# Constraining nonstandard neutrino interactions at electron colliders


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based on work in

Phys. Rev. D 104, 035043 (2021)

[arXiv:2105.11215 ]

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# Portal to New Physics


| | |
|---|---|
| **Higgs Portal** | $H^\dagger H \phi^\dagger \phi$ |
| **Neutrino Portal** | $H L N_R$ |
| **Vector Portal** | $F_{\mu\nu} X^{\mu\nu}$ |

**Only three *renormalizable* portals in the Standard Model**

# Nonstandard Interactions

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{c^{d=5}}{\Lambda}\mathcal{O}^{d=5} + \frac{c^{d=6}}{\Lambda^2}\mathcal{O}^{d=6} + \dots .$$

## Neutrino mass

$$\frac{c^{d=5}}{\Lambda}(\overline{L_L^c}\tilde{\phi}^*)(\tilde{\phi}^\dagger L_L)$$

[P. Minkowski (1977), T. Yanagida (1979), Weinberg (1979) S.L. Glashow (1980)]

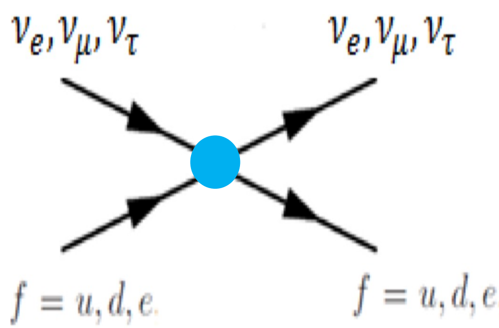

Seesaw mechanism

## Nonstandard Interactions (NSI)

$$\mathcal{L}_{\text{NC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fC}[\overline{\nu_\alpha}\gamma^\rho P_L\nu_\beta]\,[\bar{f}\gamma_\rho P_C f]\ ,$$

$$\mathcal{L}_{\text{CC-NSI}} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{ff'C}[\overline{\nu_\beta}\gamma^\rho P_L\ell_\alpha]\,[\bar{f}'\gamma_\rho P_C f]\ ,$$

[Wolfenstein, Phys. Rev., D17, 2369 (1978)]



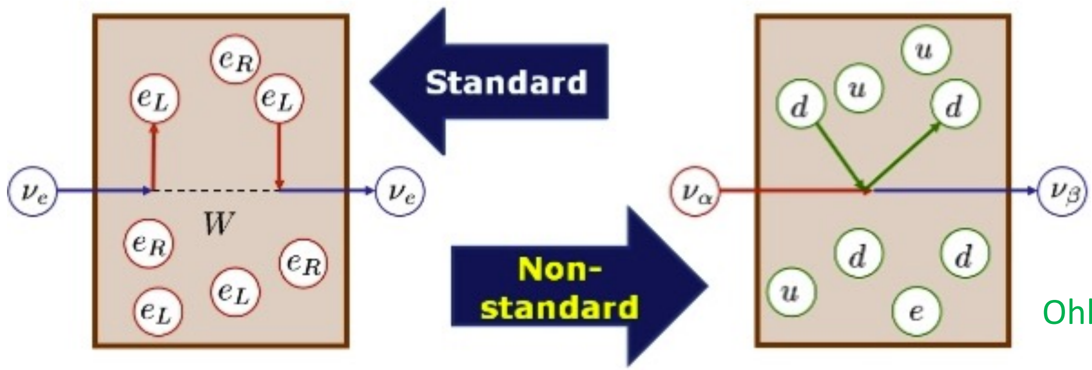
# Matter Effects

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha\beta fC} \epsilon_{\alpha\beta}^{fC} \left[\overline{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right] \left[\bar{f}\gamma_\rho P_C f\right]$$

$C = L, R,$

$f = u, d, e$

Wolfenstein, Phys. Rev. D 17, 2369 (1978)




Ohlsson, 1209.2710

Modification of matter potential

$$\mathrm{i}\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

SM

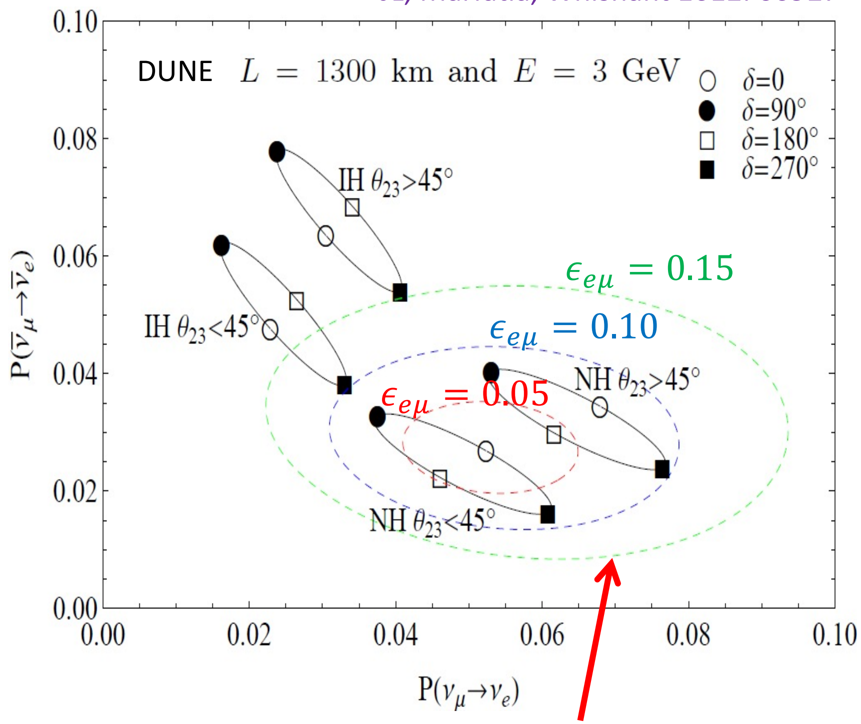
Effective coefficient $\varepsilon_{\alpha\beta} \equiv \sum_{f,C} \varepsilon_{\alpha\beta}^{fC}\frac{N_f}{N_e}$

$A \equiv 2\sqrt{2}G_F N_e E$

On earth $N_u = N_d = 3N_e$

# Oscillation experiments w/ NSI

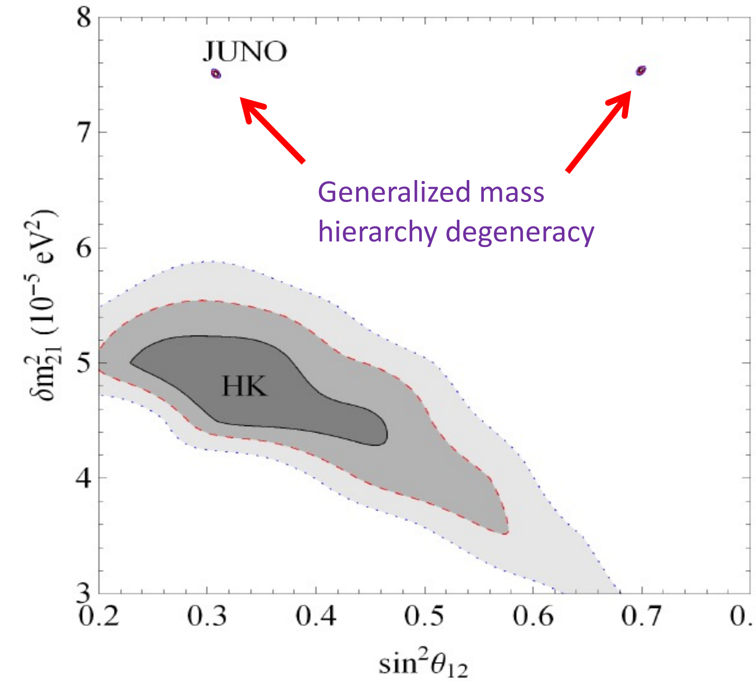
JL, Marfatia, Whisnant 1612. 00927




Continuous four-fold degeneracy

The determination of CP violation, $\theta_{23}$ octant, and the mass hierarchy at DUNE is strongly affected by NSI.

JL, Marfatia, Whisnant 1704.04711




Generalized mass hierarchy degeneracy

Bakhti, Farzan 1403.0744
Coloma, Schwetz 1604.05772

$$\delta m^2_{31} \to -\delta m^2_{32}, \quad \theta_{12} \to 90^\circ - \theta_{12}, \quad \delta \to 180^\circ - \delta,$$

$$\epsilon_{ee} \to -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} \to -\epsilon_{\alpha\beta} e^{-i\phi_{\alpha\beta}} \ (\alpha\beta \neq ee)\,,$$

$$H \to -H^*$$

Oscillation probabilities are unchanged

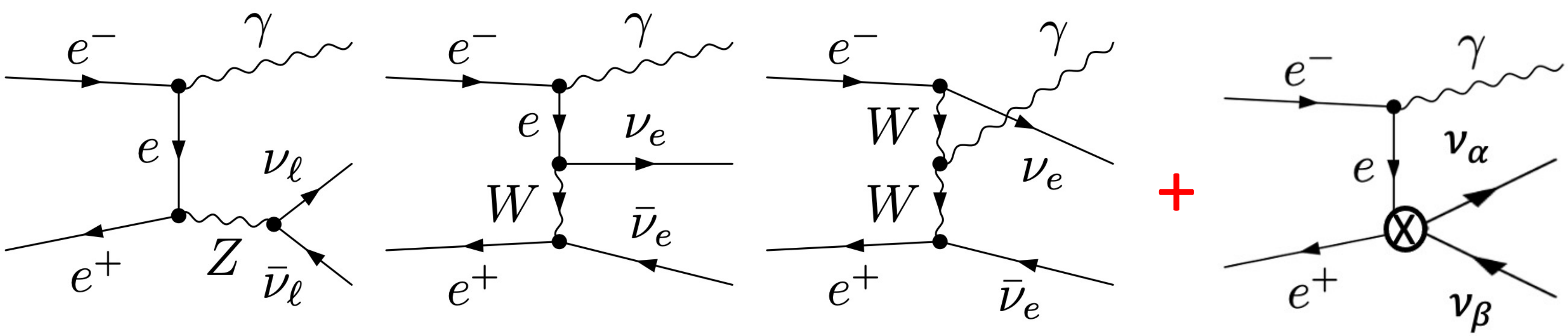
# Global constraints on NSI with u,d

| | Total Rate | Data Release t+E | Our Fit t+E Chicago | Our Fit t+E Duke |
|---|---|---|---|---|
| $\varepsilon_{ee}^{u}$ | $[-0.012, +0.621]$ | $[+0.043, +0.384]$ | $[-0.032, +0.533]$ | $[-0.004, +0.496]$ |
| $\varepsilon_{\mu\mu}^{u}$ | $[-0.115, +0.405]$ | $[-0.050, +0.062]$ | $[-0.094, +0.071] \oplus [+0.302, +0.429]$ | $[-0.045, +0.108] \oplus [+0.290, +0.399]$ |
| $\varepsilon_{\tau\tau}^{u}$ | $[-0.116, +0.406]$ | $[-0.050, +0.065]$ | $[-0.095, +0.125] \oplus [+0.302, +0.428]$ | $[-0.045, +0.141] \oplus [+0.290, +0.399]$ |
| $\varepsilon_{e\mu}^{u}$ | $[-0.059, +0.033]$ | $[-0.055, +0.027]$ | $[-0.060, +0.036]$ | $[-0.060, +0.034]$ |
| $\varepsilon_{e\tau}^{u}$ | $[-0.250, +0.110]$ | $[-0.141, +0.090]$ | $[-0.243, +0.118]$ | $[-0.222, +0.113]$ |
| $\varepsilon_{\mu\tau}^{u}$ | $[-0.012, +0.008]$ | $[-0.006, +0.006]$ | $[-0.013, +0.009]$ | $[-0.012, +0.009]$ |
| $\varepsilon_{ee}^{d}$ | $[-0.015, +0.566]$ | $[+0.036, +0.354]$ | $[-0.030, +0.468]$ | $[-0.006, +0.434]$ |
| $\varepsilon_{\mu\mu}^{d}$ | $[-0.104, +0.363]$ | $[-0.046, +0.057]$ | $[-0.083, +0.077] \oplus [+0.278, +0.384]$ | $[-0.037, +0.099] \oplus [+0.267, +0.356]$ |
| $\varepsilon_{\tau\tau}^{d}$ | $[-0.104, +0.363]$ | $[-0.046, +0.059]$ | $[-0.083, +0.083] \oplus [+0.279, +0.383]$ | $[-0.038, +0.104] \oplus [+0.268, +0.354]$ |
| $\varepsilon_{e\mu}^{d}$ | $[-0.058, +0.032]$ | $[-0.052, +0.024]$ | $[-0.059, +0.034]$ | $[-0.058, +0.034]$ |
| $\varepsilon_{e\tau}^{d}$ | $[-0.198, +0.103]$ | $[-0.106, +0.082]$ | $[-0.196, +0.107]$ | $[-0.181, +0.101]$ |
| $\varepsilon_{\mu\tau}^{d}$ | $[-0.008, +0.008]$ | $[-0.005, +0.005]$ | $[-0.008, +0.008]$ | $[-0.007, +0.008]$ |
| $\varepsilon_{ee}^{p}$ | $[-0.035, +2.056]$ | $[+0.142, +1.239]$ | $[-0.095, +1.812]$ | $[-0.024, +1.723]$ |
| $\varepsilon_{\mu\mu}^{p}$ | $[-0.379, +1.402]$ | $[-0.166, +0.204]$ | $[-0.312, +0.138] \oplus [+1.036, +1.456]$ | $[-0.166, +0.337] \oplus [+0.952, +1.374]$ |
| $\varepsilon_{\tau\tau}^{p}$ | $[-0.379, +1.409]$ | $[-0.168, +0.257]$ | $[-0.313, +0.478] \oplus [+1.038, +1.453]$ | $[-0.167, +0.582] \oplus [+0.950, +1.382]$ |
| $\varepsilon_{e\mu}^{p}$ | $[-0.179, +0.112]$ | $[-0.174, +0.086]$ | $[-0.179, +0.120]$ | $[-0.187, +0.131]$ |
| $\varepsilon_{e\tau}^{p}$ | $[-0.877, +0.340]$ | $[-0.503, +0.295]$ | $[-0.841, +0.355]$ | $[-0.817, +0.386]$ |
| $\varepsilon_{\mu\tau}^{p}$ | $[-0.041, +0.025]$ | $[-0.020, +0.019]$ | $[-0.044, +0.026]$ | $[-0.048, +0.030]$ |

**Table 2.** $2\sigma$ allowed ranges for the NSI couplings $\varepsilon_{\alpha\beta}^{u}$, $\varepsilon_{\alpha\beta}^{d}$ and $\varepsilon_{\alpha\beta}^{p}$ as obtained from the global analysis of oscillation plus COHERENT data. See text for details.

Coloma et.al., 1911.09109

# NSI@electron collider




$$e^+e^- \to \nu\bar{\nu}\gamma \qquad \frac{d^2\sigma}{dx_\gamma dz_\gamma} = H\left(x_\gamma, z_\gamma; s\right)\sigma_0(s_\gamma)$$

Nicrosini, Trentadue, PLB 231, 487 (1989)

Altarelli-Parisi radiator function
$$H\left(x_\gamma, z_\gamma; s\right) = \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left[\frac{1+(1-x_\gamma)^2}{1-z_\gamma^2} - \frac{x_\gamma^2}{2}\right]$$

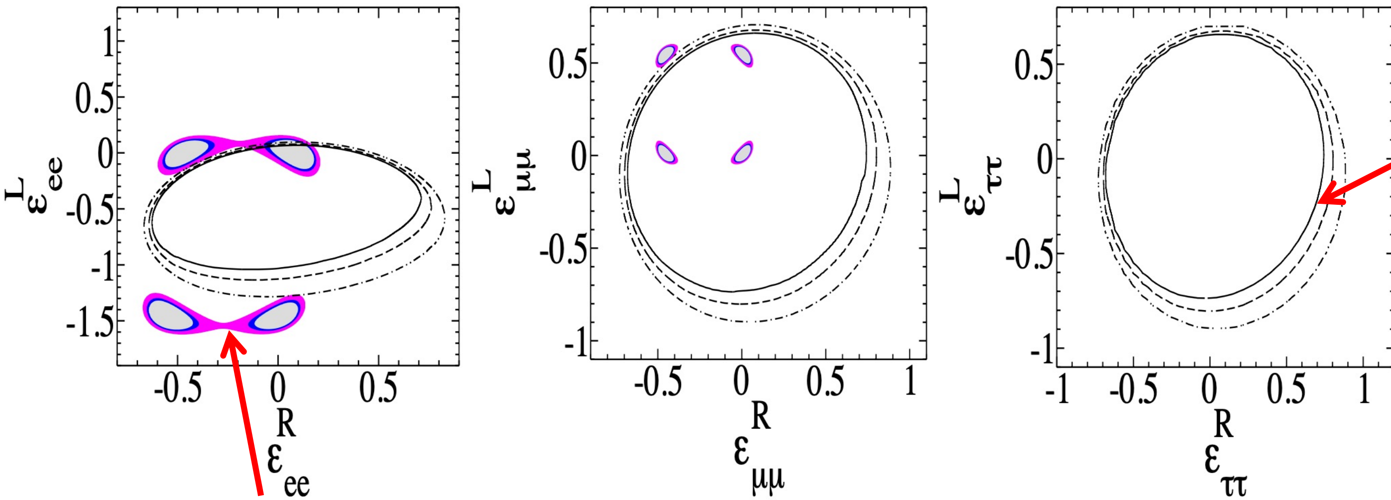
$$e^+e^- \to \nu\bar{\nu} \qquad \sigma_0^{\mathrm{SM}}(s) = \frac{N_\nu G_F^2}{6\pi} M_Z^4\left(g_L^2+g_R^2\right)\frac{s}{\left[\left(s-M_Z^2\right)^2+\left(M_Z\Gamma_Z\right)^2\right]}$$
$$+\frac{G_F^2}{\pi}M_W^2\left\{\frac{s+2M_W^2}{2s} - \frac{M_W^2}{s}\left(\frac{s+M_W^2}{s}\right)\log\left(\frac{s+M_W^2}{M_W^2}\right)\right.$$
$$\left. - g_L\frac{M_Z^2\left(s-M_Z^2\right)}{\left(s-M_Z^2\right)^2+\left(M_Z\Gamma_Z\right)^2}\times\left[\frac{\left(s+M_W^2\right)^2}{s^2}\log\left(\frac{s+M_W^2}{M_W^2}\right) - \frac{M_W^2}{s} - \frac{3}{2}\right]\right\}$$

# Electron NSI

Berezhiania , Rossi, Phys.Lett.B 535 (2002)

$$\sigma_0^{\rm NSI}(s) = \sum_{\alpha,\beta=e,\mu,\tau} \frac{G_F^2}{6\pi} s \left[ \left( (\epsilon_{\alpha\beta}^{eL})^2 + (\epsilon_{\alpha\beta}^{eR})^2 \right) - 2\left( g_L \epsilon_{\alpha\beta}^{eL} + g_R \epsilon_{\alpha\beta}^{eR} \right) \frac{M_Z^2\,(s - M_Z^2)}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \right]$$
$$+ \frac{G_F^2}{\pi} \epsilon_{ee}^{eL} M_W^2 \left[ \frac{(s + M_W^2)^2}{s^2} \log\left( \frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} - \frac{3}{2} \right] .$$

12 independent NSI parameters

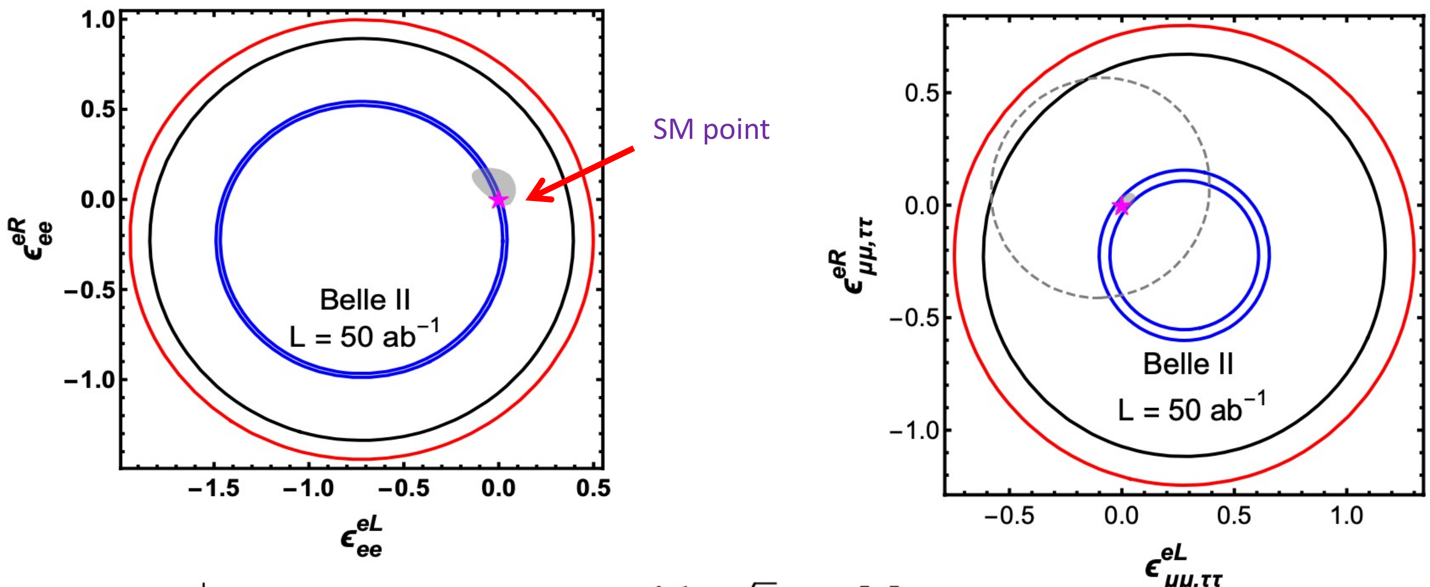



Constraints from LEP data

Constraints from neutrino scattering data

Barranco, Miranda, Moura, Valle, 0711.0698

# NSI@ Belle II




$e^+e^- \to \nu\bar{\nu}\gamma$ with $\sqrt{s} \ll M_Z$

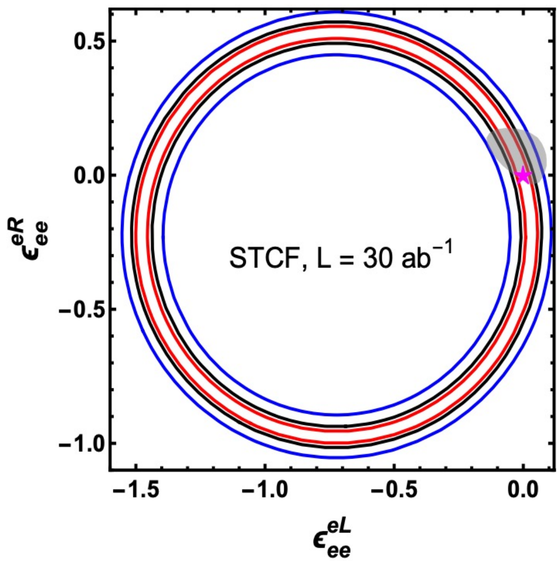
$$\frac{d\sigma^{\rm SM}}{dx_\gamma dz_\gamma} = H(x_\gamma, z_\gamma, s)\frac{G_F^2 s_\gamma}{2\pi}C^{\rm SM} \qquad C^{\rm SM} \equiv g_L^2 + g_R^2 + \tfrac{2}{3}g_L + \tfrac{1}{3}$$

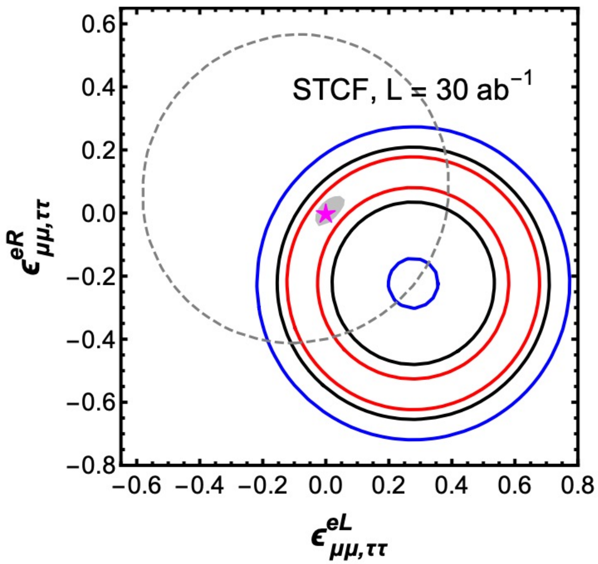
$$\frac{d\sigma^{\rm NSI}}{dx_\gamma dz_\gamma} = H(x_\gamma, z_\gamma, s)\frac{G_F^2 s_\gamma}{2\pi}C^{\rm NSI} \quad C^{\rm NSI} \equiv \tfrac{1}{3}\sum_{\alpha,\beta=e,\mu,\tau}\left[(\epsilon^{eL}_{\alpha\beta})^2 + (\epsilon^{eR}_{\alpha\beta})^2 + 2(g_L\epsilon^{eL}_{\alpha\beta} + g_R\epsilon^{eR}_{\alpha\beta})\right] + \tfrac{2}{3}\epsilon^{eL}_{ee}$$

$$\sigma = \sigma^{\rm SM} + \sigma^{\rm NSI}.$$

Iso-$\sigma$ contours form concentric circles with center at $(\epsilon^{eL}_{\alpha\alpha},\ \epsilon^{eR}_{\alpha\alpha}) = (-g_L - \delta_{\alpha e}, -g_R)$

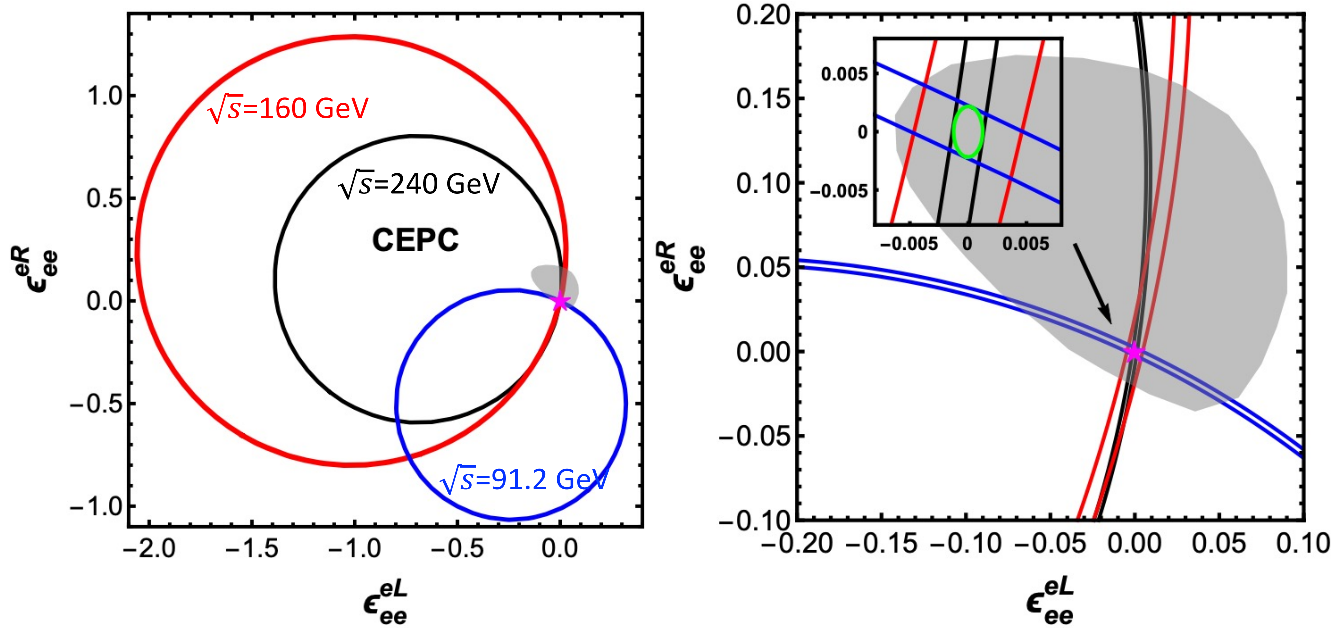
# NSI@STCF




| | STCF-2 $L = 30$ ab$^{-1}$ | STCF-4 $L = 30$ ab$^{-1}$ | STCF-7 $L = 30$ ab$^{-1}$ | Belle II $L = 50$ ab$^{-1}$ | Previous Limit 90% Allowed [45] |
|---|---|---|---|---|---|
| $\epsilon_{ee}^{eL}$ | [-0.067,0.061] | [-0.033,0.031] | [-0.018,0.018] | [-0.0091,0.0089] | [-0.03,0.08] |
| $\epsilon_{ee}^{eR}$ | [-0.60,0.15] | [-0.163,0.087] | [-0.070,0.053] | [-0.031,0.028] | [0.004,0.15] |
| $\epsilon_{\mu\mu/\tau\tau}^{eL}$ | [-0.13,0.69] | [-0.073,0.101] | [-0.044,0.052] | [-0.023,0.025] | [-0.03,0.03]/[-0.5,0.2] |
| $\epsilon_{\mu\mu/\tau\tau}^{eR}$ | [-0.60,0.15] | [-0.163,0.087] | [-0.070,0.053] | [-0.031,0.028 ] | [-0.03,0.03]/[-0.3,0.4] |

# NSI@CEPC



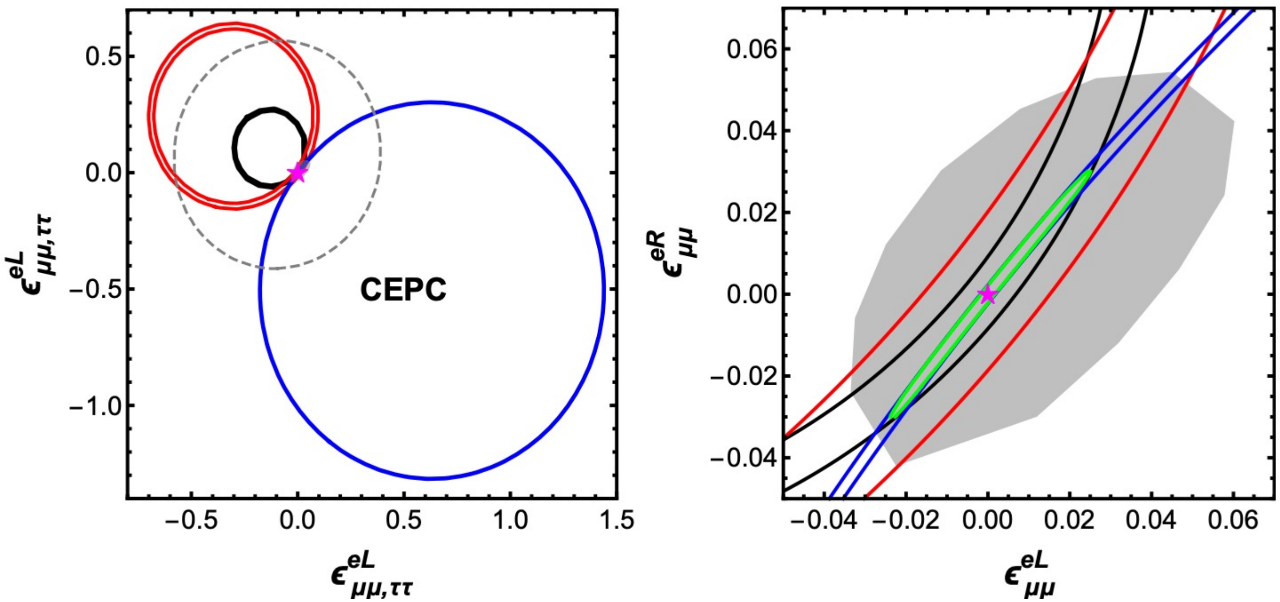

$$\sqrt{s} \geq M_Z \qquad \sigma^{\rm NSI}\left(\epsilon_{ee}^{eL}, \epsilon_{ee}^{eR}\right) = I_1\left(\left(\epsilon_{ee}^{eL}\right)^2 + \left(\epsilon_{ee}^{eR}\right)^2\right) + (I_2 + I_3)\epsilon_{ee}^{eL} + I_2\frac{g_R}{g_L}\epsilon_{ee}^{eR}$$

$$I_i \equiv \int dx \int dz_\gamma H(x_\gamma, z_\gamma, s)\left[\sigma_0^{\rm NSI}((s_\gamma))\right]_i$$ is a function of $\sqrt{s}$

Allowed regions lie between two concentric circles with the center at

$$(\epsilon_{ee}^{eL},\ \epsilon_{ee}^{eR}) = \left(-\frac{I_2 + I_3}{2I_1}, -\frac{I_2 g_R}{2I_1 g_L}\right)$$

# NSI@CEPC




| | CEPC-91.2 $L = 16$ ab$^{-1}$ | CEPC-160 $L = 2.6$ ab$^{-1}$ | CEPC-240 $L = 5.6$ ab$^{-1}$ | CEPC-combined $L = 24.2$ ab$^{-1}$ | Previous Limit 90% Allowed [45] |
|---|---|---|---|---|---|
| $\epsilon^{eL}_{ee}$ | [-0.0037,0.0037] | [-0.0036,0.0035] | [-0.0010,0.0010] | [-0.00095,0.00095] | [-0.03,0.08] |
| $\epsilon^{eR}_{ee}$ | [-0.0017,0.0017] | [-0.014,0.015] | [-0.0065,0.0070] | [-0.0017,0.0017] | [0.004,0.15] |
| $\epsilon^{eL}_{\mu\mu/\tau\tau}$ | [-0.0014,0.0014] | [-0.012,0.012] | [-0.0055,0.0053] | [-0.0013,0.0013] | [-0.03,0.03]/[-0.5,0.3] |
| $\epsilon^{eR}_{\mu\mu/\tau\tau}$ | [-0.0017,0.0017] | [-0.014,0.015] | [-0.0065,0.0070] | [-0.0017,0.0017] | [-0.03,0.03]/[-0.3,0.4] |

# Summary

- Neutrino oscillation experiments are strongly affected by NSI, it is natural to seek complementary constraints on NSI from other type experiments.
- Both Belle II and STCF can provide competitive and complementary bounds on $\varepsilon_{ee}^{eL,R}$ as compared to current global analysis, and strong improvements in the constraints on $\varepsilon_{\tau\tau}^{eL,R}$ .
- CEPC running with three CM energies $\sqrt{s} = 240, 160, 91.2$ GeV will break the degeneracy between the left- and right-handed NSI, and can reach a sub-percent level sensitivity on electron NSI.

*Thank you!*

# Backup slides

# Coordinates of the circle centers