EFFECTS OF HEAVY MAJORANA NEUTRINOS IN SEMILEPTONIC HEAVY QUARK DECAYS

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OUTLINE

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INTRODUCTION

¿ Dirac or Majorana ?

Dirac Neutrino $\rightarrow$ $\nu \neq \bar{\nu}$
Majorana Neutrino $\rightarrow$ $\nu = \bar{\nu}$

Dirac Neutrino $\rightarrow$ $L = L_e + L_\mu + L_\tau$
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- Nuclear $0\nu\beta\beta$ decay: $(A, Z) \to (A, Z+2) + e^- + e^-$

  The observation of this process will prove that $\not{L}$ and will establish the Majorana nature of the light neutrinos.

  Schechter-Valle Theorem

- $\tau^\mp \to \ell^\pm M_1^\mp M_2^\mp$
- $(K^\pm, D^\pm, D_s^\pm, B^\pm, B_c^\pm) \to \ell_1^\pm \ell_2^\pm M^\mp$
- $\Sigma^- \to \Sigma^+ e^- e^-$, $\Xi^- \to p\mu^-\mu^-$,
- $e^- \to \mu^+$, $\mu^- \to e^+$ y $\mu^- \to \mu^+$.
- $p\bar{p} \to \ell_1 \ell_2 X$

In this work, we will study alternative LNV processes in semileptonic decays of neutral B meson and top quark:

$$\bar{B}^0 \to D^+\ell^-\ell^-\pi^+, \quad t \to b\ell^+\ell^+W^-$$

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Heavy Neutrino Mixing

Standard Model $\Longrightarrow$ massless neutrinos

See-saw mechanism: $N_{kR} = (N_1, N_2, ..., N_n)_R$.

$N_R^c \equiv \mathcal{C}\bar{N}_R^T = N_R \longrightarrow$ **Majorana Neutrinos**

Yukawa Lagrangian:

$$-\mathcal{L}_Y = \bar{\mathsf{L}}_L Y_\ell H E_R + \bar{\mathsf{L}}_L Y_\nu \tilde{H} N_R + \text{h.c.}$$

$$-\mathcal{L}_M = \frac{1}{2}\bar{N}_R^c M_R N_R + \text{h.c.} \quad (\Delta L = 2).$$

Source of lepton number violation

$$-\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu^+ \sum_{\ell=e,\mu,\tau} \left[\sum_{j=1}^{3} U_{\ell j} (\bar{\ell}\gamma^\mu P_L \nu_j) + \sum_{k=1}^{n} V_{\ell k} (\bar{\ell}\gamma^\mu P_L N_k) \right] + h.c.,$$

- $P_L = (1-\gamma_5)/2$
- $U_{\ell j}$ = PMNS matrix
- $V_{\ell k}$ = mixing matrix of charged leptons with heavy neutrinos

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$\Delta L = 2$ PROCESSES AND THE RESONANT MECHANISM

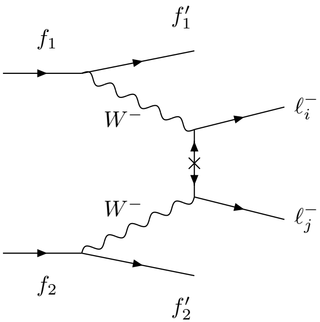
The Majorana nature of neutrinos can be experimentally verified via **LNV processes**

The leptonic $\Delta L = 2$ subprocess

$$\boxed{W^- W^- \to \ell_i^- \ell_j^-}$$

is induced via Majorana neutrino exchange.

***t*-channel**



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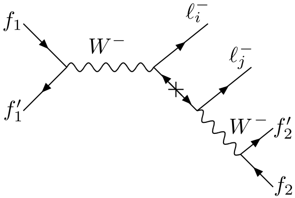

$\Delta L = 2$ PROCESSES AND THE RESONANT MECHANISM

The leptonic tensor current

$$L^{\mu\nu} = \frac{g^2}{2}\left\{ \sum_{j=1}^{3} U_{\ell_1 j} U_{\ell_2 j} m_{\nu_j} \bar{u}_{\ell_1} \left[\frac{\gamma^\mu \gamma^\nu}{q^2 - m_{\nu_j}^2 + i\Gamma_{\nu_j} m_{\nu_j}} + \frac{\gamma^\nu \gamma^\mu}{\tilde{q}^2 - m_{\nu_j}^2 + i\Gamma_{\nu_j} m_{\nu_j}} \right] P_R u_{\ell_2}^c \right.$$
$$\left. + \sum_{k=1}^{n} V_{\ell_1 k} V_{\ell_2 k} m_{N_k} \bar{u}_{\ell_1} \left[\frac{\gamma^\mu \gamma^\nu}{q^2 - m_{N_k}^2 + i\Gamma_{N_k} m_{N_k}} + \frac{\gamma^\nu \gamma^\mu}{\tilde{q}^2 - m_{N_k}^2 + i\Gamma_{N_k} m_{N_k}} \right] P_R u_{\ell_2}^c \right\}.$$

Atre, Han, Pascoli, & Zhang, **JHEP 0905, 030 (2009)**

- Light Majorana neutrinos ($q^2 \gg m_{\nu_j}^2$):

$$\boxed{\langle m_{\ell_1 \ell_2} \rangle \equiv \sum_{j=1}^{3} U_{\ell_1 j} U_{\ell_2 j}\, m_{\nu_j}}$$

Effective Majorana mass

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We will assume the dominance of only one heavy neutrino.

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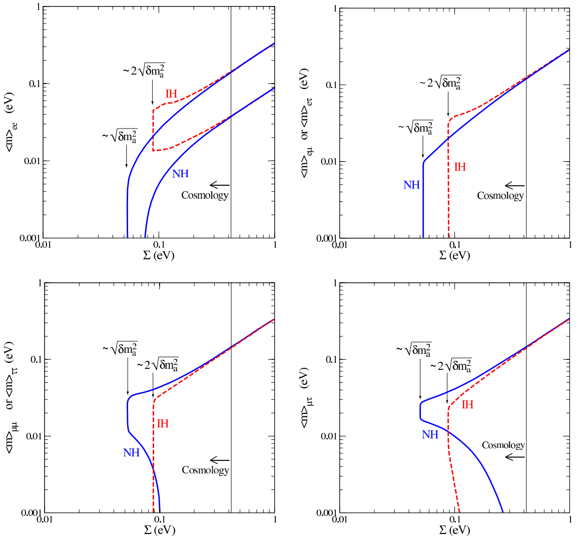
Indirect bounds on $\langle m_{\ell_1 \ell_2} \rangle$



Restrictive limits (indirect):

- Neutrino oscillations $(\Delta m^2_{ij}, \theta_{ij})$
- Cosmology $\Sigma \equiv m_1 + m_2 + m_3$

$$\langle m_{\ell_1 \ell_2} \rangle \lesssim 0{,}14 \text{ eV}$$

Atre, Barger & Han, Phys. Rev. D **71**, 113014 (2005)

Direct bounds on $\langle m_{\ell_1 \ell_2} \rangle$

Nuclei	$T^{0\nu}_{1/2}$	$\langle m_{\beta\beta} \rangle$ (eV)	
^{76}Ge	$\geq 1.9\times10^{25}$ y	$< 0{,}35$	**Heidelberg-Moscow**
^{130}Te	$\geq 3.0\times10^{24}$ y	$< (0{,}19 - 0{,}68)$	**CUORICINO**

W. Rodejohann, Int. J. Mod. Phys. E **20**, 1833 (2011)

Alternative $0\nu\beta\beta$ decays

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Experimental Limits

- $K^\pm \to \pi^\mp \mu^\pm \mu^\pm \quad \longrightarrow \quad \boxed{\langle m_{\mu\mu} \rangle < 4 \times 10^4 \text{ MeV}}$
  Zuber, Phys. Lett. B 479, 33 (2000)
- $\mu^- + (Z, A) \to e^+ + (A, Z-2) \quad \longrightarrow \quad \boxed{\langle m_{e\mu} \rangle < 17(82) \text{ MeV}}$
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$$\langle m_{\mu\mu} \rangle \lesssim 0.14 \text{ eV} \implies \boxed{\mathcal{B}_{th}(B^+ \to \pi^- \mu^+ \mu^+) \sim 10^{-26}}$$

$$\mathrm{B}_{exp}(B^+ \to \pi^- \mu^+ \mu^+) < 1.4 \times 10^{-6}$$

- Heavy Majorana neutrino N in the range of masses $\sim$ MeV up to 100 GeV
- Intermediate state at low energy LNV processes.

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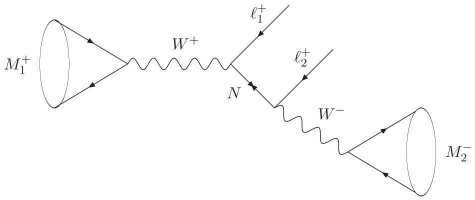
Resonant Mechanism in charged pseudoscalar mesons

$$\boxed{M_1^+ \to \ell_1^+ \ell_2^+ M_2^-} \quad (\ell, \ell_1, \ell_2 = e, \mu)$$



The dynamic of this process is given by:

$$\mathcal{M} \sim G_F^2 V_{\ell_1 N} V_{\ell_2 N} m_N \, V_{M_1}^{\rm CKM} V_{M_2}^{\rm CKM} f_{M_1} f_{M_2}$$

Table I. Experimental upper bounds (BABAR, Belle, CLEO, K experiments)

Decay mode	$\mathcal{B}_{exp}$
$K^+ \to \pi^- e^+ e^+$	$6{,}4 \times 10^{-10}$
$K^+ \to \pi^- \mu^+ \mu^+$	$3{,}0 \times 10^{-9}$
$K^+ \to \pi^- e^+ \mu^+$	$5{,}0 \times 10^{-10}$
$D^+ \to \pi^- e^+ e^+$	$9{,}6 \times 10^{-5}$
$D^+ \to \pi^- \mu^+ \mu^+$	$4{,}8 \times 10^{-6}$
$D^+ \to \pi^- e^+ \mu^+$	$5{,}0 \times 10^{-5}$
$D^+ \to K^- e^+ e^+$	$1{,}2 \times 10^{-4}$
$D^+ \to K^- \mu^+ \mu^+$	$1{,}3 \times 10^{-5}$
$D^+ \to K^- e^+ \mu^+$	$1{,}3 \times 10^{-4}$
$B^+ \to \pi^- e^+ e^+$	$1{,}6 \times 10^{-6}$
$B^+ \to \pi^- \mu^+ \mu^+$	$1{,}4 \times 10^{-6}$
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$B^+ \to K^- e^+ e^+$	$1{,}0 \times 10^{-6}$
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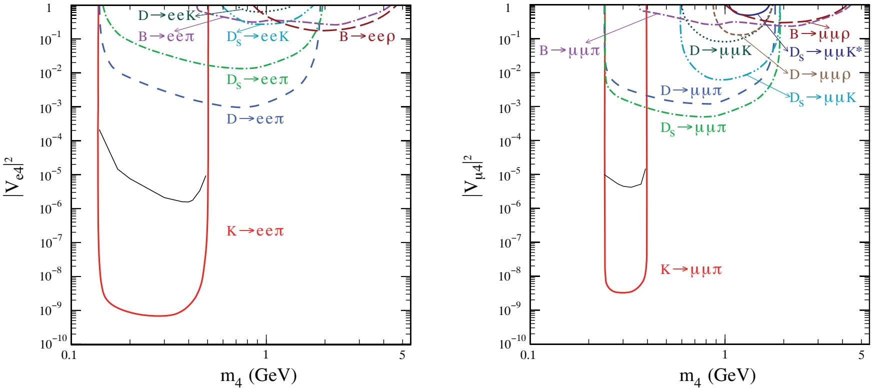
$B^+ \to K^- e^+ \mu^+$	$2{,}0 \times 10^{-6}$

Resonant Mechanism in charged pseudoscalar mesons

Atre, Han, Pascoli, & Zhang, JHEP **0905**, 030 (2009)



Recently, LHCb (**arXiv:1110.0730**):

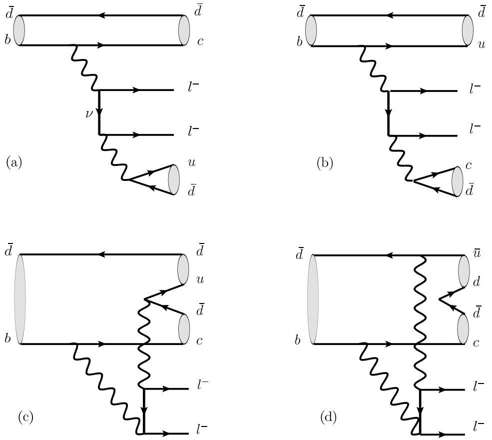
$\mathcal{B}(B^+ \to K^- \mu^+ \mu^+) < 5.4 \times 10^{-8}$, $\mathcal{B}(B^+ \to \pi^- \mu^+ \mu^+) < 5.8 \times 10^{-8}$. (95 % C.L.)

OUTLINE

1. INTRODUCTION
2. $\Delta L = 2$ PROCESSES AND THE RESONANT MECHANISM
   - Heavy Neutrino Mixing
   - General amplitude
   - Resonant Mechanism in charged pseudoscalar mesons
3. SEMILEPTONIC FOUR-BODY DECAYS
   - LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS
   - LNV $t \to b\ell^+\ell^+W^-$ DECAYS
4. CONCLUSIONS

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

LNV Decay: $\bar{B}^0(p) \to D^+(p_1)\ell^-(p_2)\ell^-(p_3)\pi^+(p_4)$



Feynman diagrams for the LNV four-body decay of neutral B meson.

Diagram (b) is suppressed with respect to diagram (a)

$$\frac{|V_{ub}V_{cd}|}{|V_{cb}V_{ud}|} \sim 0{,}02$$

In the range of neutrino masses m_N where the resonance effects dominate the decay amplitude, the diagrams (c) and (d) will give very small contributions.

Ivanov & Kovalenko, Phys. Rev. D **71**, 053004 (2005).

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

The decay amplitude

$$\mathcal{M} = G_F^2 V_{cb}^* V_{ud} |V_{\ell N}|^2 \, m_N H_\mu^1 \mathcal{L}^{\mu\nu} H_\nu^2$$

$$\mathcal{L}^{\mu\nu} = \bar{u}_\ell(p_2)\left(\frac{\gamma^\mu\gamma^\nu}{a_1 + ib} + \frac{\gamma^\nu\gamma^\mu}{a_2 + ib}\right) P_R u_\ell^c(p_3)$$

$$a_1 \equiv q^2 - m_N^2,\ a_2 \equiv \tilde{q}^2 - m_N^2,\ b \equiv \Gamma_N m_N$$

Hadronic current H_μ^1

$$\begin{aligned} H_\mu^1 &= \langle D(p_1)|\bar{c}\gamma_\mu b|B(p)\rangle \\ &= \left[(p+p_1)_\mu - \frac{(m_B^2 - m_D^2)}{Q^2} Q_\mu\right] F_1(Q^2) + \left[\frac{(m_B^2 - m_D^2)}{Q^2}\right] Q_\mu \, F_0(Q^2). \end{aligned}$$

Hadronic current H_ν^2

$$H_\nu^2 = \langle \pi(p_4)|\bar{d}\gamma_\nu\gamma_5 u|0\rangle = i f_\pi (p_4)_\nu. \quad f_\pi = 130{,}4 \text{ MeV}$$

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

The decay amplitude

$$\mathcal{M} = G_F^2 V_{cb}^* V_{ud} |V_{\ell N}|^2 \, m_N H_\mu^1 \mathcal{L}^{\mu\nu} H_\nu^2$$

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$$\begin{aligned} H_\mu^1 &= \langle D(p_1)|\bar{c}\gamma_\mu b|B(p)\rangle \\ &= \left[(p+p_1)_\mu - \frac{(m_B^2 - m_D^2)}{Q^2}Q_\mu\right]F_1(Q^2) + \left[\frac{(m_B^2 - m_D^2)}{Q^2}\right]Q_\mu \, F_0(Q^2). \end{aligned}$$

Hadronic current H_ν^2

$$H_\nu^2 = \langle \pi(p_4)|\bar{d}\gamma_\nu\gamma_5 u|0\rangle = i f_\pi (p_4)_\nu. \quad f_\pi = 130{,}4 \text{ MeV}$$

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

Resonant Region: $(m_\pi + m_\ell) \leq m_N \leq (m_B - m_D - m_\ell)$.

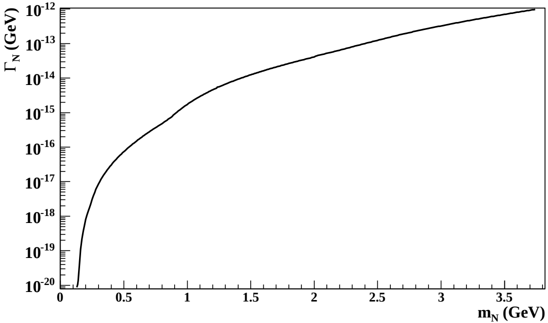


Fig. 1 Decay width of heavy neutrino for $m_N \ll m_W$.

Dominant modes ($m_N \ll m_W$):

$$N \to \quad \ell^\mp P^\pm,\ \nu_\ell P^0,\quad \ell^\mp V^\pm,\ \nu_\ell V^0,\quad \ell_1^\mp \ell_2^\pm \nu_{\ell_2},\ \nu_{\ell_1}\ell_2^-\ell_2^+,\quad \nu_{\ell_1}\nu\bar{\nu}$$

$$\Gamma_N \sim G_F^2\ |V_{\ell N}|^2$$

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

Narrow width approximation (NWA)

$$\int \frac{G(s_{34})\ ds_{34}}{(s_{34}-m_N^2)^2+\Gamma_N^2 m_N^2}\Bigg|_{\Gamma_N\to 0} = \frac{\pi}{\Gamma_N m_N}\int G(s_{34})\ \delta(s_{34}-m_N^2)\ ds_{34},$$
$$= \frac{G(m_N^2)\pi}{\Gamma_N m_N}.$$

Atre, Han, Pascoli, & Zhang, **JHEP 0905, 030 (2009)**

The decay width

$$\Gamma_B^{D\ell\ell\pi} \equiv \Gamma(\bar{B}^0 \to D^+\ell^-\ell^-\pi^+),$$
$$= \frac{1}{8(4\pi)^6 m_B^3}\left[\int f_1^B d\Phi_1 + \int f_2^B d\Phi_2\right].$$

$$\boxed{\mathcal{B}_B^{D\ell\ell\pi} = \tau_{B^0}\Gamma_B^{D\ell\ell\pi}}$$

Kinematic variables
$\{s_{12}, s_{34}, \theta_1, \theta_3, \phi\}$

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

Heavy neutrino mixing : $|V_{eN}|^2 < 3 \times 10^{-3}, \quad |V_{\mu N}|^2 < 3 \times 10^{-3}, \quad |V_{\tau N}|^2 < 6 \times 10^{-3}$

del Aguila, de Blas, & Perez-Victoria, Phys. Rev. D **78**, 013010 (2008).

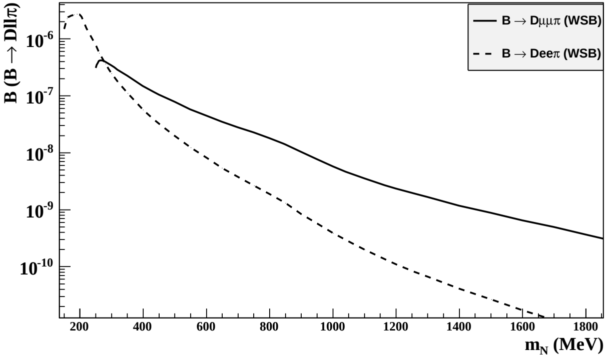


Fig. II. Branching ratios as function of m_N. The WSB model is used to evaluate the form factors of $B \to D$. [Wirbel, Stech, & Bauer, Z. Phys. C **29**, 637 (1985)]

LNV $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ DECAYS

Tabla II. Branching ratios for $\bar{B}^0 \to D^+\ell^-\ell^-\pi^+$ decays.

(WSB Model) Wirbel, Stech, & Bauer, Z. Phys. C **29**, 637 (1985)
(CLF Model) Cheng, Chua, & Hwang, Phys. Rev. D **69**, 074025 (2004)

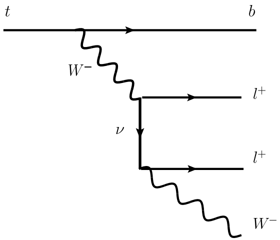
	e^-e^-			$\mu^-\mu^-$	
m_N (MeV)	WSB	CLF	m_N (MeV)	WSB	CLF
170	2.6×10^{-6}	3.4×10^{-6}	250	3.0×10^{-7}	3.9×10^{-7}
190	2.8×10^{-6}	3.6×10^{-6}	270	4.1×10^{-7}	5.4×10^{-7}
200	2.6×10^{-6}	3.4×10^{-6}	300	3.4×10^{-7}	4.3×10^{-7}
220	1.5×10^{-6}	2.0×10^{-6}	400	1.4×10^{-7}	1.9×10^{-7}
250	7.3×10^{-7}	9.7×10^{-7}	500	7.0×10^{-8}	1.0×10^{-7}
300	2.5×10^{-7}	3.3×10^{-7}	600	4.0×10^{-8}	6.0×10^{-8}

Delepine, López Castro, & Quintero, **arXiv:1108.6009**

LNV $t \to b\ell^+\ell^+W^-$ DECAYS

LNV Decay:

$$t(p) \to b(p_1)\ell^+(p_2)\ell^+(p_3)W^-(p_4)$$



Bar-Shalom *et al*, Phys. Lett. B **643**, 342 (2006)

Tabla VI. Branching ratios (units of 10^{-6}) for $t \to b\ell^+\ell^+W^-$ decays.

m_N (GeV)	ee	$\mu\mu$	$\tau\tau$
90	0.29	0.29	1.12
100	0.12	0.12	0.47
110	0.05	0.05	0.19

Delepine, López Castro, & Quintero, **arXiv:1108.6009**

OUTLINE

1. INTRODUCTION
2. $\Delta L = 2$ PROCESSES AND THE RESONANT MECHANISM
   - Heavy Neutrino Mixing
   - General amplitude
   - Resonant Mechanism in charged pseudoscalar mesons
3. SEMILEPTONIC FOUR-BODY DECAYS
   - LNV $\bar{B}^0 \to D^+ \ell^- \ell^- \pi^+$ DECAYS
   - LNV $t \to b \ell^+ \ell^+ W^-$ DECAYS
4. CONCLUSIONS

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In this work we have studied the effects of heavy Majorana neutrinos in semileptonic decays of neutral B meson:

$$\boxed{\bar{B}^0 \to D^+ \ell^- \ell^- \pi^+} \quad \boxed{t \to b \ell^+ \ell^+ W^-}$$

- Assumed the dominance of only one heavy neutrino N that falls in the resonant region.

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- Experimental sensitivity
  - BABAR $\sim 450 \times 10^6$ $B\bar{B}$
  - $\bar{B}^0 \to D^+ \ell^- \ell^- \pi^+ (D^+ \to K^- \pi^+ \pi^+)$
  - 70 % efficiency for the identification and reconstruction of each of the six charged tracks

$$\mathcal{B}(\bar{B}^0 \to D^+ \ell^- \ell^- \pi^+) \sim 2.0 \times 10^{-7}.$$

  - LHCb, Super-KEKB, Super-B factories

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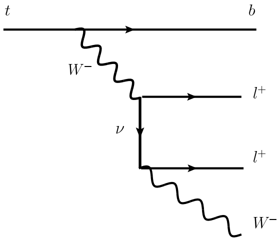
THANK YOU !!

LNV $t \to b\ell^+\ell^+W^-$ DECAYS

LNV Decay:

$t(p) \to b(p_1)\ell^+(p_2)\ell^+(p_3)W^-(p_4)$



The decay amplitude

$$\mathcal{M} = \frac{G_F m_W^2}{\sqrt{2}}\left(\frac{g}{\sqrt{2}}\right) V_{tb}|V_{\ell N}|^2\, m_N H_\mu^{t\to b}\mathcal{L}^{\mu\nu}\varepsilon_\nu^*$$

Weak transition $t \to b$

$$H_\mu^{t\to b} = \bar{u}_t(p_1)\gamma^\sigma(1-\gamma_5)u_b(p)\Pi_{\sigma\mu}^W.$$

The W boson propagator

$$\Pi_{\sigma\mu}^W = \left[-g_{\sigma\mu} + \frac{Q_\sigma Q_\mu}{m_W^2}\right]\frac{i}{(Q^2 - m_W^2) + i\Gamma_W m_W}.$$

$$\mathcal{M} = i\Big(\frac{G_F m_W^2 g}{2}\Big)V_{tb}|V_{\ell N}|^2 m_N\ \bar{u}_\ell(p_2)\Big(\frac{\not{H}\not{\epsilon}^*}{a_1 + ib} + \frac{\not{\epsilon}^*\not{H}}{a_2 + ib}\Big)P_R u_\ell^c(p_3).$$

LNV $t \to b\ell^+\ell^+W^-$ DECAYS

The decay width

$$\Gamma_t^{b\ell\ell W} \equiv \Gamma(t \to b\ell^+\ell^+W^-),$$
$$= \frac{1}{8(4\pi)^6 m_t^3}\left[\int f_1^t d\Phi_1 + \int f_2^t d\Phi_2\right].$$

$$\boxed{\mathcal{B}_t^{b\ell\ell W} = \Gamma_t^{b\ell\ell W}/\Gamma_t}$$

Phase space factors

$$d\Phi_1 = X\beta_{12}\beta_{34}\ ds_{34}ds_{12}d\cos\theta_1 d\cos\theta_3 d\phi,$$
$$d\Phi_2 = d\Phi_1(p_2 \leftrightarrow p_3).$$

Kinematicall variables
$\{s_{12}, s_{34}, \theta_1, \theta_3, \phi\}$

Kinematicall region: $m_N > m_W$

$\Gamma_N \sim (10^{-2} - 10)$ GeV

LNV $t \to b\ell^+\ell^+W^-$ DECAYS

Resonant Region: $(m_W + m_\ell) \leq m_N \leq (m_t - m_b - m_\ell)$

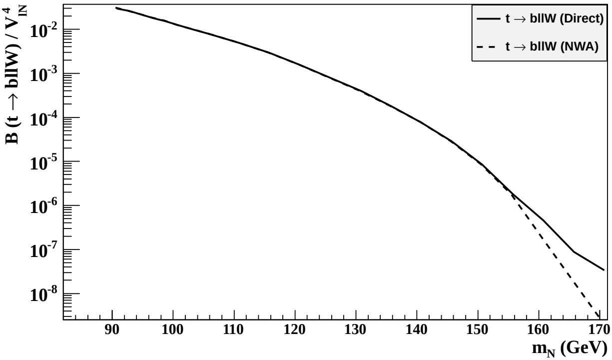


Fig. III Normalized branching ratio of $t \to b\ell^+\ell^+W^-$ decays as a function of m_N.

LNV $t \to b\ell^+\ell^+W^-$ DECAYS

Tabla VI. Branching ratios (units of 10^{-6}) for $t \to b\ell^+\ell^+W^-$ decays.

	Set I		
m_N (GeV)	ee	$\mu\mu$	$\tau\tau$
90	0.29	0.29	1.12
100	0.12	0.12	0.47
110	0.05	0.05	0.19
	Set II		
m_N (GeV)	ee	$\mu\mu$	$\tau\tau$
90	1.48 (1.4)	0.95 (1.1)	2.55 (1.9)
100	0.6 (0.6)	0.4 (0.5)	1.08 (0.8)

Bar-Shalom *et al*, Phys. Lett. B **643**, 342 (2006)
Delepine, López Castro, & Quintero, **arXiv:1108.6009**