Method of Studying $\Lambda_b$ decays with one missing particle

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Abstract

A new technique is discussed that can be applied to $\Lambda_b$ 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 $|V_{cb}|$, selected charmless decays, and detection of any exotic objects coupling to $b \rightarrow s$ decays, such as the inflaton.

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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 $B \rightarrow D\mu^{-}\bar{\nu}$, $B \rightarrow \pi\mu^{-}\bar{\nu}$, and any exotic long lived particles that could be produced in decays such as $B \rightarrow X\chi$, where the $X$ is any combination of detected particles and the $\chi$ escapes the detector. These measurements are possible at an $e^{+}e^{-}$ collider operating at the $\Upsilon(4S)$. Since $\Upsilon(4S) \rightarrow BB$, fully reconstructing either the $B$ or the $\bar{B}$ determines 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, the missing mass-squared, $m_{x}^{2}$, is calculated including the information on the initial $B$ and measurements of the found $X$ particles,

$$m_{x}^{2} = (E_{B} - E_{X})^{2} - (\vec{p}_{B} - \vec{p}_{X})^{2}, \quad (1)$$

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 $B$ hadron 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 two-fold 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 $D^{*+} \rightarrow \pi^{+}D^{0}$. This leads to more constraints than unknowns, and is quite useful for rejecting backgrounds [2].

Interesting decays of the $\Lambda_{b}^{0}$ baryon decays also exist, studies of which are not feasible in the $\Upsilon(4S)$ energy region. Determination of the CKM matrix element $|V_{cb}|$ is possible using $\Lambda_{b}^{0} \rightarrow \Lambda_{c}^{+}\ell^{-}\bar{\nu}$ decays and $|V_{ub}|$ can be found using the $\Lambda_{b}^{0} \rightarrow p\ell^{-}\bar{\nu}$ 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.

In a specific model, Bezrukov and Gorbunov predicted branching fractions and decay modes of inflatons, $\chi$, in $B$ meson decays [3]. For $B \rightarrow \chi X_{s}$ decays the branching fraction is

$$B(B \rightarrow \chi X_{s}) \simeq 0.3 \left| V_{ts}V_{tb}^{\ast} \right|^{2} \left( \frac{m_{t}}{M_{W}} \right)^{4} \left( 1 - \frac{m_{X}^{2}}{m_{b}^{2}} \right)^{2} \beta^{2} \Theta^{2}, \quad (2)$$

$$\simeq 10^{-6} \cdot \left( 1 - \frac{m_{X}^{2}}{m_{b}^{2}} \right)^{2} \left( \frac{\beta}{\beta_{0}} \right) \left( \frac{300 \text{ MeV}}{m_{X}} \right)^{2},$$

\[1\] In this paper mention of a particular decay mode implies the use of the charge-conjugated mode as well.
where $X_s$ stands for strange meson channels mostly saturated by a sum of pseudoscalar and vector kaons, $m_\chi$ and $m_t$, the inflaton and top quark masses, respectively, and $\theta$, $\beta$ and $\beta_0$ are model parameters, where $\beta/\beta_0 \approx O(1)$. Their inflaton branching fraction predictions are shown in Fig. 1(a). The branching fractions are quite similar for $\Lambda^0_b$ decays. The $\Lambda^0_b \to pK^-\chi$ channel would seem to be the most favorable, since the $\Lambda^0_b$ decay point could be accurately determined from the $pK^-$ vertex. The inflaton decay mode predictions, which depend on inflaton mass, are shown in Fig. 1(b). Collider searches that rely on decay mode detection may not be sensitive to lifetimes much below a few times 1 ns [4], because the particles mostly decay outside of the detector, while searches that could be done inclusively, e.g., without detecting the inflaton decay products, would be independent of this restriction.

Use of $\Lambda^0_b$ 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

Figure 1: Predictions from [3]. (a) Inflaton branching ratios to various two-body final states as functions of inflaton mass $m_\chi$; for the 1.5-2.5 GeV range see discussion in the main text; (b) inflaton lifetime $\tau_\chi$ as a function of the inflaton mass $m_\chi$. The lifetime can be up to two times smaller, depending on model-dependent parameters.
the lighter $B$ mesons. In addition, absolute branching fraction determinations have been made difficult by the relatively large uncertainty on $\mathcal{B}(A^+_1 \to pK^-\pi^+)$. Recently, the Belle collaboration reduced this uncertainty from 25\% to about 5\%, allowing for measurements with much better precision [5].

Inclusive decay searches using $A^0_b$ baryons can be made at high energy colliders if it were possible to find a way to estimate the $A^0_b$ momentum. The $A^0_b$ direction is measured by using its finite decay distance. To get an estimate of the $A^0_b$ energy we can use $A^0_b$'s that come from $\Sigma^0_b \to \pi^0A^0_b$ and $\Sigma^{+\pm}_b \to \pi^\pm A^0_b$ decays. The $\Sigma^{(\ast)}_b$ states were found by the CDF collaboration [6]. Their masses and widths are consistent with theoretical predictions [7].

The $A^0_b$ energy is determined from the measurement of the $\pi^\pm$ from the $\Sigma^{(\ast)}_b b$ decay along with the $A^0_b$ direction. Let us assume we have a pion from the $\Sigma^{(\ast)}_b b$ decay. Then

$$m^2_{\Sigma^{(\ast)}_b} = (E_\pi + E_{A_b})^2 - (\vec{p}_\pi + \vec{p}_{A_b})^2,$$

and after some algebraic manipulations we find

$$|p_{A_b}| = \frac{(-b \pm \sqrt{b^2 - 4ac})}{2a}$$

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

$$b = -4p_\pi \Delta^2_m \cos \theta$$

$$c = 4E_\pi^2 m_{A_b}^2 - \Delta^4_m$$

$$\Delta^2_m = m^2_{\Sigma^{(\ast)}_b} - m^2_\pi - m^2_{A_b},$$

where $\cos \theta$ is the measured angle between the pion and the $A^0_b$, and $m_{\Sigma^{(\ast)}_b}$ indicates either the $\Sigma_b$ or $\Sigma^{(\ast)}_b$ mass. With the measured $A^0_b$ direction and $A^0_b$ energy Eq. (1) can now be used to find decays with any number of detected and one missing particle. The resolution in $m^2_x$ depends on several quantities including the measurement uncertainties on momentum of the final state particles and the $A^0_b$ direction, so it may be advantageous for analyses to select long-lived decays at the expense of statistics. The relatively long $A^0_b$ lifetime of about 1.5 ps is helpful in this respect [8].

The $\Sigma^{(\ast)}_b$ states have only been seen by CDF [6]. Their data are shown in Fig. 1 and listed in Table 1.

2 Potential measurements

Although there is no measurement of the relative $\Sigma^{(\ast)}_b/A^0_b$ production cross-section, $r_{\Sigma\Lambda}$, one might imagine that the production ratio would be close to unity. The pions from the $\Sigma^{(\ast)}_b$ 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...
Table 1: Summary of the results of the fits to the $Q = M(A_0^0 \pi^+) - M(A_0^0) - m_\pi$ spectra from CDF \[6\].

| State $\Sigma_{b-}$ | $Q$ value, MeV | Natural width, $\Gamma_0$, MeV | Yield |
|---------------------|----------------|------------------------------|-------|
| $\Sigma_{b-}$       | 56.2$^{+0.6}_{-0.5}$ | $4.9^{+3.1}_{-2.1}$ | $340^{+90}_{-70}$ |
| $\Sigma_{b-}'$      | 75.8$^{+0.6}_{-0.5}$ | $7.5^{+2.2}_{-1.8}$ | $540^{+90}_{-80}$ |
| $\Sigma_{b+}$       | 52.1$^{+0.9}_{-0.8}$ | $9.7^{+3.8}_{-2.8}$ | $470^{+110}_{-90}$ |
| $\Sigma_{b+}'$      | 72.8$^{+0.7}_{-0.5}$ | $11.5^{+2.7}_{-2.2}$ | $800^{+110}_{-100}$ |

non-resonant combinations under the signal peaks, but this will not prevent searches, just limit their sensitivities with a given data sample.

Measurement of $|V_{cb}|$, determined using $A_0^0 \rightarrow A_+^0 \ell^- \nu$ decays with $A_+^+ \rightarrow pK^-\pi^+$ would provide an important cross-check on this important fundamental parameter, especially when updated lattice gauge calculations become available \[9\]. This measurement is not subject to the uncertainty on $B(A_+^+ \rightarrow pK^-\pi^+)$ provided that the total number of $A_0^0$ events in the event sample is determined using the same branching fraction \[10\]. The LHCb determination of the ratio of $A_0^0$ to $B^0$ production, for example, uses the $A_+^+ \rightarrow pK^-\pi^+$ decay mode \[11\], and then the absolute number of $A_0^0$ events produced is found by measuring the $B^0$ rate in a channel with a known branching fraction. The branching ratio for the channel $A_b \rightarrow A_+^0 \ell^- \nu$ can be determined using Eq. (1) using the measured value for the

Figure 2: The $Q = M(A_0^0 \pi^+) - M(A_0^0) - m_\pi$ spectrum for candidates with the projection of the corresponding unbinned likelihood fit superimposed, (a) for $\pi^+ A_b$ and (b) for $\pi^- A_b$ candidates. (From Ref. \[6\]).
$\Lambda_b^0$ energy determined by using Eq. (4); a signal would appear near $m_x^2$ equal to zero. To determine the four-momentum transfer squared from the $\Lambda_b^0$ to the $\Lambda_c^+$ a similar procedure as used in the decay sequence $D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\ell^+\nu$ can be implemented [2]. In this procedure, the neutrino mass is set to zero,

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

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

Theoretical calculations of the decay width from the lattice, done in a limited four-momentum transfer range [12], light cone sum rules [13,14], and QCD sum rules [15] can be used to extract $|V_{ub}|$. The $p\ell^-\bar{\nu}$ final state is subject to backgrounds from $N^*\ell^-\bar{\nu}$, where $N^* \rightarrow p\pi^0$, that are difficult to eliminate and thus the use of the $\Sigma_b^{(*)\pm} \rightarrow \pi^{\pm}\Lambda_b$ decay sequence may be crucial. The decay sequence constraint can also possibly help measure the branching fraction for $\Lambda_b^0 \rightarrow \Lambda_c^{(*)}\tau^-\bar{\nu}$ decays as measurements in the $B$ meson system of analogous decays are somewhat larger than Standard Model predictions [16].

Particles characteristic of scalar fields such as inflatons or dilatons can be searched for in $\Lambda_b^0$ 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 [4,17], where the Majorana neutrino, $\nu_M$, decays into a $\mu^-\pi^+$ pair. The initial quark content of the $\Lambda_b^0$ is $buds$. The $b$-quark can annihilate with a $\bar{u}$-quark from a $u\bar{d}$ 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 $\mu^-$ in association with a Majorana neutrino that can transform to its own anti-particle and decay into $\mu^-$ and a virtual $W^+$. In the analogous case to the $B^- \rightarrow \mu^-\mu^-\pi^+$ decay, the $W^+$ would decay into a $\pi^+$, 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 $\nu_M$ decay mode or lifetime. Other mechanisms for Majorana neutrino production discussed in Ref. [18] for $B^-$ decays when adopted to $\Lambda_b^0$ decays, would also lead to the $p\mu^-\nu_M$ final state.

A more mundane search can be considered for $\Lambda_b^0$ decays into non-charmed final states containing $\Sigma^\pm$ light baryons; these have been proposed for for flavor SU(3) tests [19]. 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 $\Sigma^-$ decay, while the $\Sigma^+$, in principle, can be detected in the $p\pi^0$ mode. The method suggested here can be adopted to search for both $\Sigma^-$ and $\Sigma^+$ baryons in $\Lambda_b^0$ decays.

Note that similar methods can be applied to $B^-$ decays by the use of the $B^{*0} \rightarrow \pi^{+}B^-$ decay sequence. The measured production ratio of $(B^{*0} \rightarrow \pi^{+}B^-) / B^-$ is about 15%, but the $B^{*0}$'s have widths of about 130 MeV which introduces very large backgrounds that has thus far precluded their use.

In conclusion, we propose a new method of analyzing $\Lambda_b^0$ decays into one missing particle, where the $\Lambda_b^0$ 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.

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