

Latest Neutrino Oscillation Results from T2K

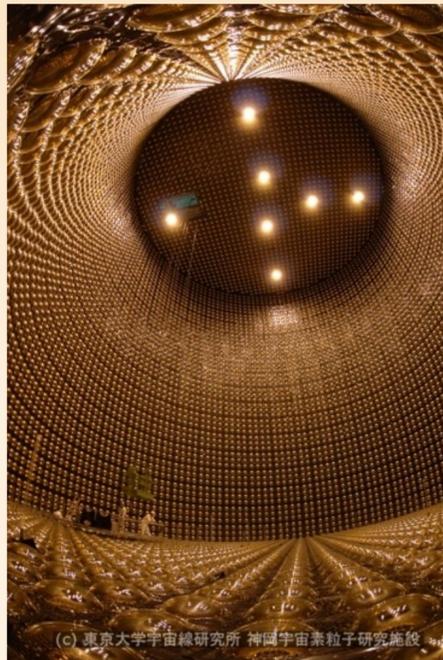
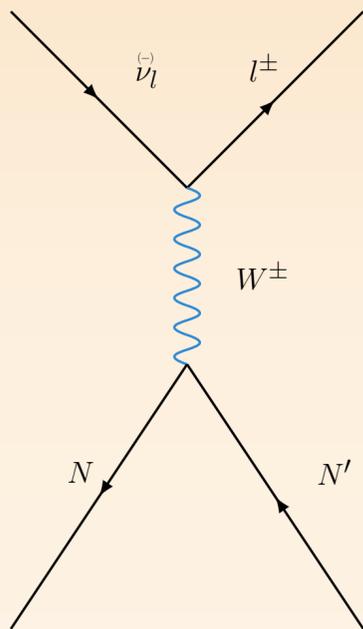


Lucile Mellet on behalf of the T2K collaboration

August 28th, 2023



The T2K Experiment



t2k-experiment.org

39 m

41 m

Super Kamiokande

Near Detector

J-PARC

Mt. Ikeno-Yama
1360 m

Mt. Noguchi-Goro
2924 m

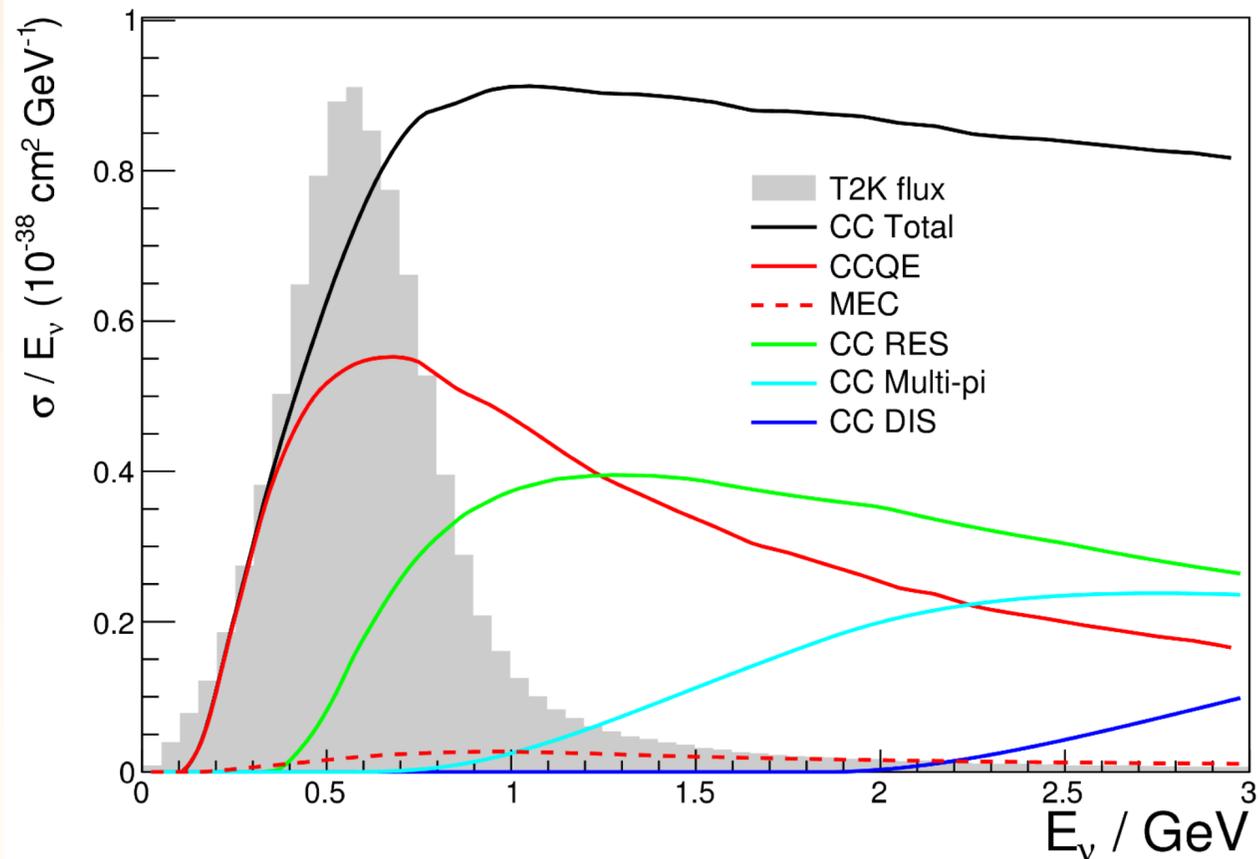
water equiv. 1700 m

Neutrino beam

600 MeV

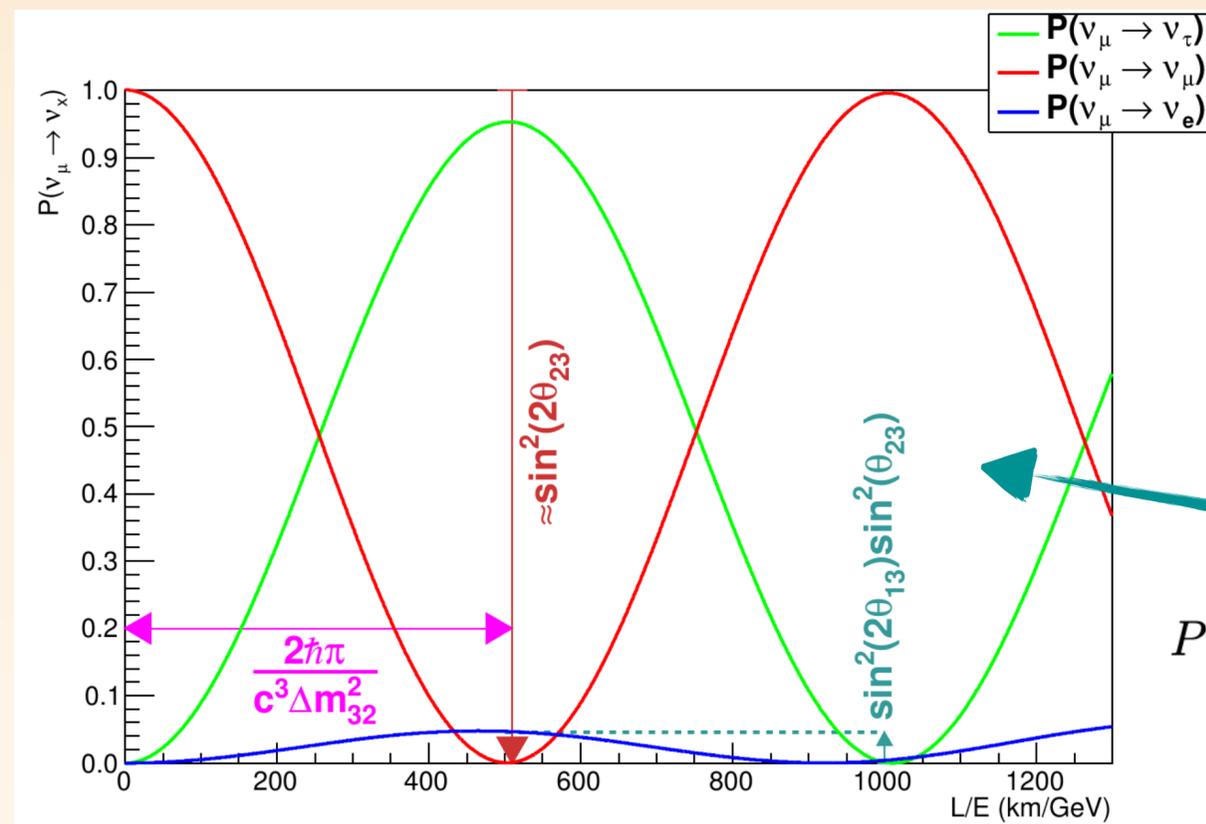
295 km

30 GeV proton
accelerator

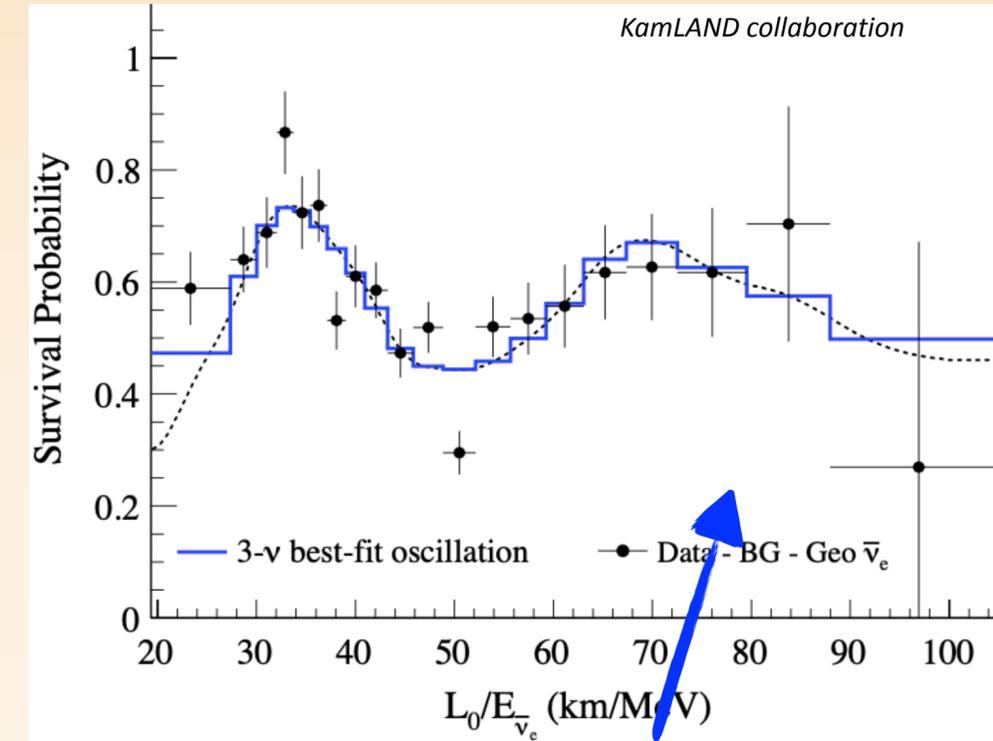


- ❖ Neutrino beam 515 kW (being upgraded)
- ❖ Two horn current polarities $\rightarrow \nu$ or $\bar{\nu}$
- ❖ Long baseline ν oscillation experiment: 295 km
- ❖ Off-axis water Cherenkov detector
 - ❖ 50 kTons of ultra-pure water (+ Gd)
 - ❖ 11000 photo-multiplier tubes (PMT) (+ 2000 for OD)
- ❖ Indirect ν detection through the outgoing charged lepton of the CC interaction
- ❖ Cherenkov light signal coincidence: ring reconstruction

About neutrino oscillation parameters measurements



- ❖ Flavor states $\nu_e \nu_\mu \nu_\tau$
- ❖ Mass states $\nu_1 \nu_2 \nu_3$
- ❖ PMNS^a flavor mixing formalism
- ❖ Parameterized by $\sin^2 \theta_{ij}$ mixing angles, Δm_{ij}^2 and one CP violation phase δ_{CP}



$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) + \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right) \\
 & + \frac{1}{2} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \delta_{CP} \sin \left(\frac{\Delta m_{21}^2 L}{4E} \right) \sin \left(\frac{\Delta m_{31}^2 L}{2E} \right) \\
 & - \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin \delta_{CP} \sin \left(\frac{\Delta m_{21}^2 L}{4E} \right) \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right).
 \end{aligned}$$

❖ T2K is mostly sensitive to :

- ❖ $\sin^2 \theta_{23}, \Delta m_{32}^2$: Atmospheric parameters
- ❖ δ_{CP} : Asymmetry in oscillation probability

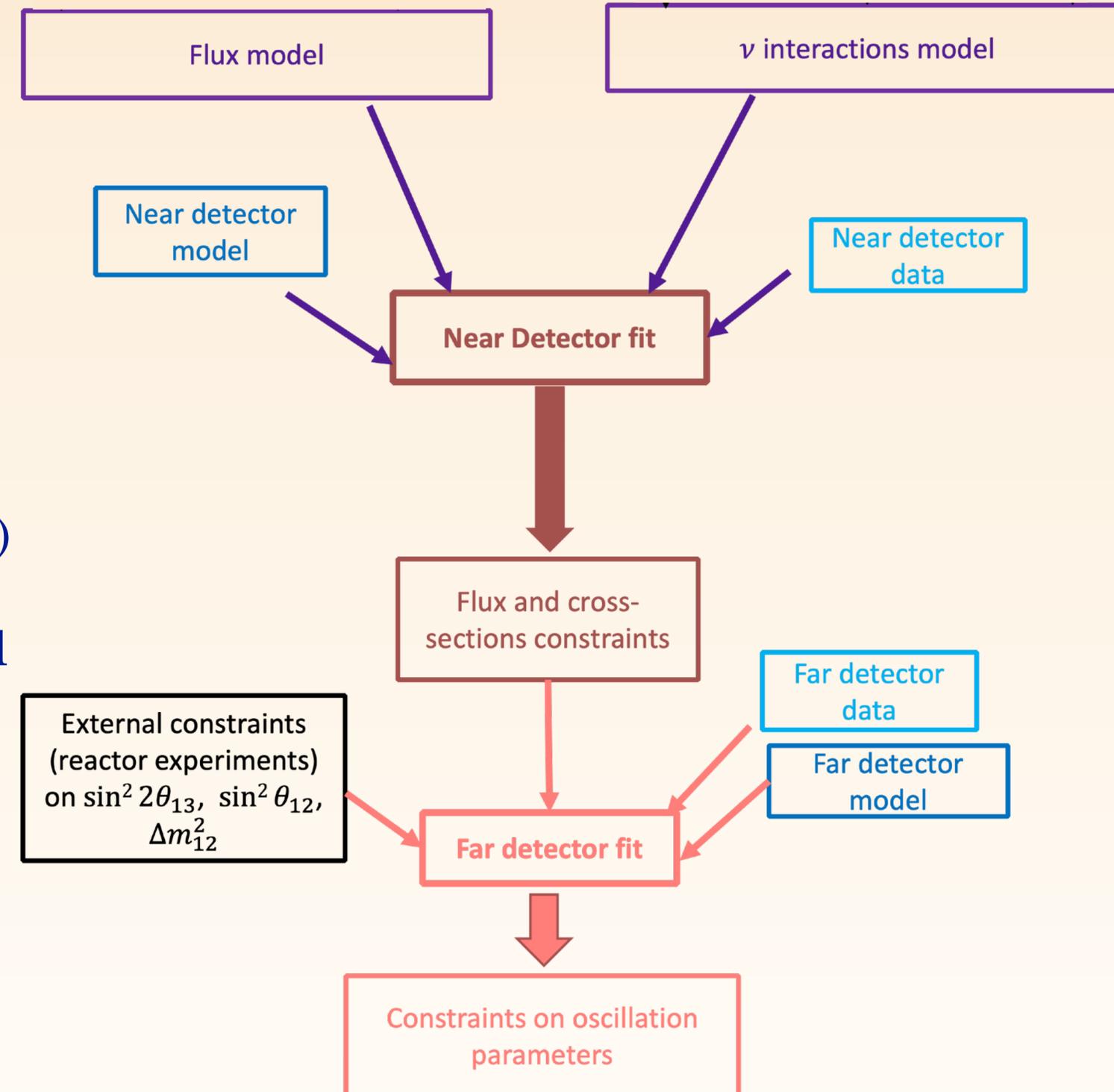
$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \propto \sin(\delta_{CP})$$

^a Pontecorvo-Maki-Nakagawa-Sakata neutrino flavor mixing matrix

The overall analysis pipeline

- ❖ Oscillation analysis
 - ❖ ν_e appearance
 - ❖ ν_μ disappearance
 - ❖ $\nu/\bar{\nu}$ asymmetry in oscillation probabilities
 - ➔ Constrain the oscillation parameters, in particular $\sin^2(\theta_{23})$, Δm_{32}^2 , δ_{CP}
- ❖ External constraints
 - ❖ On $\sin^2 \theta_{13}$, Δm_{12}^2 , $\sin^2 \theta_{12}$ (Gaussian priors)
 - ❖ On flux models (NA61/SHINE : hadron production)
- ❖ Near detector fit: constrain simultaneously the flux and cross-section
- ❖ Far detector fit, 3 fitters : P-Theta, MaCh3, (ValOR)
 - ❖ Near detector fit propagated through a covariance matrix

❖ Analysis workflow (P-Theta & ValOR)



The Near detector data

❖ A set of near detectors (ND): Flux and cross-section measurements (see *N.Latham's talk*)

❖ On-axis

❖ INGRID

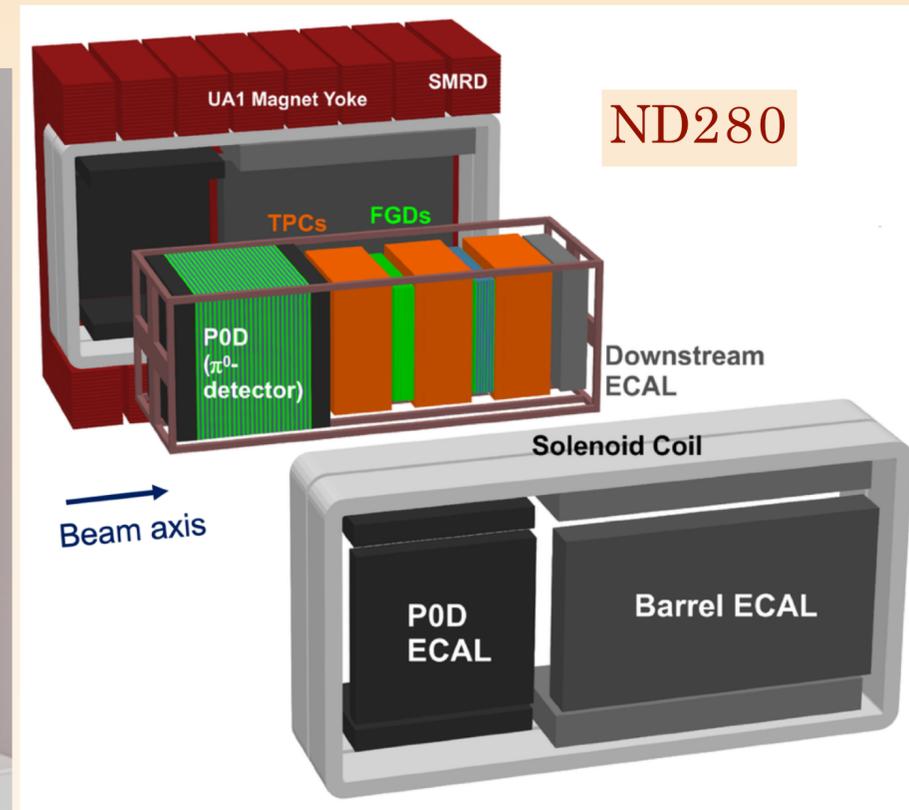
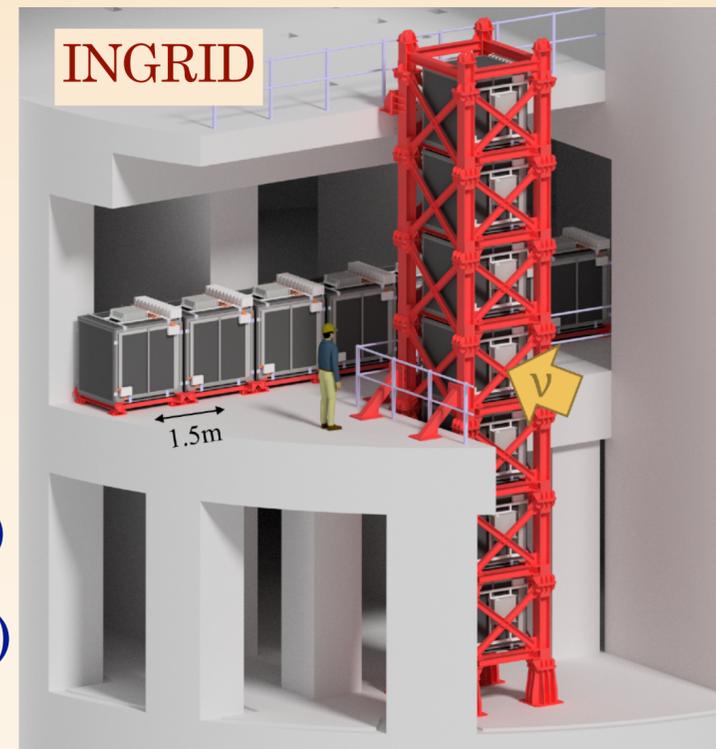
❖ MUMON (muon monitor)

❖ Off-axis

❖ ND280 (Tracker + ECAL + POD + SMRD)

➔ Being upgraded (see *next talk by S.Roth*)

❖ (WAGASCI/BABYMind)

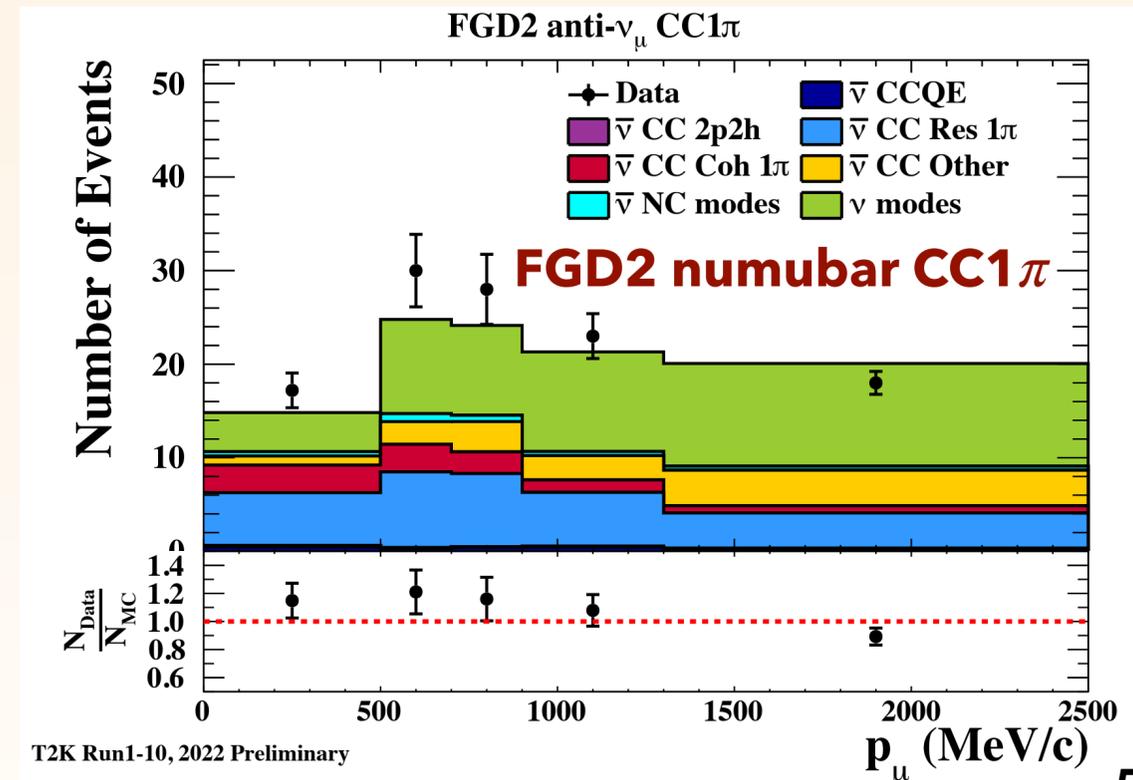
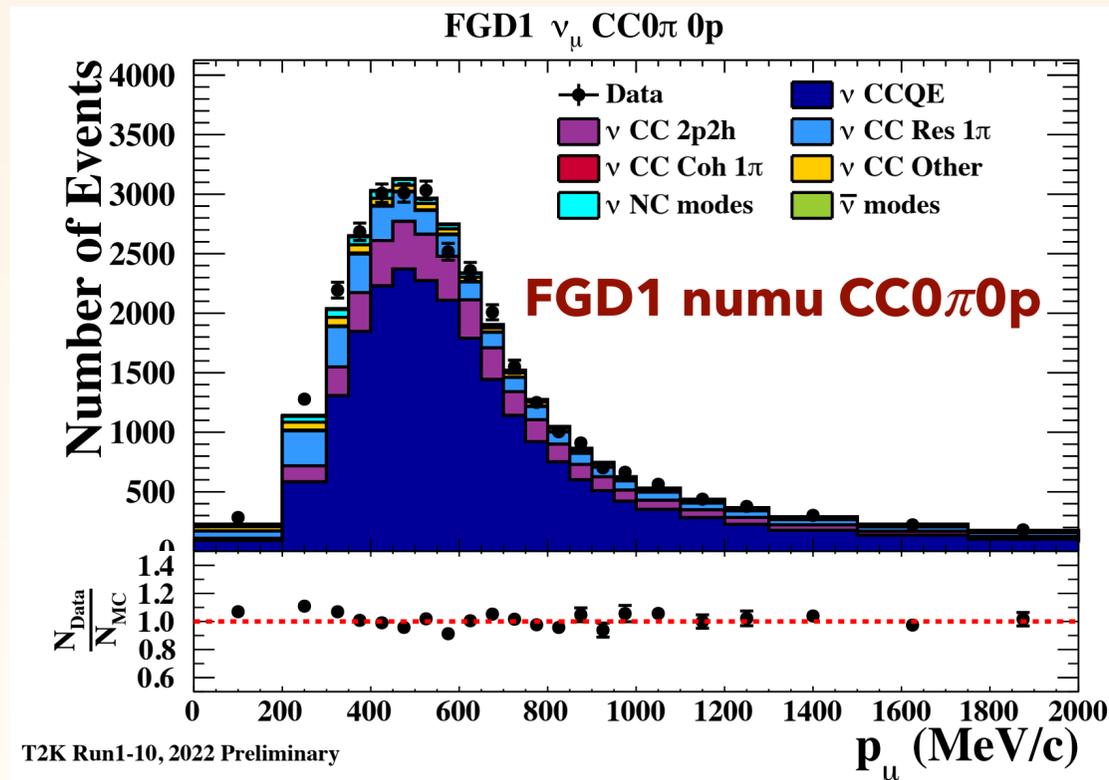


❖ 22 data samples broken down by:

❖ target sub-detector (FGD1,2),

❖ beam mode (ν or $\bar{\nu}$)

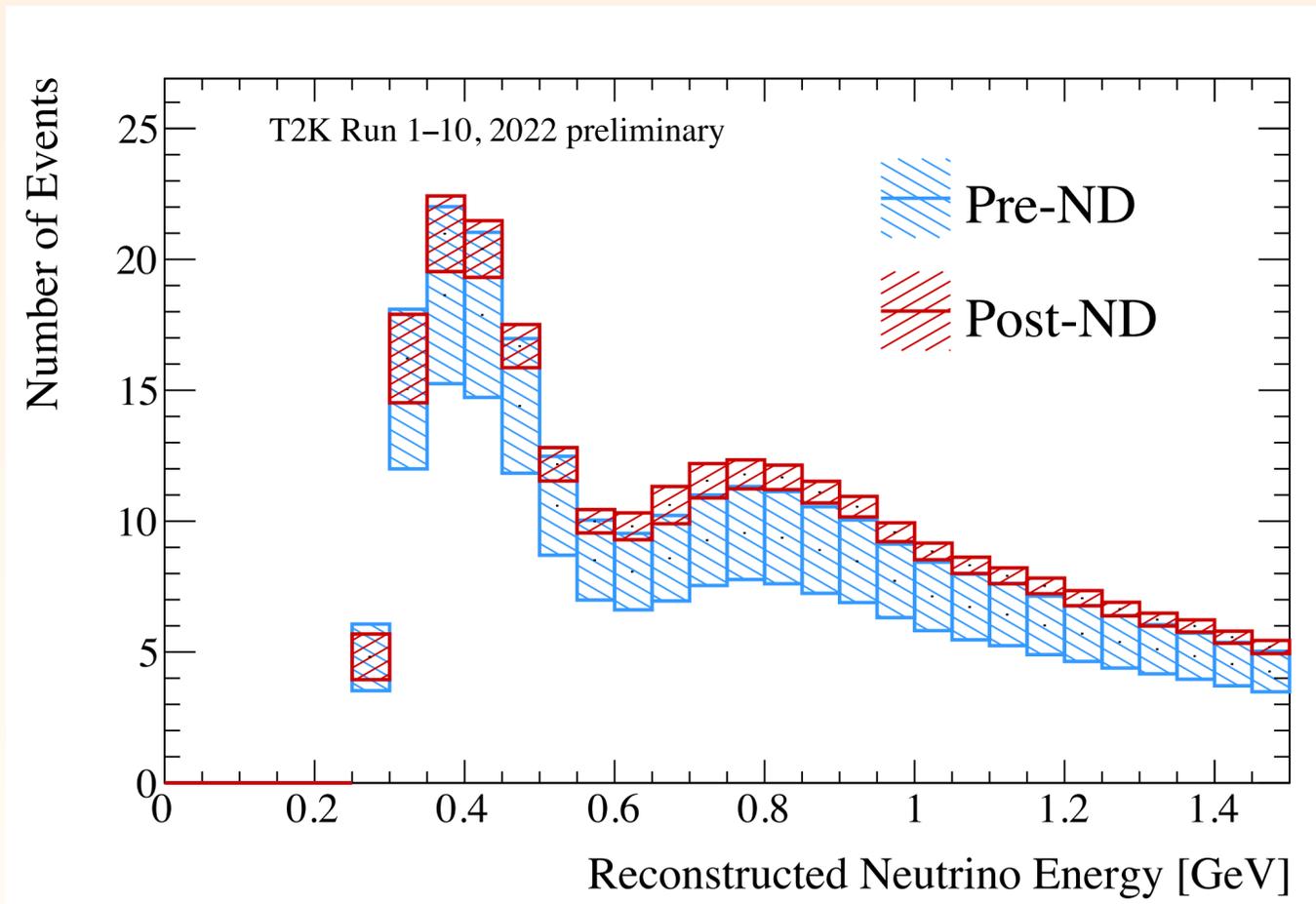
❖ Reconstruction topology (nb of γ, π, \dots)



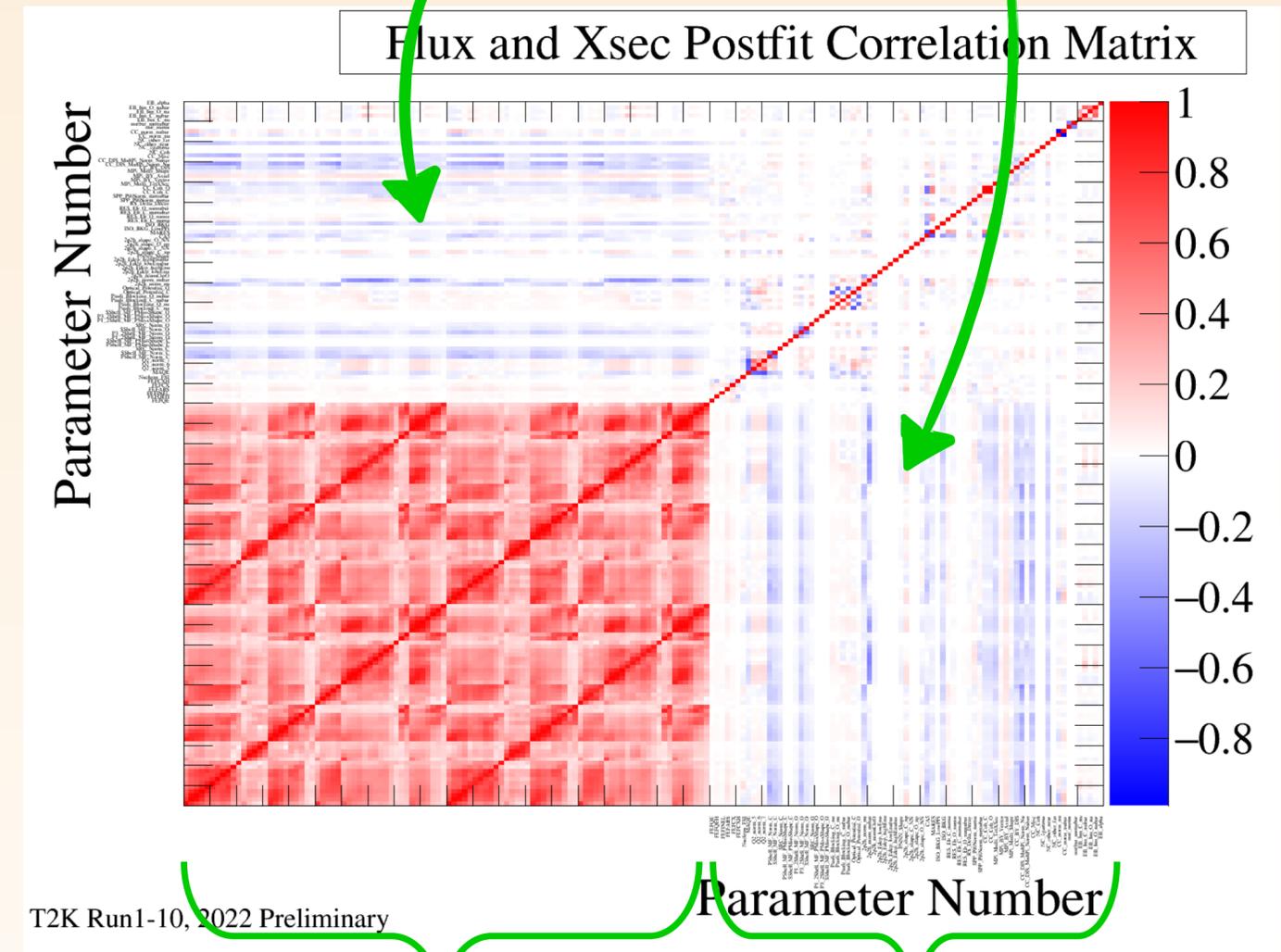
The Near detector fit output for the oscillation analysis

❖ Fit to the near detector data: likelihood maximization

❖ Output = Post ND fit values and covariance of Flux+Cross-section systematic parameters



Flux \times Cross-section correlations



Flux parameters

Cross-section parameters

The Far detector fit

MaCh3

- ❖ Markov Chain MonteCarlo with a Metropolis Hastings algorithm
- ❖ Simultaneous Near and Far detectors data fit
- ❖ Fully Bayesian
- ❖ 1D binning (neutrino reconstructed energy) for FD data

P-Theta

- ❖ Negative log likelihood minimization + marginalization over nuisance parameters
- ❖ FD data fit only, inputs from independent ND fit (BANFF)
- ❖ Semi-frequentist (frequentist analysis with priors from ND fit)
- ❖ 2D binning (Erec-theta, p-theta) or 1D (erec)

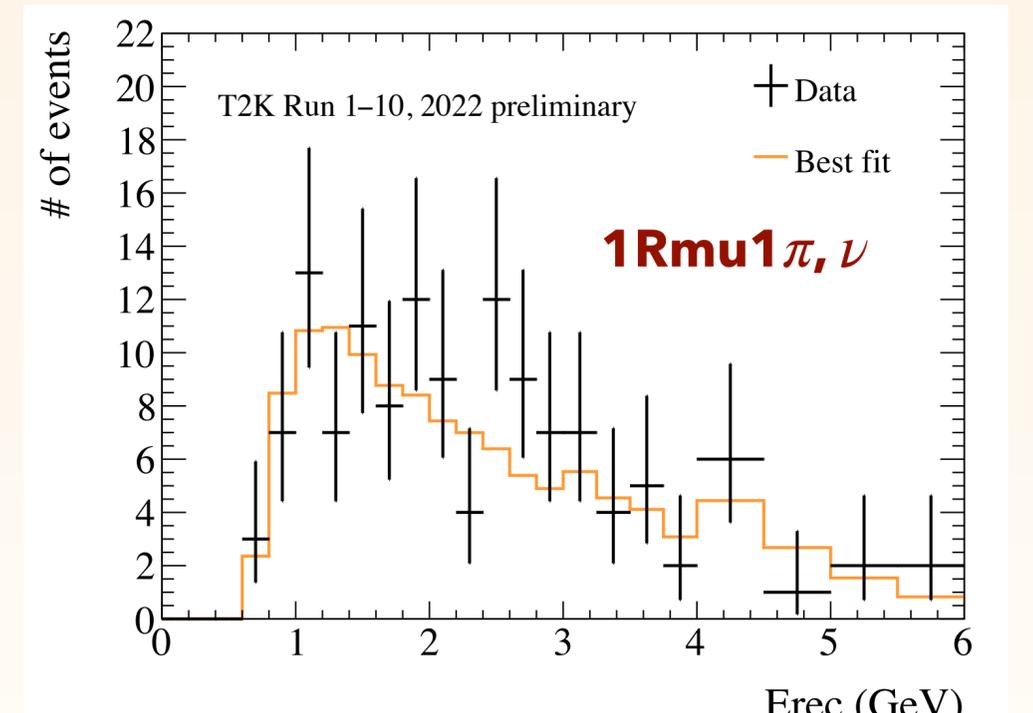
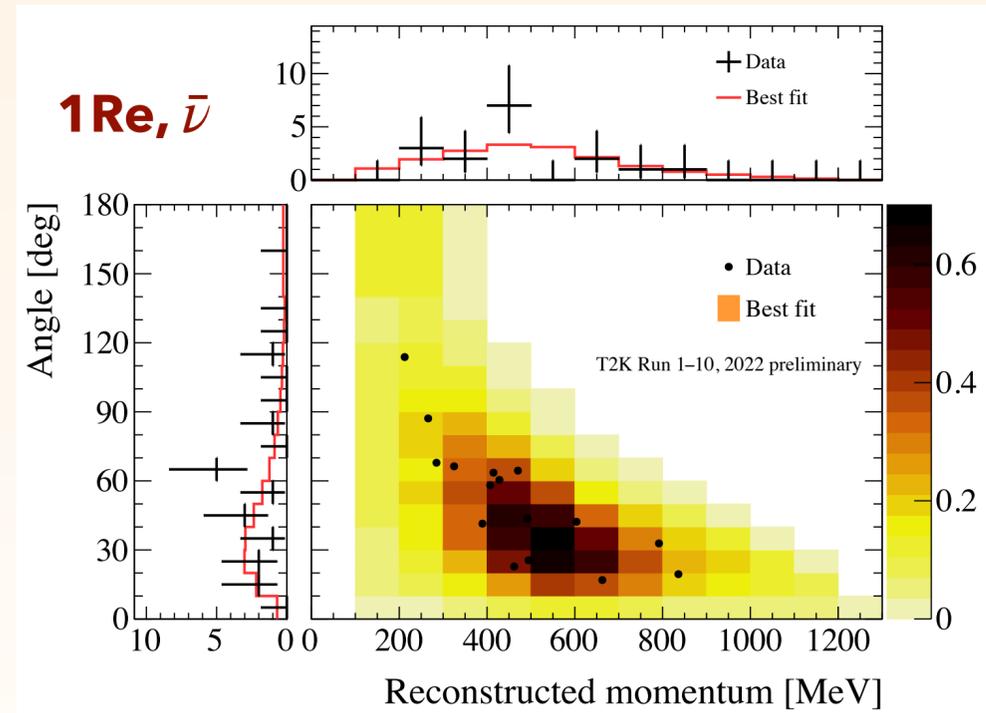
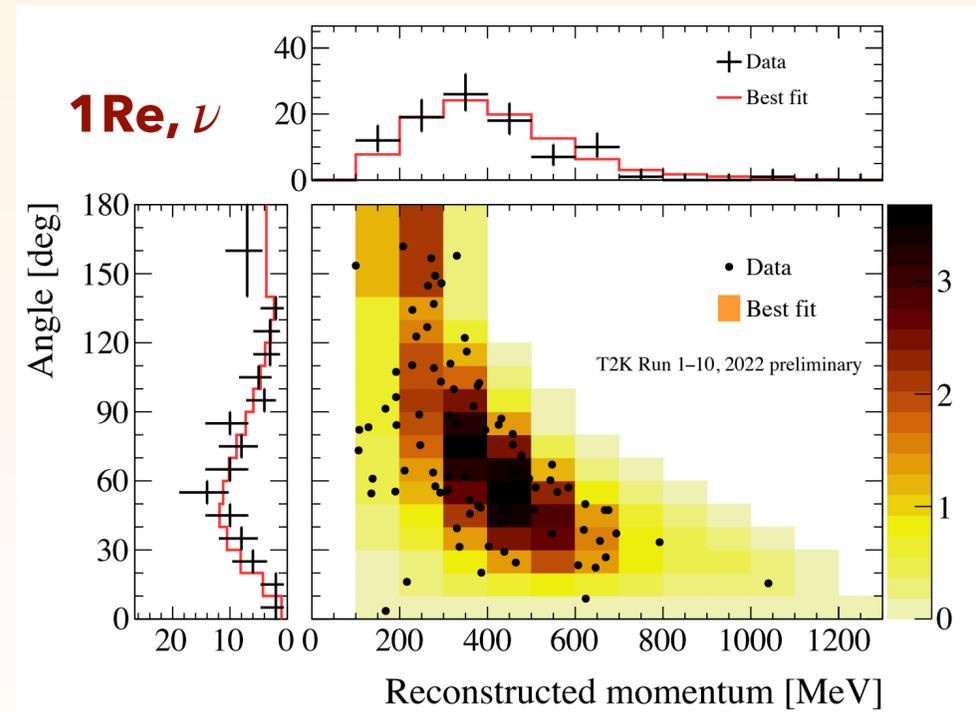
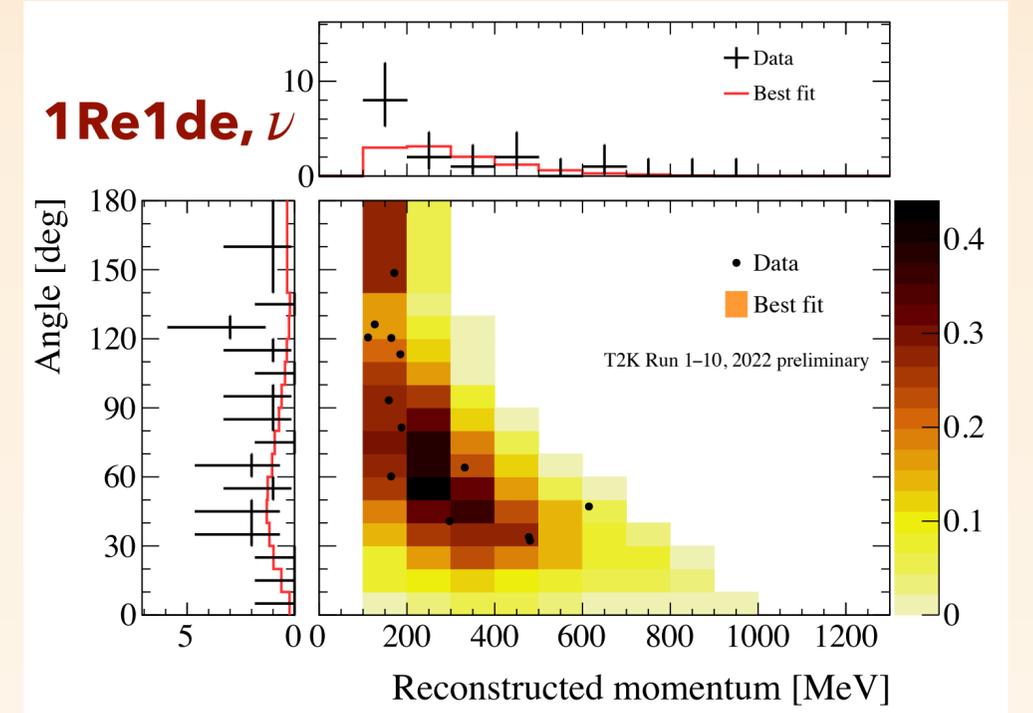
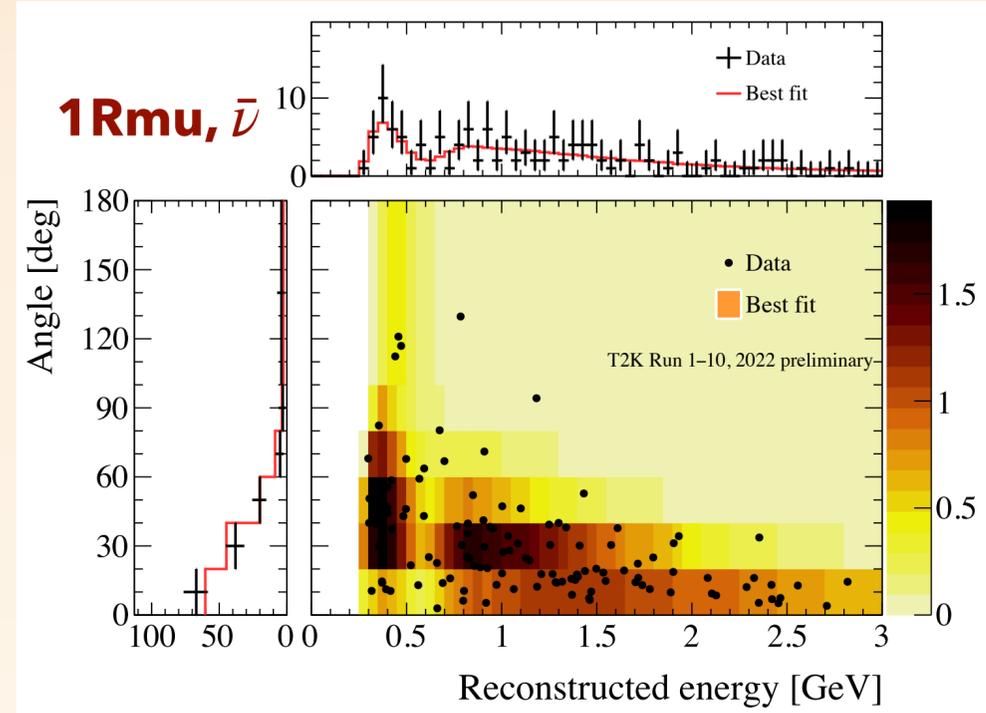
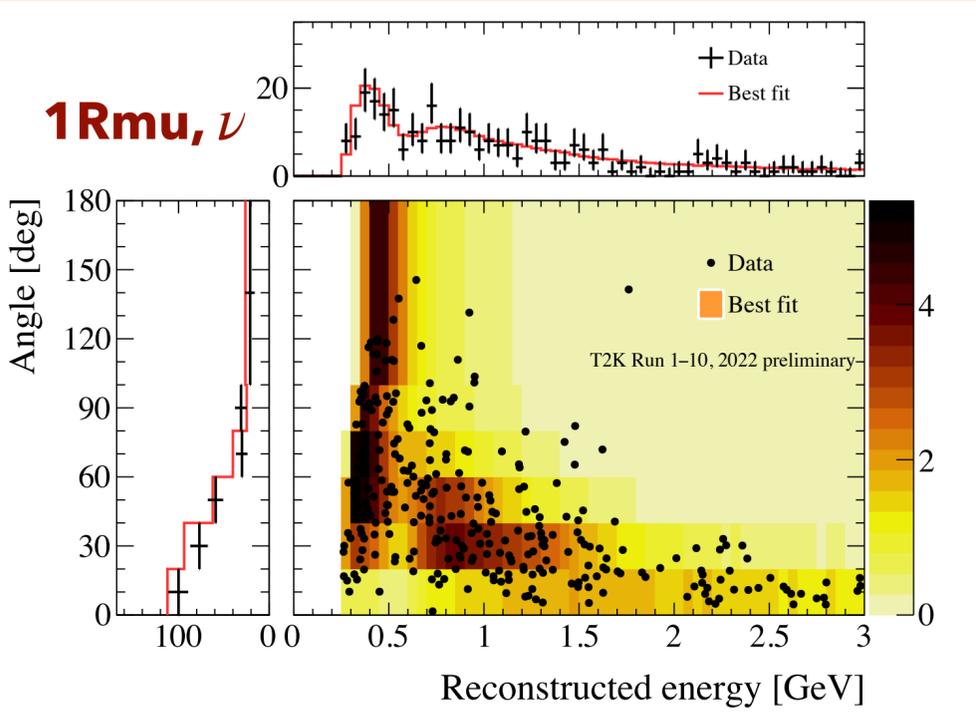
- ❖ Also **ValOR**: Similar to P-theta with a different binning, not used in this analysis

➔ **Confidence** or Credible intervals on the oscillation parameters of interest

(P-Theta results only will be shown in this presentation)

The Far detector fit

❖ 6 analysis samples: 1Re, 1Rebar, 1Rmu, 1Rmubar, 1Re1de, NumuCC1pi



Key new features in the latest analysis

First presented at Neutrino 2022

Update from : arXiv:2305.09916

❖ New analysis sample at the FD: NumuCC1 π (muon-like event, CC interaction, with one pion in the final state)

❖ $\sim 40\%$ increase in ν_μ statistics

❖ Mostly above oscillation maximum \rightarrow mostly useful to confirm robustness of the 'background' model

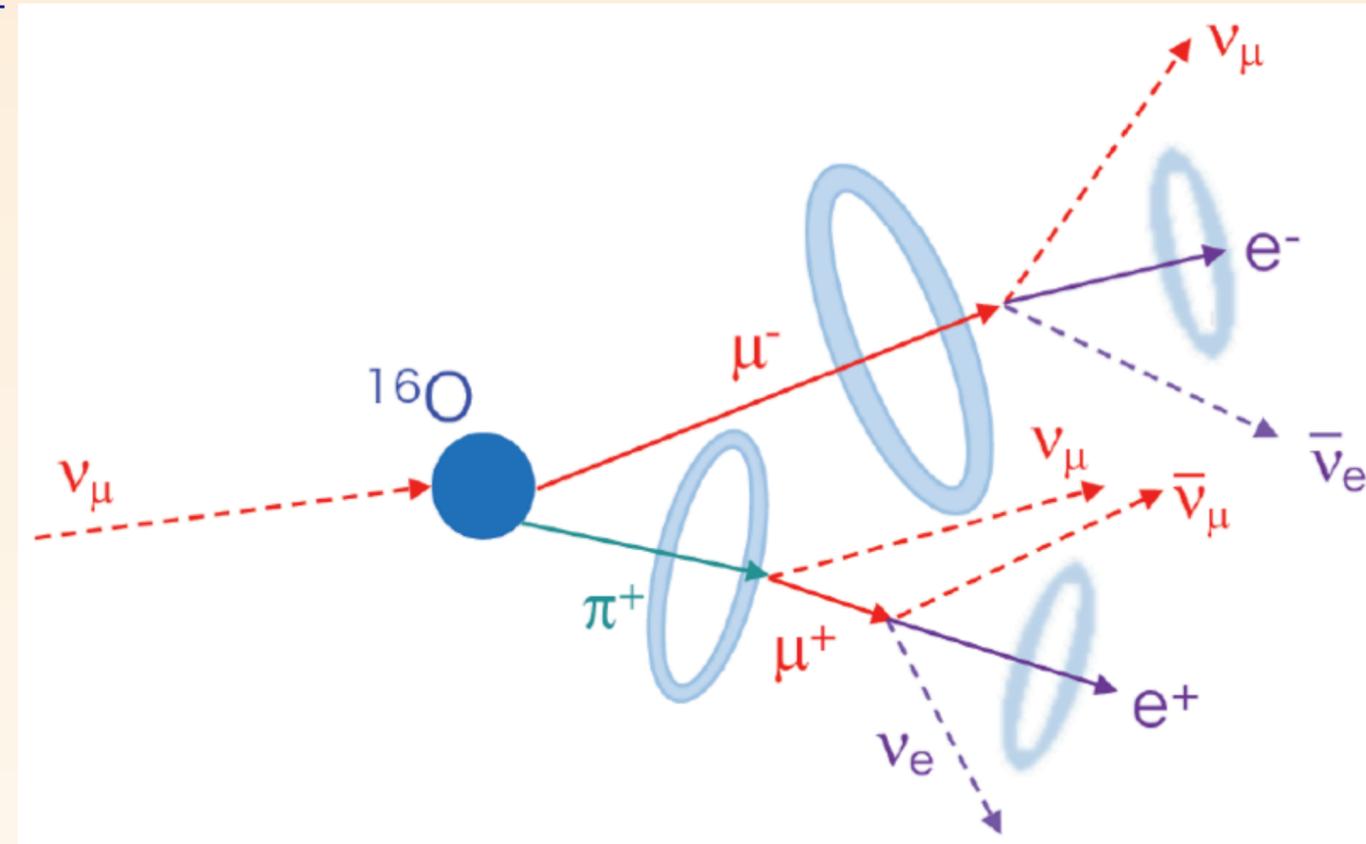
❖ More sophisticated cross section model:

❖ 21 new parameters

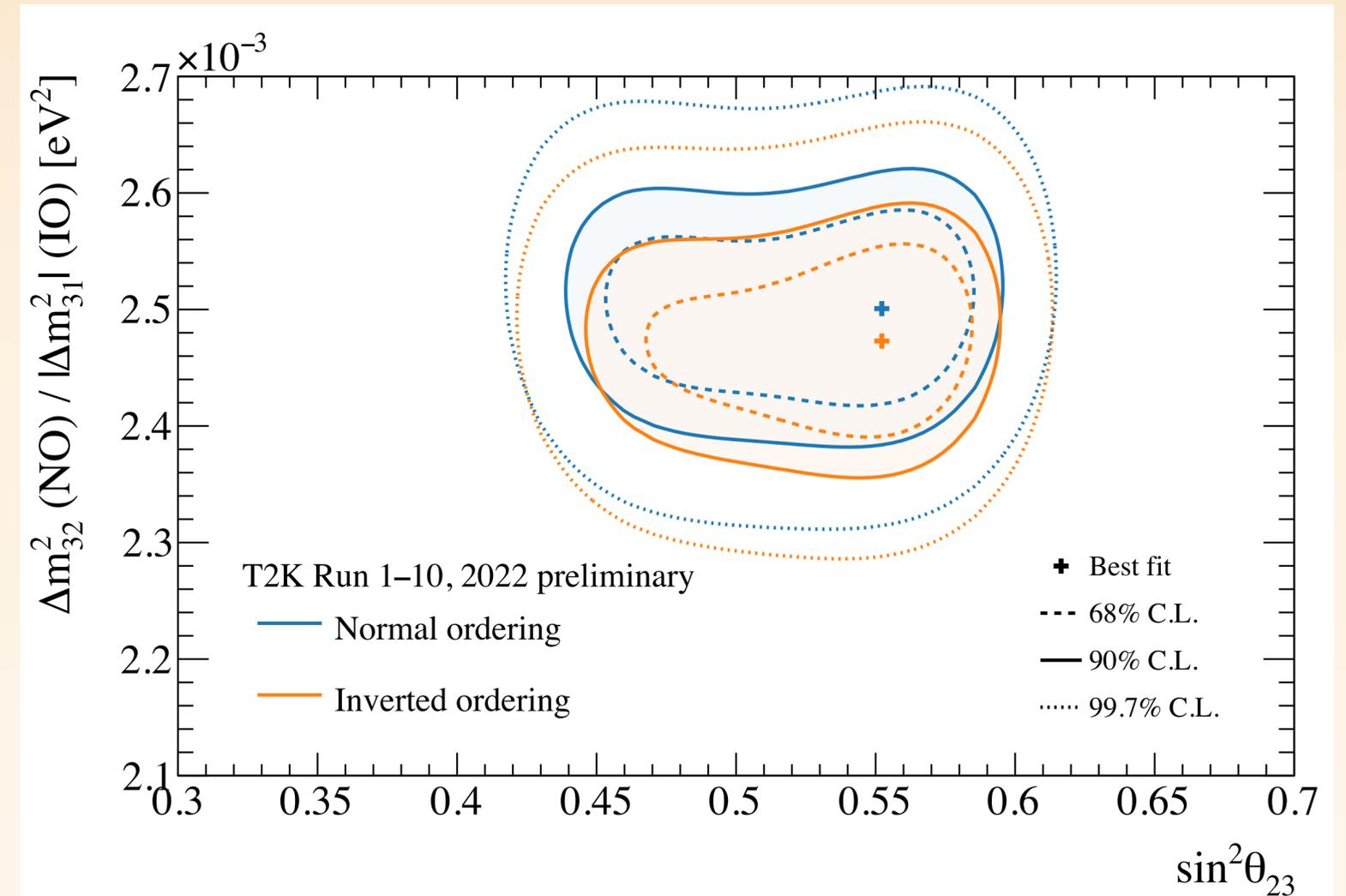
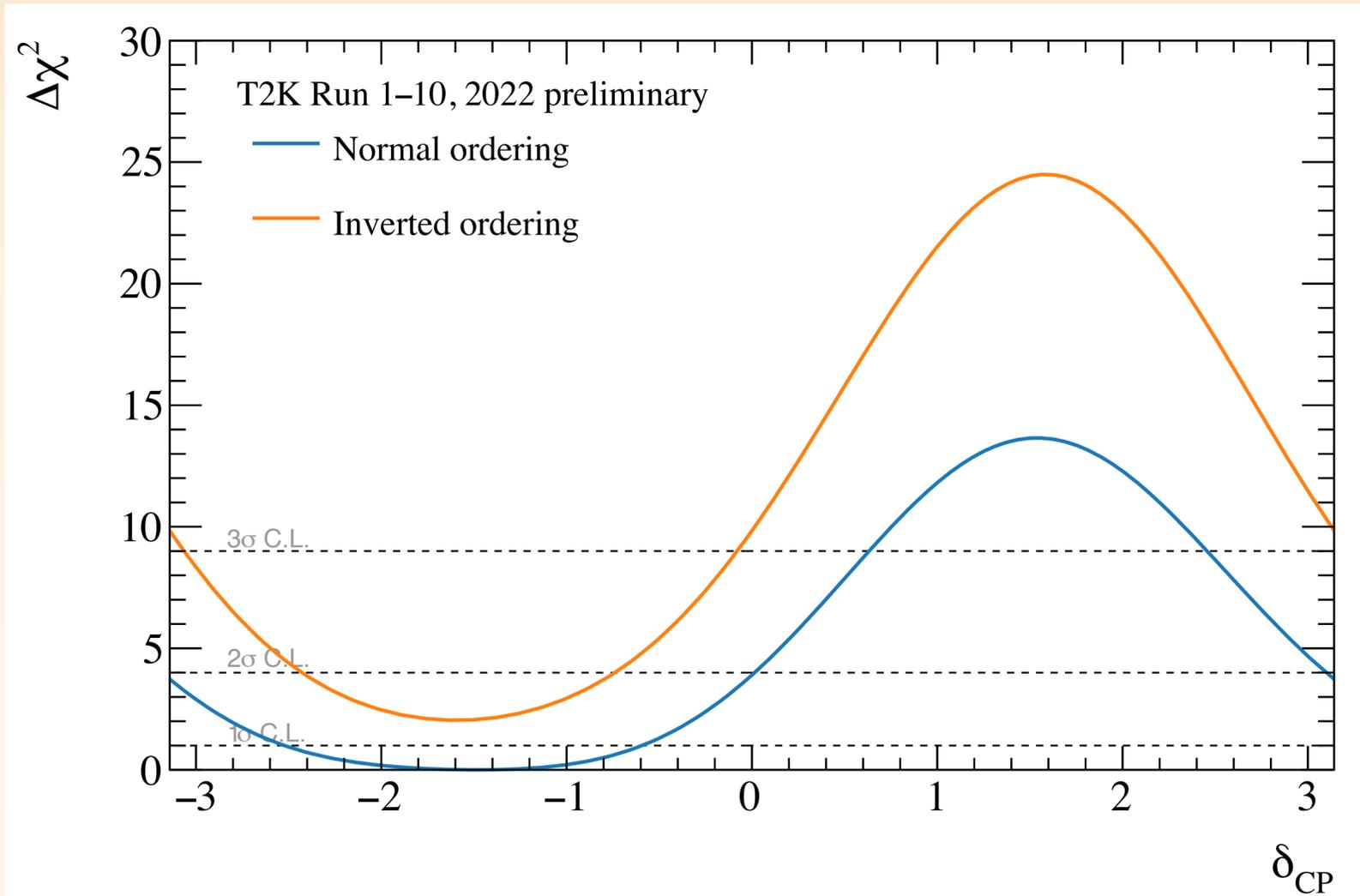
❖ A new implementation of the uncertainties on the removal energy (E_b) and the energy scale parameter

$$E_{rec}^{CCQE} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos \theta_l)}$$

❖ Update of external constraints from PDG 2021



Obtained constraints on oscillation parameters



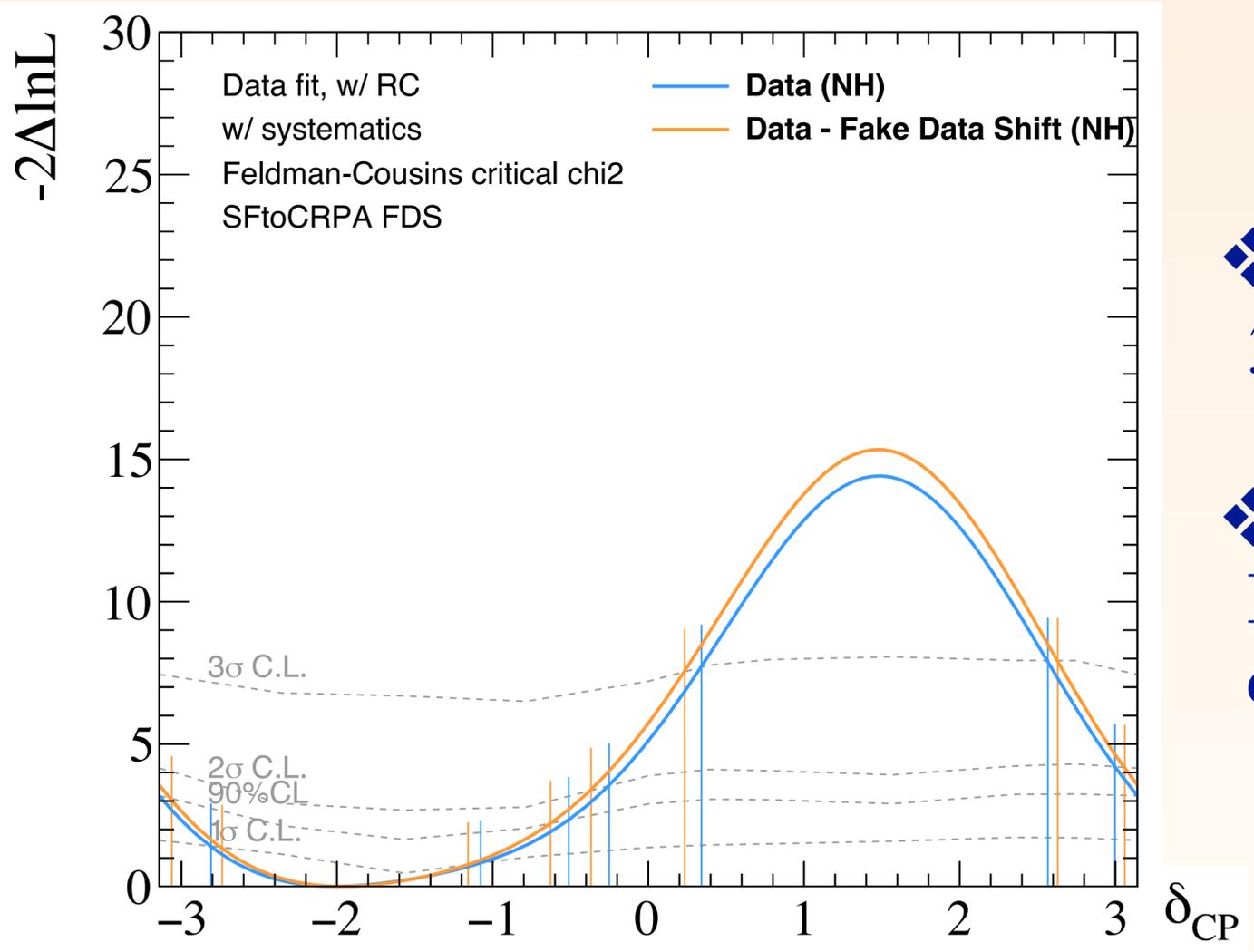
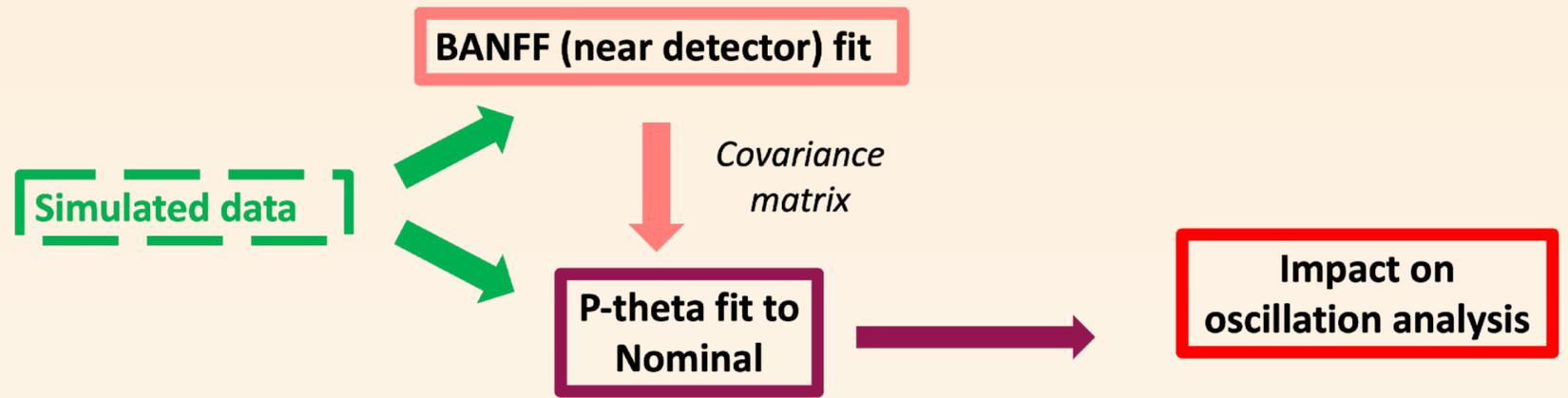
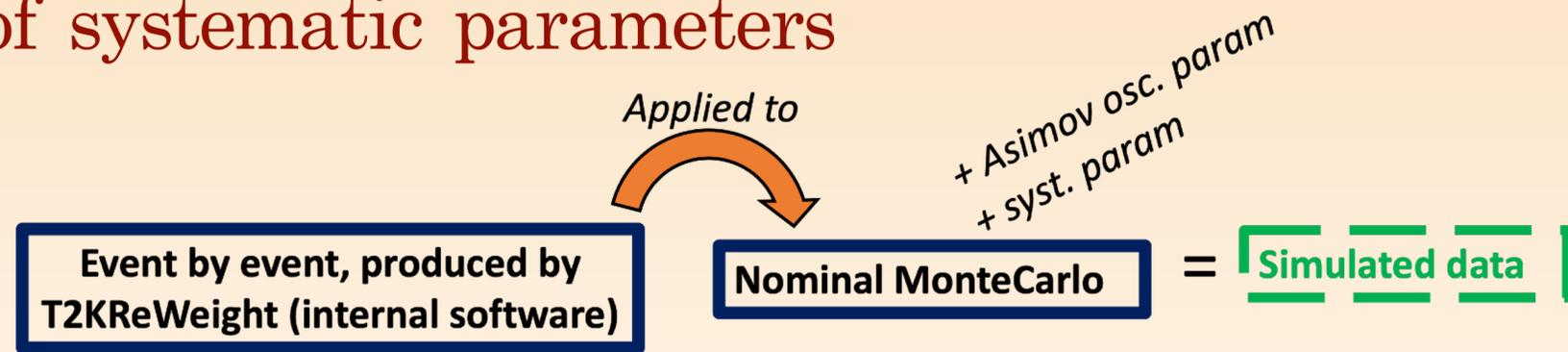
- ❖ Both $\sin^2\theta_{23}$ octants are allowed at 1σ confidence level.
- ❖ Normal mass ordering + upper octant is the favored scenario
- ❖ CP conserving values are excluded at 90% CL.
- ❖ Error at 1σ of about $\pm 5 \times 10^{-5} \text{ eV}^2$ on $\Delta m_{32}^2 \text{ (NO)} / \Delta m_{31}^2 \text{ (IO)}$

Treatment and impact of systematic parameters

- ❖ Test the robustness of the systematic error model against mis-modeling

- ❖ 12 studies

- ❖ Alternative interaction cross-section models
- ❖ Alternative nuclear effects models
- ❖ Data-driven studies



- ❖ Final additional Gaussian smearing on Δm_{3j}^2 : $3.1 \times 10^{-5} eV^2$

- ❖ Also check the impact on δ_{CP} : make sure the Physics conclusions do not change (exclusion of conservation at 90%)

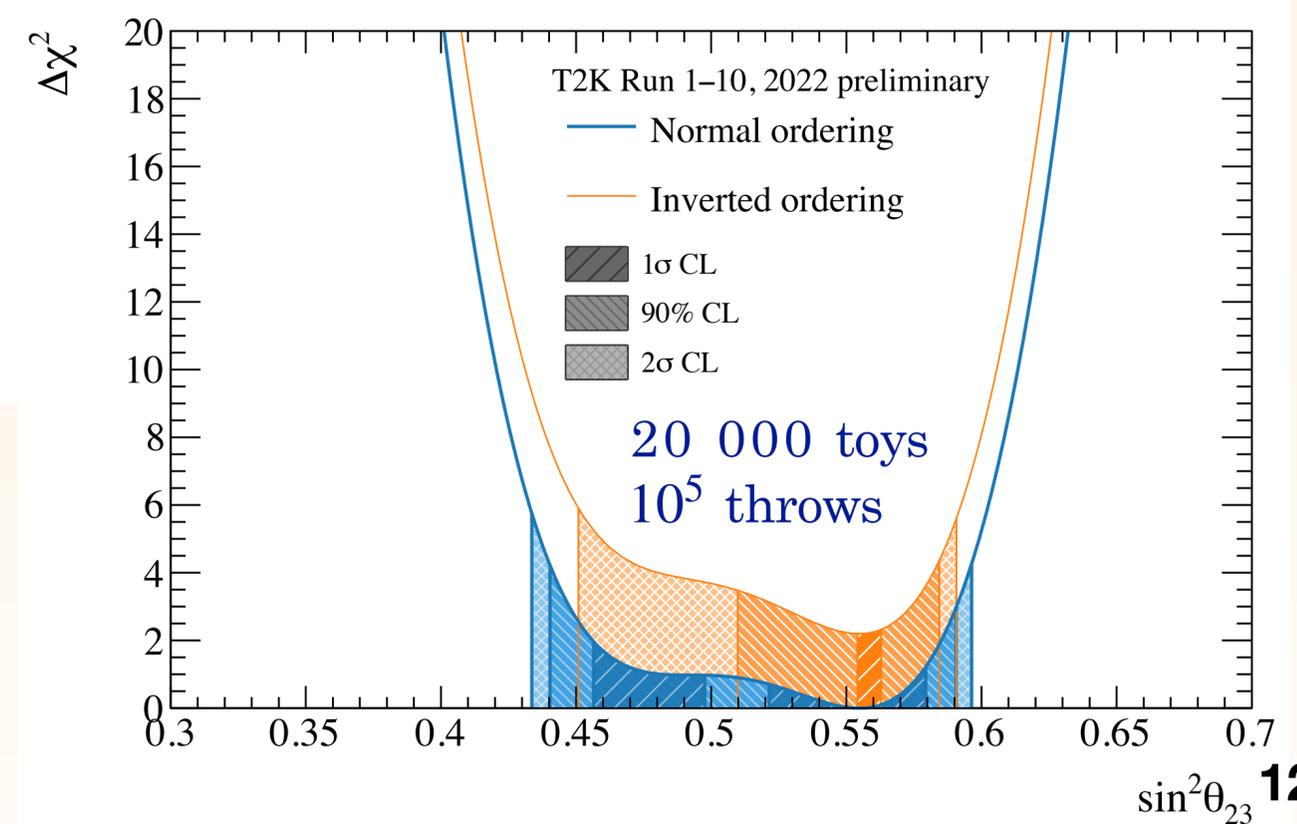
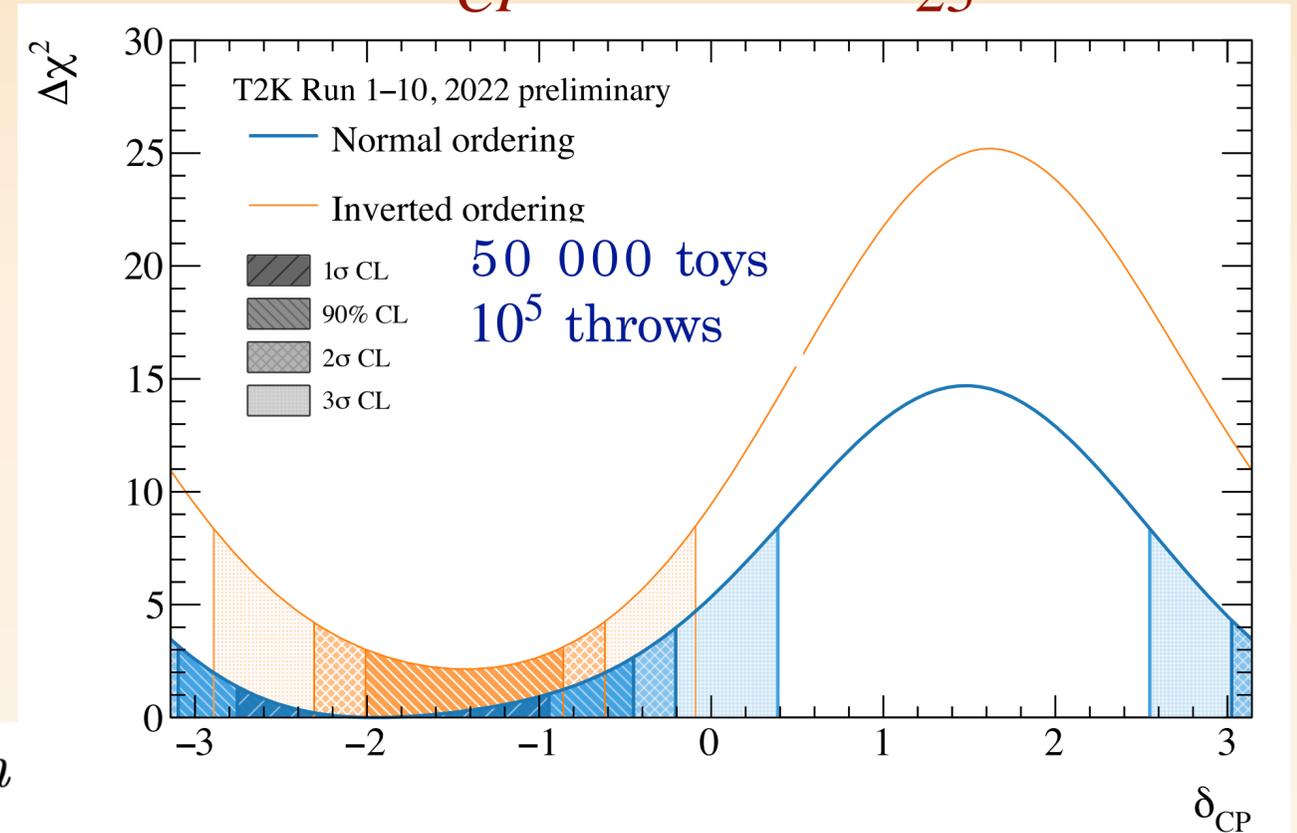
- ❖ $\Delta\chi^2$ shift: simulated data wrt nominal
- ❖ Shift applied to data fit: impact on physics conclusions ?

The Feldman-Cousins statistical treatment of δ_{CP} and $\sin^2 \theta_{23}$

- ❖ Feldman-Cousins studies performed for 2 parameters with inherently non-Gaussian likelihood curves: δ_{CP} and $\sin^2 \theta_{23}$
- ❖ Goal : compute critical χ^2 values to build intervals with the expected coverage

$\Delta\chi^2$ values for standard confidence levels under the Gaussian assumption

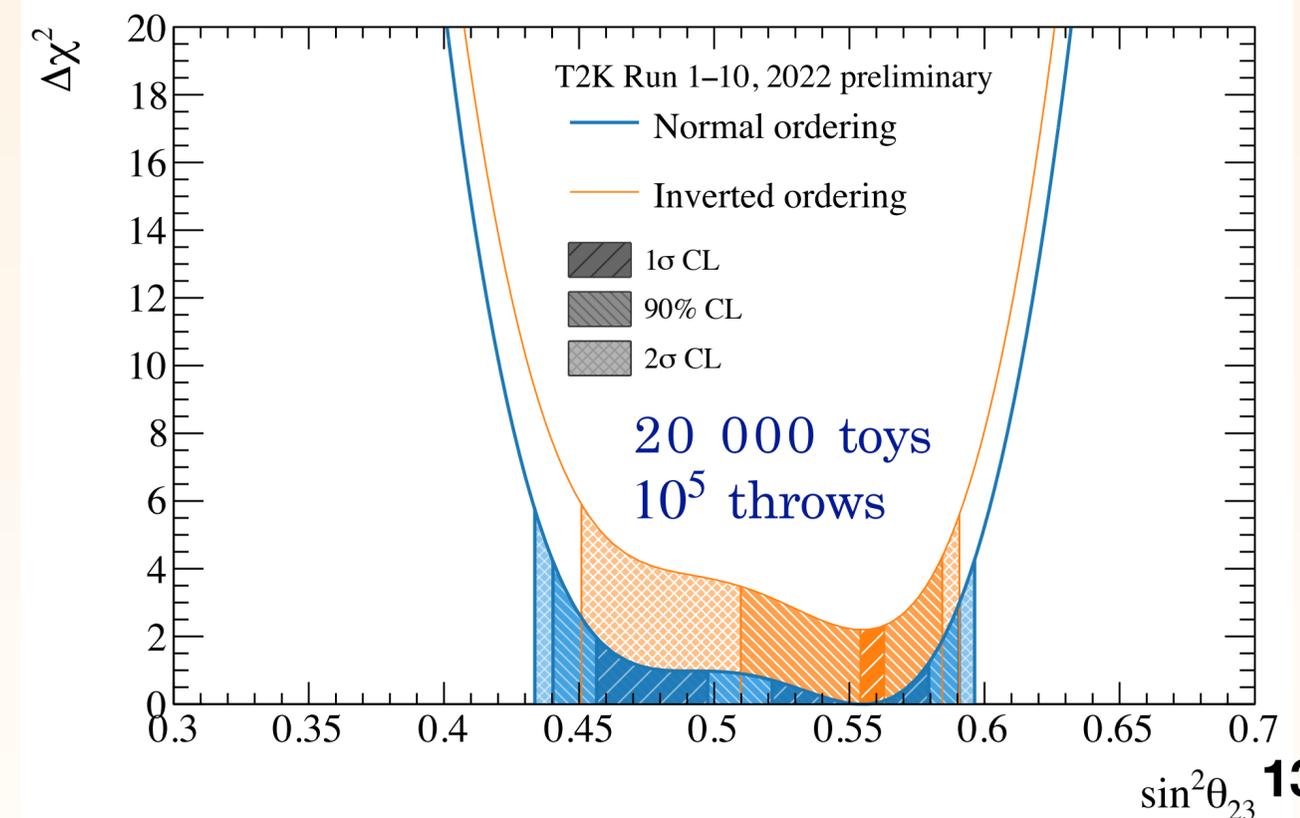
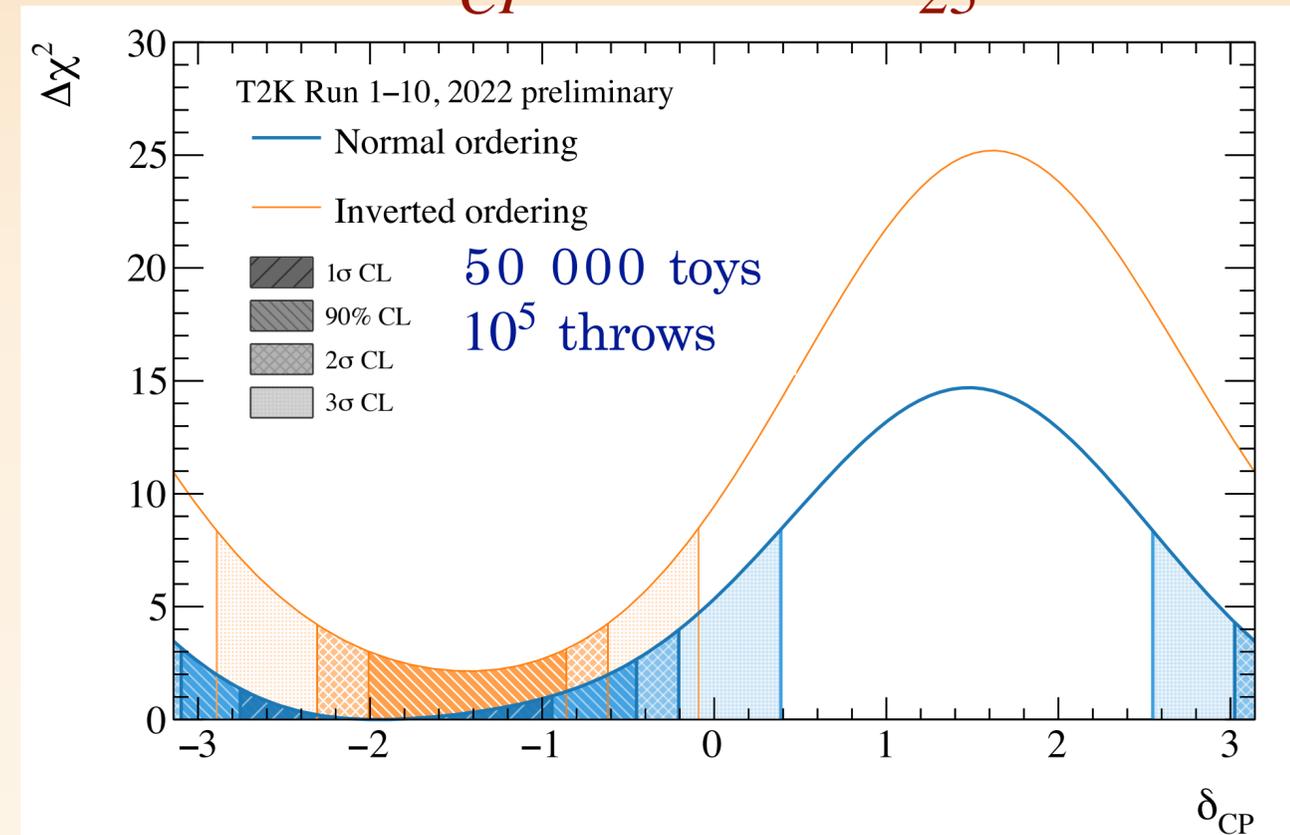
Coverage in %	Usual name	$\Delta\chi^2$ for 1D	$\Delta\chi^2$ for 2D
68.3	1σ	1	2.3
90	90 %	2.71	4.61
95.45	2σ	4	6.18
99.73	3σ	9	11.62



➔ Computed critical χ^2 values are used to build the confidence intervals we quote as our final result

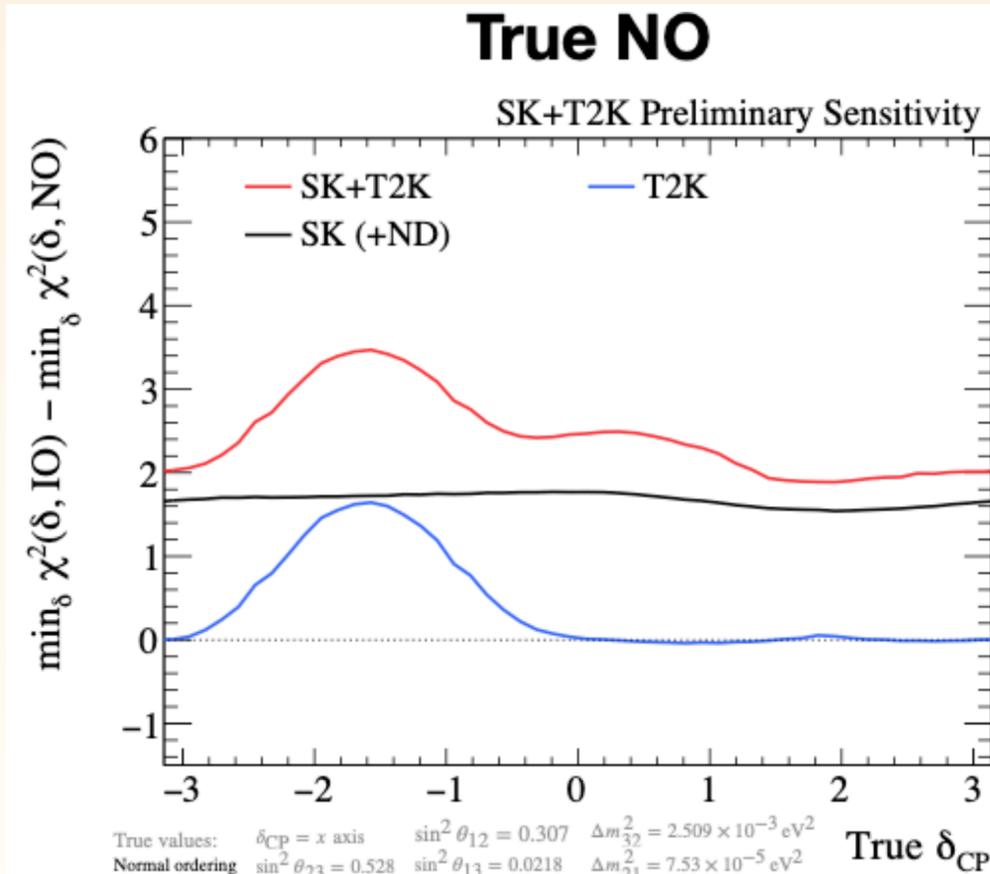
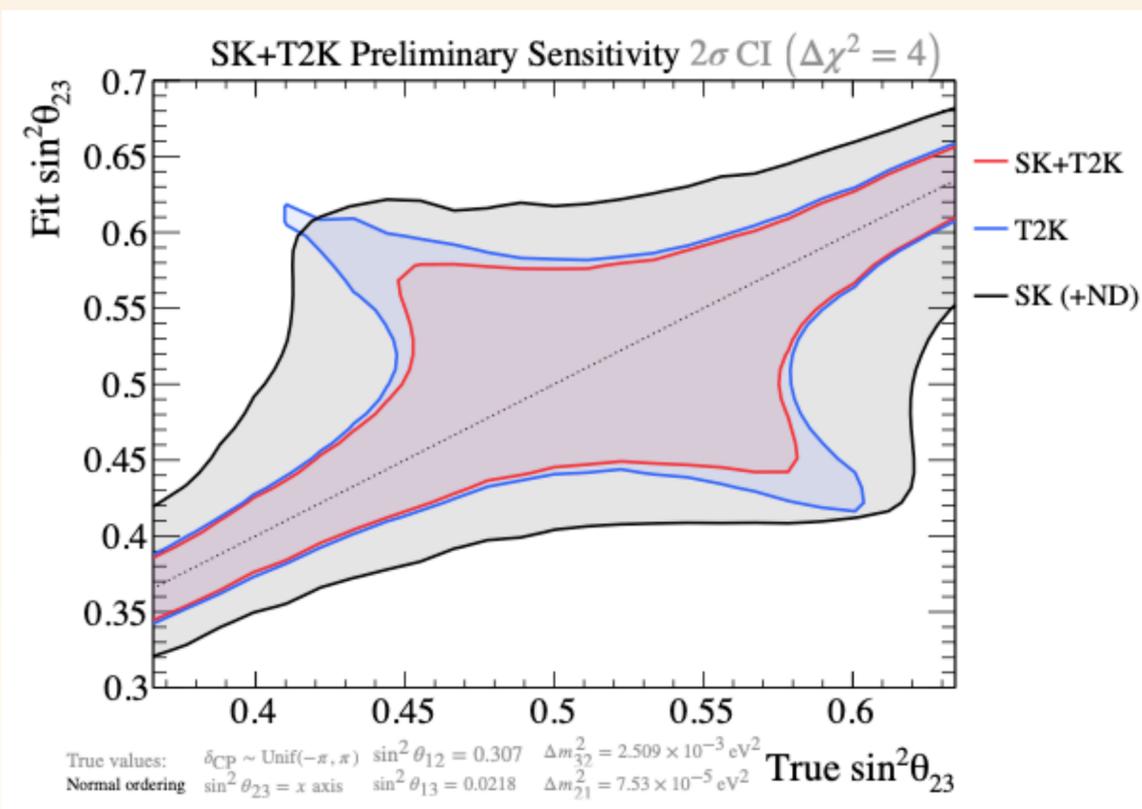
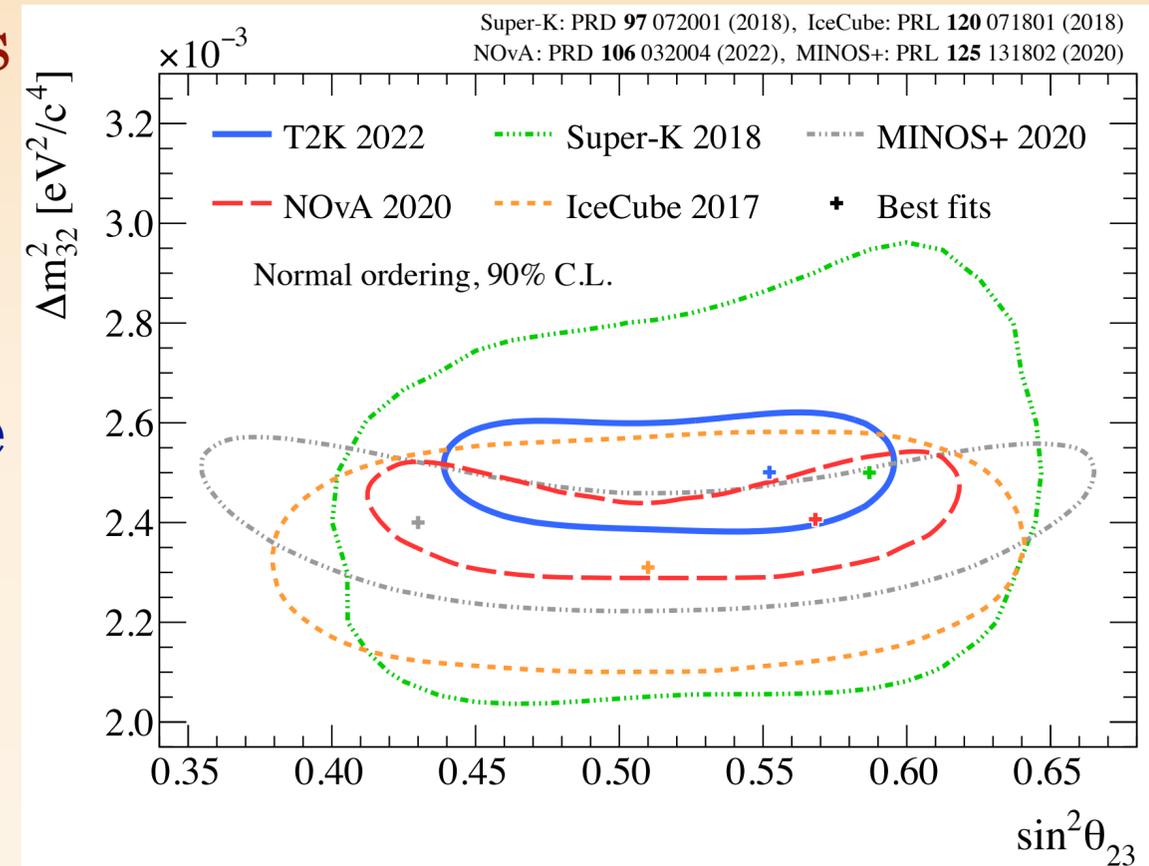
The Feldman-Cousins statistical treatment of δ_{CP} and $\sin^2 \theta_{23}$

- ❖ Feldman-Cousins studies performed for 2 parameters with inherently non-Gaussian likelihood curves: δ_{CP} and $\sin^2 \theta_{23}$
- ❖ Goal : compute critical χ^2 values to build intervals with the expected coverage
- ❖ Many toy experiments are produced and fitted as real data:
 - ❖ Throwing other osc. param from the post data-fit distributions or external Gaussian constraint (for $\sin^2 \theta_{13}$, Δm_{12}^2 , $\sin^2 \theta_{12}$)
 - ❖ Throwing syst parameters from the ND post-fit distributions
- ➔ Computed critical χ^2 values are used to build the confidence intervals we quote as our final result



With Super-Kamiokande atmospheric data:

- ❖ Complementarity (energies, matter effects)
- ❖ Data fits are being finalized (here sensitivity studies are shown)
- ❖ Joint fit expected to improve constraints on octant and mass ordering
- ❖ Step towards Hyper-Kamiokande



With NO ν A accelerator data

- ❖ Similar experiments with different energy and baseline
- ❖ Expects to reduce degeneracy MO/ δ_{CP}
- ❖ Work in progress

What's next ?

- ❖ Dissolution of Gadolinium in Super-K
 - ❖ July/August 2020: 0.01% (13 tons, ~10% of the target quantity)
—> 50% neutron capture efficiency
 - ❖ June/July 2022: 0.03% (39 tons, ~30% of the target quantity)
—> 75% neutron capture efficiency
- ❖ New analysis with Run 11 data
 - ❖ 9% increase in neutrino-mode statistics
 - ❖ Improved selection of the decay electrons (to separate from neutron capture on Gd (0.01%) signals)
 - ❖ New estimation of detector uncertainties in Super-K
- ➔ Currently being finalized

Stay tuned!

Conclusion

- ❖ More and more care is given to the treatment of systematic parameters, notably for the precision measurement of the disappearance parameters
 - ❖ More refined cross-section systematic model
 - ❖ More fake data studies
- ❖ Inclusion of a new sample (numuCC1 π) confirmed the robustness of the model including for sub-leading contributions
 - ➔ *To be published soon*
- ❖ Combined analyses are ongoing and entering final stages of the analysis
 - ❖ Prospect to reduce degeneracies between parameters
- ❖ T2K is getting ready to use neutron-tagging information from the Gadolinium loading in Super-K
- ❖ T2K near detectors and beam are being upgraded: ND280 upgrade expected to have a large impact on the OA *stay for next talk by S.Roth*
- ❖ New results are to be expected soon

Thank you for your attention !

Back-up

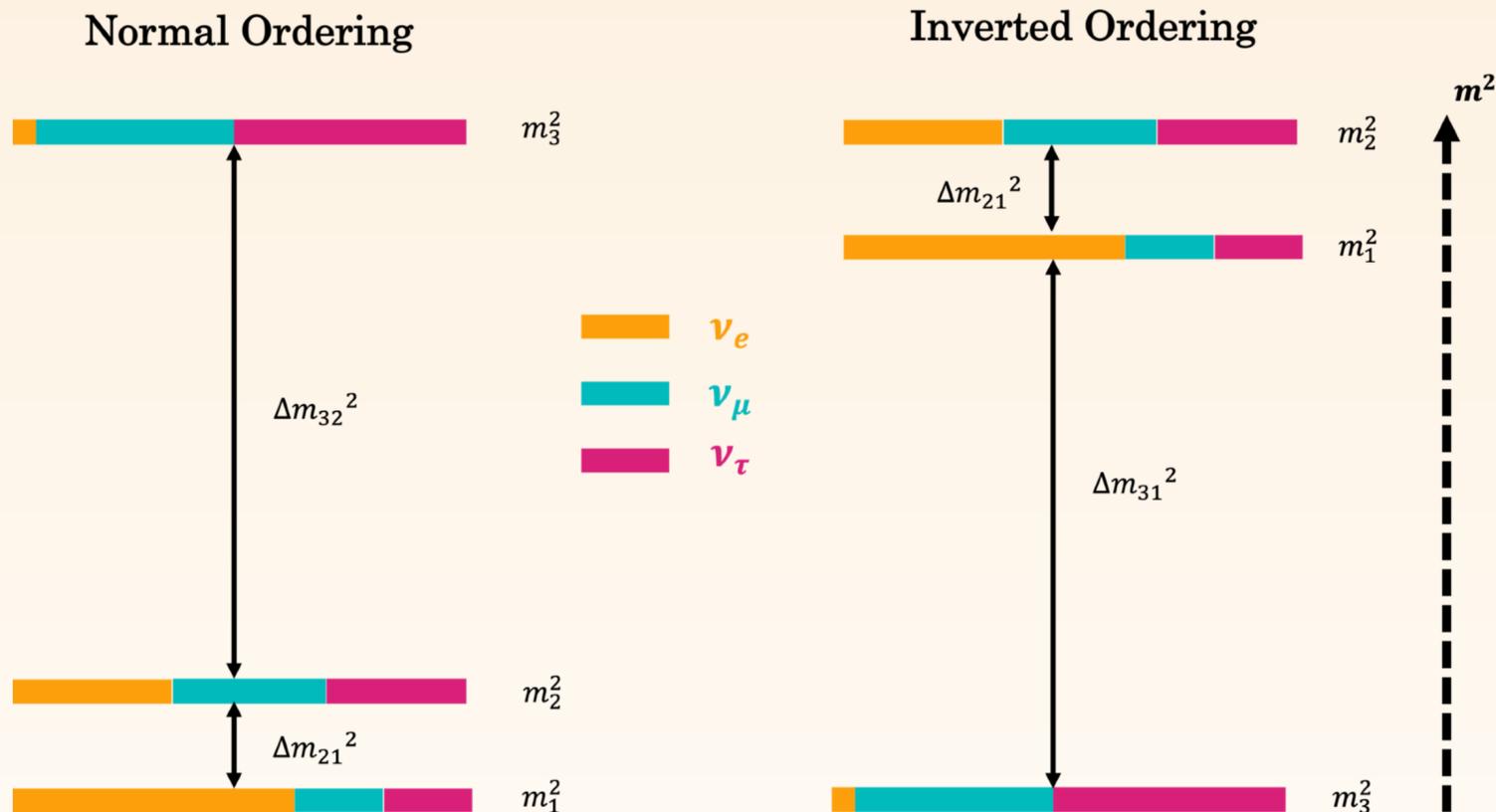
❖ Back-up

Back-up

❖ Flavor states $\nu_e \nu_\mu \nu_\tau$

❖ Mass states $\nu_1 \nu_2 \nu_3$

$$\left. \begin{array}{l} \text{Flavor states } \nu_e \nu_\mu \nu_\tau \\ \text{Mass states } \nu_1 \nu_2 \nu_3 \end{array} \right\} \boxed{|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle}$$



❖ PMNS mixing matrix

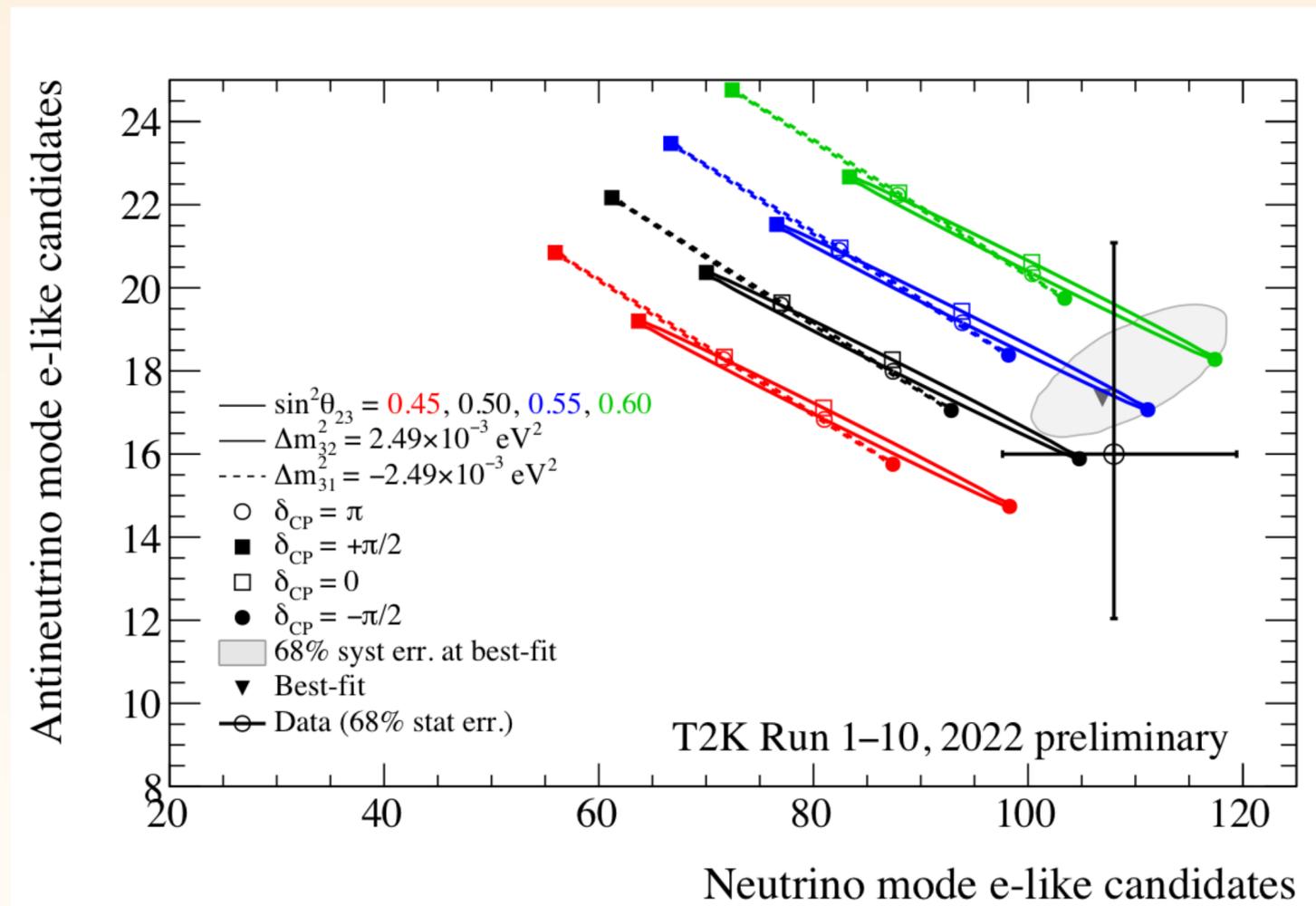
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

Back-up

❖ Disappearance formula

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \left(\cos^4 \theta_{13} \cdot \sin^2 2\theta_{23} + \sin^2 2\theta_{13} \cdot \sin^2 \theta_{23} \right) \cdot \sin^2 \frac{\Delta m_{32}^2 \cdot L}{4 E_\nu}$$

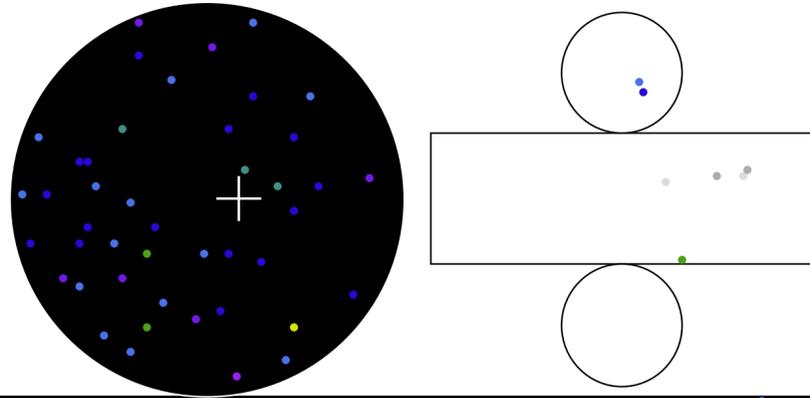
❖ Bi-probability plot : degeneracy between parameters and MO



Back-up

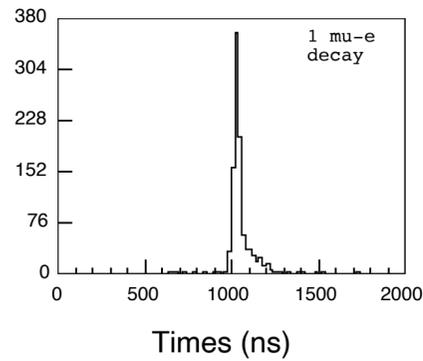
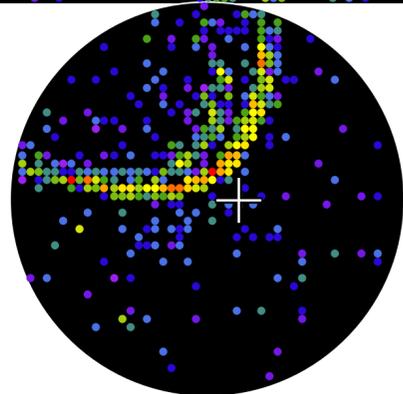
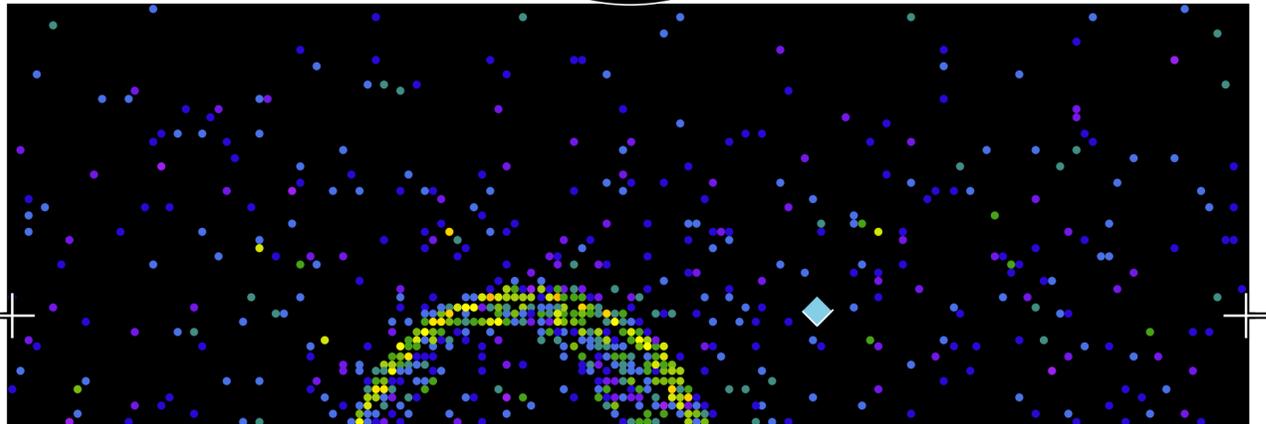
Super-Kamiokande IV

Run 999999 Sub 0 Event 40
 11-11-21:09:42:21
 Inner: 1049 hits, 3121 pe
 Outer: 3 hits, 7 pe
 Trigger: 0x07
 D_{wall}: 945.7 cm
 Evis: 356.5 MeV
 mu-like, p = 520.8 MeV/c



Charge (pe)

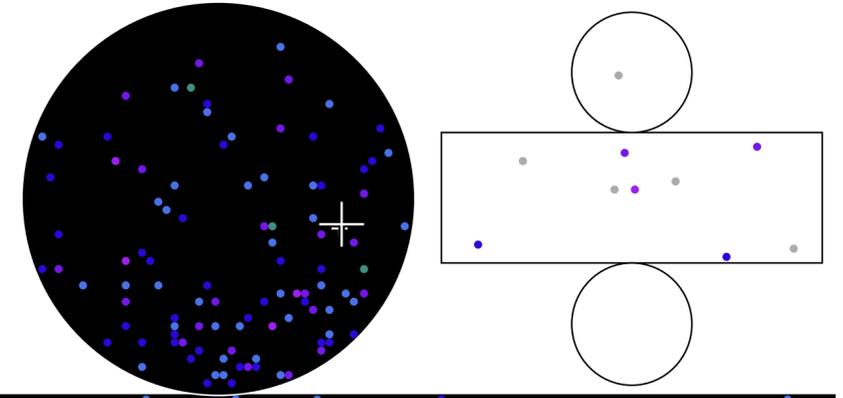
- >26.7
- 23.3-26.7
- 20.2-23.3
- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



Muon-like ring

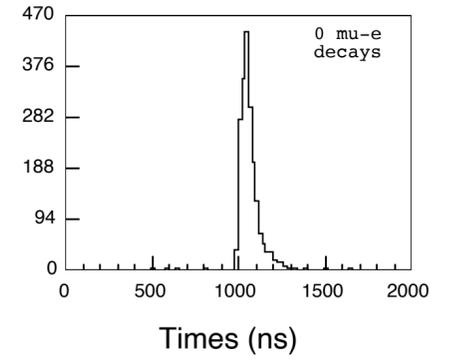
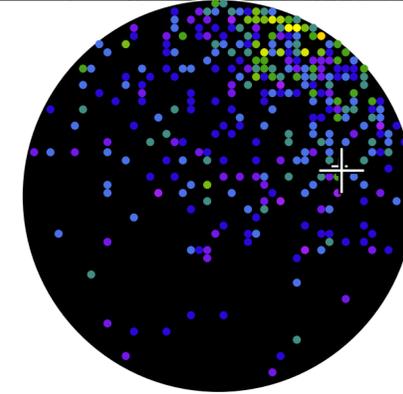
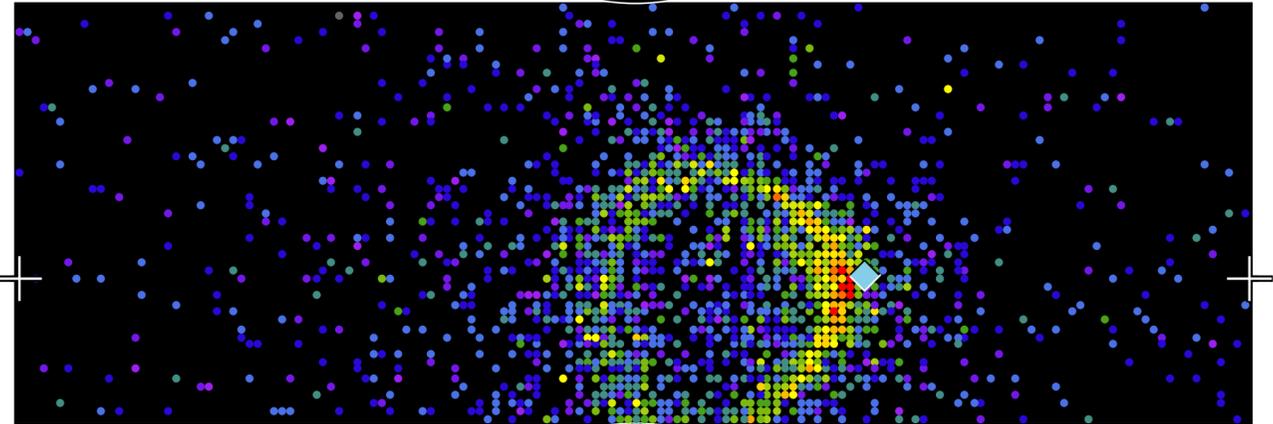
Super-Kamiokande IV

Run 999999 Sub 0 Event 99
 11-11-23:19:16:51
 Inner: 2017 hits, 5244 pe
 Outer: 5 hits, 3 pe
 Trigger: 0x07
 D_{wall}: 621.8 cm
 Evis: 550.9 MeV
 e-like, p = 550.9 MeV/c



Charge (pe)

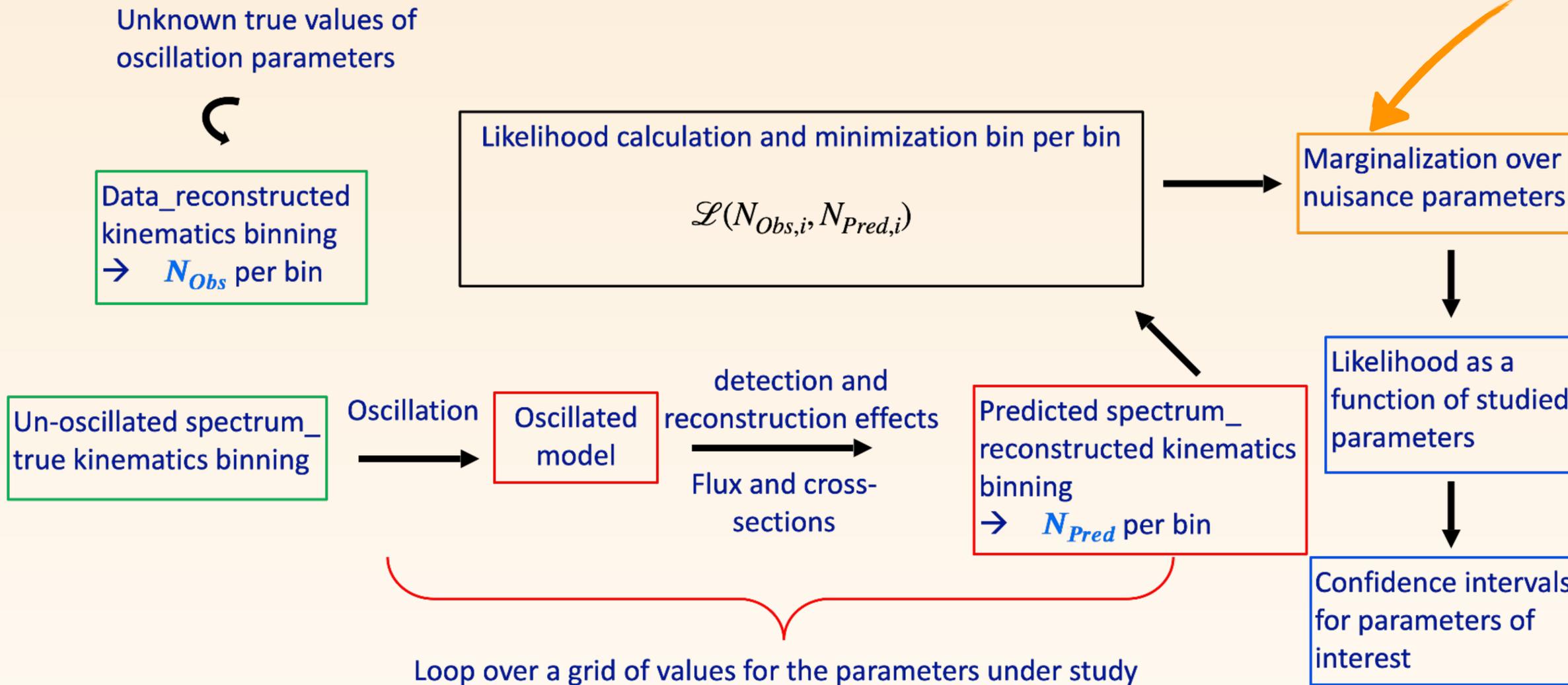
- >26.7
- 23.3-26.7
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- 17.3-20.2
- 14.7-17.3
- 12.2-14.7
- 10.0-12.2
- 8.0-10.0
- 6.2- 8.0
- 4.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- < 0.2



Electron-like ring

❖ P-Theta detailed workflow

Average likelihood over all obtained values from nuisance parameters throws



Back-up

❖ Best fit values and 1σ errors for all parameters

Parameter	Best fit			
	T2K only		T2K + reactor	
	Normal	Inverted	Normal	Inverted
$\sin^2(2\theta_{13})$	0.103	0.114	0.0861	0.0865
$\sin^2(\theta_{13})/10^{-3}$	$26.6^{+2.8}_{-5.8}$	$29.3^{+3.1}_{-6.1}$	$22.0^{+0.76}_{-0.6}$	$22.1^{+0.74}_{-0.63}$
δ_{CP}	$-2.25^{+1.39}_{-0.75}$	$-1.25^{+0.69}_{-0.91}$	$-2.18^{+1.22}_{-0.47}$	$-1.37^{+0.52}_{-0.68}$
Δm_{32}^2 (NH)/ $ \Delta m_{31}^2 $ (IH) [10^{-3} eV ² /c ⁴]	$2.506^{+0.048}_{-0.058}$	$2.474^{+0.049}_{-0.056}$	$2.506^{+0.047}_{-0.059}$	$2.473^{+0.051}_{-0.054}$
$\sin^2(\theta_{23})$	$0.466^{+0.106}_{-0.015}$	$0.465^{+0.103}_{-0.015}$	$0.559^{+0.018}_{-0.078}$	$0.560^{+0.019}_{-0.041}$
$-2 \ln L$	651.433	652.254	651.584	653.222
$-2\Delta \ln L$	0	0.821	0	1.638

T2K Run 1-10, preliminary

- ❖ FC studies :
 - ❖ δ_{CP} as it is cyclic
 - ❖ $\sin^2 \theta_{23}$ because μ -like events constrain $\sin^2 2\theta_{23}$ whereas e-like events constrain $\sin^2 \theta_{23}$ (1st order)

Back-up

❖ $(\text{Gd}_2(\text{SO}_4)_3 \cdot 8\text{H}_2\text{O})$

