Charged Current NSI and new CP-violating effects in CEνNS

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MANITOP
Massive Neutrinos: Investigating their Theoretical Origin and Phenomenology

Motivation

- What if there is new physics contributing to SNS in COHERENT in Pion and Muon decays?

- What if new CP-phases are included in the flavor changing NSI parameters at the detection in COHERENT?

- How the above two aspects can help to resolve some of the issues in neutrino oscillation experiments?

Formalism

- **At Source (CC NSI)**

$$\pi^+ \to \mu^+ + \nu_\mu \ (\nu_e, \nu_\mu, \nu_\tau)$$

$$\mu^+ \to e^+ + \nu_e \ (\nu_e, \nu_\mu, \nu_\tau) + \bar{\nu}_\mu \ (\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)$$

} LNU & LFV

✱ LNV possible, but not here!!

The relevant effective four fermion operators (dim-6):

$(q^2 \ll M^2)$

$$\mathcal{L}_{\rm CC}^{\pi^+} = -\frac{G_F}{\sqrt{2}} [\bar{\mu}\gamma^\lambda(1-\gamma_5)\nu_\beta] \, [(\underbrace{\delta_{\mu\beta}}_{\rm SM} + \underbrace{\varepsilon_{\mu\beta}^{udV}}_{\rm NSI})\bar{d}\gamma_\lambda u - (\underbrace{\delta_{\mu\beta}}_{\rm SM} + \underbrace{\varepsilon_{\mu\beta}^{udA}}_{\rm NSI})\bar{d}\gamma_\lambda\gamma_5 u]$$

$$\mathcal{L}_{\rm CC}^{\mu^+} = -\frac{G_F}{\sqrt{2}} \left(\underbrace{\delta_{\alpha e}\delta_{\beta\mu}}_{\rm SM} + \underbrace{\varepsilon_{\alpha\beta}^{\mu e L}}_{\rm NSI}\right) [\bar{\nu}_\alpha\gamma_\lambda(1-\gamma_5)e] \, [\bar{\mu}\gamma^\lambda(1-\gamma_5)\nu_\beta]$$

$(q^2 \ll M^2)$

- **At Detection (NC NSI)**

$$\nu_\beta(\bar{\nu}_\beta) + N(p,n) \to N(p,n) + \nu_\alpha(\bar{\nu}_\alpha)$$

} $\alpha = \beta$ (SM & LNU); $\alpha \neq \beta$ (LFV)

$$\mathcal{L}_{\rm NC}^{q} = -\frac{G_F}{\sqrt{2}} [\bar{\nu}_\alpha\gamma_\lambda(1-\gamma_5)\nu_\beta] \left[(\underbrace{g_{\alpha\beta}^V\delta_{\alpha\beta}}_{\rm SM} + \underbrace{\varepsilon_{\alpha\beta}^{qV}}_{\rm NSI})\bar{q}\gamma^\lambda q + (\underbrace{g_{\alpha\beta}^A\delta_{\alpha\beta}}_{\rm SM} + \underbrace{\varepsilon_{\alpha\beta}^{qA}}_{\rm NSI})\bar{q}\gamma^\lambda\gamma_5 q\right]$$

Formalism

- **CC NSI** $(q^2 \ll M^2)$

π^+ being pseudo-scalar in the SM, only axial couplings are allowed!

$$\mathcal{L}_{\rm CC}^{\pi^+} = -\frac{G_F}{\sqrt{2}}\left[\bar{\mu}\gamma^\lambda(1-\gamma_5)\nu_\beta\right]\left[(\delta_{\mu\beta}+\varepsilon^{udV}_{\mu\beta})\bar{d}\gamma_\lambda u - (\delta_{\mu\beta}+\varepsilon^{udA}_{\mu\beta})\bar{d}\gamma_\lambda\gamma_5 u\right]$$

SM NSI ✗ SM ✓ NSI

$$\mathcal{L}_{\rm CC}^{\mu^+} = -\frac{G_F}{\sqrt{2}}\left(\delta_{\alpha e}\delta_{\beta\mu}+\varepsilon^{\mu eL}_{\alpha\beta}\right)\left[\bar{\nu}_\alpha\gamma_\lambda(1-\gamma_5)e\right]\left[\bar{\mu}\gamma^\lambda(1-\gamma_5)\nu_\beta\right]$$

SM NSI

- **NC NSI** $\left(Axial\ current \approx 0, for\ heavy\ nuclei\ \frac{gA}{gV} \approx \frac{1}{Z+N}\right)$

$$\mathcal{L}_{\rm NC}^{q} = -\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_\alpha\gamma_\lambda(1-\gamma_5)\nu_\beta\right]\left[(g^V_{\alpha\beta}\delta_{\alpha\beta}+\varepsilon^{qV}_{\alpha\beta})\bar{q}\gamma^\lambda q + (g^A_{\alpha\beta}\delta_{\alpha\beta}+\varepsilon^{qA}_{\alpha\beta})\bar{q}\gamma^\lambda\gamma_5 q\right]$$

SM NSI ✓ SM NSI ✗ $(q^2 \ll M^2)$

All NSI parameters relevant for COHERENT:

CC NSI: $\varepsilon^{udA}_{\mu\beta}$, $\varepsilon^{\mu eL}_{\alpha\beta}$ **(All complex in general)**

NC NSI: $\varepsilon^{qV}_{\alpha\beta}$ **(Real flavor diagonal & complex flavor off-diagonal due to hermiticity)**

The NSI modified fluxes

$$(\nu_\mu)\ \left[\frac{d\phi_{\nu_\mu}(E_\nu)}{dE_\nu}\right]_{\rm NSI} = \left[\frac{d\phi_{\nu_\mu}(E_\nu)}{dE_\nu}\right]_{\rm SM}\left[\left(\left|1+\varepsilon^{udA}_{\mu\mu}\right|^2+\left|\varepsilon^{udA}_{\mu e}\right|^2+\left|\varepsilon^{udA}_{\mu\tau}\right|^2\right)\equiv 1+2Re(\varepsilon^{udA}_{\mu\mu})+\sum_{\alpha=e,\mu,\tau}|\varepsilon^{udA}_{\mu\alpha}|^2\right],$$

$$(\bar{\nu}_\mu)\ \left[\frac{d\phi_{\bar{\nu}_\mu}(E_\nu)}{dE_\nu}\right]_{\rm NSI} = \left[\frac{d\phi_{\bar{\nu}_\mu}(E_\nu)}{dE_\nu}\right]_{\rm SM}\left[\left(\left|1+\varepsilon^{\mu eL}_{\mu\mu}\right|^2+\left|\varepsilon^{\mu eL}_{\mu e}\right|^2+\left|\varepsilon^{\mu eL}_{\mu\tau}\right|^2\right)\equiv 1+2Re(\varepsilon^{\mu eL}_{\mu\mu})+\sum_{\alpha=e,\mu,\tau}|\varepsilon^{\mu eL}_{\mu\alpha}|^2\right],$$

$$(\nu_e)\ \left[\frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu}\right]_{\rm NSI} = \left[\frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu}\right]_{\rm SM}\left[\left(\left|1+\varepsilon^{\mu eL}_{ee}\right|^2+\left|\varepsilon^{\mu eL}_{e\mu}\right|^2+\left|\varepsilon^{\mu eL}_{e\tau}\right|^2\right)\equiv 1+2Re(\varepsilon^{\mu eL}_{ee})+\sum_{\alpha=e,\mu,\tau}|\varepsilon^{\mu eL}_{e\alpha}|^2\right],$$

where

$$\left[\frac{d\phi_{\nu_\mu}(E_\nu)}{dE_\nu}\right]_{\rm SM} = \frac{rN_{\rm pot}}{4\pi L^2}\delta\left(E_\nu-\frac{m_\pi^2-m_\mu^2}{2m_\pi}\right),$$

$$\left[\frac{d\phi_{\bar{\nu}_\mu}(E_\nu)}{dE_\nu}\right]_{\rm SM} = \frac{rN_{\rm pot}}{4\pi L^2}\frac{64E_\nu^2}{m_\mu^3}\left(\frac{3}{4}-\frac{E_\nu}{m_\mu}\right),$$

$$\left[\frac{d\phi_{\nu_e}(E_\nu)}{dE_\nu}\right]_{\rm SM} = \frac{rN_{\rm pot}}{4\pi L^2}\frac{192E_\nu^2}{m_\mu^3}\left(\frac{1}{2}-\frac{E_\nu}{m_\mu}\right),$$

$N_{pot} = 5.71\times10^{20}$
$L = 19.3\ m$
$r = 0.08\ /f/pot$

Source NSI parameters (6): $(Re(\varepsilon^{udA}_{\mu\mu}), |\varepsilon^{udA}_{\mu\alpha}|)$, $(Re(\varepsilon^{\mu eL}_{\mu\mu}), |\varepsilon^{\mu eL}_{\mu\alpha}|)$, $(Re(\varepsilon^{\mu eA}_{ee}), |\varepsilon^{\mu eL}_{e\alpha}|)$

Detector NC NSI with CP-phase

Cross section: $\frac{d\sigma_\beta}{dT}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi} Q_{W\beta}^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F^2(q^2)$ (FF: $F(q^2) = \frac{4\pi\rho_0}{Aq^3}[\sin(qR_A) - qR_A\cos(qR_A)]\left[\frac{1}{1+a^2q^2}\right]$)

$$Q_{W\beta}^2 = \left[Z(g_p^V + 2\varepsilon_{\beta\beta}^{uV} + \varepsilon_{\beta\beta}^{dV}) + N(g_n^V + 2\varepsilon_{\beta\beta}^{dV} + \varepsilon_{\beta\beta}^{uV})\right]^2 + \sum_{\alpha\neq\beta} \left|Z(2\varepsilon_{\alpha\beta}^{uV} + \varepsilon_{\alpha\beta}^{dV}) + N(2\varepsilon_{\alpha\beta}^{dV} + \varepsilon_{\alpha\beta}^{uV})\right|^2$$

Non-universal (All real)

Flavor-changing (All complex)

Define: $\varepsilon_{\alpha\beta}^{qV} \equiv \left|\varepsilon_{\alpha\beta}^{qV}\right| . e^{-i\phi_{\alpha\beta}^{qV}} \quad (\alpha \neq \beta)$

$g_p^V = 1/2 - 2\sin^2\theta_W \quad g_n^V = -1/2$

$(\nu_\mu/\bar{\nu}_\mu)$
$$Q_{W\mu/\bar{\mu}}^2 = \left[Z(g_p^V + 2\varepsilon_{\mu\mu}^{uV} + \varepsilon_{\mu\mu}^{dV}) + N(g_n^V + 2\varepsilon_{\mu\mu}^{dV} + \varepsilon_{\mu\mu}^{uV})\right]^2$$
$$+(2Z+N)^2\left(|\varepsilon_{e\mu}^{uV}|^2 + |\varepsilon_{\tau\mu}^{uV}|^2\right) + (Z+2N)^2\left(|\varepsilon_{e\mu}^{dV}|^2 + |\varepsilon_{\tau\mu}^{dV}|^2\right)$$
$$+2(2Z+N)(Z+2N)\left[|\varepsilon_{e\mu}^{uV}||\varepsilon_{e\mu}^{dV}|\cos(\Delta\phi_{e\mu}) + |\varepsilon_{\tau\mu}^{uV}||\varepsilon_{\tau\mu}^{dV}|\cos(\Delta\phi_{\tau\mu})\right]$$

$(\Delta\phi_{\alpha\beta} = \phi_{\alpha\beta}^{uV} - \phi_{\alpha\beta}^{dV})$

(ν_e)
$$Q_{We}^2 = \left[Z(g_p^V + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_n^V + 2\varepsilon_{ee}^{dV} + \varepsilon_{ee}^{uV})\right]^2$$
$$+(2Z+N)^2(|\varepsilon_{e\mu}^{uV}|^2 + |\varepsilon_{\tau e}^{uV}|^2) + (Z+2N)^2(|\varepsilon_{e\mu}^{dV}|^2 + |\varepsilon_{\tau e}^{dV}|^2)$$
$$+2(2Z+N)(Z+2N)\left[|\varepsilon_{e\mu}^{uV}||\varepsilon_{e\mu}^{dV}|\cos(\Delta\phi_{e\mu}) + |\varepsilon_{\tau e}^{uV}||\varepsilon_{\tau e}^{dV}|\cos(\Delta\phi_{\tau e})\right]$$

Detector parameters (13): $(\varepsilon_{\mu\mu}^{u/dV}, \varepsilon_{ee}^{u/dV}, \left|\varepsilon_{e\mu}^{u/dV}\right|, \left|\varepsilon_{\tau\mu}^{u/dV}\right|, \left|\varepsilon_{\tau e}^{u/dV}\right|, \Delta\phi_{e\mu}^{udV}, \Delta\phi_{\tau\mu}^{udV}, \Delta\phi_{\tau e}^{udV})$

Analysis

- **The expected energy spectrum**:

$$\frac{dN_{\nu_\alpha}}{dT} = tN \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \underbrace{\frac{d\sigma}{dT}}_{\text{cross section}}(E_\nu, T) \underbrace{\frac{d\phi_{\nu_\alpha}(E_\nu)}{dE_\nu}}_{\text{flux}} \epsilon(T),$$

t = 308.1 days

$$N = (2m_{\rm det}/M_{\rm CsI})\, N_A$$

$\epsilon(T) \equiv$ Efficiency

$$E_\nu^{\min} = \sqrt{MT/2}$$

- **Integrated events in each energy bin**:

$$N^{\rm i} = \int_{T^i}^{T^{i+1}} \frac{dN_{\nu_\alpha}}{dT}\, dT,$$

- **Relation between the nuclear recoil (T) and the photo-electrons ($n_{p.e}$)**

$$n_{\rm p.e.} = f_Q(T) \times T \times \left(\frac{0.0134}{\rm MeV}\right),$$

$f_Q(T) \equiv$ Quenching factor

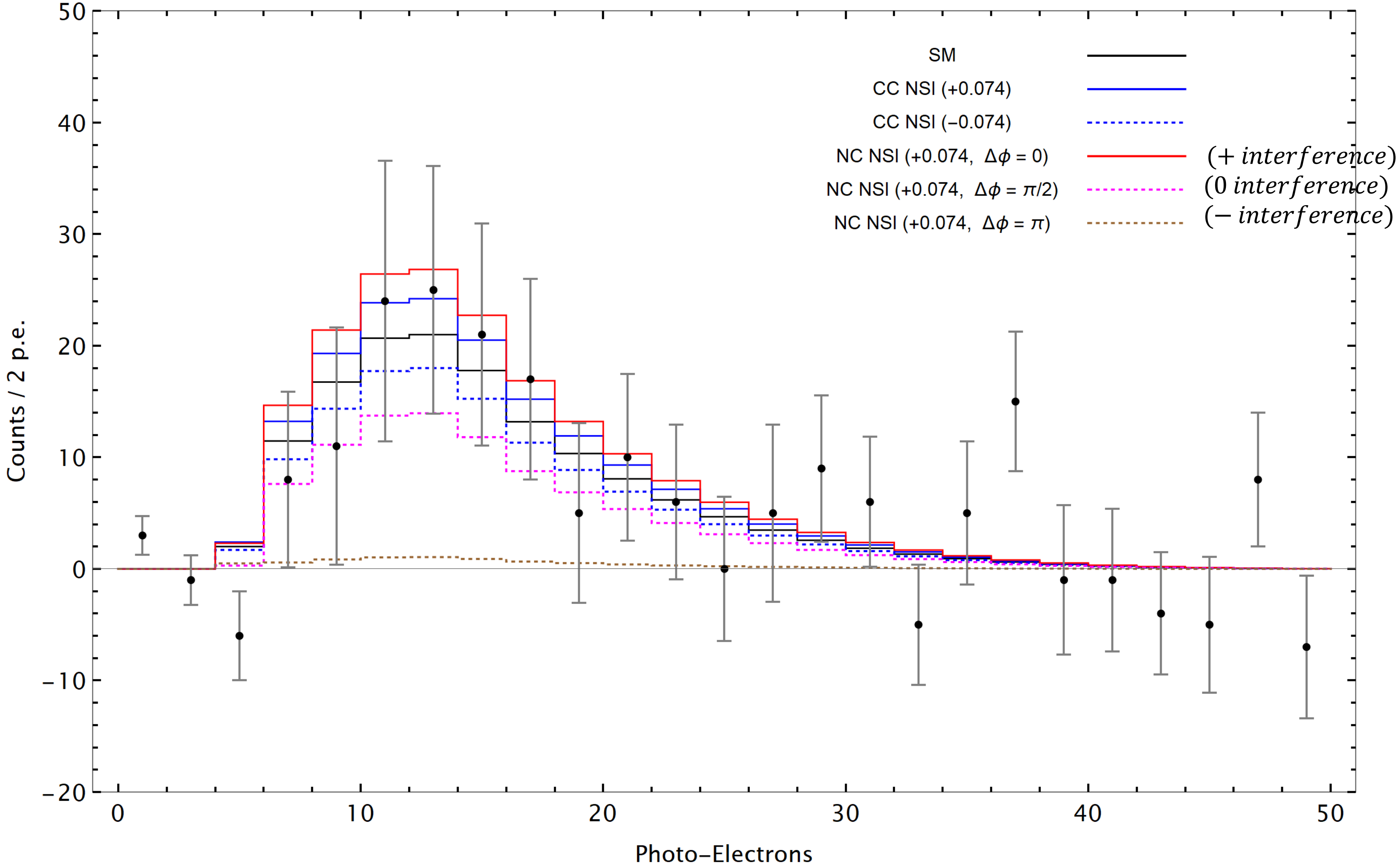
(J. Collar et al,PRD 100, 033003 (2019))

- **The Statistical Function:**

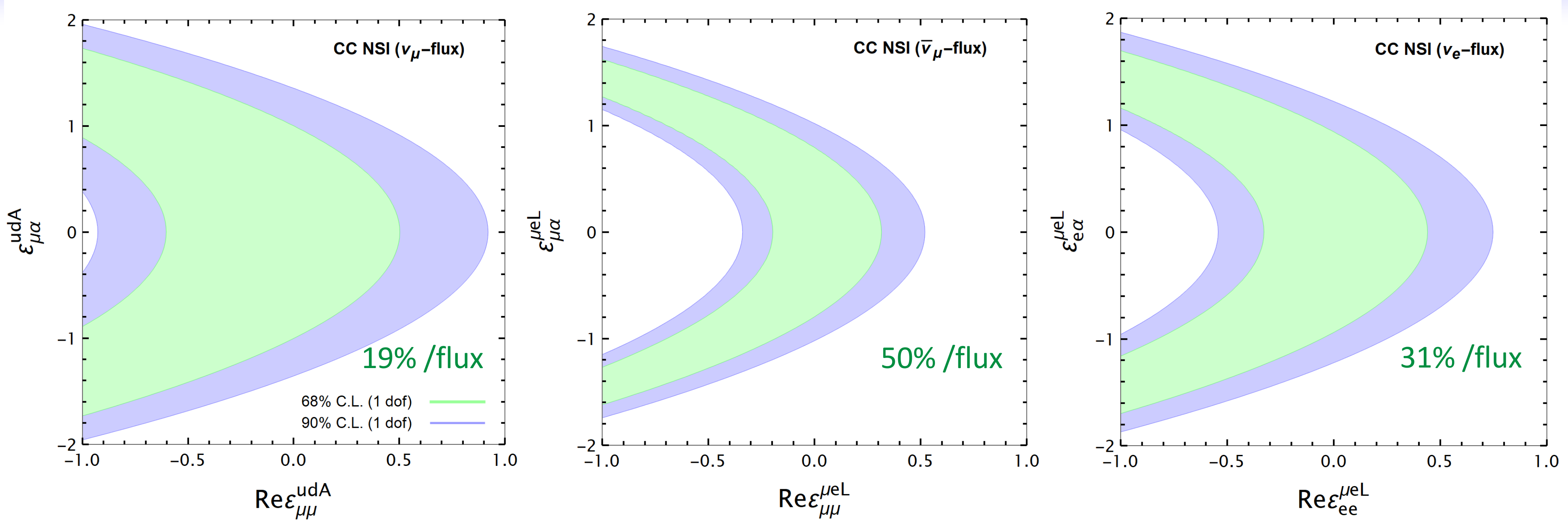
$$\chi^2 = \sum_{i=4}^{20} \frac{[N^i_{\rm obs} - N^i_{\rm exp}(1+\alpha) - B^i(1+\beta)]^2}{(\sigma^i)^2} + \left(\frac{\alpha}{\sigma_\alpha}\right)^2 + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

All information are from: D. Akimov et al. (COHERENT), Science 357, 1123 (2017)

The COHERENT Energy Spectrum (CsI)



CC NSI neutrino production



- In general weaker constraints due to $(1+\varepsilon) \propto flux * cross - section$
- See the factor of "2" effects in the real part of 1+ $2Re(\varepsilon_{\alpha\alpha})$
- Improve with larger flux and long exposure

1 parameter at-a-time limits

parameter	COHERENT (this work)	other bounds
$Re(\varepsilon^{udA}_{\mu\mu})$	$[-0.9, 0.9]$	$[-0.007, 0.012]$ (Br.)
$\varepsilon^{udA}_{\mu\alpha}$	$[-1.3, 1.3]$	$[-0.118, 0.118]$ (Br.)
$Re(\varepsilon^{\mu eL}_{\mu\mu})$	$[-0.3,\ 0.5]$	$[-0.030,\ 0.030]$ (Kin.)
$\varepsilon^{e\mu L}_{\mu\alpha}$	$[-1.1, 1.1]$	$[-0.087,\ 0.087]$ (Osc.)
$Re(\varepsilon^{\mu eL}_{ee})$	$[-0.5,\ 0.7]$	$[-0.025,\ 0.025]$ (Osc.)
$\varepsilon^{\mu eL}_{e\alpha}$	$[-1.2,\ 1.2]$	$[-0.030,\ 0.030]$ (Kin.)

Other bounds
If $SU(2)_L$ invariance
is presumed!

CP-phase effects on NC-NSI

$$\frac{d\sigma_\beta}{dT}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi}\left[(Zg_p^V + Ng_n^V)^2 + \sum_{\alpha\neq\beta}\left[(2Z+N)^2|\varepsilon_{\alpha\beta}^{uV}|^2 + (Z+2N)^2|\varepsilon_{\alpha\beta}^{dV}|^2 \right.\right.$$
$$\left.\left. +2(2Z+N)(Z+2N)|\varepsilon_{\alpha\beta}^{uV}||\varepsilon_{\alpha\beta}^{dV}|\cos(\Delta\phi_{\alpha\beta})\right]\right]\left(1-\frac{MT}{2E_\nu^2}\right)F^2(q^2)\,.$$

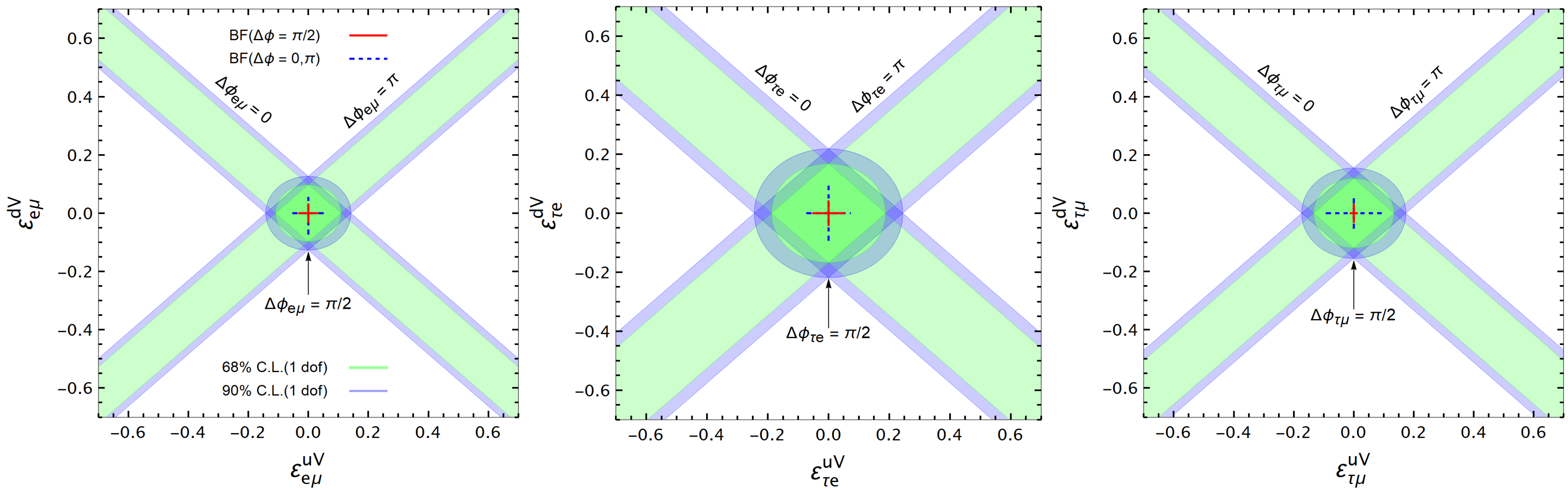
Interference term

3 extreme cases:

$i)\ \Delta\phi_{\alpha\beta} = 0$ $(postive\ interference)$

$ii)\ \Delta\phi_{\alpha\beta} = \pi$ $(negative\ interference)$

$iii)\ \Delta\phi_{\alpha\beta} = \pi/2$ $(zero\ interference)$



Complementarity to Oscillation Experiments

- **Survival probability for reactor experiments**

$$\bar{P}_{ee} = 1 - [(P_{21} + \cos(2x_{31})P_{32})\sin^2 x_{21} + (P_{31} + P_{32})\sin^2 x_{31} - \frac{1}{2}P_{32}\sin(2x_{21})\sin(2x_{31})],$$

A. Khan et al, PRD 88,113006, (2013)

$$P_{21} = \sin^2(2\theta_{12})c_{13}^4 + 4c_{13}^3\sin(2\theta_{12})\cos(2\theta_{12})c_{23}K_- - 4c_{13}^3 s_{13}\sin^2(2\theta_{12})c_{23}K_+,$$

$$P_{31} = \sin^2(2\theta_{13})c_{12}^2 - 4s_{13}^2 c_{13}\sin(2\theta_{12})c_{23}K_- + 4c_{12}^2\cos(2\theta_{13})\sin(2\theta_{13})c_{23}K_+,$$

$$\mathcal{E} \equiv K$$

$$P_{32} = \sin^2(2\theta_{13})s_{12}^2 + 4s_{13}^2 c_{13}\sin(2\theta_{12})c_{23}K_- + 4s_{12}^2\cos(2\theta_{13})\sin(2\theta_{13})c_{23}K_+.$$

$$c_{23}K_+ \equiv |K_{e\mu}|\cos(\delta + \phi_{e\mu})s_{23} + |K_{e\tau}|\cos(\delta + \phi_{e\tau})c_{23},$$
$$c_{23}K_- \equiv |K_{e\mu}|\cos\phi_{e\mu}c_{23} - |K_{e\tau}|\cos\phi_{e\tau}s_{23}.$$

- **Survival probability for solar experiments**

A. Khan et al, JHEP 07, 143, (2017)

$$\langle P\rangle_{ee}^{NSI} = (1 + 2\,\mathrm{Re}\,\varepsilon_{ee}^{udL} + |\varepsilon_{ee}^{udL}|^2)\langle P\rangle_{ee}^{SMM} - (c_{23}\varepsilon_-)c_{13}^3\sin 2\theta_{12}\cos 2\theta_{12} + (c_{23}\varepsilon_+)(\frac{1}{2}c_{13}^2\sin 2\theta_{13}\sin^2 2\theta_{12} - \sin 2\theta_{13}\cos 2\theta_{13}),$$

$$c_{23}\varepsilon_+ \equiv \left|\varepsilon_{e\mu}^{udL}\right|\cos(\phi_{e\mu} + \delta_{CP})s_{23} + \left|\varepsilon_{e\tau}^{udL}\right|\cos(\phi_{e\tau} + \delta_{CP})c_{23}$$
$$c_{23}\varepsilon_- \equiv \left|\varepsilon_{e\mu}^{udL}\right|\cos\phi_{e\mu}c_{23} - \left|\varepsilon_{e\tau}^{udL}\right|\cos\phi_{e\tau}s_{23},$$

Complementarity to Oscillation Experiments

- **Conversion probability for long baseline experiments**

J. Kopp et al, PRD 77,0133007, (2008)

$$
\begin{aligned}
P^{\rm mat}_{\nu^s_\mu \to \nu^d_e} &= 4\tilde{s}_{13}^2 s_{23}^2 \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E} \\
&+ \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2 c_{23}^2 s_{2\times12}^2 \left(\frac{\Delta m^2_{31}}{a_{\rm CC}}\right)^2 \sin^2 \frac{a_{\rm CC}L}{4E} \\
&- \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \tilde{s}_{13} s_{2\times12} s_{2\times23} \cos\delta_{\rm CP} \frac{\Delta m^2_{31}}{a_{\rm CC}} \left[\sin^2 \frac{a_{\rm CC}L}{4E} - \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E}\right] \\
&- \frac{1}{2}\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \tilde{s}_{13} s_{2\times12} s_{2\times23} \sin\delta_{\rm CP} \frac{\Delta m^2_{31}}{a_{\rm CC}} \left[\sin \frac{a_{\rm CC}L}{2E} - \sin \frac{\Delta m^2_{31} L}{2E} + \sin \frac{(\Delta m^2_{31} - a_{\rm CC})L}{2E}\right] \\
&- 4|\epsilon^s_{\mu e}| \tilde{s}_{13} s_{23} \cos(\phi^s_{\mu e} + \delta_{\rm CP}) \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E} \\
&- 2|\epsilon^s_{\mu e}| \tilde{s}_{13} s_{23} \sin(\phi^s_{\mu e} + \delta_{\rm CP}) \sin \frac{(\Delta m^2_{31} - a_{\rm CC})L}{2E} \\
&+ 4|\epsilon^d_{\mu e}| \tilde{s}_{13} s_{23} \cos(\phi^d_{\mu e} + \delta_{\rm CP}) \left[c_{23}^2 \sin^2 \frac{a_{\rm CC}L}{4E} - c_{23}^2 \sin^2 \frac{\Delta m^2_{31} L}{4E} + s_{23}^2 \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E}\right] \\
&+ 2|\epsilon^d_{\mu e}| \tilde{s}_{13} s_{23} \sin(\phi^d_{\mu e} + \delta_{\rm CP}) \left[c_{23}^2 \sin \frac{a_{\rm CC}L}{2E} - c_{23}^2 \sin \frac{\Delta m^2_{31} L}{2E} - s_{23}^2 \sin \frac{(\Delta m^2_{31} - a_{\rm CC})L}{2E}\right] \\
&- 4|\epsilon^d_{\tau e}| \tilde{s}_{13} s_{23}^2 c_{23} \cos(\phi^d_{\tau e} + \delta_{\rm CP}) \left[\sin^2 \frac{a_{\rm CC}L}{4E} - \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E}\right]
\end{aligned}
$$

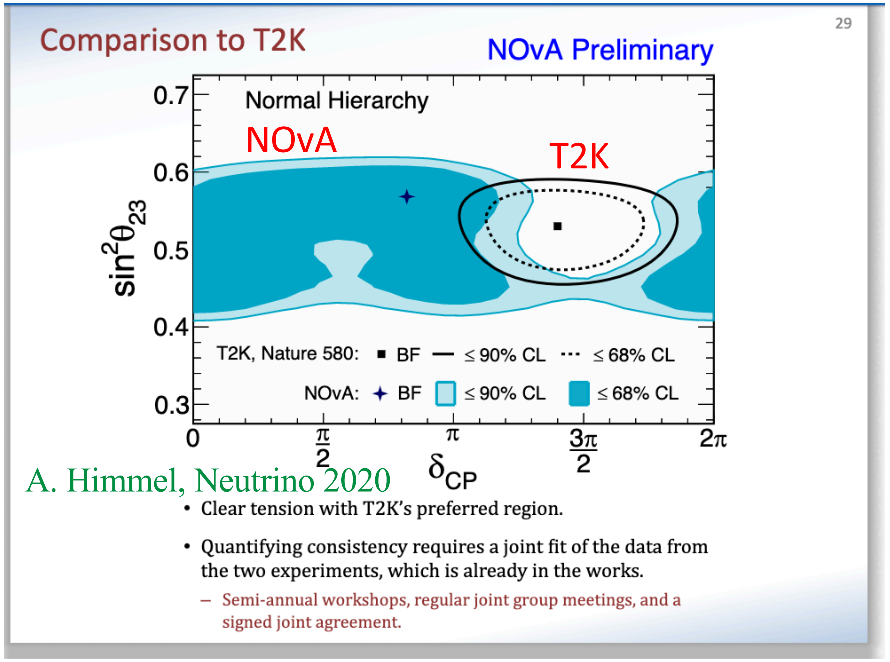
....

$$
\begin{aligned}
&+ 8|\epsilon^m_{e\mu}| \tilde{s}_{13} s_{23}^3 \cos(\phi^m_{e\mu} + \delta_{\rm CP}) \frac{a_{\rm CC}}{\Delta m^2_{31} - a_{\rm CC}} \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E} \\
&+ 4|\epsilon^m_{e\tau}| \tilde{s}_{13} s_{23}^2 c_{23} \cos(\phi^m_{e\tau} + \delta_{\rm CP}) \left[\sin^2 \frac{a_{\rm CC}L}{4E} - \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E}\right] \\
&+ 2|\epsilon^m_{e\tau}| \tilde{s}_{13} s_{23}^2 c_{23} \sin(\phi^m_{e\tau} + \delta_{\rm CP}) \left[\sin \frac{a_{\rm CC}L}{2E} - \sin \frac{\Delta m^2_{31} L}{2E} + \sin \frac{(\Delta m^2_{31} - a_{\rm CC})L}{2E}\right] \\
&+ 8|\epsilon^m_{e\tau}| \tilde{s}_{13} s_{23}^2 c_{23} \cos(\phi^m_{e\tau} + \delta_{\rm CP}) \frac{a_{\rm CC}}{\Delta m^2_{31} - a_{\rm CC}} \sin^2 \frac{(\Delta m^2_{31} - a_{\rm CC})L}{4E}
\end{aligned}
$$

....

Complementarity to Oscillation Experiments

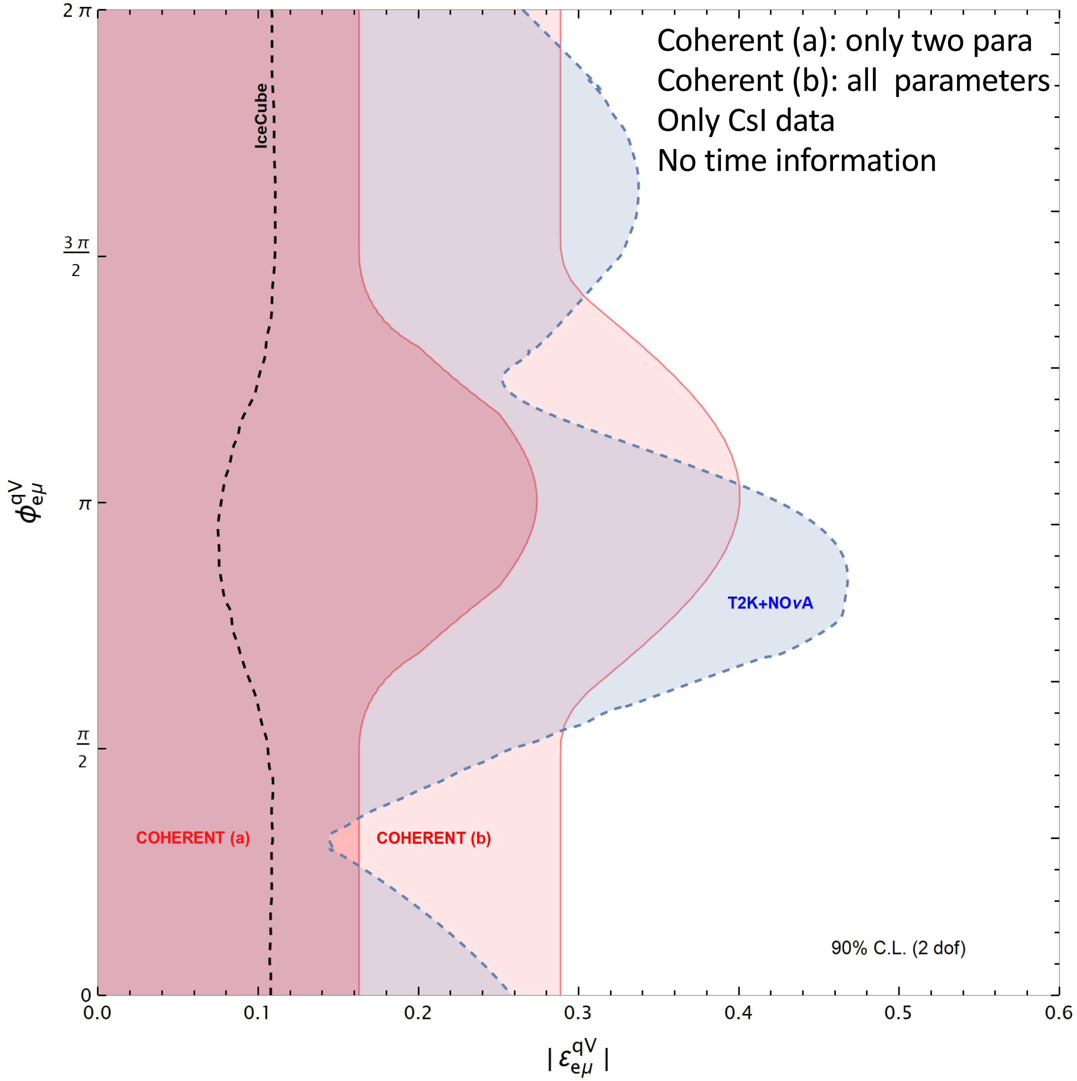
Fig. 1 Long baseline experiments



S. Chatterjee et al, PRL 126, 051802 (2021)
P. Denton *et al.* PRL 126 051801, (2021)

To summarize, we have shown that the tension of the recent NOvA and T2K data can be resolved in a BSM scenario with the introduction of CP-violating NSI parameters, which can be further probed with near-future experiments. It would be interesting to see if other new physics models could also explain the discrepancy, such as the presence of sterile neutrinos, decoherence, or neu-

Fig. 2

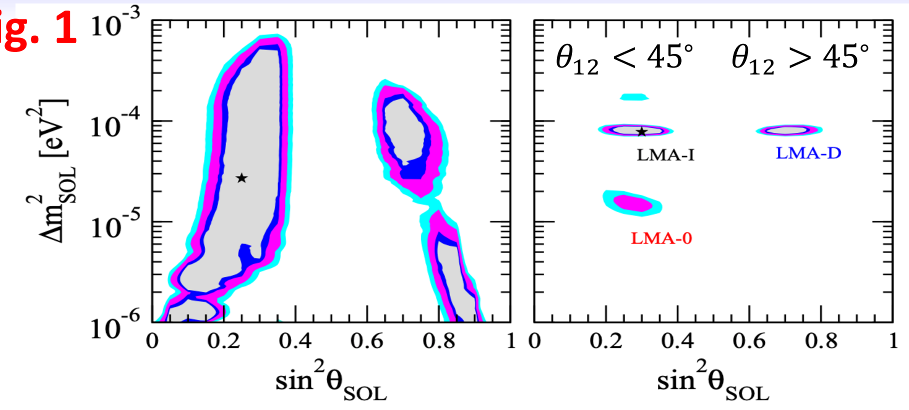


T. Ehrhardt PPNT,Uppsala, (2019) : IceCube
P. Denton et al, PRL 126 051801, (2021) : T2K+NOvA

Like wise: $(|\varepsilon_{\tau\mu}^{qV}|\ vs\ \phi_{\tau\mu}^{qV})$ and $(|\varepsilon_{\tau e}^{qV}|\ vs.\ \phi_{\tau e}^{qV})$

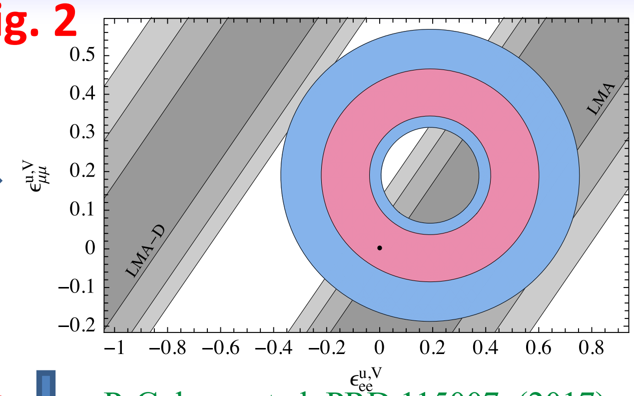
LMA-Dark solution re-visited

Fig. 1



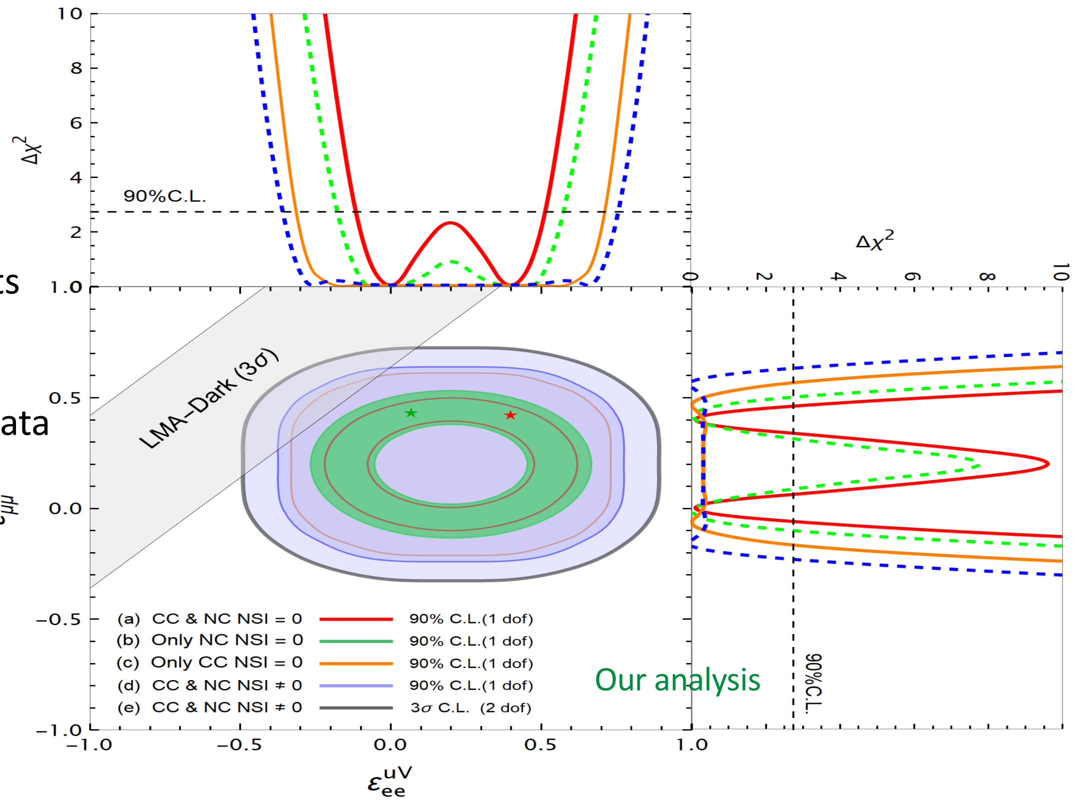
O. Miranda et al, JHEP, 10 008 (2006)

Fig. 2



P. Coloma et al, PRD,115007, (2017)

Fig. 3



- Four cases were studied with constrained fits in the ranges: absolutes $\in [0, -0.1]$, reals $\in [-0.1, 0.1]$, phases $\in [0, 2\pi]$
- The CC NSI and the CP-phases are included in the fits
- CC NSI effects in *red* and *green* & in *orange* & *blue*
- Including the NC loses the absolute minimum requiring more data+ time information and Argon data might improve.
- Currently, the CC and CP-phases worsen the 3 σ LMA-Dark exclusion.

Conclusion & Future Outlook

- $CE\nu NS$ proves to be a promising way of BSM testing.

- A detailed statistical analysis (Argon + timing info) is needed when all the *source (CC)* and *detector (NC)* NSI & CP-phases are taken into account. All the limits needs to be derived again.

- A detailed analysis is needed for the CP-phases and limits on them from COHERENT and how are they related to the individual oscillation experiments.

- The LMA-Dark solution should be revisited with a quantitative treatment in presence of source and detector NSI discussed here in combination with the solar data.

Thanks!