- CP-conserving value of the Jarlskog invariant is excluded with 1.9σ or higher significance depending on prior
- Moderately favor the normal mass ordering (P(NO)=0.58 vs P(IO)=0.08)
- Insignificant deviation from maximal mixing of θ_{23}

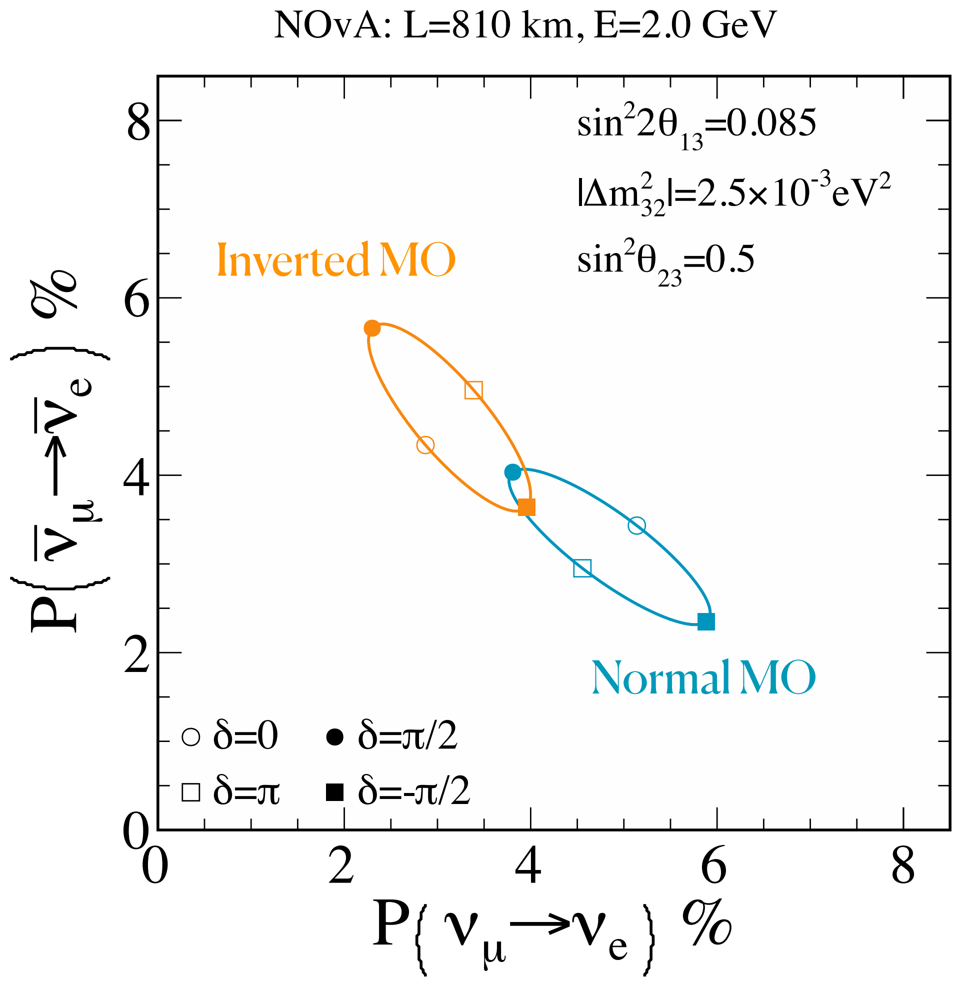
Joint analysis with NOvA

T2K & NOvA: Motivation for joint analysis

	T2K	NOvA
Peak neutrino energy	0.6 GeV	1.8 GeV
Baseline	295 km	810 km
Far detector mass	50 kton	14 kton
Far Detector technique	Water Cherenkov	Scintillator calormimeter

- Both are 2nd generation of accelerator-based long-baseline neutrino experiments
- The two exp. with different baseline/energy and detection technique are complementary to study neutrino oscillations:
  - CPV effect in T2K's appearance sample is relatively higher than NOvA
  - Longer baseline of NOvA renders relatively higher sensitivity to mass ordering
  - Expect to improve precision in $\theta_{13},\ \theta_{23},\ |\Delta m^2_{32}|$

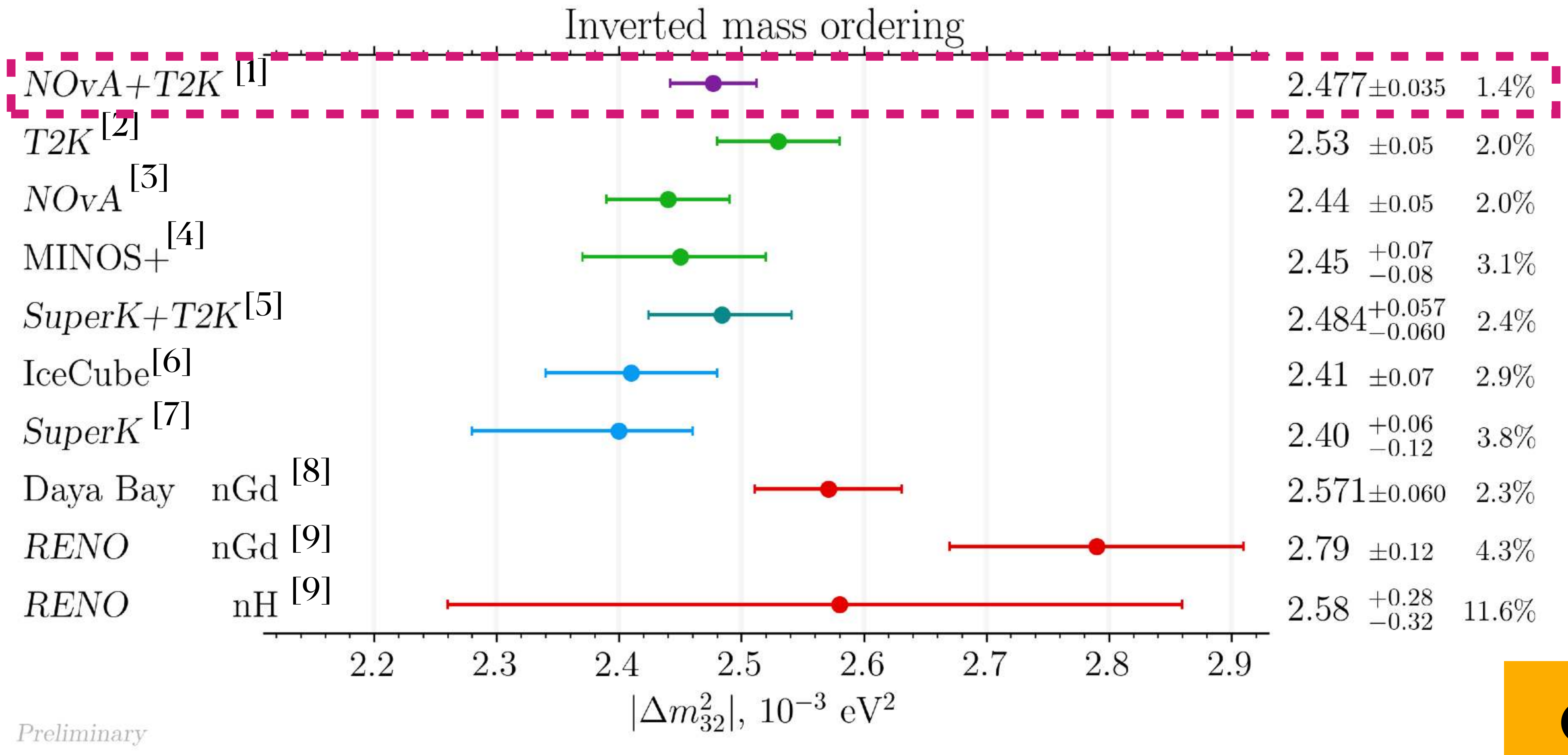




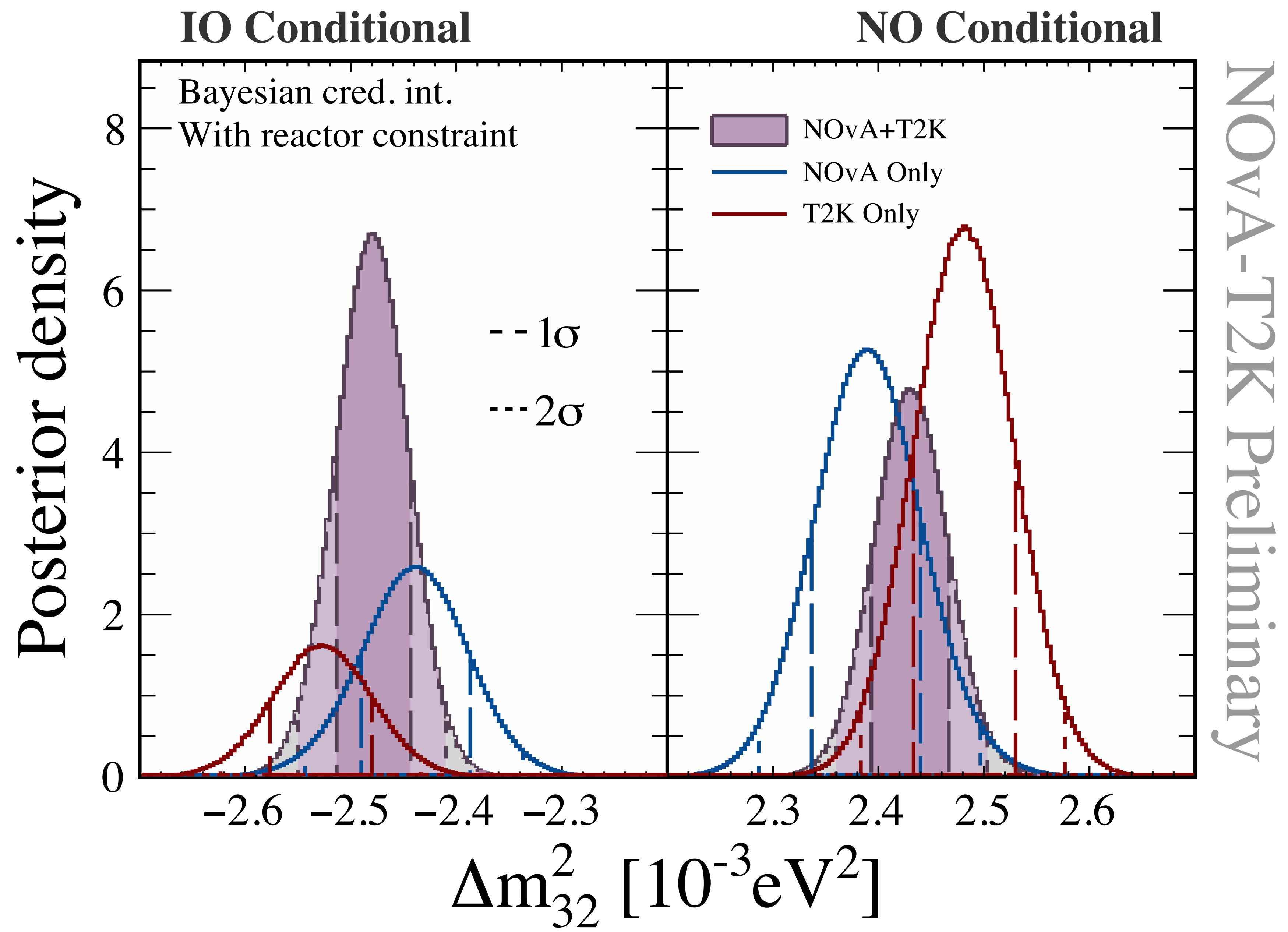
T2K & NOvA: Joint fit's results

On mass ordering: slightly favor the inverted ordering,
Quite depending on prior from reactor-based exp.

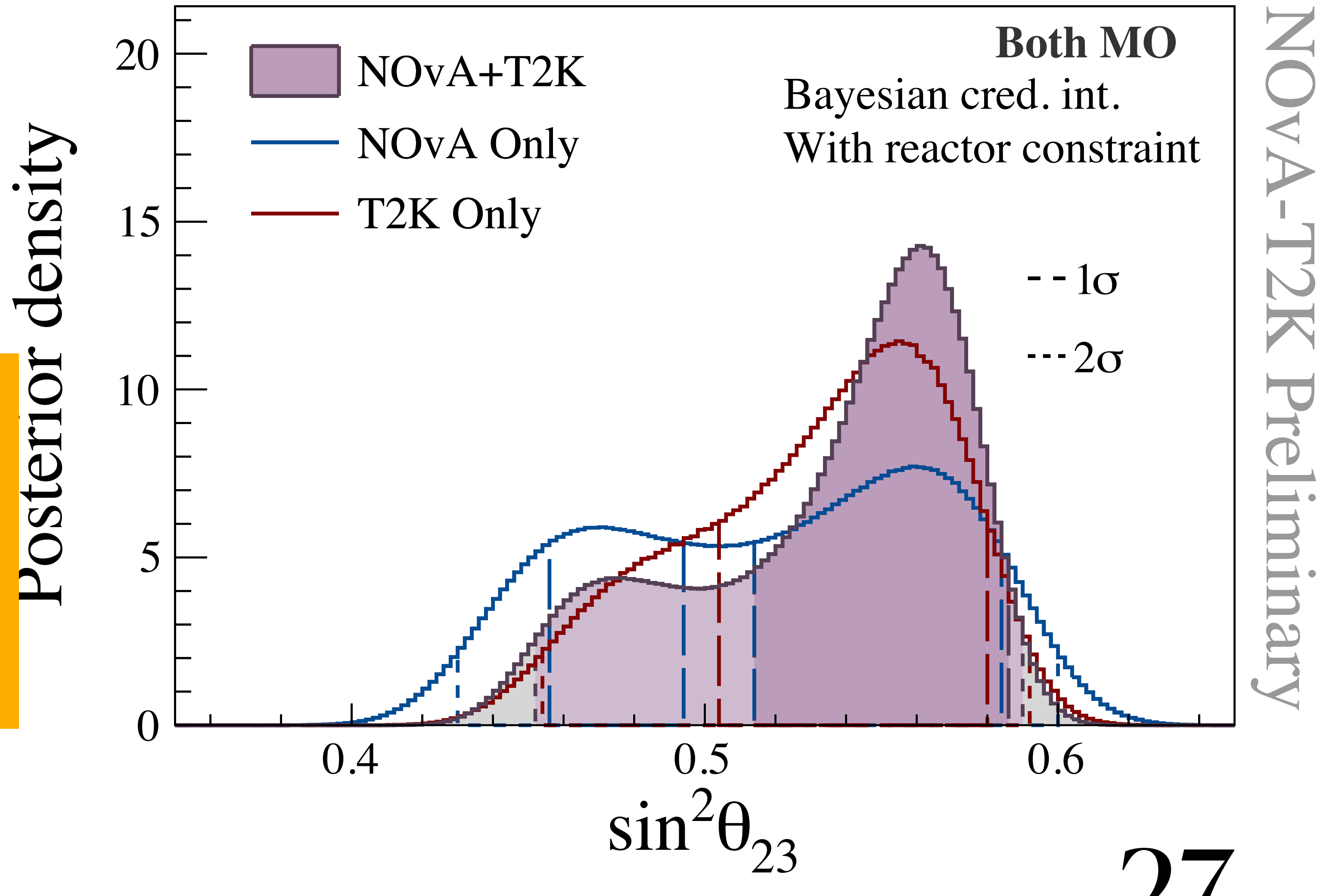
NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)



Reach 1.4% (IO) / 1.5% (NO) precision of $|\Delta m^2_{32}|$



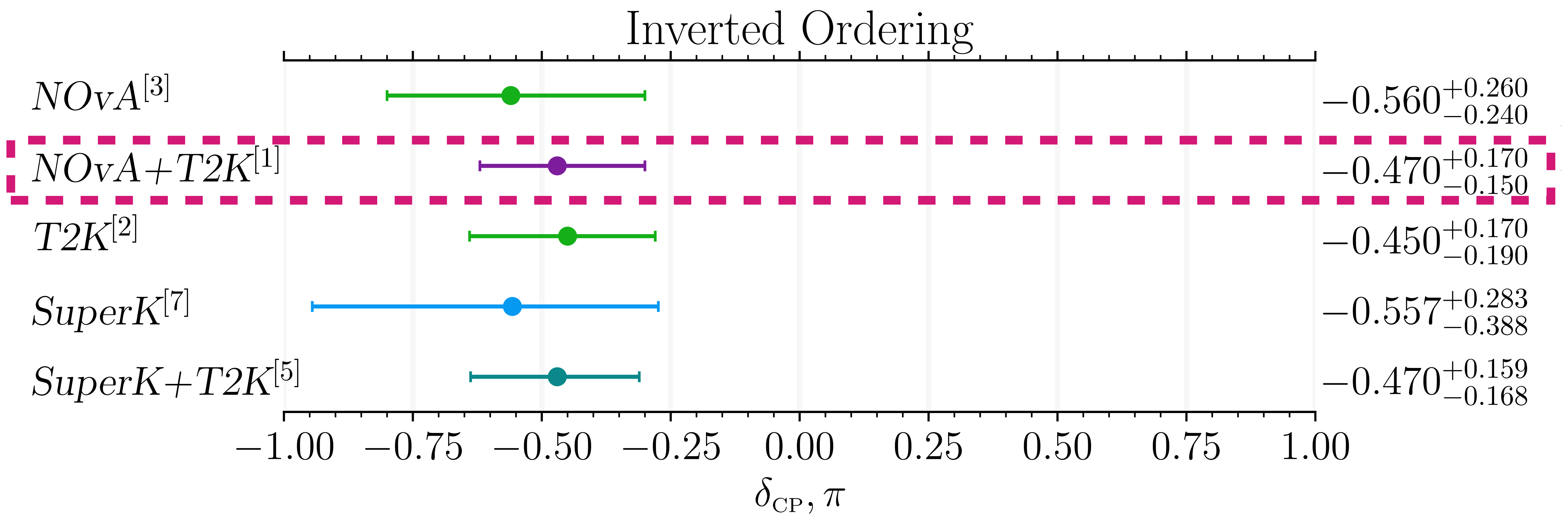
On θ_{23}: slightly favor higher octant, still consistent w/ maximal mixing in 2σ

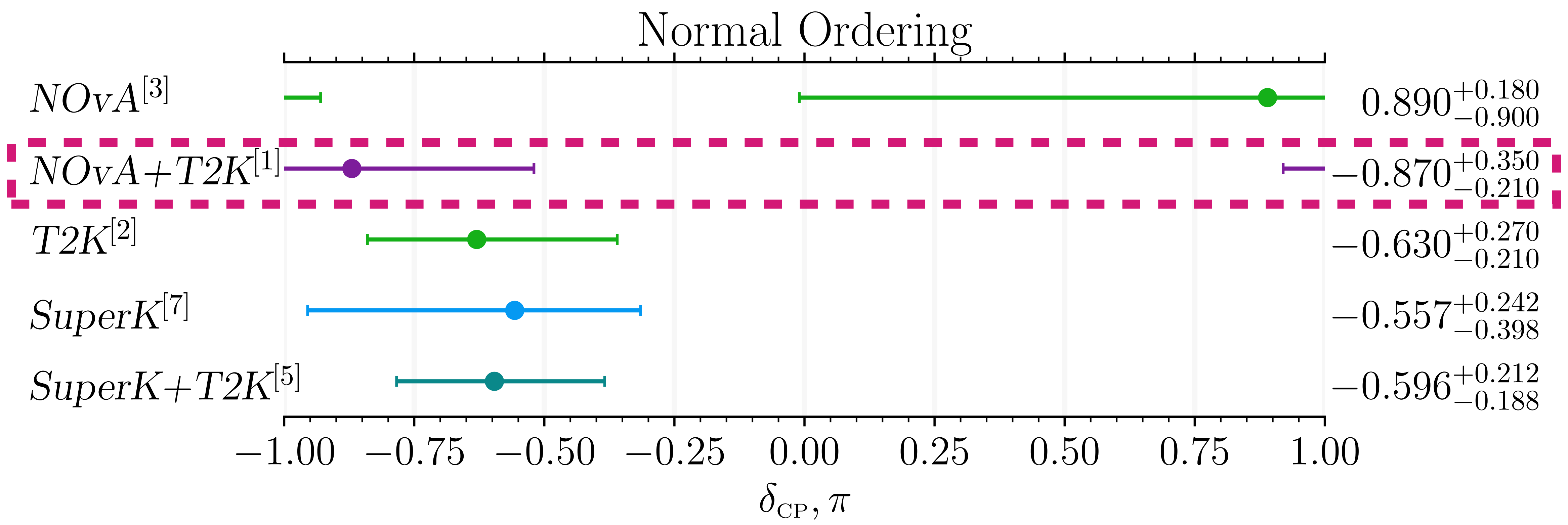


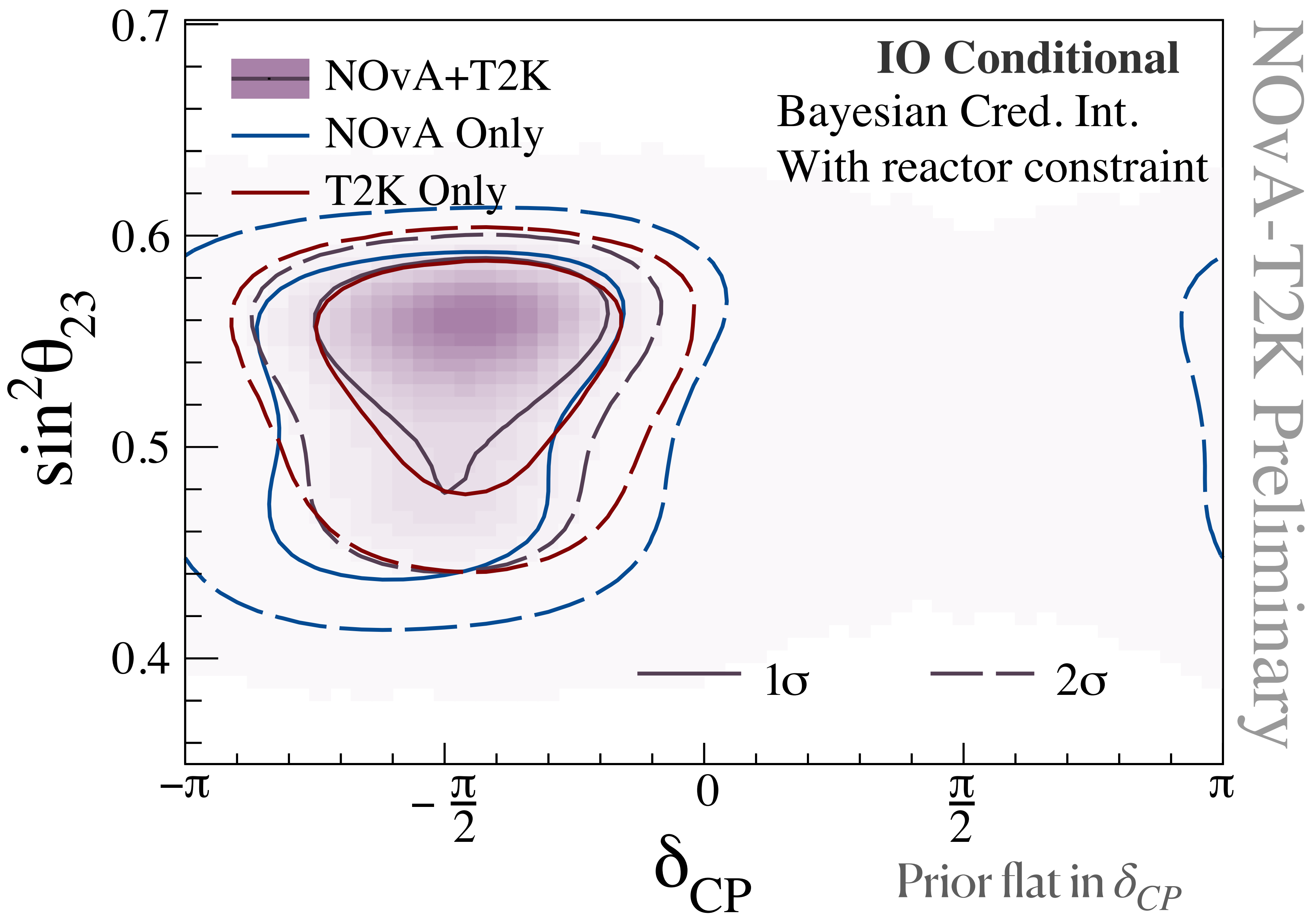
[1] KEK IPNS seminar, FNAL JETP seminar
[2] Eur. Phys. J. C83, 782 (2023)
[3] Phys. Rev. D106, 032004 (2022)
[4] Phys. Rev. Lett. 125, 131802 (2020)
[5] arXiv:2405.12488
[6] arXiv:2405.02163
[7] Phys. Rev. D109, 072014 (2024)
[8] Phys. Rev. Lett. 130, 161802 (2023)
[9] RENO @ Neutrino 2020 [10.5281/zenodo.3959697]

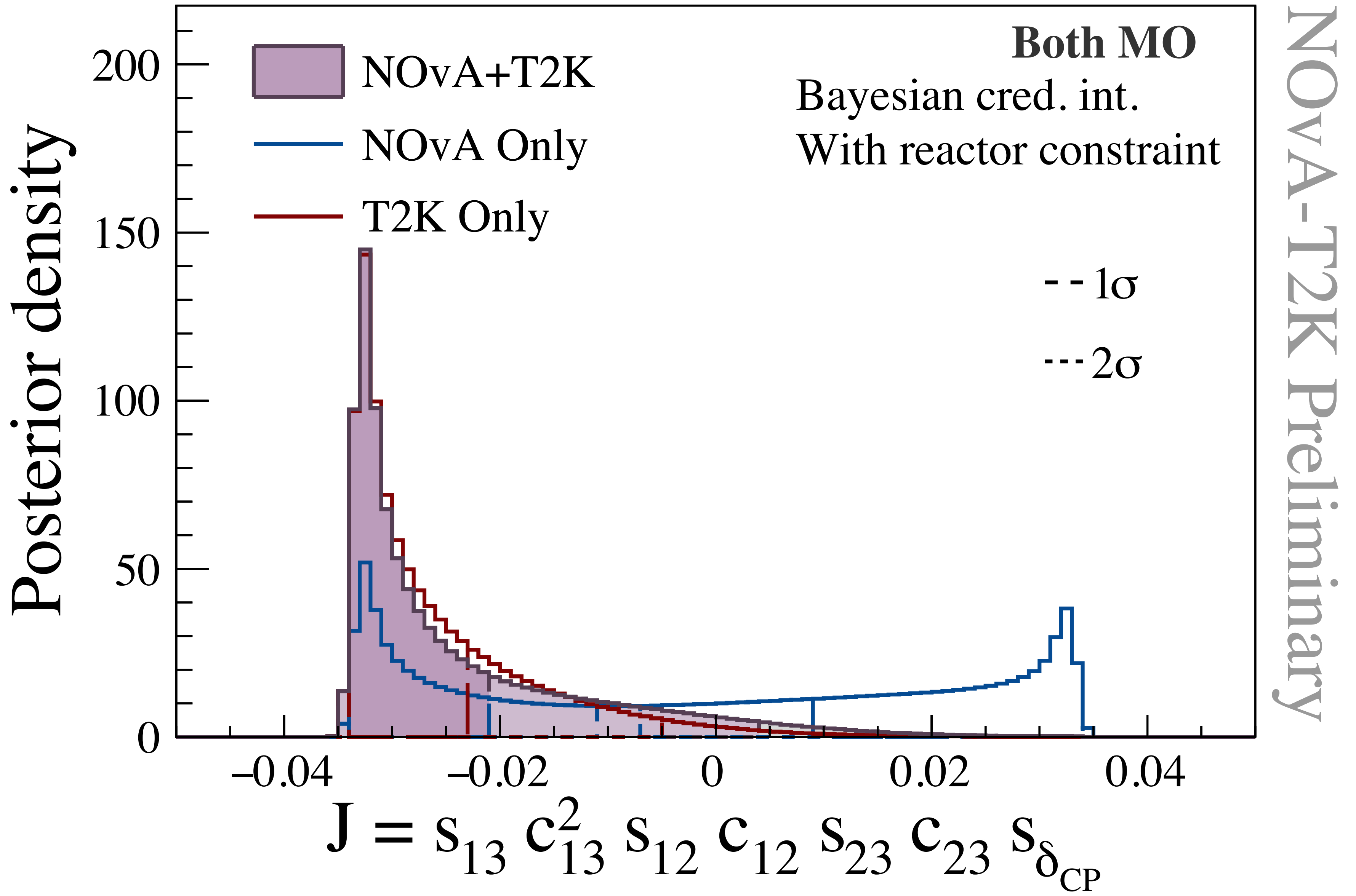
T2K & NOvA: Joint fit's results

On CPV search: if mass ordering is inverted , both exp. agrees well and a joint analysis strongly favor CPV with more than 3σ. In case of normal ordering, CPV preference is not strong.









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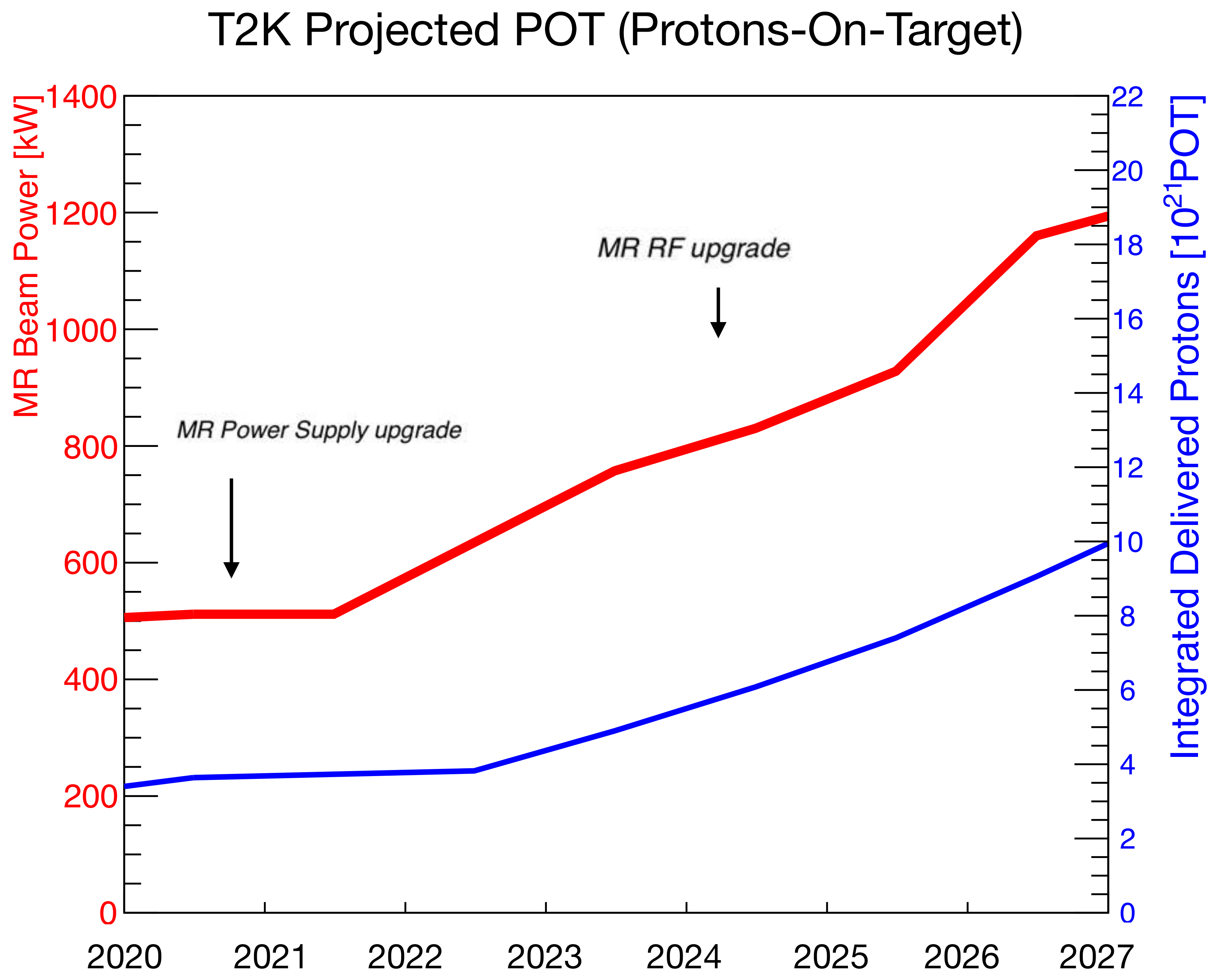
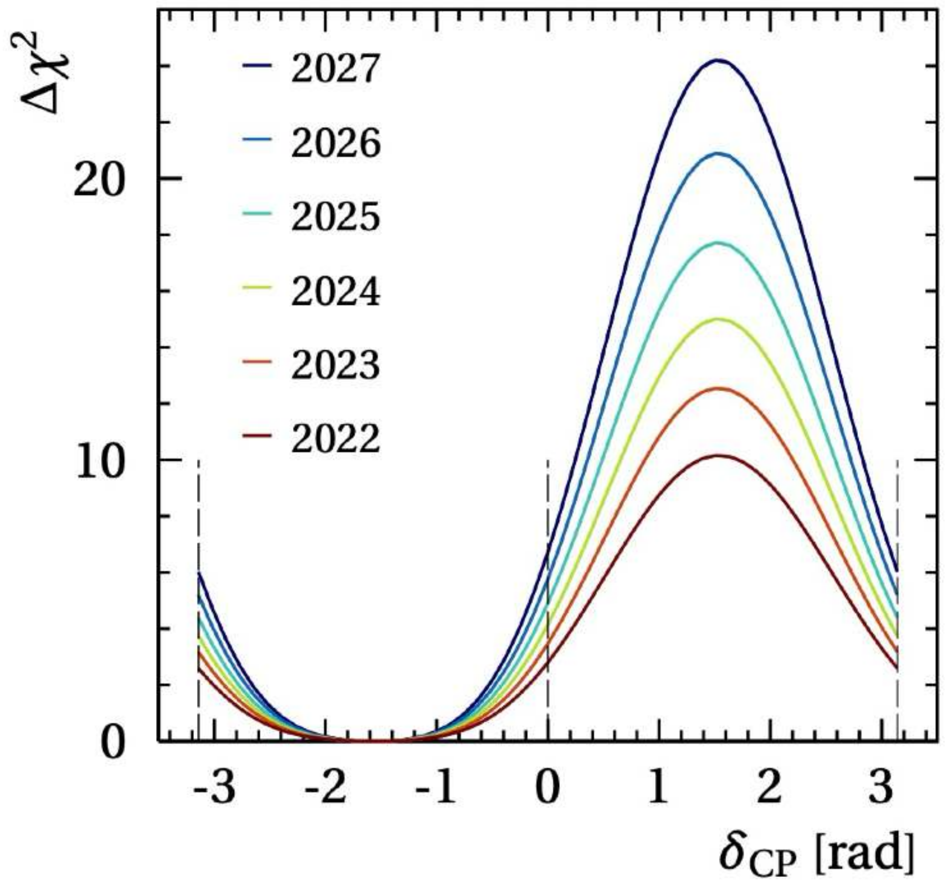
Future prospects

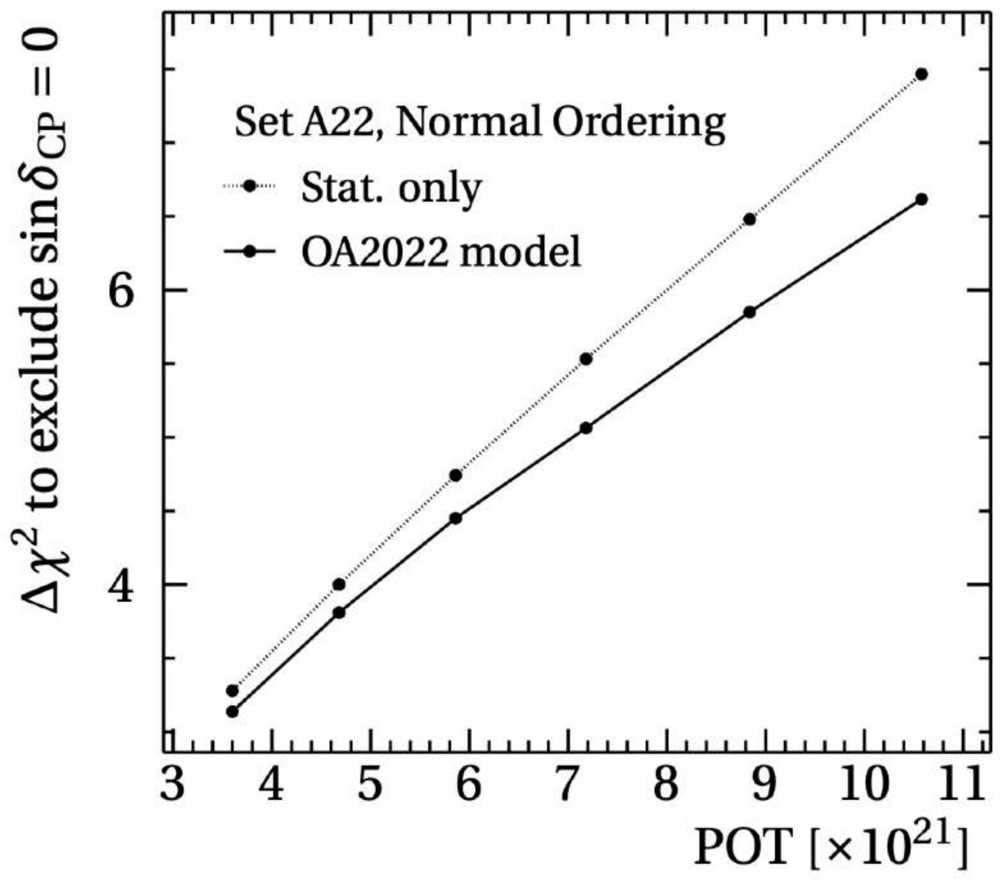
The completion for leptonic mixing and neutrino mass ordering is currently underway, and will get more intriguing as more data is collected and analyzed.

Prospects with T2K

- **More intense neutrino beam** with upgrades from accelerator and neutrino beamline toward MW-power level, now 800kW
  - Expect to collect x2 more statistics by the end of run (*~10e21 POT in total*)
  - Improve significantly the CPV search and precision of other parameters
- Data from the **upgraded Near Detector** allows us to better comprehend the neutrino-nucleon/nuclei interaction models ➜ better control of systematics
- **New period of observation with Gd-doped Far Detector, Super-K**, further assists neutrino energy reconstruction and $\nu - \overline{\nu}$ classification







Prospects and the need of joint analyses

Success of collaboration among neutrino experiments encouraging greater efforts in the near future with well-established joint analyses

- To explore wider range of oscillation parameter space, particularly for leptonic CP violation, ν mass ordering, precise mixing angle θ_{23} and θ_{13}
- To take full likelihood maps from each individual experiments
- To study and examine neutrino interaction models used and tuned in each experiment
- To correlate the systematic uncertainties where appropriate

Data [POT]	T2K	NOvA	Super-K
Total jointly-analyzed data	3.60E+21	2.61E+21	3244.4 days (pure water)
Expectation by the operation end	10.E+21	7.2E+21	+4 years (Gd-doped water)

??

Summary

- **Latest data from T2K**
  - Described best with $\sin\delta_{CP} \approx -1$, still consistent with CP conservation ($\sin\delta_{CP} = 0$) within 2σ
  - Normal mass ordering and higher octant of θ_{23} are weakly preferred (*Bayes factors of 3.2 and 2.6 respectively*).
- **Joint analysis with Super-K**
  - Jarlskog invariant's CP-conserving value is excluded with 1.9σ or higher significance depending on prior
  - Moderately favor the normal mass ordering; insignificant deviation from maximal mixing of θ_{23} (*p(NO)=0.58 vs. P(IO)=0.08*)
- **Joint analysis with NOvA**
  - Mildly favor the inverted ordering; statement depends on prior from reactor-based exp.
  - if mass ordering is inverted , both exp. agrees well and a joint analysis strongly favor CPV with more than 3 σ. In case of normal ordering, CPV preference is not strong.

We are excited with more intense neutrino beam, better detector performance to elucidate the remaining unknowns in the leptonic mixing and neutrino mass ordering. Stay tuned!