Lepton number violating/conserving heavy baryon decays, in presence of two almost degenerated heavy neutrinos

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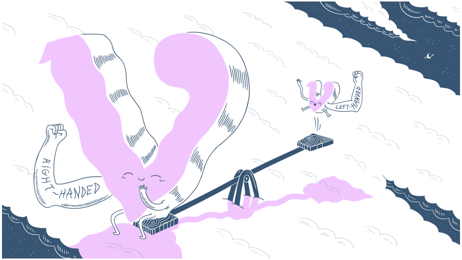
Motivation

Motivation

Several extensions of the Standard Model (SM) aiming at explaining oscillation phenomena invoke the introduction of right-handed (RH) neutrinos.

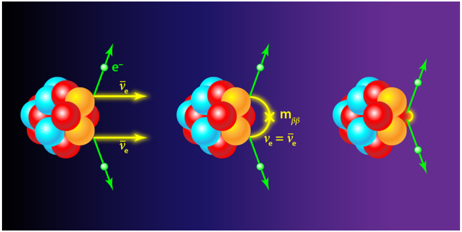
The embedding of the seesaw mechanism onto the SM is one of the most economical mechanisms for the generation of neutrino masses and lepton mixings.



The presence of relatively light RH neutrinos (sterile fermions from the gauge point of view), which have non-negligible mixings with the active ones, leads to the modification of the charged and neutral lepton currents.

Lepton Number Violation

A typical example of LNV is the neutrinoless double beta decay, $0\nu\beta\beta$.



This process is only possible if neutrinos are Majorana.

LNC & LNV baryon decays

Framework

- Simplified SM extensions that involve the addition of extra neutral Majorana fermions.

The leptonic charged current is modified as follows:

$$\mathcal{L}_{\text{c.c}} \quad = \quad -\frac{g}{\sqrt{2}} U_{\alpha i}\, \bar{\ell}_\alpha \gamma_\mu P_L \nu_i W^-_\mu + \text{h.c.}, \tag{1}$$

where $P_L = (1-\gamma_5)/2$ is the left-handed chirality projector, the subindex i refers to the physical neutrino states (3 light plus 2 heavy states), and the subindex α represents the flavor of the charged leptons.

Matrix elements for the heavy-light mixings are denoted by

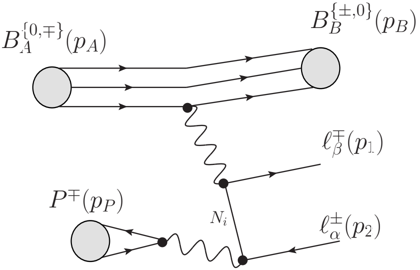
$$U_{\alpha i} = e^{i\phi_{\alpha i}} |U_{\alpha i}|, \quad \alpha = e, \mu, \tau, \quad i = 4, 5 \tag{2}$$

where $\phi_{\alpha i}$ is the phase of the associated mixing element.

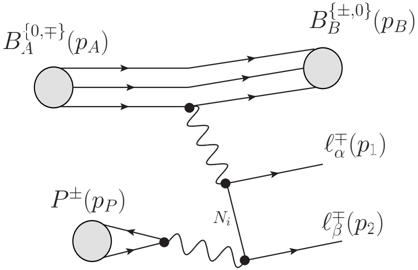
*More realistic models (motivated to accommodate the mass generation mechanism [1]) invoke two almost degenerate Majorana neutrinos, with masses in the GeV region.

[1] Eur. Phys. J. C 82, 1030 (2022), J. High Energy Phys. 07 (2024) 060.

LNC & LNV baryon decays



LNC



LNV

$$m_P + m_{\ell_\alpha} \le m_N \le m_A - m_B - m_{\ell_\beta}$$

$$m_P + m_{\ell_\beta} \le m_N \le m_A - m_B - m_{\ell_\alpha}$$

LNC $B_A^{\{0,\mp\}} \to B_B^{\{\pm,0\}} P^{\mp} \ell_\alpha^{\mp} \ell_\beta^{\pm}$ Decays

We focus on lepton flavor violating (LFV) decays , i.e., with $\ell_\alpha \neq \ell_\beta$, to isolate the sterile neutrino contributions. We obtain the amplitude for $B_A^{\{0,-\}}(p_A) \to B_B^{\{+,0\}}(p_B)\ P^-(p_P)\ell_\beta^-(p_1)\ell_\alpha^+(p_2)$

$$\mathcal{M}_{\text{LNC}} = G\, p_P^\nu \sum_{i=4,5} U_{\beta i}\, U_{\alpha i}^*\, \ell_{\mu\nu}^{\text{LNC}}\, P_{1i}\, H^\mu(p_B, p_A)\,, \tag{3}$$

where we have defined $G \equiv G_F^2 V_{AB} V_P f_P$, with V_P and V_{AB} the mixing quark elements of the CKM matrix, and f_P the decay constant of the meson state. The leptonic part is given by

$$\ell_{\mu\nu}^{\text{LNC}} \equiv \bar{u}(p_1)\gamma_\mu \not{a}_1 \gamma_\nu (1-\gamma_5) v(p_2), \tag{4}$$

where $a_1 \equiv p_A - p_B - p_1$ is the momentum carried out by either of the heavy neutrinos, and we have defined

$$P_{1i} \equiv \frac{1}{a_1^2 - m_i^2 + i m_i \Gamma_i}. \tag{5}$$

Hadronic part

- The meson production coming from the W is parameterized by $if_P p_P^\nu$.
- Baryon transition matrix element

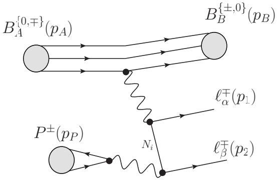
$$H^\mu(p_B, p_A) \equiv \langle B_B(p_B)|J^\mu|B_A(p_A)\rangle\,, \tag{6}$$

in the most general form is parameterized by six form factors, as follows

$$\begin{aligned}
&\langle B_B(p_B)|J_\mu|B_A(p_A)\rangle = \\
&\bar{u}(p_B)\Big[f_1(q^2)\gamma_\mu + if_2(q^2)\frac{\sigma_{\mu\nu}q^\nu}{M_A} + \frac{q_\mu f_3(q^2)}{M_A} \\
&+ g_1(q^2)\gamma_\mu\gamma_5 + ig_2(q^2)\frac{\sigma_{\mu\nu}q^\nu\gamma_5}{M_A} + \frac{q_\mu g_3(q^2)\gamma_5}{M_A}\Big]u(p_A),
\end{aligned} \tag{7}$$

with $q^2 = (p_A - p_B)^2$ the squared momentum transferred in the baryonic transition.

LNV $B_A^{\{0,\mp\}} \to B_B^{\{\pm,0\}} P^\pm \ell_\alpha^\mp \ell_\beta^\mp$ Decays



We obtain the amplitude for the specific decay mode $B_A^{\{0,+\}}(p_A) \to B_B^{\{-,0\}}(p_B)\ P^-(p_P)\ell_\alpha^+(p_1)\ell_\beta^+(p_2)$

$$\mathcal{M}_{\text{LNV}} = G\, p_P^\nu \sum_i U_{\alpha i}^* U_{\beta i}^* m_i H^\mu(p_B, p_A) \left(\ell_{\mu\nu}^{\text{LNV}}(p_1,p_2)P_{1i} + \ell_{\nu\mu}^{\text{LNV}}(p_1,p_2)P_{2i}\right), \tag{8}$$

where the leptonic part in this case is written as

$$\ell_{\mu\nu}^{\text{LNV}}(p_1,p_2) \equiv \bar{u}(p_1)\gamma_\mu\gamma_\nu(1+\gamma_5)v(p_2), \tag{9}$$

We used $\ell_{\mu\nu}^{\text{LNV}}(p_2,p_1) = -\ell_{\nu\mu}^{\text{LNV}}(p_1,p_2)$, obtained by applying charge-conjugation relations.

Two almost degenerate case

The total squared amplitude can be recast into a single Majorana neutrino process, provided the following conditions are satisfied:

- the masses are $m_4 \simeq m_5 \equiv m_N$ and $\Delta m_N \equiv m_5 - m_4 \gtrsim 0$
- the decay widths are $\Gamma_4 \simeq \Gamma_5 \equiv \Gamma_N$
- the mixing parameters are thus also required to fulfill $|U_{\alpha 4}||U_{\beta 4}| = |U_{\alpha 5}||U_{\beta 5}| = |U_{\alpha N}||U_{\beta N}|$

Full LNC & LNV results, in the two almost degenerate case

The average square amplitudes become:

$$\overline{|\mathcal{M}_{\mathsf{LNC}}(2N)|^2} = \overline{|\mathcal{M}_{\mathsf{LNC}}(1N)|^2} R[y, \psi_-], \tag{10}$$

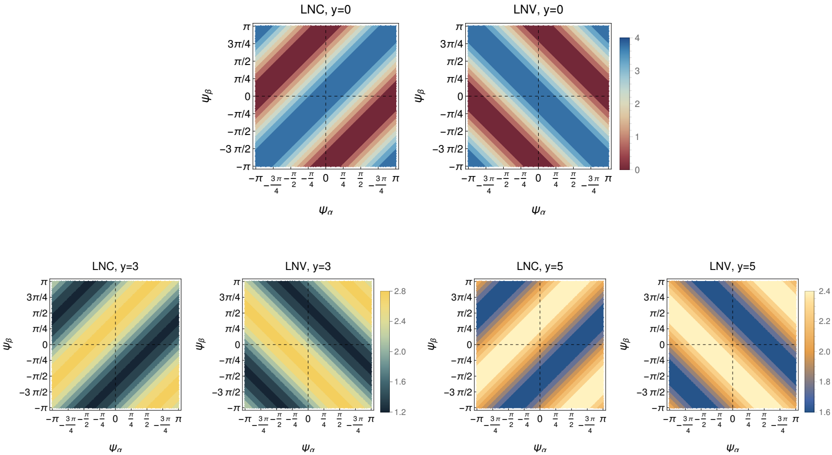
$$\overline{|\mathcal{M}_{\mathsf{LNV}}(2N)|^2} = \overline{|\mathcal{M}_{\mathsf{LNV}}(1N)|^2} R[y, \psi_+], \tag{11}$$

where $y = \Delta m_N / \Gamma_N$, $\psi_\alpha \equiv \phi_{\alpha 5} - \phi_{\alpha 4}$ and $R[y, \psi]$ is the recast function

$$R[y, \psi_\mp] \equiv 2\Big\{1 + \kappa(y)\big(\cos(\psi_\alpha \mp \psi_\beta) - y \sin(\psi_\alpha \mp \psi_\beta)\big)\Big\}, \tag{12}$$

with $\kappa(y) = 1/(1 + y^2)$.

Recast function



Detector length considerations

- We take into account the probability that the on-shell neutrino will decay inside the detector.

This effect is incorporated in the following probability weight:

$$P_\nu = 1 - \mathrm{Exp}\left(-L_{\mathrm{det}}\,\Gamma_N \frac{m_N}{|p_N|}\right), \tag{13}$$

where

- L_{det} is the detector length
- Γ_N the total decay width of the heavy neutrino
- p_N the heavy neutrino three-momentum in the laboratory frame of the decaying baryon

Therefore, the differential decay rate can be written as:

$$d\Gamma = P_\nu \overline{|\mathcal{M}|^2}\, dPS, \tag{14}$$

being dPS the corresponding differential Phase Space according to the transition.

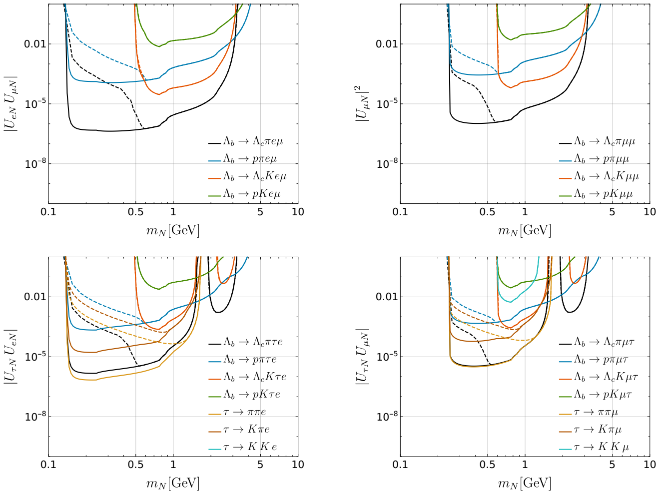
Considerations for calculation

- The neutrino decay width is taken as dependent on
  - the mass of the heavy neutrinos,
  - the heavy-light mixing parameters,
  - and the corresponding open channels.

- The exclusion regions were obtained under the assumption of an upper limit for the branching fraction of the four-body Λ_b decays to be $\mathrm{BR} \leq \mathcal{O}(10^{-8})$, motivated by the expected sensitivity to the process $\Lambda_b \to \Lambda_c(p)\pi\mu\mu$ at CMS and LHCb experiments [2].

[2] Jhovanny Mejia-Guisao, et al. Exploring GeV-scale Majorana neutrinos in lepton-number-violating Λ_b^0 baryon decays. *Phys.Rev.D 96 (2017) 1, 015039*

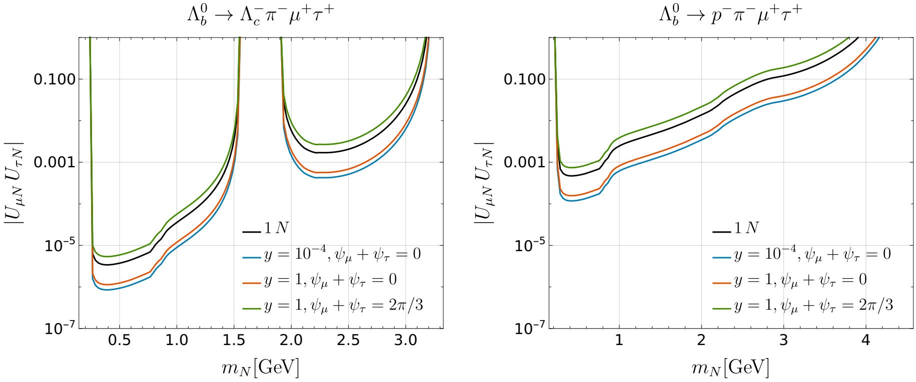
Exclusion region: heavy-light mixing vs heavy neutrino mass



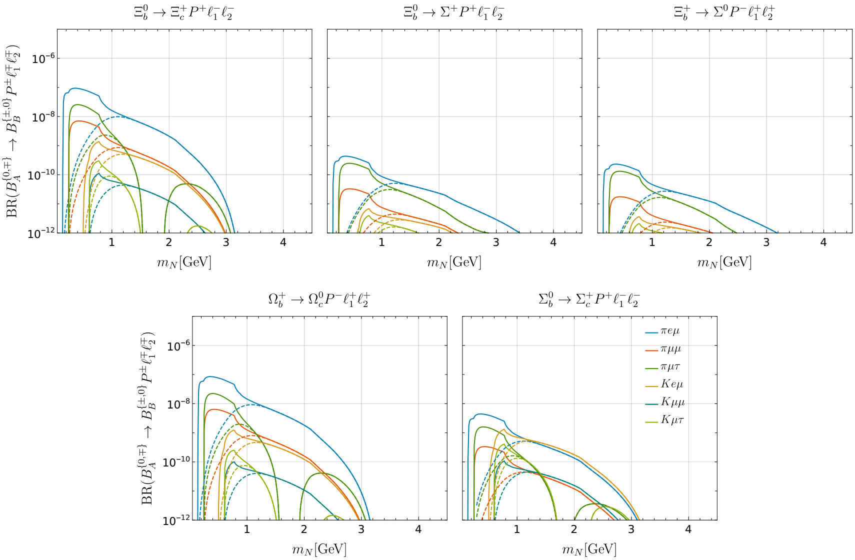
*LNV processes with only one Majorana neutrino.

*The dotted lines include the detector effects.

Scenario with two quasi-degenerate Majorana neutrinos



Branching ratios



*The dotted lines include detector effects.

Conclusions

Conclusions

- We have studied the LNC and LNV four-body decays of heavy baryons.
- Our analysis extends beyond the simplified assumption of a single heavy neutrino mixing with the active sector, by including two nearly degenerate heavy neutrinos.
- We profit from the so-called recast function, to illustrate the effect of the two-almost degenerate heavy neutrinos, as compared to the single case.
- A large set of heavy hadron transitions was considered.
- We determined the potential exclusion region for the mass and heavy-light mixing parameters of the neutrinos driving the decay.

Thank you!

Framework

- Simplified SM extensions that involve the addition of N extra neutral Majorana fermions.
- We don't make any assumptions about the mechanism responsible for neutrino mass generation (i.e., treating neutrino masses and lepton mixings as independent).

The leptonic charged current is modified as follows:

$$\mathcal{L}_{\rm c.c} \quad = \quad -\frac{g}{\sqrt{2}} U_{\alpha i}\, \bar{\ell}_\alpha \gamma_\mu P_L \nu_i W^-_\mu + {\rm h.c.}, \tag{15}$$

where $P_L = (1-\gamma_5)/2$ is the left-handed chirality projector, the subindex i refers to the physical neutrino states (3 light plus N heavy states), and the subindex α represents the flavor of the charged leptons.

Matrix elements for the heavy-light mixings are denoted by

$$U_{\alpha i} = e^{i\phi_{\alpha i}} |U_{\alpha i}|, \quad \alpha = e, \mu, \tau, \quad i = 4, 5 \tag{16}$$

where $\phi_{\alpha i}$ is the phase of the associated mixing element.
*More realistic models (motivated to accommodate the mass generation mechanism [3]) invoke two almost degenerate Majorana neutrinos, with masses in the GeV region.

[3] Eur. Phys. J. C 82, 1030 (2022), J. High Energy Phys. 07 (2024) 060.

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We focus on lepton flavor violating (LFV) decays , i.e., with $\ell_\alpha \neq \ell_\beta$, to isolate the sterile neutrino contributions. We obtain the amplitude for $B_A^{\{0,-\}}(p_A) \to B_B^{\{+,0\}}(p_B)\ P^-(p_P)\ell_\beta^-(p_1)\ell_\alpha^+(p_2)$

$$\mathcal{M}_{\text{LNC}} = G\, p_P^\nu \sum_{i=4,5} U_{\beta i}\, U_{\alpha i}^*\, \ell_{\mu\nu}^{\text{LNC}}\, P_{1i}\, H^\mu(p_B, p_A)\,, \tag{17}$$

where we have defined $G \equiv G_F^2 V_{AB} V_P f_P$, with V_P and V_{AB} the mixing quark elements of the CKM matrix, and f_P the decay constant of the meson state. The leptonic part is given by

$$\ell_{\mu\nu}^{\text{LNC}} \equiv \bar{u}(p_1)\gamma_\mu \not{a}_1 \gamma_\nu (1-\gamma_5) v(p_2), \tag{18}$$

where $a_1 \equiv p_A - p_B - p_1$ is the momentum carried out by either of the heavy neutrinos, and we have defined

$$P_{1i} \equiv \frac{1}{a_1^2 - m_i^2 + i m_i \Gamma_i}. \tag{19}$$

Hadronic part

- The meson production coming from the W is parameterized by $if_P p_P^\nu$.
- Baryon transition matrix element

$$H^\mu(p_B, p_A) \equiv \langle B_B(p_B)|J^\mu|B_A(p_A)\rangle\,, \tag{20}$$

in the most general form is parameterized by six form factors, as follows

$$\begin{aligned}
&\langle B_B(p_B)|J_\mu|B_A(p_A)\rangle = \\
&\bar{u}(p_B)\Bigg[f_1(q^2)\gamma_\mu + if_2(q^2)\frac{\sigma_{\mu\nu}q^\nu}{M_A} + \frac{q_\mu f_3(q^2)}{M_A} \\
&+ g_1(q^2)\gamma_\mu\gamma_5 + ig_2(q^2)\frac{\sigma_{\mu\nu}q^\nu\gamma_5}{M_A} + \frac{q_\mu g_3(q^2)\gamma_5}{M_A}\Bigg]u(p_A),
\end{aligned} \tag{21}$$

with $q^2 = (p_A - p_B)^2$ the squared momentum transferred in the baryonic transition.

Interference terms

After squaring the amplitude for the LNC case, the interference terms can be stated in terms of the relative phases as

$$U^*_{\alpha 4}U_{\beta 4}U_{\alpha 5}U^*_{\beta 5}P_{14}P^*_{15} + U_{\alpha 4}U^*_{\beta 4}U^*_{\alpha 5}U_{\beta 5}P^*_{14}P_{15} = \\ |U_{\alpha 4}||U_{\beta 4}||U_{\alpha 5}||U_{\beta 5}|\left(e^{i(\psi_\alpha-\psi_\beta)}P_{14}P^*_{15} + e^{-i(\psi_\alpha-\psi_\beta)}P^*_{14}P_{15}\right)$$

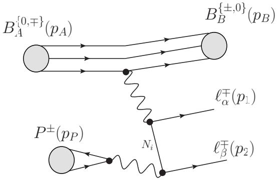
where $\psi_\alpha \equiv \phi_{\alpha 5} - \phi_{\alpha 4}$.

This squared amplitude can be recast into a single Majorana neutrino process, provided the masses satisfy $m_4 \simeq m_5 \equiv m_N$ and $\Delta m_N \equiv m_5 - m_4 \gtrsim 0$, the decay widths are $\Gamma_4 \simeq \Gamma_5 \equiv \Gamma_N$, the mixing parameters are thus also required to fulfill $|U_{\alpha 4}||U_{\beta 4}| = |U_{\alpha 5}||U_{\beta 5}| = |U_{\alpha N}||U_{\beta N}|$ and the relation between the $P_{1i}P^*_{1j}$

$$P_{14}P^*_{15} = \kappa(y)(1+iy)\frac{\pi}{m_N\Gamma_N}\delta\left(a_1^2 - m_N^2\right), \tag{22}$$

with $y = \Delta m_N/\Gamma_N$ and $\kappa(y) = 1/(1+y^2)$.

LNV $B_A^{\{0,\mp\}} \to B_B^{\{\pm,0\}} P^\pm \ell_\alpha^\mp \ell_\beta^\mp$ Decays



We obtain the amplitude for the specific decay mode $B_A^{\{0,+\}}(p_A) \to B_B^{\{-,0\}}(p_B)\ P^-(p_P)\ell_\alpha^+(p_1)\ell_\beta^+(p_2)$

$$\mathcal{M}_{\text{LNV}} = G\, p_P^\nu \sum_i U_{\alpha i}^* U_{\beta i}^* m_i H^\mu(p_B, p_A)$$
$$\left(\ell_{\mu\nu}^{\text{LNV}}(p_1,p_2) P_{1i} + \ell_{\nu\mu}^{\text{LNV}}(p_1,p_2) P_{2i}\right), \quad (23)$$

where the leptonic part in this case is written as

$$\ell_{\mu\nu}^{\text{LNV}}(p_1,p_2) \equiv \bar{u}(p_1)\gamma_\mu\gamma_\nu(1+\gamma_5)v(p_2), \quad (24)$$

We used $\ell_{\mu\nu}^{\text{LNV}}(p_2,p_1) = -\ell_{\nu\mu}^{\text{LNV}}(p_1,p_2)$, obtained by applying charge-conjugation relations.

Detector length considerations

- We take into account the probability that the on-shell neutrino will decay inside the detector.
- The detector consideration will directly affect the constraint on the branching fraction (and consequently to the heavy-light mixings), mainly for neutrinos with masses smaller than ~ 500 MeV (due to the large values of their lifetimes).

This effect is incorporated in the following probability weight:

$$P_\nu = 1 - \mathrm{Exp}\left(-L_{\mathrm{det}}\,\Gamma_N\,\frac{m_N}{|p_N|}\right), \tag{25}$$

where L_{det} is the detector length, Γ_N the total decay width of the heavy neutrino and p_N its three-momentum in the laboratory frame of the decaying baryon.

Therefore, the differential decay rate can be written as:

$$d\Gamma = P_\nu \overline{|\mathcal{M}|^2}\, dPS, \tag{26}$$

being dPS the corresponding Phase Space integral according to the transition.

Considerations for calculation

- For the estimations of the form factors, we use those obtained in the light-front model.
- The neutrino decay width is taken as dependent on
  - the mass of the heavy neutrinos,
  - the heavy-light mixing parameters,
  - and the corresponding open channels.
- In order to simplify the numerical evaluation, we take the universal coupling assumption, i.e., we consider $|U_{eN}| = |U_{\mu N}| = |U_{\tau N}|$.
- The exclusion regions were obtained under the assumption of an upper limit for the branching fraction of the four-body Λ_b decays to be $\mathrm{BR} \leq \mathcal{O}(10^{-8})$, motivated by the expected sensitivity to the process $\Lambda_b \to \Lambda_c(p)\pi\mu\mu$ at CMS and LHCb experiments [4].

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