

Neutrino mass ordering obscured by the non-standard interactions

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Based on PRL. 124 (2020) 11, 111801 by F. Capozzi, S.S. Chatterjee, & A. Palazzo

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Over the past few years tremendous efforts and invaluable contributions from the neutrino experiments established the standard three-neutrino framework beyond any doubt.

However the standard interpretation of that framework might not be the ultimate picture. There may exist many new physics scenarios for which we will need to invoke new interpretation on top of the standard interpretation.

One of the most popular new physics scenarios is the **non-standard interactions of neutrinos (NSI)**.

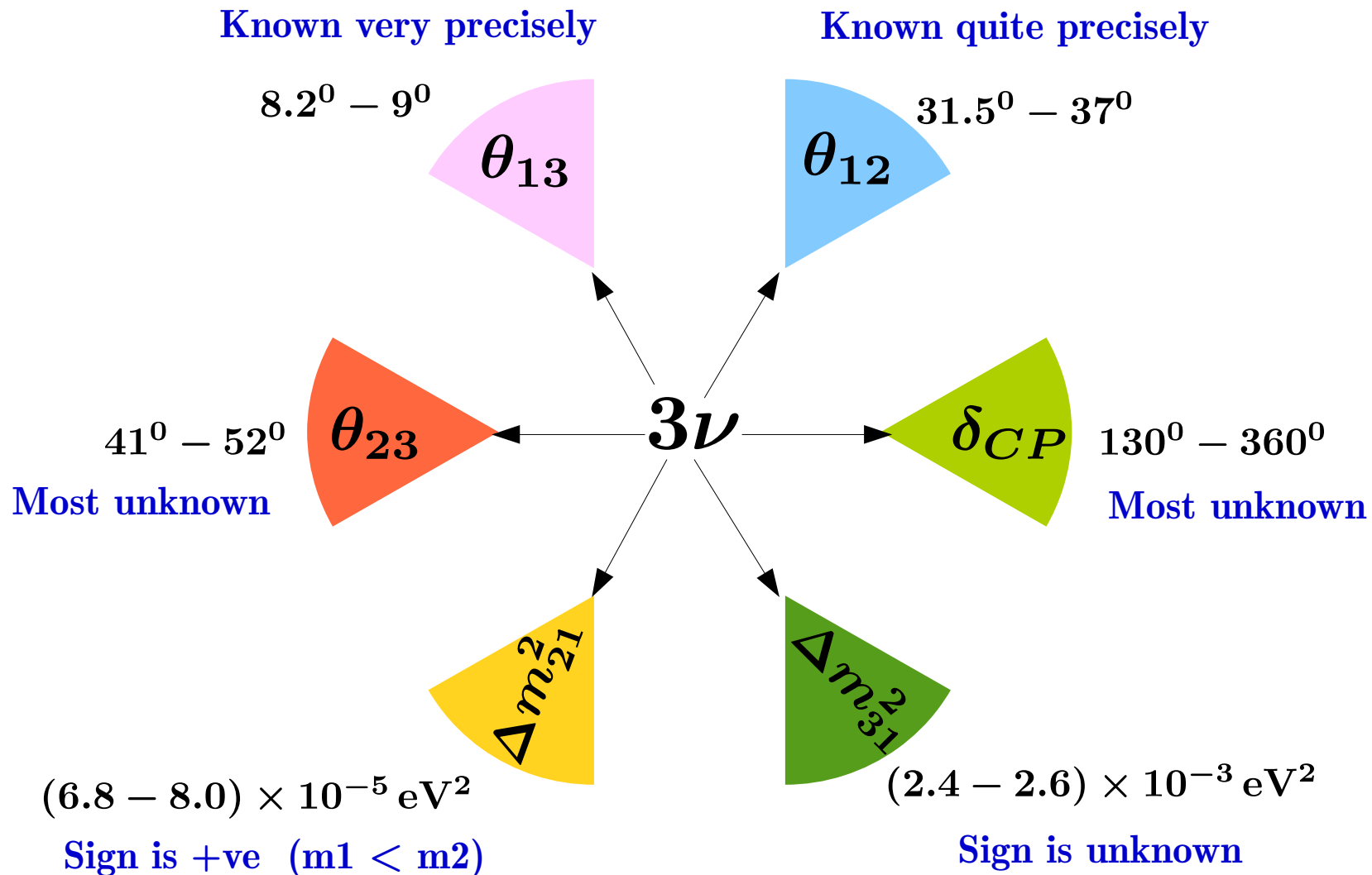
In this work we explore the impact of NSI in the interpretation of current T2K and NOvA data. Specifically, we focus on the determination of the neutrino mass ordering (NMO).

$m_1 < m_2 < m_3$, called **Normal Ordering**.

$m_3 < m_1 < m_2$, called **Inverted Ordering**.

It is worth to mention that the current global fits prefer **Normal Ordering** over **Inverted Ordering** at around 3σ confidence level.

Current status of 3ν parameters (3σ uncertainties)



ArXiv: 2006.11237 by P. Salas et al., arXiv: 1811.05487 by Esteban et al., and arXiv: 1804.09678 by F. Capozzi et al.

NSI and its presence in the oscillation framework

The effect of the effective 4-Fermi flavor changing neutral current non-standard interactions (NSI) in neutrino oscillation physics is realized through this Lagrangian :

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

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

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

N is the number density of fermions

$$\varepsilon_{\alpha\beta} \simeq \varepsilon_{\alpha\beta}^e + 3\varepsilon_{\alpha\beta}^u + 3\varepsilon_{\alpha\beta}^d \quad \longrightarrow \quad \text{Strength of NSI}$$

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,

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

$$V_{CC} = \pm \sqrt{2} G_F N_e \quad V_{NC} = \mp \frac{G_F N_n}{\sqrt{2}}$$

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.

+ : Neutrino, - : Antineutrino

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

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

NSI (e- μ) sector

$$P_0 \simeq 4s_{13}^2 s_{23}^2 f^2$$

$$P_1 \simeq 8s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta)$$

$$P_2 \simeq 8s_{13} s_{23} v |\varepsilon_{e\mu}| [s_{23}^2 f^2 \cos(\delta + \phi_{e\mu}) + c_{23}^2 f g \cos(\Delta + \delta + \phi_{e\mu})]$$

NSI (e- τ) sector

$$P_0 \simeq 4s_{13}^2 s_{23}^2 f^2$$

$$P_1 \simeq 8s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta)$$

$$P_2 \simeq 8s_{13} s_{23} v |\varepsilon_{e\tau}| [s_{23} c_{23} f^2 \cos(\delta + \phi_{e\tau}) - s_{23} c_{23} f g \cos(\Delta + \delta + \phi_{e\tau})]$$

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

Current constraints on neutral current NSI parameters

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

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

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

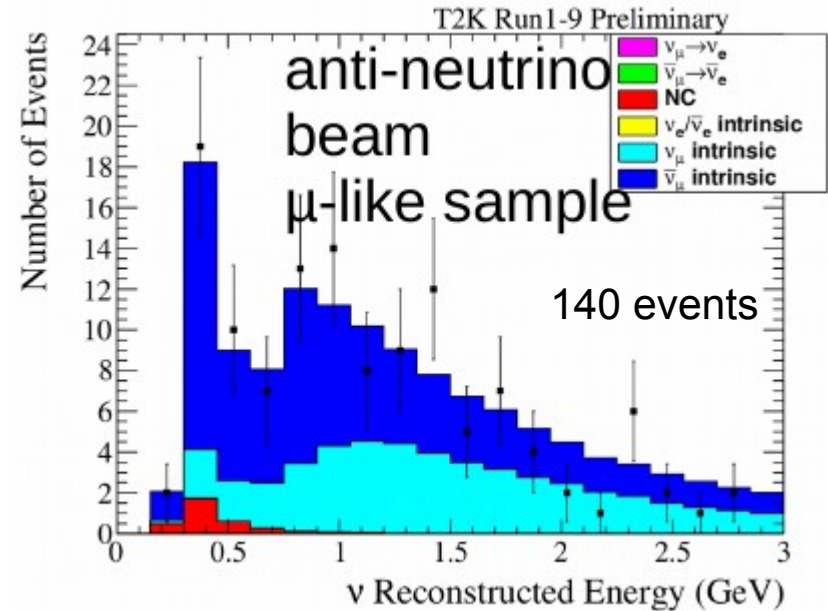
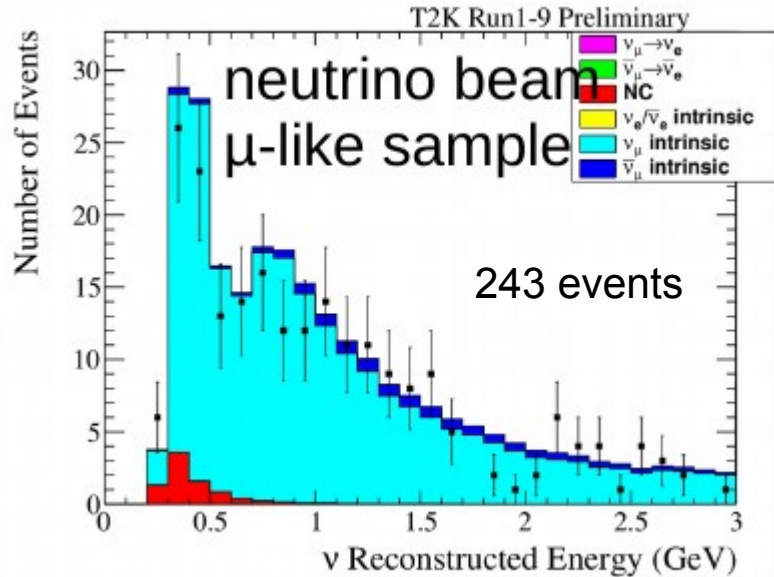
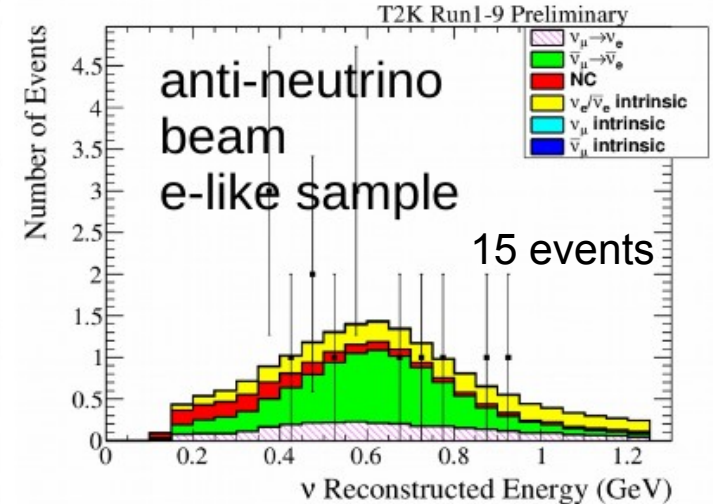
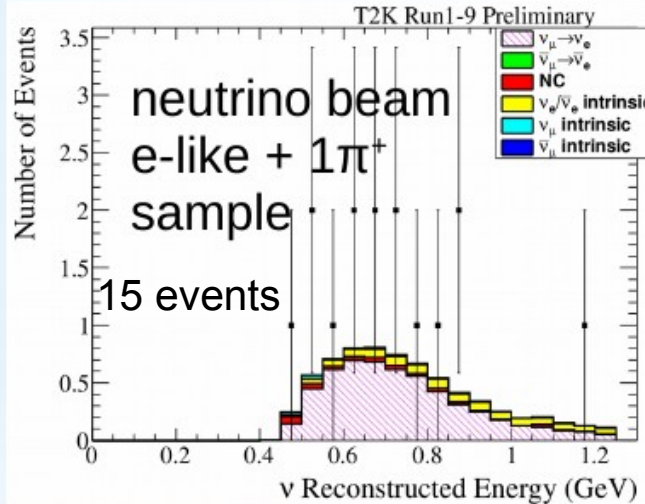
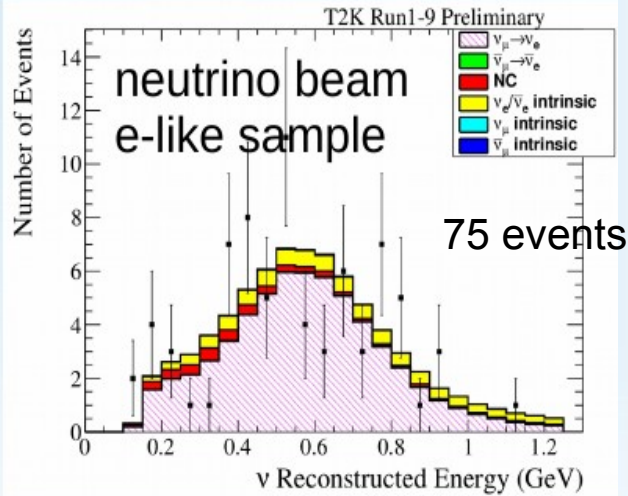
$$-0.5 \lesssim \varepsilon_{ee} - \varepsilon_{\mu\mu} \lesssim 0.5 \text{ (90\% C.L.)}$$

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

ArXiv: 1905.05203 by I. Esteban et al.

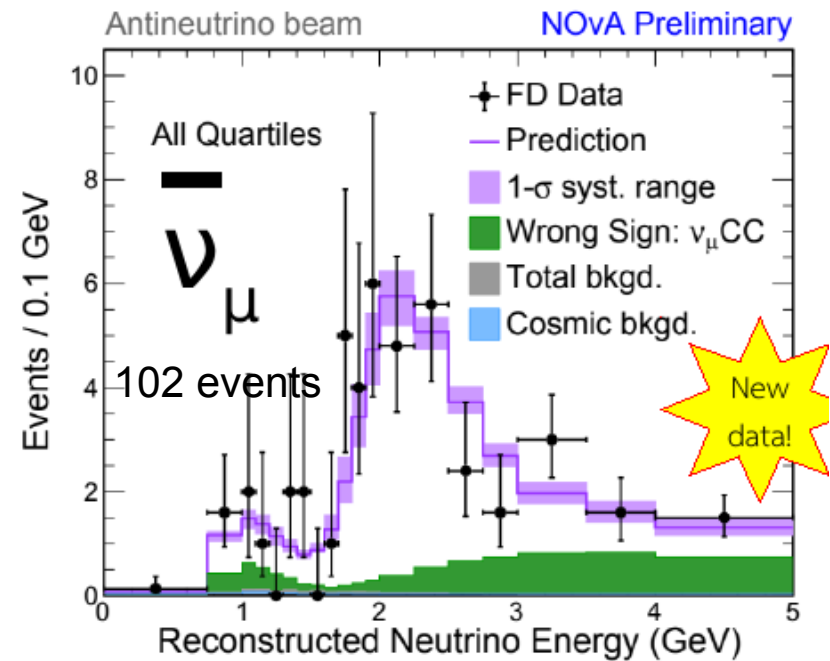
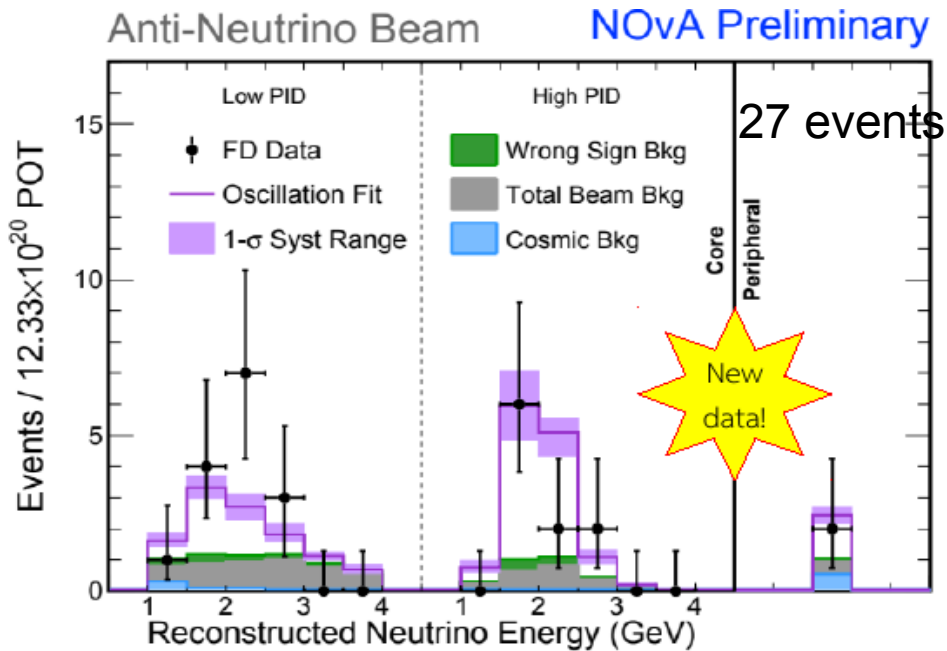
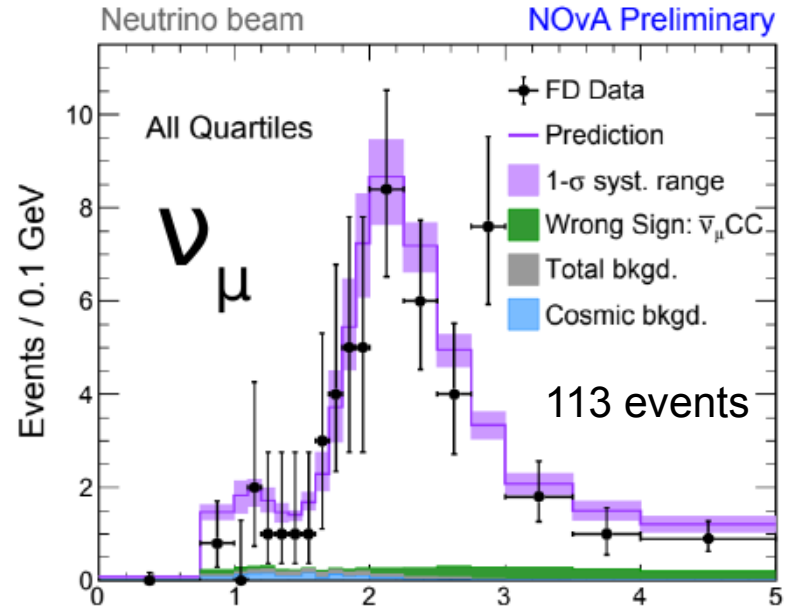
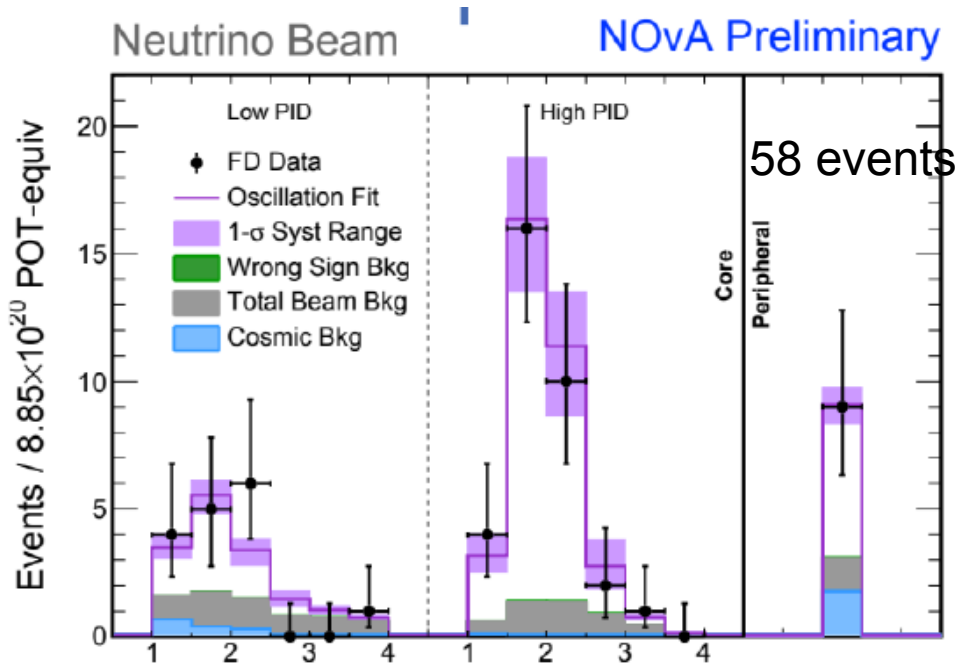
ArXiv: 1710.09360 a review by Y. Farzan et al.

T2K Run1-9 Dataset



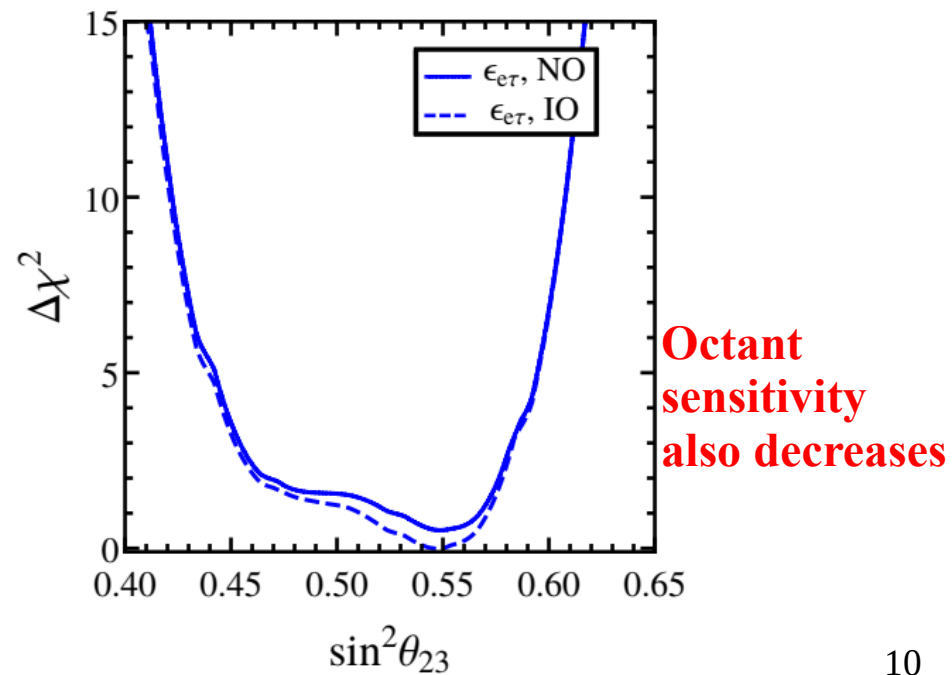
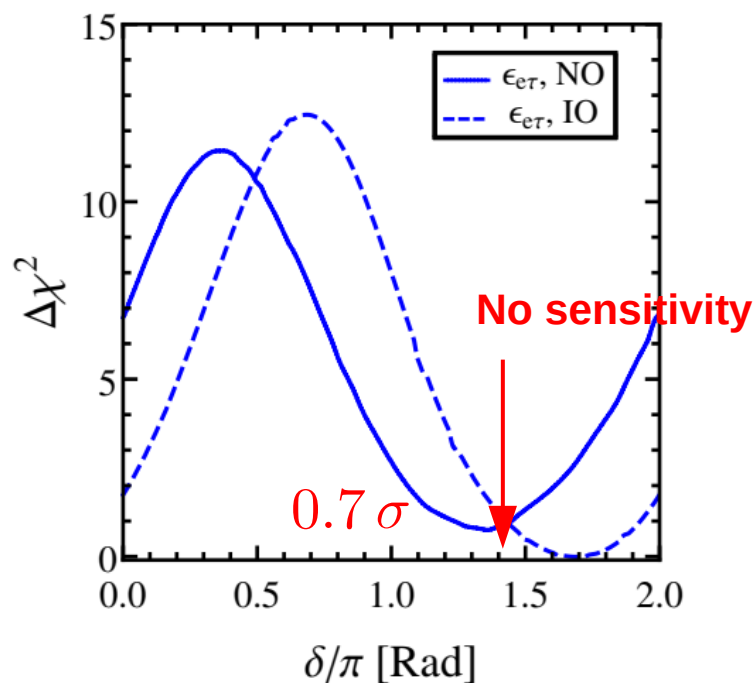
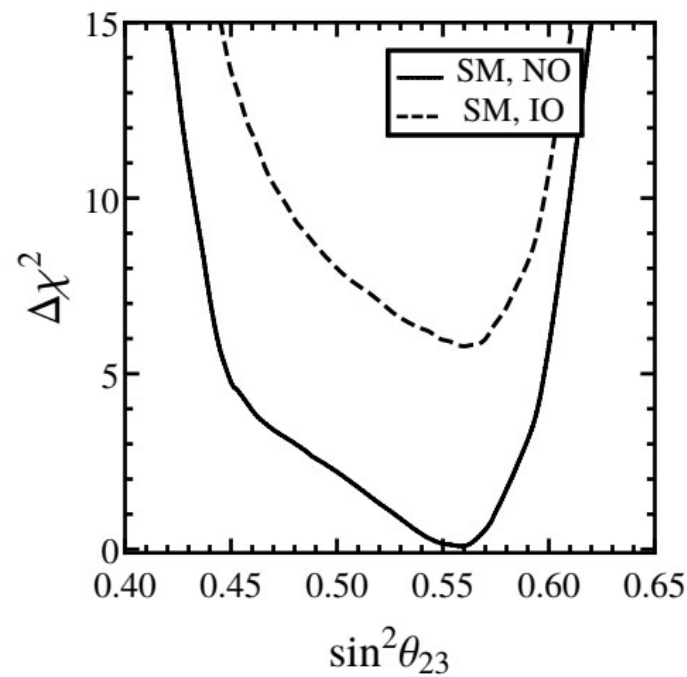
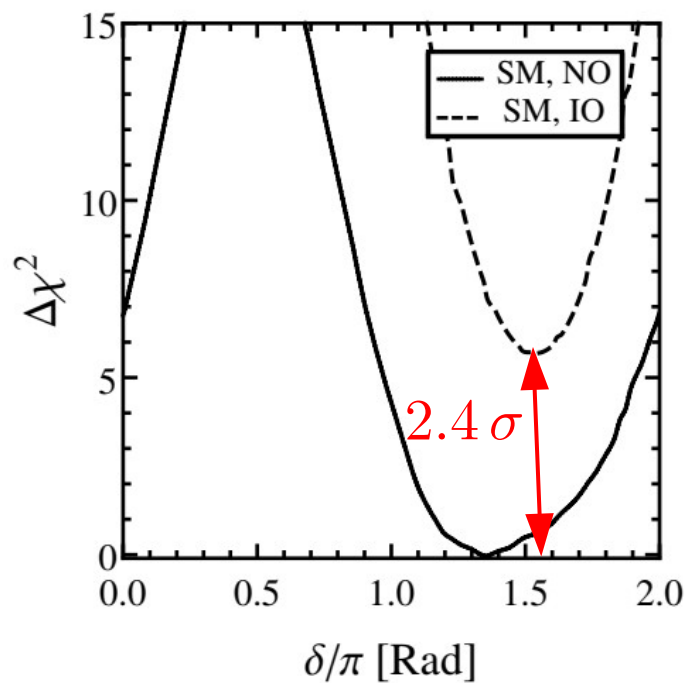
Please see arXiv: 1910.03887, and Grzegorz Zarnecki's talk

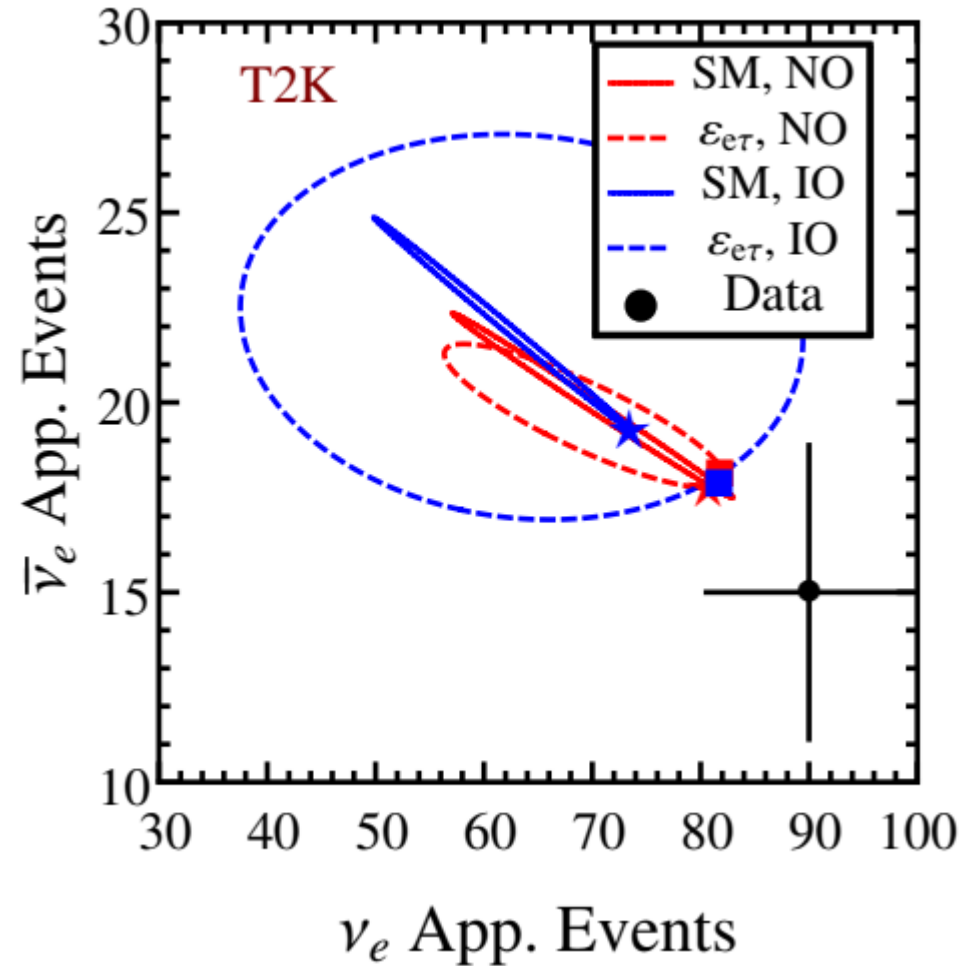
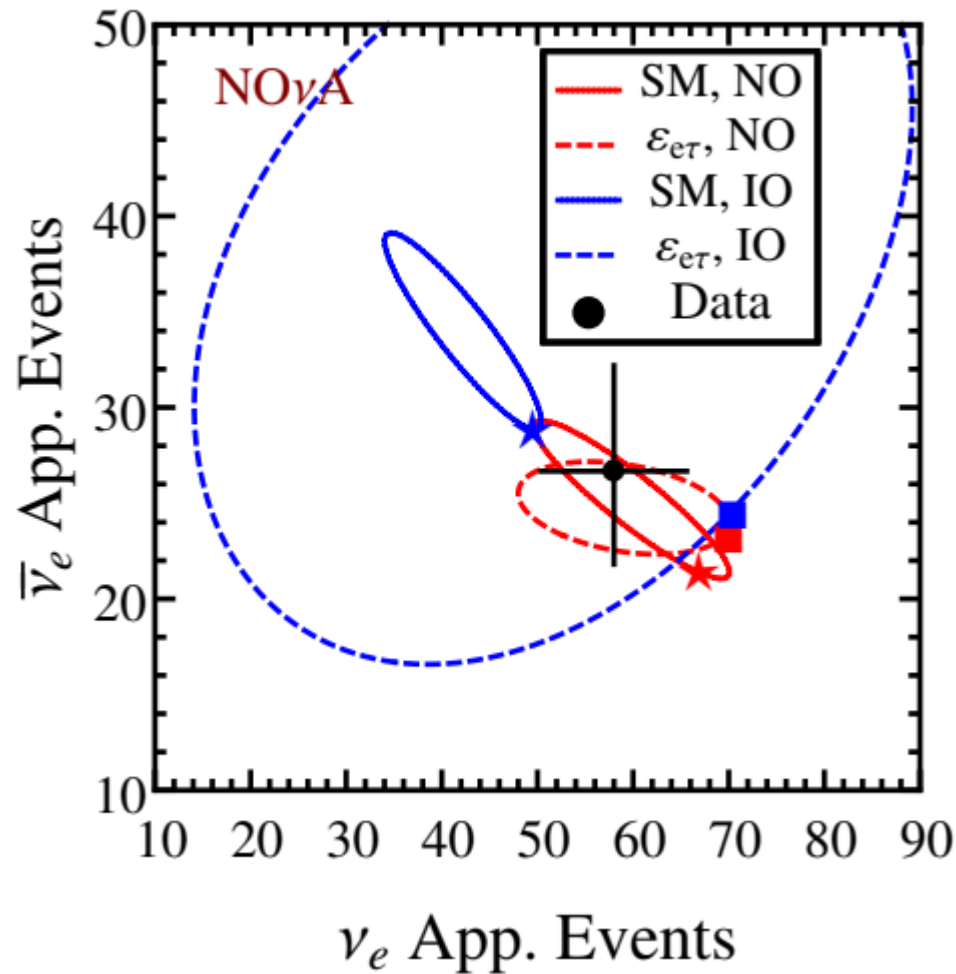
NOvA Dataset



Please see arXiv: 1906.04907, and Jeremy Wolcott's talk

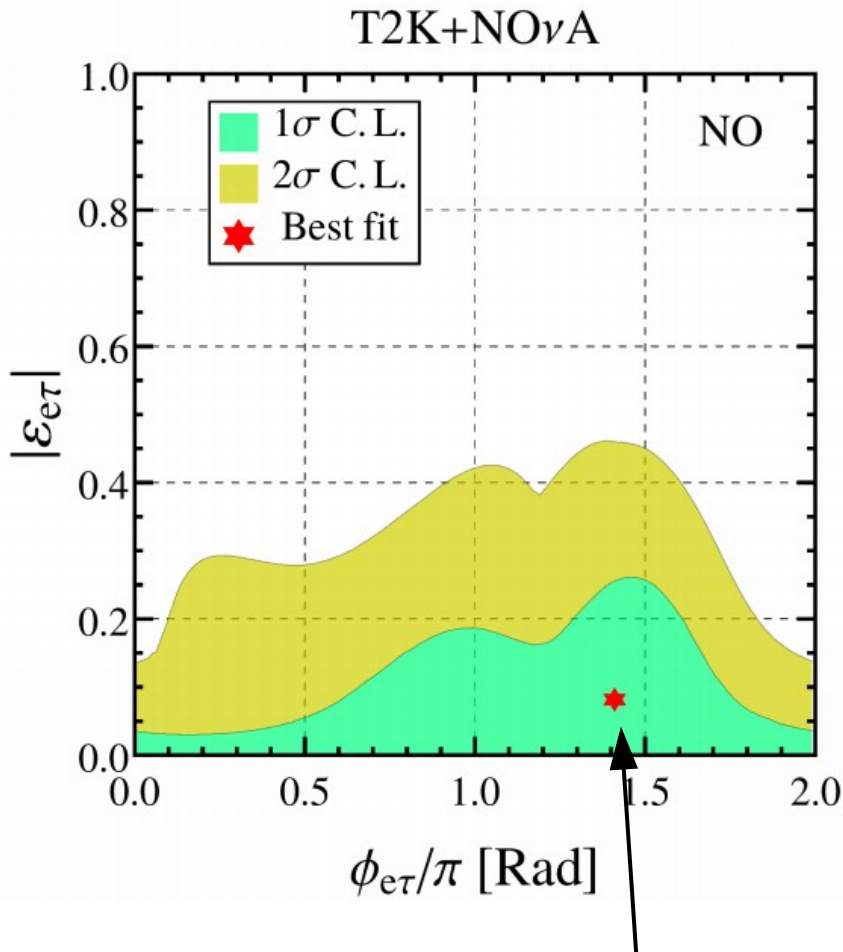
Combined analysis of T2K and NOvA



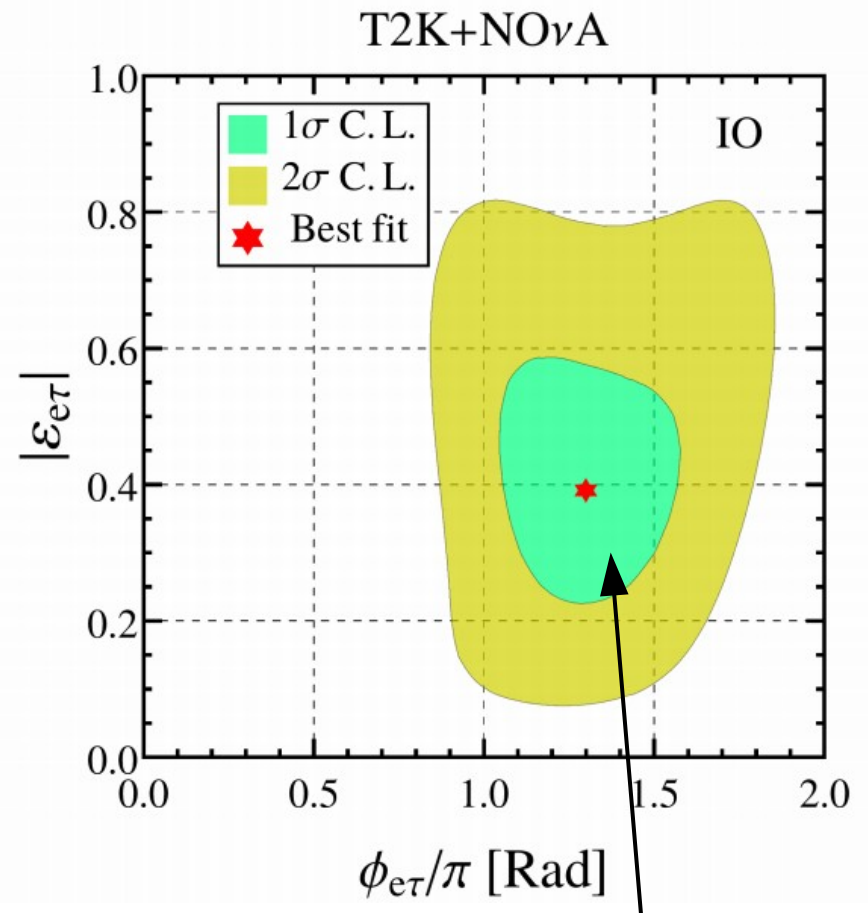


In presence of NSI the best fit points (square) for both NO & IO lie at the same Distance from the data point in T2K as well as in NOvA.

Allowed region of the new parameters



0.7 σ preference for non-zero NSI

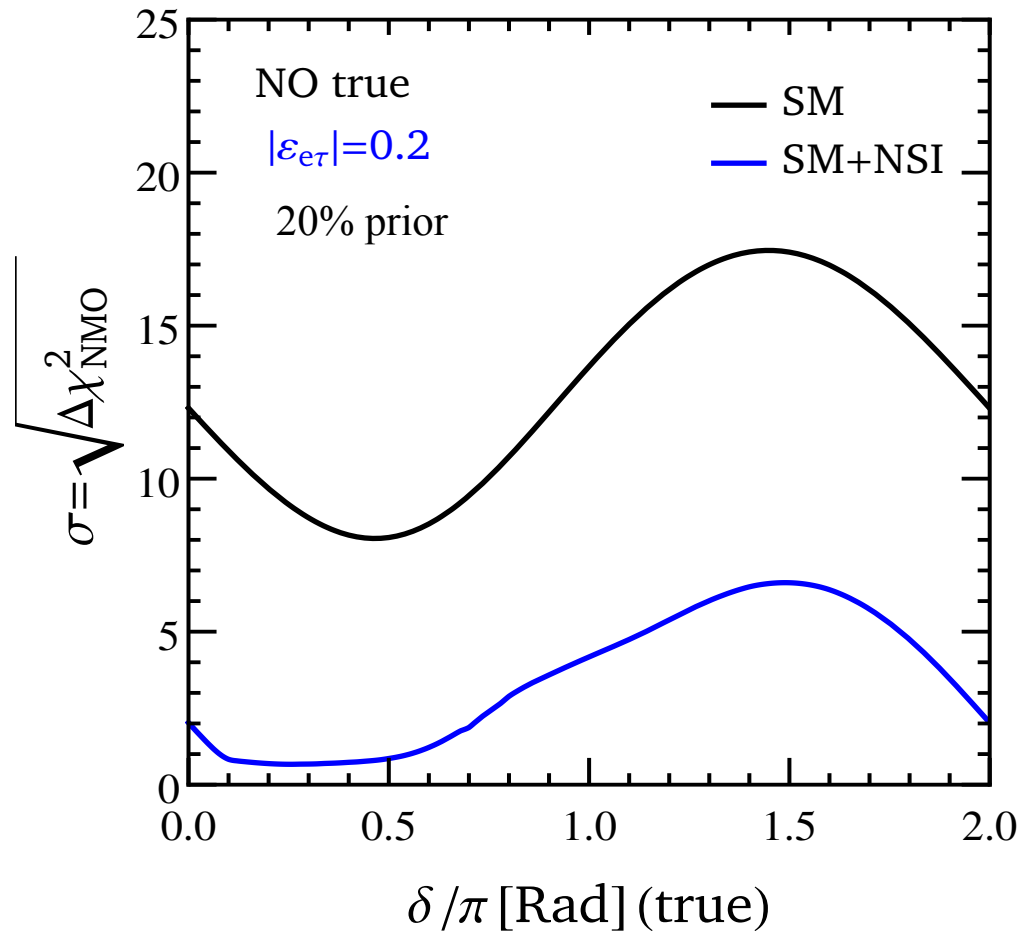


2.5 σ preference for non-zero NSI

We have checked that the best fit value for $\varepsilon_{e\mu}$ is 0.15 (0.10) for NO (IO).

Also NO is preferred over IO at 2.5 σ C.L. in presence of $\varepsilon_{e\mu}$

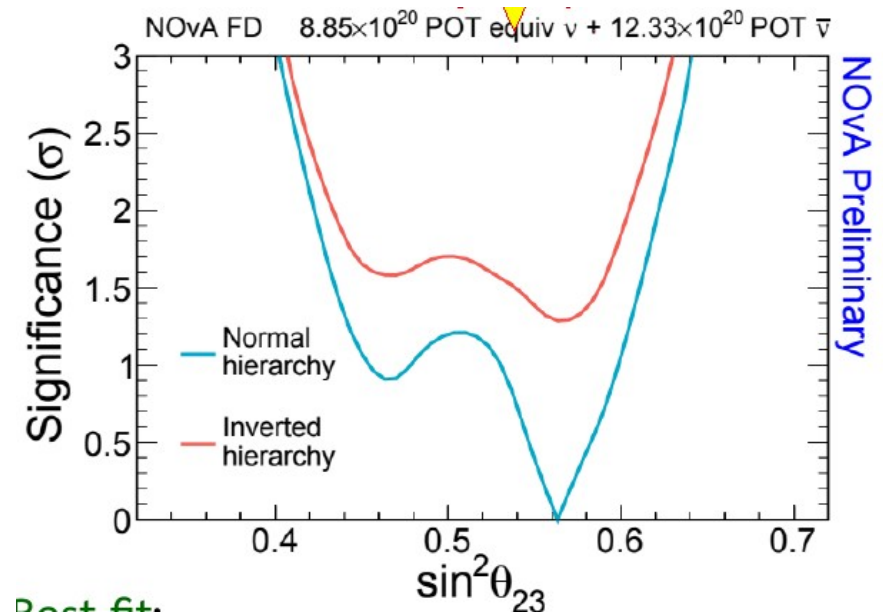
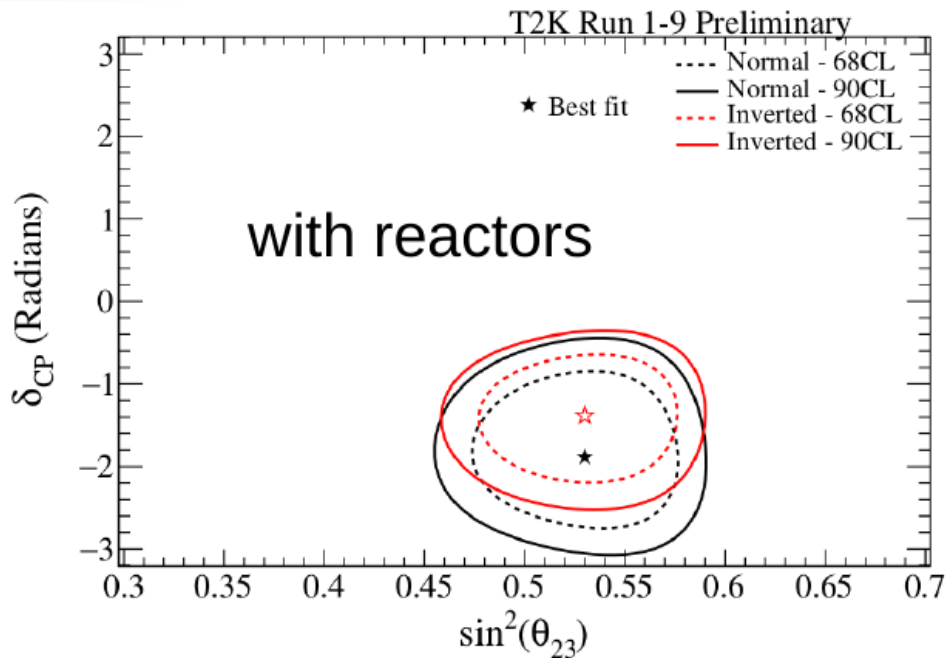
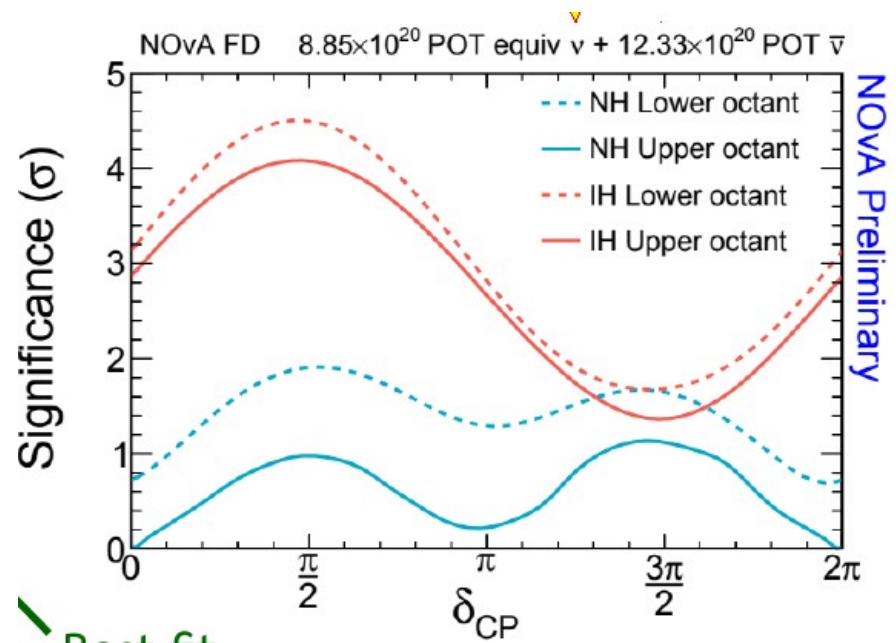
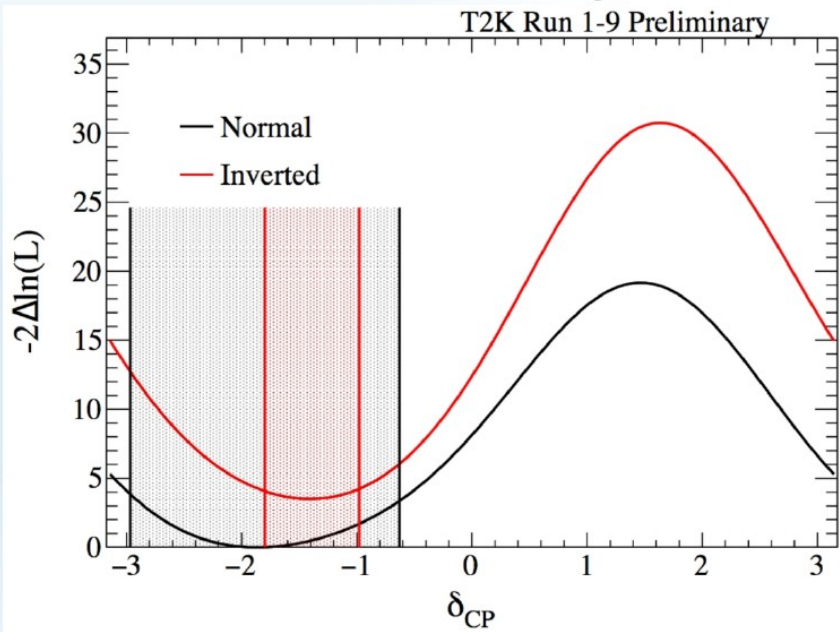
NMO sensitivity in DUNE



Conclusion

- We have investigated the impact of NSI on the current data of T2K and NOvA.
- ◆ We have shown that the indication towards the NO in SM does not hold anymore in presence of NSI of type $\epsilon_{e\tau}$
- ◆ Our result also shows that the NO is preferred over IO at 2.5σ C.L. in presence of NSI of type $\epsilon_{e\mu}$
- The sensitivity towards the resolution of octant of θ_{23} goes to very low confidence level.
- Very recent data presented in Neutrino 2020 and here in ICHEP 2020 make the mass ordering sensitivity more fragile even in standard framework without any new physics.
- Future long-baseline experiments like DUNE and atmospheric current and future data may help resolving this ambiguity. Our work also evidences the importance of JUNO like experiment which is very very less sensitive to the standard and non-standard matter effects.

Thank you!



Please see arXiv: 1910.03887,
and Grzegorz Zarnecki's talk

Please see arXiv: 1906.04907,
and Jeremy Wolcott's talk