Study of lepton flavor and lepton number violating processes

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Outline

- Introduction

Phenomenology →

- Study of cLFV processes
  - *current and future limits*
  - *cLFV in νSM and Type-I Seesaw*
  - *LSSM*
    - *Effects of heavy Majorana states:* $\ell \to \ell' \gamma$, $\mu \to e\,C$, $\ell \to \ell' \ell'' \ell'''$, $\{Z, H\} \to \ell \ell'$.
    - *Inverse seesaw model*
    - *Non-unitary effects*
- Study of LNV processes ($\Delta L = 2$)
  - $\beta\beta 0\nu$ *decays in nuclei*
  - *LNV on hyperon decays*
    - *Three body decays*
    - *Four body decays*

- Summary and conclusions

Introduction and Motivation

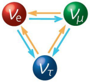
- Original formulation of the SM (Weinberg-Glashow-Salam)

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

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}\,\phi^+ \\ v + H + i\phi_z\end{pmatrix},$$

$\Phi \rightarrow$ Higgs doblet
$H \rightarrow$ Physical Higgs
$\phi^+, \phi_z \rightarrow$ Goldstone bosons

No incorporation of right-handed neutrinos $\Rightarrow$ { *Massless neutrinos* / *LF and LN are conserved* }



Neutrino oscillation $\Rightarrow$ { $m_{\nu_i} \neq 0$ *Massive neutrinos* / *LF is not conserved (Neutrino sector).* }

Mixing in the leptonic sector 2006.11237

Parameter	Normal ordering (3σ range)	Inverted ordering (3σ range)
$\sin^2\theta_{12}$	0.271 - 0.369	0.271 - 0.369
$\sin^2\theta_{23}$	0.434 - 0.610	0.433 -0.608
$\sin^2\theta_{13}$	0.2000 - 0.2405	0.2018 - 0.2424
$\delta_{CP}/^\circ$	128 - 359	200 - 353
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	6.94 - 8.14	6.94 -8.14
$\frac{\lvert\Delta m^2_{31}\rvert}{10^{-3}\text{eV}^2}$	2.47 -2.63	2.37 - 2.53

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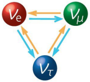

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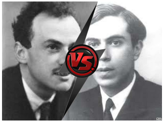


Remained unanswered questions:
- *Neutrinos are Dirac or Majorana particles?*
- *Is there a new underlying mechanism that explains the tiny observed masses?*

We have to extend the SM to consider massive neutrinos

- ***Simplest scenario*** *($\nu SM = SM + \nu_R$)?*

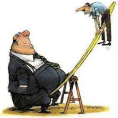
Neutrinos are different from the other fermions in that the $SU(2)_L$ singlet required to give them an EW mass is not protected by chirality

Seesaw models (An attractive scenario)

- Allowed Majorana mass terms $\frac{1}{2} M \bar{N}_R^c N_R$ *($\Delta L = 2$)*
- Possible natural explanation for the tiny masses

$$m_\nu (\sim 0{,}05\,\text{eV}) \simeq \frac{m_D^2 (\sim 10^4 \;\; \text{GeV}^2)}{M(\sim 10^{14}\,\text{GeV})} \qquad (2)$$

$$\mathcal{M} = \begin{bmatrix} m_M^L & m_D \\ m_D & m_M^R \end{bmatrix}$$



cLFV in massive neutrino models

charged Lepton Flavor Violating Processes (cLFV)

- Simplest scenario ($\nu SM = SM + \nu_R$)

Cheng. and Li, Sov. J. Nucl. Phys. 25, 340 (1977)

$$BR(\mu \to e\gamma) = \boxed{\frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^{*}_{ek}m^{2}_{\nu k}}{m^{2}_{W}}\right|^{2} \sim 10^{-54}}$$

✗ $\mathrm{BR}(\tau \to 3\mu) > 10^{-14}$

X.Y Pham, EPJC 8, 513 (1999).

✓ $\mathrm{BR}(\tau \to 3\mu) > 10^{-54}$

GHT, PR, GLC, EPJC 79. (2018).

P. Blackstone et al, EPJC 80, 506 (2020).

- Type-I Seesaw: (***High energy hypothesis*** $M \gg m_D$)

$$m_\nu(\sim 0{,}05\,\mathrm{eV}) \simeq \frac{m_D^2(\sim 10^4\ \ \mathrm{GeV}^2)}{M(\sim 10^{14}\,\mathrm{GeV})},$$

$$\boxed{\theta(\sim 10^{-6}) \simeq \sqrt{\frac{m_D}{M}}} \to (\textit{Heavy states decoupled})$$

with $m_D = y_\nu v$.

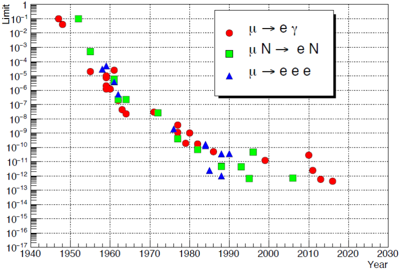
Evidence of these transitions would be a smoking gun for NP

LOW SCALE SEESAW MODELS :

Inverse seesaw, Linear seesaw.

- There isn't a strong relationship between masses and mixings of the new heavy states.
- Richer phenomenology: NP scale accessible to current experiments

Experimental Limits



No evidence of cLFV so far.

- Very strong limits for $\mu - e$ processes.
- The expected sensitivity for $\mu - e$ C and $\mu \to 3e$ is surprising ***(Mu2e-II, MEG-II, Mu3e-II).***
- For the search of these processes in BELLE-II see the poster of Marcela .

Reaction	Present Limit 90% C.L.	Future Sensitivity	Reaction	Present Limit 90% C.L.	Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13} [50]	6×10^{-14} [60]	$\mu \to ee\bar{e}$	1.0×10^{-12} [51]	10^{-16} [61]
$\mu - e$ (Au)	7.0×10^{-13} [52]	—	$\mu - e$ (Ti)	4.3×10^{-12} [52]	10^{-18} [62]
$\tau \to e\gamma$	3.3×10^{-8} [53]	3×10^{-9} [63]	$\tau \to \mu\gamma$	4.4×10^{-8} [53]	10^{-9} [63]
$\tau \to ee\bar{e}$	2.7×10^{-8} [54]		$\tau \to \mu\mu\bar{\mu}$	2.1×10^{-8} [54]	
$\tau \to e\mu\bar{\mu}$	2.7×10^{-8} [54]	$(2-5) \times 10^{-10}$ [63]	$\tau \to \mu e\bar{e}$	1.8×10^{-8} [54]	$(2-5) \times 10^{-10}$ [63]
$\tau \to ee\bar{\mu}$	1.5×10^{-8} [54]		$\tau \to \mu\mu\bar{e}$	1.7×10^{-8} [54]	
Reaction	**Present Limit 95% C.L.**	**Future Sensitivity**	**Reaction**	**Present Limit 95% C.L.**	**Future Sensitivity**
$Z \to \mu e$	7.3×10^{-7} [55]	10^{-10} [64]	$h \to \mu e$	3.4×10^{-4} [58]	—
$Z \to \tau e$	9.8×10^{-6} [56]	10^{-9} [64]	$h \to \tau e$	6.2×10^{-3} [59]	5×10^{-4} [65]
$Z \to \tau\mu$	1.2×10^{-5} [57]	10^{-9} [64]	$h \to \tau\mu$	2.5×10^{-3} [59]	

A minimal model for the study of heavy-light neutrino mixing

GHT, JI, MM, PR, GL, PRD 101 (2020) 7, 075020

• A minimimal parametrization to capture the effects of HNS:

$$\mathcal{M} = \begin{pmatrix} 0 & 0 & 0 & 0 & m_1 \\ 0 & 0 & 0 & 0 & m_2 \\ 0 & 0 & 0 & 0 & m_3 \\ 0 & 0 & 0 & 0 & M \\ m_1 & m_2 & m_3 & M & \mu \end{pmatrix}$$

After diagonalization:

• Two heavy states $N_{1,2}$

$$m_{N_{\{1,2\}}} = \frac{1}{2}\left(\sqrt{4\,(M') + \mu^2} \mp \mu\right),$$

with $M' = \sqrt{m_1^2 + m_2^2 + m_3^2 + M^2}$

• Three massless neutrinos ν_i.

• m_1, m_2, m_3, M are Dirac masses

Dirac singlet vs Two Majorana states:

• μ breaks LN. When $\mu = 0$ both states form a heavy Dirac neutrino singlet of mass M.

- A Dirac fermion has 4 four independent components.
- A Majorana fermion ($\psi^c \equiv \eta^* \psi$) has only two free components.

All the phenomenology is described by only five free parameters:

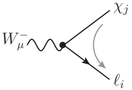
$$m_{N_1} = m_{\chi_4}, \quad m_{N_2} = m_{\chi_5}, \left(r \equiv \frac{m_{N_2}^2}{m_{N_1}^2}\right), \quad s_{\nu_i} = \frac{m_i}{\sqrt{m_{N_1} m_{N_2}}}.$$

A minimal model for the heavy-light neutrino mixing

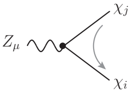
The charged and neutral currents are defined by:

$$B_{ij} = \sum_{k=1}^{3} \delta_{ik} U^{\nu}_{kj}\,, \quad C_{ij} = \sum_{k=1}^{3} (U^{\nu}_{ki})^{*} U^{\nu}_{kj}\,.$$

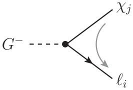
$$\mathcal{L}_{W^{\pm}} = -\frac{g}{\sqrt{2}} W^{-}_{\mu} \sum_{i=1}^{3}\sum_{j=1}^{5} B_{ij}\, \bar{\ell}_i \gamma^{\mu} P_L \chi_j + \text{h.c.},$$



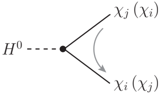
$$\mathcal{L}_{Z} = -\frac{g}{4c_W} Z_{\mu} \sum_{i,j=1}^{5} {\color{red}\bar{\chi}_i} \gamma^{\mu} \left(C_{ij} P_L - C^{*}_{ij} P_R \right) {\color{blue}\chi_j}\,,$$



$$\mathcal{L}_{G^{\pm}} = -\frac{g}{\sqrt{2} M_W} G^{-} \sum_{i=1}^{3}\sum_{j=1}^{5} B_{ij} \times \bar{\ell}_i \left(m_{\ell_i} P_L - m_{\chi_j} P_R \right) \chi_j + \text{h.c.},$$



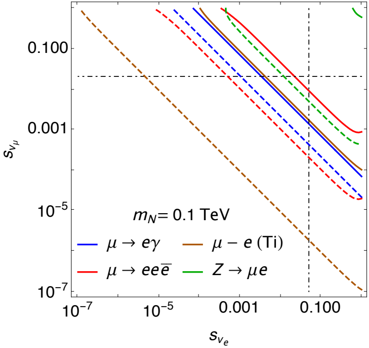
$$\mathcal{L}_{H} = -\frac{g}{4M_W} H \sum_{i,j=1}^{5} {\color{red}\bar{\chi}_i} [(m_{\chi_i} C_{ij} + m_{\chi_j} C^{*}_{ij}) P_L + (m_{\chi_i} C^{*}_{ij} + m_{\chi_j} C_{ij}) P_R] {\color{blue}\chi_j}$$

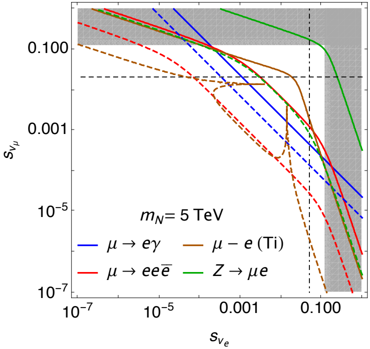


Limits on low scale seesaw models from the search of cLFV

Reaction	Present Limit		Future Sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	90% C.L.	6×10^{-14}
$\mu \to ee\bar{e}$	1.0×10^{-12}	90% C.L.	10^{-16}
$Z \to \mu e$	7.3×10^{-7}	95% C.L.	10^{-10}
$\mu - e$ (Ti)	4.3×10^{-12}	90% C.L.	10^{-18}

GHT, JI, MM, PR, GL, Phys.Rev.D 101 (2020) 7, 075020

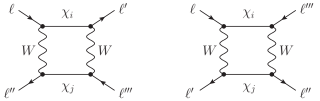


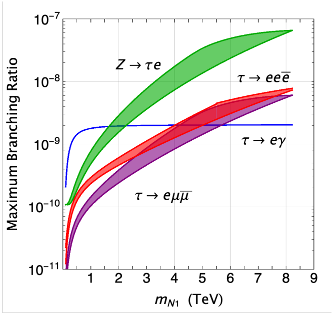


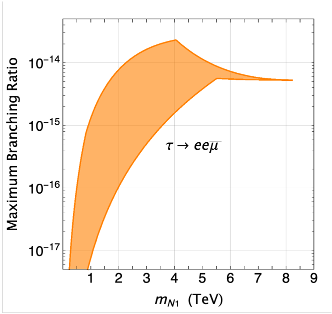
Limits on the heavy-light mixings by considering the current (solid lines) and future limits (dashed lines).

cLFV processes in low scale seesaw models

- Genuine LNV contributions from Majorana particles must vanish if LN is conserved (that is when $r = 1$).



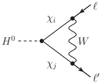




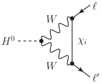
$$\mathrm{BR}(\tau \to e\gamma) = 2{,}0 \times 10^{-9},$$
$$\mathrm{BR}(Z \to \tau e) = 6{,}0 \times 10^{-8}.$$

$$\mathrm{BR}(\tau \to ee\bar{e}) = 7{,}3 \times 10^{-9},$$
$$\mathrm{BR}(\tau \to e\mu\bar{\mu}) = 6{,}0 \times 10^{-9},$$
$$\mathrm{BR}(\tau \to ee\bar{\mu}) = 2{,}3 \times 10^{-14}.$$

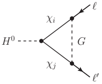
$H^0 \to \bar{\ell}_i \ell_j$



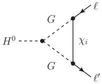
$W\chi\chi$



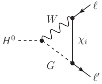
χWW

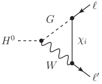


$G\chi\chi$ (UV div)

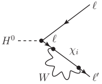


χGG

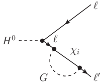




χWG (UV div)



$W\chi$



$G\chi$ (UV div)

J. L.Diaz-Cruz and J.J. Toscano, PRD 62 (2000), 116005.

GHT, JI and MM, PRD, 102 (2020) no.11, 113006

- ***$G\chi\chi$ and $G\chi$ cancel each other.***
- ***χWG is finite when summing over all neutrino states.***
- ***The other diagrams are finite.***

• One may expect that $G\chi\chi$ and $G\chi$ dominate with a contribution of order $\mathcal{M} \approx y_i\, y_j\, y_{\ell_i}/(16\pi^2)$. Using this rough estimate:

$$\mathcal{B}(H^0 \to \tau e) = \mathcal{B}(H^0 \to \bar{b}b)\,\frac{2\,\Gamma(H^0 \to \bar{\tau}e)}{\Gamma(H^0 \to \bar{b}b)}$$

$$\approx \mathcal{B}(H^0 \to \bar{b}b)\,\frac{2}{3}\left(\frac{y_3\, y_1\, y_\tau}{y_b\, 16\pi^2}\right)^2 .$$

•Taking $y_i < \sqrt{4\pi}$ this gives:

$$\mathcal{B}(H^0 \to \tau e) < 4 \times 10^{-4}.?$$

• All these diagrams are proportional to

$$y_i\, y_j\, y_{\ell_i} = 2\sqrt{2}\, s_{\nu_i} s_{\nu_j}\, \frac{m_{N_1} m_{N_2} m_{\ell_i}}{v^3} .$$

• Diagrams $W\chi\chi$, χWG and $W\chi$ are proportional to g^2, χWW is proportional to g^4, and χGG to the Higgs quartic coupling λ.

$H^0 \to \bar{\ell}_i \ell_j$

However

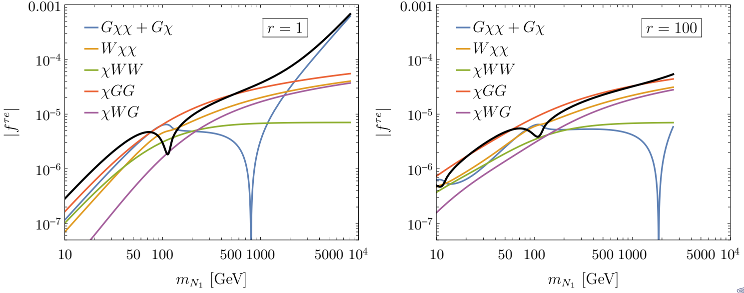
- Although their sum is finite, the diagrams $G\chi\chi$ and $G\chi$ are both divergent. There is a value of the heavy neutrino mass that exactly cancels the sum of both contributions. For $m_{N_1} = m_{N_2}$ this is

$$\widetilde{m}_N \approx 0{,}57 \frac{M_H}{\sqrt{s^2_{\nu_e} + s^2_{\nu_\mu} + s^2_{\nu_\tau}}}.$$

- At masses of the heavy neutrinos above $\widetilde{m}_N$ there are decoupling effects.

$$\mathcal{M}(H^0 \to \bar{\tau} e) = \bar{u}(p_2)\frac{f^{\tau e}}{v}\left[m_\tau P_R + m_e P_L\right] v(p_1).$$

$$\boxed{\mathcal{B}(H^0 \to \tau e) < 1{,}4 \times 10^{-8}.}$$



cLFV and non-unitary violation in the Inverse Seesaw Model (ISS)

What about non-unitary mixing effects?

By introducing a number n of singlet states in addition to the three light active neutrinos

$$\mathcal{M}_{n'\times n'} = \begin{pmatrix} 0_{3\times 3} & \mathcal{M}_{D_{3\times n}} \\ \mathcal{M}^T_{D_{n\times 3}} & \mathcal{M}_{R_{n\times n}} \end{pmatrix}.$$

$$||\mathcal{M}_D|| \ll ||\mathcal{M}_R||$$

J. Schechter and J. W. F. Valle, PhysRevD.25.774

Block Matrix Diagonalization (BMD)

$$(\mathcal{U}^\nu)^T \mathcal{M}\, \mathcal{U}^\nu = \mathcal{M}^{\text{diag}}, \quad \mathcal{M}^{\text{diag}}_{n'\times n'} = \begin{pmatrix} m^{\text{diag}}_{\nu_{3\times 3}} & 0_{3\times n} \\ 0_{n\times 3} & M^{\text{diag}}_{N_{n\times n}} \end{pmatrix},$$

$$m_{\nu_{3\times 3}} = -(\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T)_{3\times 3}, \quad M_{N_{n\times n}} =\approx \mathcal{M}_{R_{n\times n}}.$$

$$U^\nu_{n'\times n'} = \boxed{\begin{pmatrix} \mathbb{I}_{3\times 3} - \frac{1}{2}(\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1}\mathcal{M}_R^{-1}\mathcal{M}_D^T)_{3\times 3} & (\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1})_{3\times n} \\ -(\mathcal{M}_R^{-1}\mathcal{M}_D^T)_{n\times 3} & \mathbb{I}_{n\times n} - \frac{1}{2}(\mathcal{M}_R^{-1}\mathcal{M}_D^T\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1})_{n\times n} \end{pmatrix}}$$

- *The charged currents are given by*

$$B_{L_{3\times 3}} = \left(\mathbb{I} - \frac{1}{2}(\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1}\mathcal{M}_R^{-1}\mathcal{M}_D^T)\right)\cdot V_1,$$

$$B_{H_{3\times n}} = \left(\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1}\right)\cdot V_2,$$

$$B_L = (\mathbb{I} - \eta)\cdot V_1,$$

$$\eta_{3\times 3} = \frac{1}{2}(\mathcal{M}_D^*(\mathcal{M}_R^*)^{-1}\mathcal{M}_R^{-1}\mathcal{M}_D^T),$$

- *V_1 is identified with the PMNS matrix*
- *η is the matrix that quantifies the deviation from unitarity of the mixing among three active light neutrino states.*

Inverse Seesaw Model

- Let us focus in the so-called ISS model. The appealing idea behind this model require extend the neutrino sector not only with right-handed singlet neutrinos N_{Ri} but also with the presence of new singlets S_{Li}.

- Here, an explanation of the active light neutrinos states is based on the presence of a small lepton number violating parameter μ.

$$N_R = 3, S_L = 3(case)$$

- ***Since $\parallel \mu \parallel \ll \parallel M_D \parallel \ll \parallel M \parallel$ the BMD can be applied by doing the identification:***

$$\mathcal{M}^{\rm ISS}_{9\times 9} = \begin{pmatrix} 0_{3\times 3} & M_{D_{3\times 3}} & 0_{3\times 3} \\ (M_D^T)_{3\times 3} & 0_{3\times 3} & M_{3\times 3} \\ 0_{3\times 3} & (M^T)_{3\times 3} & \mu_{3\times 3} \end{pmatrix}.$$

$$\mathcal{M}^{\rm ISS}_{D_{3\times 6}} = (M_{D_{3\times 3}}, 0_{3\times 3})$$

$$\mathcal{M}^{\rm ISS}_{R_{6\times 6}} = \begin{pmatrix} 0_{3\times 3} & M_{3\times 3} \\ M^T_{3\times 3} & \mu_{3\times 3} \end{pmatrix}.$$

$$m^{\rm ISS}_{\nu_{3\times 3}} = (M_D (M^T)^{-1} \mu M^{-1} M_D^T)_{3\times 3},$$

$$M^{\rm ISS}_{N_{6\times 6}} = \mathcal{M}^{\rm ISS}_{R_{6\times 6}}.$$

$$(\mathcal{M}^{\rm ISS}_R)^{-1}_{6\times 6} = \begin{pmatrix} -((M^T)^{-1}\mu M^{-1})_{3\times 3} & (M^T)^{-1}_{3\times 3} \\ M^{-1}_{3\times 3} & 0_{3\times 3} \end{pmatrix}.$$

Non-unitary effects in the ISS

$$B^{\rm ISS}_{3\times 9} = (B^{\rm ISS}_{L_{3\times 3}}, B^{\rm ISS}_{H_{3\times 6}})$$

$$B^{\rm ISS}_{L_{3\times 3}} = \left(\mathbb{I}_{3\times 3} - \eta^{\rm ISS}_{3\times 3}\right) \cdot V_{1_{3\times 3}},$$

$$B^{\rm ISS}_{H_{3\times 6}} \approx \left(0_{3\times 3}, (M_D^*(M^{*T})^{-1})_{3\times 3}\right) \cdot V_{2_{6\times 6}},$$

$$\boxed{\eta^{\rm ISS}_{3\times 3} \approx \frac{1}{2}(M_D^*(M^{T*})^{-1} M^{-1} M_D^T)_{3\times 3}.}$$

cLFV and non-unitary violation in the ISS

Extension of the so-called Casas-Ibarra parametrization *Forero et al, JHEP 09, 1107.6009, (2011).*

$$M_{D_{3\times3}} = \left(V_1 \sqrt{m_\nu^{\rm diag}} R^T \left(\sqrt{\mu}\right)^{-1} M^T \right),$$

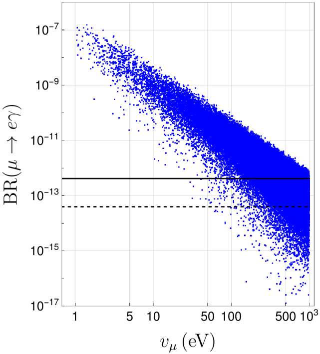
with R a real 3×3 orthogonal matrix described by three arbitrary rotation angles (θ, ϕ, ψ).

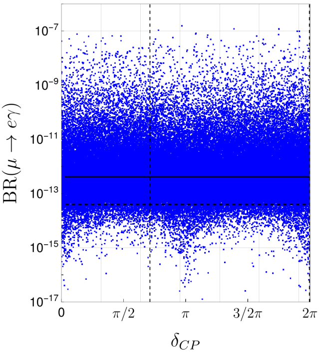
$$M_{3\times3} = v_M \cdot {\rm diag}(\epsilon_{M_{11}}, \epsilon_{M_{22}}, \epsilon_{M_{33}}),$$
$$\mu_{3\times3} = v_\mu \cdot {\rm diag}(\epsilon_{\mu_{11}}, \epsilon_{\mu_{22}}, \epsilon_{\mu_{33}}).$$

We performed a scan considering ***16 free parameters***:

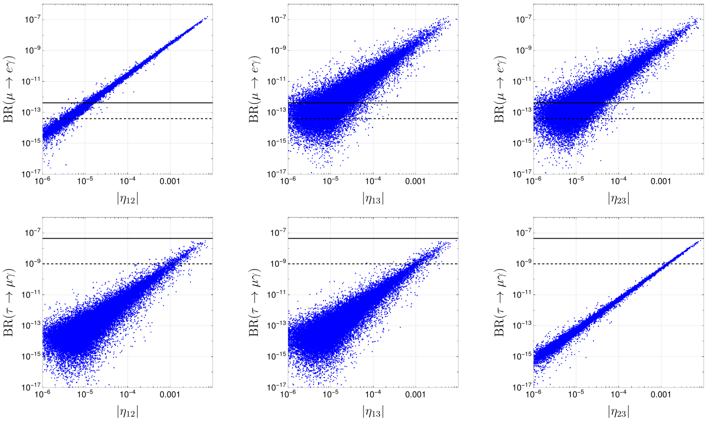
- 3 angles + 1 CP phase (PMNS)
- 3 light masses in $m_\nu^{\rm diag}$
- 3 rotation angles in matrix R, $(\theta,\ \phi,\ \psi)\,\epsilon\,[0, 2\pi]$.
- 3 parameters in the μ matrix, $\epsilon_{\mu_{ii}}\,\epsilon\,[-0{,}5, 0{,}5]$ $(i =, 1, 2, 3)$
- 3 parameters in the diagonal M matrix, $\epsilon_{M_{ii}}\,\epsilon\,[-0{,}5, 0{,}5]$ $(i =, 1, 2, 3)$.

The scale v_M is fixed to the value 1 TeV, whereas $v_\mu\,\epsilon\,[1, 1000]$ eV. ***Work in progress in collaboration with EP and CG.***





Non-unitary effects in the ISS

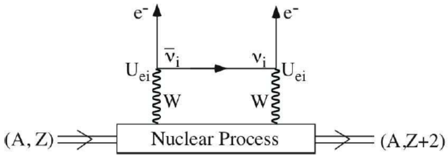


Lepton number violating (ΔL=2) processes

$\Delta L=2$ processes

A clear test to the Majorana nature of neutrinos: ***ΔL=2 processes ⇒ Neutrinos Majorana***

- Neutrinoless doble-beta decay ($\beta\beta0\nu$) – the most promising scenario to study the effects of light Majorana neutrinos



- Matrix nuclear elements (model depend uncertainty)

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |\mathcal{M}^{0\nu}|^2 \cdot \langle m_{ee}\rangle^2, \quad (3)$$

'*Effective mass*' $m_{ee} \equiv \sum_i U^2_{ei} m_{\nu_i}$

- No observation ⇒ **KamLAND-Zen. PRL, 117, no.8, 082503 (2016**

$$|\langle m_{ee}\rangle| \sim (61 - 165)\,\text{meV}. \quad (4)$$

- Background

$$\beta\beta_{2\nu}: \quad (A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e \quad \text{LN is conserved}$$

Allowed in standard interactions.

Hyperon physics program at BES-III

- BES-III works as a factory J/ψ y $\psi(2S)$ ($\sim 10^{10}$ events per year)

Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$)	Sensitivity $\mathcal{B}$ (90% C.L.) ($\times 10^{-6}$)	Type
$\Lambda \to n e^+ e^-$	–	< 0.8	
$\Sigma^+ \to p e^+ e^-$	< 7	< 0.4	
$\Xi^0 \to \Lambda e^+ e^-$	7.6 ± 0.6	< 1.2	
$\Xi^0 \to \Sigma^0 e^+ e^-$	–	< 1.3	**EM-PENGUIN** Type A
$\Xi^- \to \Sigma^- e^+ e^-$	–	< 1.0	
$\Omega^- \to \Xi^- e^+ e^-$	–	< 26.0	
$\Sigma^+ \to p \mu^+ \mu^-$	$(0.09^{+0.09}_{-0.08})$	< 0.4	
$\Omega^- \to \Xi^- \mu^+ \mu^-$	–	< 30.0	
$\Lambda \to n \nu \bar{\nu}$	–	< 0.3	
$\Sigma^+ \to p \nu \bar{\nu}$	–	< 0.4	
$\Xi^0 \to \Lambda \nu \bar{\nu}$	–	< 0.8	**Z-PENGUIN** Type B
$\Xi^0 \to \Sigma^0 \nu \bar{\nu}$	–	< 0.9	
$\Xi^- \to \Sigma^- \nu \bar{\nu}$	–	–*	
$\Omega^- \to \Xi^- \nu \bar{\nu}$	–	< 26.0	

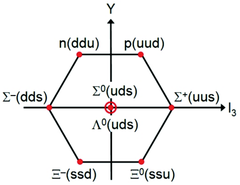
Li, Hai-Bo, Front.Phys 12, 121301, (2016)

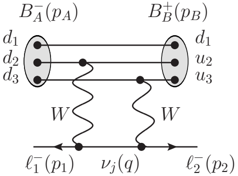
Decay mode	Current data $\mathcal{B}$ ($\times 10^{-6}$)	Sensitivity $\mathcal{B}$ (90% C.L.) ($\times 10^{-6}$)
$\Sigma^- \to \Sigma^+ e^- e^-$	–	< 1.0
$\Sigma^- \to p e^- e^-$	–	< 0.6
$\Xi^- \to p e^- e^-$	–	< 0.4
$\Xi^- \to \Sigma^+ e^- e^-$	–	< 0.7
$\Omega^- \to \Sigma^+ e^- e^-$	–	< 15.0
$\Sigma^- \to p \mu^- \mu^-$	–	< 1.1
$\Xi^- \to p \mu^- \mu^-$	< 0.04	< 0.5
$\Omega^- \to \Sigma^+ \mu^- \mu^-$	–	< 17.0
$\Sigma^- \to p e^- \mu^-$	–	< 0.8
$\Xi^- \to p e^- \mu^-$	–	< 0.5
$\Xi^- \to \Sigma^+ e^- \mu^-$	– **LNV** Type C	< 0.8
$\Omega^- \to \Sigma^+ e^- \mu^-$	–	< 17.0

PDG, HyperCP collaboration (2005)
$\Xi^- \to p\mu^-\mu^- < 4{,}0 \times 10^{-8}$

BESIII (2020)
$\Sigma^- \to pe^-e^- < 6{,}7 \times 10^{-5}$

ΔL=2 HYPERON DECAYS





$\Delta S = 0$	$\Delta S = 1$	$\Delta S = 2$
$\Sigma^- \to \Sigma^+ e^- e^-$	$\Sigma^- \to p e^- e^-$	$\Xi^- \to p e^- e^-$
	$\Sigma^- \to p e^- \mu^-$	$\Xi^- \to p e^- \mu^-$
	$\Sigma^- \to p \mu^- \mu^-$	$\Xi^- \to p \mu^- \mu^-$
	$\Xi^- \to \Sigma^+ e^- e^-$	
	$\Xi^- \to \Sigma^+ e^- \mu^-$	

Kinematically allowed ΔL=2 decays of (1/2-spin) hyperons.

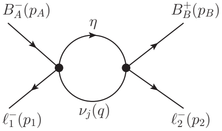
Motivación:

- Hadronic matrix elements (HME) simpler than $\beta\beta_{0\nu}$ decays in nuclei ⇒ can shed light on the correct evaluation of matrix elements in nuclear decays.
- They open the possibility of studying channels with muons not allowed in nuclear decay.

C. Barbero, GLC. y A. Mariano, PLB 566 (2003)
C. Barbero, L. F. Li, GLC. y A. Mariano, PRD 76, 116008 (2007)

- Background: $\beta\beta_{2\nu}$ $\quad B_i^- \to B^{*0}\ell^-\bar{\nu} \to B_f^+\ell^-\ell'^-\bar{\nu}\bar{\nu}'$

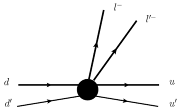
Complementary searches



Example: $\Sigma^- \to p\mu\mu$

- One loop mechanism (long distance effects). C. Barbero et al PLB 566 (2003) 98-107 C. Barbero et al (2007)
- Hadronic states as the relevant free degrees of freedom.
- A first approoximation: constant HME. ***(divergent behaviour).***
- ***New results (No div.)*** GHT, GL, DP, PRD 105 (2022) 11, 113001

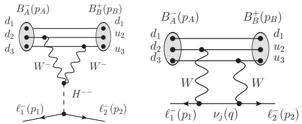
$$BR(\Sigma^- \to pe^-e^-) \sim \mathcal{O}(10^{-33}).$$



- *MIT bag model* (Short distant effects). C. Barbero,et al PRD 036010 (2013)

$$BR(\Sigma^- \to pe^-e^-) \sim O(10^{-23}).$$

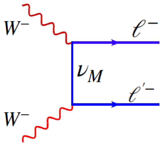
- EFT approach: 6-fermion operators (dim=9)
- We computed the WC in two particular UV completions: (HMN and doubly Higgs charged scalar in the HTM).



$$BR(\Sigma^- \to pe^-e^-)_{HTM} \sim O(10^{-30}).$$

Complementary searches of ΔL=2 processes

Another interesting possibility is the search of ΔL=2 processes mediated by an on-shell heavy Majorana state A. Atre et al, JHEP05, 030 (2009)+Many others:

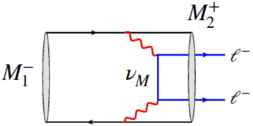


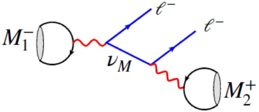
Neutrinos in the range $m_N \sim 100$ MeV to 5 GeV (*Resonant effect*)

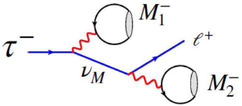
- $M_1^{\pm} \to M_2^{\mp}\ell^{\pm}\ell'^{\pm}$ ($M \equiv$Mesón $\ell = e, \mu, \tau$)
- $\tau^{\pm} \to \ell^{\mp} M_1^{\pm} M_2^{\pm}$

$$\sim G_F^2 V_{ij}^{CKM} V_{kl}^{*CKM} f_{M_1} f_{M_2} \frac{U_{\ell N} U_{\ell' N} m_N}{q^2 - m_N^2 + i m_N \Gamma_N} \tag{5}$$

Search sensitive to different scales of the mass of possible new states

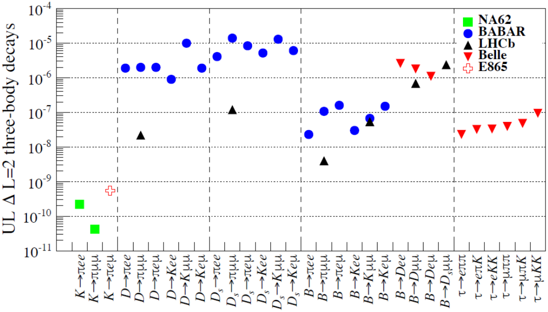




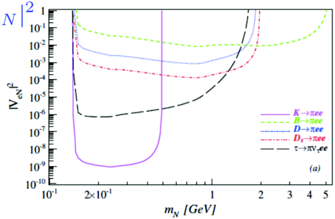


Complementary searches of ΔL=2 processes

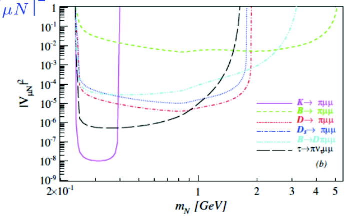
- Not observing these processes limits the parameter space of the new states in the plane $(m_{\nu_j}, |U_{\ell N}|^2)$:



$|U_{eN}|^2$

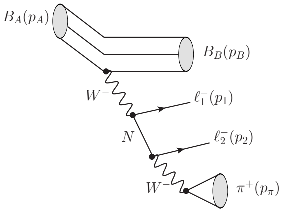


$|U_{\mu N}|^2$

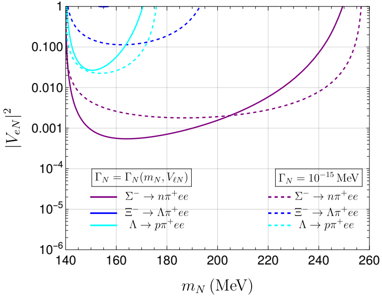


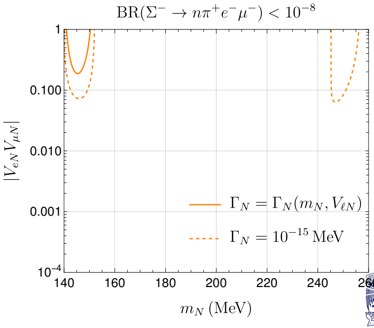
Complementary searches of ΔL=2 processes

- Novel hyperonic channels



- Four-body ΔL=2 hyperon decays mediated by a resonant heavy Majorana neutrino N. We consider the following channels: $\Sigma^- \to n\pi^+e^-\ell^-$ ($\ell = e, \mu$), $\Xi^- \to \Lambda\pi^+e^-e^-$, and $\Lambda \to p\pi^+e^-e^-$. ***Work in progress in collaboration with GT and DP.***





Summary and conclusions

- *The neutrino sector turns out a very attractive place for the search for NP. In particular, we do not know whether the observed neutrinos are Dirac or Majorana particles or if the sector includes additional fermion singlets (sterile neutrinos).*

- *These extra neutrinos, if any, would enhance cLFV processes in the so-called 'LSSSM' that are otherwise very suppressed by the tiny masses of the observed neutrinos.*

- *The observation of LVN processes would point out that neutrinos are Majorana particle unambiguously. On this subject, complementary and alternative processes to neutrinoless double beta decay in nuclei play a relevant role in diverse collaborations.*

- *Particularly, the search for a comprehensive list of LNV decays of meson, tau and baryons mediated via a resonant Majorana neutrino can test the existence of new heavy neutrino appearing in well-motivated extensions of the SM for specific energy regions.*

Thank you!

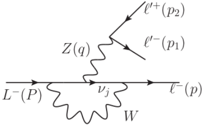
Back up

Flavor violating leptonic decays of τ and μ leptons in the Standard Model with massive neutrinos

G. Hernández-Tomé[1,2,a], G. López Castro[1,b], P. Roig[1,c]
[1] Departamento de Física, Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional, Apdo. Postal 14-740, 07000 México, D.F., Mexico
[2] CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain

- cLFV in the SM+ν (Dirac):
  - $BR(L' \to \ell\gamma) \sim 10^{-54}$ T. P. Cheng and L. F. Li, Gauge Theory Of Elementary Particle Physics
  - $BR(Z \to \ell'\ell) < 10^{-54}$ J. I. Illana and T. Riemann, Phys. Rev. D 63, 053004 (2001)
  - $BR(h \to \ell'\ell) < 10^{-55}$ 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).
  - $\mathrm{BR}(\tau^\pm \to \mu^\pm \ell^\pm \ell^\mp) > 10^{-14}$ (4×10^{-16}) † X. Y. Pham, Eur. Phys. J. C 8, 513 (1999).



$$\mathcal{M} \sim \sum_{j=1}^{3} U_{ej}^{*} U_{\mu j} \log\left(\frac{m_W^2}{m_j^2}\right)$$

- **If the prediction in † were right, there would be a difference of more than 30 orders of magnitude between $L^\pm \to \ell'^\pm\gamma$ and $L^\pm \to \ell'^\pm\ell^\pm\ell^\mp$.**
- **The amplitude won't vanish in the limit of massless neutrino.**
- **There would be no way to cure such infrared behavior.**

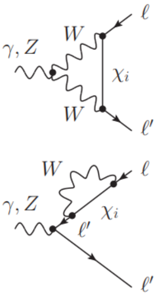


FIG. 2. One-loop diagrams contributing to the $V\ell\ell'$ vertex. We have omitted here and elsewhere diagrams with would-be-Goldstone fields, needed in the Feynman-'t Hooft gauge.

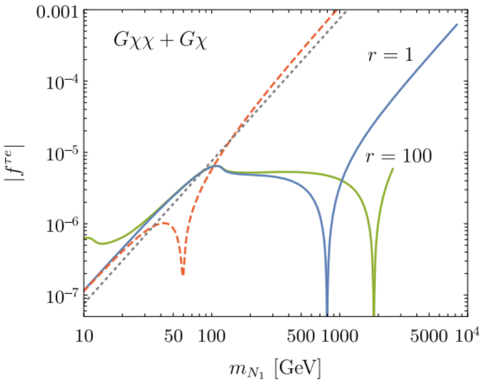


FIG. 2. Contribution to $|f^{\tau e}|$ from the dominant diagrams $G\chi\chi + G\chi$ for fixed (maximal) mixings and different heavy neutrino masses (notice that Yukawa couplings grow with the mass). UV divergences cancel in $G\chi\chi + G\chi$. The blue line ($r = 1$) shows the heavy Dirac case, whereas the red line ($r = 100$) corresponds to two Majoranas with $m_{N_2} = 10 m_{N_1}$. We have included the estimate of $|f^{\tau e}|$ in Eq. (15) for $r = 1$ (gray dots) as well as the contribution from a massive neutrino with an active left-handed component (red dashes).

Transition	η	$f_{A\eta}$	$g_{A\eta}$	$f_{B\eta}$	$g_{B\eta}$
$\Sigma^- \to \Sigma^+$	Λ	0	0.656	0	0.656
	Σ^0	$\sqrt{2}$	0.655	$\sqrt{2}$	-0.656
$\Sigma^- \to p$	n	-1	0.341	1	1.267
	Σ^0	$\sqrt{2}$	0.655	$-1/\sqrt{2}$	0.241
	Λ	0	0.656	$-\sqrt{3/2}$	-0.895
$\Xi^- \to \Sigma^+$	Ξ^0	-1	0.341	1	1.267
	Σ^0	$1/\sqrt{2}$	0.896	$\sqrt{2}$	-0.655
	Λ	$\sqrt{3/2}$	0.239	0	0.656
$\Xi^- \to p$	Σ^0	$1/\sqrt{2}$	0.896	$-1/\sqrt{2}$	0.241
	Λ	$\sqrt{3/2}$	0.239	$-\sqrt{3/2}$	-0.895

TABLE II. Vector and axial transition form factors for weak hyperon decays at zero momentum transfer. Here η stands for the intermediate baryon state, and the subscript A (B) represents the initial (final) baryon [46].

III. SHORT-RANGE CONTRIBUTIONS

If LNV is mediated by heavy particles, then an appropriate framework to deal with such effects corresponds to an effective field theory analysis [52–58]. In this regard, we will consider the most general six-fermion effective interaction describing ΔL=2 processes involving any leptonic and hadronic state with second and/or third generation of quarks [52–58], following the notation in [55] this can be written as follows

$$\mathcal{L}_{\text{eff}}^{\Delta \text{L}=2} = \frac{G_F^2}{\Lambda} \sum_{i,X,Y,Z} [C_i^{XYZ}]_{\alpha\beta} \mathcal{O}_i^{XYZ}, \tag{21}$$

where C_i are effective dimensionless couplings, and Λ is the heavy mass scale of New Physics. The dimension-9 operators are classified by

$$\begin{aligned} \mathcal{O}_1^{XYZ} &= 4[\bar{u}_i P_X d_k][\bar{u}_j P_Y d_n](j_Z), \\ \mathcal{O}_2^{XYZ} &= 4[\bar{u}_i \sigma^{\mu\nu} P_X d_k][\bar{u}_j \sigma_{\mu\nu} P_Y d_n](j_Z), \\ \mathcal{O}_3^{XYZ} &= 4[\bar{u}_i \gamma^{\mu} P_X d_k][\bar{u}_j \gamma_{\mu} P_Y d_n](j_Z), \\ \mathcal{O}_4^{XYZ} &= 4[\bar{u}_i \gamma^{\mu} P_X d_k][\bar{u}_j \sigma_{\mu\nu} P_Y d_n](j_Z)^{\nu}, \\ \mathcal{O}_5^{XYZ} &= 4[\bar{u}_i \gamma^{\mu} P_X d_k][\bar{u}_j P_Y d_n](j_Z)_{\mu}, \end{aligned} \tag{22}$$

and the leptonic currents are defined as

$$j_Z = \bar{\ell}_\alpha P_Z \ell_\beta^c, \quad j_Z^\nu = \bar{\ell}_\alpha \gamma^\nu P_Z \ell_\beta^c. \tag{23}$$

Four-body LNV hyperon decays

$$\mathcal{M}_1 = \left(\frac{G\,V_{\ell_1 N} V_{\ell_2 N} f_\pi m_N}{a_1 + i\Gamma_N m_N}\right) \ell_{\mu\nu}(p_1, p_2) \cdot H^\mu(p_B, p_A) \cdot p_\pi^\nu, \tag{2.2}$$

where $a_1 \equiv (p_A - p_B - p_1)^2 - m_N^2$, and $p_A - p_B - p_1 = p_\pi + p_2$ is the momentum carried out by the heavy neutrino N, and we have defined $G \equiv G_F^2 V_{us} V_{ud}$. The leptonic and hadronic parts are given by

$$\ell_{\mu\nu}(p_1, p_2) \equiv \bar{u}(p_1)\gamma_\mu\gamma_\nu(1+\gamma_5)v(p_2), \tag{2.3}$$

$$H^\mu(p_B, p_A) \equiv \langle B_B(p_B)|J_\mu|B_A(p_A)\rangle. \tag{2.4}$$

The hadronic current J_μ is parametrized in terms of six form factors which are determined from the well-known lepton number conserving hyperon decays $B_A \to B_B \ell^- \bar{\nu}_\ell$ ($\ell = e, \mu$) [21–23]:

$$\langle B_B(p_B)|J_\mu|B_A(p_A)\rangle = \bar{u}(p_B)\left[f_1(q^2)\gamma_\mu + if_2(q^2)\frac{\sigma_{\mu\nu}q^\nu}{M_A} + \frac{q_\mu f_3(q^2)}{M_A} + g_1(q^2)\gamma_\mu\gamma_5 + ig_2(q^2)\frac{\sigma_{\mu\nu}q^\nu\gamma_5}{M_A} + \frac{q_\mu g_3(q^2)\gamma_5}{M_A}\right]u(p_A), \tag{2.5}$$

One loop mechanism