Research Article

Method of Studying Λ_b^0 Decays with One Missing Particle

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A new technique is discussed that can be applied to Λ_b^0 baryon decays where decays with one missing particle can be discerned from background and their branching fractions determined, along with other properties of the decays. Applications include measurements of the CKM elements $|V_{ub}|$ and $|V_{cb}|$ and detection of any exotic objects coupling to $b \to s$ decays, such as the inflaton. Potential use of $\overline{B}^{0**} \to \pi^+ B^-$ and $\overline{B}_s^{0**} \to K^+ B^-$ to investigate B^- decays is also commented upon.

1. Introduction

Detection of b-flavored hadron decays with one missing neutral particle, such as a neutrino, is important for many measurements and searches. These include semileptonic decays, such as $\overline{B} \to D\mu^-\overline{\nu}$, $\overline{B} \to \pi\mu^-\overline{\nu}$, and any exotic long lived particles that could be produced in decays such as $\overline{B} \to X\chi$, where the X is any combination of detected particles and the χ escapes the detector. (In this paper mention of a particular decay mode implies the use of the charge-conjugated mode as well.) These measurements are possible at an e^+e^- collider operating at the $\Upsilon(4S)$. Since $\Upsilon(4S) \to B\overline{B}$, fully reconstructing either the B or the $\overline{B}$ determines the negative of the initial four-momentum of the other. With this information it is possible to measure final states where one particle is not detected, such as a neutrino. To implement this procedure, taking the $\overline{B}$ to be fully reconstructed, the missing mass-squared, m_x^2, is calculated including the information on the initial B four-momentum and measurements of the found X particles as

$$m_x^2 = (E_B - E_X)^2 - (\vec{p}_B - \vec{p}_X)^2, \qquad (1)$$

where E and $\vec{p}$ indicate energy and three-momentum, respectively. Peaks in m_x^2 would be indicative of single missing particles in the B decay.

A related example is charm semileptonic decays with a missing neutrino. Determinations of branching fractions and form-factors have been carried out in fixed target experiments, exploiting the measured direction of the charmed hadron and assuming that the missing particle has zero mass, which leads to a twofold ambiguity in the neutrino momentum calculation [1]. If the charm decay particle is a D^0, extra constraints can be imposed on its decay requiring it to be produced from a D^{*+} in the decay $D^{*+} \to \pi^+ D^0$. This leads to more constraints than unknowns and is quite useful for rejecting backgrounds [2, 3].

Interesting decays of the Λ_b^0 baryon also exist, but investigations are not feasible in the $\Upsilon(4S)$ energy region. Potential studies include determination of the CKM matrix element $|V_{cb}|$, which can be done using $\Lambda_b^0 \to \Lambda_c^+ \ell^-\overline{\nu}$ decays, and $|V_{ub}|$ using the $\Lambda_b^0 \to p\ell^-\overline{\nu}$ mode.

Neutral particles that have not yet been seen could be searched for, even if they are stable or have long enough lifetimes that they would have only a very small fraction of their decays inside the detection apparatus. One example of such a possibly long-lived particle is the "inflaton." This particle couples to a scalar field and is responsible for cosmological inflaton. Bezrukov and Gorbunov predicted branching fractions and decay modes of inflatons, χ, in $\overline{B}$ meson decays [4] using a specific model, which is a particular version of the simple chaotic inflation with a quartic potential
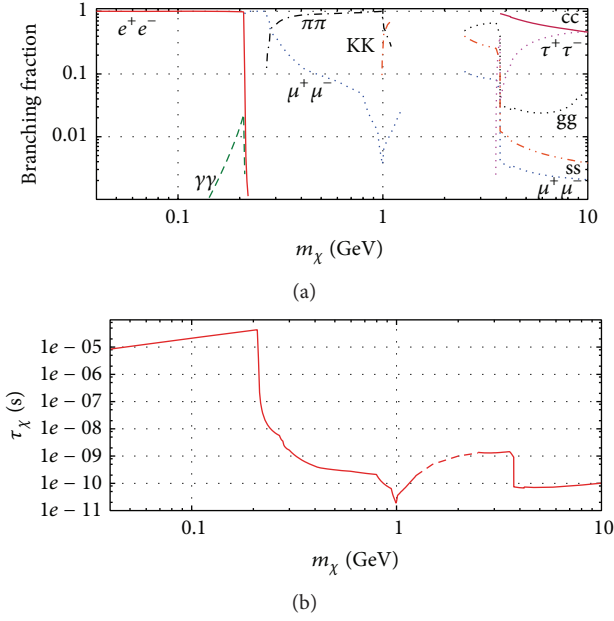
FIGURE 1: Predictions from [4]. (a) Inflaton branching ratios to various two-body final states as functions of inflaton mass for $m_\chi <$ 1.5 GeV. Above 2.5 GeV only quark-antiquark and dilepton modes are predicted. In the intermediate region no reliable prediction is given. (b) Inflaton lifetime τ_χ as a function of the inflaton mass m_χ. The lifetime can be up to two times smaller, depending on model-dependent parameters.

and having the inflaton field coupled to the SM Higgs boson via a renormalizable operator. For $\overline{B} \rightarrow \chi X_s$ decays the branching fraction is

$$
\mathcal{B}\left(\overline{B} \longrightarrow \chi X_s\right) \simeq 0.3 \frac{\left|V_{ts} V_{tb}^*\right|^2}{\left|V_{cb}\right|^2} \left(\frac{m_t}{M_W}\right)^4 \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \theta^2
$$

$$
\simeq 10^{-6} \cdot \left(1 - \frac{m_\chi^2}{m_b^2}\right)^2 \left(\frac{\beta}{\beta_0}\right) \left(\frac{300 \text{ MeV}}{m_\chi}\right)^2, \tag{2}
$$

where X_s stands for strange meson channels mostly saturated by a sum of K and $K^*(890)$ mesons, m_χ and m_t, the inflaton and top quark masses, respectively. The model parameters are θ, β, and β_0, where $\beta/\beta_0 \approx \mathcal{O}(1)$. Their inflaton branching fraction predictions are shown in Figure 1(a). The branching fractions are quite similar for Λ_b^0 decays. The $\Lambda_b^0 \rightarrow pK^-\chi$ channel would seem to be the most favorable, since the Λ_b^0 decay point could be accurately determined from the pK^- vertex. The mass dependent inflaton branching fraction predictions for different decay modes are shown in Figure 1(a). Collider searches that rely on directly detecting the inflaton decay products may not be sensitive to lifetimes much above a few times 1 ns [5], because the particles mostly decay outside of the detector, while searches that could be done inclusively, for example, without detecting the inflaton decay products, would be independent of this restriction.

Use of Λ_b^0 decays in measuring CKM matrix elements as well as new particle searches has been not as fruitful as in B meson decays because e^+e^- machines have access only to the lighter B mesons. In addition, absolute branching fraction determinations have been made difficult by the relatively large uncertainty on $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$. Recently, the Belle collaboration reduced this uncertainty from 25% to about 5%, allowing for measurements with much better precision [6].

Inclusive decay searches using Λ_b^0 baryons can be made at high energy colliders if it were possible to find a way to estimate the Λ_b^0 momentum. The Λ_b^0 direction is measured by using its finite decay distance. To get an estimate of the Λ_b^0 energy we can use Λ_b^0's that come from $\Sigma_b^\pm \rightarrow \pi^\pm \Lambda_b^0$ and $\Sigma_b^{*\pm} \rightarrow \pi^\pm \Lambda_b^0$ decays. The $\Sigma_b^{(*)\pm}$ states were found by the CDF collaboration [7]. Their masses and widths are consistent with theoretical predictions [8].

The Λ_b^0 energy is determined from the measurement of the $\pi^\pm$ from the $\Sigma_b^{(*)}$ decay along with the Λ_b^0 direction. Let us assume we have a pion from the $\Sigma_b^{(*)}$ decay. Then

$$
m_{\Sigma_b^{(*)}}^2 = \left(E_\pi + E_{\Lambda_b^0}\right)^2 - \left(\vec{p}_\pi + \vec{p}_{\Lambda_b^0}\right)^2, \tag{3}
$$

and after some algebraic manipulations we find

$$
\left|p_{\Lambda_b^0}\right| = \frac{\left(-b \pm \sqrt{b^2 - 4ac}\right)}{(2a)}
$$

$$
a = 4\left(E_\pi^2 - p_\pi^2 \cos^2\theta\right)
$$

$$
b = -4p_\pi \Delta_m^2 \cos\theta \tag{4}
$$

$$
c = 4E_\pi^2 m_{\Lambda_b^0}^2 - \Delta_m^4
$$

$$
\Delta_m^2 = m_{\Sigma_b^{(*)}}^2 - m_\pi^2 - m_{\Lambda_b^0}^2,
$$

where $\cos\theta$ is the measured angle between the pion and the Λ_b^0, and $m_{\Sigma_b^{(*)}}$ indicates either the Σ_b or Σ_b^* mass. With the measured Λ_b^0 direction and Λ_b^0 energy taken from (1) can now be used to find decays having detected charged particles and one missing particle. Two possible solutions result because of the $\pm$ sign in the first line of (4). In similar studies one solution is often unphysical. This was seen, for example, using $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ decays with one missing pion [9]. The resolution in m_χ^2 depends on several quantities including the measurement uncertainties on momentum of the final state particles and the Λ_b^0 direction, so it may be advantageous for analyses to select long-lived decays at the expense of statistics. The relatively long Λ_b^0 lifetime of about 1.5 ps is helpful in this respect [10, 11].

The $\Sigma_b^{(*)\pm}$ states have only been seen by CDF [7]. Their data are shown in Figure 2 and listed in Table 1.

2. Potential Measurements

Although there is no measurement of the relative $\Sigma_b^{(*)\pm}/\Lambda_b^0$ production cross-section, $r_{\Sigma\Lambda}$, one might imagine that the
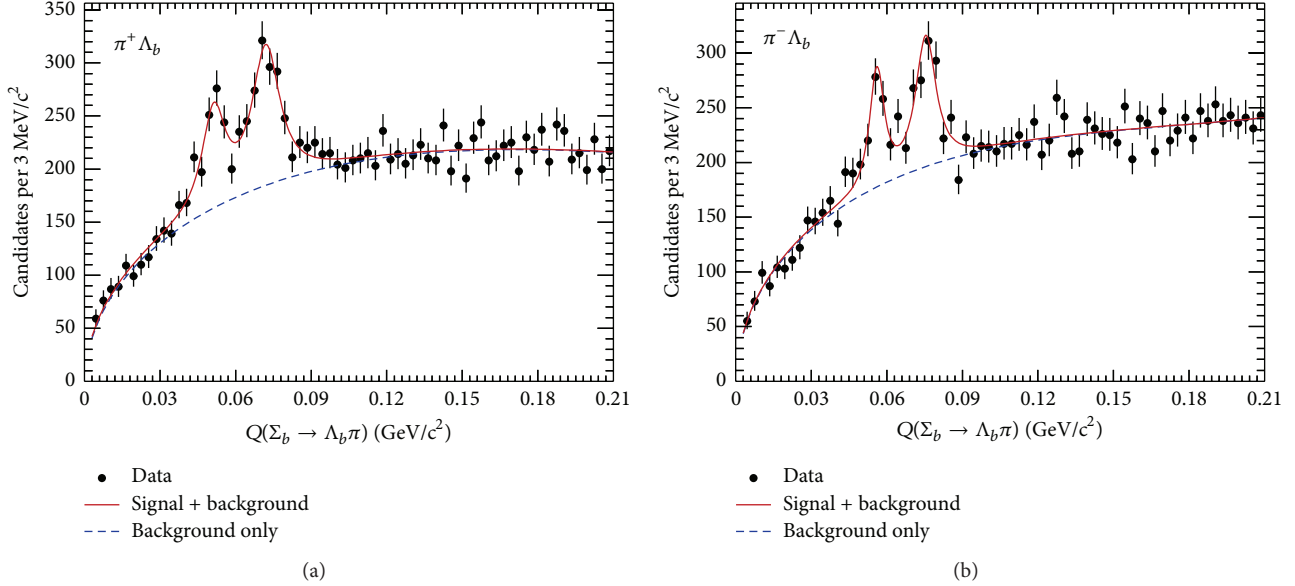
FIGURE 2: The $Q = M(\Lambda_b^0 \pi^\pm) - M(\Lambda_b^0) - m_\pi$ spectrum for candidates with the projection of the corresponding unbinned likelihood fit superimposed, (a) for $\pi^+ \Lambda_b^0$ and (b) for $\pi^- \Lambda_b^0$ candidates (from [7]).

TABLE 1: Summary of the results of the fits to the $Q = M(\Lambda_b^0 \pi^\pm) - M(\Lambda_b^0) - m_\pi$ spectra from CDF [7].

State	Q value, MeV	Natural width, Γ_0, MeV	Yield
Σ_b^-	$56.2^{+0.6}_{-0.5}$	$4.9^{+3.1}_{-2.1}$	340^{+90}_{-70}
Σ_b^{*-}	75.8 ± 0.6	$7.5^{+2.2}_{-1.8}$	540^{+90}_{-80}
Σ_b^+	$52.1^{+0.9}_{-0.8}$	$9.7^{+3.8}_{-2.8}$	470^{+110}_{-90}
Σ_b^{*+}	72.8 ± 0.7	$11.5^{+2.7}_{-2.2}$	800^{+110}_{-100}

production ratio would be close to unity. The pions from the $\Sigma_b^{(*)\pm}$ decays have relatively low momenta, so their detection efficiencies could be small. Although CDF does not report a value for the production ratio, the number of seen signal events gives an observed value of $r_{\Sigma\Lambda}$ equal to 13%. This is certainly a useful sample. Backgrounds will be an issue, however, as the CDF data do show a substantial amount of nonresonant combinations under the signal peaks, but this will not prevent searches, but just limit their sensitivities with a given data sample.

Measurement of $|V_{cb}|$ determined using $\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \overline{\nu}$ decays with $\Lambda_c^+ \rightarrow pK^- \pi^+$ would provide an important cross-check on this important fundamental parameter, especially when updated lattice gauge calculations become available [12]. This measurement is not subject to the uncertainty on $\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+)$ provided that the total number of Λ_b^0 events in the event sample is determined using the same branching fraction [13]. The LHCb determination of the ratio of Λ_b^0 to $\overline{B}^0$ production, for example, uses the $\Lambda_c^+ \rightarrow pK^- \pi^+$ decay mode [14], and then the absolute number of Λ_b^0 events produced is found by measuring the $\overline{B}^0$ rate in a channel with a known branching fraction. The branching ratio for the channel $\Lambda_b^0 \rightarrow \Lambda_c^+ \ell^- \overline{\nu}$ can be determined using (1) using the

measured value for the Λ_b^0 energy determined by using (4); a signal would appear near m_x^2 equal to zero. To determine the four-momentum transfer squared from the Λ_b^0 to the Λ_c^+, a similar procedure as used in the decay sequence $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^{*-} \ell^+ \nu$ can be implemented [2, 3]. In this procedure, the neutrino mass is set to zero,

$$\left(E_{\Lambda_b^0} - E_X\right)^2 - \left(\vec{p}_{\Lambda_b^0} - \vec{p}_X\right)^2 = m_x^2 = 0, \tag{5}$$

where X represents the sum of Λ_c^+ and ℓ^- energies and momenta. Equations (3) and (5) can be used as two constraint equations with one unknown variable $|p_{\Lambda_b^0}|$.

Measurement of $|V_{ub}|$ using $\Lambda_b^0 \rightarrow p\ell^- \overline{\nu}$ decays is subject to the uncertainty on $\mathcal{B}(\Lambda_c^+ \rightarrow pK^- \pi^+)$, but here the current precision of 5% on this branching fraction is sufficient. Theoretical calculations of the decay width from the lattice gauge calculations done in a limited four-momentum transfer range [15], light cone sum rules [16–19], and QCD sum rules [20, 21] can be used to extract $|V_{ub}|$. The $p\ell^- \overline{\nu}$ final state is subject to backgrounds from $N^* \ell^- \overline{\nu}$, where $N^* \rightarrow p\pi^0$, that are difficult to eliminate and thus the use of the $\Sigma_b^{(*)\pm} \rightarrow \pi^\pm \Lambda_b^0$ decay sequence may be crucial. The decay sequence constraint can also possibly help measure the branching fraction for $\Lambda_b^0 \rightarrow \Lambda_c^{(*)+} \tau^- \overline{\nu}$ decays as measurements in the $\overline{B}$ meson system of analogous decays are somewhat larger than Standard Model predictions [22, 23].

Particles characteristic of scalar fields such as inflatons or dilatons can be searched for in Λ_b^0 decays. It is also possible to search for Majorana neutrinos through a process similar to that used for searches in $B^- \rightarrow \mu^- \mu^- \pi^+$ decays [5, 24, 25], where the Majorana neutrino, ν_M, decays into a $\mu^- \pi^+$ pair. The initial quark content of the Λ_b^0 is bud. The b-quark can annihilate with a $\overline{u}$-quark from a $u\overline{u}$ pair

arising from the vacuum into a virtual W^- leaving a *uud* system that can form a p. The virtual W^- then can decay into μ^- in association with a Majorana neutrino that can transform to its own antiparticle and decay into μ^- and a virtual W^+. In the analogous case to the $B^- \rightarrow \mu^- \mu^- \pi^+$ decay, the W^+ would decay into a π^+; however here we do not have to detect the Majorana decays, so we can look for the decay $\Lambda_b^0 \rightarrow p\mu^- \nu_M$ independently of the ν_M decay mode or lifetime. Other mechanisms for Majorana neutrino production discussed in [26] for B^- decays when adopted to Λ_b^0 decays would also lead to the $p\mu^- \nu_M$ final state.

A more mundane search can be considered for Λ_b^0 decays into noncharmed final states containing $\Sigma^{\pm}$ light baryons; these have been proposed for flavor SU(3) tests [27]. Since the largest decay modes are $\Sigma^- \rightarrow n\pi^-$, and $\Sigma^+ \rightarrow n\pi^+$ or $p\pi^0$, there is always a missing neutron in the Σ^- decay, while the Σ^+, in principle, can be detected in the $p\pi^0$ mode. The method suggested here can be adopted to search for both Σ^- and Σ^+ baryons in Λ_b^0 decays.

Note that similar methods can be applied to B^- decays by the use of the $\overline{B}^{0**} \rightarrow \pi^+ B^-$ decay sequence. The measured production ratio of $(\overline{B}^{0**} \rightarrow \pi^+ B^-)/B^-$ is about 15%, but the B^{0**}'s have widths of about 130 MeV which introduces very large backgrounds that have thus far precluded their use. Another possible source of tagged B^- events is the decays of $\overline{B}_s^{0**}$ mesons into a $K^+ B^-$ that would have the advantage of a charged kaon tag and have a much narrower width.

In conclusion, we propose a new method of analyzing Λ_b^0 decays into one missing particle, where the Λ_b^0 is part of a detected $\Sigma_b^{(*)\pm} \rightarrow \pi^{\pm}\Lambda_b^0$ decay that provides additional kinematic constraints. This method may be useful for studies of CKM elements and searches for new particles such as inflatons, dilatons, or Majorana neutrinos. Thus, investigations of Λ_b^0 decays may present a unique opportunity in the study of b-flavored hadron decays.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.
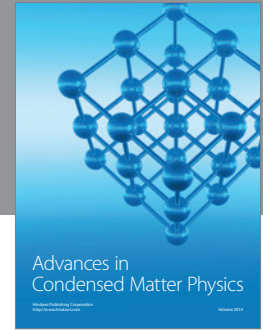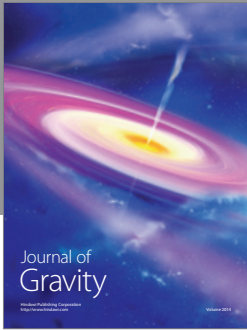
Acknowledgments

References

[1] E791 Collaboration and E. Aitala, "Measurement of the form-factor ratios for $\overline{K}^{*0} \ell^+ \nu_\ell$," *Physics Letters B*, vol. 440, p. 435, 1998.

[2] J. Link and FOCUS Collaboration, "Analysis of the semileptonic decay $D^0 \rightarrow \overline{K}^- \pi^- \mu^+ \upsilon$," *Physics Letters B*, vol. 607, p. 67, 2005.

[3] L. Agostino, "Pseudoscalar Semileptonic Decays of the D^0 Meson," FERMILAB-THESIS-2004-59, UMI-31-53801-MC, 2004.

[4] F. Bezrukov and D. Gorbunov, "Light inflaton hunter's guide," *Journal of High Energy Physics*, vol. 1005, p. 10, 2010.

[5] R. Aaij, "Search for Majorana neutrinos in $B^- \rightarrow \pi^+ \mu^- \mu^-$ decays," *Physical Reivew Letters*, vol. 112, Article ID 131802, 2014.

[6] Belle Collaboration, A. Zupanc, C. Bartel et al., "Measurement of the branching fraction $\Lambda_c^+ \rightarrow pK^- \pi^+$," *Physical Review Letters*, vol. 113, Article ID 042002, 2014.

[7] CDF Collaboration, T. Aaltonen, B. Álvarez González et al., "Measurement of the masses and widths of the bottom baryons $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$," *Physical Review D*, vol. 85, Article ID 092011, 2012.

[8] M. Karliner, B. Keren-Zur, H. J. Lipkin, and J. L. Rosner, "The quark model and b baryons," *Annals of Physics*, vol. 324, no. 1, pp. 2–15, 2009.

[9] LHCb Collaboration and R. Aaij, "Measurement of the $D_s^+ - D_s^-$ production asymmetry in 7 TeV pp collisions," *Physics Letters B*, vol. 713, p. 186, 2012.

[10] LHCb Collaboration, R. Aaij, B. Adeva et al., "Precision measurement of the Λ_b^0 baryon lifetime," *Physical Review Letters*, vol. 111, no. 10, Article ID 102003, 2013.

[11] LHCb Collaboration and R. Aaij, "Measurements of the B^+, B^0, B_s^0 meson and Λ_b^0 baryon lifetimes," *Journal of High Energy Physics*, vol. 1404, p. 114, 2014.

[12] UKQCD Collaboration, K. C. Bowler, R. D. Kenway et al., "First lattice study of semileptonic decays of Λ_b^0 and Ξ_b baryons," *Physical Review D*, vol. 57, p. 6948, 1998.

[13] LHCb Collaboration, R. Aaij, B. Adeva et al., "Study of the kinematic dependences of Λ_b^0 production in pp collisions and a measurement of the $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ branching fraction," http://arxiv.org/abs/1405.6842.

[14] LHCb Collaboration and R. Aaij, "Updated average f_s/f_d hadron production fraction ratio for 7 TeV pp collisions," LHCb-CONF-2013-011, CERN-LHCb-CONF-2013-011, 2013.

[15] W. Detmold, C. J. D. Lin, S. Meinel, and M. Wingate, "$\Lambda_b^0 \rightarrow p\ell^- \overline{\nu}$ form factors from lattice QCD with static b quarks," *Physical Review D*, vol. 88, Article ID 014512, 2013.

[16] A. Khodjamirian, C. Klein, T. Mannel, and Y.-M. Wang, "Form factors and strong couplings of heavy baryons from QCD light-cone sum rules," *Journal of High Energy Physics*, vol. 1109, article 106, 2011.

[17] Y.-M. Wang, Y.-L. Shen, and C.-D. Lu, "$\Lambda_b^0 \rightarrow p, \Lambda$ transition form factors from QCD light-cone sum rules," *Physical Review D*, vol. 80, Article ID 074012, 2009.

[18] K. Azizi, M. Bayar, Y. Sarac, and H. Sundu, "Semileptonic $\Lambda_{b,c}$ to nucleon transitions in full QCD at light cone," *Physical Review D*, vol. 80, Article ID 096007, 2009.

[19] M.-Q. Huang and D.-W. Wang, "Light cone QCD sum rules for the semileptonic decay $\Lambda_b^0 \rightarrow p\mu^- \overline{\nu}$," *Physical Review D*, vol. 69, Article ID 094003, 2004.

[20] R. S. Marques de Carvalho, F. S. Navarra, M. Nielsen et al., "Form-factors and decay rates for heavy Lambda semileptonic decays from QCD sum rules," *Physical Review D*, vol. 60, Article ID 034009, 1999.

[21] C.-S. Huang, C.-F. Qiao, and H.-G. Yan, "Decay $\Lambda_b^0 \rightarrow p\mu^- \overline{\nu}$ in QCD sum rules," *Physics Letters B*, vol. 437, p. 403, 1998.

[22] BaBar Collaboration, J. Lees, V. Poireau et al., "Measurement of an excess of $\overline{B} \rightarrow D^{(*)} \tau^- \overline{\nu}_\tau$ decays and implications for charged Higgs bosons," *Physical Review D*, vol. 88, Article ID 072012, 2013.

[23] Belle Collaboration and I. Adachi, "Measurement of $\overline{B} \rightarrow D^{(*)} \tau^- \overline{\nu}$ using full reconstruction tags," http://arxiv.org/abs/0910.4301.

[24] LHCb Collaboration, R. Aaij, C. A. Beteta et al., " Searches for Majorana neutrinos in B$^-$ decays," *Physical Review D*, vol. 85, Article ID 112004, 2012.

[25] LHCb Collaboration, R. Aaij, C. A. Beteta et al., "Search for the lepton number violating decays $B^+ \rightarrow \pi^- \mu^+ \mu^+$ and $B^+ \rightarrow K^- \mu^+ \mu^+$," *Physical Review Letters*, vol. 108, Article ID 101601, 2012.

[26] G. L. Castro and N. Quintero, "Bounding resonant Majorana neutrinos from four-body *B* and *D* decays," *Physical Review D*, vol. 87, Article ID 077901, 2013.

[27] M. Gronau and J. L. Rosner, "Flavor SU(3) and Λ_b^0 decays," *Physical Review D*, vol. 89, Article ID 037501, 2014.