Neutrino non-standard interactions : a possible solution to the NOvA and T2K tension

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Based on

PRL 126, 051802 (ArXiv: 2008.04161) by S.S. Chatterjee, & A. Palazzo

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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 the atmospheric mixing angle (θ_{23}) is unknown. This also gives rise famous 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.

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

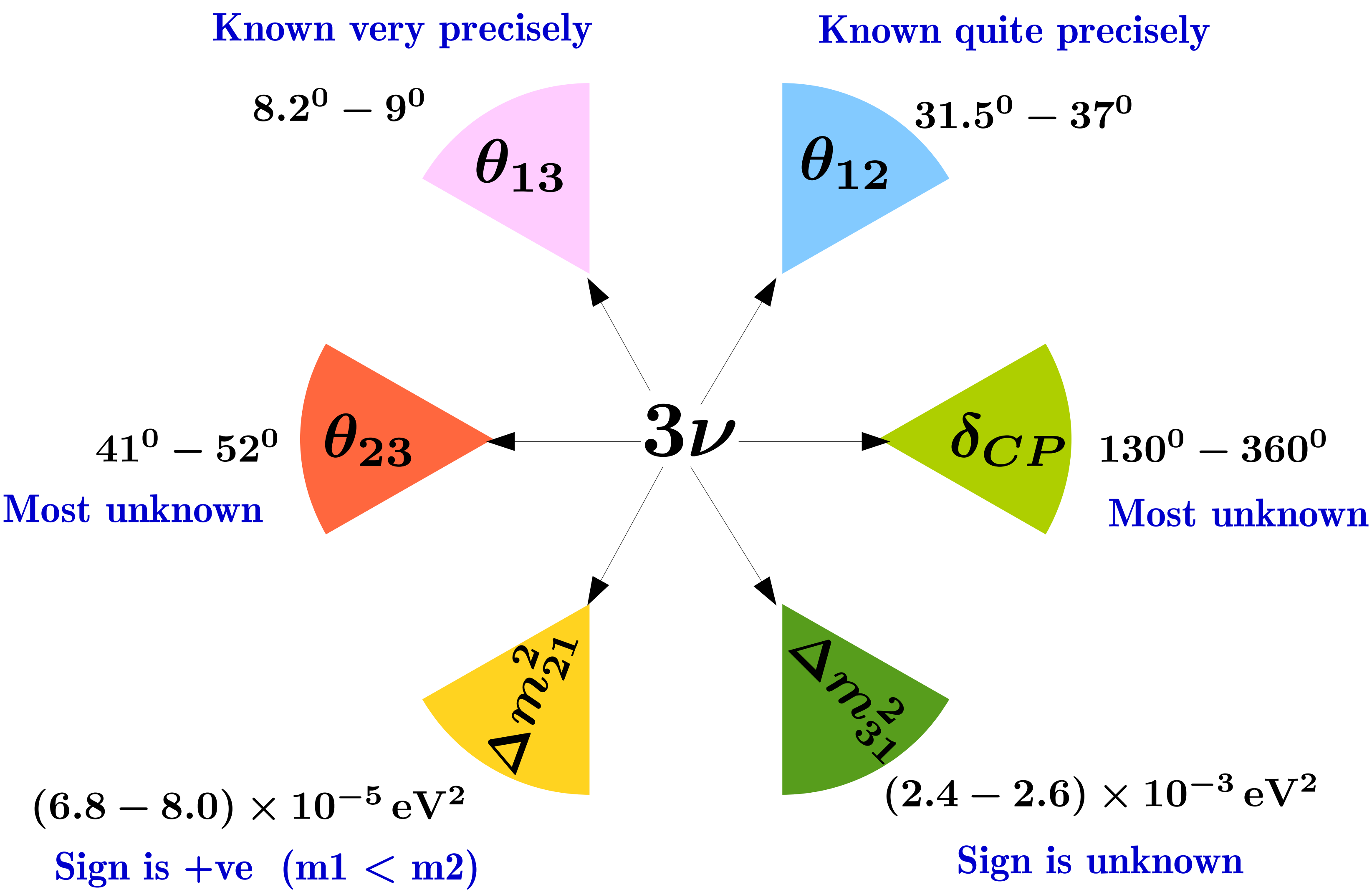
However the standard interpretation of that framework might not be the ultimate picture. There may exist many new physics scenarios for which we will need to invoke new interpreation on top of the standard interpreation.

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 tension.

See also **2008.01110** by P. B. Denton, J. Gehrlein, and R. Pestes

Current status of 3ν parameters (3σ uncertainties)



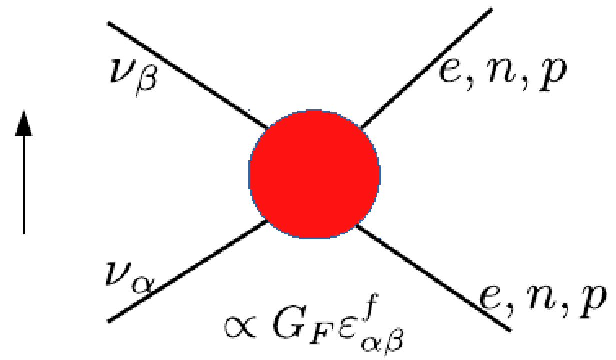
ArXiv: 2006.11237 by P. Salas et al., arXiv: 2007.14792 by Esteban et al., and arXiv: 2107.00532 by F. Capozzi et al.

NSI and its presence in the oscillation framework

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

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

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

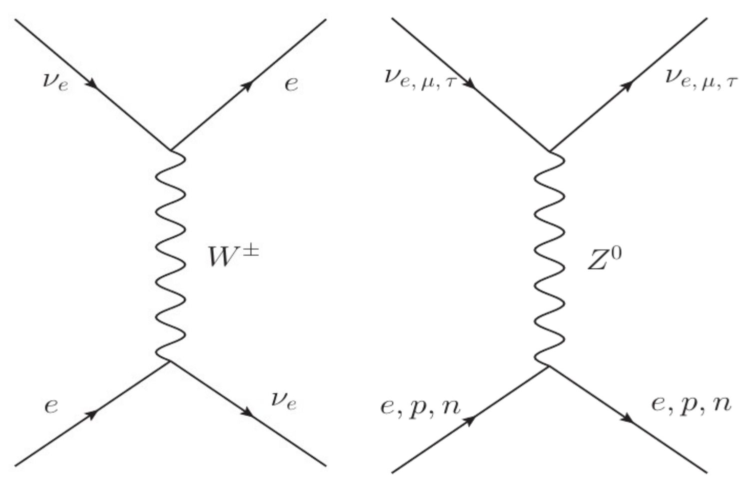


$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^{f}_{\alpha\beta} \frac{N_f}{N_e}$$

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)

Neutrino flavor eigenstates are related to the mass eigenstates as

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle ,$$

Where,

$$U = R(\theta_{23}) R(\theta_{13}, \delta_{\rm CP}) R(\theta_{12})$$

$$= \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{\rm CP}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{\rm CP}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{\rm CP}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{\rm CP}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{\rm CP}} & c_{23}\, c_{13} \end{pmatrix}$$

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

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \underbrace{\frac{1}{2E}\left[U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger\right]}_{\mathbf{H}_{vac}}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} \quad \text{...............(I)}$$

Similarly, in matter this is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \underbrace{\left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC}+V_{NC} & 0 & 0\\0 & +V_{NC} & 0\\0 & 0 & +V_{NC}\end{pmatrix}\right]}_{\mathbf{H}_{Mat}}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} \quad \text{...............(II)}$$

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

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

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

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

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

Where,

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

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

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

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

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

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

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

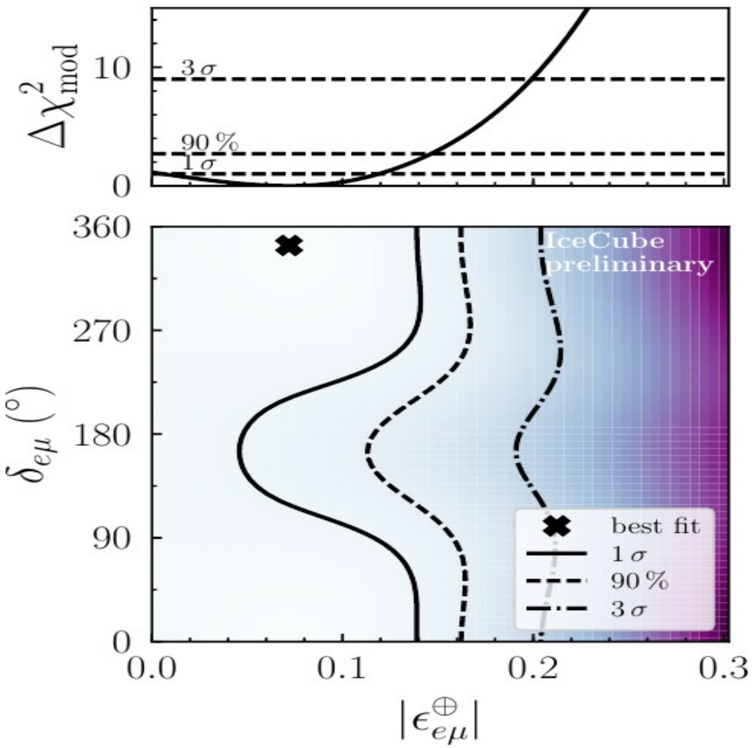
NSI (e-μ) *sector*

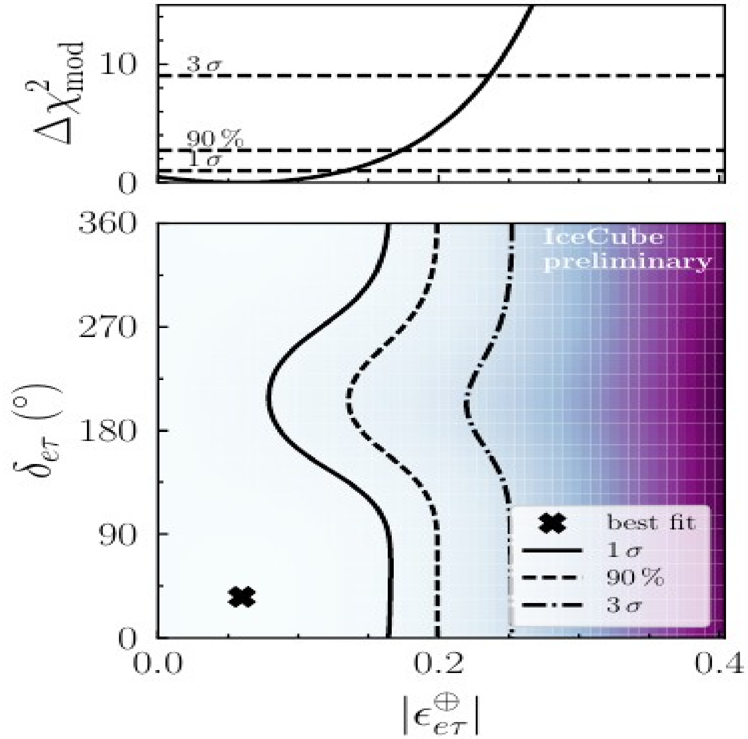
$$P_0 \simeq 4 s_{13}^2 s_{23}^2 f^2$$
$$P_1 \simeq 8 s_{13} s_{12} c_{12} s_{23} c_{23} \alpha f g \cos(\Delta + \delta)$$
$$P_2 \simeq 8 s_{13} s_{23} v |\varepsilon_{e\mu}| [s_{23}^2 f^2 \cos(\delta + \phi_{e\mu}) + c_{23}^2 f g \cos(\Delta + \delta + \phi_{e\mu})]$$

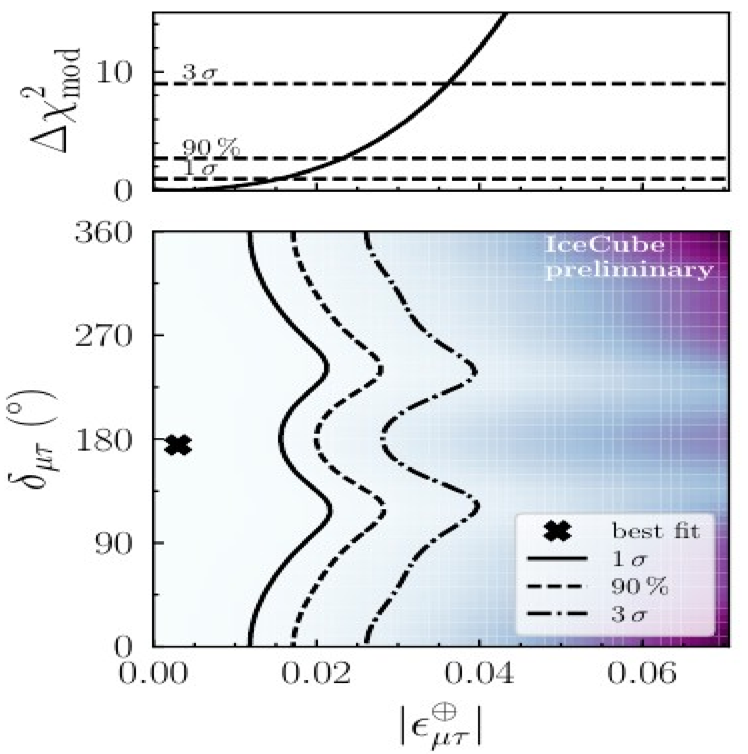
NSI (e-τ) *sector*

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

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







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

$$|\epsilon_{e\mu}^{\oplus}| \leq 0.15$$

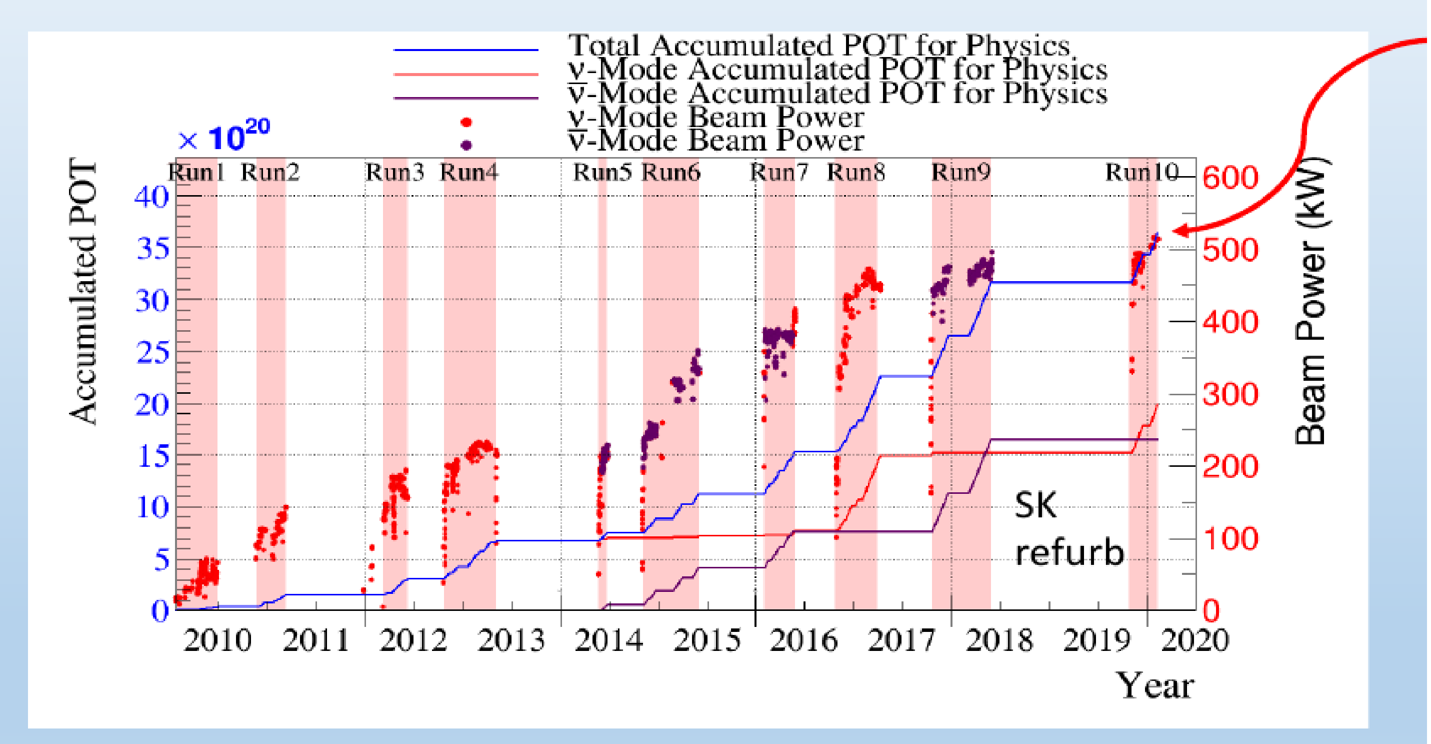
$$|\epsilon_{e\tau}^{\oplus}| \leq 0.17$$

$$|\epsilon_{\mu\tau}^{\oplus}| \leq 0.023$$

See the talk by T. Ehrhardt presesented at PPNT, Uppsala (2019)
For more details please see ArXiv: 2106.07755

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

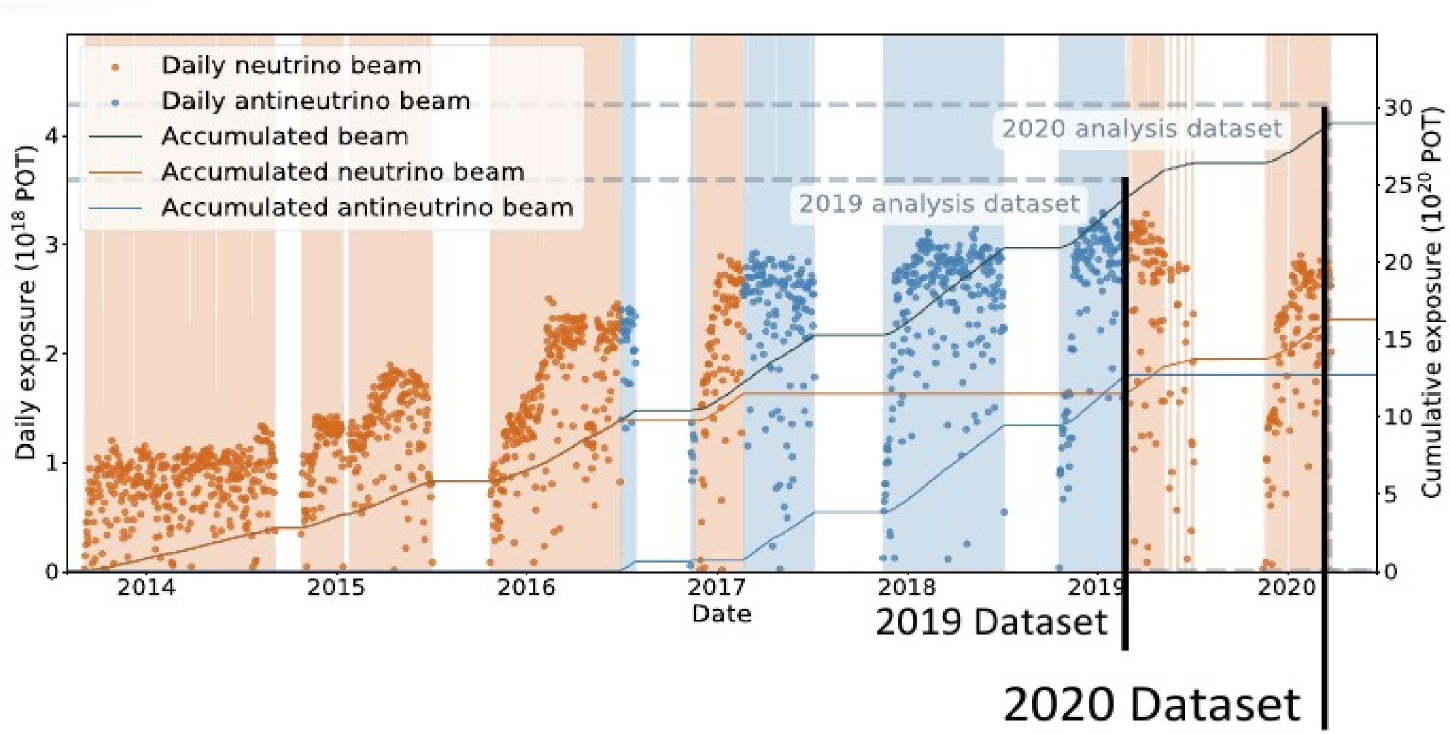
$$\nu \ : \ 1.97 \times 10^{21} \ \ \text{POT}$$

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

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



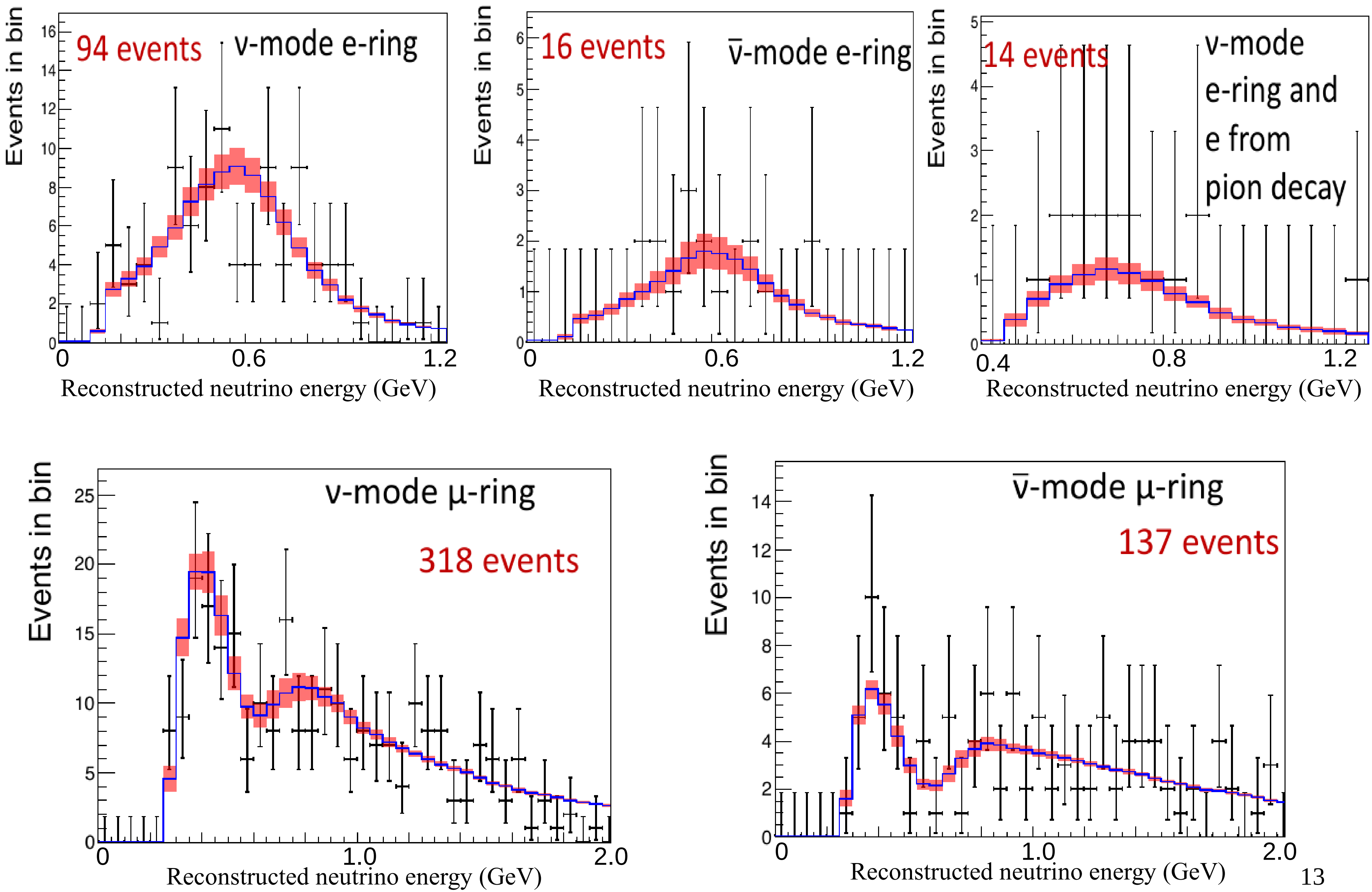
Beam Power

Typically ~ 700 kW

$$\nu \ : \ 1.6 \times 10^{21} \ \ \text{POT}$$

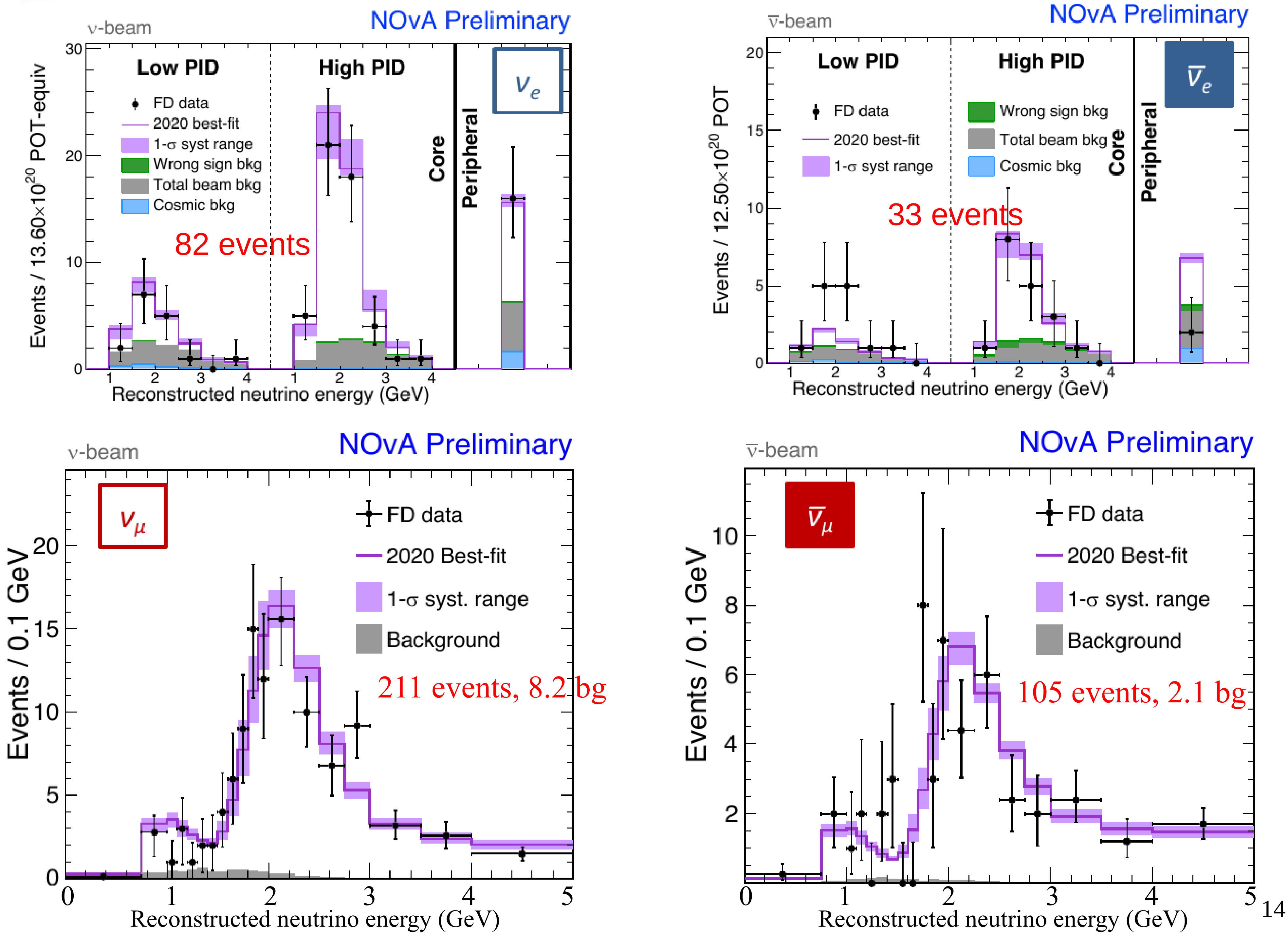
$$\bar{\nu} \ : \ 1.3 \times 10^{21} \ \ \text{POT}$$

T2K Dataset



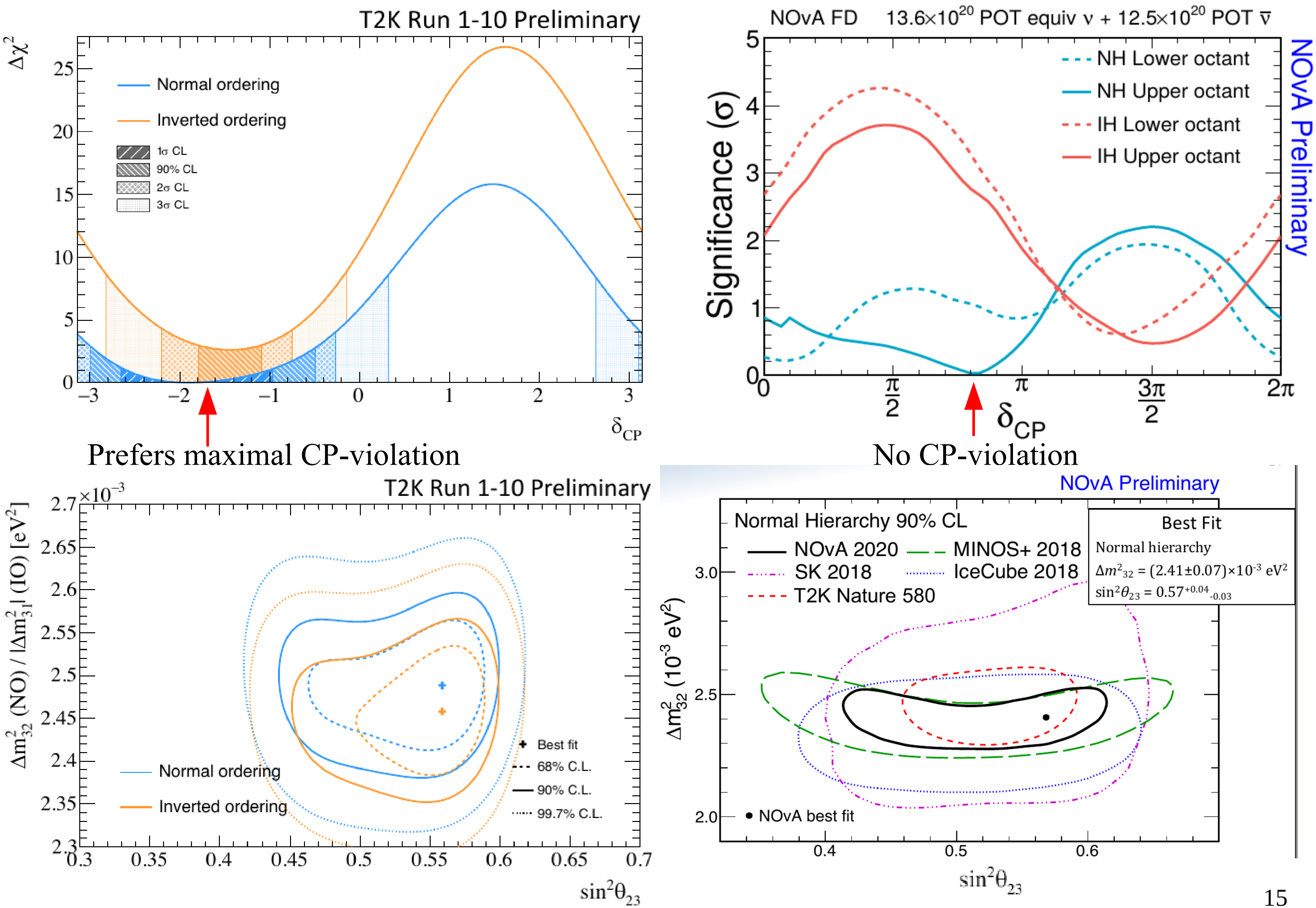
Talk by Patrick Dunne at Neutrino 2020 conference

NOvA Dataset



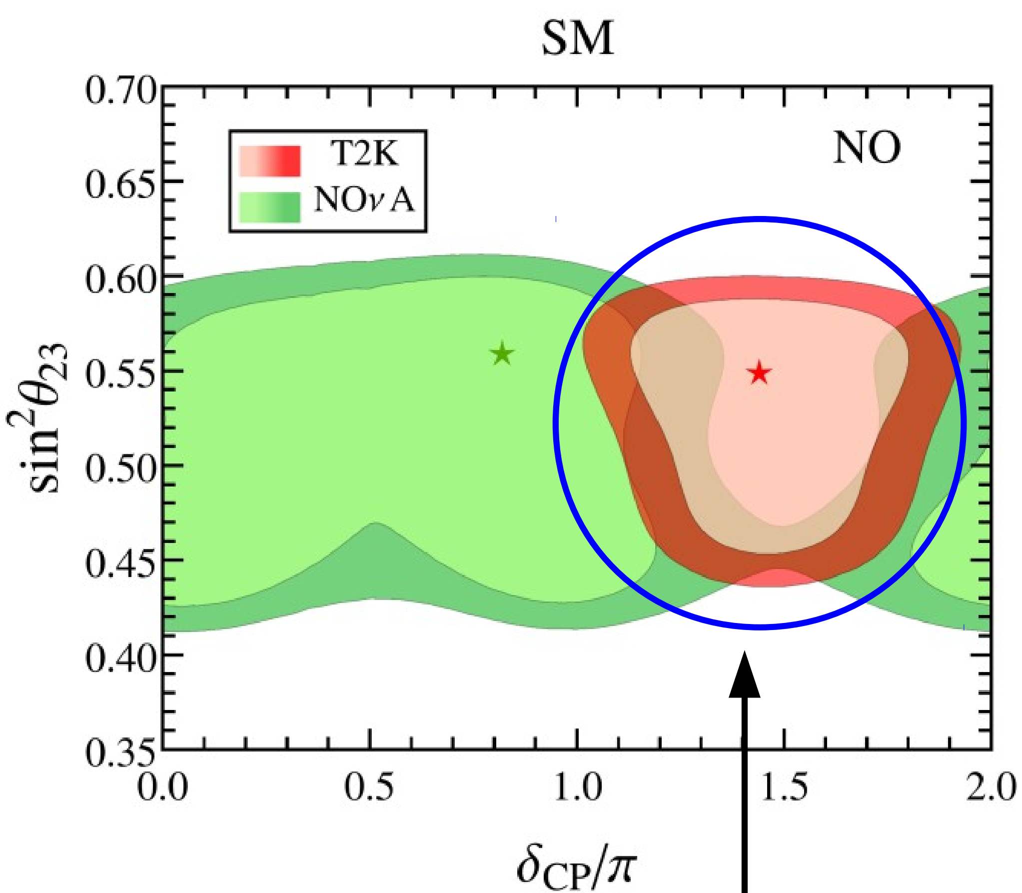
Please see the talk by Alex Himmel at Neutrino 2020

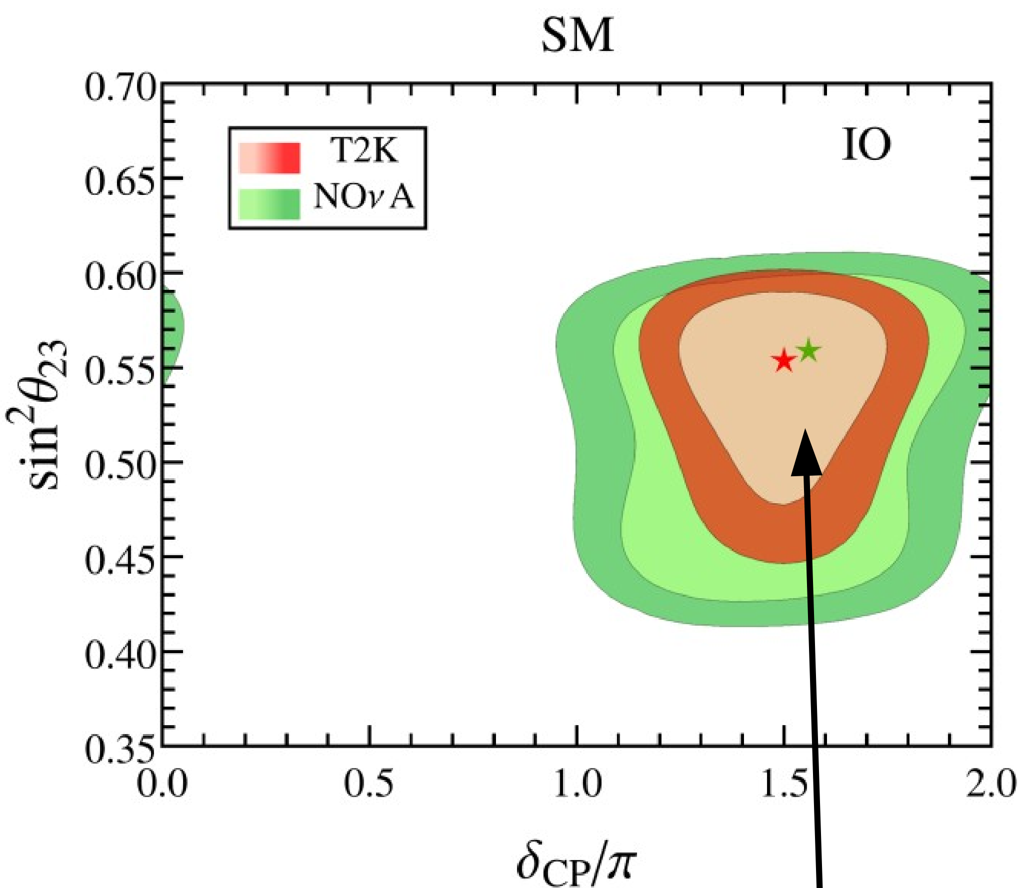
Results from the Collaborations



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

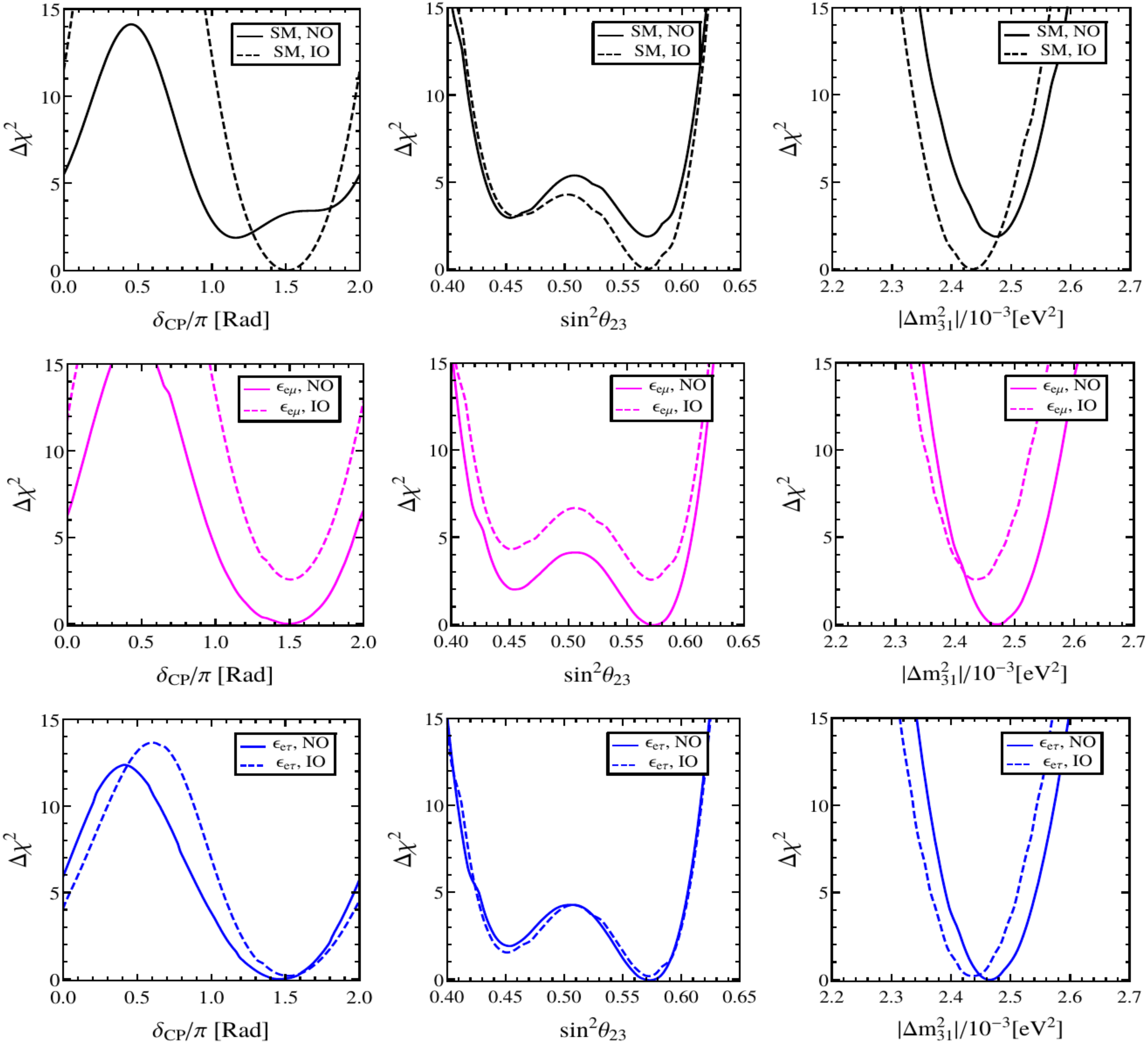
68% and 90% C.L. contours at 2 d.o.f





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

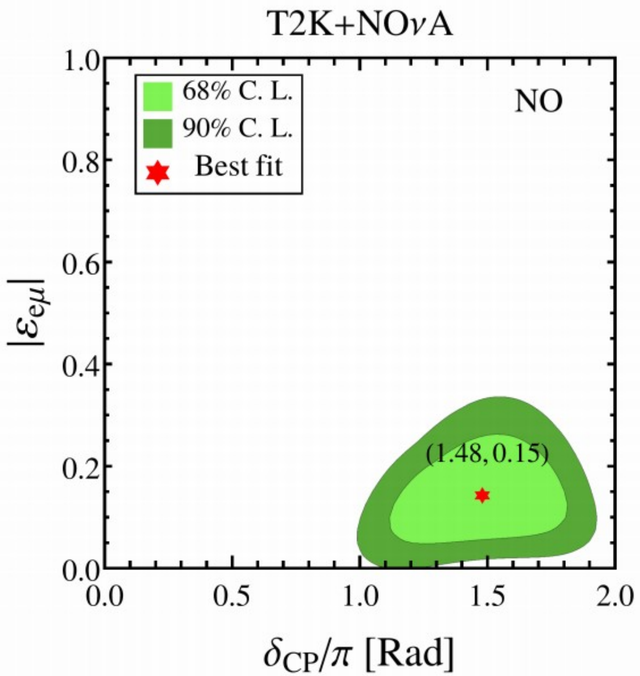
No discrepancy

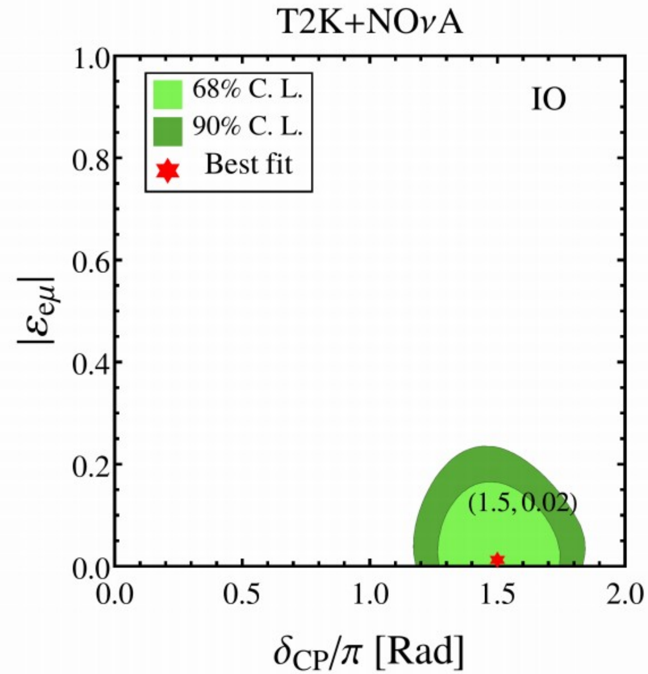


IO is preferred over NO in standard oscillation

However NO is preferred over IO in Presence of NSI

Combined analysis of T2K and NOvA





Allowed regions of NSI parameters

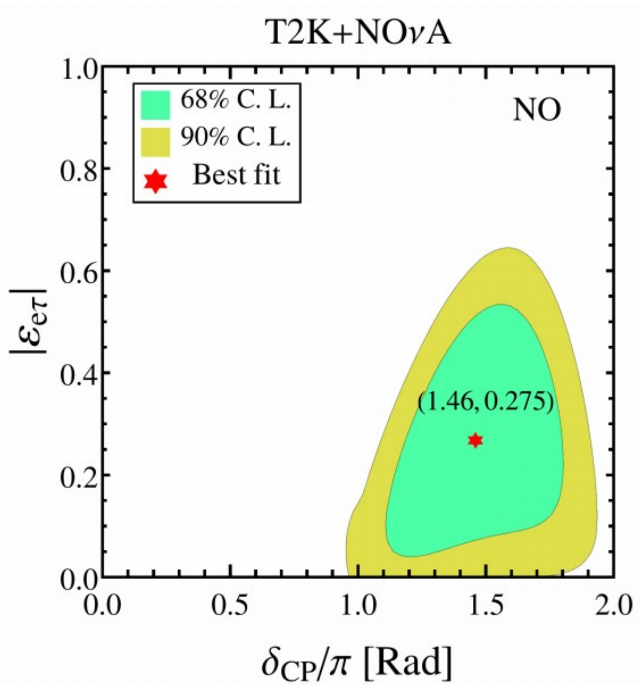
$$\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm SM+NSI}$$

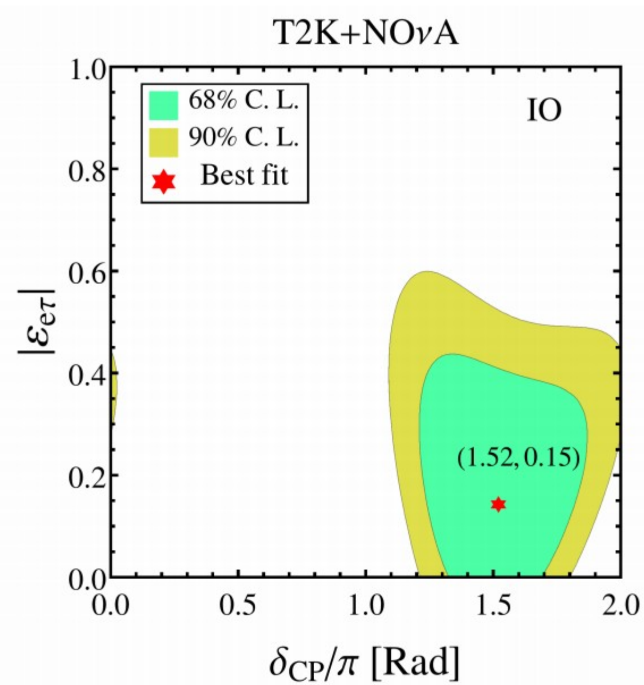
NMO	NSI	$\lvert\varepsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	$\delta_{\rm CP}/\pi$	$\Delta\chi^2$
NO	$\varepsilon_{e\mu}$	0.15	1.38	1.48	4.50
	$\varepsilon_{e\tau}$	0.27	1.62	1.46	3.75
IO	$\varepsilon_{e\mu}$	0.02	0.96	1.50	0.07
	$\varepsilon_{e\tau}$	0.15	1.58	1.52	1.01

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

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

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





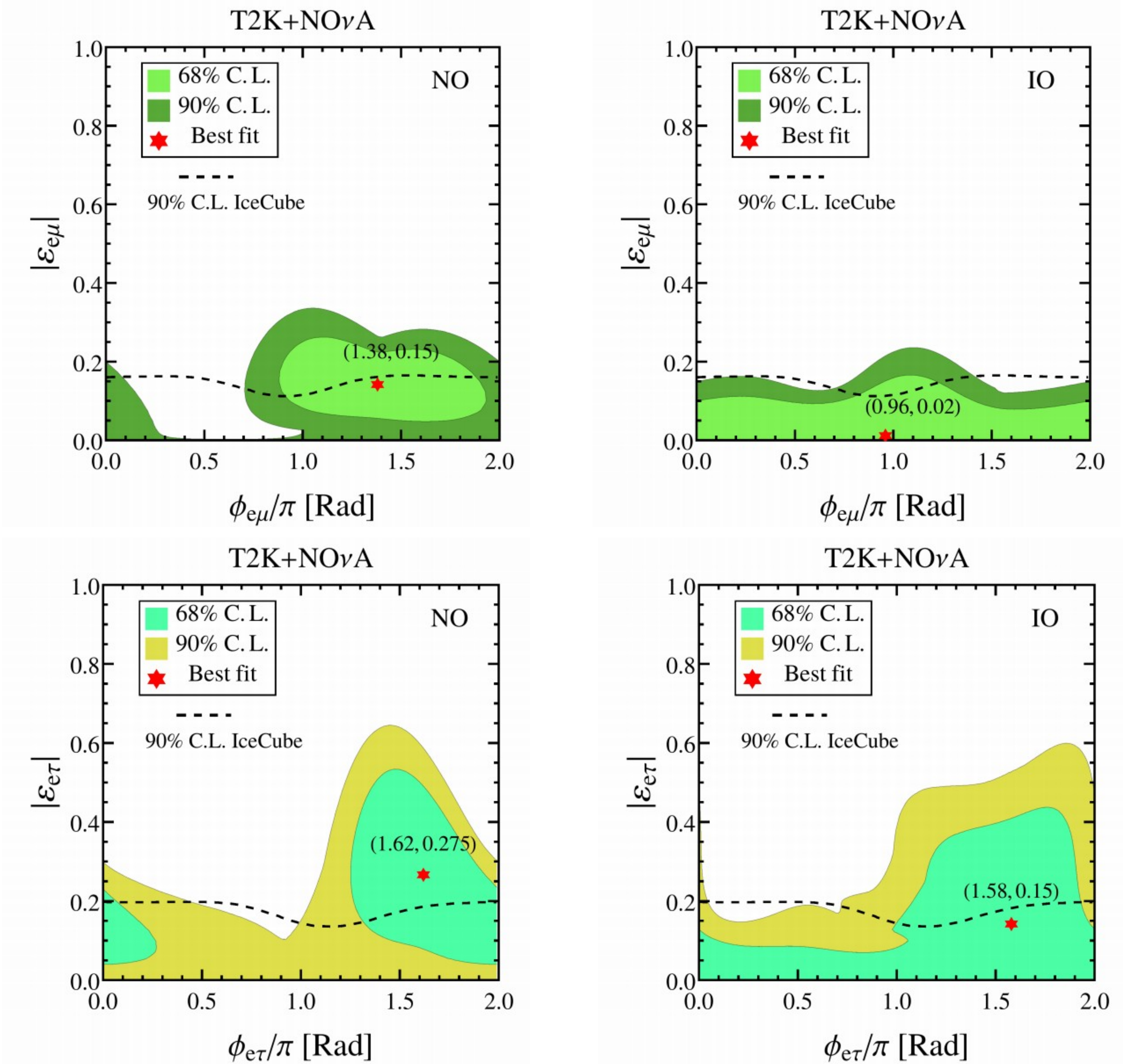
$$\chi^2_{\rm e\mu,NO} - \chi^2_{\rm SM,IO} = -2.63$$

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

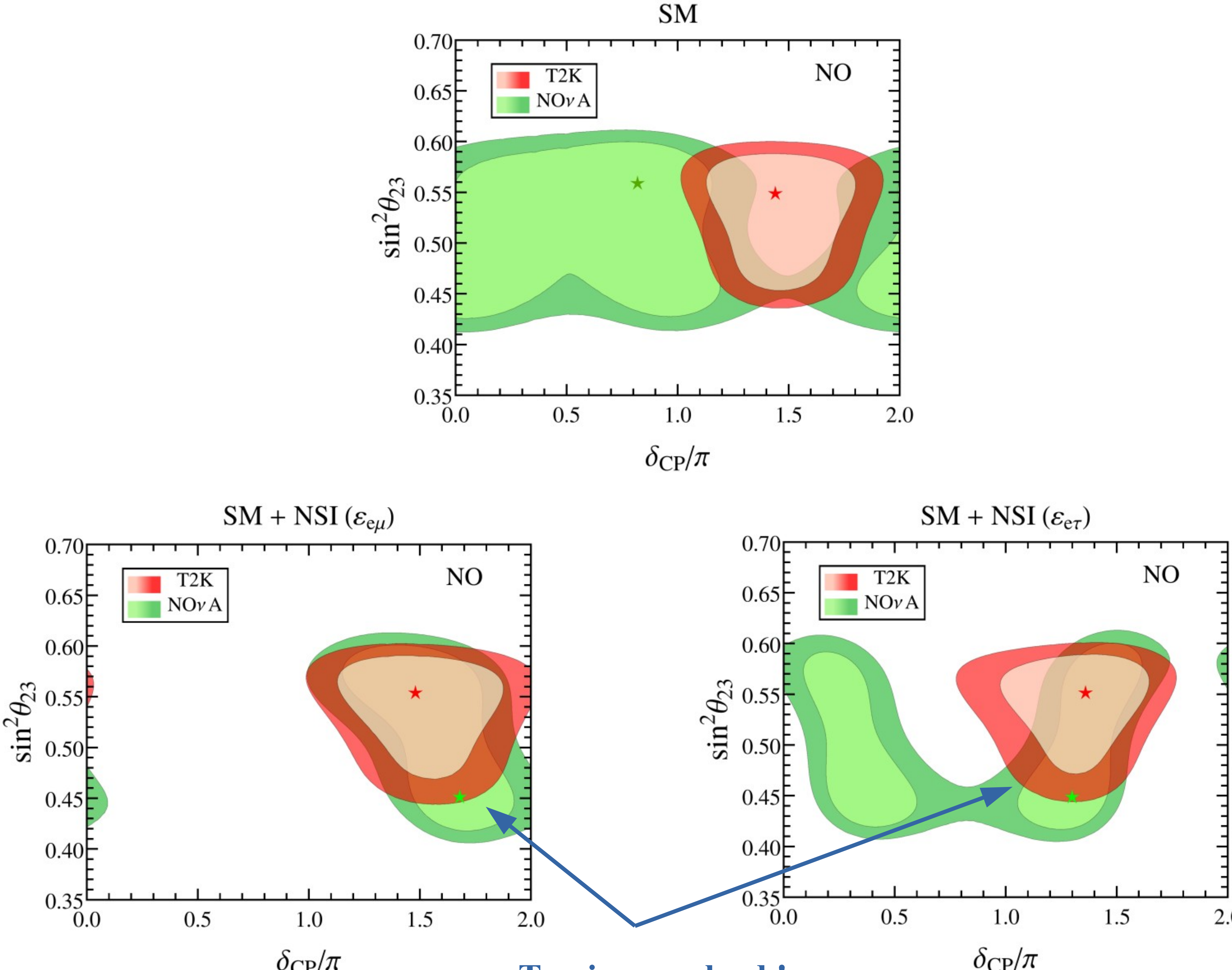
$$\chi^2_{\rm e\tau,NO} - \chi^2_{\rm SM,IO} = -1.21$$

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

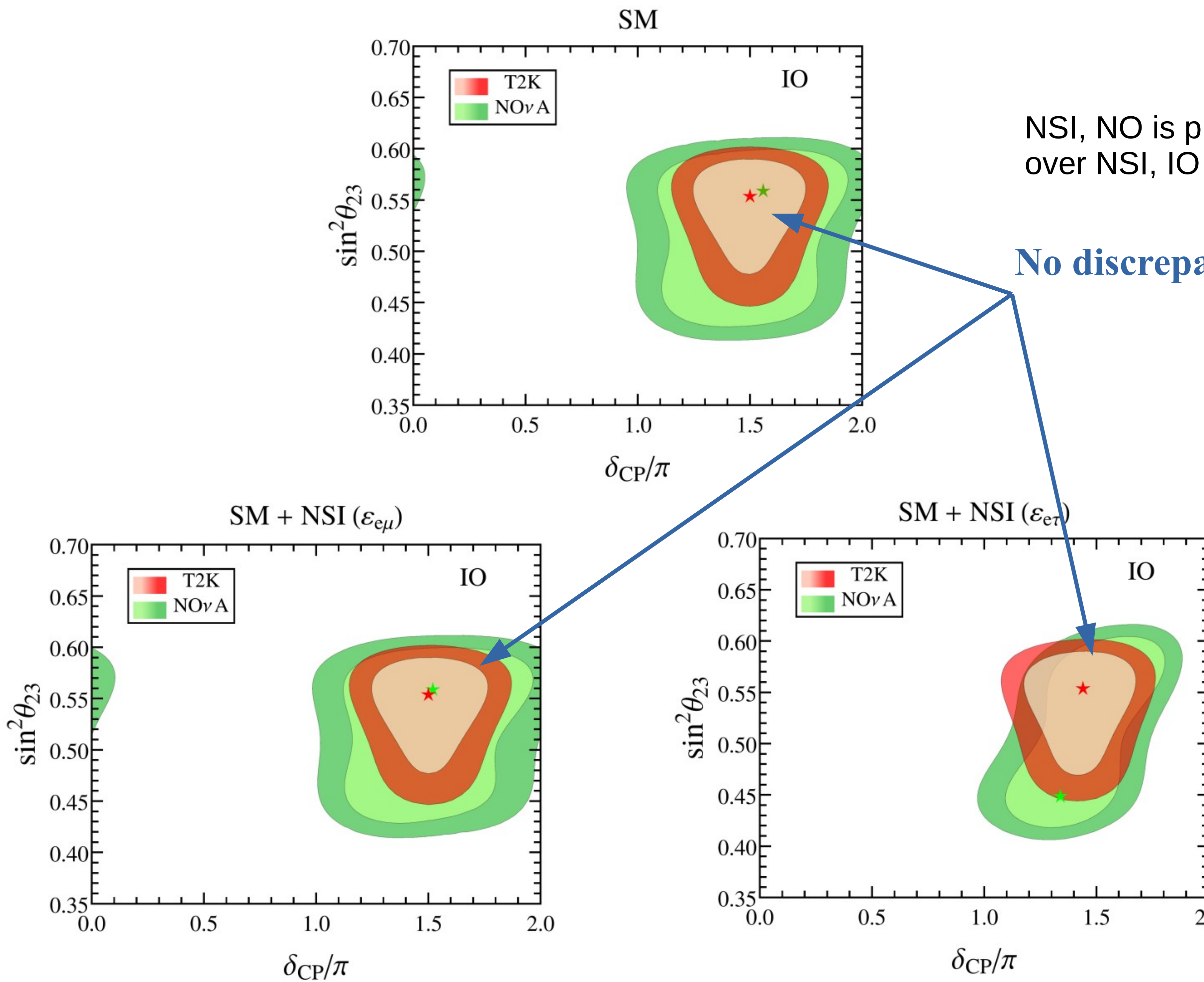
NSI with e-mu sector (NO) is better preferred over e-tau sector (NO) !



IceCube bounds are compatible !



Tension resolved !



NSI, NO is preferred over NSI, IO

No discrepancy !

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

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 $\varepsilon_{e\tau}$

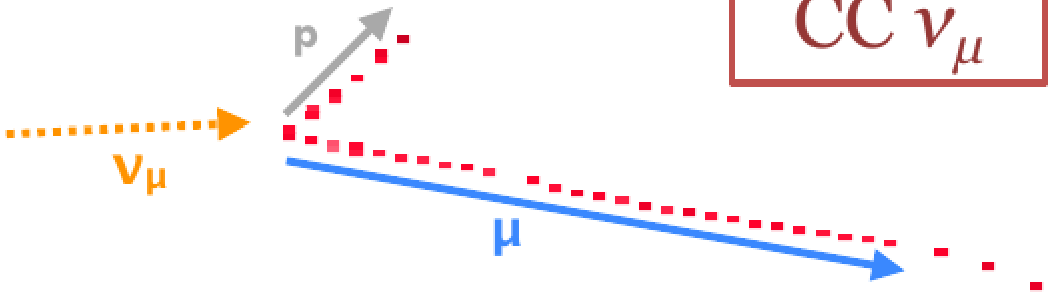
- Our result also shows that the NO is preferred over IO in presence of NSI, also $\varepsilon_{e\mu}$ is preferred slightly more than $\varepsilon_{e\tau}$

- 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 will help resolving this ambiguity.

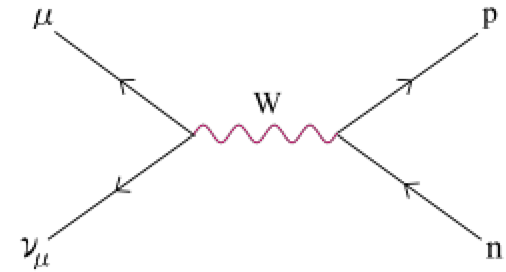
- Our work also evidences the importance of JUNO like experiment to determine NMO unambigiously, irrespective of the presence of NSI.

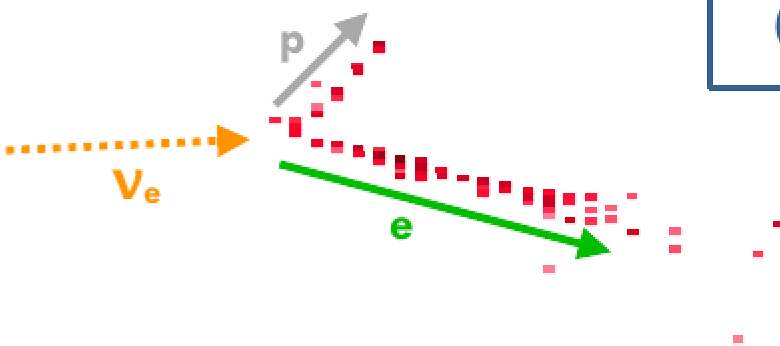
- **Might be a hint of Physics Beyond the Standard Model !**

Thank you!

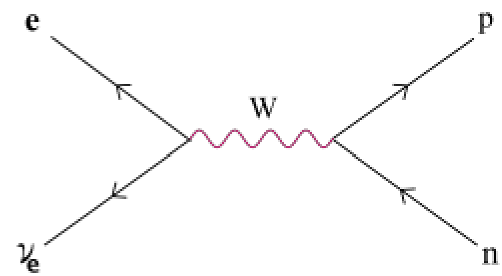


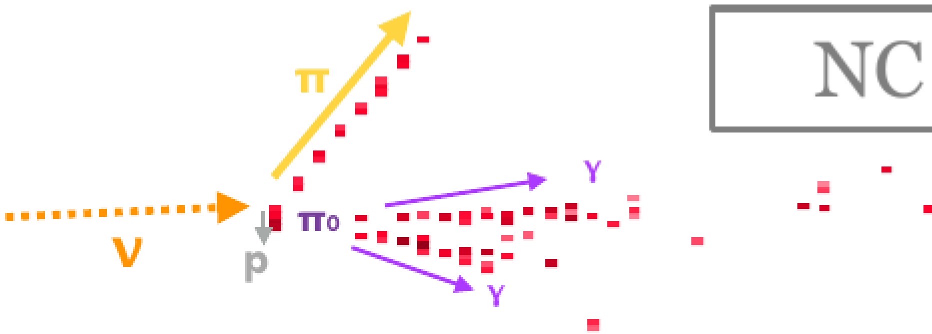
CC ν_μ



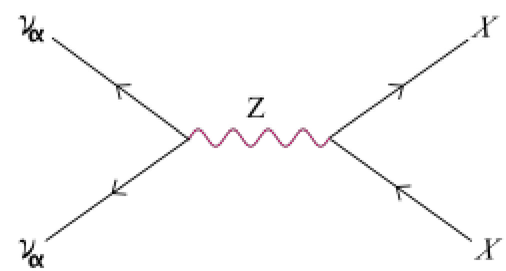


CC ν_e





NC



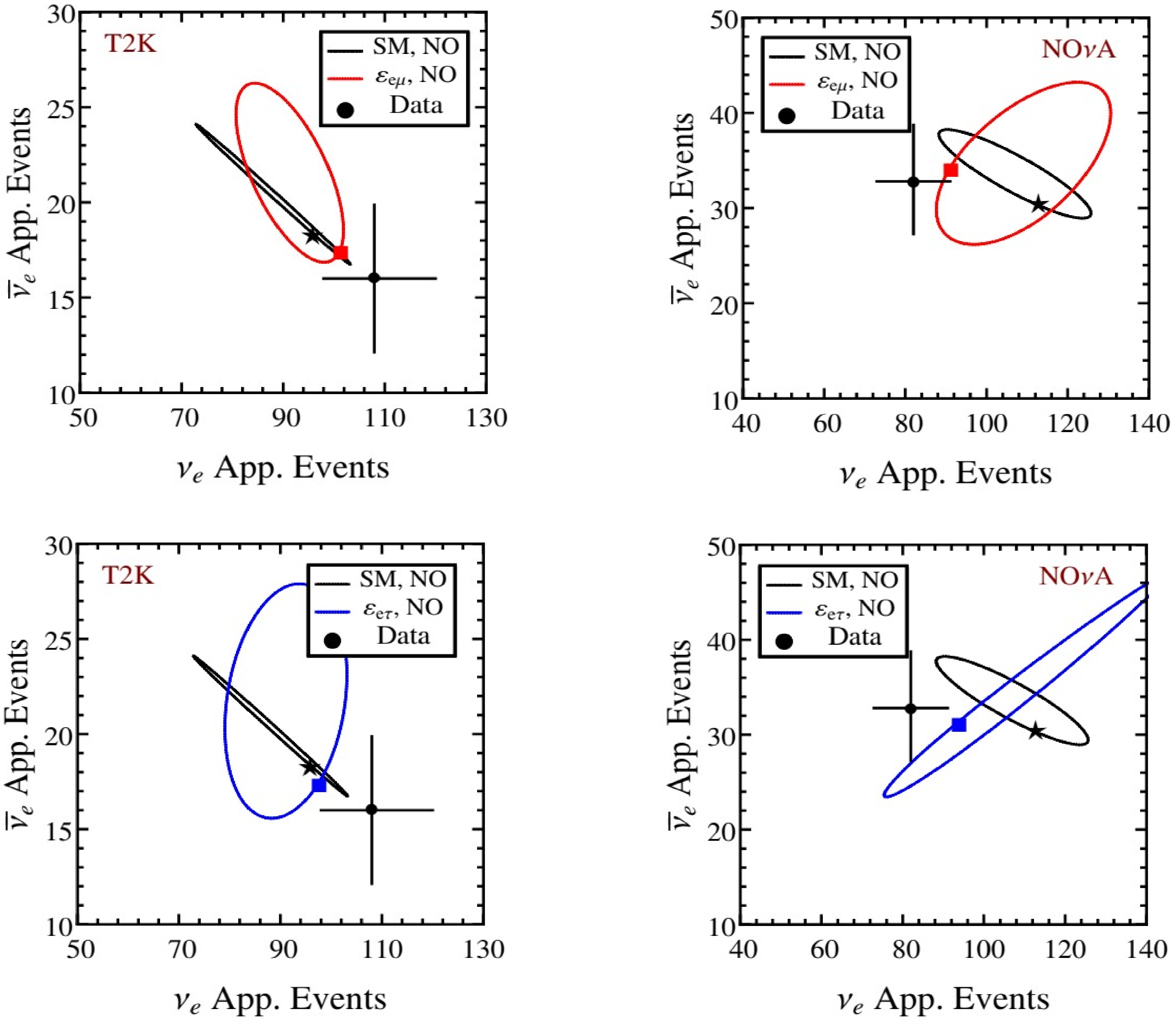
$\alpha = e,\ \mu,\ \tau$

For antineutrinos (inverse beta-decay)

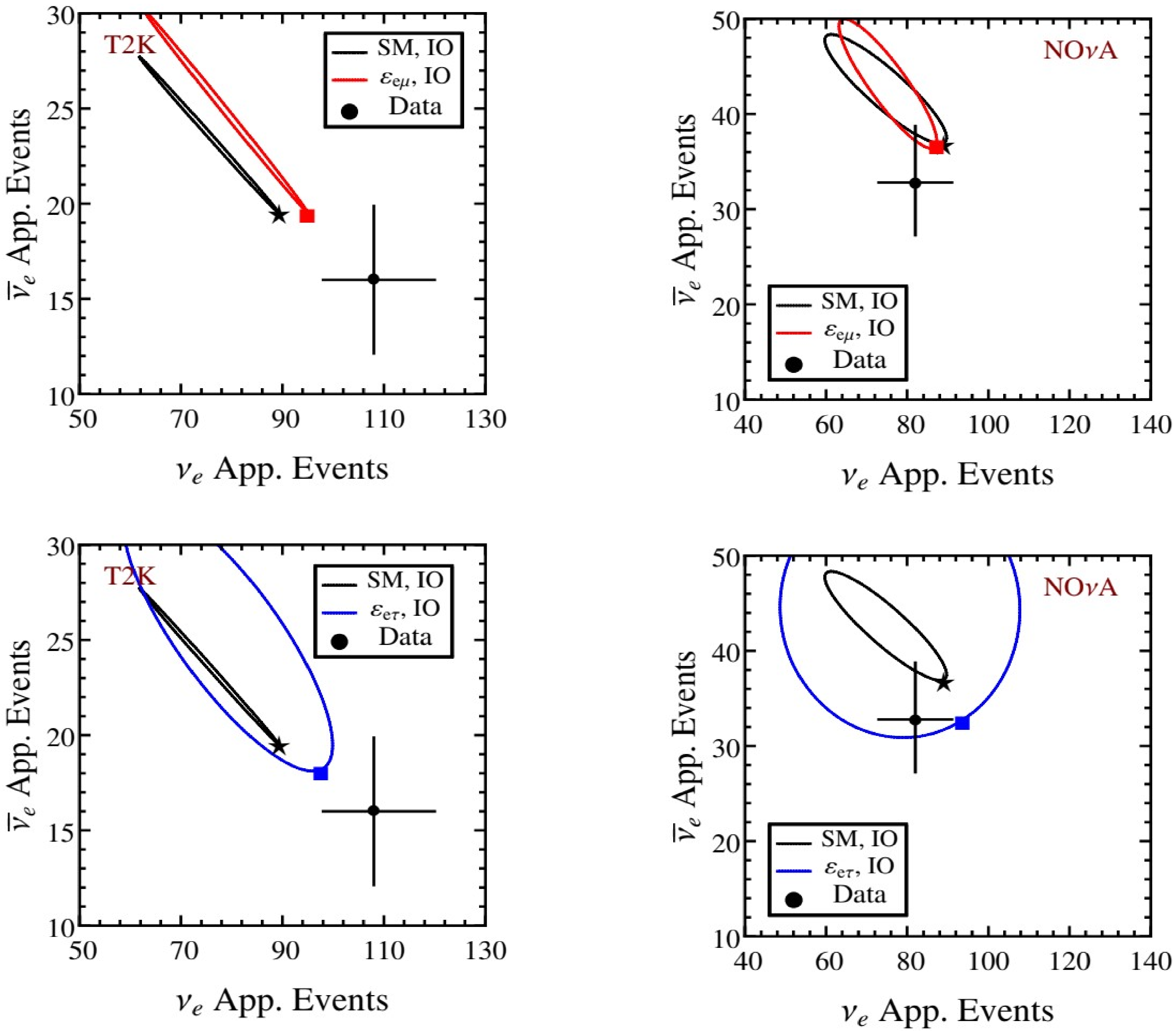
$$\bar{\nu}_l + p \to l^+ + n$$

In Liquid Ar detector

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



Bievent plots for NO



Bievent plots for IO