Resolving the NOvA and T2K tension in the presence of Neutrino Non-Standard Interactions

Sabya Sachi Chatterjee

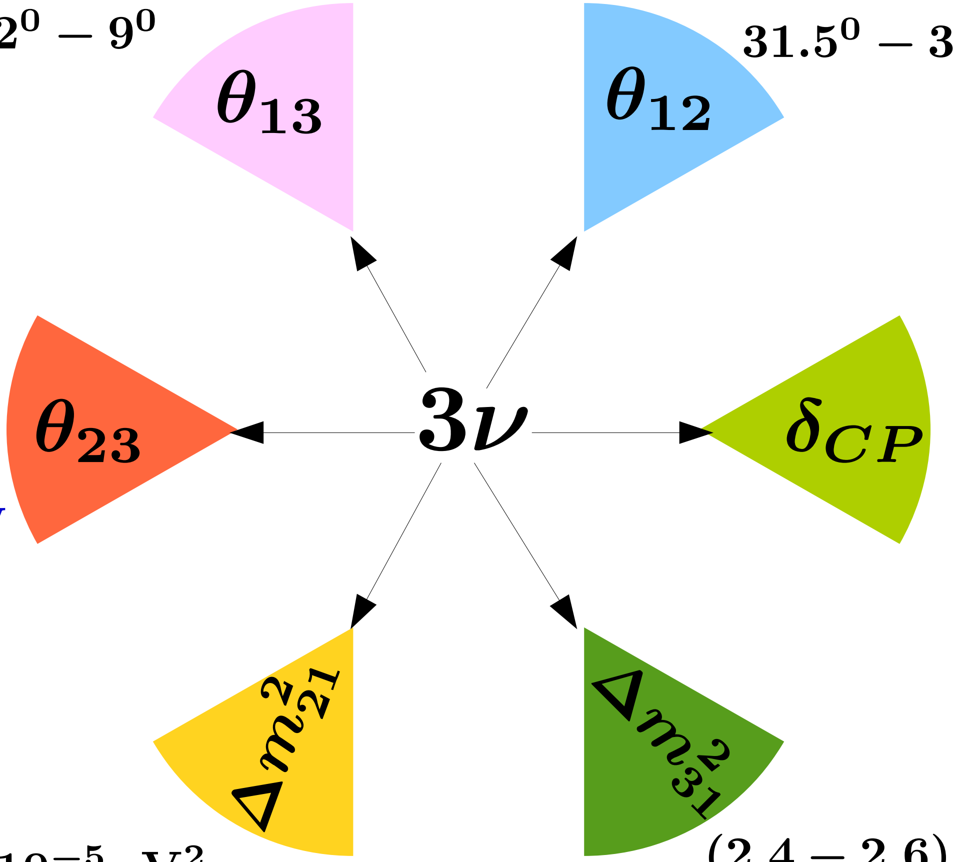
IPhT SACLAY

PASCOS 2022, MPIK, Heidelberg

Based on PRL. 126 (2021) 5, 051802 by S S Chatterjee & A Palazzo

25.07.2022

Current status of 3ν parameters (3σ bound) in the Standard framework



Known very precisely

$8.2^0 - 9^0$

Known quite precisely

$31.5^0 - 37^0$

$41^0 - 52^0$

Not known precisely

$130^0 - 360^0$

Not known precisely

$(6.8 - 8.0) \times 10^{-5}\,\mathrm{eV}^2$

Sign is +ve (m1 < m2)

$(2.4 - 2.6) \times 10^{-3}\,\mathrm{eV}^2$

Sign is unknown

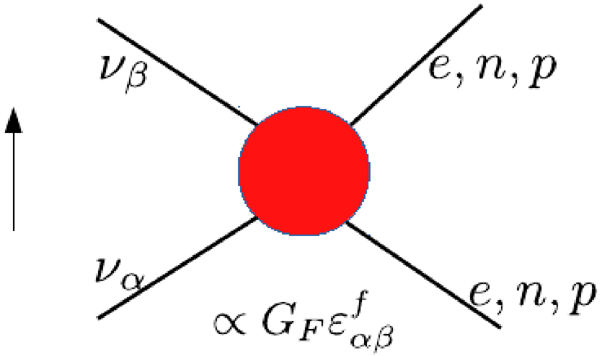
ArXiv: 2006.11237 by P. Salas et al., arXiv: 2007.14792 by Esteban et al., and arXiv: 2107.00532 by F. Capozzi et al.

NSI and its presence in the oscillation framework

The presence of the effective 4-Fermi neutral current non-standard interactions (NSI) in neutrino oscillation can be realized through the dimension-six operators as,

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

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

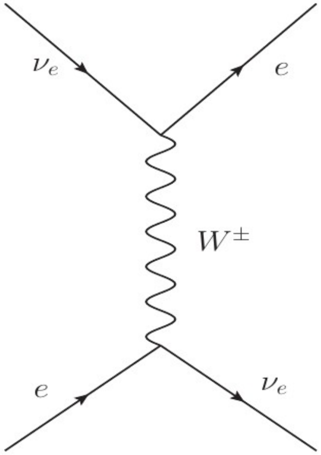


$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^f_{\alpha\beta} \frac{N_f}{N_e}$$

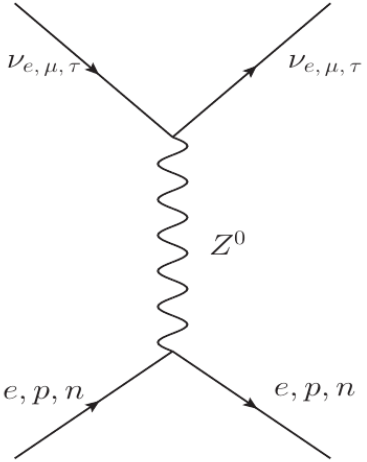
N is the number density of fermions

$$\varepsilon_{\alpha\beta} \simeq \varepsilon^e_{\alpha\beta} + 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta}$$

→ Strength of NSIs



CC-interaction



NC-interaction

L. Wolfenstein PRD 17, 2369 (1978)

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

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

…………….(III)

Where,

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

$\mathrm{V}_{CC} = \sqrt{2}\,G_F\,N_e$ → CC matter potential, $\mathrm{V}_{NC} = -\frac{G_F\,N_n}{\sqrt{2}}$ → NC matter potential

$\varepsilon_{\alpha\beta}|_{\alpha\neq\beta} = |\varepsilon_{\alpha\beta}|\,e^{i\phi_{\alpha\beta}}$ and $\varepsilon_{\alpha\beta} = (\varepsilon_{\beta\alpha})^*$

The probability for one flavor ν_α transforming to another flavor ν_β is calculated as

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = |S_{\beta\alpha}(L)|^2 = |(e^{-iHL})_{\beta\alpha}|^2$$

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

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

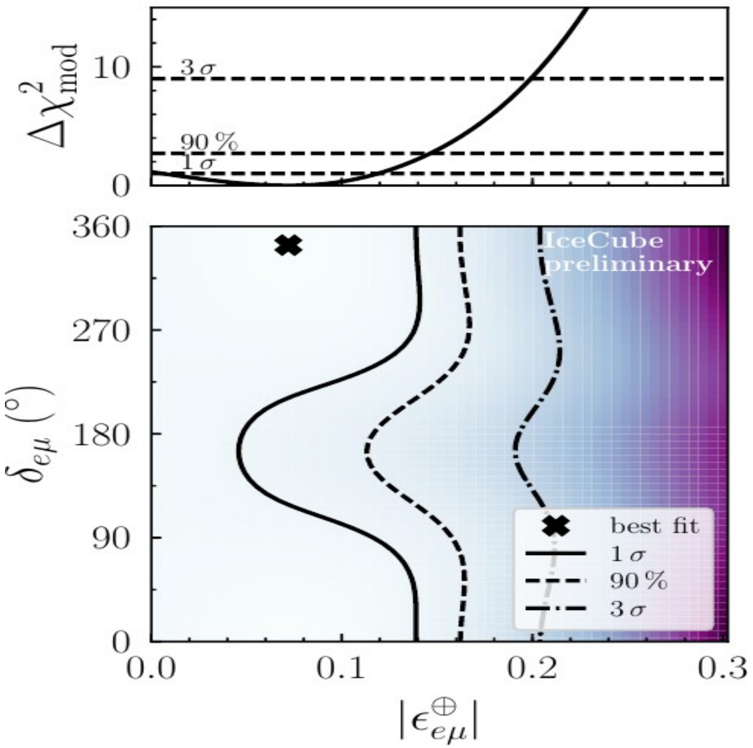
NSI (e-μ) *sector*

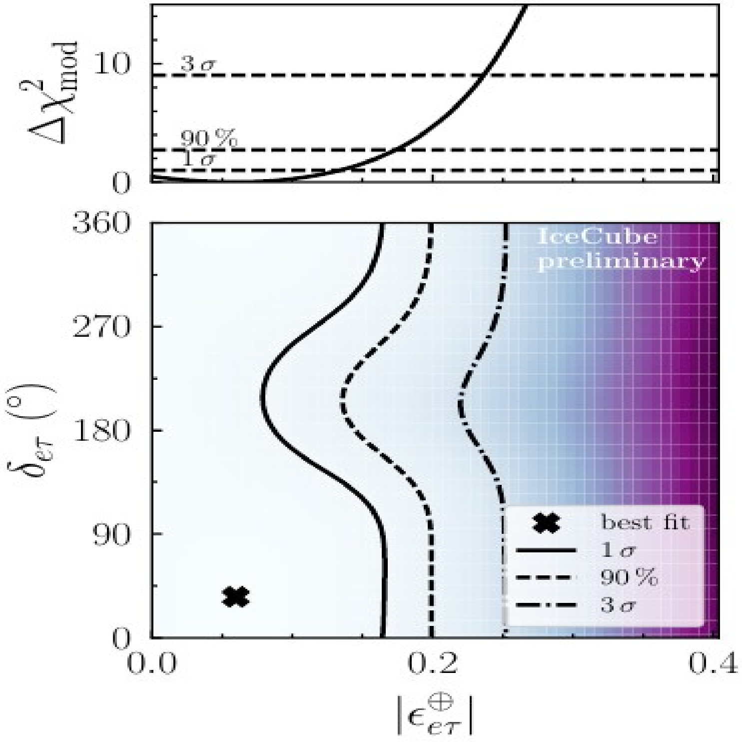
$$\begin{aligned}
P_0 &\simeq 4 s_{13}^2 s_{23}^2 f^2 \\
P_1 &\simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta) \\
P_2 &\simeq 8 s_{13} s_{23} v |\varepsilon_{e\mu}| [s_{23}^2 f^2 \cos(\delta + \phi_{e\mu}) + c_{23}^2 f g \cos(\Delta + \delta + \phi_{e\mu})]
\end{aligned}$$

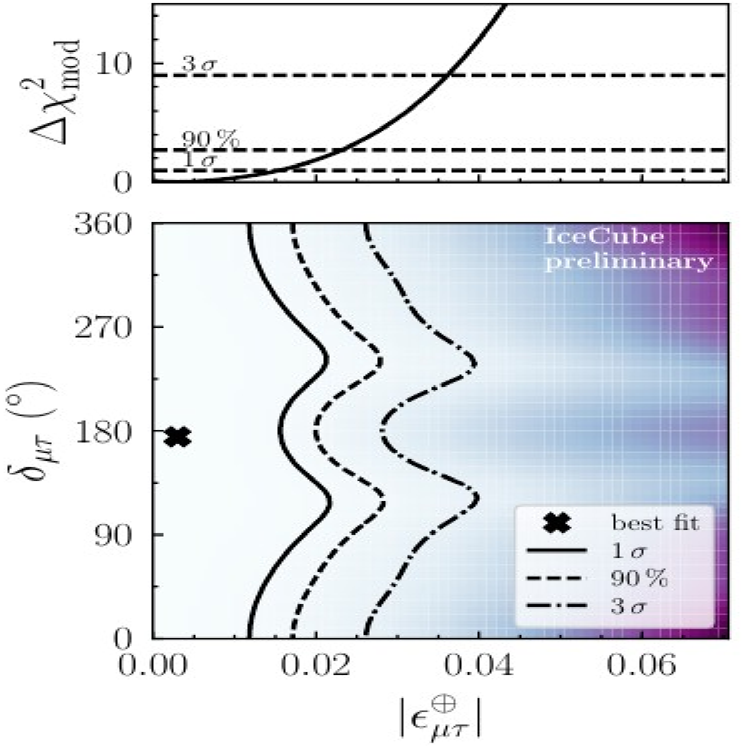
NSI (e-τ) *sector*

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

$$\Delta = \frac{\Delta m_{31}^2 L}{4E}, \qquad f \equiv \frac{\sin[(1-v)\Delta]}{1-v}\,, \qquad g \equiv \frac{\sin v\Delta}{v}\,, \qquad |v| = \left| \frac{2 V_{\rm CC} E}{\Delta m_{31}^2} \right|$$







Limits from the IceCube (90% C.L.)

$$|\epsilon^{\oplus}_{e\mu}| \leq 0.15$$

$$|\epsilon^{\oplus}_{e\tau}| \leq 0.17$$

$$|\epsilon^{\oplus}_{\mu\tau}| \leq 0.023$$

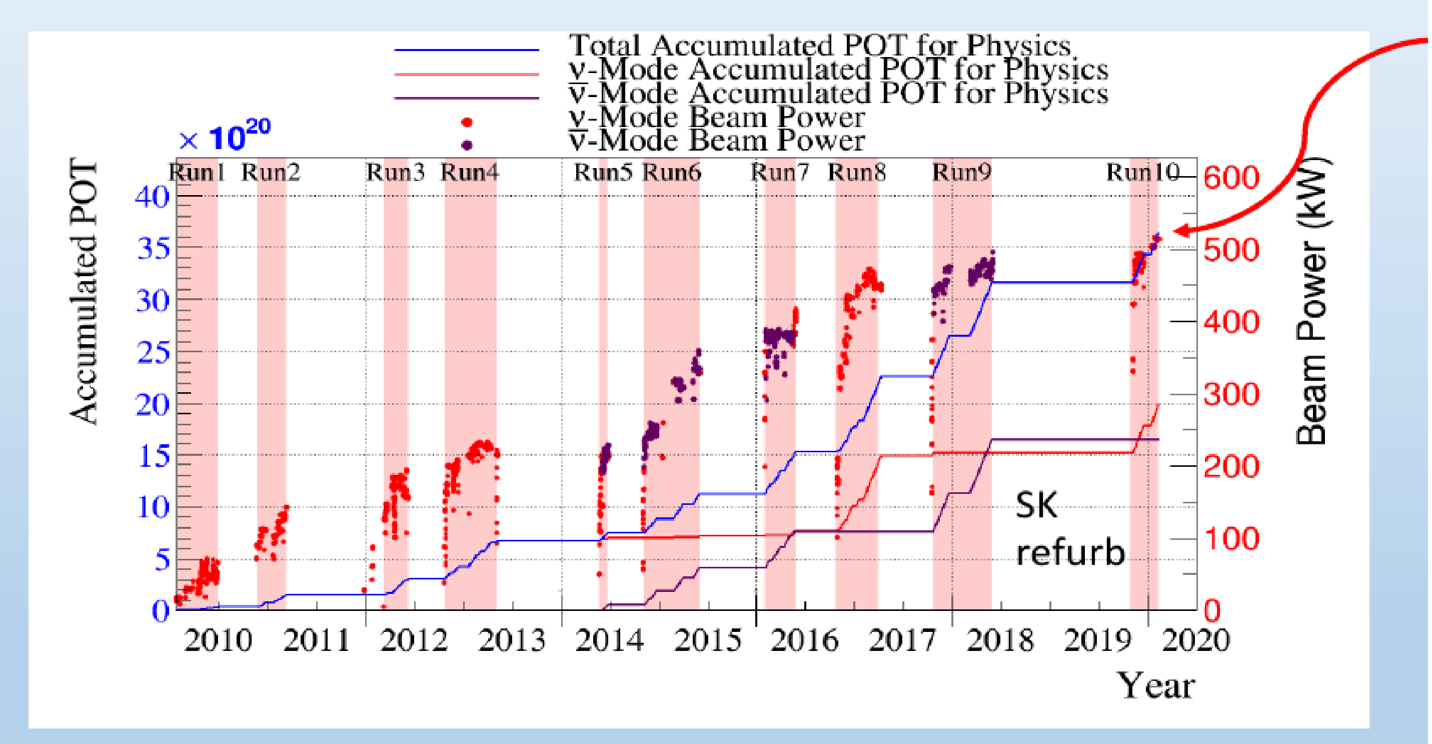
$$\epsilon^{\oplus}_{ee} - \epsilon^{\oplus}_{\mu\mu} \to [-.25, -.15]\ \&\ [-.06, .04]$$

$$\epsilon^{\oplus}_{\tau\tau} - \epsilon^{\oplus}_{\mu\mu} \to [-.04, .045]$$

See the talk by T. Ehrhardt presesented at PPNT, Uppsala (2019)
For more details please see PRD104(Oct, 2021) 072006

Brief description of the experimental setup T2K

T2K (Tokai to Kamioka)	
Baseline	295 KM
Detector mass	22.5 Kt
Proton Energy	30 GeV



515 kW stable operation achieved

$$\nu \ : \ 1.97 \times 10^{21} \ \ \textbf{POT}$$

$$\bar{\nu} \ : \ 1.63 \times 10^{21} \ \ \textbf{POT}$$

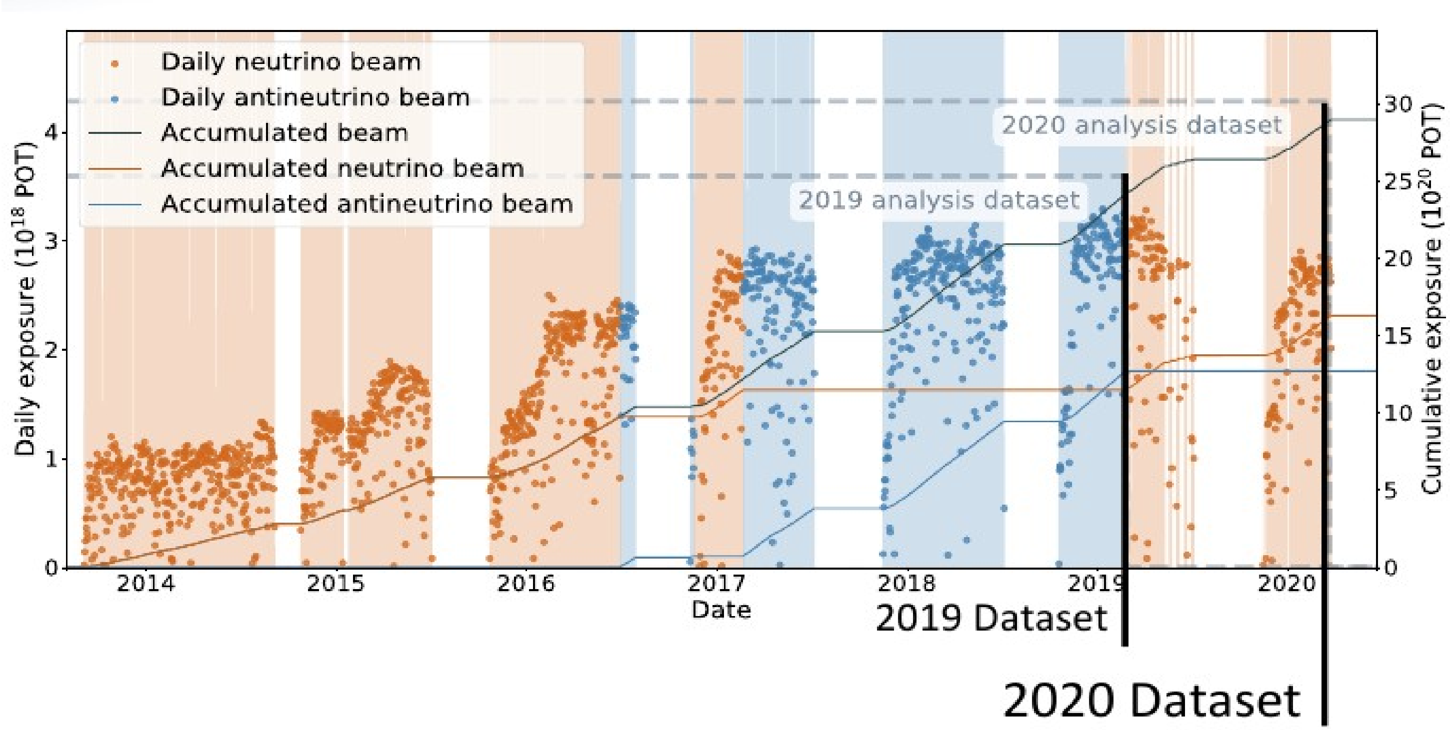
Talk by P. Dunne at Neutrino 2020

Brief description of the experimental setup NOvA

NOvA (Fermilab to Minnesota)	
Baseline	810 KM
Detector mass	14 Kt
Proton Energy	120 GeV

Beam Power

Typically ~ 700 kW

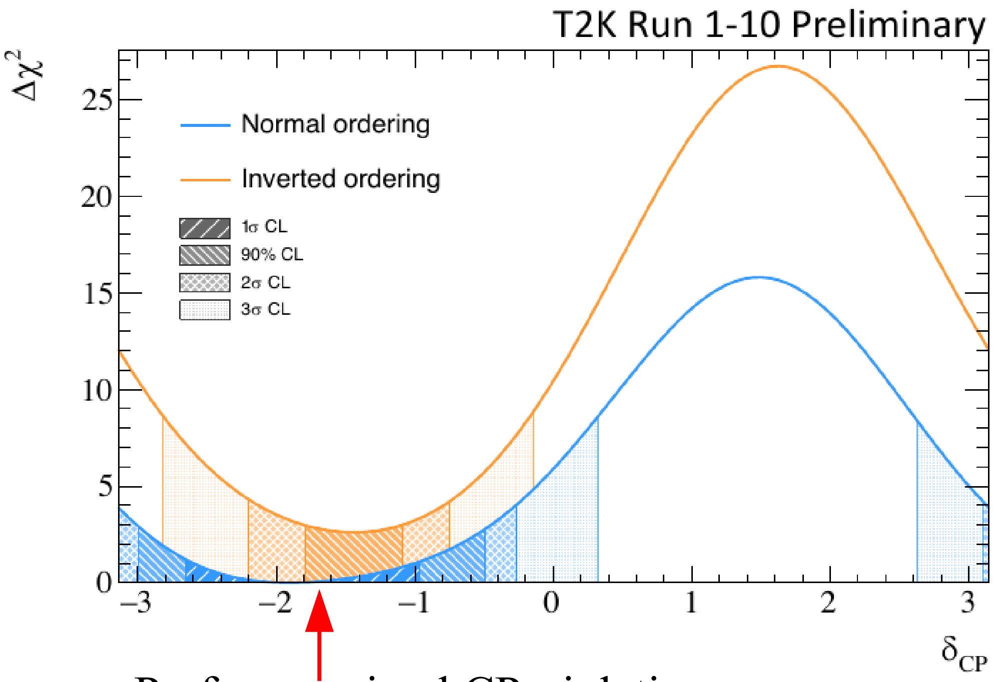


$$\nu \;:\; 1.6 \times 10^{21} \quad \mathbf{POT}$$

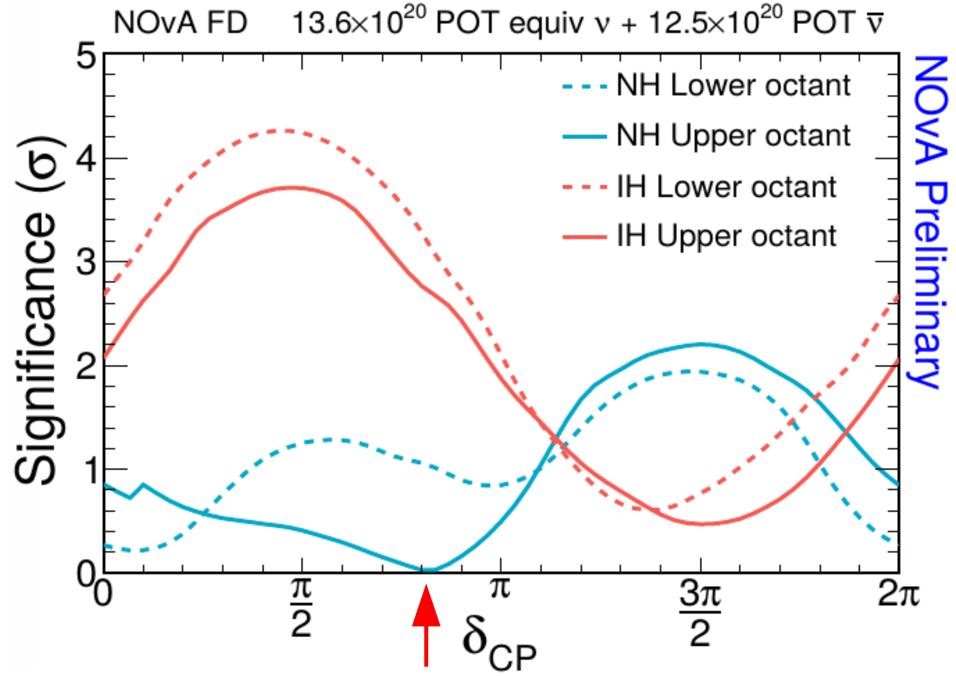
$$\bar{\nu} \;:\; 1.3 \times 10^{21} \quad \mathbf{POT}$$

Talk by Alex Himmel at Neutrino 2020

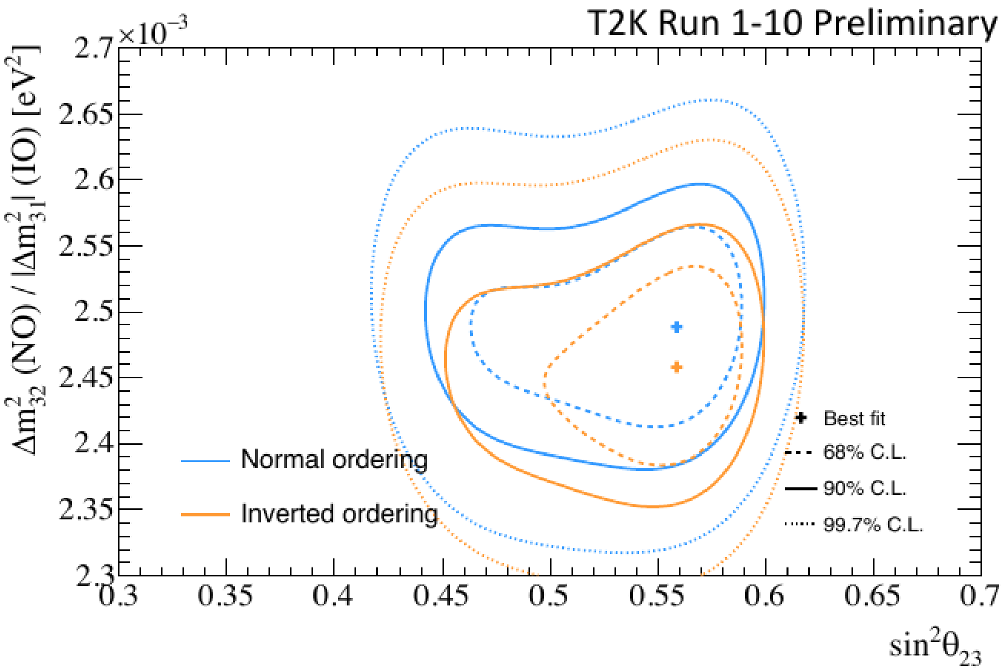
Results from the Collaborations

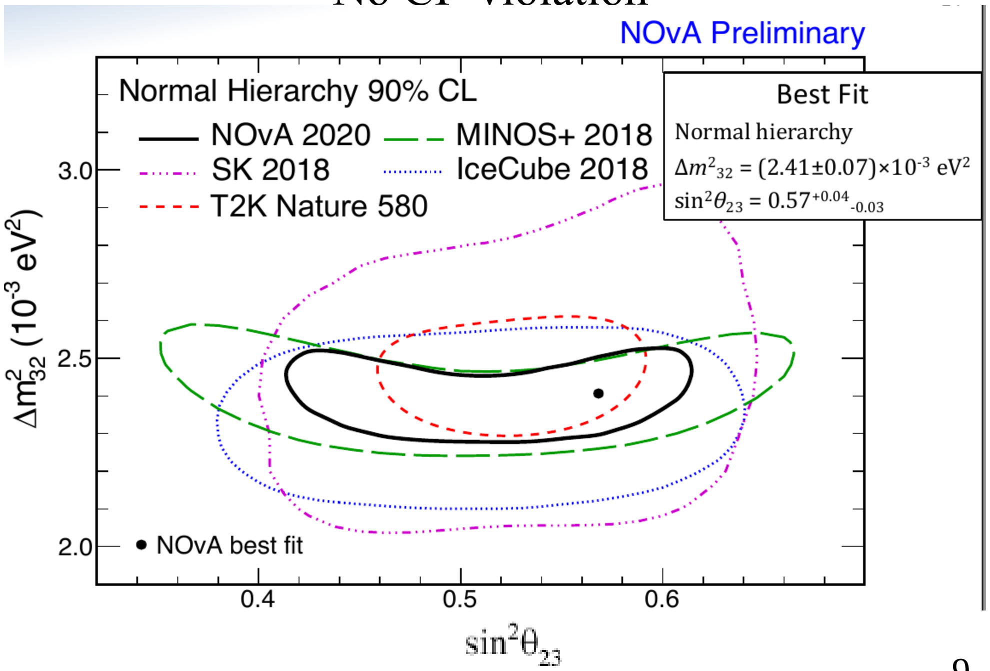


Prefers maximal CP-violation



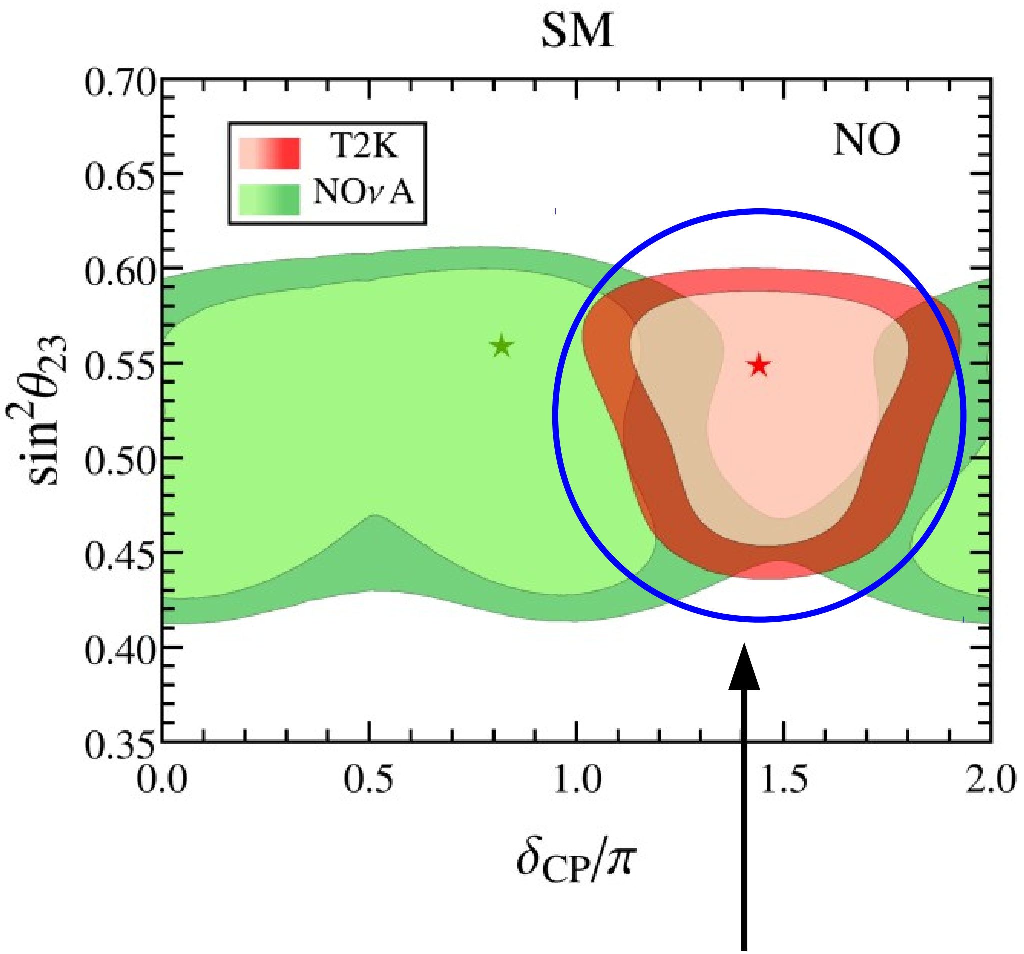
No CP-violation



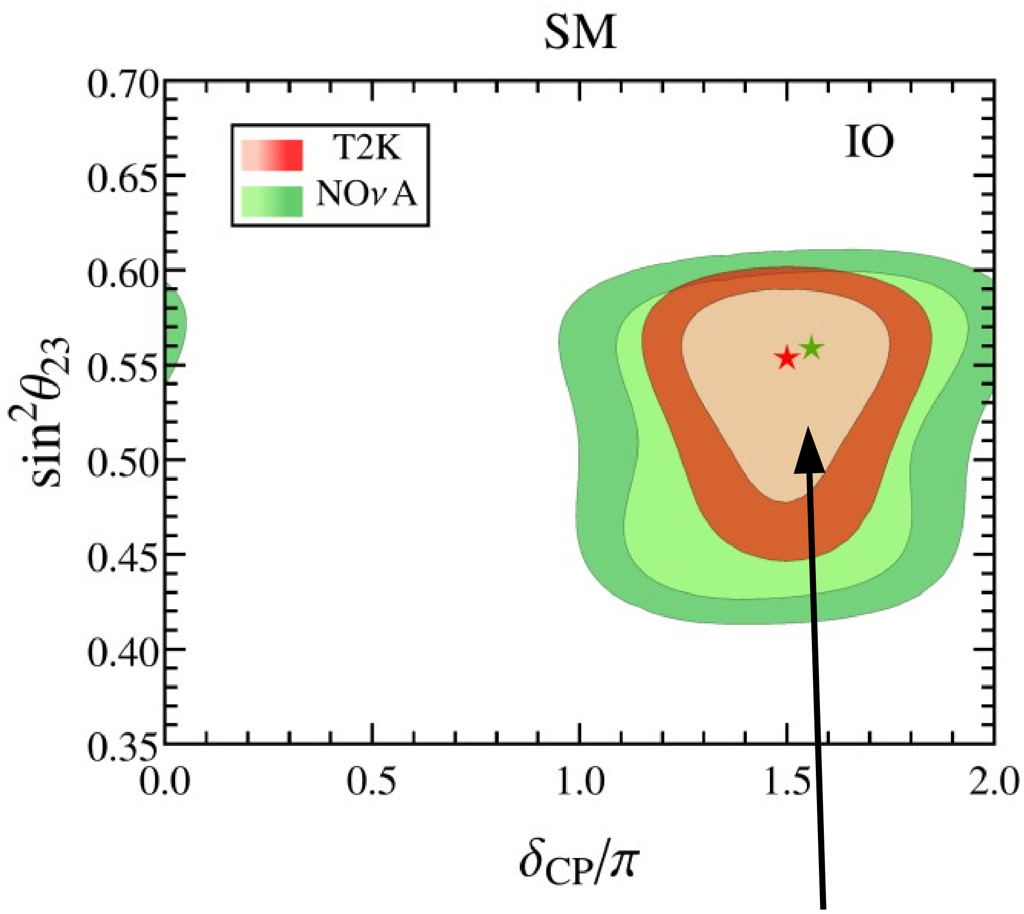


Talk by P. Dunne and A. Himmel at Neutrino 2020

68% and 90% C.L. contours at 2 d.o.f

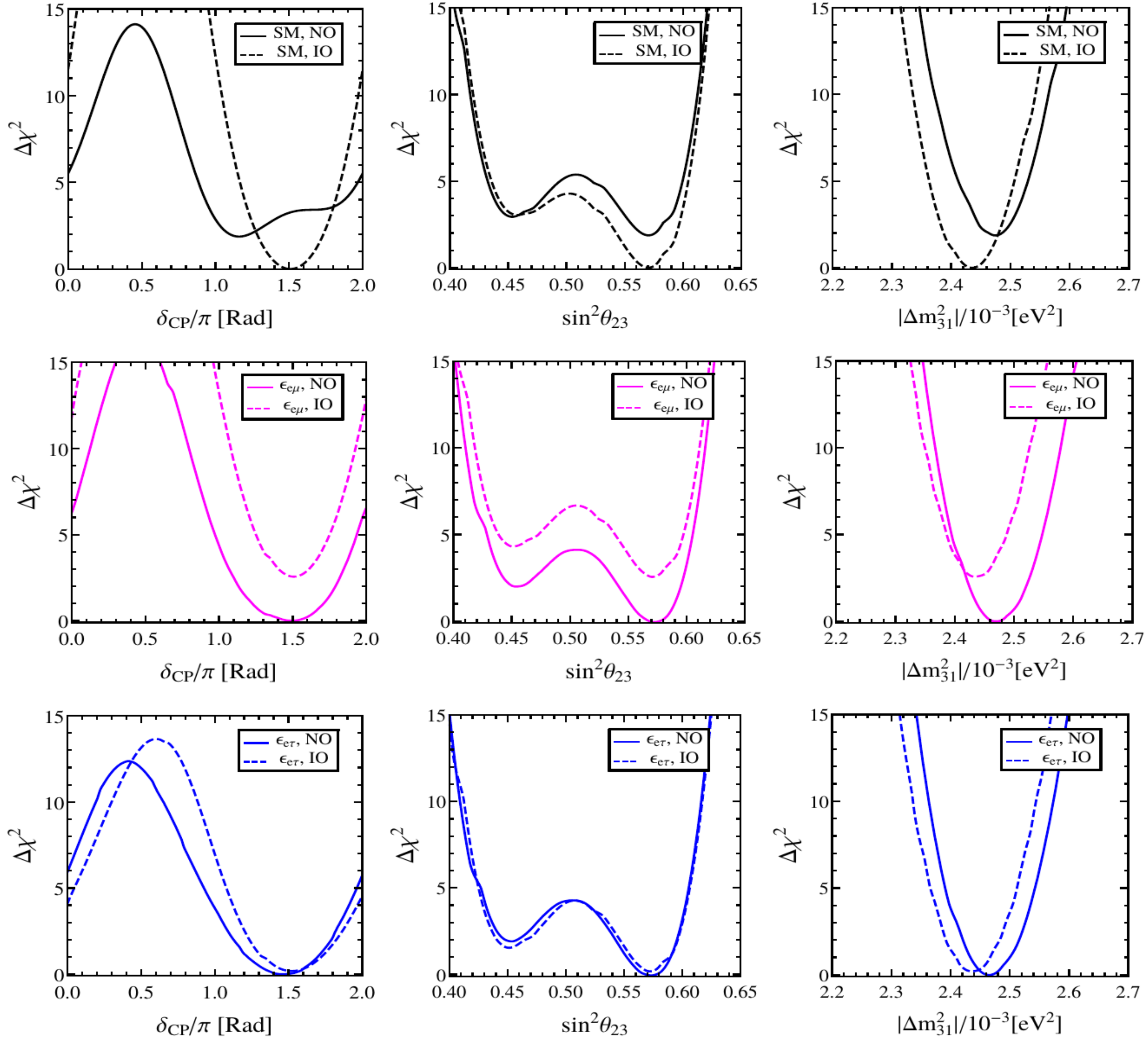


More than 90% C.L. disagreement
between T2K and NovA in the measurement
of CP-phase



No discrepancy

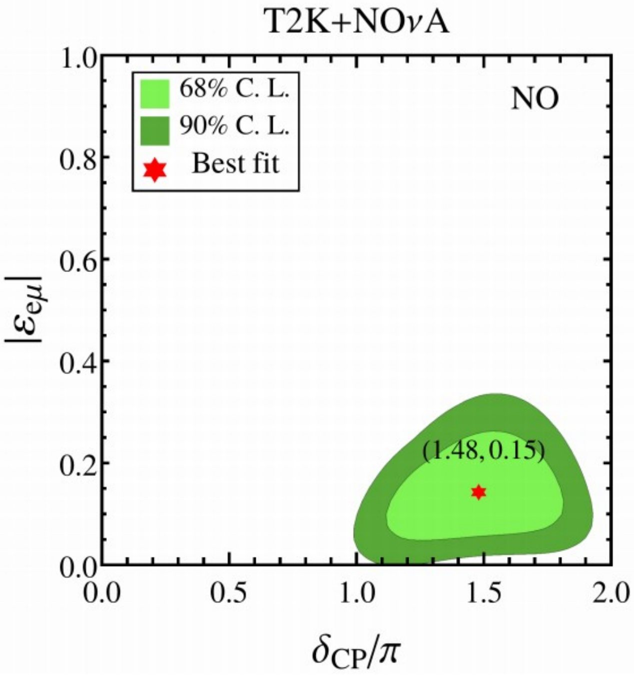
Combined analysis of T2K and NOvA

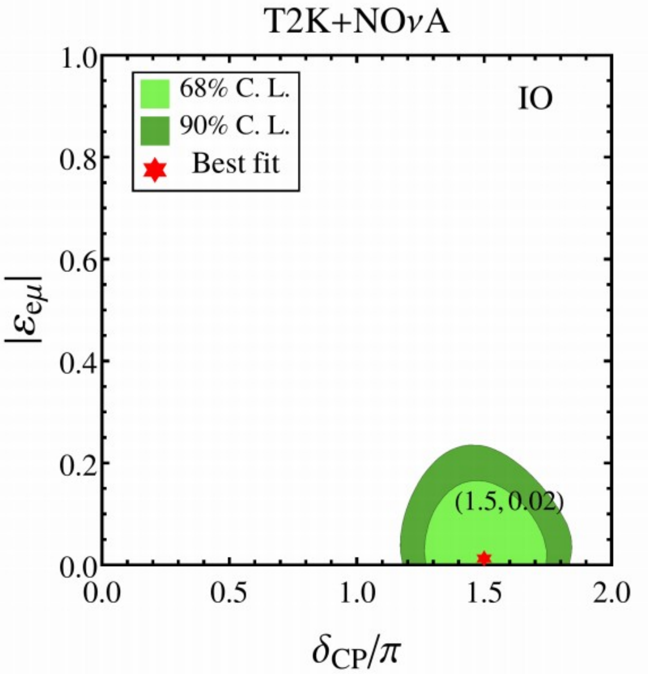


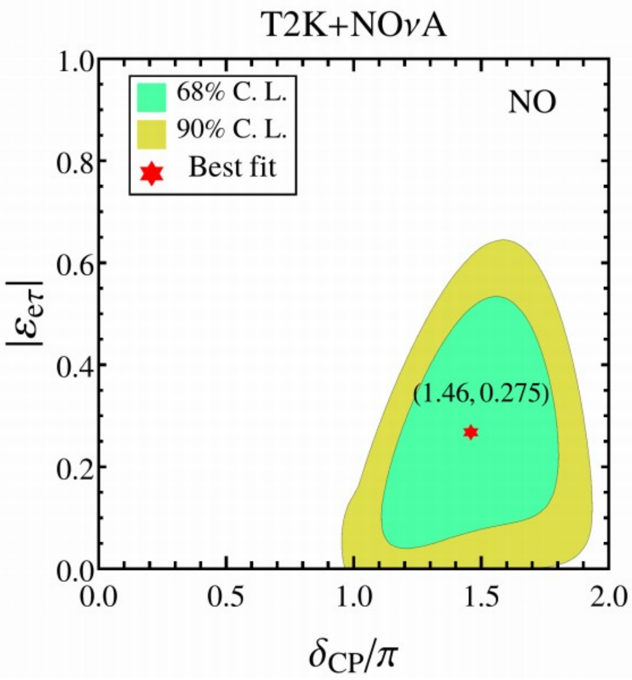
IO is preferred over NO in standard oscillation

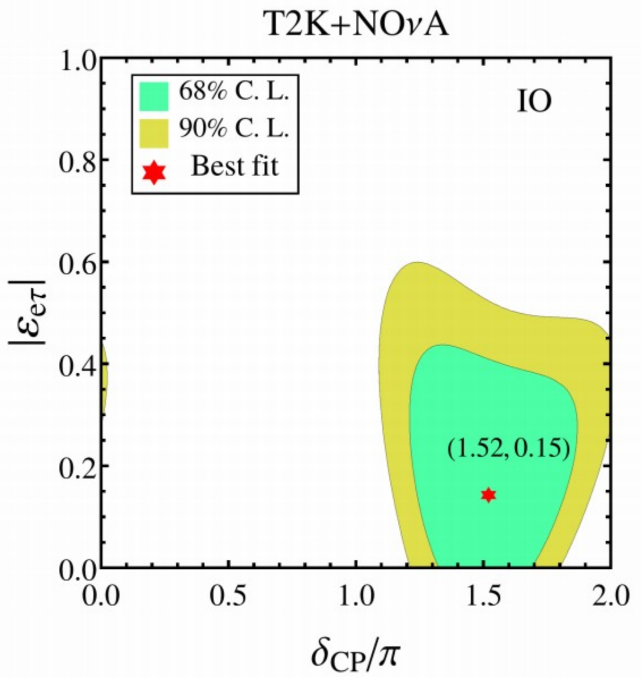
However NO is preferred over IO in Presence of NSI

See also **PRL. 126 (2021) 5, 051801** by P. B. Denton, J. Gehrlein, & R. Pestes









Allowed regions of NSI parameters

$$\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm SM+NSI}$$

NMO	NSI	$\lvert\varepsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	$\delta_{\rm CP}/\pi$	$\Delta\chi^2$
NO	$\varepsilon_{e\mu}$	0.15	1.38	1.48	4.50
	$\varepsilon_{e\tau}$	0.27	1.62	1.46	3.75
IO	$\varepsilon_{e\mu}$	0.02	0.96	1.50	0.07
	$\varepsilon_{e\tau}$	0.15	1.58	1.52	1.01

$$\chi^2_{\rm SM,NO} - \chi^2_{\rm SM,IO} = 1.87$$

$$\chi^2_{{\rm e}\mu,{\rm NO}} - \chi^2_{{\rm e}\mu,{\rm IO}} = -2.56$$

$$\chi^2_{{\rm e}\tau,{\rm NO}} - \chi^2_{{\rm e}\tau,{\rm IO}} = -0.21$$

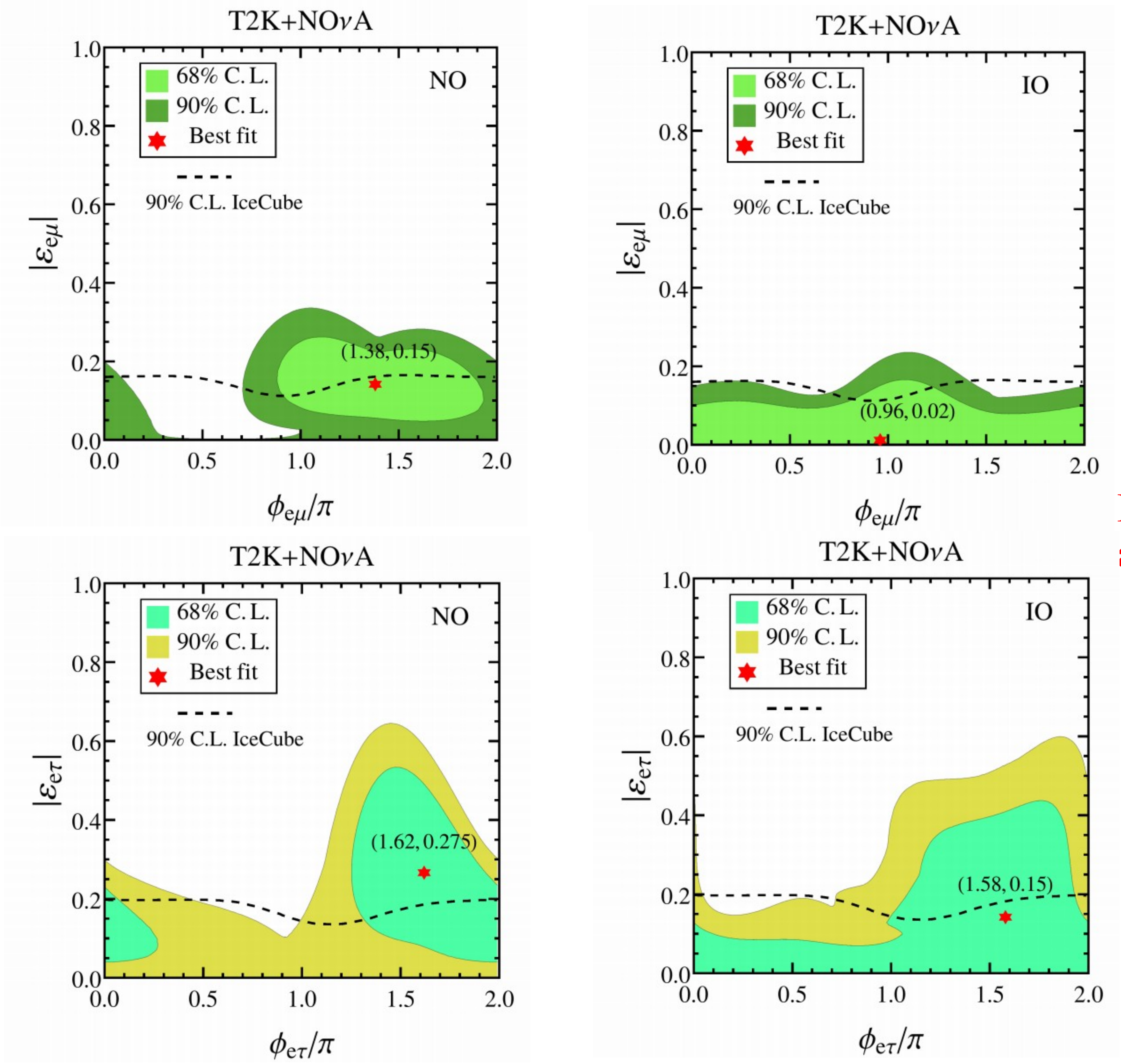
$$\chi^2_{{\rm e}\mu,{\rm NO}} - \chi^2_{\rm SM,IO} = -2.63$$

$$\chi^2_{e\mu,IO} - \chi^2_{SM,IO} = -0.07$$

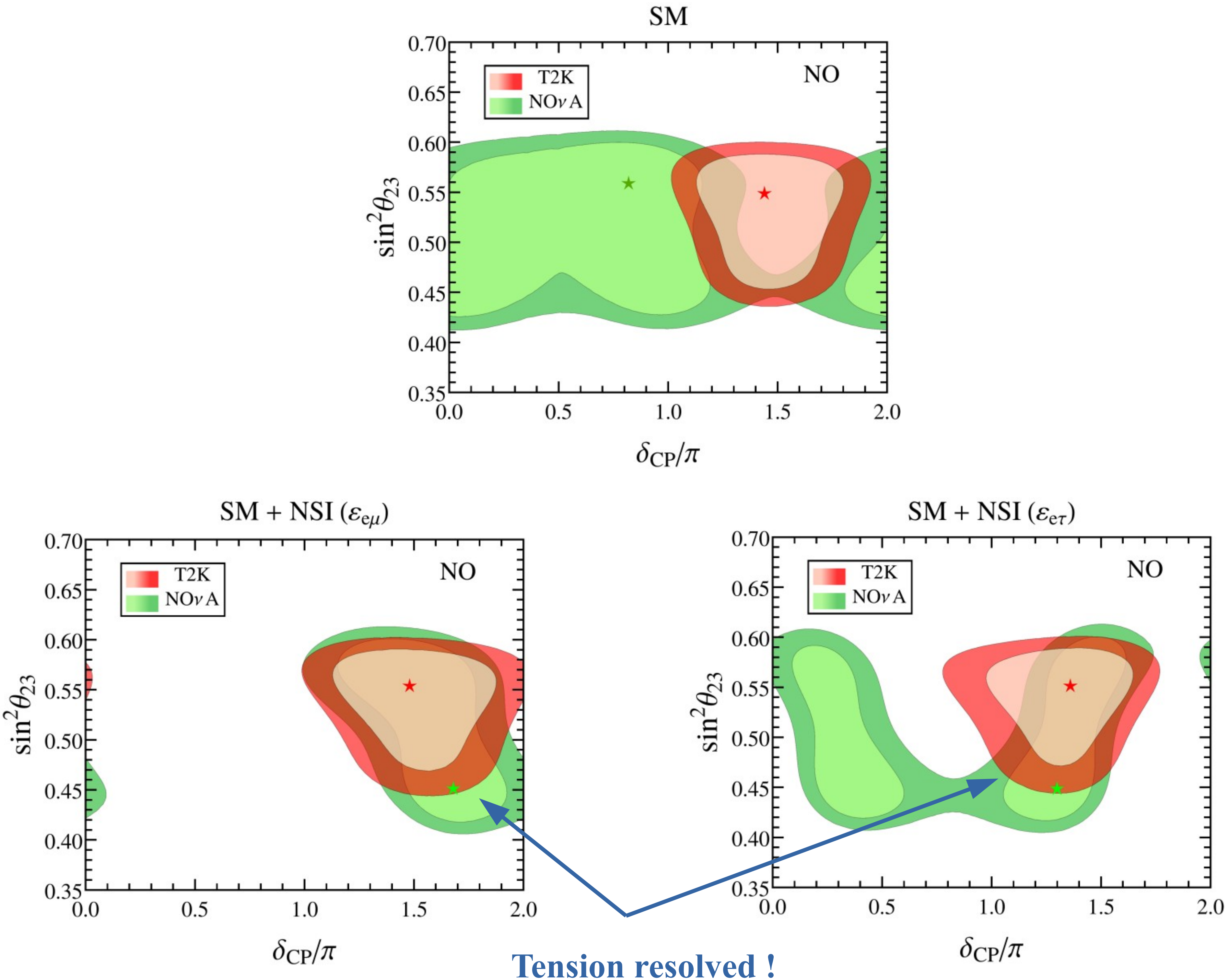
$$\chi^2_{{\rm e}\tau,{\rm NO}} - \chi^2_{\rm SM,IO} = -1.21$$

$$\chi^2_{e\tau,IO} - \chi^2_{SM,IO} = -1.01$$

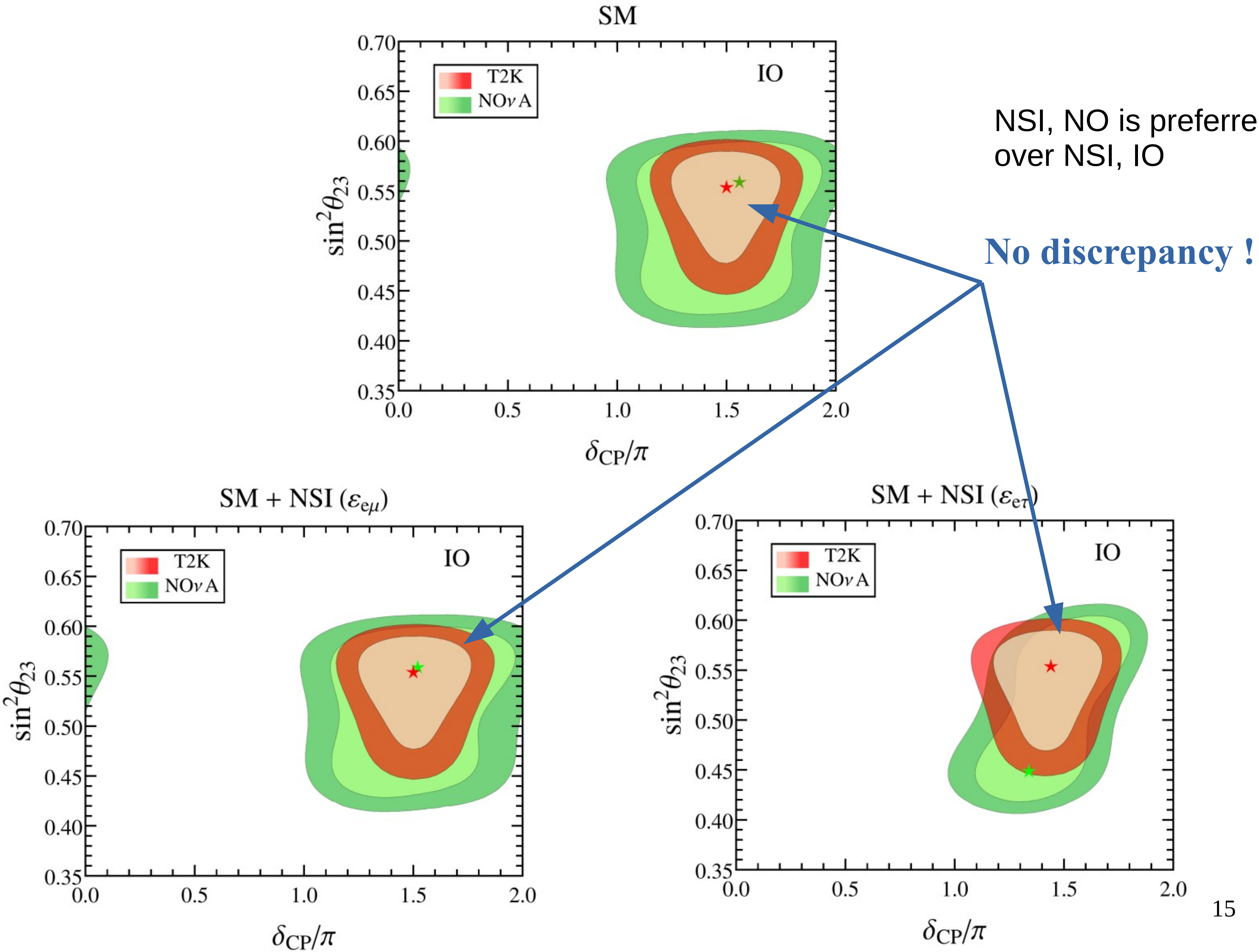
NSI with e-mu sector (NO) is better preferred over e-tau sector (NO) !



IceCube bounds are compatible !



Tension resolved !



NSI, NO is preferred
over NSI, IO

No discrepancy !

Conclusion

- We have investigated the impact of NSI on the current data of T2K and NOvA.

➔ More than 90% C.L. disagreement between T2K and NovA in the measurement of the Standard Model CP-phase. It can be resolved if one considers the presence of NSI of type $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$

- Future data from T2K and NOvA, and future experiments like T2HK, DUNE and atmospheric current and future data is expected to confirm the presence of NSI and also will help resolving this ambiguity.

✯ Our work also evidences the importance of JUNO like experiment to determine NMO unambigiously, irrespective of the presence of NSI.

✓ **The current T2K and NOvA data might be a hint of Physics Beyond the Standard Model !**

Thank you for your kind attention!

Introduction to NSI

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types.

L. Wolfenstein
Phys. Rev. D 17, 2369

Strong constraints on NC-NSI from the non-observation of charged lepton flavor violation

Possible to avoid these bounds:

1. Model with neutral light mediators

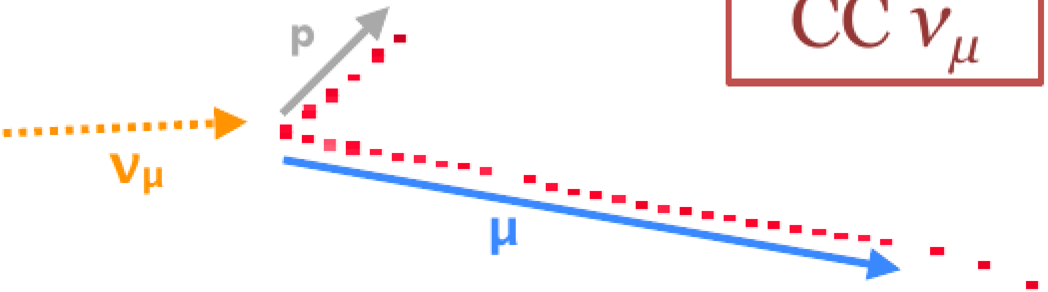
2. Heavy mediators models arising in radiative neutrino mass model

3. Models with two mediators in the framework of dimension-8 operators

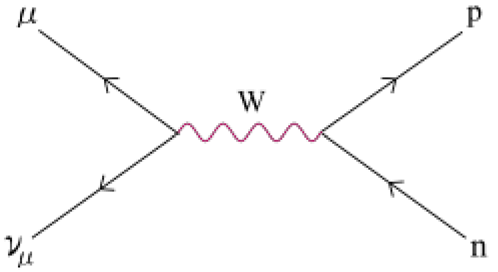
For references please see:

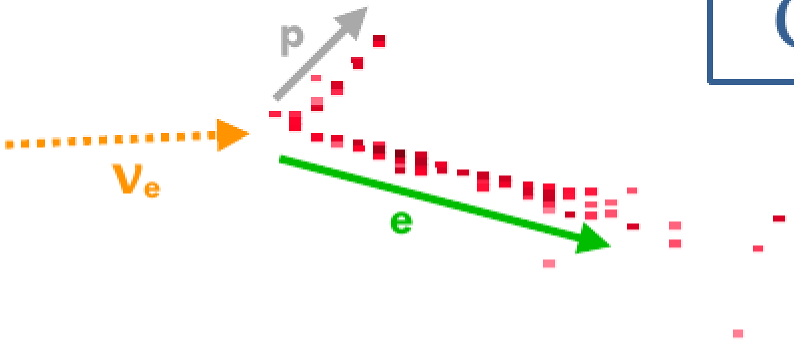
Y. Farzan 1505.06906, Y. Farzan, I. Shoemaker 1512.09147,
Y. Farzan, M. Tortola 1710.09360,
M. Gavela, D. Hernandez, T. Ota, and W. Winter 0809.3451,
K.Babu, P. B. Dev, S. Jana, and A. Thapa 1907.09498,
D. Forero and W. Huang 1608.04719
U. Dey, N. Nath and S. Sadhukhan 1804.05808
And many more.

For overview see, 1907.00991

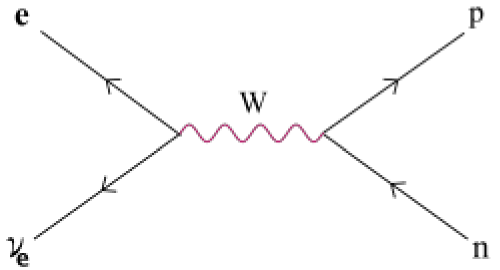


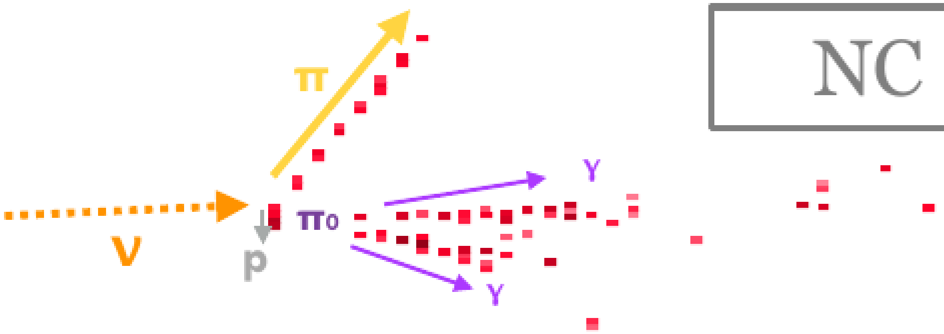
CC ν_μ



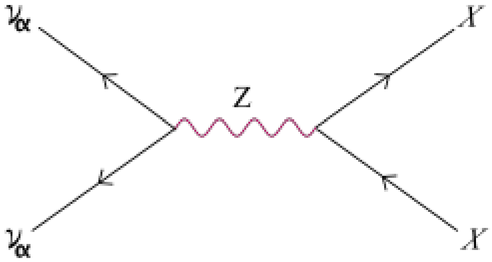


CC ν_e





NC



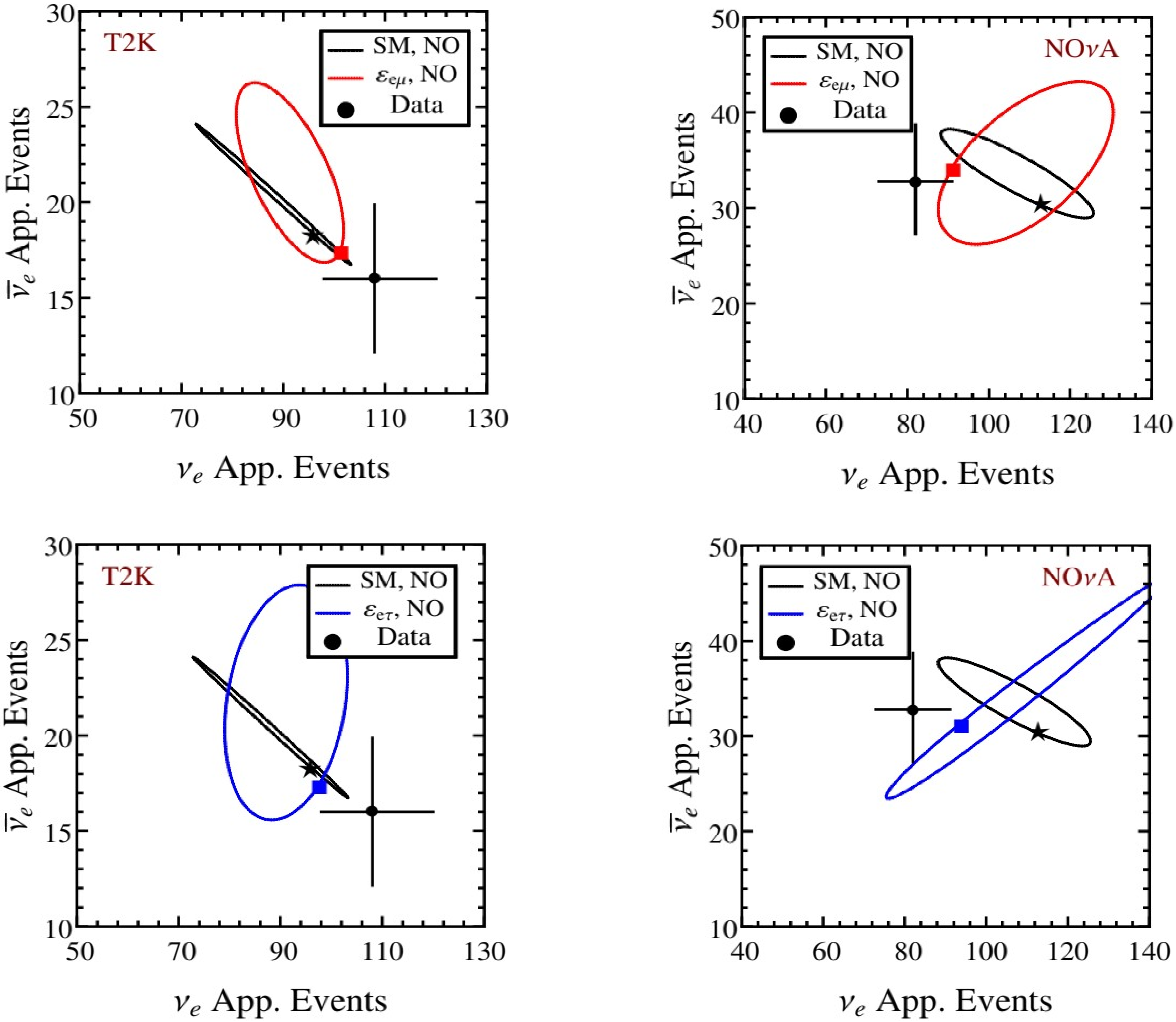
$$\alpha = e,\ \mu,\ \tau$$

For antineutrinos (inverse beta-decay)

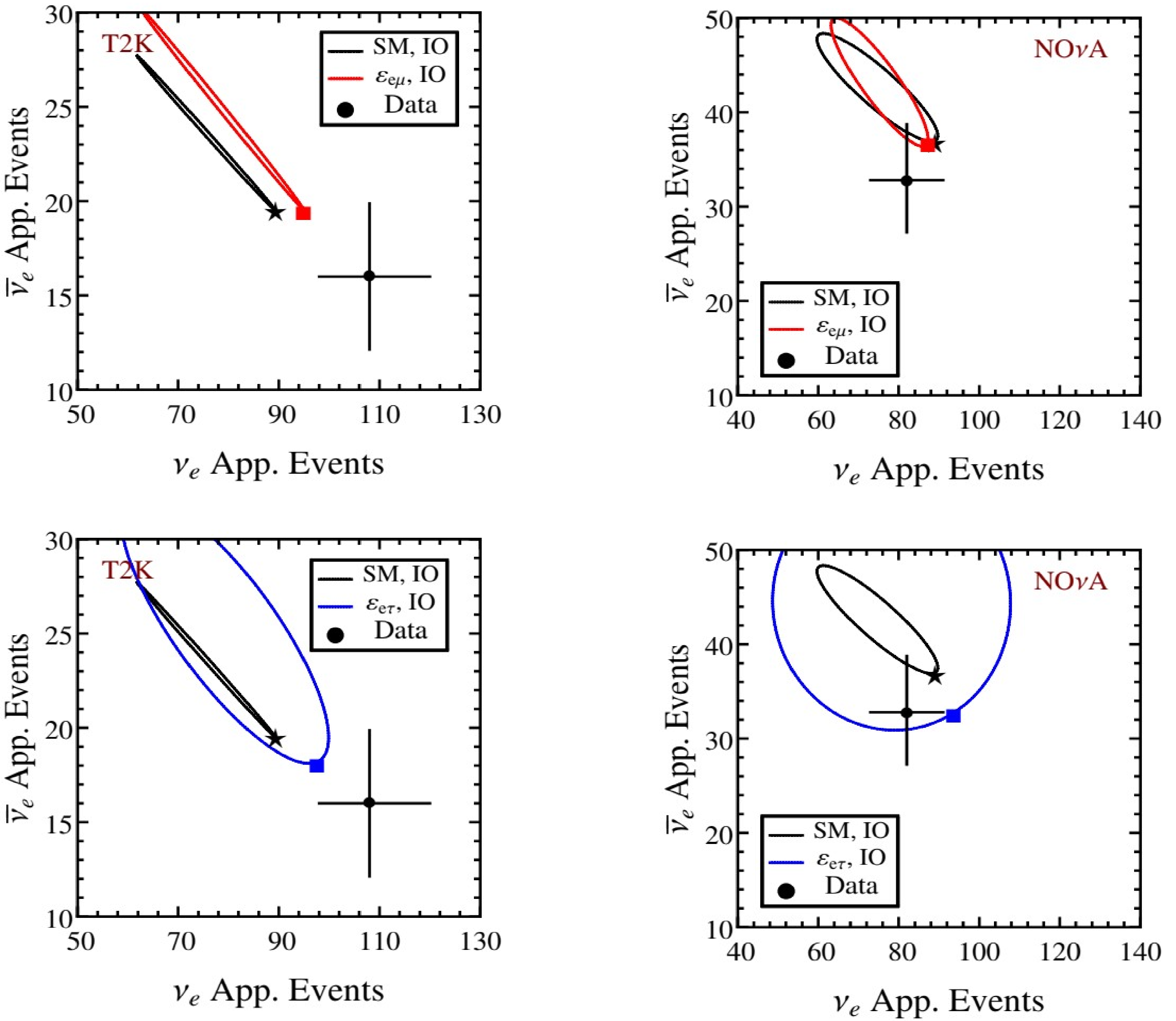
$$\bar{\nu}_l + p \to l^+ + n$$

In Liquid Ar detector

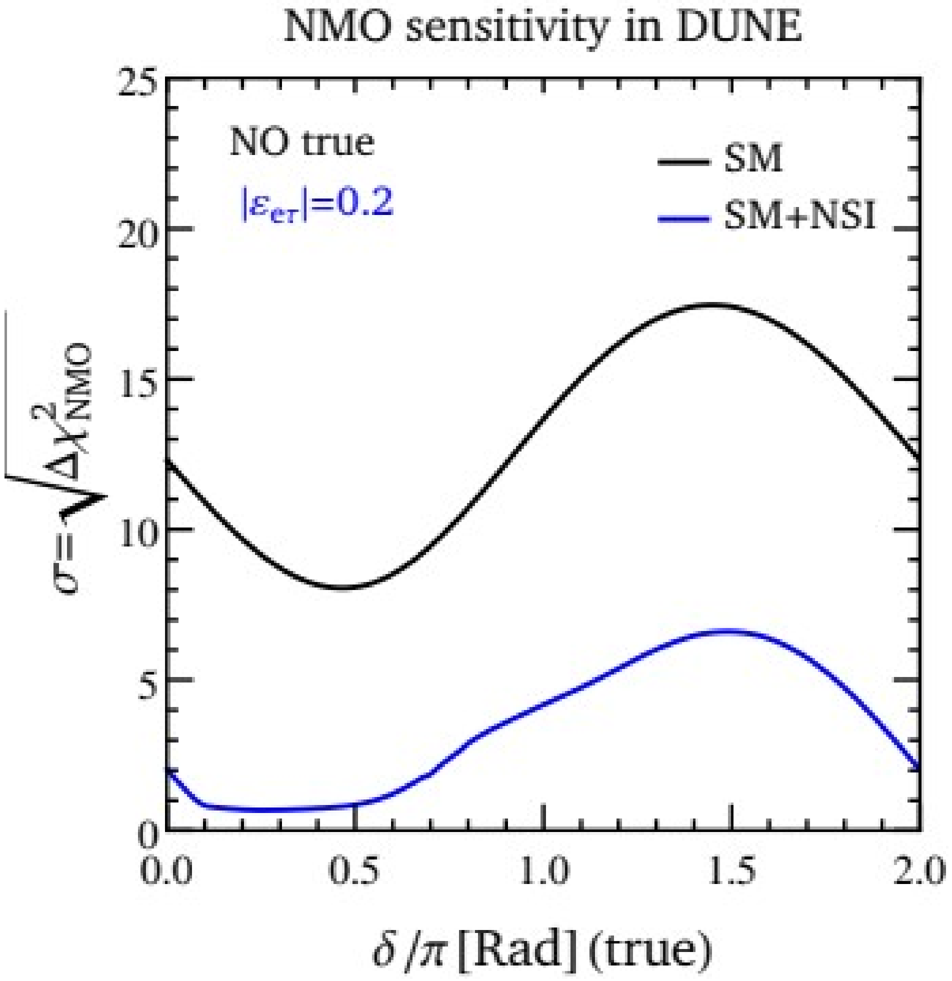
$$\nu_l + Ar \to l^- + K$$



Bievent plots for NO



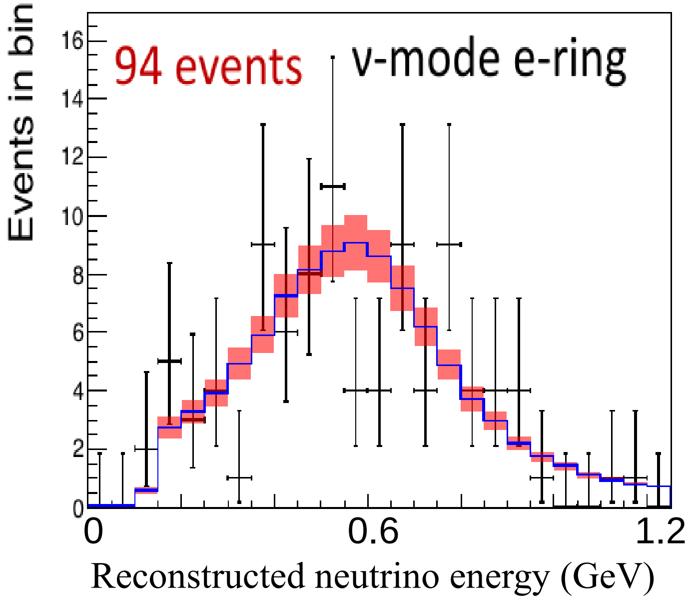
Bievent plots for IO

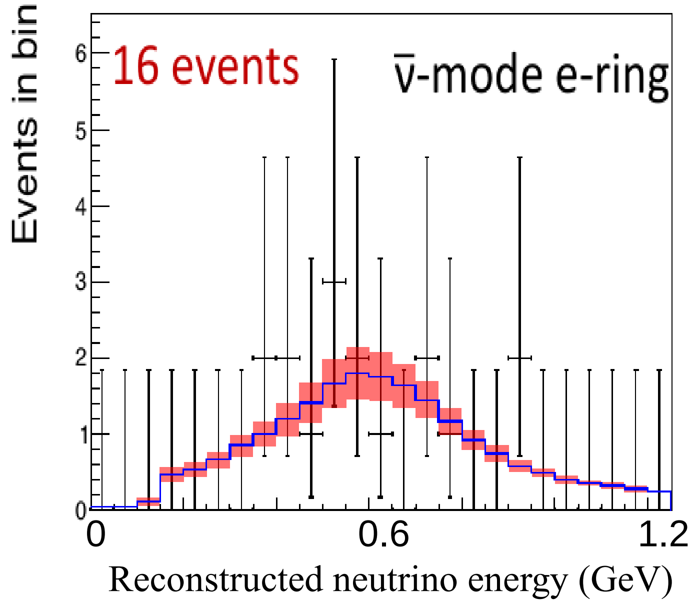


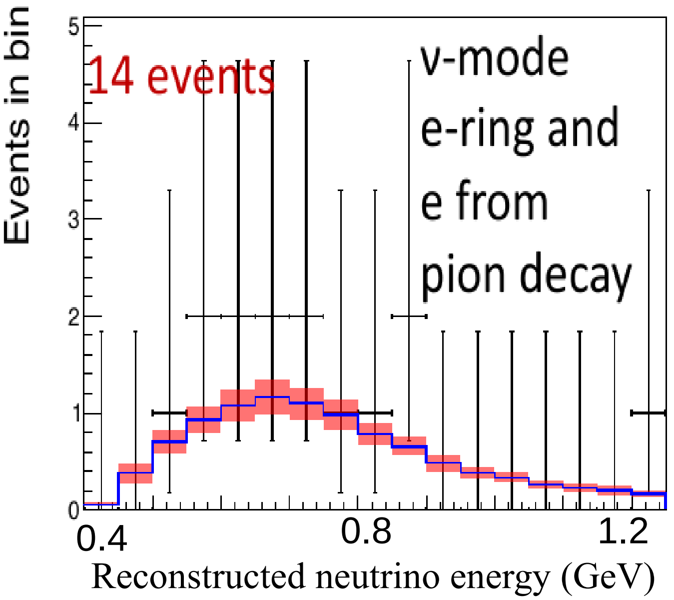
Mass hierarchy sensitivity might get highly impacted in presence of large NSI coupling in DUNE!

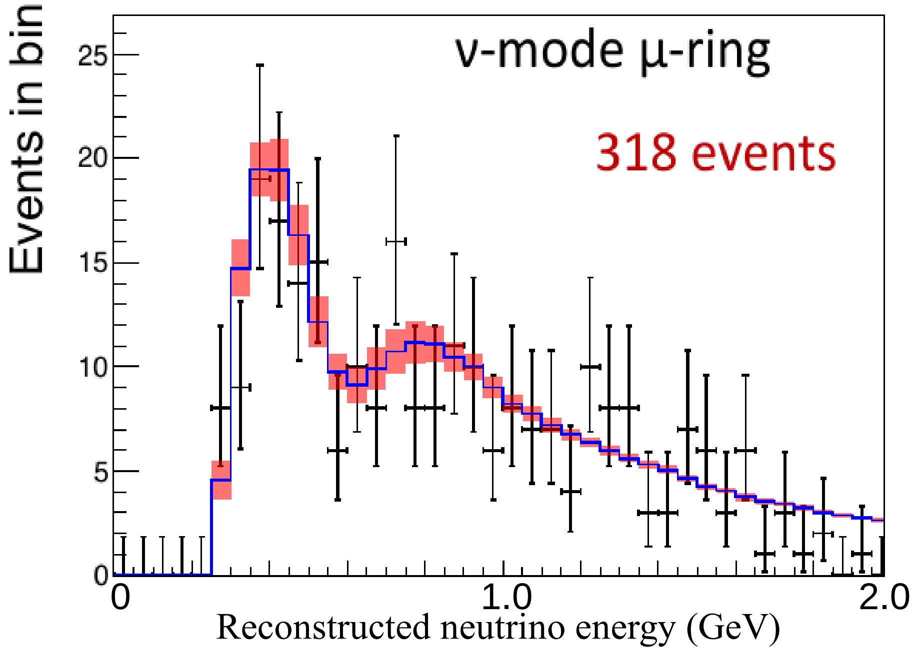
Phys.Rev.Lett. 124 (2020) 11, 111801 by F Capozzi, S S Chatterjee, & A Palazzo

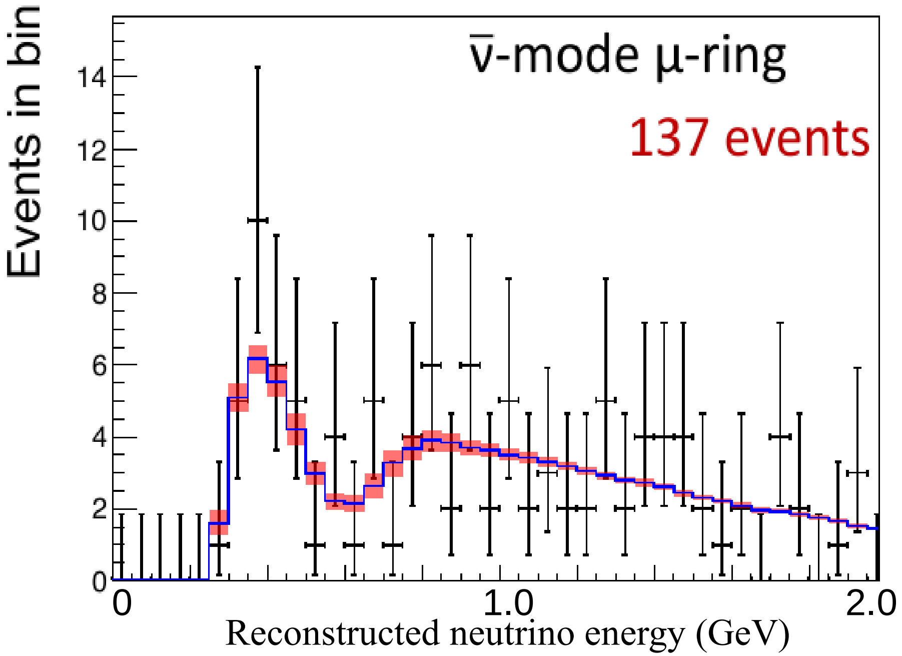
T2K Dataset





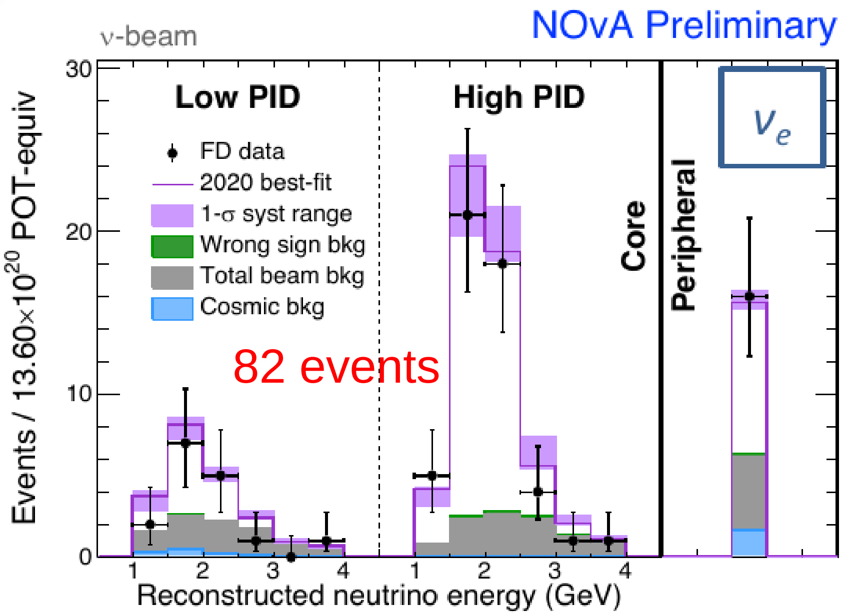


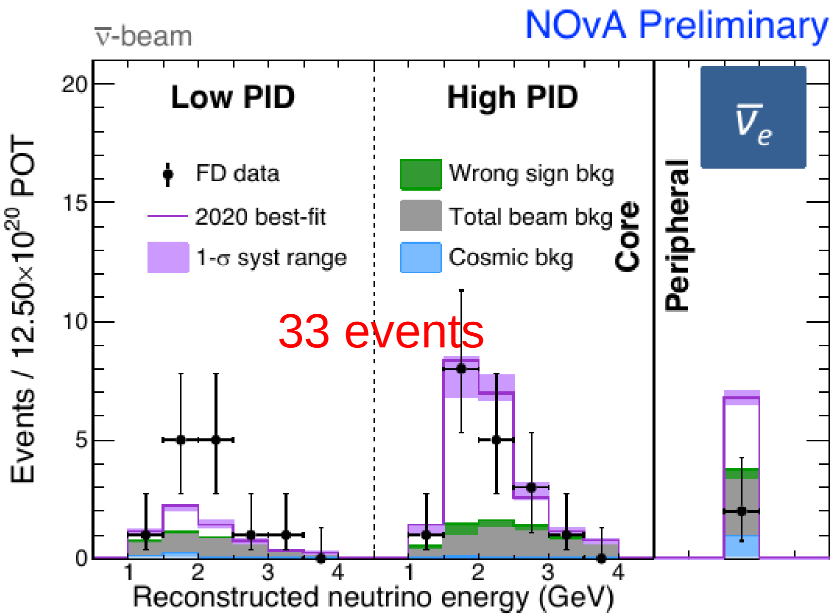


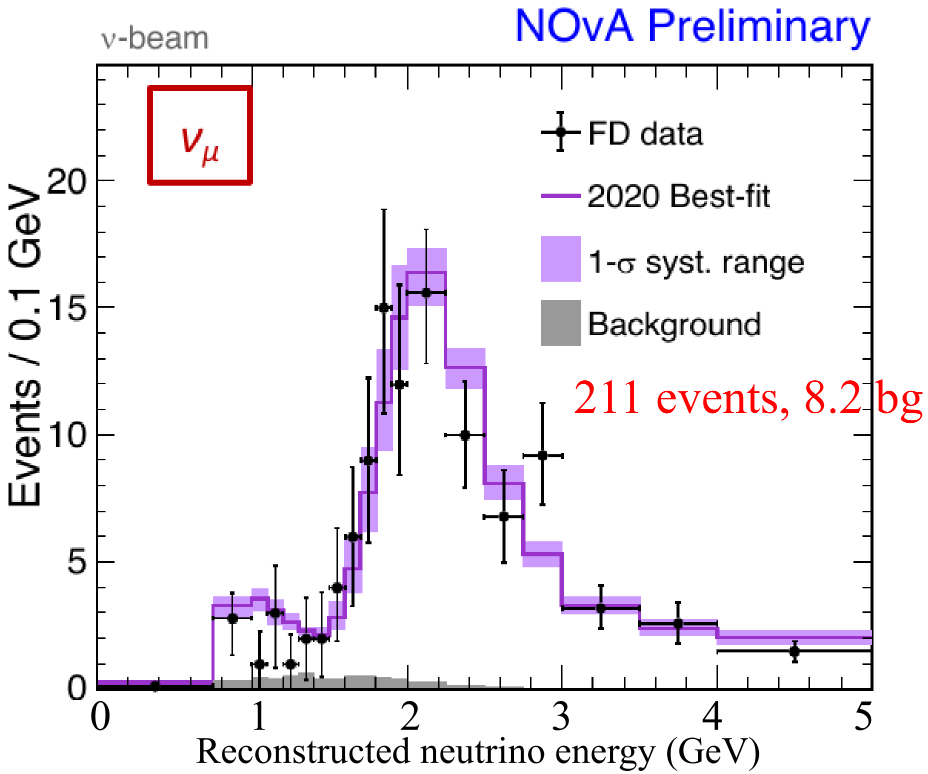


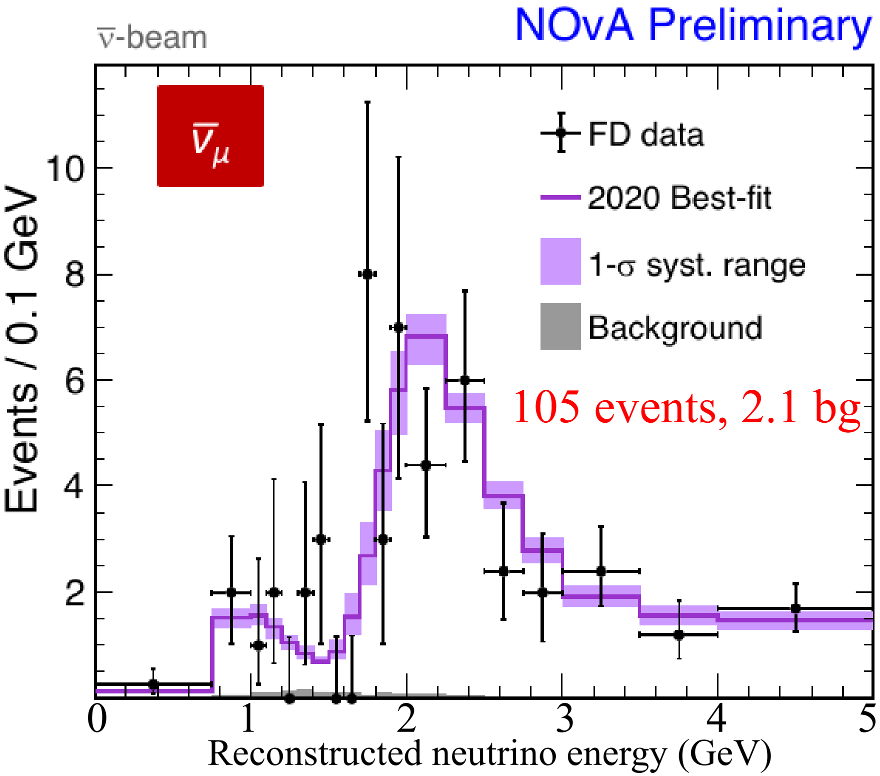
Talk by Patrick Dunne at Neutrino 2020 conference

NOvA Dataset


82 events


33 events


211 events, 8.2 bg


105 events, 2.1 bg

Talk by Alex Himmel at Neutrino 2020

Global constraints on neutral current NSI parameters

Oscillation + COHERENT data

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

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

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

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

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

JHEP 06 (2019) 055 by I. Esteban, M.C. Gonzalez-Garcia, & M. Maltoni

Inclusion of IceCube DeepCore data would definitely improve the bounds !