NSI in combination of long-baseline experiments

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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 not known precisely. This also gives rise famous octant ambiguity.

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

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

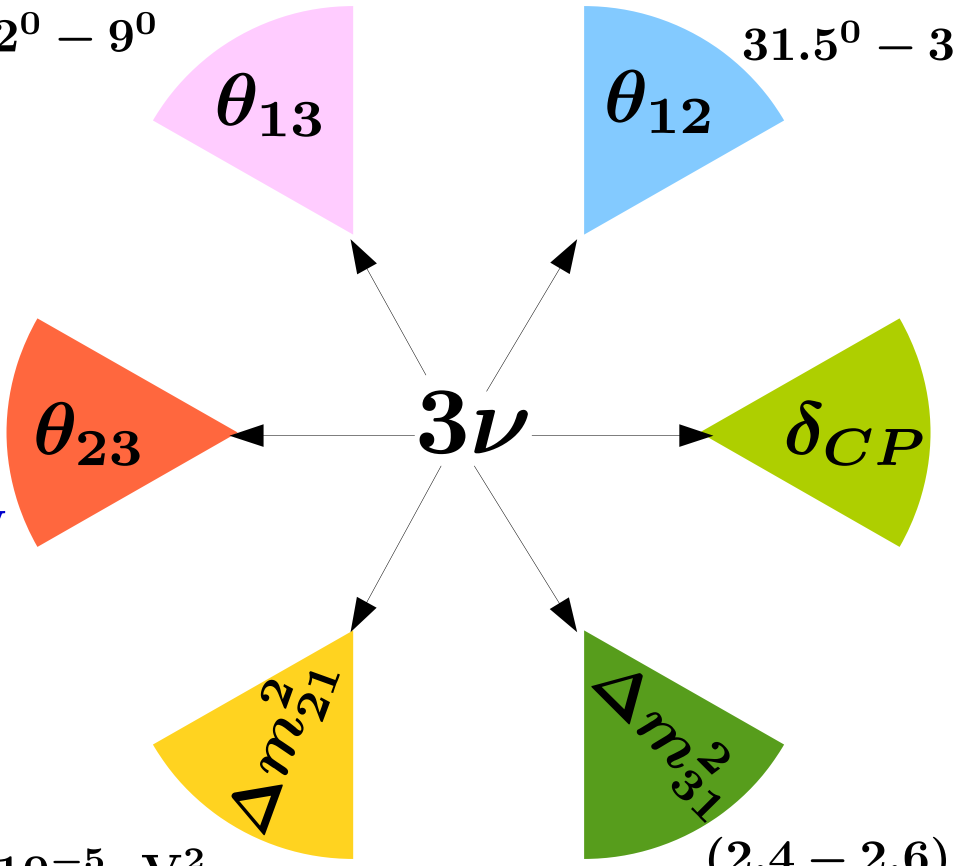
However the standard interpretation of that framework might not be the ultimate picture. There may exist many new physics scenarios for which we will need to invoke new interpretation on top of the standard interpretation.

New Physics ?

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

One of the most popular new physics scenarios is the **non-standard interactions of neutrinos (NSI),** which is the main focus of this talk.

Current status of 3ν parameters (3σ bound)



Known very precisely

$\mathbf{8.2^0 - 9^0}$

$\boldsymbol{\theta_{13}}$

Known quite precisely

$\boldsymbol{\theta_{12}}$

$\mathbf{31.5^0 - 37^0}$

$\mathbf{41^0 - 52^0}$

$\boldsymbol{\theta_{23}}$

Not known precisely

$\boldsymbol{3\nu}$

$\boldsymbol{\delta_{CP}}$

$\mathbf{130^0 - 360^0}$

Not known precisely

$\boldsymbol{\Delta m^2_{21}}$

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

Sign is +ve (m1 < m2)

$\boldsymbol{\Delta m^2_{31}}$

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

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.

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.

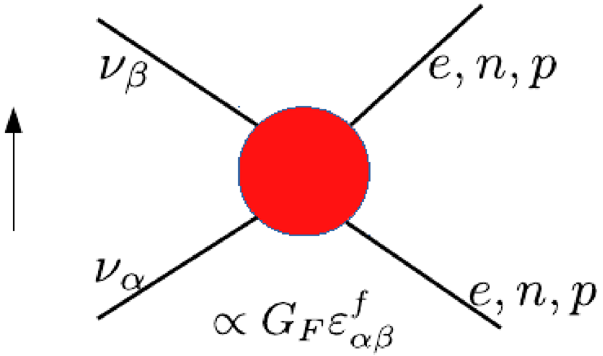
L. Wolfenstein
Phys. Rev. D 17, 2369

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,

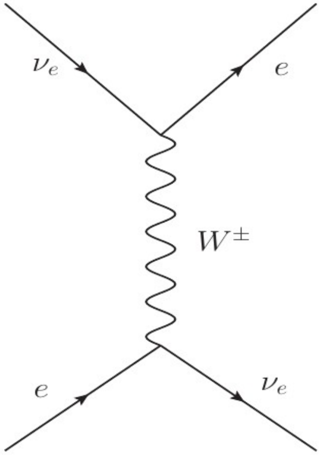
$$-\mathcal{L}_{NSI} = \frac{G_F}{\sqrt{2}} \sum_{\alpha,\beta,f} \varepsilon^f_{\alpha\beta} \left[\bar{\nu}_\alpha \gamma^\mu \left(1-\gamma^5\right) \nu_\beta\right] \left[\bar{f} \gamma_\mu \left(1 \pm \gamma^5\right) f\right]$$

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

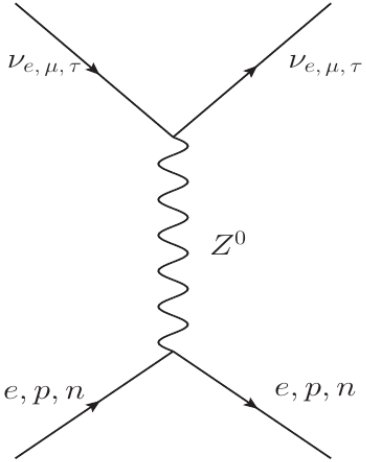


$$\varepsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \varepsilon^f_{\alpha\beta} \frac{N_f}{N_e}$$

N is the number density of fermions



CC-interaction



NC-interaction

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

→ Strength of NSIs

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,

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

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

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

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

Similarly, in matter this is given by

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

$\mathrm{V}_{CC} = \sqrt{2}\,G_F\,N_e$ **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

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

……………..(III)

Where,

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

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

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*

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

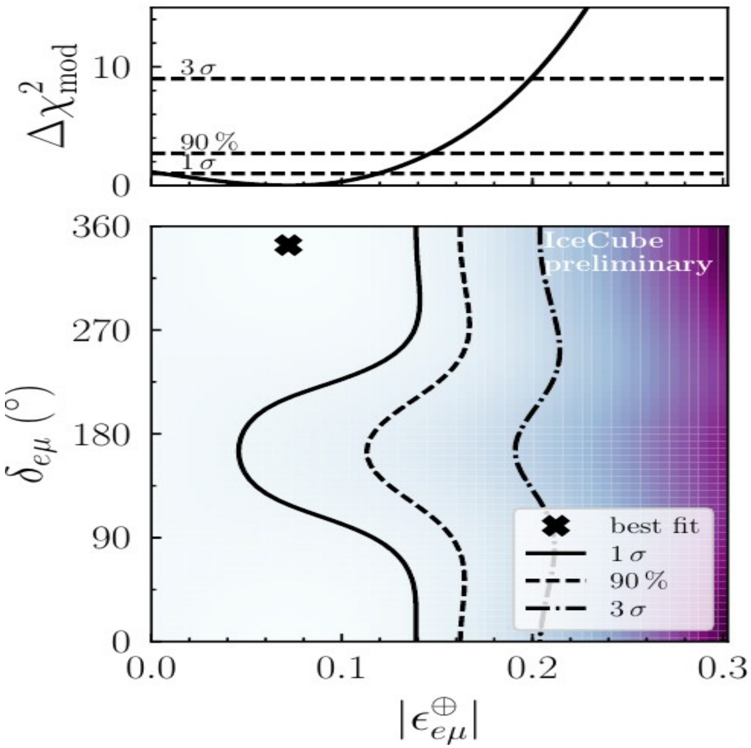
$$\Delta = \frac{\Delta m_{31}^2 L}{4E}, \qquad f \equiv \frac{\sin[(1-v)\Delta]}{1-v}, \qquad g \equiv \frac{\sin v\Delta}{v}, \qquad |v| = \left| \frac{2 V_{\mathrm{CC}} E}{\Delta m_{31}^2} \right|$$

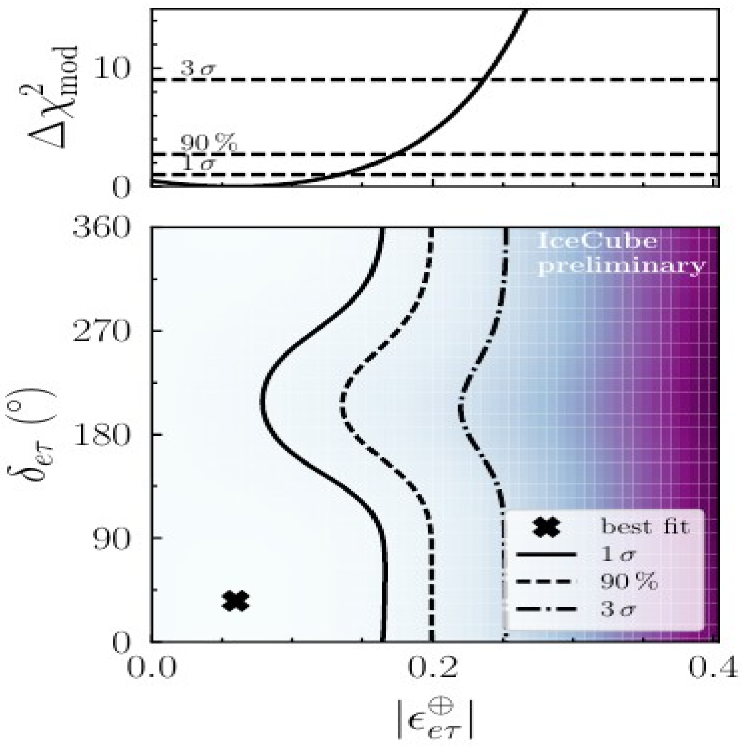
In presence of NSI, the $\nu_\mu \to \nu_\mu$ transition probability can be written approximately as,

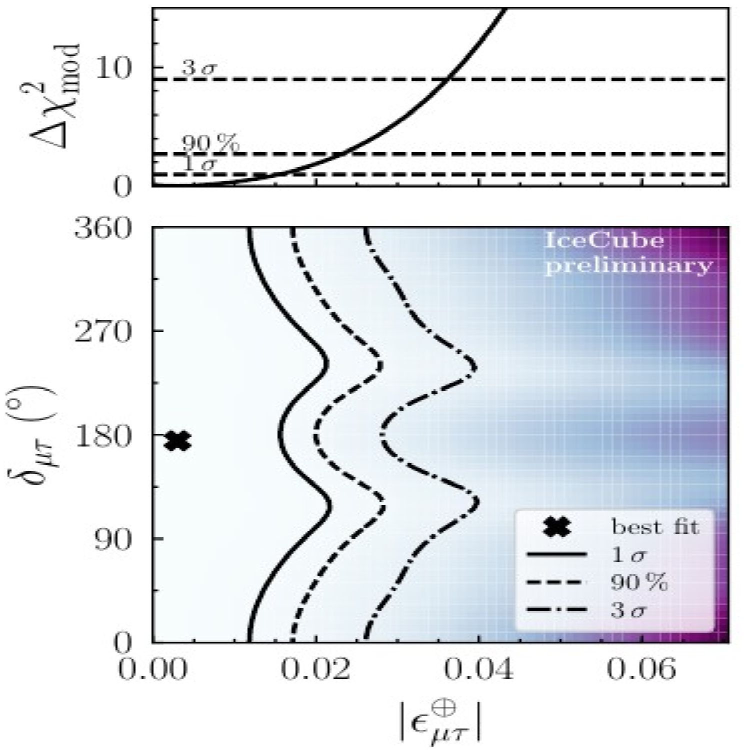
$$
\begin{aligned}
P\left(\nu_\mu \to \nu_\mu\right) \simeq\; & 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \alpha c_{12}^2 \sin^2 2\theta_{23} \Delta \sin 2\Delta - 4 s_{23}^4 s_{13}^2 \frac{\sin^2[(1-v)\Delta]}{(1-v)^2} \\
& - \frac{\sin^2 2\theta_{23} s_{13}^2}{(1-v)^2} \left\{ v\Delta \sin 2\Delta + \sin\left[(1-v)\Delta\right] \sin\left[(1+v)\Delta\right] \right\} \\
& - 2v|\varepsilon_{\mu\tau}| \cos\phi_{\mu\tau} \left(\sin^3 2\theta_{23} \Delta \sin 2\Delta + 2 \sin 2\theta_{23} \cos^2 2\theta_{23} \sin^2 \Delta \right) \\
& + \left[v \sin^2 2\theta_{23} \cos 2\theta_{23} \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right) - \frac{\hat{v}^2}{2} \sin^4 2\theta_{23} \left(\varepsilon_{\mu\mu} - \varepsilon_{\tau\tau}\right)^2 \right] \\
& \quad \times \left(\Delta \sin 2\Delta - 2 \sin^2 \Delta\right)
\end{aligned}
$$

Where,

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} \qquad |v| = \left| \frac{2 V_{\rm CC} E}{\Delta m_{31}^2} \right|$$







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

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

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

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

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

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

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

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 substantially!

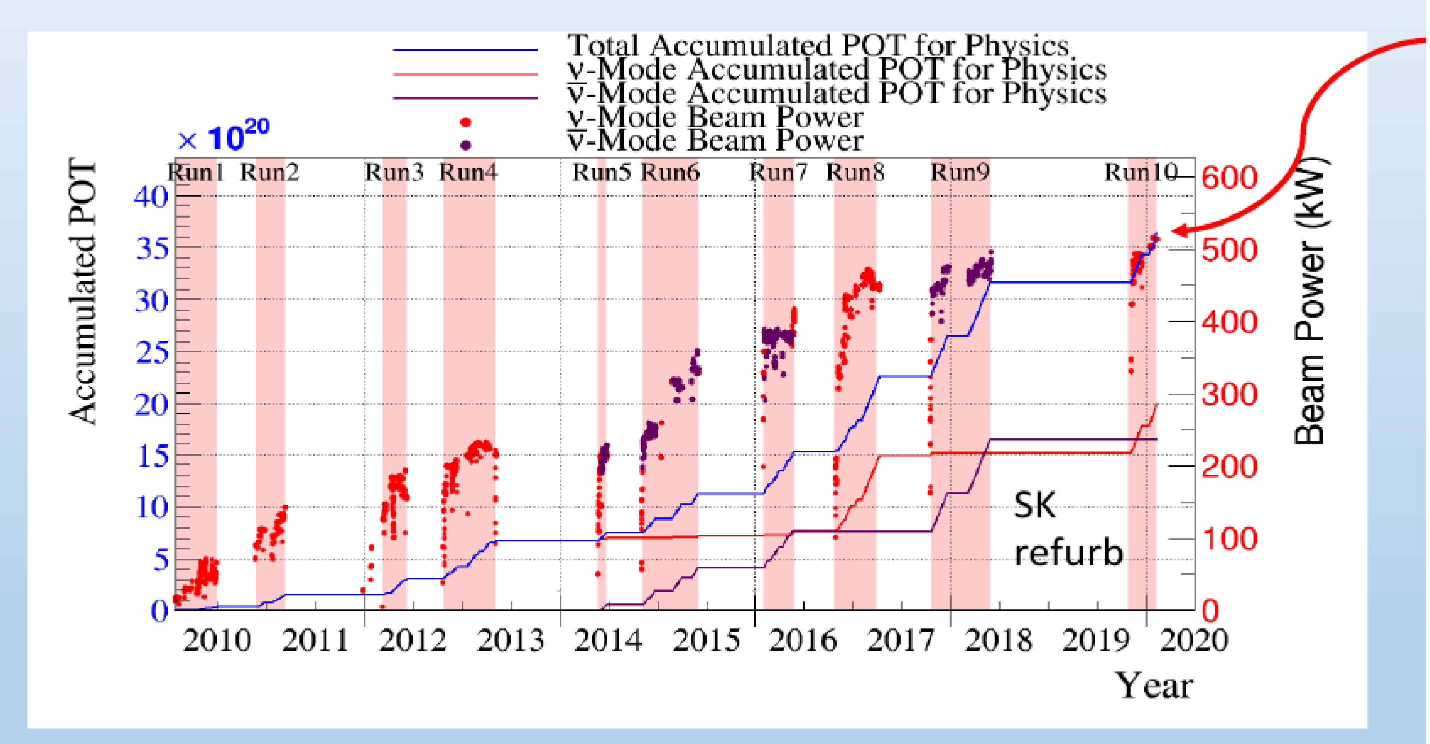
Let us discuss an important role of NSI in resolving the current T2K and NOvA tension

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

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

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

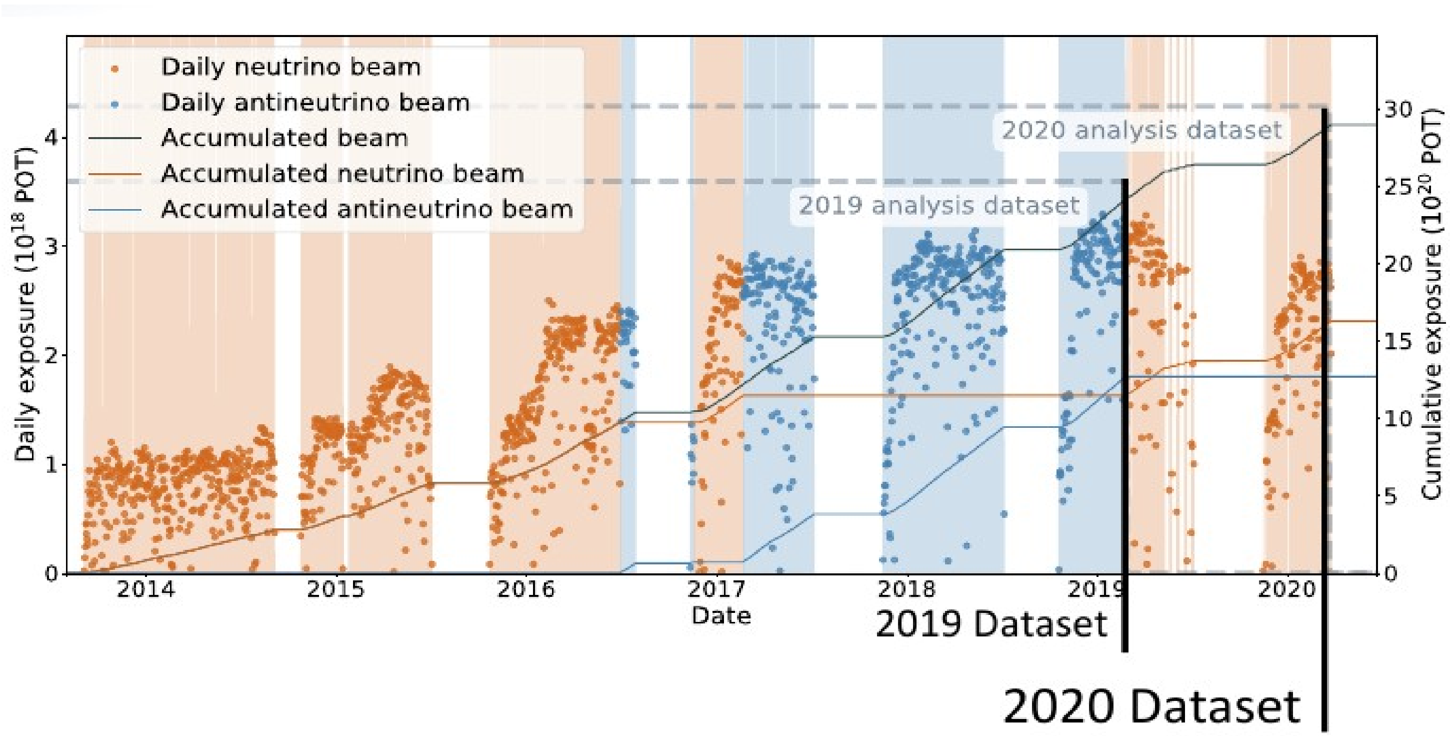
ν : 1.97×10^{21} POT

$\bar{\nu}$: 1.63×10^{21} 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

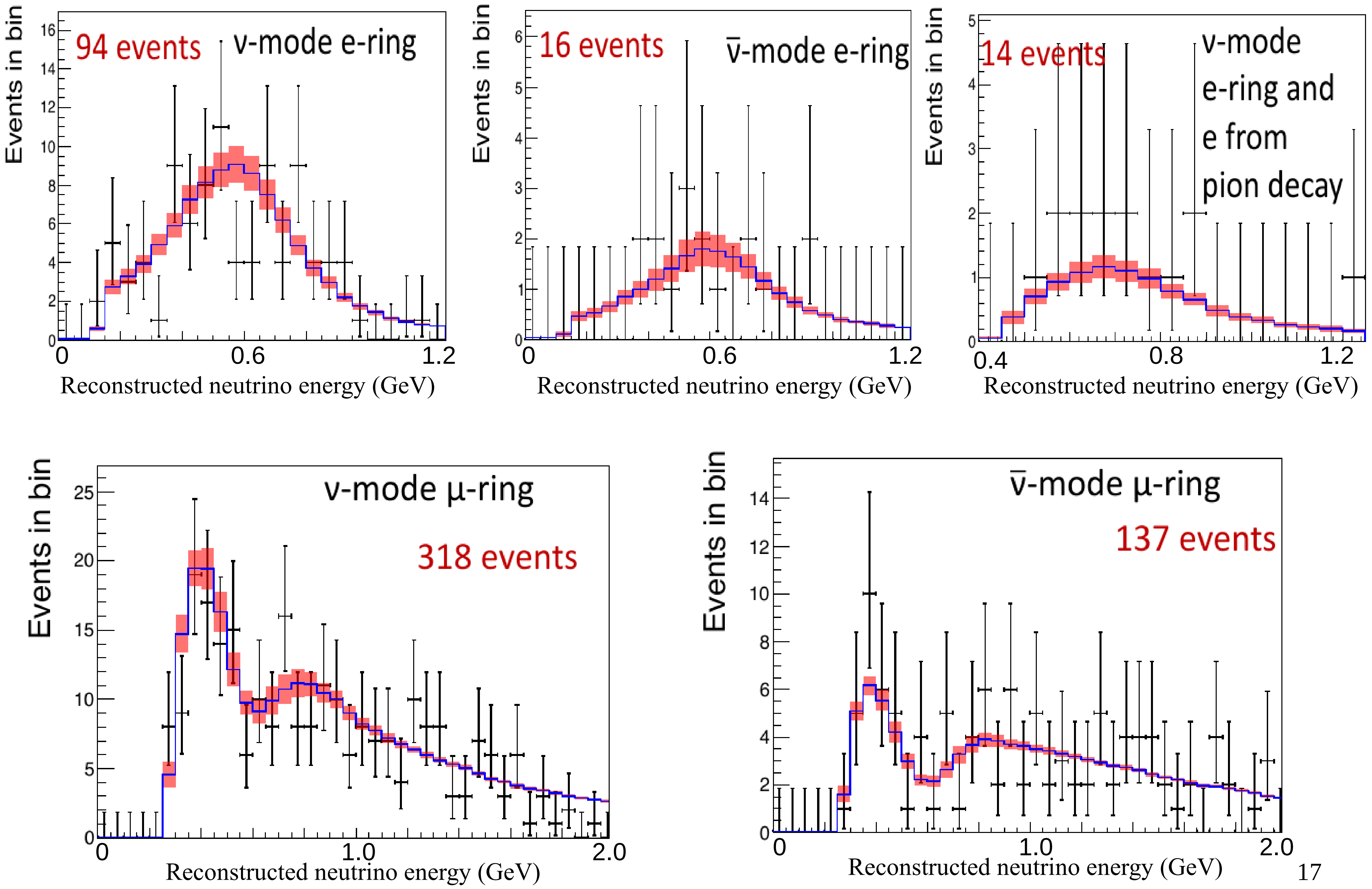
Typically ~ 700 kW

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

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

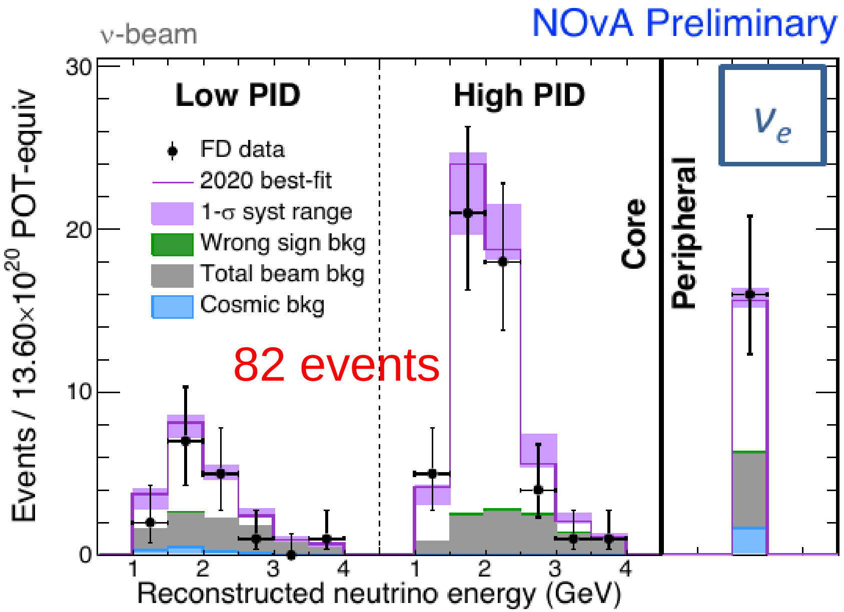
Talk by Alex Himmel at Neutrino 2020

T2K Dataset

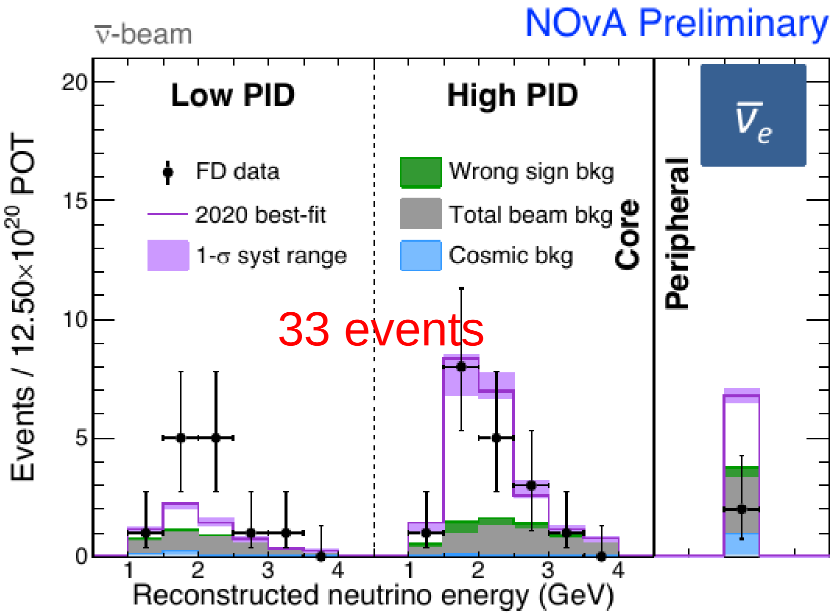


Talk by Patrick Dunne at Neutrino 2020 conference

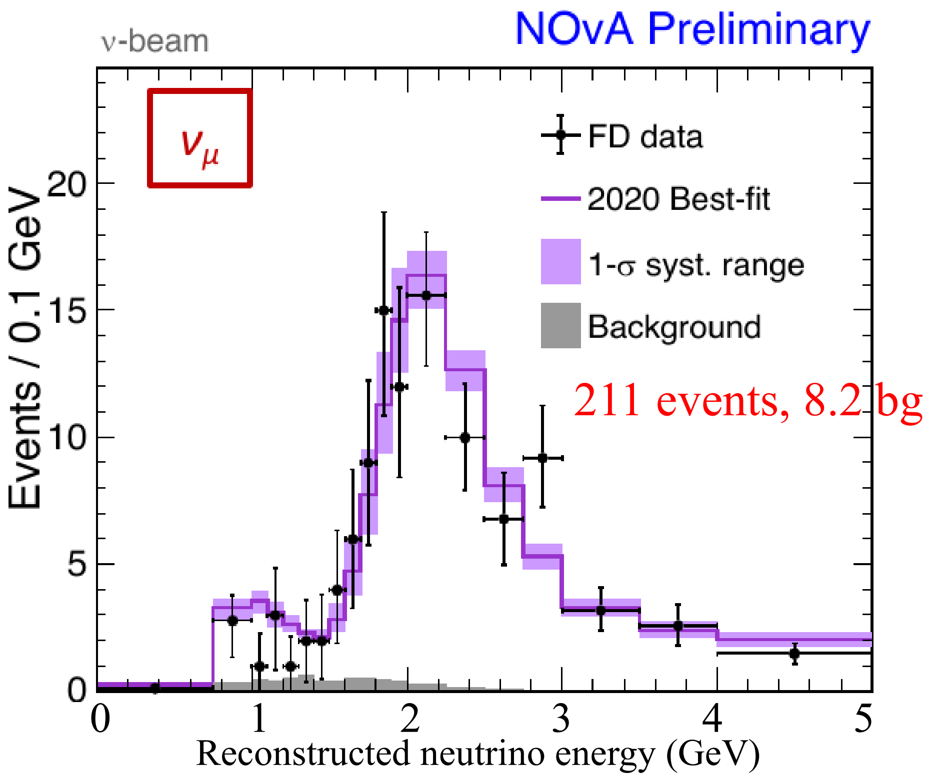
NOvA Dataset



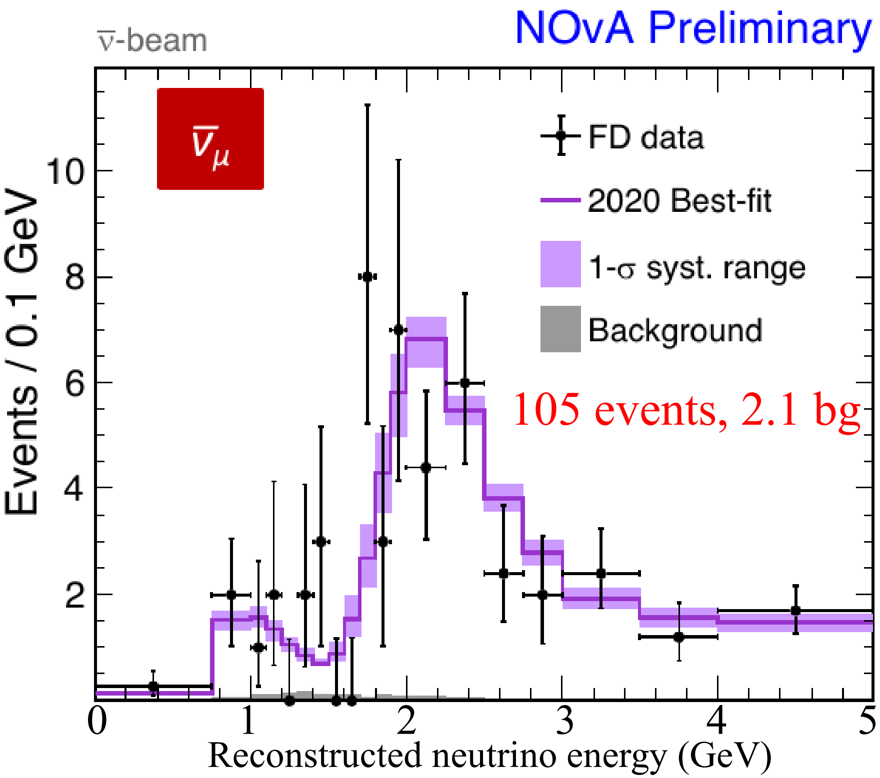
82 events



33 events



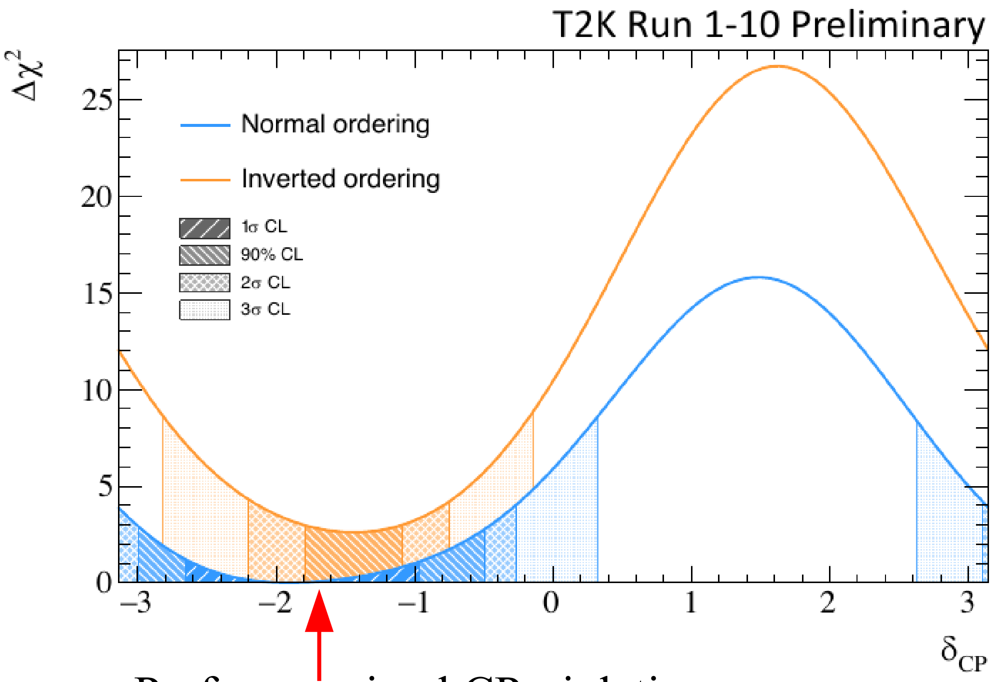
211 events, 8.2 bg

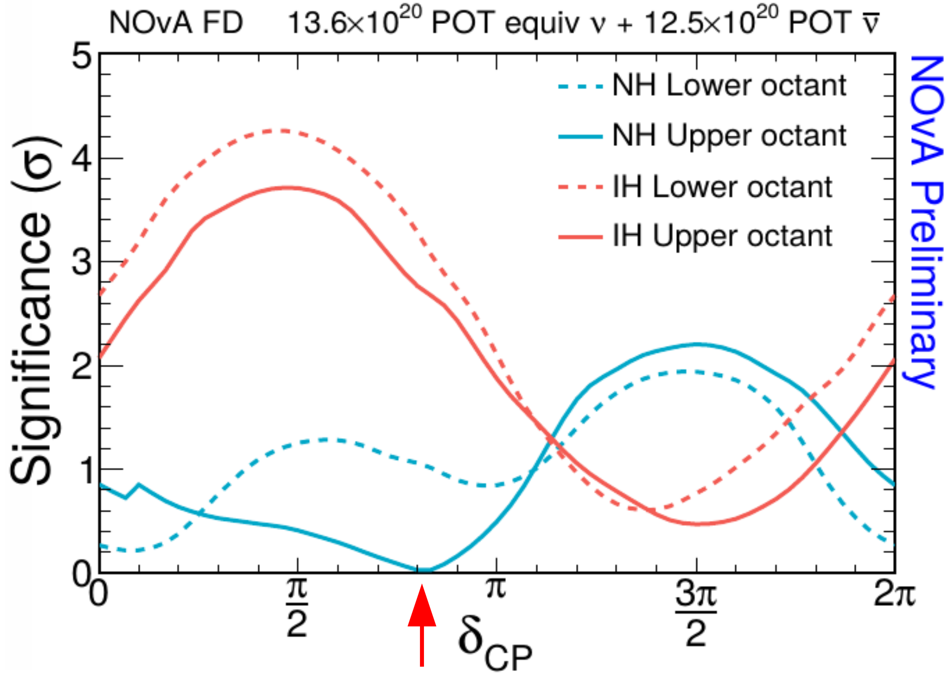


105 events, 2.1 bg

Talk by Alex Himmel at Neutrino 2020

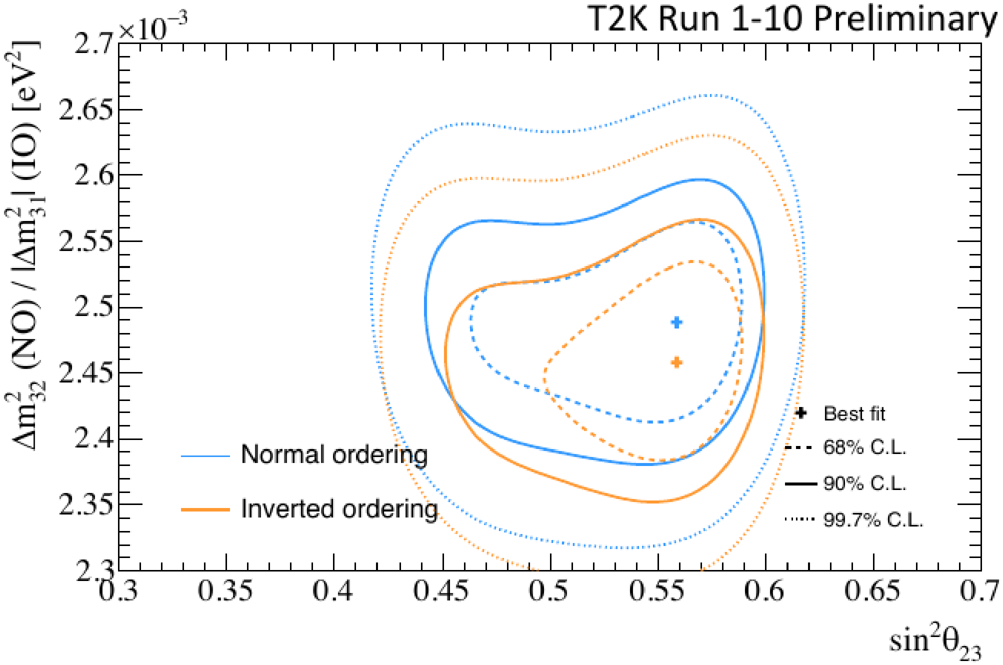
Results from the Collaborations

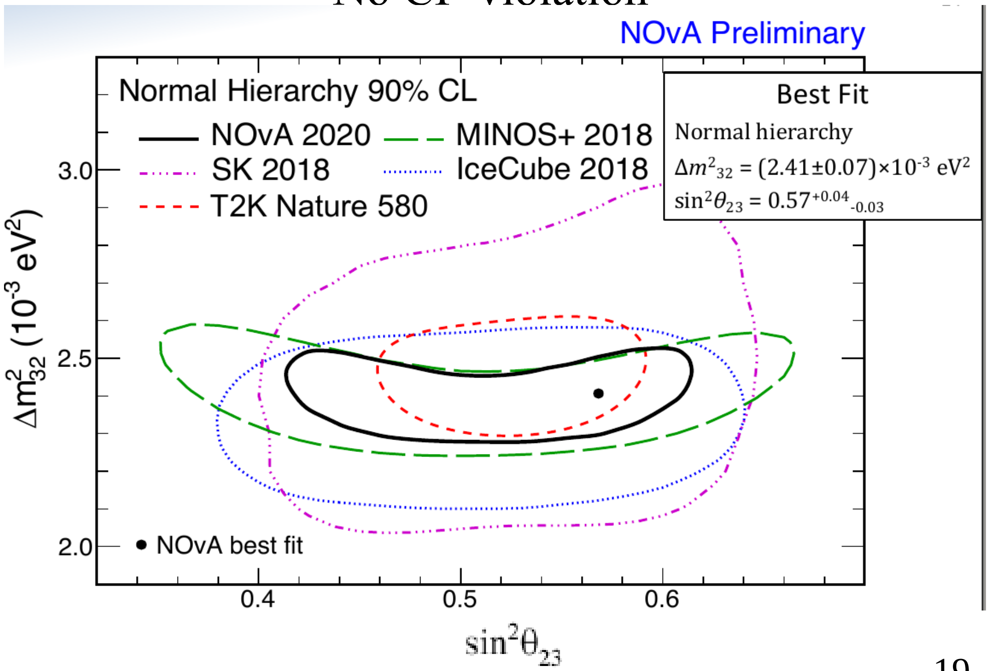




Prefers maximal CP-violation

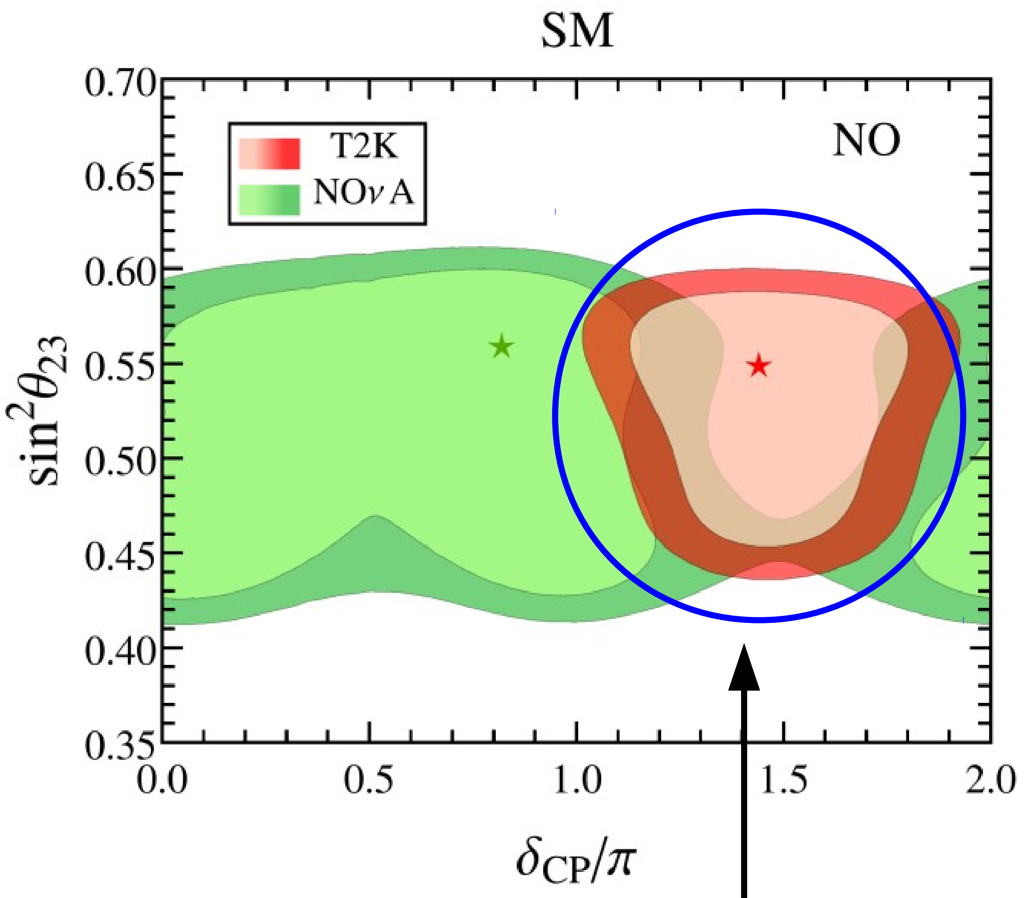
No CP-violation

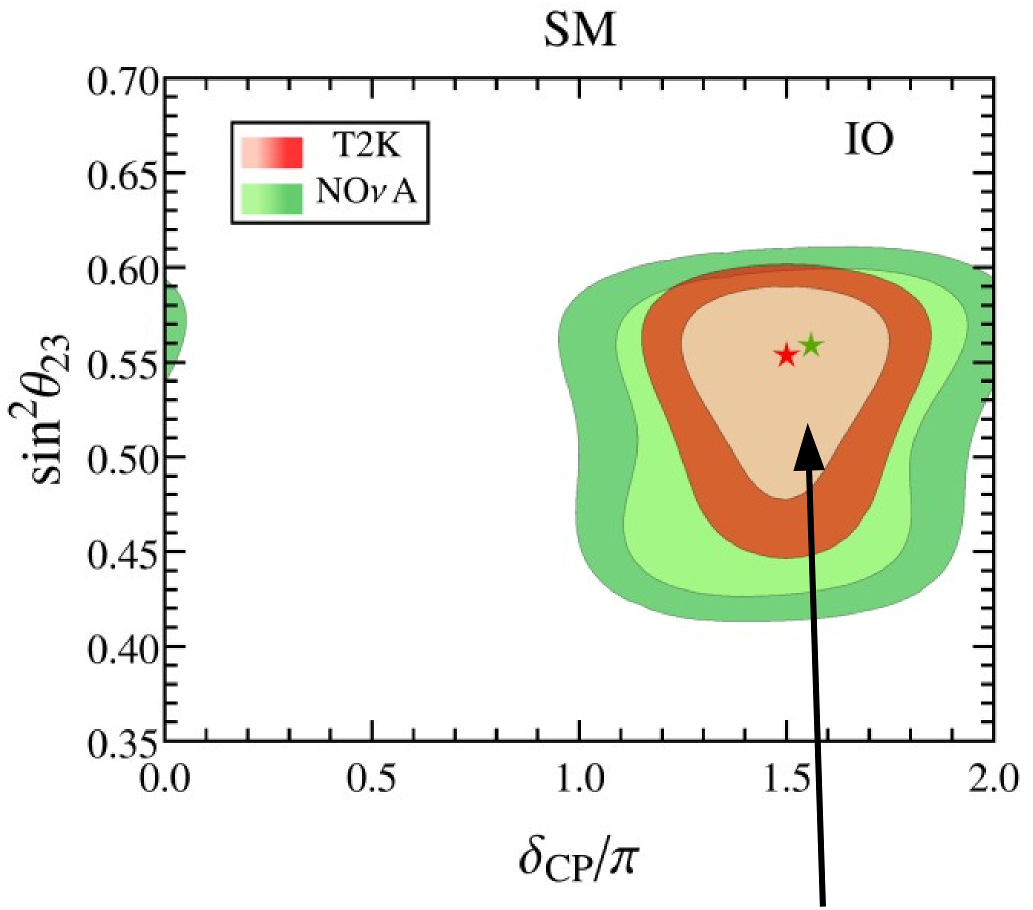




Talk by P. Dunne and A. Himmel at Neutrino 2020

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

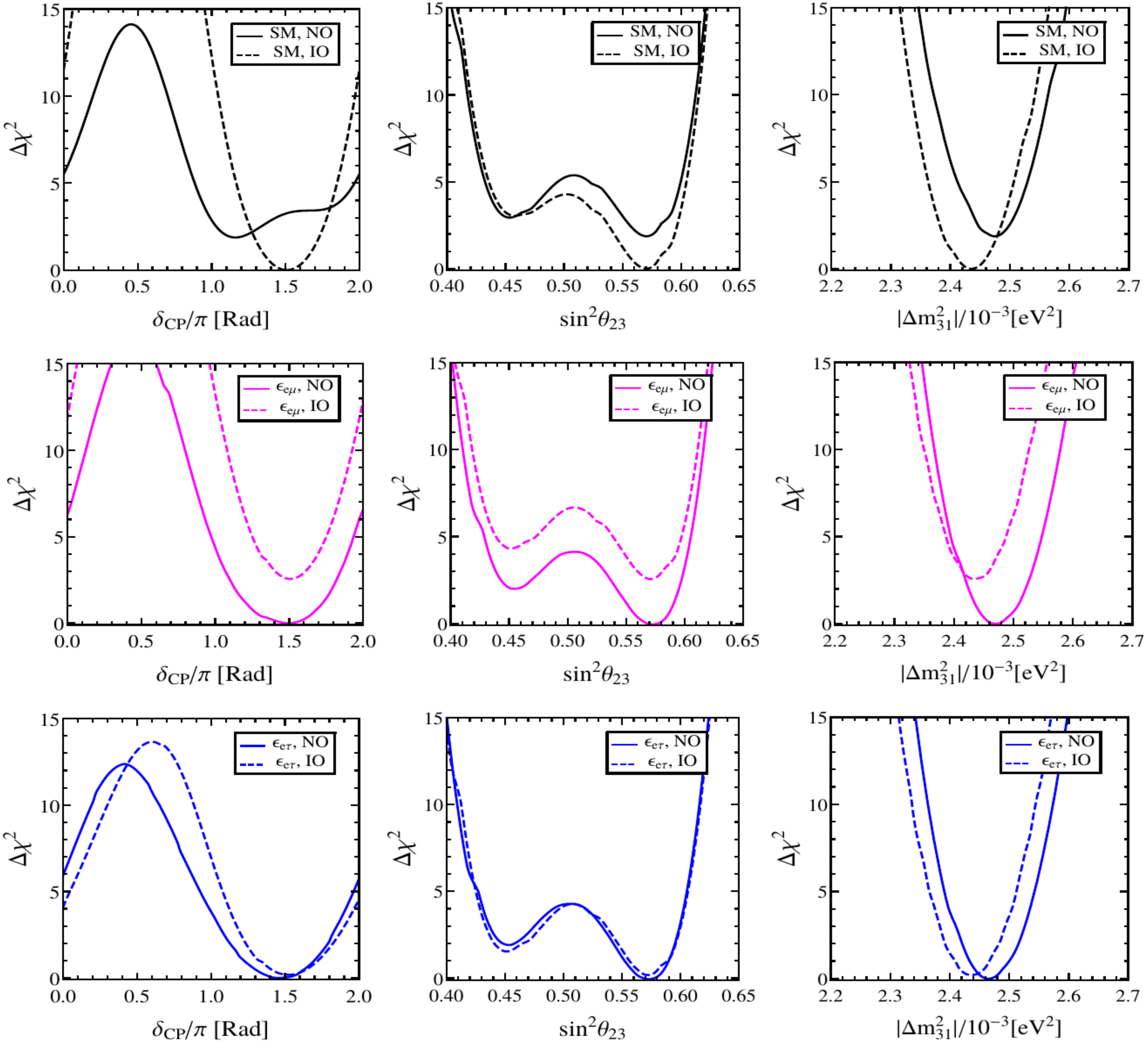




No discrepancy

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

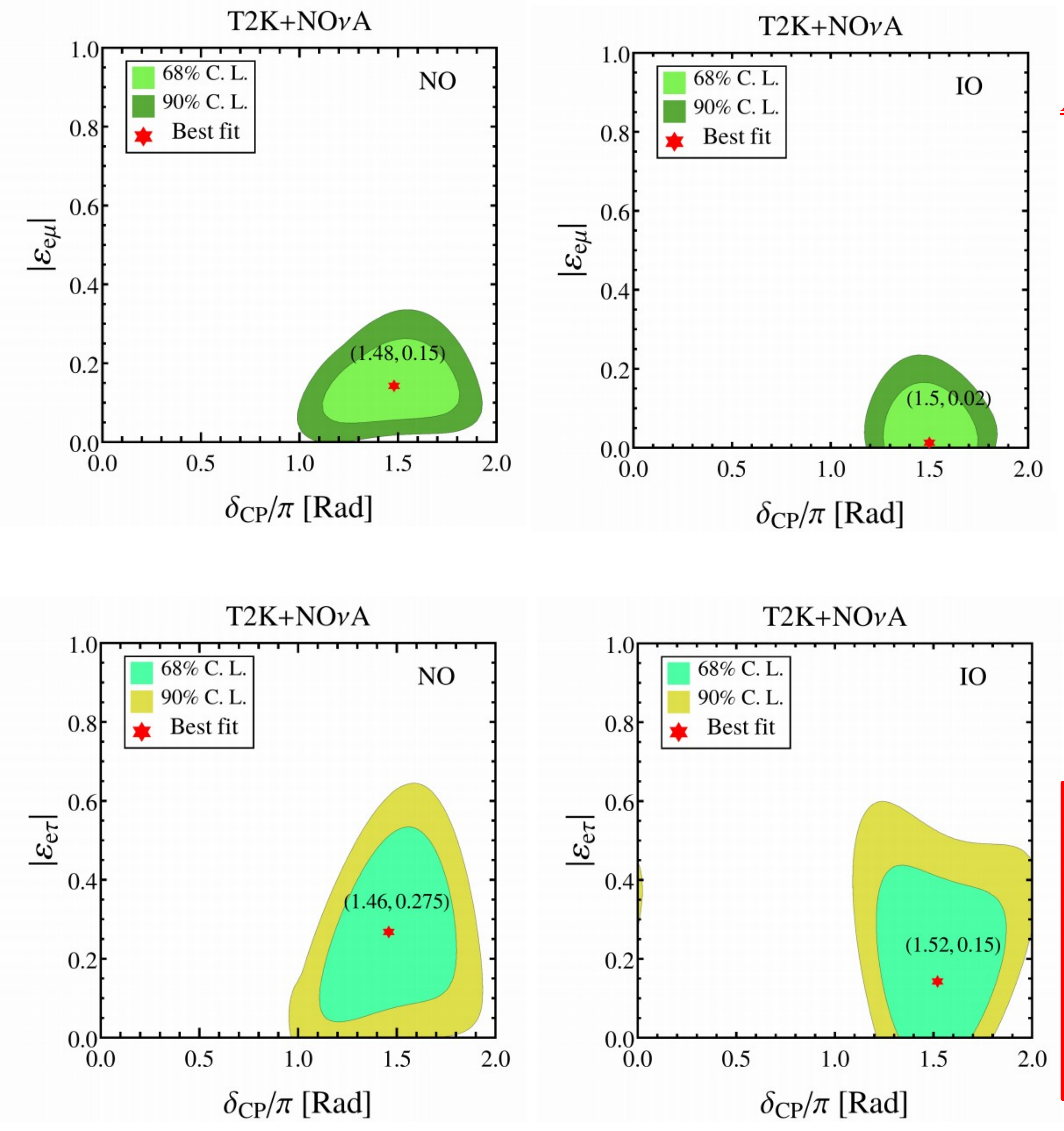
Combined analysis of T2K and NOvA



IO is preferred over NO in standard oscillation

However NO is preferred over IO in Presence of NSI

Allowed regions of NSI parameters



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

NMO	NSI	$\lvert\varepsilon_{\alpha\beta}\rvert$	$\phi_{\alpha\beta}/\pi$	δ_{CP}/π	$\Delta\chi^2$
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

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

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

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

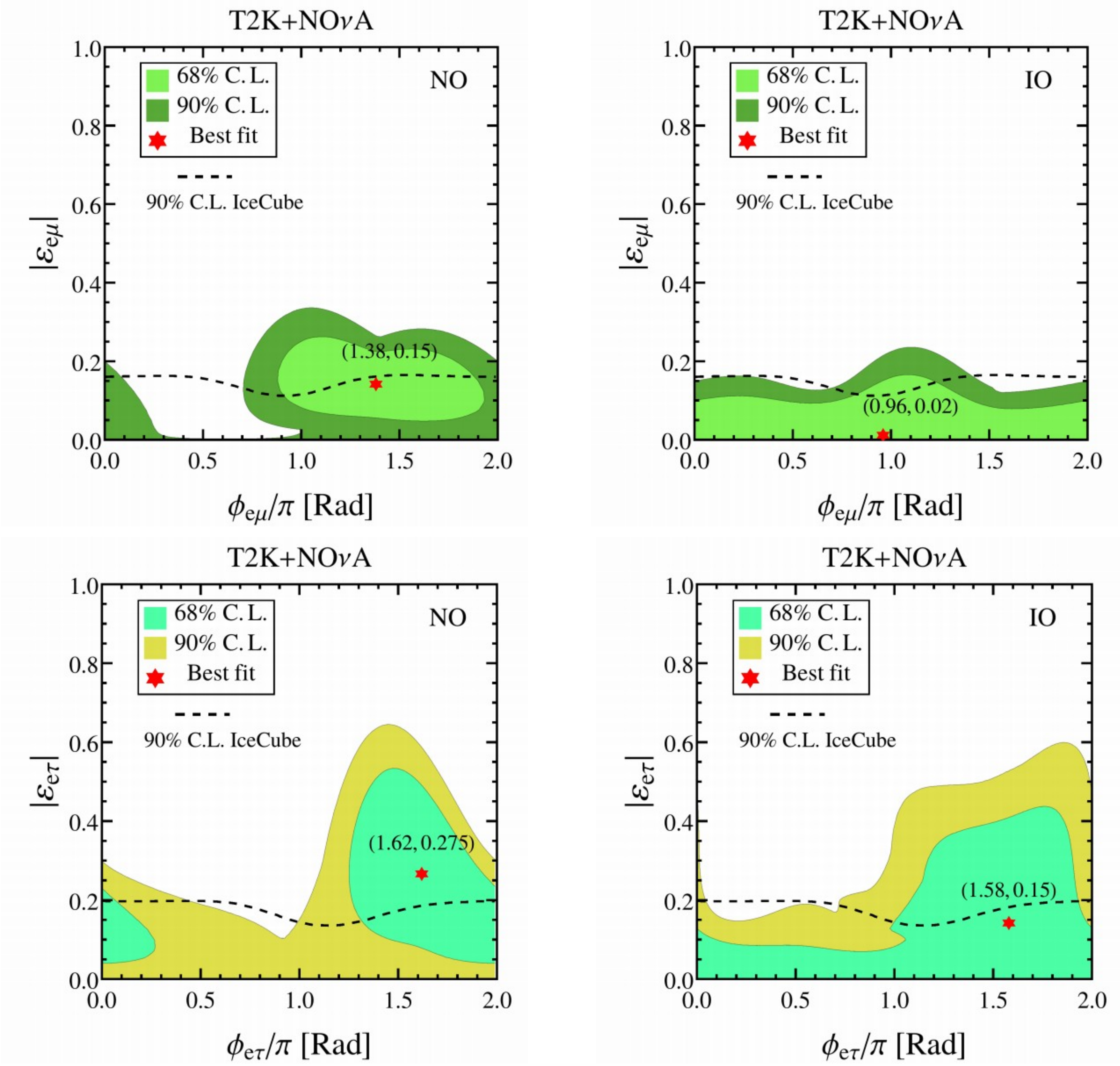
$$\chi^2_{e\mu,\mathrm{NO}} - \chi^2_{\mathrm{SM,IO}} = -2.63$$

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

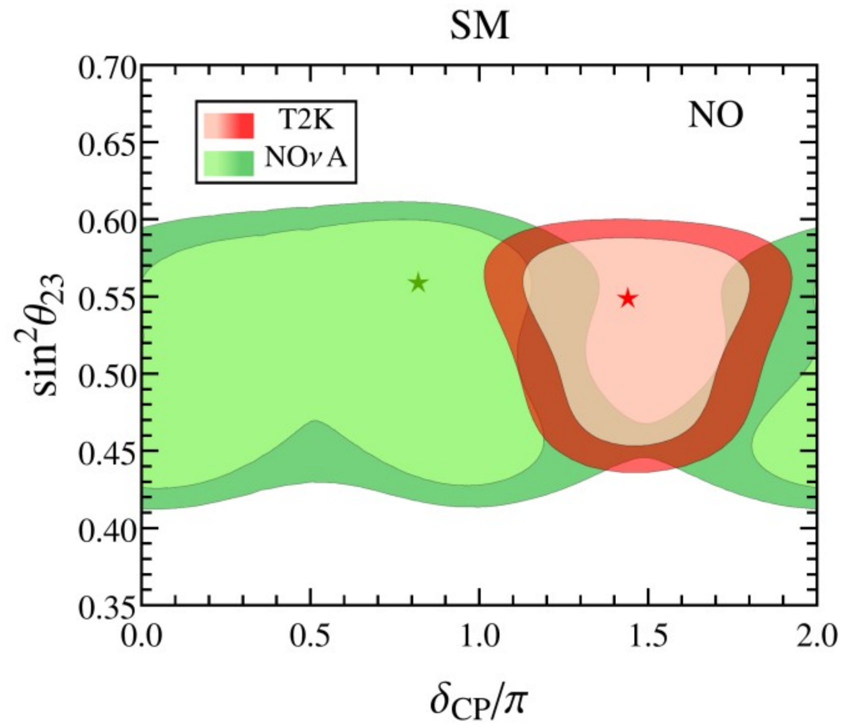
$$\chi^2_{e\tau,\mathrm{NO}} - \chi^2_{\mathrm{SM,IO}} = -1.21$$

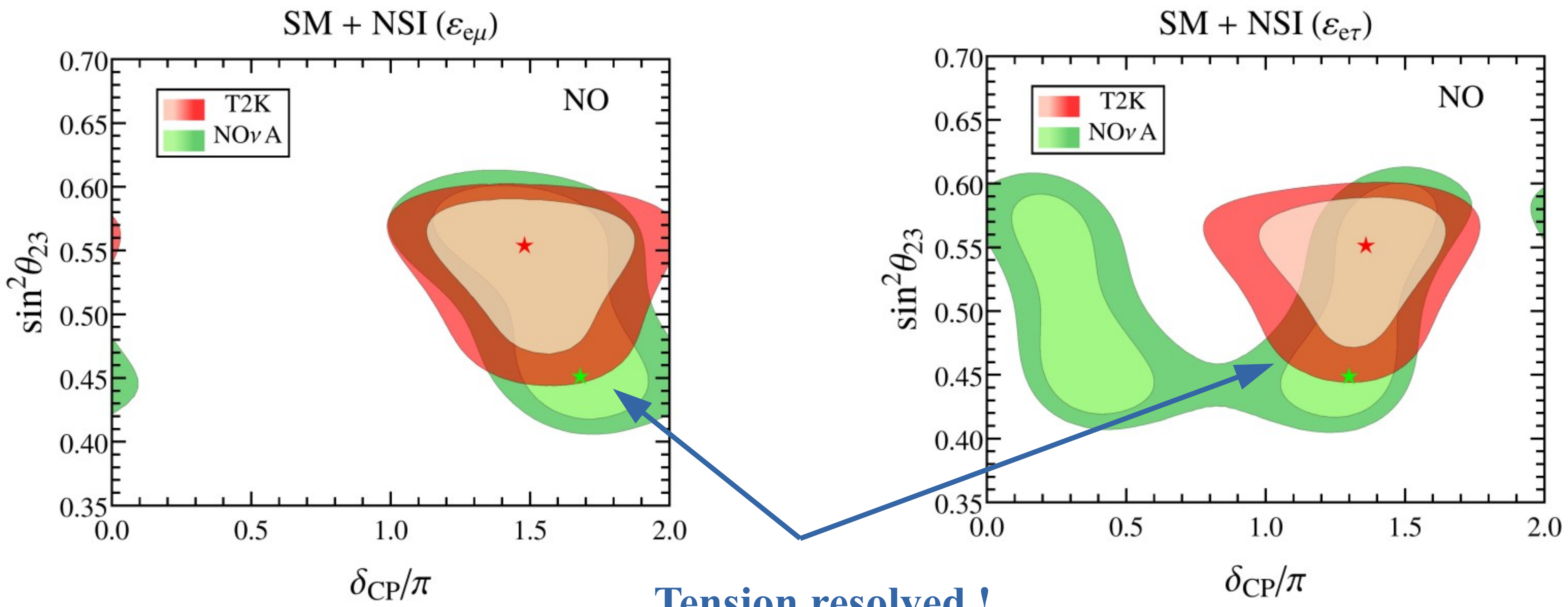
$$\chi^2_{e\tau,IO} - \chi^2_{SM,IO} = -1.01$$

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

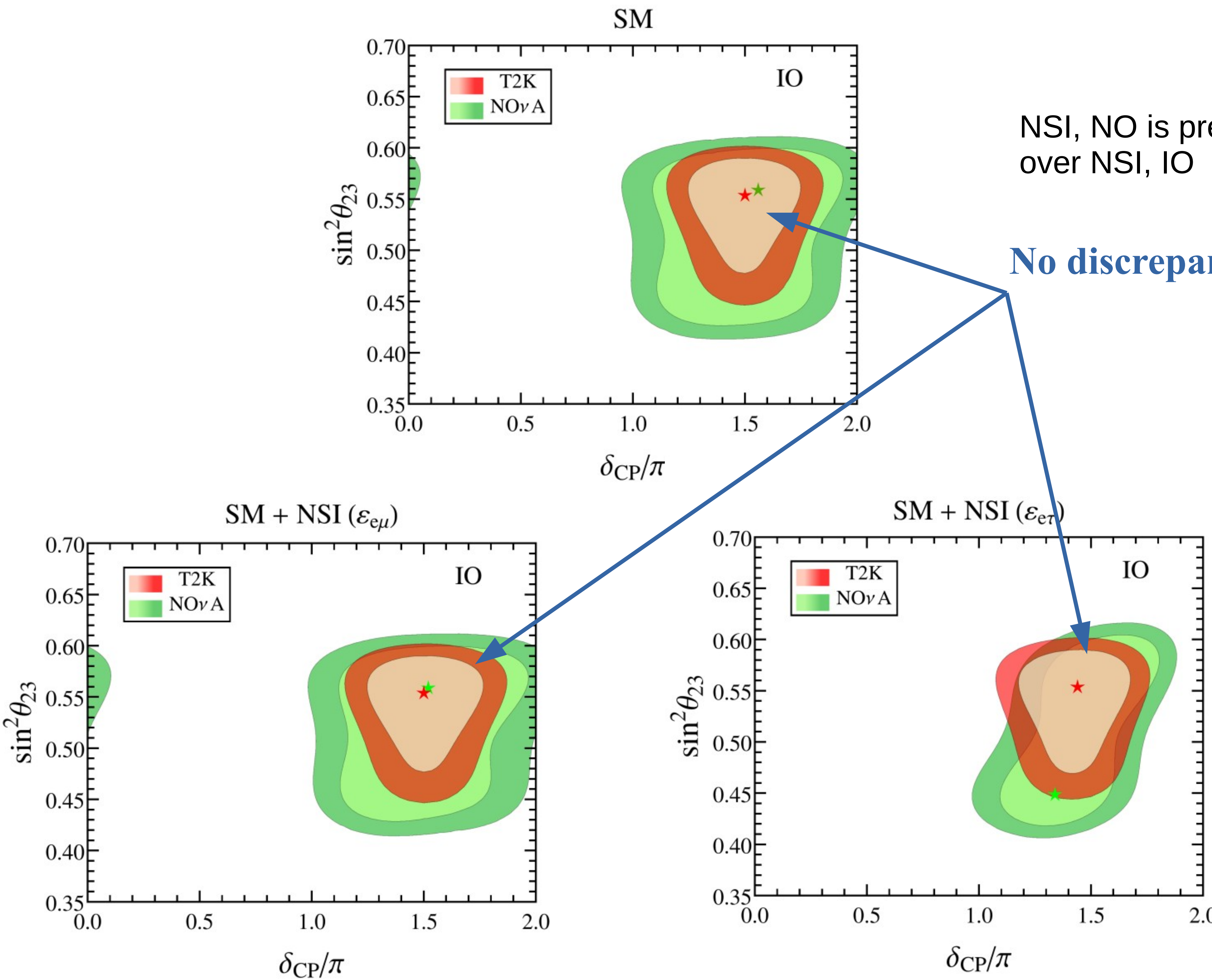


IceCube bounds are compatible !





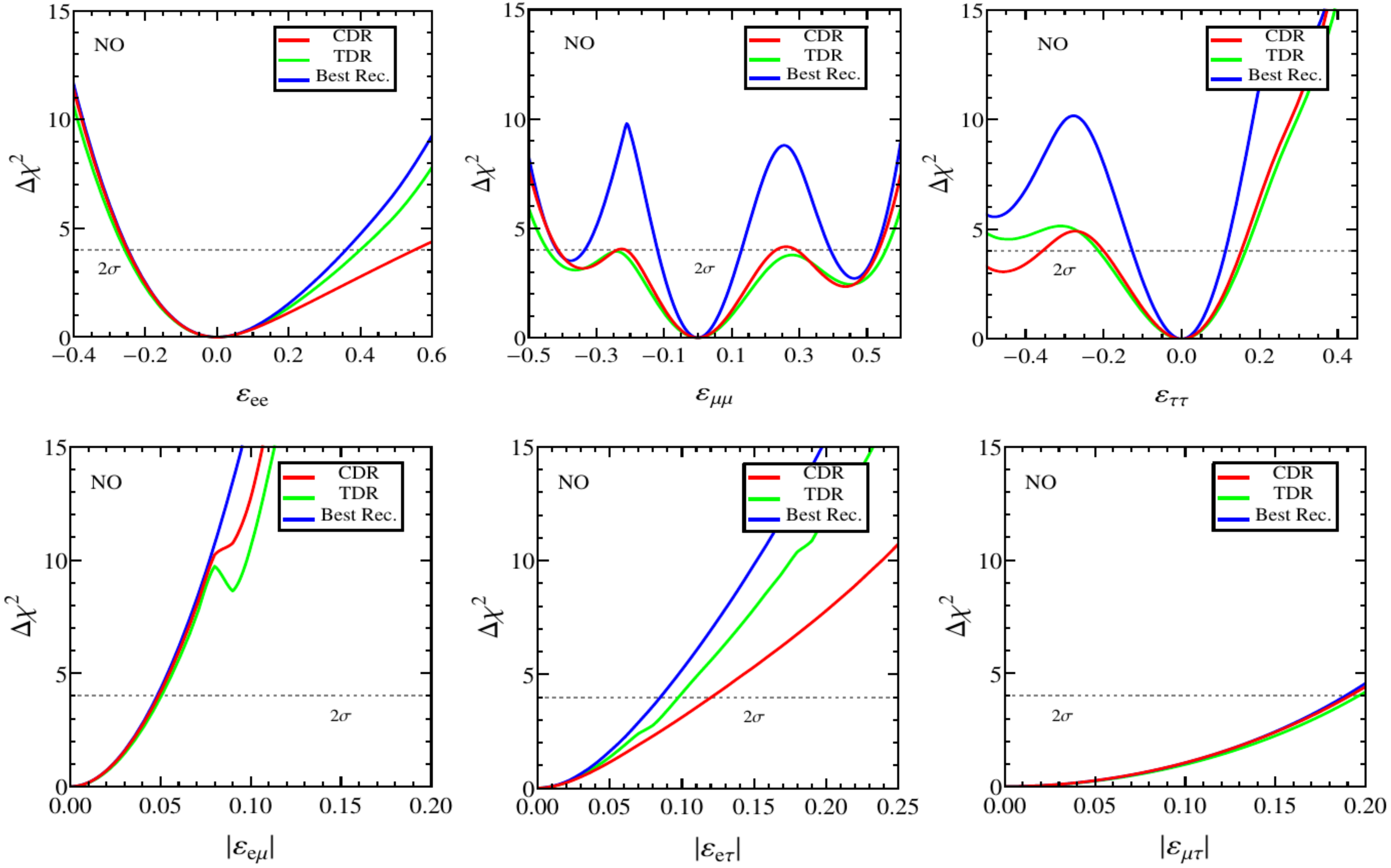
Tension resolved !



NSI, NO is preferred over NSI, IO

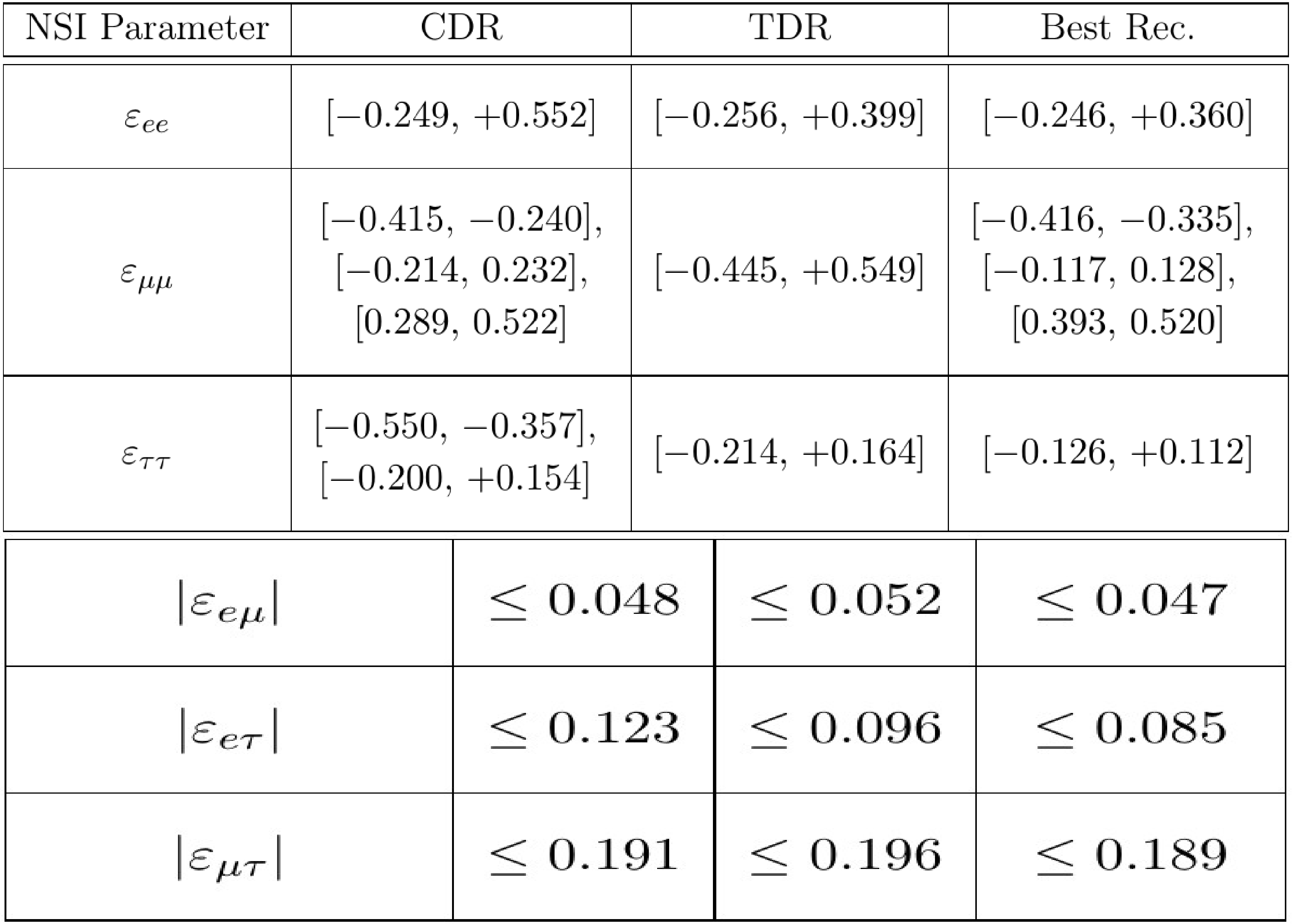
No discrepancy !

Future sensitivities to NSIs at DUNE



JHEP 08 (2021) 163 by **S S Chatterjee**, P S B Dev, & P Machado

Future constraints on NSIs from DUNE (2σ C. L.)



NSI Parameter	CDR	TDR	Best Rec.
ε_{ee}	$[-0.249, +0.552]$	$[-0.256, +0.399]$	$[-0.246, +0.360]$
$\varepsilon_{\mu\mu}$	$[-0.415, -0.240]$, $[-0.214, 0.232]$, $[0.289, 0.522]$	$[-0.445, +0.549]$	$[-0.416, -0.335]$, $[-0.117, 0.128]$, $[0.393, 0.520]$
$\varepsilon_{\tau\tau}$	$[-0.550, -0.357]$, $[-0.200, +0.154]$	$[-0.214, +0.164]$	$[-0.126, +0.112]$
$\lvert\varepsilon_{e\mu}\rvert$	≤ 0.048	≤ 0.052	≤ 0.047
$\lvert\varepsilon_{e\tau}\rvert$	≤ 0.123	≤ 0.096	≤ 0.085
$\lvert\varepsilon_{\mu\tau}\rvert$	≤ 0.191	≤ 0.196	≤ 0.189

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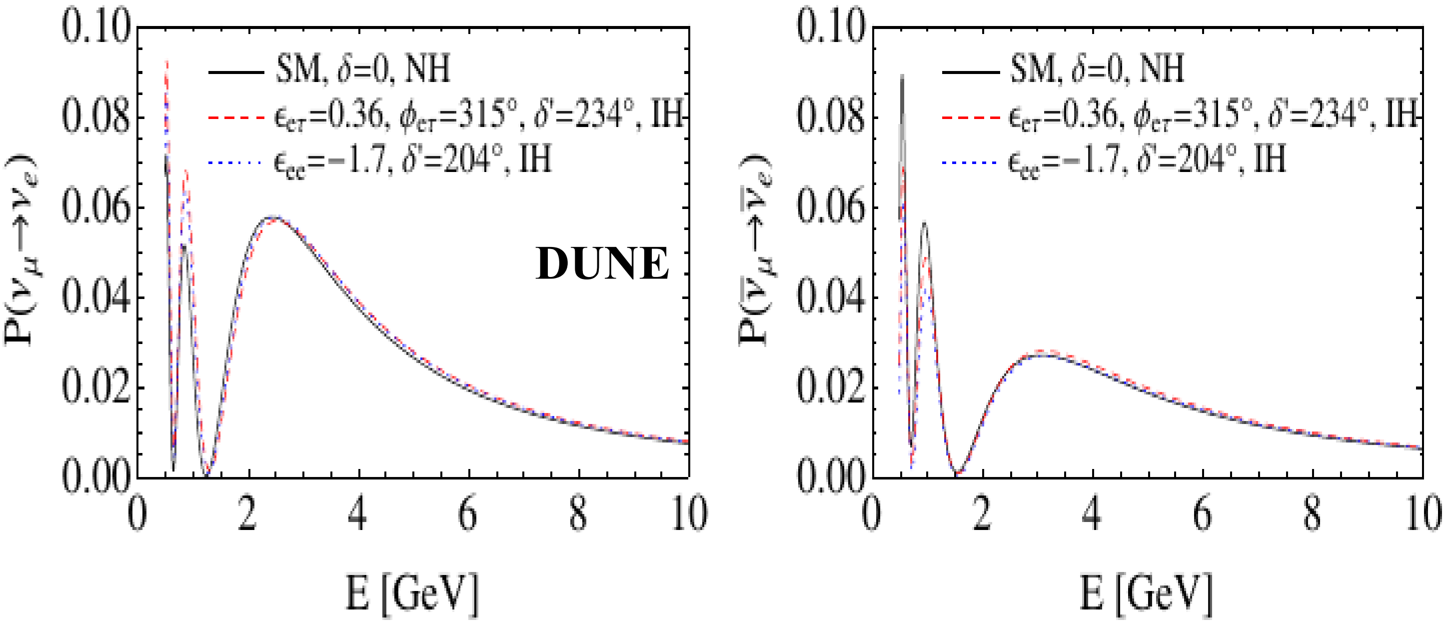
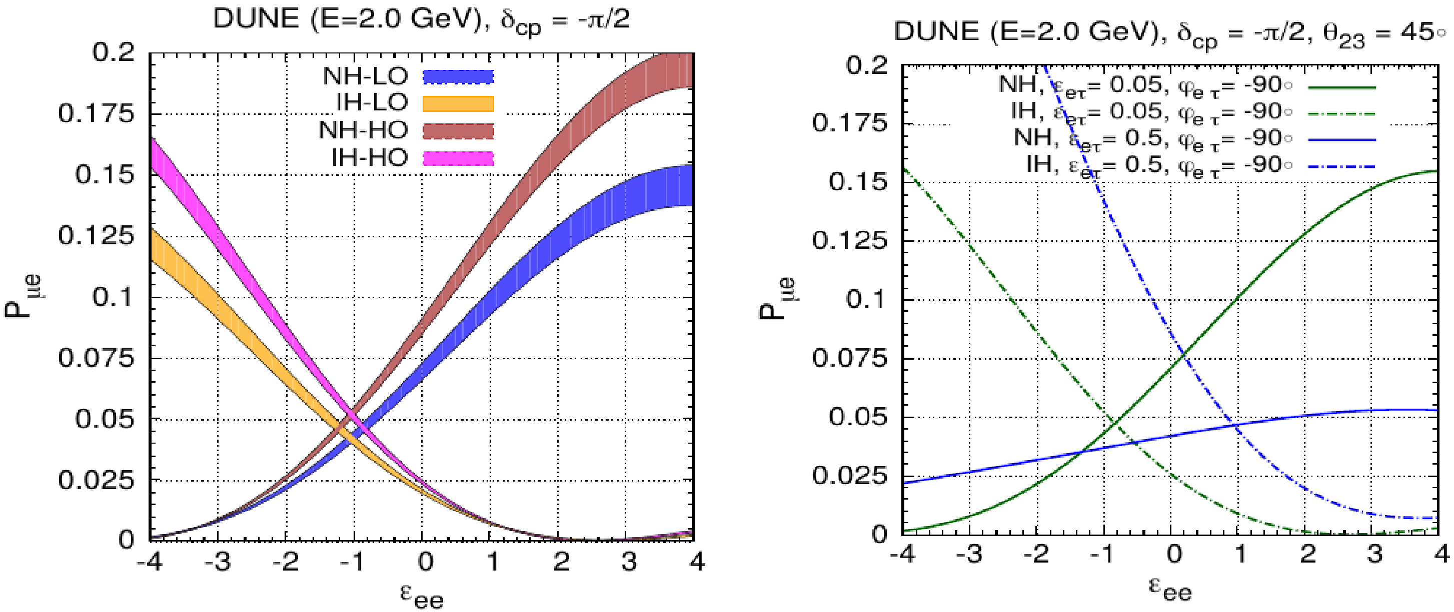
Impact of large NSI on the standard predictions

Hierarchy sensitivity

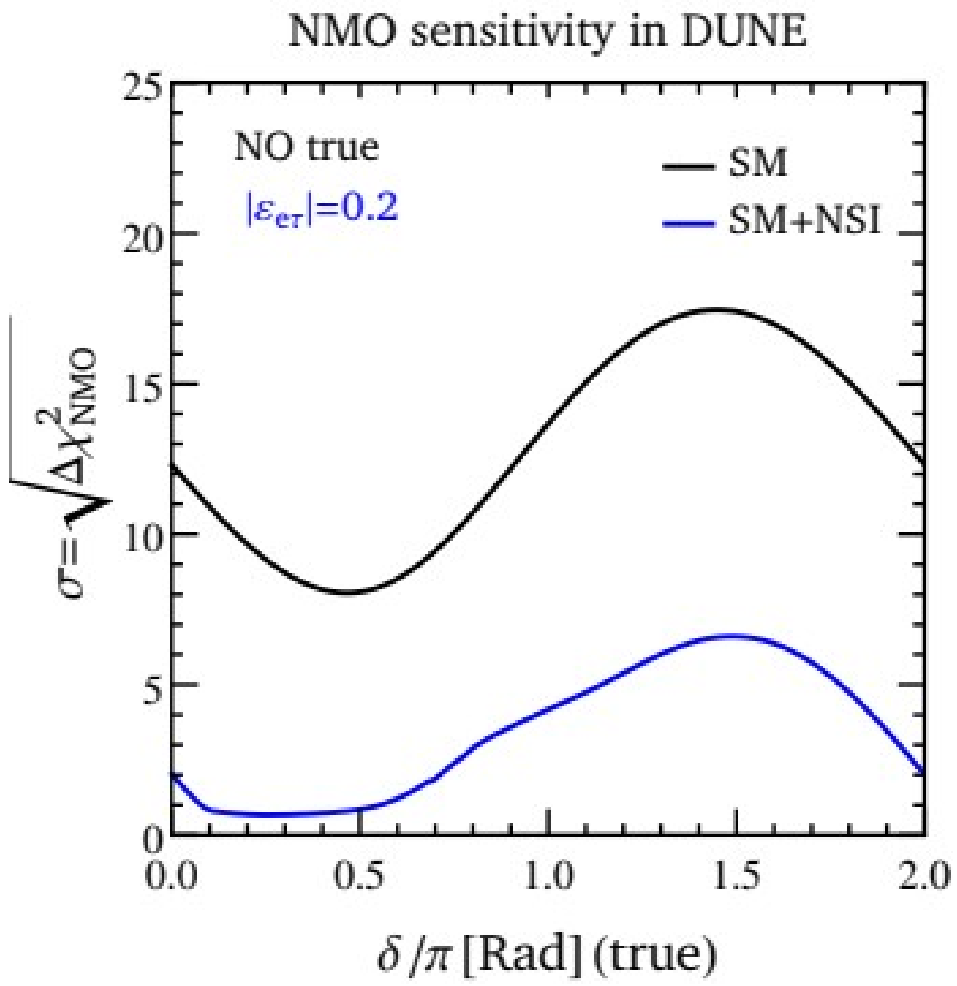
Looking to the Future



PRD 93 (2016) 9, 093016 by J. Liao, D. Marfatia, & K. Whisnant

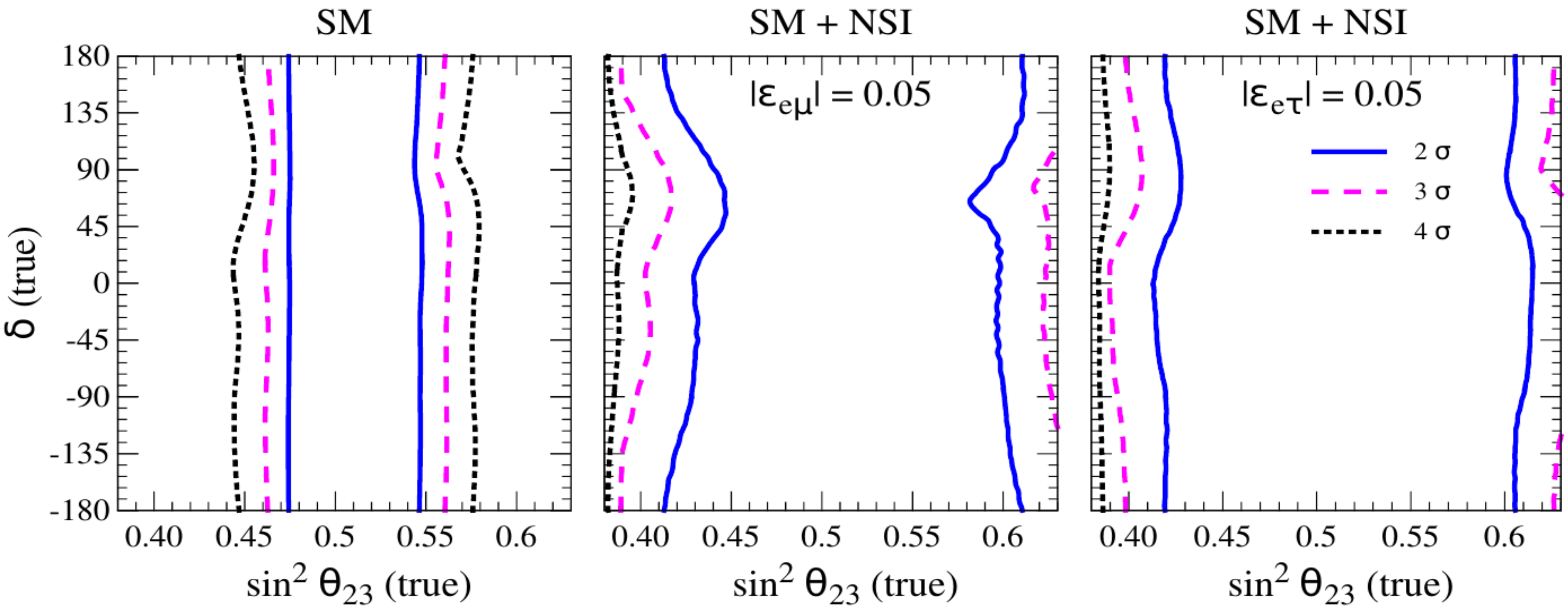


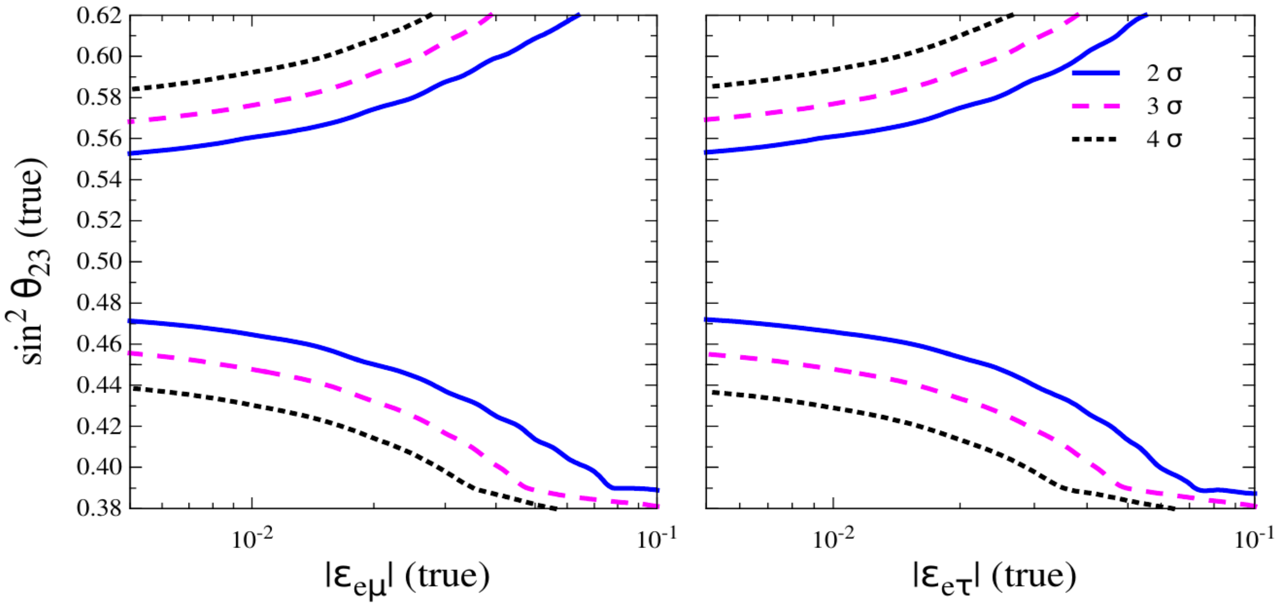
PRD 96 (2017) 7, 075023 by K. Deepthi, S. Goswami, & N. Nath



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



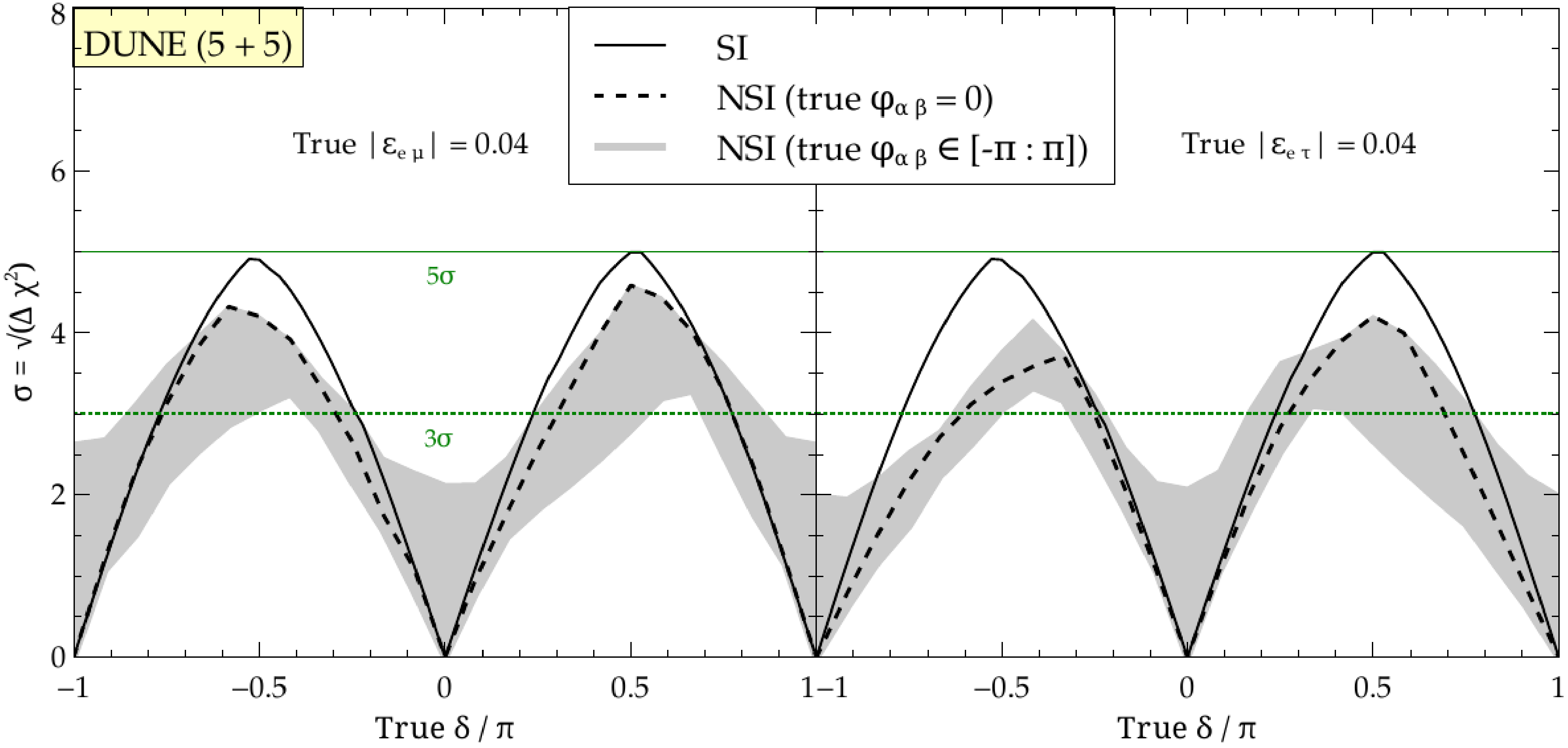


$\left|\varepsilon_{e\mu/e\tau}\right|$ have been kept fixed

Octant sensitivity might get reduced substantially in DUNE in presence of NSI

PLB 762 (2016) 64-71 by S. K. Agarwalla, S. S. Chatterjee, & A. Palazzo

Impact of NSI on CPV



J.Phys.G 43 (2016) 9, 095005 by M. Masud, A. Chatterjee, & P. Mehta

Conclusion

- We have investigated the possibilities of exploring the NSI and its impact on the current and future data of the long-baseline experiments.

- As a concrete example, we have shown how important role the NSI might play in Resolving the T2K and NOvA tension.

➔ 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 $\varepsilon_{e\tau}$

➢ We have also shown that if NSI exists in nature, it may impact the CPV, Octant, and mass ordering measurements severely, even in the highly promising experiment like DUNE.

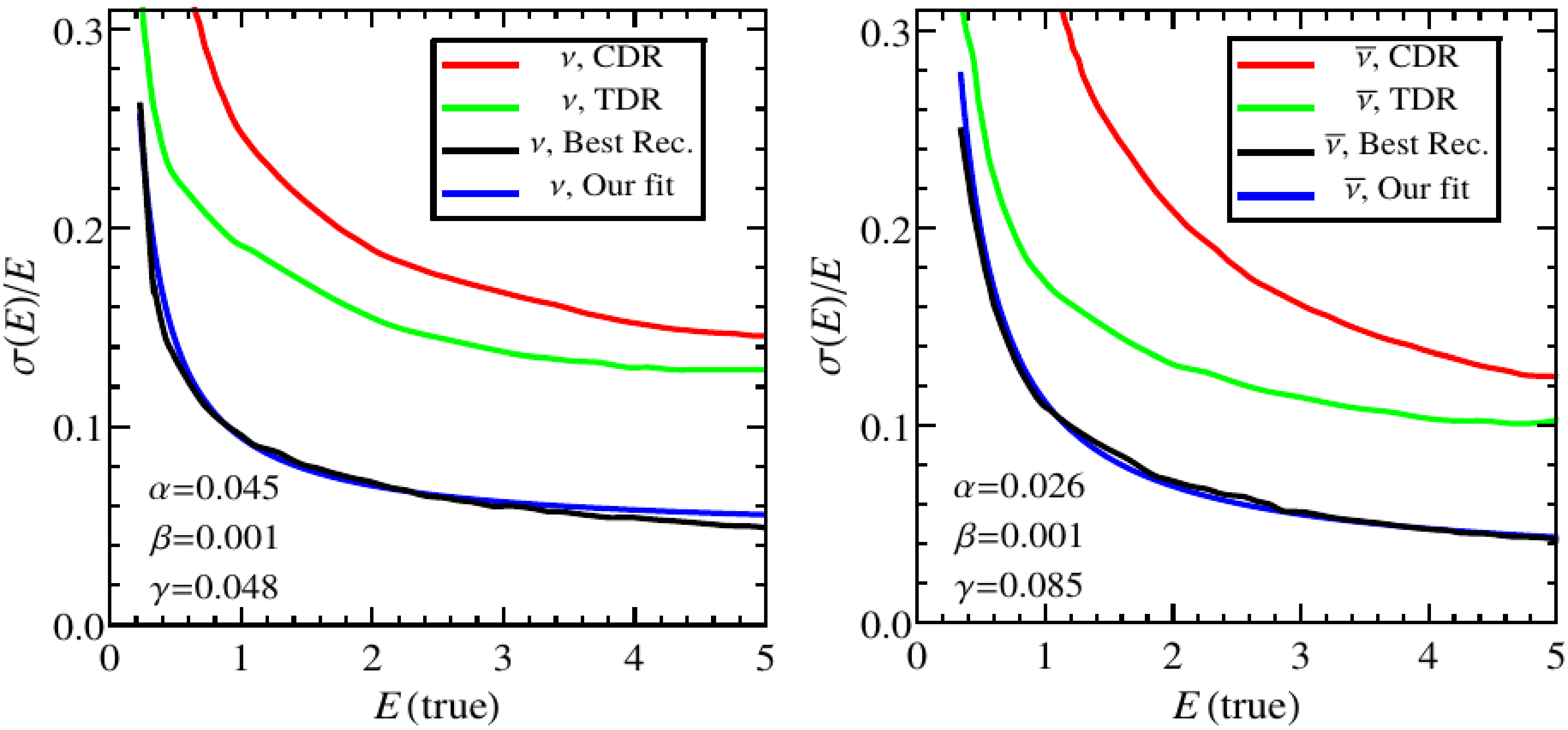
- Future data from T2K and NOvA, and future experiments like T2HK, DUNE and atmospheric current and future data is expected to confirm the presence of NSI and also will help resolving this ambiguity.

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

✗ Our work also suggests the importance of medium baseline experiments like T2HK, ESSnuSB which will be able to measure the CPV and Octant of the atmospheric angle 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!



JHEP 08 (2021) 163 by **S S Chatterjee**, P S B Dev, & P Machado

For details on the energy resolution at DUNE please see, PRD 99 (2019) 036009 by A. Friedland & S.W. Li

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

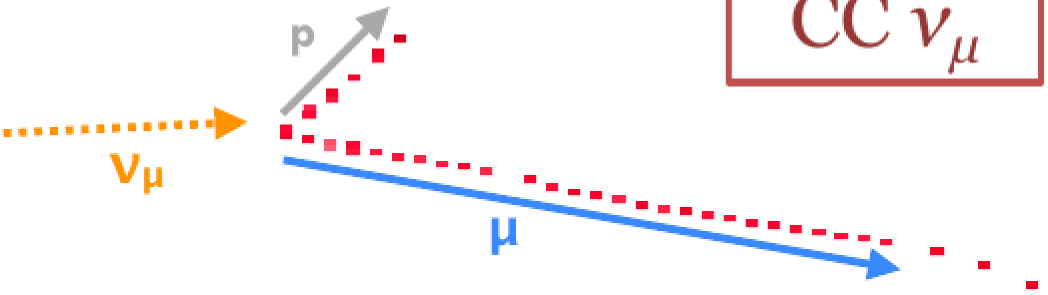
2. Heavy mediators models arising in radiative neutrino mass model

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

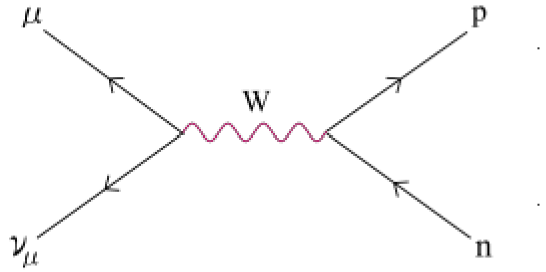
For references please see:

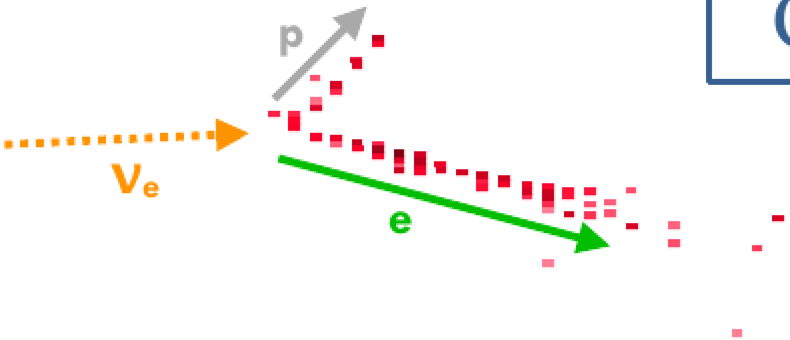
Y. Farzan 1505.06906, Y. Farzan, I. Shoemaker 1512.09147,
Y. Farzan, M. Tortola 1710.09360,
M. Gavela, D. Hernandez, T. Ota, and W. Winter 0809.3451,
K.Babu, P. B. Dev, S. Jana, and A. Thapa 1907.09498,
D. Forero and W. Huang 1608.04719
U. Dey, N. Nath and S. Sadhukhan 1804.05808
And many more.

For overview see, 1907.00991

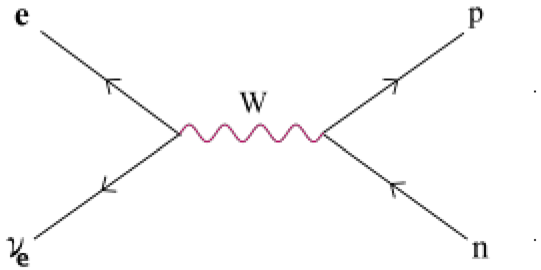


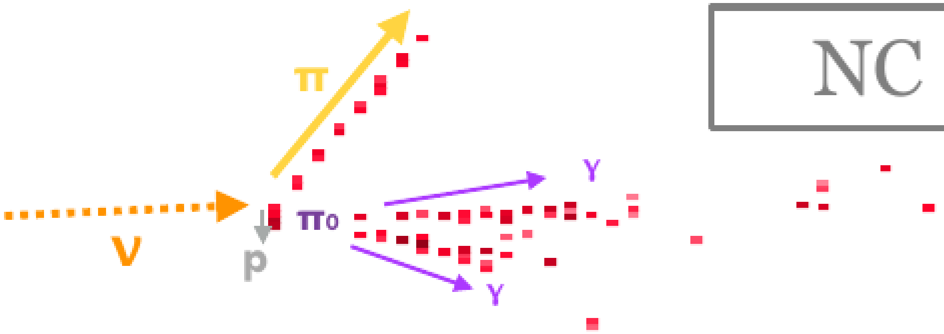
CC ν_μ



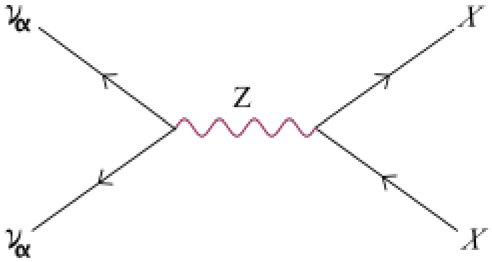


CC ν_e





NC



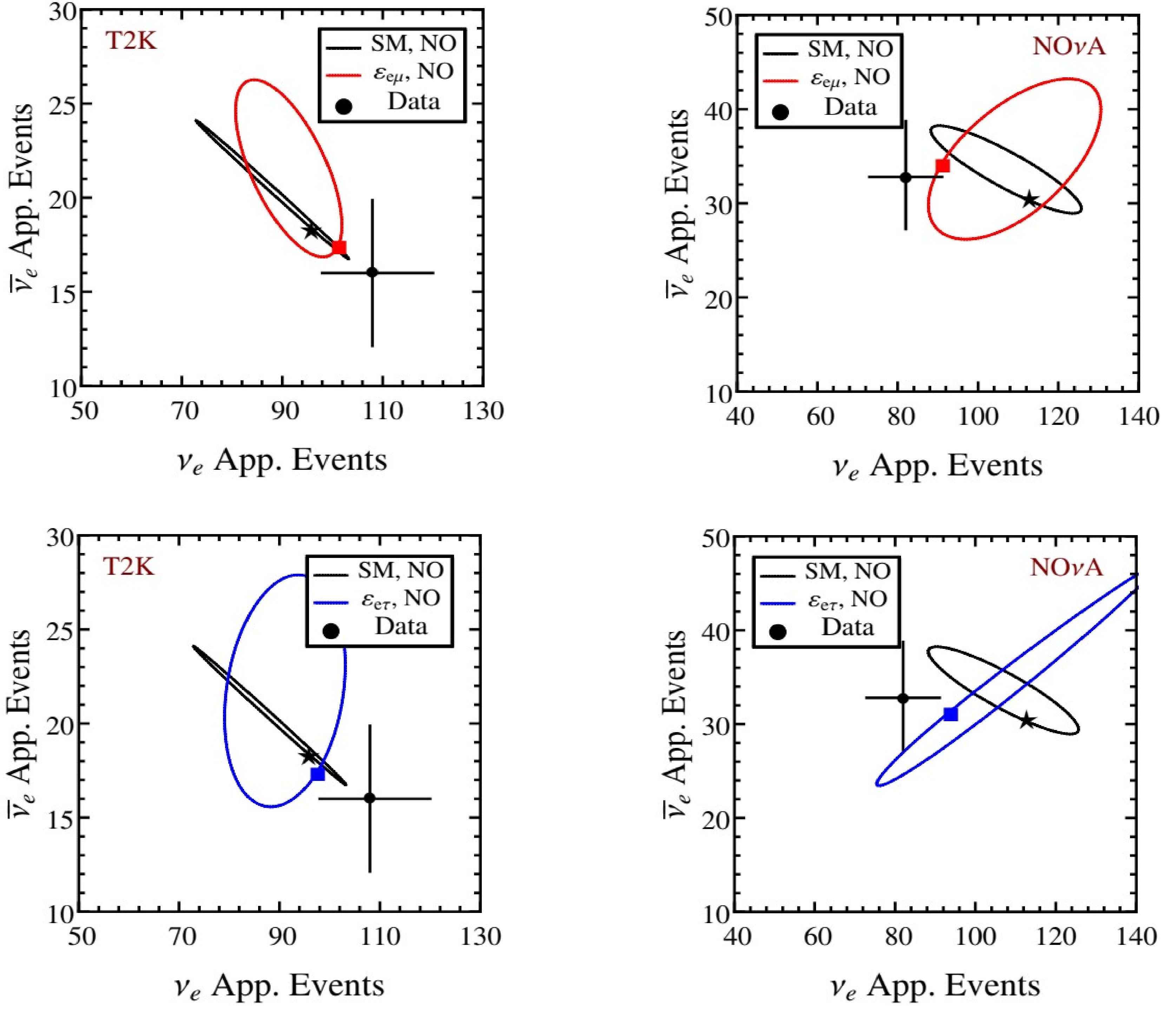
$\alpha = e,\ \mu,\ \tau$

For antineutrinos (inverse beta-decay)

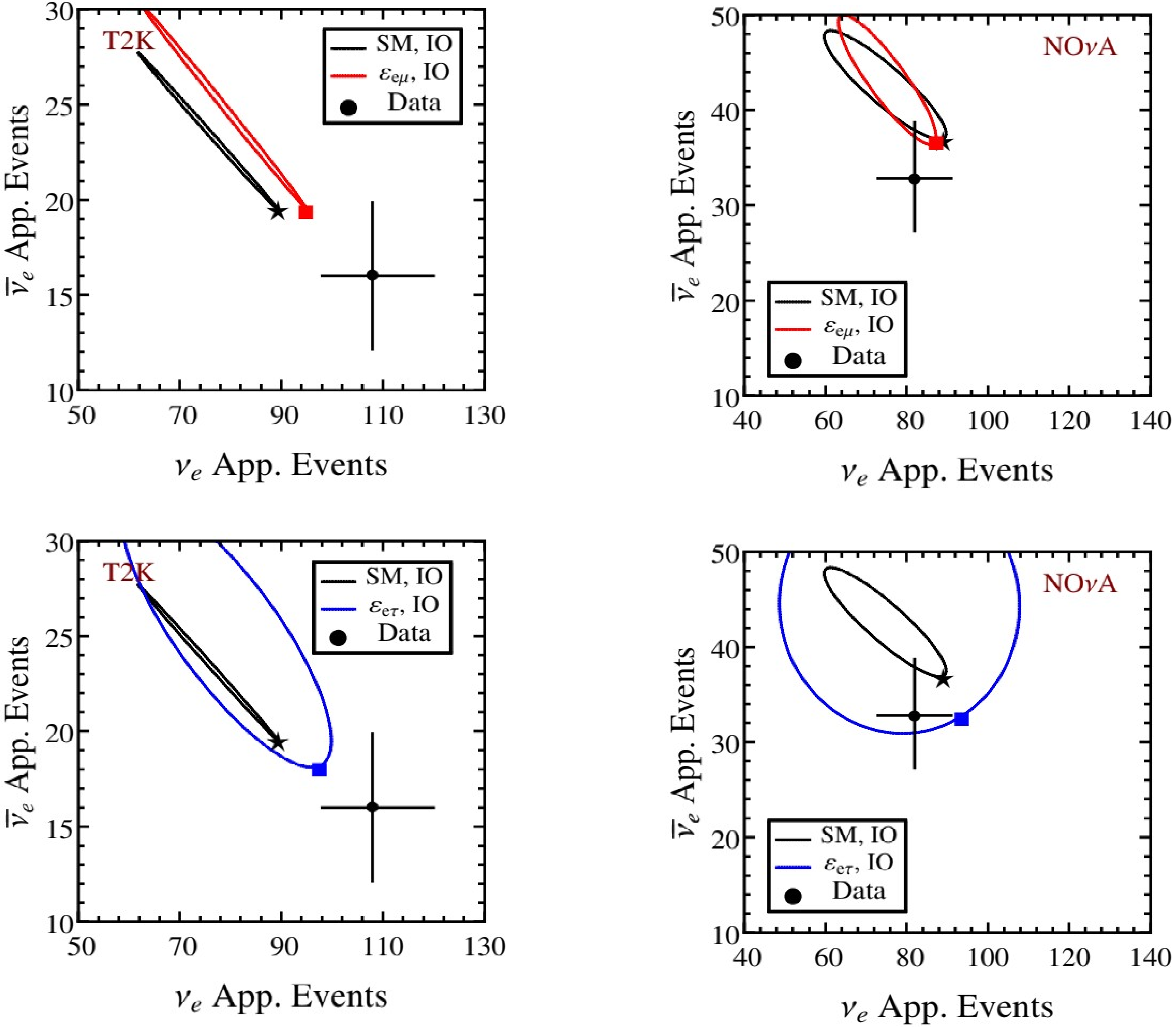
$$\bar{\nu}_l + p \rightarrow l^+ + n$$

In Liquid Ar detector

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



Bievent plots for NO



Bievent plots for IO