Nonstandard neutrino interactions at electron colliders

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based on
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[arXiv:2105.11215]

Joint Workshop of the CEPC Physics, Software and New Detector Concept
05/25/2022

Outline

- Introduction to NSI
- Current constraints on NSI
- NSI at Belle II, STCF, CEPC
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Portal to New Physics

Vector Portal	$F_{\mu\nu}X^{\mu\nu}$
Higgs Portal	$H^\dagger H \phi^\dagger \phi$
Neutrino Portal	HLN_R

Only three *renormalizable* portals in the Standard Model

Ballet, Hostert, Pascoli, 1903.07589

Nonstandard Interactions

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

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

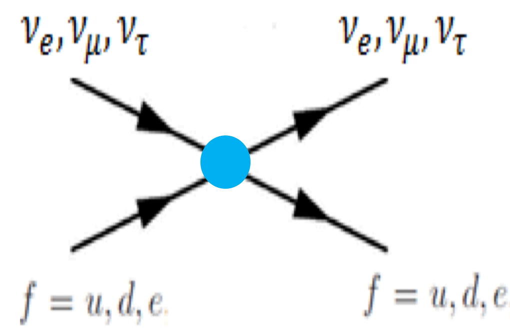
Seesaw mechanism

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

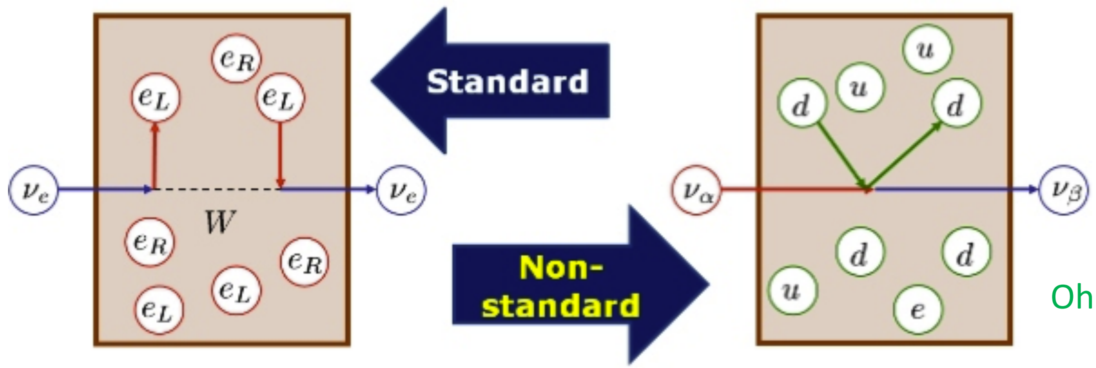
$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{\alpha\beta fC} \epsilon^{fC}_{\alpha\beta} \left[\overline{\nu}_{\alpha L}\gamma^\rho \nu_{\beta L}\right] \left[\bar{f}\gamma_\rho P_C f\right]$$

$C = L, R$

$f = u, d, e$

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

36 parameters



Ohlsson, 1209.2710

Modification of matter potential

SM

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

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

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

On earth $N_u = N_d = 3N_e$

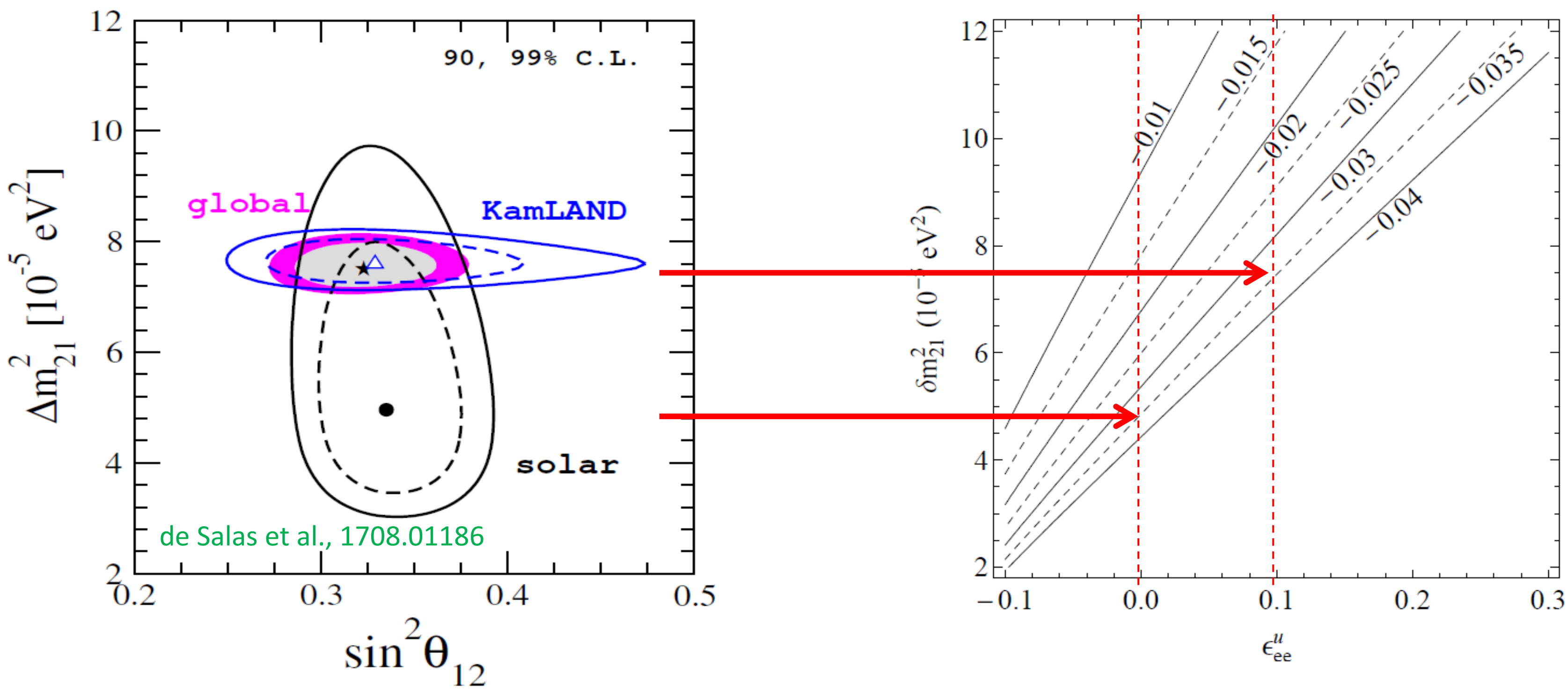
Indication of NSI

Super-K, 1606.07538

$$A_{\mathrm{DN}}^{\text{fit, SK}} = (-3.3 \pm 1.0(\text{stat.}) \pm 0.5(\text{syst.}))\%$$

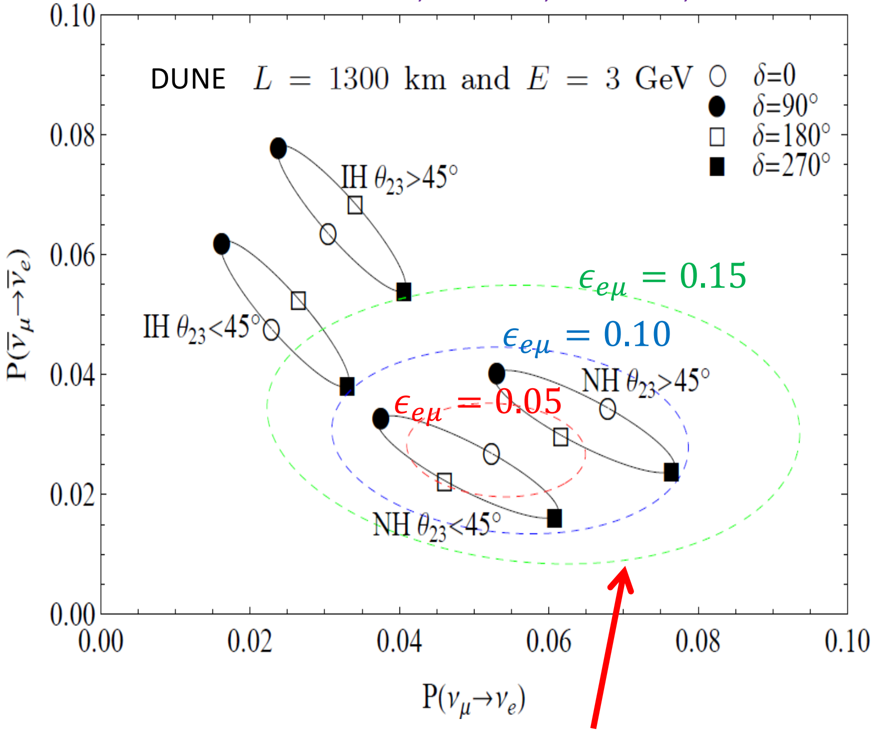
JL, Marfatia, Whisnant, 1704.04711

$$\epsilon_{ee}^{u} = \epsilon_{ee}^{d} \sim 0.1$$



NSI at future oscillation experiments

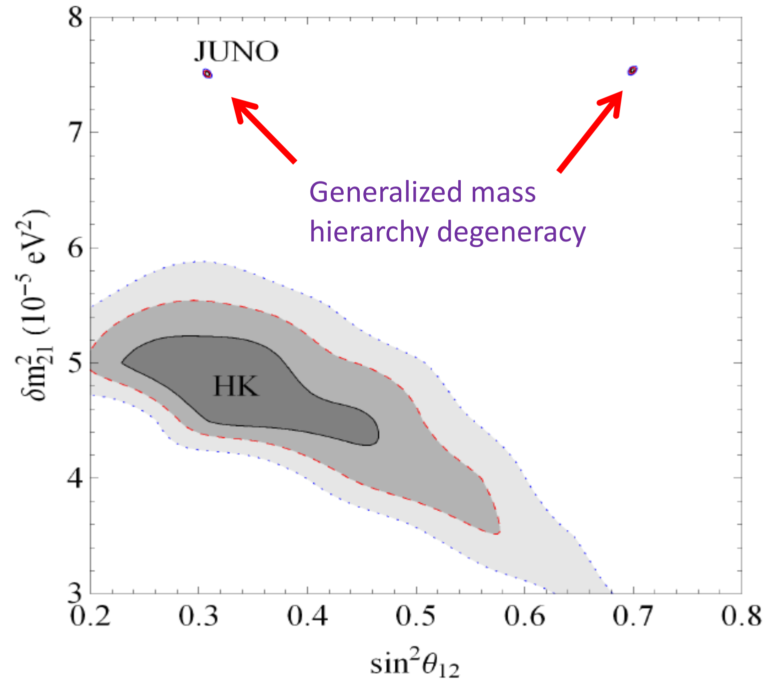
JL, Marfatia, Whisnant, 1612. 00927



Continuous four-fold degeneracy

The determination of CP violation, θ_{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

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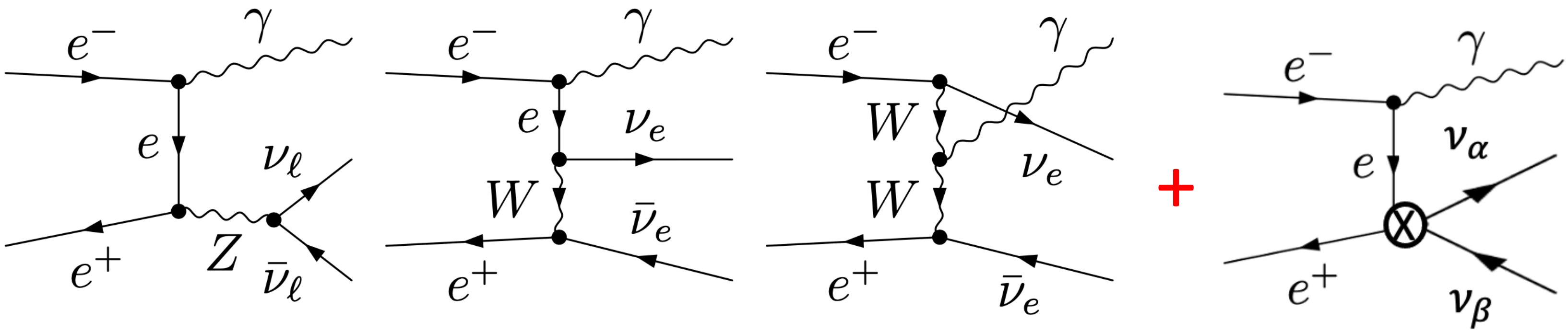
Constraints on NSI w/ u,d

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

Table 2. 2σ allowed ranges for the NSI couplings $\varepsilon^u_{\alpha\beta}$, $\varepsilon^d_{\alpha\beta}$ and $\varepsilon^p_{\alpha\beta}$ as obtained from the global analysis of oscillation plus COHERENT data. See text for details.

Coloma et.al., 1911.09109

NSI@electron collider



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

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

$e^+e^- \to \nu\bar{\nu}$

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

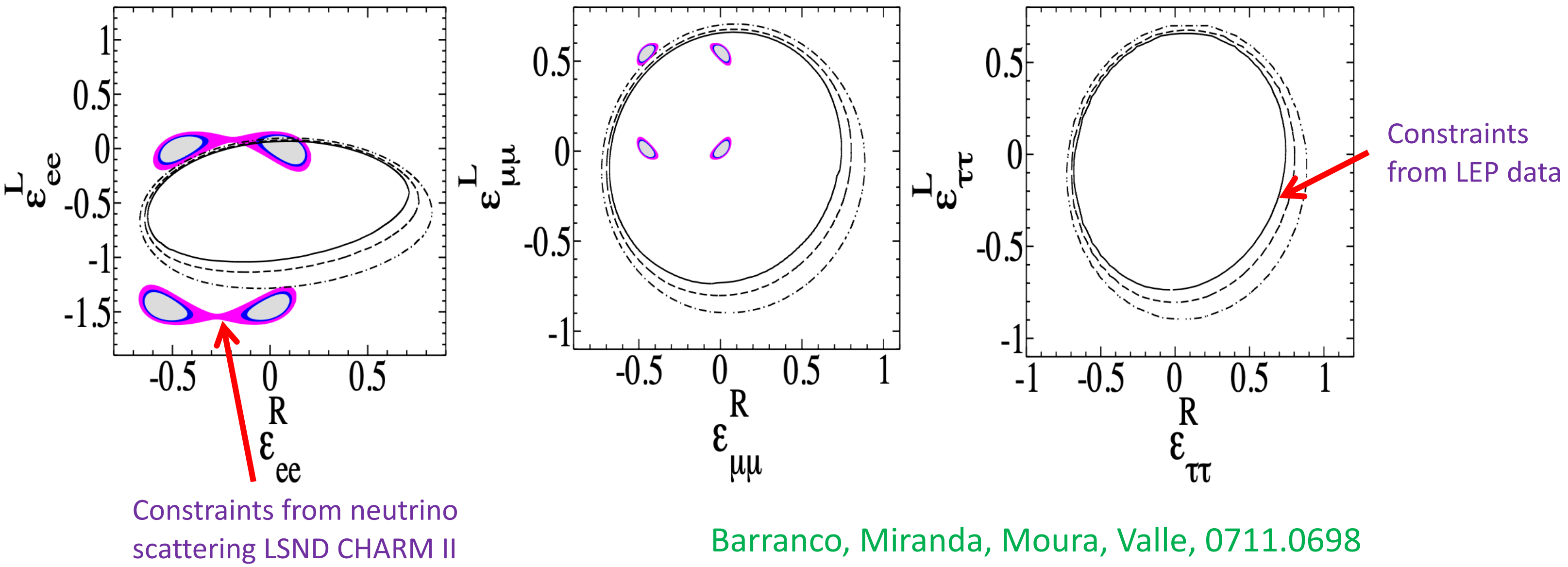
Nicrosini, Trentadue, PLB 231, 487 (1989)

Constraints on NSI w/electron

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

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

12 independent NSI parameters



Barranco, Miranda, Moura, Valle, 0711.0698

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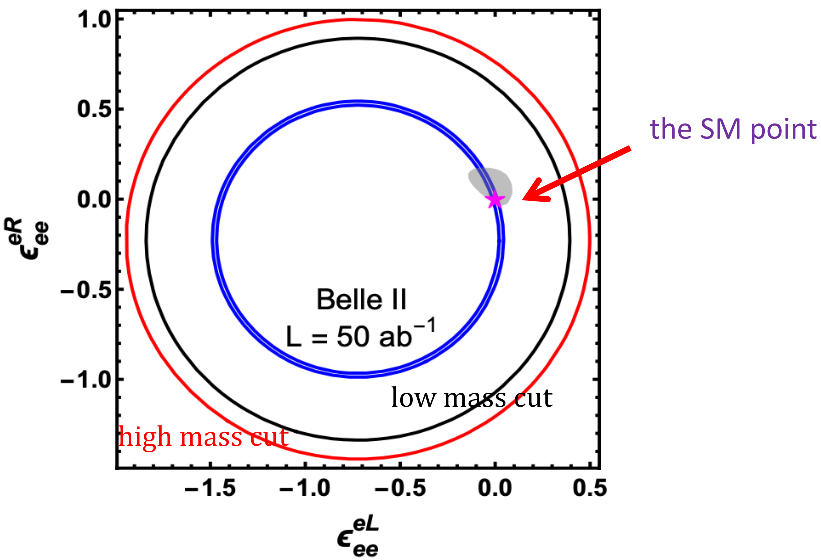
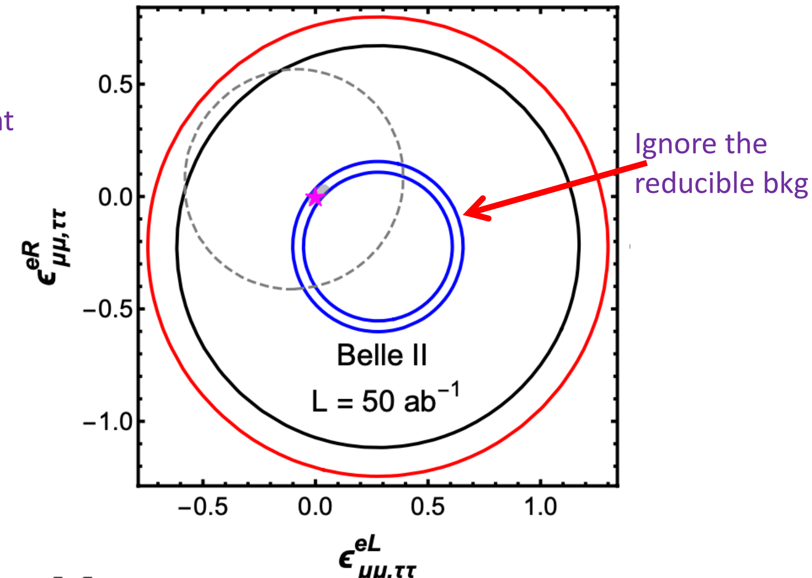
Analysis

$$\chi^2(\epsilon_{\alpha\beta}^{eL},\ \epsilon_{\alpha\beta}^{eR}) \equiv S^2(\epsilon_{\alpha\beta}^{eL},\ \epsilon_{\alpha\beta}^{eR})/(B_{\rm ir} + B_{\rm re})$$

- S is the number of events in the signal;
- B_{ir} : irreducible background with final state containing one γ and two ν in the SM;
- B_{re}: reducible background with final state containing one γ and other visible particles not detected due to limitations of the detector acceptance.

NSI@ Belle II





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

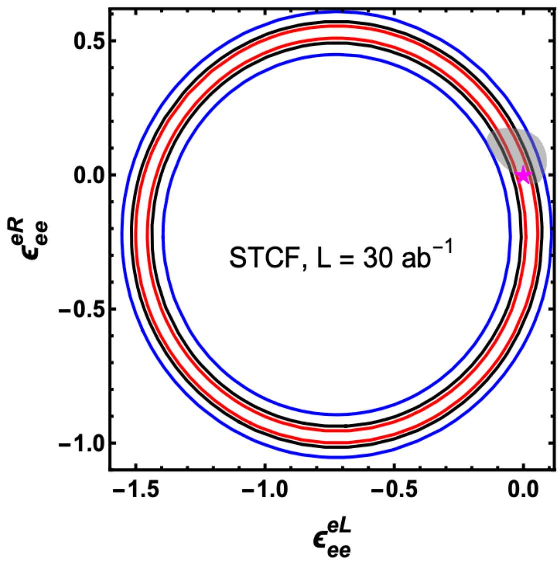
$$\frac{d\sigma^{\rm SM}}{dx_\gamma dz_\gamma} = H(x_\gamma, z_\gamma, s)\frac{G_F^2 s_\gamma}{2\pi}C^{\rm SM} \qquad C^{\rm SM} \equiv g_L^2 + g_R^2 + \frac{2}{3}g_L + \frac{1}{3}$$

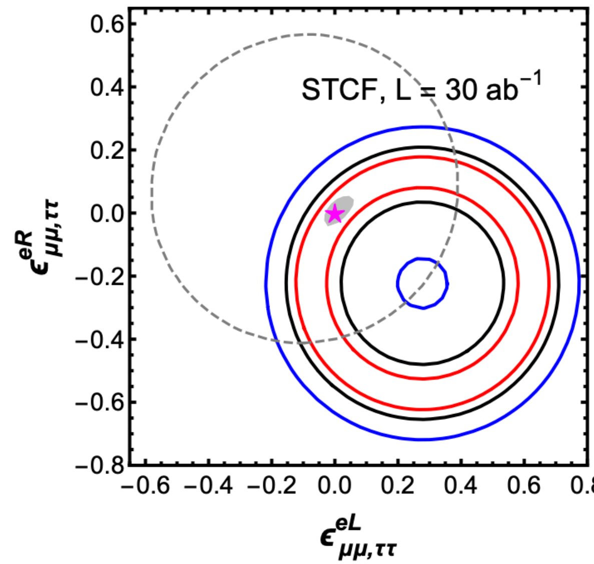
$$\frac{d\sigma^{\rm NSI}}{dx_\gamma dz_\gamma} = H(x_\gamma, z_\gamma, s)\frac{G_F^2 s_\gamma}{2\pi}C^{\rm NSI} \qquad C^{\rm NSI} \equiv \frac{1}{3}\sum_{\alpha,\beta=e,\mu,\tau}\left[(\epsilon_{\alpha\beta}^{eL})^2 + (\epsilon_{\alpha\beta}^{eR})^2 + 2(g_L\epsilon_{\alpha\beta}^{eL} + g_R\epsilon_{\alpha\beta}^{eR})\right]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

$$\chi^2 = \delta^2\sigma^{SM}L \qquad \delta \equiv C^{\rm NSI}/C^{\rm SM}$$

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

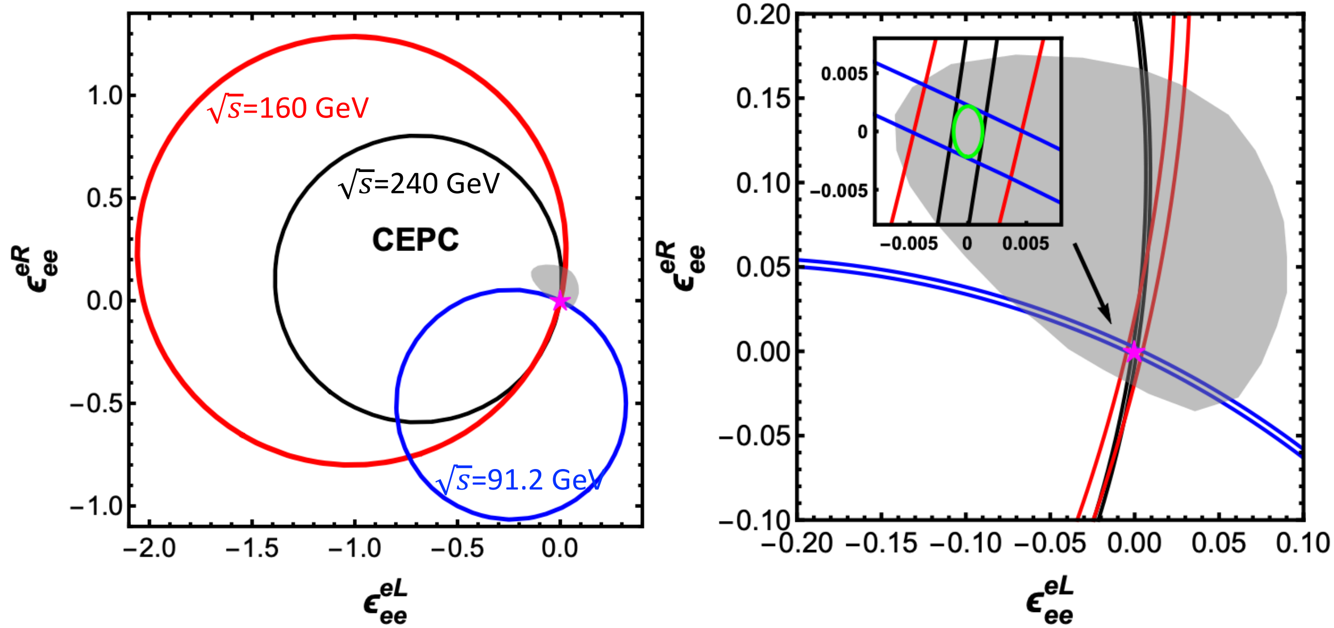
NSI@STCF





	STCF-2 $L = 30\ \mathrm{ab}^{-1}$	STCF-4 $L = 30\ \mathrm{ab}^{-1}$	STCF-7 $L = 30\ \mathrm{ab}^{-1}$	Belle II $L = 50\ \mathrm{ab}^{-1}$	Previous Limit 90% Allowed [45]
ϵ_{ee}^{eL}	[-0.067,0.061]	[-0.033,0.031]	[-0.018,0.018]	[-0.0091,0.0089]	[-0.03,0.08]
ϵ_{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

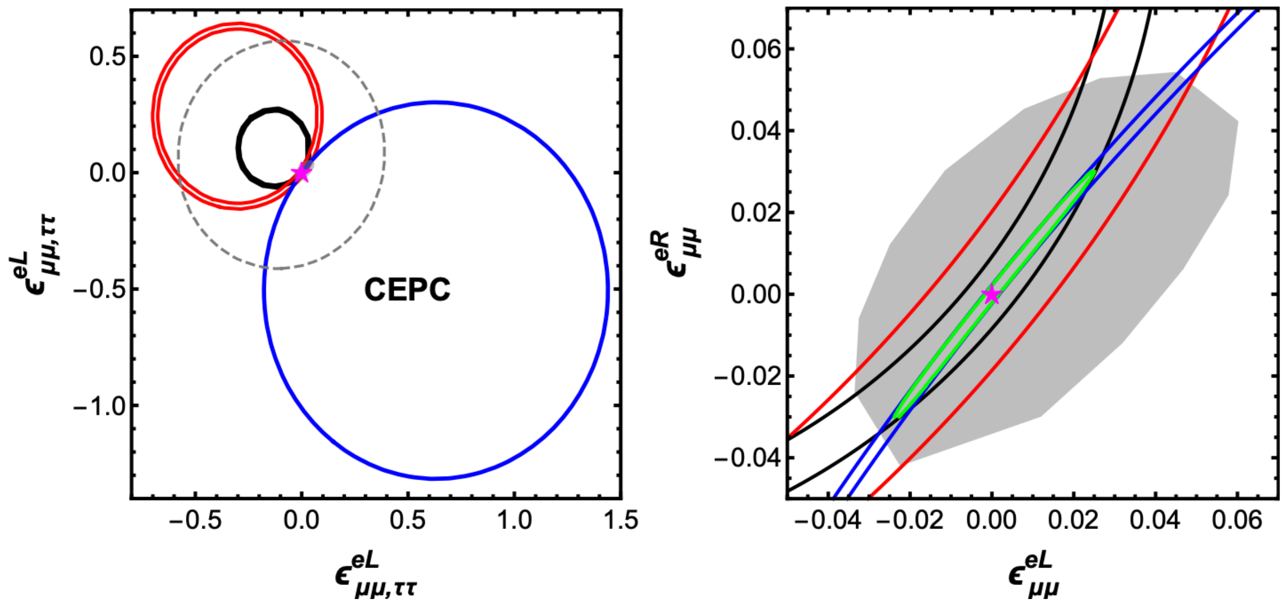


$$\sqrt{s} \geq M_Z \qquad \sigma^{\mathrm{NSI}}\left(\epsilon_{ee}^{eL}, \epsilon_{ee}^{eR}\right) = I_1\left(\left(\epsilon_{ee}^{eL}\right)^2 + \left(\epsilon_{ee}^{eR}\right)^2\right) + (I_2 + I_3)\epsilon_{ee}^{eL} + I_2\frac{g_R}{g_L}\epsilon_{ee}^{eR}$$

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

Allowed regions lie between two concentric circles with the center: $(\epsilon_{ee}^{eL},\ \epsilon_{ee}^{eR}) = (-\frac{I_2 + I_3}{2I_1}, -\frac{I_2 g_R}{2I_1 g_L})$

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]
ϵ^{eL}_{ee}	[-0.0037,0.0037]	[-0.0036,0.0035]	[-0.0010,0.0010]	[-0.00095,0.00095]	[-0.03,0.08]
ϵ^{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 collider 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 for all electron NSI.

Thank you!

Backup slides

Coordinates of the centers