T2K Neutrino Oscillation Analysis

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On behalf of the T2K collaboration

Accelerator-neutrino oscillations

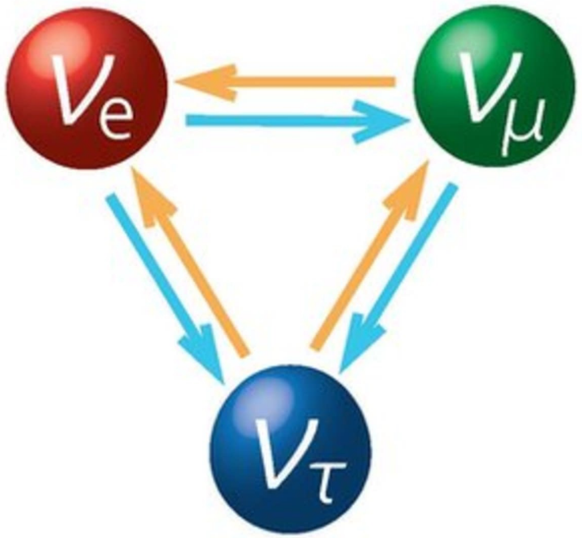
Neutrino oscillations

Flavour eigen values	"Participate" in interaction		"Participate" in propagation	Mass eigen values

$$\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \longleftrightarrow \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

$\boldsymbol{U_{PMNS}}$ parametrizes the neutrino flavour mixing and along with $\boldsymbol{\Delta m^2_{32} := m^2_3 - m^2_2}$ and $\boldsymbol{\Delta m^2_{12} := m^2_2 - m^2_1}$ **quantifies** the **neutrino oscillations:**

Neutrinos created with a specific lepton flavor can later be measured to have a different flavor.



Neutrino oscillations

1σ	Best fit
2.4%	33.4°

θ_{12}

1σ	Best fit
2.9%	UO: 48.9°
2.3%	LO: 43.5°

θ_{23}

1σ	Best fit
2.3%	7.53×10^{-5} eV^2/c^4

Δm^2_{12}

1σ	Best fit
1.7%	2.55×10^{-3} eV^2/c^4

$|\Delta m^2_{32}|$

1σ	Best fit
1.6%	8.5°

θ_{13}

?

δ_{CP}

?

MO

$\mathrm{sign}(\Delta m^2_{32})$

Oscillation probability $= P(\text{osc. params}; L/E)$,

L −oscillation distance, E −neutrino energy

Experiments with different L/E are necessary to measure different parameters

Accelerator neutrino oscillations

Accelerator neutrino experiment

Accelerator neutrino oscillations

Accelerator neutrino experiment

Enhanced muon neutrino beam

Two modes: ν_μ and $\bar{\nu}_\mu$

$L/E \sim 0.5$ km/MeV

Accelerator neutrino oscillations

Accelerator neutrino experiment

Enhanced muon neutrino beam

Two modes: ν_μ and $\bar{\nu}_\mu$

$L/E \sim 0.5$ km/MeV

Four channels are measured:
- $\nu_\mu(\bar{\nu}_\mu)$ survival
- $\nu_e(\bar{\nu}_e)$ appearance

Accelerator neutrino oscillations

Accelerator neutrino experiment

Enhanced muon neutrino beam

Two modes: ν_μ and $\bar{\nu}_\mu$

$L/E \sim 0.5$ km/MeV

Four channels are measured:
- $\nu_\mu(\bar{\nu}_\mu)$ survival
- $\nu_e(\bar{\nu}_e)$ appearance

These can be measured

θ_{13}

θ_{23}

MO

$\mathrm{sign}(\Delta m^2_{32})$

δ_{CP}

$|\Delta m^2_{32}|$

Accelerator neutrino oscillations

δ_{CP} ?

MO ?
sign(Δm^2_{32})

	1σ	Best fit
θ_{13}	1.6%	8.5°
$\lvert\Delta m^2_{32}\rvert$	1.7%	2.55×10^{-3} eV^2/c^4
θ_{23}	2.9% 2.3%	UO: 48.9° LO: 43.5°

Accelerator neutrino oscillations

$\overset{?}{\delta_{\mathrm{CP}}}$

$\overset{?}{\mathrm{MO}}$

$\mathrm{sign}(\Delta m_{32}^2)$

1σ	Best fit
1.6%	8.5°

θ_{13}

1σ	Best fit
1.7%	2.55×10^{-3} eV^2/c^4

$|\Delta m_{32}^2|$

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2.9%	UO: 48.9°
2.3%	LO: 43.5°

θ_{23}

Accelerator neutrino oscillations

- Responsible for CP-V in lepton sector
- CP-violation?
- Value?

? δ_{CP}

? MO
sign(Δm^2_{32})

	θ_{13}	$\lvert\Delta m^2_{32}\rvert$	θ_{23}
1σ	1.6%	1.7%	2.9% (UO) 2.3% (LO)
Best fit	8.5°	2.55×10^{-3} eV^2/c^4	UO: 48.9° LO: 43.5°

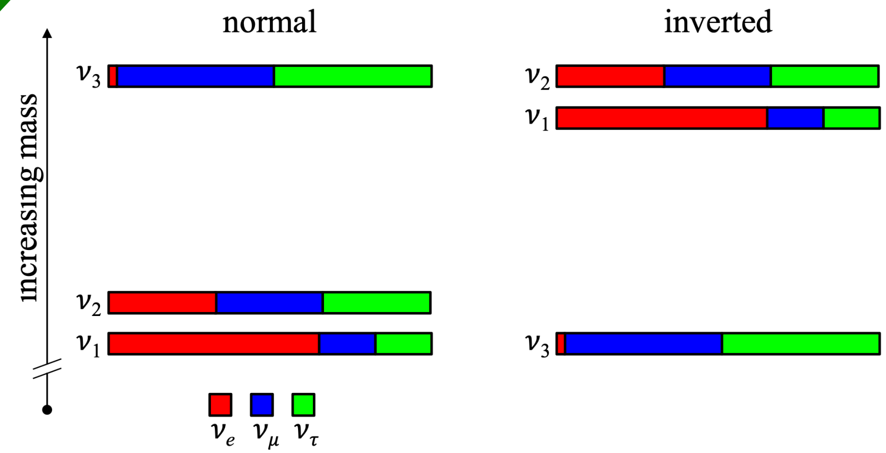
Accelerator neutrino oscillations

- Responsible for CP-V in lepton sector
- CP-violation?
- Value?

?
δ_{CP}

?
MO
$\text{sign}(\Delta m^2_{32})$

- MO = $\text{sign}(\Delta m^2_{32})$
- Mass ordering =?



1σ	Best fit
1.6%	8.5°

θ_{13}

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1.7%	2.55×10^{-3} eV^2/c^4

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2.9%	UO: 48.9°
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θ_{23}

Accelerator neutrino oscillations

- Responsible for CP-V in lepton sector
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- MO = $\text{sign}(\Delta m^2_{32})$
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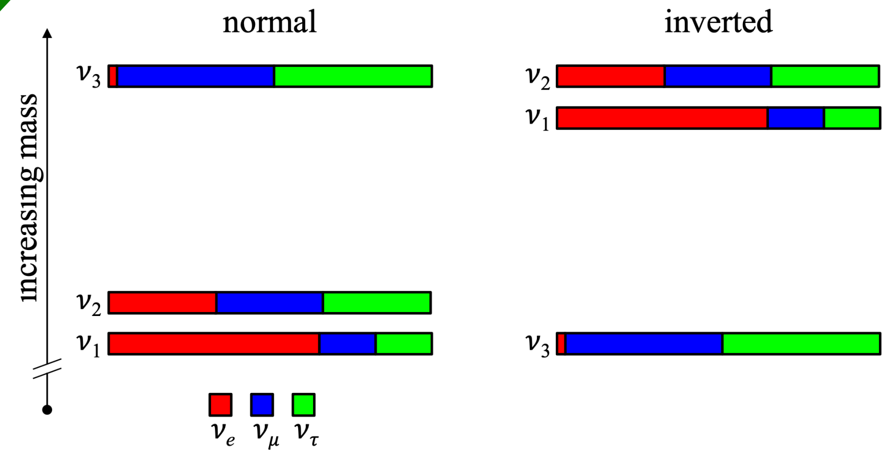


? δ_{CP}

? MO $\text{sign}(\Delta m^2_{32})$

	θ_{13}	$\lvert\Delta m^2_{32}\rvert$	θ_{23}
1σ	1.6%	1.7%	2.9% / 2.3%
Best fit	8.5°	$2.55\times10^{-3}\ eV^2/c^4$	UO: 48.9° / LO: 43.5°

Octant problem

Precision measurements

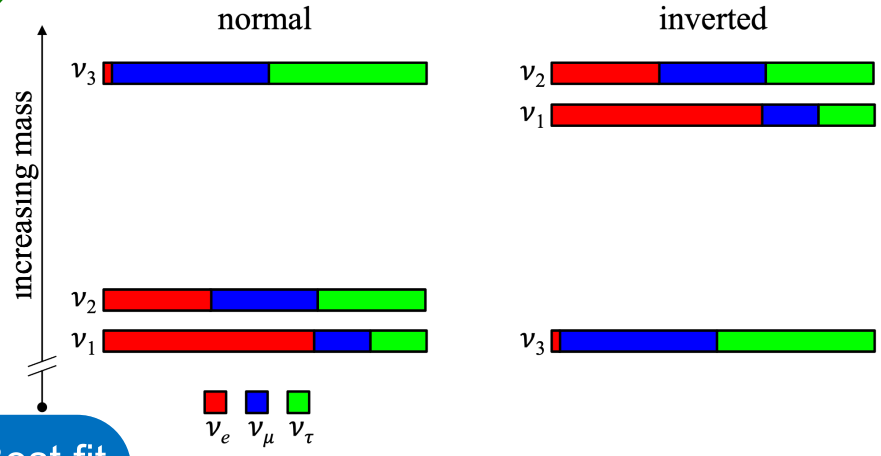
Accelerator neutrino oscillations

- Responsible for CP-V in lepton sector
- Value?
- CP-violation?

- MO = $\text{sign}(\Delta m^2_{32})$
- Mass ordering =?

?
δ_{CP}

?
MO
$\text{sign}(\Delta m^2_{32})$



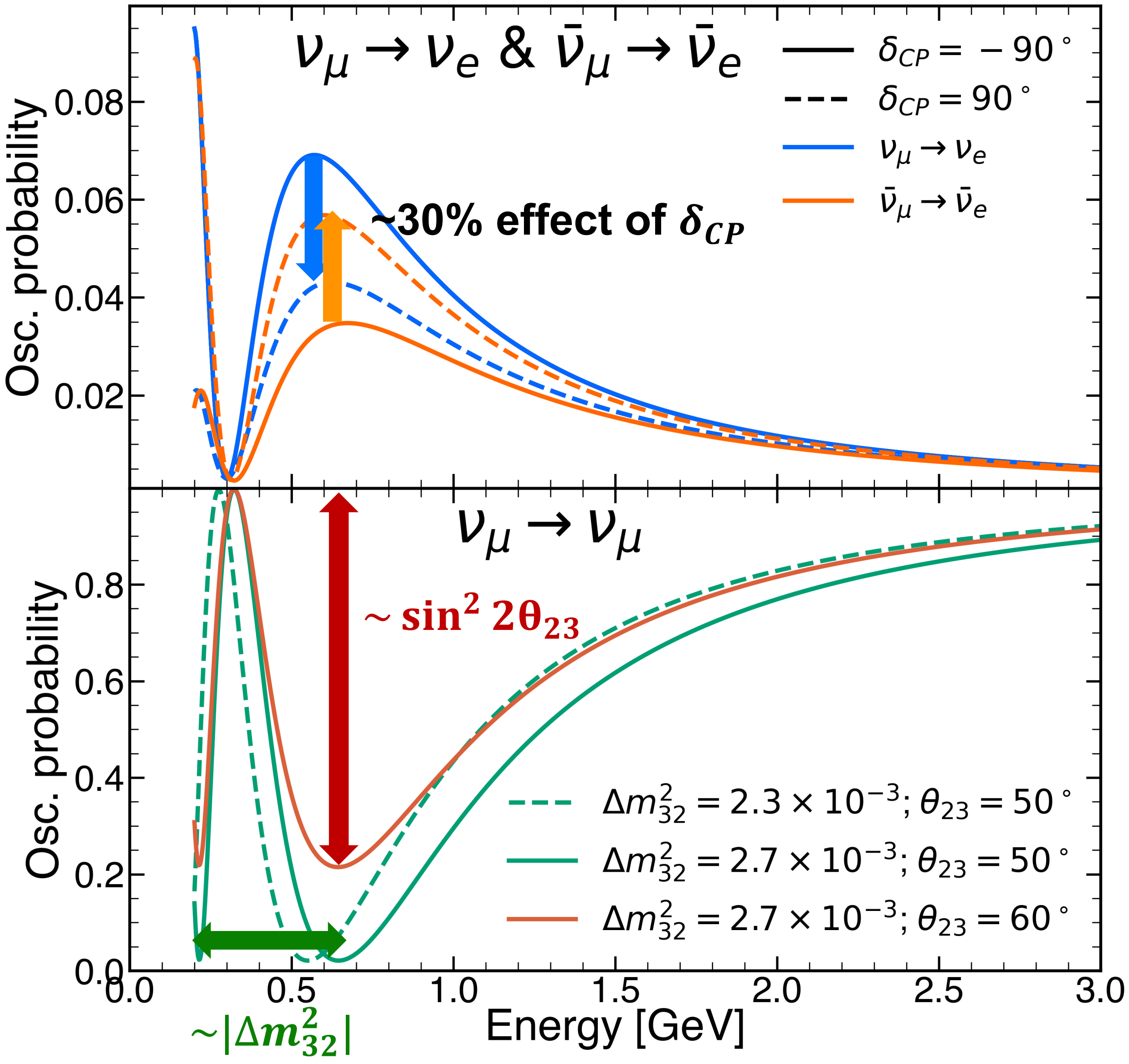
	θ_{13}	$\lvert\Delta m^2_{32}\rvert$	θ_{23}
1σ	1.6%	1.7%	2.9% / 2.3%
Best fit	8.5°	2.55×10^{-3} eV^2/c^4	UO: 48.9° / LO: 43.5°

Octant problem

Precision measurements

How these parameters can be measured?

Accelerator neutrino oscillations



Example for the T2K configuration:

- $E = [0.2;\ 3]$ GeV
- $L = 295$ km

- $\boldsymbol{\delta_{CP}}$ modulates electron appearance probability (asymmetrically for ν_e and $\bar{\nu}_e$)

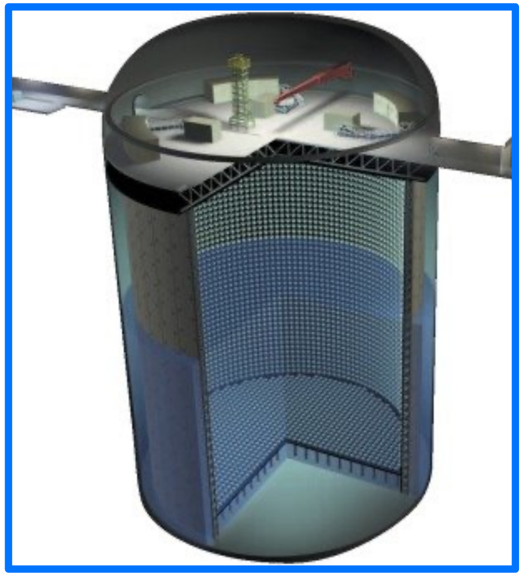
- The disappearance ($\nu_\mu \to \nu_\mu$) depth depends on $\mathbf{\sin^2 2\theta_{23}}$
- The oscillation frequency depends on $|\Delta \boldsymbol{m^2_{32}}|$

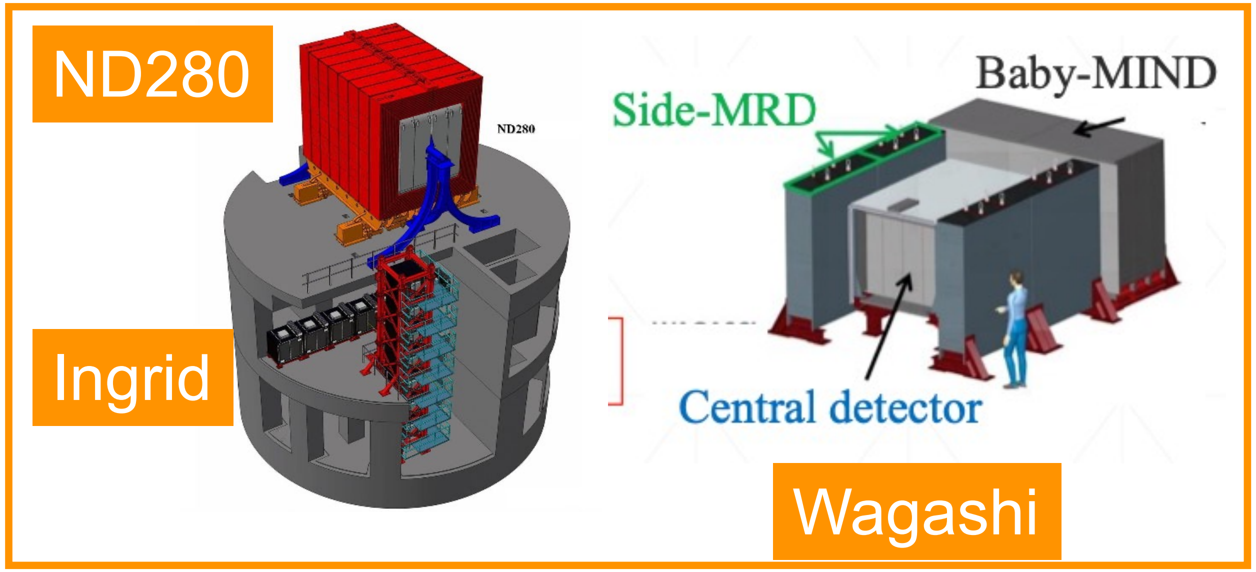
The

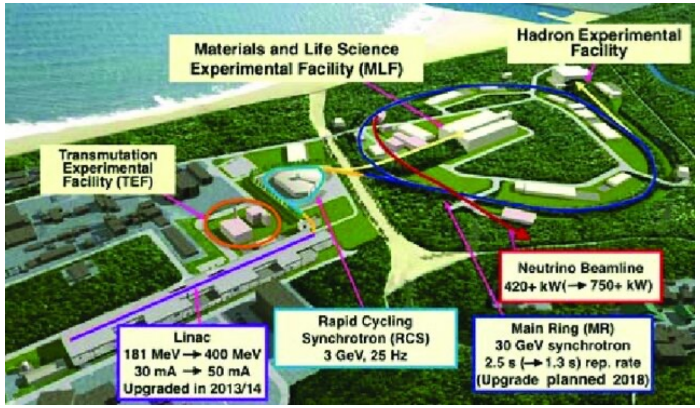
T2K

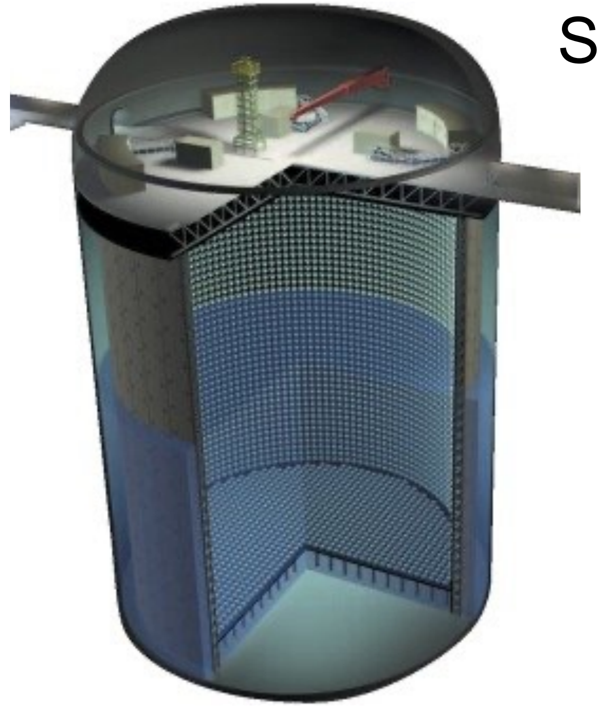
experiment

The T2K experiment





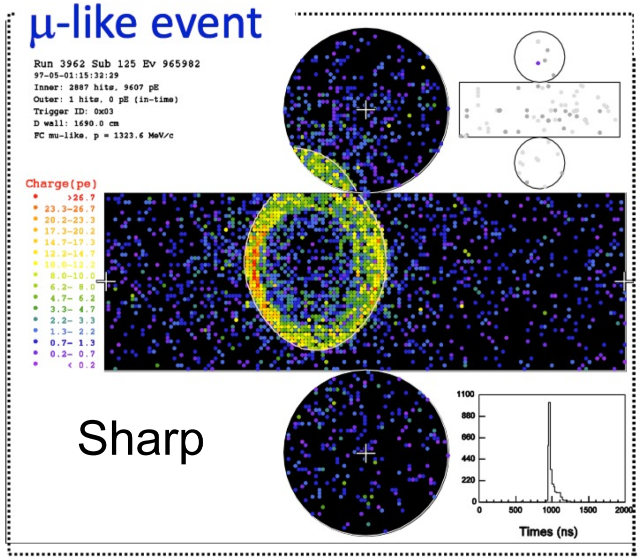


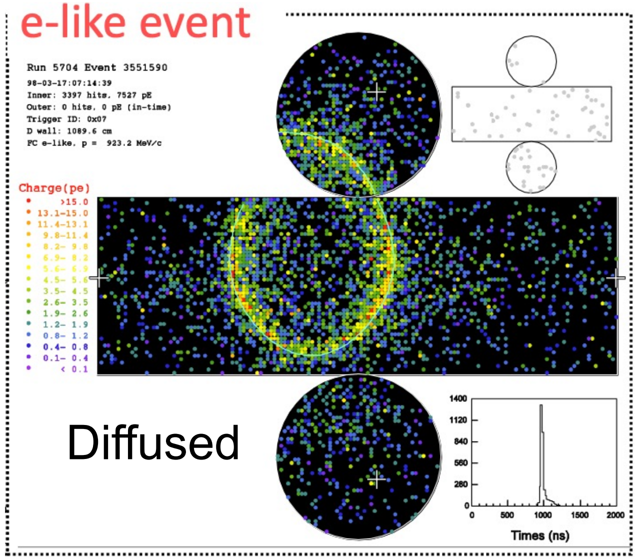


Super-Kamiokande – water cherenkov detector

Ring shape → e vs μ identification

# of cherenkov photons, hit time and ring geometry → Interaction kinematics, vertex and time





Number of ID PMTs	11,129
Photo-coverage	40%
Mass/ Fiducial Mass	50 kton/ 22.5 kton

The T2K oscillation analysis

T2K Oscillation Analysis

Directly measured at far detector

$$N_{obs}^{\nu_\alpha}(E_\nu^{reco}) \leftrightarrow N_{exp}^{\nu_\alpha}(E_\nu^{reco}) =$$

$$\Phi(E_\nu^{true}) \otimes \sigma(E_\nu^{true}) \otimes \epsilon(E_\nu^{true}) \otimes S(E_\nu^{true}, E_\nu^{reco}) \otimes P_{\nu_\mu \to \nu_\alpha}(E_\nu^{true}, \vec{o})$$

Neutrino flux

Interection cross-section

Detector efficiency

Energy smearing matrix

Oscillation probability

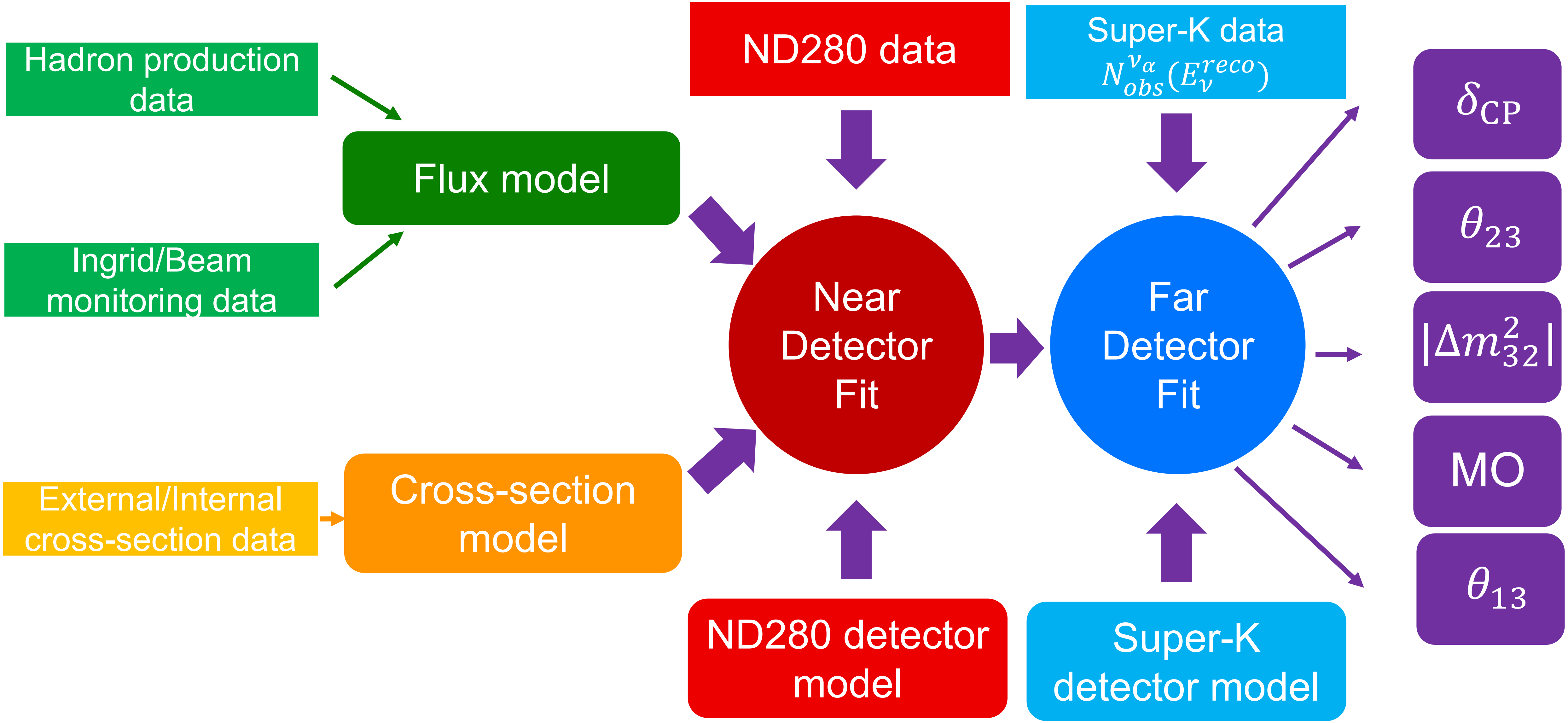
Systematics

$(\vec{f})$

We want to extract this!

$\alpha = e, \mu$

T2K oscillation analysis: Strategy



T2K oscillation analysis: Strategy

Super-K data

Far Detector Fit

Super-K detector model

Bayesian fitter

Two different statistical approches for the results cross-check

Frequentist fitter

- **MCMC Metropolis–Hastings algorithm**
- **Simultaneous ND+FD fit**
- Obtains posteriour distribution on the parameters

- Grid search
- Gradient descent and importance sampling MC marginalisation
- ND priors from the another fitter
- **Feldman-Cousins method for C.L. calculation**

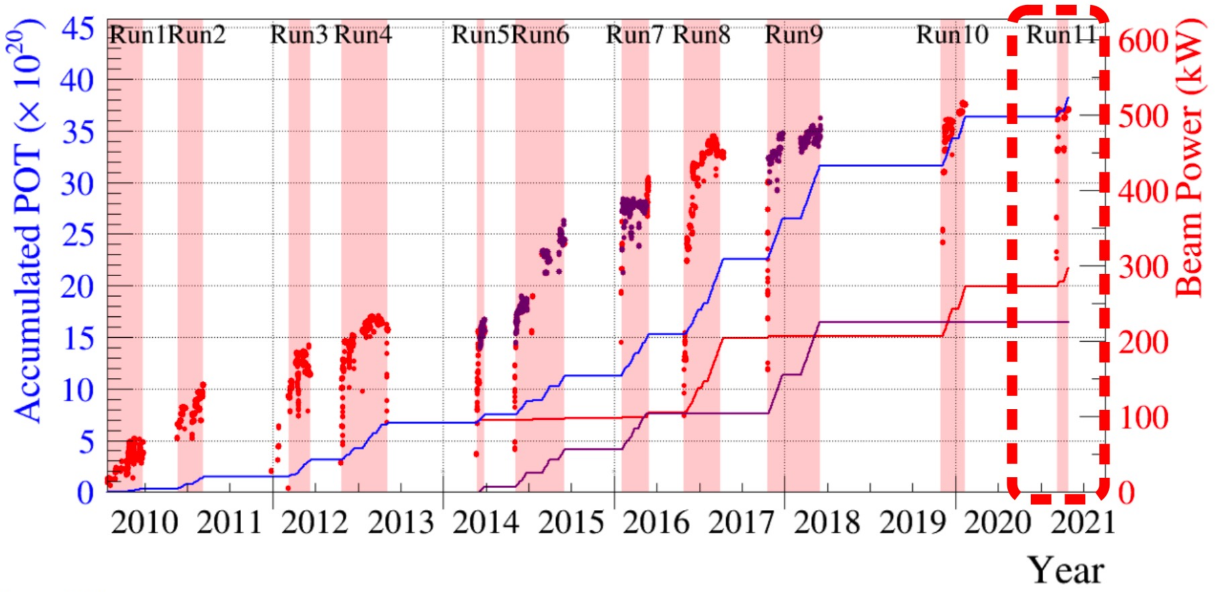
The latest T2K results

The latest T2K results

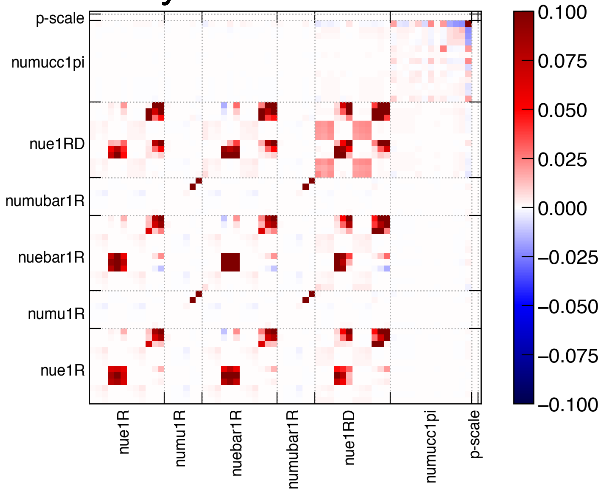
Officialised one month ago

Main updates:

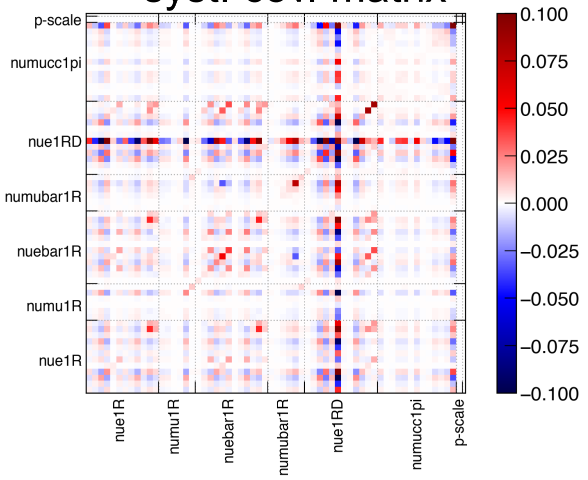
- **+ 9% of data** in neutrino mode ($1.97{\times}10^{21} \rightarrow 2.14{\times}10^{21}$ POT)
- It is first data taken after **Gd loading** in SK (0.01% Gd doping)
- Improved SK detector systematics evaluation
- Additional selections to distinguish Michel electrons from neutrons tagged events



Previous SK detector syst. cov. matrix



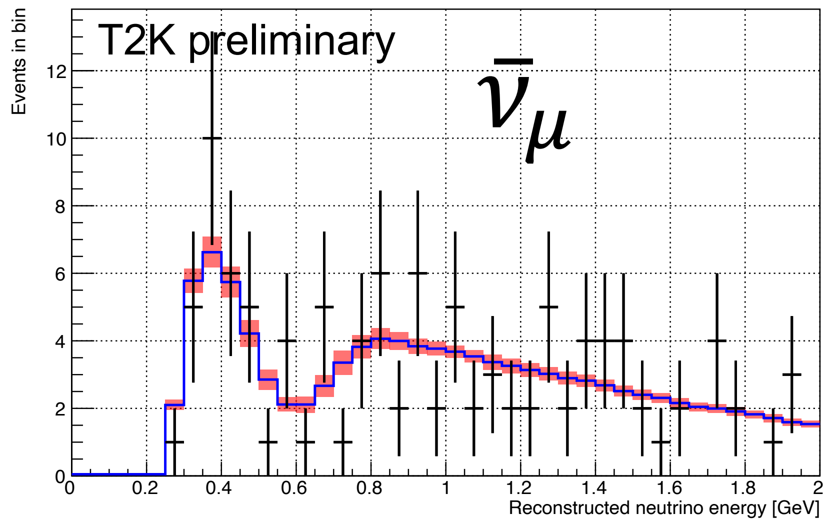
Improved SK detector syst. cov. matrix

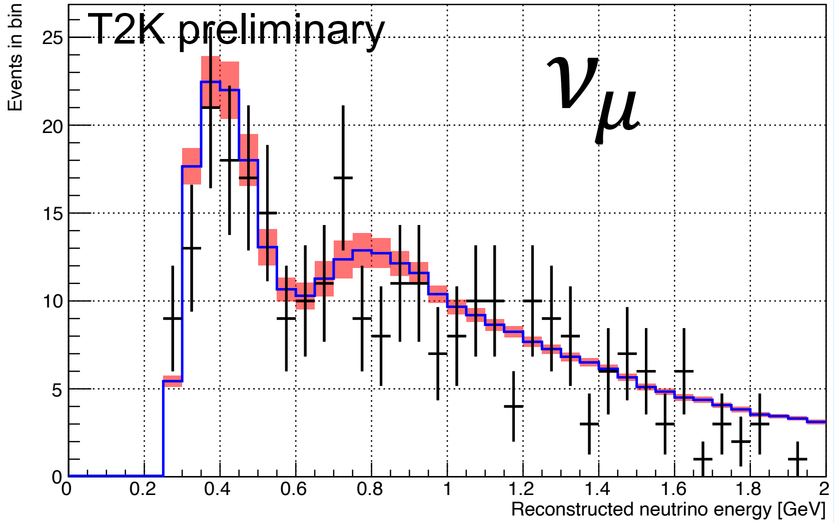


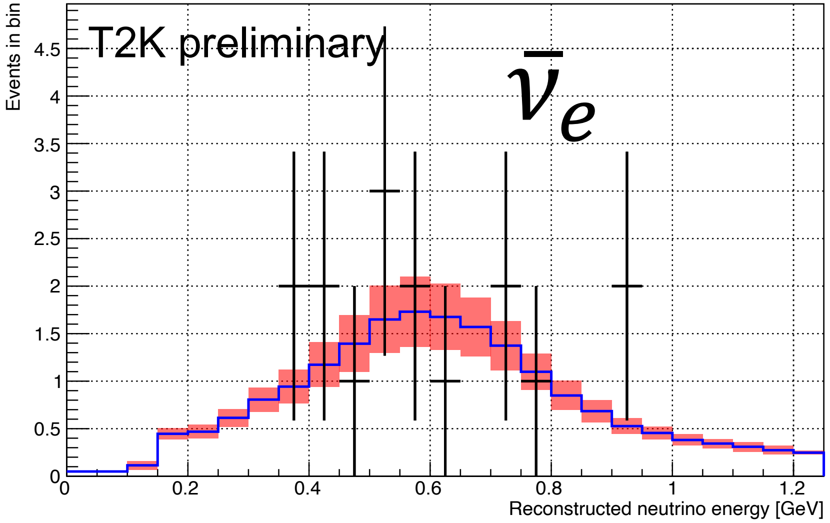
The latest T2K results

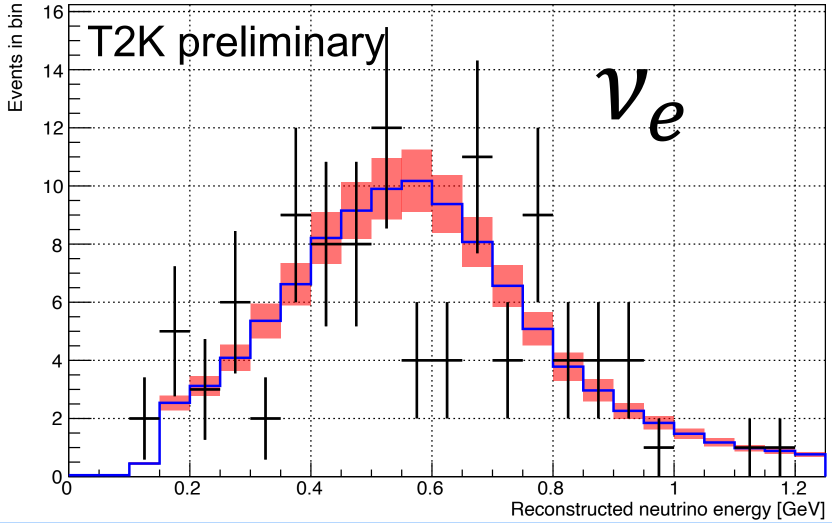
Oscillated neutrino events spectra

CCQE enhanced samples (1 ring events):

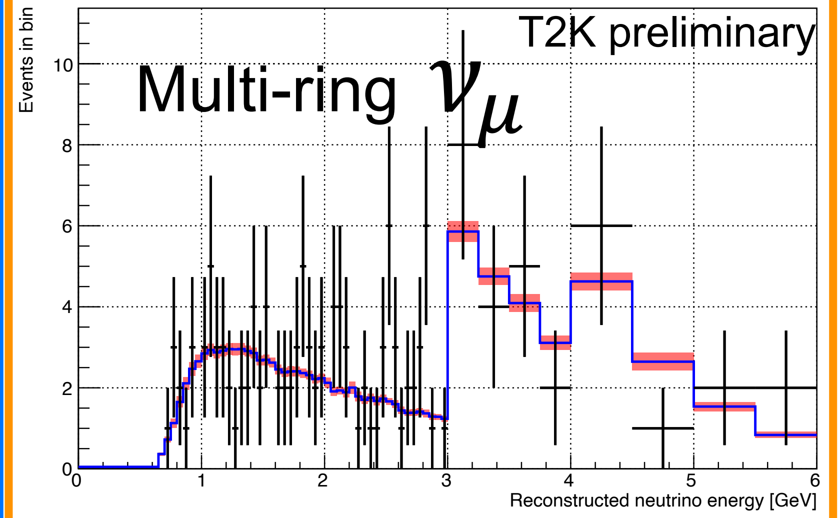


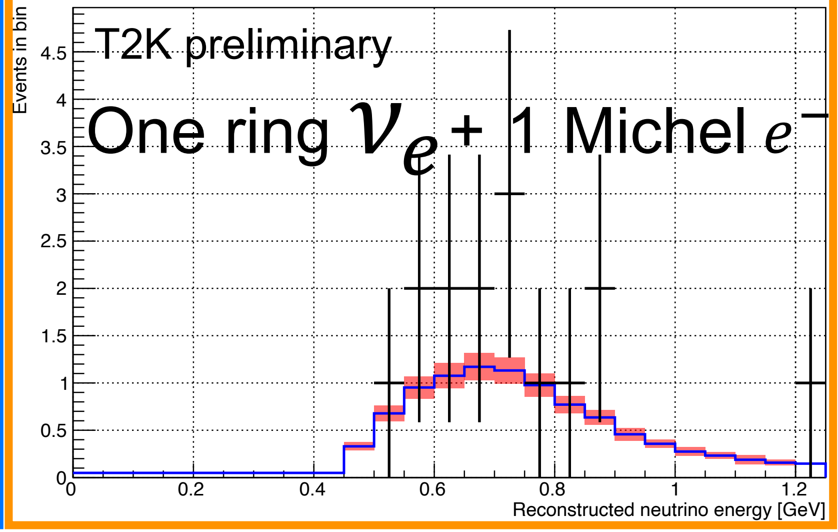




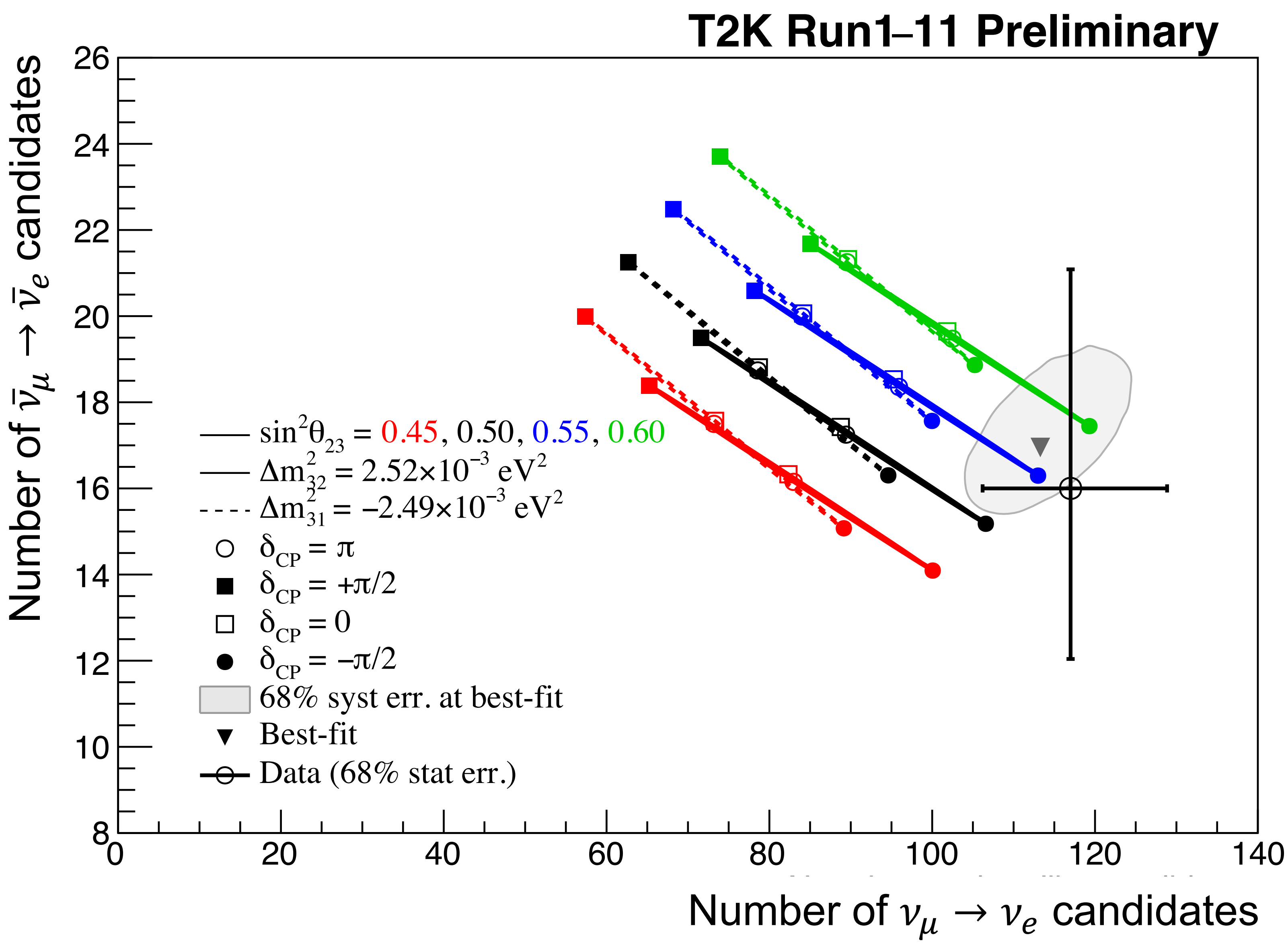


CC1π^+ enhanced samples

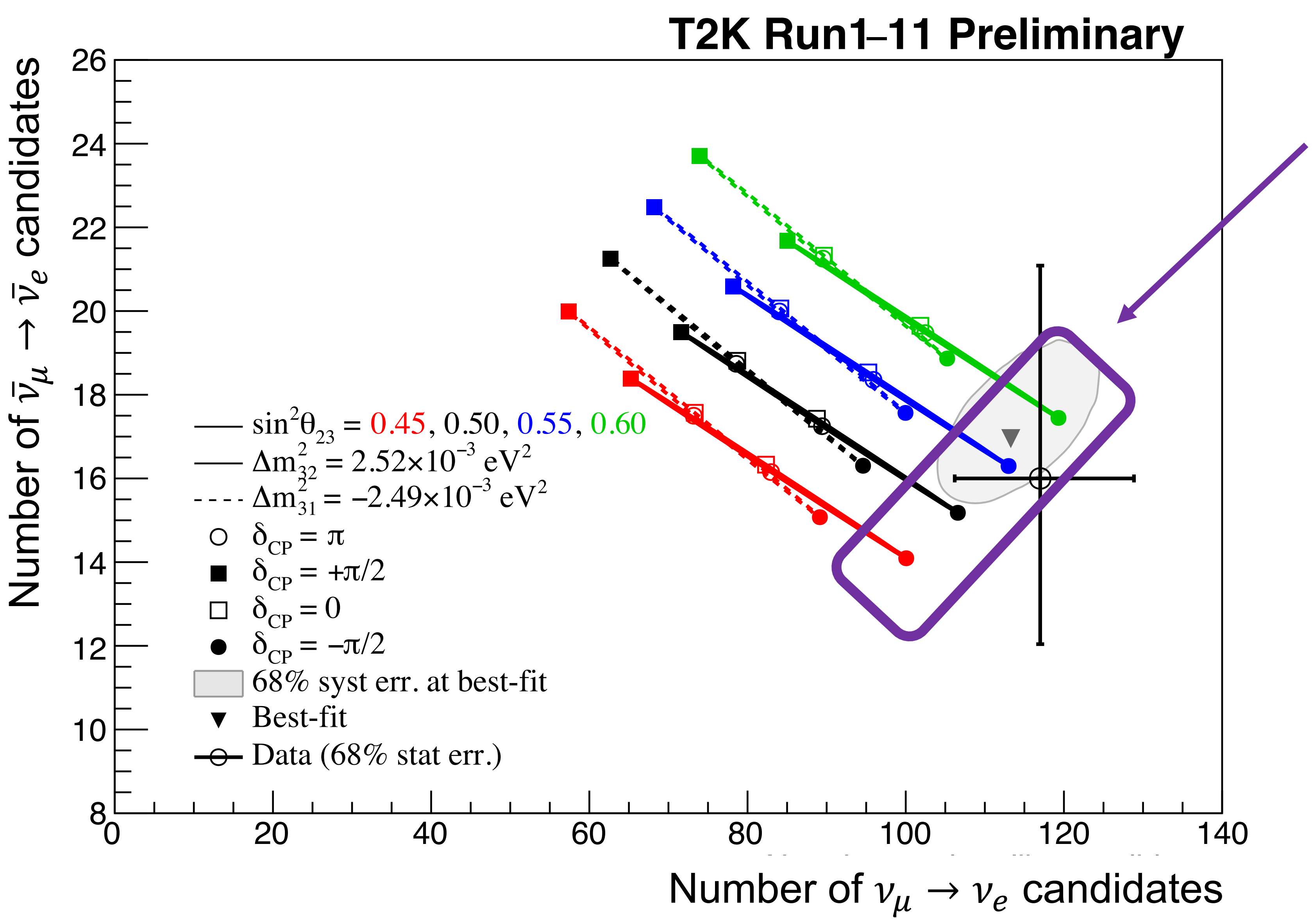




The latest T2K results



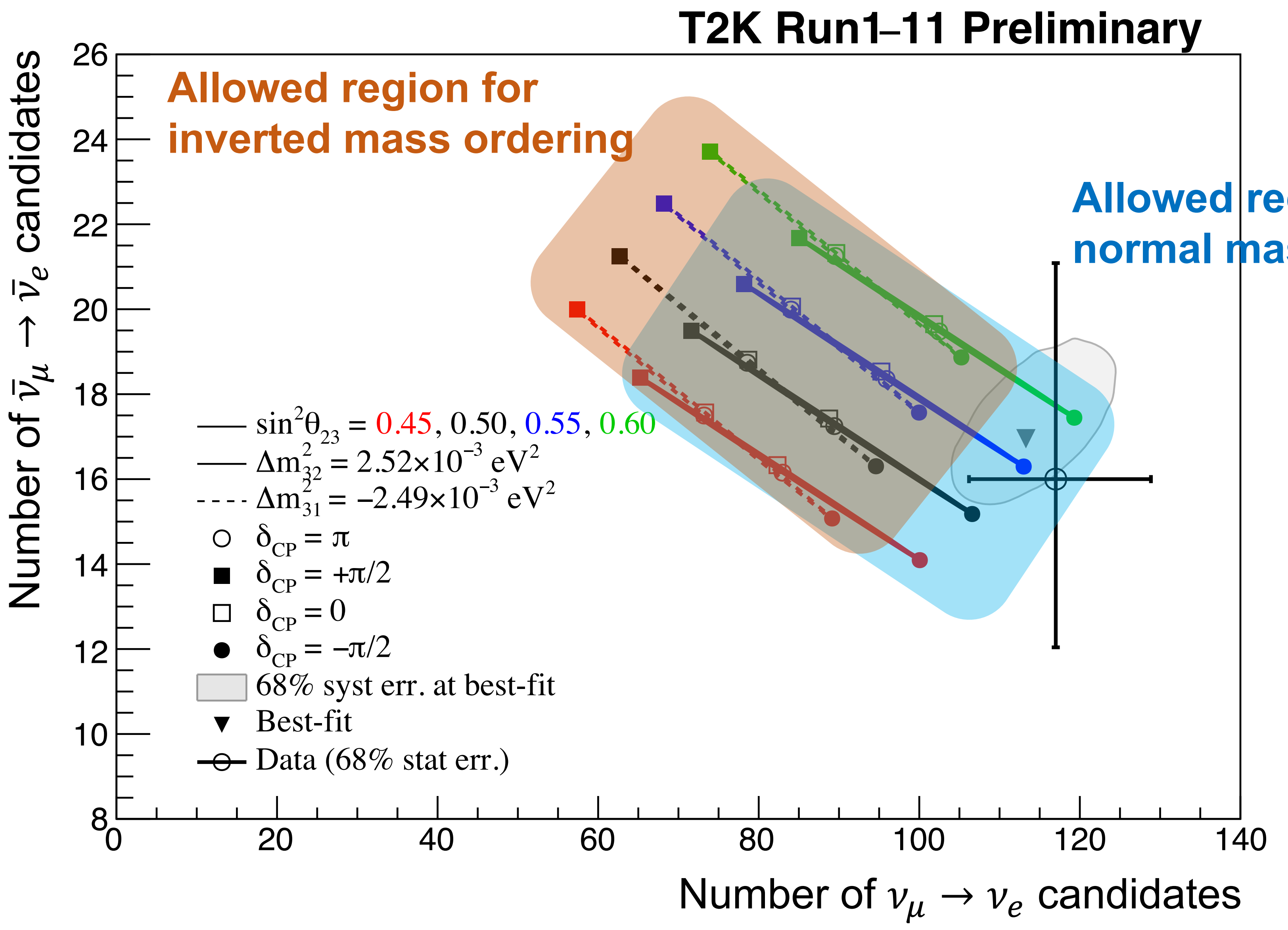
The latest T2K results



Max. CP-violation region

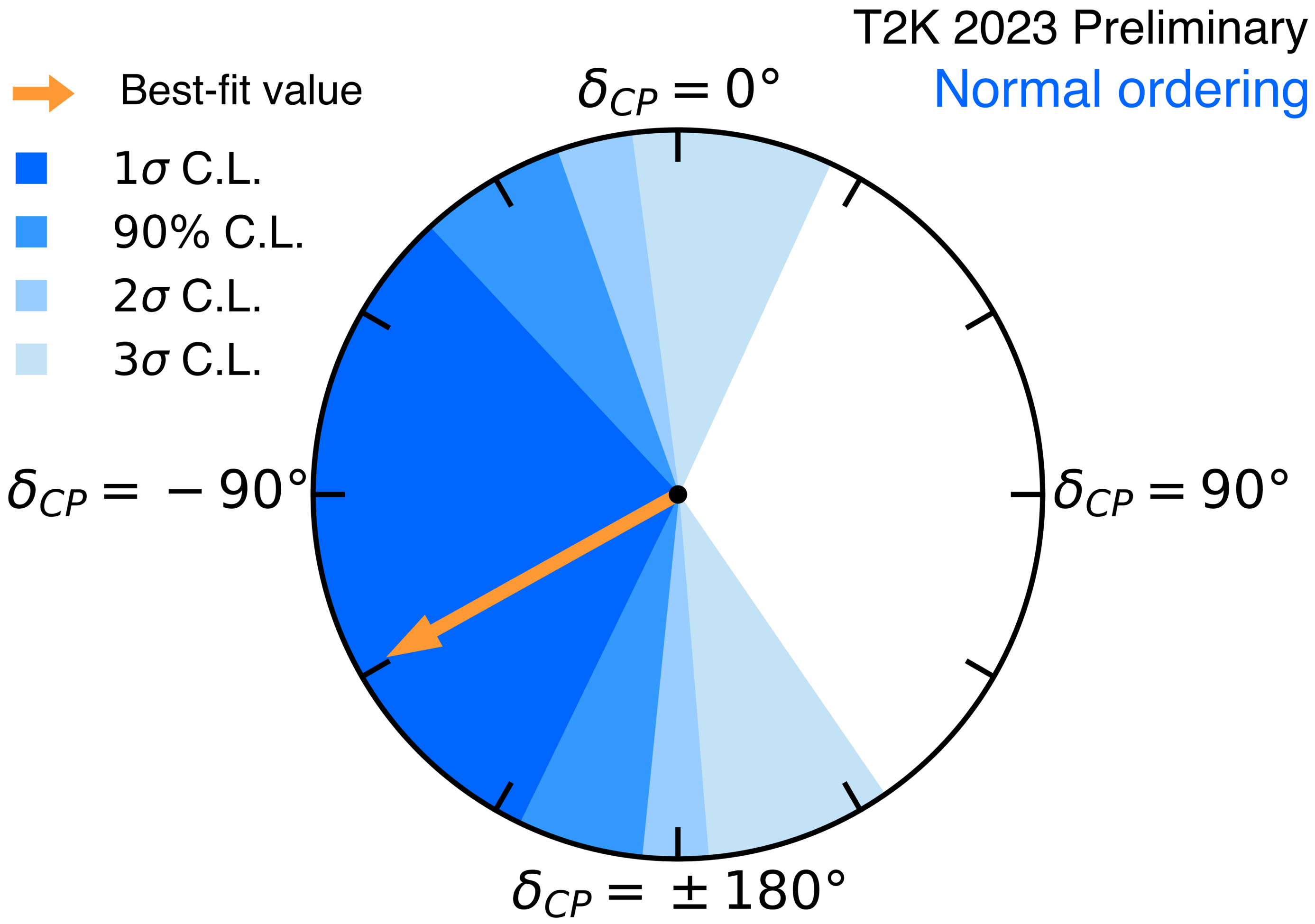
Best fit: $\delta_{CP} \approx -\frac{\pi}{2}$

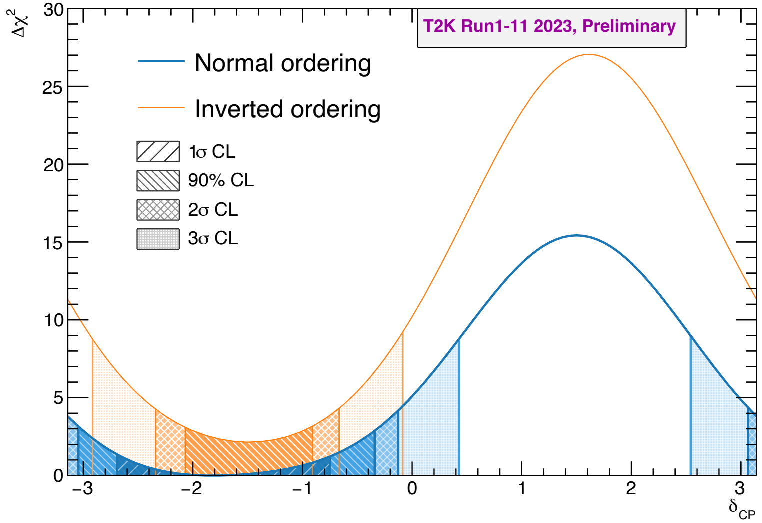
The latest T2K results



Weak preference of Normal Mass Ordering

The latest T2K results: CP-violation





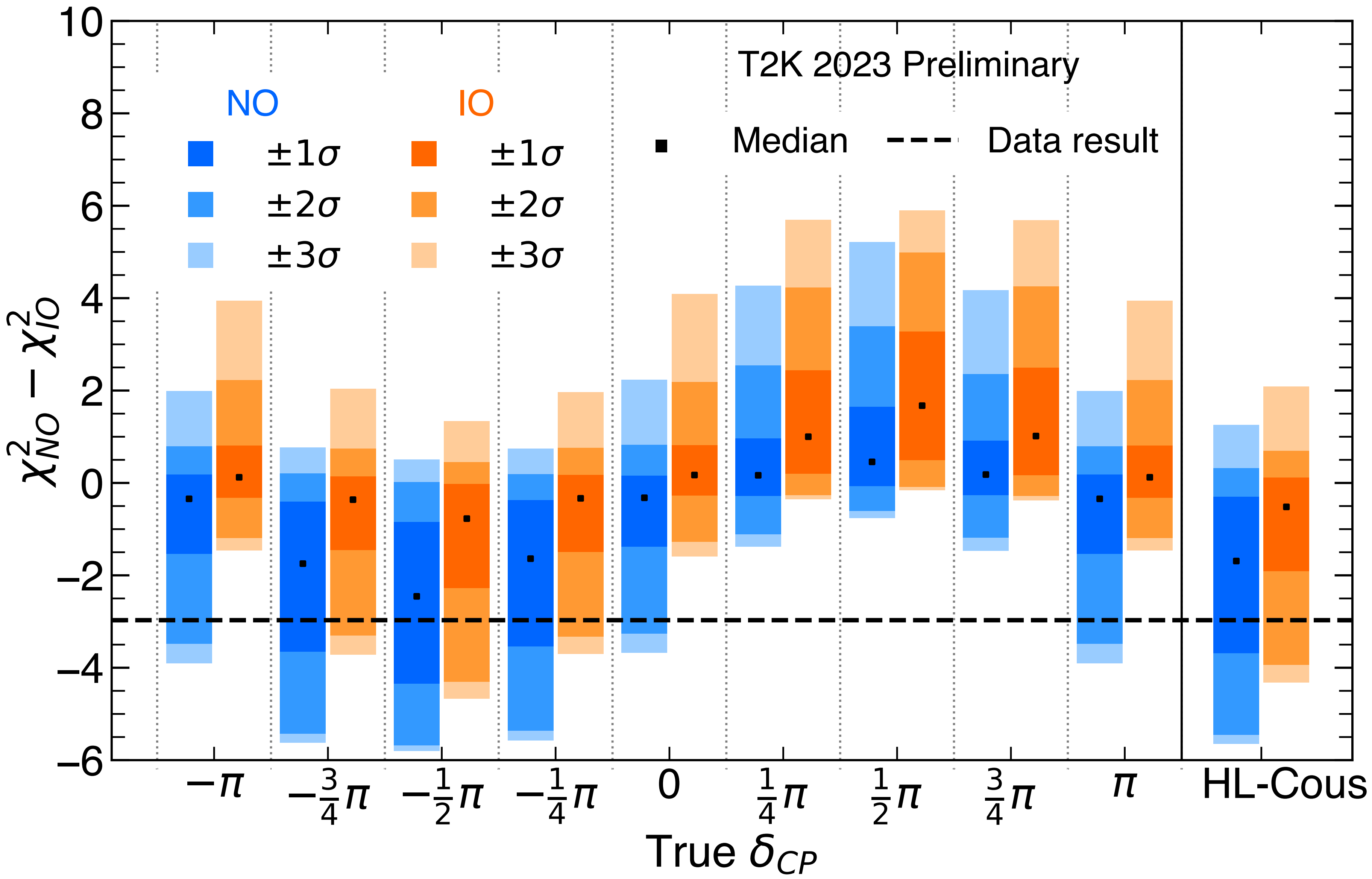
δ_{CP}

$$\delta_{CP} = -2.08^{+1.33}_{-0.61}$$

CP-conservation excluded with 90% C.L.*

*T2K performs **robustness studies of the interaction model** - for **1πLowQ2 suppression** simulated data set CP-C is not excluded with 90% C.L.

The latest T2K results: Mass ordering

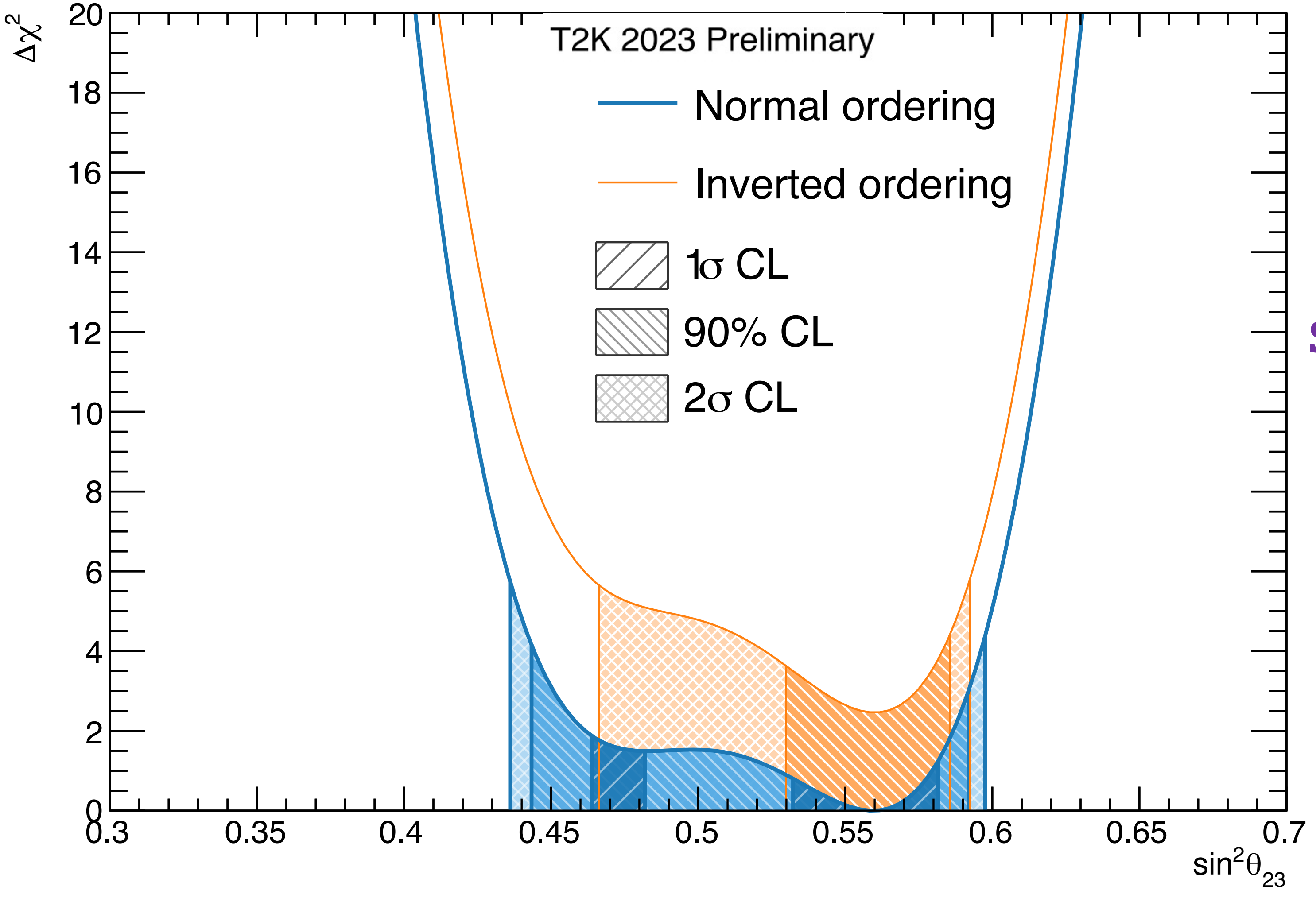


MO

IO slightly disfavoured:

p-value = 1.69σ

The latest T2K results

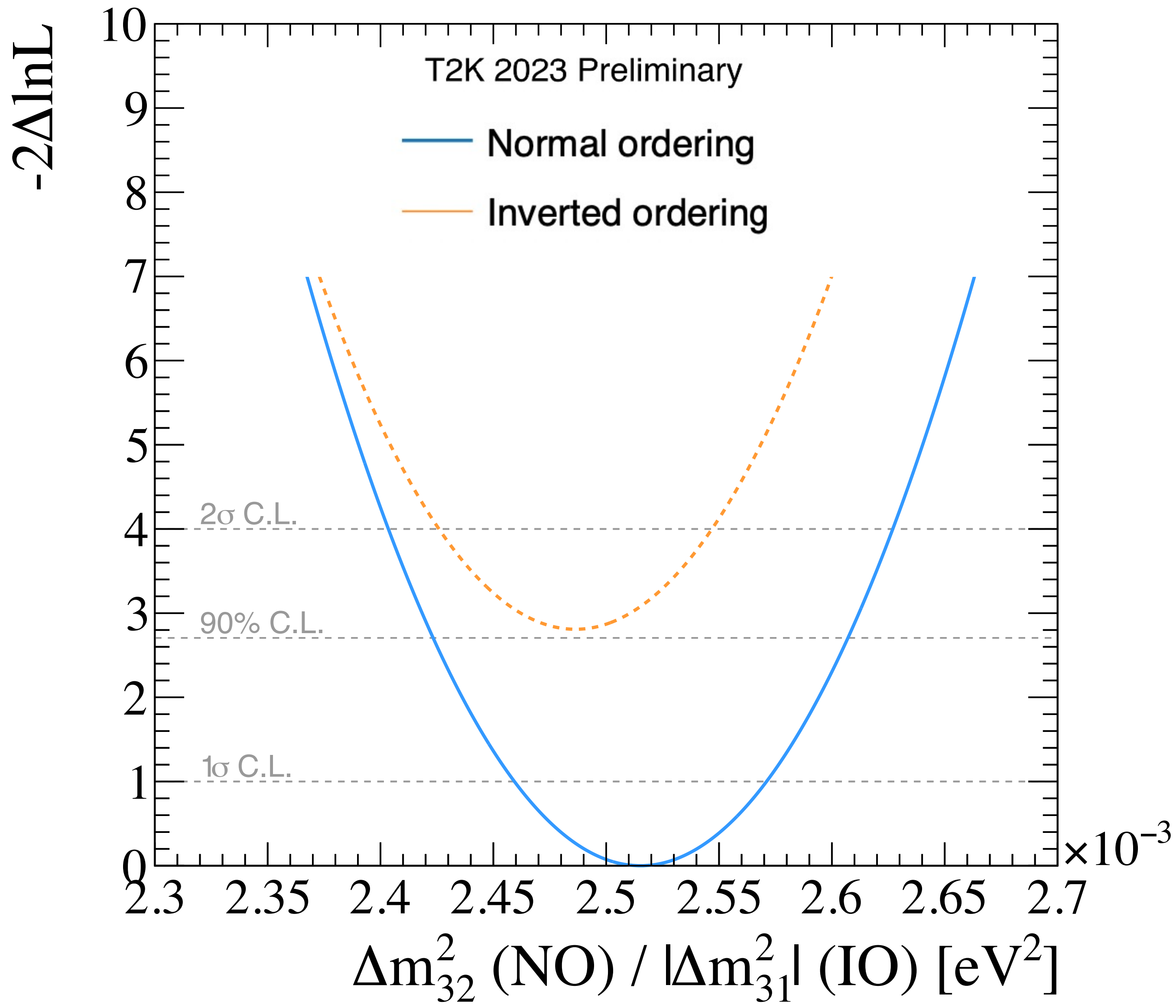


θ_{23}

$$\sin^2\theta_{23} = \begin{cases} 0.568^{+0.014}_{-0.036} - \text{Upper Octant} \\ 0.475^{+0.007}_{-0.011} - \text{Lower Octant} \end{cases}$$

- **Weak preference of upper octant**
- **Compatible with maximal mixing**

The latest T2K results



Δm^2_{32}

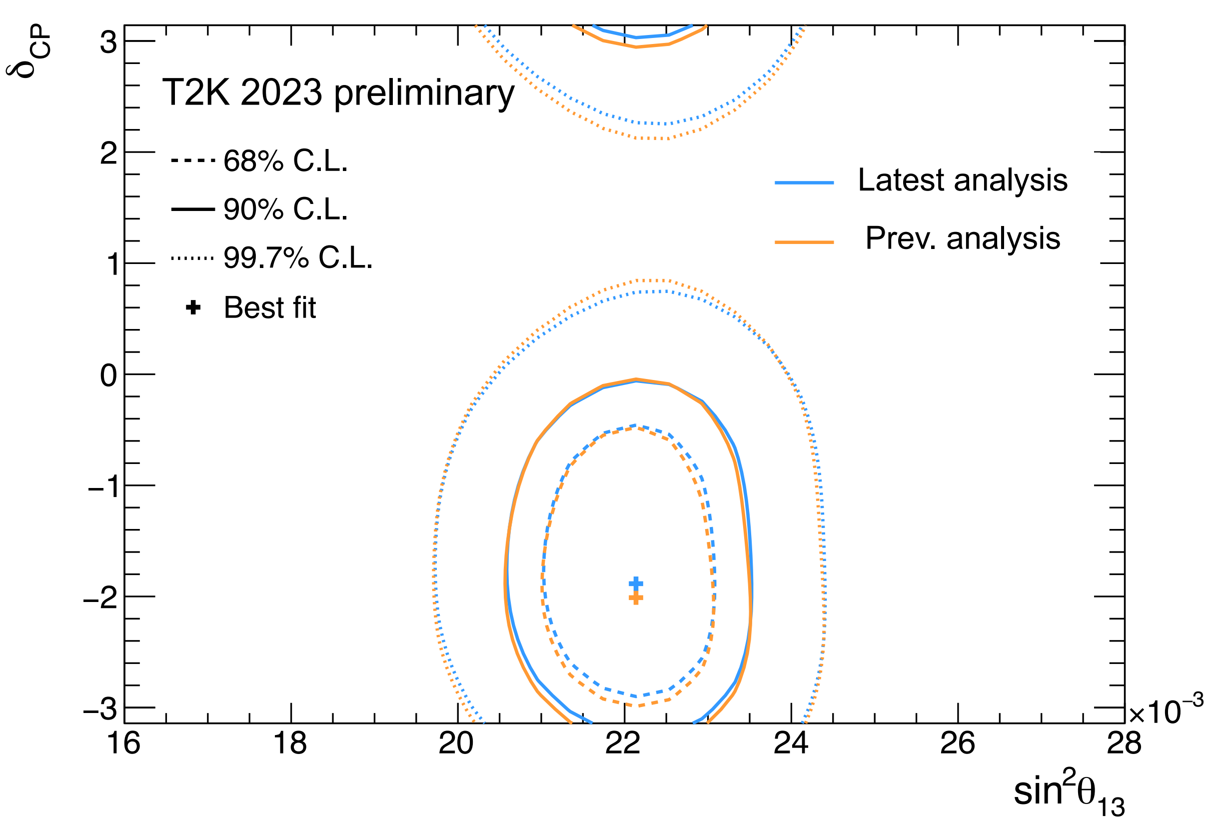
$|\Delta m^2_{32}| = 2.521^{+0.037}_{-0.050} \times 10^{-3}\ eV^2/c^4$

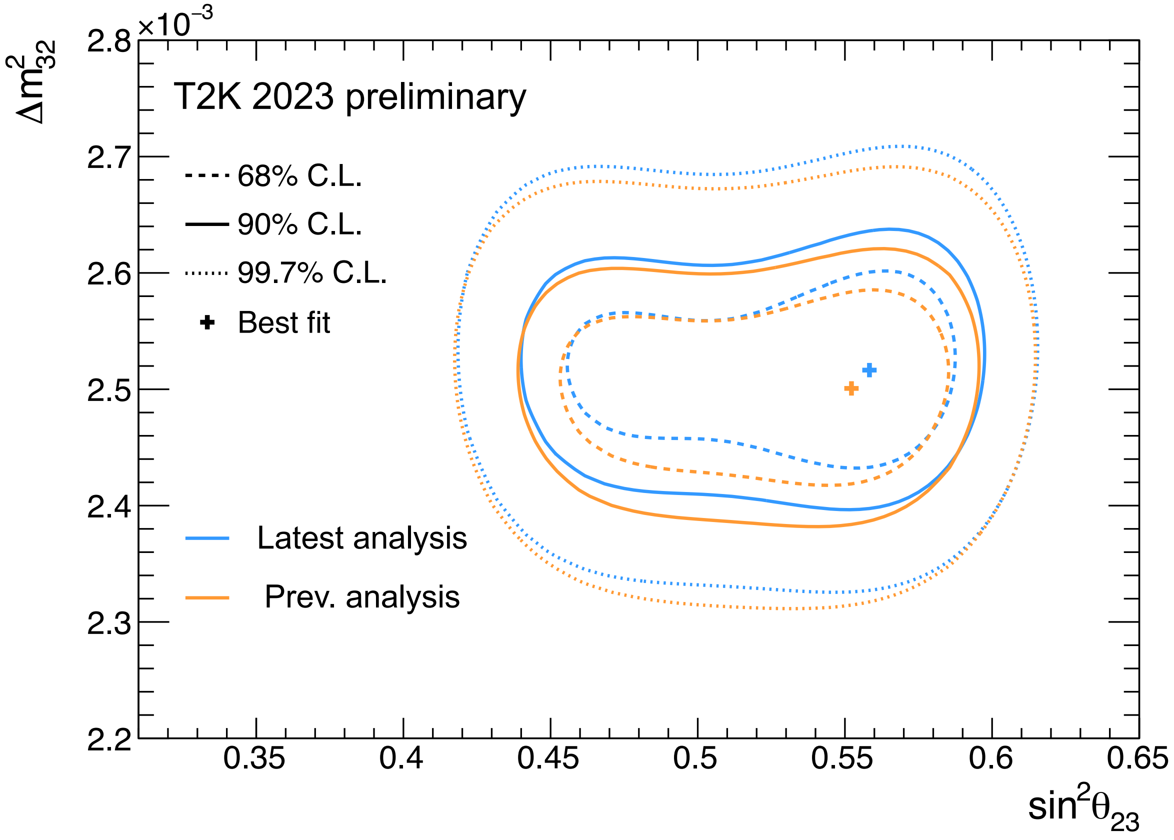
$\varepsilon_\sigma = 1.7\%$*

T2K perform **robustness studies of the interaction model.** For some of them we observe **bias in Δm^2_{32} inference – additional smearing $0.031 \times 10^{-3} eV^2/c^4$** is applied for $\Delta\chi^2$

The latest T2K results

Comparison with the previous analysis

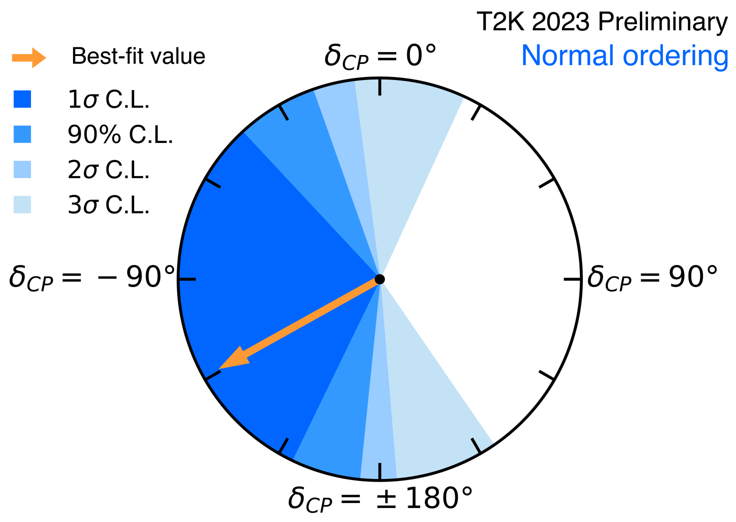




- Small improvements in precision measurements over previous T2K analysis
  - Consistent results comparing with previous analysis

Conclusion

- New T2K oscillation analysis presented which includes:
  - ➢ New data: **+ 9% of data** in neutrino mode
  - ➢ First data after Gd loading
  - ➢ Improved SK detector systematics
- New results slightly improve the precision and are consistent with the previous analysis



- **CP-conservation excluded at 90% C.L.**
- **Weak preference of Normal Ordering**
- **Weak preference of Upper Octant**

$$\delta_{CP} = -2.08^{+1.33}_{-0.61}$$

$$|\Delta m^2_{32}| = 2.521^{+0.037}_{-0.050} \times 10^{-3}\ eV^2/c^4$$

$$\sin^2\theta_{23} = \begin{cases} 0.568^{+0.014}_{-0.036} - \text{Upper Octant} \\ 0.475^{+0.007}_{-0.011} - \text{Lower Octant} \end{cases}$$

Prospectives

The future oscillation analysis improvements in T2K:

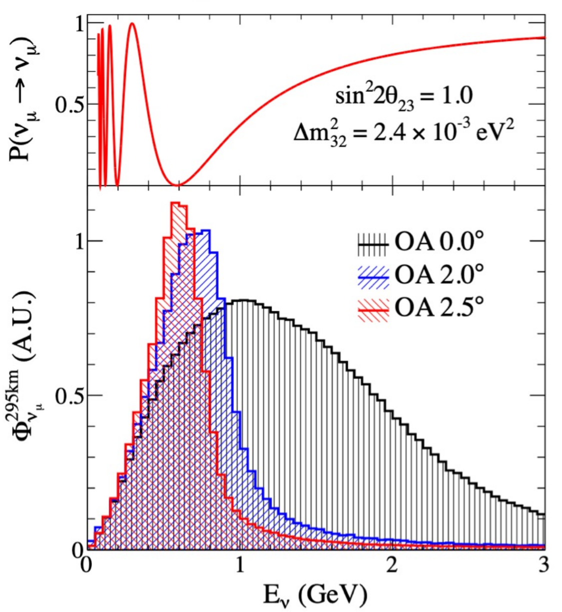
- Beamline has been upgraded → Beam power reached **800 kW** → Much more data are coming.
- **ND280 Upgrade is fully installed** → New measurements at ND280, allowing to better constrain the systematics (flux and x-sec) for the incoming high statistics.

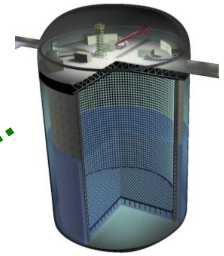
Many promising T2K oscillation analyses are expected in future!

BACKUP

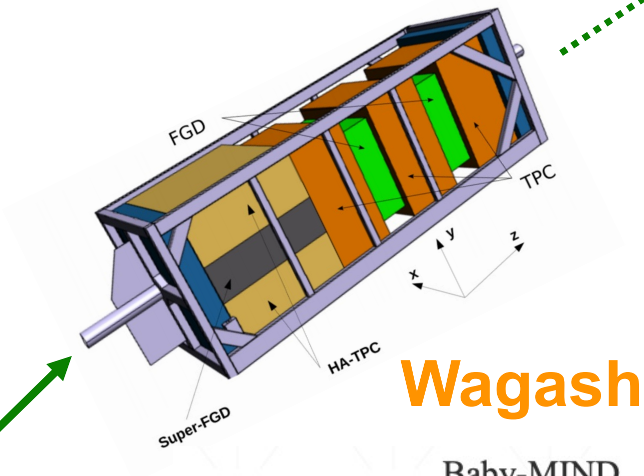
The T2K experiment

ν_μ survival probability

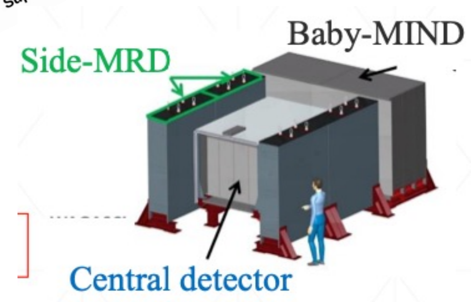




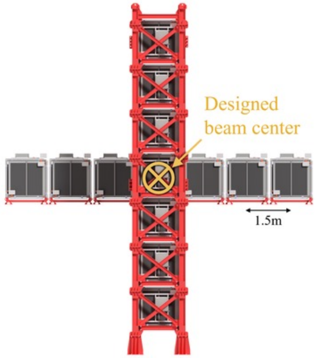
ND280

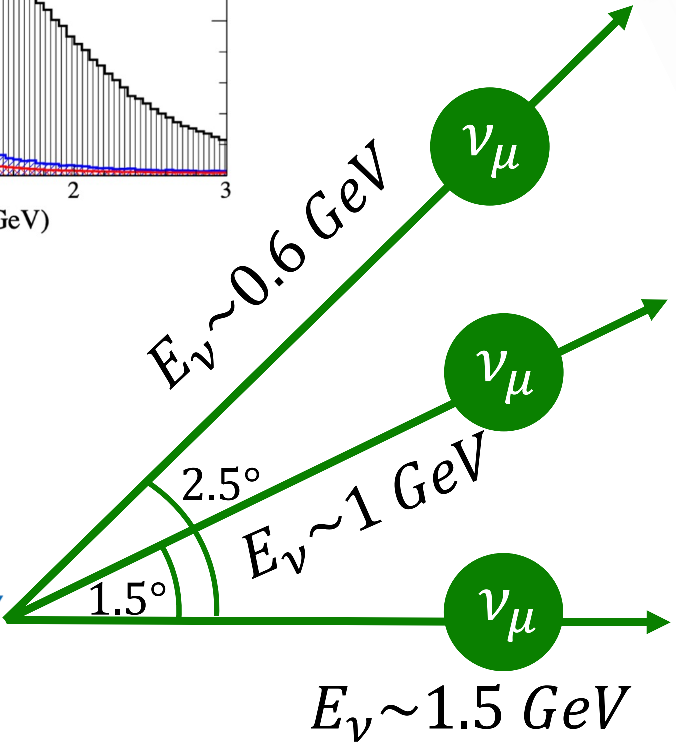


Wagashi



INGRID





- Off-Axis ND280
- Constrains flux and x-sec systematics in the T2K oscillation analysis
- Upgrade finalized in 2024

- WAGASCI/BabyMIND
- Installed in 2019
- Cross-sections on water

- On-Axis INGRID
- Monitors ν_μ beam intensity and direction

History of the T2K oscillation analysis

Key publications in oscillation analysis

T2K start: 2010

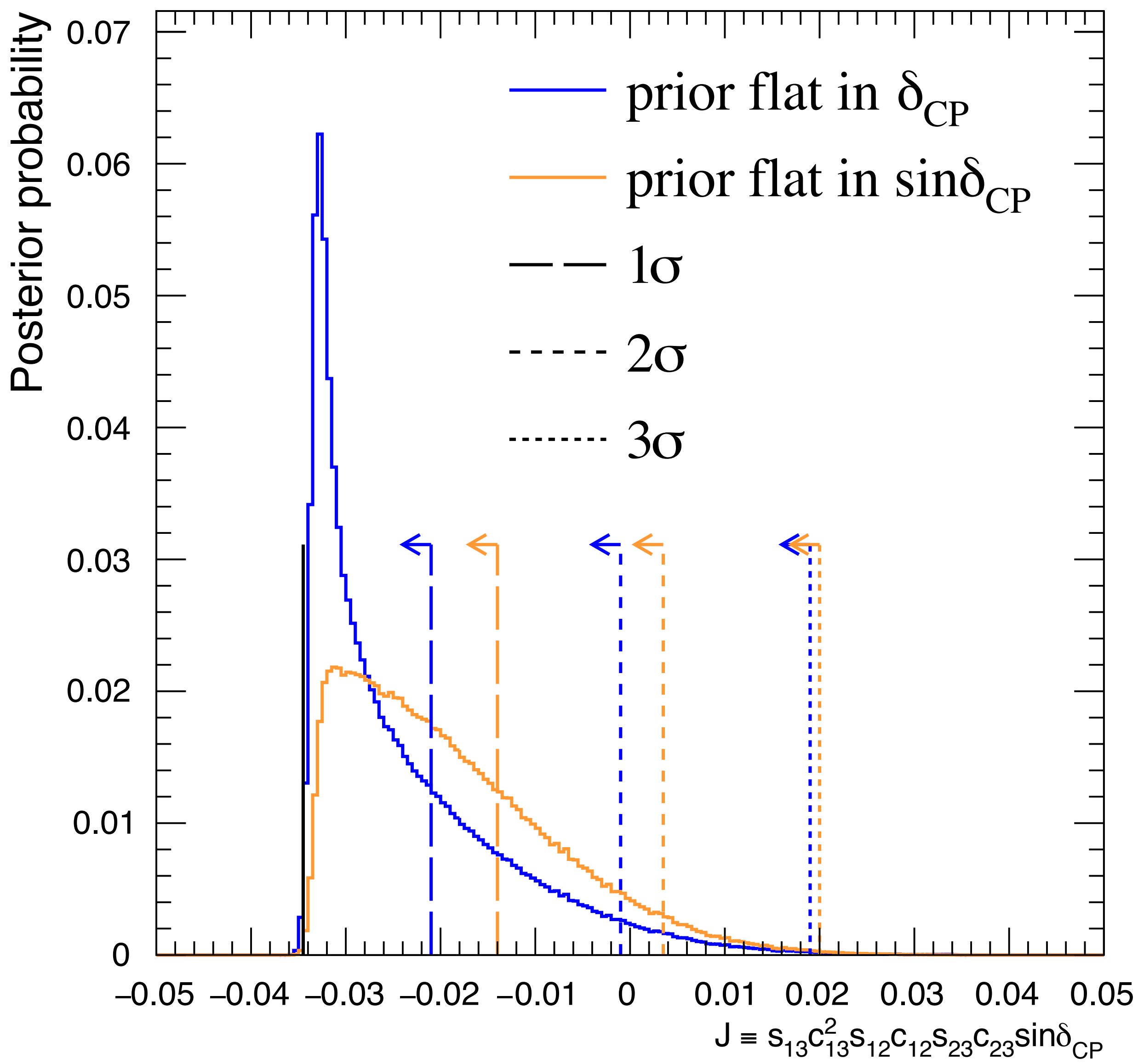
2013	PRL 111	First ν_μ analysis
2014	PRL 112	$\sin^2\theta_{13}=0$ excl. with 7.3σ
2015	PRL 91	First ν_μ+ν_e joint fit
2017	PRL 118	First $\nu+\overline{\nu}$ joint fit CP-C excl. with 90%
2020	**Nature**	CP-C excl. with ~2σ
2023	**Eur. Phys. J**	The latest publication

	2013	2014	2015	2017	2020	2023
Beam Power, kW	**200**	**220**	**220**	**230**	**500**	**500**
Statistics, 10^{20} POT	$3.01\,\nu$	$6.57\,\nu$	$6.57\,\nu$	$7.482\,\nu + 7.471\overline{\nu}$	$14.9\,\nu + 16.4\,\overline{\nu}$	$19.7\,\nu + 16.4\,\overline{\nu}$
# syst. params	**48**	**27**	**83**	**98**	**119**	**141**
# Far Det. samples	**1**	**1**	**2**	**4**	**5**	**5**

The latest T2K results

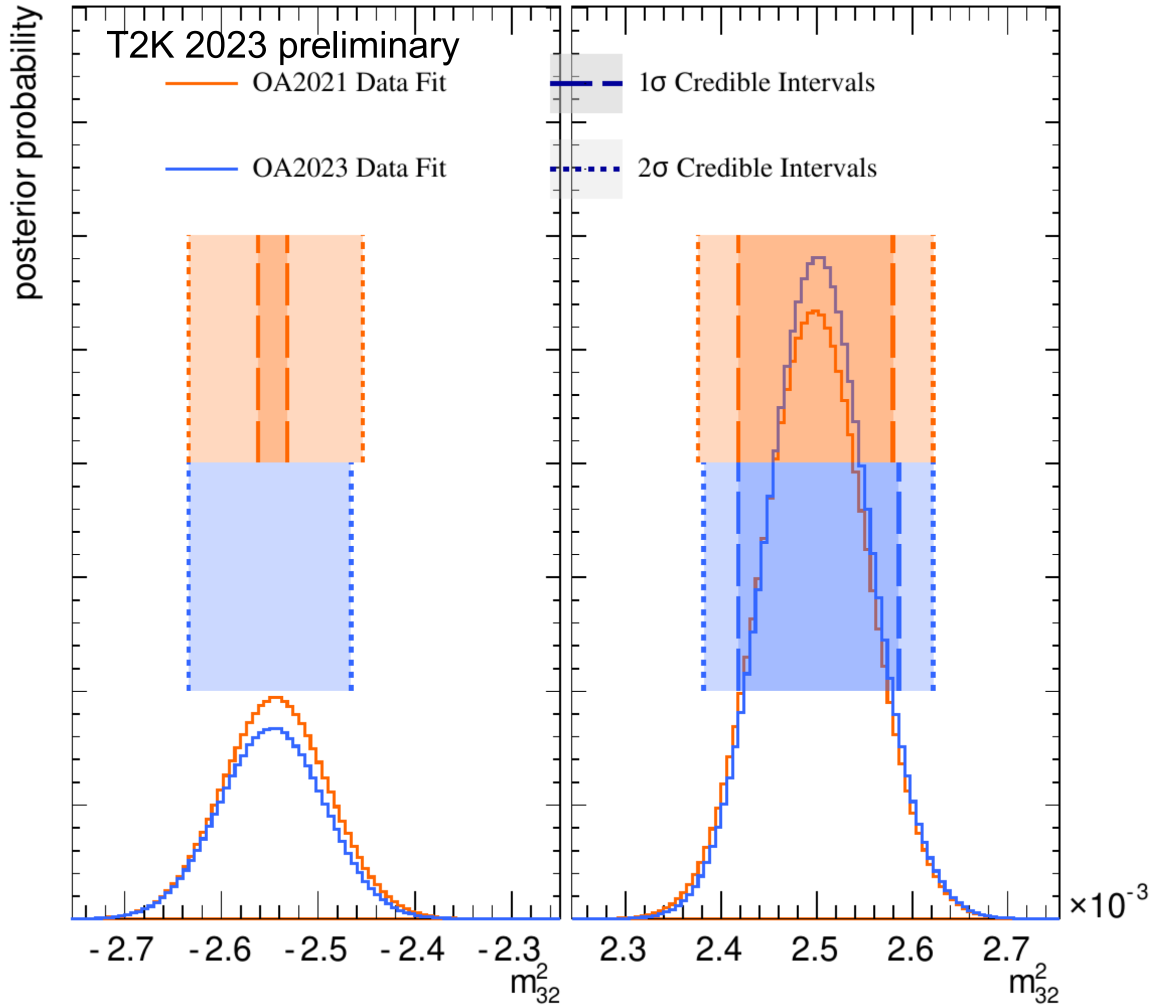
Bayesian results

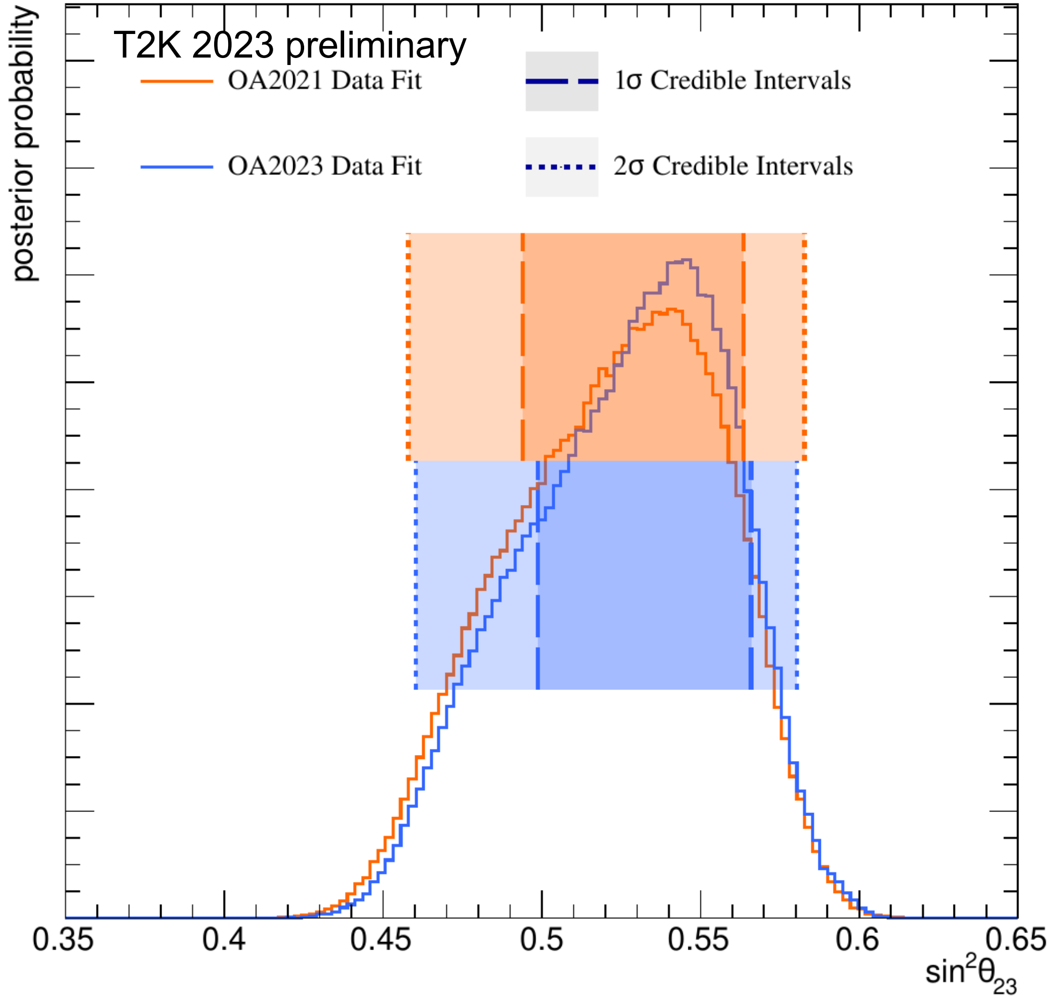
Jarlskog invariant



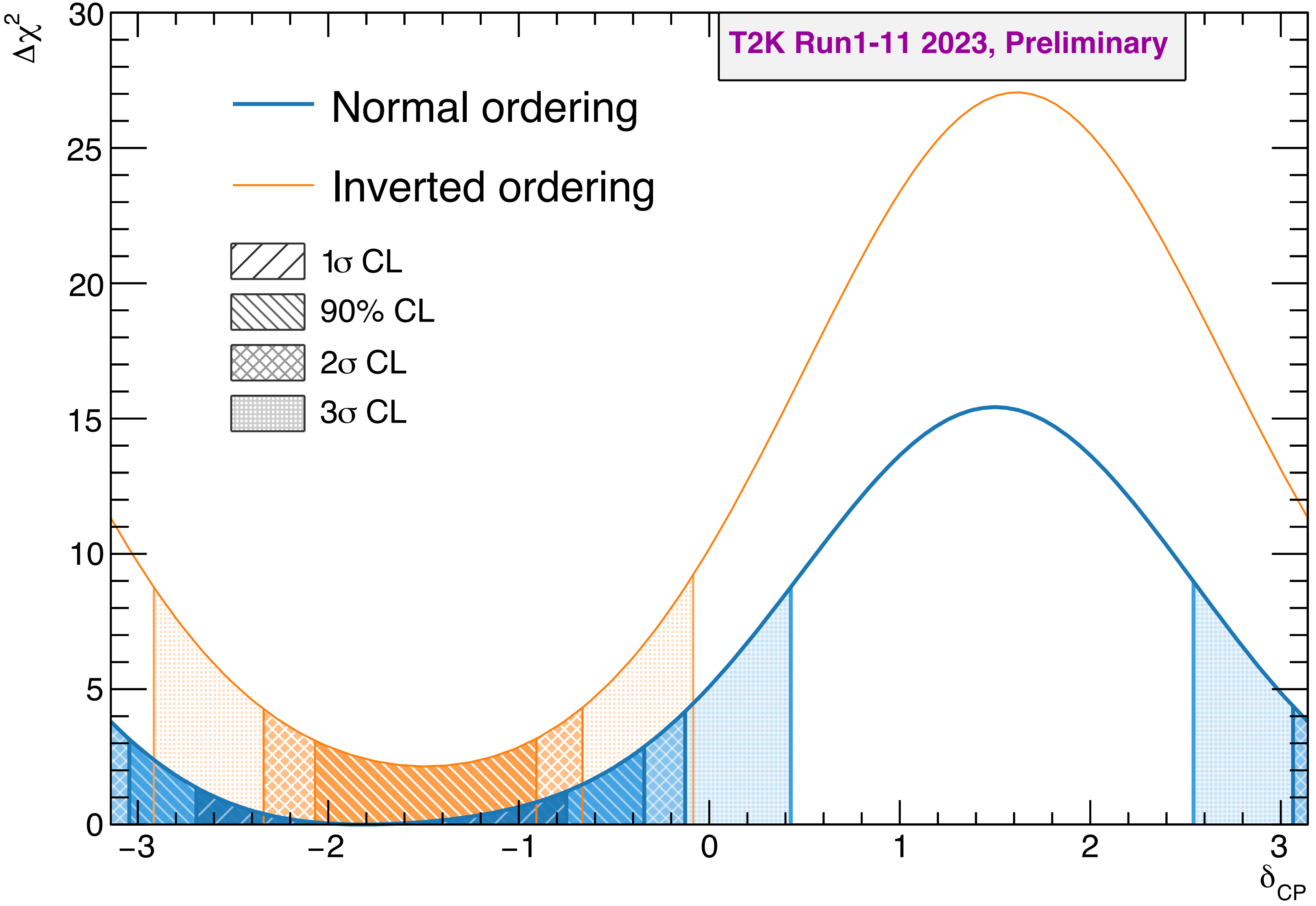
The latest T2K results

Bayesian results





The latest T2K results



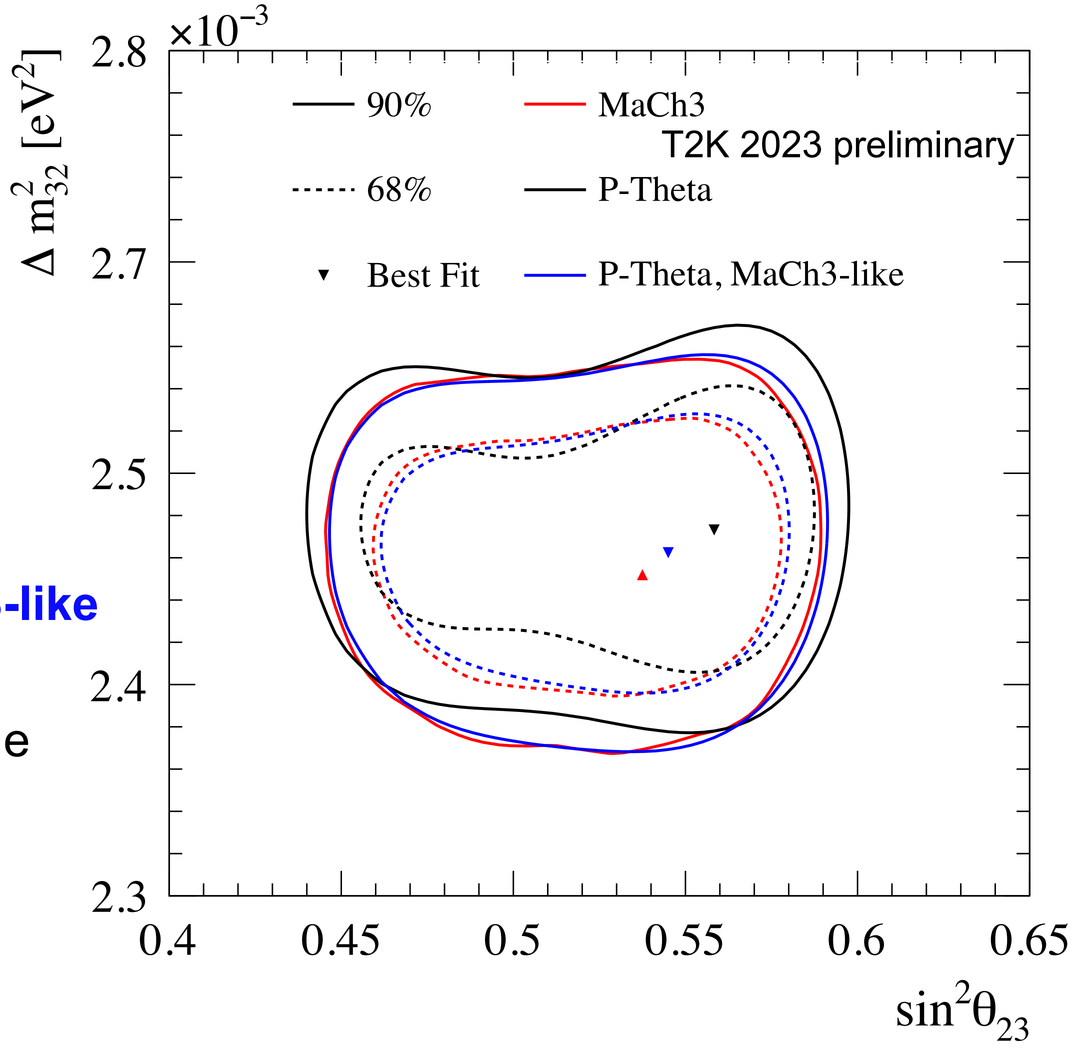
Fitter details

Differences	P-theta	MaCh3
ND samples binning	Regular	Irregular
ND constraints	BANFF	MaCh3
SK μ –like samples binning	$E_{rec} - \theta$	E_{rec}
SK e –like samples binning	$p - \theta$	$E_{rec} - \theta$
Oscillation probability weights	Bin-by-bin	Event-by-event

Other small differences:
non-gaussianity of some ND contraints

P-theta MaCh3-like

NH, wRC, Datafit, $3.1 \cdot 10^{-5}\ eV^2$



- The difference between P-theta and MaCh3 contours is visible
- Removing the main differences (blue) mostly remove the difference in the contours (MaCh3-like)
- Other differences have small impact as expected

New decay electron cut

- In fiTQun, the sub-events recorded after the main-ring event are treated as decay electron candidates.
  - Run 1-10: ~ 5% of decay electron candidates are neutron captures.
  - Run 11:~70% of neutron captures.

- **New cut designed to remove neutron captures from the decay electron signal**

⬇

The new cut:

1. Accept all events with $dt < 1.5\ \mu s$.
2. Reject all sub-events with

$(dt > 20\ \mu s) \cup (dt < 20\ \mu s \cap dt > 0.75N50 - 7.5)$

⬇

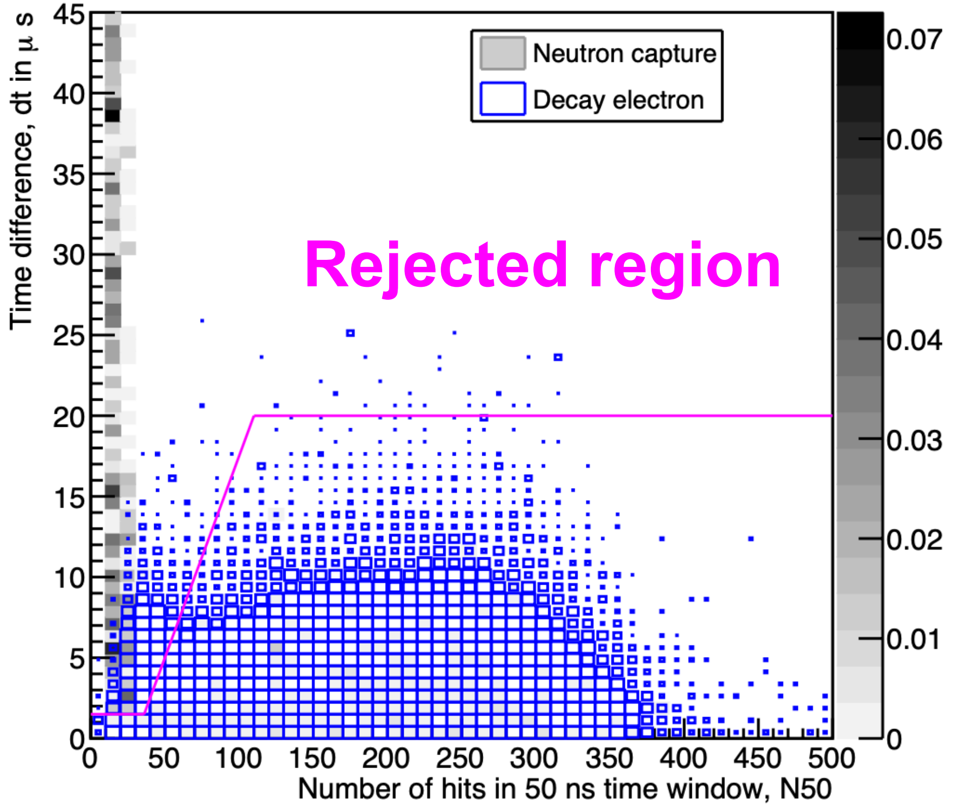
Decay electron selection efficiency and purity ~99%

It is applied to all Runs, not only Run11!

dt –time difference between particle creation time and primary particle creation time

$N50$ –number of hits in 50ns window centred at vertex time

Decay electron candidates in Run 1-10 MC



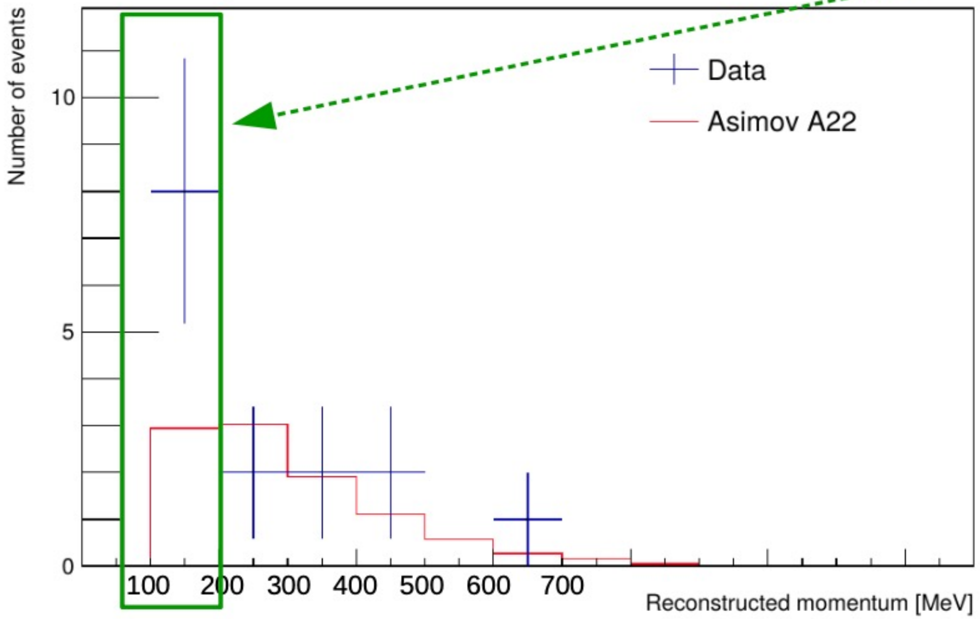
More details Maitrayee's talk: here

FDS: Low momentum excess in the 1Re1de sample

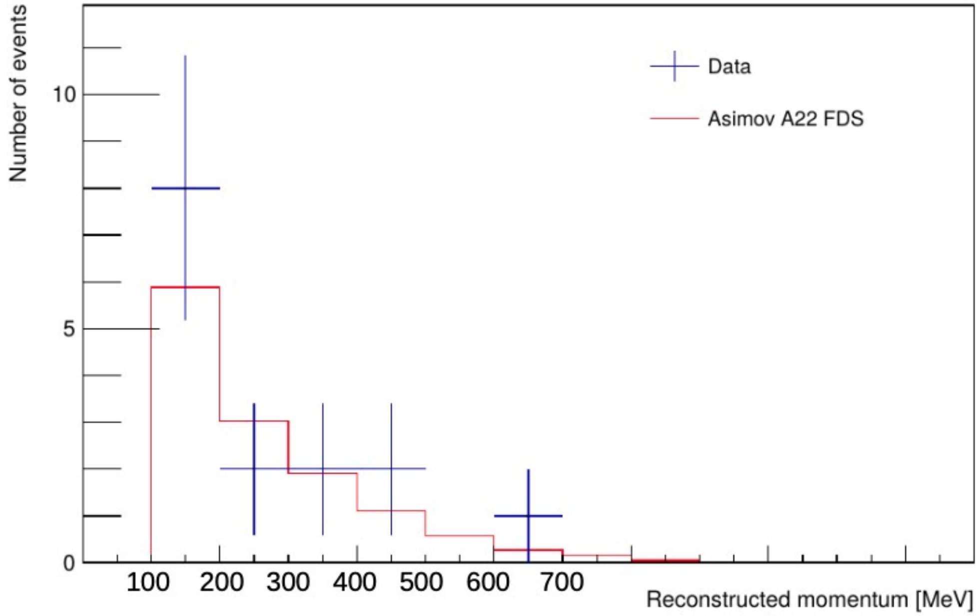
- Since adding 1Re1dcy, a data excess has been observed.

  → Recently realized that it was localized in low p_e bin (< 200 MeV/c).

Asimov 2022 vs Data



Scaled Asimov 2022 vs Data



- For OA2023: roughly evaluate the effect
- **Create a fake data: scale the low pe bin by +100 % & evaluate the impact on contours.**