Low-energy lepton number violating processes: GeV-scale Majorana neutrinos and short-range mechanisms

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28 November to 2 December
2016

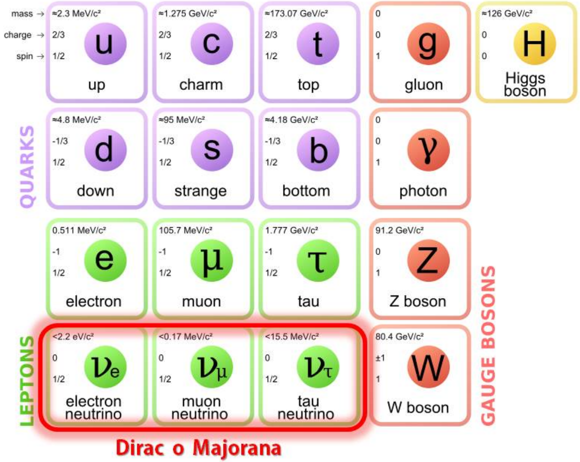
TALK BASED ON:

- D. Milanés, N. Quintero, and C. E. Vera, *Sensitivity to Majorana neutrinos in $\Delta L = 2$ decays of B_c meson at LHCb*, Phys. Rev. D **93**, 094026 (2016) [arXiv:1604.03177].
- N. Quintero, *Constraints on lepton number violating short-range interactions from $|\Delta L| = 2$ processes*, Phys. Lett. B **764** (2017) 60-65 [arXiv:1606.03477].

OUTLINE

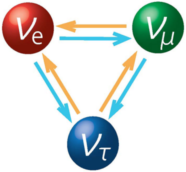
Standard Model of Elementary Particles

[Erler, Moreno & Avila talk's (1st ComHEP)]



Neutrino oscillations → massive neutrinos

[Kajita & McDonald - Nobel 2015]



Neutrino oscillations have been firmly established by several experiments: Solar, Atmospheric, Reactors and Accelerators

- Neutrinos are massive particles
- Neutrinos are mixed

$$\nu_\ell(x) = \sum_{j=1,2,3} U^{\rm PMNS}_{\ell j} \nu_j(x) \quad (\ell = e, \mu, \tau)$$

Oscillation parameters: $(\delta m^2, |\Delta m^2|, \sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}, \delta)$

[Arrieta, de Gouvêa, & Oyama talk's (1st ComHEP)]

Why Study Lepton Number Violating (LNV) Processes ?

- Establish nature of the neutrinos

¿ **Dirac** $(\nu \neq \nu^c)$ o **Majorana** $(\nu = \nu^c)$?

$$-\mathcal{L}_Y = \underbrace{\bar{\mathsf{L}}_L Y_\nu \tilde{H} N_R}_{\textbf{Dirac Term}} + \underbrace{\bar{N}_R^c M_R N_R/2}_{\textbf{Majorana Term}} + h.c.$$

- Mechanism of neutrino masses generation
- Leptogenesis (Explain baryonic asymmetry of the Universe)

Fukugita & Yanagida, PLB **174**, 45 (1986)

Davidson, Nardi, & Nir, Phys. Rept. **466**, 105 (2008)

It is important to study all possible channels that may be sensitive to the effects of **LNV $(\Delta L = 2)$ Processes**

Seesaw Tipe-I

Seesaw formula

$$m_\nu \sim 10^{-1}\ \mathrm{eV} \left(\frac{v}{246\ \mathrm{GeV}}\right)^2 \left(\frac{Y_\nu}{\mathcal{O}(1)}\right)^2 \left(\frac{10^{14}\ \mathrm{GeV}}{M_R}\right)$$

Natural explanation to the small neutrino masses

[Minkowski, PLB 67 (1977); Yanagida (1979); Gell-Mann, Ramond & Slansky (1979); Mohapatra & Senjanovic, PRL 44, 912 (1980)]

- $M_R \gg v$ $\rightarrow$Such a large mass scales can not be tested experimentally !
- Seesaw formula **do not set** Y_ν or M_R
- $10^{-12} \lesssim Y_\nu \lesssim \mathcal{O}(1)$

  $1\ \mathrm{eV} \lesssim M_R \lesssim 10^{14}\ \mathrm{GeV}$ “Seesaw scale” (Experimentally accessible)

[de Gouvêa, arXiv:0706.1732; Drewes, arXiv:1303.6912]

Ranges of sterile neutrino mass

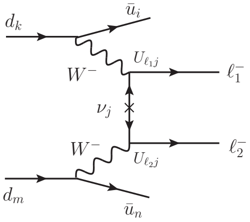
	N mass	ν masses	eV ν anoma–lies	BAU	DM	M_H stability	direct search	experi–ment
GUT see–saw	10^{10-16} GeV	YES	NO	YES	NO	NO	NO	–
EWSB	10^{2-3} GeV	YES	NO	YES	NO	YES	YES	LHC
ν MSM	keV – GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
ν scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

[Drewes, arXiv:1303.6912]

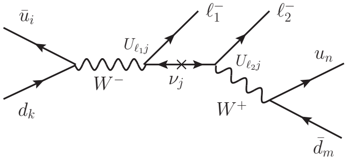
Different mass scales are technically possible and worth exploring !

[de Gouvêa, arXiv:0706.1732]

$\Delta L = 2$ processes



$(a)\ canal - t$



$(b)\ canal - s$

- Light Majorana neutrinos

$$\langle m_\nu \rangle_{\ell_1 \ell_2} = \sum_j U_{\ell_1 j} U_{\ell_2 j}\, m_{\nu_j}$$

- Heavy Majorana neutrinos

$$\langle m_N^{-1} \rangle_{\ell_1 \ell_2} = \sum_k V_{\ell_1 k} V_{\ell_2 k} / m_{N_k}$$

- **Intermediate Majorana neutrinos (on-shell)**

$$\sim \sum_k V_{\ell_1 k} V_{\ell_2 k}\, m_{N_k} / \Gamma_{N_k}$$

Searches of $\Delta L = 2$ processes

- Neutrinoless double-β ($0\nu\beta\beta$): ${}^{A}_{Z}X \rightarrow {}_{Z+2}^{\ \ A}Y + 2e^-$

Isotope	Experiments	$T^{0\nu}_{1/2} >$ [years]	$\langle m_{\beta\beta} \rangle <$ [eV]
$^{76}\mathrm{Ge}$	Heidelberg-Moscow (HdM)	1.9×10^{25}	0.32
	IGEX	1.57×10^{25}	(0.25 - 0.63)
	GERDA	2.1×10^{25}	
	GERDA + HdM + IGEX	3.0×10^{25}	(0.2 - 0.4)
$^{136}\mathrm{Xe}$	EXO-200	1.6×10^{25}	(0.14 - 0.38)
	KamLAND-Zen (KLZ)	1.9×10^{25}	
	KLZ + EXO-200	3.4×10^{25}	(0.12 - 0.25)

- Nuclear conversion processes: $e^- \rightarrow \mu^+$, $\mu^- \rightarrow e^+$ and $\mu^- \rightarrow \mu^+$

Geib, Merle & Zuber, PLB 764, 157 (2017)

Berryman, de Gouvêa, Kelly & Kobach, arXiv:1611.00032 [hep-ph]

Simkovic, Faessler, Kovalenko, & Schmidt, PRD **66**, 033005 (2002)

Búsqueda de Procesos $\Delta L = 2$

- Hyperons decays: $\Sigma^- \to \Sigma^+ e^- e^-$, $\Xi^- \to p\mu^-\mu^-(e^-\mu^-)$

Littenberg & Shrock, Phys. Rev. D **46**, R892 (1992)

Barbero, López Castro, & Mariano, Phys. Lett. B **566**, 98 (2003)

- LHC: di-lepton signals $pp \to \ell_1^\pm \ell_2^\pm X$

Cannoni *et al*, Phys. Rev. D **65**, 035005 (2002)

Han & Zhang, Phys. Rev. Lett. **97**, 171804 (2006)

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

del Aguila & Aguilar-Saavedra, Nucl. Phys. **B813**, 22 (2009)

- LNV 3-body decays: $\tau^- \to \ell^+ M_1^- M_2^-$ and $(K^-, D_{(s)}^-, B^-) \to M^+ \ell_1^- \ell_2^-$

Atre, Han, Pascoli, & Zhang, JHEP **05**, 030 (2009)

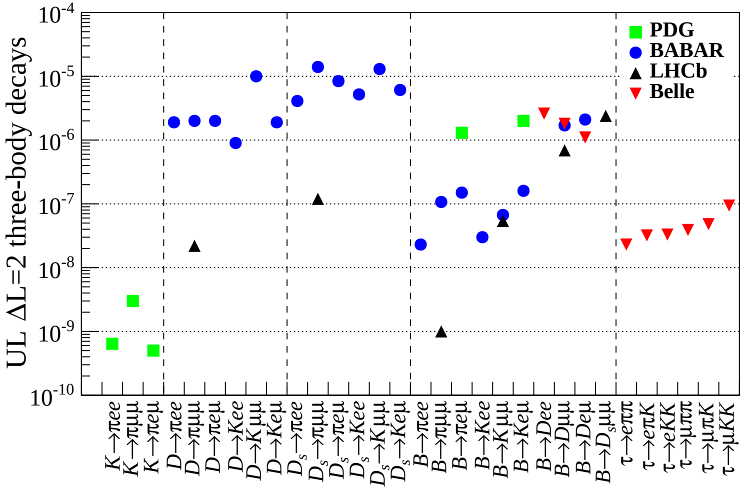
Cvetic, *et al*, PRD **82**, 053010 (2010)

Helo, Kovalenko, & Schmidt, NP**B853**, 80 (2011)

Zhang & Wang, EPJC **71**, 1715 (2011)

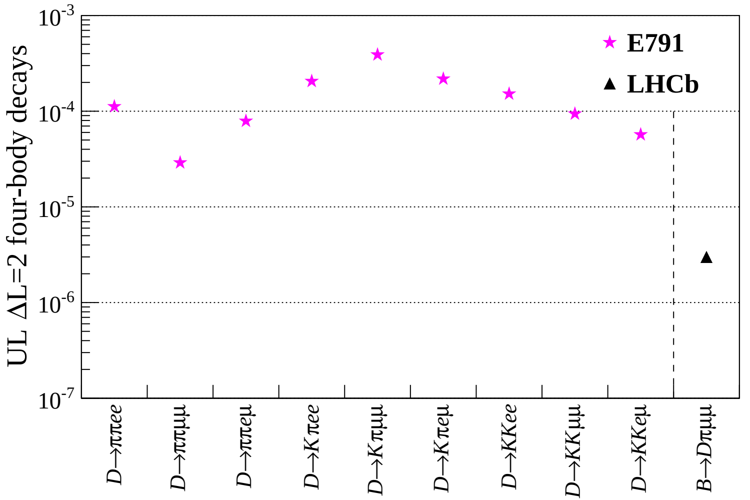
Gribanov, Kovalenko & Schmidt, NP**B607**, 355 (2001).

Experimental Limits on $\Delta L = 2$ 3-body decays



BABAR: PRD **84**, 072006 (2011), PRD **85**, 071103(R) (2012)
LHCb: PRL **108**, 101601 (2012), PRD **85**, 112004 (2012), PLB **719**, 346 (2013)
Belle: PLB **719**, 346 (2013), PRD **84**, 071106(R) (2011)

Límites Experimental Limits on $\Delta L = 2$ 4-body decays

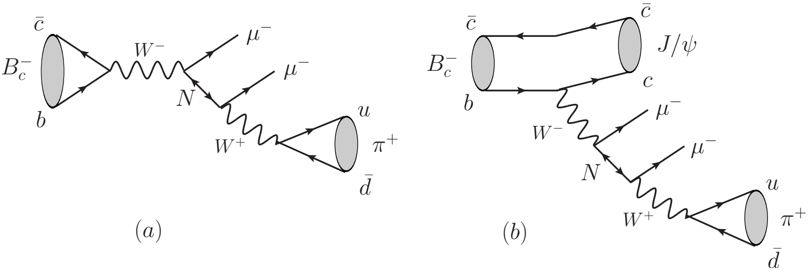


LHCb: PRD **85**, 112004 (2012), E791: PRL **86**, 3696 (2001)

GeV-scale Majorana neutrinos in B_c decays

Milanés, Quintero & Vera, Phys. Rev. D **93**, 094026 (2016)

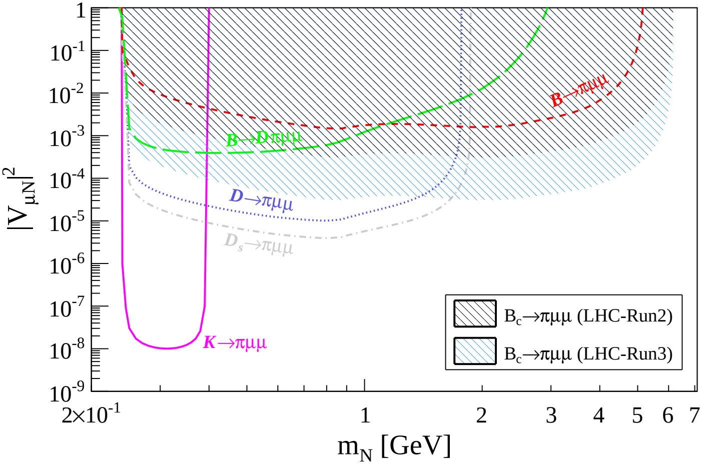
$\Delta L = 2$ decays of B_c meson



- Not very much suppressed by CKM factors
- Can be explored at the LHCb in the same-sign di-muon channel (relatively high muon reconstruction system).

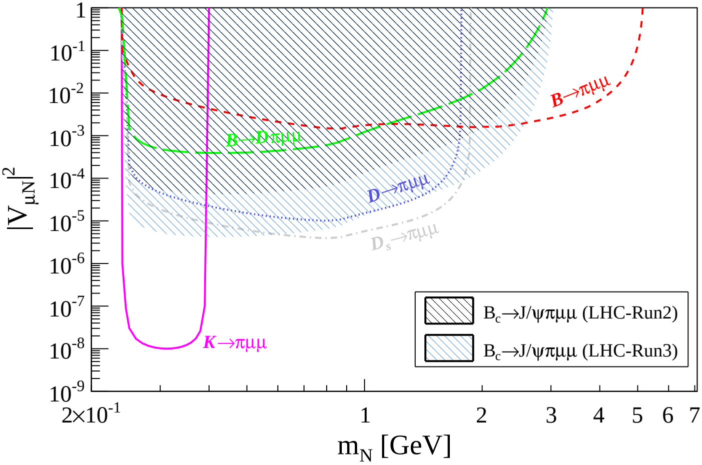
$B_c^- \to \pi^+ \mu^- \mu^-$

Constraints on $(m_N, |V_{\mu N}|^2)$



$B_c^- \to J/\psi \pi^+ \mu^- \mu^-$

Constraints on $(m_N, |V_{\mu N}|^2)$



Short-range mechanisms

Quintero, Phys. Lett. B **764** (2017) 60–65

Short-range mechanisms

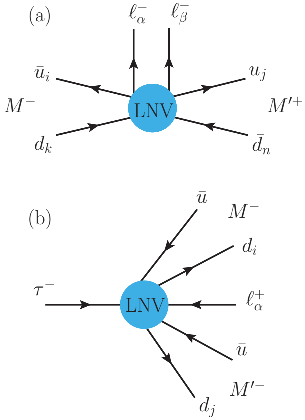
The short-range mechanisms refer to the effective interactions covering all processes mediated by heavy particles, in which no light neutrinos are exchanged.

$$\mathcal{L}_{\rm eff}^{\Delta L=2} = \frac{G_F^2}{2\Lambda} \sum_{i,XY} [C_i^{XY}]_{\alpha\beta} \mathcal{O}_i^{XY}$$

$[C_i^{XY}]_{\alpha\beta} \to$ LNV couplings

$\mathcal{O}_i^{XY} \to$ LNV operators (dimension-9)

$\Lambda \to$ mass scale dominant to the process



Päs, Hirsch, Klapdor-Kleingrothaus, & Kovalenko, PLB **498**, 35 (2001)
González, Kovalenko, & Hirsch, PRD **93**, 013017 (2016)
Bonnet, Hirsch, Ota, & Winter, JHEP **03** (2013) 055

Constraints on short-range couplings $|C_i|_{ee}$

Channel	Exp. UL	$\lvert C_1\rvert_{ee}$	$\lvert C_3\rvert_{ee}$	$\lvert C_5\rvert_{ee}$
$K^- \to \pi^+ e^- e^-$	6.4×10^{-10}	3.3×10^1	2.3×10^3	2.9×10^3
$D^- \to \pi^+ e^- e^-$	1.9×10^{-6}	4.3×10^4	3.2×10^5	1.2×10^5
$D^- \to K^+ e^- e^-$	0.9×10^{-6}	1.8×10^5	8.9×10^5	3.8×10^5
$D_s^- \to \pi^+ e^- e^-$	4.1×10^{-6}	1.7×10^4	1.2×10^5	4.5×10^4
$D_s^- \to K^+ e^- e^-$	5.2×10^{-6}	1.1×10^5	5.3×10^5	2.3×10^5
$B^- \to \pi^+ e^- e^-$	2.3×10^{-8}	6.0×10^4	1.4×10^5	6.2×10^4
$B^- \to K^+ e^- e^-$	3.0×10^{-8}	3.0×10^5	6.0×10^5	2.6×10^5
$B^- \to D^+ e^- e^-$	2.6×10^{-6}	3.6×10^6	5.2×10^6	2.8×10^6

In the case of the ee couplings, the experimental limits on $0\nu\beta\beta$ searches in $^{76}\mathrm{Ge}$ and $^{136}\mathrm{Xe}$ provide stronger bounds, typically of the order

$$(|C_1|_{ee}, |C_3|_{ee}, |C_5|_{ee}) \sim (10^{-7}, 10^{-8}, 10^{-7})$$

Constraints on short-range couplings $|C_i|_{\mu\mu,e\mu}$

Channel	Exp. UL	$\lvert C_1\rvert_{\mu\mu}$	$\lvert C_3\rvert_{\mu\mu}$	$\lvert C_5\rvert_{\mu\mu}$
$K^- \to \pi^+\mu^-\mu^-$	8.6×10^{-11}	3.4×10^{0}	2.7×10^{2}	2.5×10^{2}
$D^- \to \pi^+\mu^-\mu^-$	2.2×10^{-8}	4.7×10^{3}	3.5×10^{4}	1.3×10^{4}
$D^- \to K^+\mu^-\mu^-$	1.0×10^{-5}	6.0×10^{5}	3.1×10^{6}	1.3×10^{6}
$D_s^- \to \pi^+\mu^-\mu^-$	1.2×10^{-7}	2.9×10^{3}	2.0×10^{4}	7.7×10^{3}
$D_s^- \to K^+\mu^-\mu^-$	1.3×10^{-5}	1.7×10^{5}	8.6×10^{5}	3.6×10^{5}
$B^- \to \pi^+\mu^-\mu^-$	1.3×10^{-8}	4.5×10^{4}	1.1×10^{5}	4.8×10^{4}
$B^- \to K^+\mu^-\mu^-$	5.4×10^{-8}	4.0×10^{5}	8.0×10^{5}	3.6×10^{5}

Channel	Exp. UL	$\lvert C_1\rvert_{e\mu}$	$\lvert C_3\rvert_{e\mu}$	$\lvert C_5\rvert_{e\mu}$
$K^- \to \pi^+e^-\mu^-$	5.5×10^{-10}	2.8×10^{1}	2.0×10^{4}	2.1×10^{3}
$D^- \to \pi^+e^-\mu^-$	2.0×10^{-6}	3.2×10^{4}	2.3×10^{5}	8.8×10^{4}
$D^- \to K^+e^-\mu^-$	1.9×10^{-6}	1.8×10^{5}	9.3×10^{5}	3.9×10^{5}
$D_s^- \to \pi^+e^-\mu^-$	8.4×10^{-6}	1.7×10^{4}	1.2×10^{5}	4.6×10^{4}
$D_s^- \to K^+e^-\mu^-$	6.1×10^{-6}	8.5×10^{4}	4.1×10^{5}	1.7×10^{5}
$B^- \to \pi^+e^-\mu^-$	1.3×10^{-6}	3.2×10^{5}	7.6×10^{5}	3.3×10^{5}

$|C_i|_{\mu\mu,e\mu} \sim \mathcal{O}(1-10^1) \to$ too weak compared with those get from $0\nu\beta\beta$ decay

Constraints on short-range couplings $|C_i|_{e\tau,\mu\tau}$

Channel	Exp. UL	$\|C_1\|_{e\tau}$	$\|C_3\|_{e\tau}$	$\|C_5\|_{e\tau}$
$\tau^- \to e^+\pi^-\pi^-$	2.0×10^{-8}	3.4×10^3	5.0×10^4	8.8×10^3
$\tau^- \to e^+\pi^-K^-$	3.2×10^{-8}	1.6×10^4	2.0×10^5	3.3×10^4
$\tau^- \to e^+K^-K^-$	3.3×10^{-8}	1.4×10^5	1.5×10^6	3.6×10^5
Channel	Exp. UL	$\|C_1\|_{\mu\tau}$	$\|C_3\|_{\mu\tau}$	$\|C_5\|_{\mu\tau}$
$\tau^- \to \mu^+\pi^-\pi^-$	3.9×10^{-8}	4.6×10^3	6.8×10^4	1.2×10^4
$\tau^- \to \mu^+\pi^-K^-$	4.8×10^{-8}	2.0×10^4	2.5×10^5	4.1×10^4
$\tau^- \to \mu^+K^-K^-$	4.7×10^{-8}	1.7×10^5	1.8×10^6	4.5×10^5

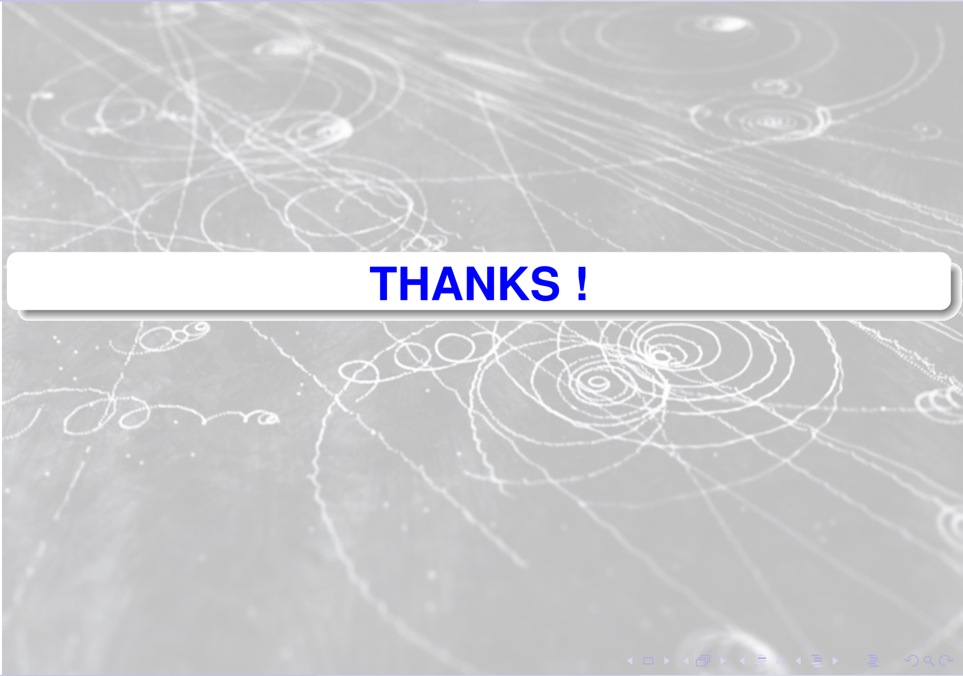
$|C_i|_{e\tau,\mu\tau} \sim \mathcal{O}(10^3) \to$ too weak compared with those get from $0\nu\beta\beta$ decay

Concluding remarks

- **¿ Dirac o Majorana ?** $\to$ Observation of $\Delta L = 2$ decays will establish the Majorana nature of neutrinos.
- GeV-scale Majorana neutrinos in $\Delta L = 2$ decays of B_c meson

$$B_c^- \to \pi^+ \mu^- \mu^-,$$
$$B_c^- \to J/\psi \pi^+ \mu^- \mu^-,$$

  Can be searched at LHCb (Run-2 and Run-3).
- Complementary and strong constraints on parameters (m_N,$|V_{\mu N}|^2$)
- Constraints on short-range couplings $|C_i|_{\mu\mu,e\mu} \sim \mathcal{O}(1-10^1)$, not accesible to $0\nu\beta\beta$.



THANKS !

BACK UP

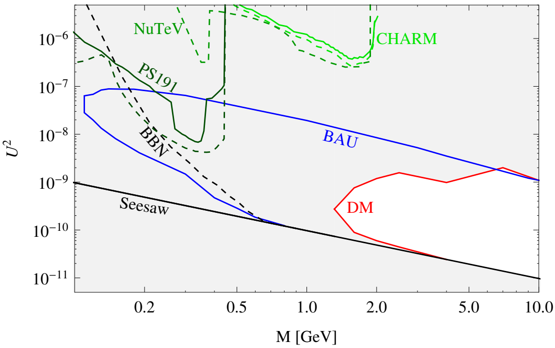
Intermediate massive neutrinos

Neutrino Minimal Standard Model (νMSM): ME + $(N_1, N_2, N_3)_R$ (estériles)

$$\nu_\ell = \sum_{j=1}^{3} V_{\ell j}^{\text{PMNS}} \nu_j + \sum_{k=1}^{3} U_{\ell k} N_k$$

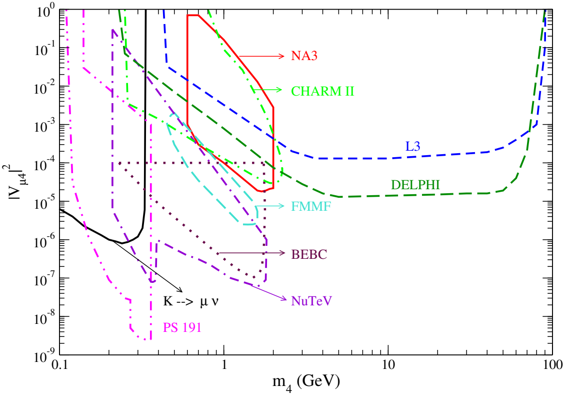
$M_{N_1} \sim$ (10 - 100) keV (Dark matter)

$M_{N_{2,3}} \sim \mathcal{O}$(1 GeV) (BAU)



Canetti, Drewes, & Shaposhnikov PRL **110**, 061801 (2013) Canetti, Drewes, Frossard, & Shaposhnikov PRD **87**, 093006 (2013) Asaka, Blanchet, & Shaposhnikov PLB **631**, 151 (2005)

Searches of Heavy Sterile Neutrino



- Peak searches: $K \to \mu N$
- Beam Dump Experiments PS191, BEBC, CHARM, NuTeV
- L3, DELPHI