Exploring Neutrino NSI

Anjan Giri

IIT Hyderabad

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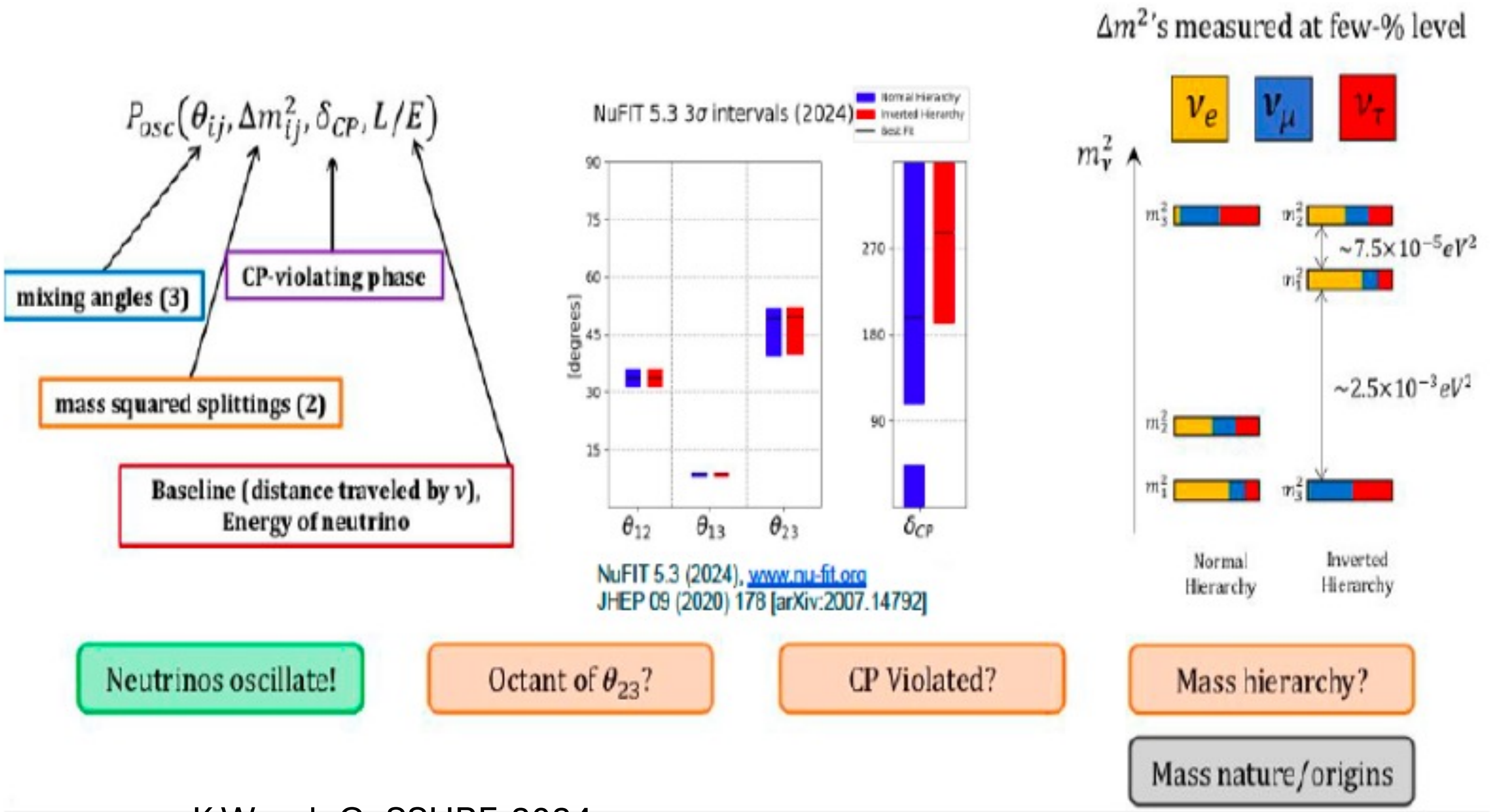
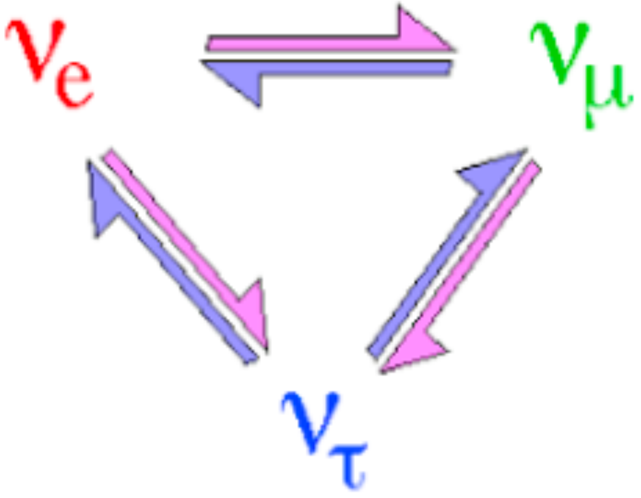
Plan of talk

- Introduction
- The current scenario
- Non-standard interaction
- Possible implications in the neutrino sector
- LFV muon decays
- Remarks

Challenges

- **Neutrino oscillation**
- **Octant theta-23**
- **CP violation**
- **Mass Hierarchy**
- **Nature/ Mass**





- Three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) are unitary linear combinations of three neutrinos mass eigenstates (ν_1, ν_2, ν_3) with masses m_1, m_2, m_3 $\rightarrow$ Neutrino mixing
- standard parameterization for PMNS matrix:

$$U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta_{cp})U_{12}(\theta_{12})$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Controls CP Violation

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- strength of CP violation is parameterized by the Jarlskog invariant:

$$J_{CP}^{PMNS} = \sin\theta_{12}\cos\theta_{12}\sin\theta_{13}\cos^2\theta_{13}\sin\theta_{23}\cos\theta_{23}\sin\delta_{cp}$$

$$J_{CKM} \approx 3 \times 10^{-5} \text{ (PDG)}$$

[arxiv:0308040 (Lepton Photon 2003) using $\gamma \approx 70^\circ$]

- Using the recent results of nuFit v5.1, in lepton sector:

$$J_{PMNS} \approx 0.034.\sin\delta_{CP}$$

CP violation

- CPV in lepton sector is essential
- CPV can be measured in oscillation experiment $P(\nu_\alpha \to \nu_\beta)$
- Comparing neutrino probability with anti-neutrino probability
- So for CP Violation in neutrino mixing matrix

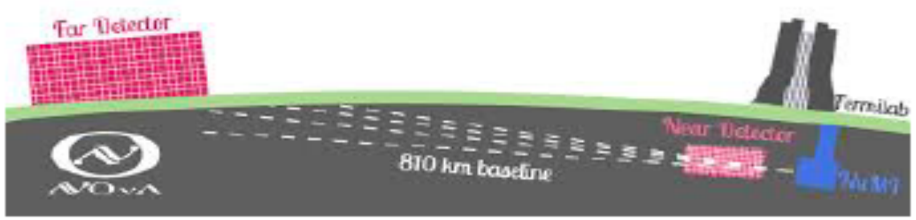
$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu_\alpha} \to \bar{\nu_\beta})$$

- In this discussion, we will use $P(\nu_\mu \to \nu_e)$ as oscillation channel.

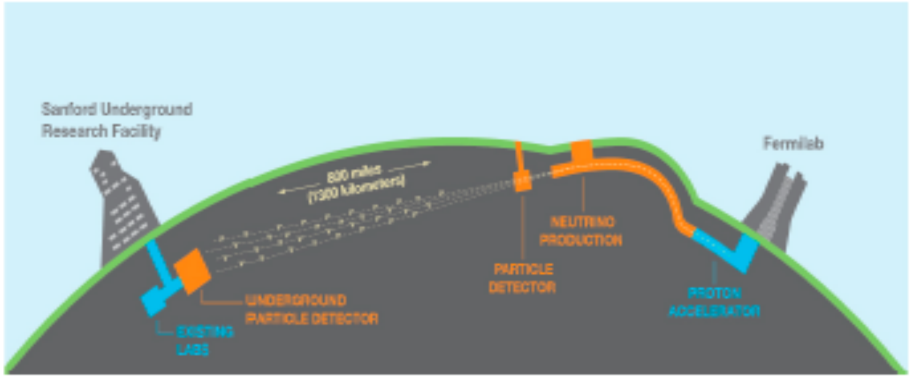
Precision frontier -> Indirect hint from high scale (multi-TeV) physics

DUNE

- Detect neutrinos in Fermilab's NuMI beam
- 14 mrad off-axis, E $\approx$ 2 GeV
- Active liquid scintillator calorimeter
- Baseline $\rightarrow$ 810 Km
- Two Detectors:
    - Near detector $\rightarrow$ 0.3 kt
    - Far Detector $\rightarrow$ 14 kt



- proposed future superbeam experiment at Fermilab
- Liquid Argon (LAr) detector of mass 40 kt
- Baseline $\rightarrow$ 1300 Km
- Far detector $\rightarrow$ Homestake mine in South Dakota.

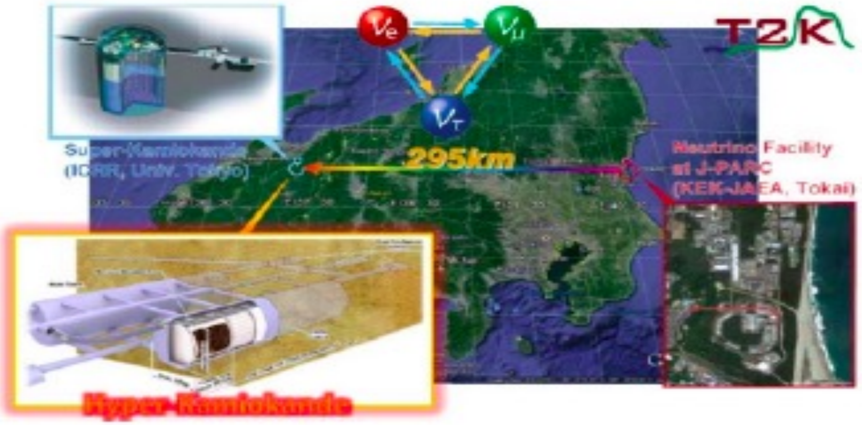


T2K

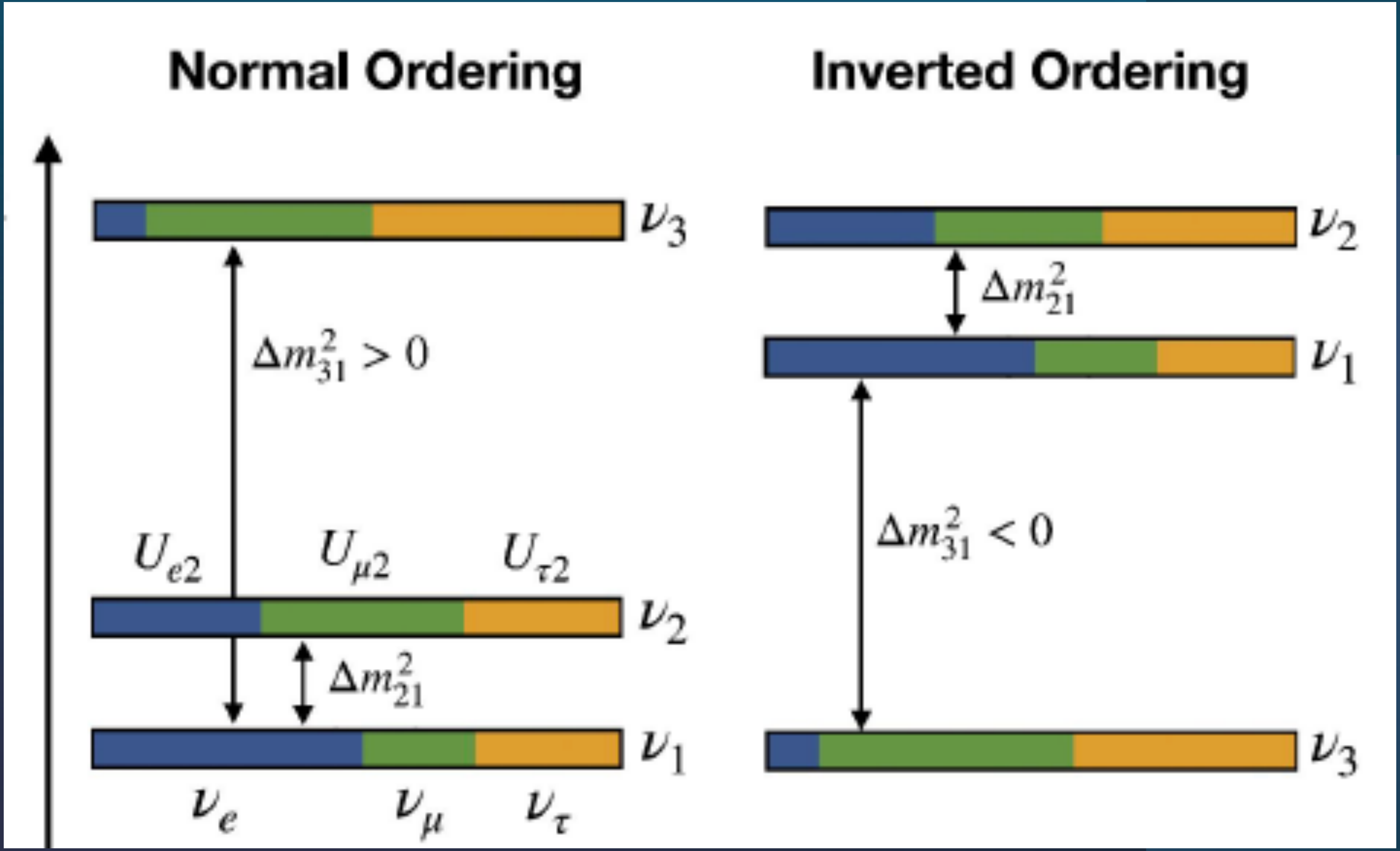
- Detect neutrinos in JPARC beam
- 43 mrad off-axis, E $\approx$ 0.65 GeV
- water Chrenkov Detector
- Baseline $\rightarrow$ 295 Km
- Two Detectors:
    - Near Detector $\rightarrow$ ND280, 280 metres from the target
    - Far Detector $\rightarrow$ (Super K), 295 km from the target in Tokai.

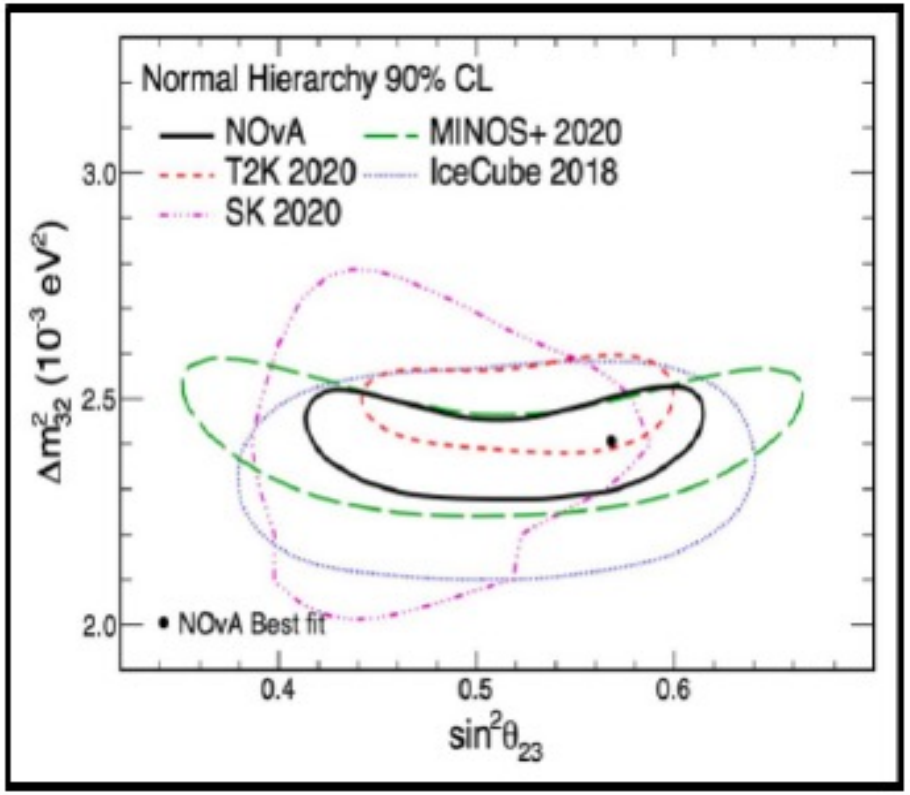
T2HK

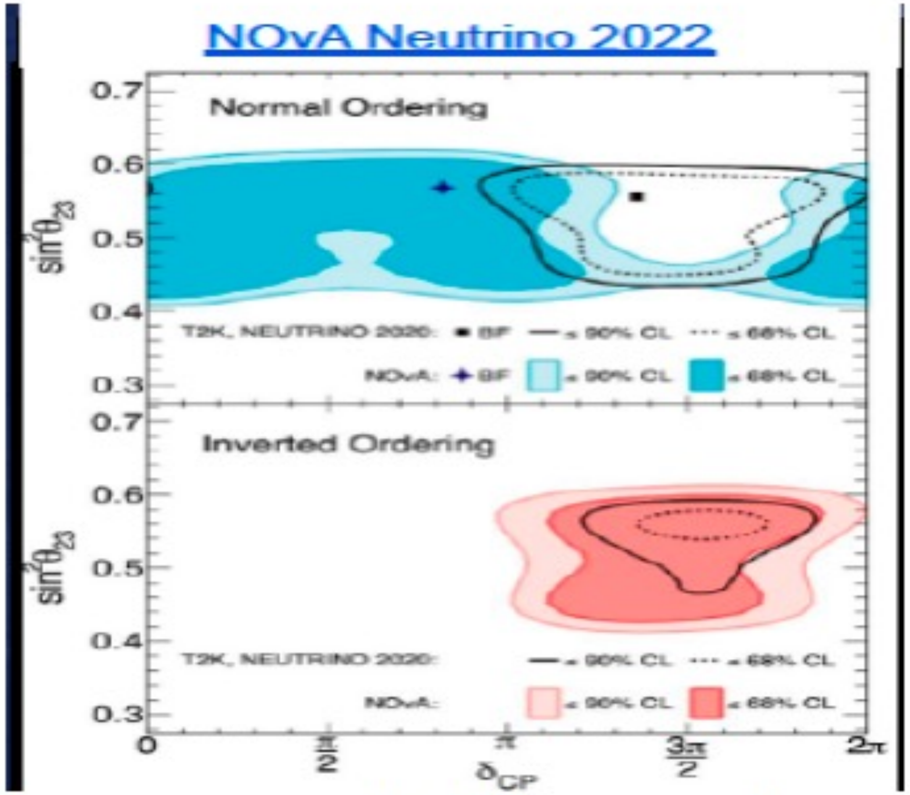
- Upgraded version of T2K
- fiducial mass will be increased by about twenty times
- will contain two 187 kt third generation Water Cherenkov detectors
- Baseline $\rightarrow$ 295 Km



Mass ordering ?

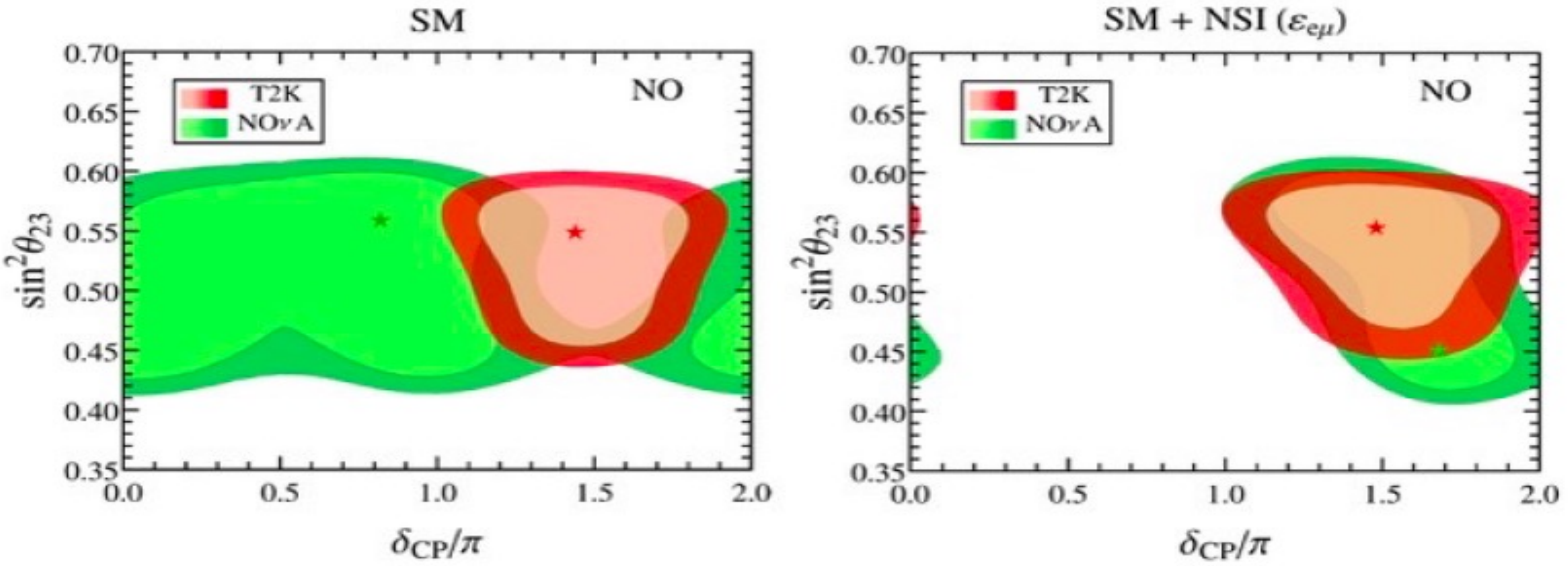






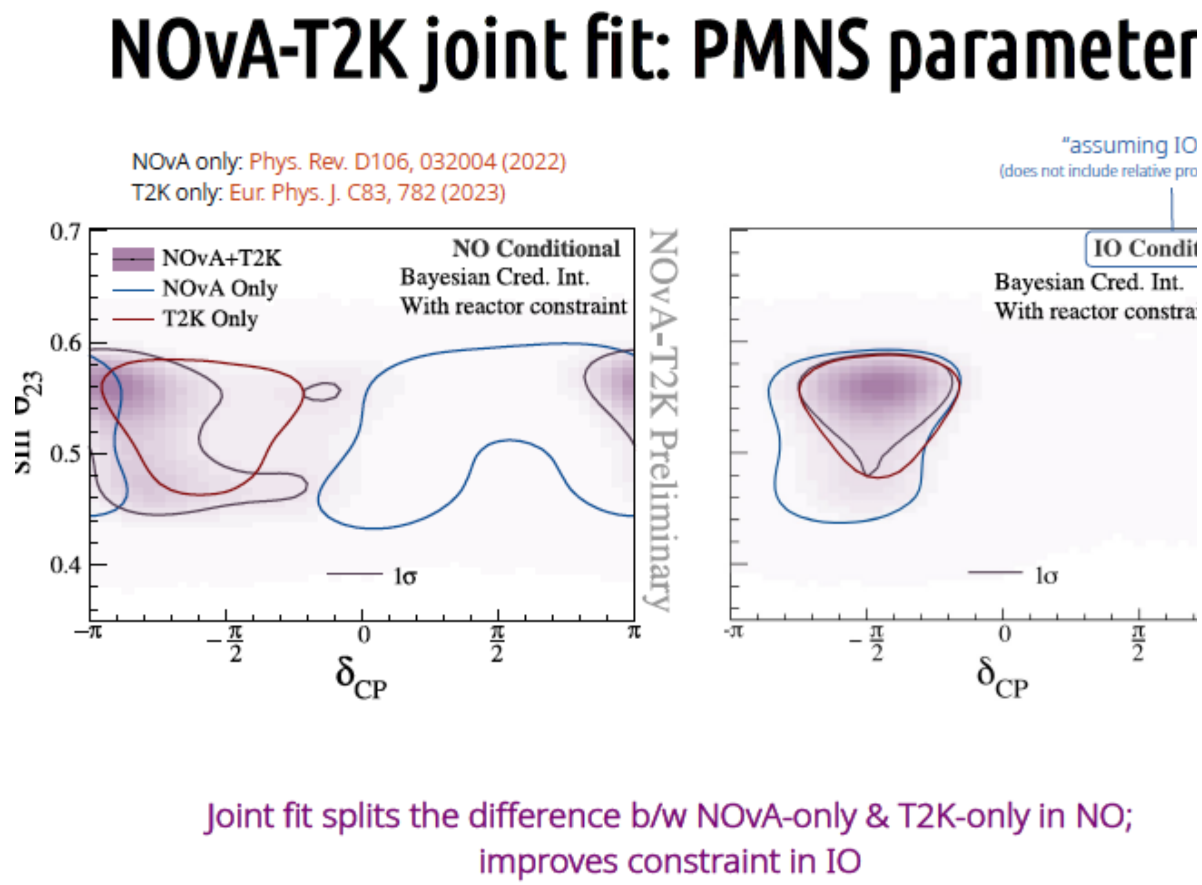
- The best fit value for θ_{23} in the higher octant and different values of δ_{CP} by NOvA for NO and IO.

Possible solution



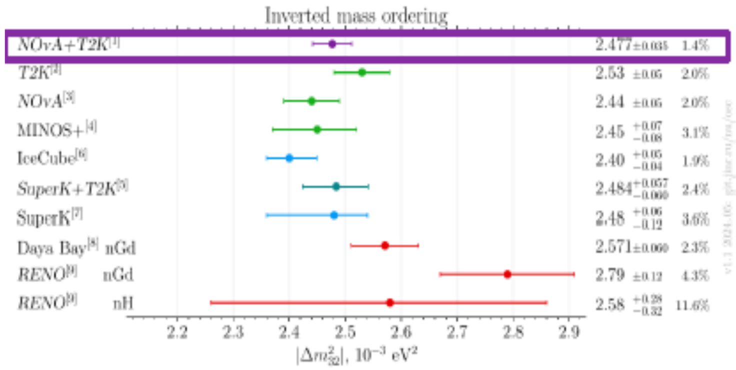
PRL,126, 051802 (2021)
PRL 126, 051801 (2021)

- Joint fit T2K-NOvA
- IO – both similar
- NO- differ
- Joint flit- split difference



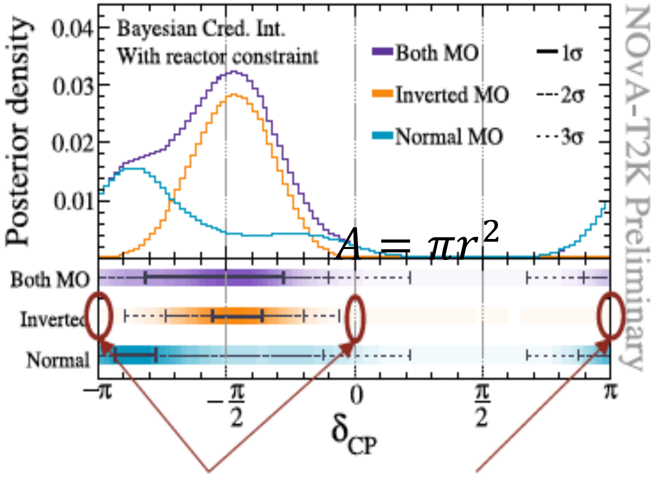
NOvA-T2K joint fit: takeaways

Advancing the precision frontier on $|\Delta m^2_{32}|$
<2% measurement!



Mild preference for Inverted Ordering
but influenced by θ_{13} constraint

NOvA+T2K only	NOvA+T2K + 1D θ_{13}	NOvA+T2K + 2D (θ_{13}, Δm^2_{32})
IO (71%)	IO (57%)	NO (59%)



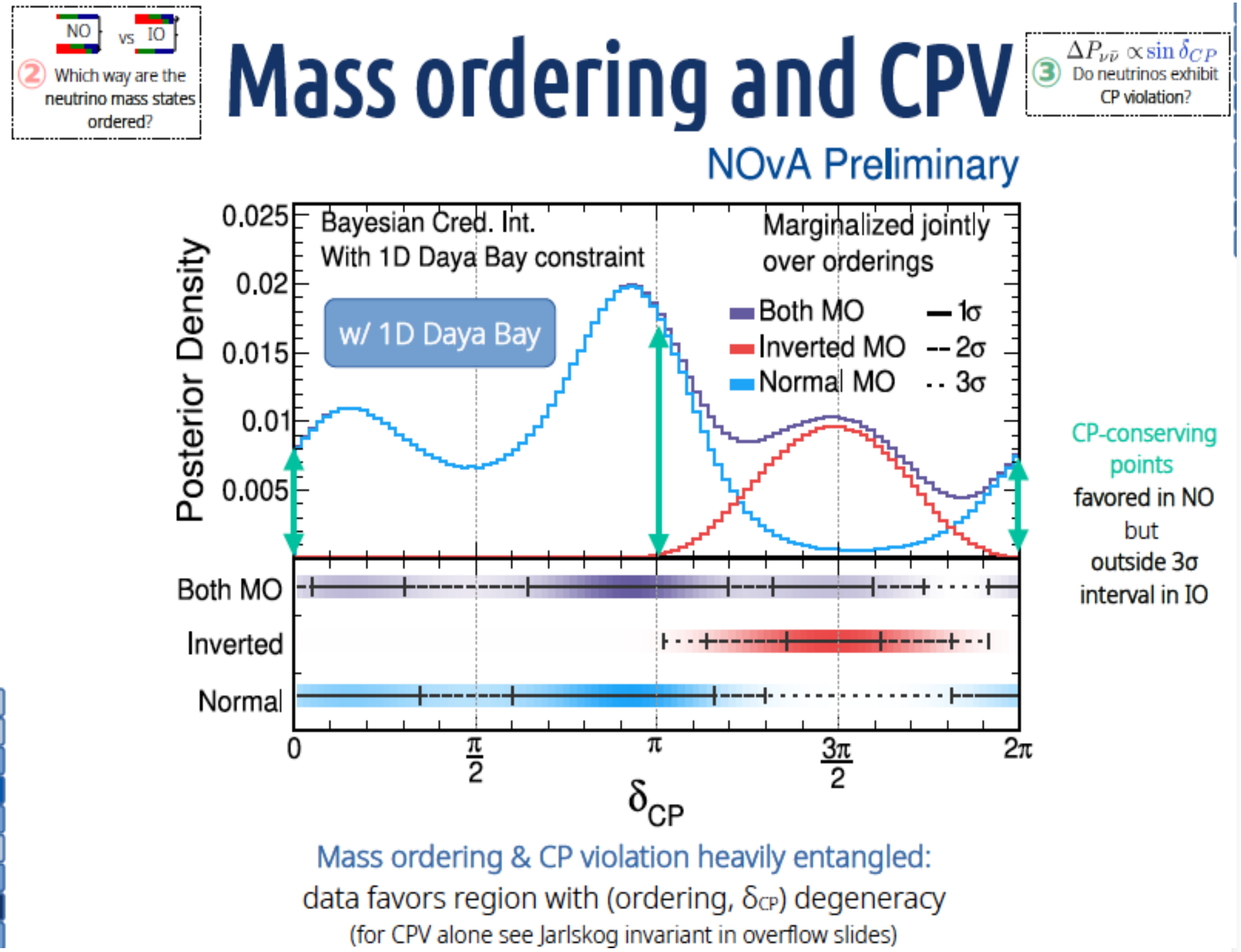
CP-conserving points are *outside* 3σ intervals in IO
Expect CPV *if* ordering is inverted

- Mild preference for NO
- CP conservation points outside of 3 sigma – IO
- Expect CPV if IO

J Wolcott, Neutrino 2024

NOvA

- CP – Conserving points favored in NO
- Outside -3 sigma IO
- Mass ordering & CPV entangled

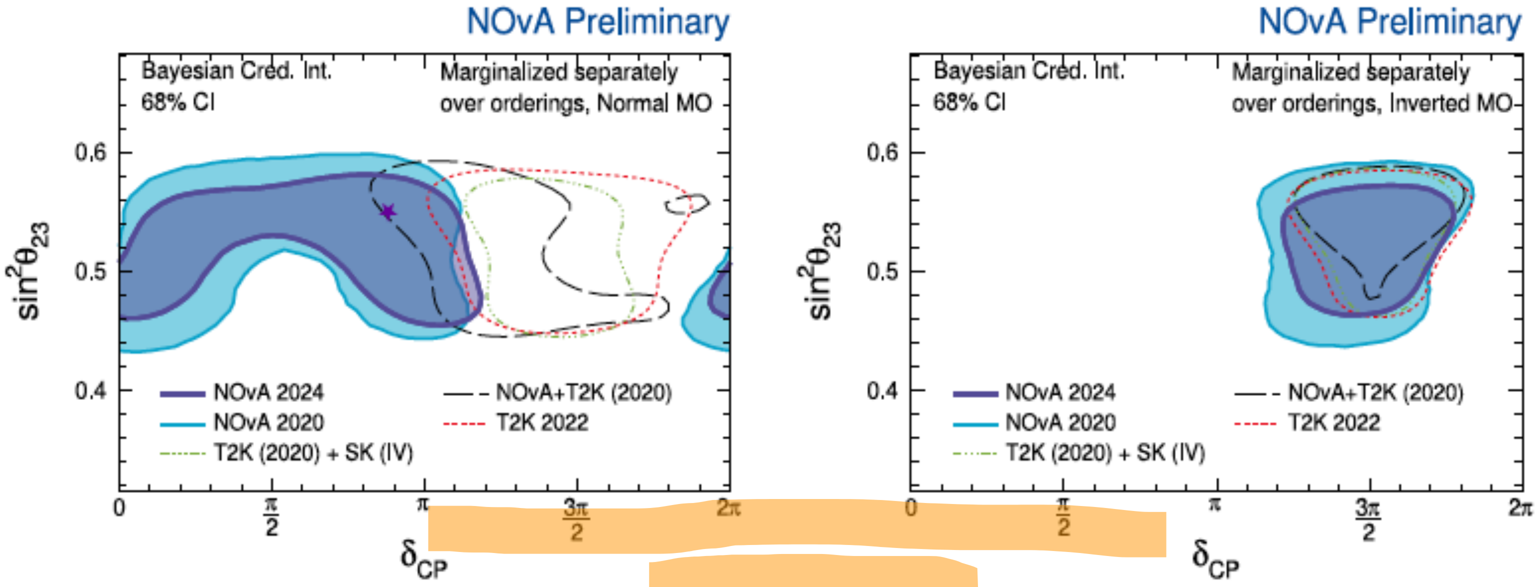


J Wolcott- Neutrino 16-22 June 2024

② Which way are the neutrino mass states ordered?

Mass ordering and CPV

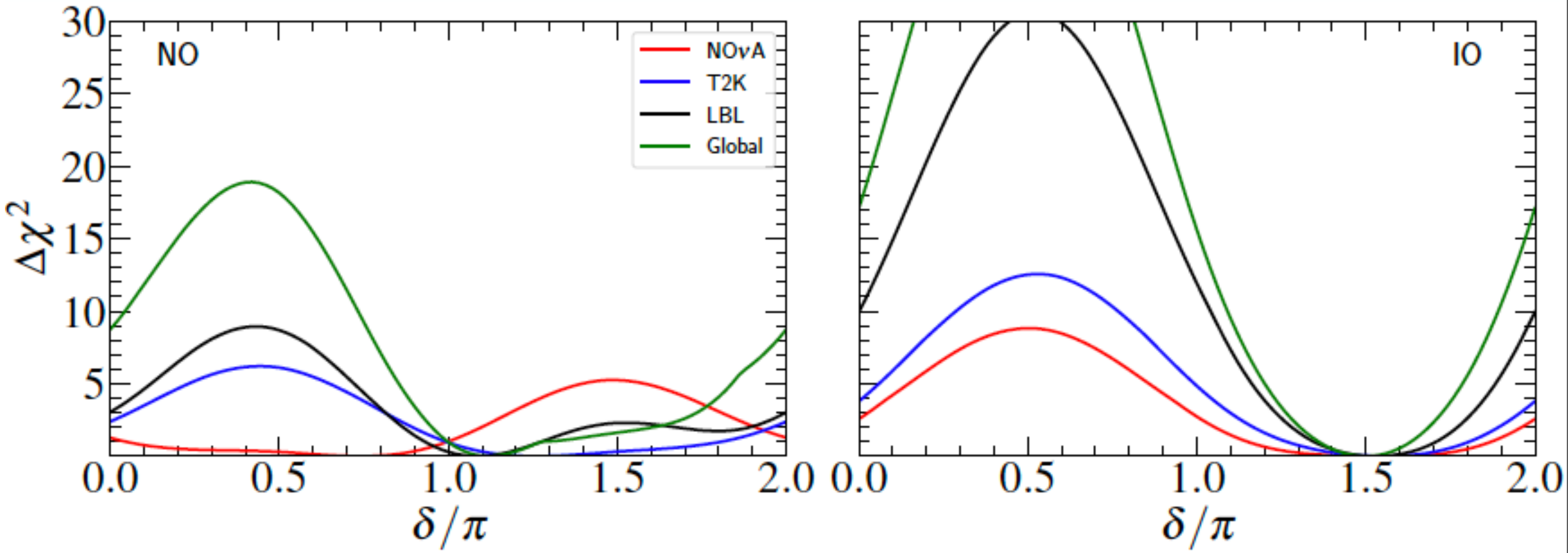
③ $\Delta P_{\nu\bar{\nu}} \propto \sin\delta_{CP}$ Do neutrinos exhibit CP violation?



NOvA vs. other data favor different regions in NO, same region in IO

The CP phase

Valencia Global Fit (Pre-Nu2024)



- NO: mismatch between NOvA and T2K and SK atmospheric results

  $\delta_{BF} = 1.12\pi$; $\delta = \pi/2$ (0) disfavored at 4.3σ (2.9σ)

- IO: all experiments prefer $\delta \approx 3\pi/2$

  $\delta_{BF} = 1.5\pi$; $\delta = \pi/2$ (π) disfavored at 6.8σ (3.9σ)

$\theta_{23} > 45°$

normal ordering preferred over IO

Tensions in global fits to 3ν oscillations ?

Tensions among datasets revealed by global fits

$\delta_{BF} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ disfavored

NSI

- The main difference between NOνA-T2K as well as DUNE-T2HK is the baseline and matter density, apart from energy.
- Neutrinos at NOνA and DUNE experience stronger matter effects than T2K and T2HK
- New physics signature could probably be inferred from this exercise
- **Non-standard Interactions (NSI) $\rightarrow$ LBL CP Sensitivity**

B Brahma, A Giri EPJ C 82, 1145 (2022)
[2302.09592, 2306.05258]

B Dev et al, 1907.00991; S Choubey, JHEP 12, 126 (2015); R Majhi et al, 2205.04269, K Babu et al, 1908.02779; Farzan and Tortola, Front. Phys. 6, 10 (2018),....

- NSI can be characterized by dimension-six four-fermion operators of the form:

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} [\overline{\nu_\alpha}\gamma^\mu \nu_\beta][\bar{f}\gamma_\mu f] \tag{1}$$

- The neutrino propagation Hamiltonian in the presence of matter, NSI, can be expressed as

$$H_{Eff} = \frac{1}{2E}\left[U_{PMNS}\begin{bmatrix}0 & 0 & 0\\ 0 & \delta m_{21}^2 & 0\\ 0 & 0 & \delta m_{31}^2\end{bmatrix}U_{PMNS}^\dagger + V\right] \tag{2}$$

where,

$$V = 2\sqrt{2}G_F N_e E \begin{bmatrix}1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}}\\ \epsilon_{\mu e}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}}\\ \epsilon_{\tau e}e^{-i\phi_{e\tau}} & \epsilon_{\tau\mu}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau}\end{bmatrix}$$

where, $\epsilon_{\alpha\beta}e^{(i\phi_{\alpha\beta})} \equiv \sum_{f=e,u,d}(\epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR})\frac{N_f}{N_e}$

- In the presence of NSI from $e\mu$ and $e\tau$ sectors, the probability can be expressed as the sum of terms *:

$$P_{\mu e} = P_{SM} + P_{\epsilon_{e\mu}} + P_{\epsilon_{e\tau}} + P_{Int} + h.o.$$

where,

$$P_0 = 4s_{13}^2 s_{23}^2 f^2 + 8 s_{13} s_{23} s_{12} c_{12} c_{23} r f g \cos(\Delta + \delta_{CP}) + 4 r^2 s_{12}^2 c_{12}^2 c_{23}^2 g^2$$

- P_0 denotes the SM probability expression

where,

$$f \equiv \frac{\sin[(1-\hat{A})\Delta]}{1-\hat{A}},\ g \equiv \frac{\sin \hat{A}\Delta}{\hat{A}},\ \hat{A} = \frac{2\sqrt{2} G_F N_e E}{\Delta m_{31}^2},\ \Delta = \frac{\Delta m_{31}^2 L}{4E},\ r = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$$

(*Phys.Rev.D77:013007,2008, JHEP 0903:114,2009, JHEP 0904:033,2009, Phys.Rev.D93,093016(2016))

$$
\begin{aligned}
P_{\epsilon_{e\mu}} &= 4\hat{A}\epsilon_{e\mu}[xf^2 s_{23}^2 \cos(\Psi_{e\mu}) + xfgc_{23}^2 \cos(\Delta + \Psi_{e\mu}) + yg^2 c_{23}^2 \cos\phi_{e\mu} \\
&+ ygfs_{23}^2 \cos(\Delta - \phi_{e\mu})] + 4\hat{A}^2\epsilon_{e\mu}^2[f^2 s_{23}^4 + g^2 c_{23}^4 + 2fgs_{23}^2 c_{23}^2 \cos\Delta]
\end{aligned}
$$

$$\text{where } \Psi_{e\mu} = \phi_{e\mu} + \delta_{CP}$$

$$
\begin{aligned}
P_{\epsilon_{e\tau}} &= 4\hat{A}\epsilon_{e\tau}[xf^2 s_{23}c_{23} \cos(\Psi_{e\tau}) - xfgs_{23}c_{23} \cos(\Delta + \Psi_{e\tau}) \\
&- yg^2 s_{23}c_{23} \cos\phi_{e\tau} + ygfs_{23}c_{23}f \cos(\Delta - \phi_{e\tau})] \\
&+ 4\hat{A}^2\epsilon_{e\tau}^2 s_{23}^2 c_{23}^2[g^2 + f^2 - 2fg\cos\Delta]
\end{aligned}
$$

$$\text{where } \Psi_{e\tau} = \phi_{e\tau} + \delta_{CP}$$

$$
\begin{aligned}
P_{Int} &= 8\hat{A}^2 c_{23}s_{23}\epsilon_{e\mu}\epsilon_{e\tau}[g^2 c_{23}^2 + f^2 s_{23}^2 + 2fgc_{23}^2 \cos(\phi_{e\mu} - \phi_{e\tau})\cos\Delta \\
&- fg\cos(\Delta - \phi_{e\mu} + \phi_{e\tau})]
\end{aligned}
$$

- The flavor changing parameter of NSI:

$$|\epsilon_{e\mu}|e^{i\phi_{e\mu}},\ |\epsilon_{e\tau}|e^{i\phi_{e\tau}},\ |\epsilon_{\mu\tau}|e^{i\phi_{\mu\tau}}$$

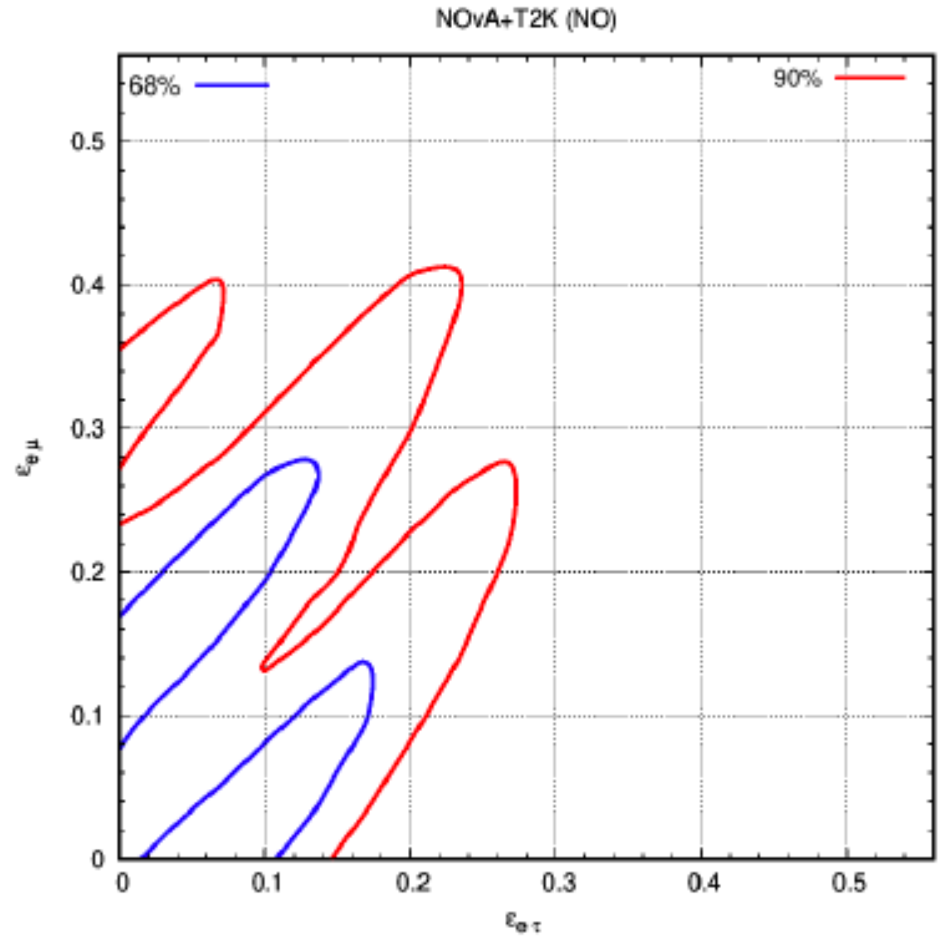
- In this work, we consider only the propagation NSI.
- Will discuss the effect of NSI ranges on sensitivity as well as oscillation probability plots for DUNE and T2HK.
- Use GLoBES and its additional public tools to deal with non-standard interactions *.

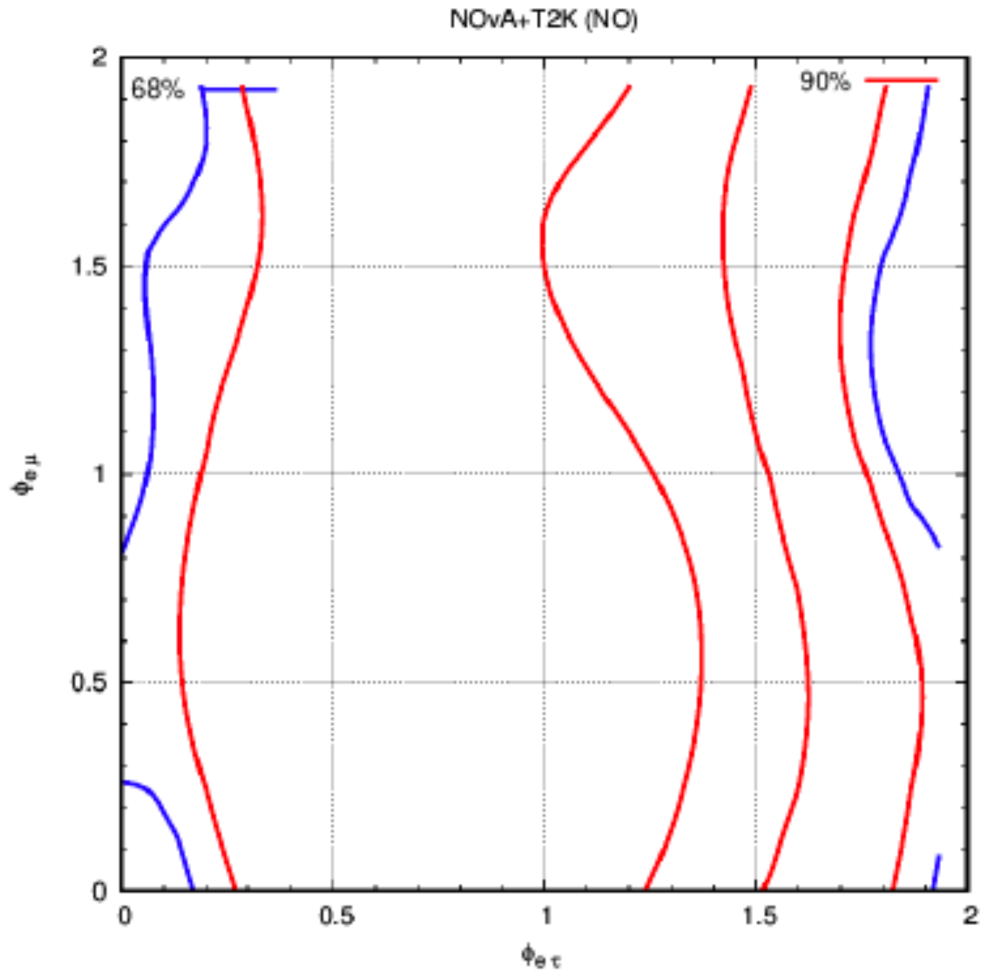
(*Comp.Phys.Comm, 167 (2005) 195; Comp. Phys. Comm, 177 (2007) 432; https://www.mpi-hd.mpg.de/personalhomes/globes/tools/snu-1.0.pdf (2010).)

Parameters used

SM Parameters	bfp $\pm 1\sigma$ NO	bfp $\pm 1\sigma$ IO
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.304^{+0.013}_{-0.012}$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.570^{+0.019}_{-0.016}$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02241^{+0.00074}_{-0.00062}$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	278^{+22}_{-30}
$\frac{\Delta m^2_{21}}{10^{-5}eV^2}$	$7.42^{+0.21}_{-0.20}$	$7.42^{+0.21}_{-0.20}$
$\frac{\Delta m^2_{3l}}{10^{-3}eV^2}$	$+2.510^{+0.027}_{-0.027}$	$-2.490^{+0.026}_{-0.028}$

2NSI constraints





Allowed regions in the plane spanned by NSI coupling for $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ by the combination of T2K and NOνA for NO

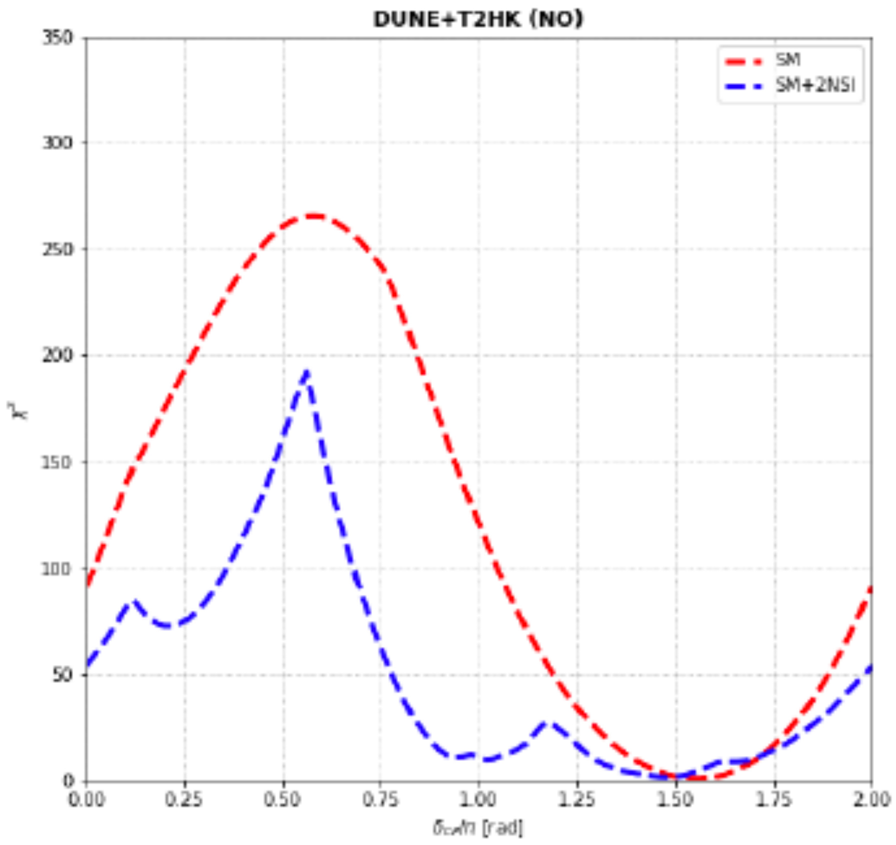
NSI Range

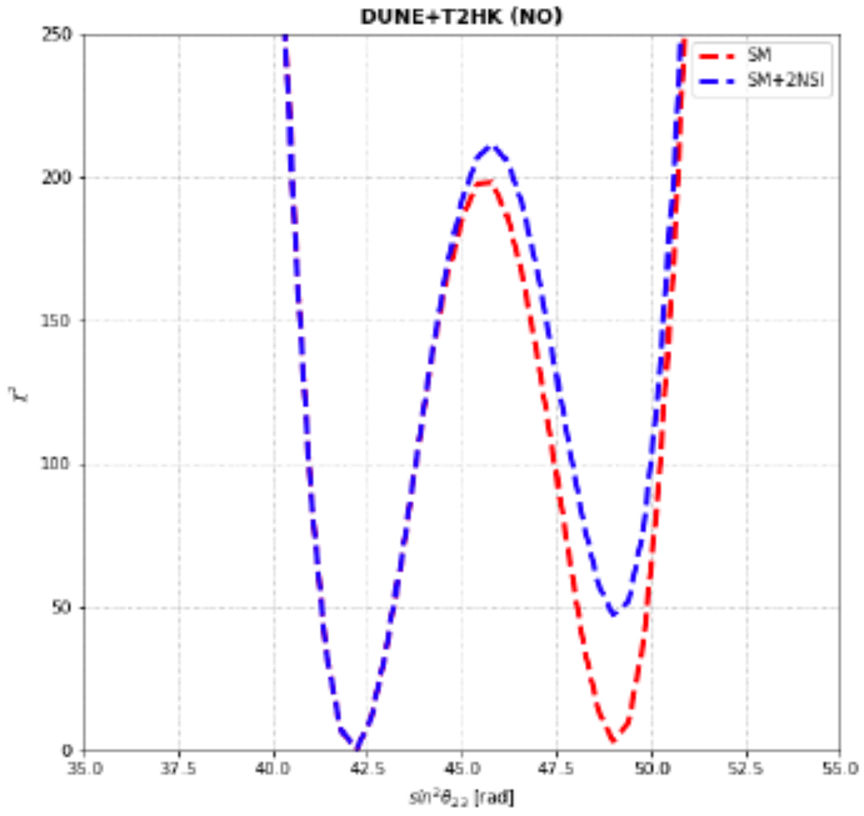
From the allowed region plots in the previous slides, the best-fit points are:

Mass Ordering	$\lvert\epsilon_{e\mu}\rvert$	$\lvert\epsilon_{e\tau}\rvert$
NO	0.22	0.06
IO	0.04	0.2
Mass ordering	$\phi_{e\mu}/\pi$	$\phi_{e\tau}/\pi$
NO	0.48	1.88
IO	1.24	1.87

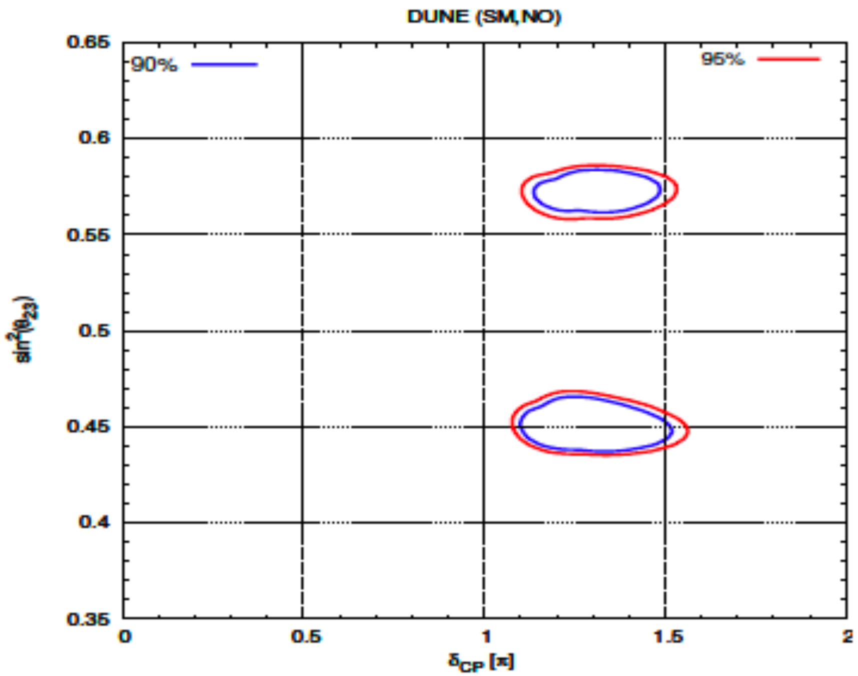
- In SM Plots the standard parameters θ_{13} is marginalized
- In SM+NSI plots, along with θ_{13} the NSI magnitudes $(|\epsilon_{e\mu}|, |\epsilon_{e\tau}|)$ as well as phase $(\phi_{e\mu}, \phi_{e\tau})$ are marginalized
- The plots display the allowed regions at the 68% and 95% level

1D plots with 2NSI

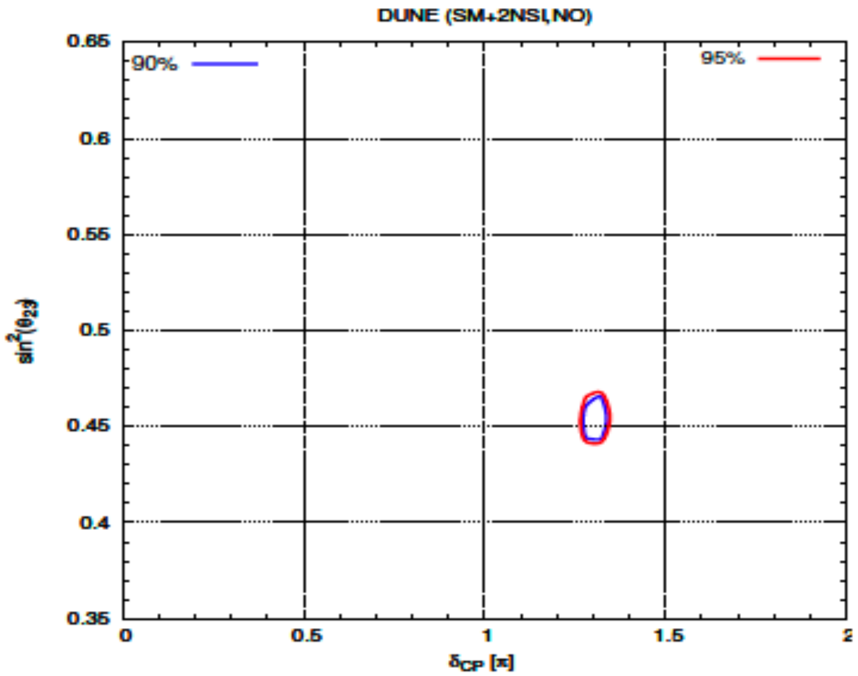




SM, NO

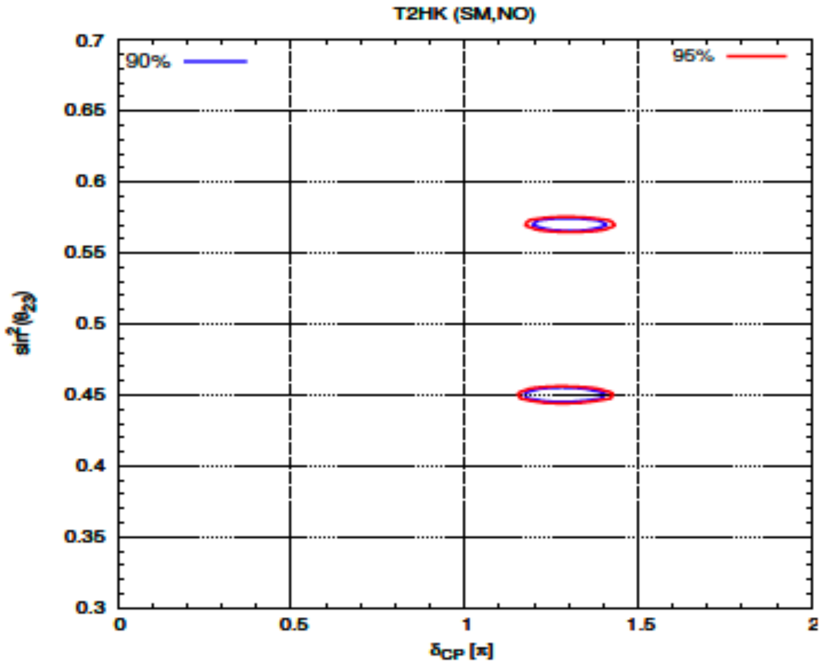


SM+ dual NSI, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ Sector, NO

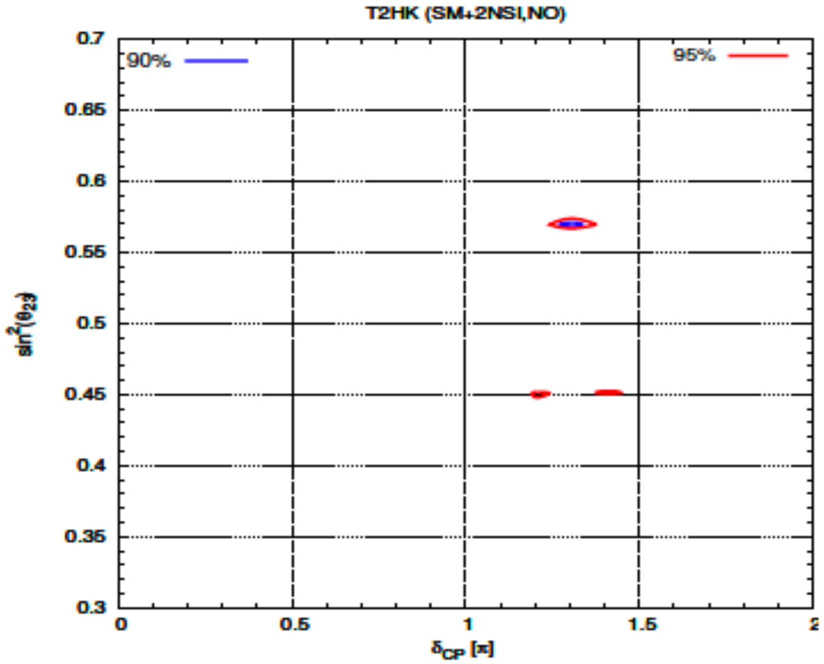


- With the inclusion of dual NSI from $e-\mu$ and $e-\tau$ sector, the allowed region corresponding to the higher octant in DUNE vanishes.

SM, NO

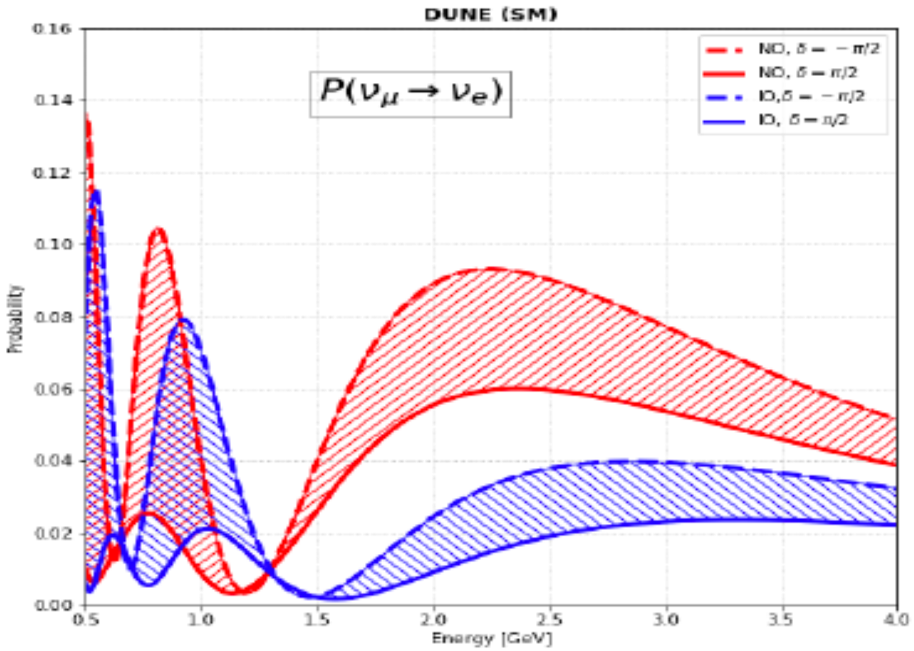


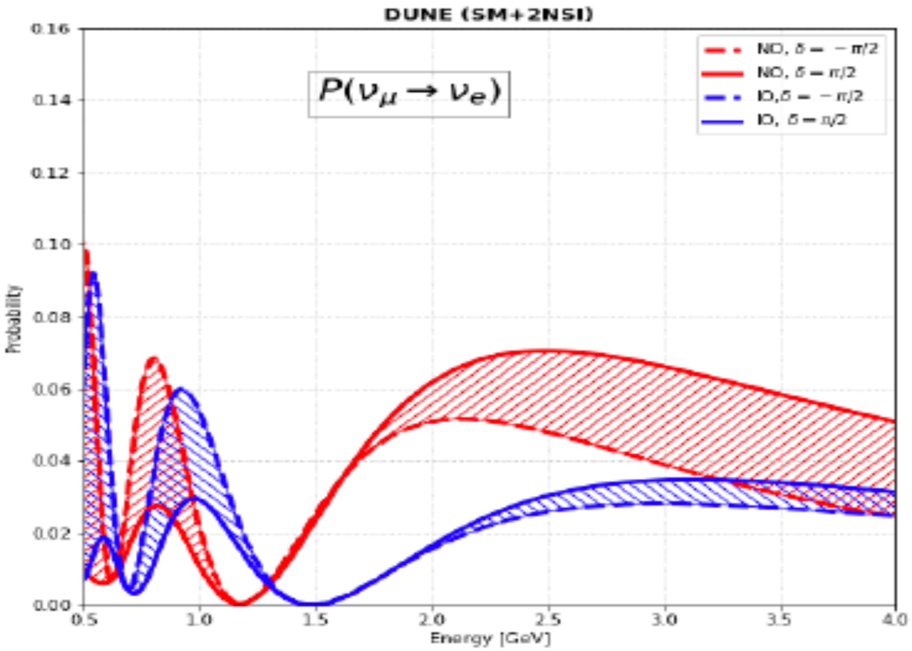
SM+dual NSI, $\epsilon_{e\mu}$ and $\epsilon_{e\tau}$ Sector, NO



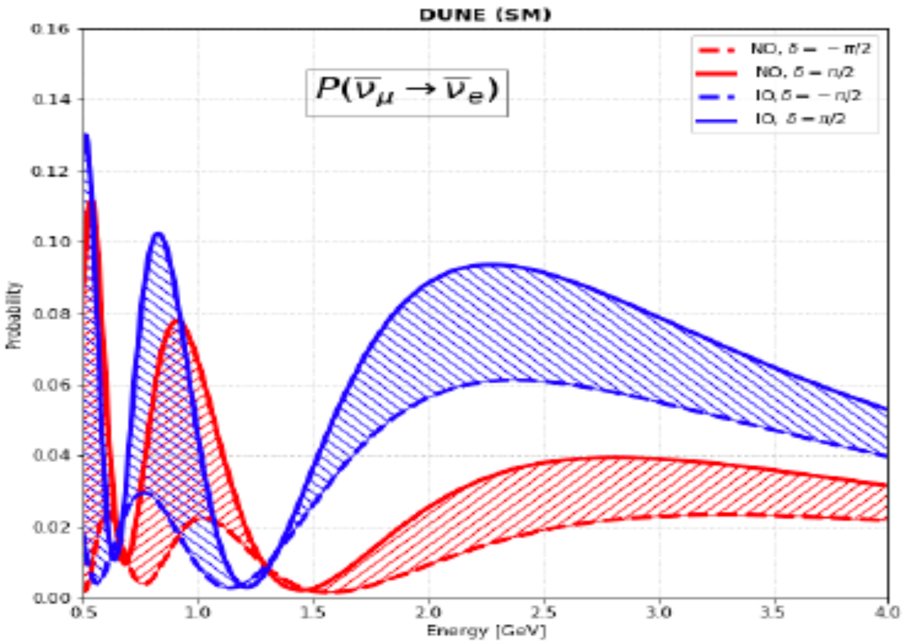
- With the inclusion of dual NSI from $e-\mu$ and $e-\tau$ sector, the allowed region corresponding to both the octants does not vanish completely.

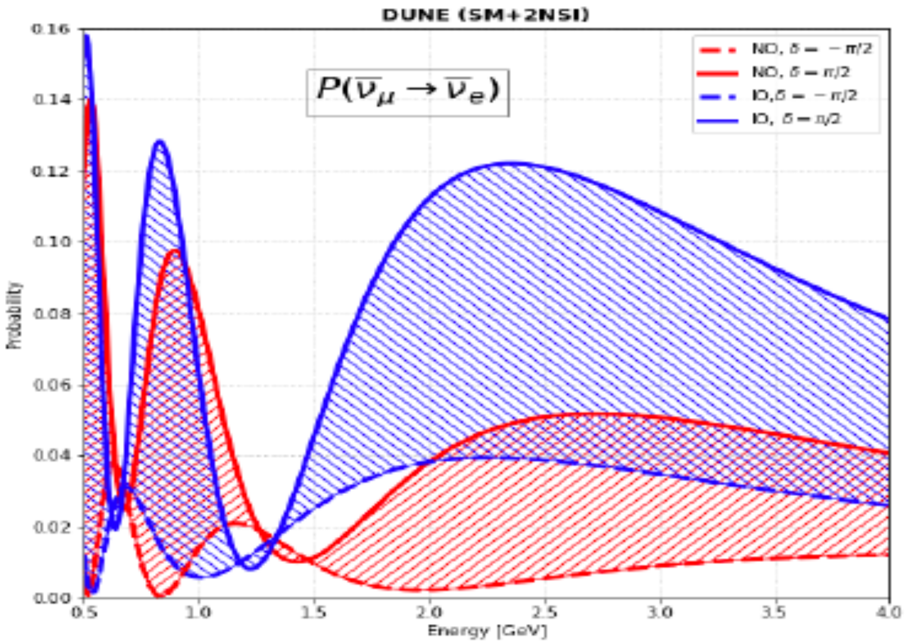
- For the SM scenario, we see a good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.
- For SM and dual NSI scenario, we still have some separation between NO-IO for $\delta_{CP} = -90^\circ$ in mid energy region, and they gradually merges around 4 GeV.



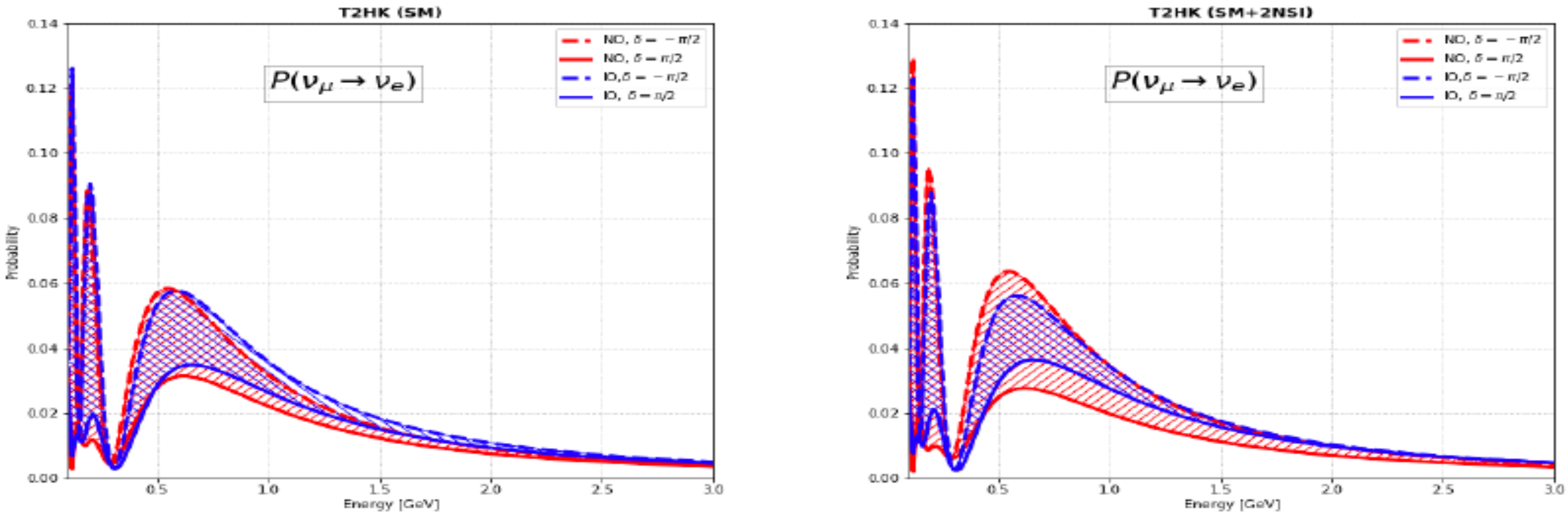


- For the SM scenario, we see a good separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$.
- For SM and dual NSI scenario, the separation between NO-IO for $\delta_{CP} = 90^\circ$ becomes more than in the SM case. Compared with the SM case, the NO-IO separation decreases for $\delta_{CP} = -90^\circ$.

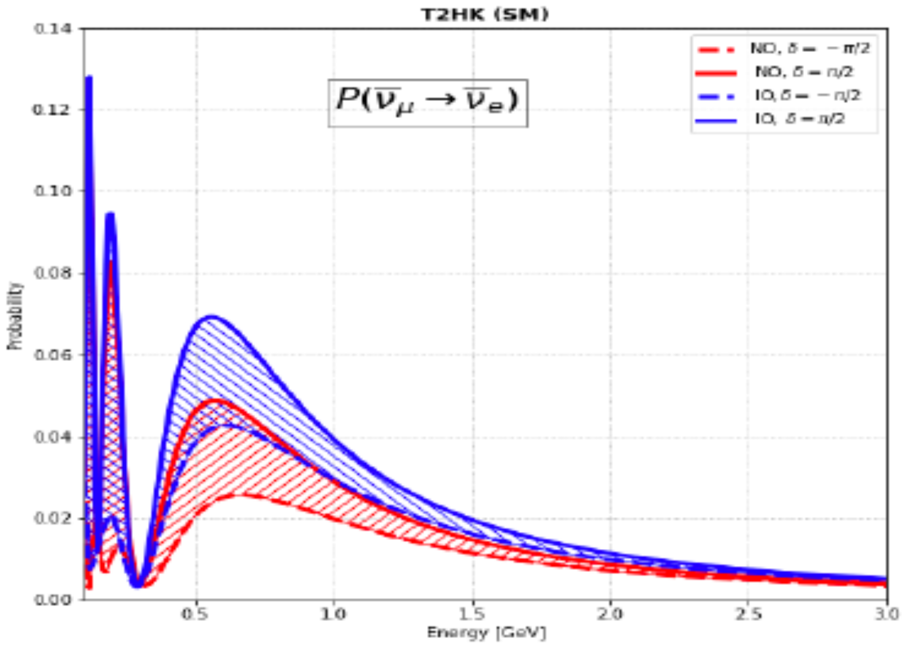


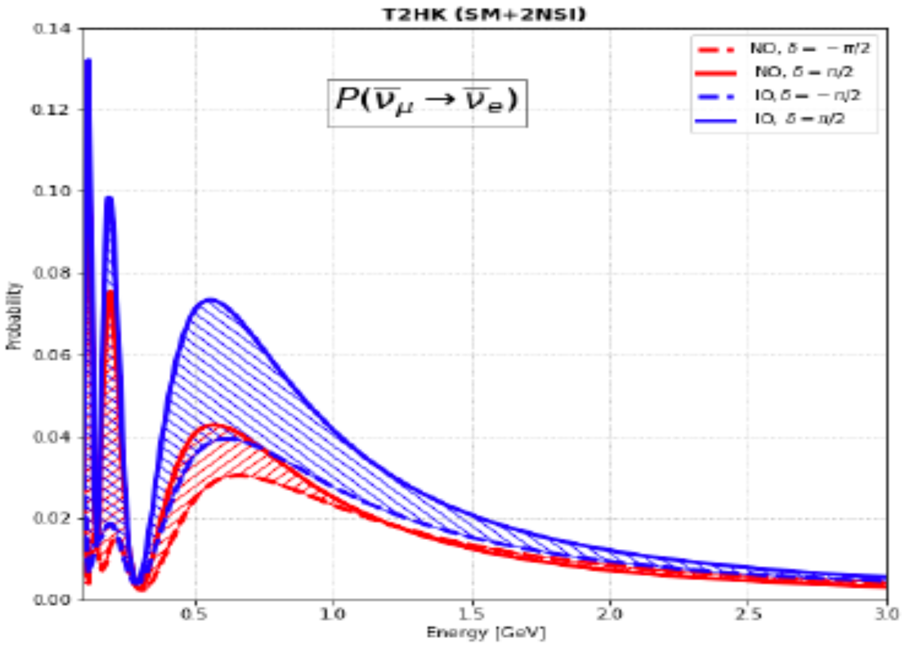


- For the SM scenario, we see a feeble separation between NO-IO for both $\delta_{CP} = 90°$ as well as $\delta_{CP} = -90°$ around 1 GeV.
- For the SM and dual NSI case, we see a better separation between NO-IO for both $\delta_{CP} = -90°$ and $\delta_{CP} = 90°$ around 1 GeV.

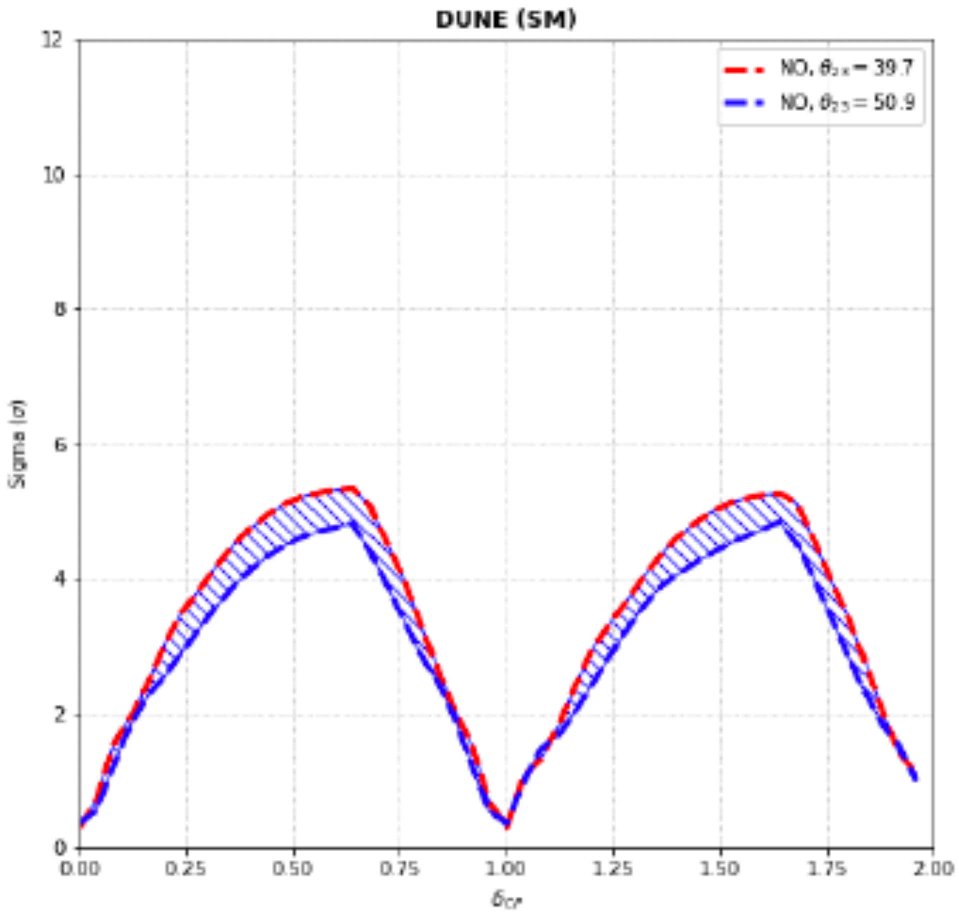


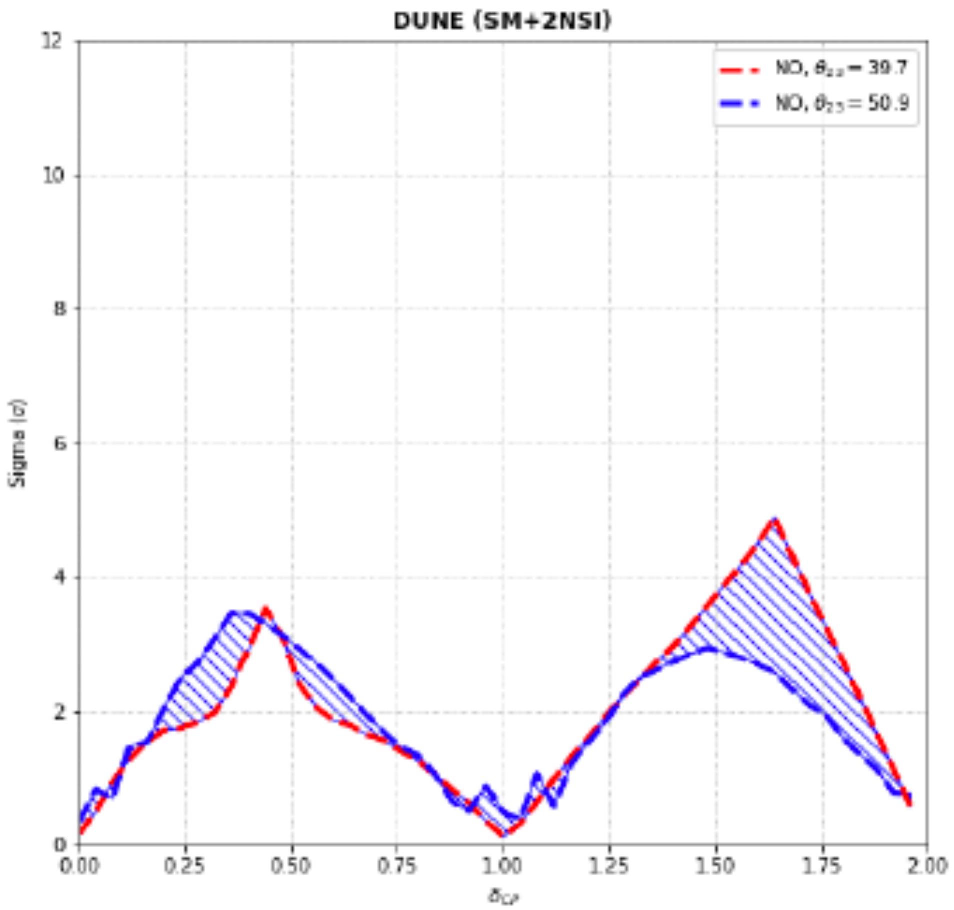
- For SM scenario, we see a perceivable separation between NO-IO for both $\delta_{CP} = 90^\circ$ as well as $\delta_{CP} = -90^\circ$ till 1.5 GeV.
- For SM and dual NSI case, we see a better separation between NO-IO for $\delta_{CP} = 90^\circ$. The NO-IO separation decreases for $\delta_{CP} = -90^\circ$ when compared to the SM case.





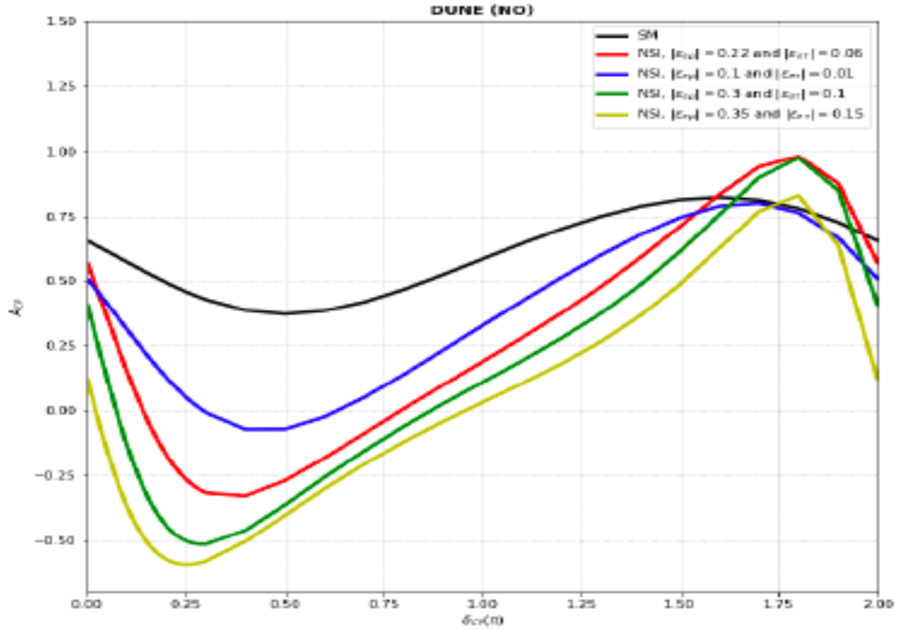
CP sensitivity with 2 NSI

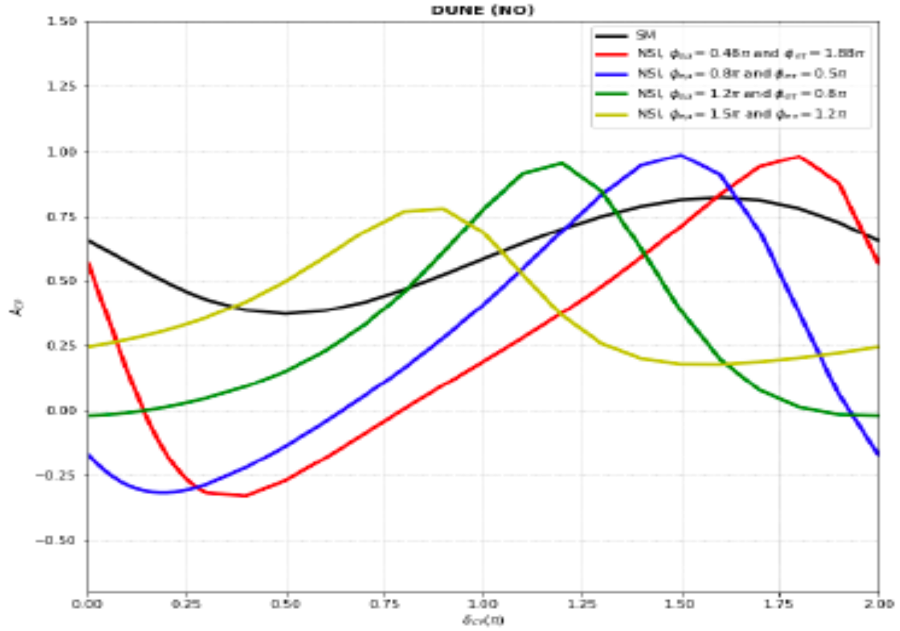




- Baseline = 1300 Km, Energy = 2.6 GeV

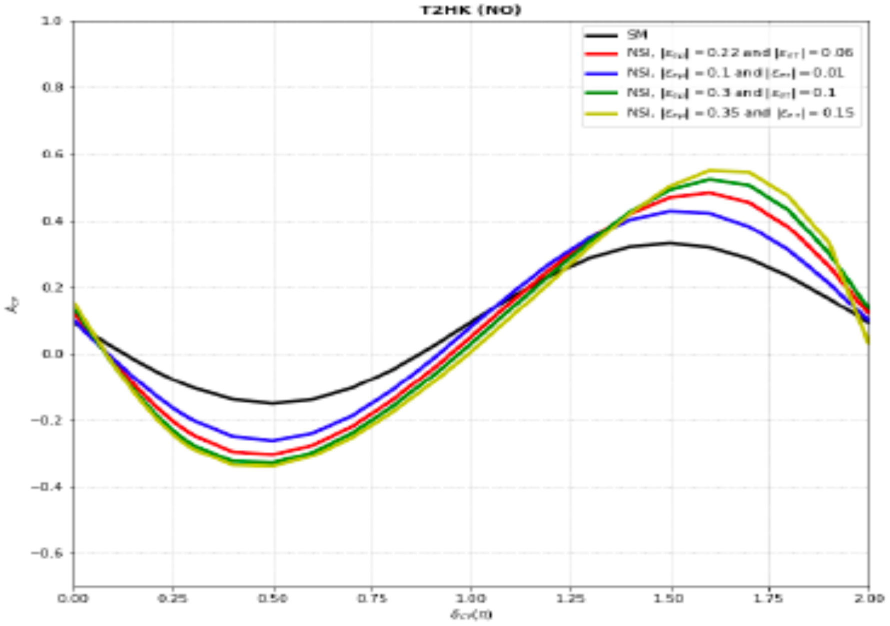
$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu_\mu} \to \bar{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\bar{\nu_\mu} \to \bar{\nu_e})}$$

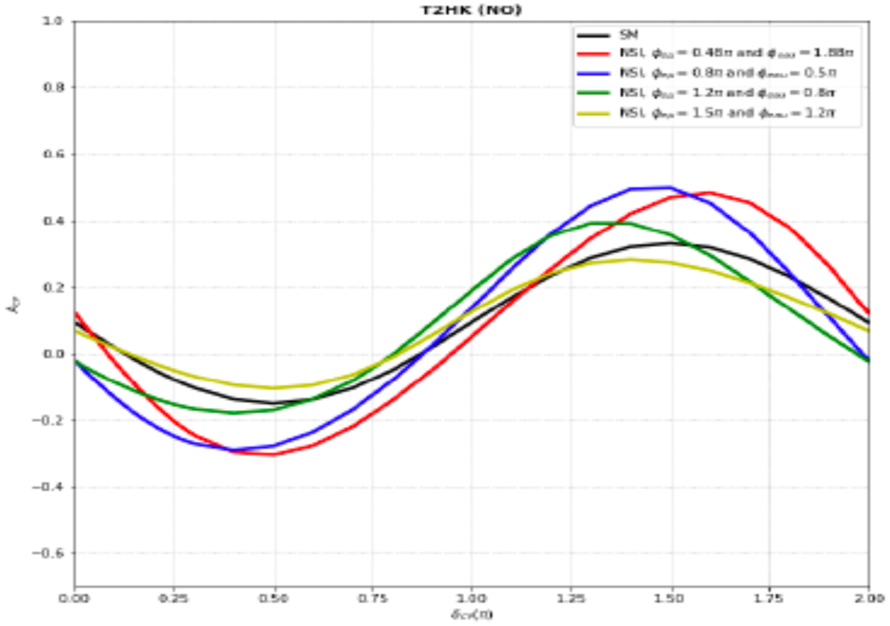




- Baseline = 295 Km, Energy = 0.6 GeV

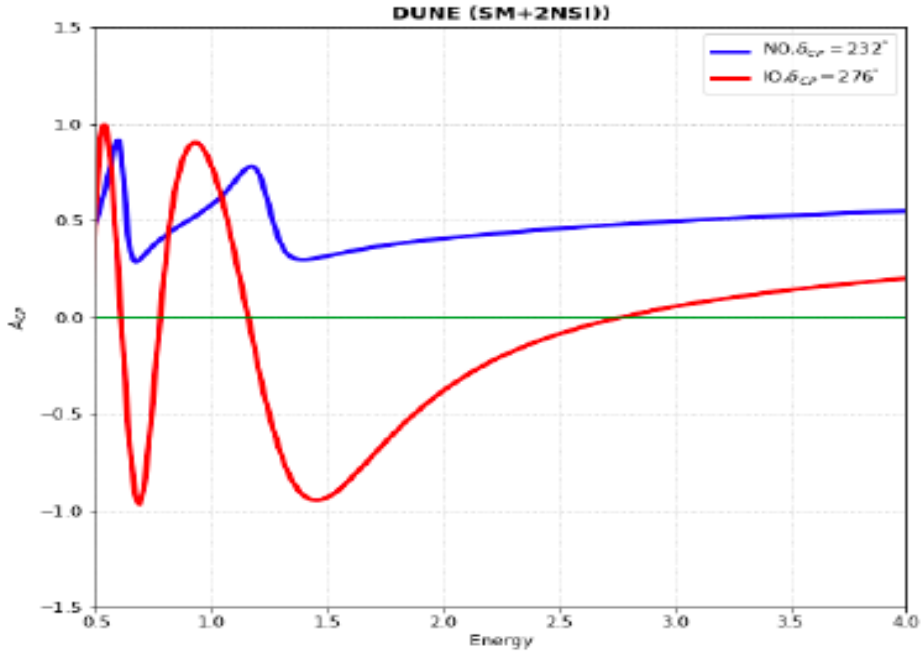
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})}$$

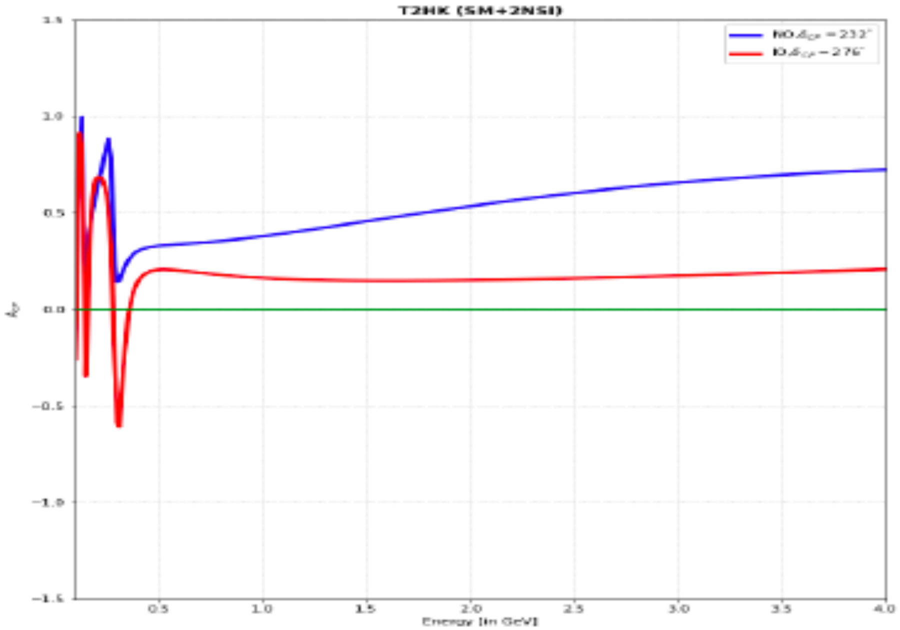




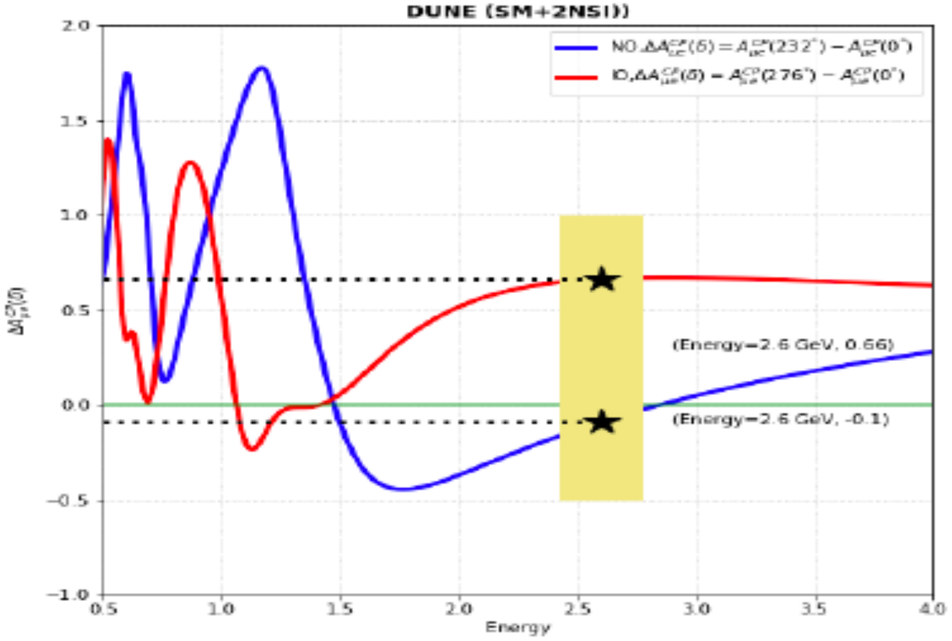
- For DUNE: Baseline $= 1300$ Km, $\delta_{CP} = 232^\circ$ (NO) and 272° (IO)
- For T2HK: Baseline $= 295$ Km, $\delta_{CP} = 232^\circ$ (NO) and 272° (IO)

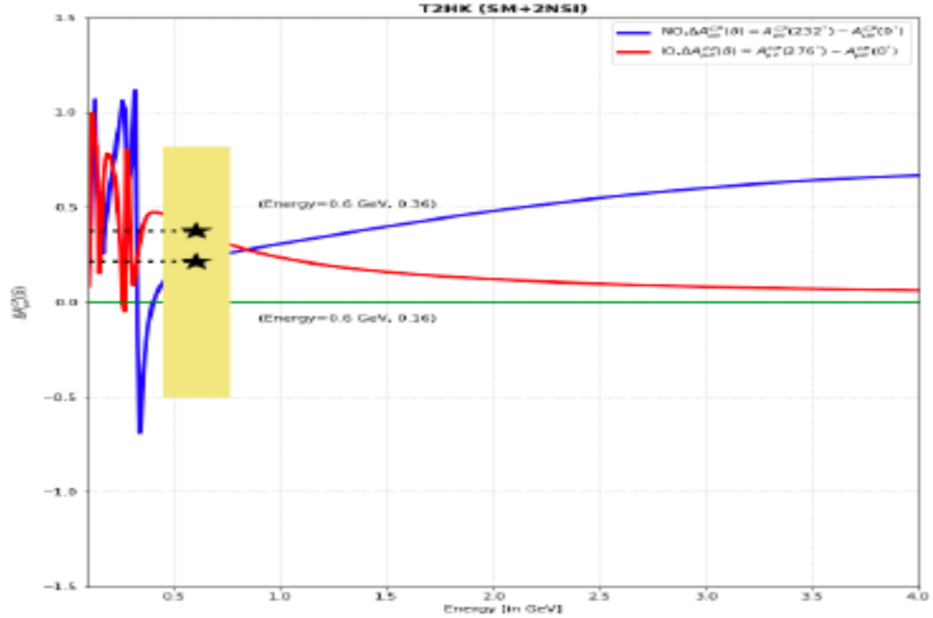
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu_\mu} \rightarrow \bar{\nu_e})}$$





- For DUNE: Baseline = 1300 Km, Energy = 2.6 GeV
- For T2HK: Baseline = 295 Km, Energy = 0.6 GeV
- SM parameter δ_{CP} is varied from 0 to 2π

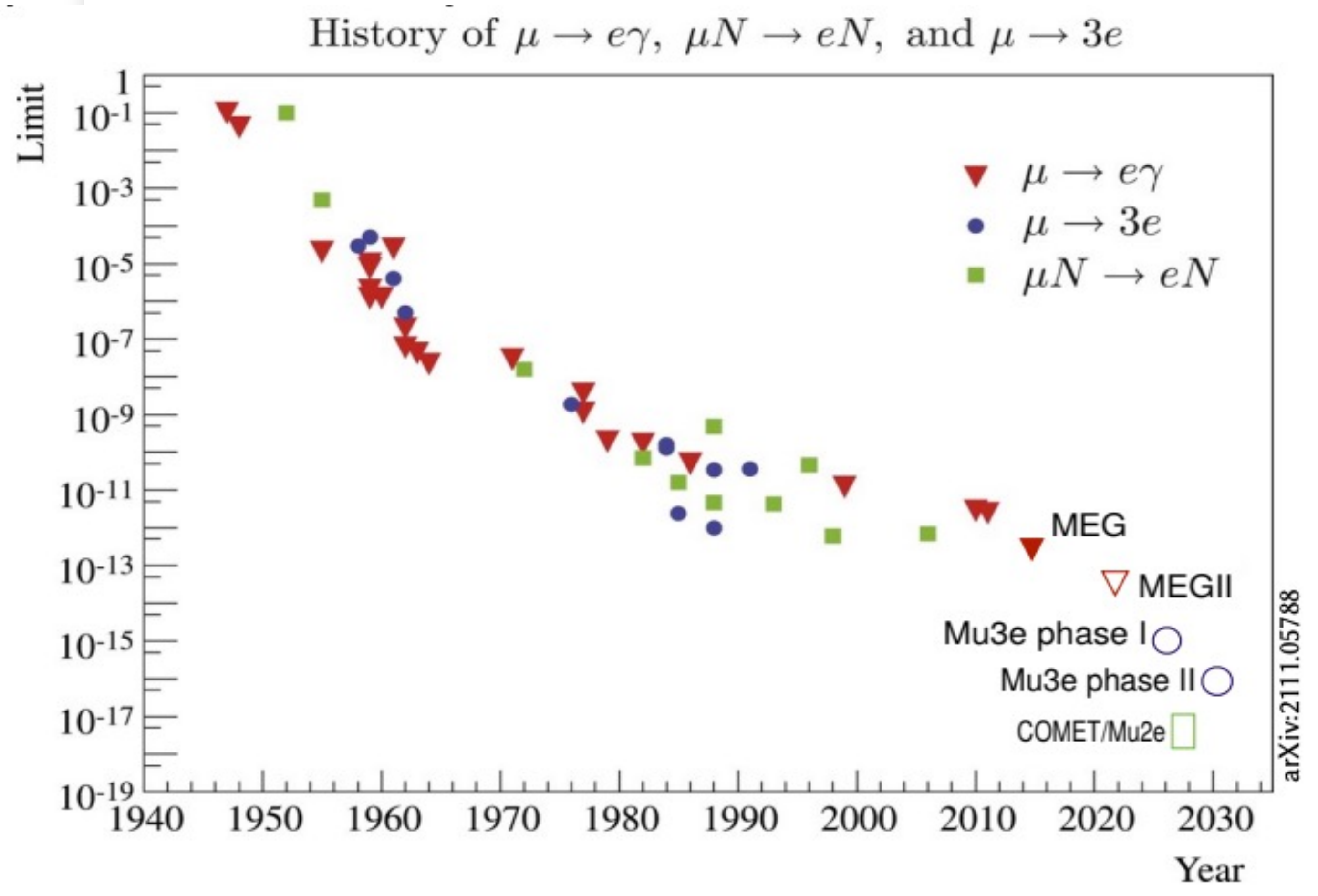




$$\Delta A_{\alpha\beta}^{CP}(\delta_{CP}) = A_{\alpha\beta}(\delta \neq 0) - A_{\alpha\beta}(\delta = 0)$$

LFV muon decays

- Precision Physics and BSM
- cLFV and BSM
- NSI and muon LFV

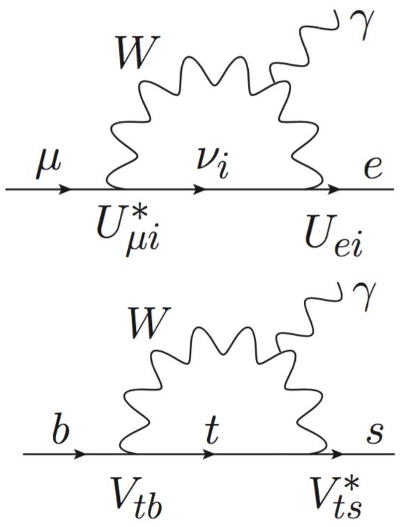


LFV

- Neutrino oscillation indicate LFV
- LFV in charged lepton sector is not seen
- In the SM negligible:

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\beta i} U_{\alpha i} \frac{m^2_{\nu_i}}{m^2_W} \right|^2 \lesssim \mathcal{O}(10^{-54})$$

- [$\mathrm{Br}(b \to s\gamma)$ ~ $(3.36 \pm 0.23) \times 10^{-4}$]
- New physics can enhance the $\mathcal{B}(\mu \to e\gamma)$by few orders
- cLFV are very clean probes-unambiguous signal of BSM physics



Leptoquark scenario

- Some anomalies in flavour and neutrino sector
- Leptoquark: probable BSM for simultaneous explanation
- Consider U_3 vector leptoquark

$$\mathcal{L} \supset \chi_{ij}^{LL} \overline{Q}_L^{i,a} \gamma^\mu (\sigma^k . U_{3,\mu}^k)^{ab} L_L^{j,b} + h.c\,.$$

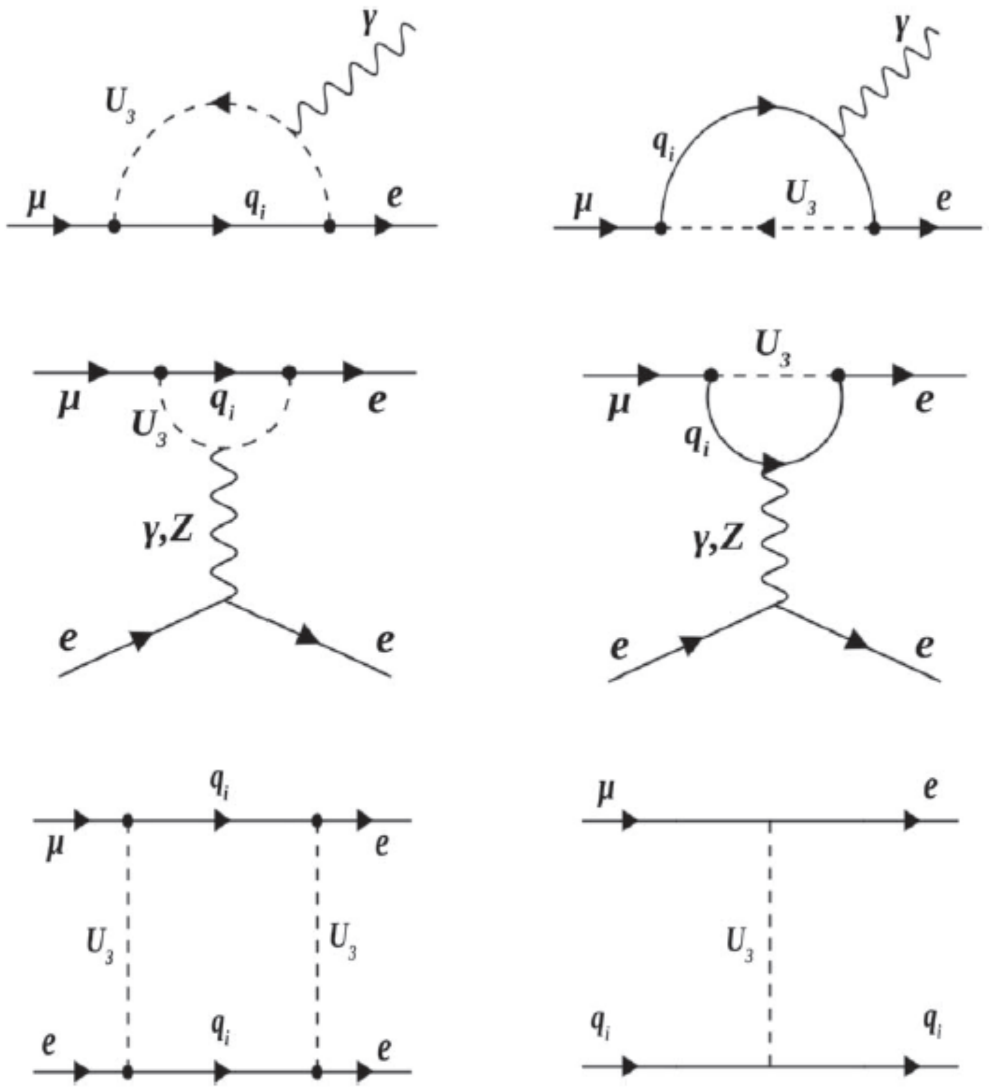
- The effective four fermion interaction

$$\mathcal{L}_{\rm eff}^{\rm down} = -\frac{2}{m_{LQ}^2} \lambda_{j\beta}^{LL} \lambda_{i\alpha}^{LL*} (\overline{d}^i \gamma_\mu P_L d^j)(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\ ,$$

$$\mathcal{L}_{\rm eff}^{\rm up} = -\frac{1}{m_{LQ}^2} \lambda_{j\beta}^{LL} \lambda_{i\alpha}^{LL*} (\overline{u}^i \gamma_\mu P_L u^j)(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\ ,$$

Leptoquark: $U_3\,(\overline{3}, 3, 2/3)$

Leptoquark contribution to LFV muon decays



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha_e N_c^2}{64\pi G_F^2}\left[\sum_{i=1}^{3} \frac{|\chi_{i2}^{LL}\chi_{i1}^{LL}|}{m_{LQ}^2}\left(\frac{1}{2}\frac{m_{d_i}^2}{m_{LQ}^2} + \frac{m_{u_i}^2}{m_{LQ}^2}\right)\right]^2$$

$$\mathcal{B}(\mu \to eee) = \frac{\alpha_e^2 N_c^2}{96\pi^2 G_F^2}\left[\frac{|\chi_{12}^{LL}\chi_{11}^{LL}|}{m_{LQ}^2}\left(\frac{m_{q_i}^2}{m_{LQ}^2}\right)\right]^2.$$

$$\mathcal{B}(\mu - e)_{Ti} = \frac{4\alpha_e^2 N_c^2}{96\pi^2} C \frac{\alpha_e^3 m_\mu^5 Z_{eff}^4 Z|\overline{F}_p|^2}{\Gamma_{capt}} \frac{2}{3\pi^2}\left[\sum_{i=1}^{3} \frac{|\chi_{i2}^{LL}\chi_{i1}^{LL}|}{m_{LQ}^2}\left(\frac{m_{q_i}^2}{m_{LQ}^2}\right)\right]^2$$

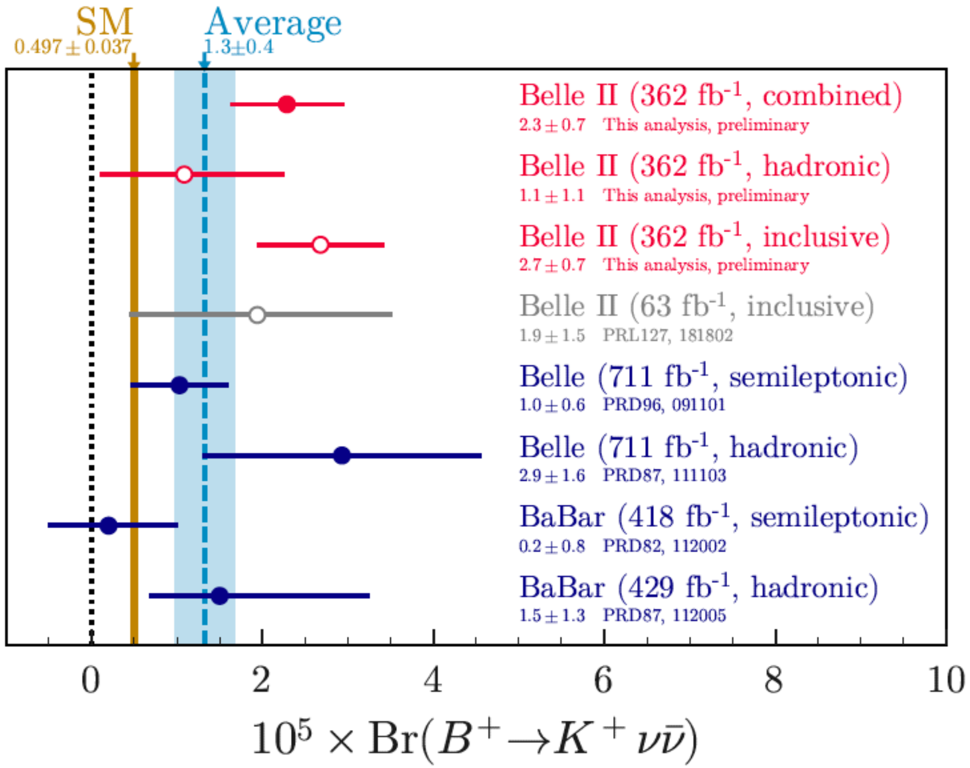
We consider Leptoquark mass 2 TeV and with standard parameters

$\mathcal{B}(\mu \to e\gamma)$ ~ 4.67×10^{-18}

$\mathcal{B}(\mu \to eee)$ ~ 1.0×10^{-20}

$\mathcal{B}(\mu \to e)_{\mathrm{Ti}}$ ~ 6.8×10^{-19}

Current Status of $BR(B^+ \to K^+ \nu\bar{\nu})$



ITA result:

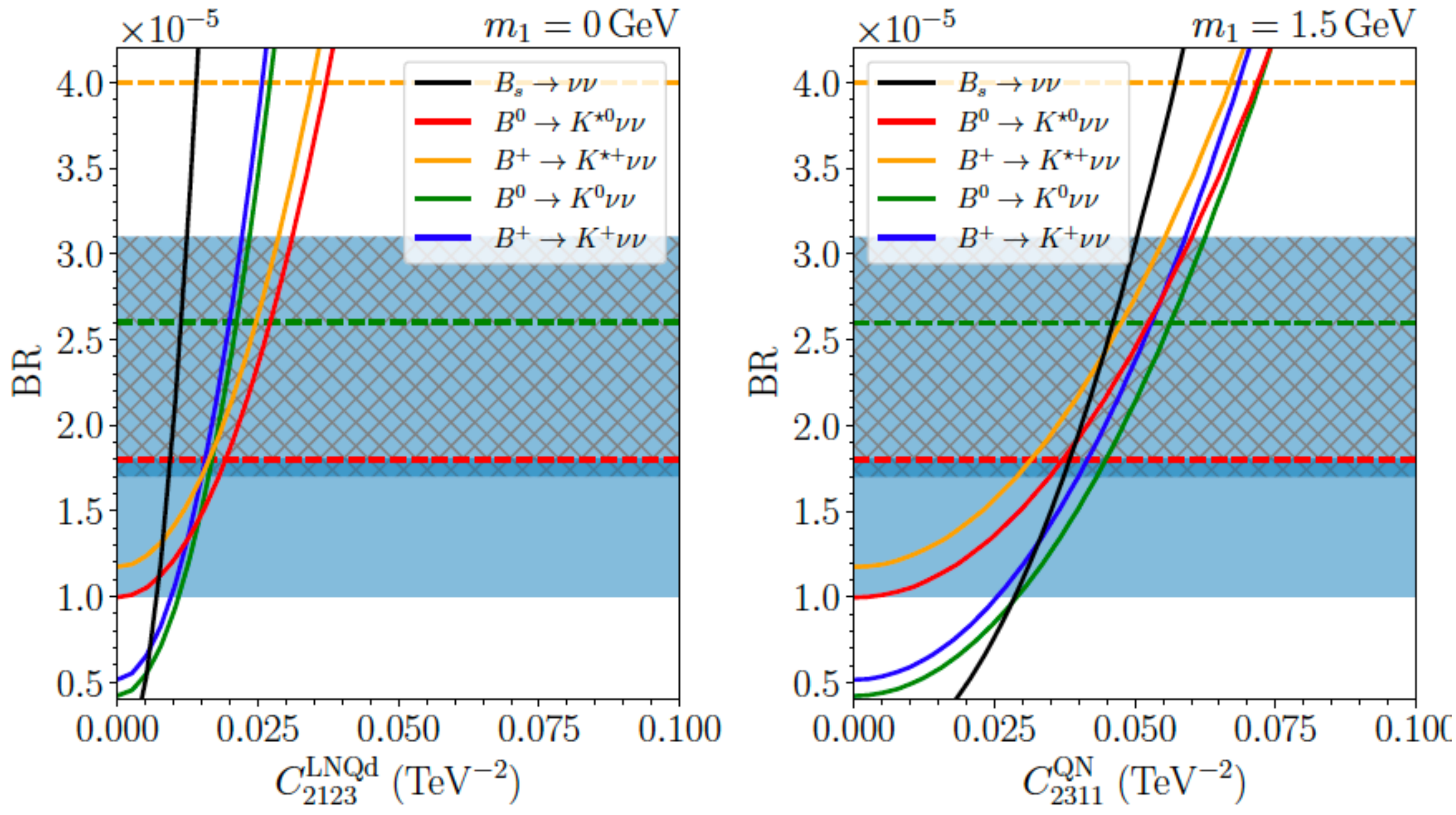
- in agreement with previous hadronic-tag and inclusive measurements
- 2.3 σ tension with BaBar semileptonic-tag analysis
- comparable precision wrt previous best measurements

HTA result:

- In agreement with all the previous measurements
- Most precise result with hadronic tag strategy

arxiv: 2311.14647

Roberta Volpe's talk @ HQL 2023



Branching ratios of several decay modes as a function of the scalar (left) and vector (right) Wilson coefficients for fixed sterile neutrino mass. The dashed horizontal contours indicate the current upper bounds for B0 → K⋆0+inv (red), B+ → K⋆+inv (orange), and B0 → K0+ inv (green). The light-blue band symbolises the simple weighted average for BR(B+ → K+ +inv) and the hatched light-blue region is compatible with the 2023 Belle II measurement

2111.04327 & 2309.02490

Remarks

- Precision Neutrino physics key to BSM physics
- Mild tension in CP phase in T2K and NOvA (NO)
- NSI can spoil the clean measurement of parameters
- Distinct prediction for DUNE and T2HK
- DUNE may exhibit signature of mass orderings
- Possible implications in muon LFV
- Interesting time ahead

Thank you!

PPC 2024

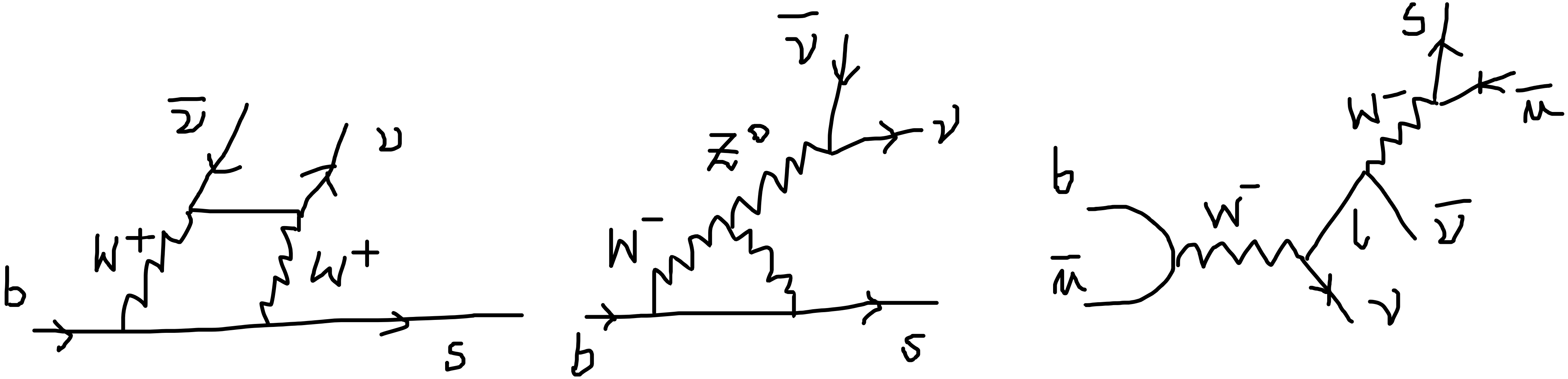
17th International Conference on interconnections between Particle Physics and Cosmology 2024

Hyderabad

14-18 October 2024

https://physics.iith.ac.in/ppc2024/

SM B→K νν



- In the SM: FCNC can occur only at the loop level, highly suppressed;
- Theoretical prediction:
- BR (B+→K+νν-bar)$_{SM}$ =(5.06 $\pm$ 0.14)x 10^{-6}
- BR (B0 →K*0νν-bar)$_{SM}$ = (9.05 $\pm$ 1.25) x 10^{-6} [2301.06990]
- Complementary to b→sl^{+}l^{-} where tension with the SM been observed

When Energy go missing? $B^+ \to K^+ + \text{inv}$

- We focus on 4 dim-6 operators in νSMEFT [PRD 96 (2017) 015012]:

$$C^{\mathrm{QN}}(\bar{Q}\gamma_\mu Q)(\bar{N}\gamma^\mu N) + C^{\mathrm{dN}}(\bar{d}\gamma_\mu d)(\bar{N}\gamma^\mu N) + C^{\mathrm{LNQd}}(\bar{L}^\alpha N)\epsilon_{\alpha\beta}(\bar{Q}^\beta d) + C^{\mathrm{LNQdT}}(\bar{L}^\alpha \sigma^{\mu\nu} N)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma_{\mu\nu} d)$$

(the operators are defined at μ=1 TeV and matched onto the LEFT at Λ_{EW}= m_Z)

- Relevant operators described by Lagrangian:

$$\mathcal{L} = \sum_{X=L,R} C_{\nu d}^{\mathrm{VLX}}\mathcal{O}_{\nu d}^{\mathrm{VLX}} + (C_{\nu d}^{\mathrm{SLL}}\mathcal{O}_{\nu d}^{\mathrm{SLL}} + C_{\nu d}^{\mathrm{TLL}}\mathcal{O}_{\nu d}^{\mathrm{TLL}} + C_{\nu edu}^{\mathrm{VLL}}\mathcal{O}_{\nu edu}^{\mathrm{VLL}} + C_{\nu edu}^{\mathrm{SLL}}\mathcal{O}_{\nu edu}^{\mathrm{SLL}} + C_{\nu edu}^{\mathrm{TLL}}\mathcal{O}_{\nu edu}^{\mathrm{TLL}} + \mathrm{h.c.})$$

- With effective operators

$$\mathcal{O}_{\nu d}^{\mathrm{VLX}} = (\overline{\nu_L}\gamma_\mu \nu_L)(\overline{d_X}\gamma^\mu d_X)\,, \quad \mathcal{O}_{\nu d}^{\mathrm{SLL}} = (\overline{\nu_L^c}\nu_L)(\overline{d_R}d_L)\,, \quad \mathcal{O}_{\nu d}^{\mathrm{TLL}} = (\overline{\nu_L^c}\sigma_{\mu\nu}\nu_L)(\overline{d_R}\sigma^{\mu\nu}d_L)$$

$$\mathcal{O}_{\nu edu}^{\mathrm{VLL}} = (\overline{\nu_L}\gamma_\mu e_L)(\overline{d_L}\gamma^\mu u_L)\,, \quad \mathcal{O}_{\nu edu}^{\mathrm{SLL}} = (\overline{\nu_L^c}e_L)(\overline{d_R}u_L)\,, \quad \mathcal{O}_{\nu edu}^{\mathrm{TLL}} = (\overline{\nu_L^c}\sigma_{\mu\nu}e_L)(\overline{d_R}\sigma^{\mu\nu}u_L)$$

2111.04327 & 2309.02490