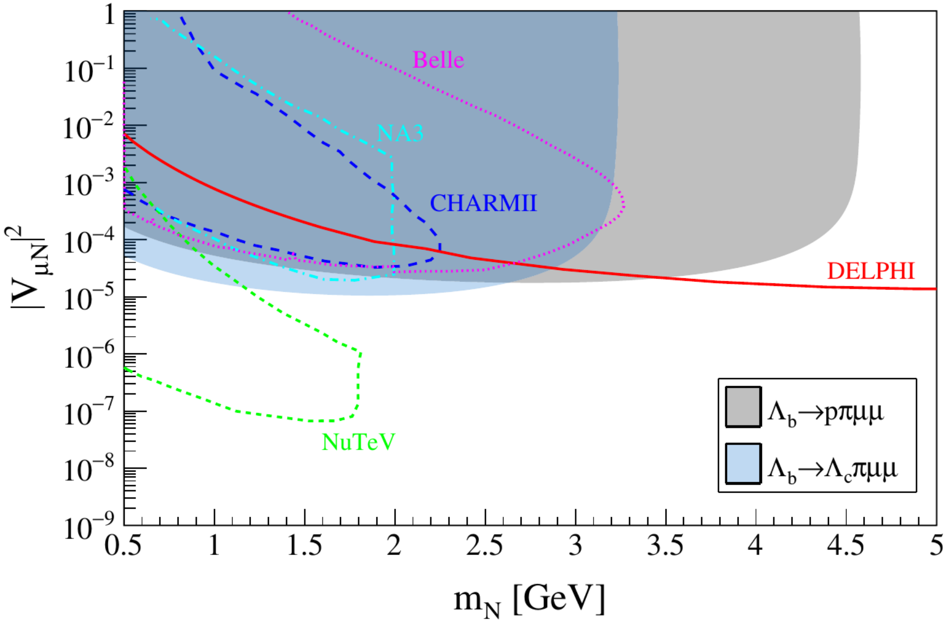


Exploring GeV-scale Majorana neutrinos in lepton-number-violating b hadrons decays

Jhovanny Andres Mejia

Néstor Quintero, Diego Milanés, and José D. Ruiz-Álvarez

Cinvestav

Reunión anual de la Red-FAE

28.09.2017

Outline

➔ Motivation

➔ Theoretical and experimental setup

➔ Overview of some results

- Exploring GeV-scale Majorana neutrinos in lepton-number-violating Λ_b^0 baryon decays.

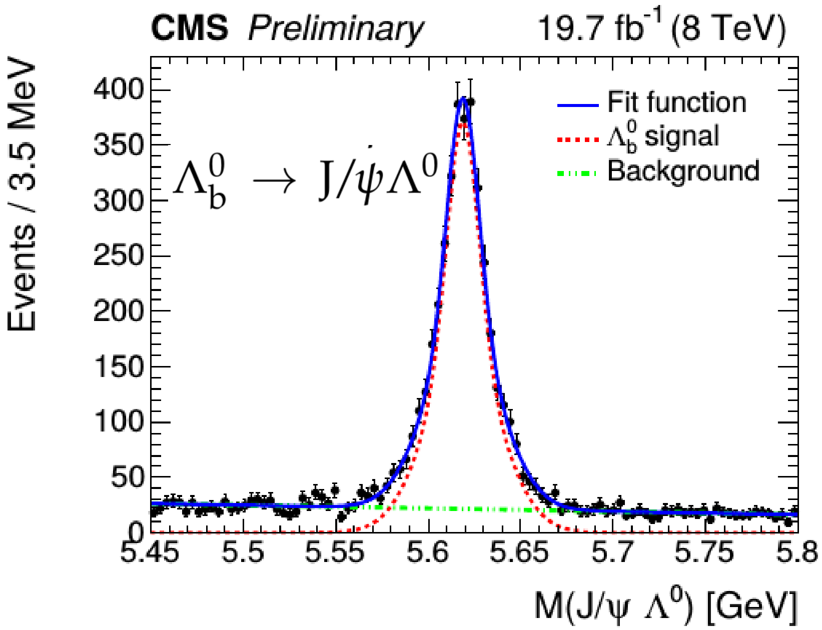
PHYSICAL REVIEW D 96, 015039 (2017)

- Lepton number violation in B_s meson decays induced by an on-shell Majorana neutrino

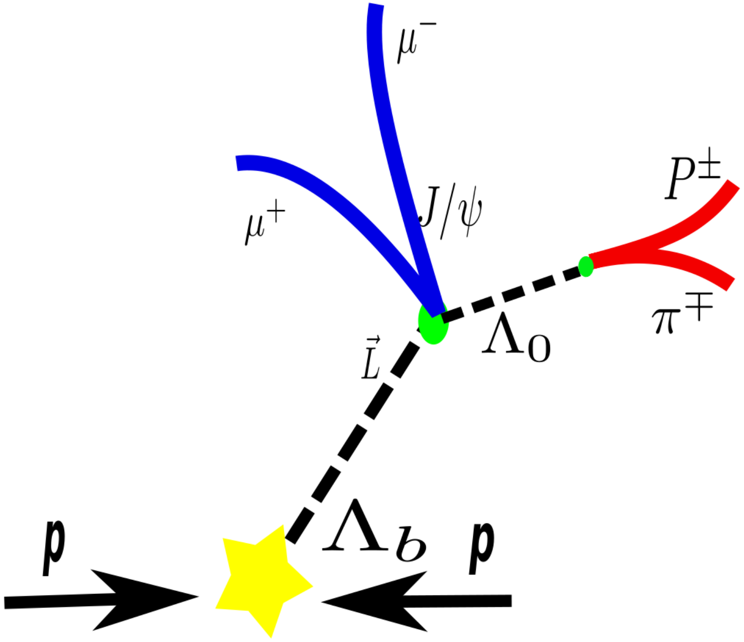
arXiv:1708.01516

Motivation

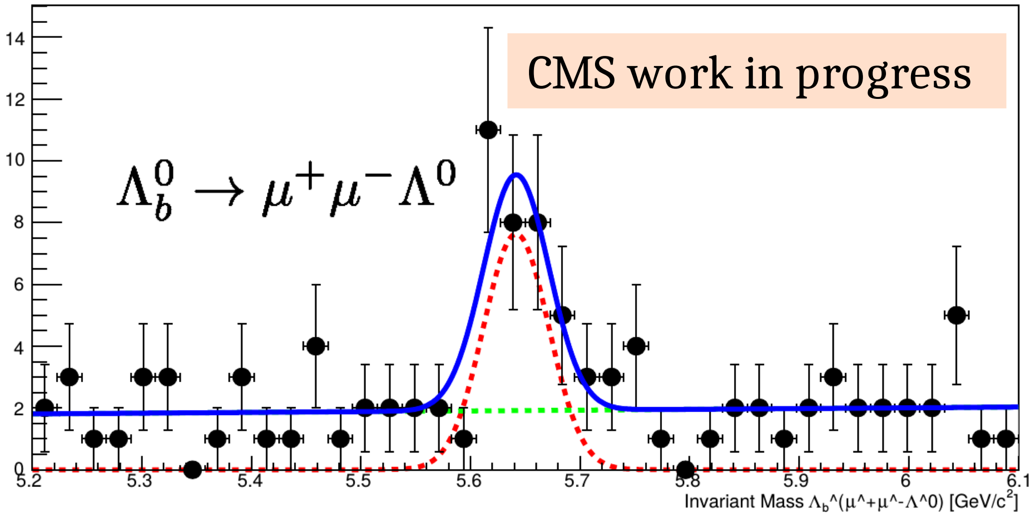
CMS-PAS-BPH-13-008



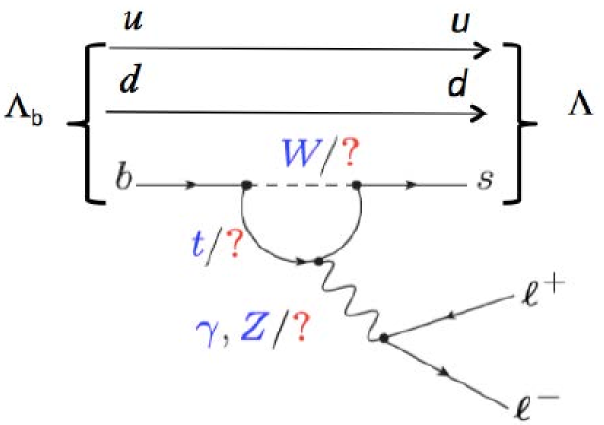
Lifetime analysis



Λ_b^0 baryonic Flavor Changing Neutral Current (FCNC)



T. Gutsche et al., PRD87 (2013) 074031



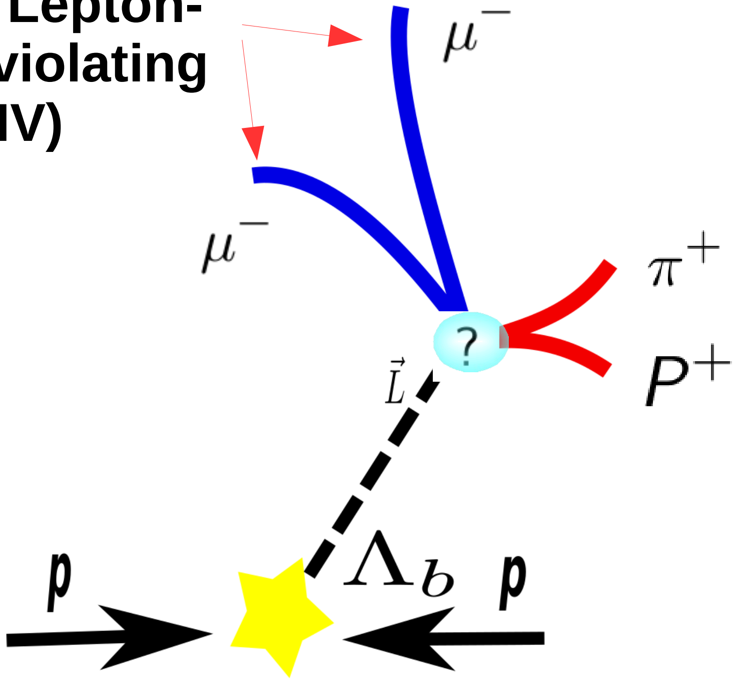
Due to the lack of manpower we could not continue this analysis.

What else can I do?

-Rare decays are suppressed in the SM and can happen at loop level only.
-Very sensitive to new physics effects.

What happens if the final hadrons are non-resonant too?

Answer: Lepton-number-violating (LNV)

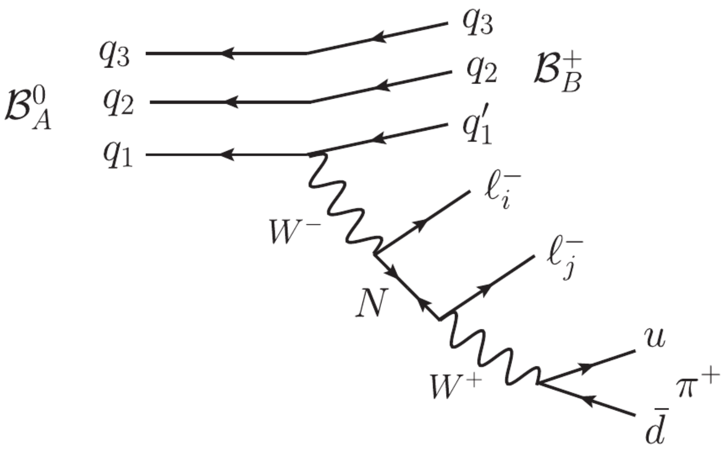


- Is it possible in Lambda system?
- Contact a theorist?
-Nestor knows about it

Theoretical and experimental setup

$\Lambda_b^0 \to p\pi^+\mu^-\mu^-$

$\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-$



- The smoking gun LNV signal is the neutrinoless double-β ($0\nu\beta\beta$)
- Recent attention: $\bar{B}^0 \to D^+\pi^+\mu^-\mu^-$, $B^- \to D^0\pi^+\mu^-\mu^-$ and $B_c^- \to J/\psi\pi^+\mu^-\mu^-$
- LHCb has reported the upper limit $\mathrm{BR}(B^- \to D^0\pi^+\mu^-\mu^-) < 1.5 \times 10^{-6}$
- The same quark level LNV transition that generates these four-body $|\Delta L| = 2$ channels, can also produce $|\Delta L| = 2$ decays in the B_s and Λ_b^0
- Experimental search is within reach of sensitivity of the LHCb, CMS and Belle II

Feynman graphs for $|\Delta L| = 2$ decays of $\mathcal{B}_A$ baryon mediated by a Majorana neutrino N: four-body $\mathcal{B}_A^0(q_1q_2q_3) \to \mathcal{B}_B^+(q_1'q_2q_3)\pi^+\ell_i^-\ell_j^-$ channels.

$$\Lambda_b^0 \to p\pi^+\mu^-\mu^-:\ m_N \in [0.25, 4.57]\ \mathrm{GeV},$$

$$\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-:\ m_N \in [0.25, 3.23]\ \mathrm{GeV},$$

Theoretical setup

Branching fraction

$$\mathrm{BR}(\Lambda_b^0 \to \mathcal{B}^+\pi^+\mu^-\mu^-) = \mathrm{BR}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N) \times \Gamma(N \to \mu^-\pi^+)\tau_N/\hbar,$$

Decay width

$$\Gamma(N \to \mu^-\pi^+) = \frac{G_F^2}{16\pi}|V_{ud}^{\mathrm{CKM}}|^2|V_{\mu N}|^2 f_\pi^2 m_N \sqrt{\lambda(m_N^2, m_\mu^2, m_\pi^2)} \times \left[\left(1-\frac{m_\mu^2}{m_N^2}\right)^2 - \frac{m_\pi^2}{m_N^2}\left(1+\frac{m_\mu^2}{m_N^2}\right)\right],$$

Amplitude

$$\mathcal{M}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N) = \frac{G_F}{\sqrt{2}} V_{Qb}^{\mathrm{CKM}} V_{\mu N}\langle \mathcal{B}(p_{\mathcal{B}})|\bar{Q}\gamma_\alpha(1-\gamma_5)b|\Lambda_b(P)\rangle \times [\bar{u}(p_\mu)\gamma^\alpha(1-\gamma_5)v(p_N)],$$

The matrix element of the vector and axial-vector currents

$$\langle \mathcal{B}(p_{\mathcal{B}})|\bar{Q}\gamma_\alpha b|\Lambda_b(P)\rangle = \bar{u}_{\mathcal{B}}(p_{\mathcal{B}})\left[\gamma_\alpha f_1^V(t) + i\sigma_{\alpha\beta}q^\beta \frac{f_2^V(t)}{m_{\Lambda_b}} + q_\alpha \frac{f_3^V(t)}{m_{\Lambda_b}}\right] u_{\Lambda_b}(P),$$

$$\langle \mathcal{B}(p_{\mathcal{B}})|\bar{Q}\gamma_\alpha\gamma_5 b|\Lambda_b(P)\rangle = \bar{u}_{\mathcal{B}}(p_{\mathcal{B}})\left[\gamma_\alpha f_1^A(t) + i\sigma_{\alpha\beta}q^\beta \frac{f_2^A(t)}{m_{\Lambda_b}} + q_\alpha \frac{f_3^A(t)}{m_{\Lambda_b}}\right] \gamma_5 u_{\Lambda_b}(P),$$

$$\mathrm{BR}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N) = \frac{G_F^2 \tau_{\Lambda_b}}{512\pi^3 m_{\Lambda_b}^3 \hbar} |V_{Qb}^{\mathrm{CKM}}|^2 |V_{\mu N}|^2 \int_{(m_\mu+m_N)^2}^{\Delta_-^2} dt \sqrt{\lambda(m_\mu^2, m_N^2, t)\lambda(m_{\Lambda_b}^2, m_{\mathcal{B}}^2, t)}$$

$$\times \left\{ \frac{16}{3t^3}[f_1^V(t)]^2 \alpha_1^V(t) + \frac{8}{3m_{\Lambda_b}^2 t^2}[f_2^V(t)]^2 \alpha_2^V(t) + \frac{8}{3m_{\Lambda_b}^2 t}[f_3^V(t)]^2 \alpha_3^V(t) + \frac{32}{m_{\Lambda_b} t^2}[f_1^V(t) f_2^V(t) \alpha_{12}^V(t) \right.$$

$$+ f_1^V(t) f_3^V(t) \alpha_{13}^V(t)] + \frac{16}{3t^3}[f_1^A(t)]^2 \alpha_1^A(t) + \frac{8}{3m_{\Lambda_b}^2 t^2}[f_2^A(t)]^2 \alpha_2^A(t) + \frac{8}{3m_{\Lambda_b}^2 t}[f_3^A(t)]^2 \alpha_3^A(t)$$

$$\left. + \frac{32}{m_{\Lambda_b} t^2}[f_1^A(t) f_2^A(t) \alpha_{12}^A(t) + f_1^A(t) f_3^A(t) \alpha_{13}^A(t)] \right\},$$

we will use the theoretical predictions obtained by Lattice QCD on the form factors (f_1^V, f_2^V, f_3^V) and (f_1^A, f_2^A, f_3^A)

$$\alpha_1^{V/A}(t) = m_\mu^2[t(\Sigma_-^2 - 2m_N^2\Sigma_+) - 2t^2(m_N^2 \mp m_{\Lambda_b} m_{\mathcal{B}} + \Delta_\mp^2) + 4m_N^2\Sigma_-^2 + t^3]$$
$$+ (t - m_N^2)[m_N^2(t\Sigma_+ - 2\Sigma_- + t^2) - t(\Delta_\mp^2 - t)(\Sigma_\pm^2 + 2t)],$$

$$\alpha_2^{V/A}(t) = [t(m_\mu^2 + m_N^2) + (m_\mu^2 - m_N^2)^2 - 2t^2][t(\Sigma_\pm^2 \pm 4m_{\Lambda_b} m_{\mathcal{B}}) - 2(\Sigma_-^2 + t^2)],$$

$$\alpha_3^{V/A}(t) = \Delta_\pm^2 - t^2)[m_\mu^2(t + 2m_N^2 - m_\mu^2) + m_N^2(t - m_N^2)],$$

with $\Delta_\pm = m_{\Lambda_b} \pm m_{\mathcal{B}}$ and $\Sigma_\pm = m_{\Lambda_b}^2 \pm m_{\mathcal{B}}^2$

$$\alpha_{12}^{V/A}(t) = \Delta_\pm(\Delta_\mp - t)[m_\mu^2(t - 2m_N^2) + m_\mu^4 + m_N^4 + m_N^2 t - 2t^2],$$

$$\alpha_{13}^{V/A}(t) = \Delta_\mp(\Delta_\pm - t)[(m_\mu^2 - m_N^2)^2 - t(m_\mu^2 + m_N^2)],$$

Experimental setup

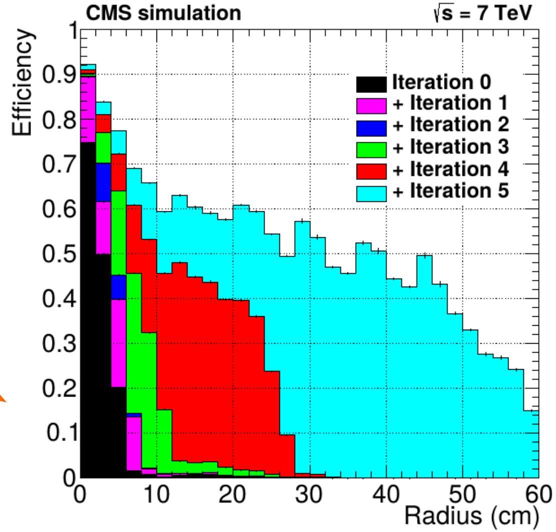
$$N_{\rm exp}^{\rm CMS} = \sigma(pp \to \Lambda_b^0 X){\rm BR}(\Lambda_b^0 \to \Delta L = 2)$$
$$\times\, \epsilon_D^{\rm CMS}(\Lambda_b^0 \to \Delta L = 2) P_N^{\rm CMS} \mathcal{L}_{\rm int}^{\rm CMS}$$

- $\mathcal{L}_{\rm int}^{\rm CMS}$ The integrated luminosity
- $\sigma(pp \to \Lambda_b X)$ The production cross section
- ϵ_D^{CMS} CMS experiment efficiency
- $P_N^{\rm CMS}$ The acceptance factor at the CMS
- ${\rm BR}(\Lambda_b^0 \to |\Delta L| = 2)$ Respective branching ratio

Phys. Lett. B 714, 136 (2012)

$$\epsilon_D^{CMS}(p\pi^+\mu^-\mu^-) = (0.73 \pm 0.07)\%$$
$$\epsilon_D^{CMS}(\Lambda_c^+\pi^+\mu^-\mu^-) = (0.59 \pm 0.06)\%$$

J. Instrum. 9, P10009 (2014).



$$\epsilon_D^{\rm CMS}(\Lambda_b^0 \to p\pi^+\mu^-\mu^-) P_N^{\rm CMS} \simeq 0.073 \pm 0.015$$
$$\epsilon_D^{\rm CMS}(\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-) P_N^{\rm CMS} \simeq 0.059 \pm 0.013$$

$0.55 \le P_N \le 1$ for 1 ps $\le \tau_N \le 1000$ ps

A maximum variation of about 18%

Experimental setup

Phys. Lett. B 714, 136 (2012)

$$\sigma(\Lambda_b) \times \mathrm{BR}(\Lambda_b \to J/\psi\Lambda) = 1.16 \pm 0.06 \pm 0.12 \text{ nb}$$

PDG

$$\mathrm{BR}(\Lambda_b \to J/\psi\Lambda) \times f(b \to \Lambda_b) = (5.8 \pm 0.8) \times 10^{-5}$$

I. Heredia-De La Cruz (D0 Collaboration), Proceedings of the DPF-2011 Conference, Providence, RI, 2011

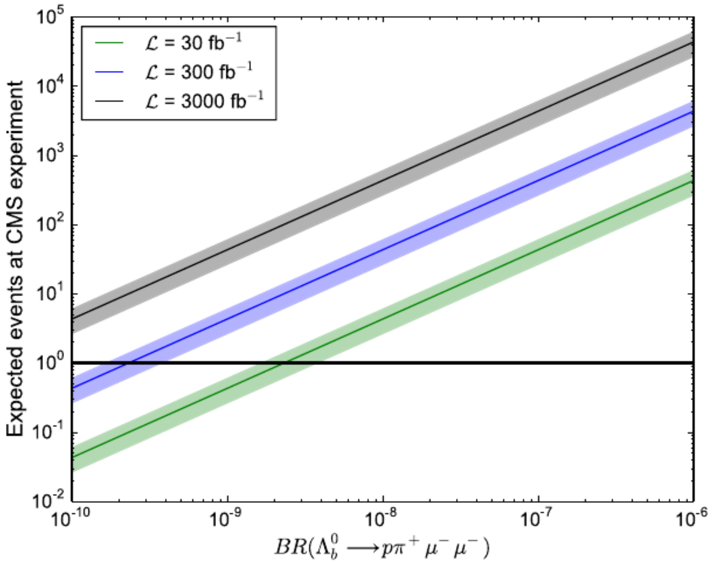
$$f(b \to \text{baryons}) \simeq f(b \to \Lambda_b)(1 + 2f(b \to B_s^0)/f(b \to B^0))$$

Heavy Flavor Averaging Group CollaborationAverages of b-hadron, c-hadron, and τ-lepton properties as of summer 2016, arXiv:1612.07233.

$$f(b \to \text{baryons}) = 0.088 \pm 0.012$$

$$f(b \to B_s^0) = 0.103 \pm 0.005$$

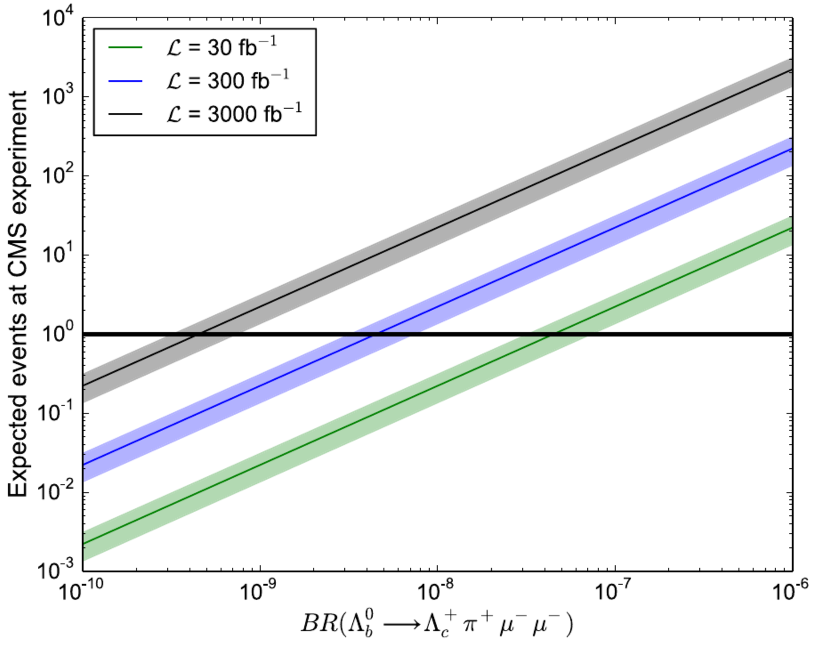
$$f(b \to B^0) = 0.404 \pm 0.006$$



Number of expected events at CMS

TABLE II. Number of expected events at the CMS for some selected values of the branching ratio of $\Lambda_b^0 \to p\pi^+\mu^-\mu^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-$.

Mode	$\mathcal{L}_{\text{int}}^{\text{CMS}}$ (fb^{-1})	BR	Number of events
$\Lambda_b^0 \to p\pi^+\mu^-\mu^-$	30	10^{-6}	431 ± 164
		10^{-7}	43 ± 16
		10^{-8}	4 ± 2
	300	10^{-8}	43 ± 16
		10^{-9}	4 ± 2
$\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-$	30	10^{-6}	27 ± 10
		10^{-7}	3 ± 1
	300	10^{-7}	27 ± 10
		10^{-8}	3 ± 1

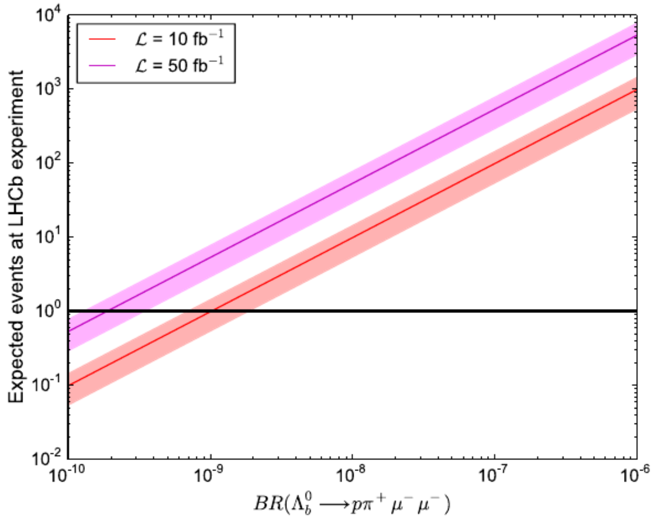


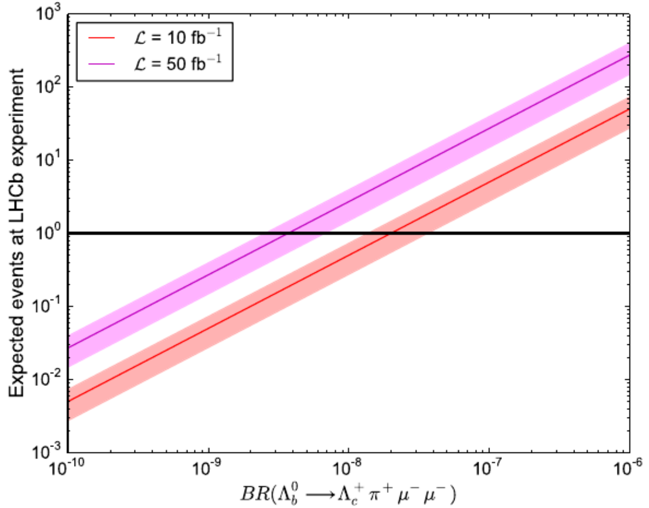
Number of expected events at LHCb

TABLE I. Number of expected events at the LHCb for some selected values of the branching ratio of $\Lambda_b^0 \to p\pi^+\mu^-\mu^-$ and $\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-$.

Mode	$\mathcal{L}_{\rm int}^{\rm LHCb}$ (fb^{-1})	BR	Number of events
$\Lambda_b^0 \to p\pi^+\mu^-\mu^-$	10	10^{-6}	981 ± 441
		10^{-7}	98 ± 44
		10^{-8}	10 ± 4
	50	10^{-7}	530 ± 238
		10^{-8}	53 ± 24
		10^{-9}	5 ± 2
$\Lambda_b^0 \to \Lambda_c^+\pi^+\mu^-\mu^-$	10	10^{-6}	50 ± 23
		10^{-7}	5 ± 2
	50	10^{-6}	272 ± 122
		10^{-7}	27 ± 12
		10^{-8}	3 ± 1

We contacted a colleague from the LHCb collaboration



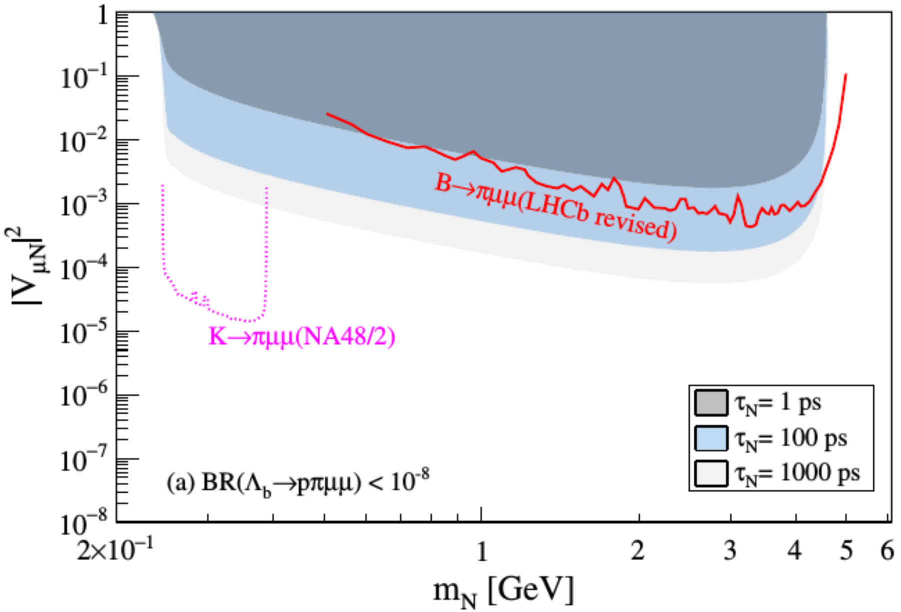


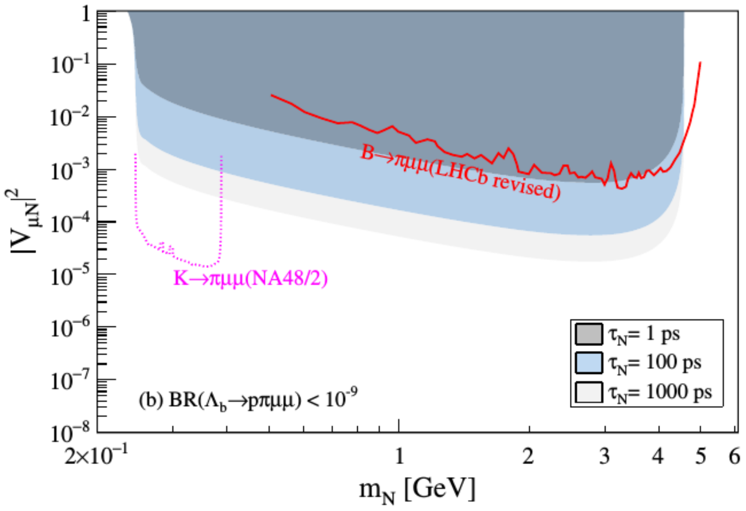
Overview of some results

$$\overline{\mathrm{BR}}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N) = \mathrm{BR}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N)/|V_{\mu N}|^2$$

$$\bar{\Gamma}(N \to \mu^-\pi^+) = \Gamma(N \to \mu^-\pi^+)/|V_{\mu N}|^2$$

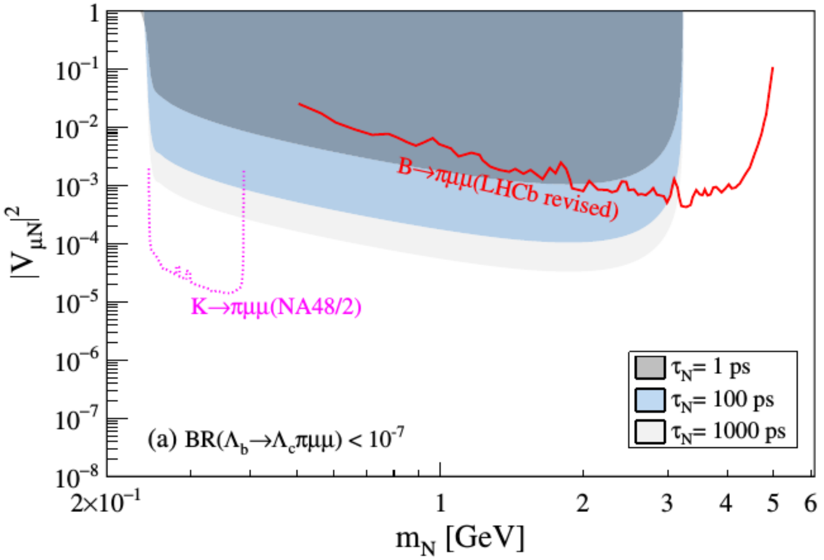
$$|V_{\mu N}|^2 = \left[\frac{\hbar \mathrm{BR}(\Lambda_b^0 \to \mathcal{B}^+\pi^+\mu^-\mu^-)}{\overline{\mathrm{BR}}(\Lambda_b^0 \to \mathcal{B}^+\mu^- N) \times \bar{\Gamma}(N \to \mu^-\pi^+)\tau_N}\right]^{1/2}$$

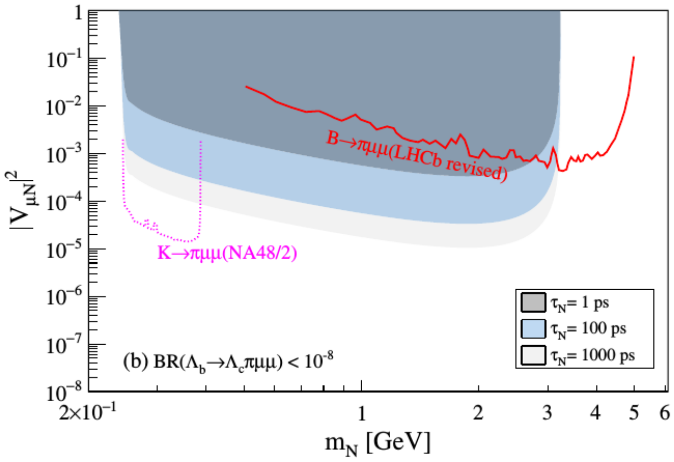


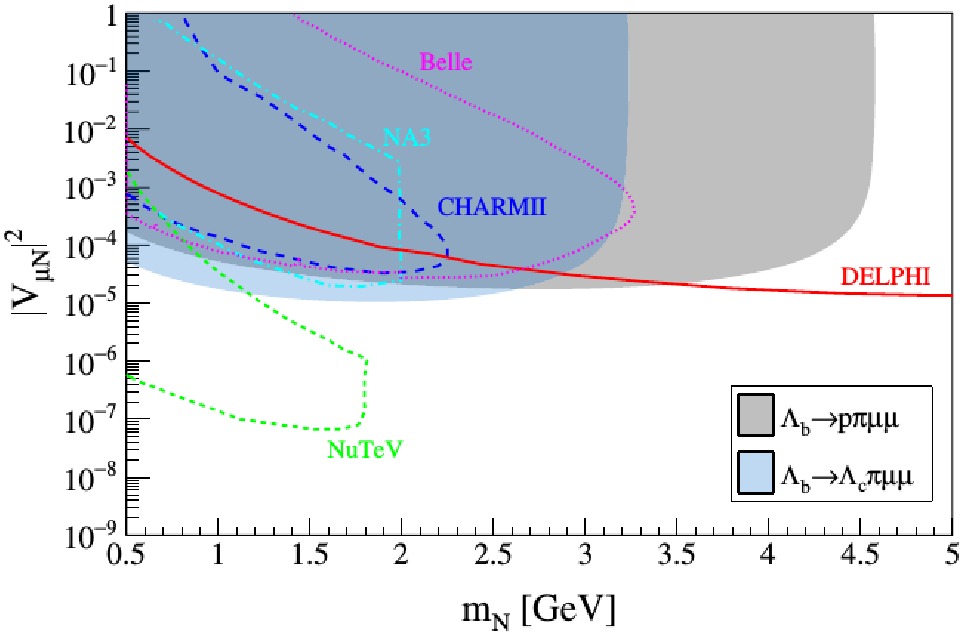


We show the exclusion regions on $|V_{\mu N}|^2$ as a function of m_N obtained by taking an expected sensitivity in the branching fractions of the order $\mathrm{BR}(\Lambda_b^0 \to p\pi^+\mu^-\mu^-) < 10^{-8}$ and $< 10^{-9}$, respectively.

Overview of some results



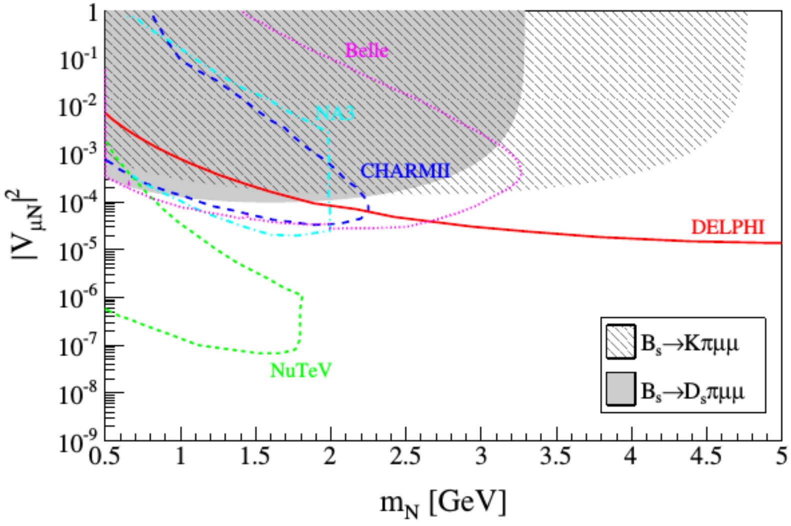


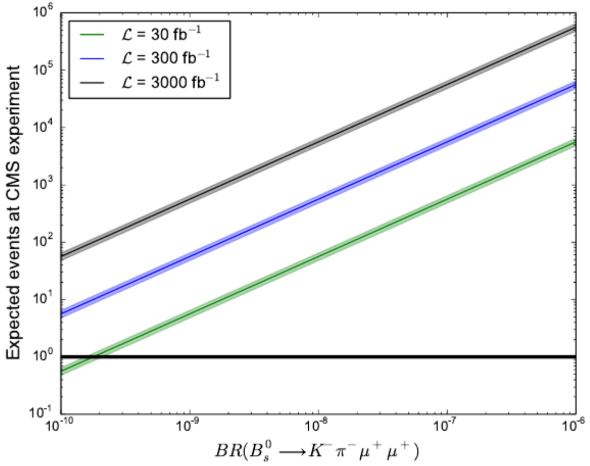


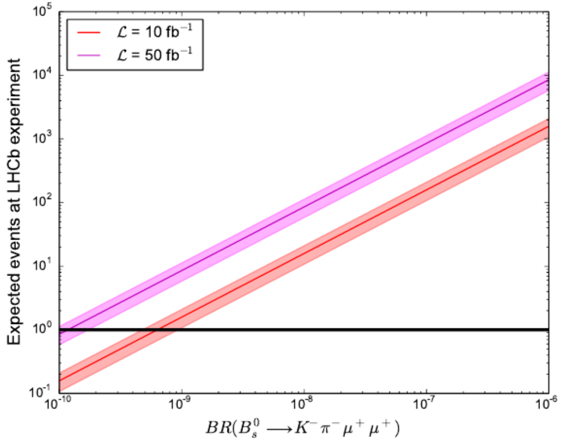
Lepton number violation in B_s meson decays induced by an on-shell Majorana neutrino

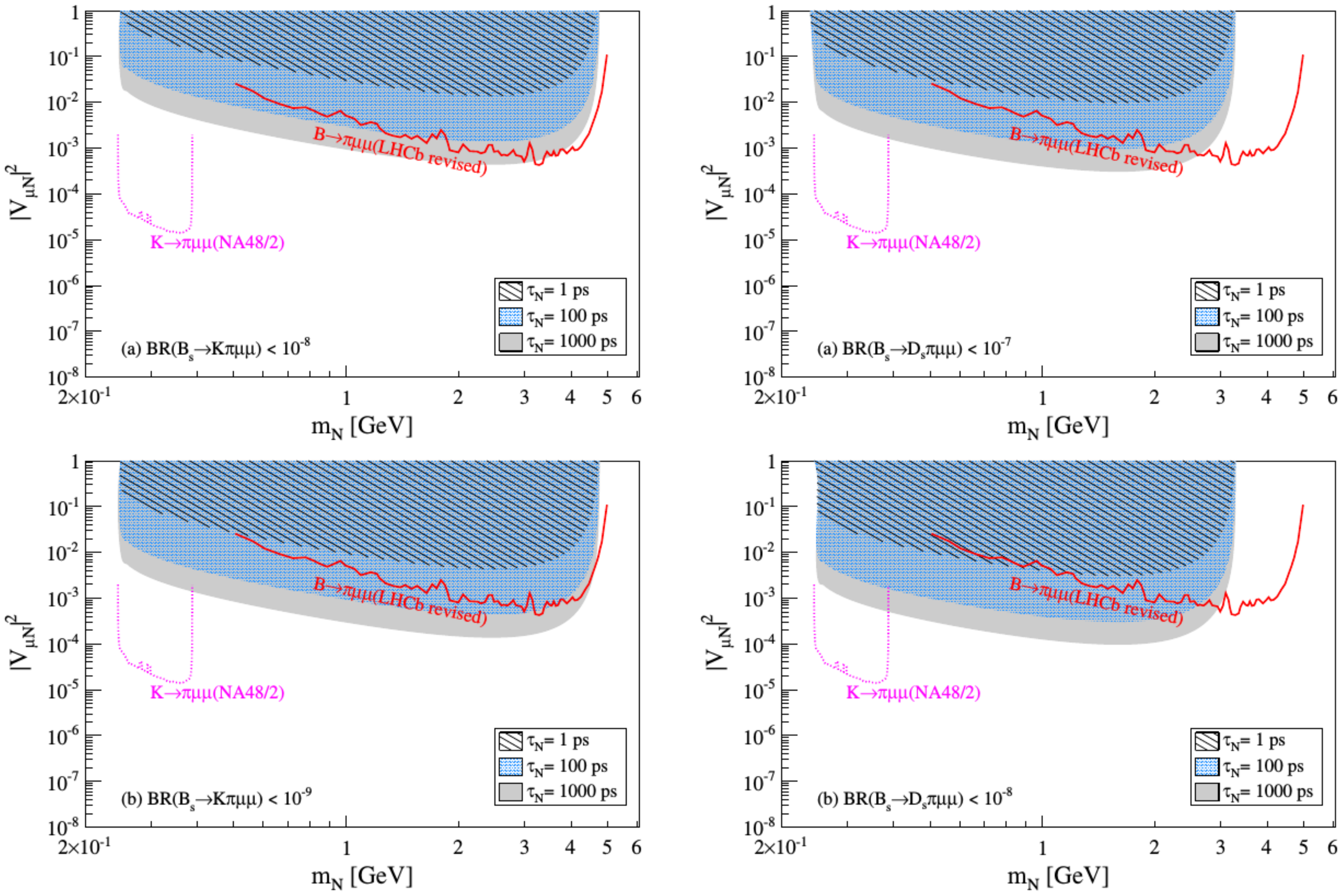
$$B_s^0 \to K^- \pi^- \mu^+ \mu^+$$

$$B_s^0 \to D_s^- \pi^- \mu^+ \mu^+$$









$|V_{\mu N}|^2$
m_N [GeV]
B→πμμ(LHCb revised)
K→πμμ(NA48/2)
τ_N= 1 ps
τ_N= 100 ps
τ_N= 1000 ps
(a) BR(B_s→Kπμμ) < 10^{-8}
(a) BR(B_s→D_sπμμ) < 10^{-7}
(b) BR(B_s→Kπμμ) < 10^{-9}
(b) BR(B_s→D_sπμμ) < 10^{-8}

Summary

- ➔ We studied Lepton-number-violation in b hadrons decays induced by an on-shell Majorana neutrino
- ➔ We collaborated with theorists and experimentalists
- ➔ People from LHCb and CMS were involved
- ➔ I would like to repeat this experience with colleagues from the RedFAE