

Improved Constraints from the T2K Oscillation Analysis

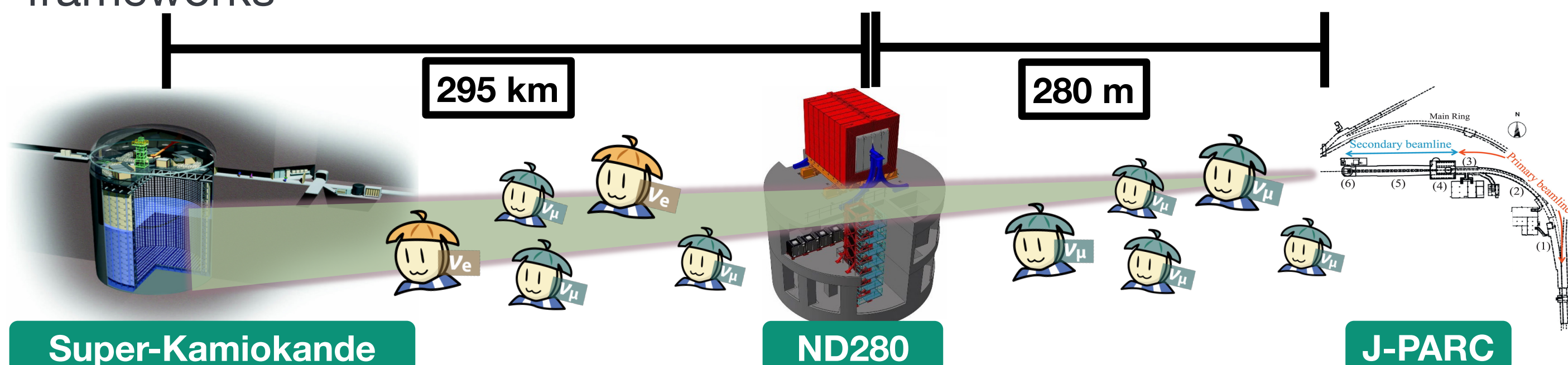
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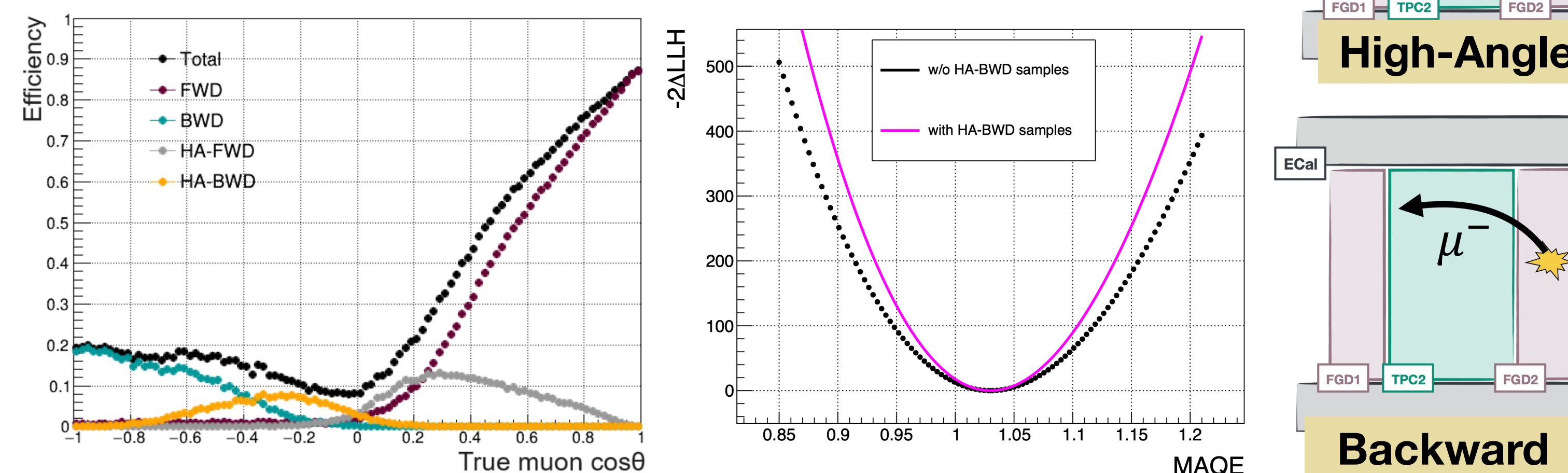
Constraining Neutrino Oscillations at T2K

- T2K measures oscillations from a $\nu_\mu/\bar{\nu}_\mu$ beam delivered by J-PARC.
- Detectors located off-axis (2.5°) – centering beam energy ~ 0.6 GeV
 - Enhances CCQE event-rate and reduces uncertainty on ν -energy
- Sensitive to $\Delta m_{32}^2, \delta_{CP}, \sin^2 \theta_{23}$, and some sensitivity to $\sin^2 \theta_{13}$
- Oscillation results reported from Bayesian and Hybrid-Frequentist frameworks

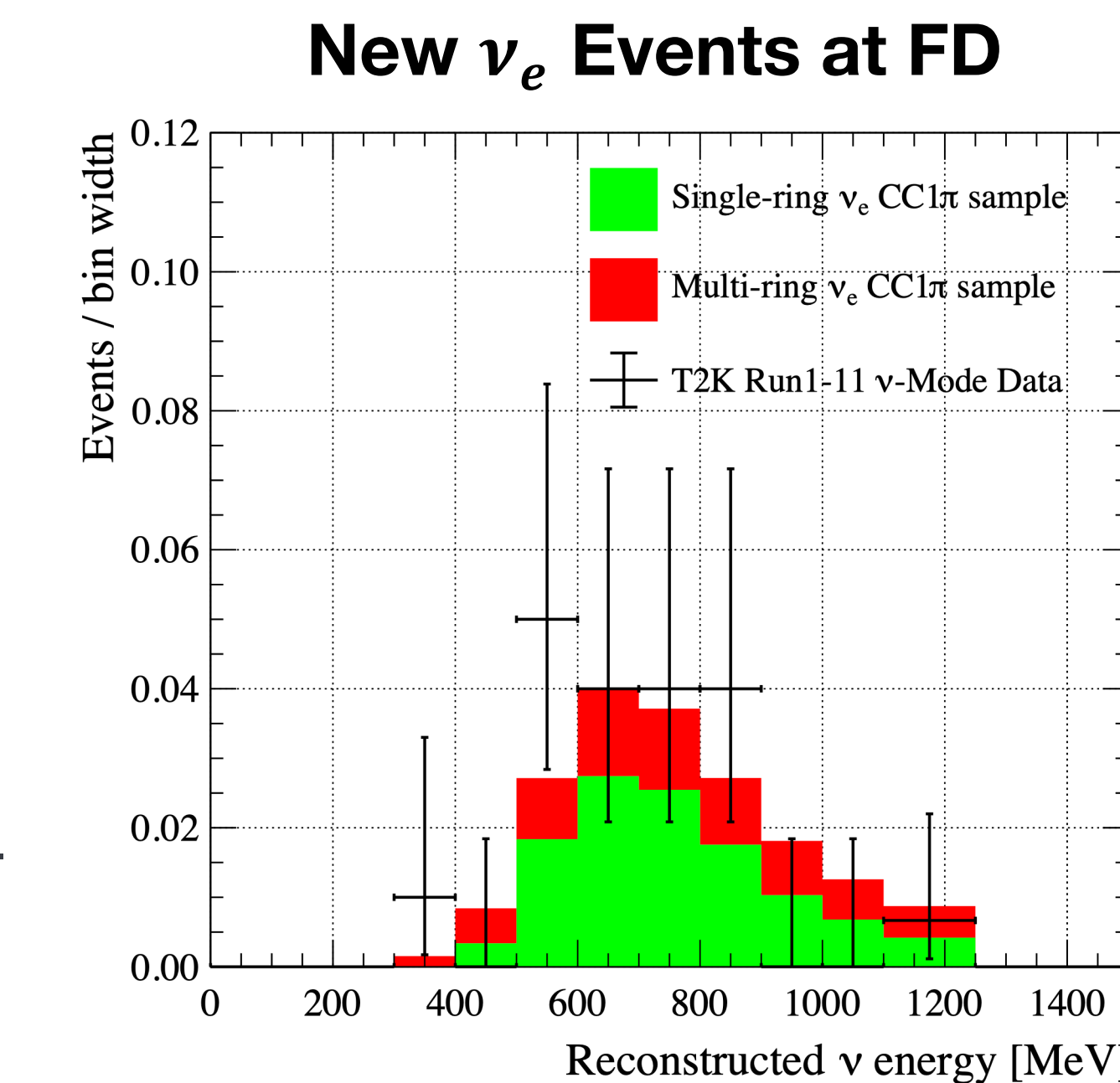


Updates to the Near and Far Detector Constraints

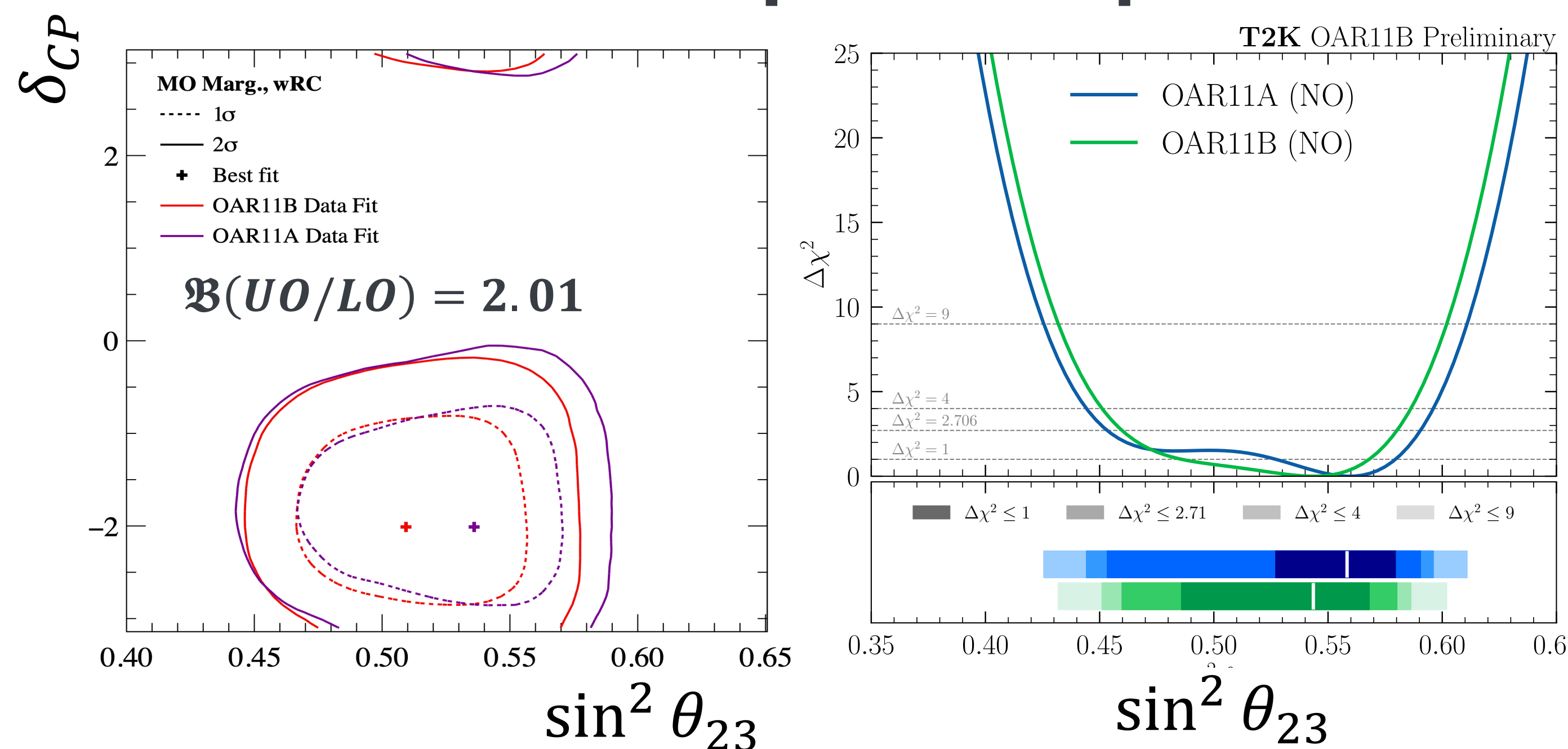
- Low- ω systematics introduced to improve robustness to alternative interaction models**
- New samples increase statistics by $\sim 12\%$, improving sensitivity to key systematics.**



- New expanded phase-space Monte Carlo production with increased statistics
- Refactored systematic uncertainties \rightarrow **reduction in detector uncertainties by 40% for $\bar{\nu}_e/\bar{\nu}_\mu$ -CCQE samples**
- New Multi-Ring ν_e CC1 π^+ Super-Kamiokande topology **adds 4 additional ν_e events (pred. 6.28)**

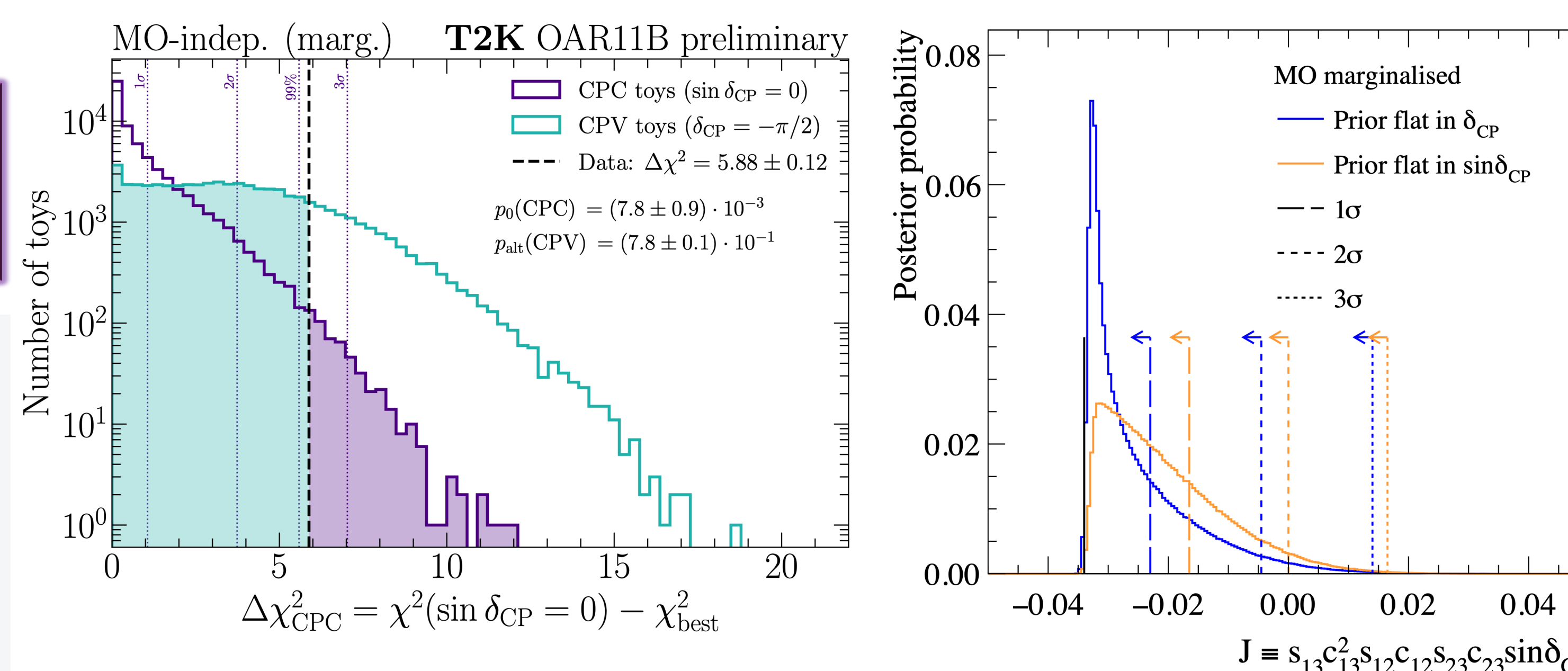


Impact of Updated Analysis on Oscillation Inference



Multi-Ring ν_e CC1 π^+ events and improved low-energy model predict more maximal mixing of $\sin^2 \theta_{23}$

- Shift towards maximal mixing of $\sin^2 \theta_{23}$ in Bayesian and Frequentist analyses \rightarrow Differences stem from ND constraint.
- Additional ν_e -events weaken pull from data, new interaction model increases number of relevant systematics



CP-conserving scenarios still excluded at 95% C.L. (Freq.) and 95% C.I. (Bayes.)

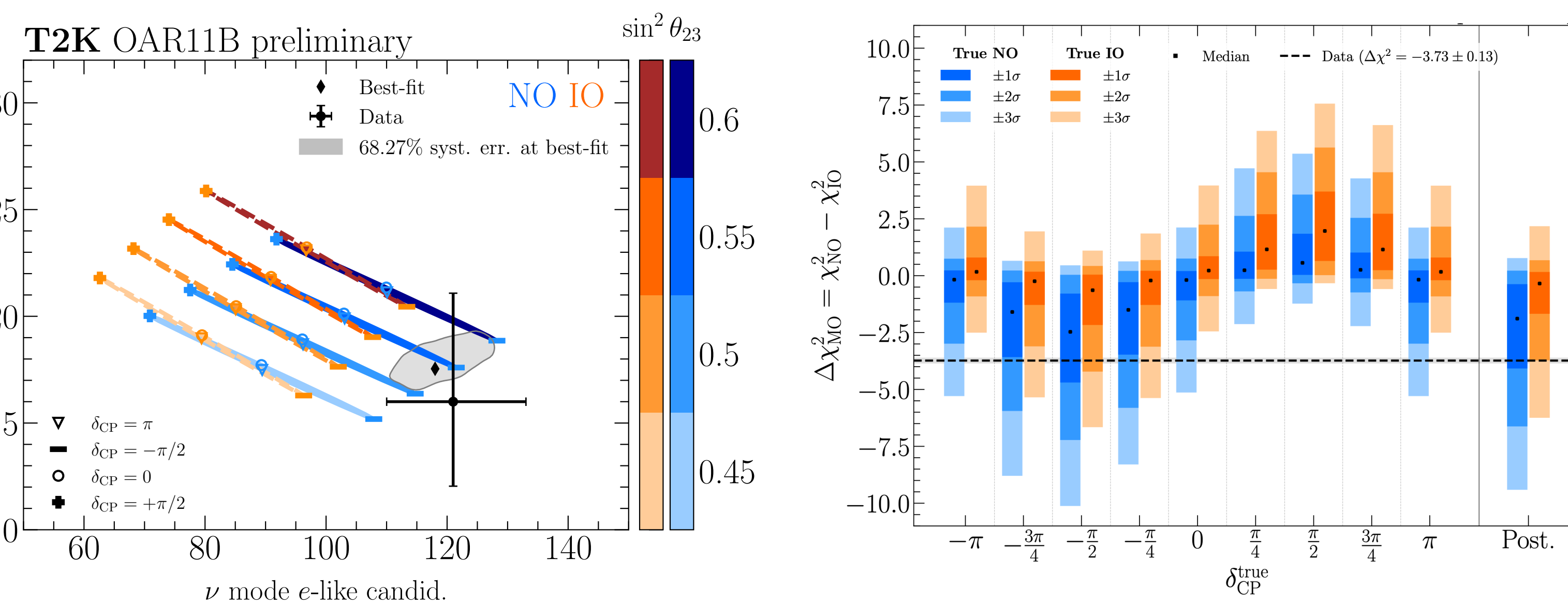
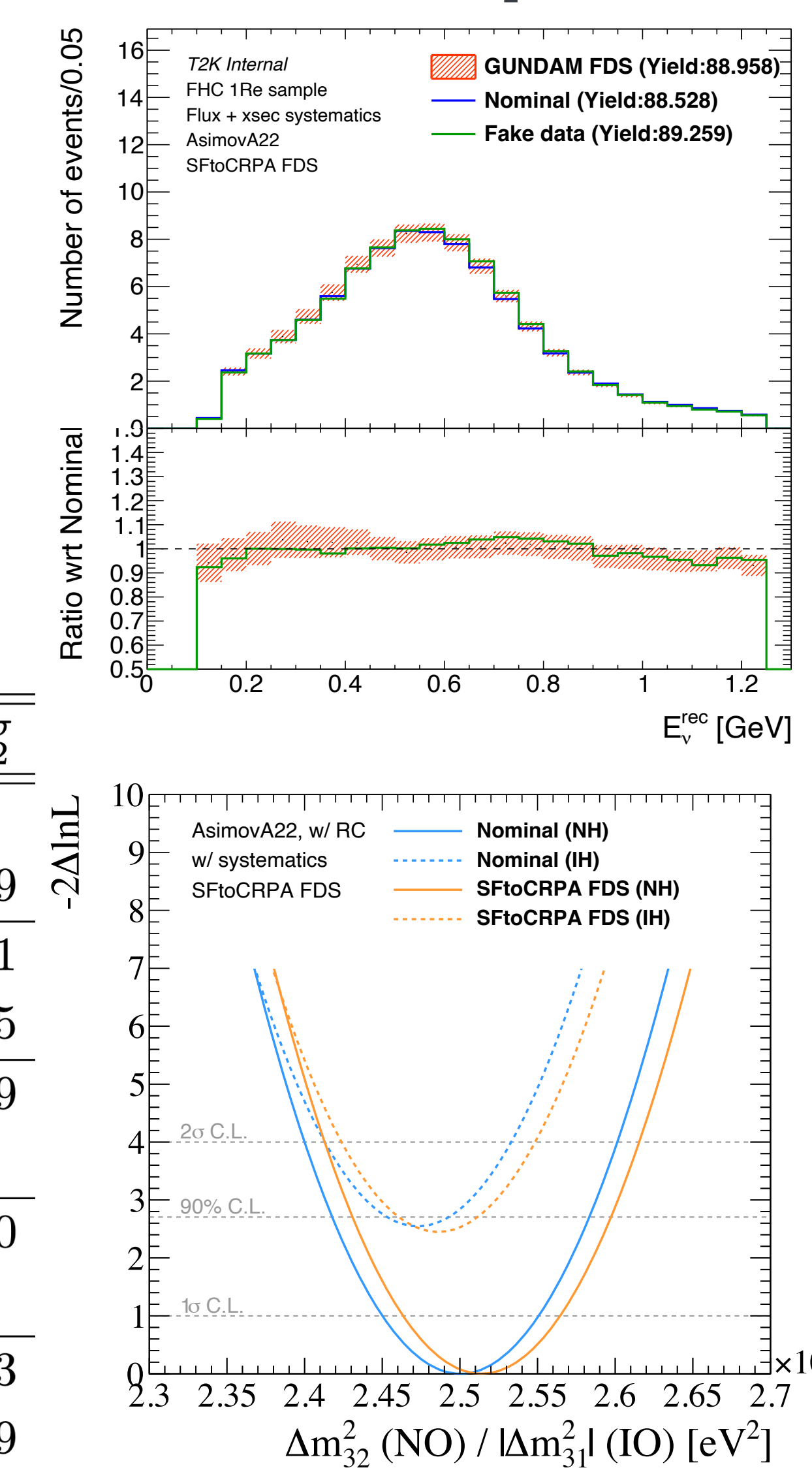
- Best-fit value of $\delta_{CP} \rightarrow -\pi$. Still favor maximal CP-violating values of δ_{CP}

$$\delta_{CP} = -2.04_{-0.56}^{+0.81} (NO), \quad -1.37_{-0.69}^{+0.58} (IO)$$
- Frequentist results now report rejection of CP-conservation via p-value studies \rightarrow **stronger statement on CP-conservation than Feldman-Cousins alone**

Interaction Model Robustness Improved

- Impact from fitting nominal model to alternative cross-section predictions tests robustness
- Biases (B^{syst}) and 2σ interval size changes ($R^{2\sigma}$) in 1D- χ^2 recorded for each alternative model fit.
- Δm_{32}^2 constraint correction estimated from observed biases and applied to uncertainties

Fake Data Study	Analysis	$B_{32}^{syst.}$	$R_{32}^{2\sigma}$
LFG	OAR11b	-56.5%	1
	OAR11a	-46%	0.99
CRPA	OAR11b	62.2%	1.01
	OAR11a	85%	0.95
1 π Kin. +3 σ	OAR11b	-4.2%	0.99
	OAR11a	-8%	—
1 π Kin. -3 σ	OAR11b	9.4%	1.00
	OAR11a	7%	—
Data-driven nonQE	OAR11b	-25.3%	1.03
	OAR11a	-76%	0.99



Mild preference for Normal Ordering (78% significance) for both analyses
Bayes Factor: $\mathfrak{B}(NO/IO) = 3.55$

- Observed constraint on mass-ordering made from δ_{CP} posterior \rightarrow reduces impact of δ_{CP} on MO conclusion
- Slightly stronger constraint on MO than expected sensitivity in T2K

New model shows robustness to alternative cross-section model predictions
 $\Delta m_{32}^2 / |\Delta m_{31}^2| = 2.502_{-0.044}^{+0.052} / 2.486_{-0.037}^{+0.058} \text{ eV}^2$
Most precise T2K constraint on Δm_{atm}^2 to date!

Future Work

This model will be applied to new data from the 320kA horn current period \rightarrow **more events with reduced background from beam impurities.**
Expected increase of 19% in FHC and 5% in RHC data.

References: [1] K. et al. The T2K experiment. Nucl. Instrum. Meth. A 659, 106–135 (2011), [2] K et al. Measurements of neutrino oscillation parameters from the T2K experiment using protons on target. Eur. Phys. J. C 83, 782 (2023).