Constraint to the CPT violation with neutrino oscillation experiments

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1. Introduction

Testing CPT invariance with neutrino oscillation experiment

- CPT theorem: All interactions described by a Lorentz-invariant local quantum field theory must be invariant under combined CPT transformation.

- CPT invariance => $m_{\text{particle}} = m_{\text{antiparticle}}$
- Direct CPT testing: comparing m_{particle} and $m_{\text{antiparticle}}$ at oscillation experiments: $K^0 - \overline{K}^0, B^0 - \overline{B}^0, \ldots$, and neutrino

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

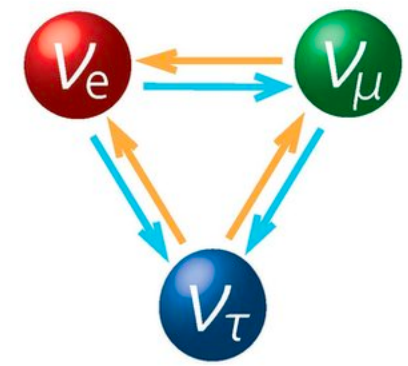
$$\left|\frac{m(K^\circ) - m(\overline{K}^\circ)}{m_K}\right| < 6 \times 10^{-19} \Rightarrow |m^2(K^\circ) - m^2(\overline{K}^\circ)| < 0.3\ eV^2$$

- In neutrino sector: $\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$, $\Delta m^2_{31} \approx 2.55 \times 10^{-3} eV^2$ => possible explore CPT violation at lower mass-squared level

1. Introduction

Testing CPT invariance with neutrino oscillation experiment

Neutrino oscillation: ν changes its flavor after traveling some distance



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

Flavor eigenstates — **Mass eigenstates**

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

Oscillation probability

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

ν mass — **distance traveled** — **$\propto \rho$ in matter** — **ν energy** — $\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$

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

1. Introduction

Testing CPT invariance with neutrino oscillation experiment

- CPT asymmetry: $\mathscr{A}_{CPT} = P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\beta \to \overline{\nu}_\alpha)$
- Accelerator-based experiments study 4 channels: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$
- Accelerator-based experiments can 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

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

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

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

1. Introduction

Testing CPT invariance with neutrino oscillation experiment

- The most up-to-date bounds on CPTV at 3σ with ν experiments ($|\delta(X)| = |X - \overline{X}|$)

$$|\delta(sin^2\theta_{12})| < 0.14$$

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

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

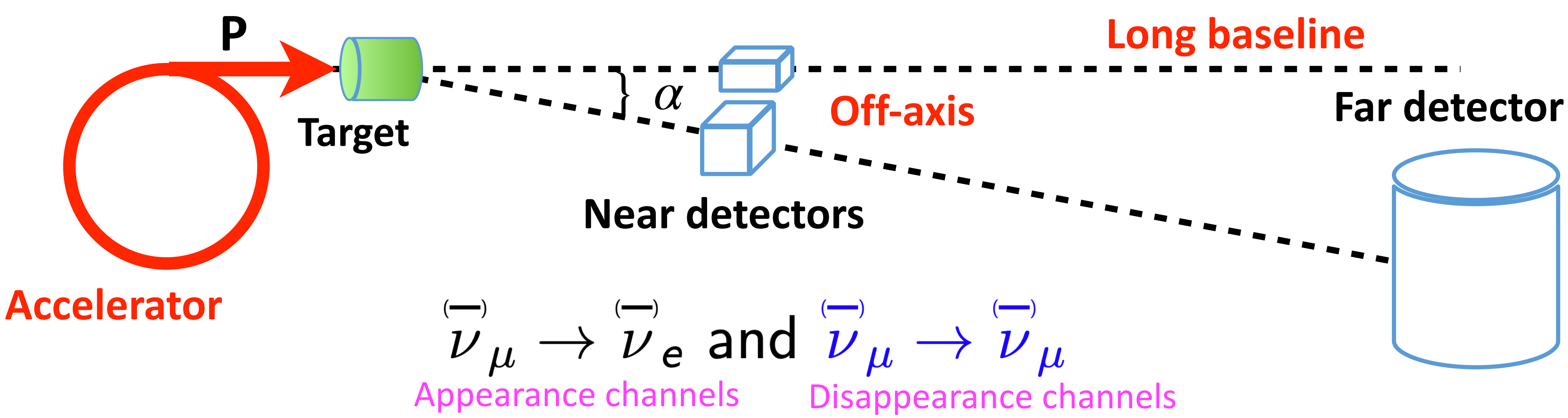
$$|\delta(\Delta m^2_{21})| < 4.7 \times 10^{-5}\ eV^2$$

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

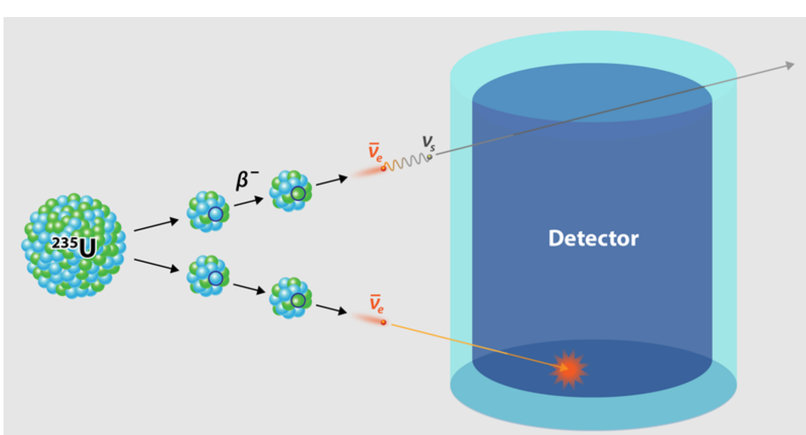
1. Introduction

Neutrino oscillation experiments

- Accelerator-based experiments: T2K(-II), NOvA(-II), Hyper-K, and DUNE



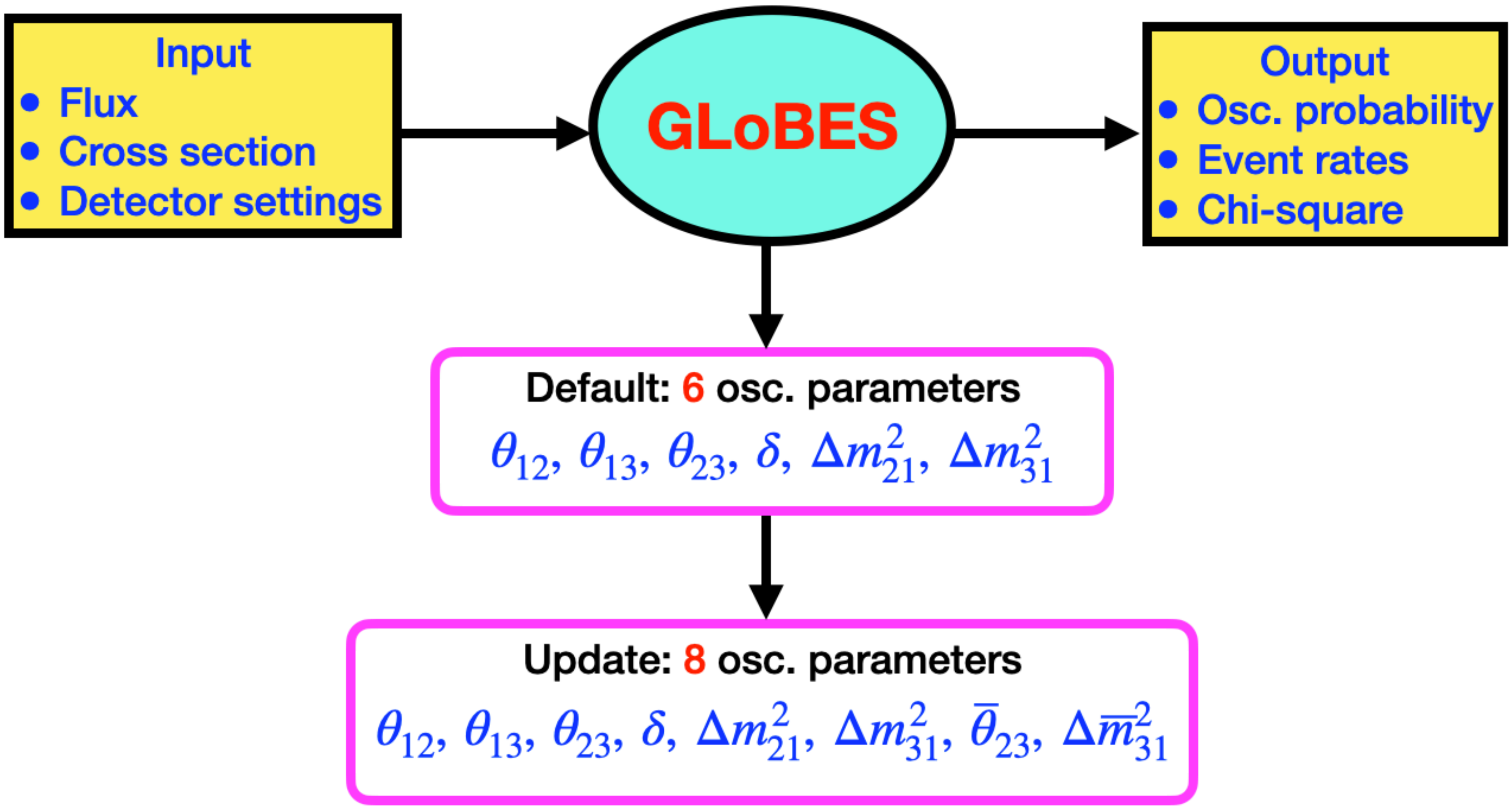
- Reactor-based experiment: JUNO



$$P(\overline{\nu}_e \to \overline{\nu}_e) \approx 1 - 2\sin^2 2\overline{\theta}_{13} \boxed{\sin^2 \frac{\Delta \overline{m}^2_{31} L}{4E}} - \sin^2 2\overline{\theta}_{12} \overline{s}^4_{13} \sin^2 \frac{\Delta \overline{m}^2_{21} L}{4E}$$

2. Experiment simulation

- GLoBES: The General Long Baseline Experiment Simulator



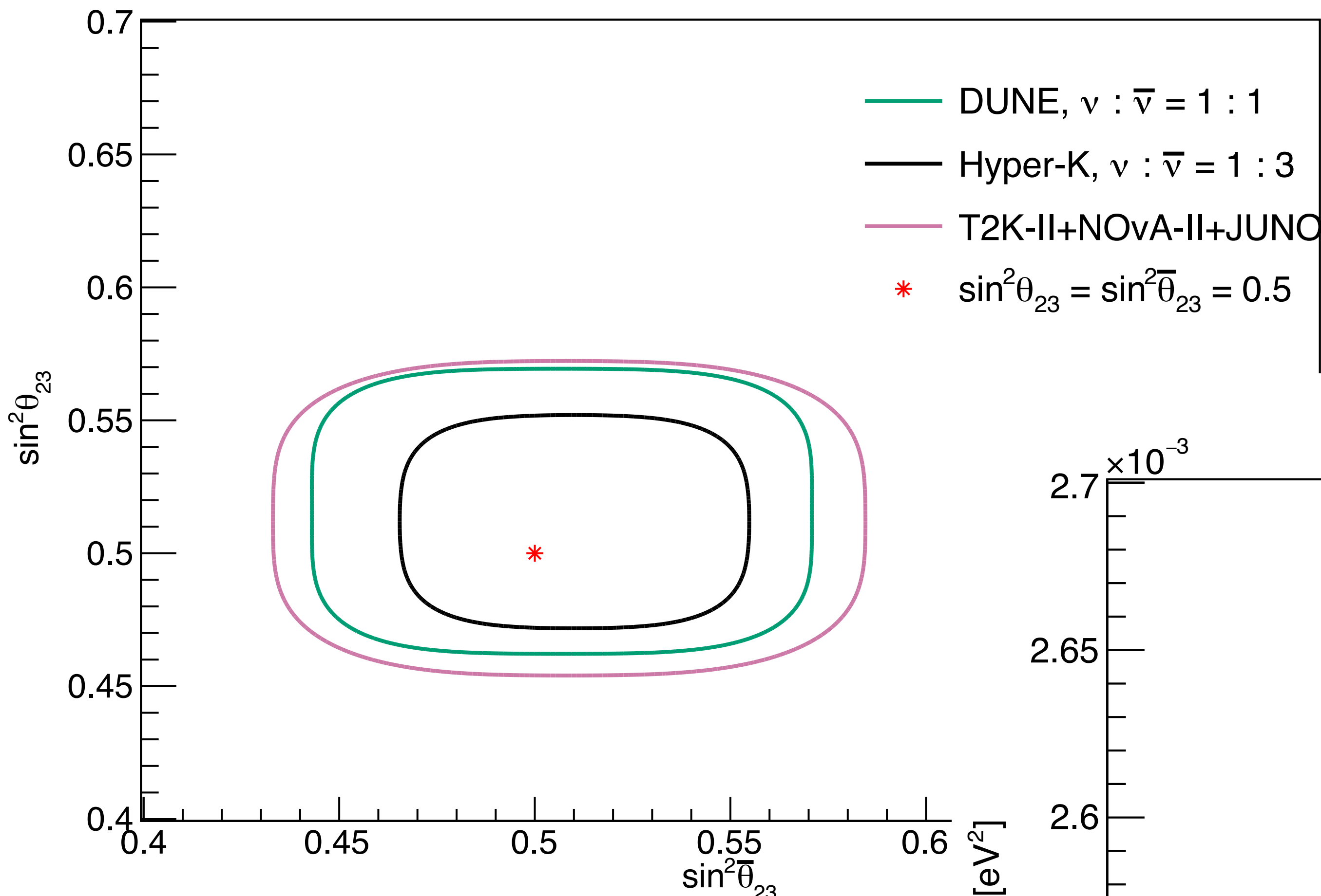
2. Experiment simulation

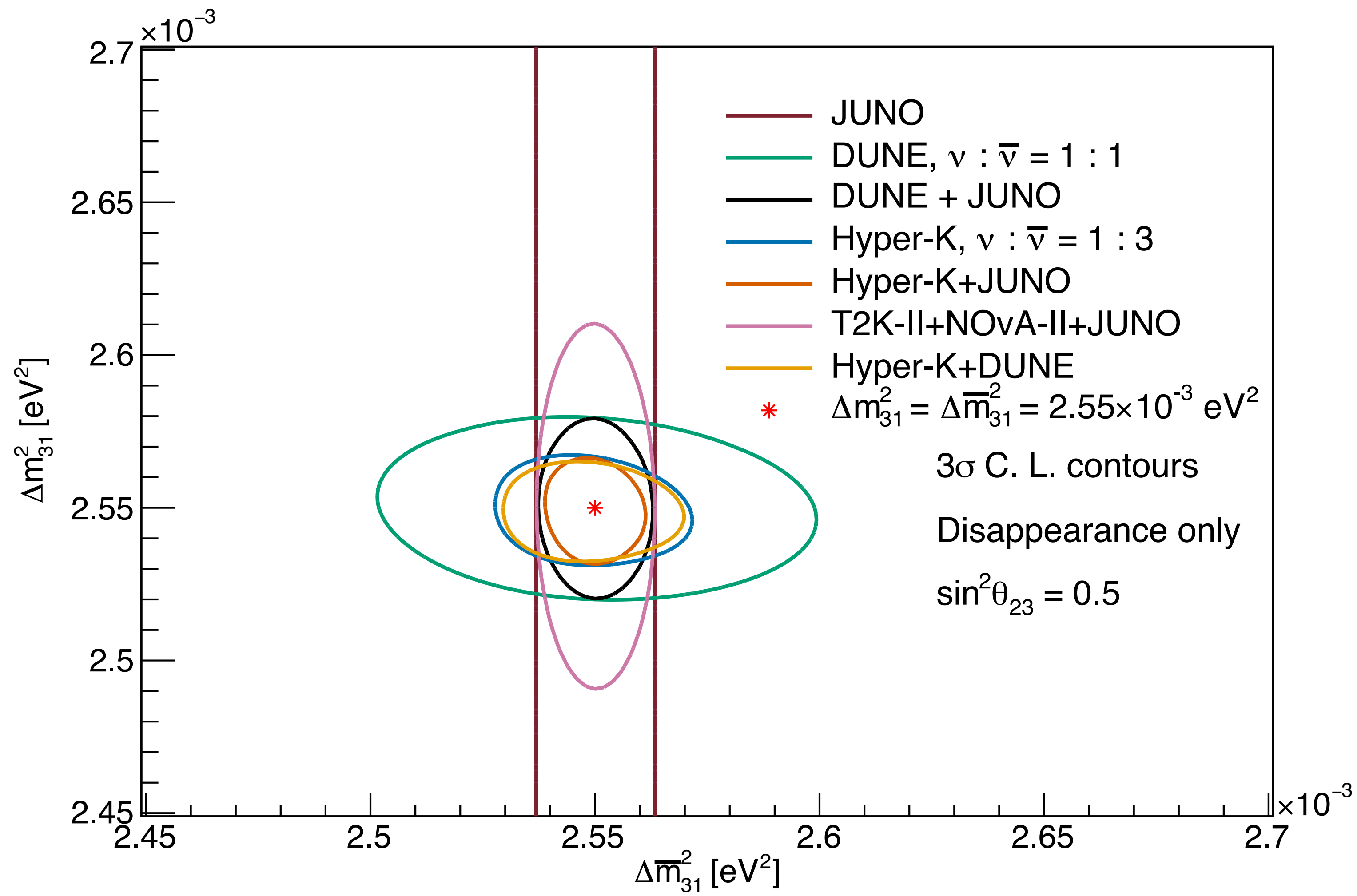
- GLoBES setup for T2K-II, NOvA-II, JUNO, Hyper-K, and DUNE

	T2K-II	NOvA-II	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

3. Constraint to the CPT violation

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



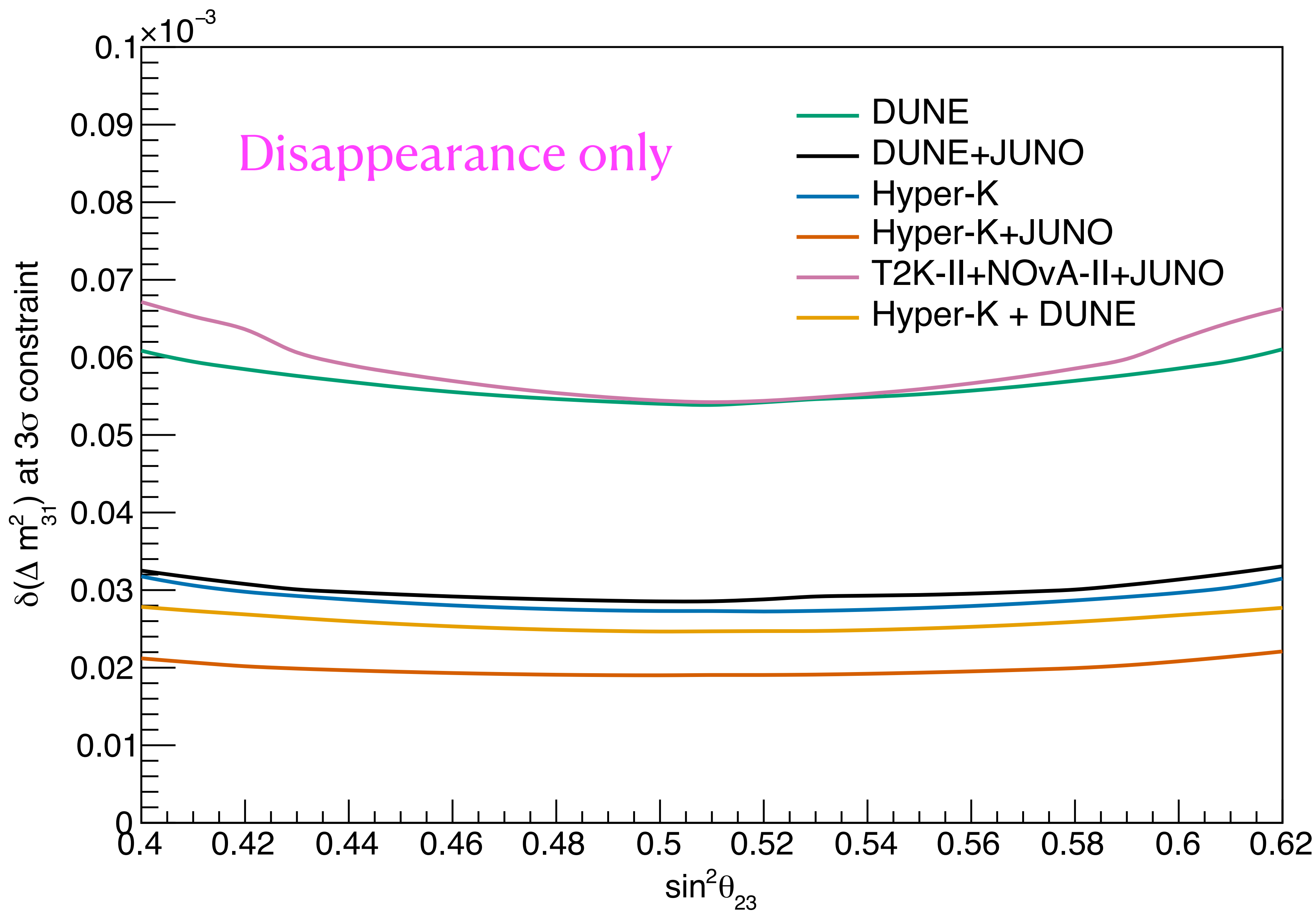


3. Constraint to the CPT violation

Constraint with $\delta(\Delta m^2_{31})$

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

- Hyper-K will provide the best constraint to the CPTV in terms of Δm^2_{31} among single detector experiments
- Hyper-K + JUNO will give best constraint that ever made



3. Constraint to the CPT violation

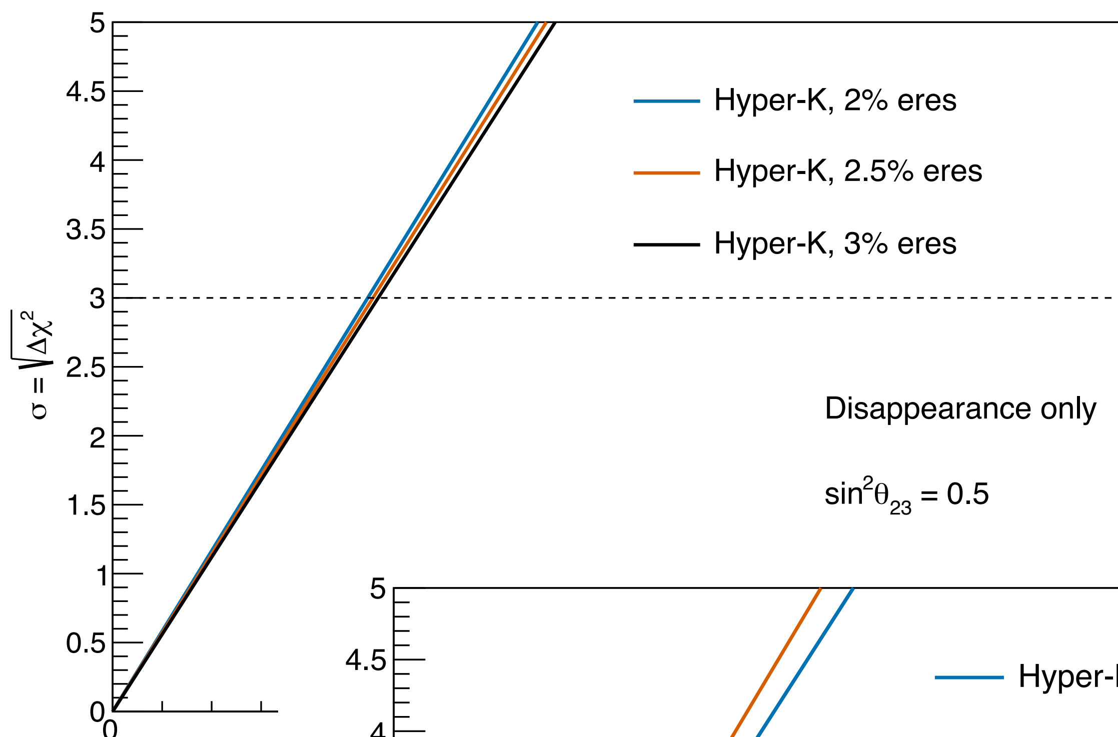
Constraint with $\delta(\Delta m^2_{31})$

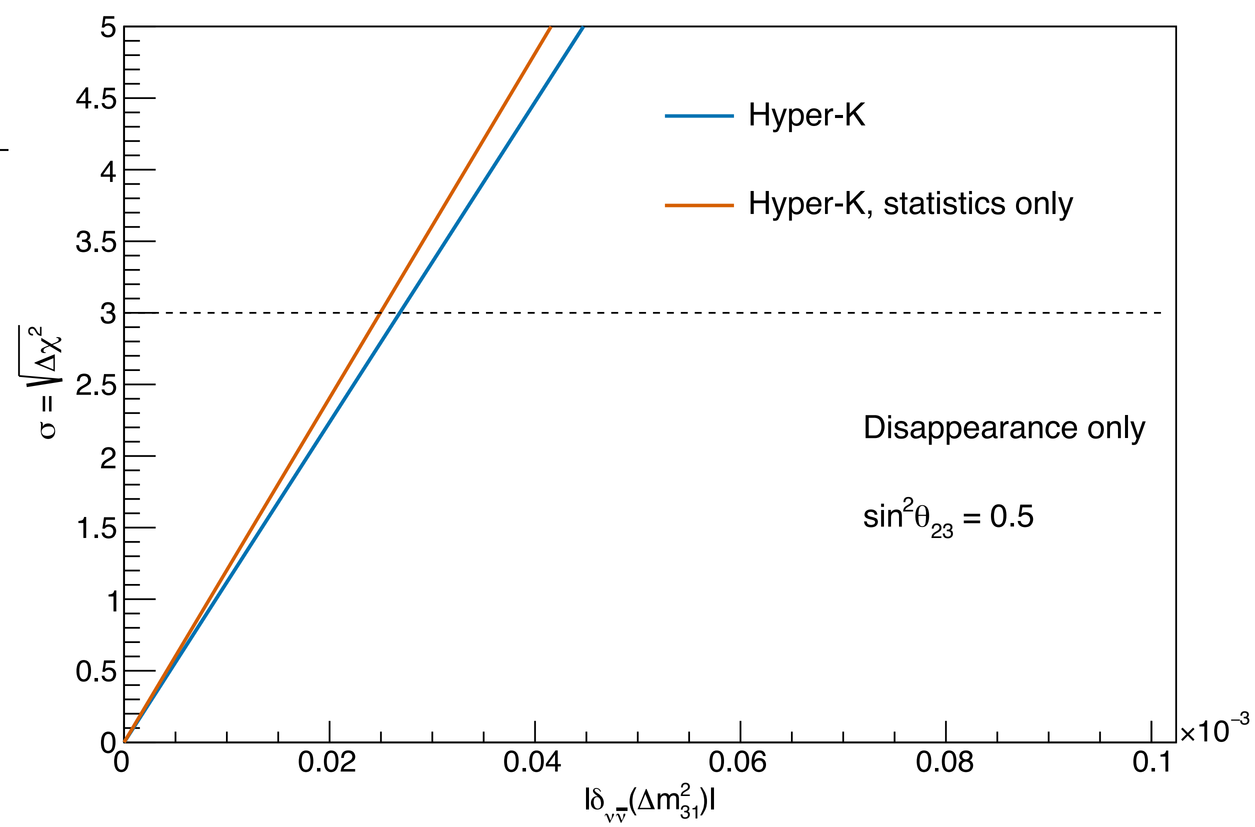
- Energy resolution, systematics, and neutrino mode configuration slightly affect to the bound on CPTV

- 2% difference for each 0.5% improvement in energy resolution

- 7% increase in bound value if using statistics only

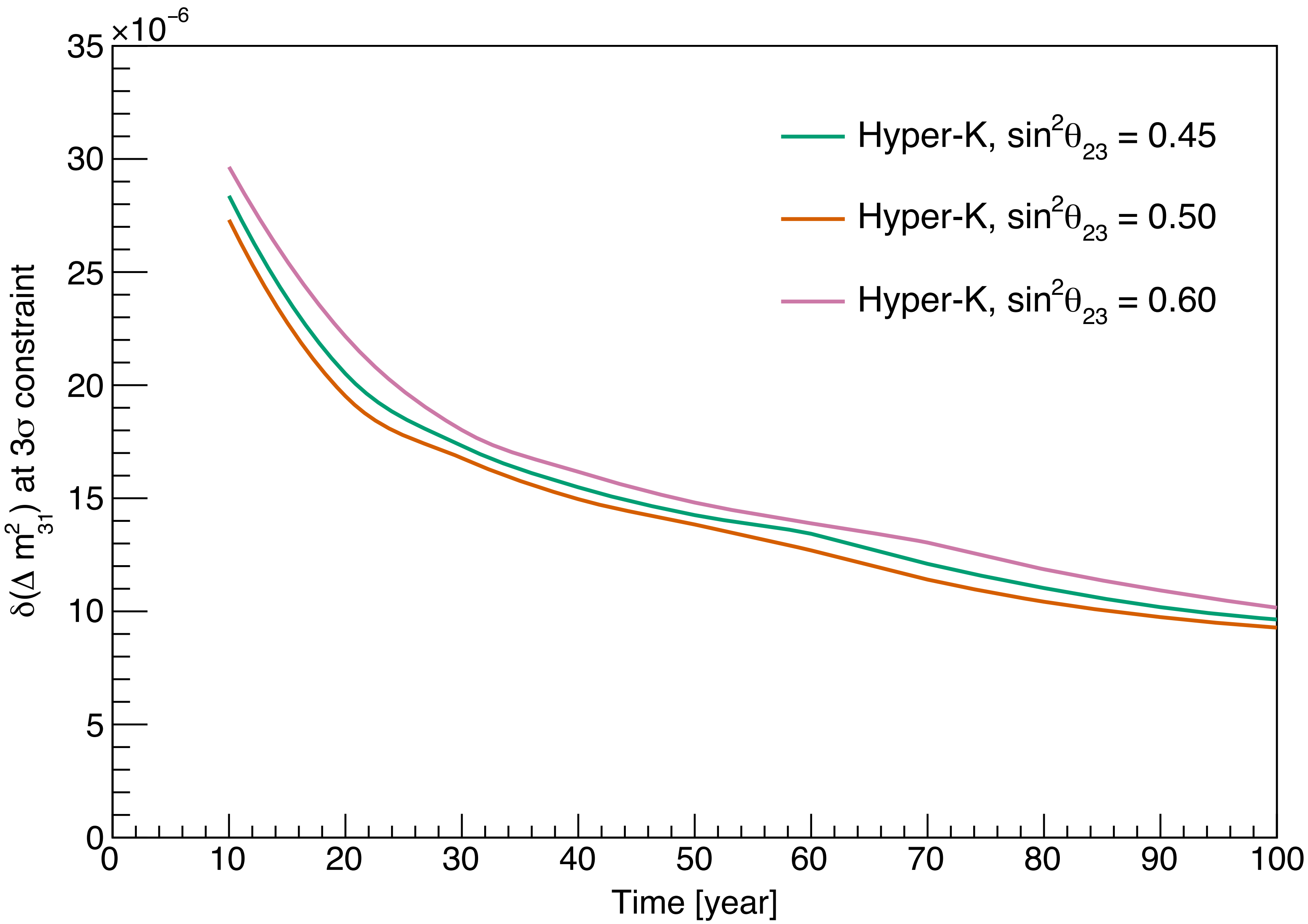
- 2% better constraint of $\nu : \bar{\nu} = 1 : 1$ configuration than $\nu : \bar{\nu} = 3 : 1$ configuration





3. Constraint to the CPT violation

Constraint with $\delta(\Delta m^2_{31})$

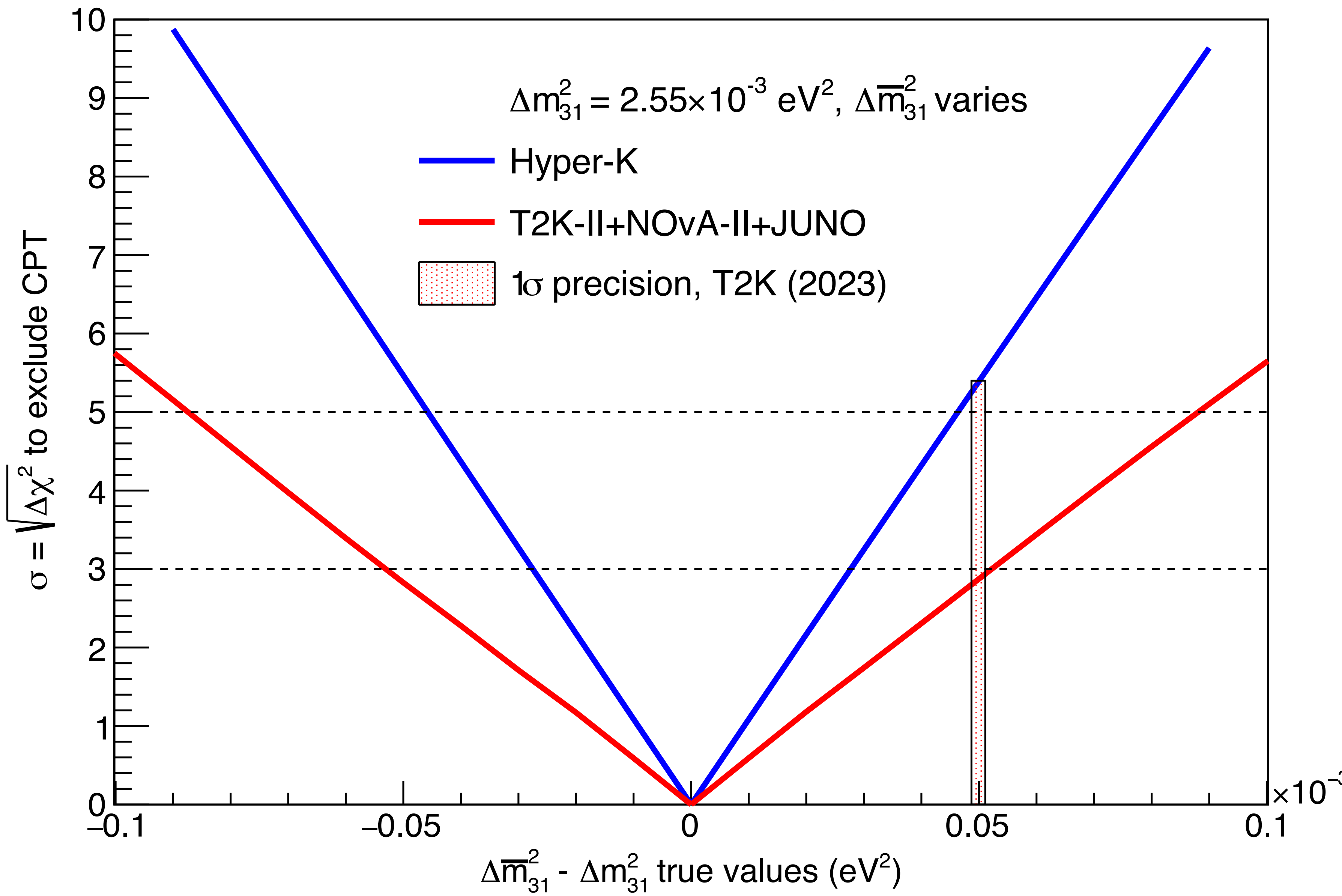


- The bound on $\delta(\Delta m^2_{31})$ reduce half compared to nominal setup (10 years) after 50 years
- Improved one order after 100 years

The bound on $\delta(\Delta m^2_{31})$ at $3\sigma\ C.L.$ versus statistics (run time)

3. Sensitivity to CPT violation

with $\delta(\Delta m^2_{31})$



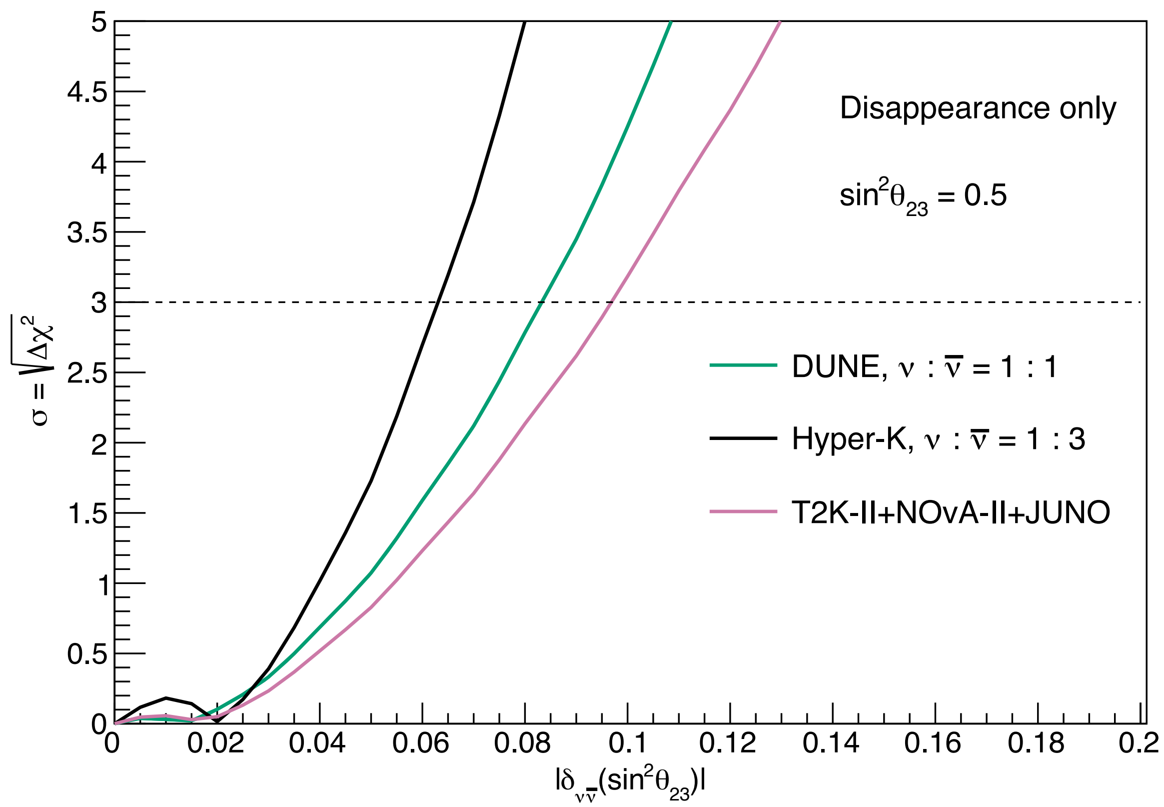
- If T2K best fits on Δm^2_{31} and $\Delta\overline{m}^2_{31}$ are assumed to be true, Hyper-K will be able to exclude CPT conservation at $5\sigma\ C.L.$

3. Constraint to the CPT violation

Constraint with $\delta(\sin^2\theta_{23})$

- Assume CPT is conserved, we calculate the bound on CPTV with $\delta(\sin^2\theta_{23})$

  - Hyper-K will provide the best constraint to the CPTV in terms of mixing angle θ_{23}



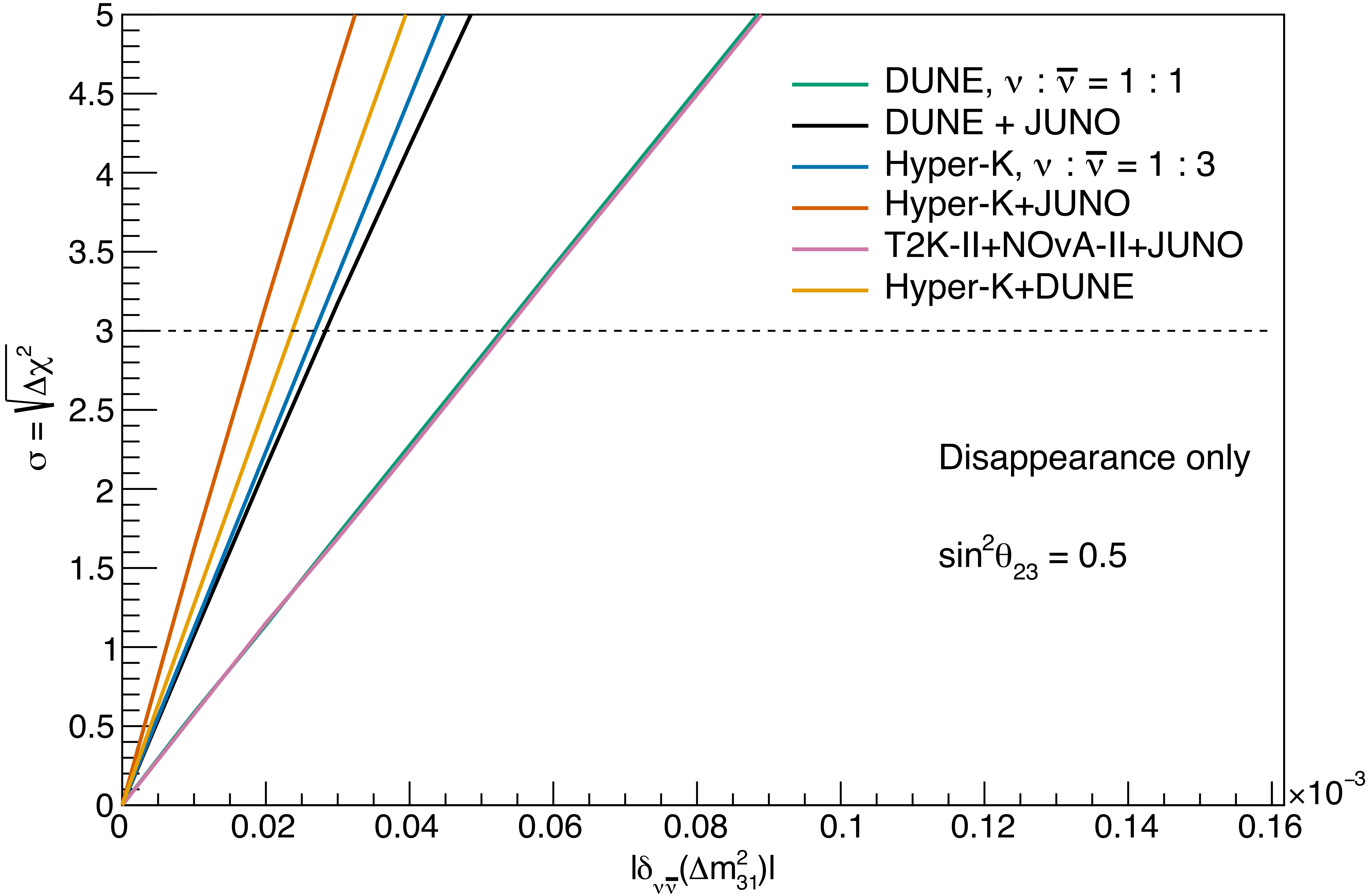
- The bound with $\delta(\sin^2\theta_{23})$ at 3σ

Exp	DUNE	Hyper-K	T2K-II + NOvA-II + JUNO
$\sin^2\theta_{23} = 0.45$	0.145	0.135	0.161
$\sin^2\theta_{23} = 0.50$	0.083	0.063	0.097
$\sin^2\theta_{23} = 0.60$	0.192	0.188	0.211

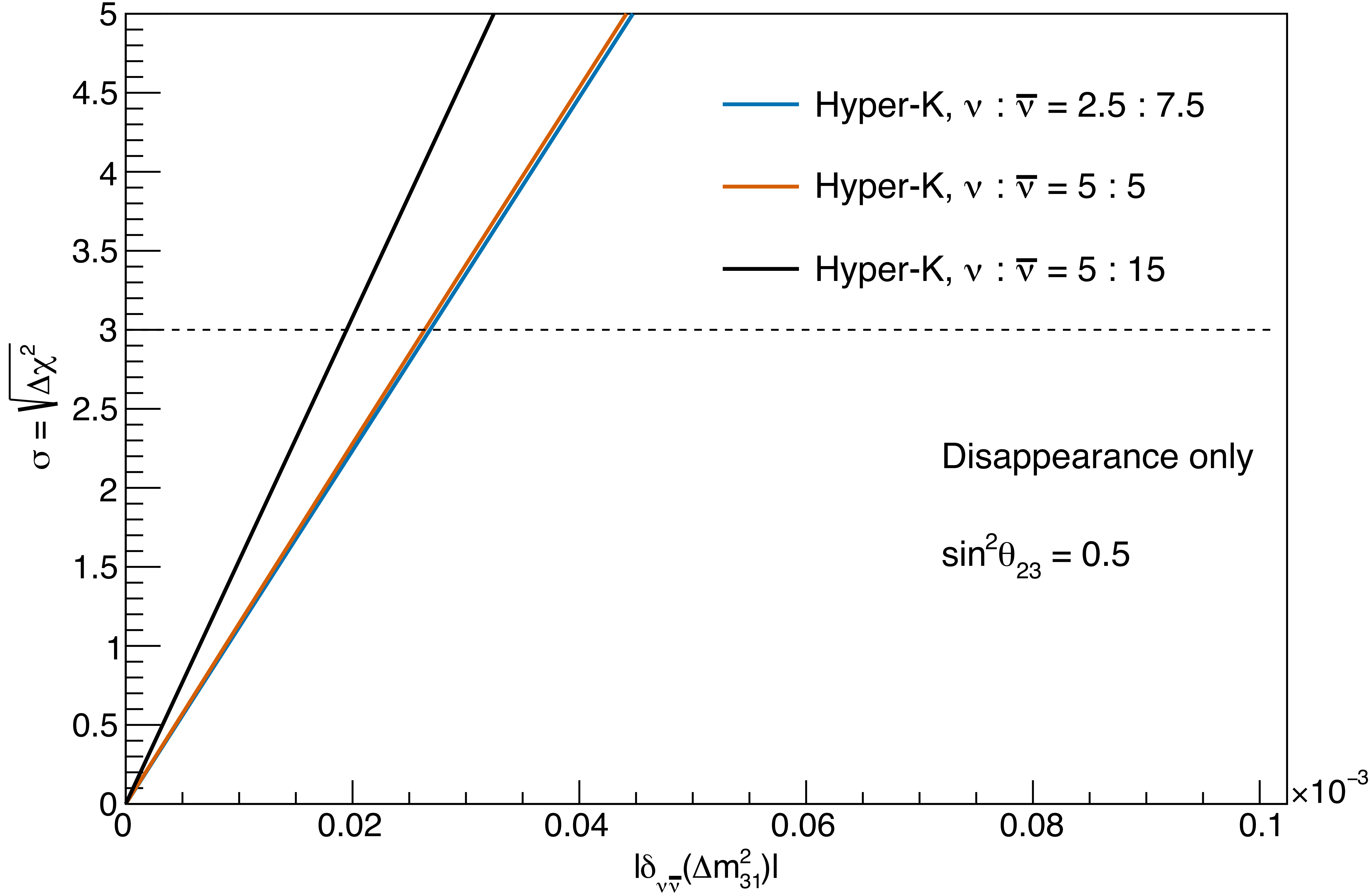
Conclusion

- Hyper-K will provide the best constraint on CPTV in terms of mass squared difference and mixing angle among the single detector experiments
- Hyper-K + JUNO has more stringent constraint to the CPTV than Hyper-K + DUNE
- Improvement in energy resolution and systematics slightly affect to the CPTV sensitivity
- $\nu : \bar{\nu} = 1 : 1$ configuration has slightly better constraint to the CPTV than $\nu : \bar{\nu} = 3 : 1$ configuration
- Hyper-K has the sensitivity to CPTV at $5\sigma\ C.L.$ if the current best fits of T2K on Δm^2_{31} and $\Delta \overline{m}^2_{31}$ are still true

Thank you very much for your attention



DUNE, ν : ν̄ = 1 : 1
DUNE + JUNO
Hyper-K, ν : ν̄ = 1 : 3
Hyper-K+JUNO
T2K-II+NOvA-II+JUNO
Hyper-K+DUNE
Disappearance only
$\sin^2\theta_{23} = 0.5$
$\sigma = \sqrt{\Delta\chi^2}$
$|\delta_{\nu\bar{\nu}}(\Delta m^2_{31})|$
$\times 10^{-3}$
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16


Hyper-K, ν : ν̄ = 2.5 : 7.5
Hyper-K, ν : ν̄ = 5 : 5
Hyper-K, ν : ν̄ = 5 : 15
Disappearance only
$\sin^2\theta_{23} = 0.5$
$\sigma = \sqrt{\Delta\chi^2}$
$|\delta_{\nu\bar{\nu}}(\Delta m^2_{31})|$
$\times 10^{-3}$
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.02
0.04
0.06
0.08
0.1

3. Constraint to the CPT violation

Constraint with $\delta(\Delta m^2_{31})$

	DUNE	DUNE	DUNE + JUNO	Hyper-K	Hyper-K+JUNO	T2K-II+NOvA-II+JUNO
$sin^2\theta_{23} = 0.45$	5.75E-05	5.54E-05	2.93E-05	2.81E-05	1.94E-05	5.75E-05
$sin^2\theta_{23} = 0.50$	5.48E-05	5.28E-05	2.83E-05	2.68E-05	1.89E-05	5.33E-05
$sin^2\theta_{23} = 0.60$	6.03E-05	5.83E-05	3.09E-05	2.96E-05	2.05E-05	6.15E-05

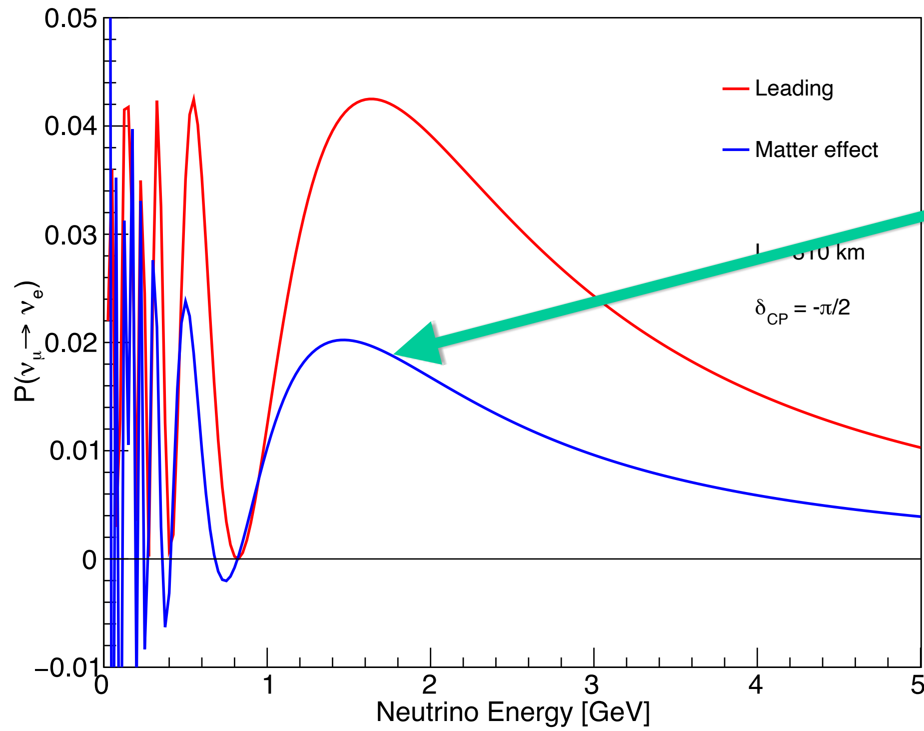
Backup: Matter effect in CPT violation search

- Under CPT symmetry:

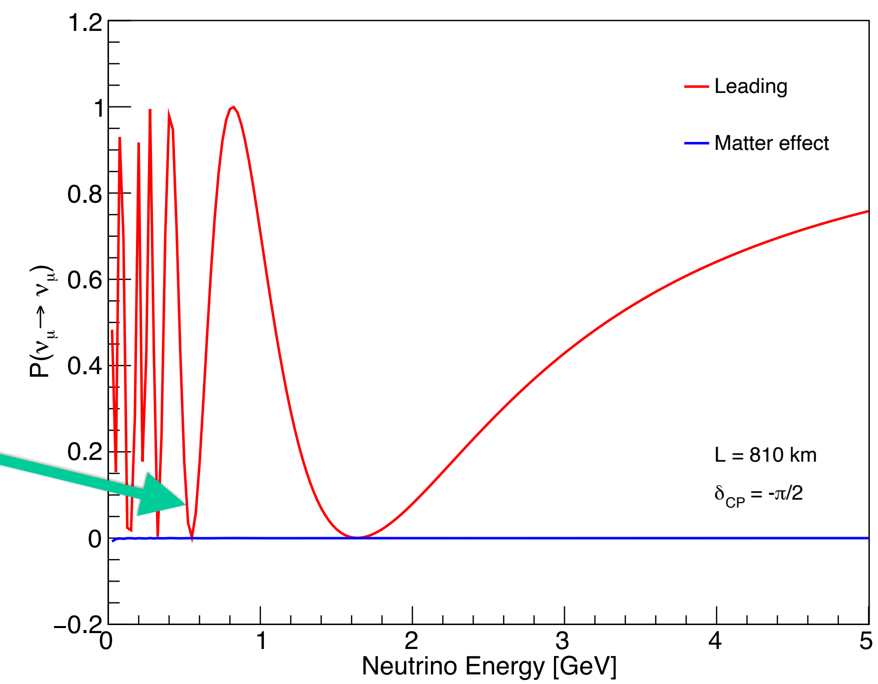
$$P(\nu_\alpha \rightarrow \nu_\beta) \xrightarrow{CPT} P(\overline{\nu}_\beta \rightarrow \overline{\nu}_\alpha) = P(\nu_\alpha \rightarrow \nu_\beta)$$

- The CPT asymmetry: $\mathscr{A}^{CPT}_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\overline{\nu}_\beta \rightarrow \overline{\nu}_\alpha)$

$$= \mathscr{A}^{CPT}_{intrinsic} + \mathscr{A}^{CPT}_{extrinsic}$$



Matter effect is large in appearance channels, negligible in disappearance channels



If $\mathscr{A}^{CPT}_{\alpha\beta} \neq 0$ in disappearance channels => more chance it is $\mathscr{A}^{CPT}_{intrinsic}$

3. Constraint to the CPT violation

Constraint with $\delta(\sin^2\theta_{23})$

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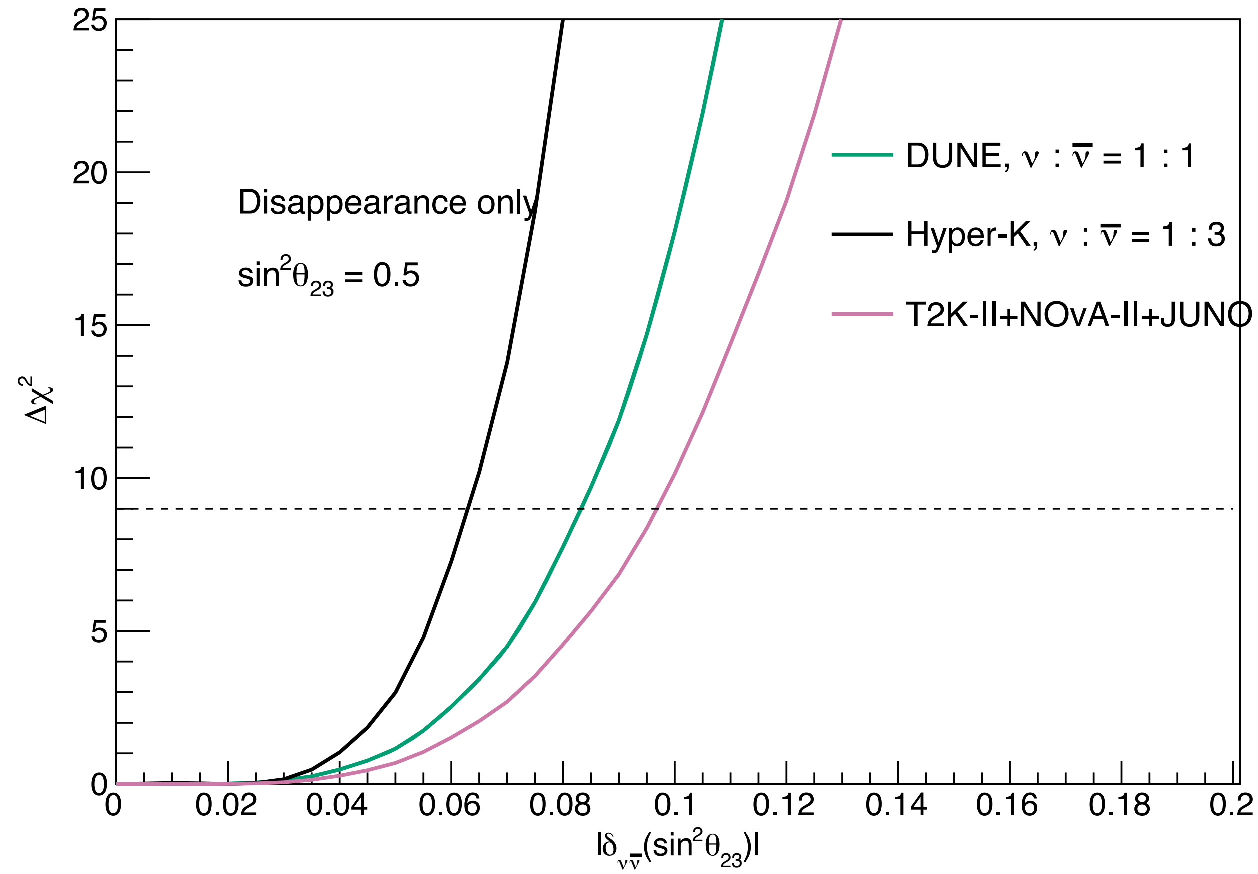
  - Hyper-K will provide the best constraint to the CPTV in terms of mixing angle θ_{23}



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