Looking for lepton-number-violating processes in $|\Delta L| = 2$ decays of B_s meson and Λ_b baryon

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3rd Colombian Meeting on High Energy Physics
Universidad Santiago de Cali (Cali)
3 - 7 December
2018

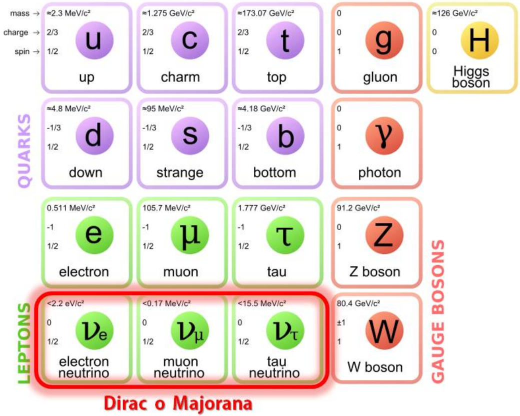
TALK BASED ON:

- J. Mejía-Guisao, D. Milanés, N. Quintero and J. D. Ruiz-Álvarez, Lepton-number violation in B_s meson decays induced by an on-shell Majorana neutrino, Physical Review D **98**, 075018 (2018) [arXiv:1708.01516 [hep-ph]].
- J. Mejía-Guisao, D. Milanés, N. Quintero and J. D. Ruiz-Álvarez, Exploring GeV-scale Majorana neutrinos in lepton-number-violating Λ_b^0 baryon decays, Physical Review D **96**, 015039 (2017) [arXiv:1705.10606 [hep-ph]].

OUTLINE

1. Introduction
   - Why Study Lepton Number Violating (LNV) Processes
   - Searches of $\Delta L = 2$ processes
2. New search possibilities in $\Delta L = 2$ decays of Λ_b y B_s hadrons
3. Concluding Remarks

Standard Model of Elementary Particles

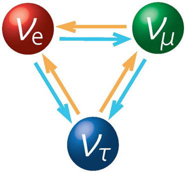


So far, no new physics phenomena have been observed at the LHC.

[Talks of Florez, Ferrari, Segura, Ruiz-Alvarez, & Fraga (3rd ComHEP)]

Neutrino oscillations $\rightarrow$ 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

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

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

[Talks of Moreno, Martínez, Rivera, & Miranda (3rd ComHEP)]

Why Study Lepton Number Violating (LNV) Processes ?

- Establish nature of the neutrinos

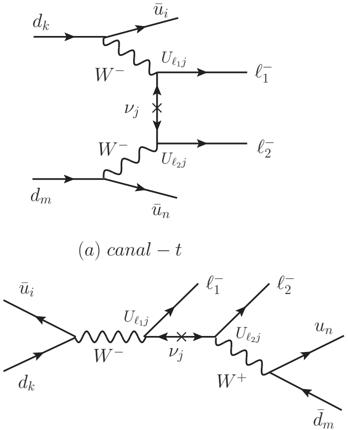
  ¿ Dirac $(\nu \neq \nu^c)$ o **Majorana** $(\nu = \nu^c)$?

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

- Mechanism of neutrino masses generation **[Talks of Yaguna, Restrepo, & Peinado (3rd ComHEP)]**
- Leptogenesis (Explain baryonic asymmetry of the Universe)

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

Lepton-number-violating ($\Delta L = 2$) 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)**

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

Ranges of sterile neutrino masses

	N mass	ν masses	eV ν anomalies	BAU	DM	M_H stability	direct search	experiment
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

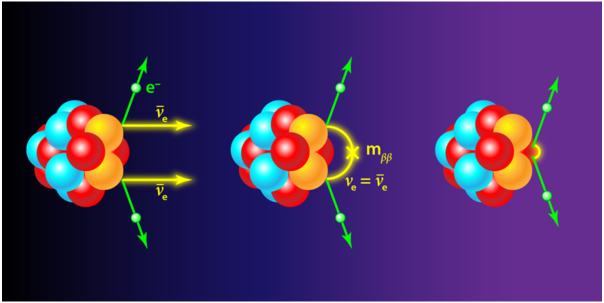
[Drewes, arXiv:1303.6912]
[de Gouvêa, arXiv:0706.1732]

Different mass scales are technically possible and worth exploring !

[Talks of Bernal & Helo (3rd ComHEP)]

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

The $0\nu\beta\beta$ nuclear decay is considered as the most attractive and sensitive way to prove that neutrinos are their own antiparticles (or not), i.e., elucidate if neutrinos are Majorana particles (or Dirac ones) .



Furry, Phys. Rev. 56, 1184 (1939).

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

Isotope	Experiment	$T^{0\nu}_{1/2} >$ [years]	$\langle m_{\beta\beta}\rangle <$ [eV]
${}^{76}\mathrm{Ge}$	Heidelberg-Moscow (HdM)	$= 1.9 \times 10^{25}$	0.32
	GERDA Phase II	8×10^{25}	(0.12 - 0.26)
	MAJORANA	1.9×10^{25}	(0.24 - 0.52)
${}^{136}\mathrm{Xe}$	EXO-200	1.8×10^{25}	(0.14 - 0.38)
	KamLAND-Zen (KLZ)	1.9×10^{25}	(0.12 - 0.25)
${}^{130}\mathrm{Te}$	CUORE	1.5×10^{25}	(0.11 - 0.52)

[NEXT-White experiment - Yohany's talk (3rd ComHEP)]

Drawbacks:

- Very difficult to calculate due to the nature of many bodies of nuclear physics.
- Calculations by different models (methods) do not agree very well: Quasi-particle Random Phase Approximation (QRPA), Interacting Boson Model (IBM), Nuclear Shell Model (NSM), ...
- It would test the LNV ee sector.

Alternative $\Delta L = 2$ processes

- Hyperon 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)

- Nuclear conversion processes: $e^- \to \mu^+$, $\mu^- \to e^+$ y $\mu^- \to \mu^+$

Geib, Merle & Zuber, PLB 764, 157 (2017)
Berryman, de Gouvêa, Kelly & Kobach, PRD **95**, 115010 (2017)
Yeo, Kuno, Lee, Kai & Zuber, PRD **96**, 075027 (2017).

- LHC (same-sign dilepton signals): $pp \to \ell^\pm \ell'^\pm X$

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)

- top quark decays: $t \to bW^-\ell^+\ell'^+$

Delepine, López-Castro, & Quintero, PRD 84, 096011 (2011)

Alternative $\Delta L = 2$ processes

- Low-energy processes: $\tau^- \to \ell^+ M_1^- M_2^-$
  $(K, D, D_s, B, B_c) \to M\ell^-\ell'^-$
  $(D, B, B_c) \to M_1 M_2 \ell^- \ell'^-$

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

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

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

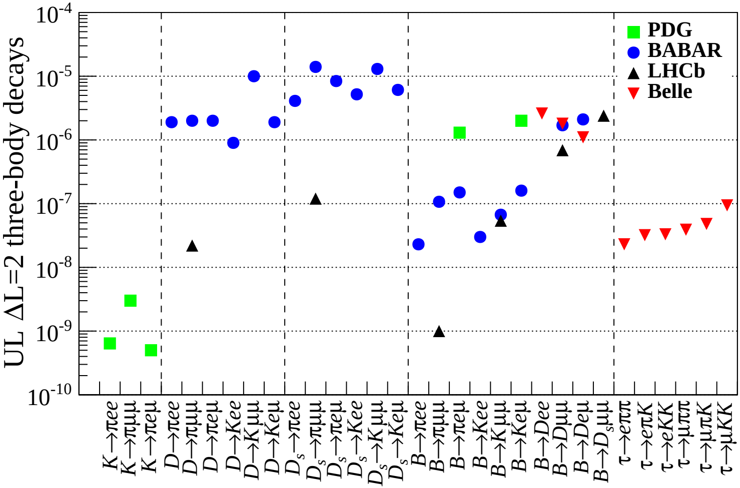
Advantages:

- Hadronic uncertainties (form factors, decay constants) under control.
- Production of an on-shell neutrino (amplitude enhancement).
- Search in different experiments: BABAR, Belle, NA48/2, LHCb y Belle II.
- Constraints on the parameter space of a heavy Majorana neutrino.
- It would prove different LNV sectors $(e\mu, \mu\mu, \mu\tau)$.

Drawbacks:

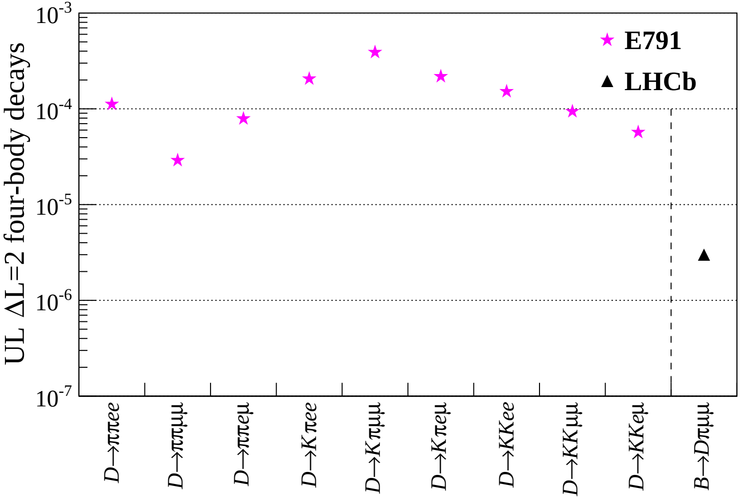
- Very difficult to reach the sensitivity of the $0\nu\beta\beta$ decay.

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)

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

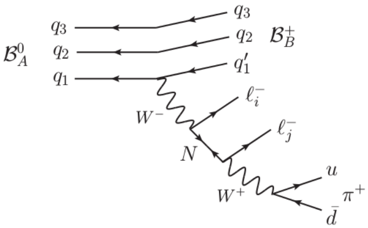


LHCb: PRD **85**, 112004 (2012), E791: PRL **86**, 3696 (2001)

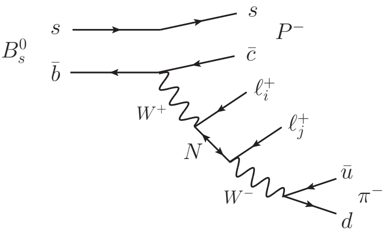
New search possibilities at LHCb and CMS

$$\Lambda_b \to (\Lambda_c^+, p)\pi^+\mu^-\mu^-$$

$$B_s^0 \to (K^-, \pi^-)\pi^+\mu^-\mu^-$$



(b) $\mathcal{B}_A^0 \to \mathcal{B}_B^+\pi^+\ell_i^-\ell_j^-$



$B_s^0 \to P^-\pi^-\ell_i^+\ell_j^+$

- Explore experimental sensitivity on $\mu^+\mu^+$ channels.
- Simplified approach in which one heavy neutrino N mixes with one flavor of SM lepton ℓ and its interactions are completely determined by the mixing angle $V_{\ell N}$.
- We will treat the mass m_N and mixing $V_{\mu N}$ of this heavy sterile neutrino as unknown phenomenological parameters.

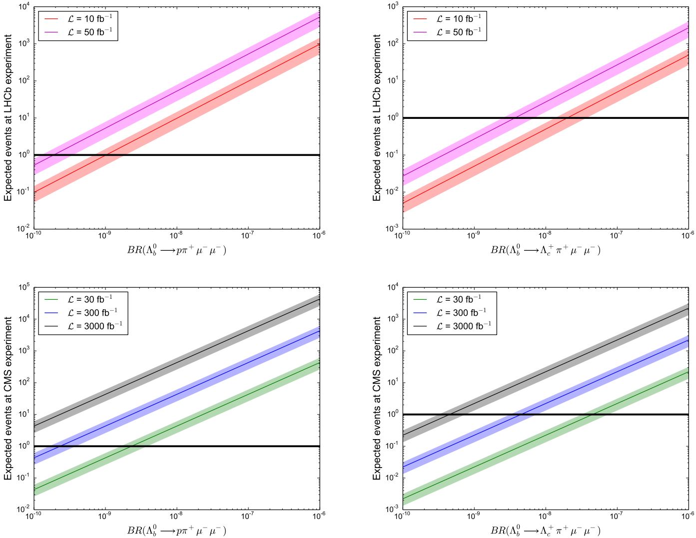
Number expected of events (LHCb and CMS)

$$N_{\rm exp} \;=\; \sigma(pp \to H_b X) f(b \to \Lambda_b) {\rm BR}(H_b \to \Delta L = 2) \epsilon_D (H_b \to \Delta L = 2) P_N \mathcal{L}_{\rm int}.$$

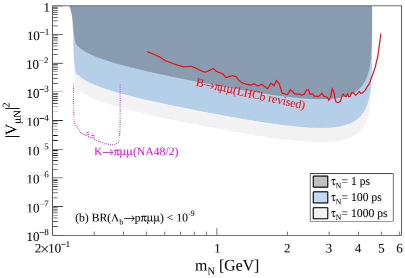
- $\sigma(pp \to H_b X)$ is the production cross section of b-hadrons inside the geometrical acceptance.
- $f(b \to H_b)$ is the hadronization factor of a b-quark to b-hadrons (Λ_b or B_s).
- $\mathcal{L}_{\rm int}$ is the integrated luminosity.
- ${\rm BR}(H_b \to \Delta L = 2)$ corresponds to the branching fraction of the given LNV process .
- $\epsilon_D(H_b \to \Delta L = 2)$ is the detection efficiency of involving reconstruction, selection, trigger, particle misidentification, and detection efficiencies.
- P_N is the acceptance factor, which accounts for the probability of the on-shell neutrino N decay products to be inside the detector acceptance

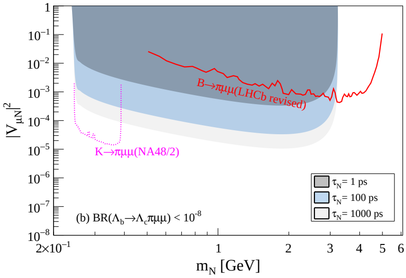
$$1 \text{ ps} \leq \tau_N \leq 1000 \text{ ps}.$$

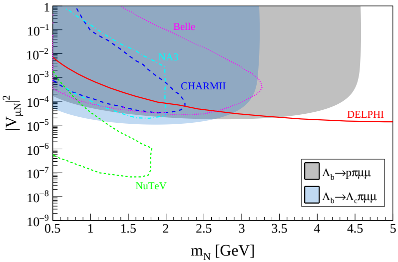
$\Delta L = 2$ decays of Λ_b baryon



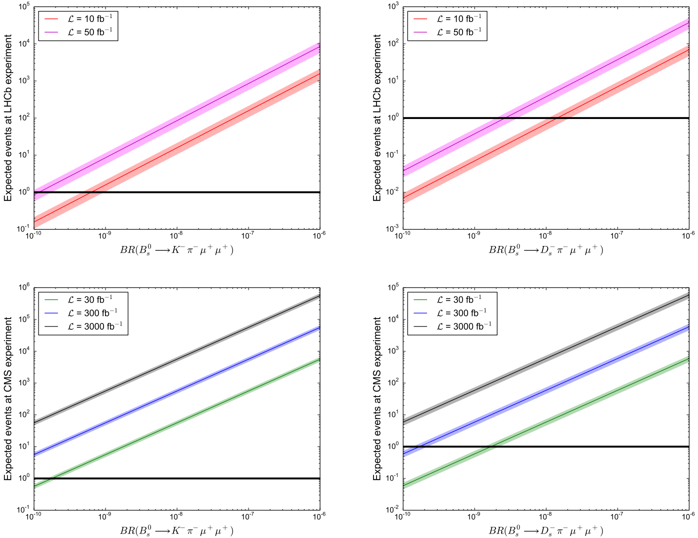
Exclusion regions $(m_N, |V_{\mu N}|^2)$



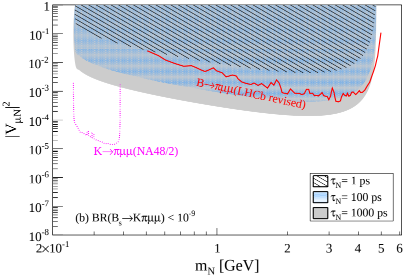


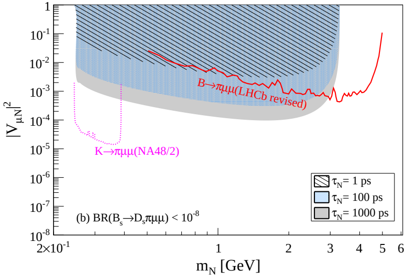


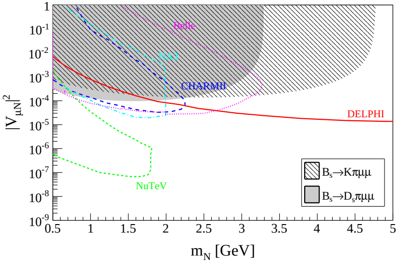
$\Delta L = 2$ decays of B_s meson



Exclusion regions $(m_N, |V_{\mu N}|^2)$

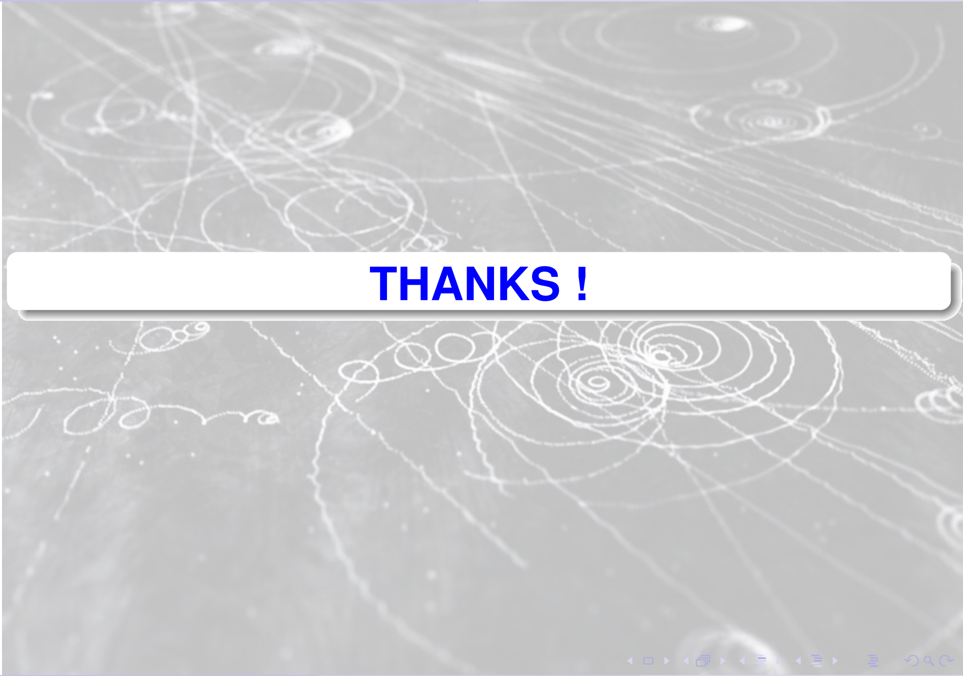






Concluding remarks

- **¿ Dirac o Majorana ?** $\rightarrow$ Observation of $\Delta L = 2$ decays will establish the Majorana nature of neutrinos.
- New search possibilities in $\Delta L = 2$ decays of Λ_b y B_s hadrons at LHCb (50 fb^{-1}) and CMS (1000 fb^{-1}) .
- Complementary (and strong) constraints on parameters $(m_N, |V_{\mu N}|^2)$



THANKS !

BACK UP

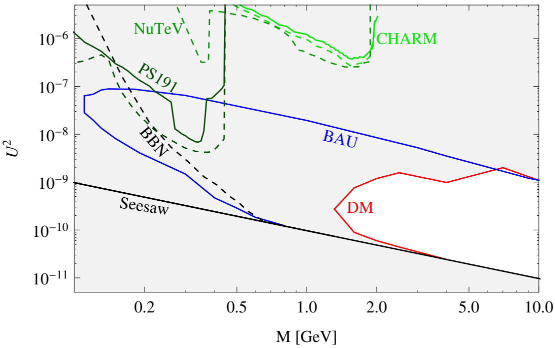
Intermediate massive neutrinos

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

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

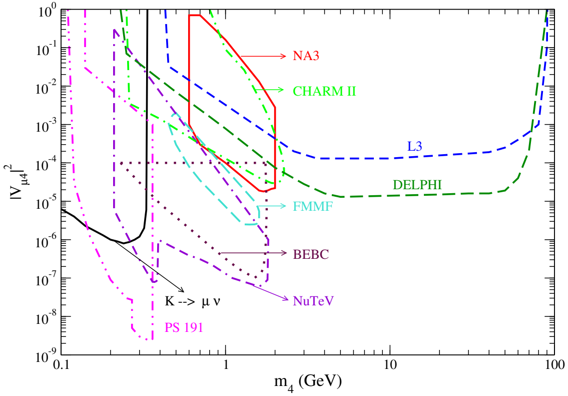
$M_{N_1} \sim$ (10 - 100) keV (Dark matter)

$M_{N_{2,3}} \sim \mathcal{O}$(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