Constraints on light Z' models with flavor changing couplings

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Invent the Future

Collaborators

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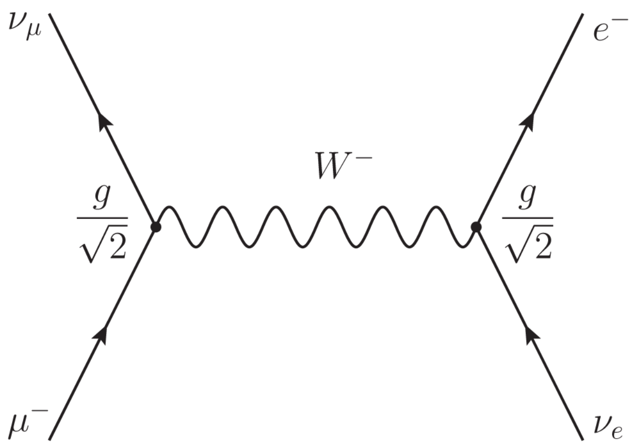
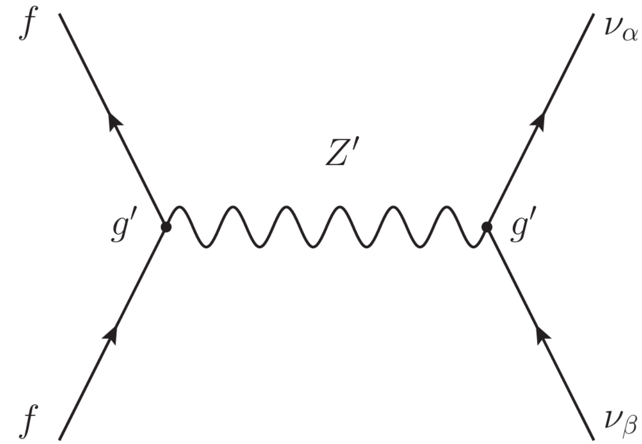
Non-Standard Interactions of the Neutrino

$$\mathcal{L}_{\text{NSI}} \;=\; -2\sqrt{2}G_F \sum_{\alpha,\beta,f,C} \varepsilon_{\alpha\beta}^{fC} \left(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\overline{f}\gamma_\mu P_C f\right)$$

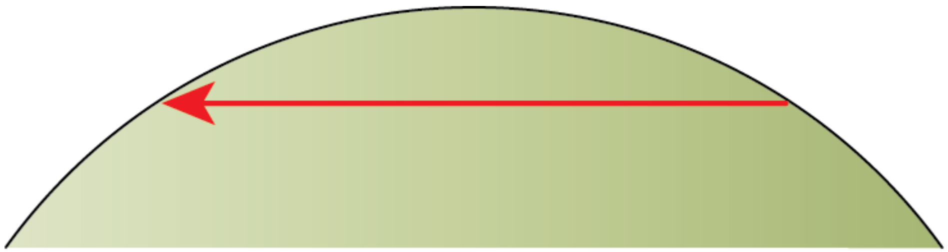
- Many models of New Physics Beyond the Standard Model predict neutrino NSI's





$$\varepsilon \;=\; 2\left(\frac{g'}{g}\right)^2 \left(\frac{M_W}{M_{Z'}}\right)^2 \;=\; 0.03\, g'^2 \left(\frac{1000\,\text{GeV}}{M_{Z'}}\right)^2$$

Non-Standard Interactions of the Neutrino



- Neutrino Oscillation experiments on the Earth are sensitive to:

$$\begin{aligned} \varepsilon_{\alpha\beta} &= \sum_{f=u,d,e} \left(\varepsilon^{fL}_{\alpha\beta} + \varepsilon^{fR}_{\alpha\beta}\right) \frac{N_f}{N_e} \\ &= 3\left(\varepsilon^{uL}_{\alpha\beta} + \varepsilon^{uR}_{\alpha\beta}\right) + 3\left(\varepsilon^{dL}_{\alpha\beta} + \varepsilon^{dR}_{\alpha\beta}\right) + \left(\varepsilon^{eL}_{\alpha\beta} + \varepsilon^{eR}_{\alpha\beta}\right) \end{aligned}$$

- Expected DUNE sensitivities (from P. Coloma JHEP03(2016)016)

$$\left|\varepsilon_{\alpha\beta}\right| < 0.1 \sim 0.01$$

- Do models exist that predict such large NSI's ?

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

Recent Proposals

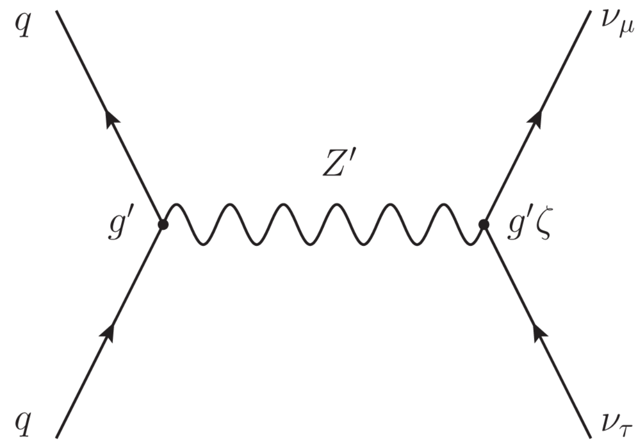
Y. Farzan, “A model for large non-standard interactions of neutrinos leading to the LMA-Dark solution,” Phys. Lett. B748 (2015) 311-315, arXiv:1505.06906

- Y. Farzan and I. M. Shoemaker, “Lepton Flavor Violating Non-Standard Interactions via Light Mediators,” JHEP07(2016)033, arXiv:1512.09147
- Y. Farzan and J. Heeck, “Neutrinophilic Non-Standard Interactions,” Phys. Rev. D 94, 053010 (2016), arXiv:1607.07616
- D. V. Forero and W.-C. Huang, “Sizable NSI from the $SU(2)_L$ scalar doublet-singlet mixing and the implications in DUNE,” JHEP03(2017)018, arXiv:1608.04719
- K. S. Babu, A. Friedland, P. A. N. Machado, I. Mocioiu, “Flavor Gauge Models Below the Fermi Scale,” arXiv:1705.01822
- etc.

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 $v_+ = v_- = \frac{w}{\sqrt{2}}$ (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:

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

so that the decays

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

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:

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

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:

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

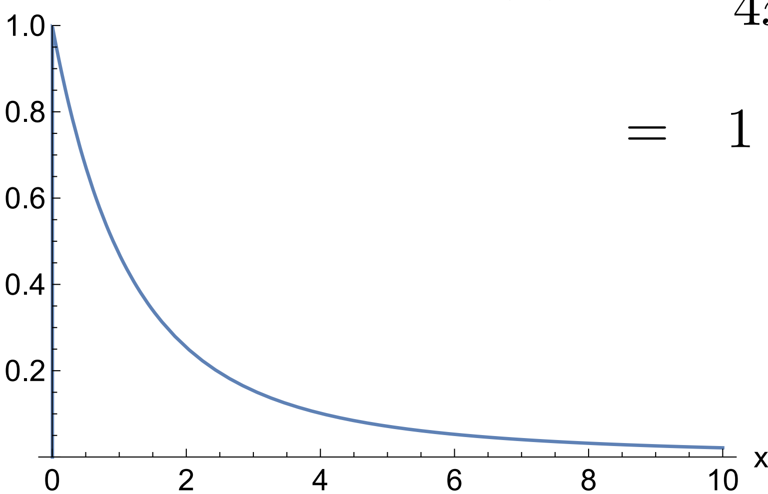
Z' potential energy:

- Z' potential energy term:

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

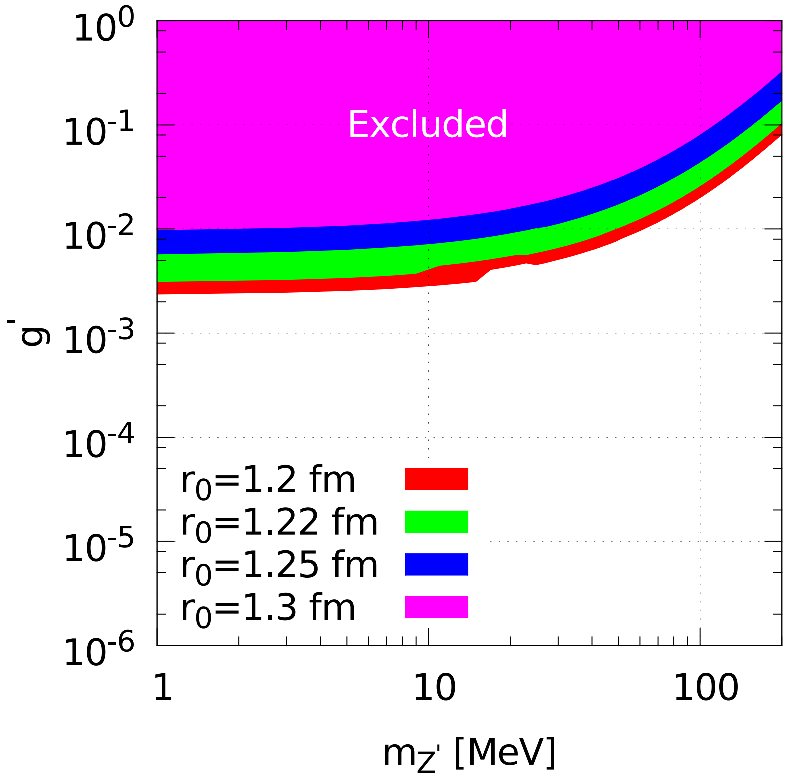
where

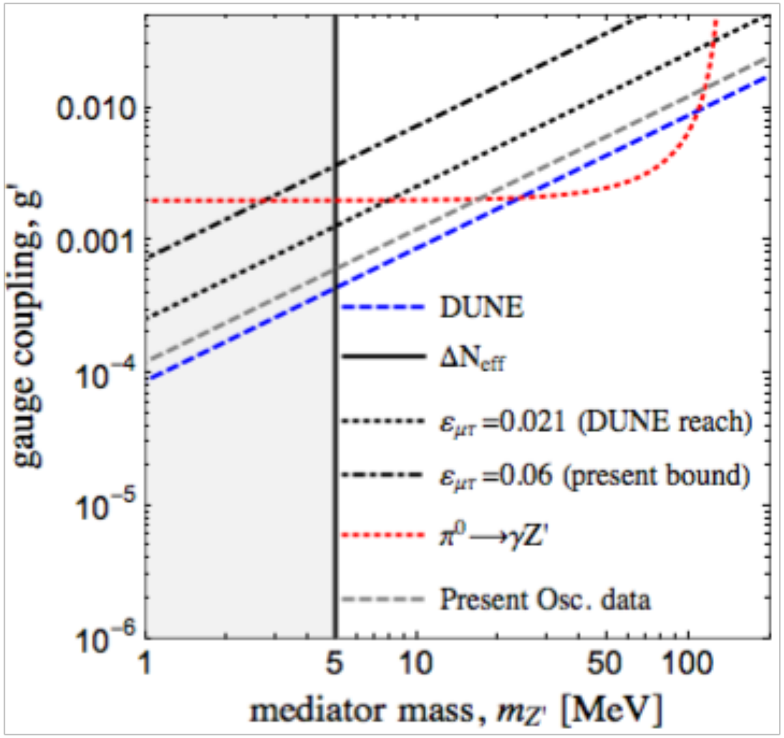
$$
\begin{aligned}
f(x) &\equiv \frac{15}{4x^5}\left[1 - x^2 + \frac{2x^3}{3} - (1+x)^2 e^{-2x}\right] \\
&= 1 - \frac{5x}{6} + \frac{3x^2}{7} - \frac{x^3}{6} + \cdots
\end{aligned}
$$



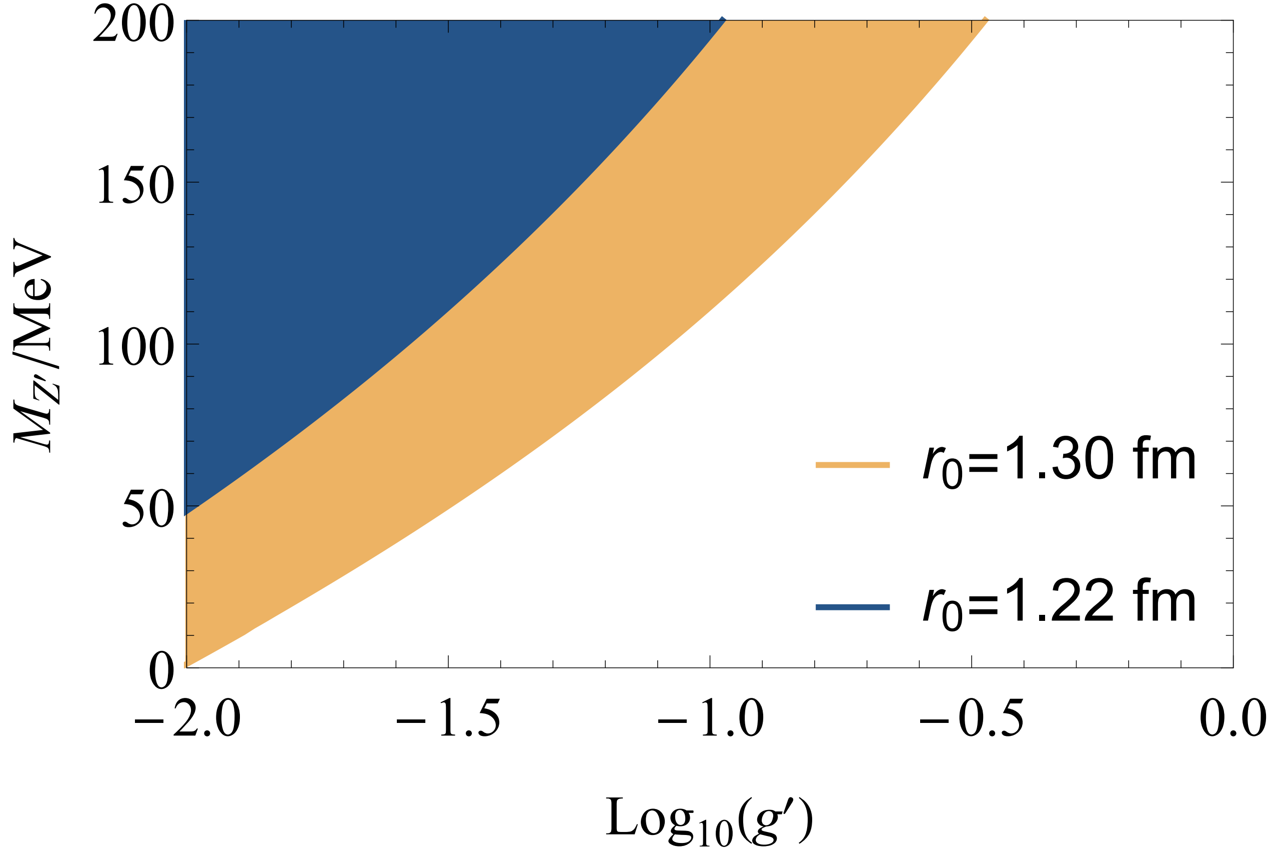
Result of Fit:

- 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:

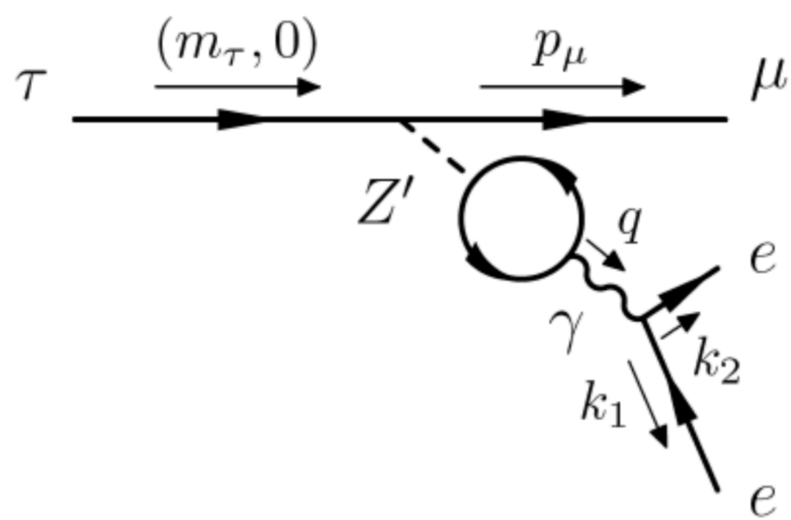


Coupling to the electron from photon-Z' mixing:

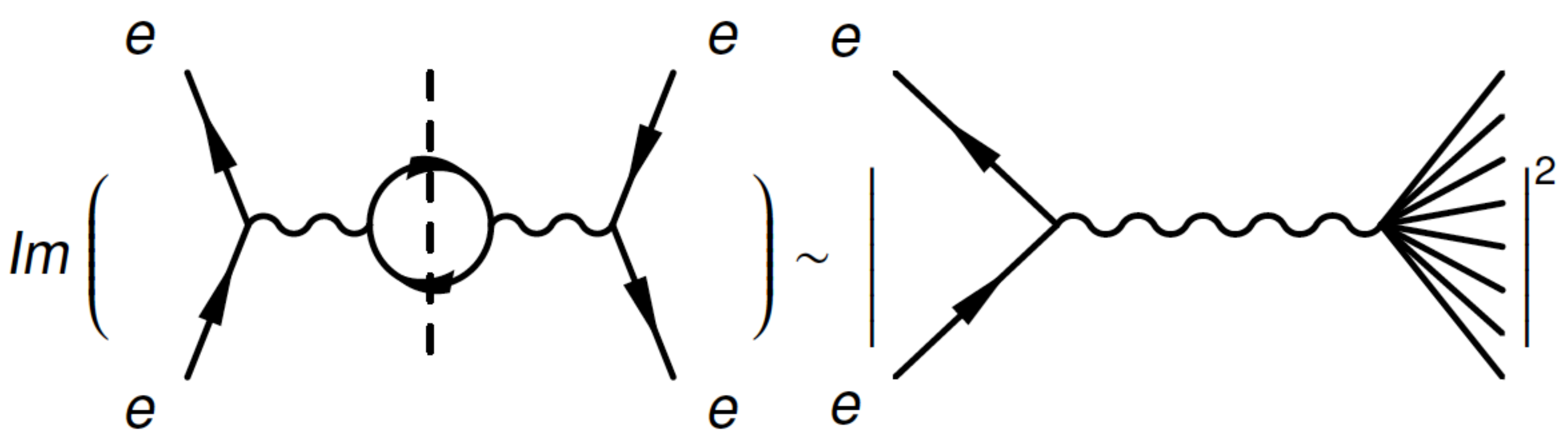
- Recall that $\tau \to \mu e e$ is strongly bounded:

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

- 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

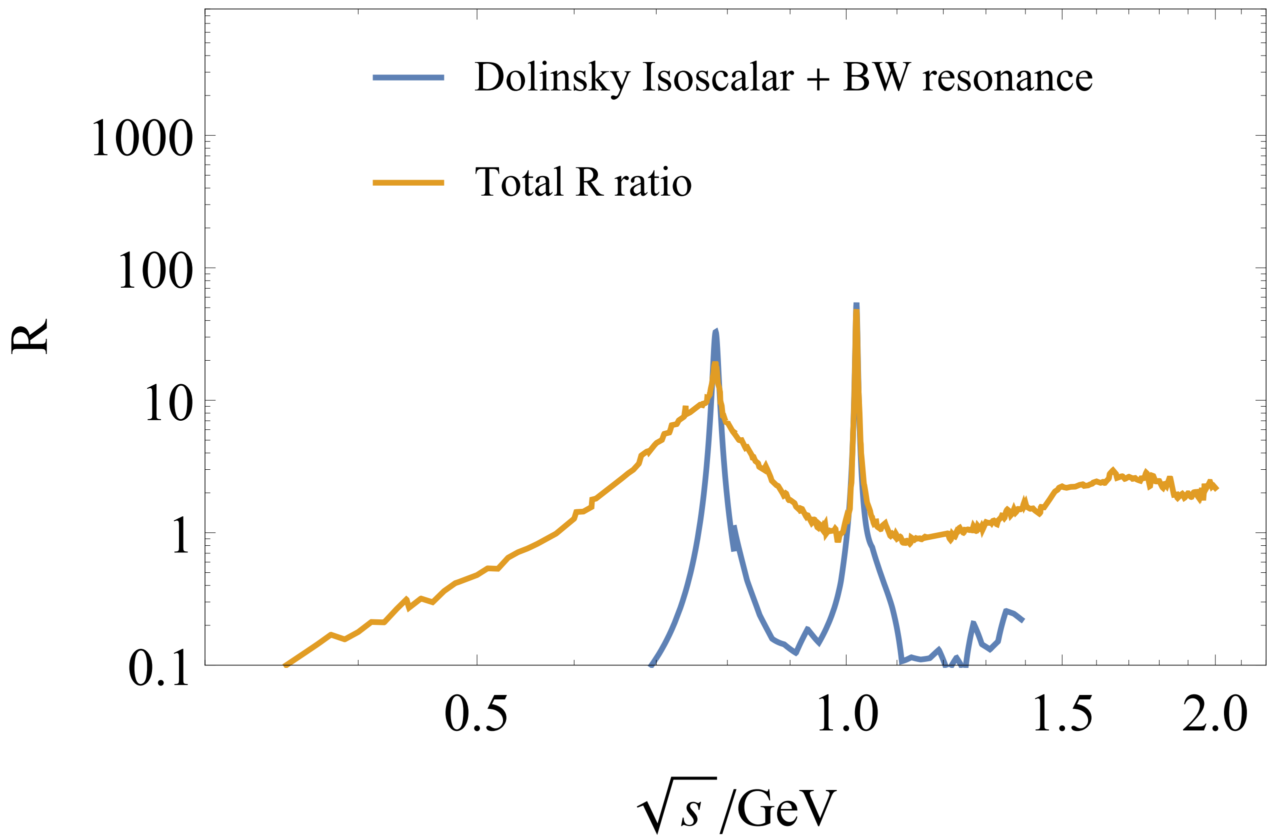
$$R(s) \;=\; \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

photon-photon and photon-Z' correlations:

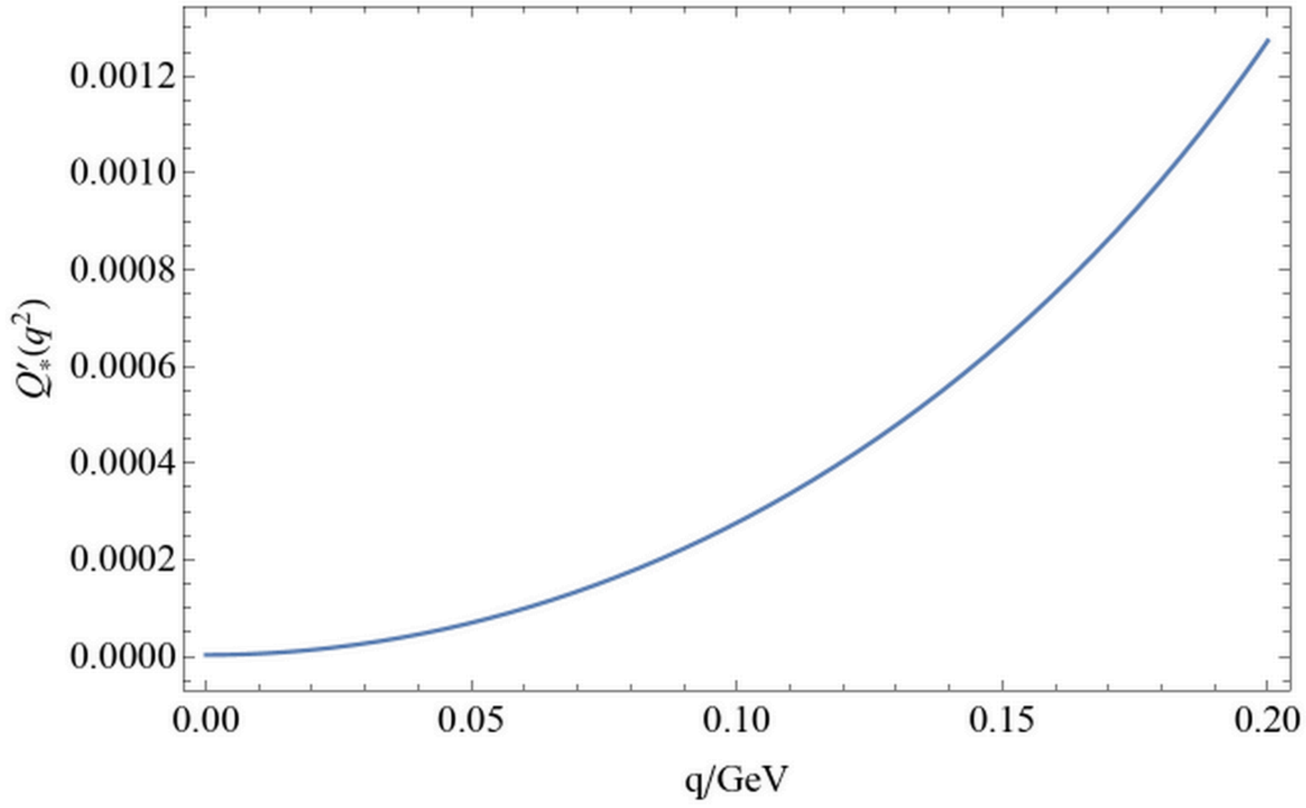
$$\begin{aligned}
\Pi'_{\gamma\gamma} &\propto \left\langle \left(\frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d\right)\left(\frac{2}{3}\overline{u}\gamma_\nu u - \frac{1}{3}\overline{d}\gamma_\nu d\right)\right\rangle \\
&\approx \left(\frac{1}{6}\right)^2 \langle(\overline{u}\gamma_\mu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

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

Separation of Isovector and Isoscalar parts:

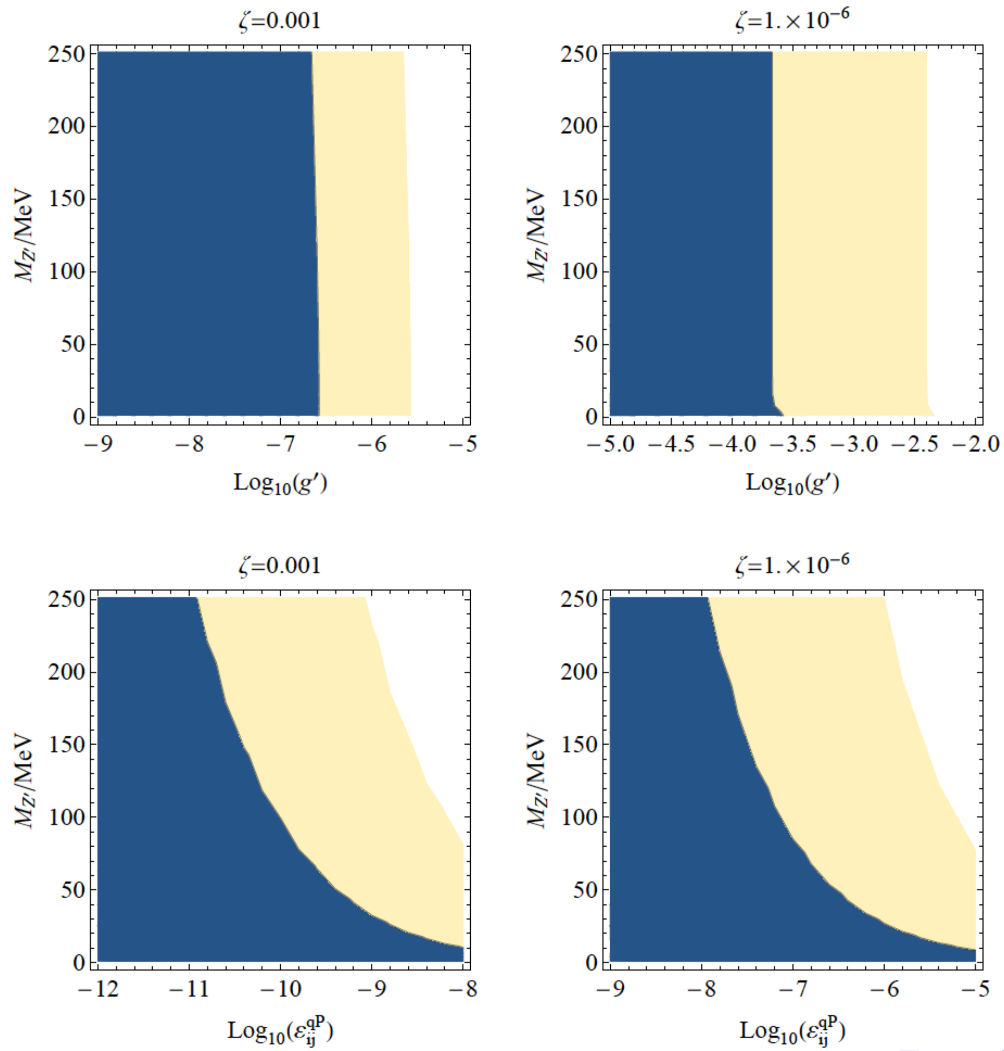


Running of the effective coupling to electrons:



Resulting bounds:

$Br(\tau \to \mu e e) \leq 1.8 \times 10^{-8}$ (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

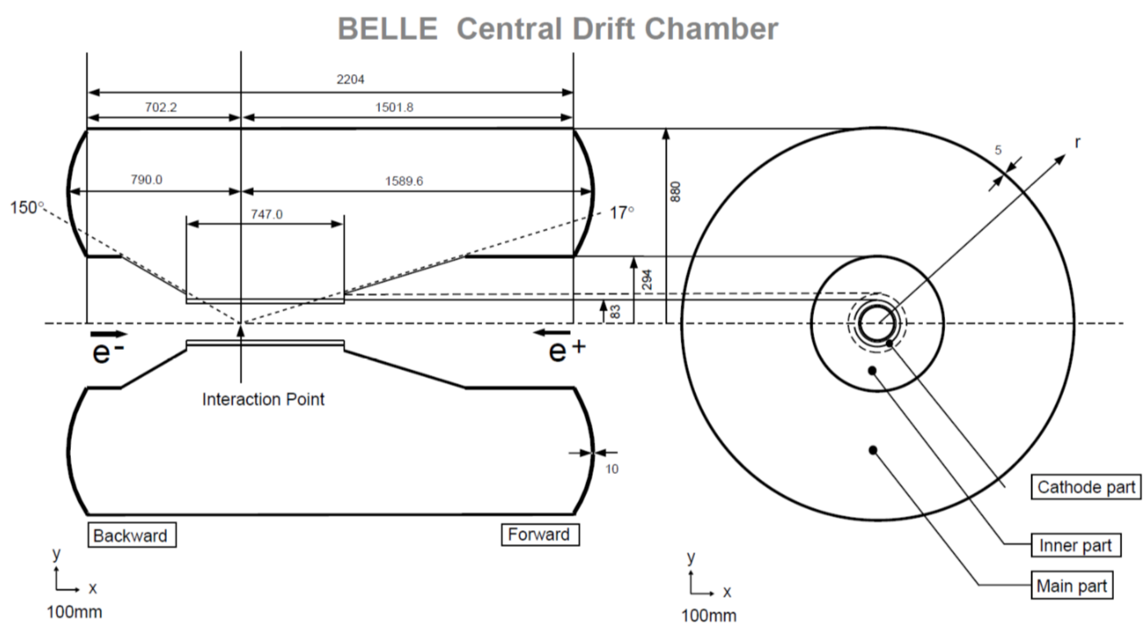


Fig. 22. Overview of the CDC structure. The lengths in the figure are in units of mm.

Two-body decay bound:

- Argus (1995)

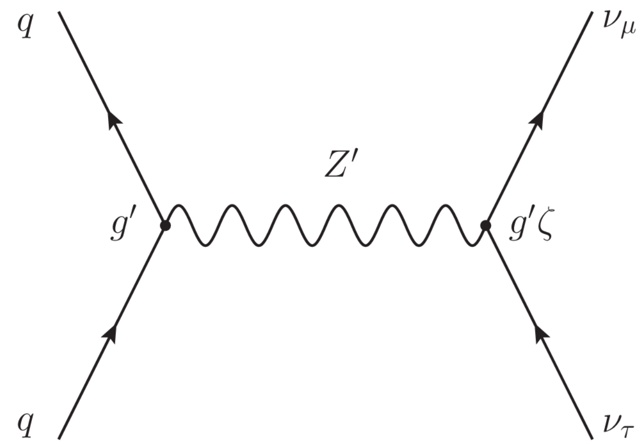
$$
\begin{aligned}
B(\tau \to \mu + Z') &< 5 \times 10^{-3} \\
&\downarrow \\
g'\zeta &< 6 \times 10^{-8} \left(\frac{M_{Z'}}{200\mathrm{MeV}} \right)
\end{aligned}
$$

- Belle has 2000 times more statistics and is expected to improve the bound to $1{\times}10^{-4}$ (Yoshinobu and Hayasaka, 2016)

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

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!