Current status and prospects of CPT tests with neutrino oscillation experiments

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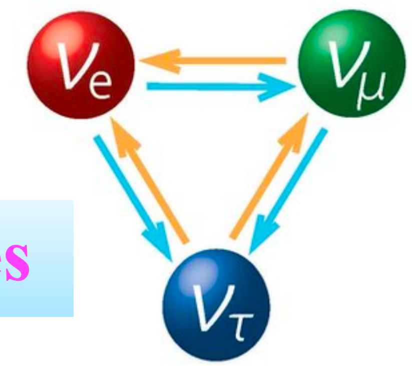
1. Introduction

Testing CPT invariance with neutrino oscillation experiments

Neutrino oscillation: ν changes its flavor when traveling in spacetime



Flavor eigenstates ← $|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$ → **Mass eigenstates** $(\alpha = e, \nu, \tau)$

3 x 3 PMNS unitary matrix: 3 mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$, 1 CP-violating phase δ_{CP}

Oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i\frac{m_i^2 L}{2E}} \right|^2$$

- $U^*_{\alpha i} U_{\beta i}$: $\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$
- m_i^2: **ν mass**
- L: **distance traveled**
- **$\propto \rho$ in matter**
- E: **ν energy**

- Under CPT transformation: $(\nu_\alpha \rightarrow \nu_\beta) \xrightarrow{CPT} (\overline{\nu}_\beta \rightarrow \overline{\nu}_\alpha)$

1. Introduction

Testing CPT invariance with neutrino oscillation experiments

- CPT asymmetry: $\mathscr{A}_{CPT} = P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$
- Accelerator-based experiments (T2K, NOvA, Hyper-K, DUNE) study 4 channels: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
- Accelerator-based experiments do not test CPT symmetry via appearance channels since they don't focus on $\overline{\nu}_e \to \overline{\nu}_\mu$ channel

- Accelerator-based experiments can test CPT by their own disappearance channels

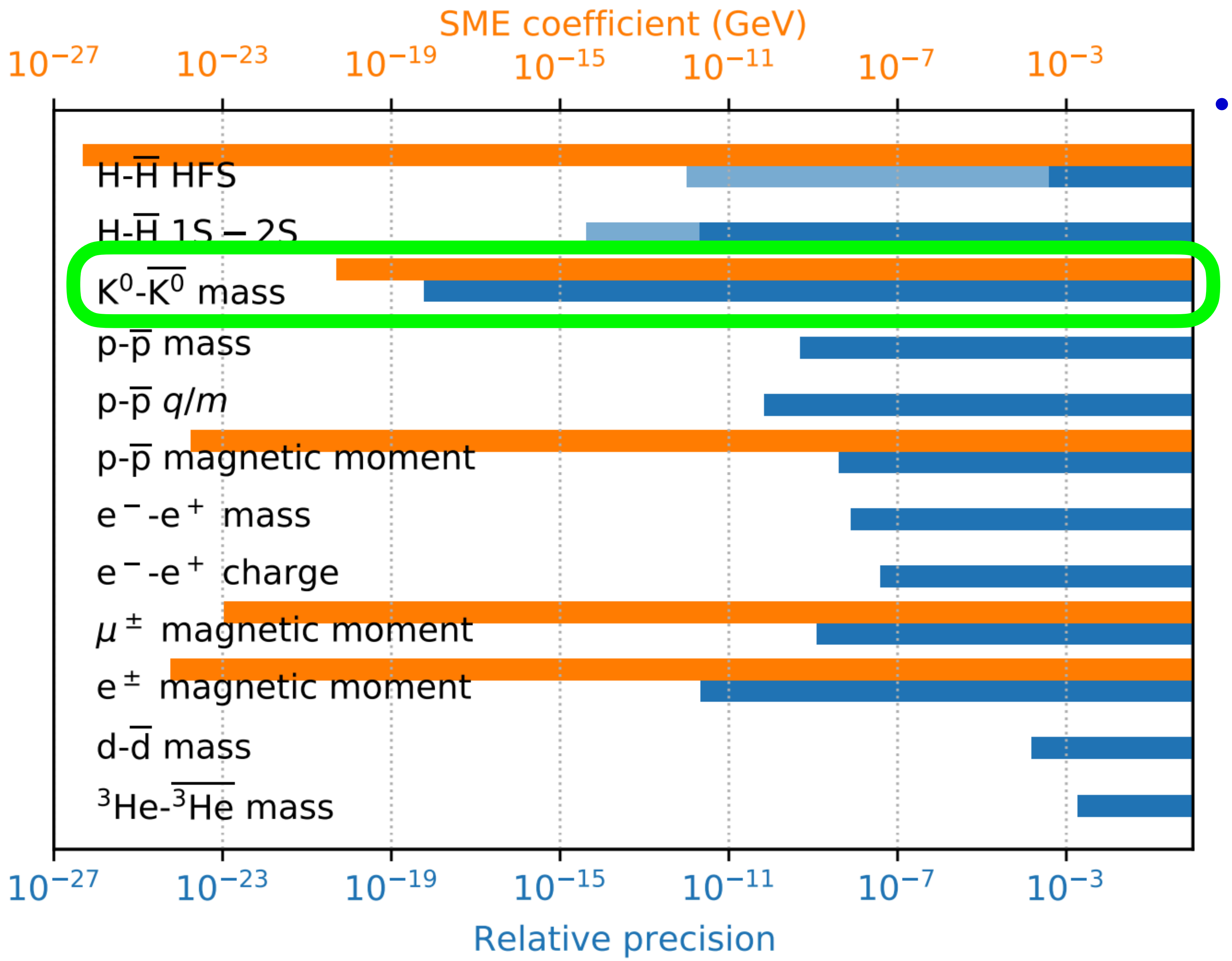
$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\overset{(-)}{\theta}_{23} \sin^2\left(\frac{\Delta \overset{(-)}{m}{}^2_{31} L}{4E}\right)$$

$$\mathscr{A}^{CPT}_{\mu\mu}(\sin^2\theta_{23}) \qquad \mathscr{A}^{CPT}_{\mu\mu}(\Delta m^2_{31})$$

$\propto \delta_{\nu\overline{\nu}}(sin^2\theta_{23}) = sin^2\theta_{23} - sin^2\overline{\theta}_{23}$ $\qquad$ $\propto \delta_{\nu\overline{\nu}}(\Delta m^2_{31}) = \Delta m^2_{31} - \Delta\overline{m}^2_{31}$

2. Current status of CPT tests

Current bounds on the direct CPT tests [arXiv:2111.04056 hep-ex]



- Current best constraint in terms of relative mass difference is given by $K^0 - \overline{K}^0$ system:

$$\left| \frac{m(K^\circ) - m(\overline{K}^\circ)}{m_K} \right| < 6 \times 10^{-19}$$

- This value looks very stringent. However, when converted to mass squared difference, it becomes much weaker

$$m^2(K^\circ) - m^2(\overline{K}^\circ) < 0.3\ eV^2$$

2. Current status of CPT tests

The most up-to-date bounds on CPTV at $3\sigma\ C.L.$ with ν experiments **[arXiv:2305.06384v1]**

$$|\delta(sin^2\theta_{12})| < 0.187$$

$$|\delta(sin^2\theta_{13})| < 0.029$$

$$|\delta(sin^2\theta_{23})| < 0.19$$

$$|\delta(\Delta m^2_{21})| < 3.7 \times 10^{-5}\ eV^2$$

$$|\delta(\Delta m^2_{31})| < 2.5 \times 10^{-4}\ eV^2$$

$$(|\delta(X)| = |X - \overline{X}|)$$

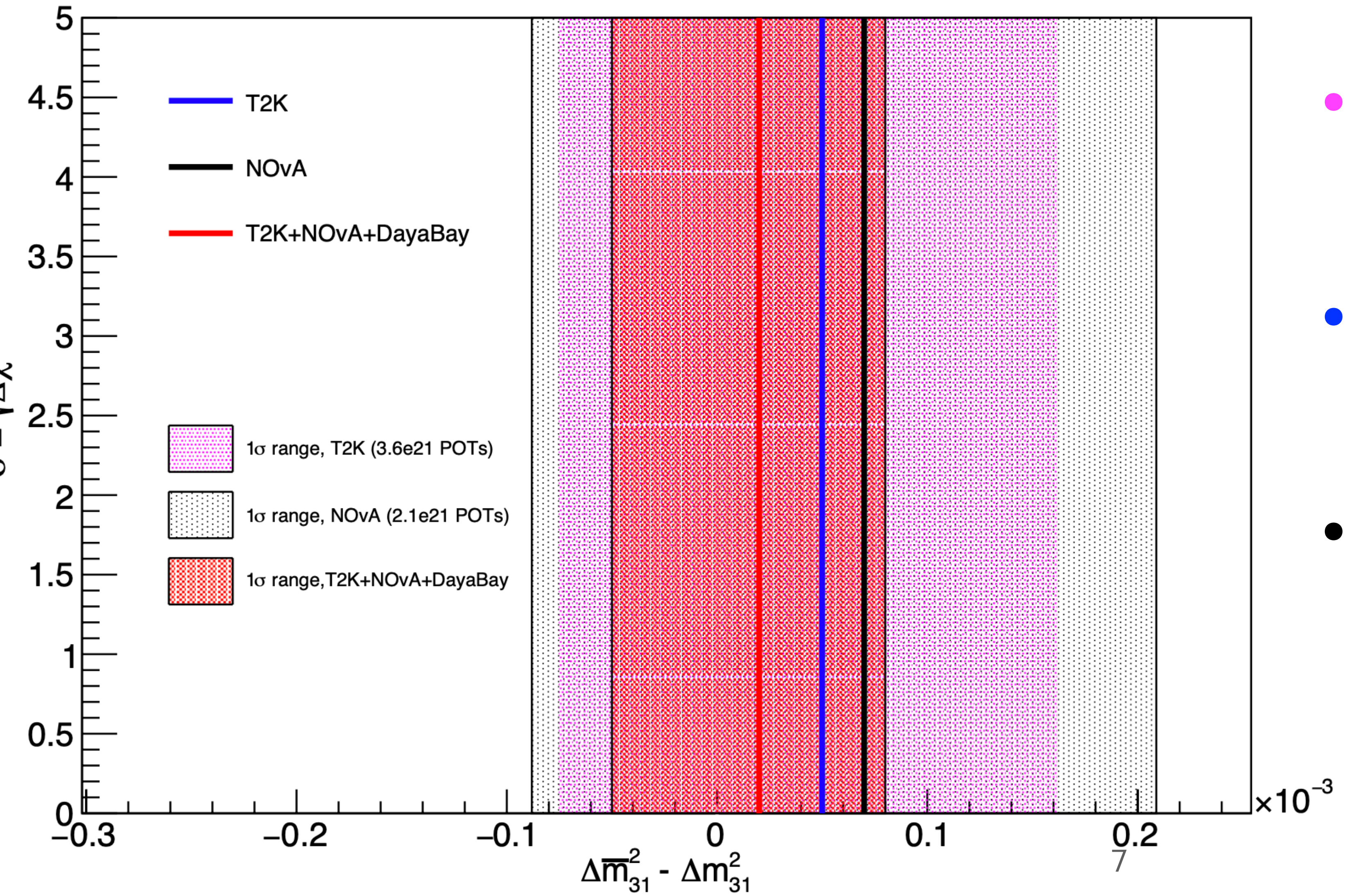
$$|m^2(K^\circ) - m^2(\overline{K}^\circ)| < 0.3\ eV^2$$

- In terms of mass squared difference, neutrino oscillation provides few orders better constraint on CPTV than neutral Kaon system

2. Current status of CPT tests

Current measurements of T2K, NOvA, and DayBay experiments

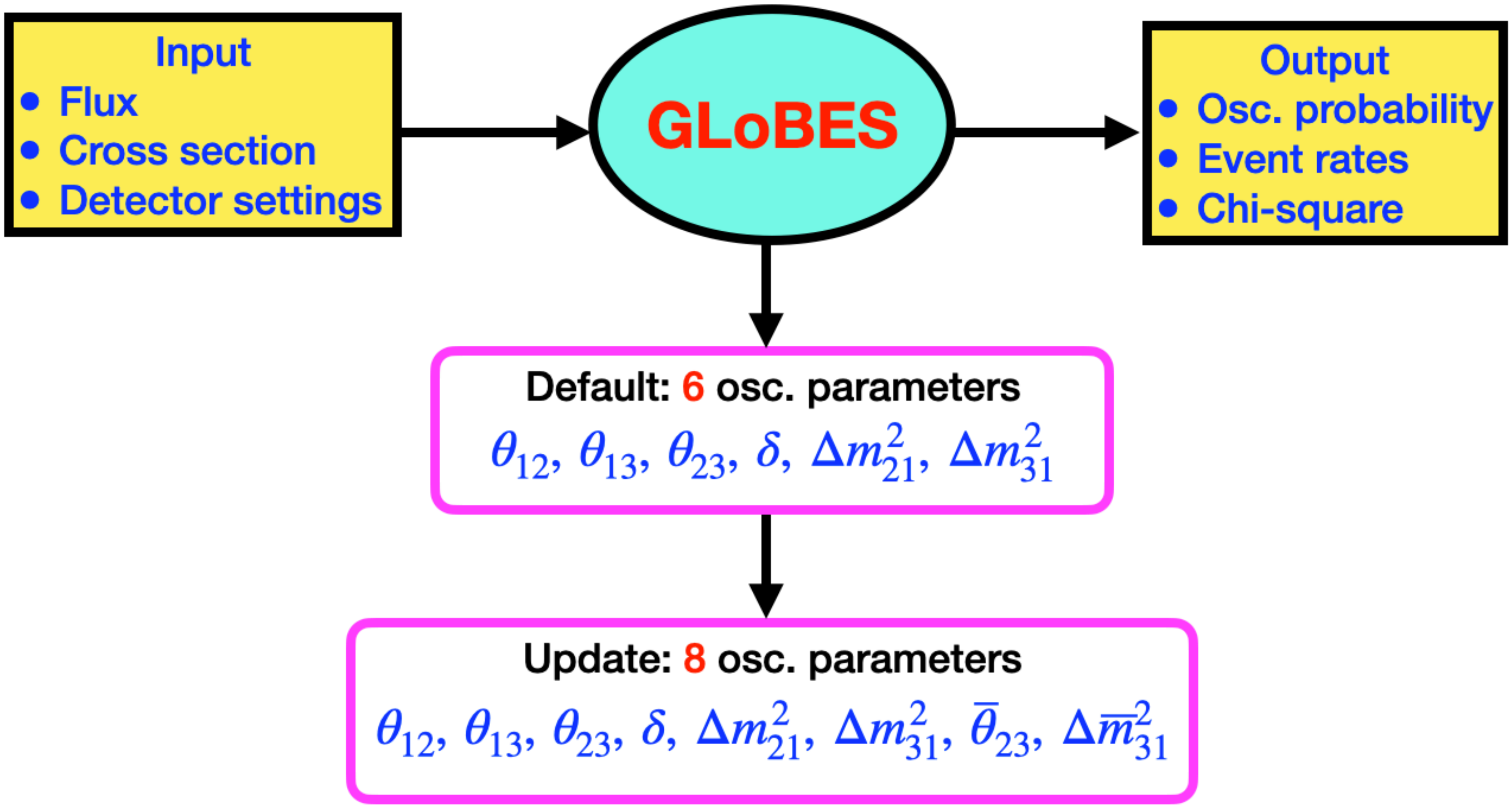
NO is assumed	T2K (3.6e21 POTs) *P.R.D 108 (2023) 7, 072011*	NOvA (2.1e21 POTs) *Mendez PhD thesis (2019)*	DayaBay (3158 days) *P.R.L 130, 161802 (2023)*	Combined
$\Delta m^2_{31}/10^{-3}\ eV^2$	$2.55^{+0.05}_{-0.06}$	$2.56^{+0.07}_{-0.09}$		$2.55^{+0.04}_{-0.05}$
$\Delta \overline{m}^2_{31}/10^{-3}\ eV^2$	$2.60^{+0.10}_{-0.11}$	$2.63^{+0.12}_{-0.13}$	$2.54^{+0.06}_{-0.06}$	$2.57^{+0.05}_{-0.05}$
$\delta(\Delta m^2_{31})/10^{-3}\ eV^2$	$0.05^{+0.11}_{-0.12}$	$0.07^{+0.14}_{-0.16}$		$0.02^{+0.06}_{-0.07}$



- Current T2K and NOvA data are consistent with CPT conservation hypothesis
- Combined data of T2K, NOvA, and Daya Bay is consistent with CPT conservation hypothesis
- Combine with DayaBay data significant improves the precision on $\Delta \overline{m}^2_{31}$

3. Prospects of CPT tests with neutrino oscillation experiments

- GLoBES: The General Long Baseline Experiment Simulator



- Use disappearance channels only
- In this report, we only focus on parameter $\delta(\Delta m^2_{31})$

3. Prospects of CPT tests with neutrino oscillation experiments

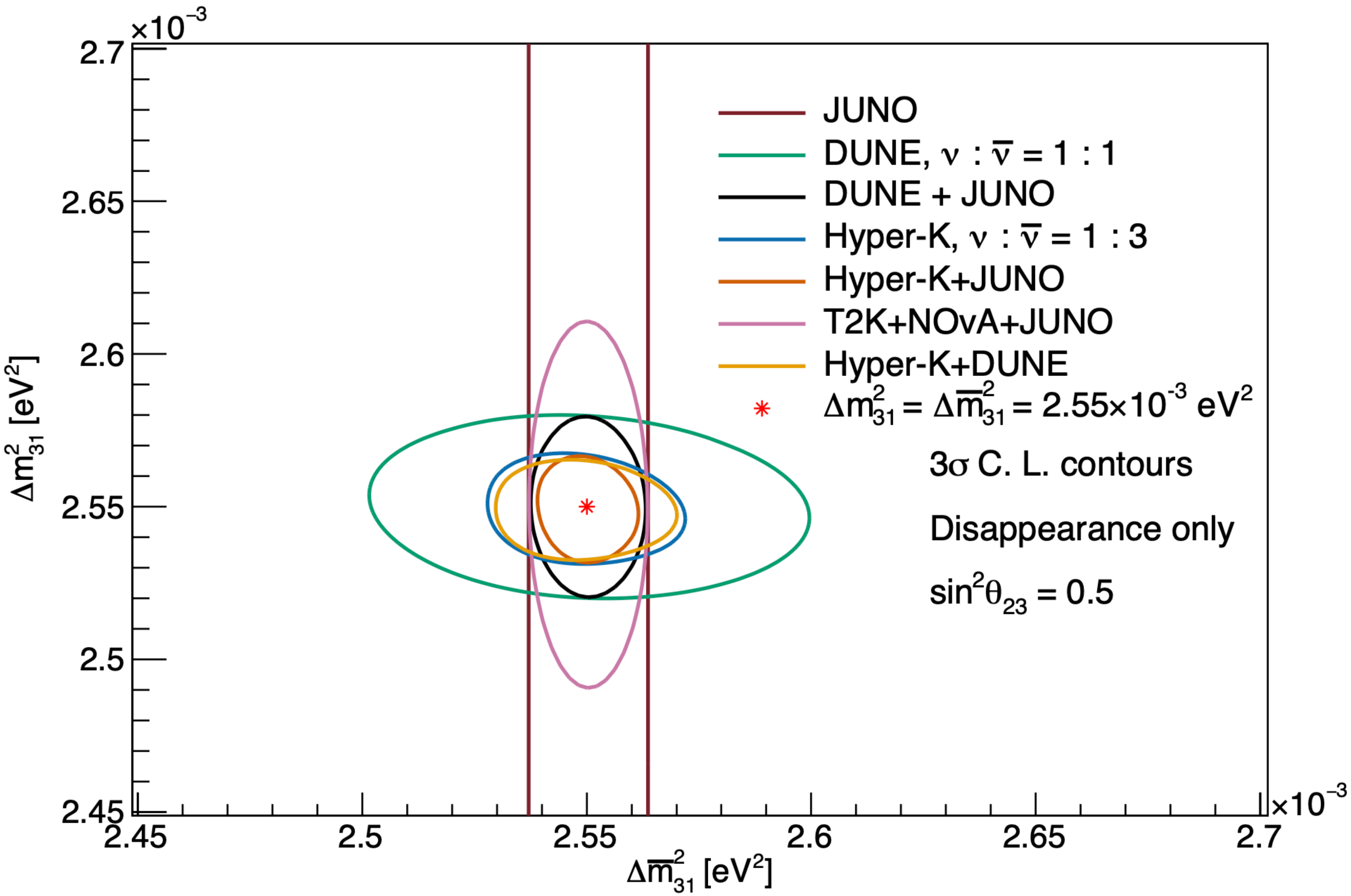
- GLoBES setup for T2K, NOvA, JUNO, Hyper-K, and DUNE

	T2K	NOvA	JUNO	Hyper-K	DUNE
Baseline (km)	295	810	52,5	295	1285
Matter density g/cm^3	2,6	2,8	2,6	2,6	2,85
Detector mass (kt)	22,5	14	20	187	40
Exposure	$10 \times 10^{21} POT$	$7.2 \times 10^{21} POT$	6 years	10 years	10 years nominal
Power	0.77 MW	0.74 MW	26.6 GWth	1.3 MW	1.2 MW

- The exposures of T2K and NOvA are expected at the end of their runs

3. Prospects of CPT tests with neutrino oscillation experiments

- Assume CPT is conserved, 2D contours at 3σ C. L. bound on CPTV are made

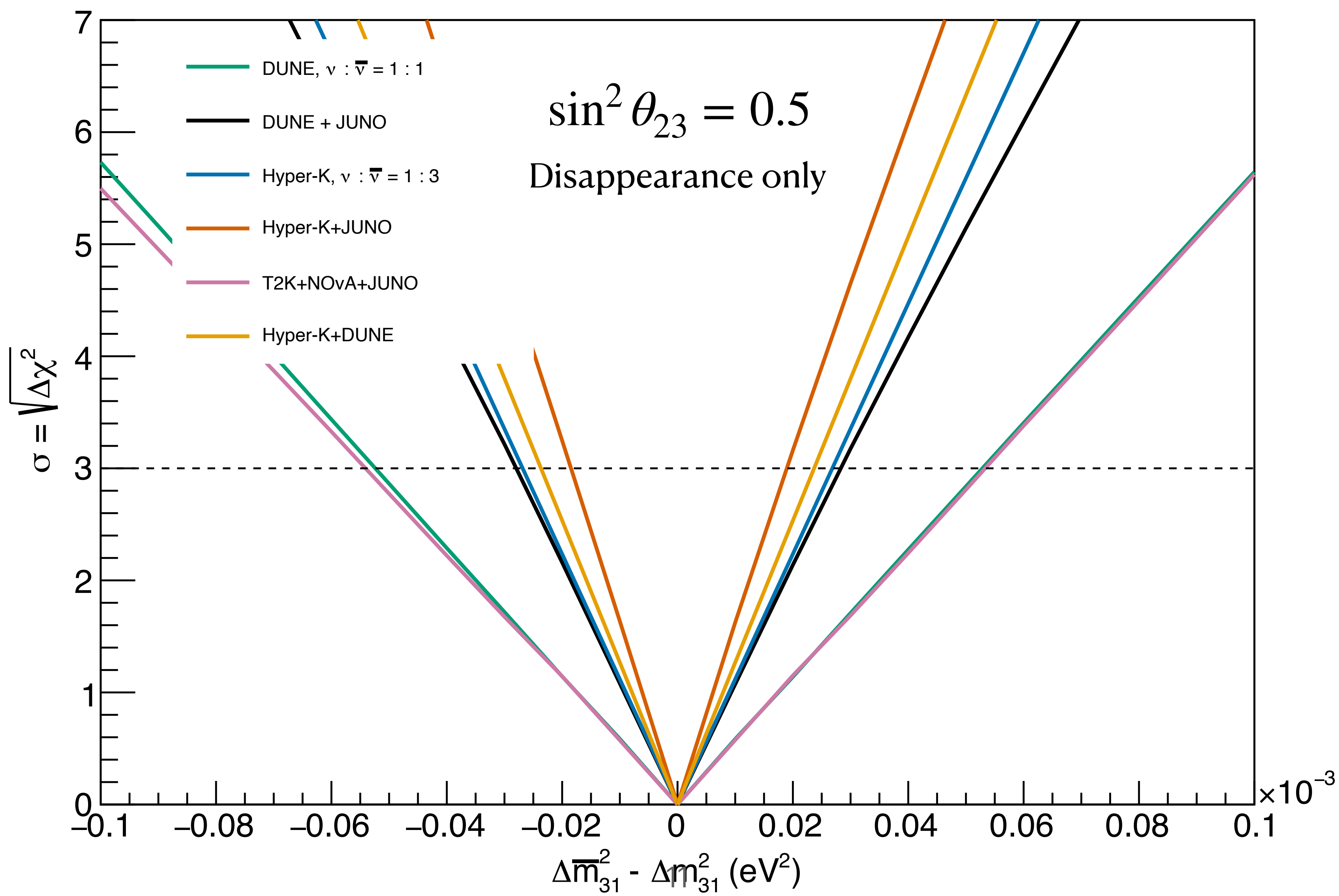


- JUNO will have better than 0.5% precision on $\Delta \overline{m}^2_{31}$ => it can help to improve constraint on CPTV when combined data of other experiments with JUNO

3. Prospects of CPT tests with neutrino oscillation experiments

The bounds on CPTV with $\delta(\Delta m^2_{31})$ at $3\sigma\ C.L.$ from different experimental configurations

$sin^2\theta_{23}$	Hyper-K +JUNO	Hyper-K $\nu : \bar{\nu} = 1:3$	DUNE + JUNO	DUNE $\nu : \bar{\nu} = 1:1$	T2K+NOvA+ JUNO
0,45	**1.94E-05**	**2.76E-05**	**2.93E-05**	**5.54E-05**	**5.75E-05**
0,50	**1.89E-05**	**2.64E-05**	**2.83E-05**	**5.28E-05**	**5.33E-05**
0,60	**2.05E-05**	**2.91E-05**	**3.09E-05**	**5.83E-05**	**6.15E-05**

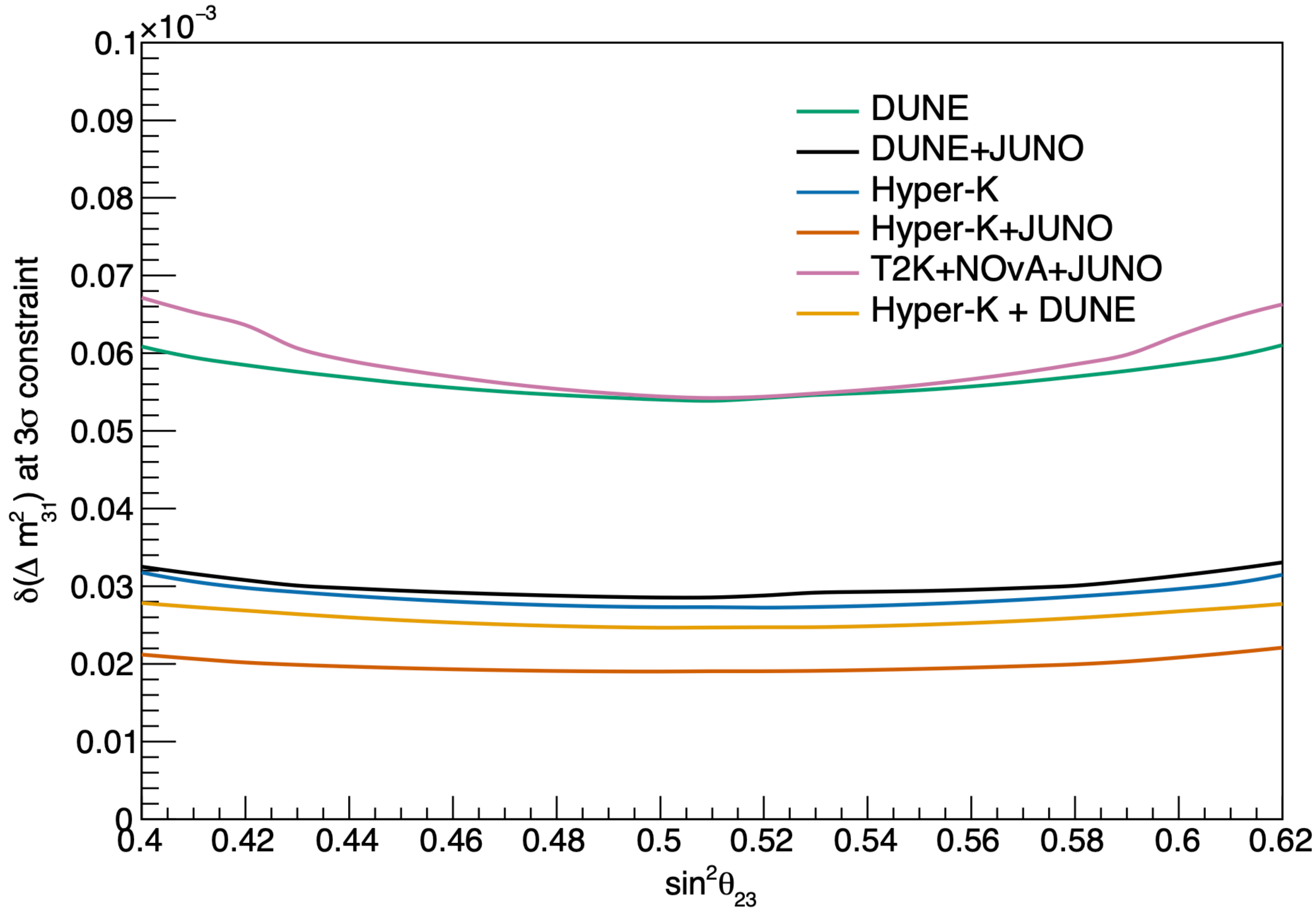


3. Prospects of CPT tests with neutrino oscillation experiments

- Assume CPT is conserved, we calculate the bound on CPTV with $\delta(\Delta m^2_{31})$ at $3\sigma\ C.L.$ within 3σ range of $\sin^2\theta_{23}$ [0.40 - 0.62]

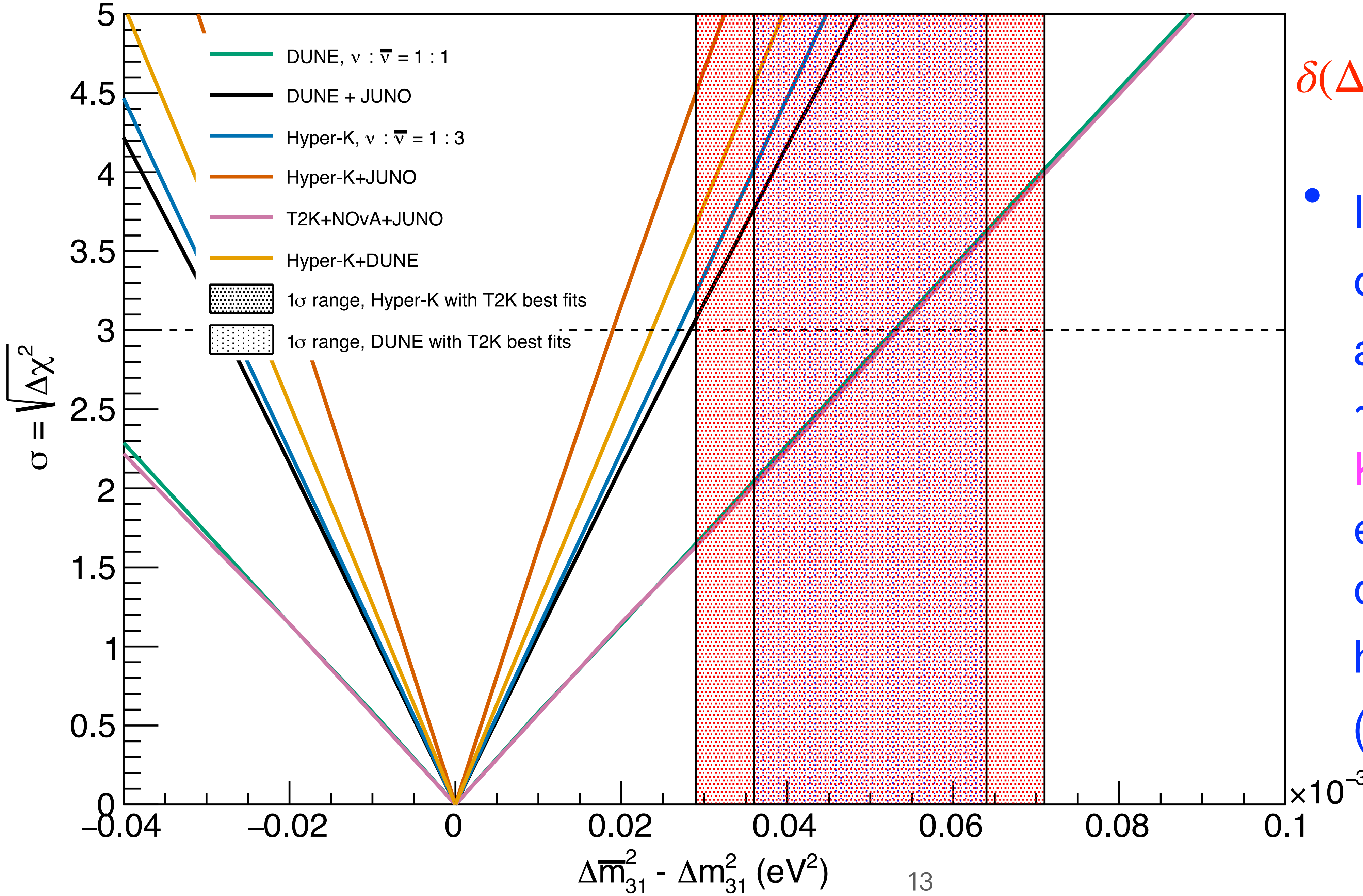
- Hyper-K will provide the best constraint on the CPTV in terms of Δm^2_{31} among single detector experiments

- Hyper-K + JUNO will give best constraint on the CPTV among the considered experimental configurations



3. Prospects of CPT tests with neutrino oscillation experiments

1 sigma uncertainty	**HyperK** (TDR) *arXiv:1805.04163v2*	**DUNE** *EPJC (2020) 80:978*
$\Delta m^2_{31}\ eV^2$	1.5×10^{-5}	1.0×10^{-5}
$\Delta \overline{m}^2_{31}\ eV^2$	1.5×10^{-5}	1.0×10^{-5}
$\delta(\Delta m^2_{31})\ eV^2$	2.1×10^{-5}	1.4×10^{-5}



$\delta(\Delta m^2_{31})_{\mathbf{T2K}} = 5 \times 10^{-5} eV^2$

- If current T2K best fits on Δm^2_{31} and $\Delta \overline{m}^2_{31}$ are still true until ~2037, DUNE (Hyper-K) will be able to exclude CPT conservation hypothesis at ~2.0σ (~3.2σ) C. L.

3. Prospects of CPT tests with neutrino oscillation experiments

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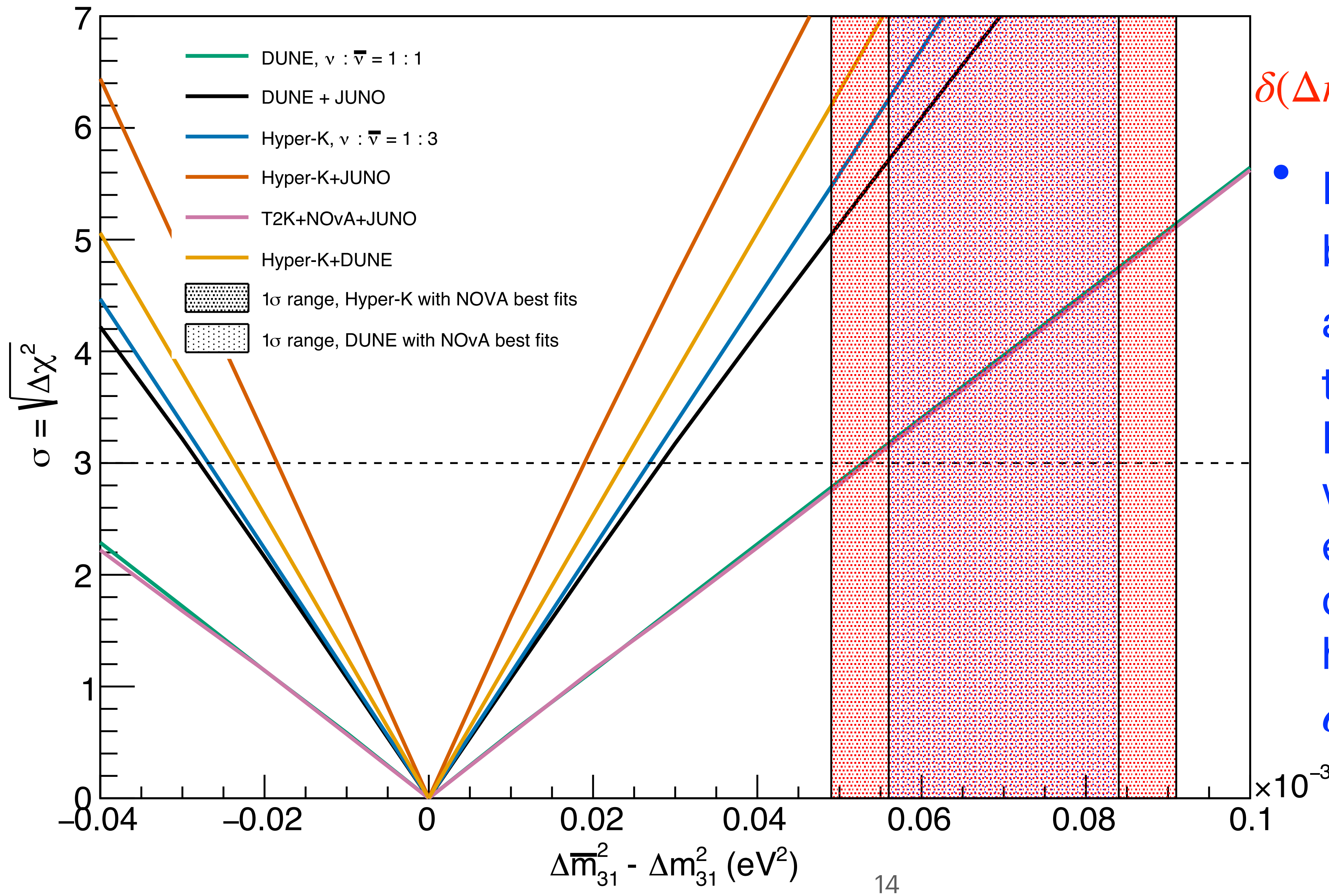
$\Delta m^2_{31}\ eV^2$	1.5×10^{-5}	1.0×10^{-5}
$\Delta \overline{m}^2_{31}\ eV^2$	1.5×10^{-5}	1.0×10^{-5}
$\delta(\Delta m^2_{31})\ eV^2$	2.1×10^{-5}	1.4×10^{-5}

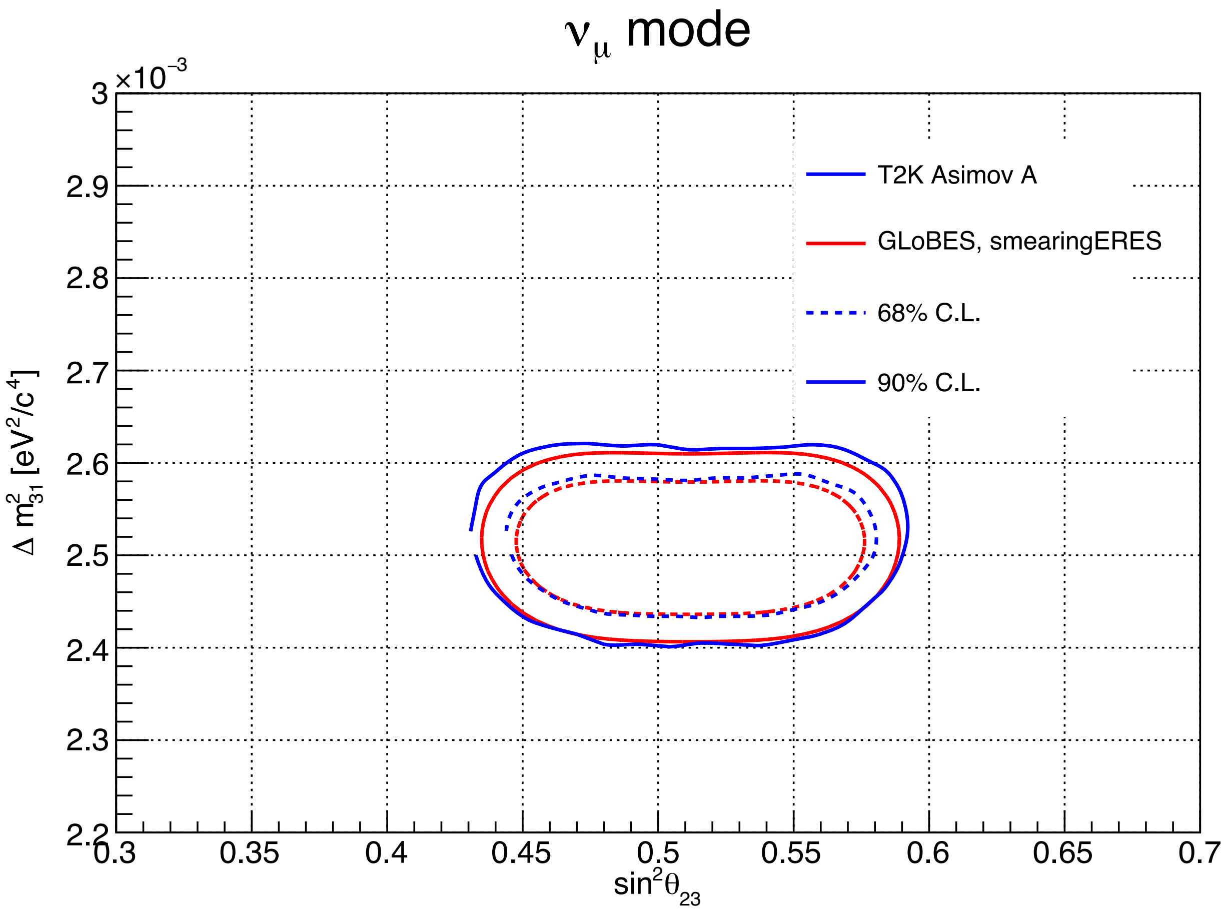


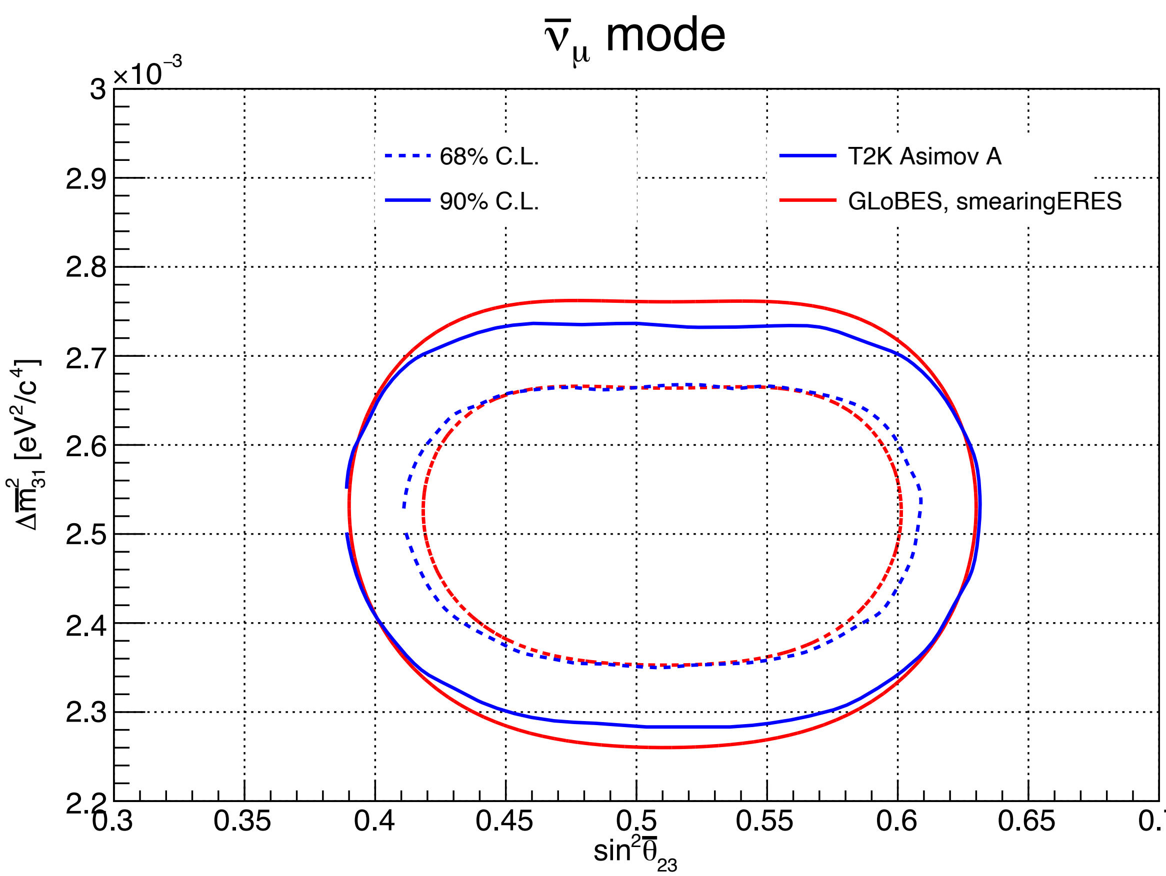
$\delta(\Delta m^2_{31})_{\mathrm{NOvA}} = 7 \times 10^{-5} eV^2$

- If current NOvA best fits on Δm^2_{31} and $\Delta \overline{m}^2_{31}$ are still true until ~2037, DUNE (Hyper-K) will be able to exclude CPT conservation hypothesis at ~3.2 σ (~5.5σ) C. L.

3. Prospects of CPT tests with neutrino oscillation experiments

- We are developing a framework for global data fit using GLoBES
  - Update GLoBES to include interested oscillation parameters for anti-neutrino
  - Validate the experiments with real setups and their released data
  - Combine the data for the experiments
- We have tried to validate the T2K
  - Thinking of how to evaluate the difference between the two as an uncertainty in the data fit result





4. Conclusion

- Current T2K, NOvA and combined T2K+NOvA+DayaBay data are consistent with CPT conservation
- Hyper-K will provide the best constraint on CPTV in terms of $\delta(\Delta m^2_{31})$ among the single detector experiments
- Hyper-K + JUNO has best constraint to the CPTV among the considered configurations
- HyperK can exclude CPT conservation at (5.5σ) $3.2\sigma\ C.L.$ if the current best fits of (NOvA) T2K on Δm^2_{31} and $\Delta\overline{m}^2_{31}$ are still true until ~2037
- DUNE can exclude CPT conservation at (3.2σ) $2.0\sigma\ C.L.$ if the current best fits of (NOvA) T2K on Δm^2_{31} and $\Delta\overline{m}^2_{31}$ are still true until ~2037
- A framework for global data fit on CPTV constraint has being developed

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