Constraints on Models with Potentially Large Neutrino NSI's

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Collaborators

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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:

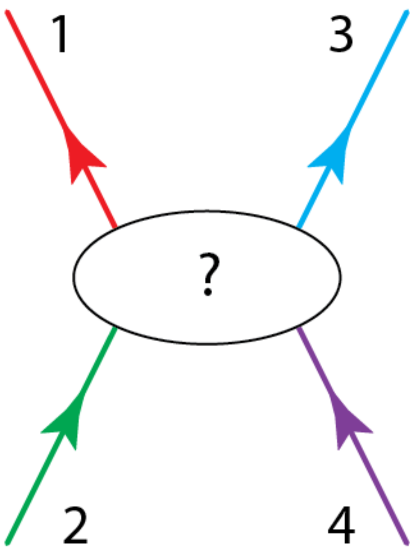
$$e_S(1234) = \left(\bar{\psi}_1 \psi_2\right)\left(\bar{\psi}_3 \psi_4\right)$$

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

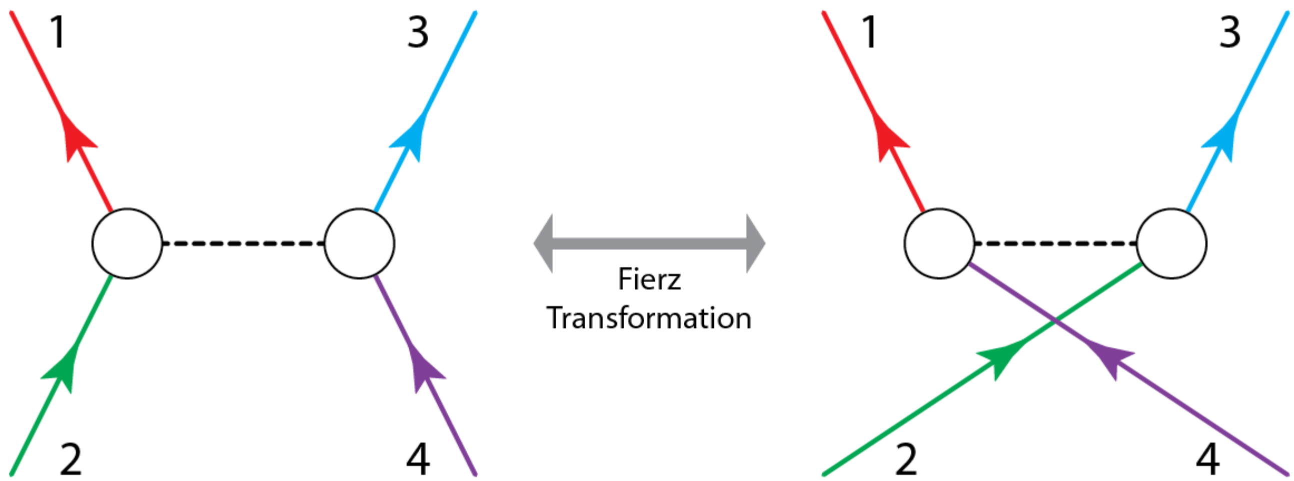
$$e_T(1234) = \left(\bar{\psi}_1 \sigma_{\mu\nu} \psi_2\right)\left(\bar{\psi}_3 \sigma^{\mu\nu} \psi_4\right)$$

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

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



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

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

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

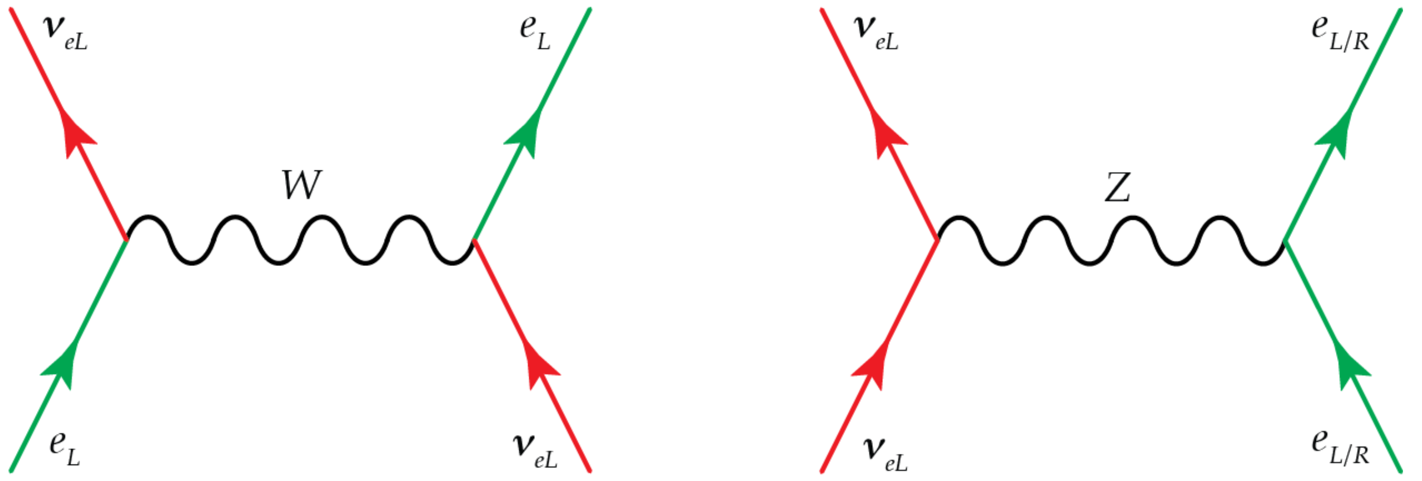
$$e_T(12_{L/R}34_{L/R}) = -6e_S(14_{L/R}32_{L/R}) + \frac{1}{2}e_T(14_{L/R}32_{L/R})$$

- 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:



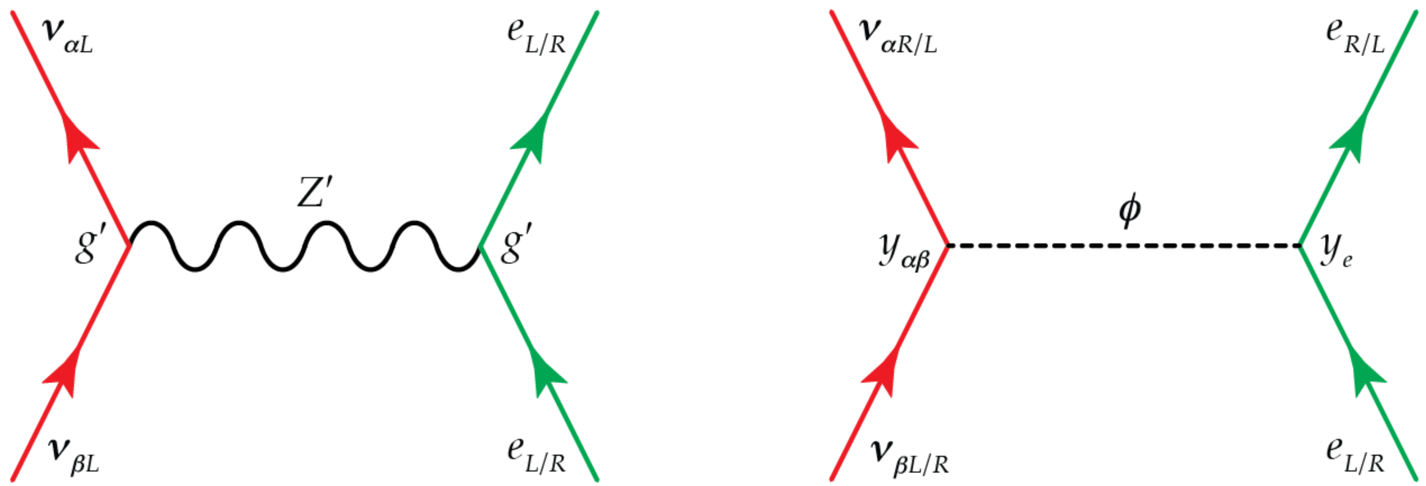
- neutrino-electron interaction from *W* exchange :

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

- neutrino-electron interaction from *Z* exchange :

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

New Physics:



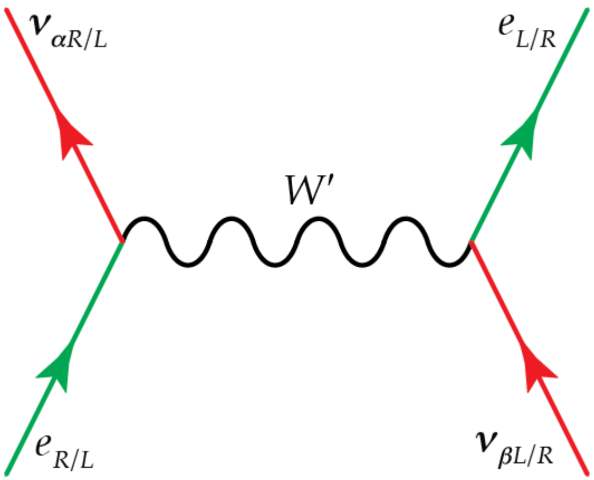
- Vector exchange:

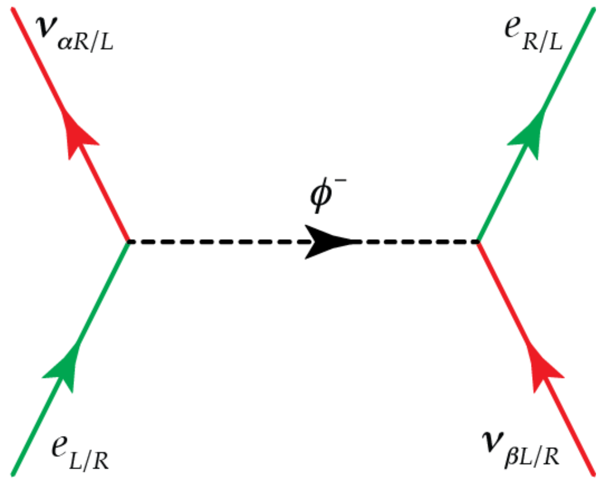
$$\left(\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L}\right)\frac{(g')^2}{m_{Z'}^2}\left(\bar{e}_{L/R}\gamma^{\mu}e_{L/R}\right) \quad \rightarrow \quad 2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{eL/R}\left(\bar{\nu}_{\alpha L}\gamma_{\mu}\nu_{\beta L}\right)\left(\bar{e}_{L/R}\gamma^{\mu}e_{L/R}\right)$$

- 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 :

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

  - 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, PRL 122 (2019) 211801

- Tensor NSI's ?

Vector NSI's of the Neutrino

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

- Neutrino Oscillation experiments in which the neutrinos traverse the Earth are sensitive to:

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

- Note: Different collaborations use different normalizations! e.g.: Super-K (?) and IceCube:

$$\varepsilon_{\alpha\beta} = \left(\varepsilon_{\alpha\beta}^{dL} + \varepsilon_{\alpha\beta}^{dR}\right)$$

Existing Constraints

- Conservative model independent constraints:
T. Ohlsson, Rep. Prog. Phys. 76 (2013) 044201, arXiv:1209.2710

$$\begin{bmatrix} |\varepsilon_{ee}| < 4.2 & |\varepsilon_{e\mu}| < 0.33 & |\varepsilon_{e\tau}| < 3.0 \\ & |\varepsilon_{\mu\mu}| < 0.07 & |\varepsilon_{\mu\tau}| < 0.33 \\ & & |\varepsilon_{\tau\tau}| < 21 \end{bmatrix} \quad (90\%\ \text{C.L.})$$

- More recent bounds:
  - Ice Cube, Phys.Rev. D97 (2018) 072009, arXiv:1709.07079

$$-0.020 < \varepsilon_{\mu\tau} < 0.024 \qquad (90\%\ \text{C.L.})$$

  - Borexino, arXiv:1905.03512

$$-0.8 < \varepsilon_{ee} < 0.2, \qquad |\varepsilon_{\tau\tau}| < 1 \qquad (90\%\ \text{C.L.})$$

Expected Future Constraints

- Expected DUNE constraints:
P. Coloma, JHEP03 (2016) 016;
A. de Gouvea & K. J. Kelly, Nucl. Phys. B908 (2016) 318-335

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

- Expected IceCube constraint:
J. Salvado, O. Mena, S. Palomares-Ruiz, and N. Rius, JHEP 1701 (2017) 141, arXiv:1609.03450

$$-0.01 < \varepsilon_{\mu\tau} < 0.009 \qquad \text{(90\% C.L., 10 years of data)}$$

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

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

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

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

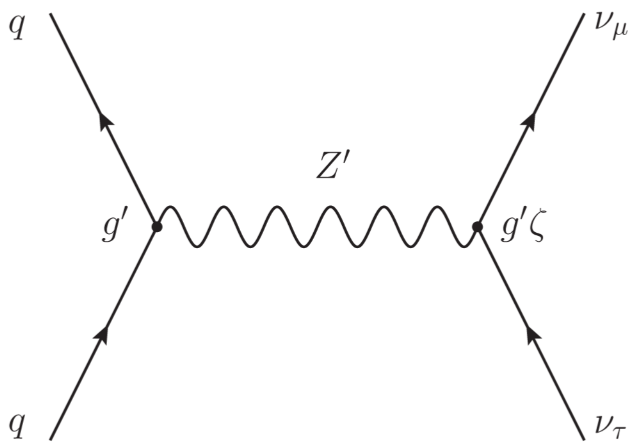
$$= \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L\nu_\tau\right)\left(\overline{e}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_e}\gamma^\mu P_L\nu_\tau\right)\left(\overline{\mu}\gamma_\mu P_L e\right) - \frac{1}{2}\left(\overline{\nu_\mu}\gamma^\mu P_L\nu_e\right)\left(\overline{e}\gamma_\mu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

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, JHEP07(2016)033, arXiv:1512.09147

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



$$\varepsilon_{\mu\tau}^{qL/R} \sim 0.005 \quad \rightarrow \quad \varepsilon_{\mu\tau} = 3(\varepsilon_{\mu\tau}^{uL} + \varepsilon_{\mu\tau}^{uR}) + 3(\varepsilon_{\mu\tau}^{dL} + \varepsilon_{\mu\tau}^{dR}) \sim 0.06$$

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

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

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:

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

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:

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

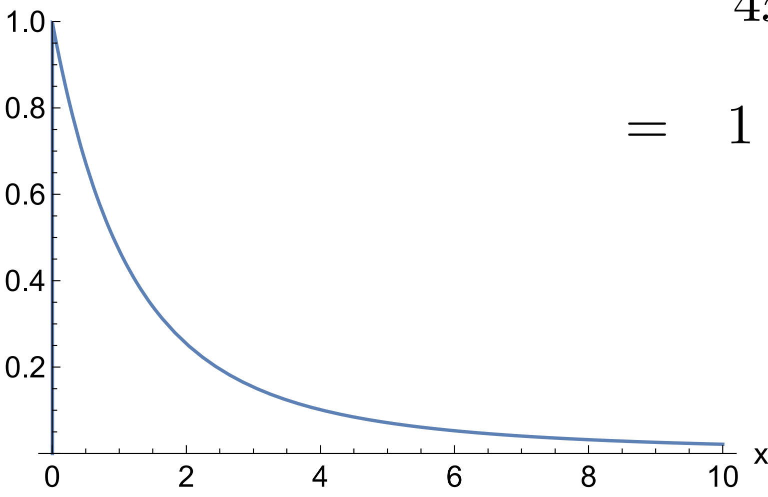
Z' potential energy:

- Z' potential energy term:

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

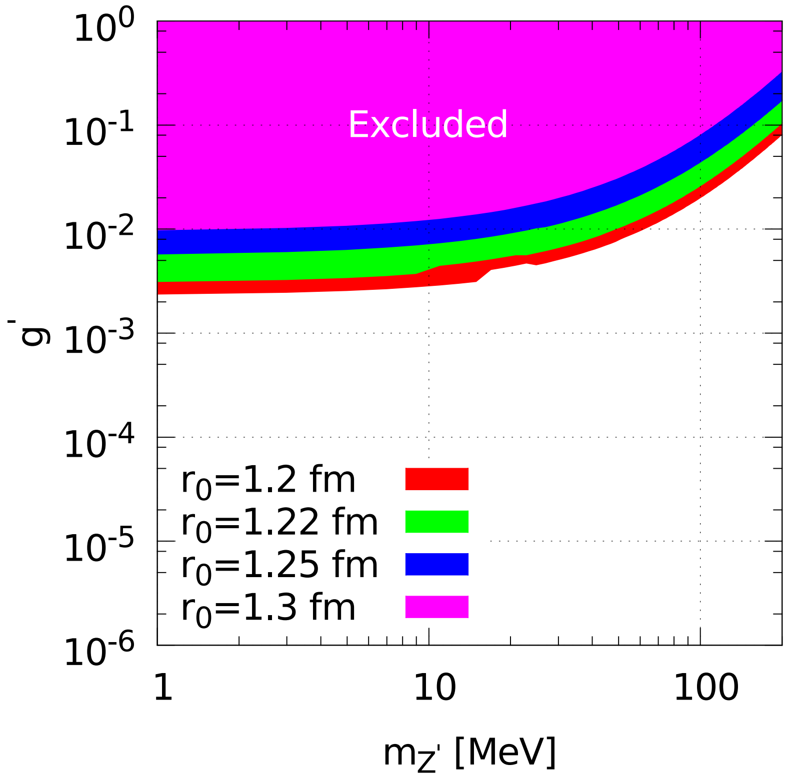
where

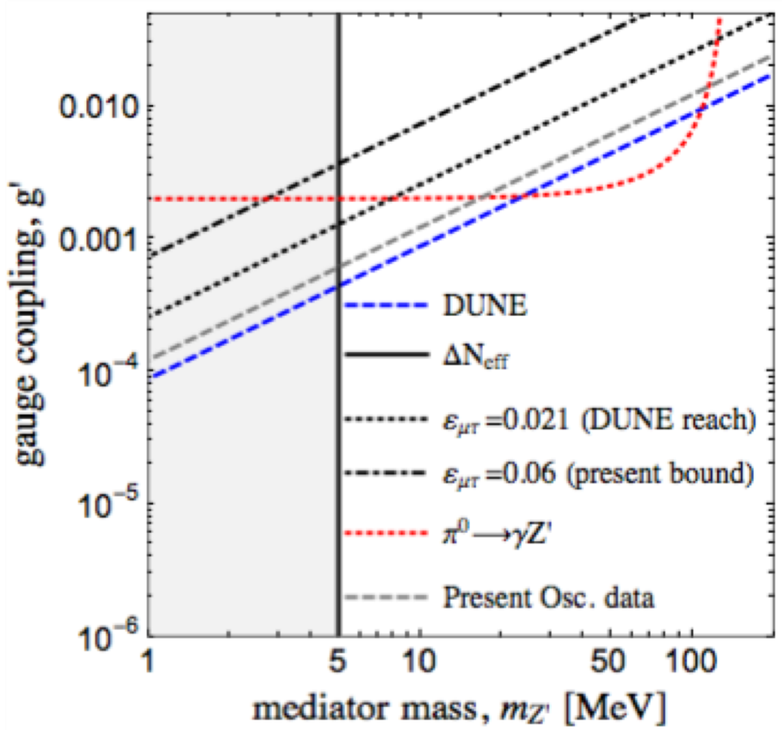
$$
\begin{aligned}
f(x) &\equiv \frac{15}{4x^5}\left[1 - x^2 + \frac{2x^3}{3} - (1+x)^2 e^{-2x}\right] \\
&= 1 - \frac{5x}{6} + \frac{3x^2}{7} - \frac{x^3}{6} + \cdots
\end{aligned}
$$



Result of Fit:

- Fit (preliminary) to stable nuclei (90% C.L. left) compared to Figure from JHEP07(2016)033



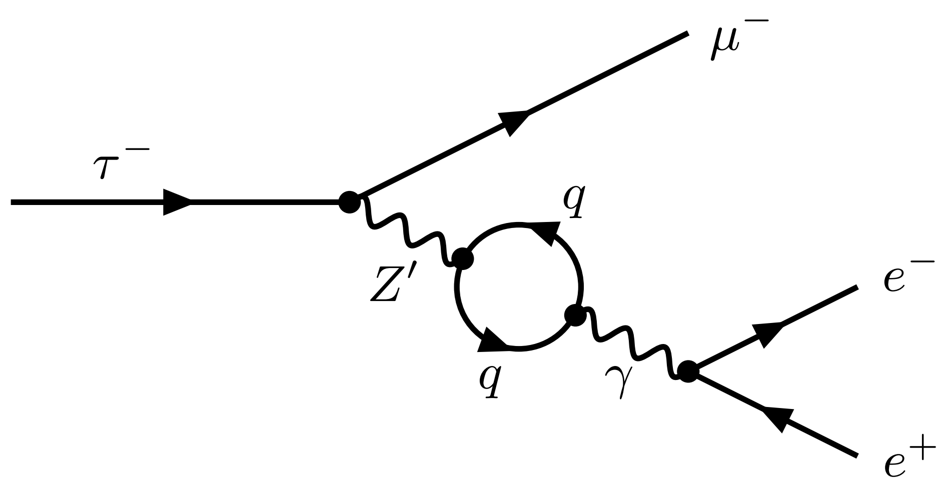


Coupling to the electron from photon-Z' mixing:

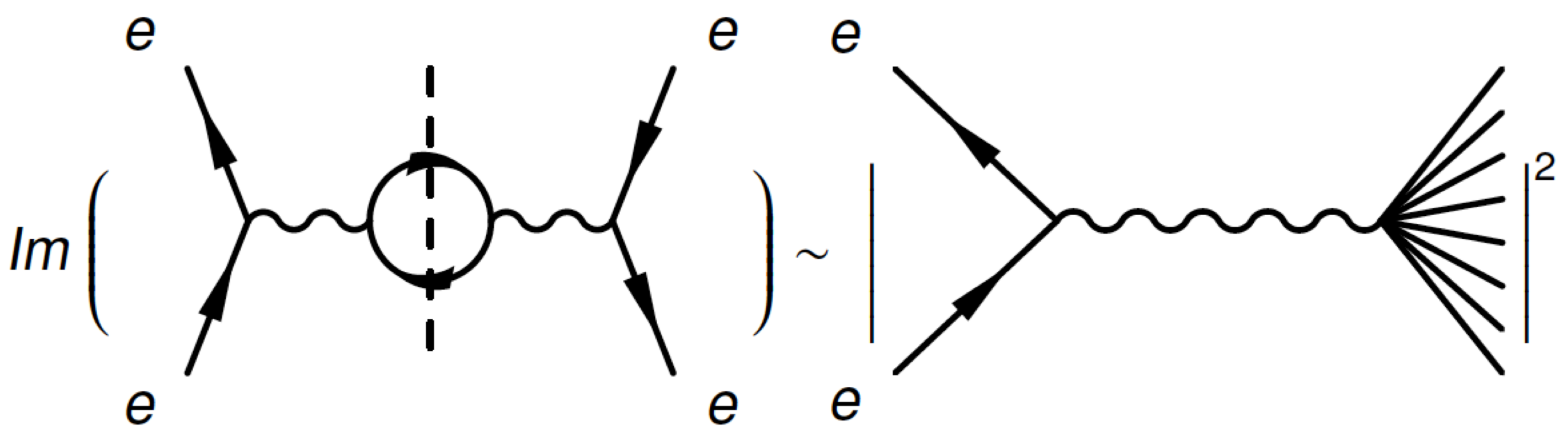
- Recall that $\tau \to \mu e e$ is strongly bounded:

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

- 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

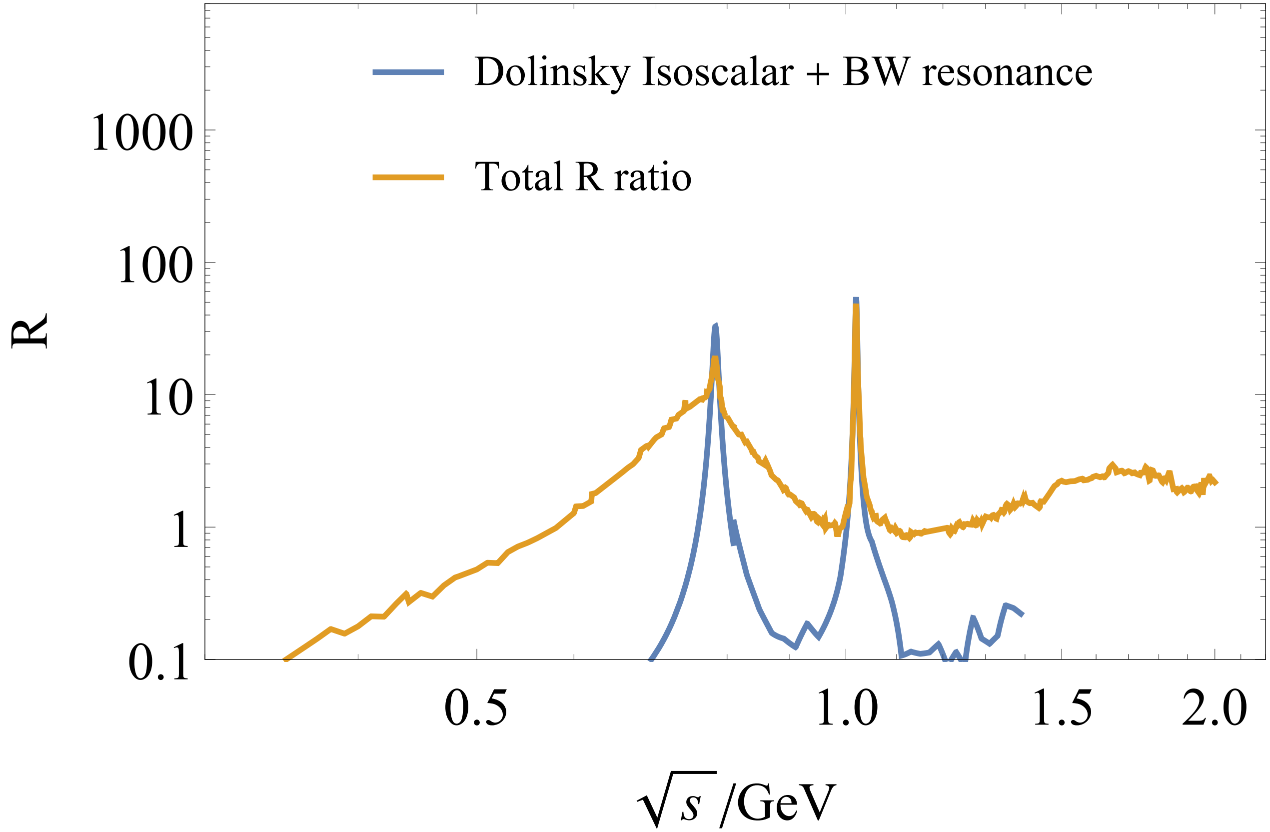
$$R(s) \;=\; \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

photon-photon and photon-Z' correlations:

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

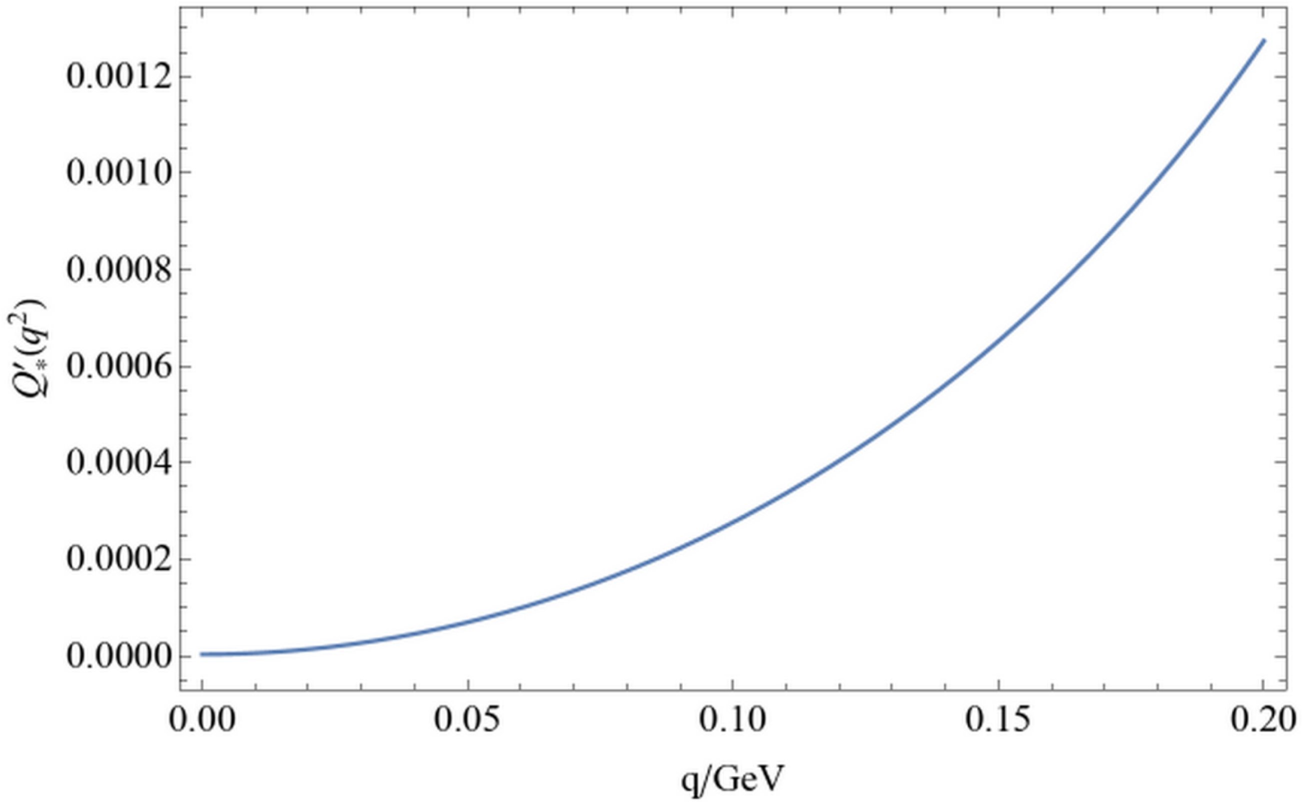
$$
\begin{aligned}
\Pi'_{\gamma Z'} &\propto \left\langle \left(\frac{2}{3}\overline{u}\gamma_\mu u - \frac{1}{3}\overline{d}\gamma_\mu d\right)\left(\overline{u}\gamma_\nu u + \overline{d}\gamma_\nu d\right)\right\rangle \\
&\approx \frac{1}{6}\left\langle \left(\overline{u}\gamma_\mu u + \overline{d}\gamma_\mu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

Separation of Isovector and Isoscalar parts:

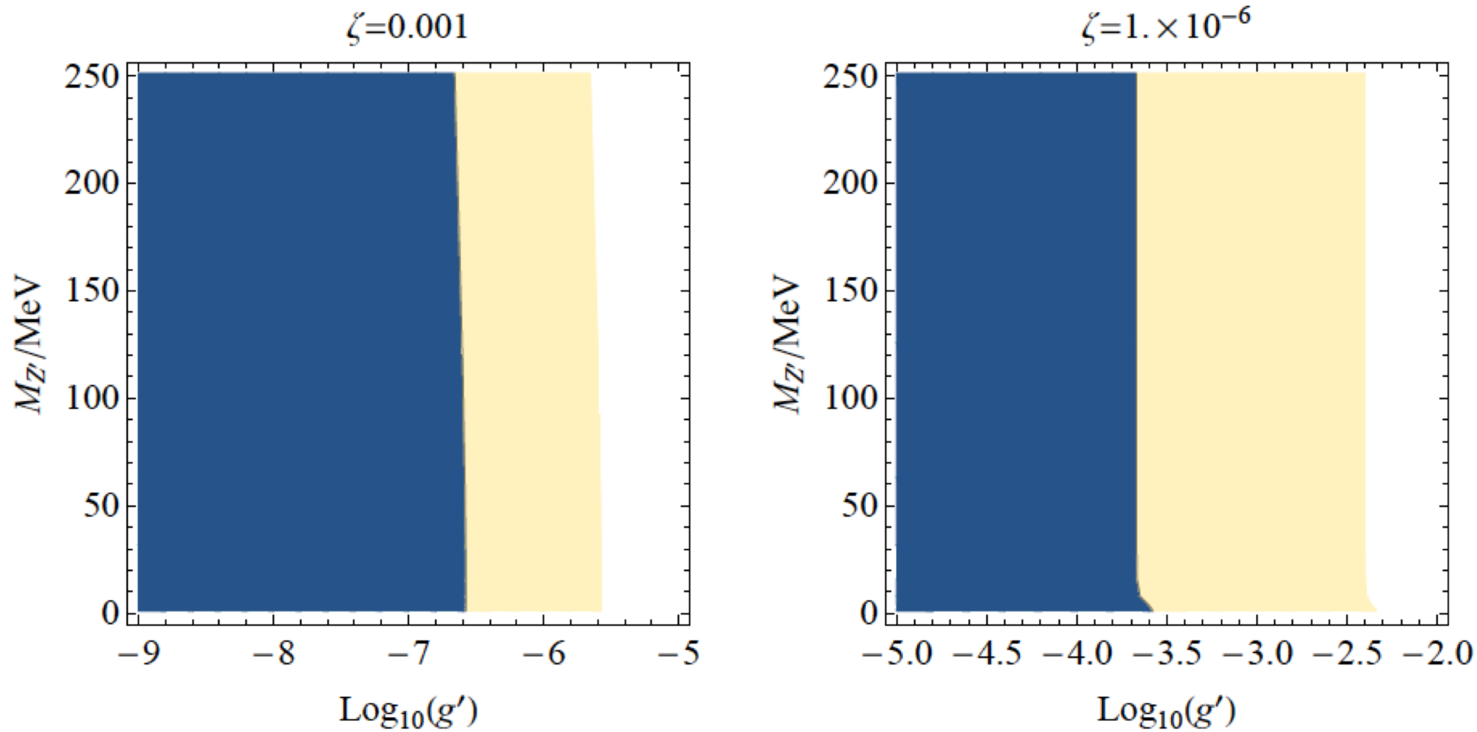


- VEPP-2M, S. I. Dolinsky et al., Phys. Rep. 202 (1991) 99-170

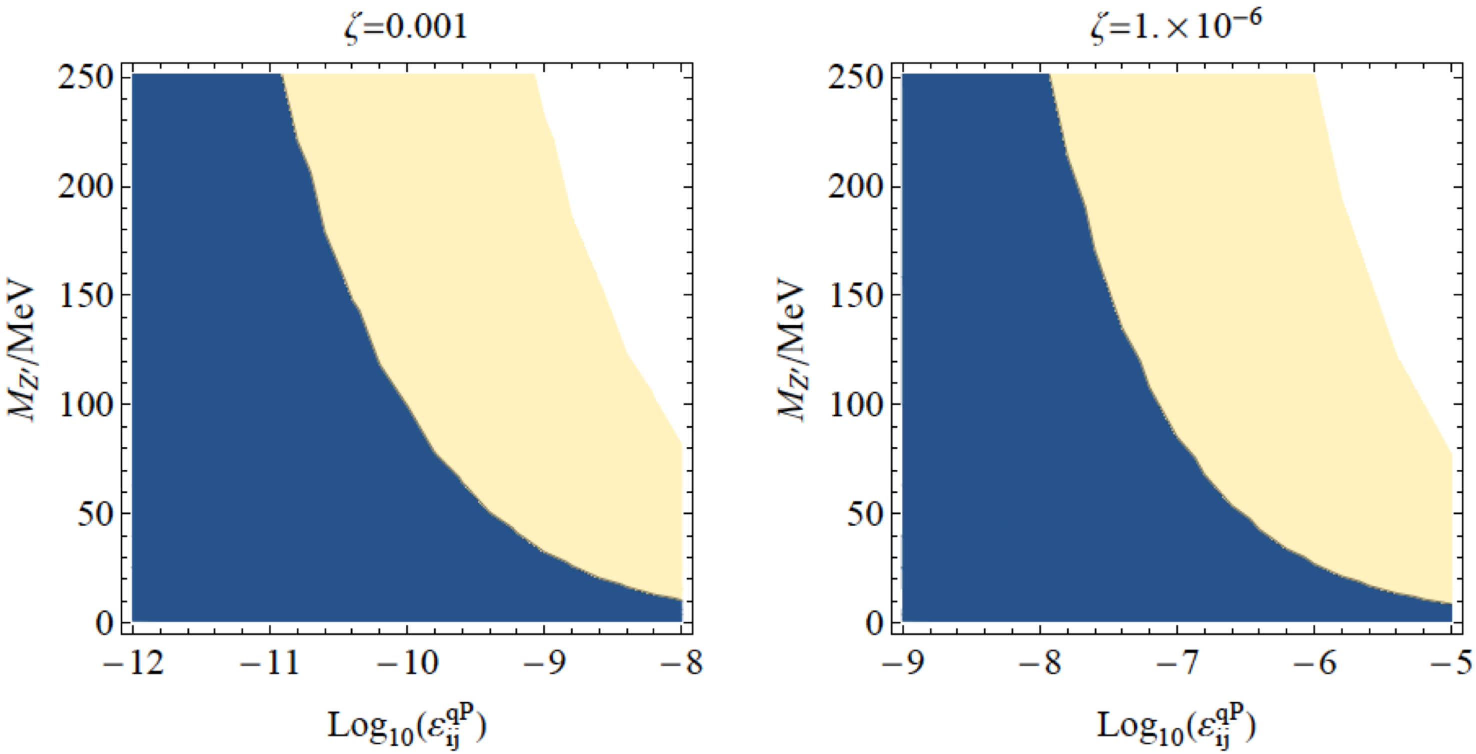
Running of the effective coupling to electrons:



Resulting bounds:



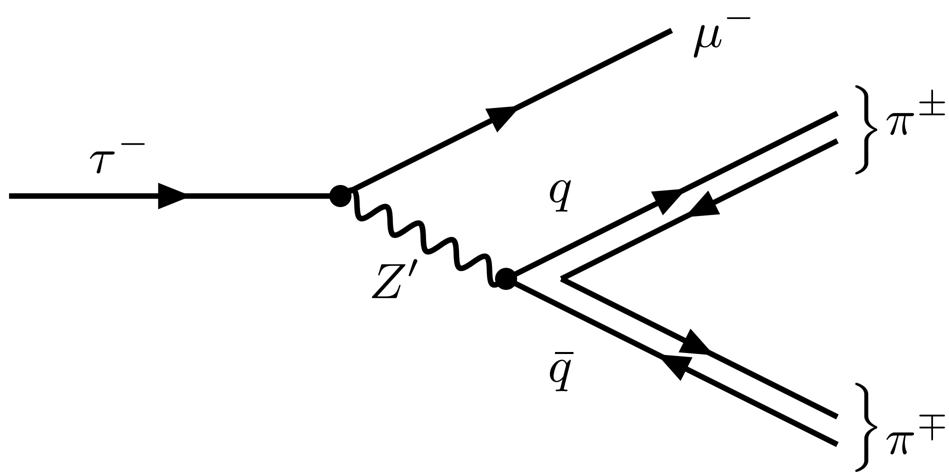
Resulting bounds:



Work in Progress:

- $\tau \to \mu\pi\pi$ is also strongly bounded:

$$B(\tau^- \to \mu^-\pi^+\pi^-) < 2.1 \times 10^{-8} \quad (90\% \text{ C.L.})$$



- No loop suppression → Stronger bound?

Does the $\tau \rightarrow \mu ee$ bound apply to the F-S Model?

- 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

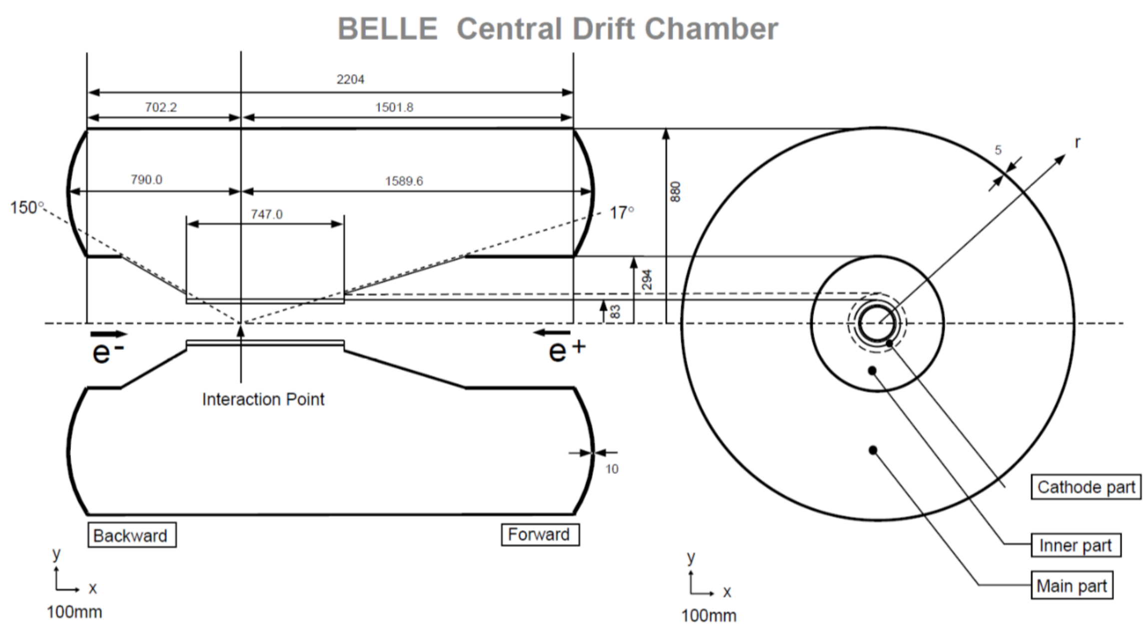


Fig. 22. Overview of the CDC structure. The lengths in the figure are in units of mm.

Two-body decay bound:

- Argus (1995)

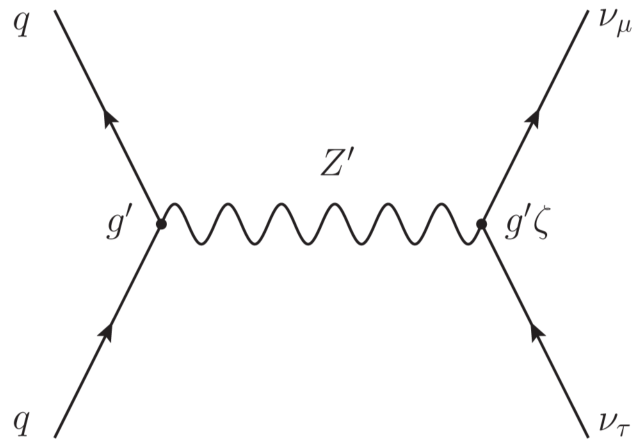
$$B(\tau \to \mu + Z') < 5 \times 10^{-3}$$
$$\downarrow$$
$$g'\zeta < 6 \times 10^{-8} \left(\frac{M_{Z'}}{200\text{MeV}} \right)$$

- 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)

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

Conclusion :

- Both g' and $g'\zeta$ are more tightly bounded than originally assumed



- Constructing viable models that predict detectable neutrino NSI's is not easy!