The octant of θ_{23} and neutrino non-standard interactions degeneracy

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Outline

- Current status of neutrino oscillation parameters
- Theoretical and analytical framework of neutrino non-standard interactions
- Impact of NSI on the resolution of octant of θ_{23} taking DUNE as a case study
- Some other kind of degeneracies
- Conclusion

A Few Known Unknowns in Neutrino Physics

3ν Framework

1. Whether neutrino is Dirac or Majorana particle.

2. Absolute masses (m_1, m_2, and m_3) of neutrinos are unknown. We know the magnitude of mass squared differences ($|\Delta m^2_{21}|$, $|\Delta m^2_{31}|$, or $|\Delta m^2_{32}|$).

3. The sign of the solar mass splitting ($|\Delta m^2_{21}|$) is known that is +ve that is $m_2 > m_1$. But the sign of the atmospheric mass splitting ($|\Delta m^2_{31}|$) is unknown. This is known as mass hierarchy problem. $m_1 < m_2 < m_3$, called normal hierarchy, and $m_3 < m_1 < m_2$ called inverted hierarchy.

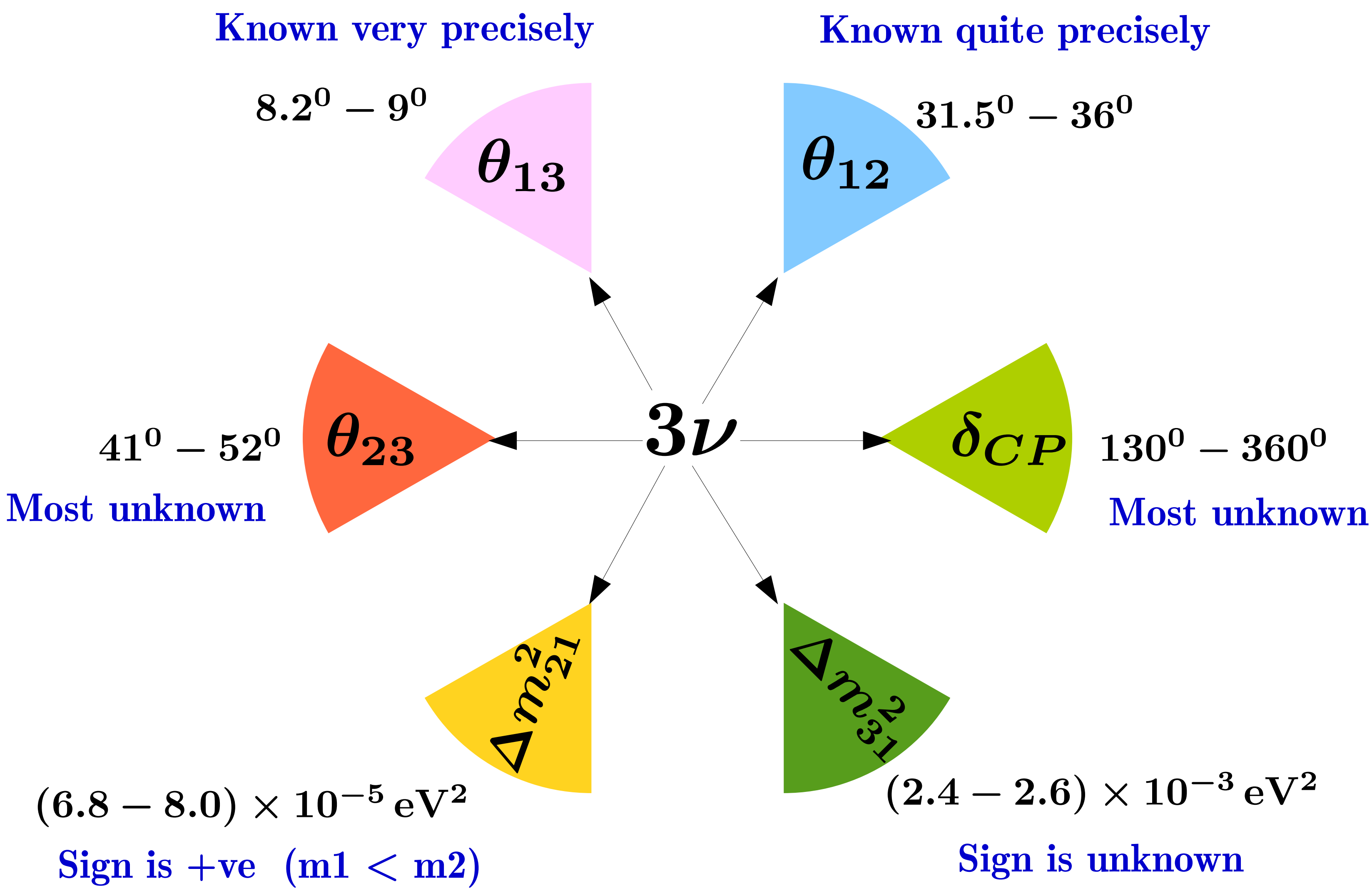
4. The magnitude of 2-3 mixing angle (θ_{23}) is unknown. This is known as octant ambiguity.

5. No confirmation yet about the CP-violation in leptonic sector.

New Physics ?

Presence of sterile neutrino, long-range forces, non-unitary nature of PMNS matrix, CPT violation, non-standard neutrino interactions, and many others.

Current status of 3ν parameters (3σ uncertainties)



For details please see arXiv: 1811.05487 by Esteban et al.

NSI and its presence in the oscillation framework

The effective 4-Fermi flavor changing neutral current non-standard interactions can be written as

$$\mathcal{L}_{\mathcal{NSI}} = \frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta,f} \varepsilon^{f}_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\mu \left(1-\gamma^5\right) \nu_\beta\right] \left[\bar{f} \gamma_\mu \left(1 \pm \gamma^5\right) f\right]$$

$$\alpha,\ \beta = e,\ \mu,\ \tau \text{ and } f = e, u, d$$

$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^{f}_{\alpha\beta} \frac{N_f}{N_e}$$

$$\varepsilon_{\alpha\beta} \simeq \varepsilon^{e}_{\alpha\beta} + 3\,\varepsilon^{u}_{\alpha\beta} + 3\,\varepsilon^{d}_{\alpha\beta}$$

→ Strength of NSI

The time evolution Schrödinger equation for the neutrino flavor eigenstates in vacuum is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix}$$

Similarly, in matter this is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC}+V_{NC} & 0 & 0\\0 & +V_{NC} & 0\\0 & 0 & +V_{NC}\end{pmatrix}\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix}$$

$\mathrm{V}_{CC} = \sqrt{2}\,G_F\,N_e$ **Charge current potential for neutrino**

$\mathrm{V}_{NC} = -\frac{G_F\,N_n}{\sqrt{2}}$ **Neutral current potential for neutrino**

For antineutrino, $\mathrm{V}_{CC} \rightarrow -V_{CC}$ **and** $\mathrm{V}_{NC} \rightarrow -V_{NC}$

Now, the time evolution equation for the neutrino flavor eigenstates in presence of NSI is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger + V + V_{NSI}\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix}$$

Where,

$$V = \begin{pmatrix}V_{CC}+V_{NC} & 0 & 0\\0 & +V_{NC} & 0\\0 & 0 & +V_{NC}\end{pmatrix}, \qquad V_{NSI} = V_{CC}\begin{pmatrix}\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\\varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\\varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}$$

In our analysis we assume one NSI parameter at a time and we have explored the impact of two NSI parameters $\varepsilon_{e\mu}$ & $\varepsilon_{e\tau}$ respectively.

Current constraints on neutral current NSI parameters

$$-0.006 < \varepsilon^{dV}_{\mu\tau} < 0.0054 \ (90\% \text{ C.L.})$$

ArXiV: 1609.03450
Salvado et al.

ArXiV: 1905.05203 (I. Esteban et al.)

$$-0.12 \lesssim \varepsilon_{e\mu} \lesssim 0.12 \ (90\% \text{ C.L.})$$

$$-0.3 \lesssim \varepsilon_{e\tau} \lesssim 0.3 \ (90\% \text{ C.L.})$$

$$-0.028 \lesssim \varepsilon_{\mu\tau} \lesssim 0.028 \ (90\% \text{ C.L.})$$

$$-0.5 \lesssim \varepsilon_{ee} - \varepsilon_{\mu\mu} \lesssim 0.5 \ (90\% \text{ C.L.})$$

$$-0.05 \lesssim \varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} \lesssim 0.2 \ (90\% \text{ C.L.})$$

Impact of NSI on the octant resolution

The vacuum survival Probability $\nu_\mu \to \nu_\mu$ in 3-flavor is given by

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\Delta + \alpha\, \Delta\, c_{12}^2 \sin^2 2\theta_{23}\, \sin 2\Delta - 4\, s_{13}^2\, s_{23}^2 \sin^2\Delta$$

Insensitive to the resolution of octant as it gives rise to octant degeneracy

Where, $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$, $\Delta = \frac{\Delta m_{31}^2 L}{4E}$

In a simplified case, we can write

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\Delta$$

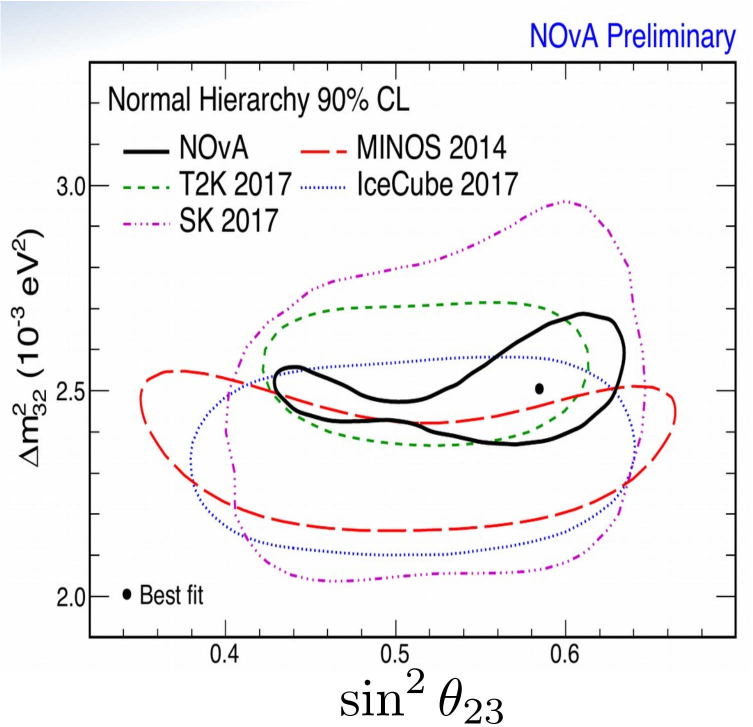
$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$$

$\theta_{23} < 45^0$ **Known as lower octant**

$\theta_{23} > 45^0$ **Known as higher octant**

$\theta_{23} = 45^0$ **Called maximal mixing**

See the talk by Alex Himmel



There are two solutions, called Octant degeneracy

Our goal here is to see the capability of an experiment (say, DUNE) to distinguish between the two octants of θ_{23} in presence of NSI.

The appearance probability $\nu_\mu \to \nu_e$ is given by

$$P_{\mu e} \simeq 4\sin^2\theta_{13}\sin^2\theta_{23}\sin^2\Delta + 2\sin\theta_{13}\,\sin 2\theta_{12}\,\sin 2\theta_{23}\,(\alpha\Delta)\sin\Delta\,\cos(\Delta \pm \delta_{13})$$

Sensitive to the resolution of octant degeneracy

$$P_{\mu e}(\theta_{23}) \neq P_{\mu e}(\pi/2 - \theta_{23})$$

Both appearance and survival channels play complementary role in resolving octant degeneracy.

We can rewrite θ_{23} as, $\theta_{23} = \pi/4 \pm \eta$

+ (-) corresponds to HO (LO). η is a deviation from maximality

In presence of NSI, the $\nu_\mu \to \nu_e$ transition probability can be written approximately as,

$$P_{\mu e} \simeq P_0 + P_1 + P_2 \,.$$

NSI (e-μ) *sector*

$$\begin{aligned}
P_0 &\simeq 4 s_{13}^2 s_{23}^2 f^2 \\
P_1 &\simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta) \\
P_2 &\simeq 8 s_{13} s_{23} v |\varepsilon_{e\mu}| [s_{23}^2 f^2 \cos(\delta + \phi_{e\mu}) + c_{23}^2 f g \cos(\Delta + \delta + \phi_{e\mu})]
\end{aligned}$$

NSI (e-τ) *sector*

$$\begin{aligned}
P_0 &\simeq 4 s_{13}^2 s_{23}^2 f^2 \\
P_1 &\simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta) \\
P_2 &\simeq 8 s_{13} s_{23} v |\varepsilon_{e\tau}| [s_{23} c_{23} f^2 \cos(\delta + \phi_{e\tau}) - s_{23} c_{23} f g \cos(\Delta + \delta + \phi_{e\tau})]
\end{aligned}$$

$$f \equiv \frac{\sin[(1-v)\Delta]}{1-v} \,, \qquad g \equiv \frac{\sin v\Delta}{v} \,. \qquad |v| = \left| \frac{2 V_{\rm CC} E}{\Delta m_{31}^2} \right|$$

An experiment can be sensitive to the octant if, despite the freedom introduced by the unknown CP phases and other parameters, there is still a difference between the probabilities in the two octants, i.e.,

$$\Delta P \equiv P_{\mu e}^{\rm HO}(\theta_{23}^{\rm HO}, \delta^{\rm HO}, \phi^{\rm HO}) - P_{\mu e}^{\rm LO}(\theta_{23}^{\rm LO}, \delta^{\rm LO}, \phi^{\rm LO}) \neq 0$$

$$\Delta P = \Delta P_0 + \Delta P_1 + \Delta P_2$$

$$\Delta P_0 \simeq 8\eta s_{13}^2 f^2$$ → +ve definite

$$\Delta P_1 = A\left[\cos(\Delta + \delta^{\rm HO}) - \cos(\Delta + \delta^{\rm LO})\right]$$ → can be +ve or -ve

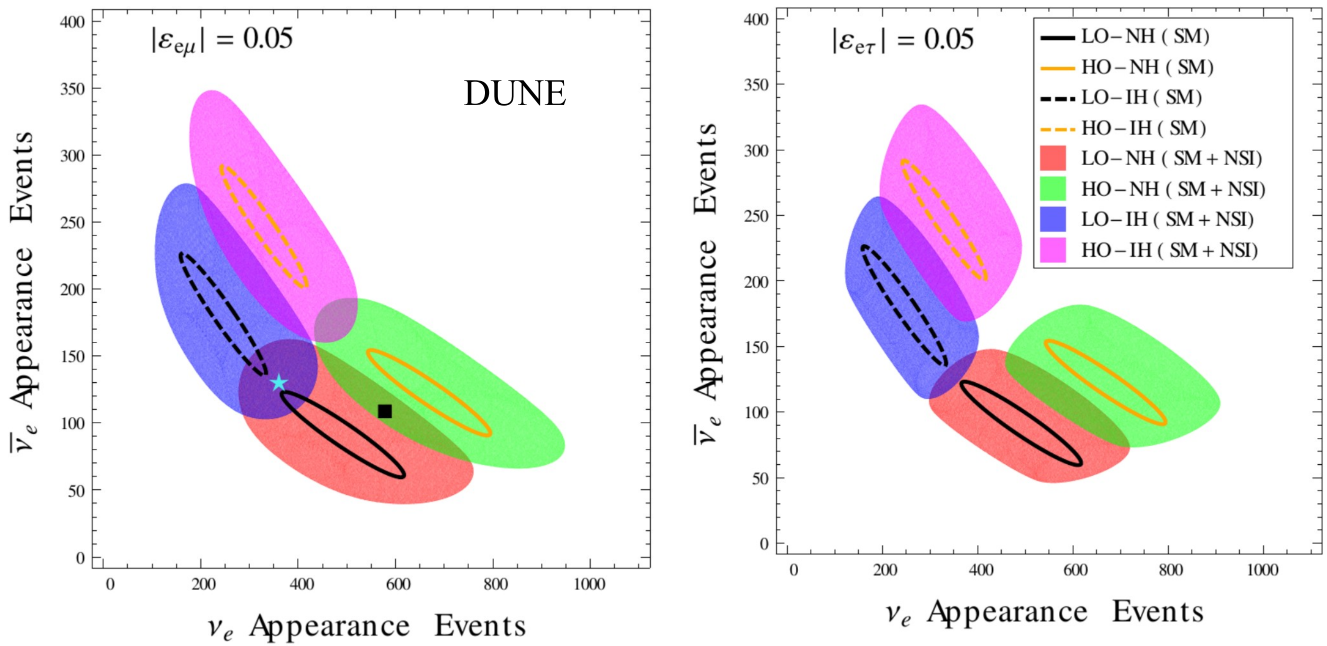
$$\Delta P_2 = B\left[\cos(\delta^{\rm HO} + \phi^{\rm HO}) - \cos(\delta^{\rm LO} + \phi^{\rm LO})\right] \pm C\left[\cos(\Delta + \delta^{\rm HO} + \phi^{\rm HO}) - \cos(\Delta + \delta^{\rm LO} + \phi^{\rm LO})\right]$$ → can be +ve or -ve

$$\theta_{23} = \frac{\pi}{4} \pm \eta$$ Here η is the deviation from the maximality

$$A = 4 s_{13} s_{12} c_{12} \alpha f g\,, \qquad B = 2\sqrt{2} v |\varepsilon| s_{13} f^2\,, \qquad C = 2\sqrt{2} v |\varepsilon| s_{13} f g\,.$$

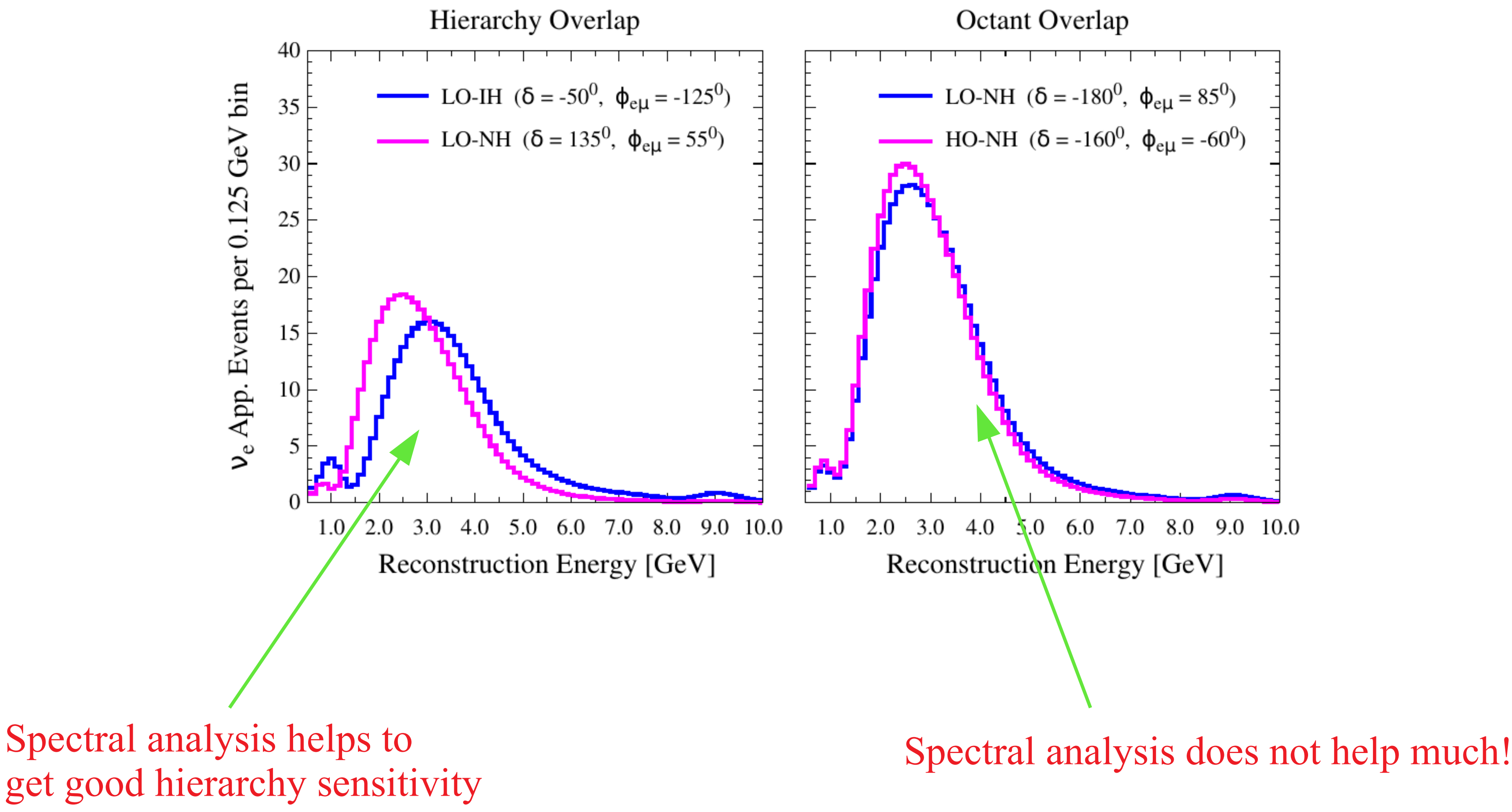
Phys.Lett. B762 (2016) 64-71 by Agarwalla, Chatterjee, and Palazzo

Bievents plot



$$\sin^2\theta_{23}(\text{true}) = 0.42(0.58)\ \text{as LO(HO)}$$

In presence of NSI, ellipses become blobs. Color blobs are the convolution of different combinations of δ_{13} & $\phi_{e\mu}$ (δ_{13} & $\phi_{e\tau}$) in the left (right) panel.



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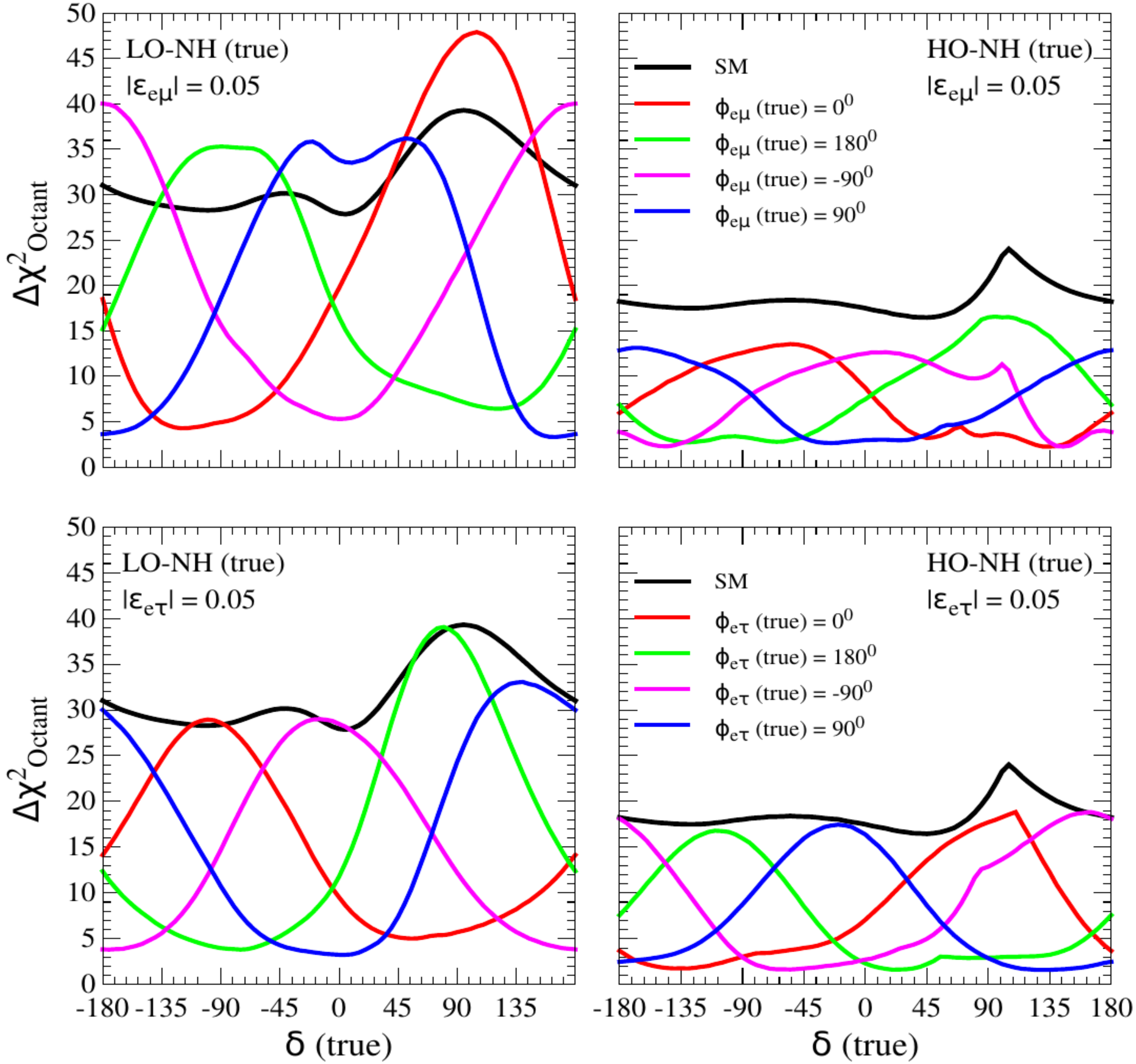
A good sensitivity to an octant means if an experiment excludes the wrong octant at certain confidence level, provided the true data is generated with the right octant.

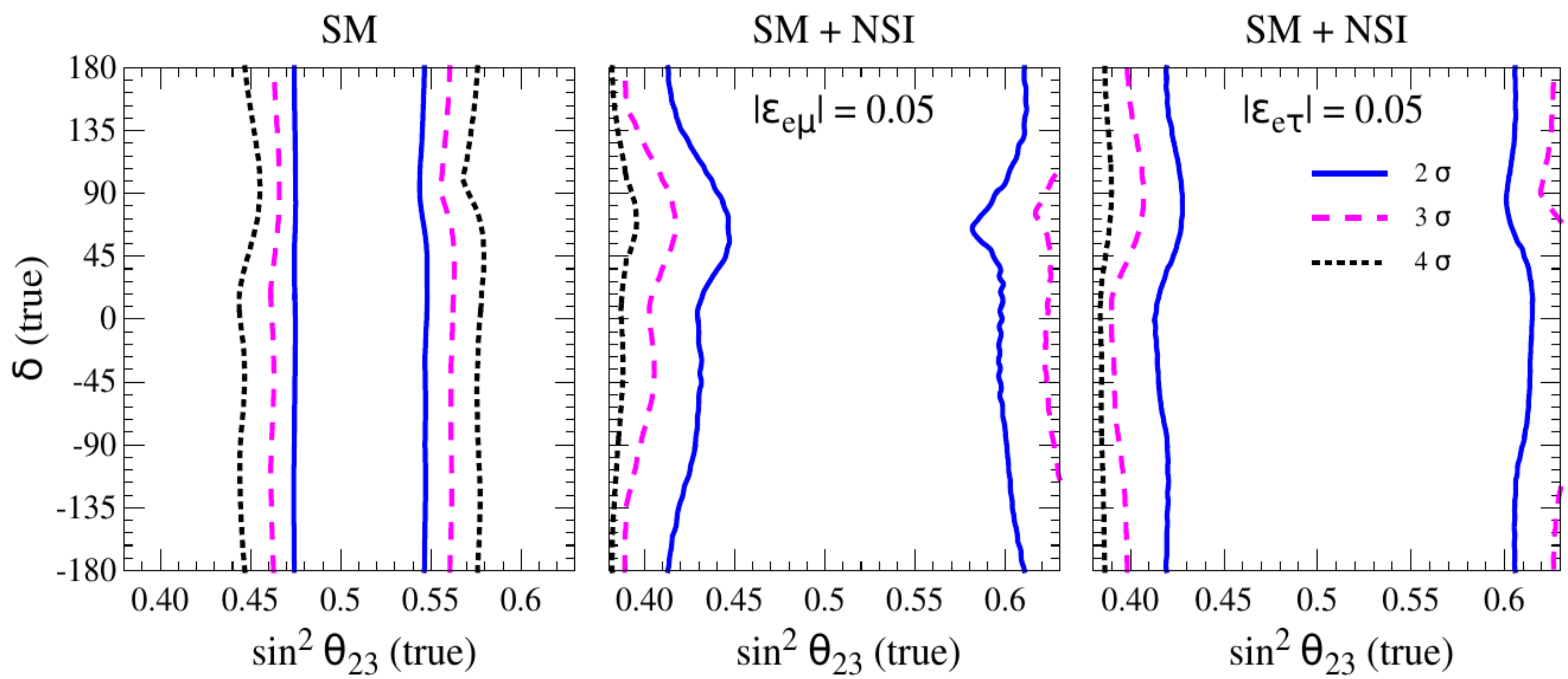


$\sin^2\theta_{23}$**(true) = 0.42(0.58) as LO (HO)**

Sensitivity in presence of NSI goes down in compare to SM

$$\Delta\chi^2_{\rm octant} = \chi^2_{\rm test\ octant} - \chi^2_{\rm true\ octant}$$

Octant sensitivity in the full parameter space of $\left[\sin^2\theta_{23}, \delta\right]$ (true) plane



$$\Delta P_2 = B\left[\cos(\delta^{\rm HO} + \phi^{\rm HO}) - \cos(\delta^{\rm LO} + \phi^{\rm LO})\right]$$
$$\pm C\left[\cos(\Delta + \delta^{\rm HO} + \phi^{\rm HO}) - \cos(\Delta + \delta^{\rm LO} + \phi^{\rm LO})\right]$$

extra degree of freedom

In SM+NSI, the sensitivity to the octant of θ_{23} gets completely lost.

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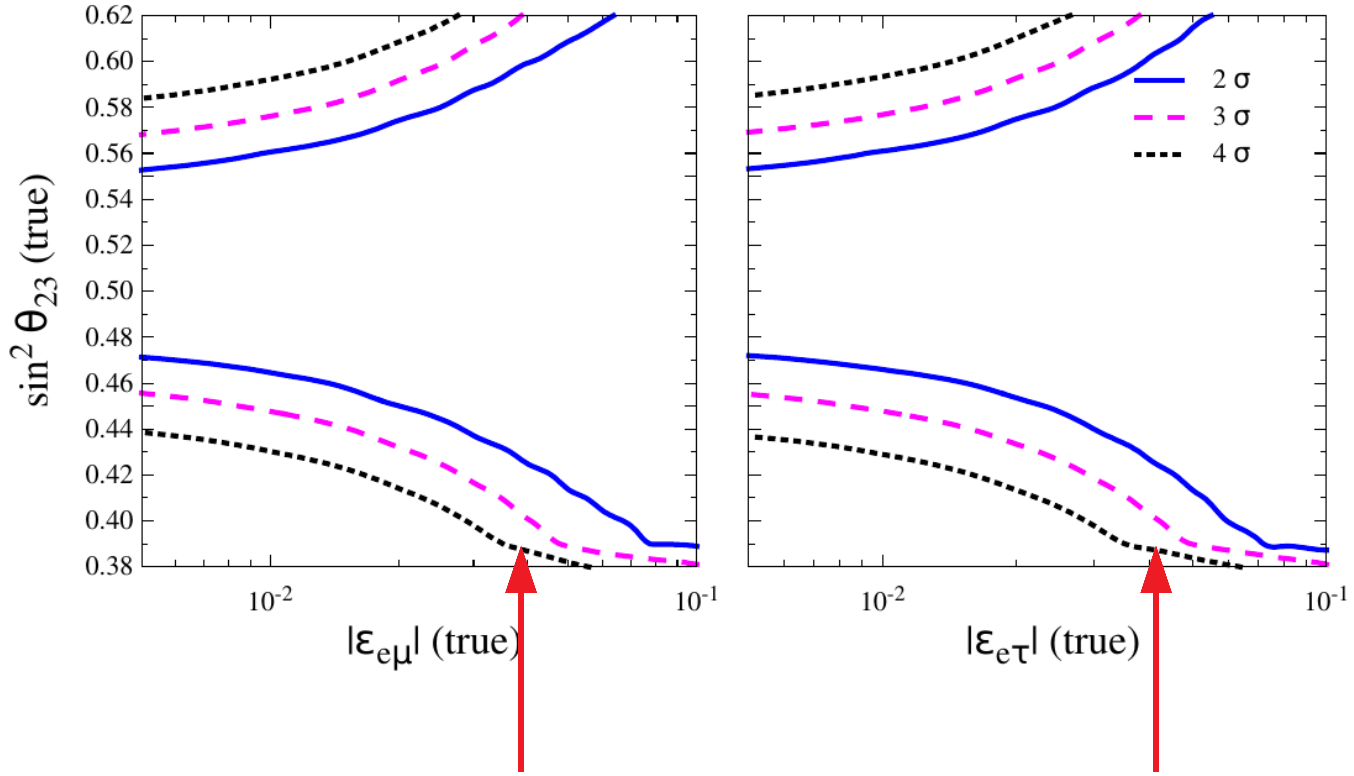


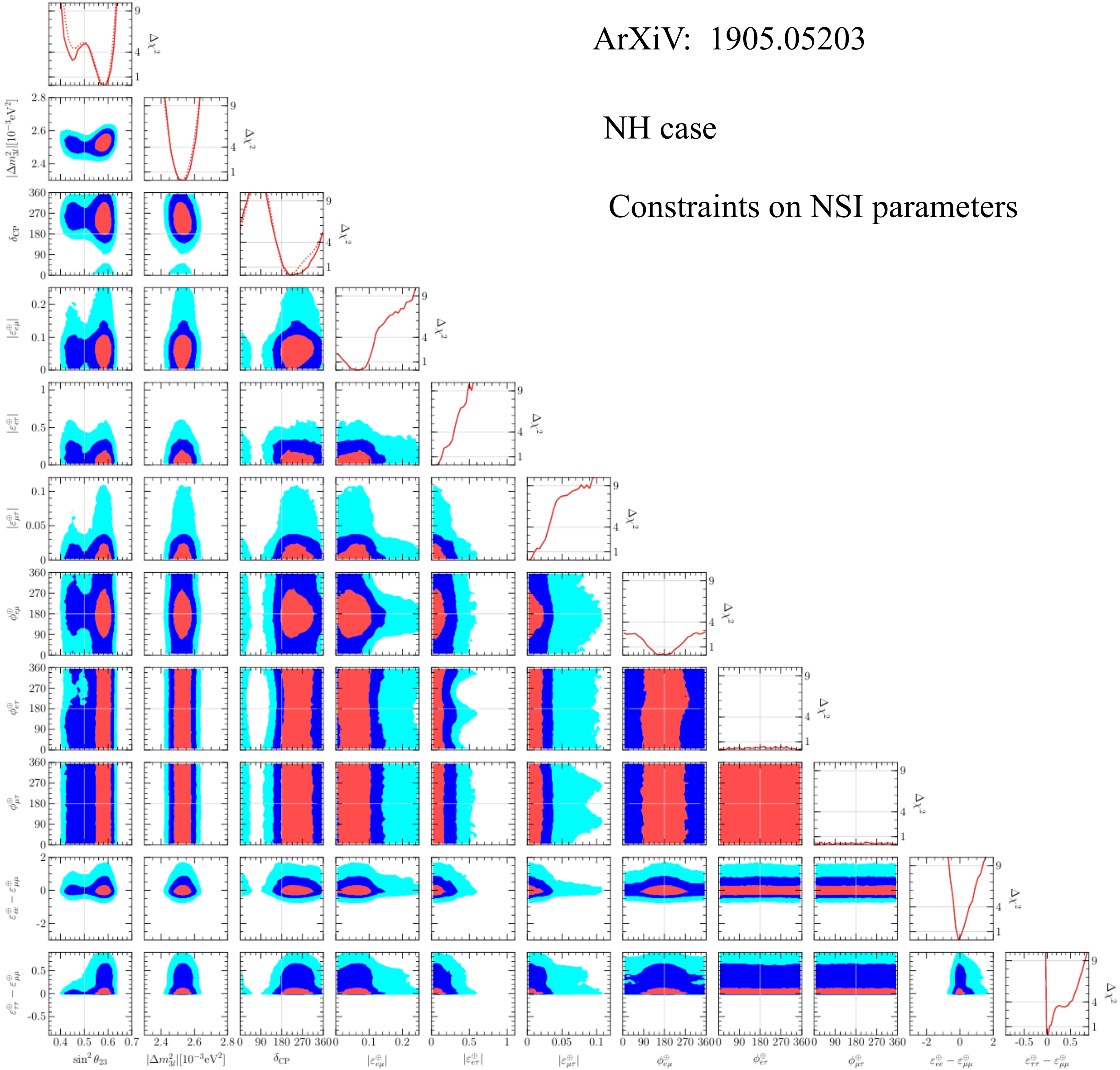
Even a small magnitude of NSI can spoil the sensitivity of distinguishing the two octants of θ_{23}

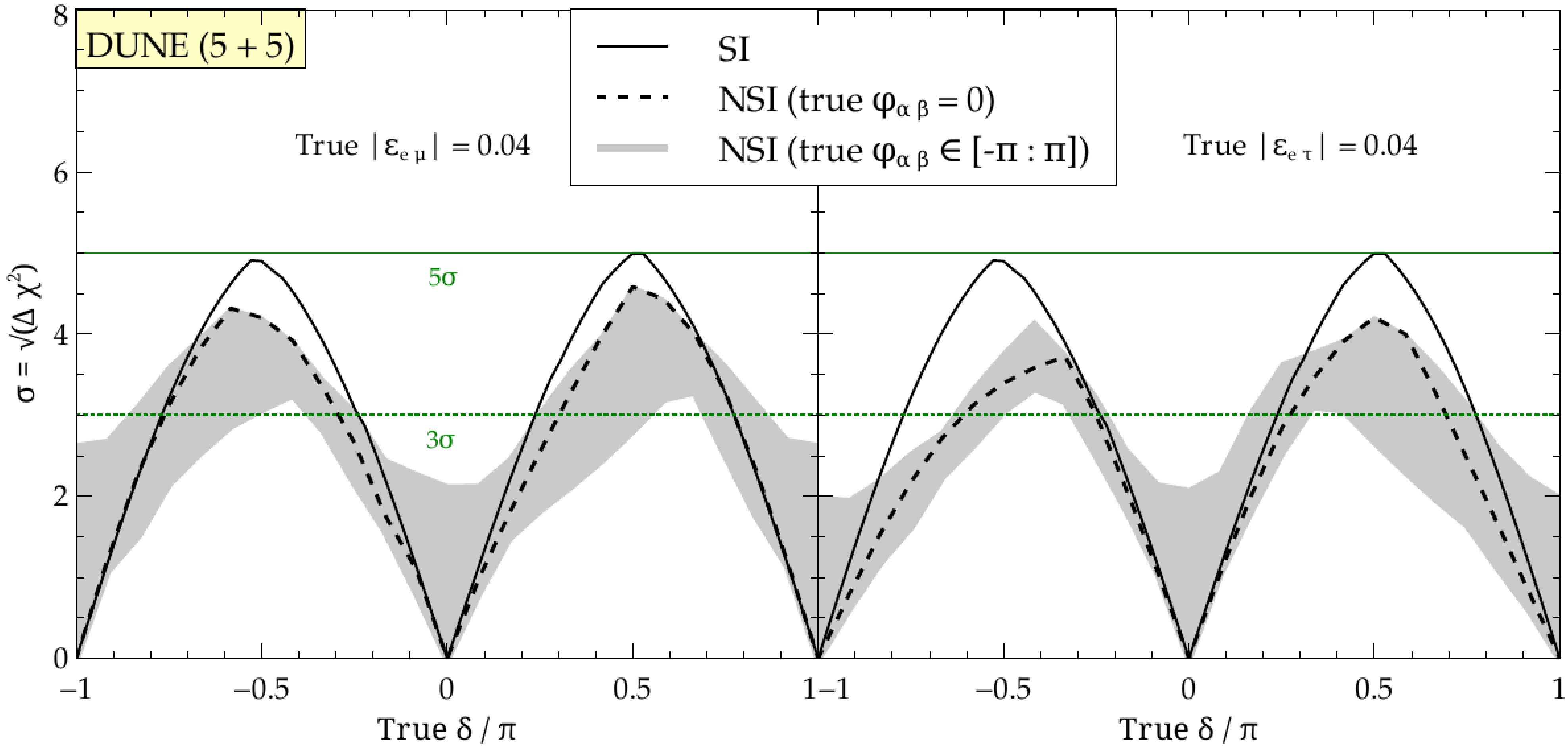
Phys.Lett. B762 (2016) 64-71 by Agarwalla, Chatterjee, and Palazzo

ArXiV: 1905.05203

NH case

Constraints on NSI parameters

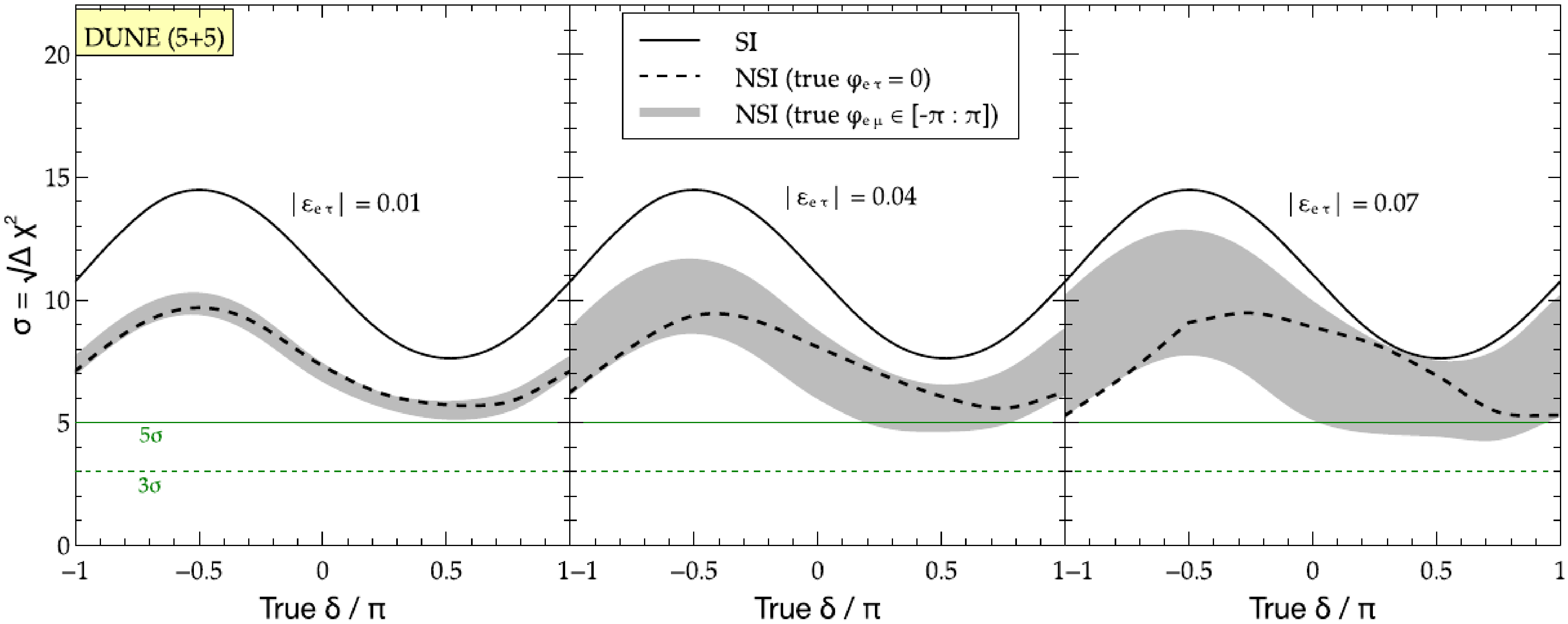




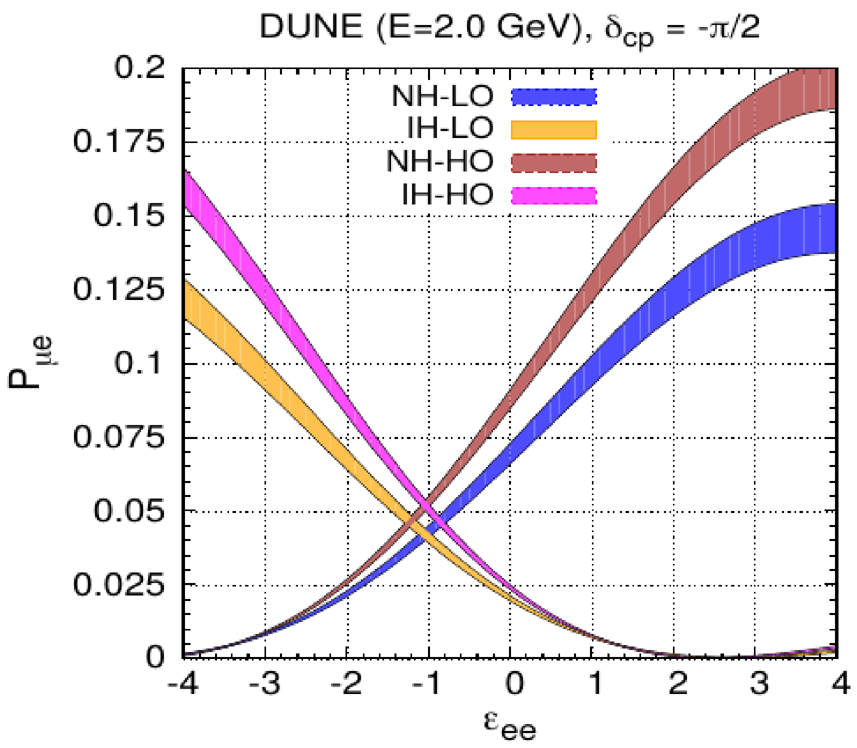
NSI can have drastic effect on CPV measurement

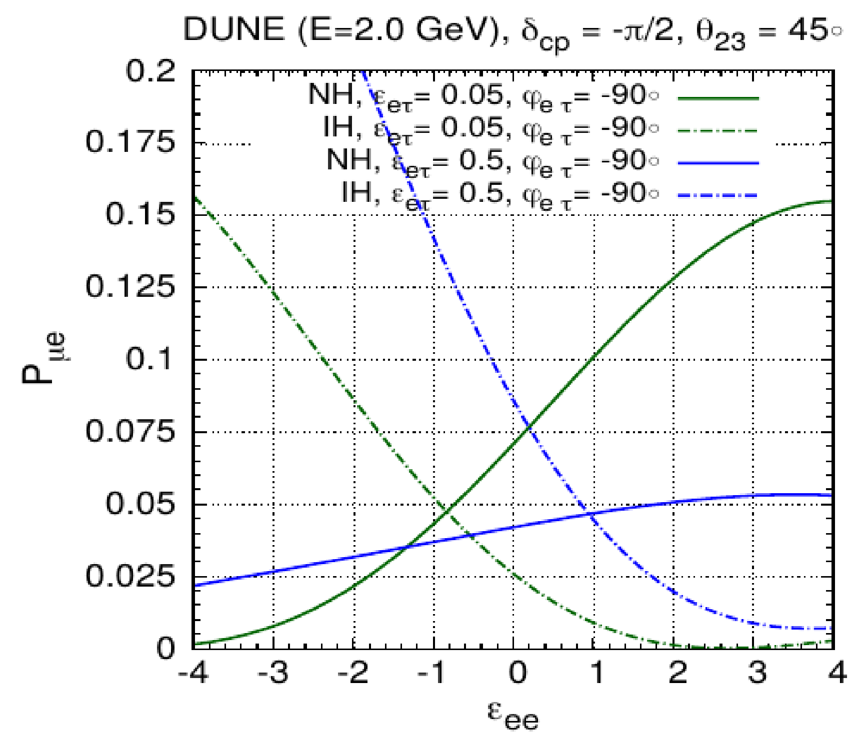
1510.08261 Masud, A Chatterjee, and Mehta

Impact of NSI on MH determination



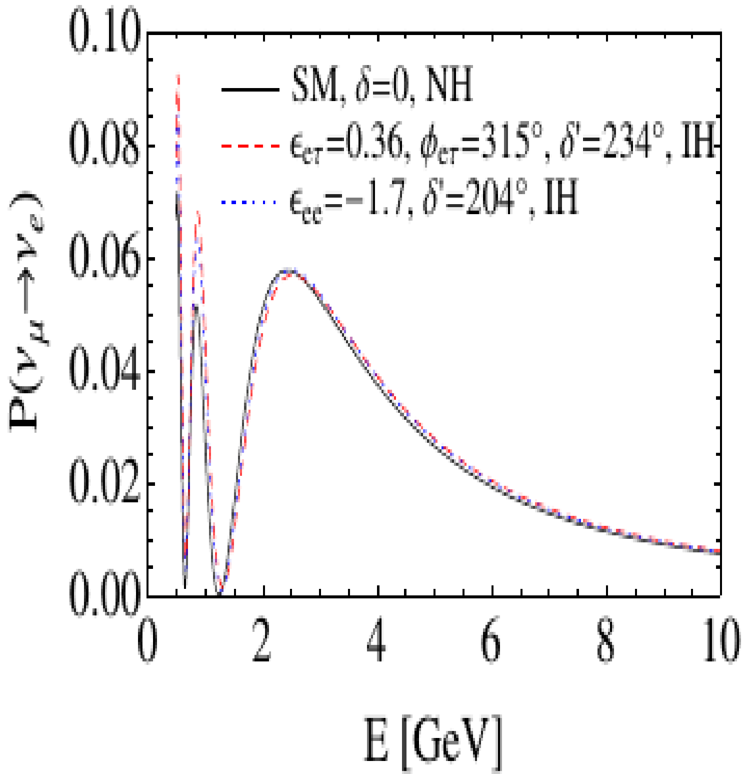
ArXiv: 1606.05662   Masud, and Mehta

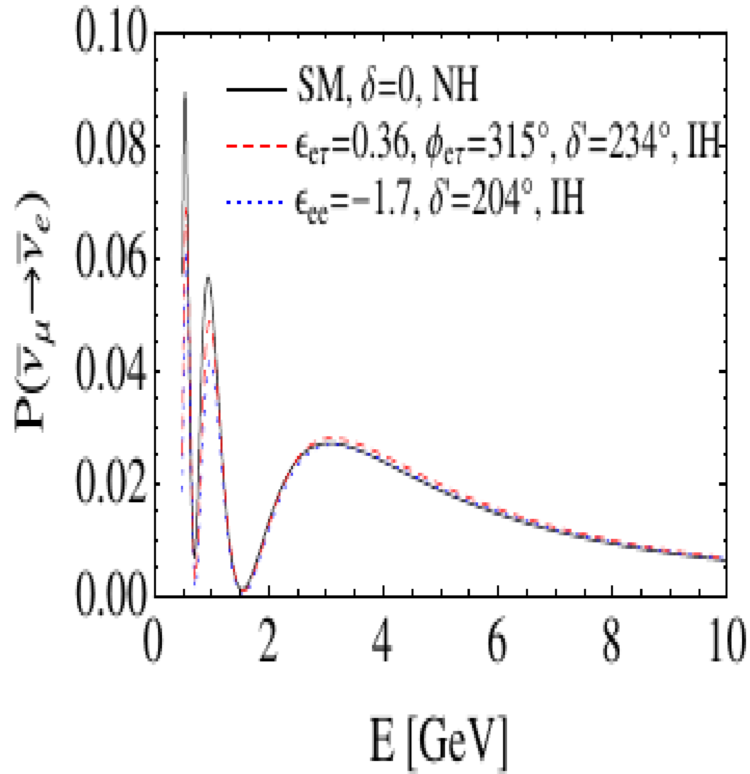




MH sensitivity can get seriously impacted

ArXiv: 1612.00784 Deepthi, Goswami, and Nath





ArXiv: 1601.00927 Liao, Marfatia, and Whisnant

There are many more……………………………………..!

Conclusion

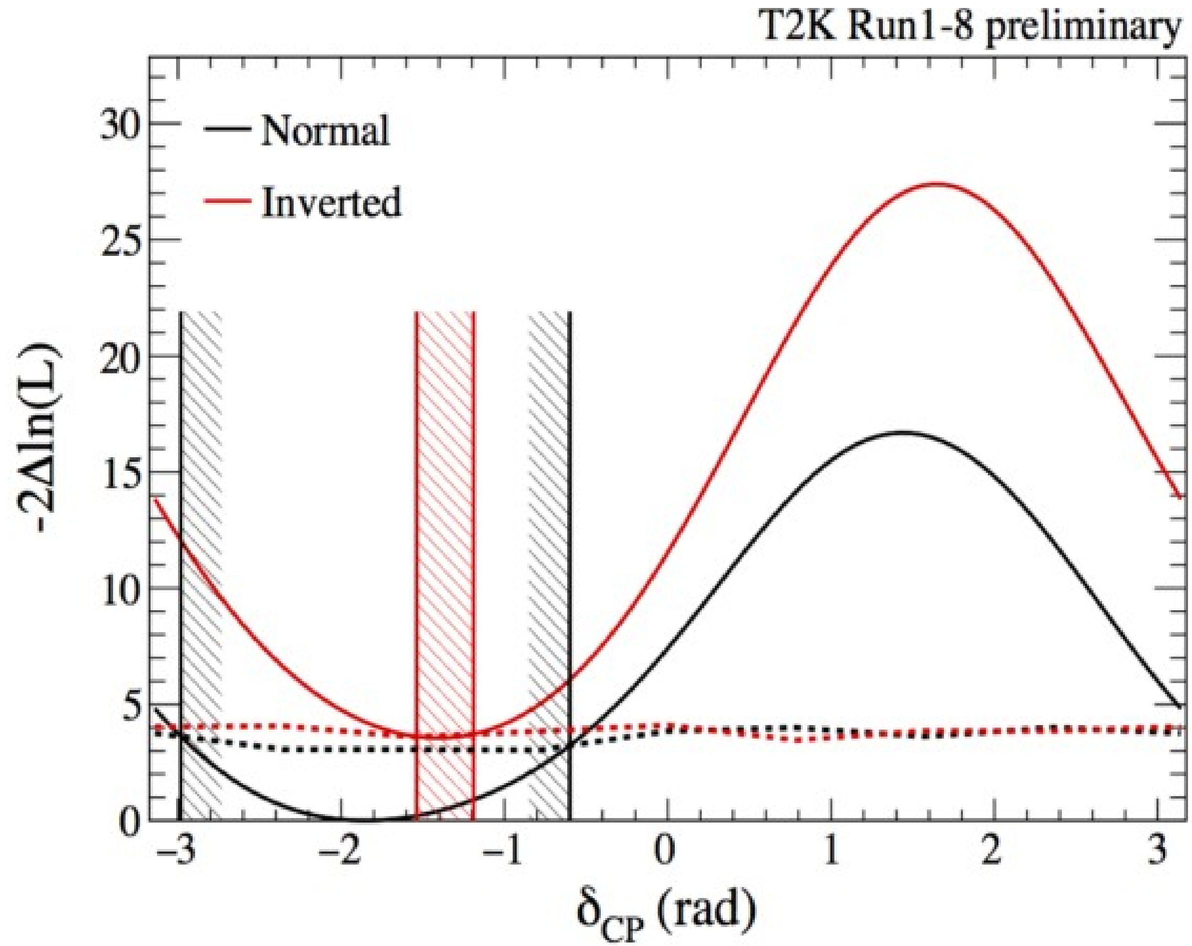
- We have investigated the impact of NSI on the reconstruction of octant of θ_{23} in the next generation LBL experiment DUNE.

- We have shown that in presence of NSI, a new interference term that enters into the $\nu_\mu \rightarrow \nu_e$ transition probability can perfectly mimic a swap of the octant of θ_{23} and as a result the sensitivity towards the resolution of octant of θ_{23} may goes to very low confidence level.

- This result has now become more important in the light of recent T2K and NOvA data which indicate towards the non maximal value of θ_{23} .

- We hope that the analysis performed in these papers may give deep insight in exploring this new type of interactions.

- It remains to be seen whether any other kinds of experiments can lift or alleviate these kind of degeneracies.

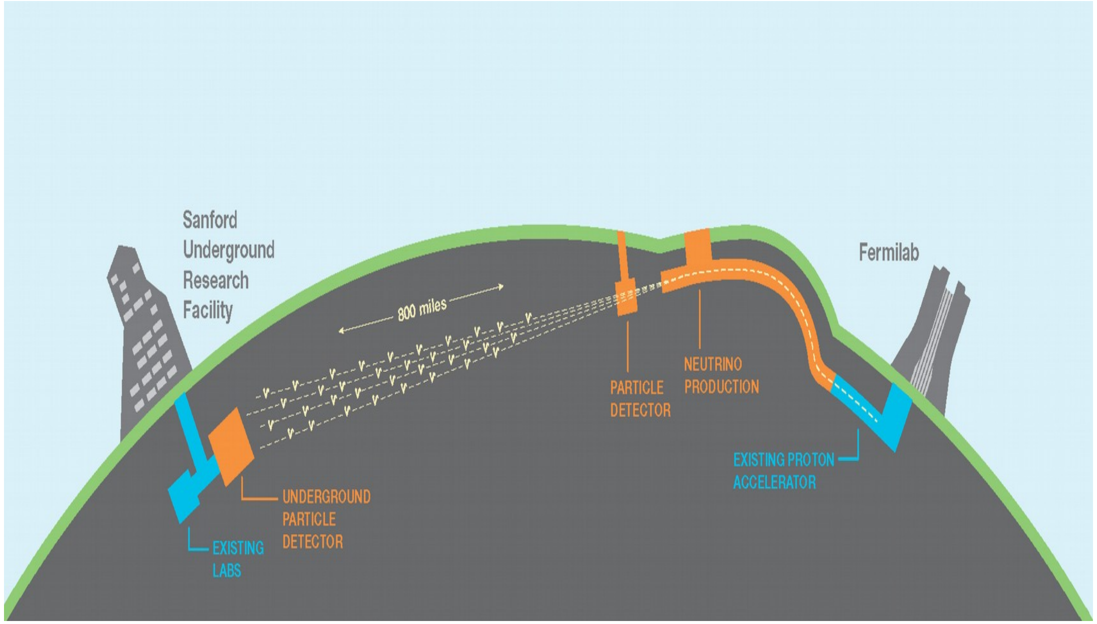


T2K result of MH and CPV indication at 95% C.L.

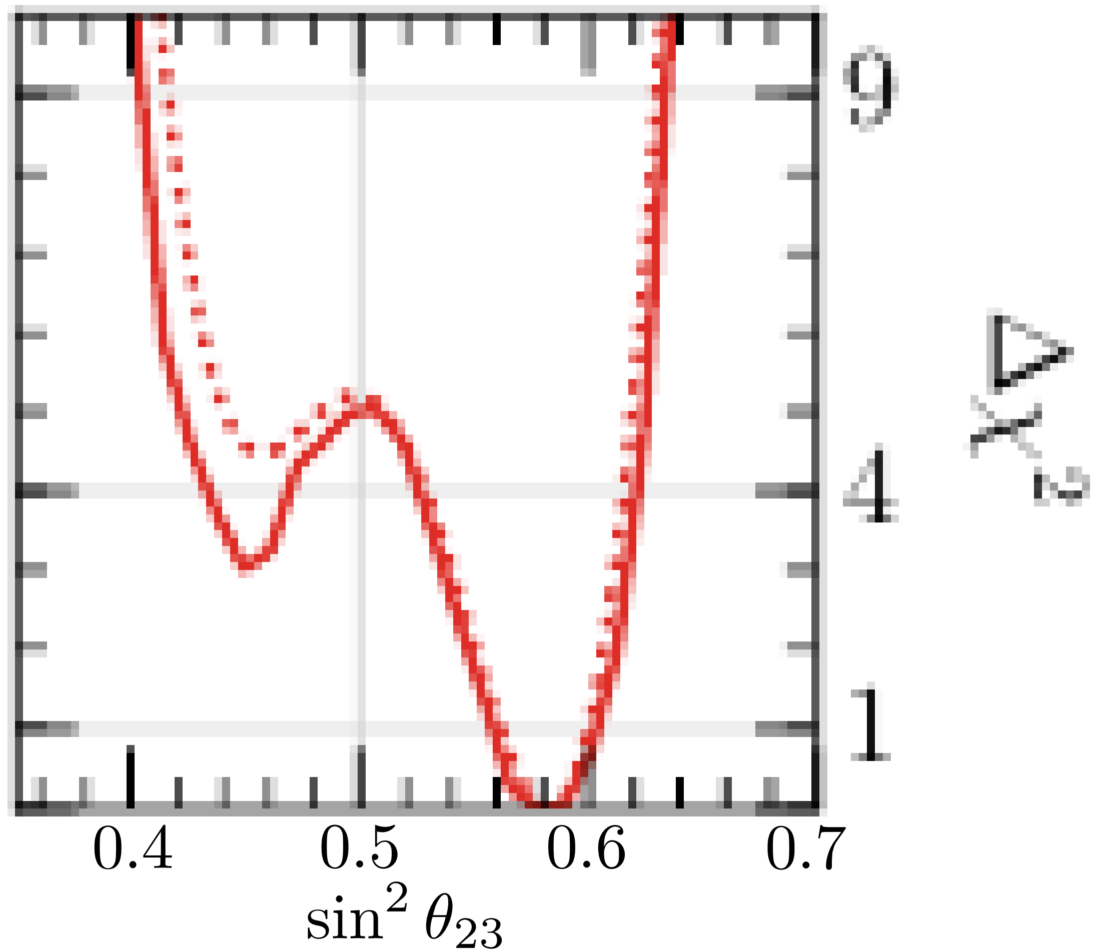
Brief description of Long-Baseline Set-up

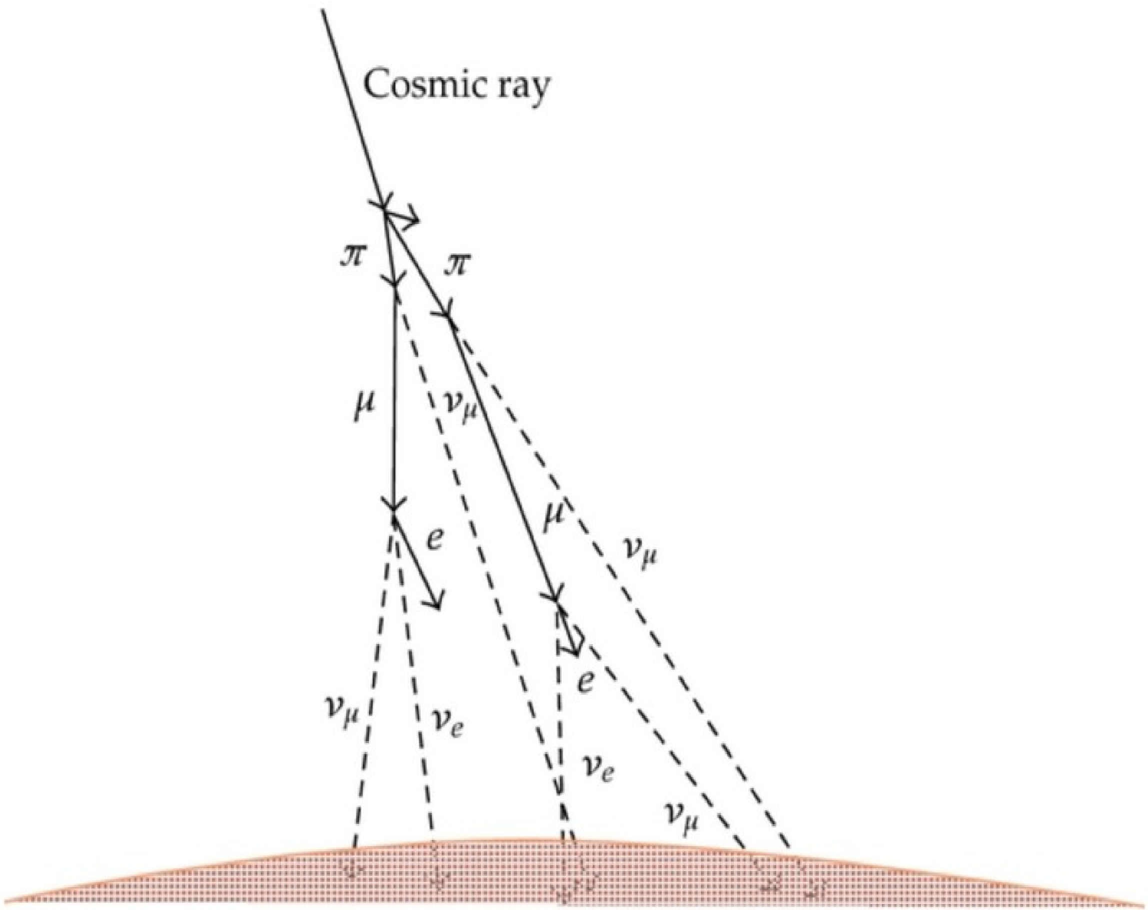
We have mainly considered the DUNE set-up to explore the impact of this new physics.

DUNE (Fermilab to South Dakota)	
Baseline	1300 KM
Detector mass	35 Kt
Run time	5 yrs + 5 yrs
Proton Energy	120 GeV
Beam Power	708 KW
Total POT / yr	6×10^{20}
Signal app. error	5%
Signal disapp. error	5%
Background app. error	5%
Background disapp. error	5%



ArXiV: 1905.05203





Cosmic ray
π
π
μ
ν_μ
μ
ν_μ
e
e
ν_μ
ν_e
ν_e
ν_μ

Definition of χ^2 function (implemented in GLoBES software)

$$\chi^2\left(\omega^{\text{true}}, \lambda^{\text{true}}; \omega^{\text{test}}, \lambda^{\text{test}}, \xi_s, \xi_b\right) = \min_{\{\xi_s, \xi_b\}} \left[2 \sum_{i=1}^{n} (\tilde{y}_i - x_i - x_i \ln \frac{\tilde{y}_i}{x_i}) + \frac{\xi_s^2}{\sigma_{\xi_s}^2} + \frac{\xi_b^2}{\sigma_{\xi_b}^2} \right]$$

$$\tilde{y}_i(\{\omega^{\text{test}}, \lambda^{\text{test}}\}, \{\xi_s, \xi_b\}) = N_i^{pr}(\{\omega^{\text{test}}, \lambda^{\text{test}}\})[1+\pi^s \xi_s] + N_i^b(\{\omega^{\text{test}}, \lambda^{\text{test}}\})[1+\pi^b \xi_b]$$

Test events in ith reconstructed energy bin

π^s, π^b **are systematic errors on signal and background events**

ξ_s, ξ_b **are nuisance parameters, known with some accuracy** σ_{ξ_s} and $\sigma_{\xi_{\text{b}}}$ **respectively**

$x_i = N_i^{obs} + N_i^b$ **True events in ith reconstructed energy bin**

$$\chi^2_{\text{total}} = \sum_{channel} \chi^2\left(\omega^{\text{true}}, \lambda^{\text{true}}; \omega^{\text{test}}, \lambda^{\text{test}}, \xi_s, \xi_b\right)$$

$$\chi^2_{\text{total}} = \chi^2_{\nu_\mu \to \nu_e} + \chi^2_{\nu_\mu \to \nu_\mu} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_e} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_\mu}$$ **For our case**

$$\Delta\chi^2_{\text{min}} = \min_{\{\omega, \lambda\}} \left[\sum_{channel} \chi^2\left(\omega, \lambda, \xi_s, \xi_b\right) \right]$$ **Final result**

Now, if we solve the above equation, we get the probability of oscillation from one flavor to another flavor with neutrino energy E and baseline L, given as

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin 2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

Where, $\Delta m^2_{ij} = m^2_i - m^2_j$