Recent T2K Results and Perspectives

Thomas Holvey (University of Oxford), on behalf of the T2K Collaboration

Abstract

The T2K experiment is a long baseline neutrino oscillation experiment designed to measure the disappearance of muon (anti-)neutrinos and appearance of electron (anti-)neutrinos in a predominantly muon (anti-)neutrino beam. T2K's latest oscillation results include key analysis improvements, with the incorporation of new NA61/SHINE flux tuning, an updated interaction model, refined near-detector selections including photon/proton tagging, and the introduction of a new far-detector multi-ring muon-like sample. Our results exclude CP conservation at the 90% confidence level, and precisely constrain the mass splitting Δm^2_{32} and mixing angle $\sin^2\theta_{23}$. T2K also performs neutrino cross-section measurements at its suite of near detectors.

When performing a joint fit with the Super-Kamiokande experiment, we exclude CP conservation at around the 2σ confidence level, and find a stronger preference for normal mass ordering.

Exciting prospects lie ahead for T2K, with ongoing efforts to incorporate SK-Gd data into analyses, results from the joint analysis with the NOνA collaboration expected soon, and the ongoing upgrade of the beam and off-axis near detector expected to be completed in the near future.

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Tom Holvey on behalf of the T2K Collaboration

XX International Workshop on Neutrino Telescopes, Venice
25.10.23

T2K

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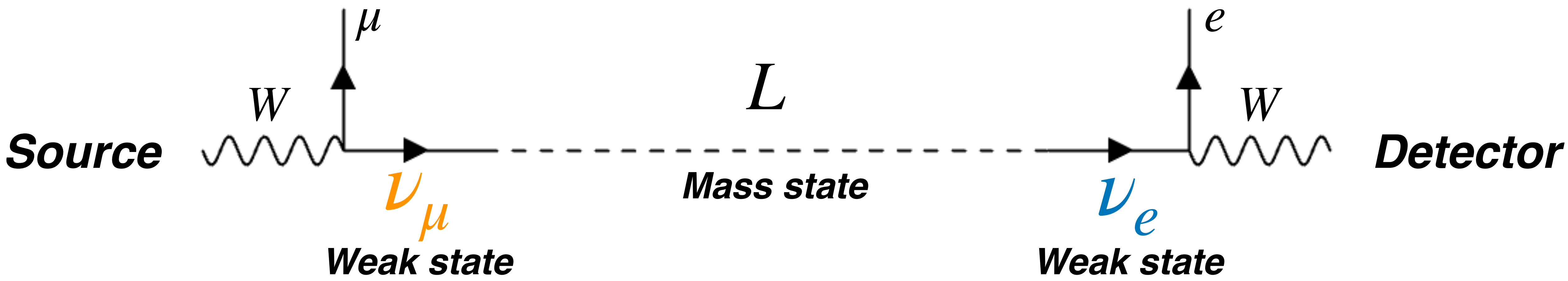
Outline

1. Long-baseline neutrino oscillations
2. The T2K experiment
    - Overview, physics goals
3. Latest T2K Results
    - T2K oscillation analysis
    - T2K+SK joint-fit analysis
4. Future of T2K
    - T2K+NOνA joint fits
    - SK-Gd
    - Near detector upgrade

1. Long-baseline Neutrino Oscillations

Neutrino oscillations



- Neutrino produced in **defined flavour state**, e.g. ν_μ
- After travelling distance L:
  - Detector observes **deficit** in ν_μ events $\Longrightarrow$ **Disappearance**
  - Detector observes **increase** in ν_e events $\Longrightarrow$ **Appearance**

Neutrino Mixing Matrix (PMNS):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS parameterisation

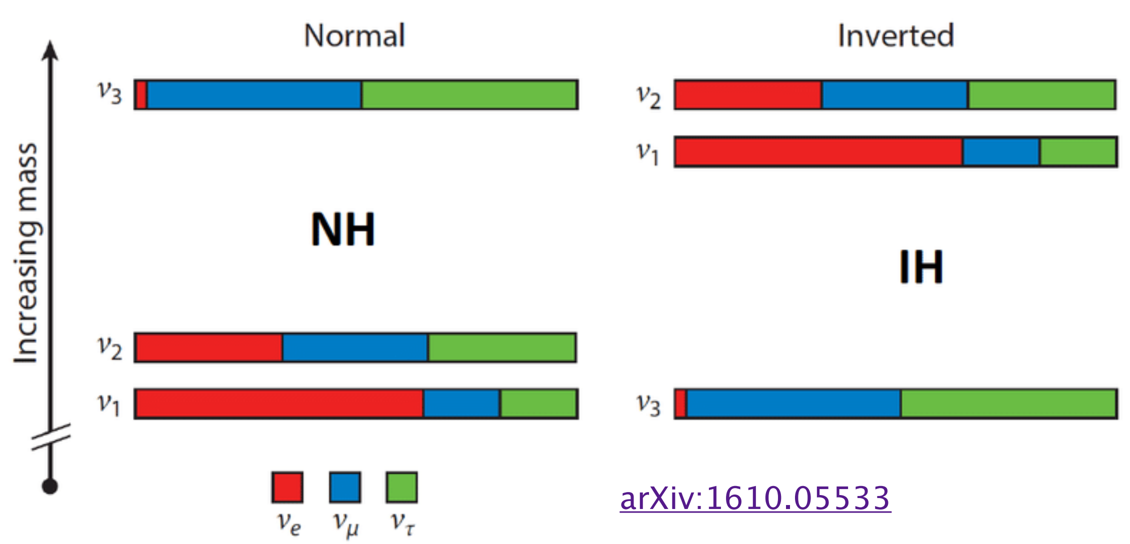
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

Atmospheric *Reactor/accelerator* *Solar*

- 3 mixing angles: θ_{12}, θ_{13}, θ_{23}
- 1 CP-violating phase: δ_{CP}

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



arXiv:1610.05533

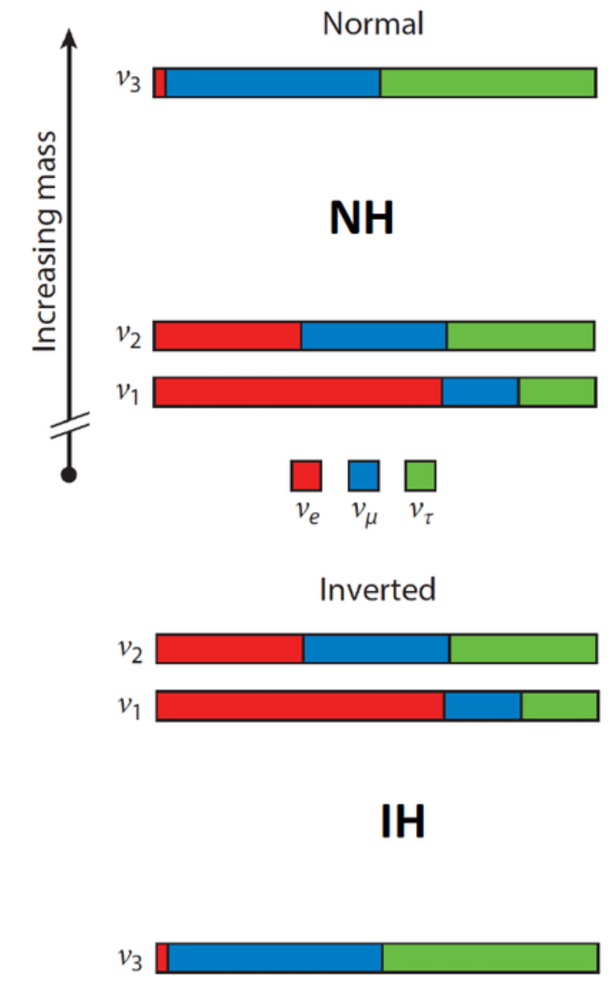
Oscillation probabilities depend on:

- Neutrino energy
- Propagation distance (baseline)
- Difference in neutrino mass states
- PMNS mixing parameters

Current status/open questions

NuFIT 5.2 (2022) arXiv:2007.14792

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$



Open questions:

1. Ordering (hierarchy) of mass states, **Normal** or **Inverted**?
2. **Octant of** θ_{23} - upper ($>45^\circ$) or lower octant ($<45^\circ$) or maximal mixing ($=45^\circ$)
3. CP-symmetry - is $\delta_{CP} \neq 0,\pi$?
4. Steriles? Non-unitarity?

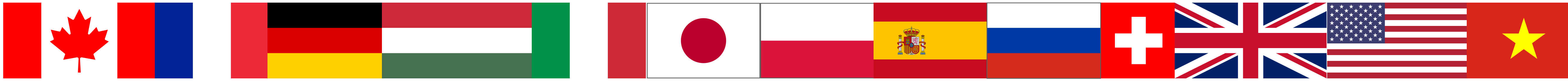
Long-baseline sensitivity:

Normal vs **Inverted** Ordering, θ_{23} and δ_{CP} (some sensitivity to θ_{13})

T2K: $L = 295$ km, $E_\nu = 0.6$ GeV
NOνA: $L = 810$ km, $E_\nu = 2.0$ GeV

2. The T2K Experiment

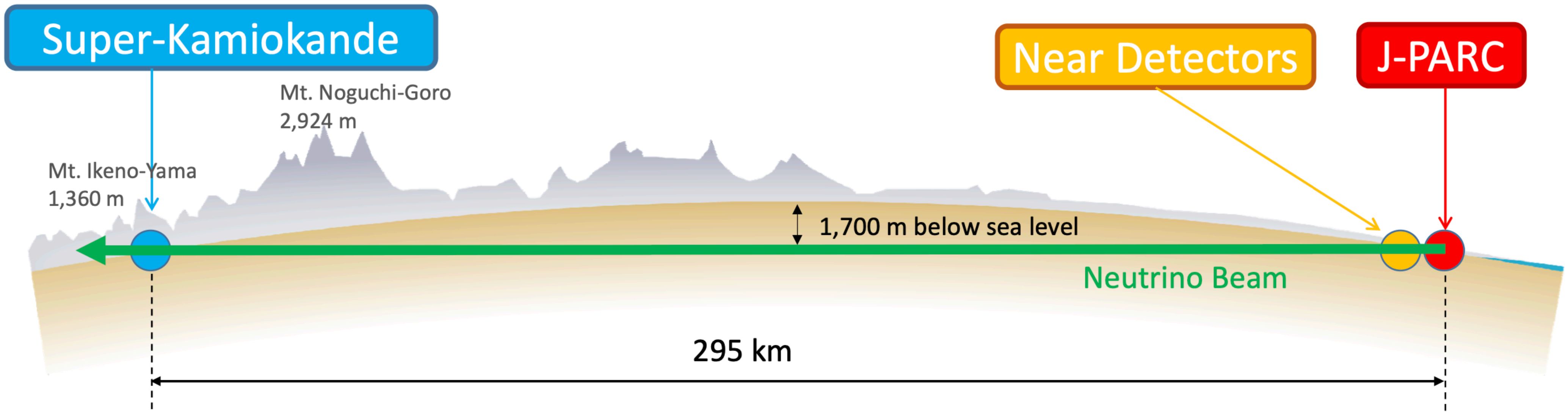
The T2K Collaboration



577 collaborators, 75 institutions, 13 countries

July 2023 Collaboration Meeting, J-PARC

Experiment Overview



- T2K: Tokai to Kamioka
- High intensity **neutrino beam** produced at **J-PARC**
- **Unoscillated beam** measured at suite of **near detectors**
- **Oscillated beam** measured at **Super-K**, 295 km downstream

Physics Goals:

1. **Precise measurements** of θ_{23} and Δm^2_{32}
2. **Constrain** the **CP-violating** phase, δ_{CP}
3. **Neutrino cross-section** measurements

Neutrino beam

- 30 GeV proton beam impinged on carbon target

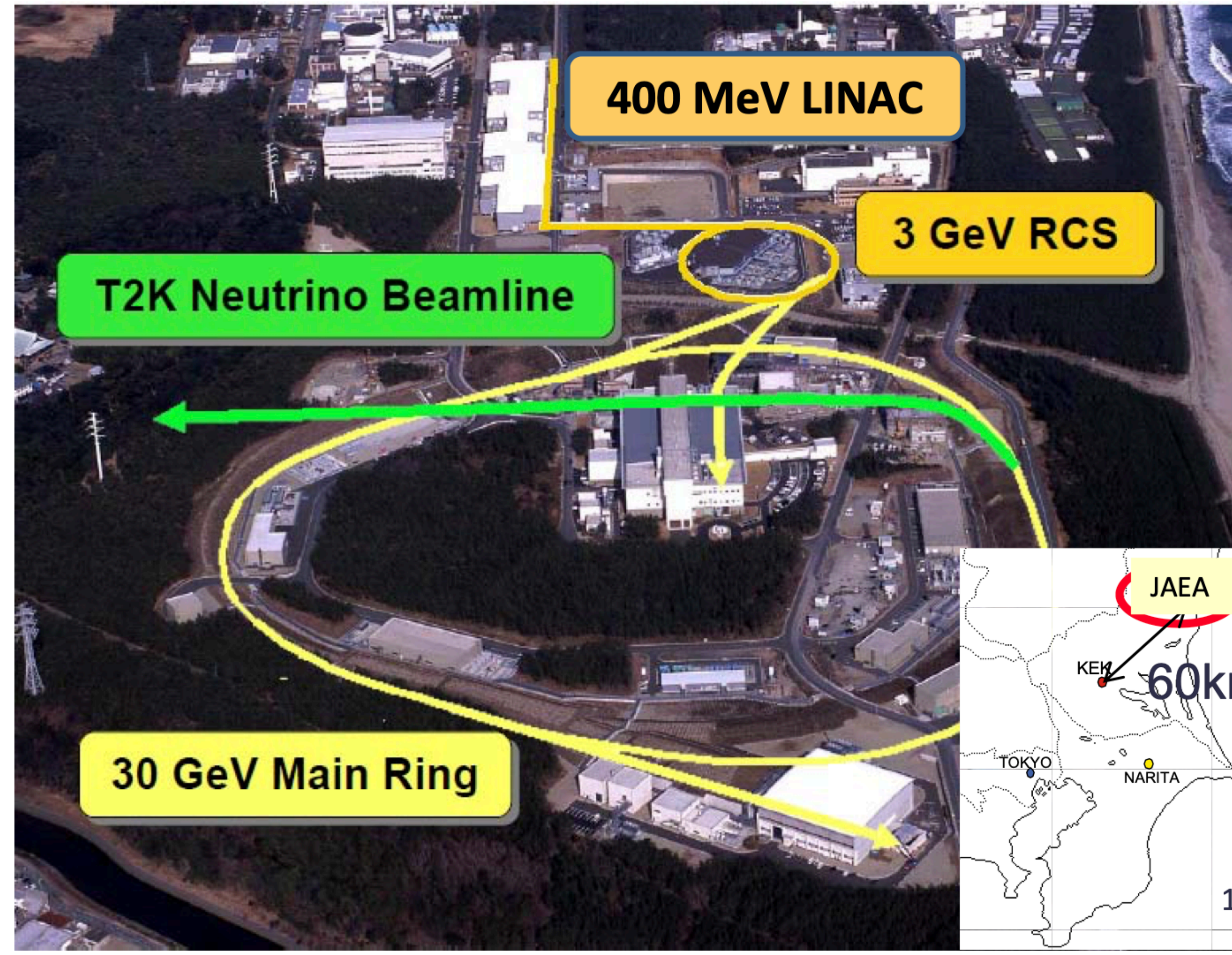
- Magnetic horns focuses outgoing hadrons (mostly $\pi^{\pm}/K^{\pm}$)

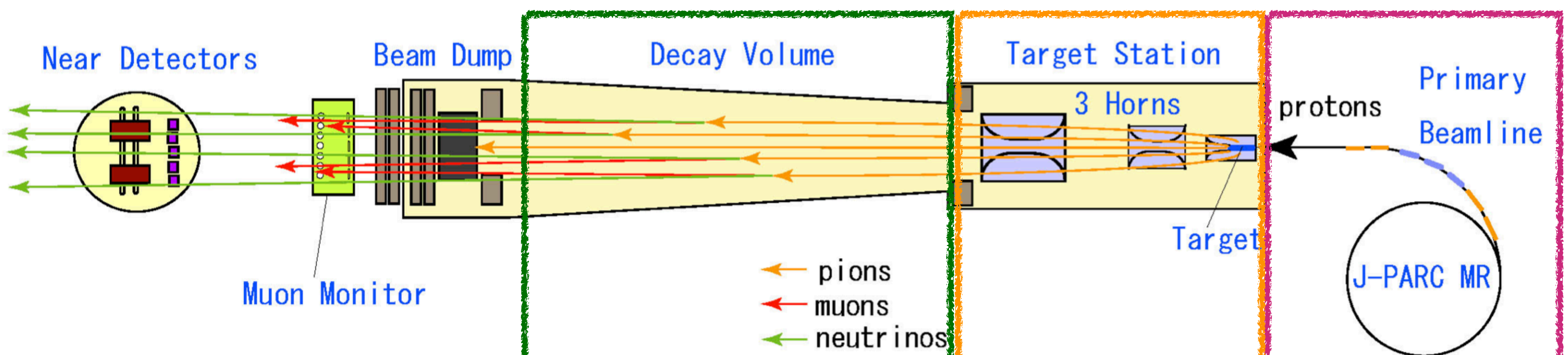
- ν_μ beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$

  Forward horn current (FHC) or neutrino mode

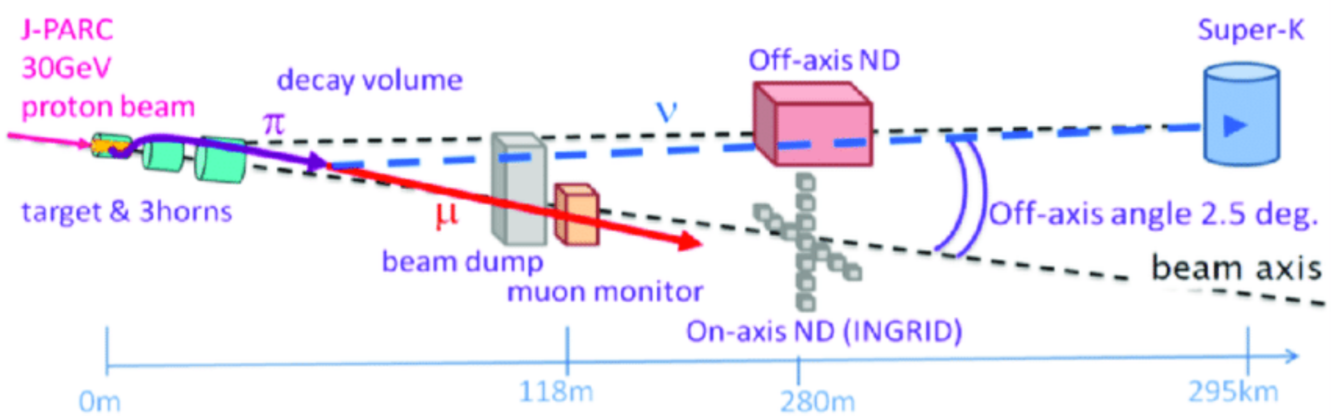
- $\bar{\nu}_\mu$ beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

  Reverse horn current (RHC) or antineutrino mode

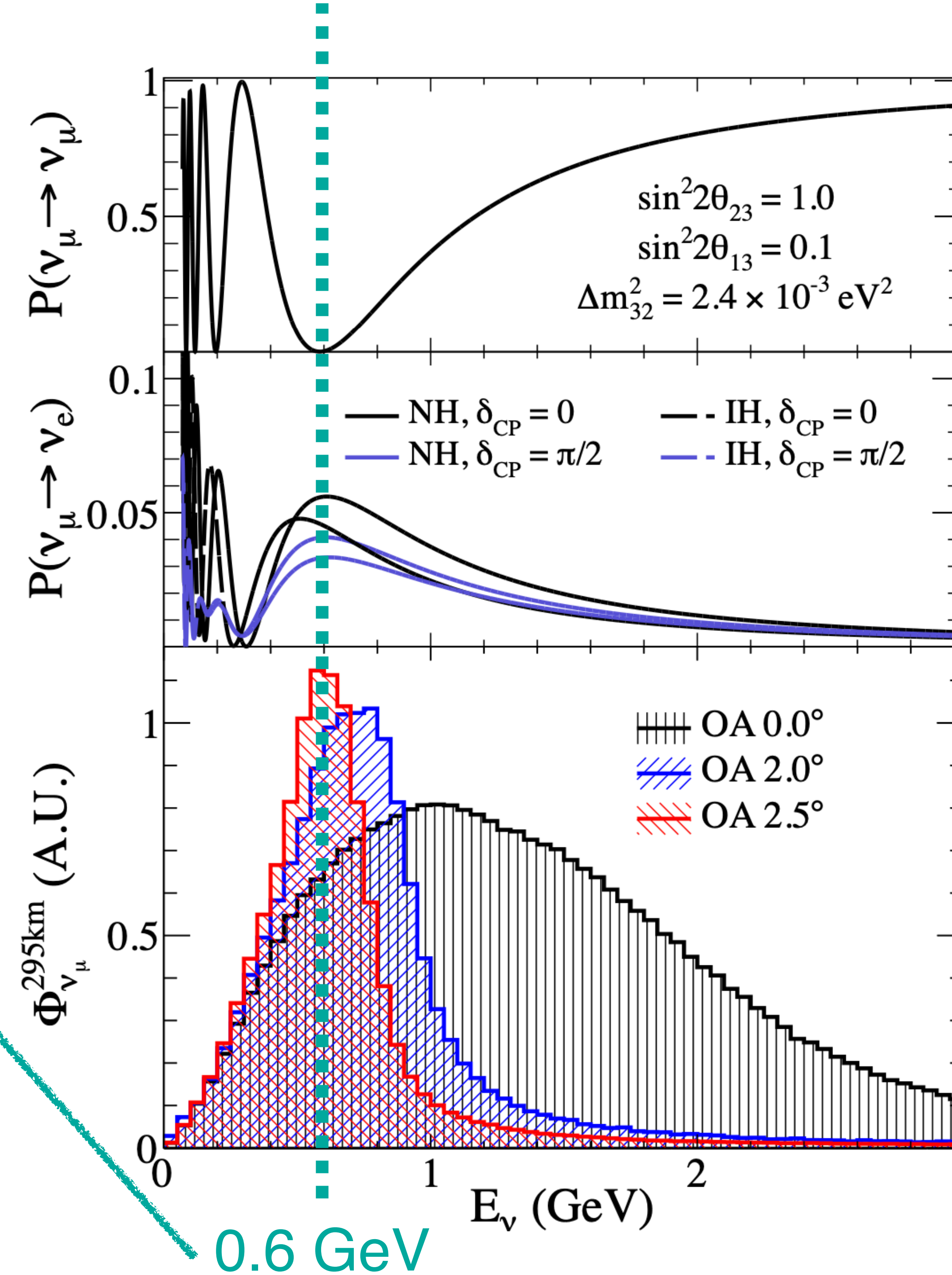




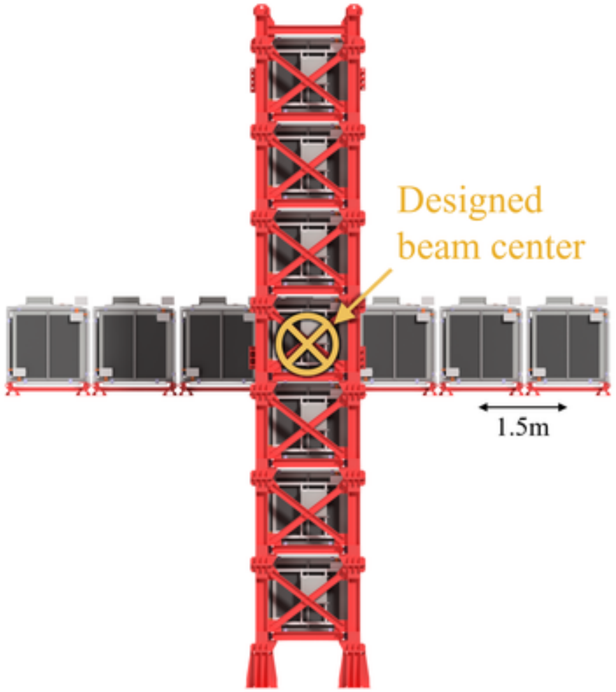
Off-axis 'trick'



- Take advantage of neutrino two-body decay spectrum → detectors placed **2.5° off-axis**
- Detector sees neutrinos with **reduced spread of energies**
- Neutrino energy peaked at **0.6 GeV**
  - **Aligned** with **oscillation maximum** (maximum ν_e appearance and ν_μ disappearance respectively)

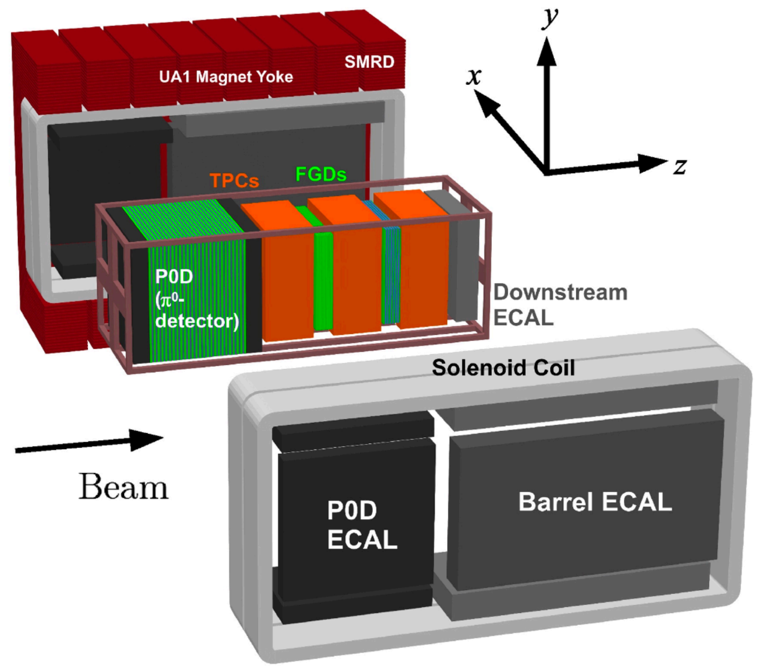


Near detectors



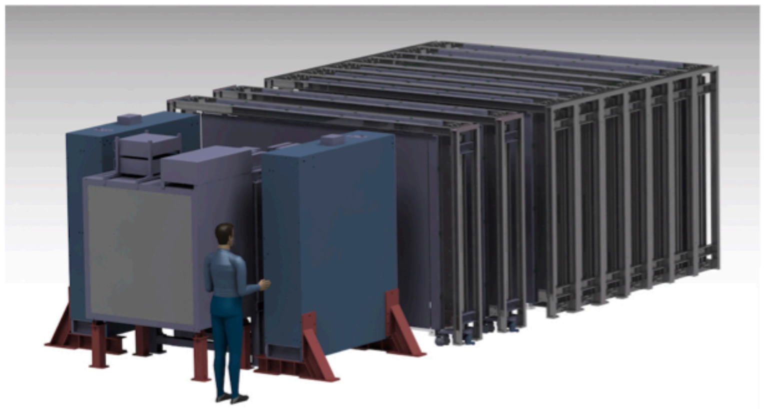
INGRID on-axis detector

- **Iron sandwich scintillator** detector
- Monitors neutrino **beam direction** and **intensity**



ND280 off-axis detector

- **Active scintillator** + passive water targets
- **Tracking/PID** with **time projection chambers**
- **Magnetised** for **charge** and **momentum** measurement

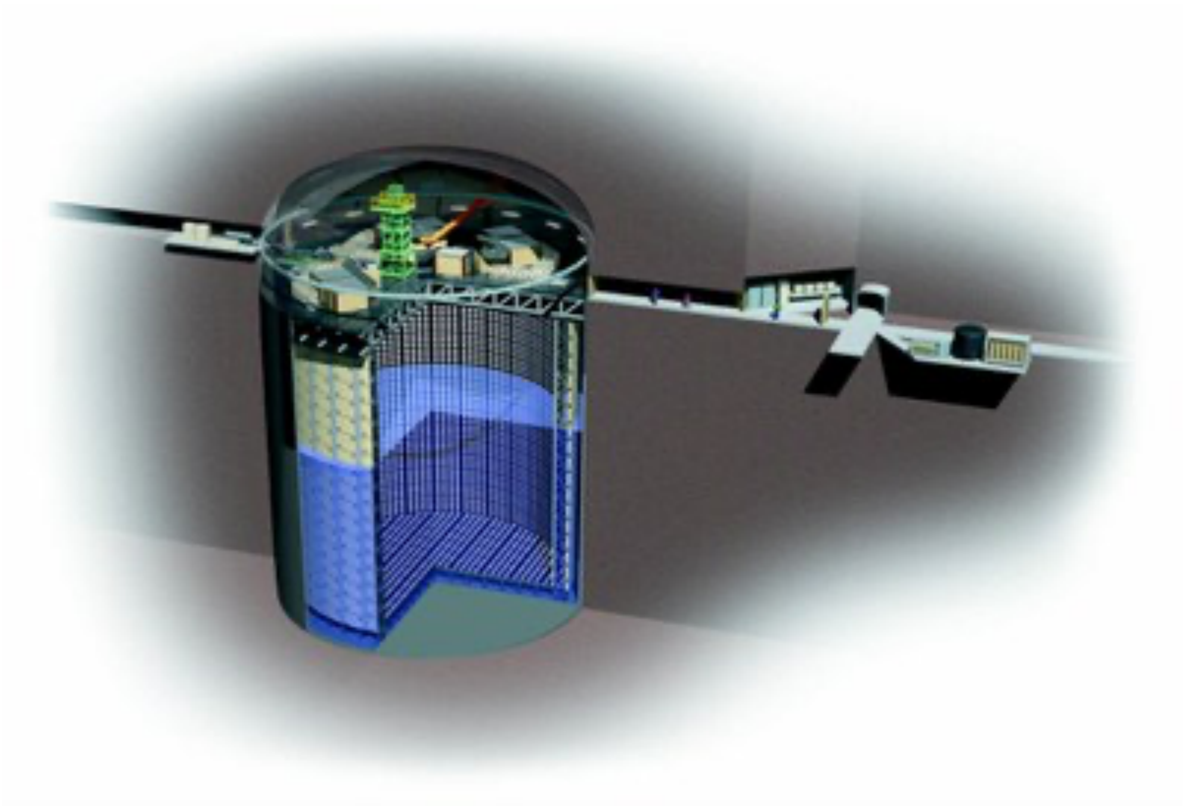


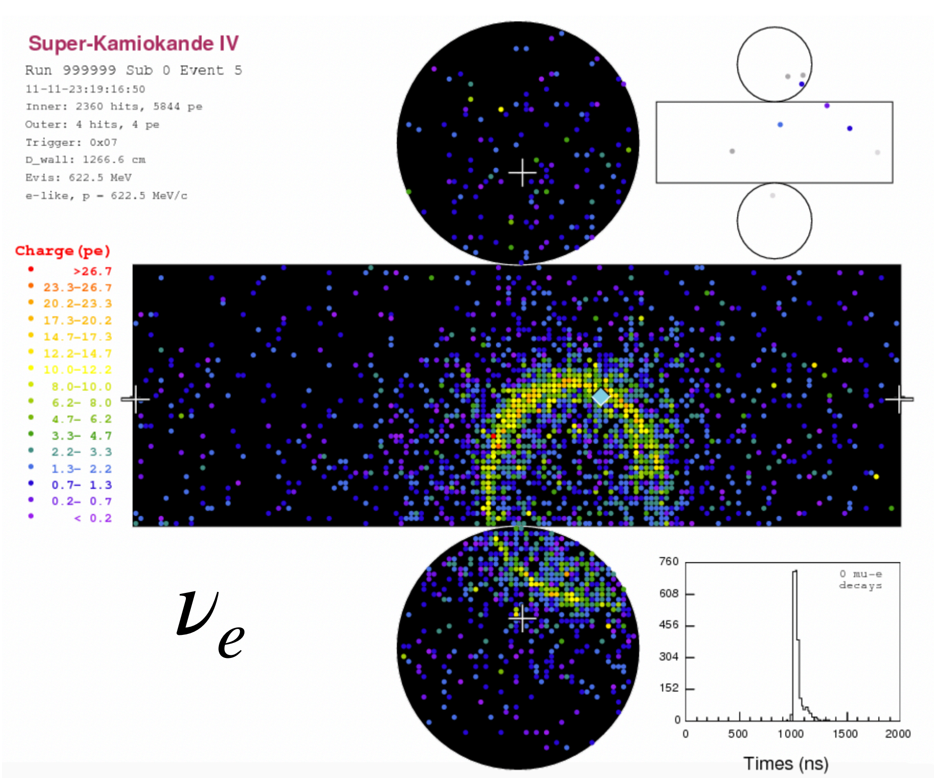
WAGASCI + BabyMIND

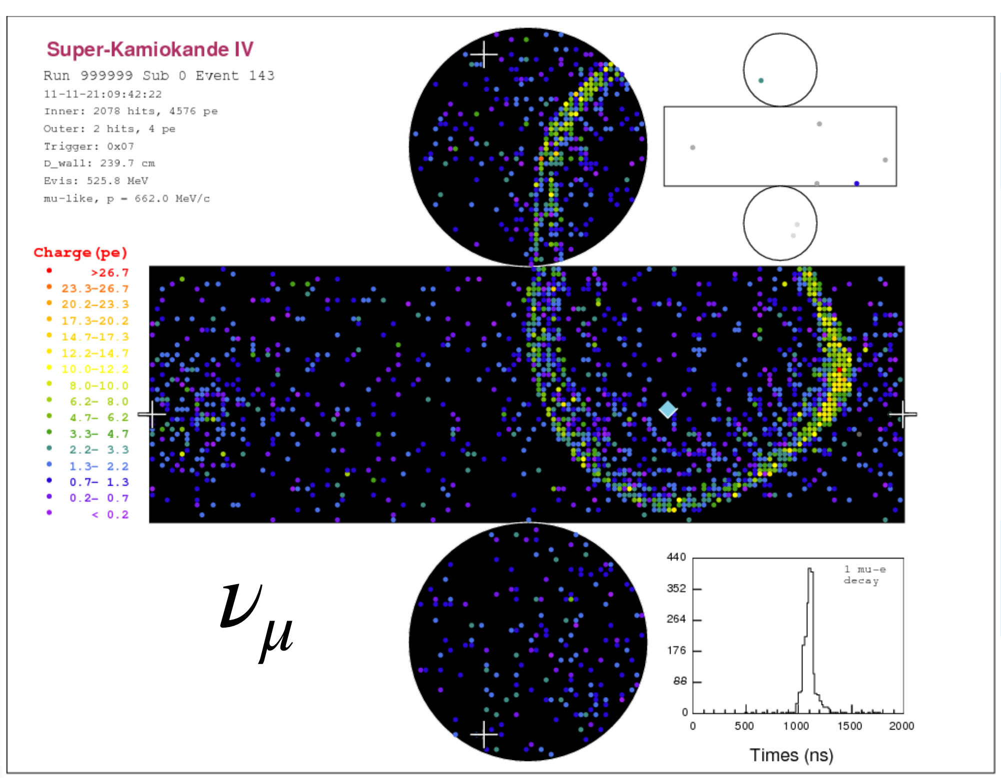
- Latest addition at intermediate **1.5° off-axis flux**
- **Water target** with cuboid lattice scintillators for high angle acceptance
- Compact **magnetised** ion muon range detector
- First xsec measured, published here

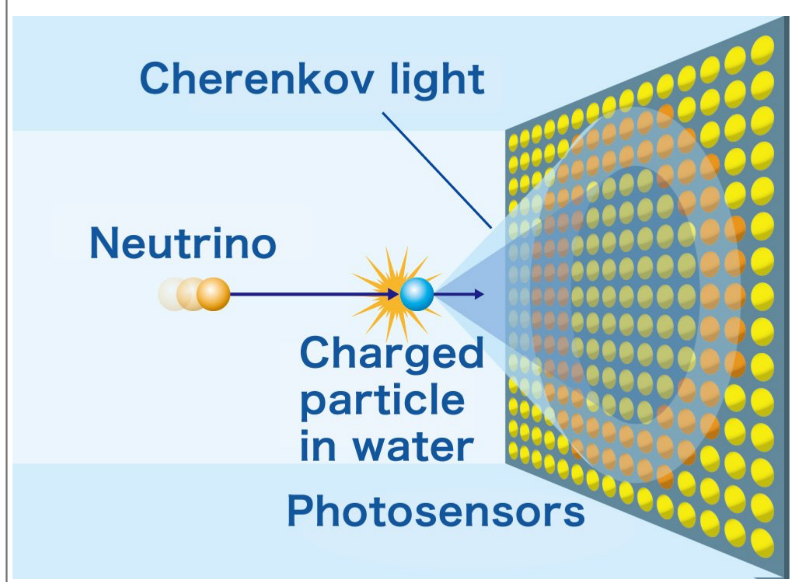
Super-Kamiokande (SK)

- **50 kton** water Cherenkov detector
- Excellent e/μ **separation;** less than 1% mis-PID at 1 GeV for single-ring events
- Cannot separate ν from $\bar{\nu}$ on event-by-event basis
- Only sees **charged particles** and photons **above Cherenkov threshold**









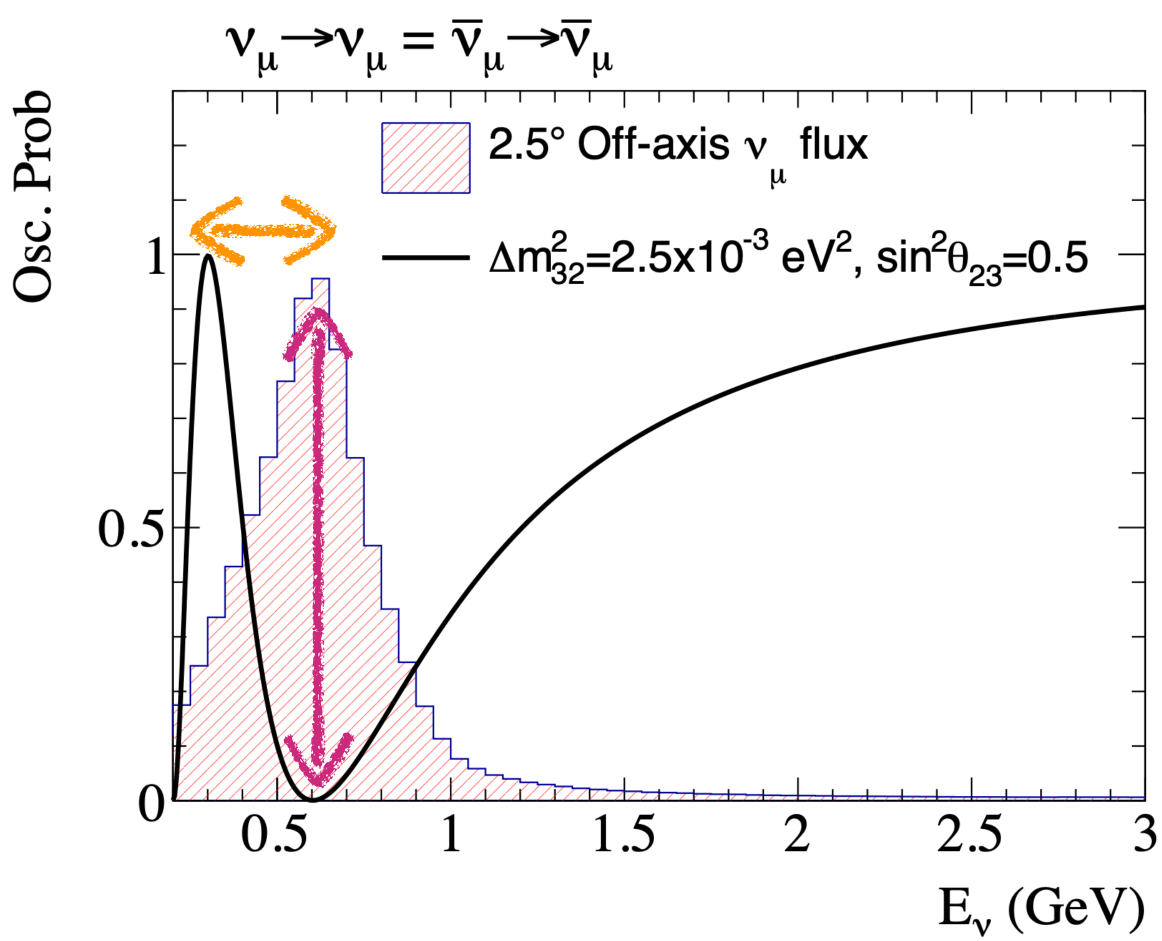
Oscillations at T2K

Jarlskog Invariant

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

Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

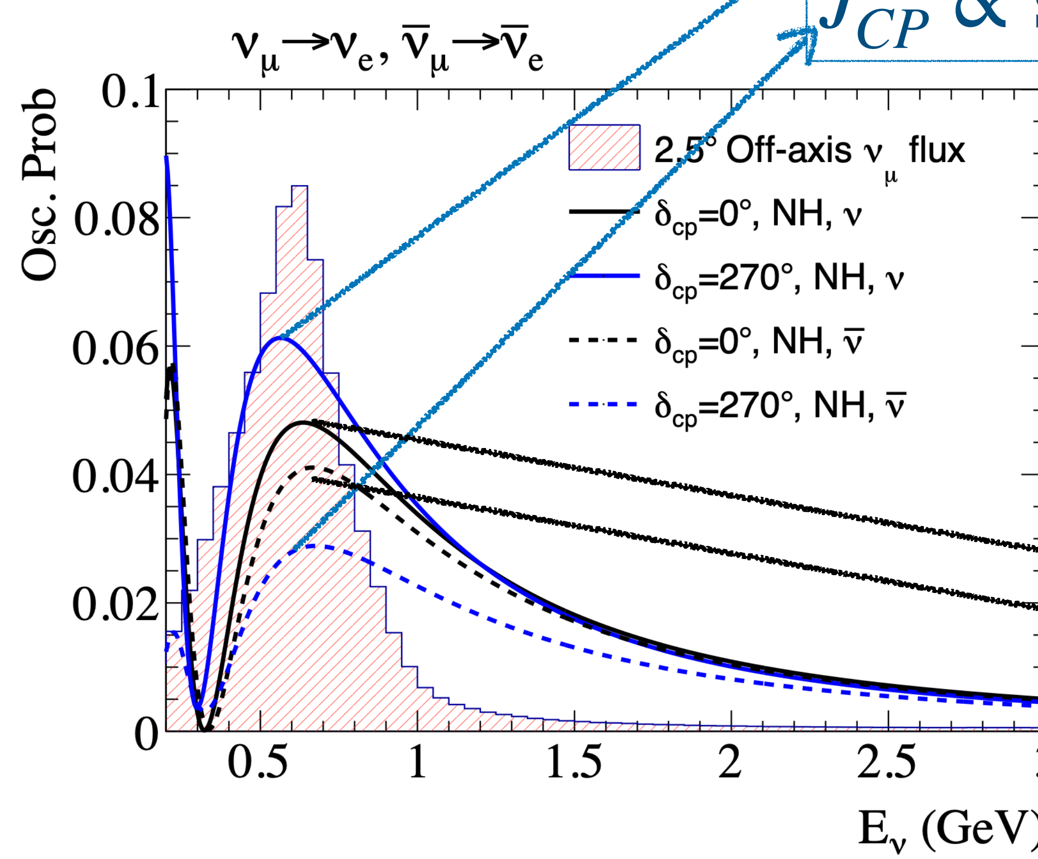


Appearance

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

$$\mp \frac{1.27\Delta m_{21}^2 L}{E} 8J_{CP}\sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)$$

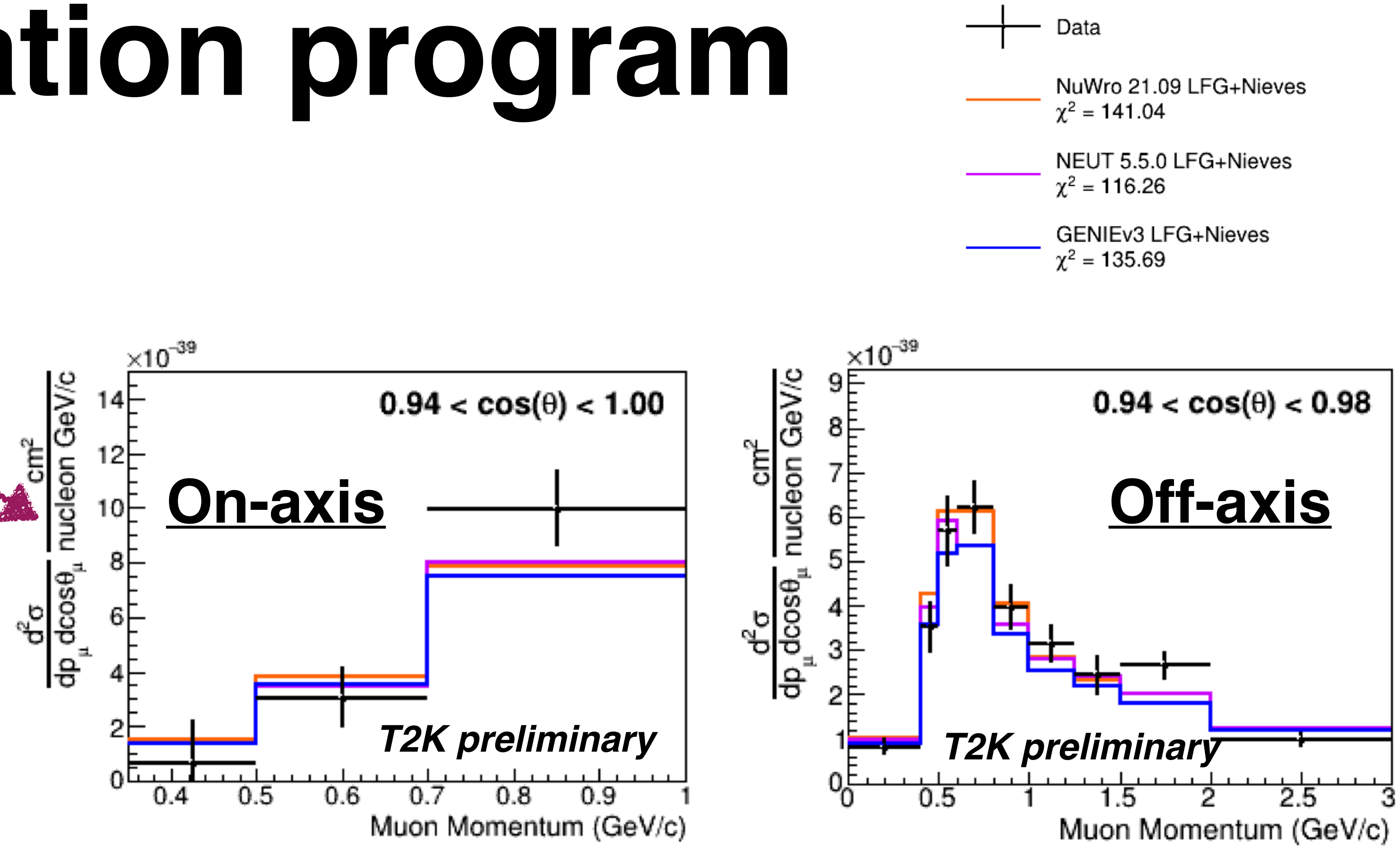
CP effect
$J_{CP} \propto \sin\delta_{CP}$



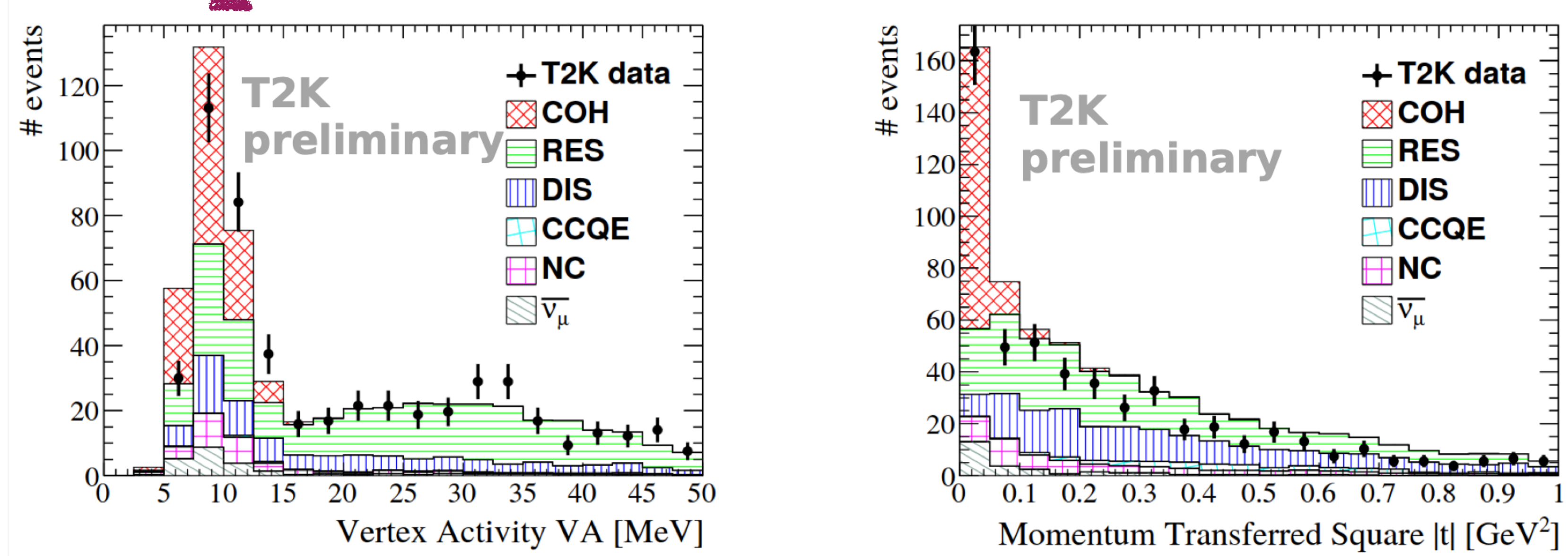
Matter effect

Beyond oscillation program

- **Cross-section measurements**
  - ν_μ CC 0π on/off-axis measurement (**world first!**)
  - ν_μ and $\bar{\nu}_\mu$ CC coherent pion production cross section on carbon



- **BSM searches**
  - Dark photon and heavy neutrino searches at ND280
- Neutron multiplicities at SK



Beyond oscillation program

- **Cross-section measurements**
  - ν_μ CC 0π on/of
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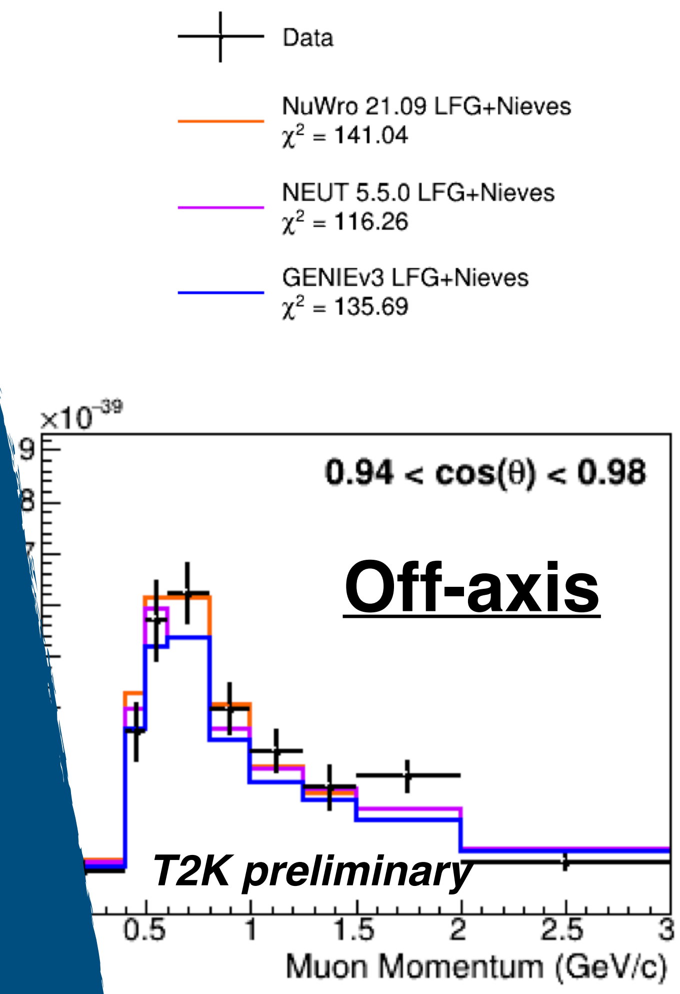
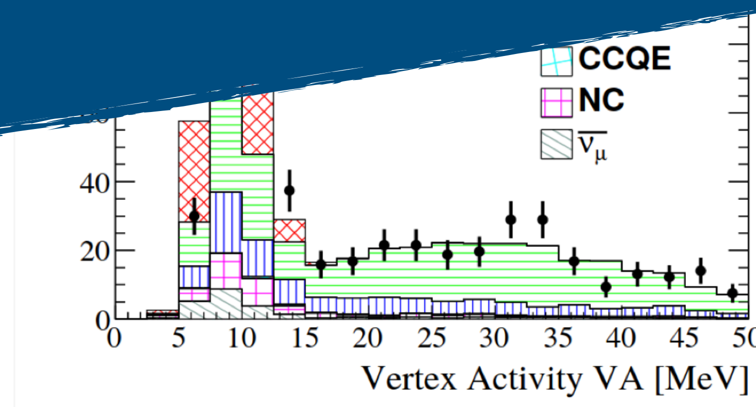
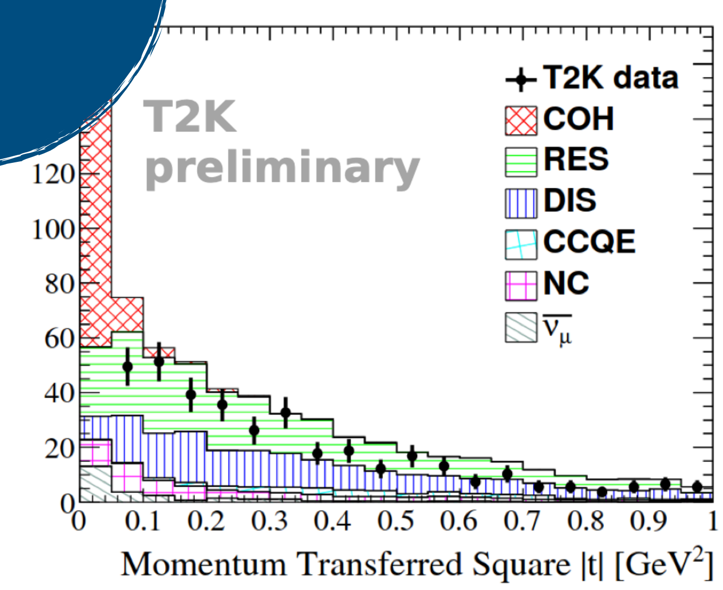


For more on T2K latest cross section results see Shilin Liu's slides





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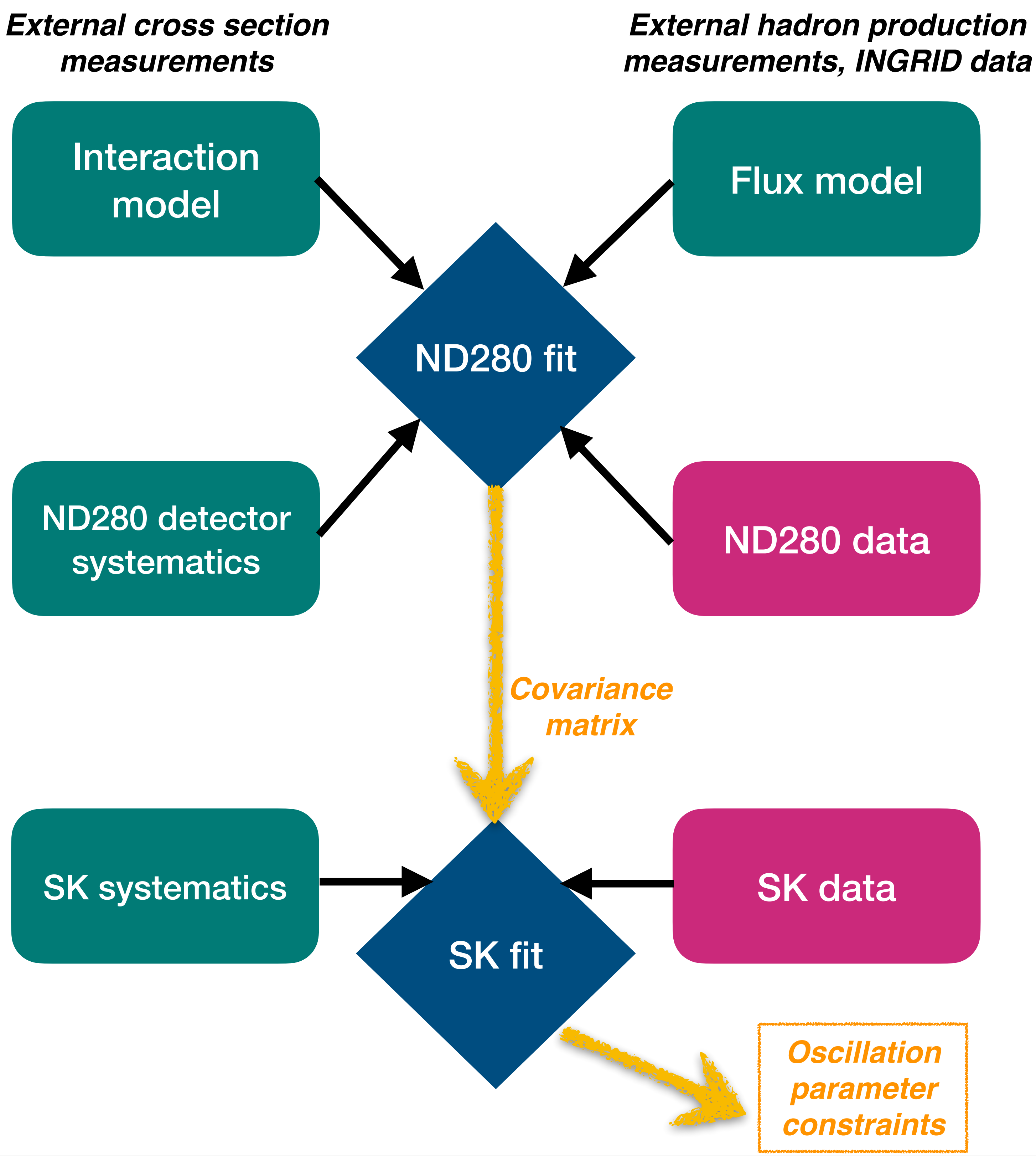
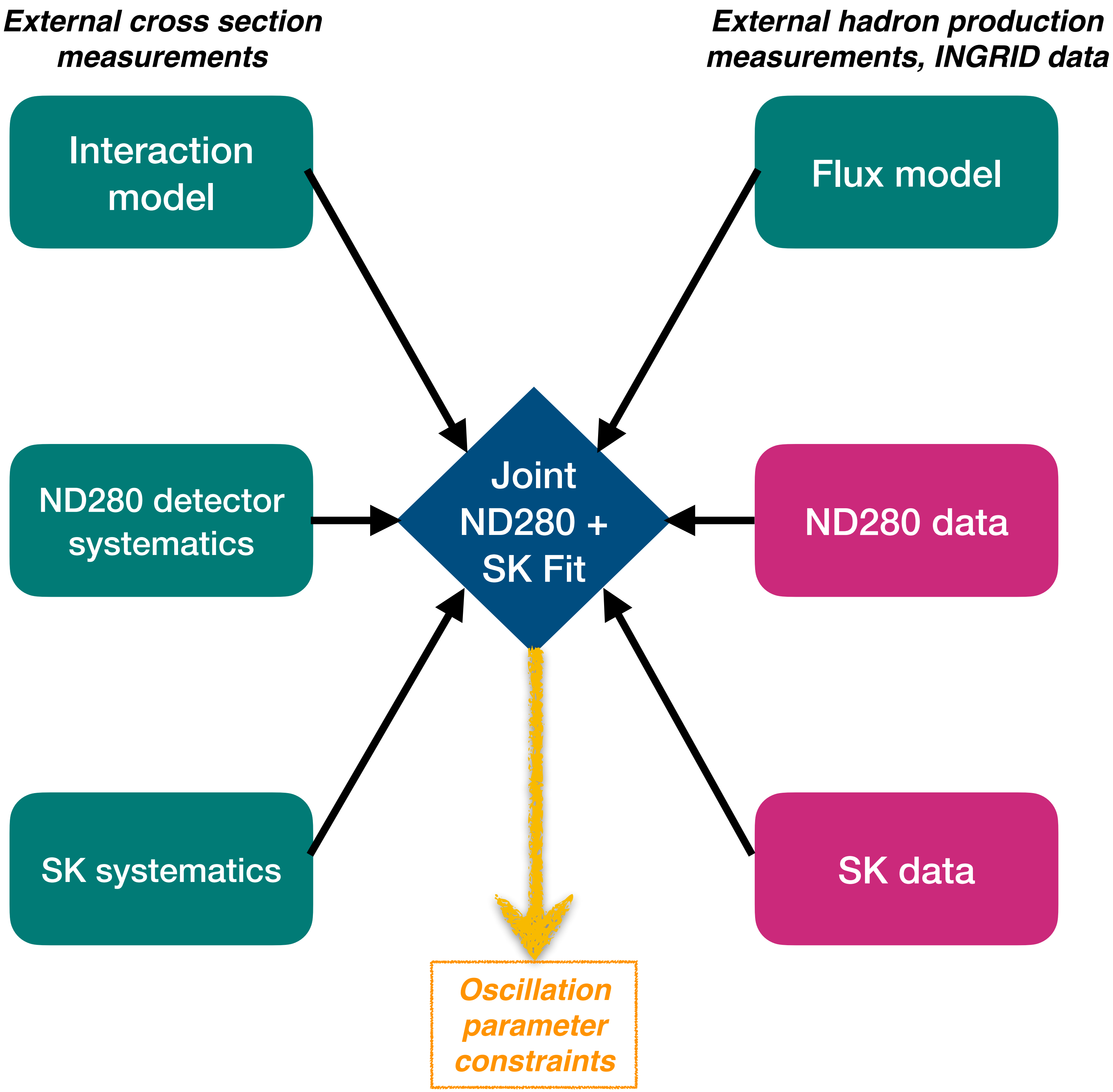
3.1 Latest Results - T2K Oscillation Analysis

Analysis strategy - Hybrid-Frequentist



- Hybrid-Frequentist analysis performed in **two sequential fits**
- ND280 fit **constrains flux** and **interaction** model
- Constraints enter SK fit as a **covariance matrix**
- Gradient descent algorithm/ **grid search**
- **Feldman-Cousins** to construct confidence intervals
- Can also produce Bayesian outputs, though primary result is frequentist

Analysis strategy - Bayesian



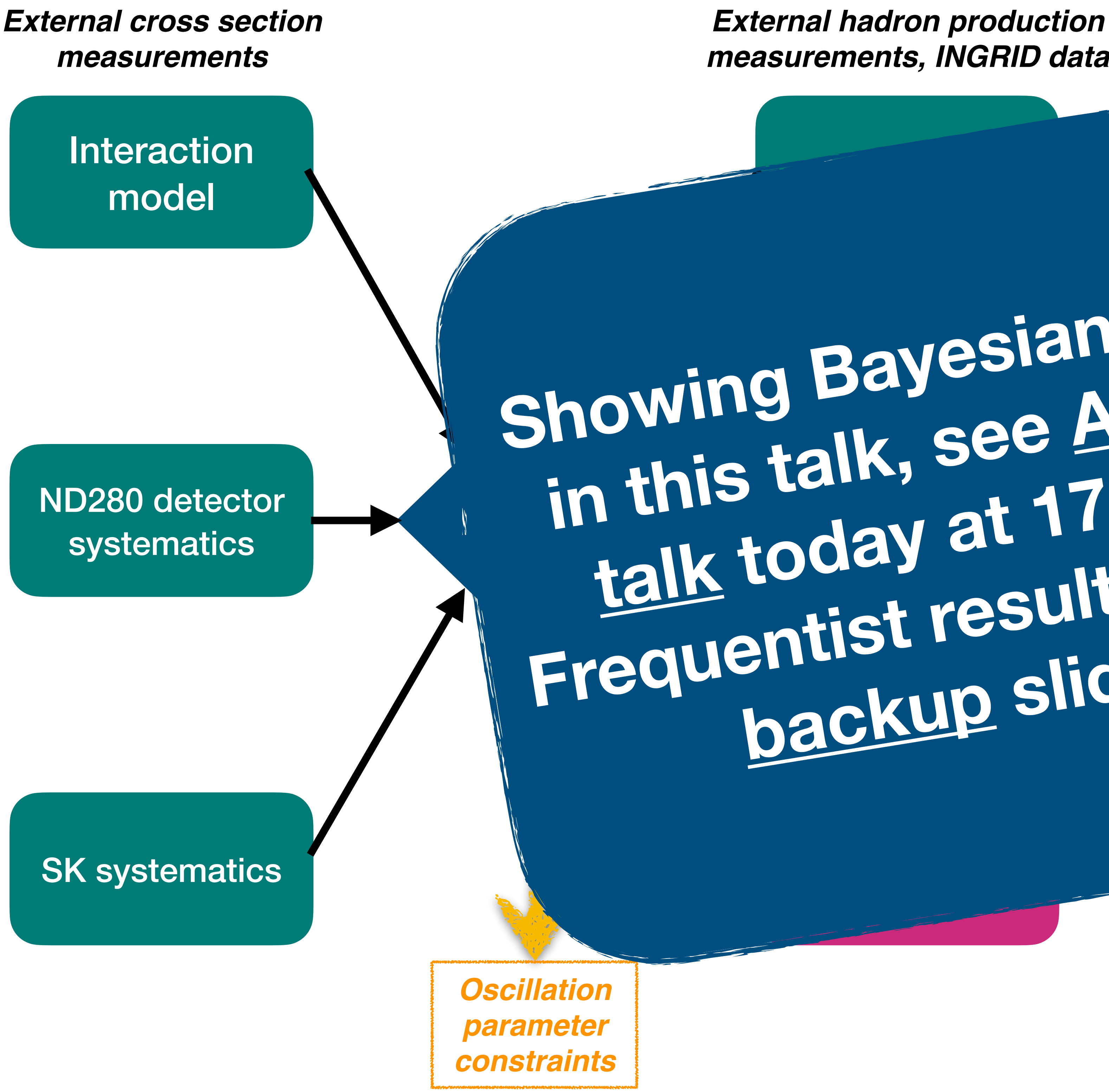
- Based on Bayes' theorem:

$$P(\vec{\theta}\,|\,D) \propto P(D\,|\,\vec{\theta}) \cdot \pi(\vec{\theta})$$

Posterior Likelihood Prior

- **Near** and **far detector** data and systematics fitted **simultaneously**
- Markov chain Monte Carlo (**MCMC**) method used to construct posterior
- **Smearing** applied to Δm^2_{32} in both Bayesian and hybrid-Frequentist fits based on testing alternative interaction models

Analysis strategy - Bayesian



Showing Bayesian results in this talk, see Adrien's talk today at 17:00 for Frequentist results (also in backup slides)

- Based on Bayes' theorem:

$\propto P(D|\vec{\theta}) \cdot \pi(\vec{\theta})$

Likelihood Prior

far detector data
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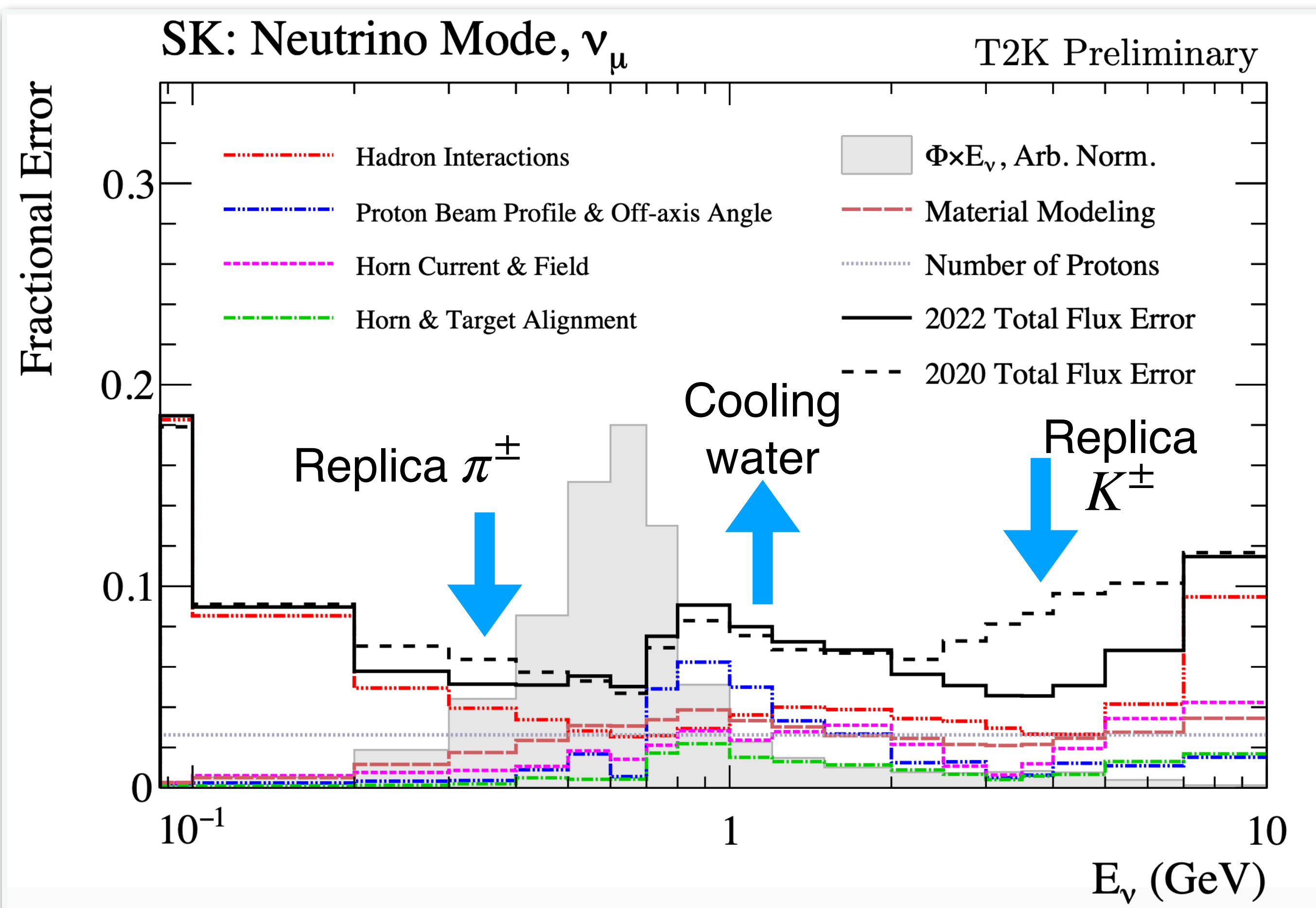
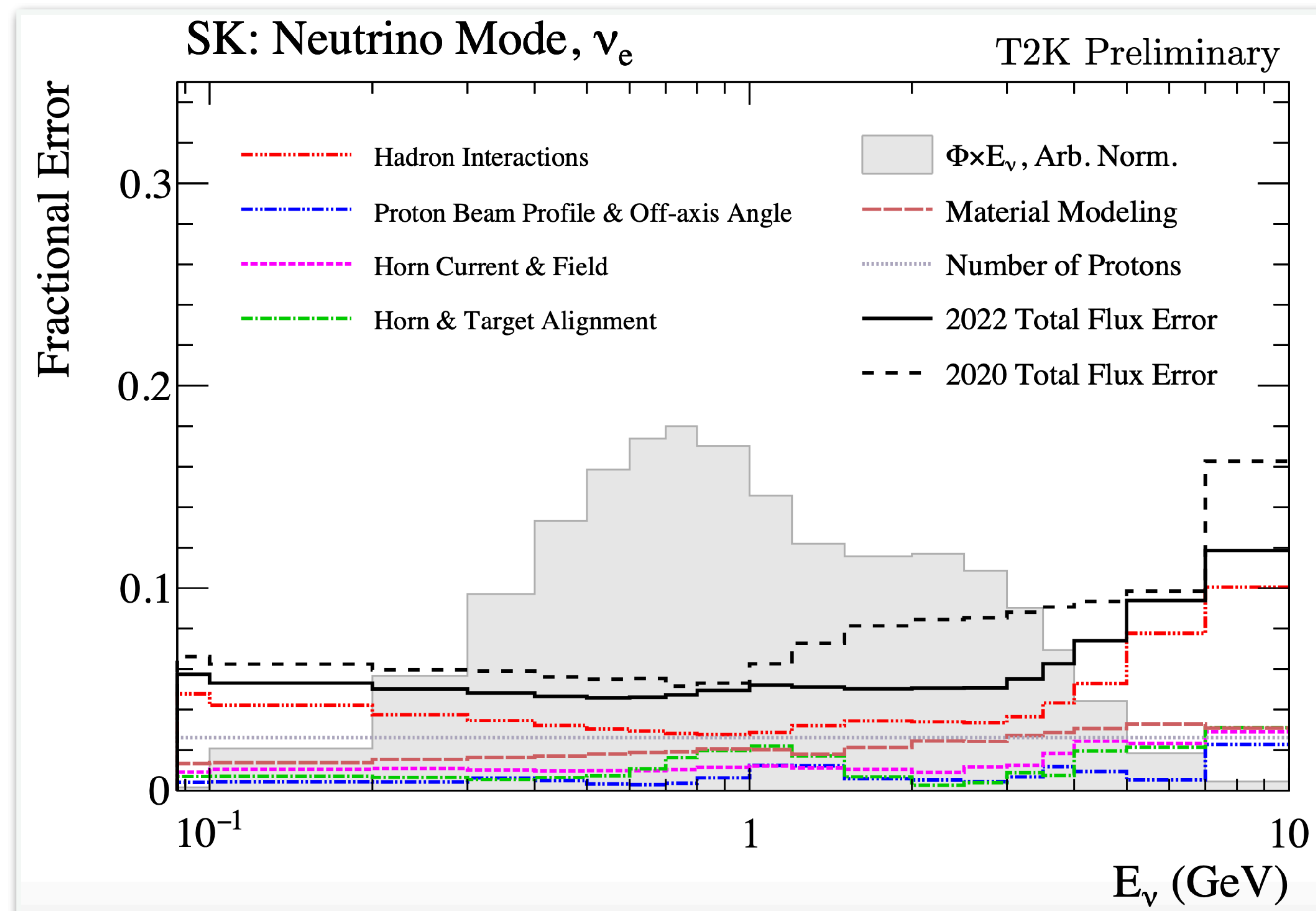
g applied to Δm^2_{32} in both Bayesian and hybrid-Frequentist fits based on testing alternative interaction models

New to 2022 - flux model

- Updated tune to new NA61/SHINE **T2K replica target** measurement (Eur. Phys. J. C79, 100)
  - **More statistics** for $\pi^{\pm}$ production
  - Adds $K^{\pm}$ and **proton data**
- Other model updates include **cooling water flow** in magnetic horns
- Significant **reduction** of **hadron production uncertainties (~6%)**





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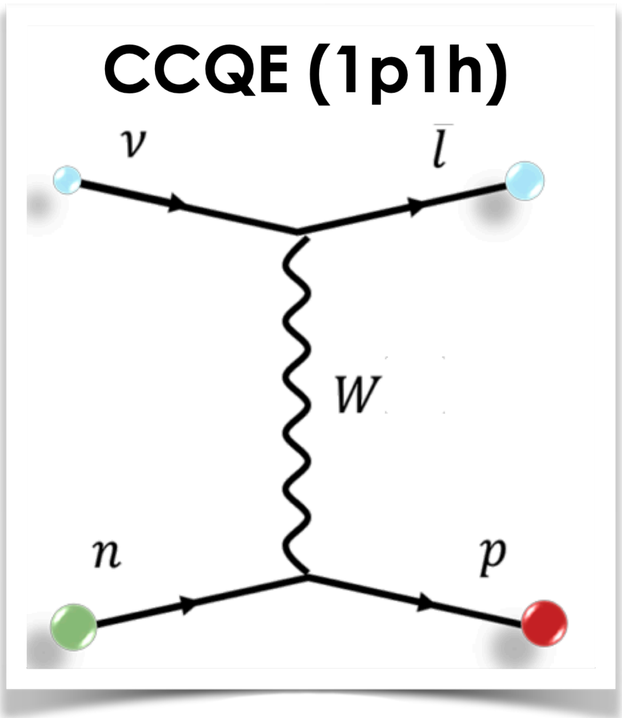
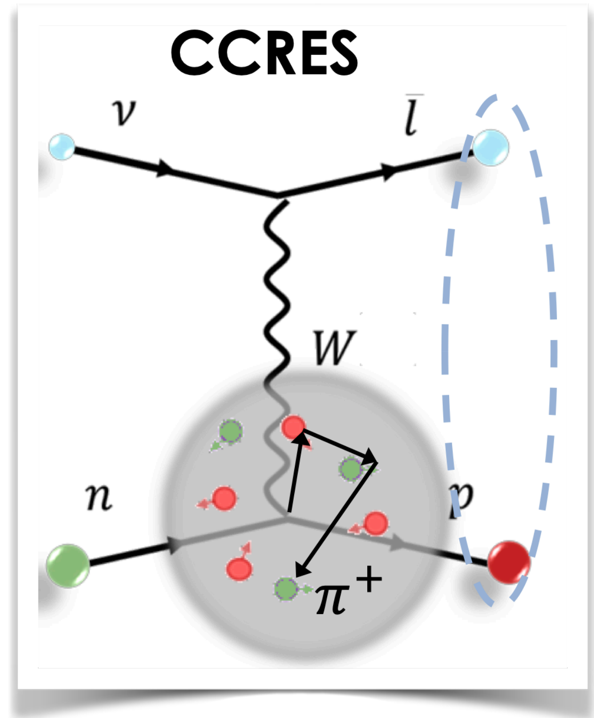
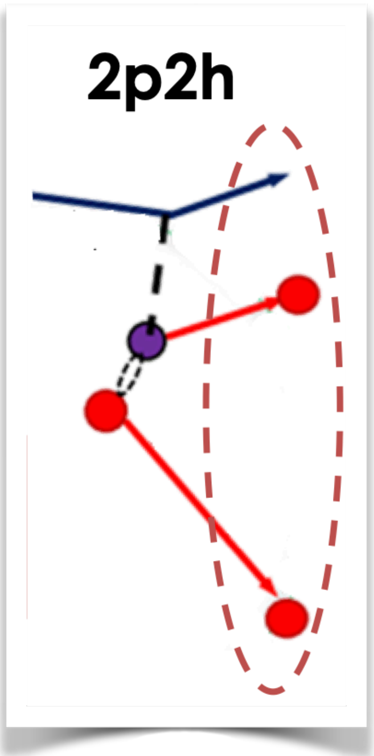
New to 2022 - interaction model







Charged-current quasi-elastic

- More **theory-driven** uncertainties (SF)
- New uncertainties on **nuclear shell structure, nuclear potential and Pauli blocking**
- Nucleon **removal energy** dependent on **momentum transfer**

Resonant pion production

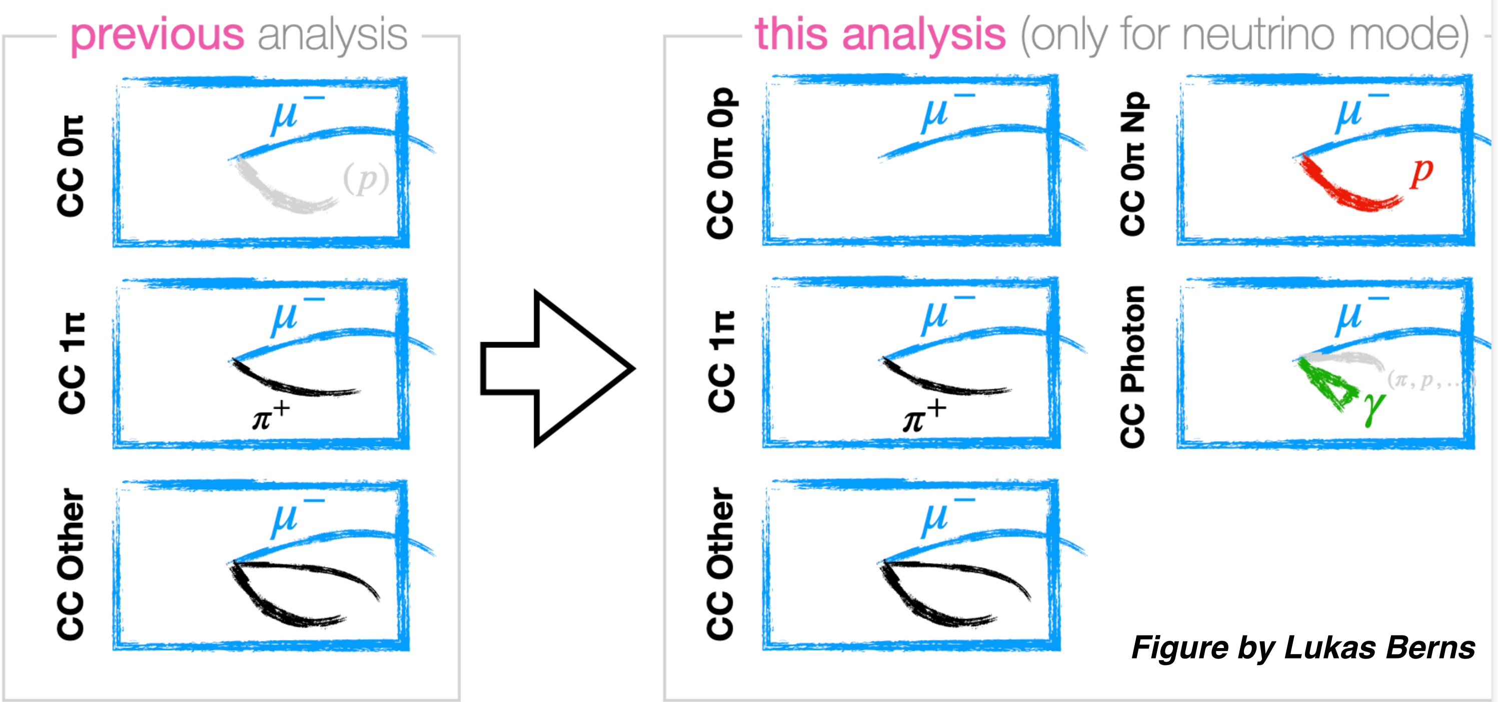
- New **bubble chamber tune**
- New **resonance decay uncertainties**
- Effective inclusion of **binding energy**
- New uncertainty in $\pi^{\pm}$ vs π^{0} production

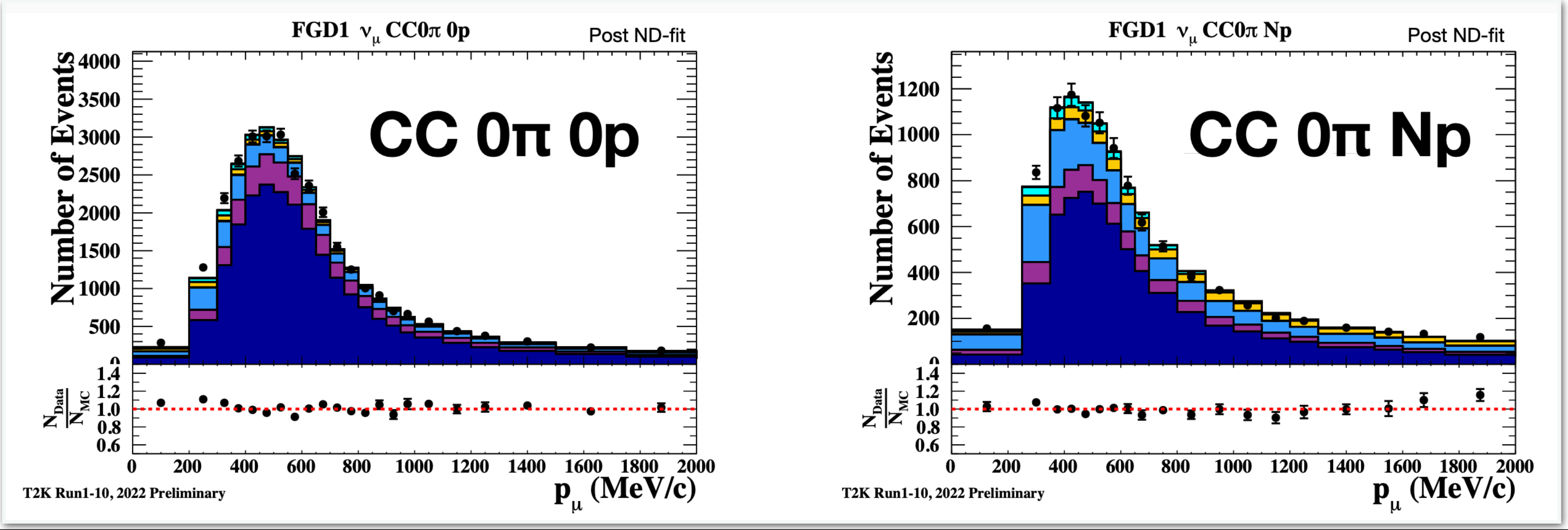
2p2h/Multi-nucleon

- New dials to alter **nucleon pair contributions**
- **Shape dial** split by **nucleon pair type**

New to 2022 - new ND280 samples

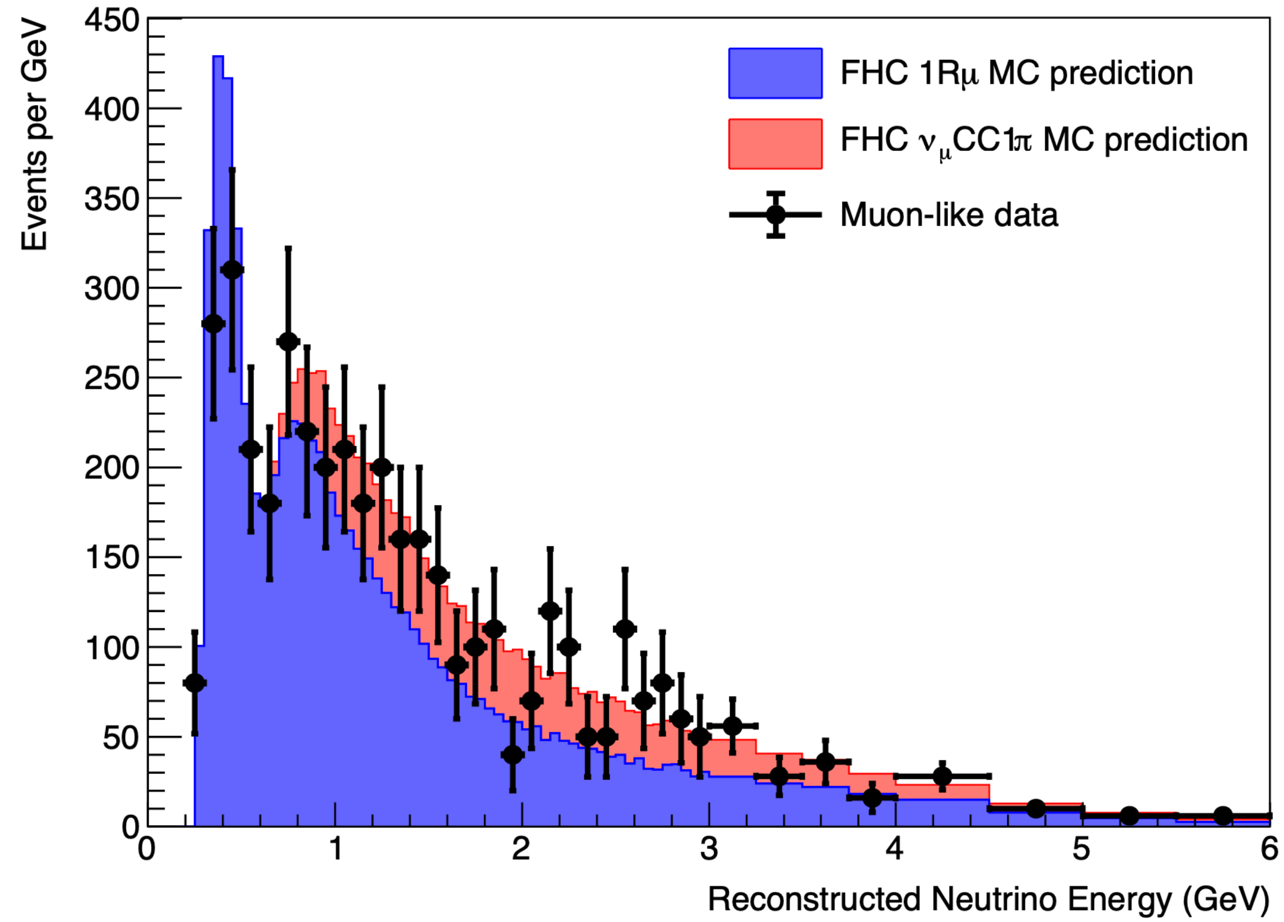
- **22 ND280 samples** based on reconstructed topology
- New ND280 ν samples with γ/p **tagging**
  - p: better able to **constrain CCQE** and **2p2h** models
  - γ: **filter out DIS** and **resonant** CCπ^0 background to **increase purity** in CC0π and CC1π samples
- $\bar{\nu}$ samples unchanged



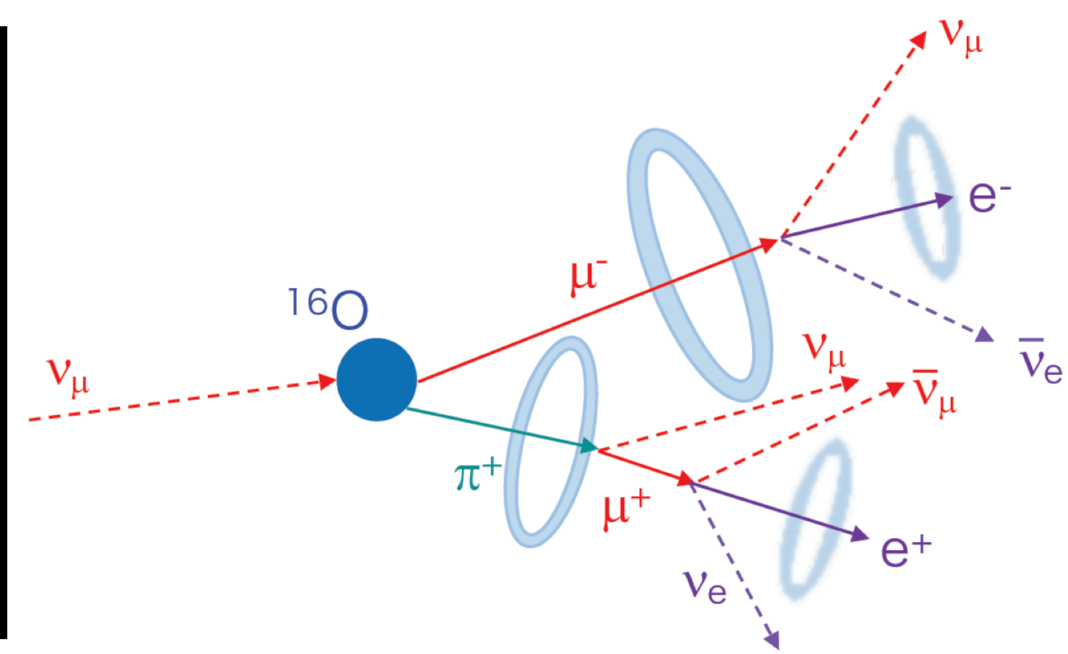


New to 2022 - new SK sample

- **New far detector sample** targeting $\nu_\mu CC1\pi^+$ interactions in ν-mode
- **30% increase** to μ-like, ν-mode **statistics**
- **Small sensitivity to oscillations,** higher energy than single-ring μ-like sample, tests robustness of our model

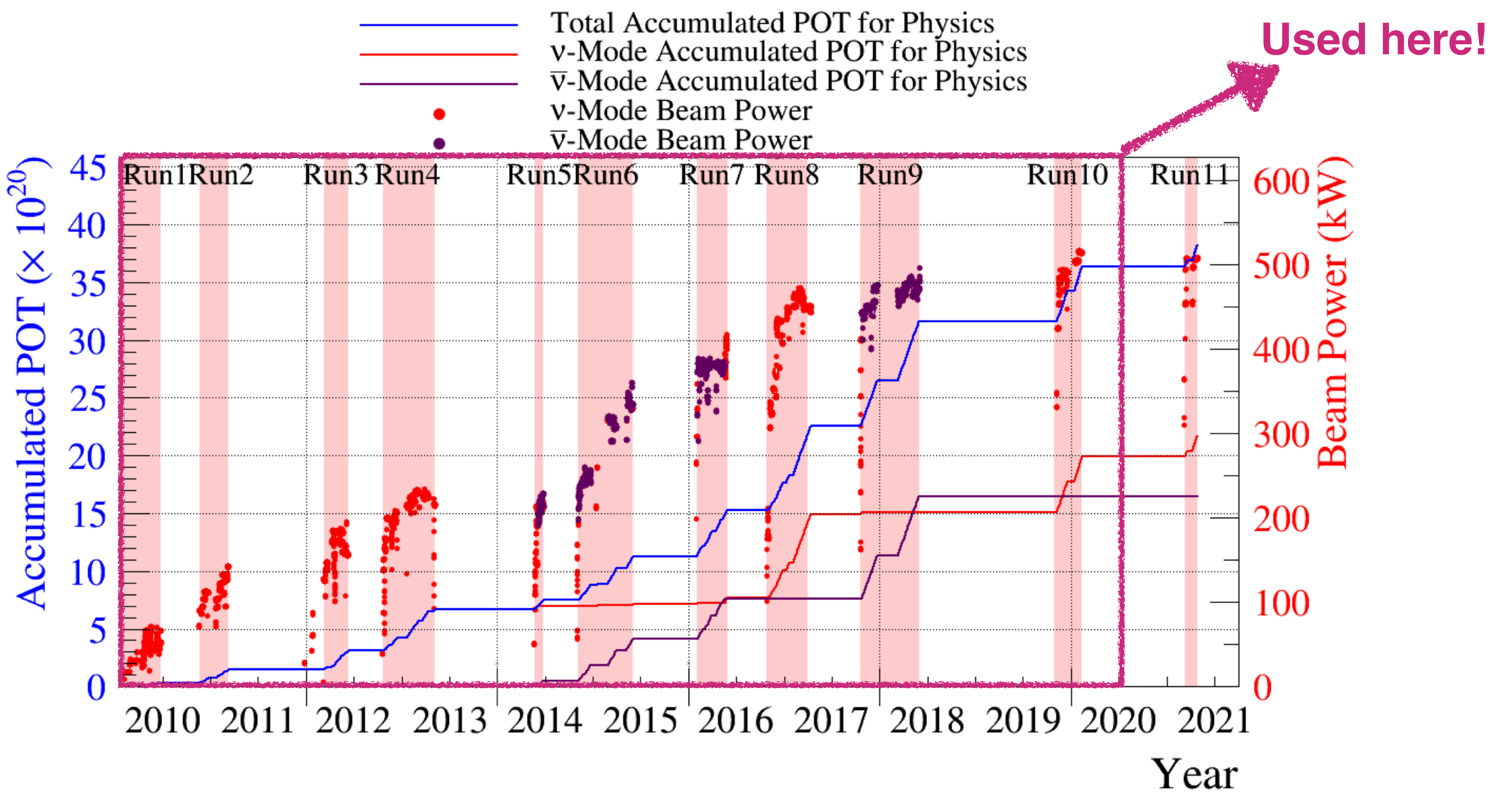


	Sample	Description
ν-mode	FHC 1Rμ	1 μ-like ring, 0 decay electrons
	FHC 1Re	1 e-like ring, 0 decay electrons
	FHC 1Re $CC1\pi^+$	1 e-like ring, 1 decay electron
	FHC MR $\nu_\mu CC1\pi^+$	**1 μ-like ring, 2 decay electrons / 1 μ-like ring + π^+ ring + 1 decay electron**
$\bar{\nu}$-mode	RHC 1Rμ	1 μ-like ring, 0 decay electrons
	RHC 1Re	1 e-like ring, 0 decay electrons



Data collected

Same data set as Neutrino 2020 result, with added analysis improvements and new samples



New analysis with additional Run 11 data ongoing

Data collected

Same data set as Neutrino 2020 result, with added analysis improvements and new samples

New analysis with additional Run 11 data ongoing

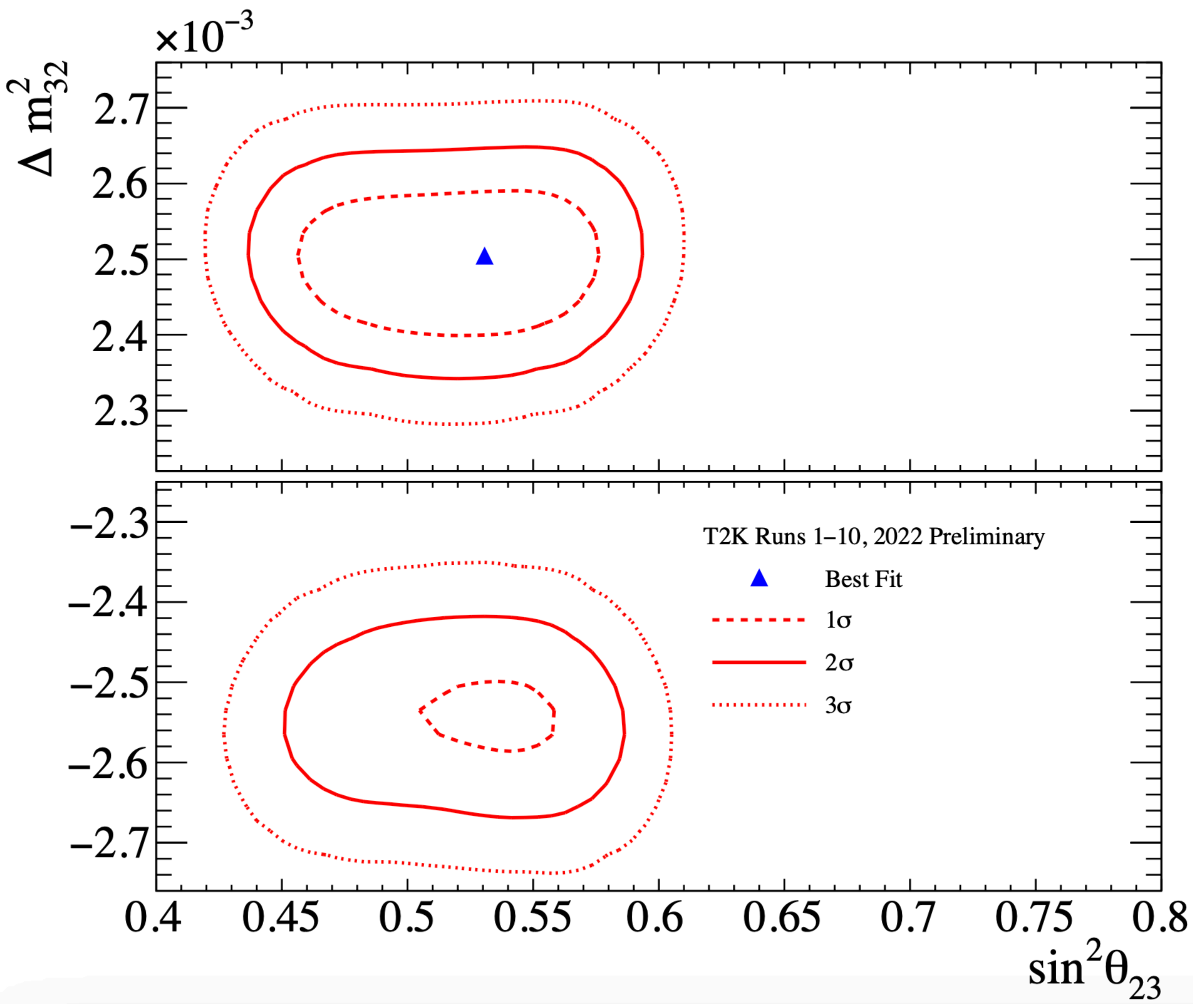
Disappearance parameters

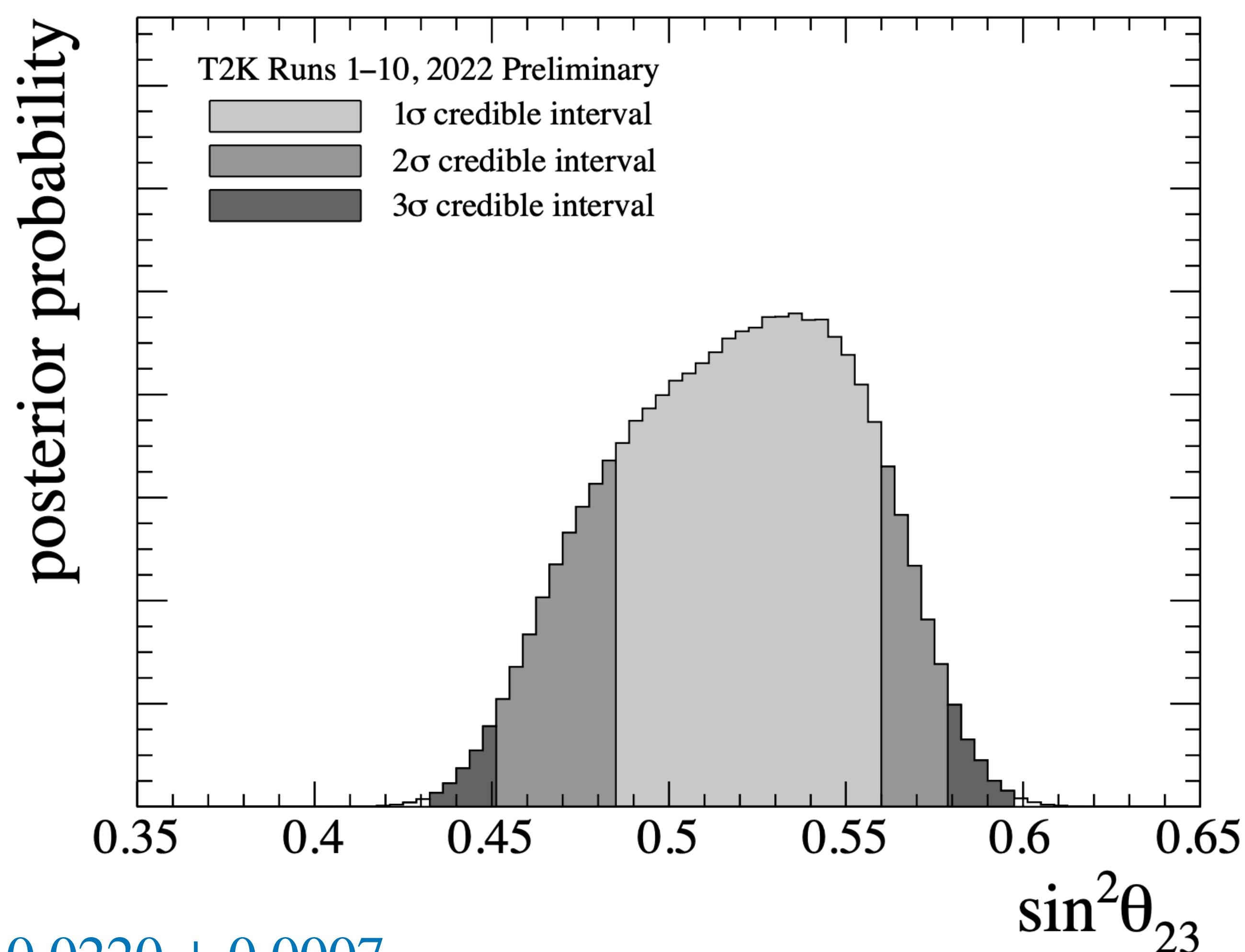
- Prefer **upper octant** and **normal ordering**, with Bayes factors of 2.2 and 2.7 respectively
- **Lower octant** and **inverted ordering** still **just allowed at 1σ**

Posterior probabilities for octant and mass ordering:

T2K Runs 1-10, 2022 Preliminary

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.24	0.49	0.73
IH ($\Delta m^2_{32} < 0$)	0.07	0.20	0.27
Sum	0.31	0.69	1.00

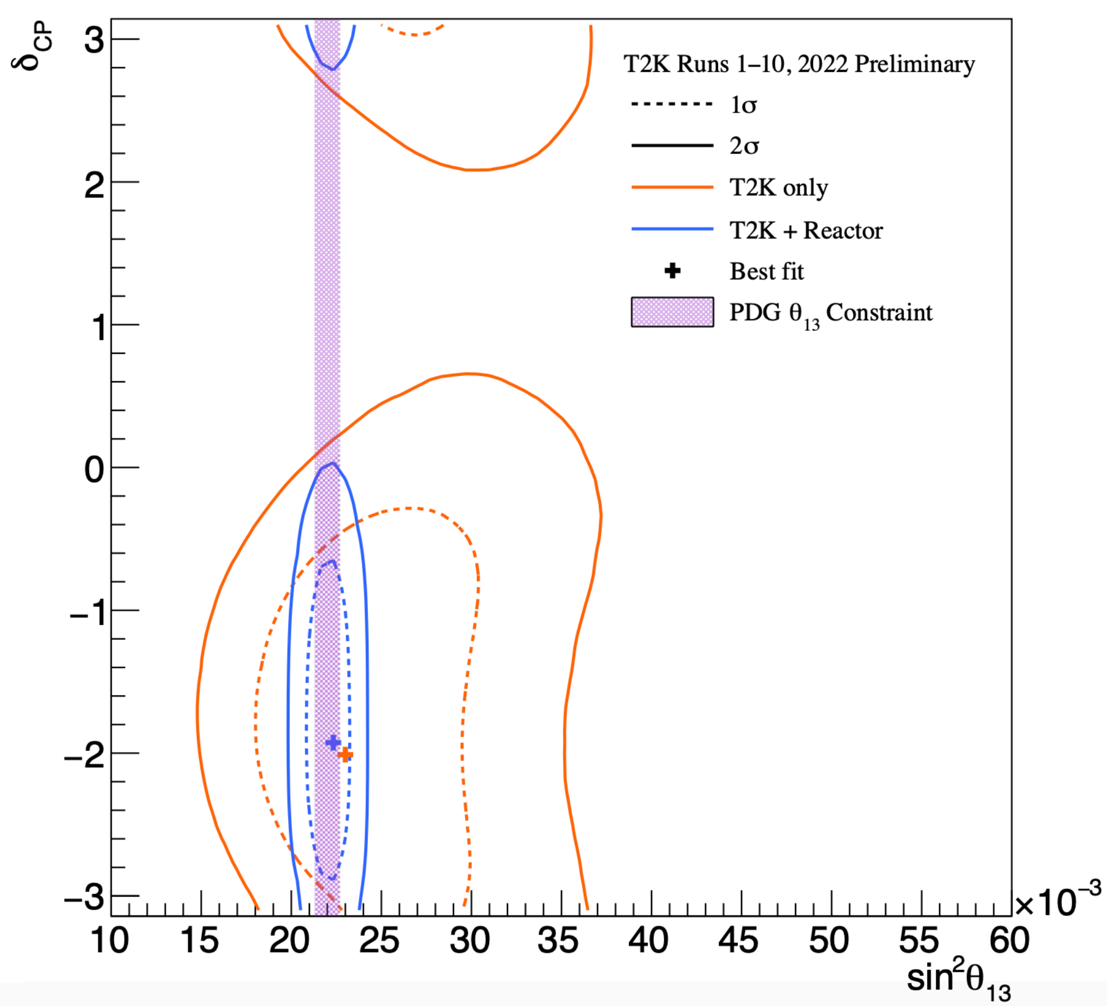


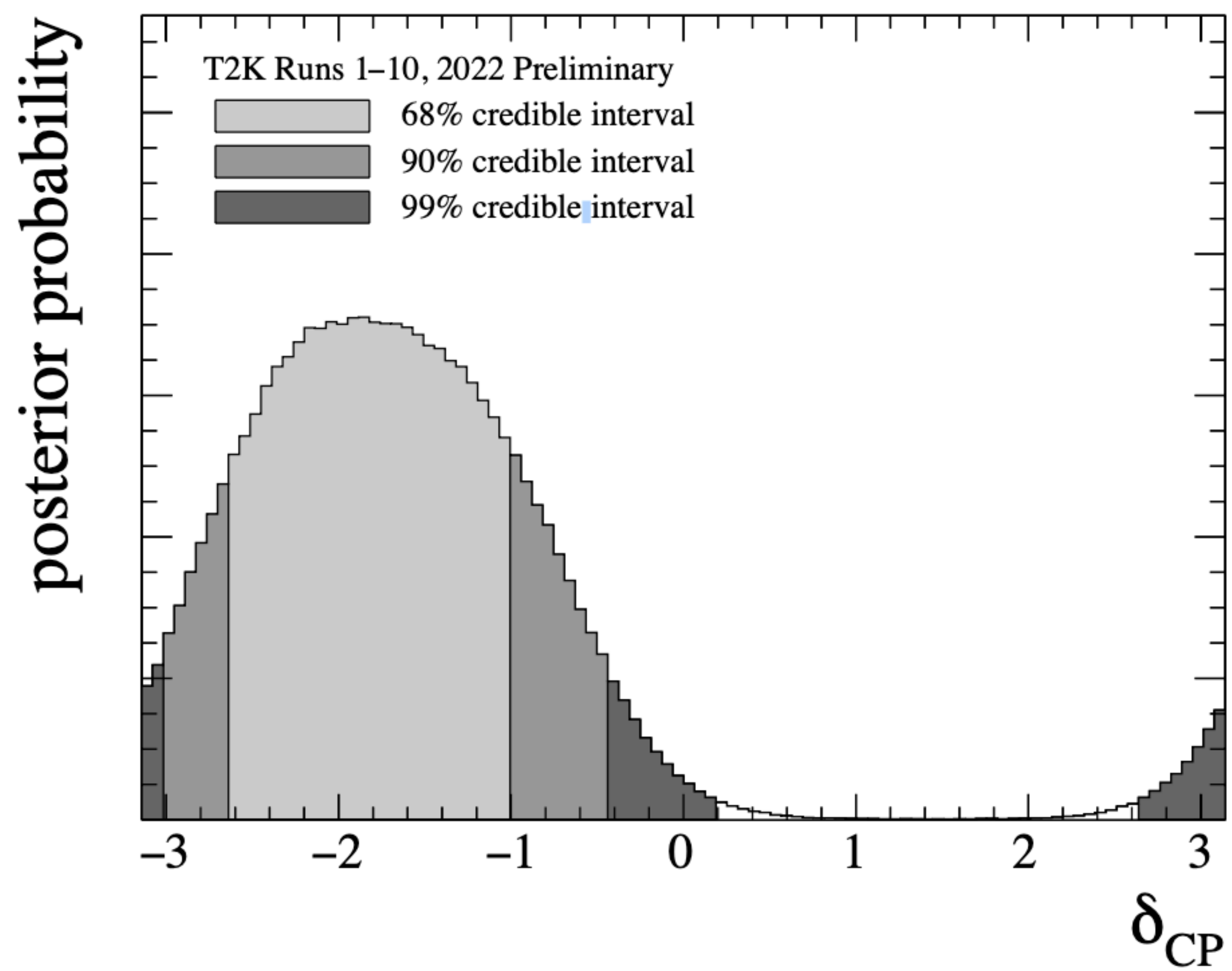


Using θ_{13} constraint from reactor experiments: $\sin^2\theta_{13} = 0.0220 \pm 0.0007$

Appearance parameters

- $\delta_{CP} = 0$ **and** π (CP-conservation) excluded at **90% credible interval**
- This conclusion is **prior independent** (tested flat priors in δ_{CP} and $\sin \delta_{CP}$)
- **Good agreement** in $\sin^2 \theta_{13}$ **between T2K and reactor** experiments
- Excellent agreement between Bayesian and Hybrid-Frequentist results (see <u>backup</u>)

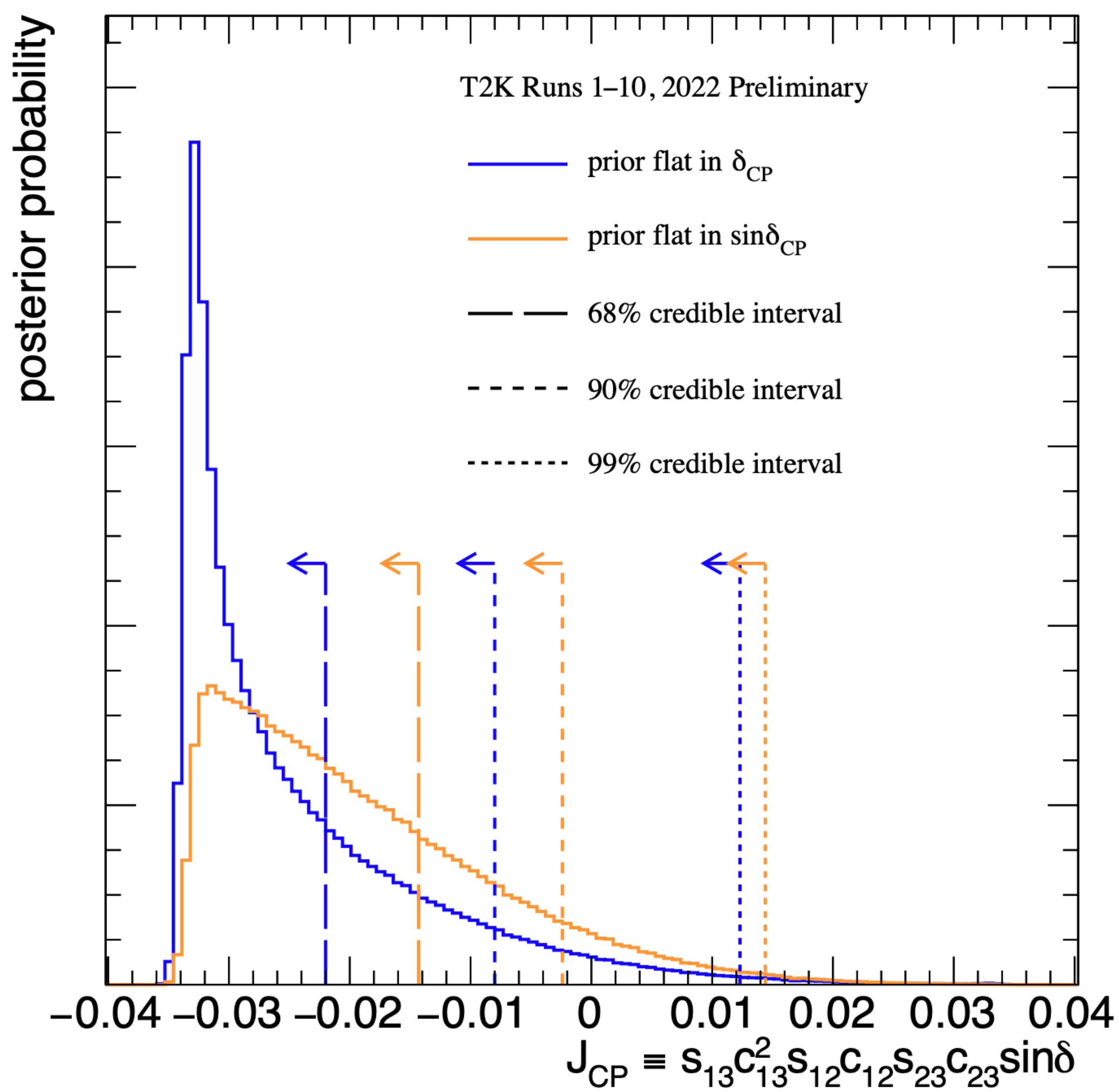


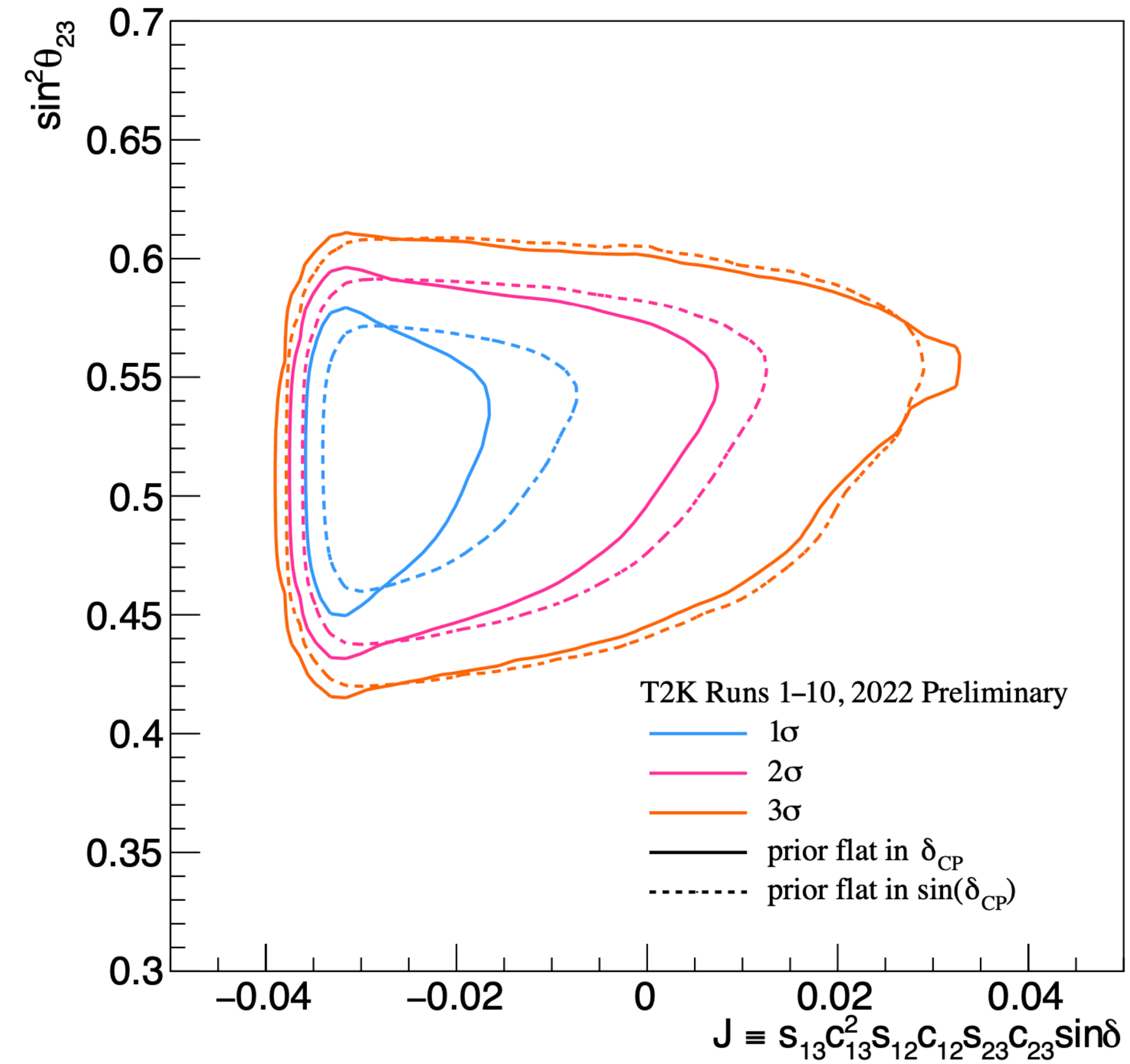


Using θ_{13} ***constraint from reactor experiments:*** $\sin^2 \theta_{13} = 0.0220 \pm 0.0007$

Jarlskog invariant

- $J_{CP} = 0$ (CP-conservation) **excluded** at the **90% credible interval**
- $J_{CP} = 0$ excluded at 2σ when using our nominal flat prior in δ_{CP}, but not when applying flat prior in $\sin \delta_{CP}$





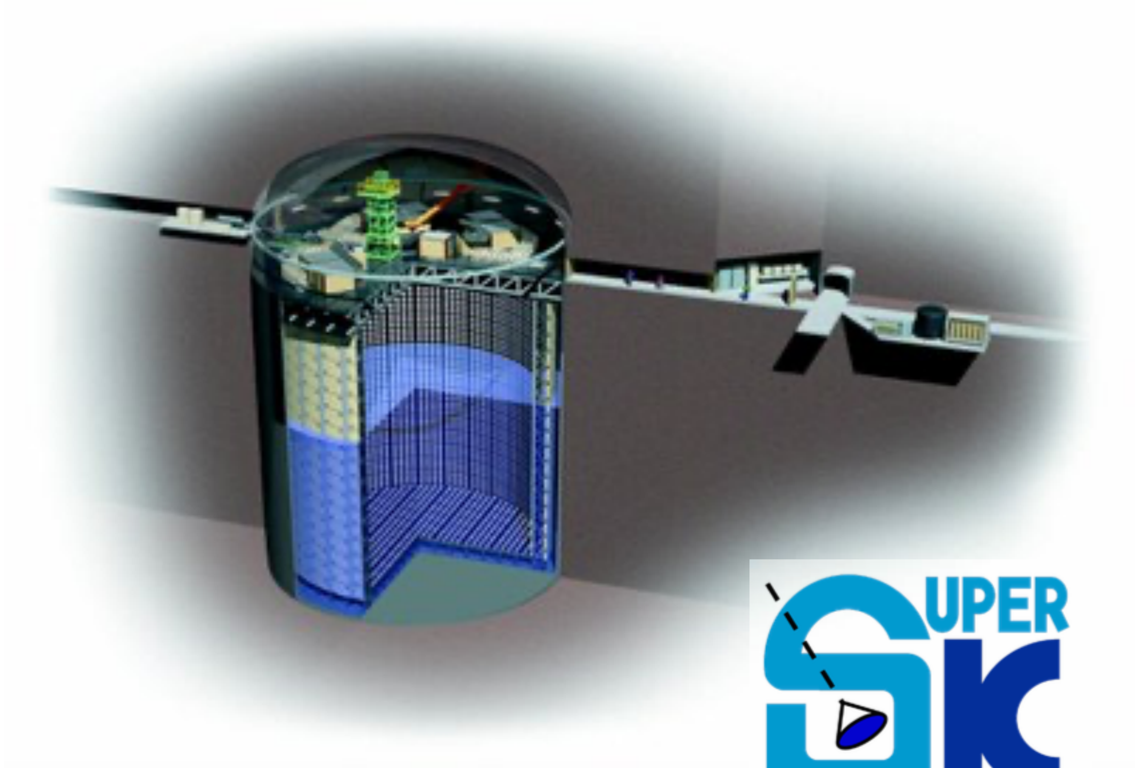
Using θ_{13} constraint from reactor experiments: $\sin^2\theta_{13} = 0.0220 \pm 0.0007$

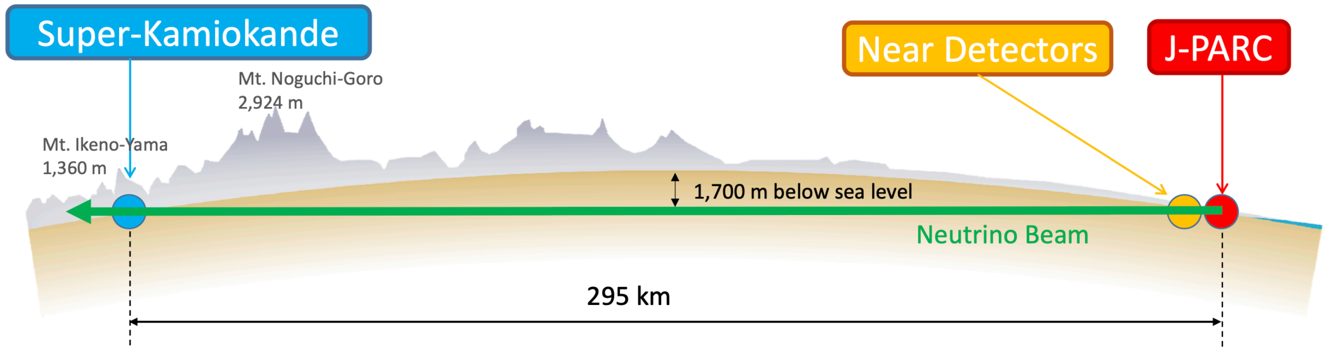
3.2 Latest Results - T2K+SK joint-fit

T2K+SK atmospherics joint analysis

- Results recently presented at NNN23 showing the results of a joint T2K + SK oscillation analysis

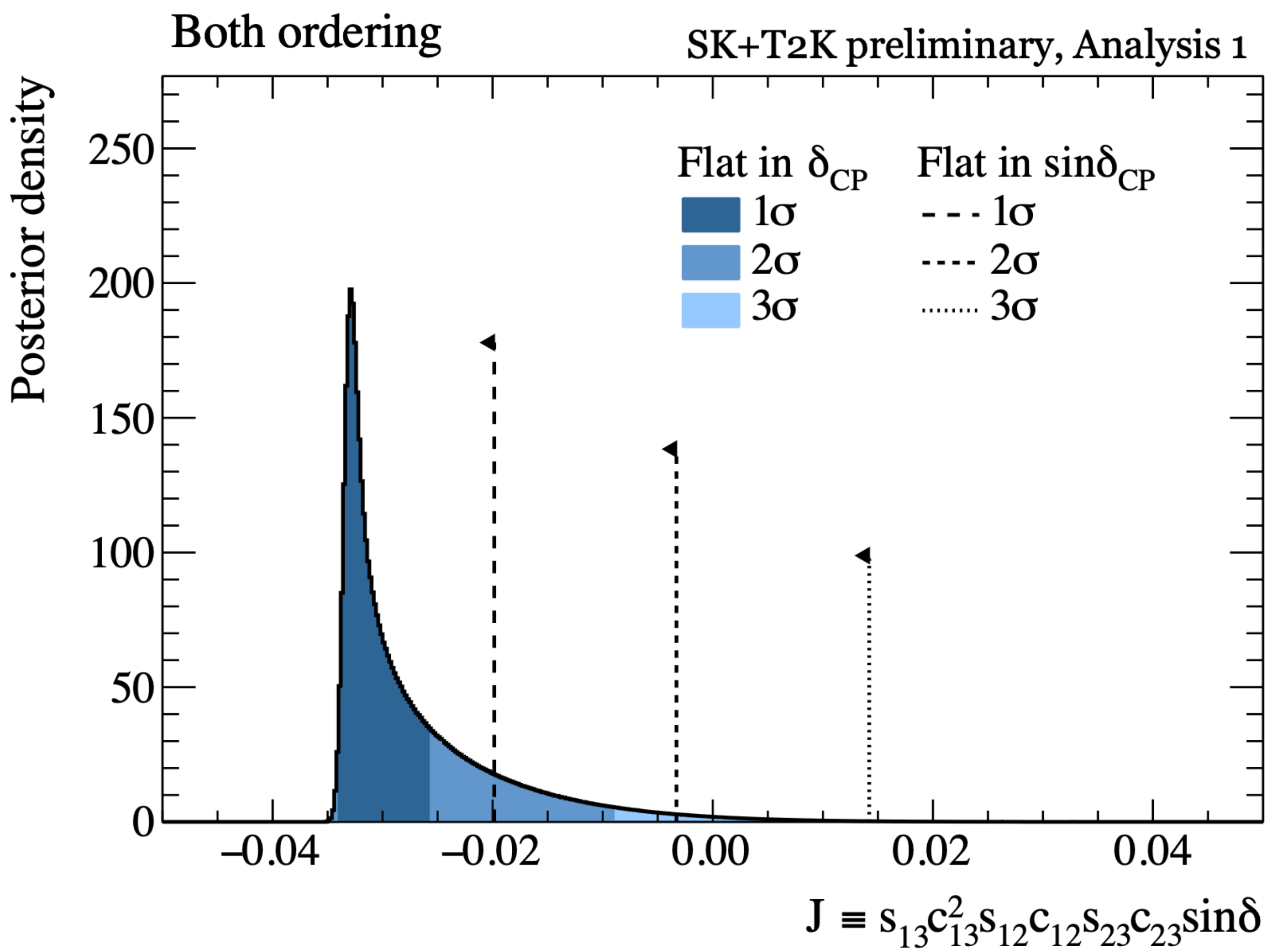
- **Motivations**:
  - T2K **near detector** can **constrain** cross-section uncertainties for low-energy **atmospheric samples**
  - Atmospheric neutrino oscillation can **break degeneracy** between δ_{CP} and **mass ordering**

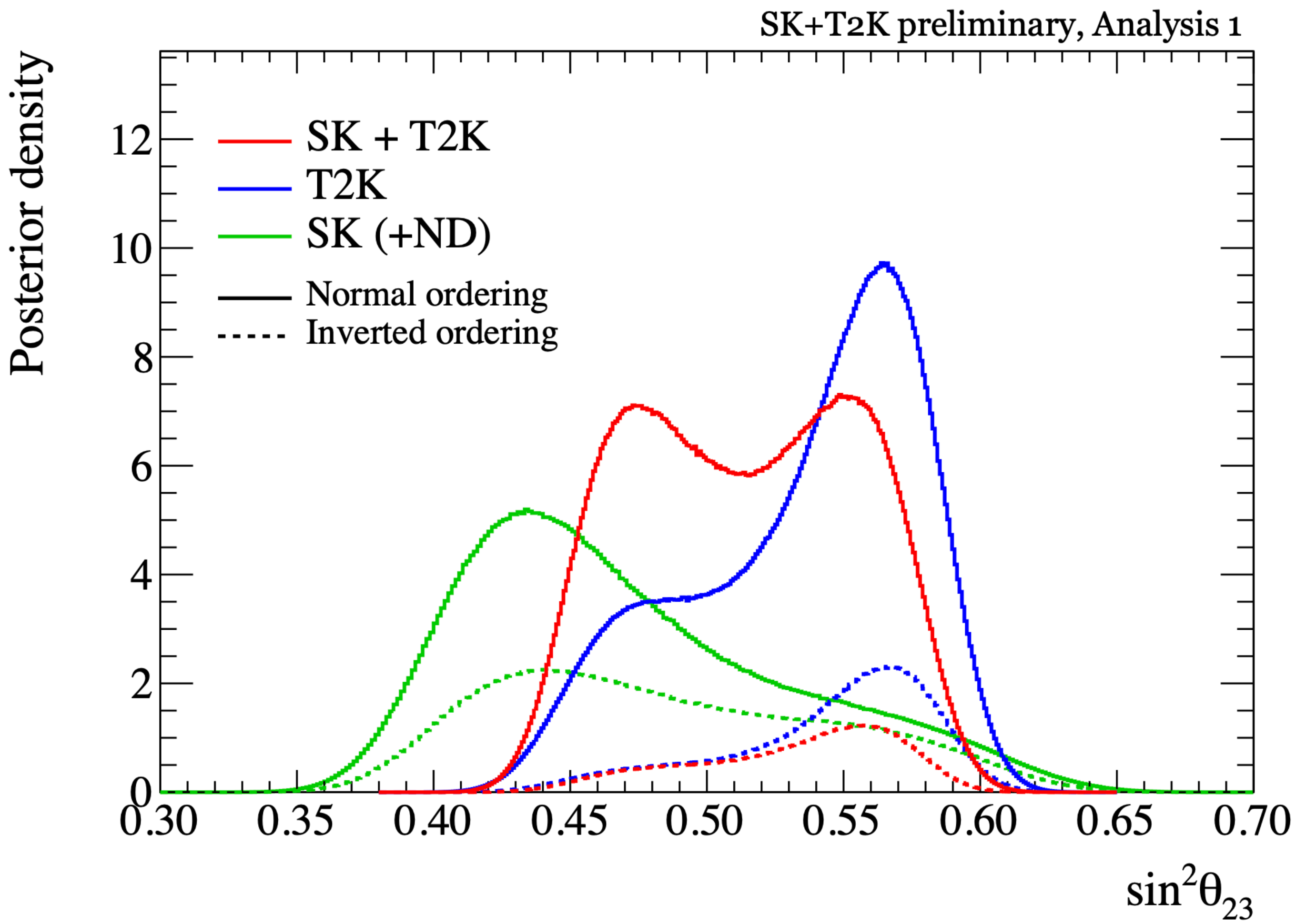




T2K+SK joint analysis results

- **CP-conservation** ($J_{CP} = 0$) **excluded** around **2σ** when applying reactor constraint
- **Preference** for **normal mass ordering**, Bayes factor of ~9
- Almost **equal preference** for lower and upper **octant**
- **Good agreement** with T2K's results, **slightly stronger constraints for δ_{CP}** and mass ordering

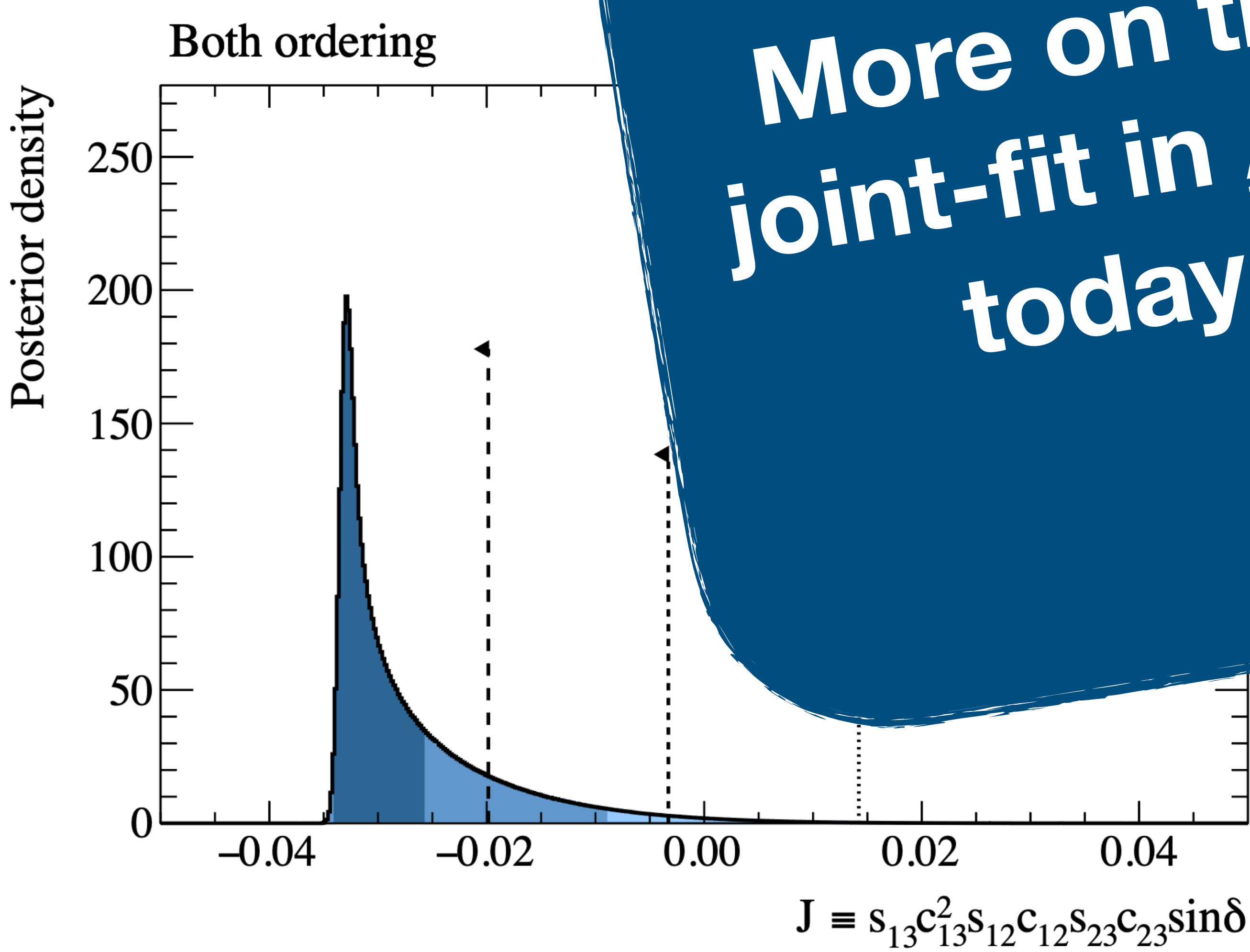


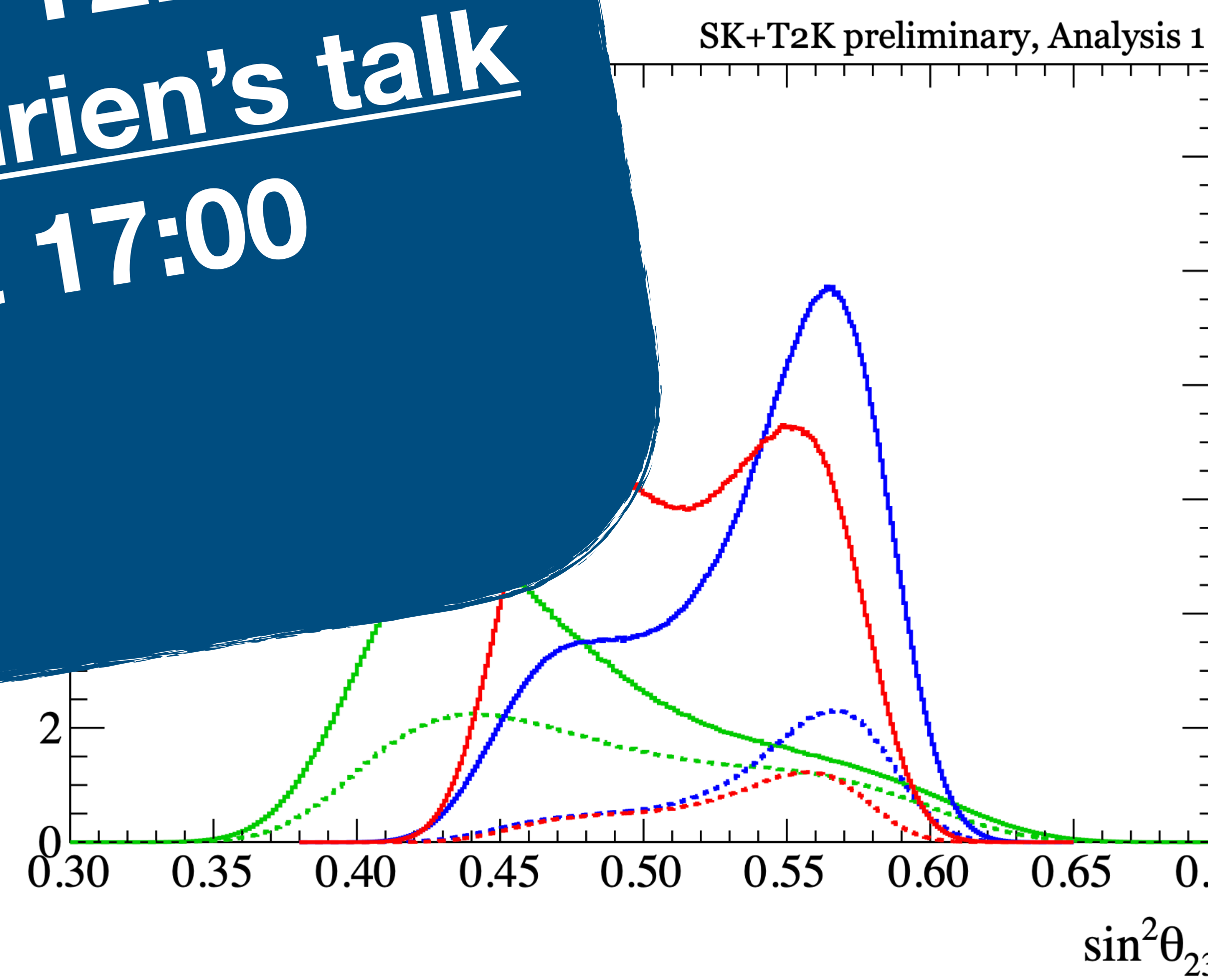


T2K+SK joint analysis results

- **CP-conservation** ($J_{CP} = 0$) **excluded** around **2σ** when applying reactor constraint
- **Preference** for **normal mass ordering**, B… 9
- Almost **equal pref**…
- **Good agreeme**… **traints for** δ_{CP} and mass ordering

More on the T2K+SK joint-fit in Adrien's talk today at 17:00





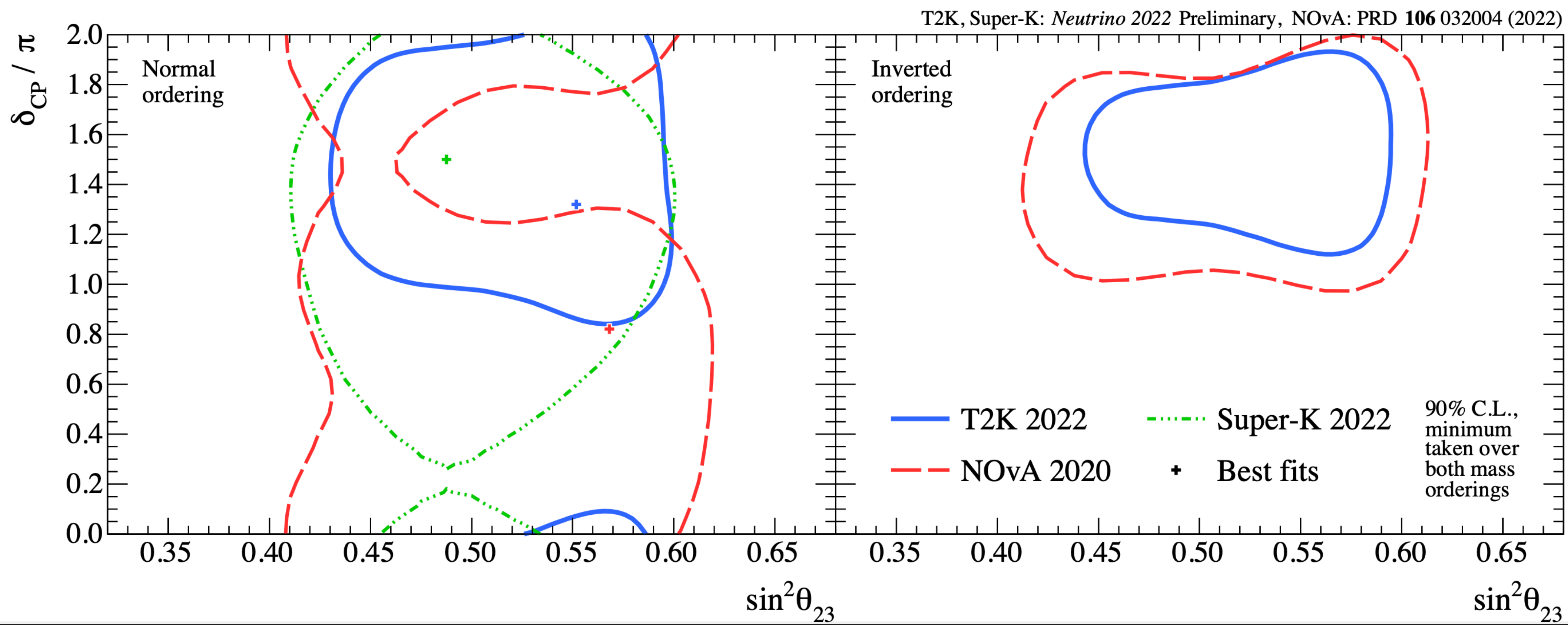
4. Future of T2K

T2K+NOνA joint-analysis

* minimum difference of $\sin\delta_{CP} = 0$ and $\sin\delta_{CP} = \pm 1$, neutrinos and antineutrinos

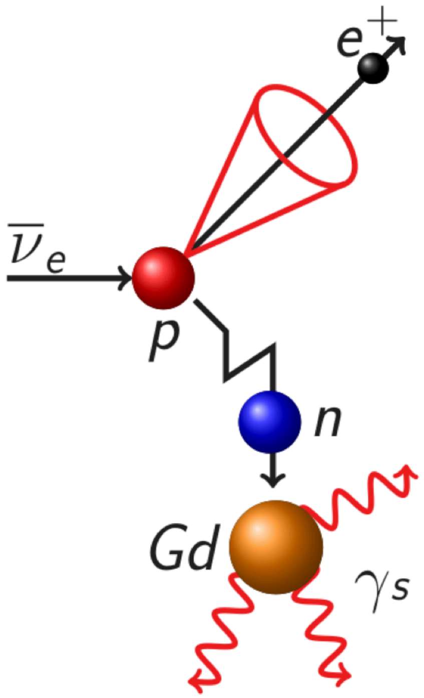
- Two **complementary** long-baseline experiments
  - **Increased sensitivity** to **mass ordering**, δ_{CP} and θ_{23} due to **breaking degeneracies**
- **Not just combining $\Delta\chi^2$**, extensive work on analysing the effect of experiment's systematic models
- Analysis under review, preliminary results **expected soon**

	T2K	NOvA
Proton beam Energy	30 GeV	120 GeV
Baseline	**295 km**	**810 km**
Peak neutrino energy	0.6 GeV	2 GeV
Detector technology	Water Cherenkov	Segmented liquid scintillator bars
CP effect*	**32%**	**22%**
Matter effect	**9%**	**29%**

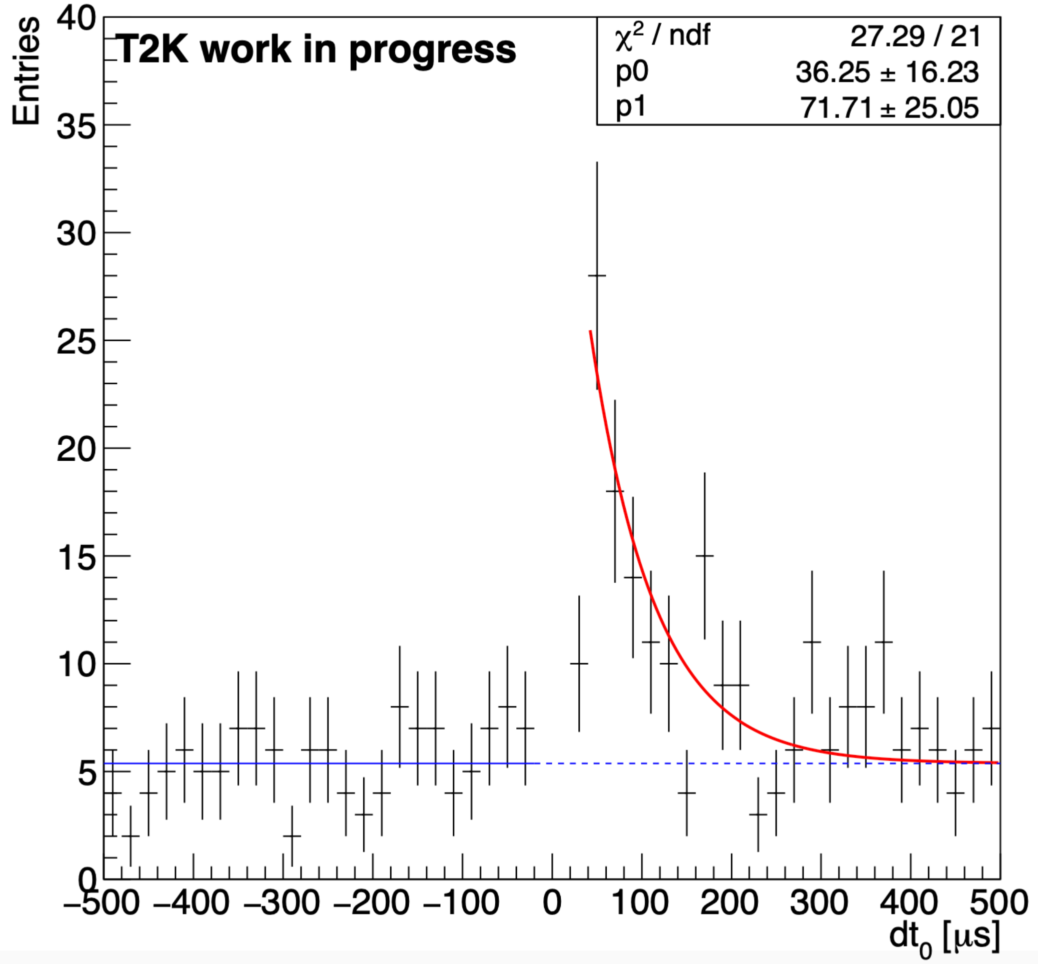


SK-Gd

- SK **loaded with Gd** (now at 0.03% concentration) sulphate to improve **neutron tagging** ability
- **Data already taken** from SK-Gd phase (0.01% Gd concentration)
- Implementation into T2K analysis **in progress**
- $\bar{\nu}$ can be identified through n captures, helping to **discriminate between neutrino** and **antineutrino interactions**

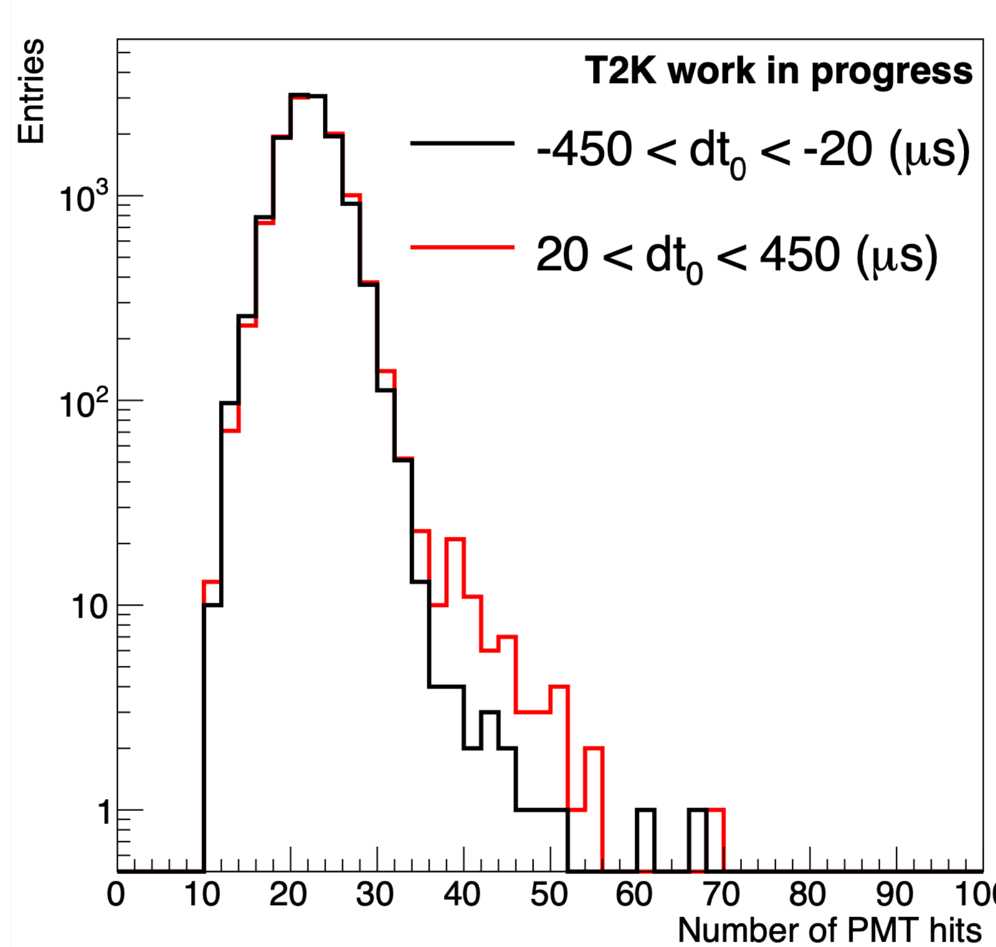


8 MeV γ cascade

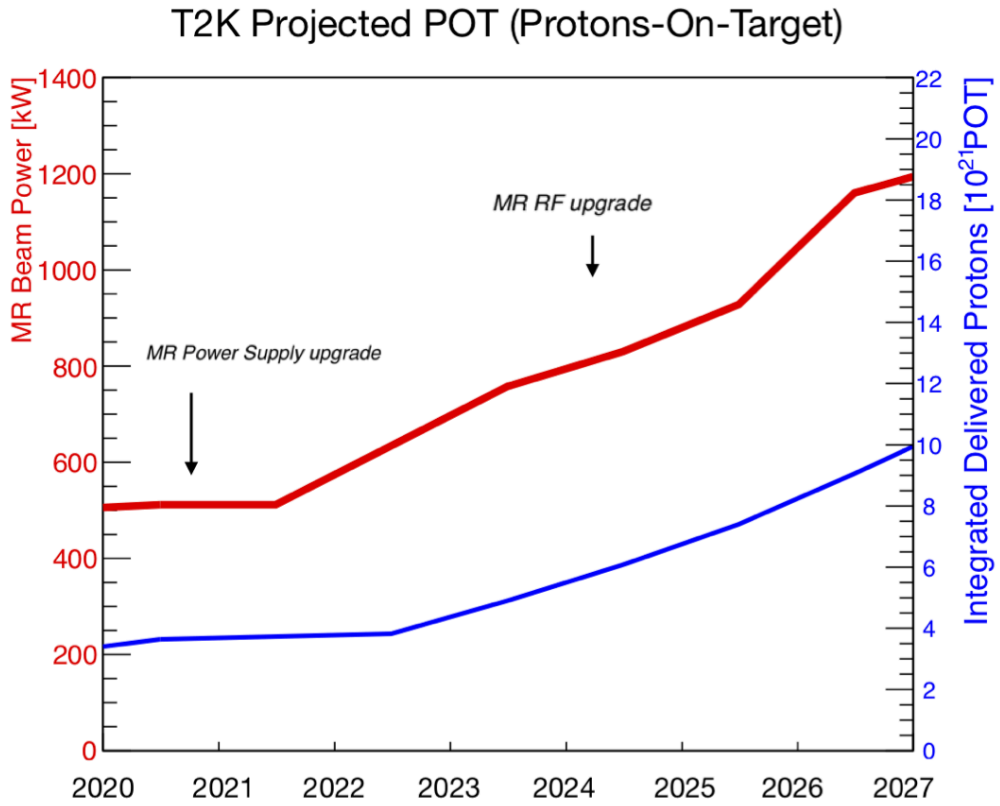


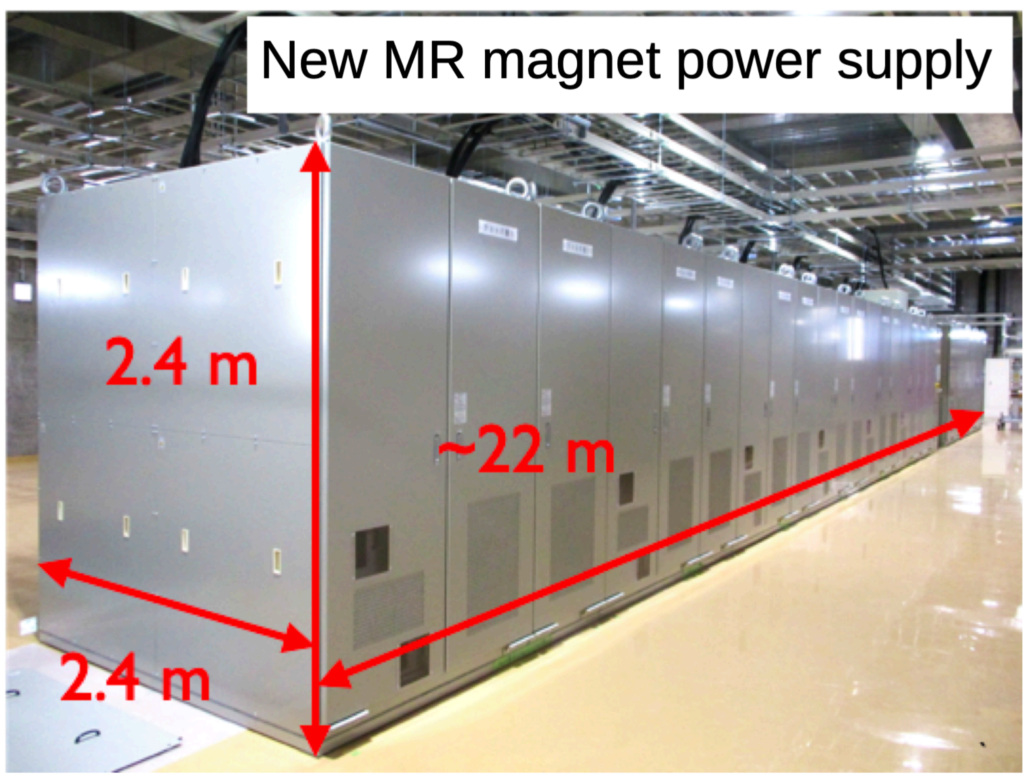
Increase in time-delayed signals indicates presence of GD in SK

Time-of-flight of Cherenkov light subtracted



Beam upgrade

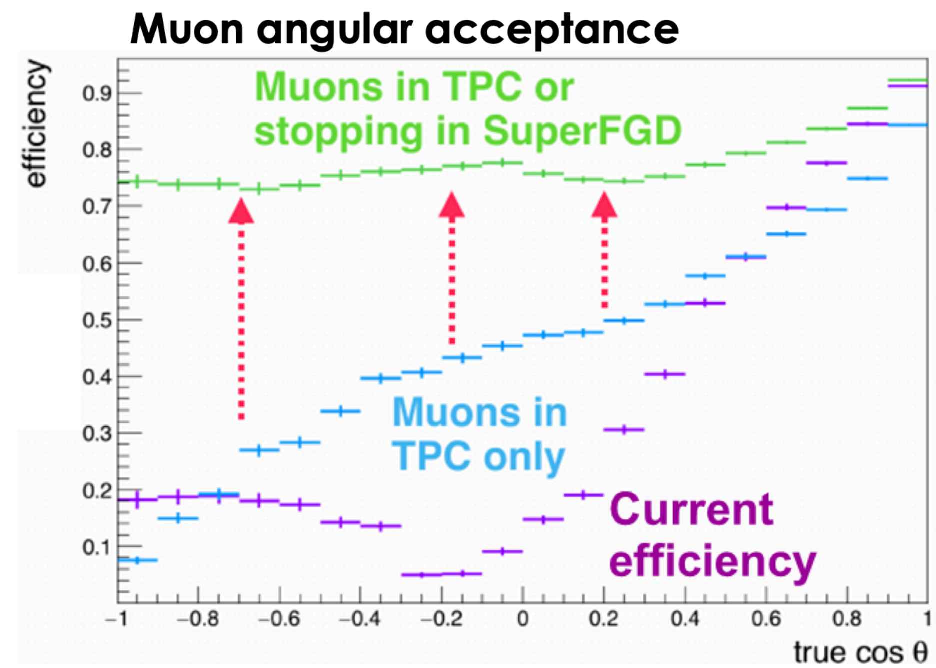


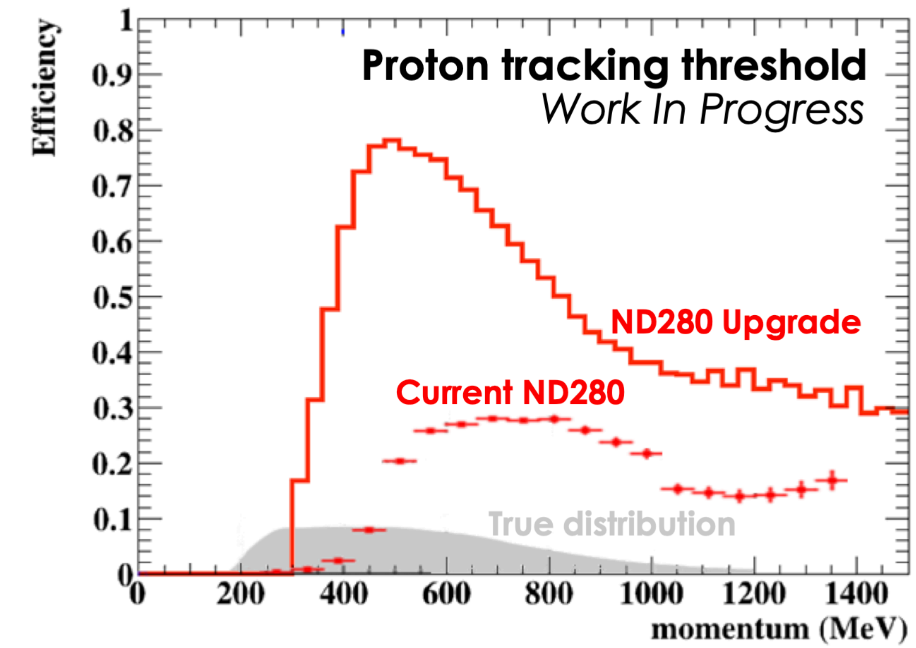


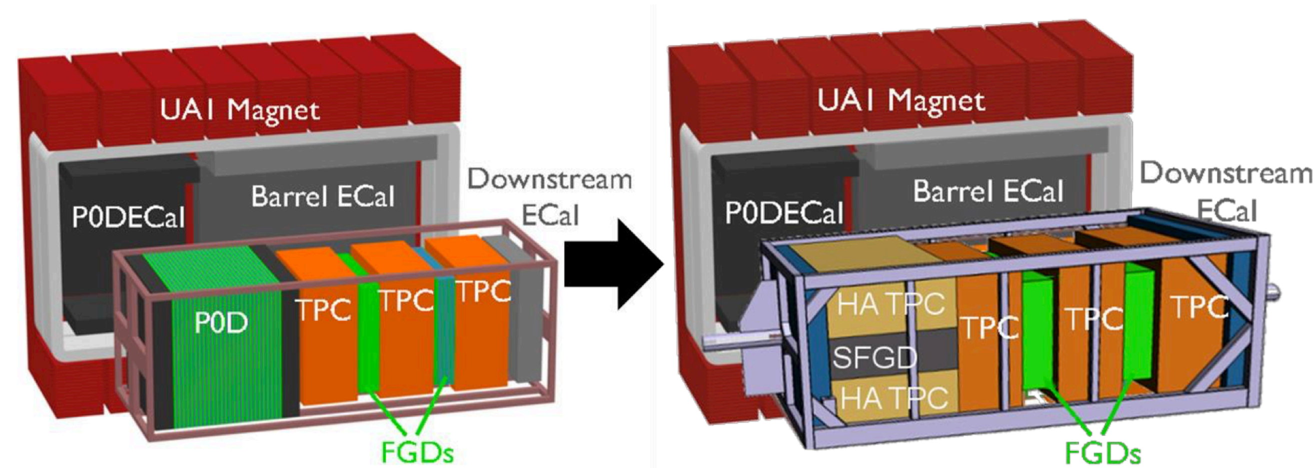
- Proton beam reached **~515 kW stable operation** in recent runs
- Upgrades during 2-year shutdown:
  - **New** MR fast **extraction magnets** and **power supply**
  - **New** proton **focusing magnet**
  - **New** beam and μ **monitors**
  - **New target** and target **cooling system**
  - **New focusing horns** and power supplies (**250** → **320 kA**)
- **Data taking** to start again **later this year**

ND280 upgrade

- P0D replaced by complex of new detectors: **Super-FGD**, **high-angle TPC** and **time-of-flight**
- Expected analysis improvements:
    - Improved **reconstruction** at **high** and **backwards angles** → better interaction **model constraints**
    - **Increased target mass** (x2) → more **statistics**
    - Better **reconstruction** of outgoing **nucleus** → **new observables**
    - Neutrino interaction measurements beyond $p_{\mu} - \cos\theta_{\mu}$







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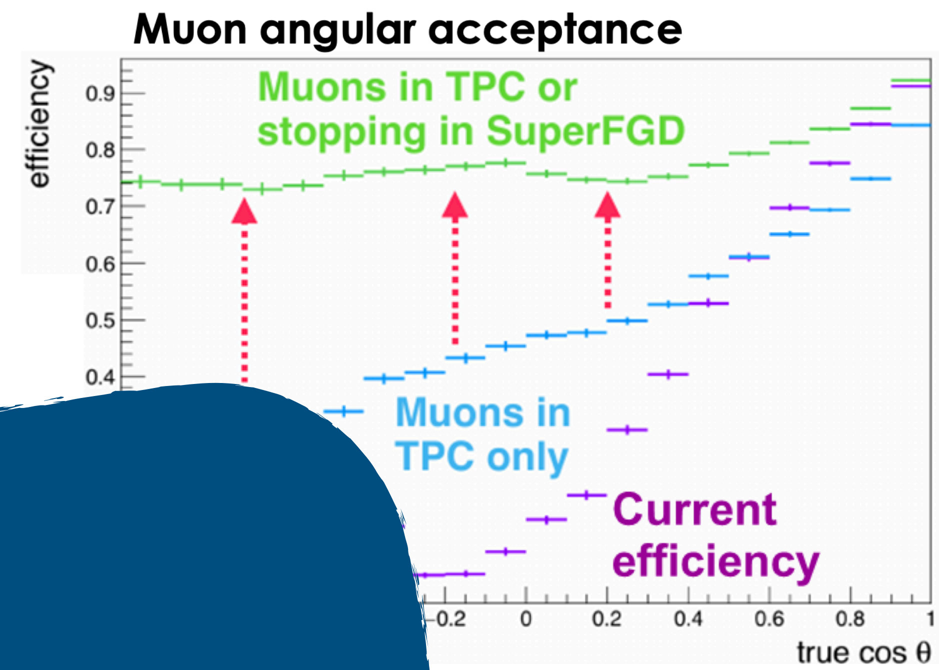
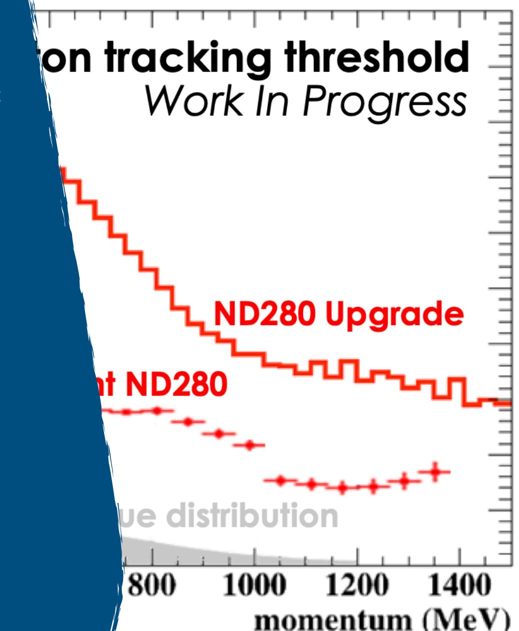
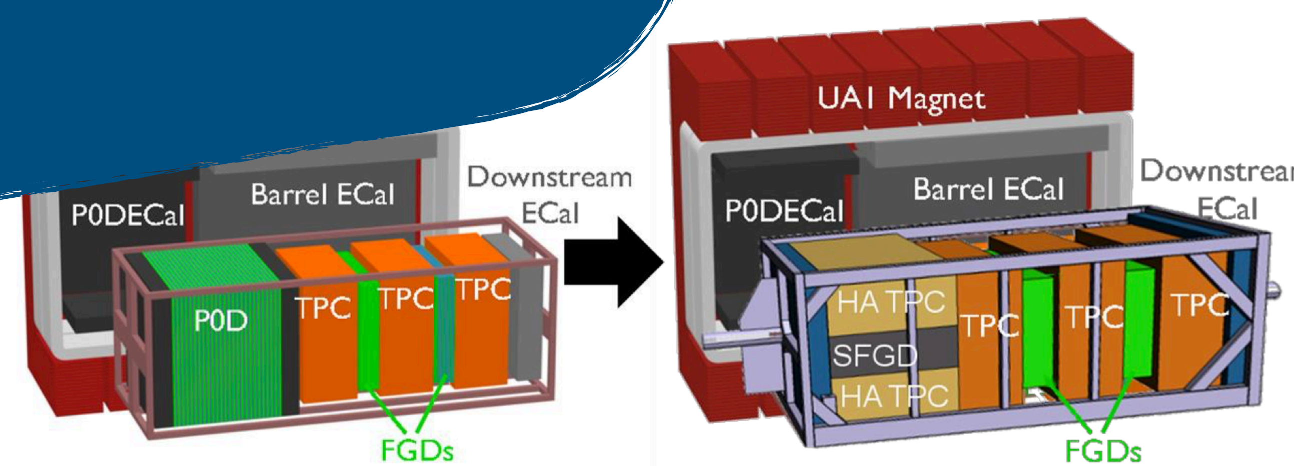
  - **Increased tar**
    more **statistic**
  - Better **reconstr**
    nucleus → new
  - Neutrino interaction measurements beyond $p_\mu - \cos\theta_\mu$







More on ND280 upgrade in Weijun's talk tomorrow at 17:00

Summary and outlook

- T2K is a long baseline experiment studying neutrino oscillations, aiming for precise measurements of θ_{23} and Δm^2_{32}, and constraining the CP-violating phase δ_{CP}
- New analysis has **significant improvements** over the last iteration:
  - **New** NA61/SHINE **flux tuning** and **interaction model**
  - **New near-detector selections** with **photon/proton tagging**
  - **New far-detector** multi-ring μ-like **sample**
- **CP-conserving** values of δ_{CP} excluded at **90% CL level**
- **Mild preference** for **normal ordering** and **upper octant**
- **T2K+SK** joint analysis **excludes CP-symmetry** around 2σ **CL level**
- Exciting physics ahead for T2K!
  - **T2K+NOνA joint analysis** in review, results expected soon
  - **SK-Gd data** being incorporated into T2K analyses
  - **Beam** and **near-detector upgrade** to be completed soon, **data taking** starting **later this year**!

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T2K talks

T2K results on neutrino cross-sections *Liu Shilin*

Slides available on Indico

T2K latest neutrino oscillation results *Adrien Blanchet*

Today at 17:00

Characterisation and validation of the Super-FGD Front-End electronics for the T2K Near Detector upgrade
Lorenzo Giannessi
Tomorrow at 10:38

Assembly, test and analysis development of the T2K upgr…
Weijun Li
Tomorrow at 17:15

Latest T2K papers

Measurements of the ν_μ and $\bar{\nu}_\mu$-induced Coherent Charged Pion Production Cross Sections on ^{12}C by the T2K experiment #1

T2K Collaboration • K. Abe (Kamioka Observ.) et al. (Aug 31, 2023)

e-Print: 2308.16606 [hep-ex]

pdf cite claim reference search 0 citations

Updated T2K measurements of muon neutrino and antineutrino disappearance using 3.6×10^{21} protons on target #2

T2K Collaboration • K. Abe (Kamioka Observ.) et al. (May 16, 2023)

Published in: *Phys.Rev.D* 108 (2023) 7, 072011 • e-Print: 2305.09916 [hep-ex]

pdf DOI cite claim reference search 2 citations

First measurement of muon neutrino charged-current interactions on hydrocarbon without pions in the final state using multiple detectors with correlated energy spectra at T2K #4

K. Abe (Kamioka Observ.), N. Akhlaq (Queen Mary, U. of London), R. Akutsu (KEK, Tsukuba), H. Alarakia-Charles, A. Ali (Manitoba U. and TRIUMF) et al. (Mar 24, 2023)

e-Print: 2303.14228 [hep-ex]

pdf cite claim reference search 3 citations

Measurements of neutrino oscillation parameters from the T2K experiment using 3.6×10^{21} protons on target #5

T2K Collaboration • K. Abe (Kamioka Observ.) et al. (Mar 6, 2023)

Published in: *Eur.Phys.J.C* 83 (2023) 9, 782 • e-Print: 2303.03222 [hep-ex]

pdf DOI cite claim reference search 25 citations

Scintillator ageing of the T2K near detectors from 2010 to 2021 #7

T2K Collaboration • K. Abe (Kamioka Observ.) et al. (Jul 26, 2022)

Published in: *JINST* 17 (2022) 10, P10028 • e-Print: 2207.12982 [physics.ins-det]

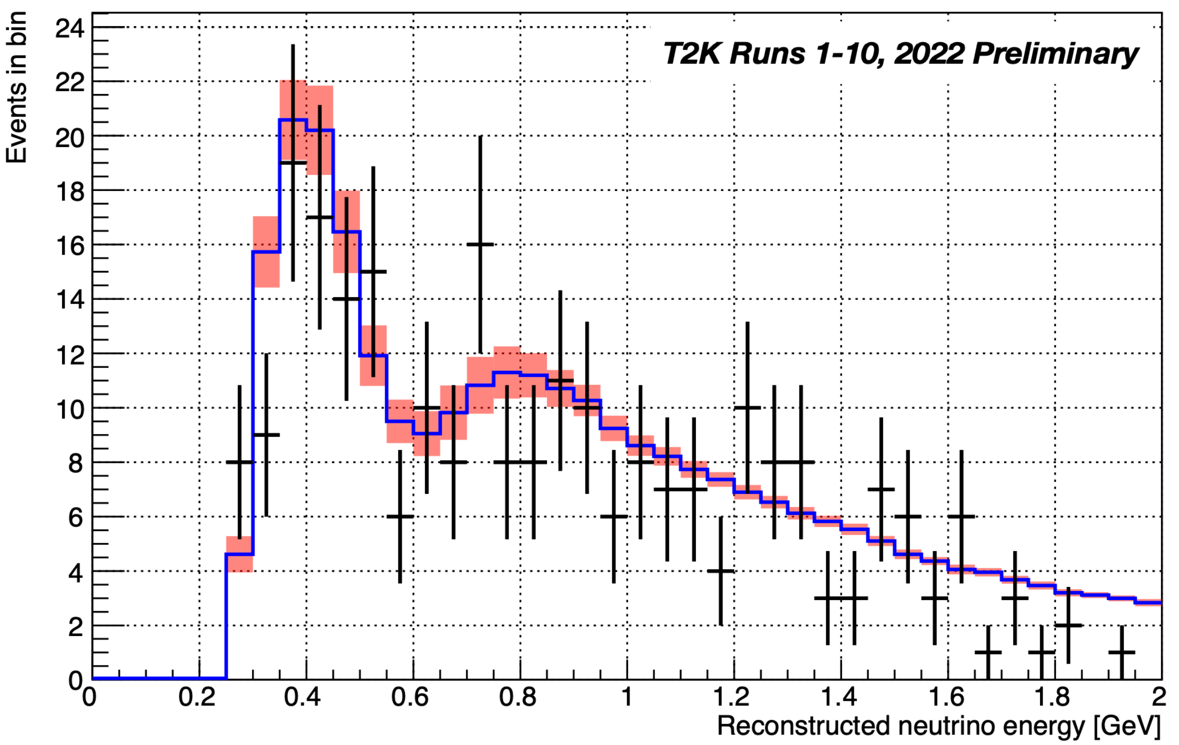
pdf DOI cite claim reference search 3 citations

Thank you for listening!

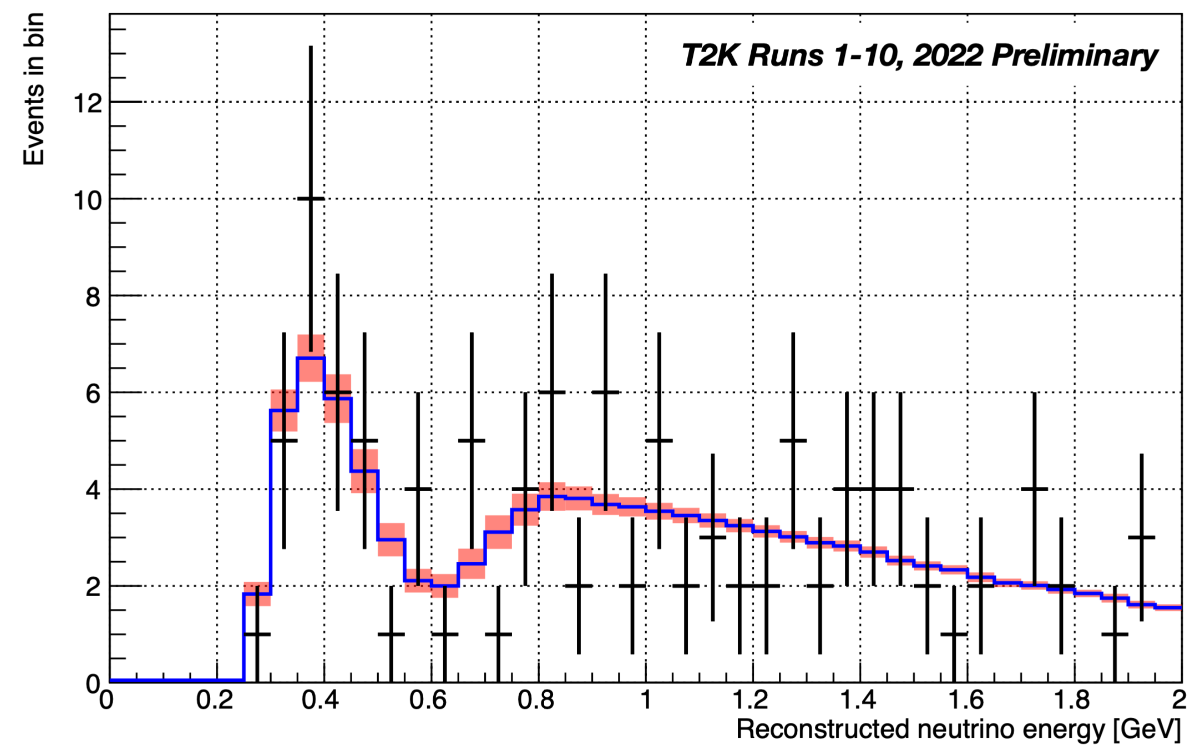
Backup

Posterior predictive distributions

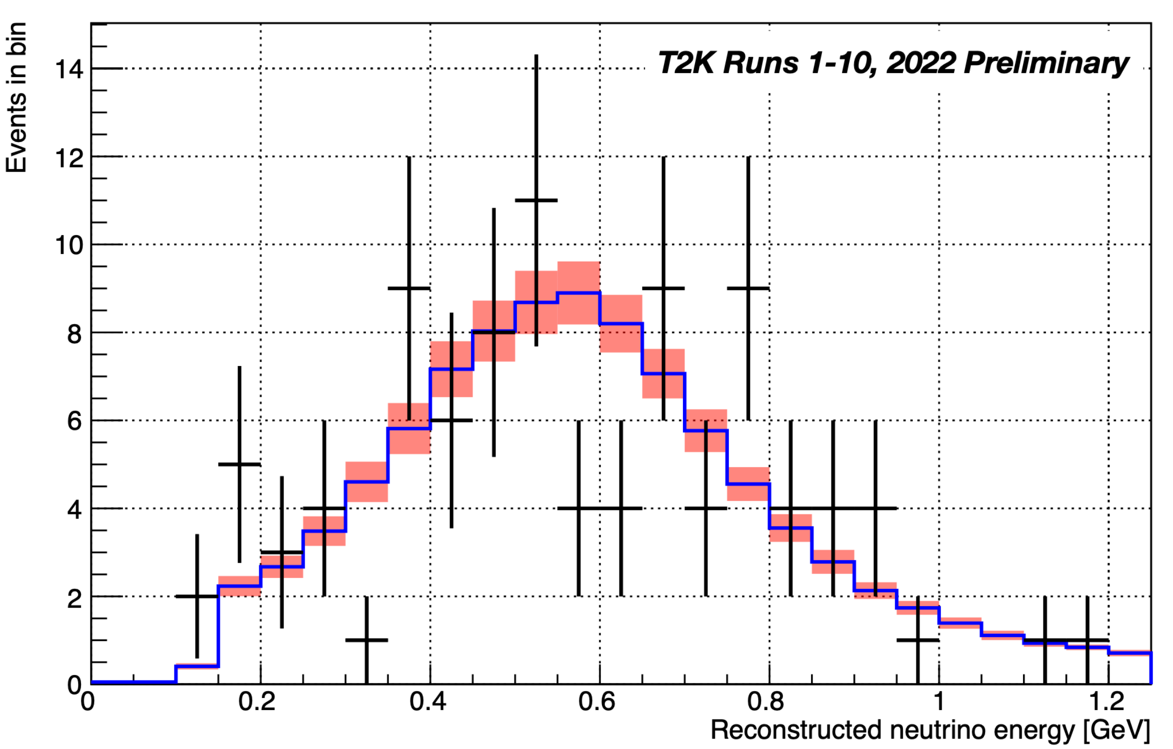
FHC 1Rμ



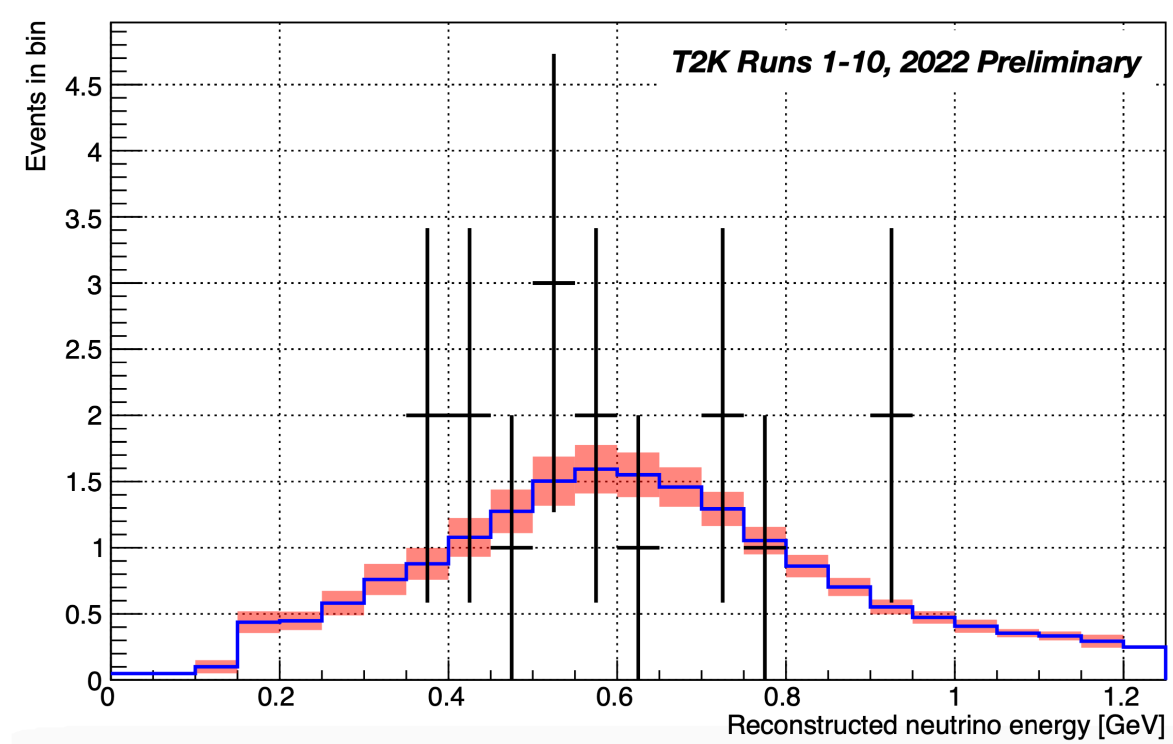
RHC 1Rμ



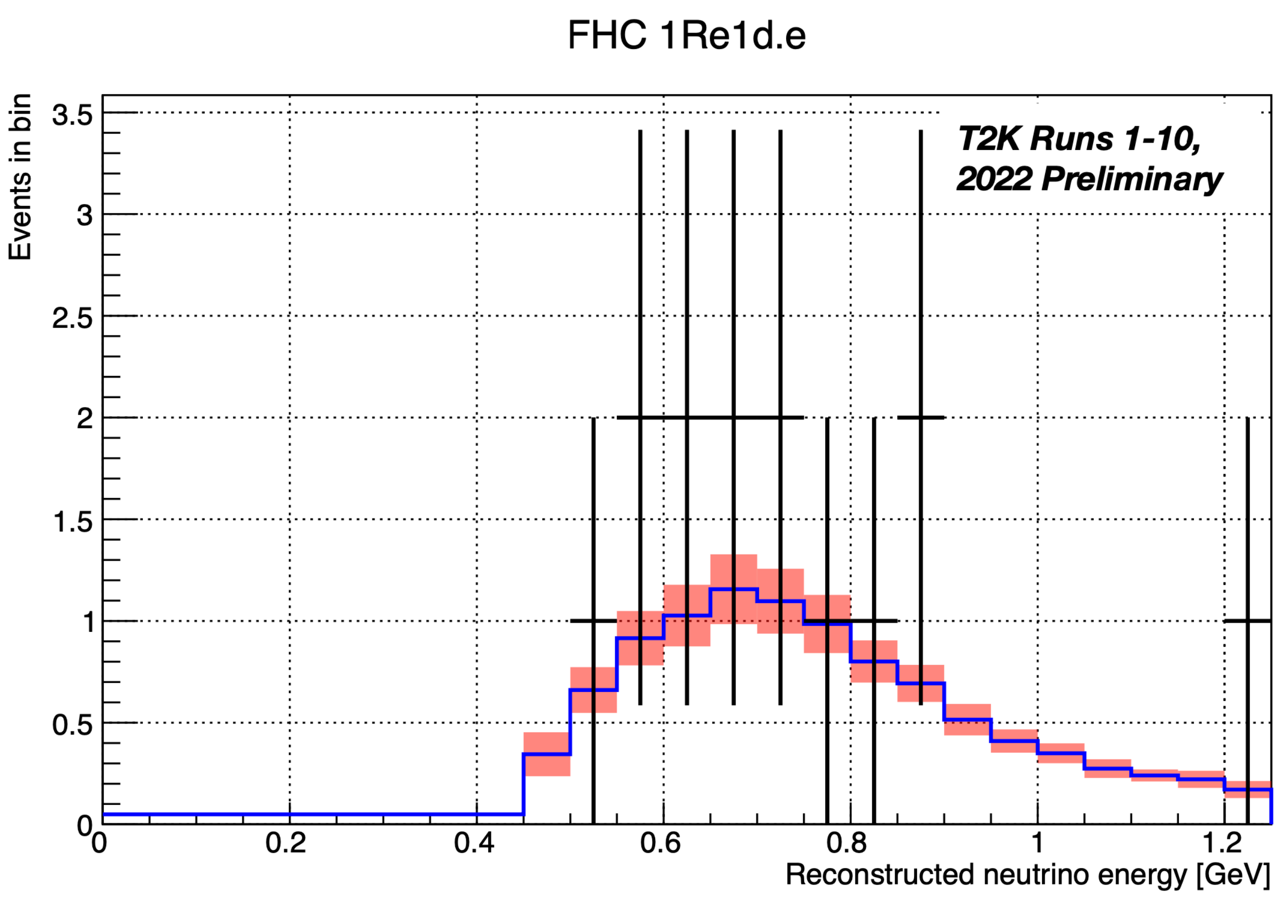
FHC 1Re

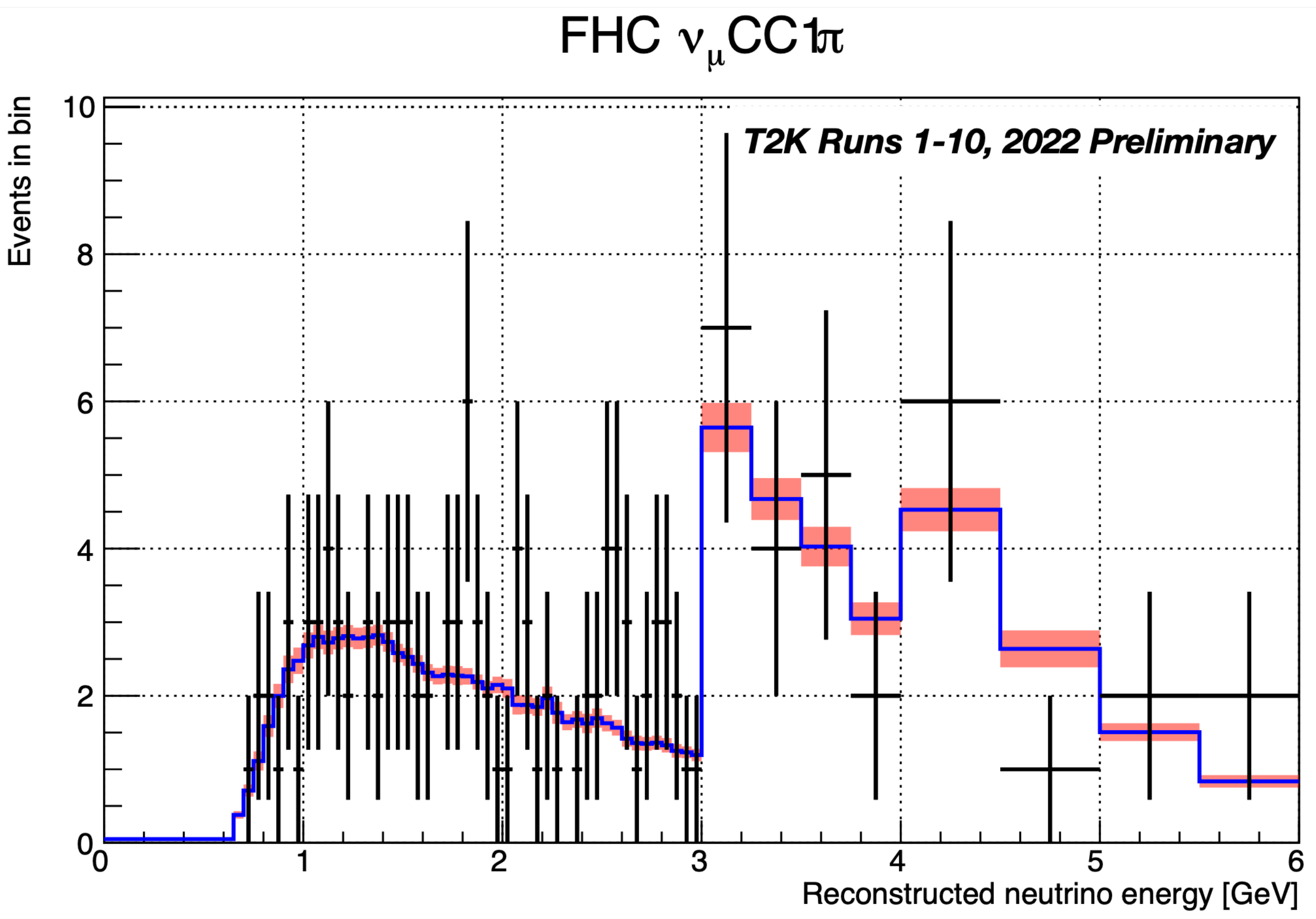


RHC 1Re

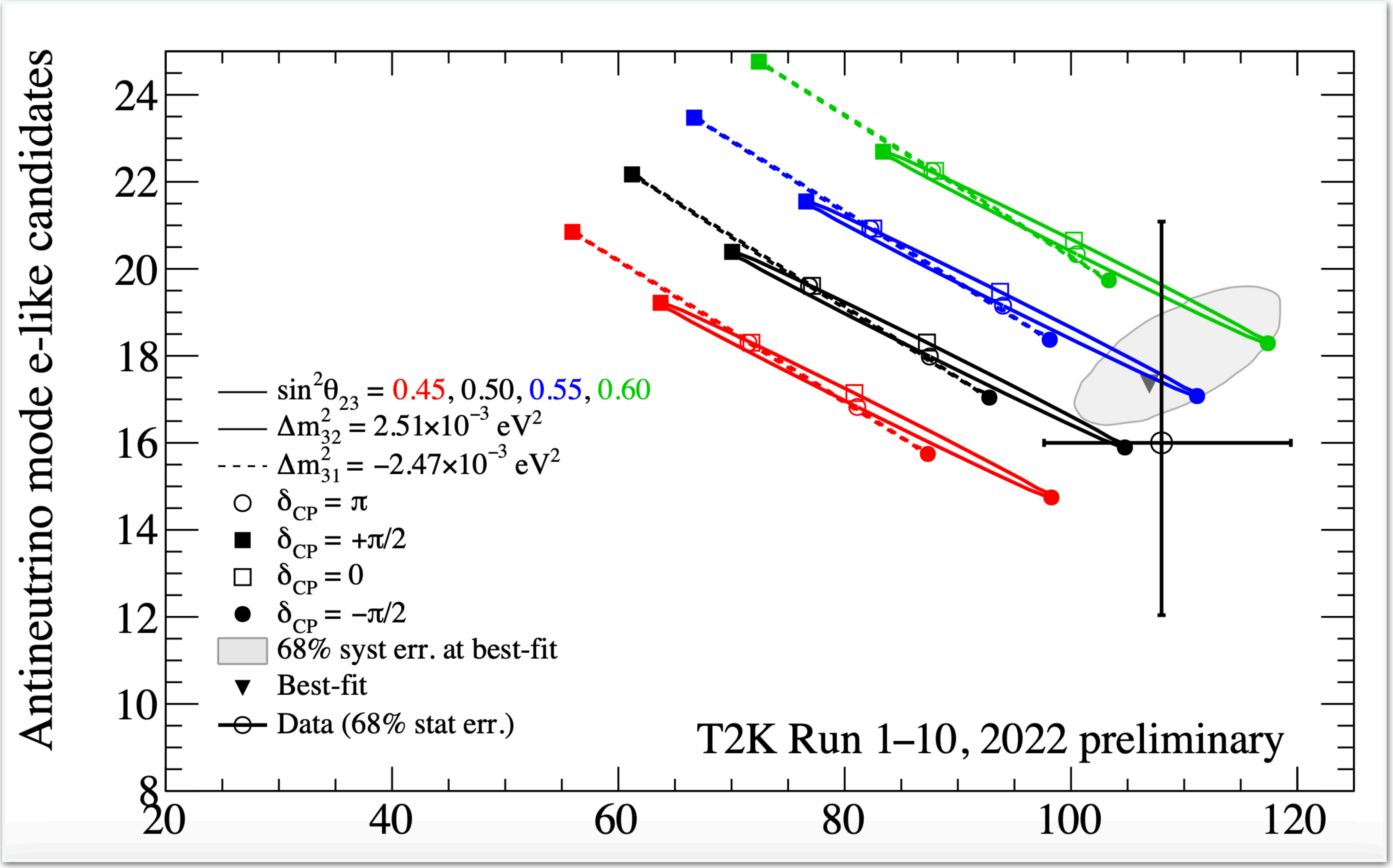


Posterior predictive distributions



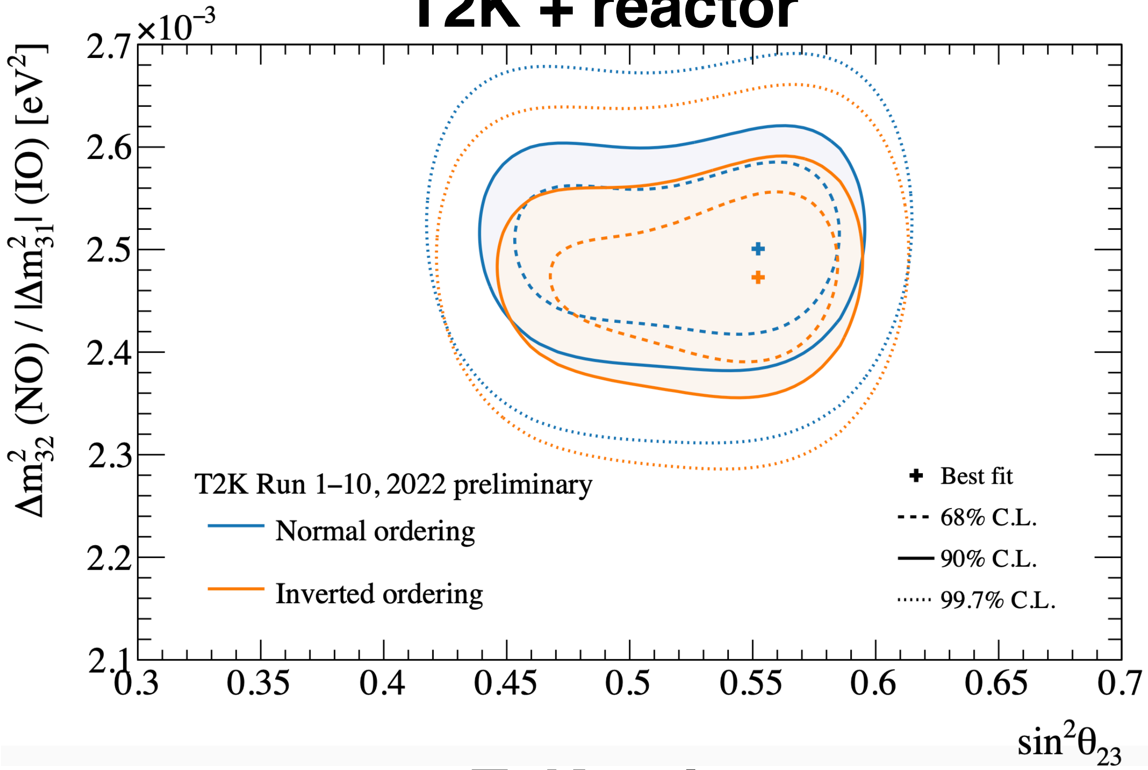


Bi-probability plot

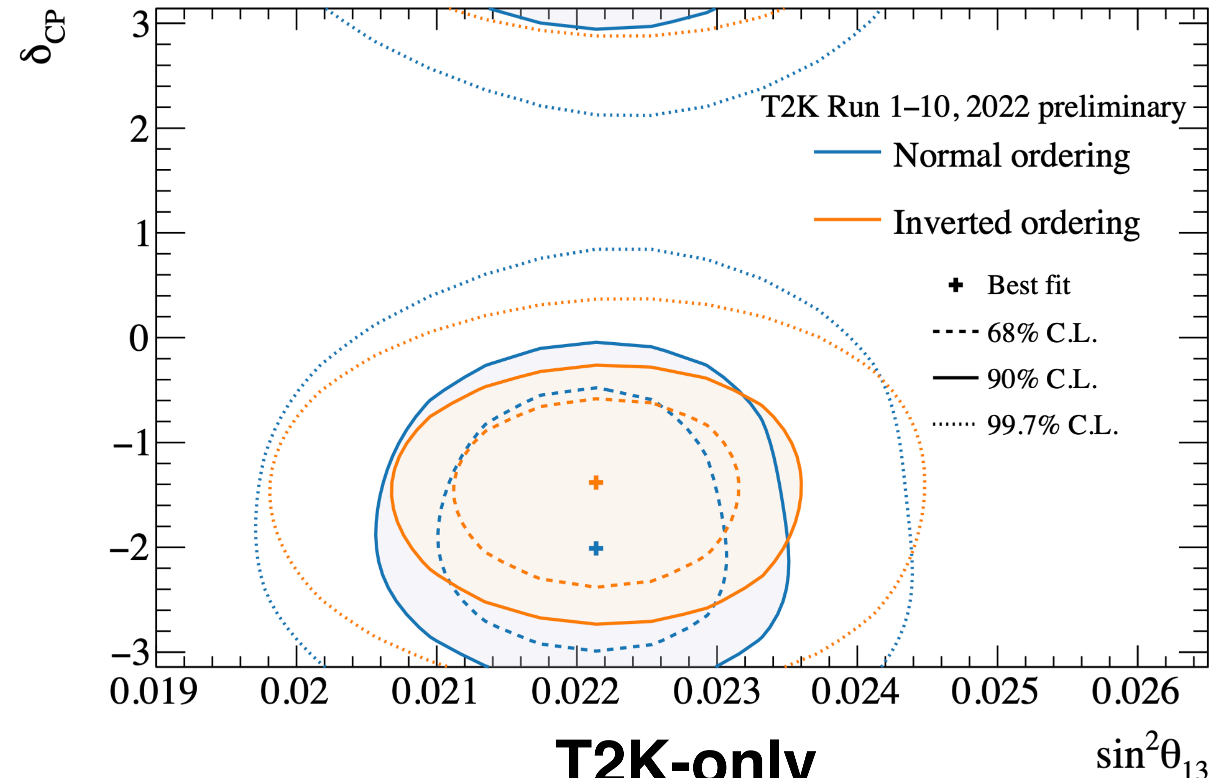


Frequentist results

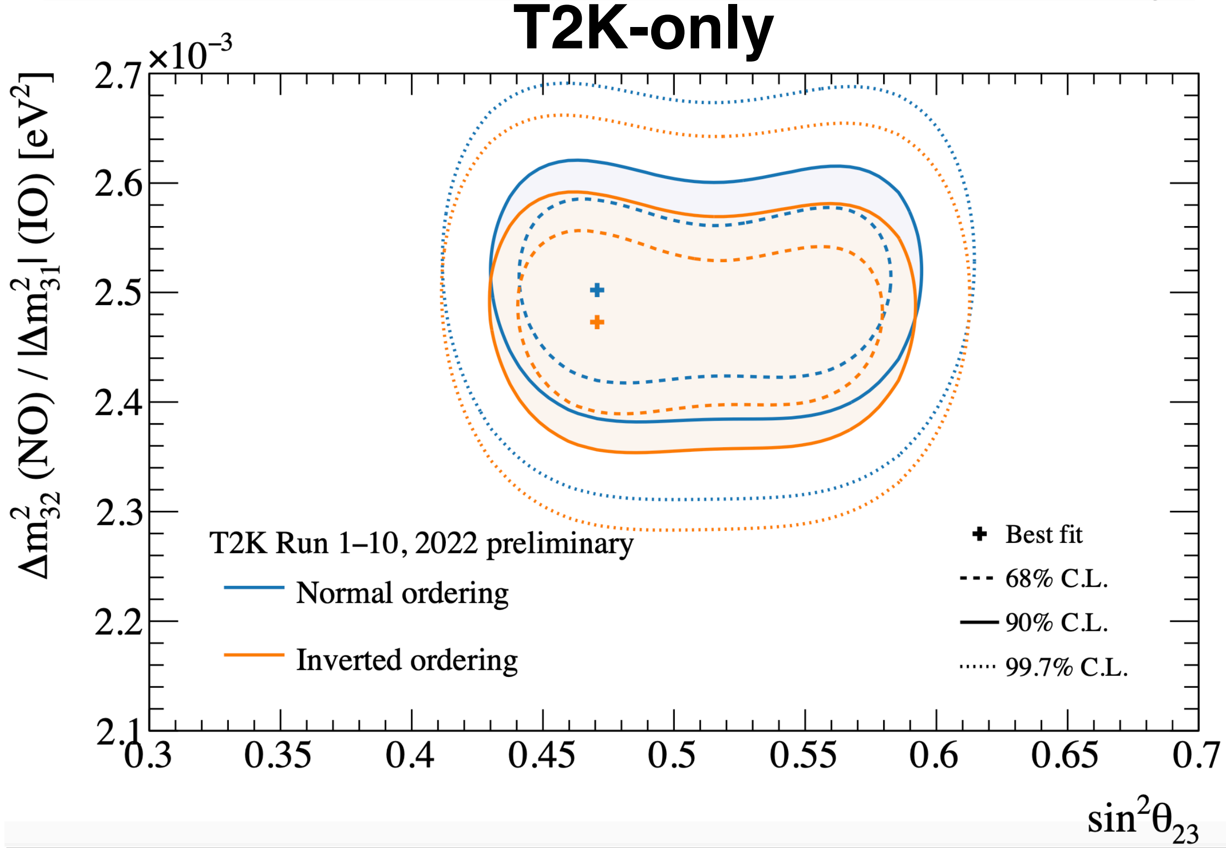
T2K + reactor



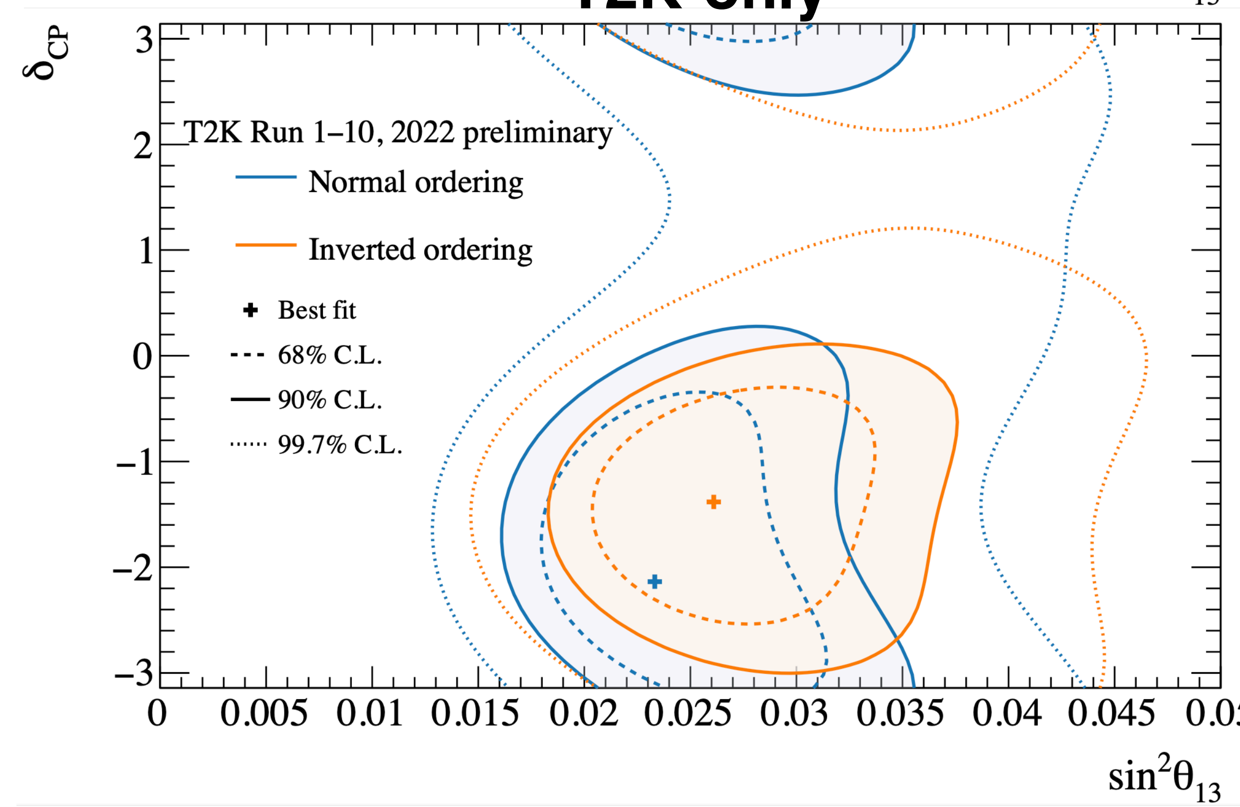
T2K + reactor



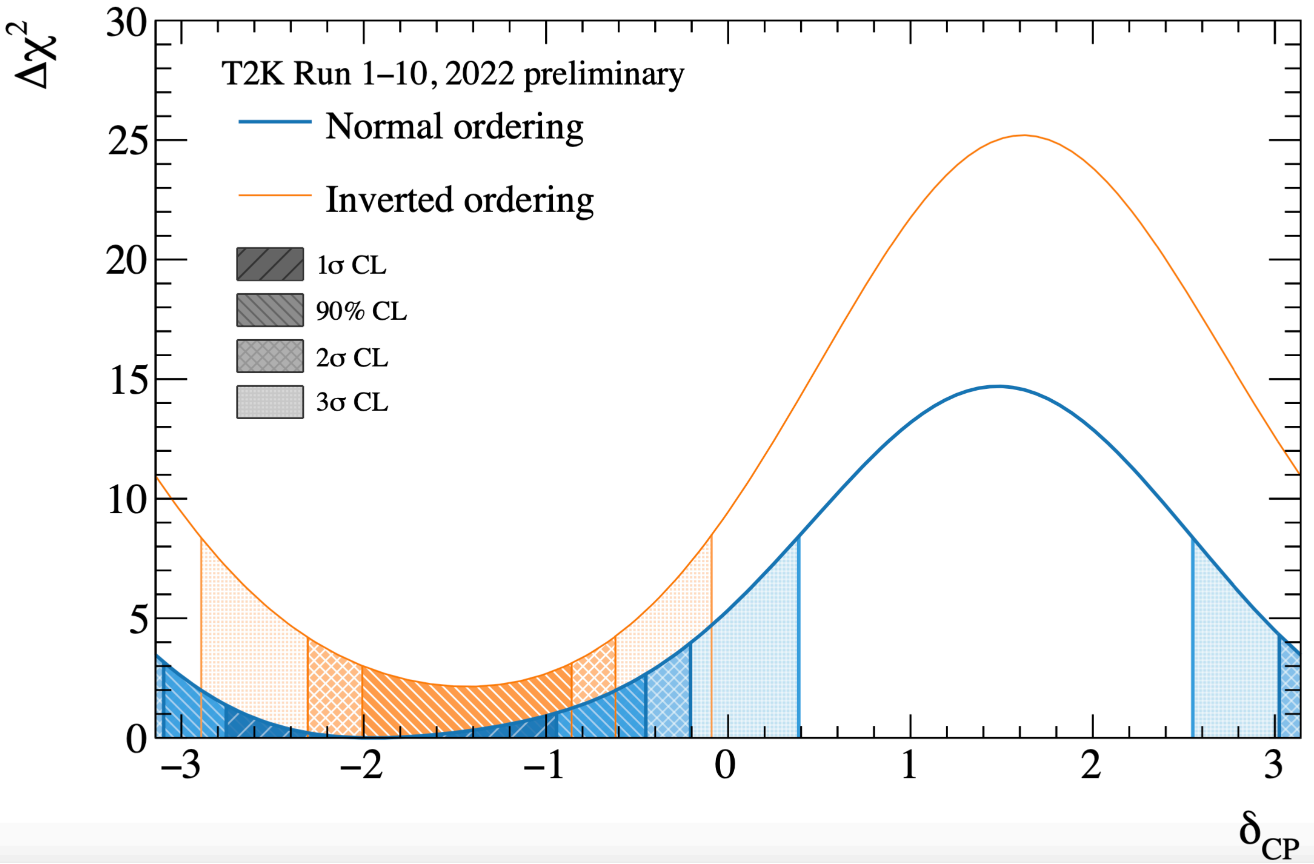
T2K-only

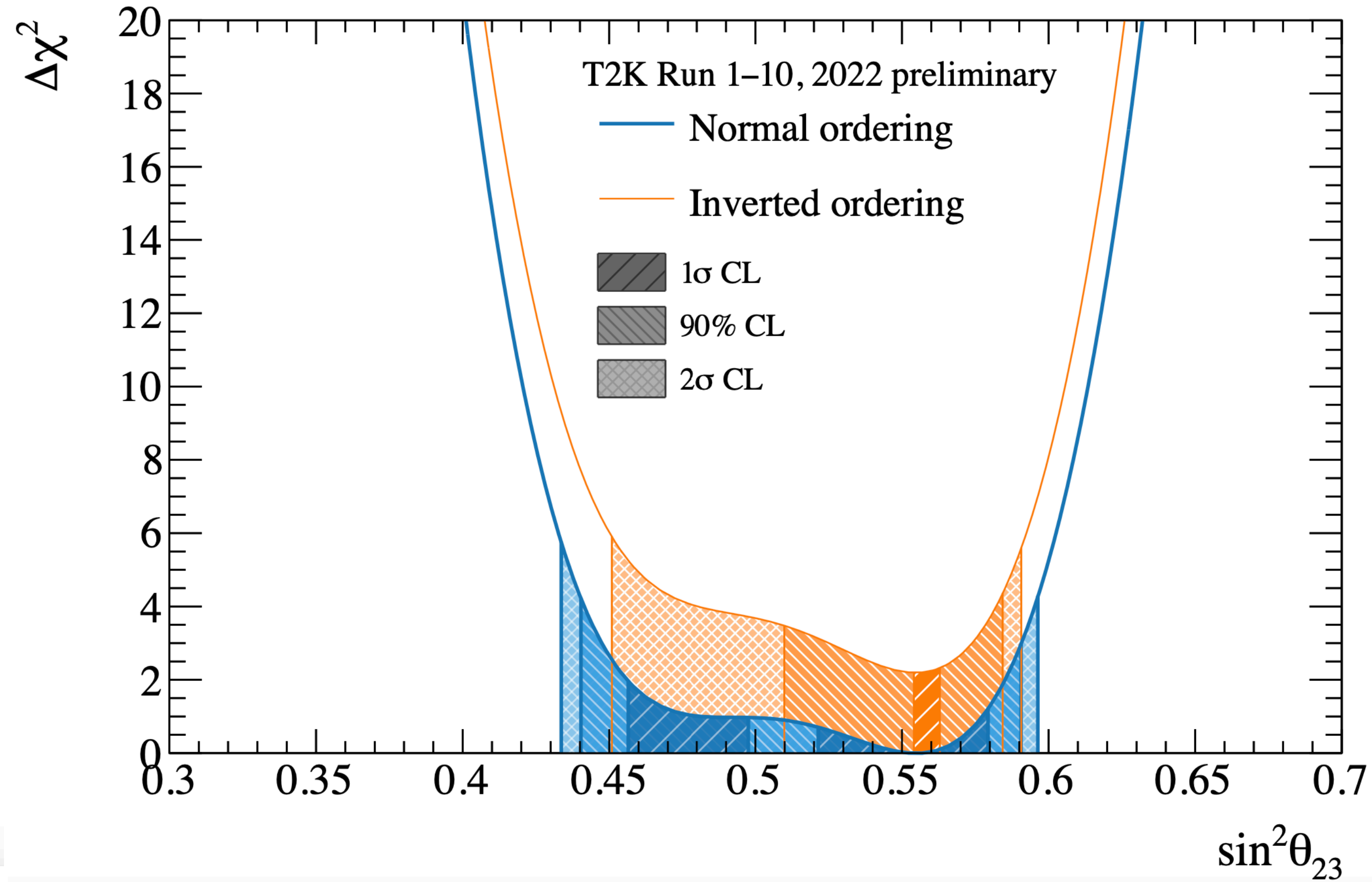


T2K-only

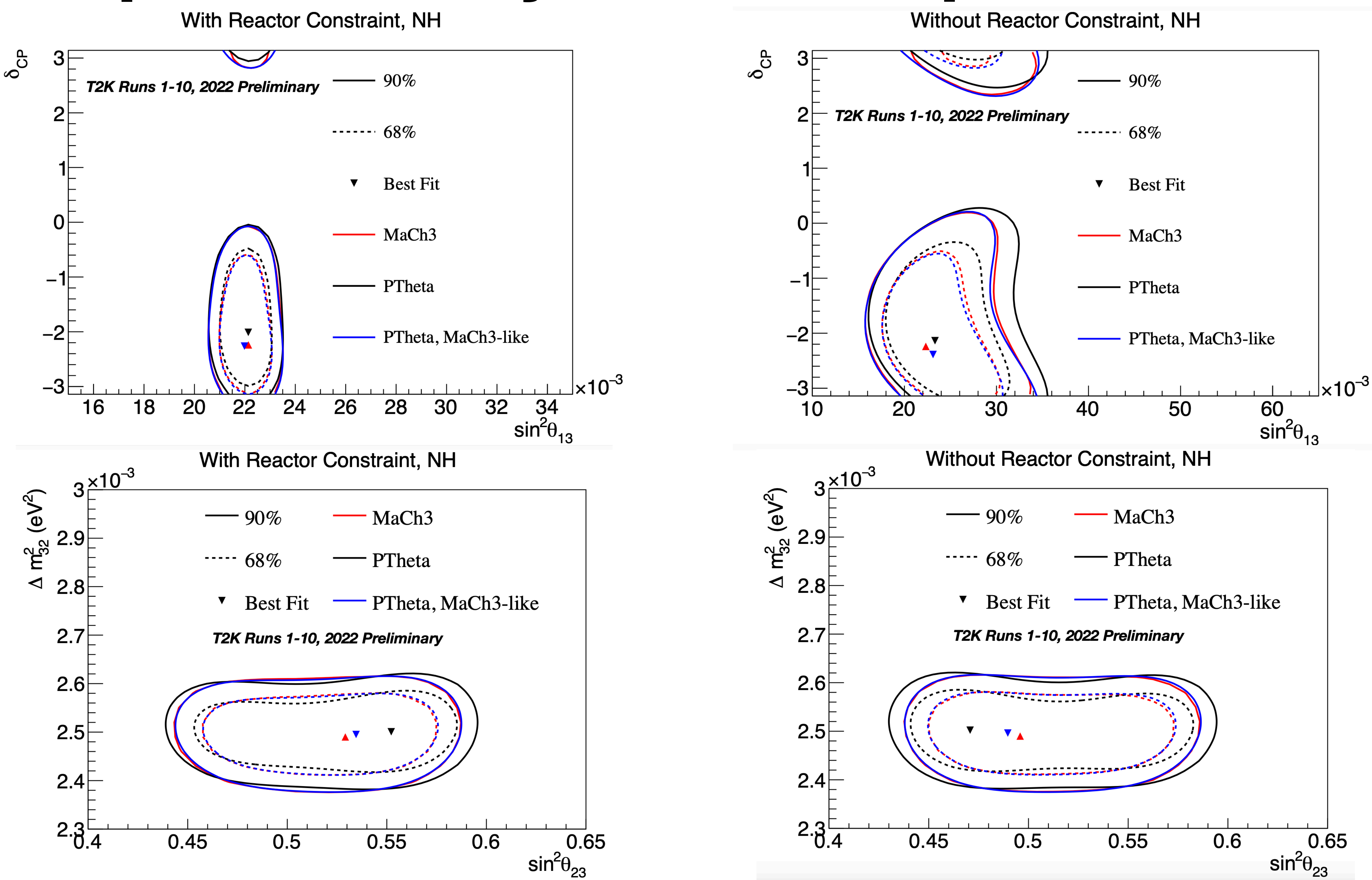


Feldman-Cousins intervals



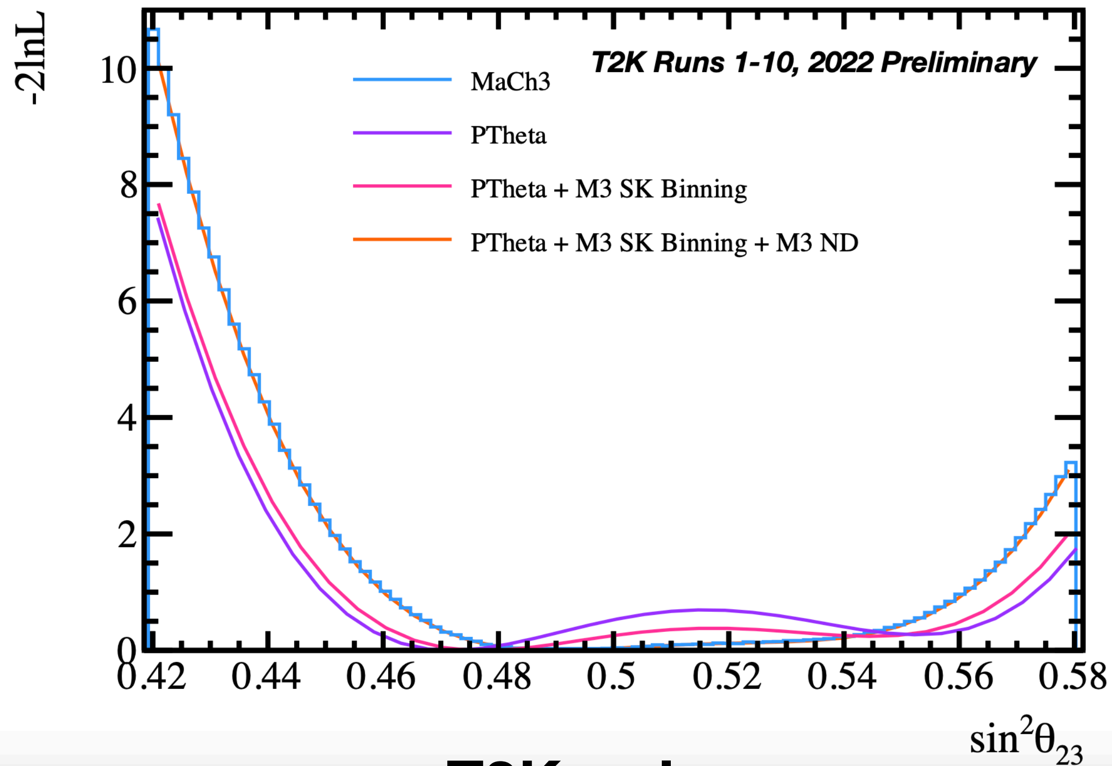


Frequentist-Bayesian comparisons

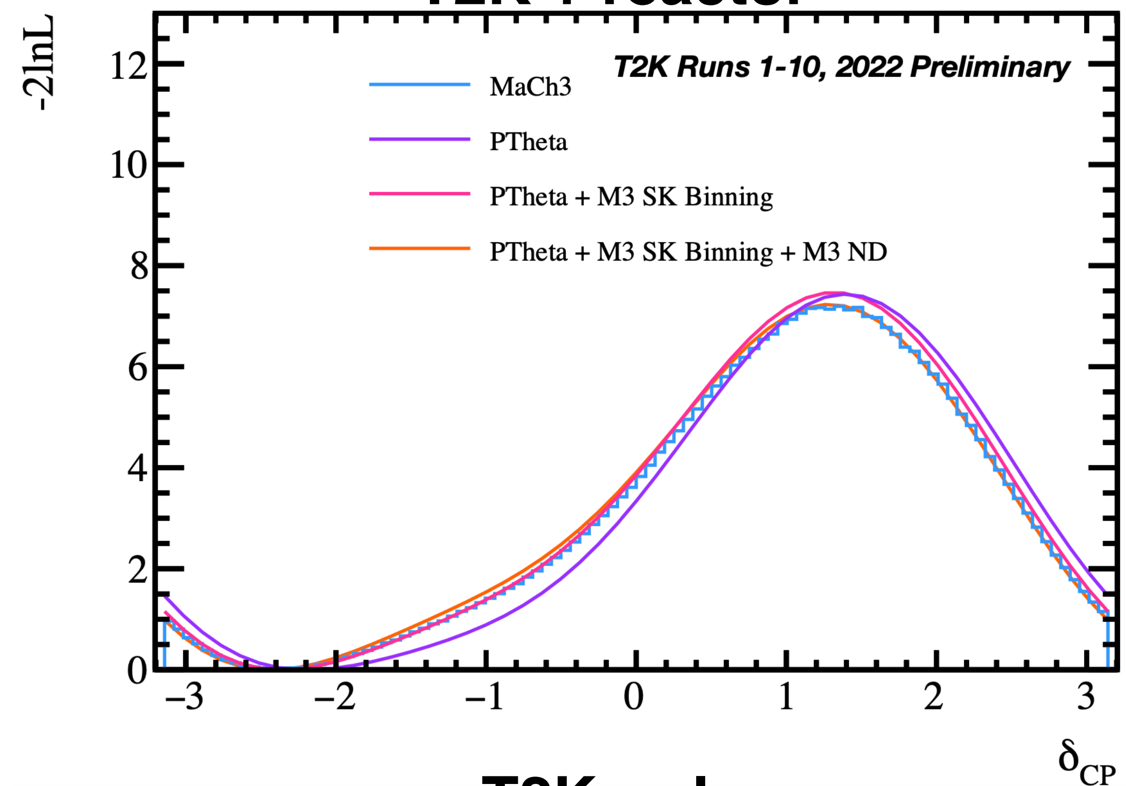


Frequentist-Bayesian comparisons

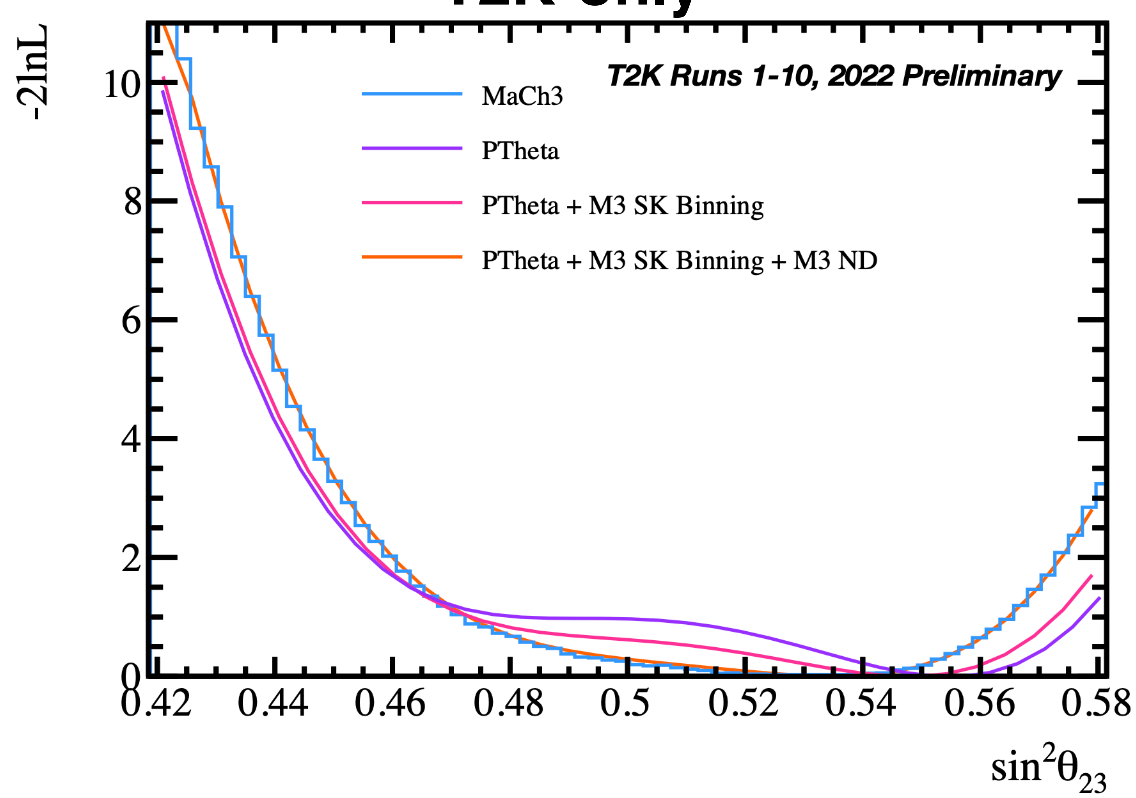
T2K + reactor



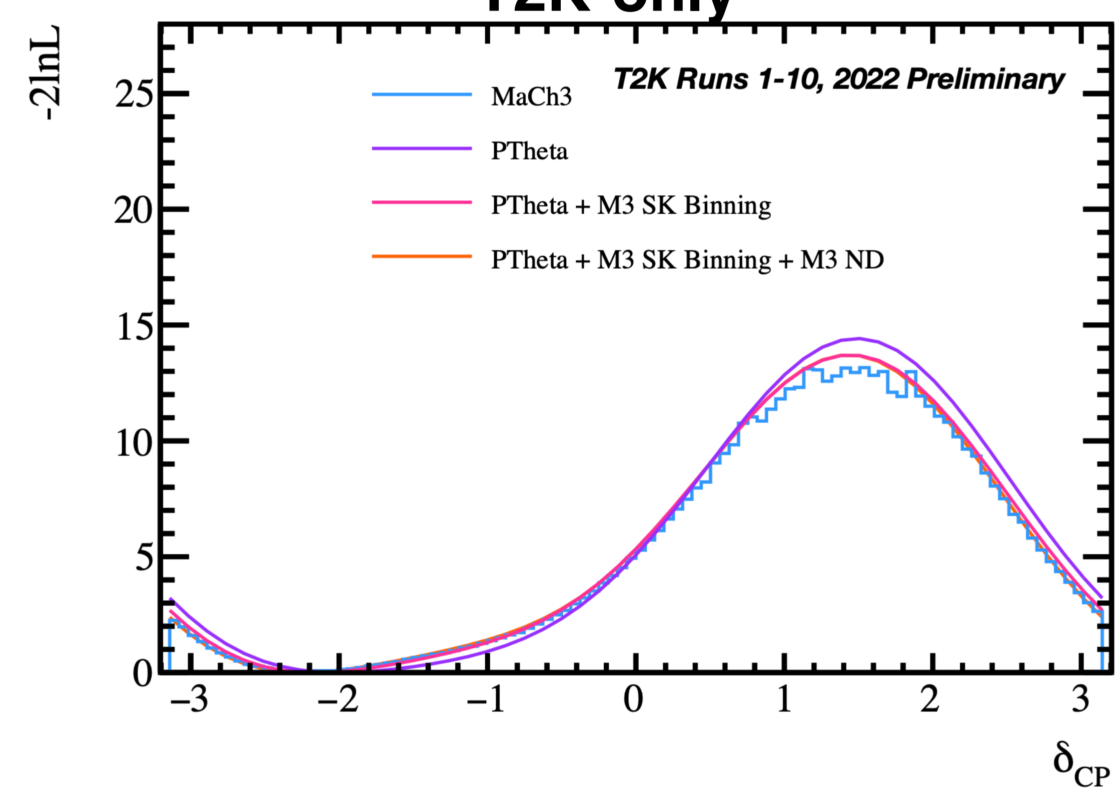
T2K + reactor



T2K-only

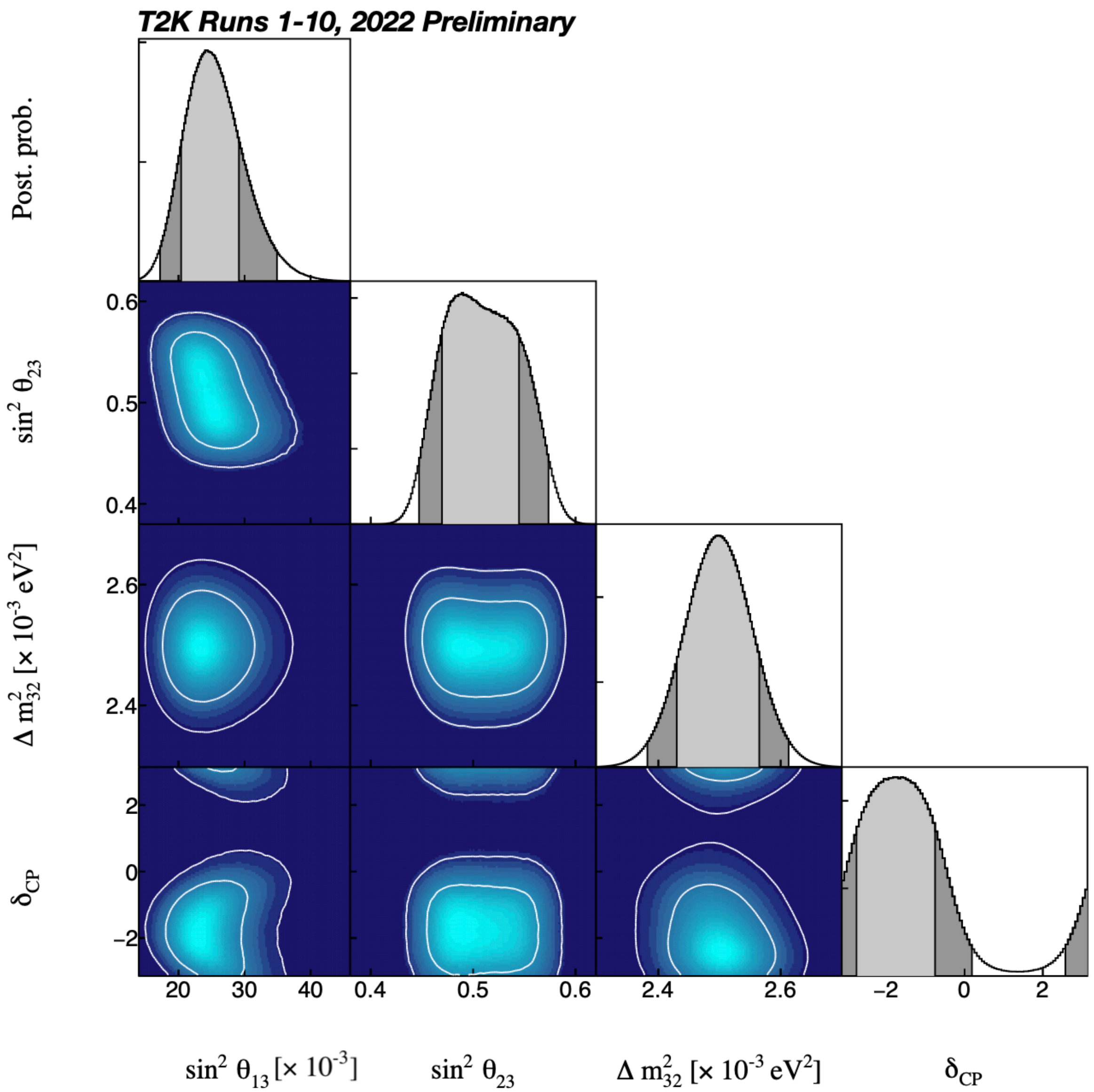


T2K-only

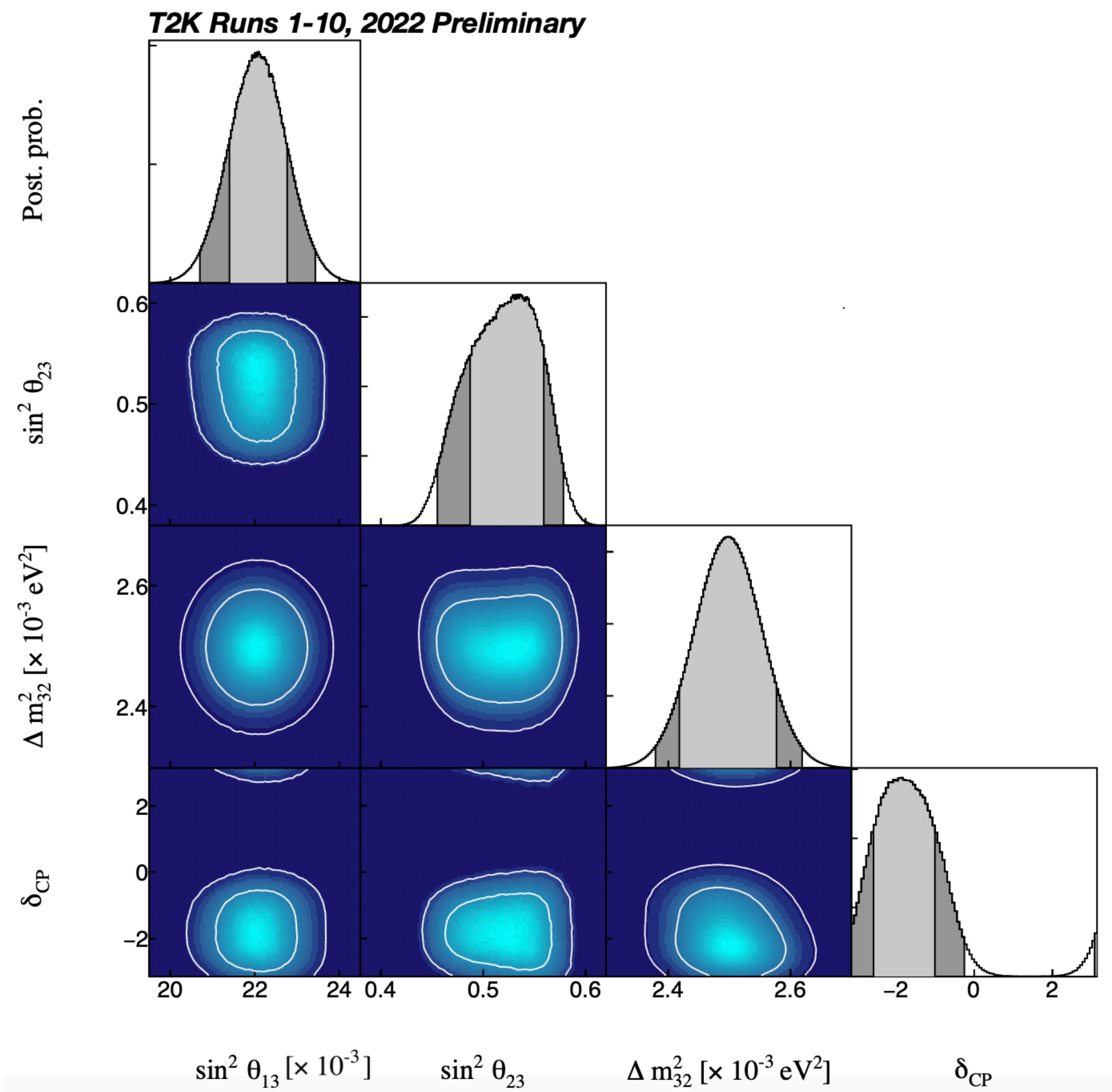


‘Triangle’ posterior plots

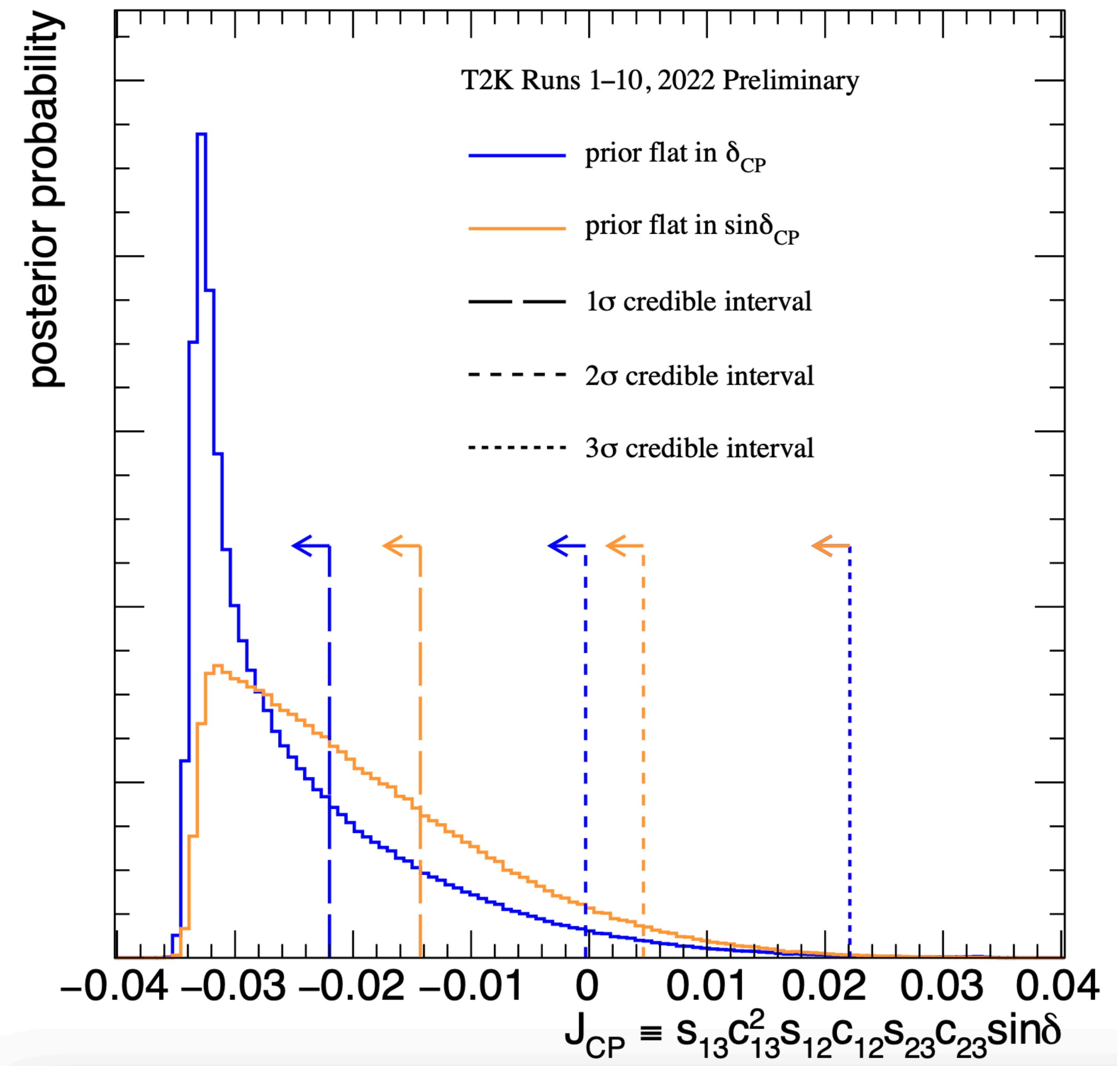
T2K-only



T2K + reactor



Jarlskog Plots (1/2/3 sigma)



Best-fit points, T2K-data only

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.488	2.51
68% C.I. (1σ) range	0.470 – 0.545	-2.58 – -2.51 $\cup$ 2.43 – 2.57
90% C.I. range	0.455 – 0.564	-2.62 – -2.47 $\cup$ 2.40 – 2.60
95.4% (2σ) C.I. range	0.448 – 0.575	-2.65 – -2.45 $\cup$ 2.38 – 2.62
99.73% (3σ) C.I. range	0.429 – 0.594	-2.70 – -2.39 $\cup$ 2.33 – 2.67

	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0235	-1.92
68% C.I. (1σ) range	0.0204 – 0.0291	-2.76 – -0.75
90% C.I. range	0.0181 – 0.0325	-π – -0.13 & 2.95 – π
95.4% (2σ) C.I. range	0.0173 – 0.0348	-π – 0.19 & 2.58 – π
99.73% (3σ) C.I. range	0.0143 – 0.0413	-π – 1.13 & 1.51 – π

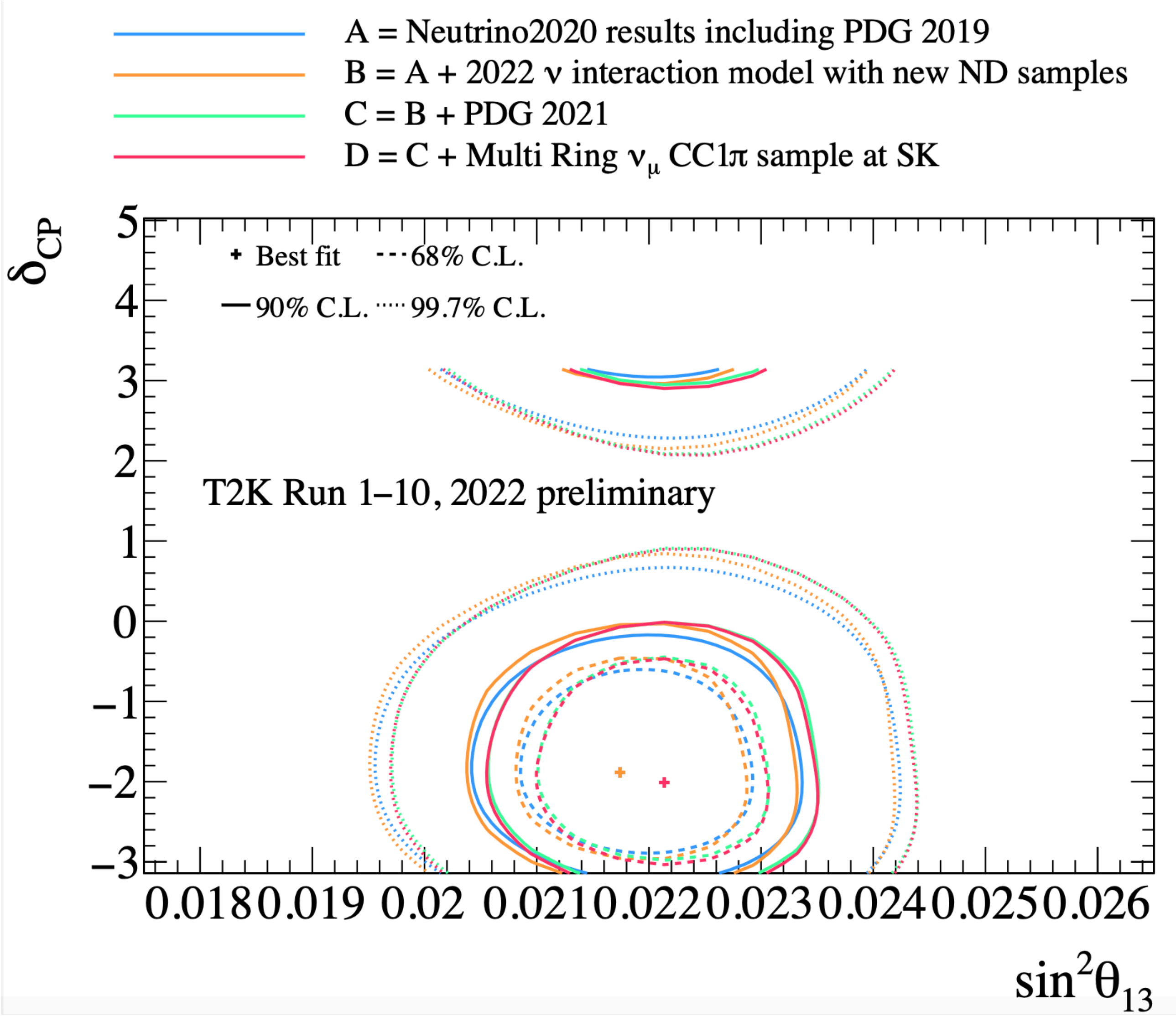
Best-fit points, T2K + reactor constraint

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.531	2.51
68% C.I. (1σ) range	0.489 – 0.560	-2.56 – -2.53 ∪ 2.42 – 2.58
90% C.I. range	0.466 – 0.571	-2.61 – -2.48 ∪ 2.39 – 2.60
95.4% (2σ) C.I. range	0.455 – 0.579	-2.63 – -2.45 ∪ 2.38 – 2.62
99.73% (3σ) C.I. range	0.436 – 0.598	-2.70 – -2.39 ∪ 2.33 – 2.67

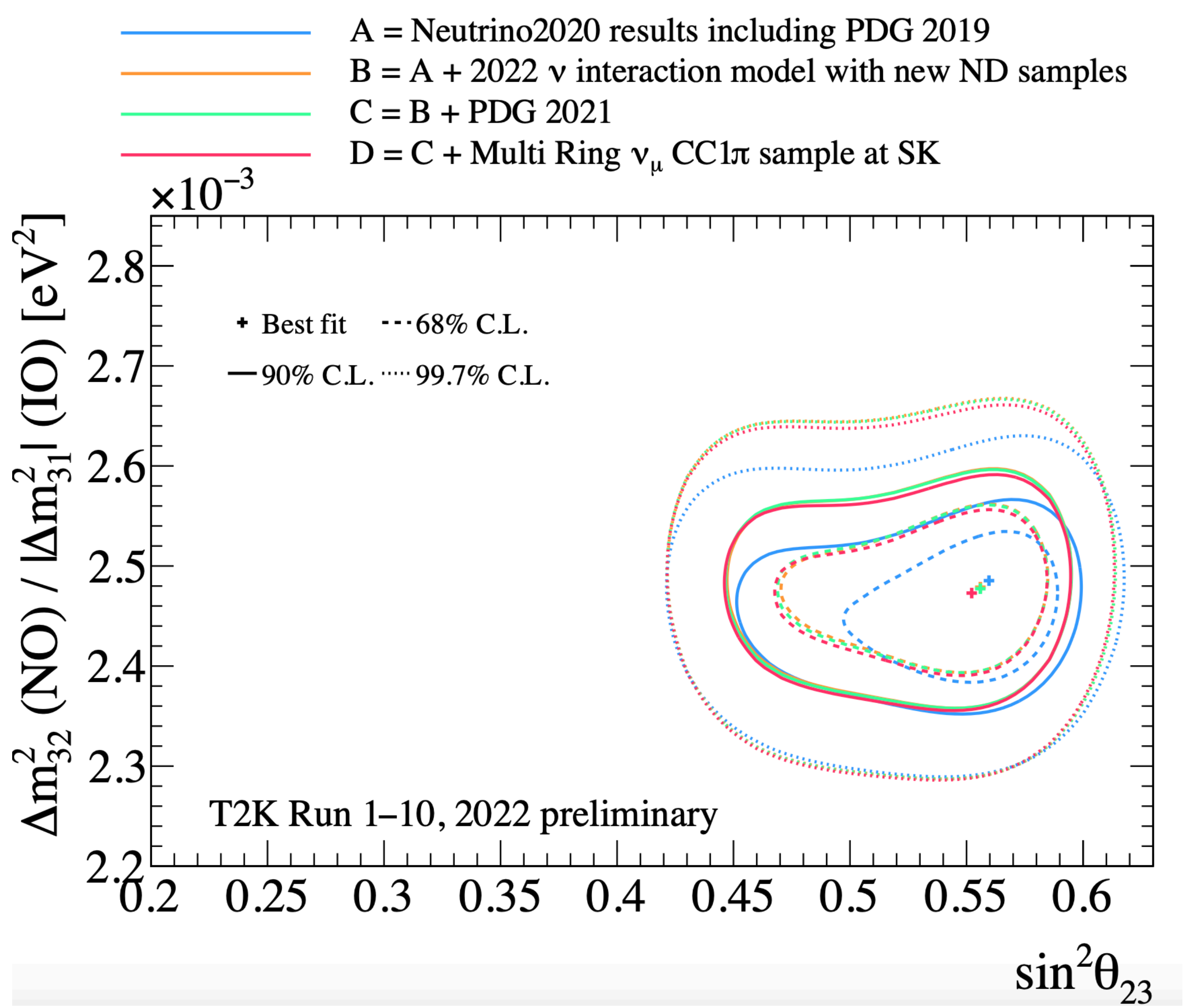
	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0221	−1.84
68% C.I. (1σ) range	0.0214 – 0.0227	-2.58 – -1.01
90% C.I. range	0.0210 – 0.0232	-3.02 – -0.50
95.4% (2σ) C.I. range	0.0207 – 0.0234	$-\pi$ – -0.25 & 3.08 - π
99.73% (3σ) C.I. range	0.0200 – 0.0241	$-\pi$ – 0.50 & 2.39 – π

Comparison to 2020

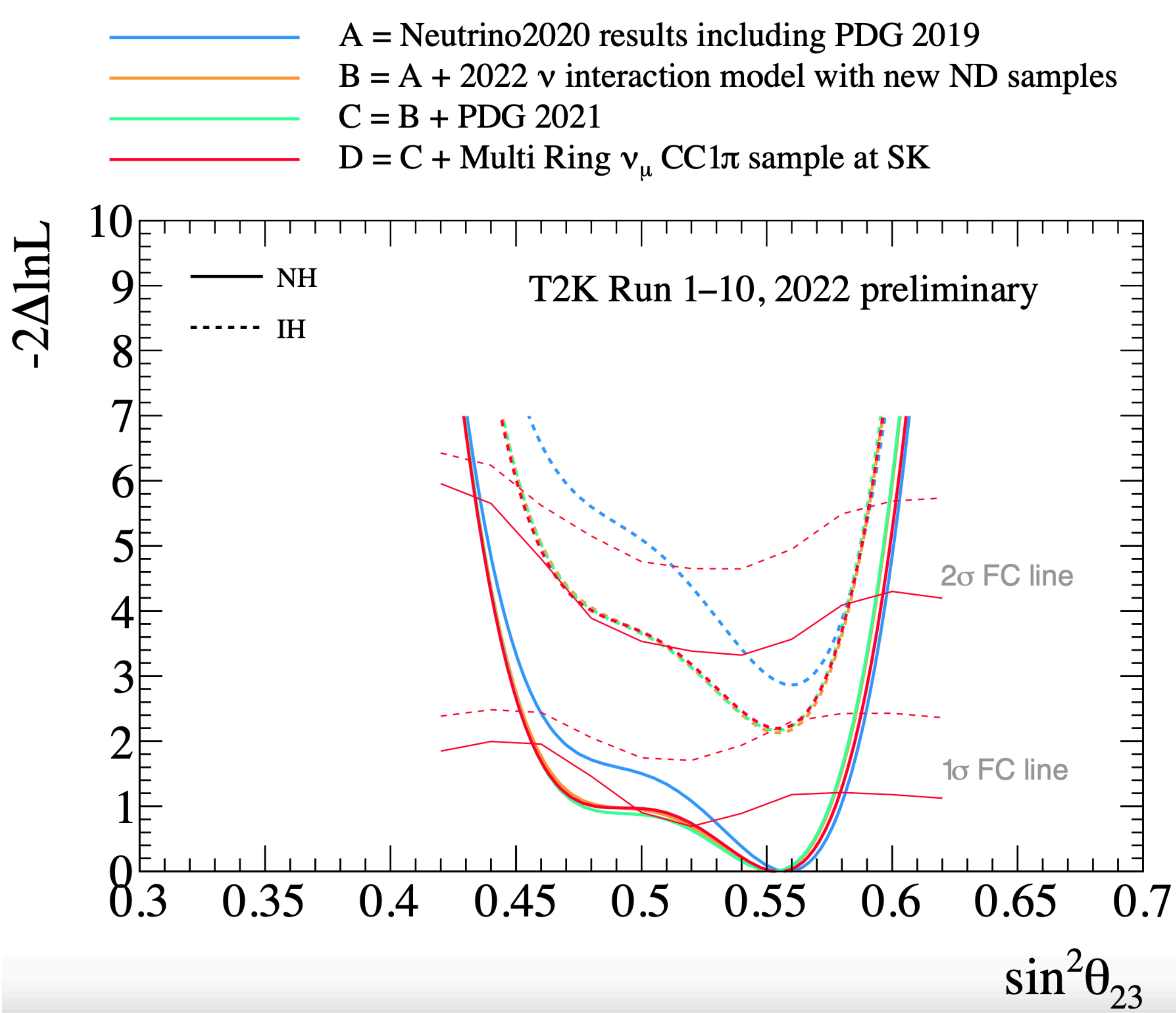
T2K + reactor

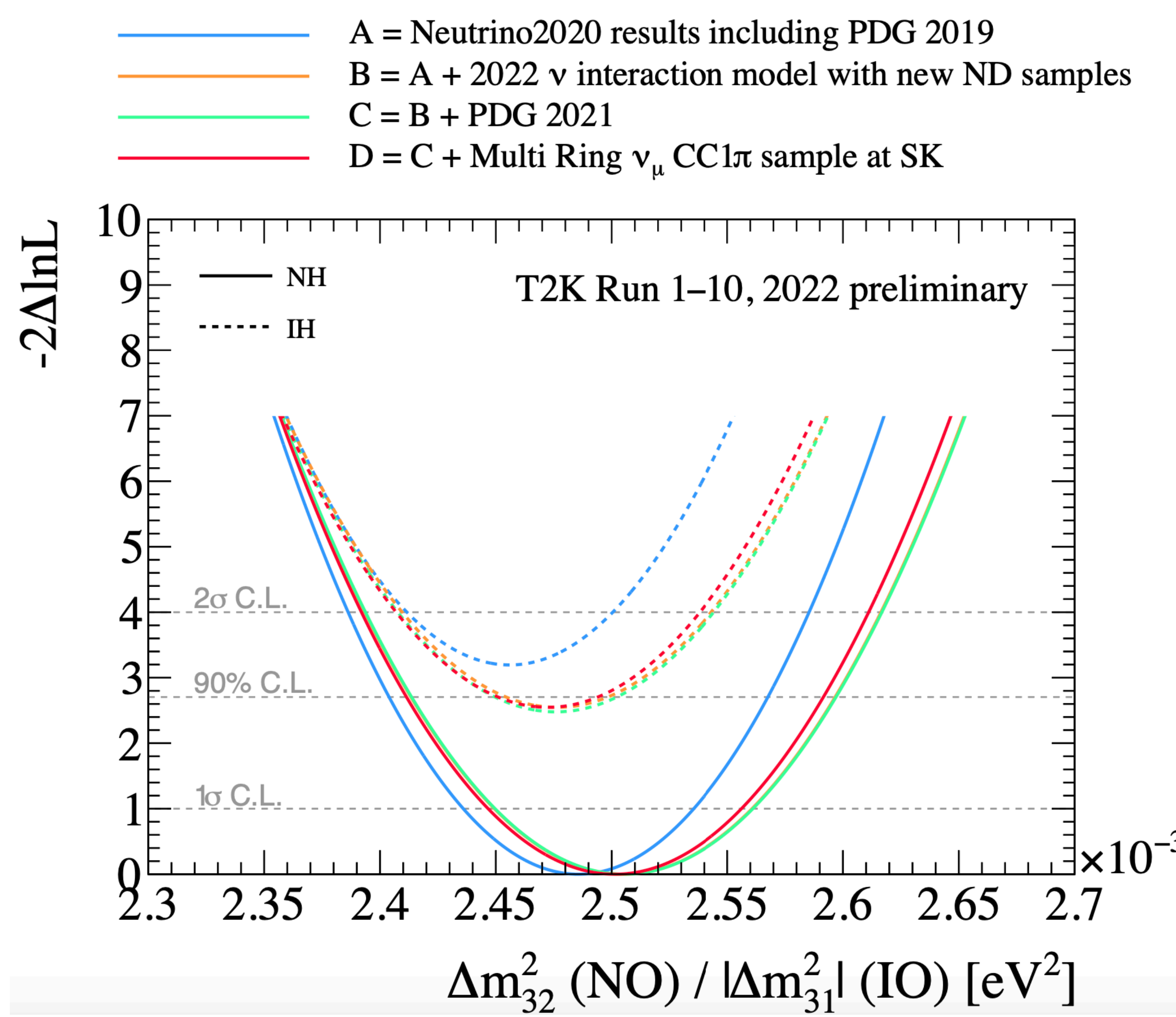


T2K + reactor



Comparison to 2020

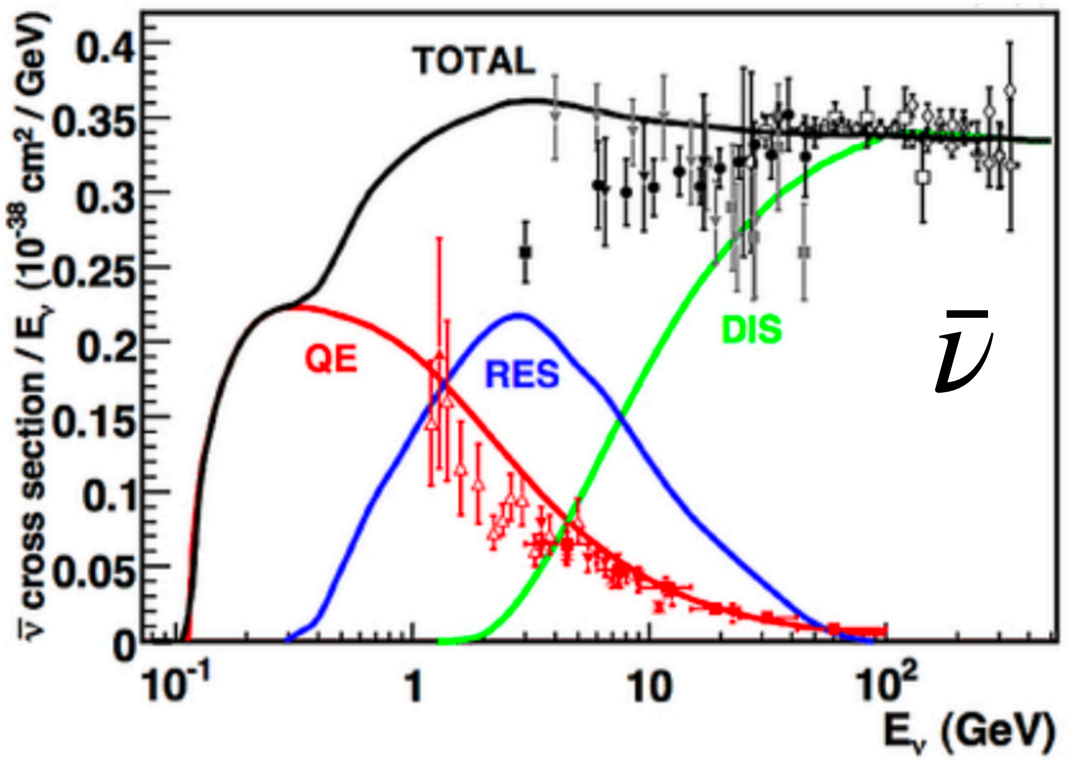


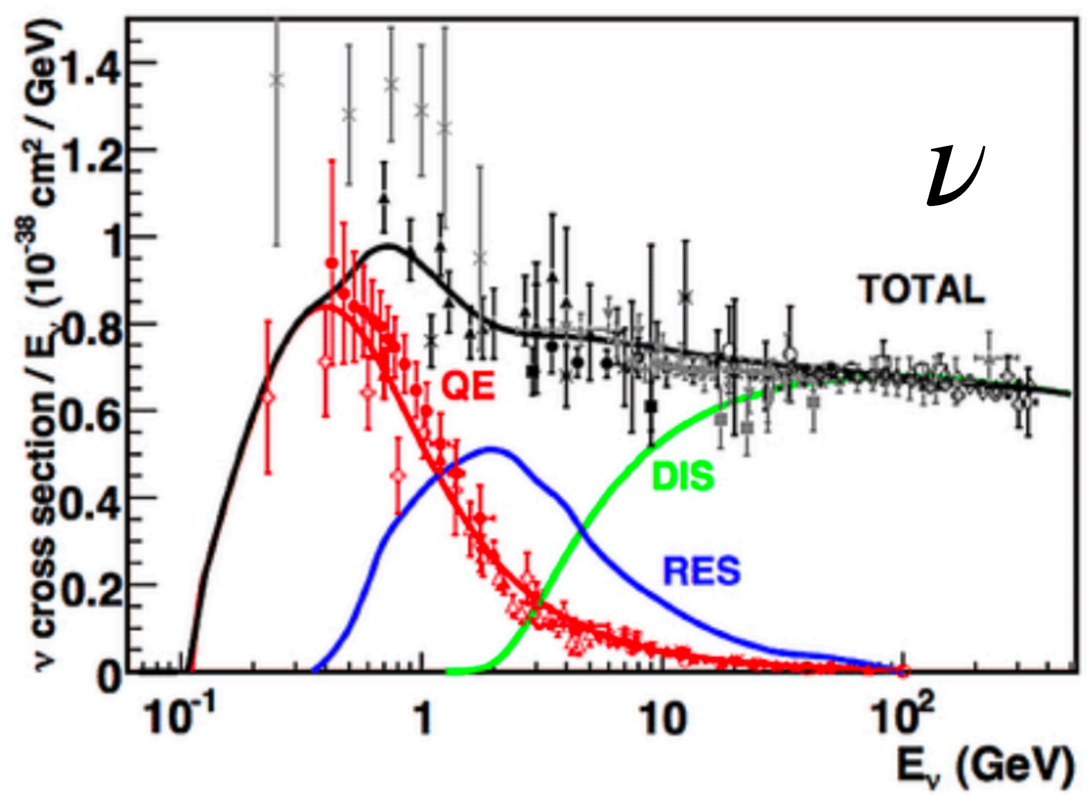


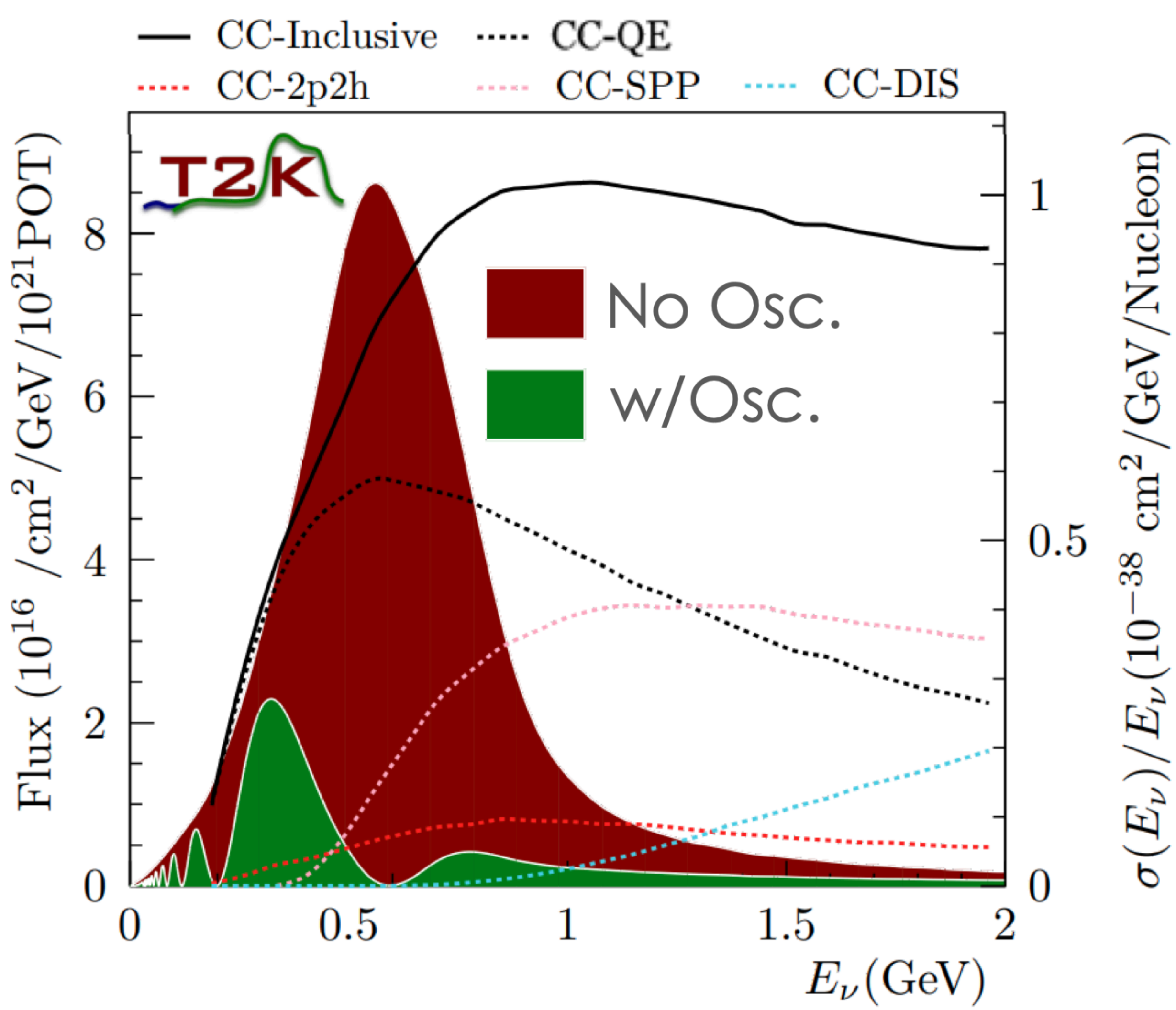
Systematic errors at SK

Error source	FHC1Rμ	RHC1Rμ	FHCν_μCC1π^+	FHC1Re	RHC1Re	FHCCC1π^+
Flux	2.45%	2.81%	2.65%	2.70%	3.00%	2.73%
Cross section	3.34%	4.53%	3.29%	4.44%	5.08%	4.58%
Cross section (ND const.)	2.45%	2.35%	2.14%	3.75%	3.55%	4.01%
2p2h Edep	0.46%	0.47%	0.06%	0.20%	0.22%	0.03%
IsoBkg Low-p$_\pi$	0.45%	3.20%	1.28%	0.08%	2.79%	0.08%
$\sigma(\nu_e)$, $\sigma(\bar{\nu}_e)$	0.00%	0.00%	0.00%	2.56%	1.48%	2.58%
NC γ	0.00%	0.00%	0.00%	1.24%	2.08%	0.00%
NC Other SK	0.21%	0.20%	1.00%	0.17%	0.34%	0.77%
Flux x cross-section	2.40%	3.77%	2.57%	3.73%	4.50%	4.04%
Flux x cross-section (ND const.)	2.45%	2.34%	2.14%	3.75%	3.55%	4.01%
SK det	1.84%	1.59%	3.61%	2.97%	3.52%	11.38%
Total Syst.	2.79%	3.84%	4.14%	4.81%	5.80%	12.09%
Total Inc. Osc.	3.02%	3.85%	4.27%	9.04%	14.60%	13.72%

Neutrino interactions







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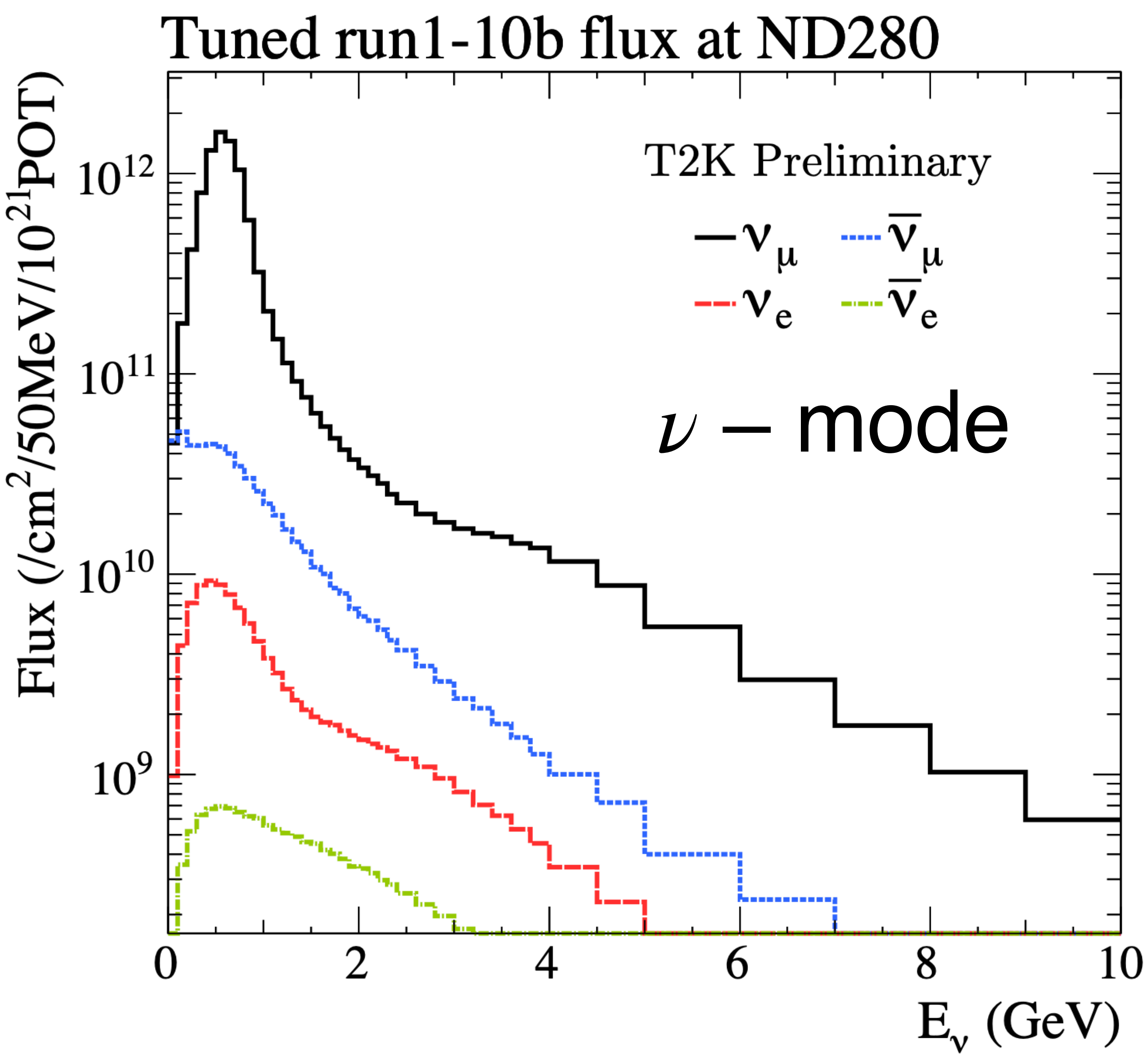
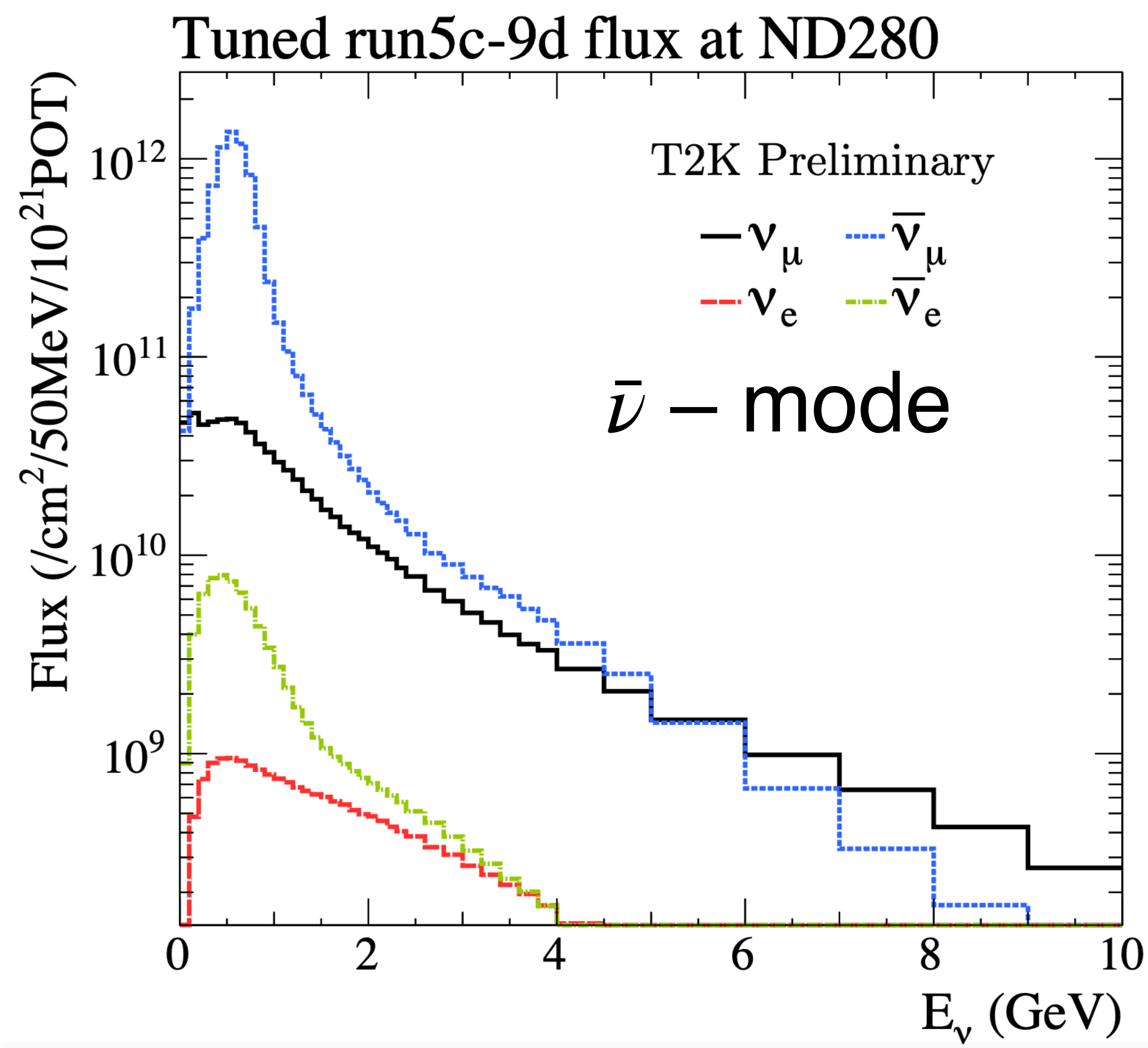
Flux prediction



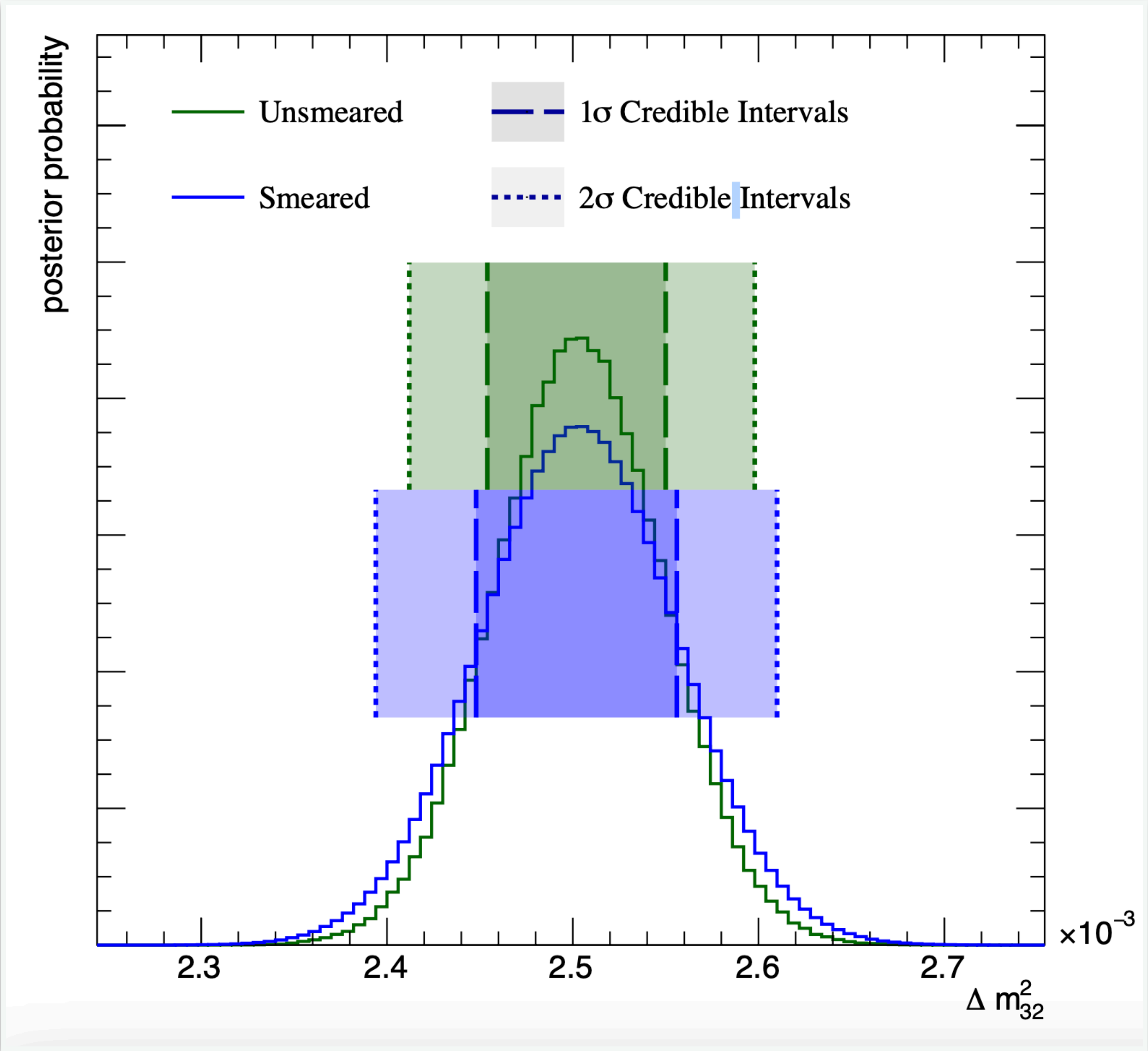


Smearing of Δm^2_{32}

- Common practise on T2K to test alternative interaction models to discover potential biases on oscillation parameters

- If alternative models produce a large bias, we **smear** Δm^2_{32} to include this as an uncertainty

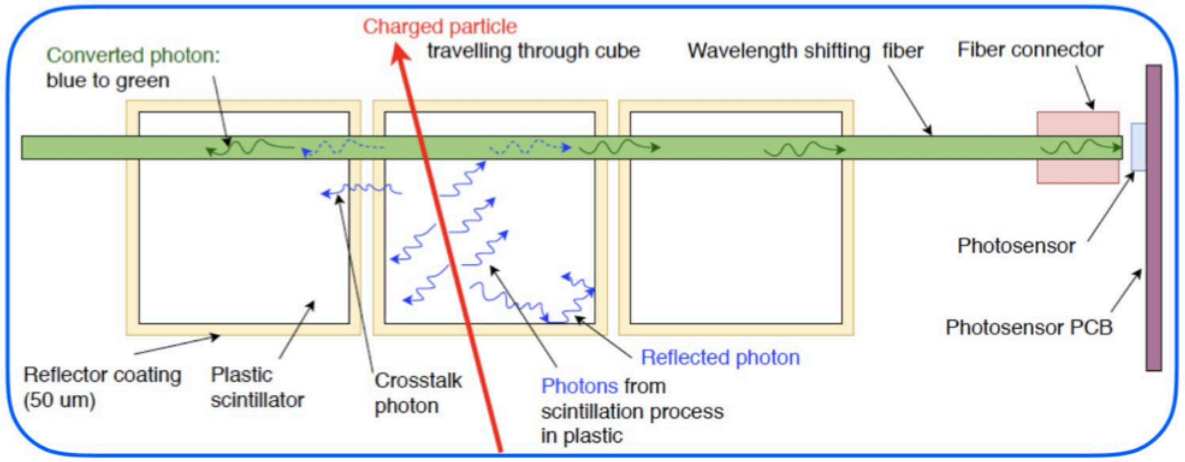
- 2022 results smeared with: $\sigma = 3.10 \times 10^{-5} eV^2$



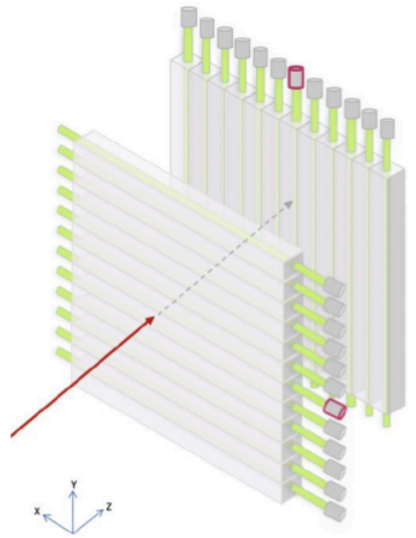
Super-FGD

Super-FGD [JINST 13 P02006 (2018)](#) 14

- ~2 million 1x1x1 cm3 cubes made of plastic scintillator ⟶ ~2 tons
- Cubes covered by reflector will be read out with 3 orthogonal WLS fibres each with MPPC on one end
⟶ total of 56,382 fibers

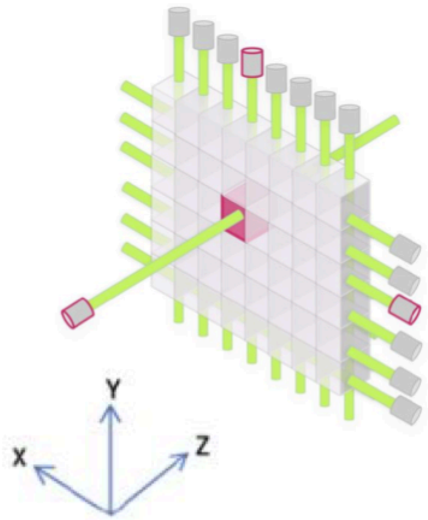


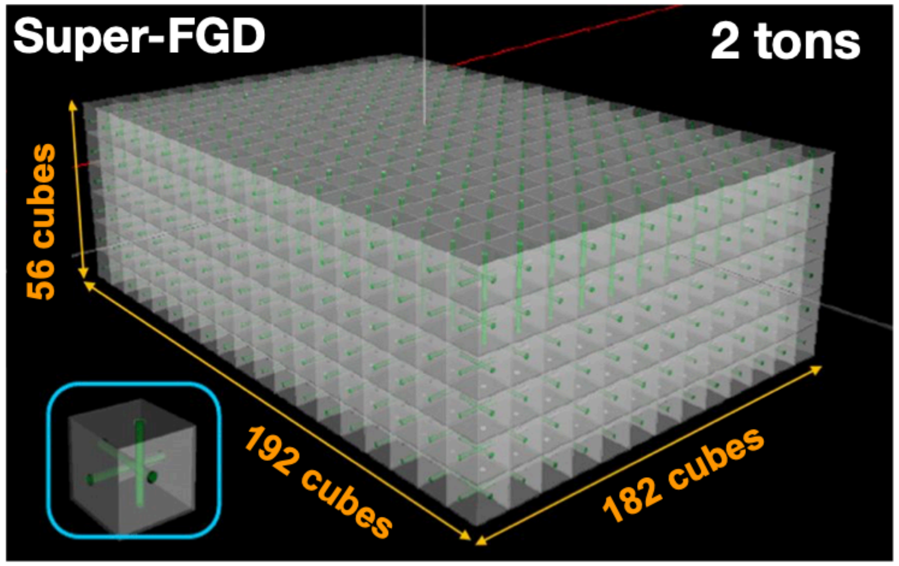
FGD1&2



vs.

Super-FGD





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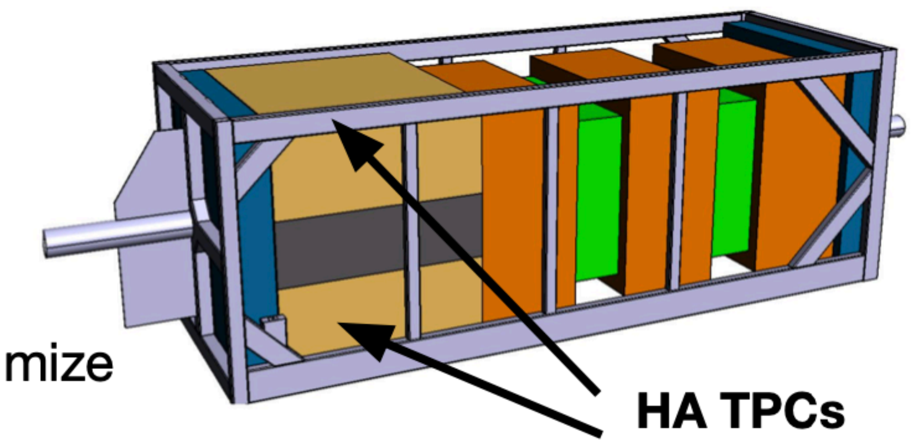
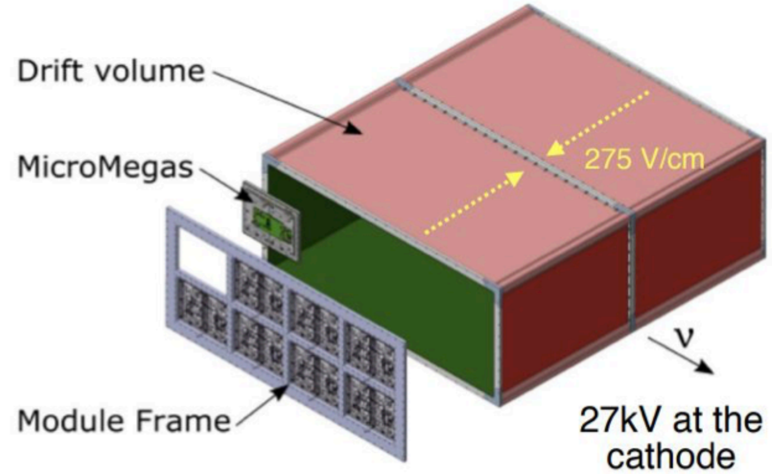
High-angle TPCs

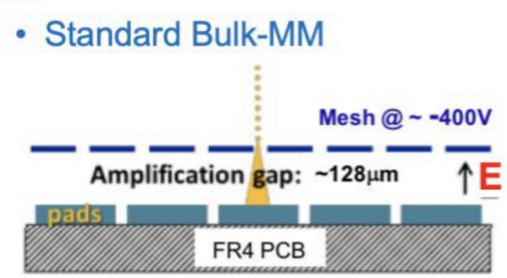
High-Angle Time Projection Chambers

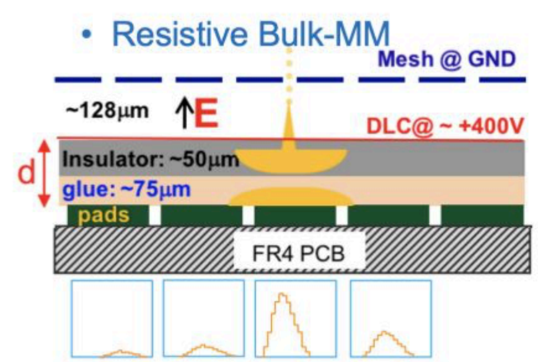
- Two new TPCs will be added:
  - Similar design as current TPCs
  - High resolution tracking and particle identification
- New additions w.r.t. current TPC design:
  - New field cage design to minimize dead space and maximize the tracking volume





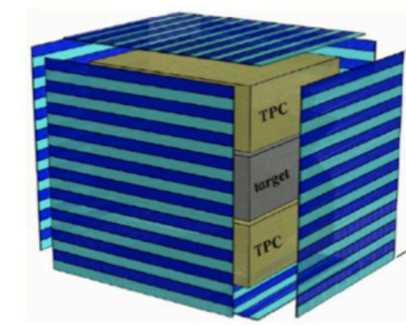
  - Replace the standard bulk-MicroMegas with new resistive MicroMegas Modules:
    - Signal induced on multiple pads thanks to the resistive layer
      → better spatial resolution with less pads



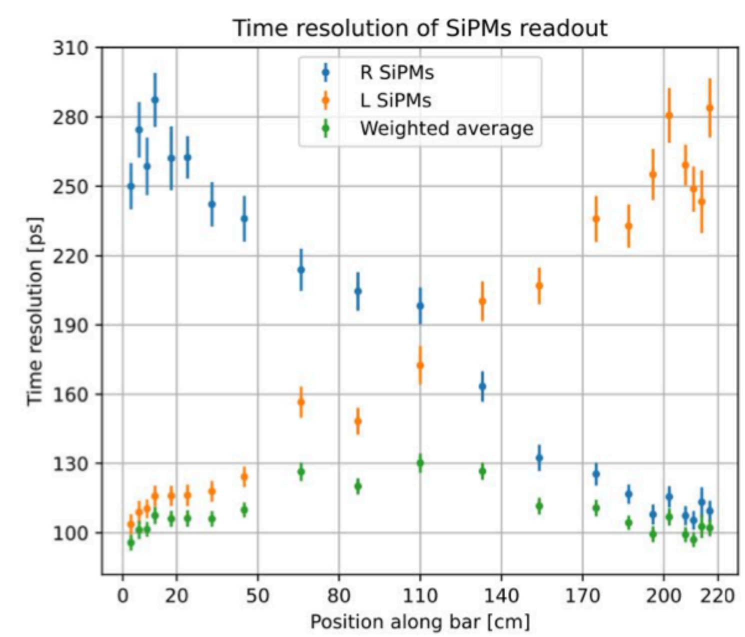


TOF

Time-of-Flight (ToF) detector [JPS Conf. Proc. 27, 011005 (2019)] 28



- 6 ToF planes fully covering the 2 HA-TPC and Super-FGD
  - Each plane of consists of 20 scintillator bars (EJ200)
  - Readout with 16 MPPCs at both ends of each bar
  - Fully built and tested, currently finalizing DAQ
- **Goals:**
  - <u>precisely measure the **crossing time** of charged particles</u>
  - ↪ Separate inward going background from products of neutrino interactions in fiducial volume
  - ↪ Can be used as cosmic trigger for the calibration of Super-FGD and HA-TPCs
  - ↪ Could also improve particle identification with timing information
- **Performances:**
  - Excellent timing resolution ~ 130 ps



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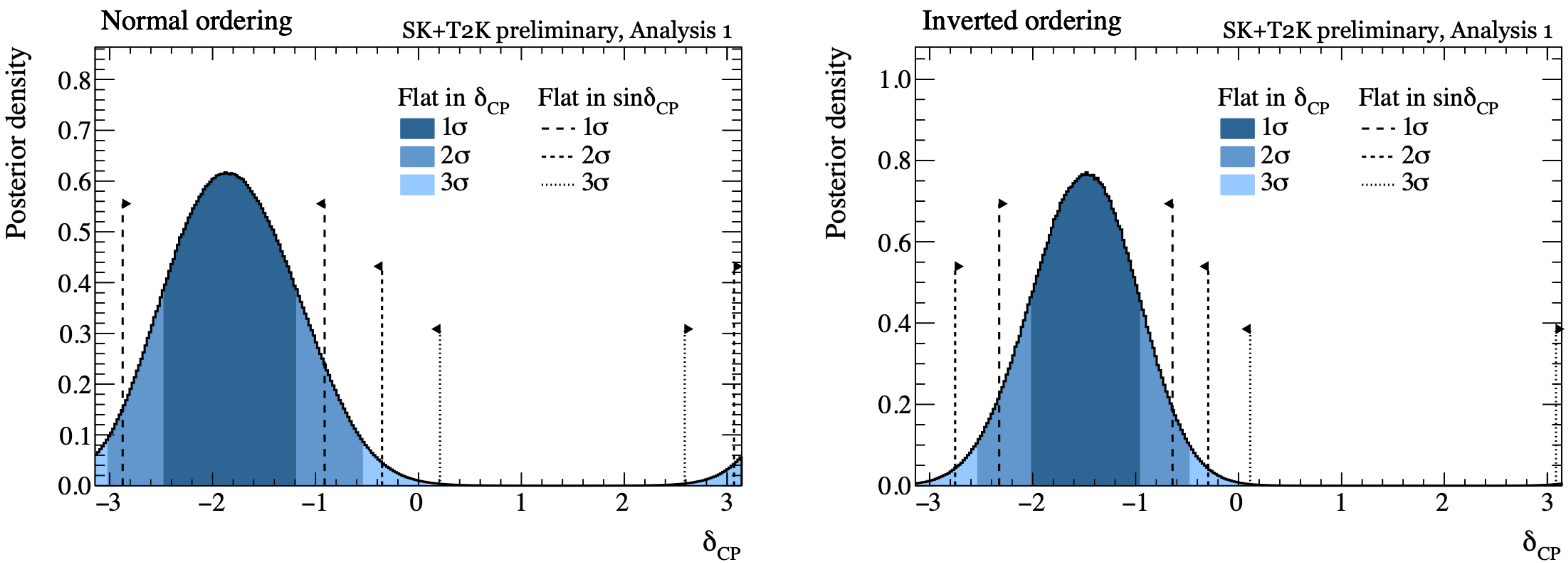
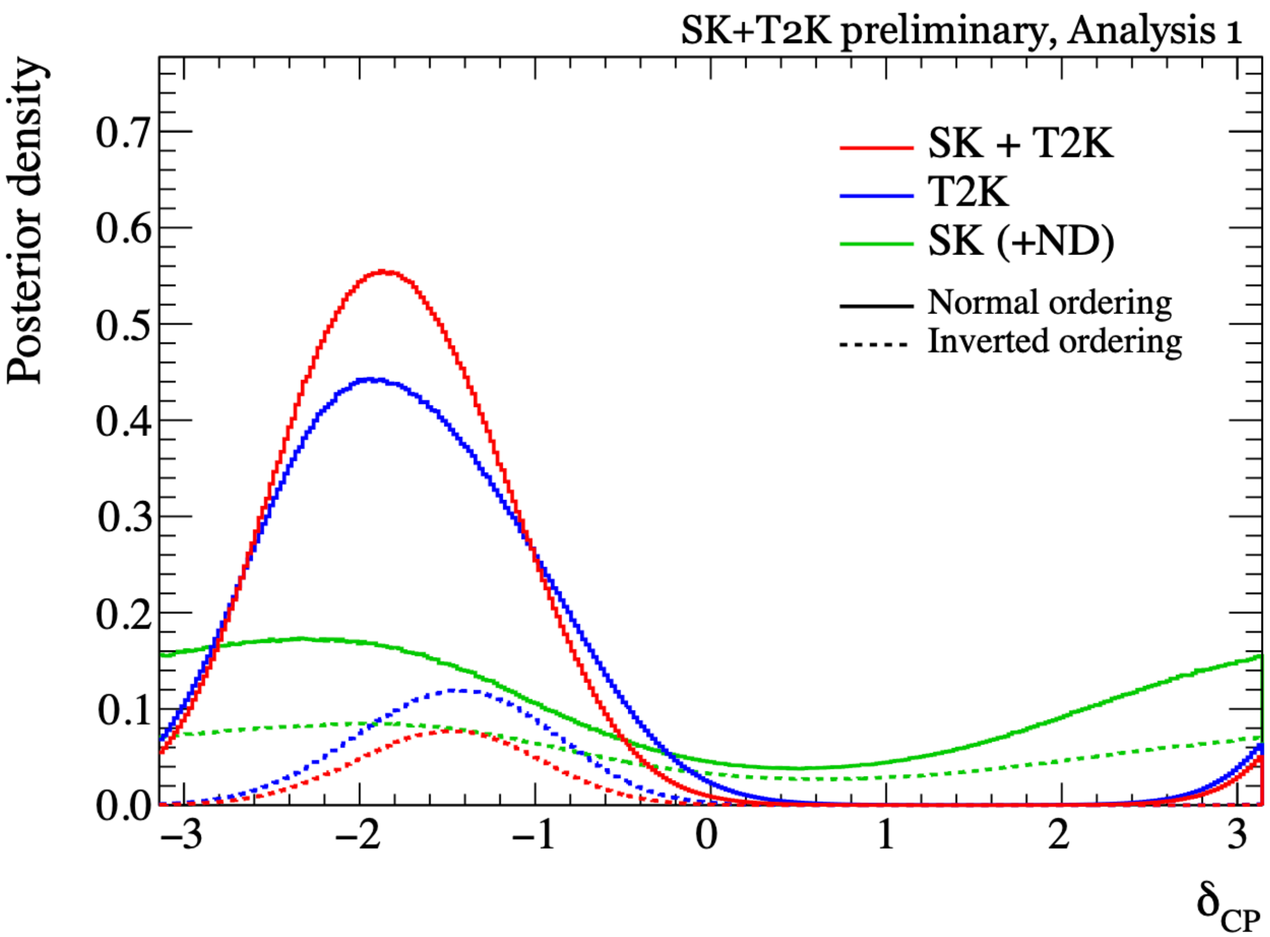
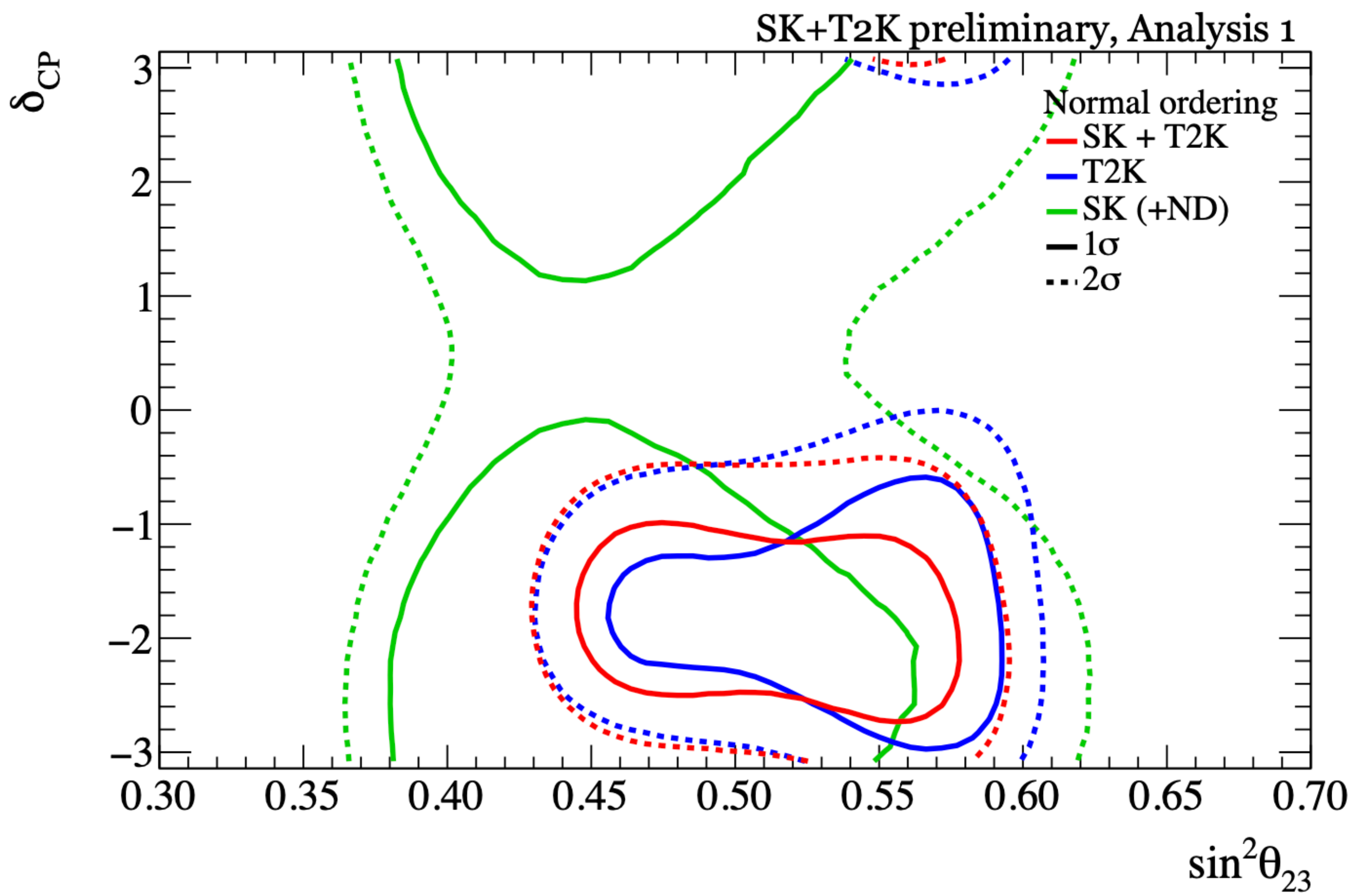
T2K-SK δ_{CP} results

δ_{CP} posterior distributions with reactor constraint



T2K-SK δ_{CP} results





T2K-SK δ_{CP} results

Main Conclusion on CP Symmetry

- The table below summarizes the conclusion on CP symmetry from different analyses.
  - Based on this, we concluded that **CP conservation ($\delta_{CP} = 0, \pi$, $J_{CP} = 0$) is excluded around** 2σ when the reactor constraint is applied.

SK+T2K preliminary

Analysis	Prior	CP conserving value	1σ	90%	2σ	3σ
Analysis 1	Flat in δ_{CP}	$\delta_{CP} = 0, \pi$	✓	✓	✓	×
		$J_{CP} = 0$	✓	✓	✓	×
	Flat in $\sin\delta_{CP}$	$\delta_{CP} = 0, \pi$	✓	✓	×	×
		$J_{CP} = 0$	✓	✓	✓	×
Analysis 2	Flat in δ_{CP}	$\delta_{CP} = 0, \pi$	✓	✓	✓	×
		$J_{CP} = 0$	✓	✓	✓	×
	Flat in $\sin\delta_{CP}$	$\delta_{CP} = 0, \pi$	✓	✓	×	×
		$J_{CP} = 0$	✓	✓	✓(×)	×

✓: excluded ×: not excluded ✓(×): excluded but may not be robust against the possible bias from an out-of-model effect

A. Eguchi SK+T2K joint analysis NNN23 @ Procida Wednesday, 11th October, 2023 52