About heavy neutrinos: Lepton-flavor violation in decays of charged leptons

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Abstract

We investigate the impact of charged currents that couple

- *Heavy gauged bosons*
- *Heavy neutrinos*
- *Standard Model (SM) leptons*

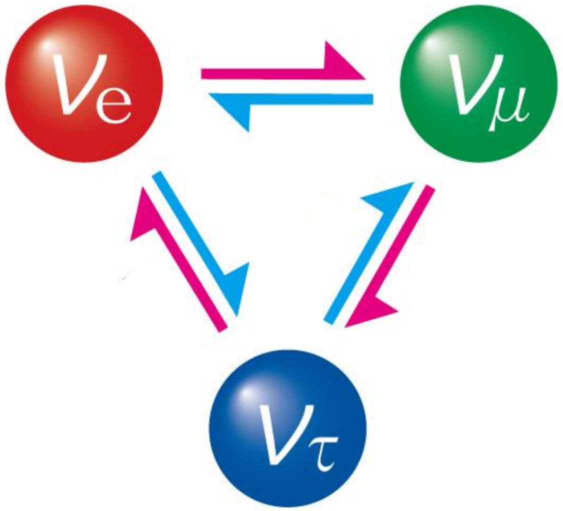
On the LFV decays of SM leptons into three charged leptons

$$l_\alpha \to l_\beta \, l_\sigma \, l_\sigma$$

Introduction

- ***Neutrino oscillations*** → Clear experimental evidence that neutrinos are massive and mix

First observed in Super Kamiokande (1998) [1]
then confirmed at Subdury Neutrino Observatory (2001)[2]



Introduction

- ***Seesaw mechanism***

Purpose of explaining neutrino mass

The high-energy description of fundamental physics, beyond the Standard Model, may include heavy neutrinos with masses depending on some energy scale, Λ, characterizing the formulation [3].

Introduction

- ***Charged currents***

$$\sum_{j=1}^{3}\sum_{\alpha=e,\mu,\tau}\left[\frac{v_{j\alpha}}{\sqrt{2}}W'^{+}_{\rho}\bar{N}_j\gamma^{\rho}P_R l_\alpha+\text{H.c.}\right] \qquad (1)$$

- Characterize the mixing of heavy neutrinos.
- Allow LFV.
- 3 × 3 matrix approximately unitary:

$\sum_{j=1}^{3} v^{*}_{j\alpha}v_{j\alpha}\approx 1$

$\sum_{j=1}^{3} v^{*}_{j\beta}v_{j\alpha}=0$ for $\alpha\neq\beta$

Introduction

Assumptions:

- Λ is large
- $\left.\begin{matrix} m_j \\ m_{W'} \end{matrix}\right\}$ Are approximately proportional to the high energy scale

-Left-right symmetric models [3-6],

-The simplest little Higgs model [7],

-331 models [8],

-5-dimensional extension of the Standard Model [9].

Thus:

$$m_{W'} \approx \kappa_j m_j ,$$

With κ_j independent of Λ for any j

Introduction

Possible decays:

$$\left[\begin{aligned} \mu^- &\to e^- e^+ e^- . \\ \tau^- &\to e^- \mu^+ \mu^- \\ \tau^- &\to \mu^- e^+ e^- \\ \tau^- &\to \mu^- \mu^+ \mu^- \\ \tau^- &\to e^- e^+ e^- \end{aligned}\right.$$

Features:

- Independent model as far as possible.
- Scenario where two heavy neutrinos have quasi-degenerate masses but the third is different .
- m_j and $m_{W'}$ within hundreds of GeV to few TeV.

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- ***The amplitude*** $\mathcal{M}_{\alpha\rightarrow\beta\sigma\sigma}$

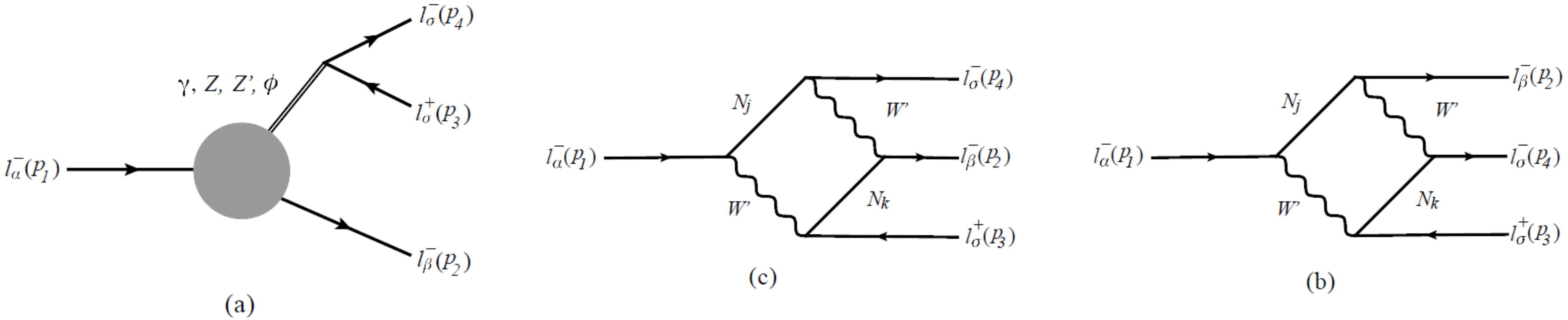
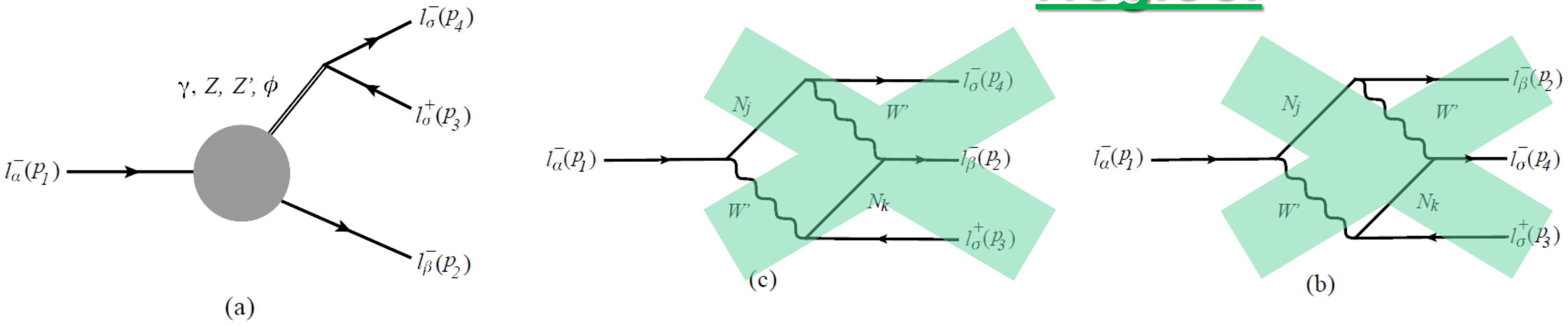


FIG. 1: Feynman diagrams that produce contributions, at one loop, to the decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$ by means of neutrino mixing: (a) reducible diagrams; and (b) and (c) box diagrams.

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- ***The amplitude*** $\mathcal{M}_{\alpha\rightarrow\beta\sigma\sigma}$

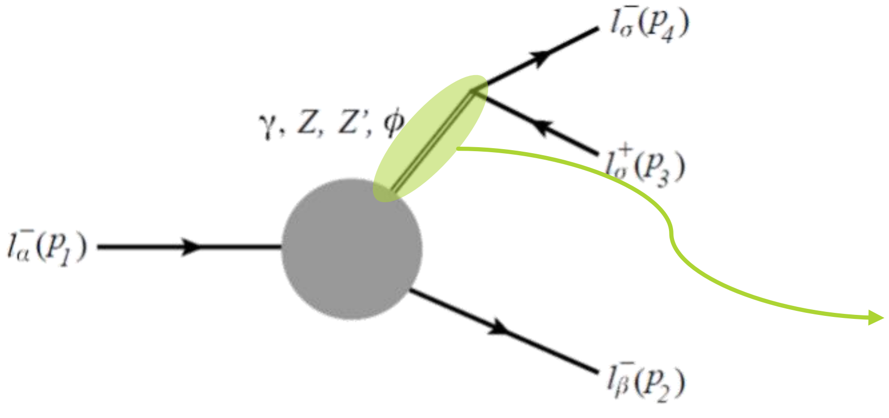


Neglect

FIG. 1: Feynman diagrams that produce contributions, at one loop, to the decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$ by means of neutrino mixing: (a) reducible diagrams; and (b) and (c) box diagrams.

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- Concerning the reducible diagrams…



(a)

Introduce a factor

- $\frac{1}{q^2}$ photon
- $\frac{1}{q^2-m^2}$ (massive boson of mass m)

The decay rate for $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$ restricts q^2 to very small variables $4m_\sigma^2 < q^2 < (m_\alpha - m_\beta)^2$

The mass of any virtual particle that can contribute satisfies: $m^2 \gg q^2$

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- The leading contributions from the charged currents are produced by:

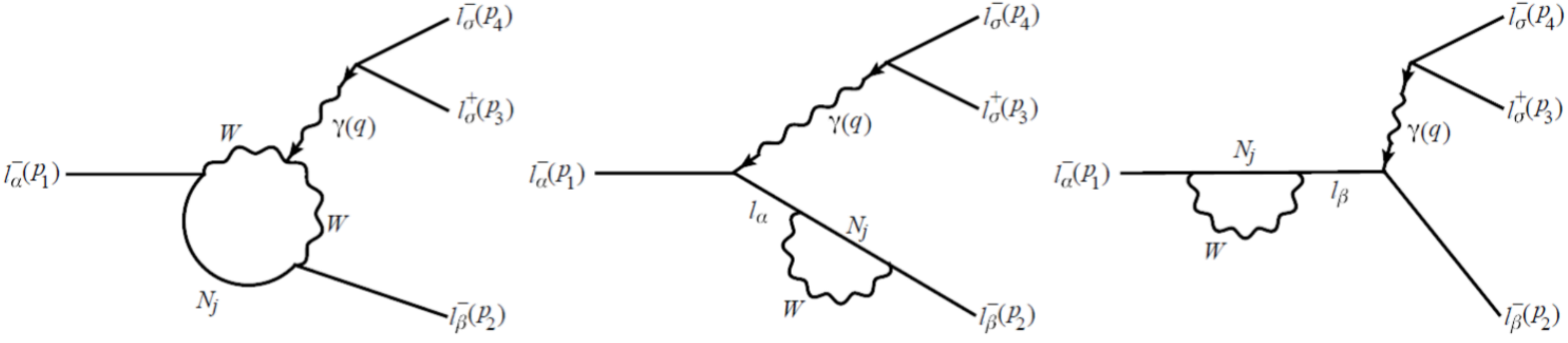


FIG. 2: Feynman diagrams corresponding to the dominant contribution from the charged currents of Eq. (1) to the decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$.

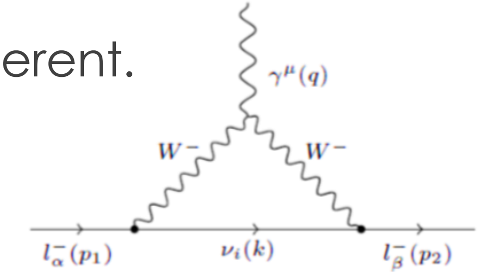
The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- Neutrinos being electrically neutral and massive can be described by

Dirac fields

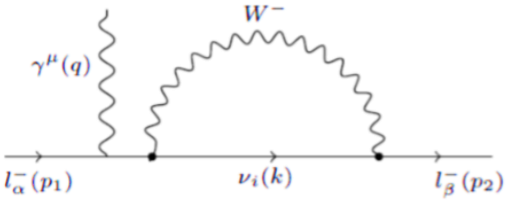
Majorana fields

Feynman rules (number of diagrams) are different.

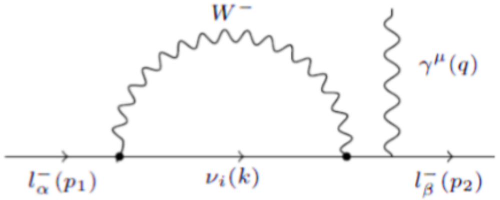


(a)

However, the contributions from the reducible diagrams with the one loop electromagnetic vertex are the same.



(b)



(c)

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- The sum of subdiagrams produces the total contribution $\bar{u}_\beta(p_2)\Gamma_\mu^{\alpha\beta}(q)u_\alpha(p_1)$ with the general **gauge invariant** structure [10-12]

With respect to the electromagnetic gauge group (Ward identity)

$$\Gamma_\mu^{\alpha\beta}(q) \;=\; ie\sum_{j=1}^{3} v_{j\beta}^* v_{j\alpha}\Big[\Big(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\Big)\big(\underline{f_Q^j} + \underline{f_A^j}q^2\gamma_5\big) - i\sigma_{\mu\nu}q^\nu\big(\underline{f_M^j} + i\underline{f_E^j}\gamma_5\big)\Big] \qquad (2)$$

sum over the heavy-neutrinos

charge form factor

anapole form factor

magnetic form factor

electric form factor

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- Contributions of electromagnetic form factors:

$$f_\Omega^j = \frac{1}{\Delta_\Omega}\left[f_{\Omega,0}^j B_0^j + f_{\Omega,12}^j(B_1^j - B_2^j) + f_{\Omega,23}^j(B_2^j - B_3^j) + f_{\Omega,34}^j(B_3^j - B_4^j) + f_{\Omega,5}^j C_0^j\right]. \qquad (3)$$

with

$$B_0^j = 1. \qquad B_1^j = B_0(0, m_{W'}^2, m_j^2), \qquad B_2^j = B_0(q^2, m_{W'}^2, m_{W'}^2), \qquad B_3^j = B_0(m_\alpha^2, m_{W'}^2, m_j^2), \qquad B_4^j = B_0(m_\beta^2, m_{W'}^2, m_j^2),$$

$$C_0^j = C_0(m_\alpha^2, m_\beta^2, q^2, m_{W'}^2, m_j^2, m_{W'}^2),$$

- Dimensional-regularization approach [13]

$$B_0 = \Delta_{\text{div}} + f_{\text{fin}} \qquad (4)$$

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- ***Decoupling of new physics***

-Spectrum of heavy neutrino masses m_j:

$m_2 \approx m_3 \approx m_N$ but $m_1 \neq m_2$ and $m_1 \neq m_3$ [69]

-Form factors:

$$F_\Omega = v_{1\beta}^* v_{1\alpha} \left[\frac{1}{m_{W'}^2} \eta_{\Omega 1} + \frac{1}{m_{W'}^4} \eta_{\Omega 2} + \frac{1}{m_{W'}^6} \eta_{\Omega 3} \right] \tag{8}$$

The amplitude $\mathcal{M}_{\alpha\to\beta\sigma\sigma}$ decouples as $\Lambda \to \infty$: $\lim_{\Lambda\to\infty} F_\Omega = 0.$

The trileptonic decay $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

- The amplitude for the process $l_\alpha \longrightarrow l_\beta l_\sigma l_\sigma$

$$i\mathcal{M}_{\alpha\to\beta\sigma\sigma} = \bar{u}_\beta(p_2)\Gamma^{\alpha\beta}_\mu u_\alpha(p_1)\frac{-ig^{\mu\nu}}{q^2}\bar{u}_\sigma(p_4)(-ie\gamma_\nu)v_\sigma(p_3). \tag{5}$$

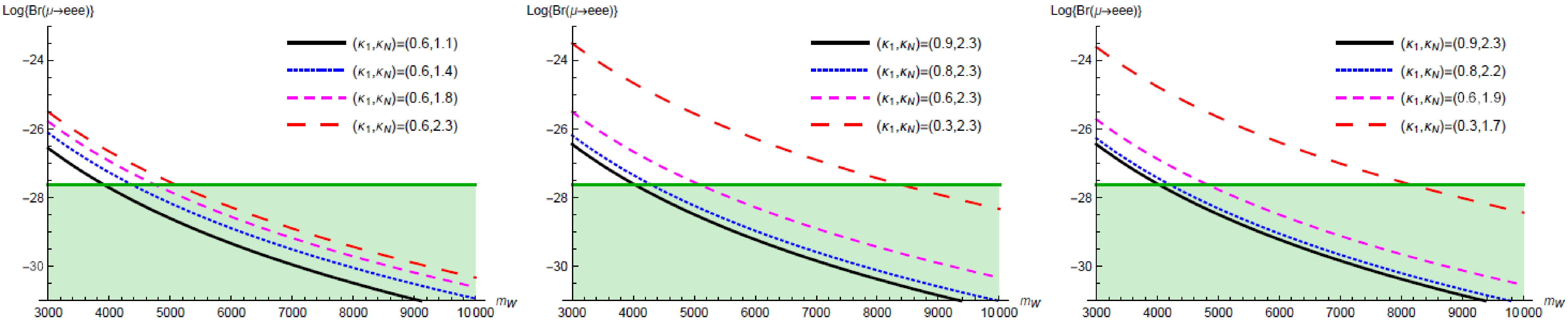
$$\begin{aligned} |\overline{\mathcal{M}}_{\alpha\to\beta\sigma\sigma}|^2 &= \frac{1}{2}\sum_{s_1=\pm}\sum_{s_2=\pm}\sum_{s_3=\pm}\sum_{s_4=\pm}|\mathcal{M}_{\alpha\to\beta\sigma\sigma}|^2 \\ &= \frac{e^4}{2(q^2)^2}\Big[g_1^{\alpha\beta}|F_Q|^2 + g_2^{\alpha\beta}|F_A|^2 + g_3^{\alpha\beta}|F_M|^2 + g_4^{\alpha\beta}|F_E|^2 + g_5^{\alpha\beta}\mathrm{Re}\{F_Q F_M^*\} + g_6^{\alpha\beta}\mathrm{Im}\{F_A F_E^*\}\Big] \end{aligned} \tag{6}$$

- Decay rate

$$\Gamma_{\alpha\to\beta\sigma\sigma} = \frac{2m_{W'}}{(8\pi\sqrt{x_\alpha})^3}\int_{x_{\min}}^{x_{\max}} dx \int_{y_{\min}}^{y_{\max}} dy\, |\overline{\mathcal{M}}_{\alpha\to\beta\sigma\sigma}|^2, \tag{7}$$

The decay $\mu \longrightarrow 3e$

$$m_{W'} \approx \kappa_j m_j ,$$



Graph (1) Graph (2) Graph (3)

FIG. 3: Contributions to Br($\mu \longrightarrow 3e$) as a function of $m_{W'}$ (in GeV units), for different (κ_1, κ_N), with $\kappa_1 < 1 < \kappa_N$:

(1) constant κ_1 and increasing κ_N,
(2) Constant κ_N and decreasing κ_1,
(3) Decreasing κ_1 and κ_N, but constant κ_1- κ_N.

The graphs have been plotted in logarithmic scale.

SINDRUM bound [14]
$BR(\mu \rightarrow 3e) < 10^{-12}$

Expected improvement by the *mu3e experiment* [15] $\approx 10^{-16}$

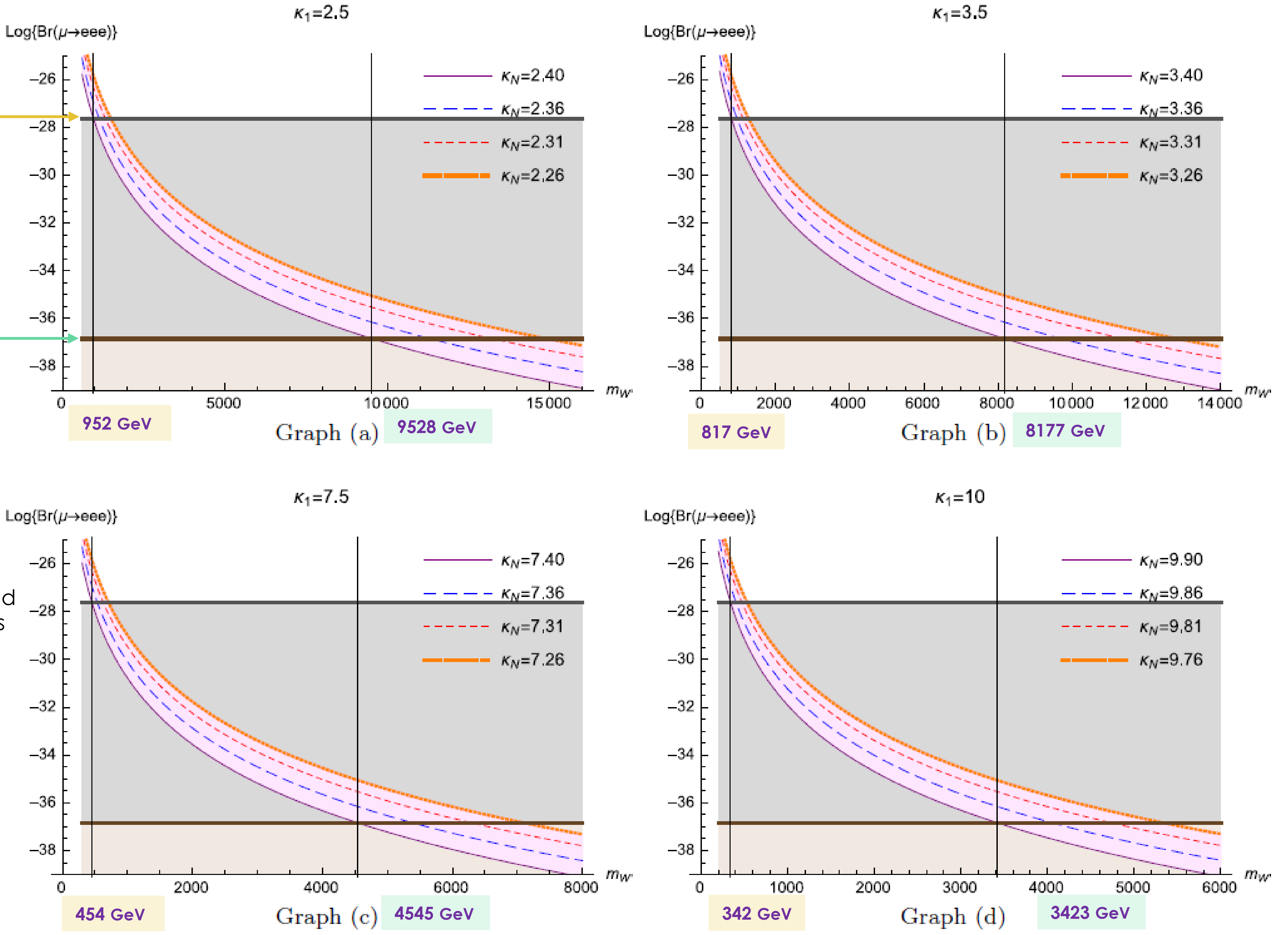
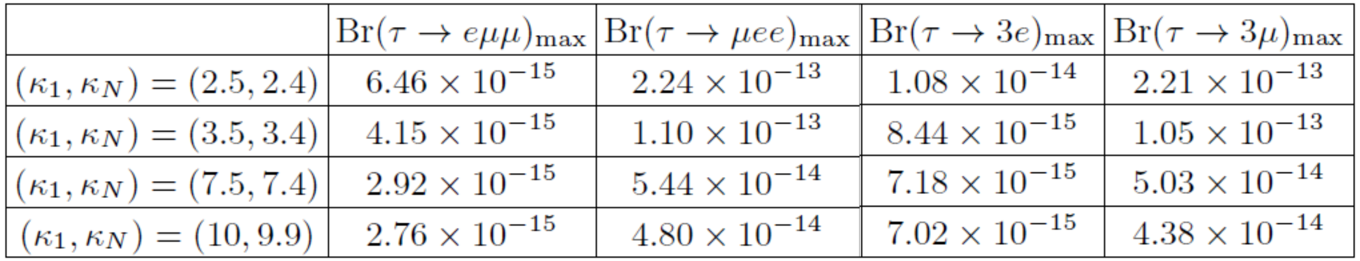


FIG. 4: Lower bounds on the W' mass through suitable choices of κ_1 and κ_N . In all cases, mass units are GeVs

Increasing kappas, corresponding to smaller heavy-neutrino masses.

New-physics contributions $\tau \longrightarrow l_\beta l_\sigma l_\sigma$



	$\mathrm{Br}(\tau \to e\mu\mu)_{\mathrm{max}}$	$\mathrm{Br}(\tau \to \mu ee)_{\mathrm{max}}$	$\mathrm{Br}(\tau \to 3e)_{\mathrm{max}}$	$\mathrm{Br}(\tau \to 3\mu)_{\mathrm{max}}$
$(\kappa_1, \kappa_N) = (2.5, 2.4)$	6.46×10^{-15}	2.24×10^{-13}	1.08×10^{-14}	2.21×10^{-13}
$(\kappa_1, \kappa_N) = (3.5, 3.4)$	4.15×10^{-15}	1.10×10^{-13}	8.44×10^{-15}	1.05×10^{-13}
$(\kappa_1, \kappa_N) = (7.5, 7.4)$	2.92×10^{-15}	5.44×10^{-14}	7.18×10^{-15}	5.03×10^{-14}
$(\kappa_1, \kappa_N) = (10, 9.9)$	2.76×10^{-15}	4.80×10^{-14}	7.02×10^{-15}	4.38×10^{-14}

TABLE I: Values of the branching ratios for $\tau \rightarrow e\mu\mu$, $\tau \rightarrow \mu ee$, $\tau \rightarrow 3e$ and $\tau \rightarrow 3\mu$ determined by the parameters $\kappa_1, \kappa_N, m_{w\prime}$. For each selected pair (κ_1, κ_N) the corresponding minimal allowed mass is $m_{w\prime}$.

Conclusions

- One loop contributions from charged currents of the μ and τ decays (heavy neutrinos and heavy charged bosons) ⟶ flavor is not preserved (neutrino mixing).
- Dominant contributions from reducible diagrams (electromagnetic vertex).
- The results do not make a distinction between Dirac and Majorana Neutrinos.
- The results are ultraviolet finite, gauge invariant and decoupled.
- Spectrum of heavy neutrinos.
- $\tau \longrightarrow l_\beta l_\sigma l_\sigma$ branching ratios can be found $\sim 10^{-15} - 10^{-13}$.

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