Vector vs. Scalar NSI's, Light Mediators, and other considerations

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Amherst Center for Fundamental Interactions
"Neutrino-Electron Scattering at Low Energies"

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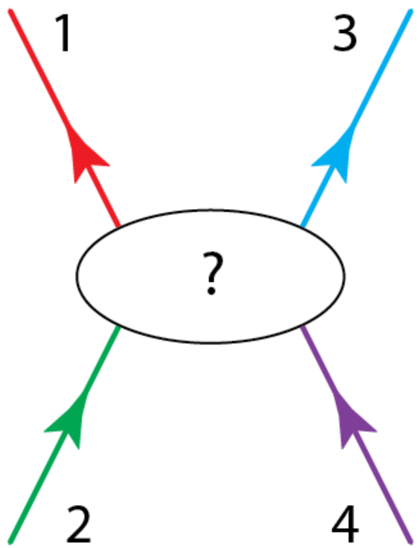
Non-Standard Interactions:

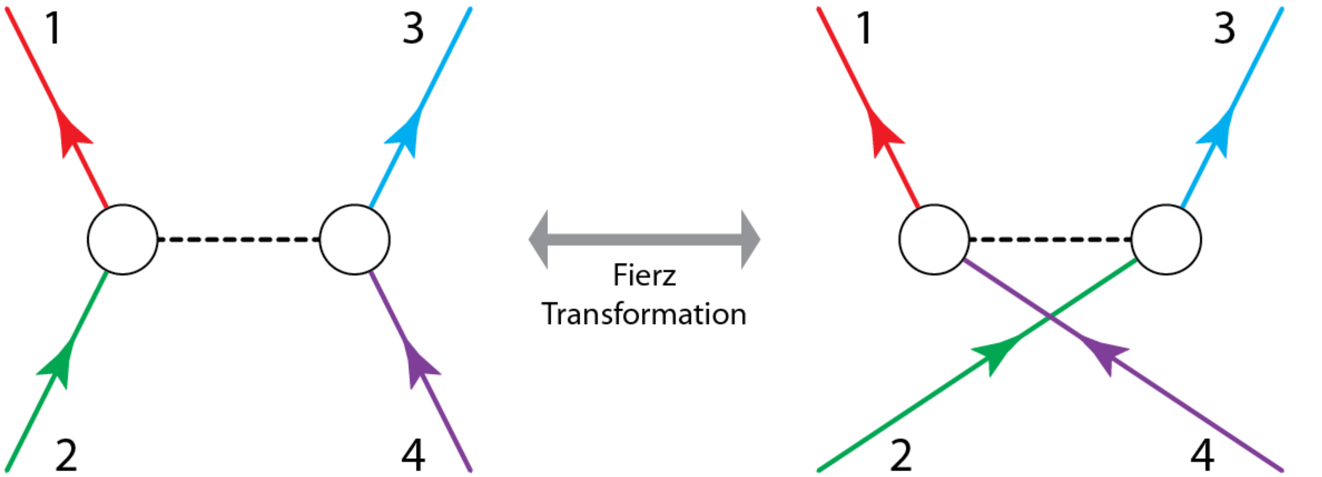
- Effects of new physics at low energies can be expressed via dimension-six four-fermion operators
- There are five types:

$$e_S(1234) = (\bar{\psi}_1\psi_2)(\bar{\psi}_3\psi_4)$$
$$e_V(1234) = (\bar{\psi}_1\gamma_\mu\psi_2)(\bar{\psi}_3\gamma^\mu\psi_4)$$
$$e_T(1234) = (\bar{\psi}_1\sigma_{\mu\nu}\psi_2)(\bar{\psi}_3\sigma^{\mu\nu}\psi_4)$$
$$e_A(1234) = (\bar{\psi}_1\gamma_\mu\gamma^5\psi_2)(\bar{\psi}_3\gamma^\mu\gamma^5\psi_4)$$
$$e_P(1234) = (\bar{\psi}_1\gamma^5\psi_2)(\bar{\psi}_3\gamma^5\psi_4)$$



- Operators relevant for neutrino-electron scattering are those in which two of the operators are neutrinos and the other two operators are electrons

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

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

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

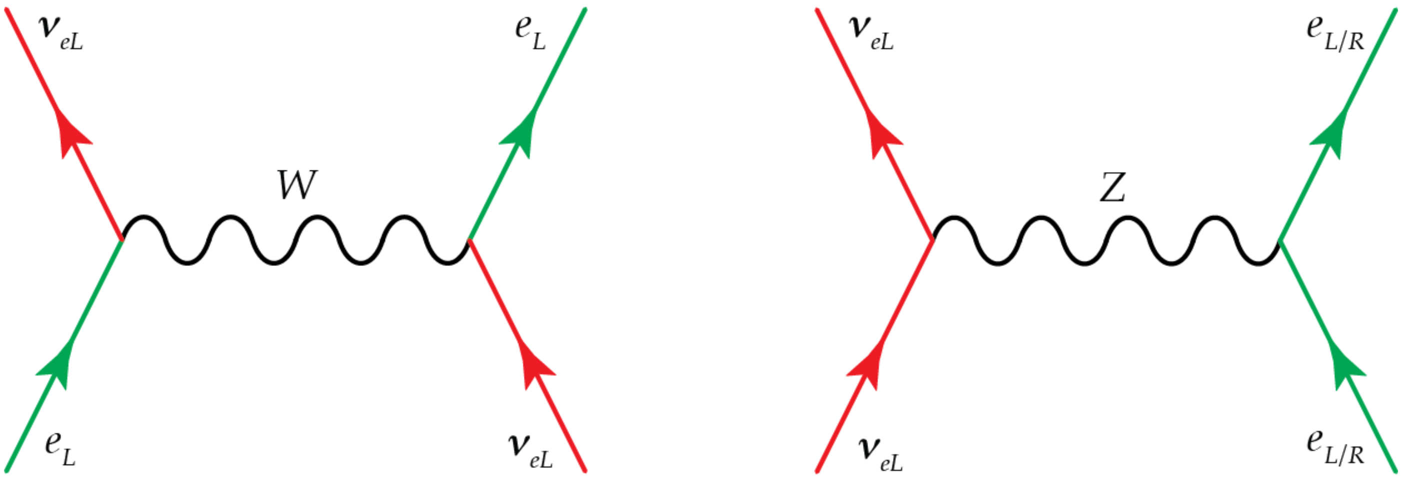
$$e_T(12_{L/R}34_{L/R}) = -6e_S(14_{L/R}32_{L/R}) + \frac{1}{2}e_T(14_{L/R}32_{L/R})$$

- 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:



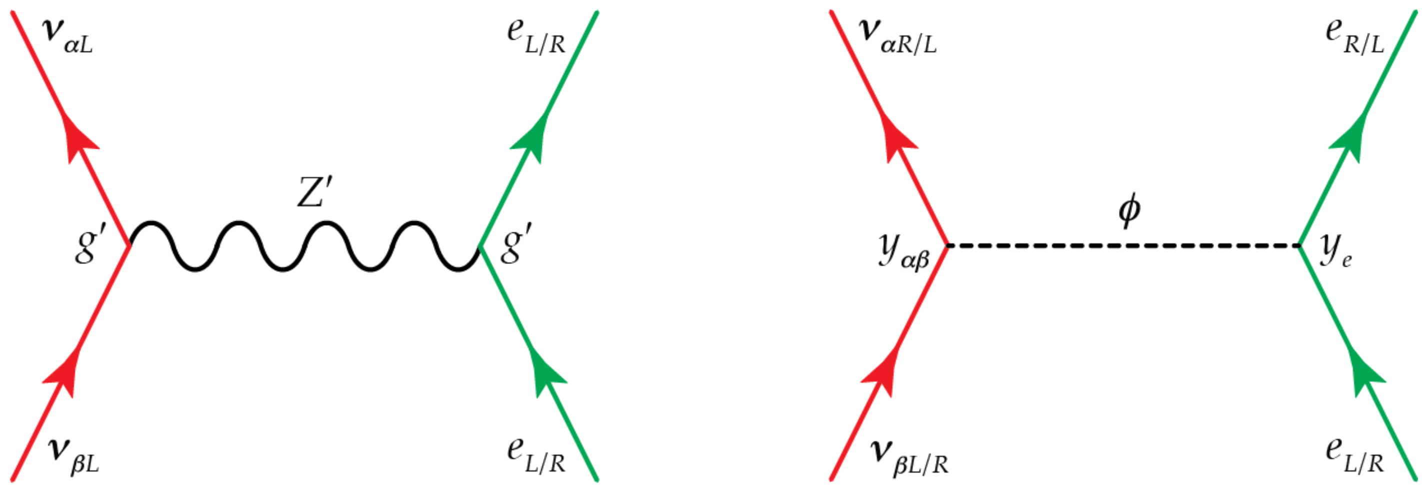
- neutrino-electron interaction from *W* exchange :

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

- neutrino-electron interaction from *Z* exchange :

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

New Physics:



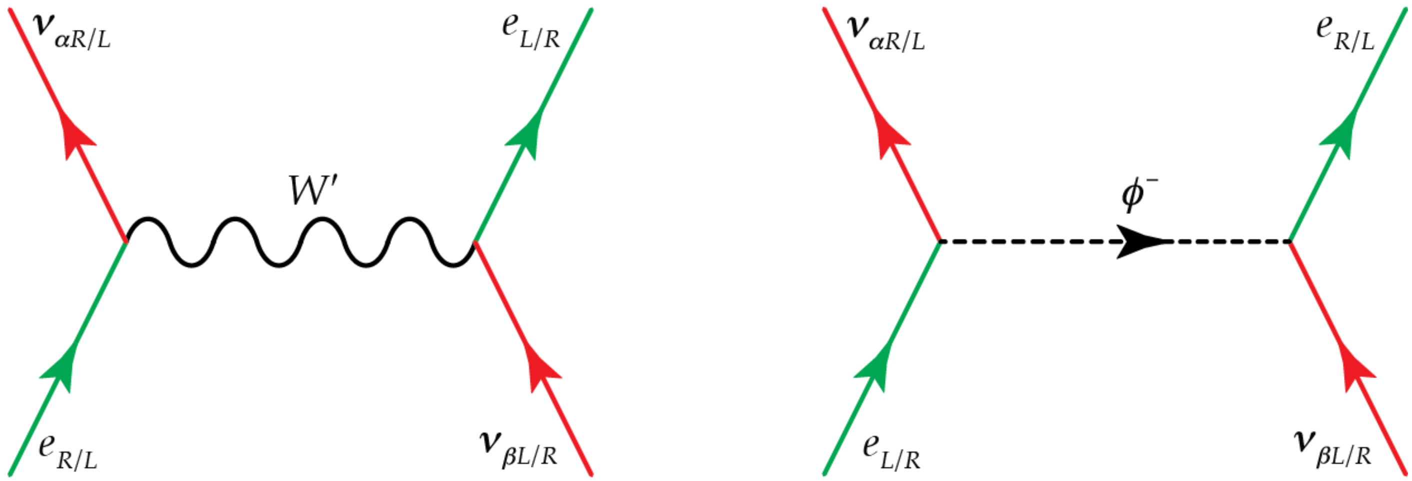
- Vector exchange:

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

- 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 :

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

- See talk by Chen Sun from yesterday

- Scalar NSI's :

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

- 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:

$$\frac{y_{\alpha\beta} y_e}{m_\phi^2} (\bar{\nu}_\alpha \nu_\beta) \underbrace{(\bar{e}\, e)}_{n_e} \rightarrow \frac{n_e y_{\alpha\beta} y_e}{m_\phi^2} (\bar{\nu}_\alpha \nu_\beta) \equiv M_S = \sqrt{\Delta m_{31}^2} \begin{bmatrix} \eta_{ee} & \eta_{\mu e}^* & \eta_{\tau e}^* \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\tau\mu}^* \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{bmatrix}$$

- Mass matrix is shifted:

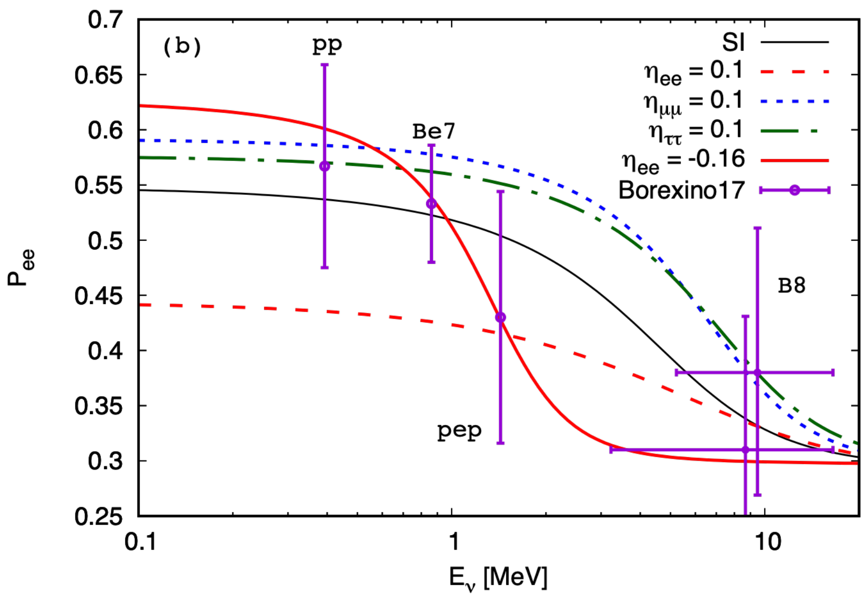
$$M \rightarrow M + M_S$$

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

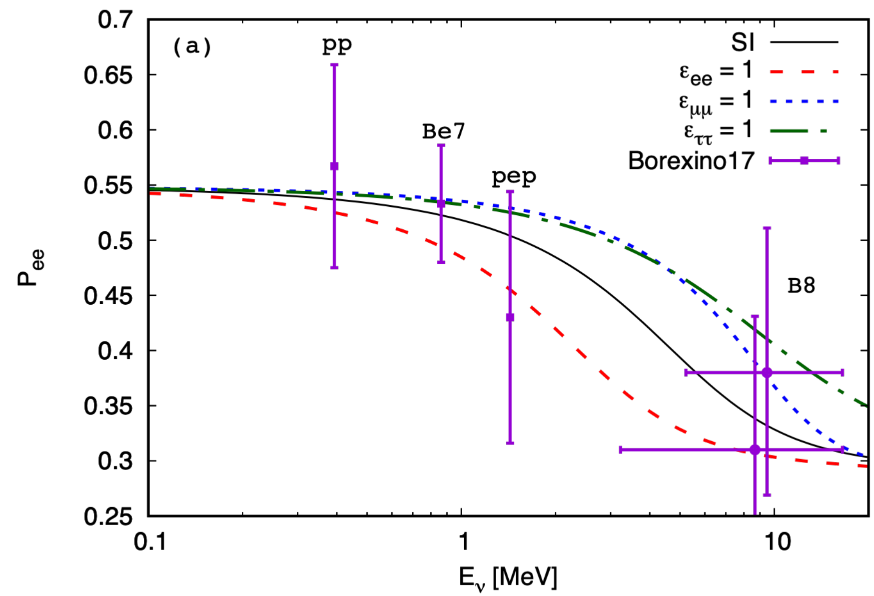
Bounds from Borexino:

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

- electron-neutrino survival probability:



Scalar NSI's



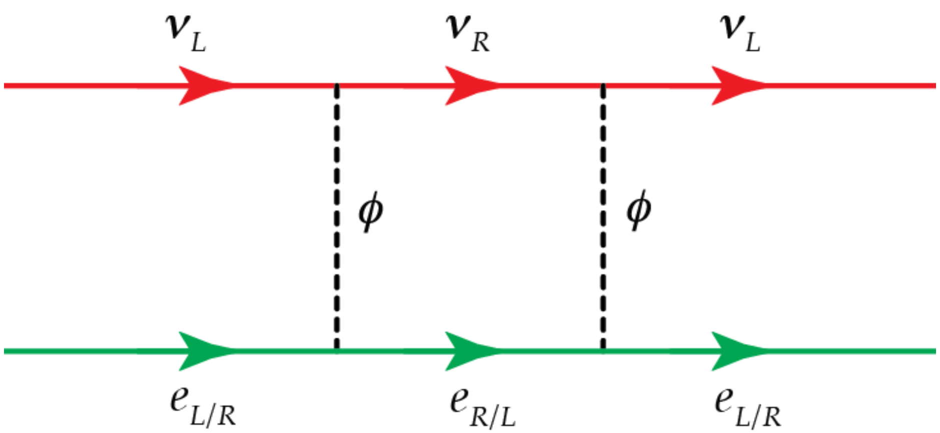
Vector NSI's

Further points to consider:

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

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

- 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:

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

- 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 $\tau \to \mu e e$: $\left|\varepsilon_{\mu\tau}^{eL}\right| < 10^{-4}$

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

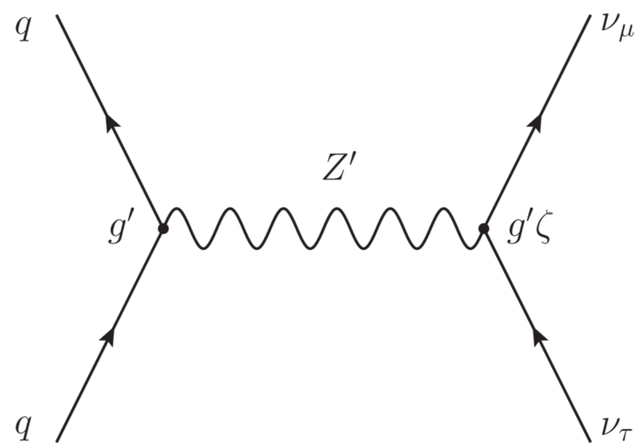
$$= \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L\nu_\tau\right)\left(\overline{e}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_e}\gamma^\mu P_L\nu_\tau\right)\left(\overline{\mu}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L\nu_e\right)\left(\overline{e}\gamma_\mu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

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

Farzan-Shoemaker Model

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

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



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

- Is the model truely viable?

Farzan-Shoemaker Model : Fermion Content

- $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$ gauge theory
- Quarks:

$$Q_i = \begin{bmatrix} u_{Li} \\ d_{Li} \end{bmatrix} \sim \left(3, 2, +\frac{1}{6}, 1\right), \quad u_{Ri} \sim \left(3, 1, +\frac{2}{3}, 1\right), \quad d_{Ri} \sim \left(3, 1, -\frac{1}{3}, 1\right)$$

- Leptons:

$$\begin{aligned} L_0 &= \begin{bmatrix} \nu_{L0} \\ \ell_{L0} \end{bmatrix} \sim \left(1, 2, -\frac{1}{2}, 0\right), \quad \ell_{R0} \sim (1, 1, -1, 0), \\ L_+ &= \begin{bmatrix} \nu_{L+} \\ \ell_{L+} \end{bmatrix} \sim \left(1, 2, -\frac{1}{2}, +\zeta\right), \quad \ell_{R+} \sim (1, 1, -1, +\zeta), \\ L_- &= \begin{bmatrix} \nu_{L-} \\ \ell_{L-} \end{bmatrix} \sim \left(1, 2, -\frac{1}{2}, -\zeta\right), \quad \ell_{R-} \sim (1, 1, -1, -\zeta), \end{aligned}$$

- Extra (heavy) fermions for anomaly cancellation (?)

Farzan-Shoemaker Model : Scalar Content

- Higgses:

$$
\begin{aligned}
H &= \begin{bmatrix} H^{+} \\ H^{0} \end{bmatrix} \sim \left(1, 2, +\frac{1}{2}, 0\right) \;, \\
H_{++} &= \begin{bmatrix} H^{+}_{++} \\ H^{0}_{++} \end{bmatrix} \sim \left(1, 2, +\frac{1}{2}, +2\zeta\right) \;, \\
H_{--} &= \begin{bmatrix} H^{+}_{--} \\ H^{0}_{--} \end{bmatrix} \sim \left(1, 2, +\frac{1}{2}, -2\zeta\right) \;.
\end{aligned}
$$

- Yukawa couplings:

$$
\begin{aligned}
&\sum_{i=1}^{3}\sum_{j=1}^{3}\left(\lambda_{ij}\overline{d_{Ri}}H^{\dagger}Q_j + \tilde{\lambda}_{ij}\overline{u_{Ri}}\widetilde{H}^{\dagger}Q_j\right) + h.c. \\
&+ \sum_{j=0,+,-}\left(f_j\,\overline{\ell_{Rj}}H^{\dagger}L_j\right) + h.c. \\
&+ \left(c_{-}\overline{\ell_{R+}}H^{\dagger}_{--}L_{-} + c_{+}\overline{\ell_{R-}}H^{\dagger}_{++}L_{+}\right) + h.c.
\end{aligned}
$$

Farzan-Shoemaker Model : Symmetry Breaking

- Higgs VEV's:

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}} \,, \quad \langle H^0_{++} \rangle = \frac{v_+}{\sqrt{2}} \,, \quad \langle H^0_{--} \rangle = \frac{v_-}{\sqrt{2}} \,,$$

- Assume $v_+ = v_- = \dfrac{w}{\sqrt{2}}$ (no Z-Z' or γ-Z' mixing at tree-level)

- Gauge boson masses:

$$M_W = \frac{g_2}{2}\sqrt{v^2 + w^2} \,, \quad M_Z = \frac{\sqrt{g_1^2 + g_2^2}}{2}\sqrt{v^2 + w^2} \,, \quad M_{Z'} = 2\zeta g' w$$

Farzan-Shoemaker Model : Z’ Mass & Coupling

- The mass of the Z’ is chosen to be:

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

so that the decays

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

cannot occur

- Range of the Z’-exchange force comparable to that of strong interactions → Z’ interactions between quarks can be sizable but still be masked by the strong force (?)
- Z’ coupling to the leptons are strongly constrained by:

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

Farzan-Shoemaker Model : Problems

- *U(1)* charges are ill defined in models with multiple *U(1)'*s
→ They necessarily mix under renormalization group running
(See W. A. Loinaz and T. Takeuchi, Phys.Rev. D60 (1999) 115008)

- Constraint on $\zeta g'$ does not allow the generation of Z' mass in the 135~200 MeV range without making the Higgs VEV w too large for the *W* and *Z* masses
→ Need to introduce a SM-singlet scalar

- Full MNS neutrino mixing matrix cannot be generated.
The U(1)' singlet lepton cannot mix with the non-singlet leptons.
→ Need to introduce a more scalars

- Not clear whether the fermions necessary for anomaly cancelation can be made heavy → Even more scalars?

Constraints on the Z’ couplings revisited:

- Z’-quark coupling
- Z’-lepton coupling

- 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:

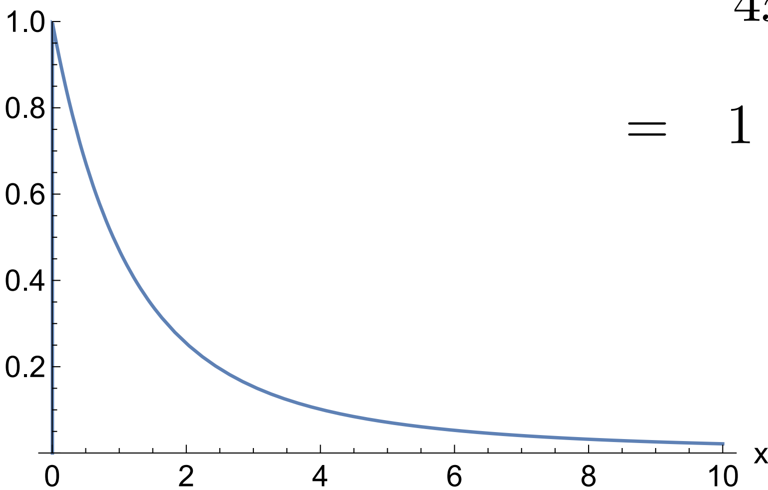
$$E_{Z'} = \frac{3}{5}\frac{Q'^2}{R}f(mR) = \frac{3}{5}\frac{(3g'A)^2}{(r_0A^{1/3})}f(mr_0A^{1/3})$$

$$= (0.691\,\mathrm{MeV})\frac{(1.25\,\mathrm{fm})}{r_0}\left(\frac{3g'}{e}\right)^2 A^{5/3}f(mr_0A^{1/3})$$

where

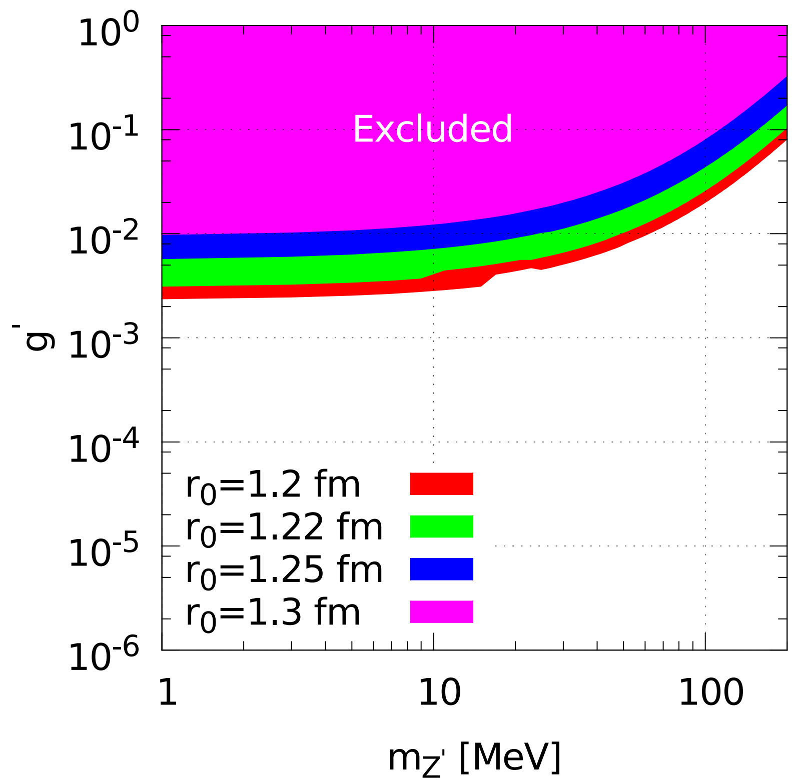
$$f(x) \equiv \frac{15}{4x^5}\left[1 - x^2 + \frac{2x^3}{3} - (1+x)^2e^{-2x}\right]$$

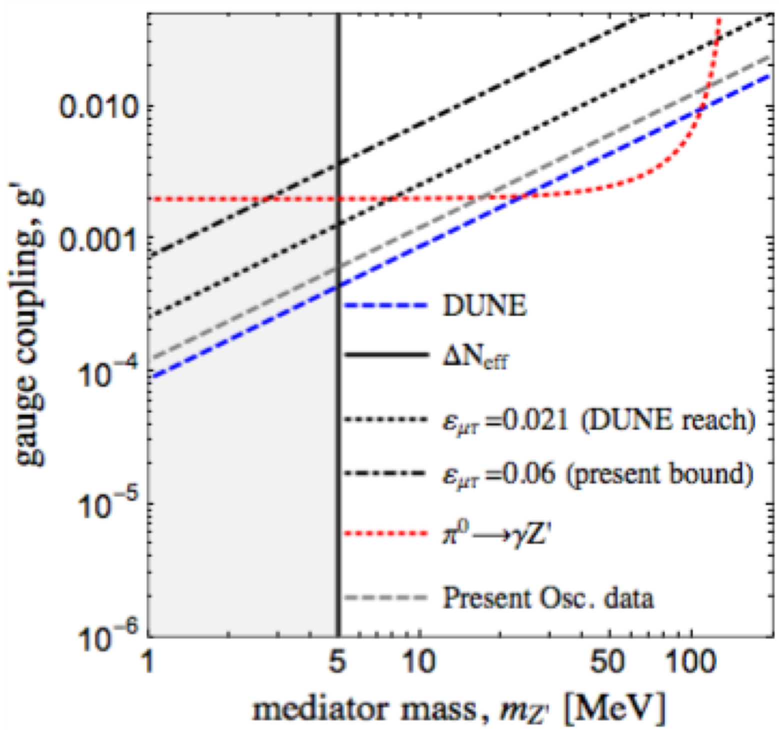
$$= 1 - \frac{5x}{6} + \frac{3x^2}{7} - \frac{x^3}{6} + \cdots$$



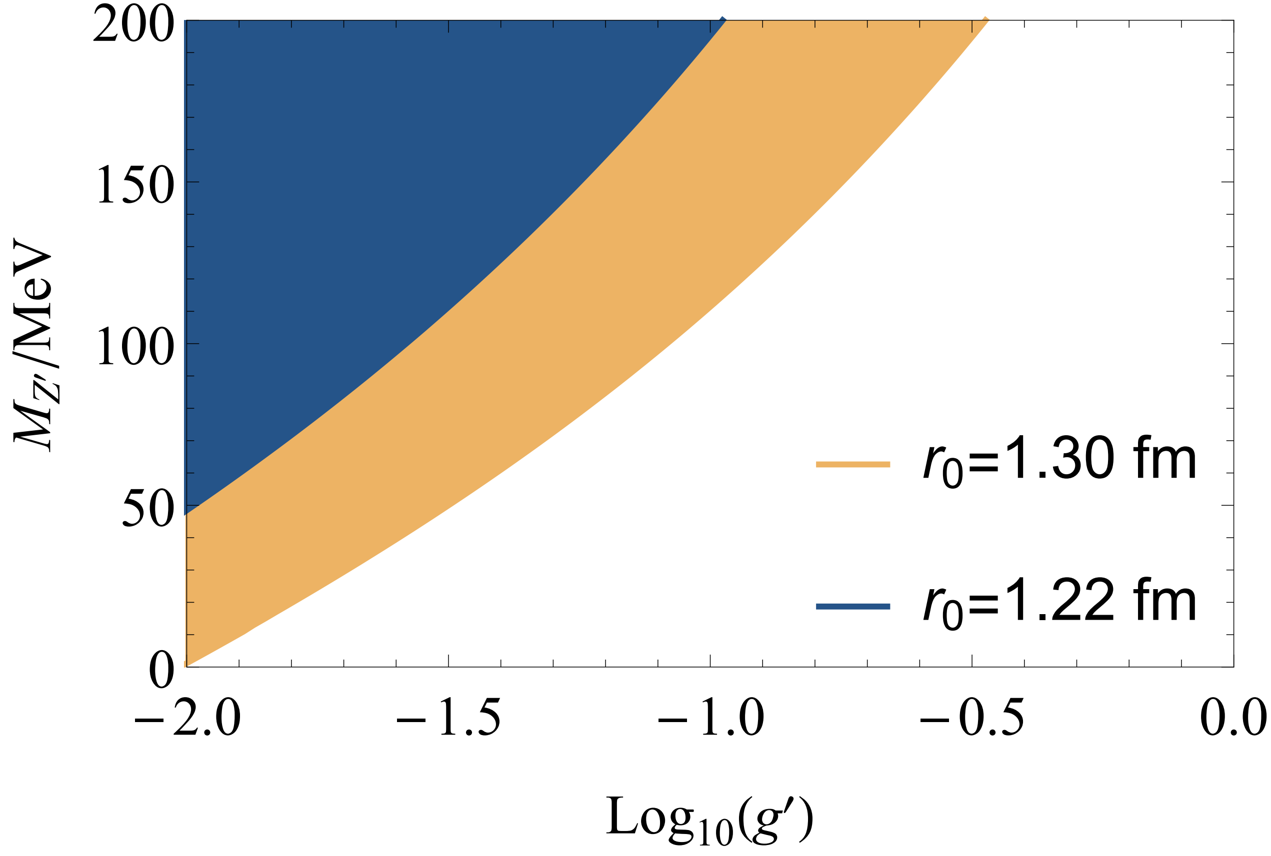
Result of Fit:

- Our result from fit to stable nuclei (90% C.L. left) compared to Figure from Farzan-Shoemaker paper (JHEP07(2016)033 right)





Result of Fit:

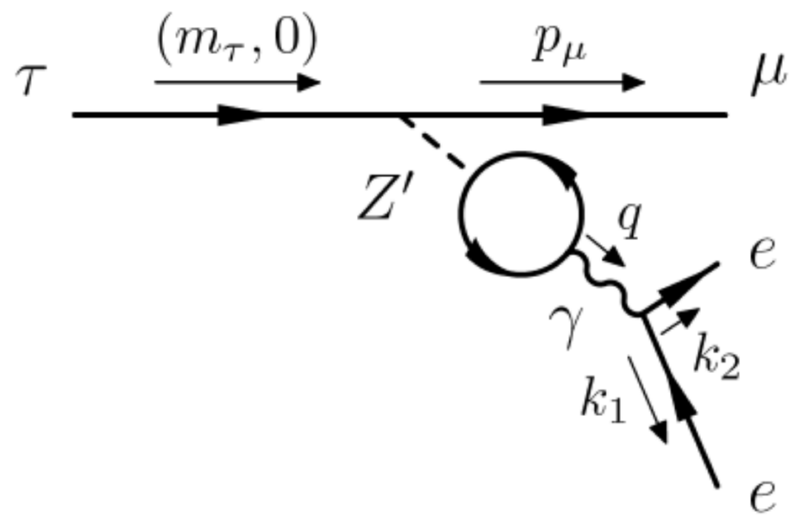


Coupling to the electron from photon-Z' mixing:

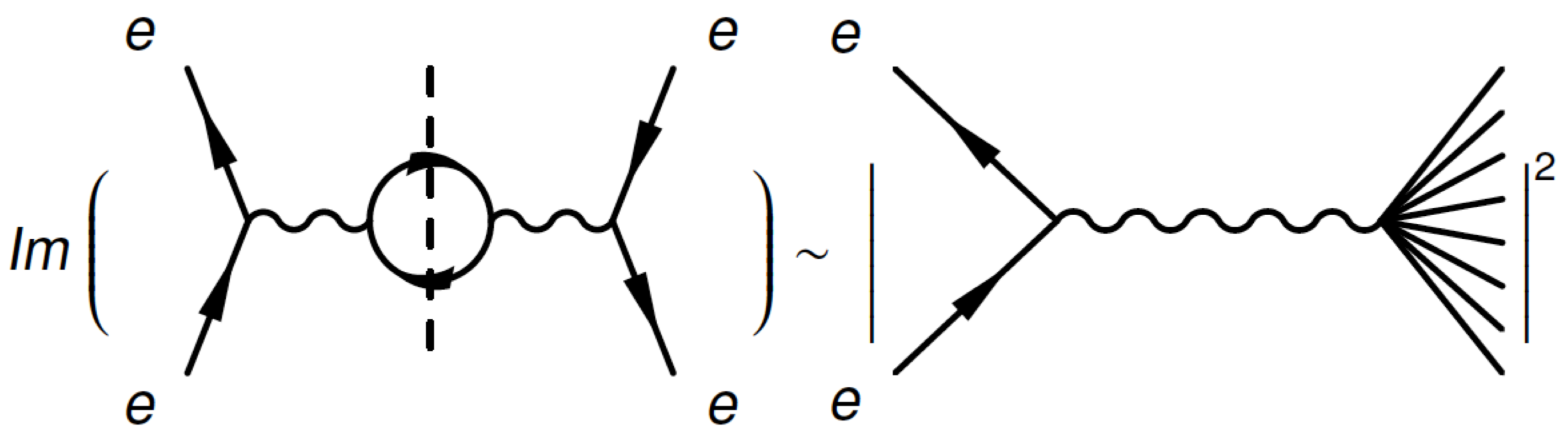
- Recall that $\tau \to \mu ee$ is strongly bounded:

$$B(\tau^- \to \mu^- e^- e^+) < 1.8 \times 10^{-8}$$

- At tree level the Z' does not couple to electrons
- But Z' and the photon can mix!



Optical Theorem:



$$\Pi'_{\gamma\gamma}(q^2) - \Pi'_{\gamma\gamma}(0) \quad = \quad -\frac{1}{12\pi^2}\int_{4m_\pi^2}^{\infty} \frac{q^2}{s(s-q^2)} R(s)ds$$

where

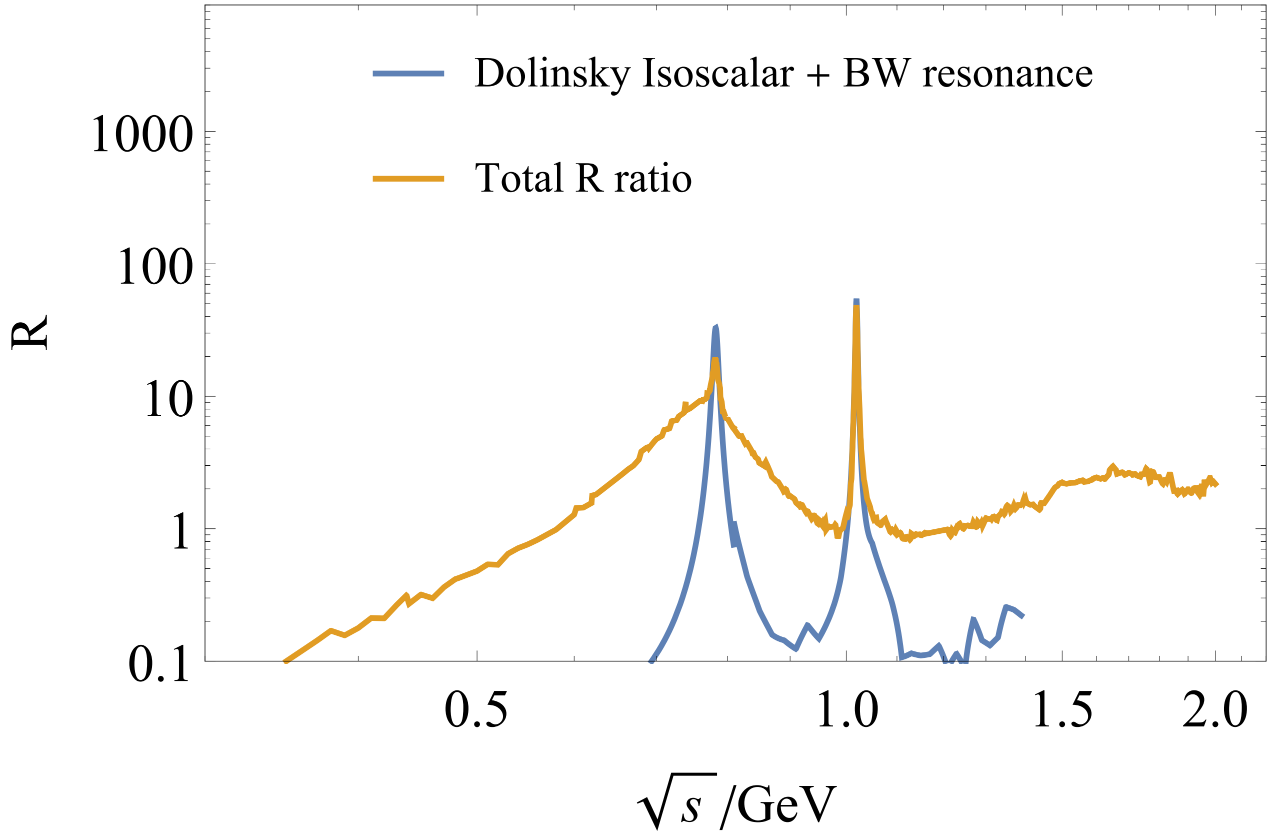
$$R(s) \;=\; \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

photon-photon and photon-Z' correlations:

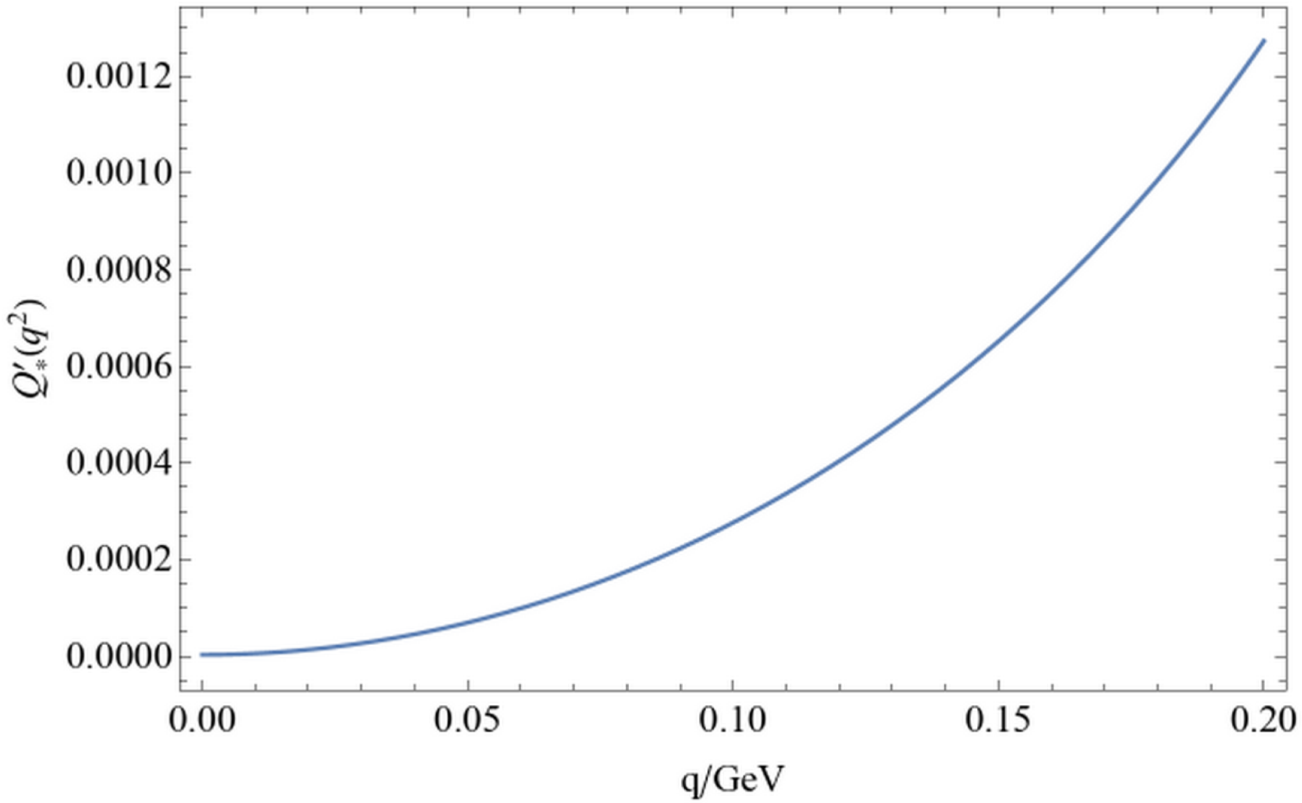
$$\begin{aligned}
\Pi'_{\gamma\gamma} &\propto \left\langle \left(\frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d\right)\left(\frac{2}{3}\overline{u}\gamma_\nu u - \frac{1}{3}\overline{d}\gamma_\nu d\right)\right\rangle \\
&\approx \left(\frac{1}{6}\right)^2 \langle (\overline{u}\gamma_\mu u + \overline{d}\gamma_\mu d)(\overline{u}\gamma_\nu u + \overline{d}\gamma_\nu d)\rangle \\
&\quad + \left(\frac{1}{2}\right)^2 \langle (\overline{u}\gamma_\mu u - \overline{d}\gamma_\mu d)(\overline{u}\gamma_\nu u - \overline{d}\gamma_\nu d)\rangle
\end{aligned}$$

$$\begin{aligned}
\Pi'_{\gamma Z'} &\propto \left\langle \left(\frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d\right)(\overline{u}\gamma_\nu u + \overline{d}\gamma_\nu d)\right\rangle \\
&\approx \frac{1}{6}\langle (\overline{u}\gamma_\mu u + \overline{d}\gamma_\mu d)(\overline{u}\gamma_\nu u + \overline{d}\gamma_\nu d)\rangle
\end{aligned}$$

Separation of Isovector and Isoscalar parts:

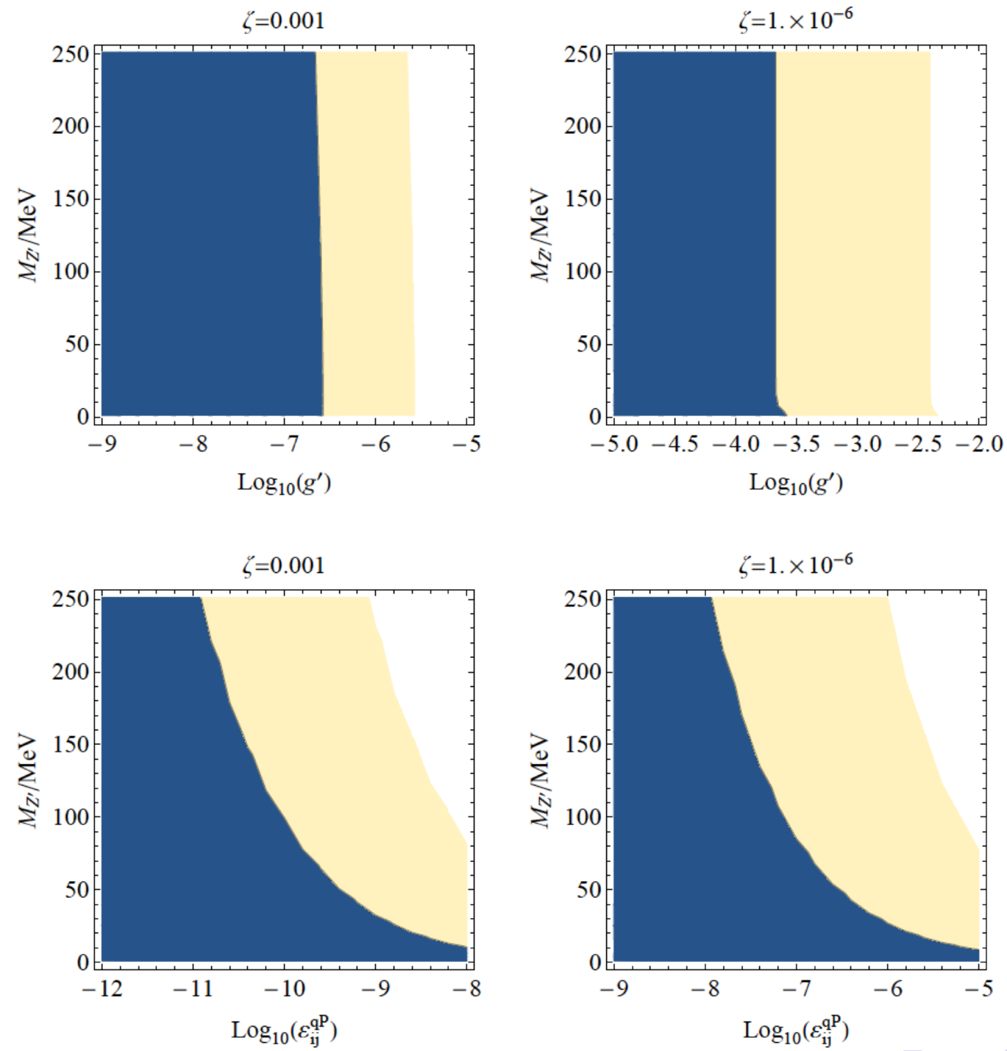


Running of the effective coupling to electrons:



Resulting bounds:

$Br(\tau \to \mu ee) \leq 1.8 \times 10^{-8}$ (Belle, PDG):



Does this bound apply?

- For the Z' decay into an electron-positron decay to be observable, the Z' must decay inside the detector

- Belle central drift chamber:
Z' must decay within 0.88 m to 1.7 m

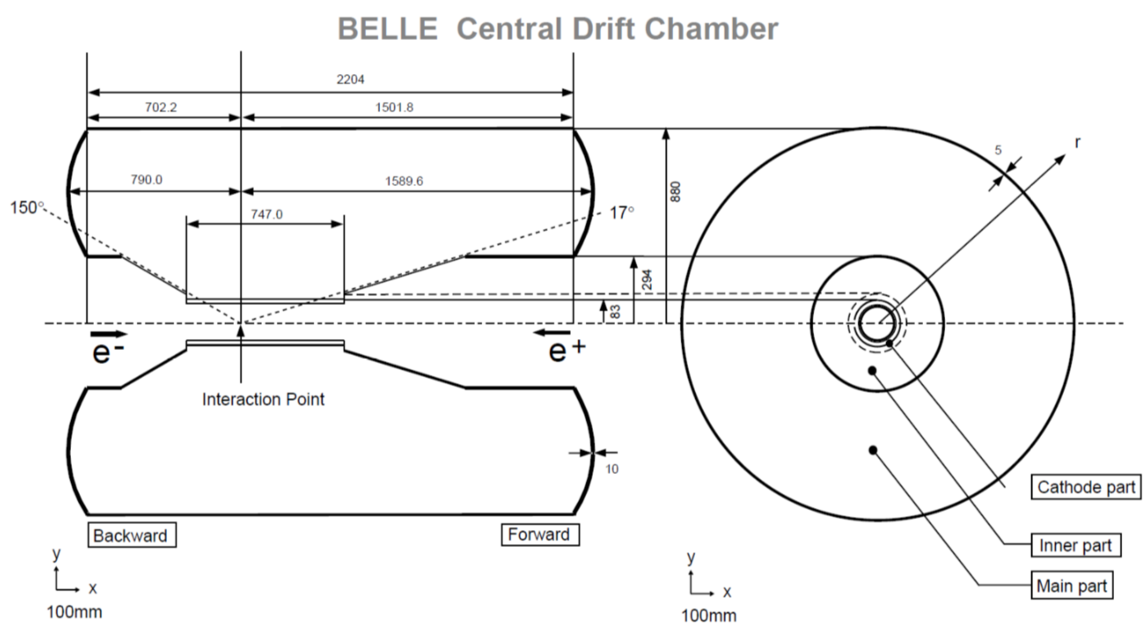


Fig. 22. Overview of the CDC structure. The lengths in the figure are in units of mm.

Two-body decay bound:

- Argus (1995)

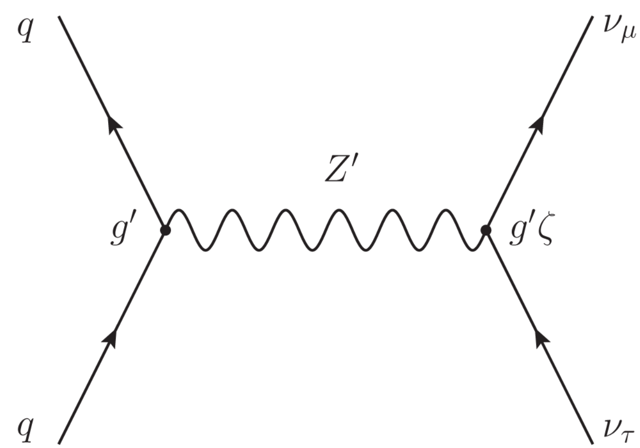
$$B(\tau \to \mu + Z') \quad < \quad 5 \times 10^{-3}$$
$$\downarrow$$
$$g'\zeta \quad < \quad 6 \times 10^{-8} \left(\frac{M_{Z'}}{200\text{MeV}} \right)$$

- 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)

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

Conclusion :

❖ Both g' and $g'\zeta$ are more tightly bound than originally assumed



❖ Constructing viable models that predict sizable neutrino NSI's is not easy!