Vector vs. Scalar NSI's of the Neutrino

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VT Center for Neutrino Physics Research Day

Non-Standard Interactions:

- Effects of new physics at low energies can be expressed via dimension-six four-fermion operators

- There are five types:

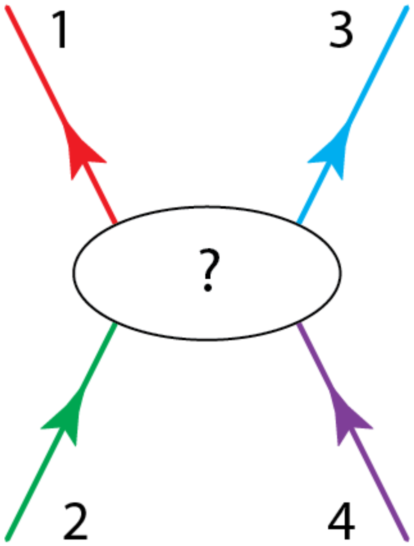
$$e_S(1234) = \left(\bar{\psi}_1\psi_2\right)\left(\bar{\psi}_3\psi_4\right)$$

$$e_V(1234) = \left(\bar{\psi}_1\gamma_\mu\psi_2\right)\left(\bar{\psi}_3\gamma^\mu\psi_4\right)$$

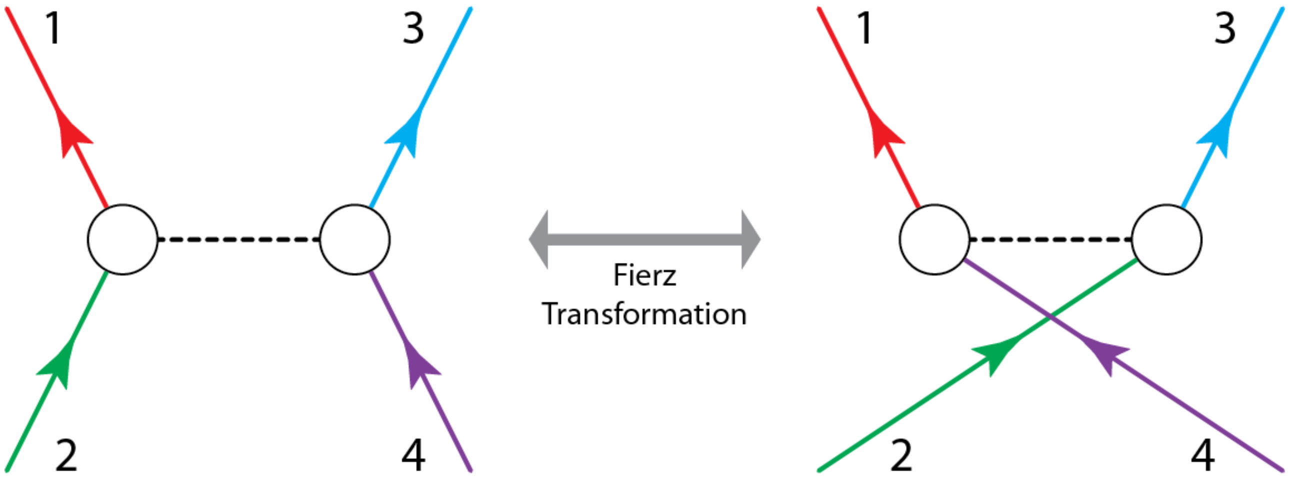
$$e_T(1234) = \left(\bar{\psi}_1\sigma_{\mu\nu}\psi_2\right)\left(\bar{\psi}_3\sigma^{\mu\nu}\psi_4\right)$$

$$e_A(1234) = \left(\bar{\psi}_1\gamma_\mu\gamma^5\psi_2\right)\left(\bar{\psi}_3\gamma^\mu\gamma^5\psi_4\right)$$

$$e_P(1234) = \left(\bar{\psi}_1\gamma^5\psi_2\right)\left(\bar{\psi}_3\gamma^5\psi_4\right)$$



Fierz Identities



$$e_S(1234) = -\frac{1}{4}e_S(1432) - \frac{1}{4}e_V(1432) - \frac{1}{8}e_T(1432) + \frac{1}{4}e_A(1432) - \frac{1}{4}e_P(1432)$$

$$e_V(1234) = -e_S(1432) + \frac{1}{2}e_V(1432) + \frac{1}{2}e_A(1432) + e_P(1432)$$

$$e_T(1234) = -3e_S(1432) + \frac{1}{2}e_T(1432) - 3e_P(1432)$$

$$e_A(1234) = +e_S(1432) + \frac{1}{2}e_V(1432) + \frac{1}{2}e_A(1432) - e_P(1432)$$

$$e_P(1234) = -\frac{1}{4}e_S(1432) + \frac{1}{4}e_V(1432) - \frac{1}{8}e_T(1432) - \frac{1}{4}e_A(1432) - \frac{1}{4}e_P(1432)$$

Fierz Identities for Chiral Fields

- LL, RR cases

$$e_S(12_{L/R}34_{L/R}) = -\frac{1}{2}e_S(14_{L/R}32_{L/R}) - \frac{1}{8}e_T(14_{L/R}32_{L/R})$$

$$e_V(12_{L/R}34_{L/R}) = +e_V(14_{L/R}32_{L/R})$$

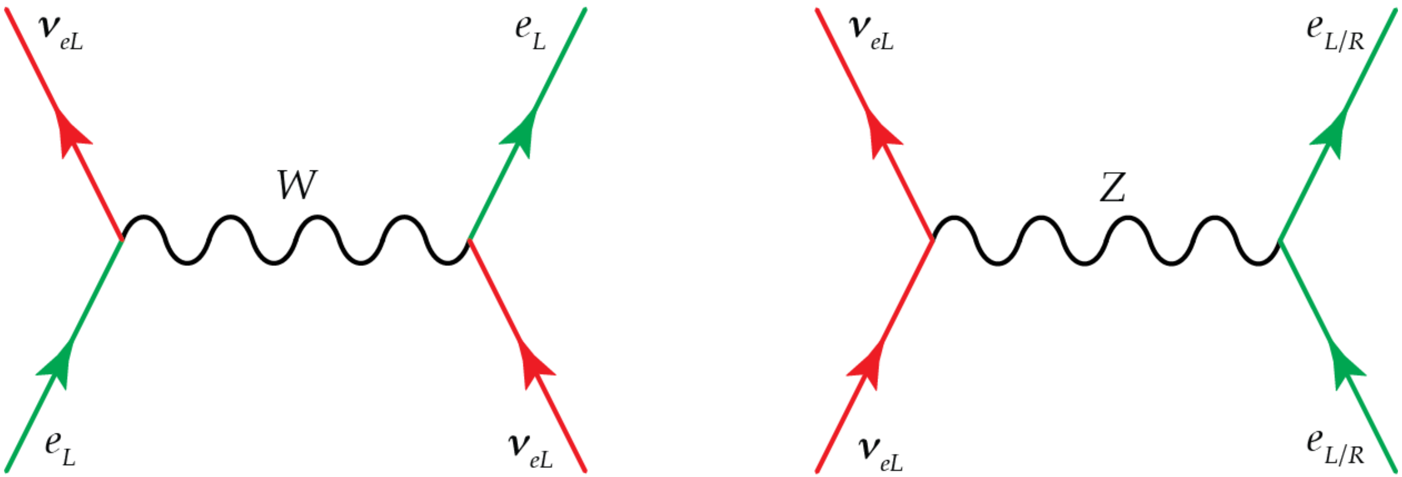
$$e_T(12_{L/R}34_{L/R}) = -6e_S(14_{L/R}32_{L/R}) + \frac{1}{2}e_T(14_{L/R}32_{L/R})$$

- LR, RL cases

$$e_S(12_{L/R}34_{R/L}) = -\frac{1}{2}e_V(14_{R/L}32_{L/R})$$

$$e_T(12_{L/R}34_{R/L}) = 0$$

Fierz Transformation Example:



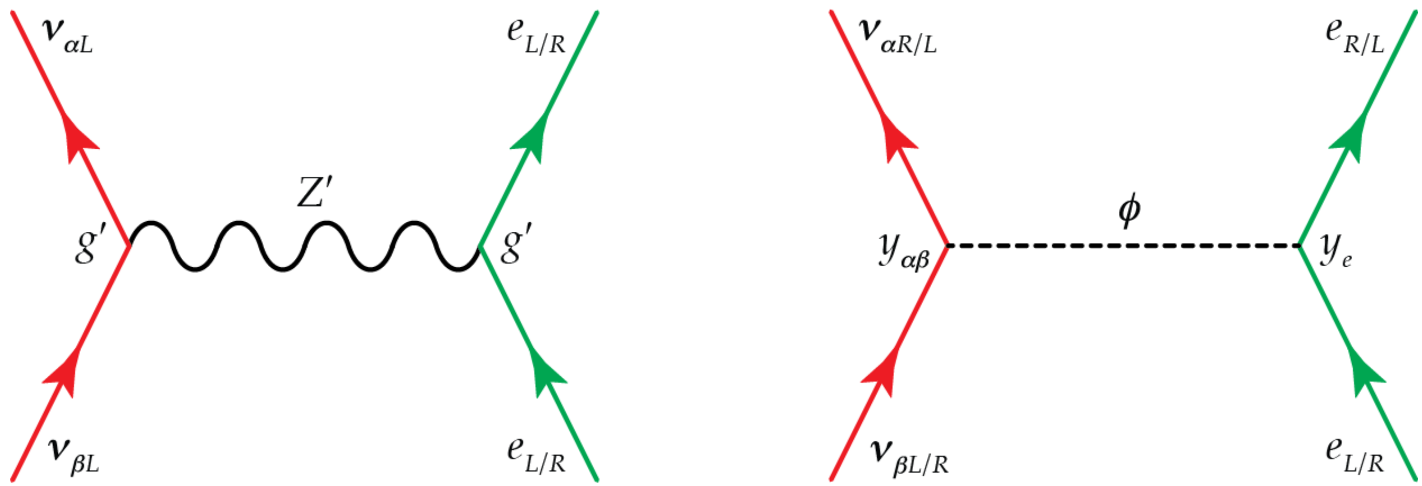
- neutrino-electron interaction from *W* exchange :

$$2\sqrt{2}G_F\left(\overline{\nu}_{eL}\gamma_\mu e_L\right)\left(\overline{e}_L\gamma^\mu \nu_{eL}\right) \quad \rightarrow \quad 2\sqrt{2}G_F\left(\overline{\nu}_{eL}\gamma_\mu \nu_{eL}\right)\left(\overline{e}_L\gamma^\mu e_L\right)$$

- neutrino-electron interaction from *Z* exchange :

$$2\sqrt{2}G_F\left(\overline{\nu}_{eL}\gamma_\mu \nu_{eL}\right)\left\{g_{LL}^{\nu e}\left(\overline{e}_L\gamma^\mu e_L\right)+g_{LR}^{\nu e}\left(\overline{e}_R\gamma^\mu e_R\right)\right\}$$

New Physics:



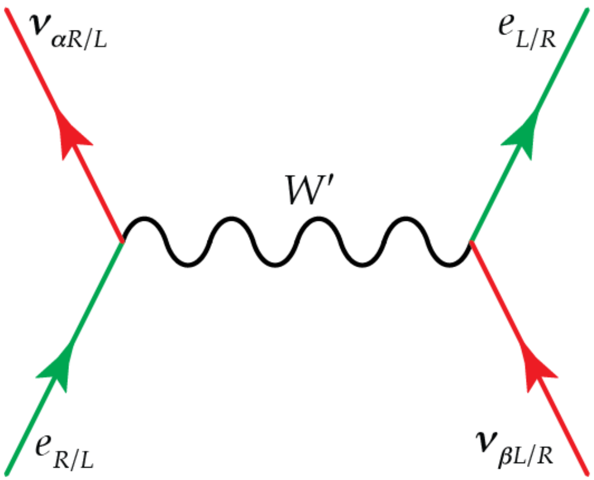
- Vector exchange:

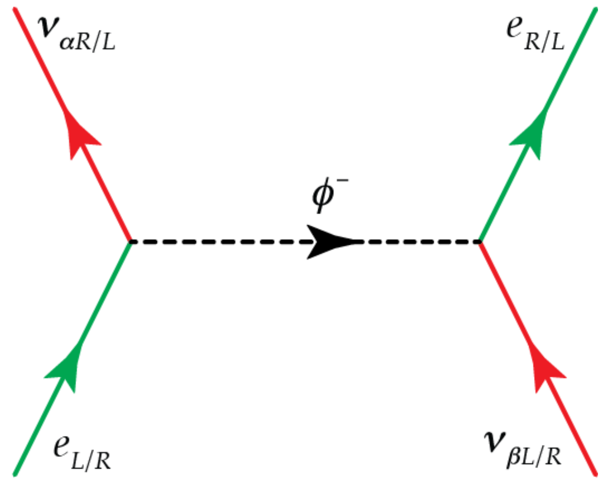
$$\left(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L}\right)\frac{(g')^2}{m_{Z'}^2}\left(\bar{e}_{L/R}\gamma^\mu e_{L/R}\right) \rightarrow 2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{eL/R}\left(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\beta L}\right)\left(\bar{e}_{L/R}\gamma^\mu e_{L/R}\right)$$

- Scalar exchange:

$$\left(\bar{\nu}_{\alpha L}\nu_{\beta R} + \bar{\nu}_{\alpha R}\nu_{\beta L}\right)\frac{y_{\alpha\beta}y_e}{m_\phi^2}\left(\bar{e}_L e_R + \bar{e}_R e_L\right)$$

Fierz Transformed New Physics:





- Charged vector exchange:

$$\left(\bar{\nu}_{\alpha R/L}\gamma_\mu e_{R/L}\right)\left(\bar{e}_{L/R}\gamma^\mu \nu_{\beta L/R}\right) = -2\left(\bar{\nu}_{\alpha R/L}\nu_{\beta L/R}\right)\left(\bar{e}_{L/R}e_{R/L}\right)$$

- Charged scalar exchange:

$$\left(\bar{\nu}_{\alpha R/L}e_{L/R}\right)\left(\bar{e}_{R/L}\nu_{\beta L/R}\right)$$

$$= -\frac{1}{2}\left(\bar{\nu}_{\alpha R/L}\nu_{\beta L/R}\right)\left(\bar{e}_{R/L}e_{L/R}\right) - \frac{1}{8}\left(\bar{\nu}_{\alpha R/L}\sigma_{\mu\nu}\nu_{\beta L/R}\right)\left(\bar{e}_{R/L}\sigma^{\mu\nu}e_{L/R}\right)$$

Vector and Scalar NSI:

- Vector NSI's :

$$-2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{eL/R}\left(\overline{\nu}_{\alpha L}\gamma_\mu\nu_{\beta L}\right)\left(\overline{e}_{L/R}\gamma^\mu e_{L/R}\right)$$

- Most commonly considered form of NSI's
- New Borexino bounds: arXiv:1905.03512

- Scalar NSI's :

$$\left(\overline{\nu}_{\alpha L}\nu_{\beta R}+\overline{\nu}_{\alpha R}\nu_{\beta L}\right)\frac{y_{\alpha\beta}y_e}{m_\phi^2}\left(\overline{e}_L e_R+\overline{e}_R e_L\right)$$

- Shao-Feng Ge and Stephen J. Parke, arXiv:1812.08376

Effect of Scalar NSI to Neutrino Propagation:

- Shao-Feng Ge and Stephen J. Parke, arXiv:1812.08376
- In matter:

$$\frac{y_{\alpha\beta} y_e}{m_\phi^2} (\bar{\nu}_\alpha \nu_\beta) \underbrace{(\bar{e} e)}_{n_e} \rightarrow \underbrace{\frac{n_e y_{\alpha\beta} y_e}{m_\phi^2}}_{(M_S)_{\alpha\beta}} (\bar{\nu}_\alpha \nu_\beta)$$

- Normalize to larger mass-squared difference:

$$M_S = \sqrt{\Delta m_{31}^2} \begin{bmatrix} \eta_{ee} & \eta_{\mu e}^* & \eta_{\tau e}^* \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\tau\mu}^* \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{bmatrix}$$

Effect of Scalar NSI to Neutrino Propagation:

- Shao-Feng Ge and Stephen J. Parke, arXiv:1812.08376
- Mass matrix is shifted in matter:

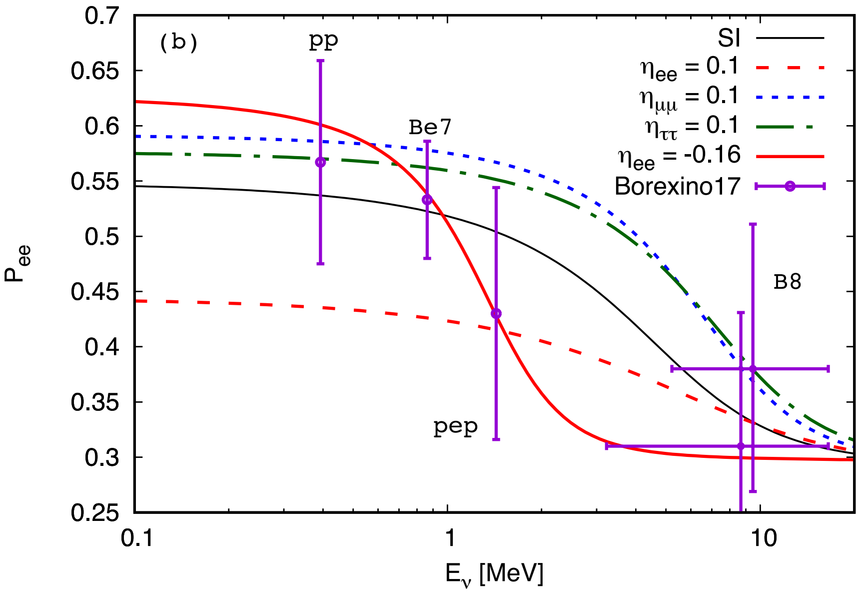
$$M \rightarrow M + M_S$$

$$\frac{M^2}{2E_\nu} \rightarrow \frac{(M + M_S)(M + M_S)^\dagger}{2E_\nu}$$

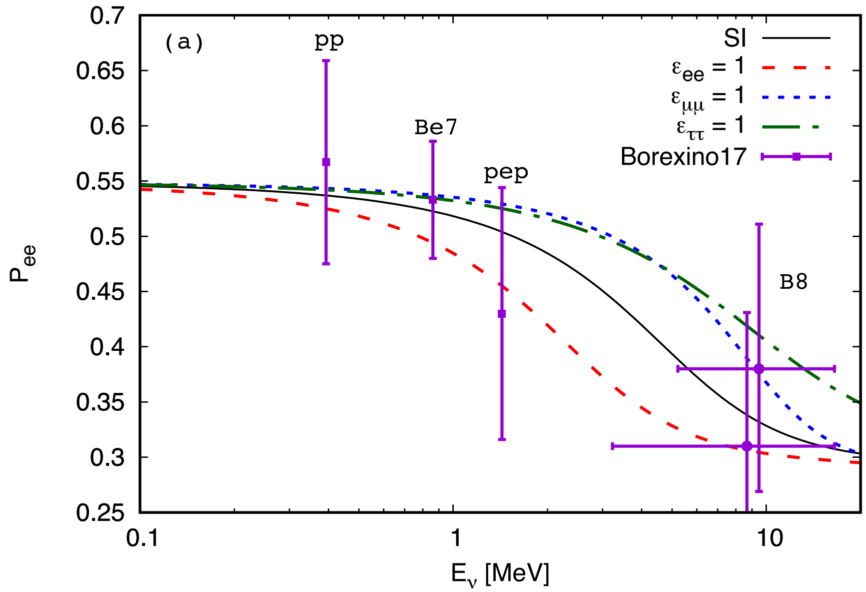
- Note: this assumes that neutrino masses are Dirac

Bounds from Borexino:

- Affects the MSW effect on Solar Neutrinos as they propagate out of the Sun
- Solar electron-neutrino survival probability:



Scalar NSI's



Vector NSI's

Large Scalar NSI's? :

- Is $\eta_{\mathrm{ee}} = -0.16$ possible?
- The electron density at the center of the Sun is:

$$n_e = 6\times10^{25}\,/\,\mathrm{cm}^3 = 5\times10^{11}\,(\mathrm{eV}\,/\,\hbar c)^3$$

- so the Yukawa couplings and scalar mass must satisfy:

$$\frac{y_{ee}y_e}{m_\phi^2} = \frac{\sqrt{\Delta m_{31}^2}}{n_e}\eta_{ee} = \frac{\sqrt{2.56\times10^{-3}\,\mathrm{eV}^2}}{5\times10^{11}\,(\mathrm{eV}\,/\,\hbar c)^3}\times(-0.16)$$

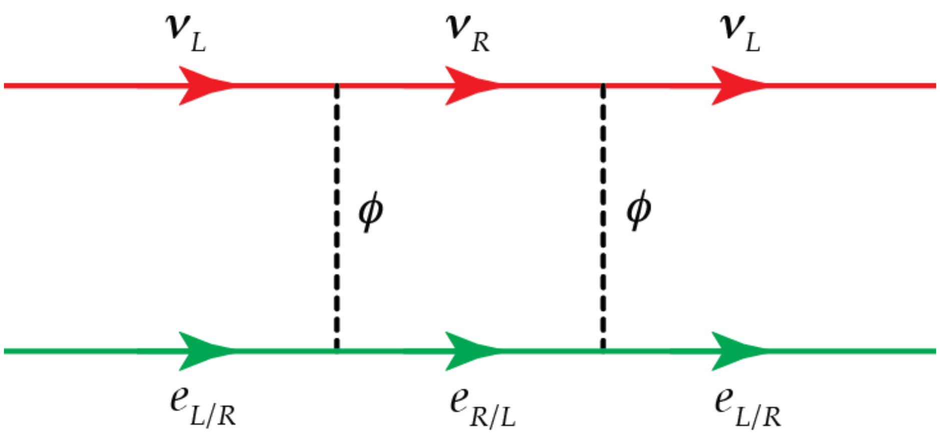
$$= \left(0.1\,\frac{(\hbar c)^3}{\mathrm{MeV}^2}\right)\times(-0.16) = -0.016\,\frac{(\hbar c)^3}{\mathrm{MeV}^2}$$

Further points to consider:

- The Ge-Parke analysis assumes Dirac masses
- If neutrino masses are Majorana

$$M = \frac{M^2_{Dirac}}{M_{Majorana}} \rightarrow \frac{(M_{Dirac} + M_S)^2}{M_{Majorana}}$$

- There is also a matter potential effect:



Can we generate large NSI's?

- Generating large NSI's from heavy mediators is very difficult

- Can light mediators help us?

Interactions must be SU(2) x U(1) invariant:

$$\mathcal{L} = -2\sqrt{2}G_F \varepsilon^{eL}_{\mu\tau} \left(\overline{\nu_\mu}\gamma^\mu P_L \nu_\tau\right)\left(\overline{e}\gamma_\mu P_L e\right)$$

- Case 1: $\left(\overline{L_\mu}\gamma^\mu L_\tau\right)\left(\overline{L_e}\gamma_\mu L_e\right)$

$$= \Big[\left(\overline{\nu_\mu}\gamma^\mu P_L \nu_\tau\right)\left(\overline{\nu_e}\gamma_\mu P_L \nu_e\right) + \left(\overline{\nu_\mu}\gamma^\mu P_L \nu_\tau\right)\left(\overline{e}\gamma_\mu P_L e\right) + \left(\overline{\mu}\gamma_\mu P_L \tau\right)\left(\overline{\nu_e}\gamma^\mu P_L \nu_e\right) + \left(\overline{\mu}\gamma^\mu P_L \tau\right)\left(\overline{e}\gamma_\mu P_L e\right)\Big]$$

Constrained by $\tau \to \mu e e$: $\left|\varepsilon^{eL}_{\mu\tau}\right| < 10^{-4}$

- Case 2: $\left(\overline{L_\mu} i\sigma_2 L^c_e\right)\left(\overline{L^c_\tau} i\sigma_2 L_e\right)$

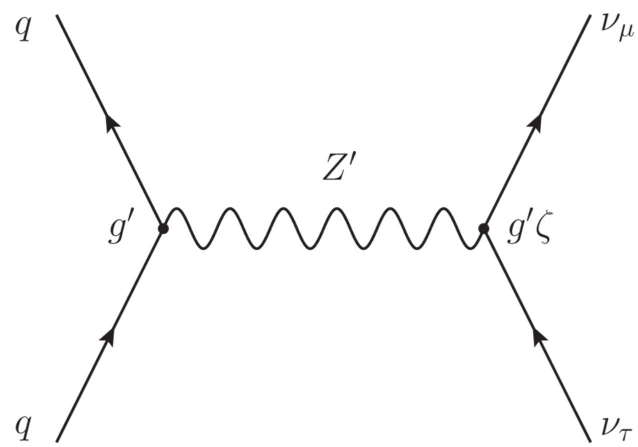
$$= \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L \nu_\tau\right)\left(\overline{e}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_e}\gamma^\mu P_L \nu_\tau\right)\left(\overline{\mu}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L \nu_e\right)\left(\overline{e}\gamma_\mu P_L \tau\right) + \frac{1}{2}\left(\overline{\nu_e}\gamma^\mu P_L \nu_e\right)\left(\overline{\mu}\gamma_\mu P_L \tau\right)$$

Constrained by $\mu \to e\nu_e\nu_\tau, \tau \to e\nu_e\nu_\mu, \tau \to \mu\nu_e\nu_e$: $\left|\varepsilon^{eL}_{\mu\tau}\right| < 10^{-3}$

Farzan-Shoemaker Model

- Y. Farzan and I. M. Shoemaker, "Lepton Flavor Violating Non-Standard Interactions via Light Mediators," JHEP07(2016)033, arXiv:1512.09147

$$\varepsilon = 2\left(\frac{g'}{g}\right)^2\left(\frac{M_W}{M_{Z'}}\right)^2 = 0.03\, g'^2\left(\frac{1000\,\mathrm{GeV}}{M_{Z'}}\right)^2 = 0.03\left(\frac{g'}{10^{-4}}\right)^2\left(\frac{100\,\mathrm{MeV}}{M_{Z'}}\right)^2$$



$$\varepsilon^{qC}_{\mu\tau} \sim 0.005 \quad \rightarrow \quad \varepsilon_{\mu\tau} \sim 0.06$$

Farzan-Shoemaker Model : Z' Mass & Coupling

- The mass of the Z' is chosen to be:

$$135\,\mathrm{MeV} \;<\; M_{Z'} \;<\; 200\,\mathrm{MeV}$$

so that the decays

$$\pi^0 \;\to\; \gamma + Z' \,, \qquad\qquad Z' \;\to\; \mu^+ + \mu^-$$

cannot occur

- Z' coupling to the leptons are strongly constrained by:

$$\tau \;\to\; \mu + Z'$$

Two-body decay bound:

- Argus (1995)

$$B(\tau \to \mu + Z') < 5 \times 10^{-3}$$
$$\downarrow$$
$$g'\zeta < 6 \times 10^{-8} \left(\frac{M_{Z'}}{200\mathrm{MeV}}\right)$$

- Belle has 2000 times more statistics and is expected to improve the bound to 1×10^{-4} (Yoshinobu and Hayasaka, Nucl. Part. Phys. Proc. 287-288 (2017) 218-220)

$$B(\tau \to \mu + Z') < 1 \times 10^{-4}$$
$$\downarrow$$
$$g'\zeta < 9 \times 10^{-9} \left(\frac{M_{Z'}}{200\mathrm{MeV}}\right)$$

Constraints on the Z'-quark couplings:

- Semi-Empirical Mass Formula of Nuclei:

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A} \pm \delta(A,Z)$$

- Coulomb term:

$$E_C = \frac{3}{5}\frac{Q^2}{R} = \frac{3}{5}\frac{(eZ)^2}{(r_0 A^{1/3})} = (0.691\,\mathrm{MeV})\frac{(1.25\,\mathrm{fm})}{r_0}\frac{Z^2}{A^{1/3}}$$

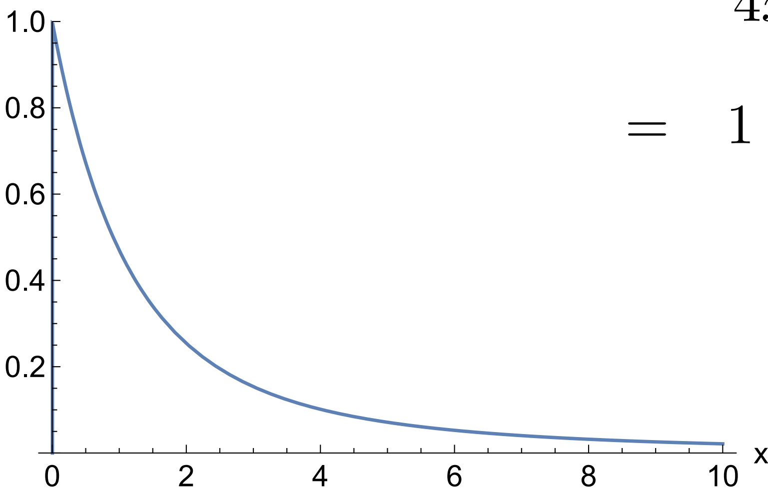
Z' potential energy:

- Z' potential energy term:

$$
\begin{aligned}
E_{Z'} &= \frac{3}{5}\frac{Q'^2}{R} f(mR) = \frac{3}{5}\frac{(3g'A)^2}{(r_0 A^{1/3})} f(m r_0 A^{1/3}) \\
&= (0.691\,\mathrm{MeV})\frac{(1.25\,\mathrm{fm})}{r_0}\left(\frac{3g'}{e}\right)^2 A^{5/3} f(m r_0 A^{1/3})
\end{aligned}
$$

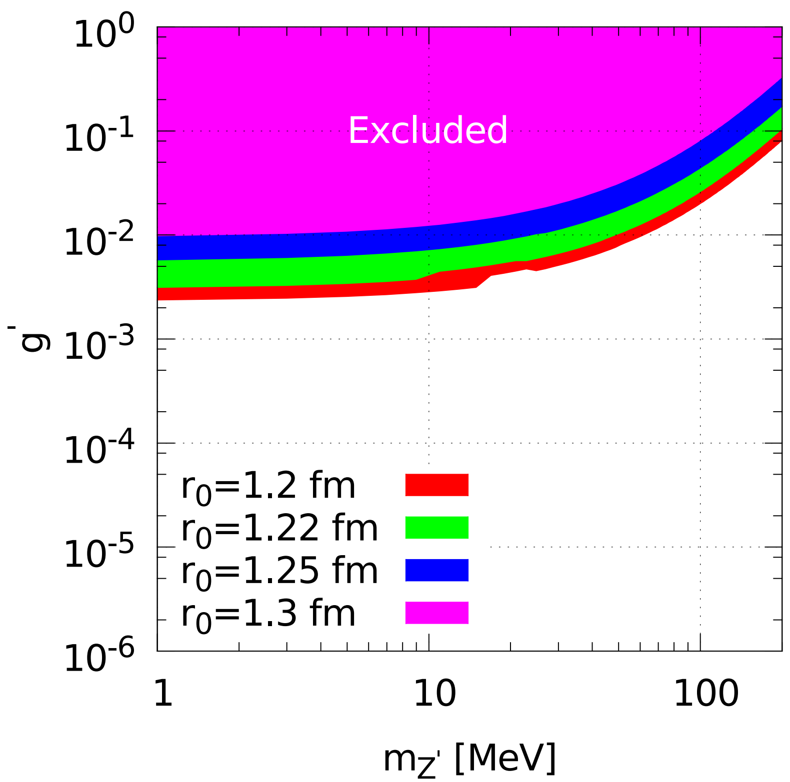
where

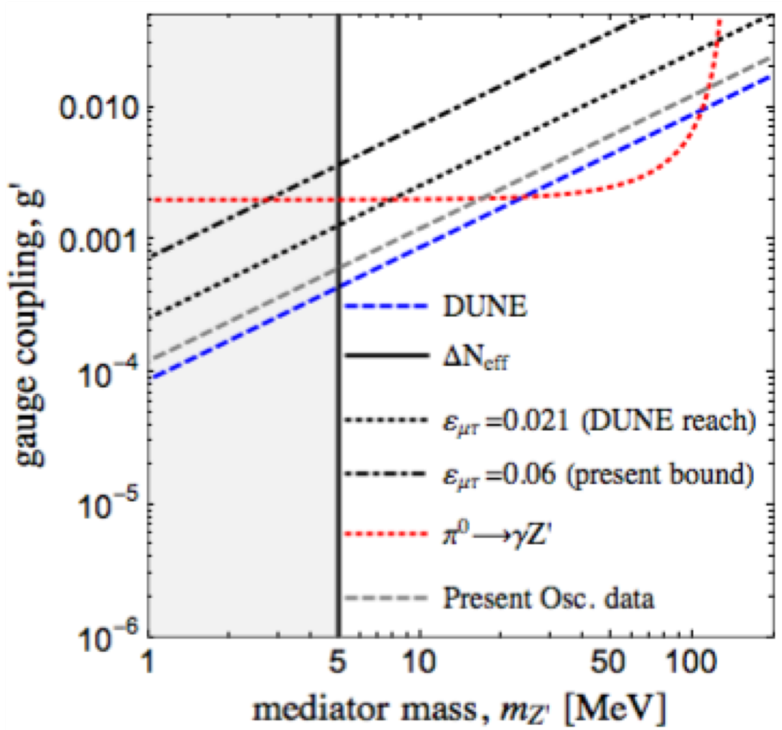
$$
\begin{aligned}
f(x) &\equiv \frac{15}{4x^5}\left[1 - x^2 + \frac{2x^3}{3} - (1+x)^2 e^{-2x}\right] \\
&= 1 - \frac{5x}{6} + \frac{3x^2}{7} - \frac{x^3}{6} + \cdots
\end{aligned}
$$



Preliminary Result:

- By David Vanegas Forero
- Fit to stable nuclei (90% C.L. left) compared to Figure from Farzan-Shoemaker paper (JHEP07(2016)033 right)





Conclusions:

- NSI’s beyond the usual vector type can exist

- Current and near future experiments are only sensitive to large NSI’s (both vector and scalar)

- Generating large NSI’s is very difficult