Charged Lepton Flavor Violation in low scale seesaw models

G. H. Tomé*, J. I. Illana*, M. Masip*
G. López†, and P. Roig.†

* CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada
† Departamento de Física, CINVESTAV México.

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XI CPAN DAYS (OVIEDO)

Motivation

- Original formulation of the SM (massless neutrinos)

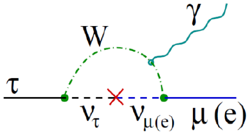
$$-\mathcal{L}_Y = (Y_u)_{ij}\bar{Q}_{L_i}u_{R_j}\tilde{\Phi} + (Y_d)_{ij}\bar{Q}_{L_i}d_{R_j}\Phi + (Y_e)_{ij}\bar{L}_{L_i}e_{R_j}\Phi + h.c. \qquad (1)$$

No incorporation of right-handed neutrinos

> The minimality construction of eq. (1) implies massless neutrinos and the conservation of both lepton flavor and lepton number.

- **Experimental evidence of neutrino oscillation ⇒ LF numbers are not conserved, being required an extended model with tiny neutrino mass.**

- Minimal extension (νSM) $\Rightarrow$ already results in cLFV transitions at one loop level, although strongly suppressed



- $BR(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^*_{ek} m^2_{\nu k}}{m^2_W} \right|^2 \sim 10^{-54}$.
  - T. P. Cheng and L. F. Li, S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).
- $BR(Z \to \ell' \ell) \sim 10^{-54}$
  - J. I. Illana and T. Riemann, Phys. Rev. D 63, 053004 (2001).
- $BR(h \to \ell' \ell) \sim 10^{-55}$
  - E. Arganda, A. M. Curiel, M. J. Herrero and D. Temes, Phys. Rev. D 71, 035011 (2005).
- $\mathrm{BR}(\mu^\pm \to e^\pm e^\pm e^\mp) \sim 10^{-53}$
  - S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).
- $\mathrm{BR}(\tau^\pm \to \mu^\pm \ell^\pm \ell^\mp) \sim 10^{-54}$
  - G. Hernández-Tomé, G. López Castro and P. Roig, Eur. Phys. J. C 79. (2018)

Far away from any possible detection!

- The νSM incorporates further features
  - **Very tiny Yukawa couplings in order to explain the observed neutrino masses**
  - **Possible invariant Majorana mass terms $\frac{1}{2}MN_RN_R$? $(\Delta L = 2)$**

Type-I Seesaw (High-scale scenario $M \gg m_D$)

- Natural explanation for the tiny ν masses via new dynamics with a heavy scale

Seesaw Relations

In the case of only one generation of heavy neutrinos, the light-heavy mixings are fixed to be very small

$$m_\nu(\sim 0{,}05\,\mathrm{eV}) \simeq \frac{m_D^2(\sim 10^4\ \ \mathrm{GeV}^2)}{M(\sim 10^{14}\,\mathrm{GeV})}, \qquad \theta(\sim 10^{-6}) \simeq \sqrt{\frac{m_v}{M}}.$$

with $m_D = y_\nu v$.

New Heavy effects decoupled!
Again, cLFV very suppresed!

Low Scale Seesaw Models

- Inverse Seesaw
  - PhysRevD.34.1642
- Linear Seesaw
  - PhysRevLett.95.161801

Based on approximate symmetries or ansatz on the neutrino matrix.

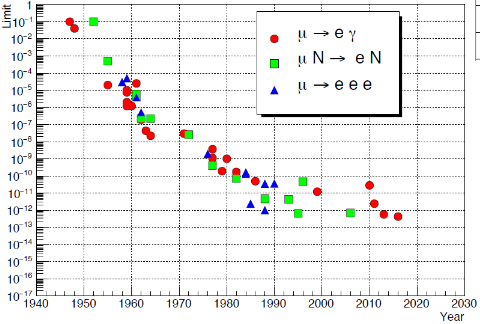
More that one sterile neutrino!

Masses and mixings can be taken as free parameters, constrained only by experimental limits!

A new window to new Physics via cLFV transitions and $\Delta L = 2$ processes!

Experimental limits

So far, no evidence of cLFV!

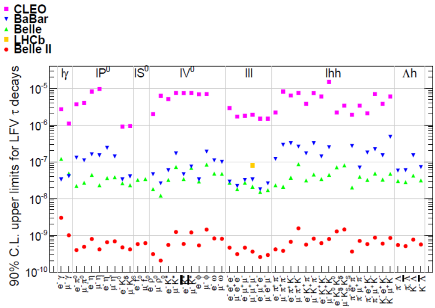


Reaction	Present Limit 90% C.L	Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	4×10^{-14}
$\mu - e$ (Au)	7.0×10^{-13}	-
$\mu - e$ (Ti)	4.3×10^{-12}	10^{-18}
$\mu \to ee\bar{e}$	1.0×10^{-12}	10^{-16}
$\tau \to \mu\gamma$	4.4×10^{-8}	1×10^{-9}

Future experiments MEG-II, Mu3e, PRISM and COMET

- A. M. Baldini *et al.*, arXiv:1301.7225
- A. Blondel *et al.*, arXiv:1301.6113.
- A. Alekou *et al.*, arXiv:1310.0804
- Y. Kuno [COMET Collaboration], PTEP **2013**, 022C01 (2013).

Experimental limits



Belle-II will be improved until two orders of magnitude when they achieve their maximum luminosity

- E. Kou *et al.* [Belle-II Collaboration], arXiv:1808.10567 [hep-ex]

Reaction	Present Limit 90% C.L	Future Sensitivity
$\tau \to e\gamma$	3.3×10^{-8}	3×10^{-9}
$\tau \to \mu\gamma$	4.4×10^{-8}	1×10^{-9}
$\tau \to ee\bar{e}$	2.7×10^{-8}	$\sim (2-5) \times 10^{-10}$
$\tau \to \mu\mu\bar{\mu}$	2.1×10^{-8}	$\sim (2-5) \times 10^{-10}$
$\tau \to \mu e\bar{e}$	1.8×10^{-8}	$\sim (2-5) \times 10^{-10}$
$\tau \to e\mu\bar{\mu}$	2.7×10^{-8}	$\sim (2-5) \times 10^{-10}$
$\tau \to \mu\mu\bar{e}$	1.7×10^{-8}	$\sim (2-5) \times 10^{-10}$
$\tau \to ee\bar{\mu}$	1.5×10^{-8}	$\sim (2-5) \times 10^{-10}$

- Other channels

Reaction	Present Limit 95% C.L.	Future Sensitivity
$Z \to \mu e$	7.3×10^{-7} [34]	10^{-13}[44]
$Z \to \tau e$	9.8×10^{-6} [35]	-
$Z \to \tau\mu$	1.2×10^{-5} [36]	-

FCC-ee would improve the current limits to $Z \to \bar{\ell}\ell'$ by about four orders of magnitude

- Phys. Rev. D **95**, no. 7, 075028 (2017)

cLFV in low Scale Seesaw Models

We consider an interfamily seesaw scenario where the neutrino sector is formed by

- n_R of right-handed (Majorana) neutrino singlets
- n_G left-handed neutrinos ($\nu_L^0 = \nu_e,\, \nu_\mu,\, \nu_\tau,\, ...$)

Charged and neutral currents involving neutrinos

$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} W_\mu^- \sum_{i=1}^{n_G} \sum_{j=1}^{n_G+n_R} B_{\ell_i j}\, \bar{\ell}_i \gamma^\mu P_L \nu_j + \text{h.c.}, \qquad (2)$$

$$\mathcal{L}_Z = -\frac{g}{4c_W} Z_\mu \sum_{i,j=1}^{n_G+n_R} \bar{\nu}_i \gamma^\mu \left(C_{ij} P_L - C_{ij}^* P_R \right) \nu_j, \qquad (3)$$

$$\mathcal{L}_{G^\pm} = -\frac{g}{\sqrt{2} m_W} G^- \sum_{i=1}^{n_G} \sum_{j=1}^{n_G+n_R} B_{\ell_i j}\, \bar{\ell}_i \left(m_{\ell_i} P_L - m_j P_R \right) \nu_j + \text{h.c}, \qquad (4)$$

- A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995)
- F. del Aguila and J. A. Aguilar-Savedra, Nucl. Phys. B 813, 22 (2009)

In the case of $n_R = 2$**,** the neutrino mass spectrum consists of three light Majorana neutrinos which have been identified with the three known neutrinos, ν_e, ν_μ and ν_τ and two heavy ones denoted by N_1 and N_2. The light-heavy mixings correspond to

$$s_{\nu_k}^2 = \sum_i |B_{\ell_k N_i}|^2. \tag{5}$$

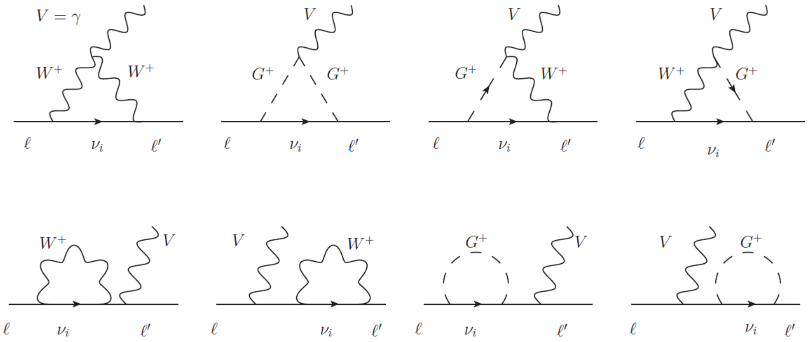
In the simple of $n_R = 2$, and considering the light neutrinos massless

$$B_{\ell_k N_1} = \frac{r^{\frac{1}{4}}}{\sqrt{1 + r^{\frac{1}{2}}}} s_{\nu k}, \quad B_{\ell_k N_2} = \frac{i}{\sqrt{1 + r^{\frac{1}{2}}}} s_{\nu k}, \tag{6}$$

$$C_{N_1 N_1} = \frac{r^{\frac{1}{2}}}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s_{\nu k}^2, \quad C_{N_1 N_2} = -C_{N_2 N_1} = \frac{i r^{\frac{1}{4}}}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s_{\nu_k}^2, \tag{7}$$

$$C_{N_2 N_2} = \frac{1}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s_{\nu k}^2, \quad r = \left(\frac{m_{N_2}}{m_{N_1}}\right)^2. \tag{8}$$

- A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995)

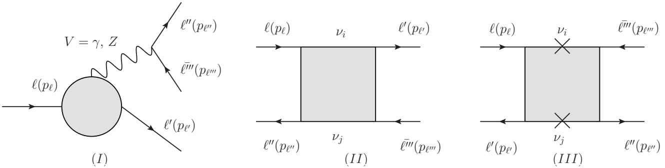


- $\ell \to \ell'\gamma$ $(\mu \to e\gamma,\, \tau \to e\gamma,\, \tau \to \mu\gamma)$

$$\Gamma(\ell \to \ell'\gamma) = \frac{\alpha}{2} m_\ell^3 \left(|F_M^\gamma|^2 + |F_E^\gamma|^2\right) . \tag{9}$$

cLFV Observables

- $\ell \to \ell' \ell'' \bar{\ell}'''$



	$\ell \to \ell' \ell'' \bar{\ell}'''$
Type 1 ($\ell' = \ell''$ and $\ell'' = \ell'''$)	$\mu \to e e \bar{e}$ $\tau \to \mu\mu\bar{\mu}$ $\tau \to e e \bar{e}$
Type 2 ($\ell' \neq \ell''$ and $\ell'' = \ell'''$)	$\tau \to \mu e \bar{e}$ $\tau \to e \mu \bar{\mu}$
Type 3 ($\ell' = \ell''$ and $\ell'' \neq \ell'''$)	$\tau \to \mu\mu\bar{e}$ $\tau \to e e \bar{\mu}$

- Type-1

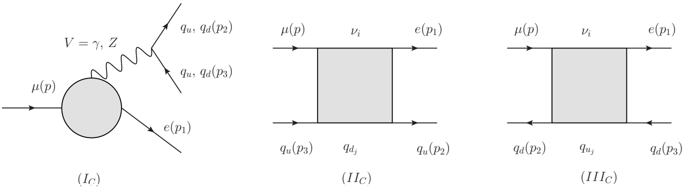
$$\begin{aligned} \Gamma &= \frac{\alpha^2 m_\ell^5}{96\pi} \Bigg\{ 3\,|A_L|^2 + 2\,|A_R|^2 \left(8 \log\left(\frac{m_\ell}{m_{\ell''}}\right) - 13 \right) + 2\,|F_{LL}|^2 + |F_{LR}|^2 + \frac{1}{2}\,|B_L|^2 \\ &- \Big[6 A_L A_R{}^* - (A_L - 2A_R)(2F_{LL}{}^* + F_{LR}{}^* + B_L{}^*) - F_{LL} B_L{}^* + \text{h.c} \Big] \Bigg\}, \qquad (10) \end{aligned}$$

cLFV Observables

- $Z \to \ell\bar{\ell}'$ ($Z \to \mu\bar{e}$, $Z \to \tau\bar{\mu}$, $Z \to \tau\bar{e}$)

$$\Gamma(Z \to \bar{\ell}\ell') = \frac{\alpha}{3} m_Z |\mathcal{A}_L^Z|^2. \tag{11}$$

- $\mu N - eN$ Conversion



$$\Gamma(\mu \to e) = \frac{\alpha^5 Z_{\rm eff}^4}{Z} F(q)^2 m_\mu^5 \left| 2Z \left(A_1^L + A_2^R \right) - (2Z+N)\,\bar{B}_{1u}^L - (Z+2N)\,\bar{B}_{1d}^L \right|^2, \tag{12}$$

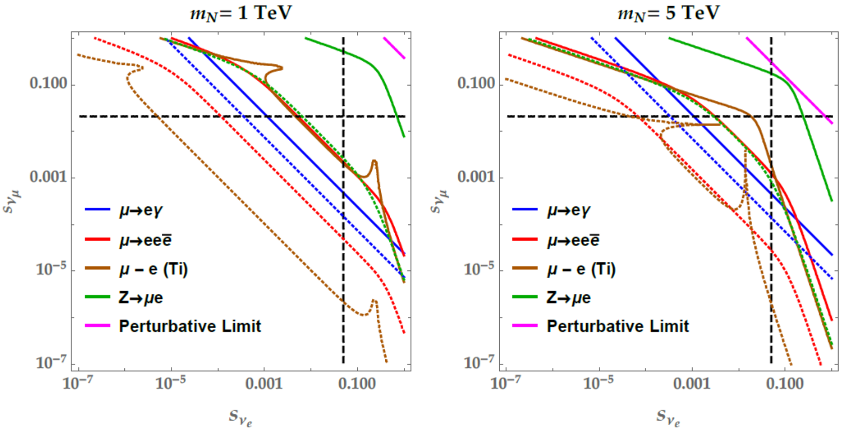
Limits on light heavy-mixings

- Indirect limits on the light heavy mixing angles

$$s_{\nu_e} < 0{,}050\,(0{,}031), \quad s_{\nu_\mu} < 0{,}021\,(0{,}011), \quad s_{\nu_\tau} < 0{,}075\,(0{,}044). \quad (13)$$

  - E. Fernández-Martínez, J. Hernández-García and J. López-Pavon, JHEP **1608**, 033 (2016)

- Direct limits from cLFV

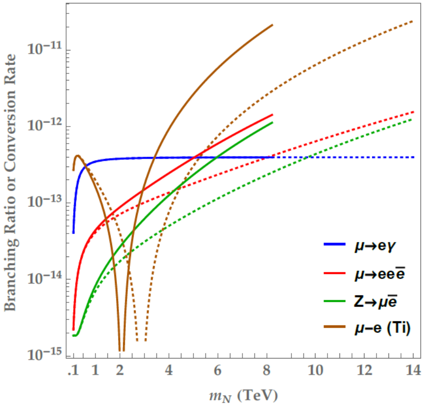


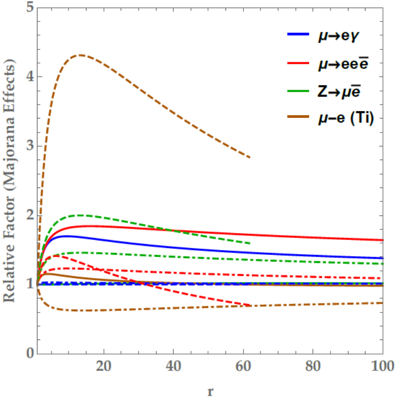
Genuine Majorana effects $\mu - e$ transitions

Perturbative Unitarity condition

$$Y_{N_\alpha} = \frac{\sqrt{2 m_{N_1} m_{N_2}}}{v} s_{\nu_\alpha} < \sqrt{4\pi}.$$

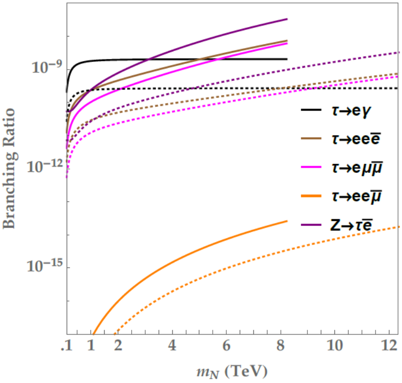
Maximum predictions for $\mu - e$ transitions

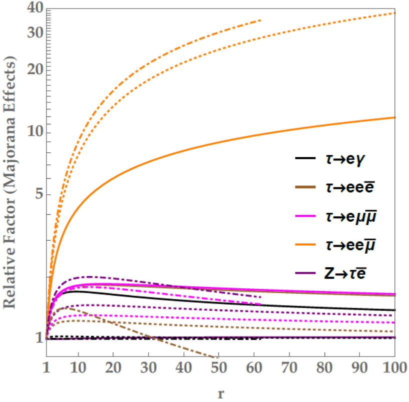




Genuine Majorana effects $\tau - e$ transitions

- Maximum predictions for $\tau - e$ transitions





Conclusions

- CLFV processes are strongly suppressed in the νSM and the usual $Type - I$ seesaw model. However low scale seesaw models offer a possibility for those effects.
- We have obtained updated estimations for some of the most attractive cLFV processes in low scale seesaw models. Some of these values are at the reach of future experiments.
- We focused on the differences between the degenerate and non-degenerate (Genuine Majorana effects) case of two Majorana neutrinos.
- The no observation of such effects set strong limits on the parameter-space of these hypothetical scenarios.

Thank you!

Back up

The dimension of the rectangular B mixing matrix is $n_G \times (n_G + n_R)$, whereas the C matrix has dimension $(n_G + n_R) \times (n_G + n_R)$; they are determined as follows

$$B_{\ell_i j} = \sum_{k=1}^{n_G} (U^{\ell}_{ki})^* U^{\nu}_{kj}, \quad C_{ij} = \sum_{k=1}^{n_G} (U^{\nu}_{ki})^* U^{\nu}_{kj}, \tag{14}$$

where U^{ℓ}_{ij} and $B_{\ell_i j}$ represent the PMNS mixing matrix and its generalized version, respectively.

In the simple case of $n_R = 2$,

$$B_{\ell_k N_1} = \frac{r^{\frac{1}{4}}}{\sqrt{1 + r^{\frac{1}{2}}}} s_{\nu k}, \quad B_{\ell_k N_2} = \frac{i}{\sqrt{1 + r^{\frac{1}{2}}}} s_{\nu k}, \tag{15}$$

$$C_{N_1 N_1} = \frac{r^{\frac{1}{2}}}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s^2_{\nu k}, \quad C_{N_1 N_2} = -C_{N_2 N_1} = \frac{i r^{\frac{1}{4}}}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s^2_{\nu_k}, \tag{16}$$

$$C_{N_2 N_2} = \frac{1}{1 + r^{\frac{1}{2}}} \sum_{k=1}^{n_G} s^2_{\nu k}. \tag{17}$$

- A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995)

The matrices B and C satisfy the following identities, which are crucial to maintaining the renormalizability of the model

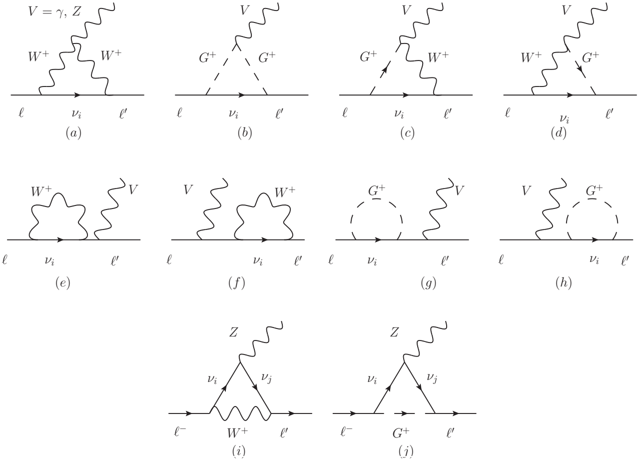
$$\sum_{k=1}^{n_G+n_R} B_{\ell_1 k} B^*_{\ell_2 k} = \delta_{\ell_1 \ell_2}, \quad \sum_{k=1}^{n_G+n_R} C_{ik} C^*_{jk} = \sum_{k=1}^{n_G} B_{\ell_k i} B^*_{\ell_k j} = C_{ij}, \tag{18}$$

$$\sum_{k=1}^{n_G+n_R} B_{\ell_i k} C_{kj} = B_{\ell_i j} \tag{19}$$

$$\sum_{k=1}^{n_G+n_R} m_k C_{ik} C_{jk} = \sum_{k=1}^{n_G+n_R} m_k B_{\ell k} C^*_{ki} = \sum_{k=1}^{n_G+n_R} m_k B_{\ell_1 k} B_{\ell_2 k} = 0. \tag{20}$$

- A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995)

- Effective $V\ell\ell'$ vertex generated in the presence of massive neutrinos



The dipole form factors relevant in the $\ell \to \ell' \gamma$ decay are given by

$$\begin{aligned} F_M^\gamma(0) = -iF_E^\gamma(0) &= \frac{m_\ell \alpha_W}{16\pi m_W^2} \sum_i^{n_G+n_R} B_{\ell i}^* B_{\ell' i} f_M^\gamma(x_i), \\ &= \frac{m_\ell \alpha_W}{16\pi m_W^2} \sum_{N_i}^{n_R} B_{\ell N_i}^* B_{\ell' N_i} \left[f_M^\gamma(x_{N_i}) - f_M^\gamma(0) \right], \end{aligned} \tag{21}$$

where we have defined $x_i = m_i^2/m_W^2$, and

$$f_M^\gamma(x) = \frac{3x^3 \log(x)}{2(x-1)^4} - \frac{2x^3 + 5x^2 - x}{4(x-1)^3} + \frac{5}{6}, \qquad f_M^\gamma(0) = \frac{5}{6}. \tag{22}$$

In the $\ell \to \ell' \ell'' \bar{\ell}'''$ decays, the photon is off-shell, as a consequence, they also involve the vector and axial-vector F_V^γ and F_A^γ form factors, but since $F_V = F_A$ it turns out convenient to define

$$
\begin{aligned}
2F_V^\gamma = F_L^\gamma(q^2) &= \frac{\alpha_W}{8\pi m_W^2} \sum_i^{n_G+n_R} B_{\ell i}^* B_{\ell' i} f_L^\gamma(q^2, x_i), \\
&= \frac{\alpha_W}{8\pi m_W^2} \sum_{N_i}^{n_R} B_{\ell N_i}^* B_{\ell' N_i} \left[f_L^\gamma(q^2, x_i) - f_L^\gamma(q^2, 0) \right], \quad (23)
\end{aligned}
$$

where

$$
f_L^\gamma(q^2, x) = \frac{q^2 x^2 \left(x^2 - 10x + 12\right) \log(x)}{6(x-1)^4} + \frac{q^2 \left(7x^3 - x^2 - 12x\right)}{12(x-1)^3} - \frac{5q^2}{9} + 2m_W^2 \Delta, \quad (24)
$$

$$
f_L^\gamma(q^2, 0) = -\frac{5q^2}{9} + 2m_W^2 \Delta, \quad (25)
$$

and $\Delta = \frac{1}{\epsilon} - \gamma_E + \log(4\pi) + \log\left(\frac{\mu^2}{m_W^2}\right)$ stands for an ultraviolet divergence.

In the approximation where masses and momenta of the external particles are neglected, the effective $Z\ell\ell'$ is given in terms of only one form factor associated with a $V - A$ Lorentz structure

$$A_L^Z = \frac{\alpha_W}{8\pi s_W c_W} \sum_{i,j}^{n_G+n_R} B^*_{\ell i} B_{\ell' j} \left[F_Z(x_i)\delta_{ij} + C^*_{ij} G_Z(x_i, x_j) + C_{ij}\sqrt{x_i x_j} H_Z(x_i, x_j) \right], \tag{26}$$

$$F_Z(x) = \frac{5x^2 \log(x)}{2(x-1)^2} - \frac{5x}{2(x-1)} + \frac{1}{4} - \Delta \left(\frac{5}{2} - 2s_W^2 \right), \tag{27}$$

$$G_Z(x, y) = \frac{1}{2(x-y)} \left(\frac{x^2(y-1)\log(x)}{(x-1)} - \frac{(x-1)y^2 \log(y)}{(y-1)} \right) + \frac{1}{2}\left(\Delta - \frac{1}{2} \right), \tag{28}$$

$$H_Z(x, y) = \frac{1}{4(x-y)} \left(\frac{(x-4)x\log(x)}{x-1} - \frac{(y-4)y\log(y)}{y-1} \right) - \frac{1}{4}\left(\Delta + \frac{1}{2} \right). \tag{29}$$