Testing the Direct and Indirect Unitarity Violation at a Neutrino Factory

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Based on the work in collaboration with
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- **Motivations**
- **Arrangements and assumptions of DUV and IUV**
- **Physics sensitivity at the neutrino factory**
- **Summary**

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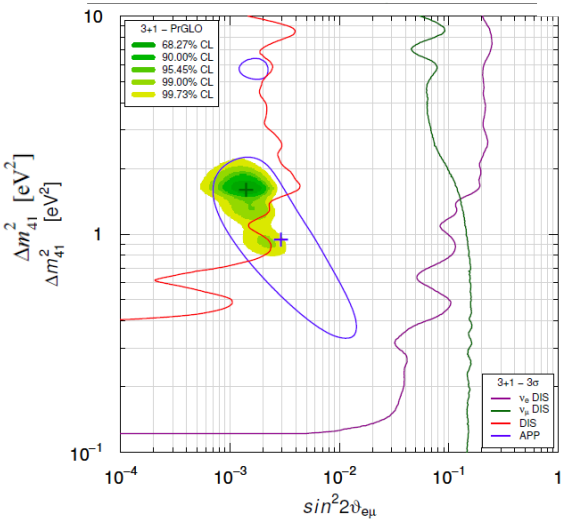
Tests of different unitarity violations: why?

- **Light sterile neutrino anomaly (eV scale)**
- **Heavy sterile neutrinos from see-saw model(GeV scale)**
- **Dark matter candidate (keV scale)**
- **IUV(indirect unitary violation) by heavy sterile neutrinos**
- **DUV(direct unitary violaiton) by light sterile neutrinos: oscillation with active ones**

- Reactor anomaly: a recomputation of $\bar{\nu}_e$ fluxes from nuclear reactors is about 3% higher than those in the reactor neutrino oscillation experiments. It implies that all the reactor neutrino oscillation experiments have observed deficits of $\bar{\nu}_e$s.
- LSND anomaly: An experiment searching for oscillations $\bar{\nu}_\mu \to \bar{\nu}_e$ reaches the best fit Δm^2 around $\mathcal{O}(1)$ eV^2.
- Release of MiniBooNE antineutrino results consistent with LSND.
- Globally fitted results (ref: 1507.08204



- Sterile neutrinos to accommodate the tension.
- Global fits show hints rather than compelling evidence.
- Still doubt on the existence of sterile neutrinos.

- Many discussions of sterile neutrinos.
- Preparation of perturbative oscillation probability was just given by Dr. Shu Luo.
- Can we see signals in any future's experiment?
- Let's go to the powerful proposal: Neutrino Factory!

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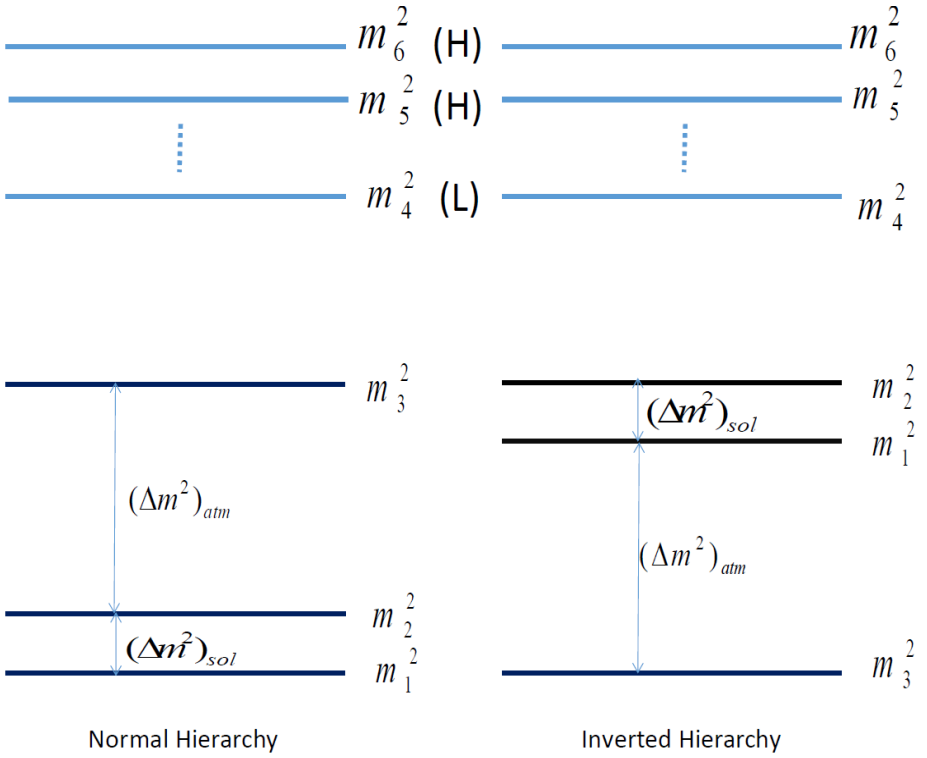
Arrangements of mass eigenstates and assumptions



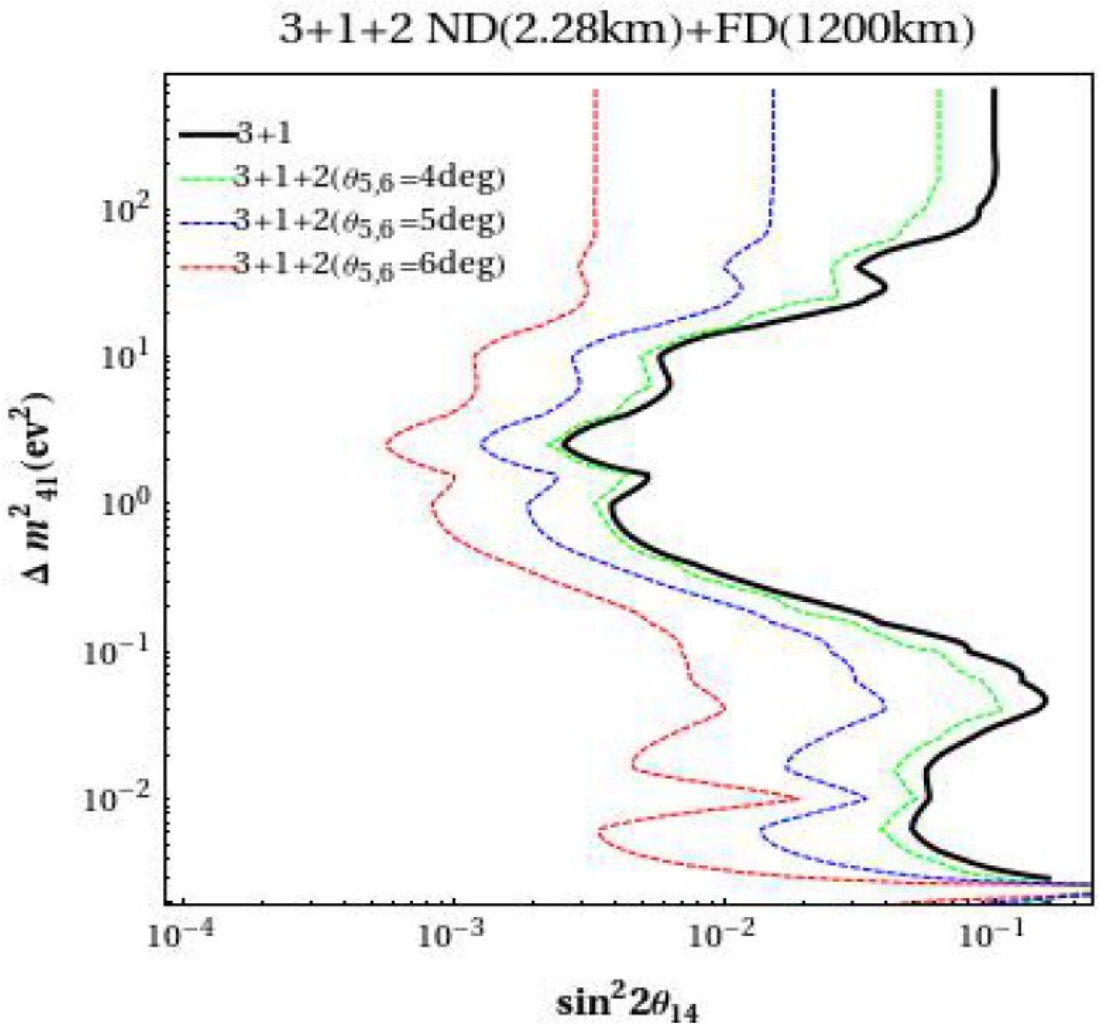
- Two detectors are assumed: L1 = 2.28km ;L2 = 1200km
- Parent energy :5 GeV
- The oscillation parameters are take as follows:
- Oscillation parameters

$$\theta_{12} = 33.48^\circ$$
$$\theta_{23} = 45^\circ$$
$$\theta_{13} = 8.5^\circ$$
$$\delta_{cp} = 90^\circ$$
$$\Delta m^2_{21} = 7.5 \times 10^{-5}$$
$$\Delta m^2_{31} = 2.5 \times 10^{-3}$$
$$\delta_{14} = \delta_{15} = \delta_{16} = \delta_1 \qquad \theta_{14} = \theta_{24} = \theta_{34} = \theta_4$$
$$\delta_{24} = \delta_{25} = \delta_{26} = \delta_2 \qquad \theta_{15} = \theta_{25} = \theta_{35} = \theta_5$$
$$\delta_{34} = \delta_{35} = \delta_{36} = \delta_3 \qquad \theta_{16} = \theta_{26} = \theta_{36} = \theta_6$$

For convenience

- **Simplifying the mixing matrix to deal with DUV and IUV, Phys. Lett., B718:1447-1453, 2013.**
- **Perturbation study of oscillation probabilities for DUV & IUV, Phys. Rev., D93(3):033008, 2016.**
- **Arbitrary choose of new CP phases as inputs for GLoBES if necessary.**

Simulation of accelerator neutrino oscillation



Very good sensitive region:

(1) $\Delta m^2_{41} \sim 1eV^2$

(2) $\Delta m^2_{41} \sim 10^{-3}eV^2$

- The exclusion limit at 90%CL,
- Dashed lines show effects induced by heavy neutrinos.

Understanding of two cases: case I

For $\Delta m^2_{41} \sim 1 eV^2$

$$\tilde{P}_{e\mu} \approx \frac{4 s_{23} s_{13}}{1 - A_{CC}} \left\{ \frac{s_{23}}{1 - A_{CC}} (s_{13} + 2 R_b A_{NC}) \sin(1 - A_{CC}) \Delta_{31} \right.$$

$$+ R_{12} \sin(1 - A_{CC}) \Delta_{31} + I_{12} \cos(1 - A_{CC}) \Delta_{31}$$

$$+ \frac{c_{23}}{A_{CC}} [(\alpha \sin 2\theta_{12} \cos\delta - 2 R_a A_{NC}) \cos \Delta_{31}$$

$$\left. + (\alpha \sin 2\theta_{12} \sin\delta + 2 I_a A_{NC}) \sin \Delta_{31}] \overset{\Delta m^2_{41} \sim 1 eV^2}{\sin}(A_{CC} \Delta_{31}) \right\} \sin(1 - A_{CC}) \Delta_{31}$$

The oscillation terms for light sterile neutrinos are averaged out!

where

$$R_a \equiv -R_{12} c_{23} + R_{13} s_{23} ,$$

$$R_b \equiv R_{12} s_{23} + R_{13} c_{23} ,$$

$$R_c \equiv R_{12} c_{23} + R_{13} s_{23} ,$$

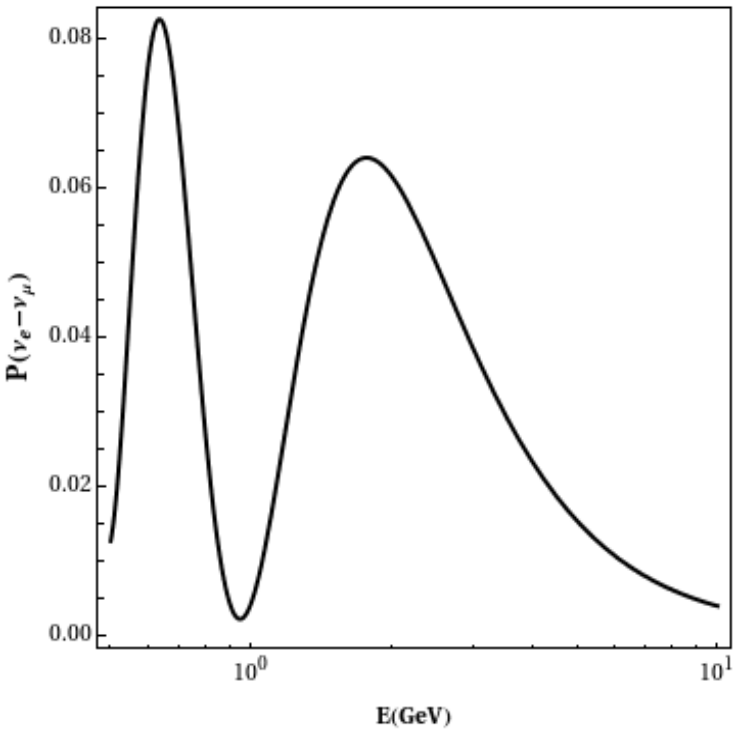
$$I_a \equiv -I_{12} c_{23} + I_{13} s_{23} ,$$

$$I_b \equiv I_{12} s_{23} + I_{13} c_{23} .$$

$$R_{12} \equiv \mathrm{Re}\left[(\hat{s}_{14} \hat{s}^*_{24} + \hat{s}_{15} \hat{s}^*_{25} + \hat{s}_{16} \hat{s}^*_{26}) e^{-i\delta} \right] ,$$

$$R_{13} \equiv \mathrm{Re}\left[(\hat{s}_{14} \hat{s}^*_{34} + \hat{s}_{15} \hat{s}^*_{35} + \hat{s}_{16} \hat{s}^*_{36}) e^{-i\delta} \right] ,$$

$$R_{23} \equiv \mathrm{Re}\left[\hat{s}_{24} \hat{s}^*_{34} + \hat{s}_{25} \hat{s}^*_{35} + \hat{s}_{26} \hat{s}^*_{36} \right] ,$$



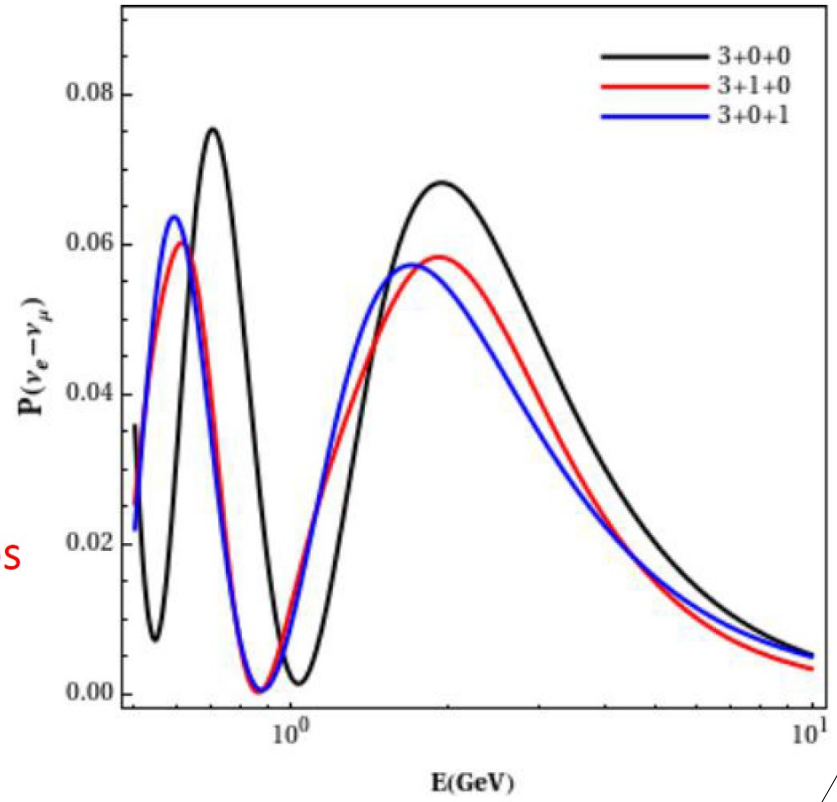
- Permutation symmetry shows up for new mixing angles.
- No difference for mixing angles induced by light/heavy sterile neutrinos, separately.
- This case is not so interesting to test DUV and IUV.

Understanding of two cases: case II

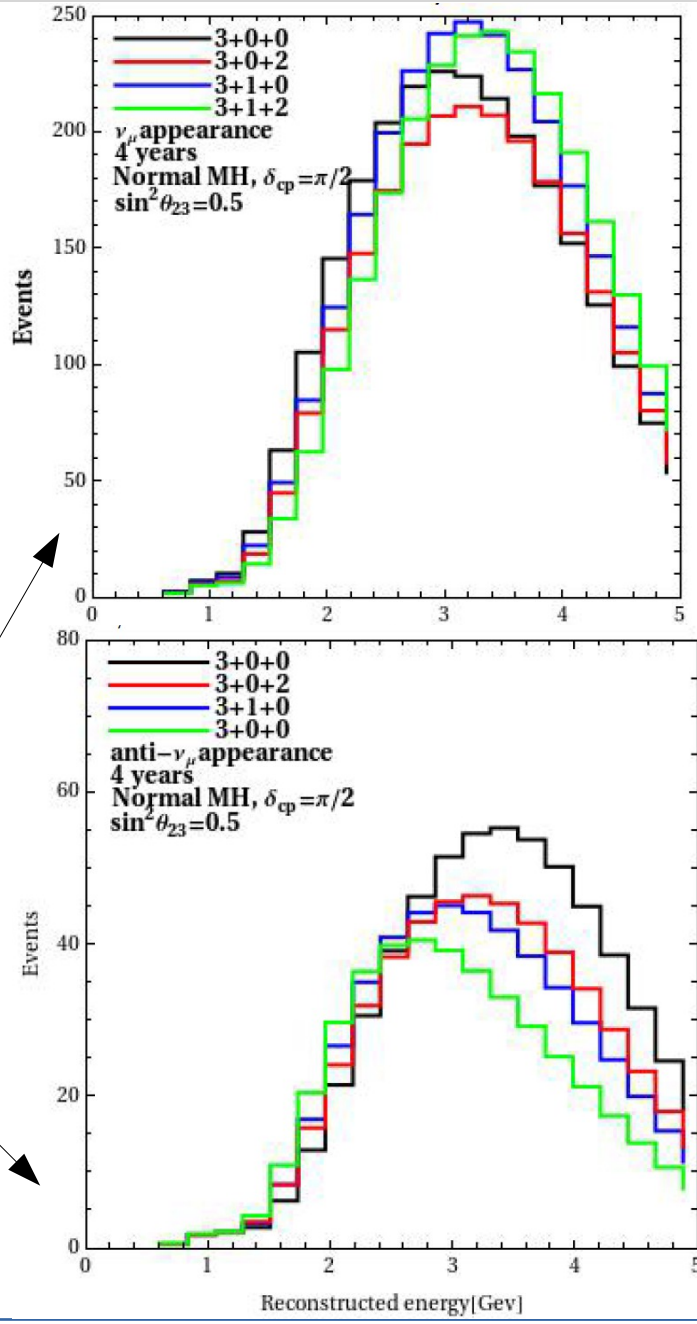
For

$$\Delta m^2_{41} \sim 10^{-3} eV^2$$

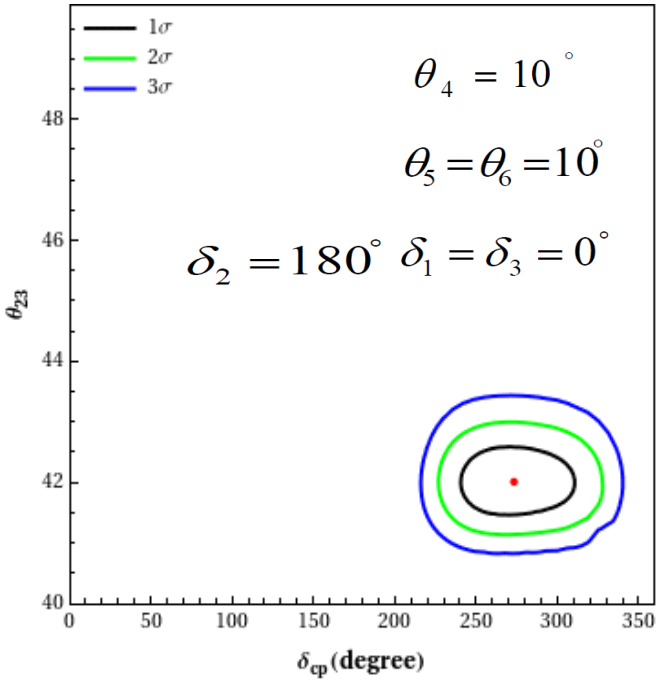
The appearance channel probability if different for light and heavy neutrinos



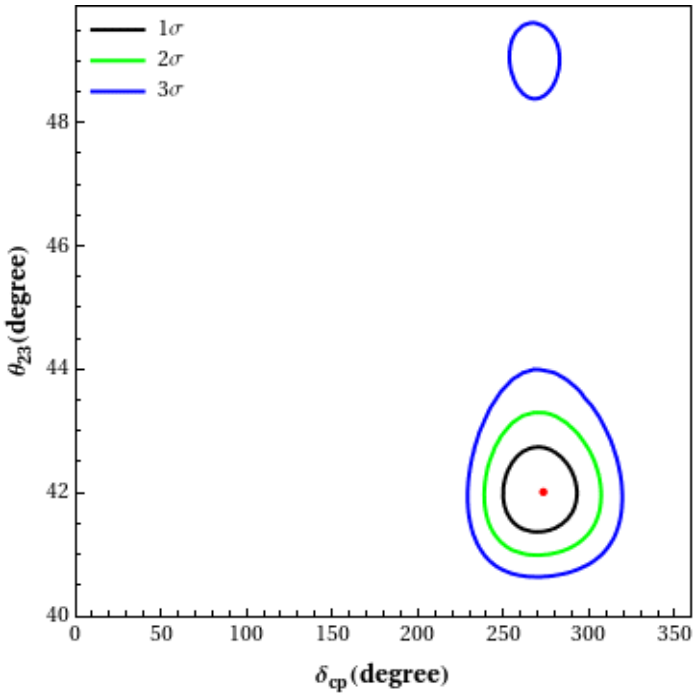
Reconstructed event rates at the neutrino factory



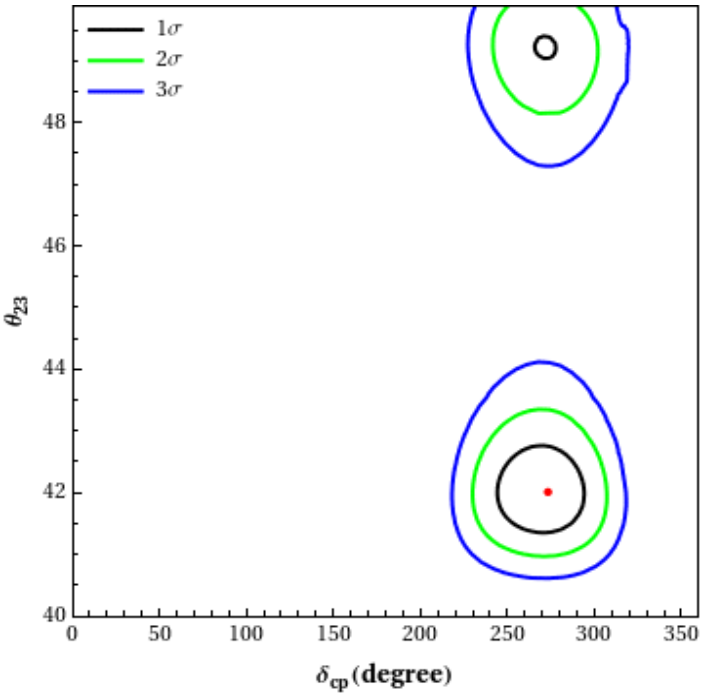
The impact on theta23 octant determination



3 active neutrinos



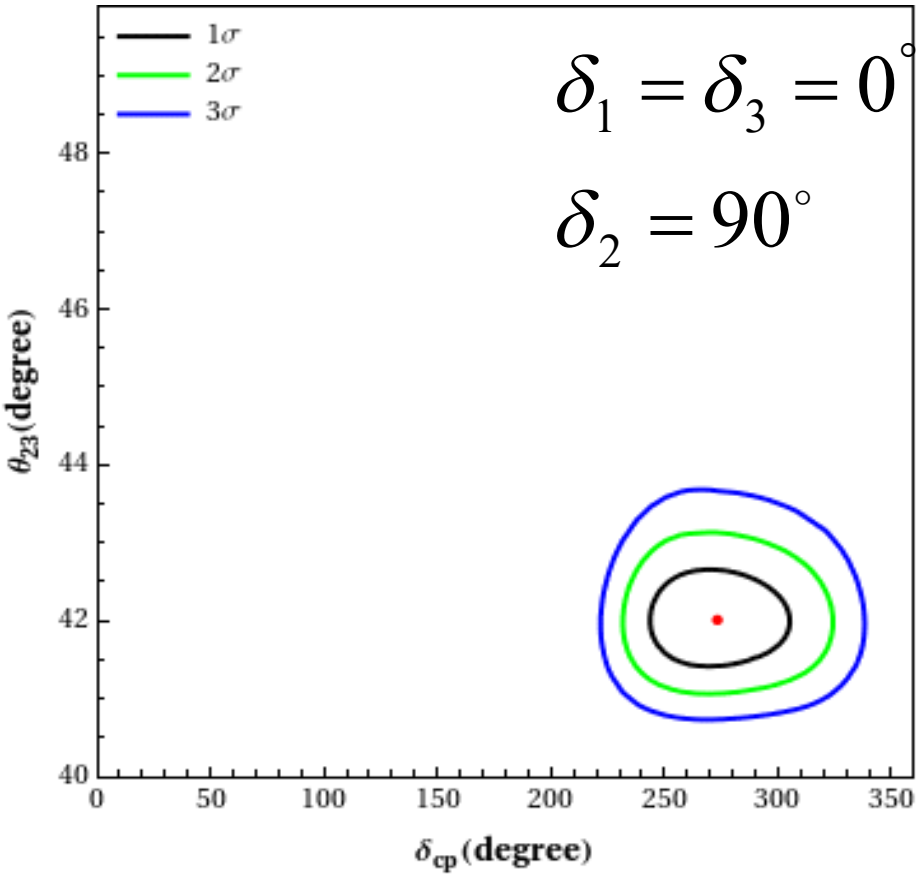
3 active neutrinos+1L



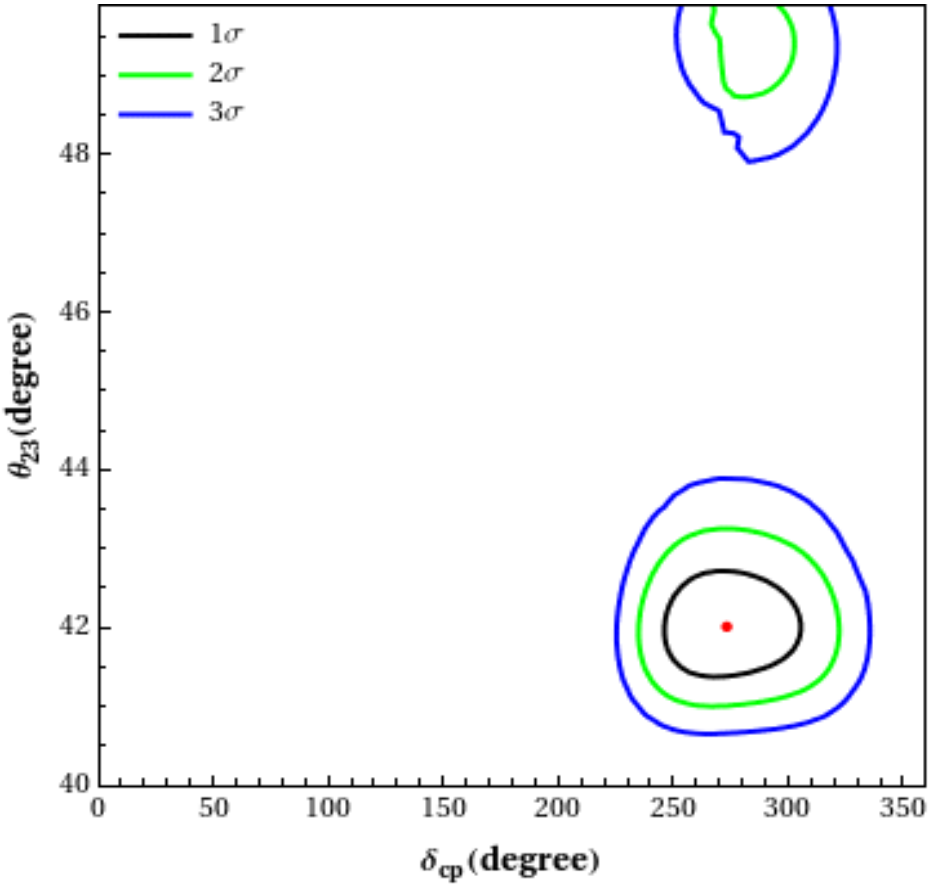
3 active neutrinos+1L+2H

- **Additional mixing angles or CP phases are given as an example.**
- **Though a good determination at the lower octant, DUV fakes it and IUV makes it worse.**

The impact on theta23 octant determination



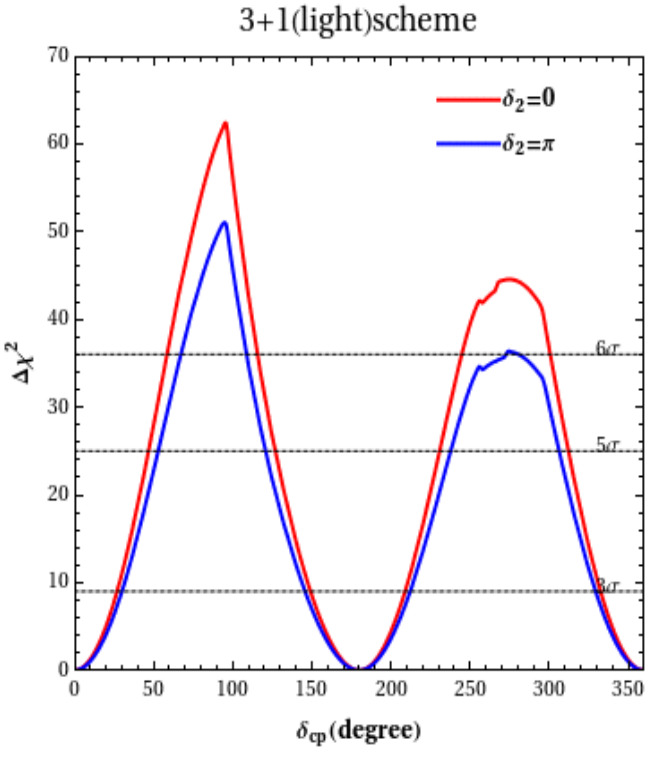
3 active neutrinos+1L

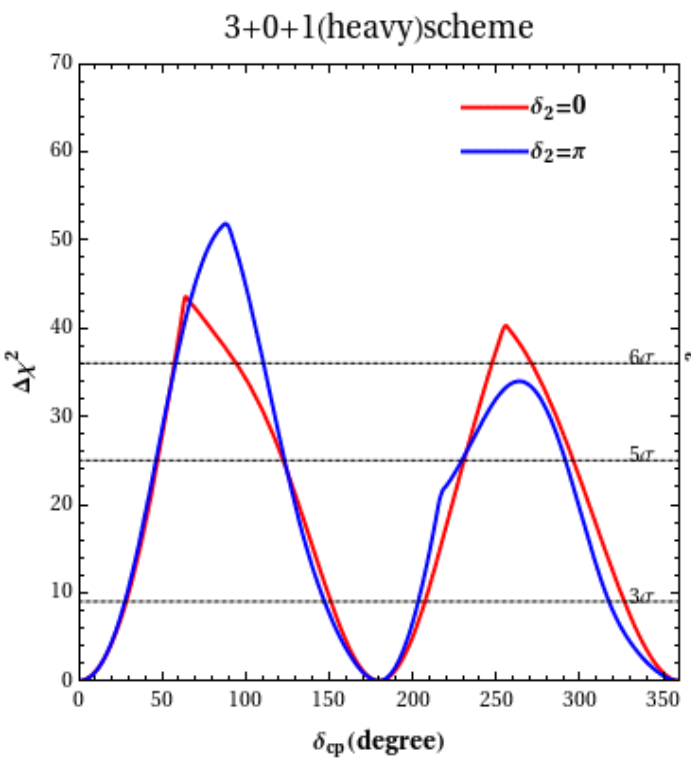


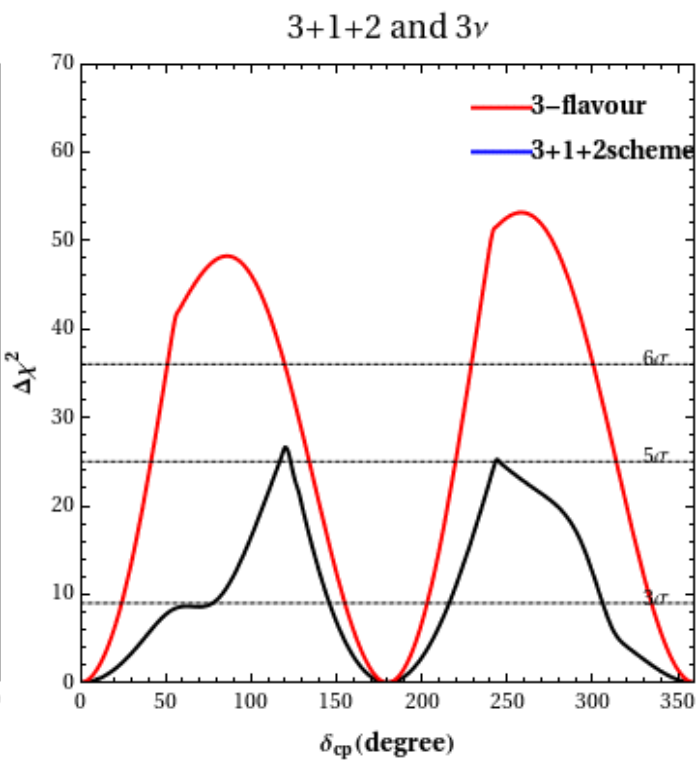
3 active neutrinos+1L+2H

Though a good determination at the lower octant by DUV, IUV can provide the fake result at the upper region.

The impact on CPV discovery







- **Clear difference after introducing light & heavy sterile neutrinos.**
- **Here we only consider discovery of the CPV from 3 active neutrino mixing.**
- **A definition of new parameters to discriminate DUV & IUV on the way.**

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- Physics study for International Study of Neutrino Factory
- CP Violation(CPV) study by neutrino beams from MOMENT
- Preliminary study on discrimination of non-unitarity violation with muon decay neutrino beams
- **Summary**

Summary

- **Too many types of sterile neutrinos: eV, keV, GeV scale...**
- **Species, mass scales, patterns are unknown.**
- **Assuming sterile neutrinos exist, DUV and IUV can be induced by light and heavy sterile neutrinos.**
- **We try to simulate the DUV and IUV induced by sterile neutrinos at a neutrino factory(ND+FD).**
- **Preliminary results shows some difference of DUV & IUV at CPV sensitivity, and theta23 octant determination.**
- **We are still working on new parameters to discriminate DUV & IUV at a neutrino factory (ND+FD).**
- **Please feel free to share your comments/suggestions.**

Thanks for your attention!