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Semileptonic decay of the Λ_b baryon

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A phenomenological analysis of semileptonic decay of Λ_b is carried out motivated by the suggestion that the exclusive semileptonic decay of B mesons into τ leptons is enhanced by the presence of nonstandard model interactions. The ratio of exclusive semileptonic Λ_b decay rates into τ and light $(l = e, \mu)$ leptons is calculated in a model constrained by the corresponding ratio observed in B decays.

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1. Introduction

A number of puzzles exist in the decay of B mesons [1]. One of them is the disagreement of standard model predictions for the ratio of exclusive semileptonic B decay rates into τ and light $(l = e, \mu)$ leptons. These ratios are quite robust predictions in the standard model. The measured ratios of branching fractions

$$R(D) = \frac{\mathscr{B}(\overline{B} \to D\tau\overline{\nu}_\tau)}{\mathscr{B}(\overline{B} \to Dl\overline{\nu}_l)},\ R(D^*) = \frac{\mathscr{B}(\overline{B} \to D^*\tau\overline{\nu}_\tau)}{\mathscr{B}(\overline{B} \to D^*l\overline{\nu}_l)} \tag{1.1}$$

disagree with the expected values at the level of 2.0σ and 2.7σ respectively [2 – 4].

This has been the subject of a number of papers, for example [5 – 10]. One idea is to posit a new interaction [8 – 10] which affects only the decay channel with τ. To test this idea and to determine if new physics is present more measurements are needed. One possibility is

$$R(\Lambda_c) = \frac{\mathscr{B}(\Lambda_b \to \Lambda_c\tau\overline{\nu}_\tau)}{\mathscr{B}(\Lambda_b \to \Lambda_c l\overline{\nu}_l)}. \tag{1.2}$$

in Λ_b decay.

The effective Hamiltonian is motivated by studies of B decay [8 – 10] and takes the form

$$\begin{aligned}\mathscr{H}_{eff} = \frac{G_F V_{cb}}{\sqrt{2}} &\{ [\bar{c}\gamma_\mu(1-\gamma_5)b + h_V\bar{c}\gamma_\mu b + h_A\bar{c}\gamma_\mu\gamma_5 b]\,\bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell \\ &+ [h_S\bar{c}b + h_P\bar{c}\gamma_5 b]\,\bar{\ell}(1-\gamma_5)\nu_\ell + [h_T\bar{c}\sigma_{\mu\nu}b]\,\bar{\ell}\sigma^{\mu\nu}(1-\gamma_5)\nu_\ell + h.c.\}\end{aligned} \tag{1.3}$$

where the h coefficients of the non-standard-model interactions are assumed to be nonzero only for $\ell = \tau$.

For Λ_b decay the matrix elements are

$$\begin{aligned}\langle \Lambda_c, p' | \bar{c}\gamma_\mu b | \Lambda_b, p \rangle &= \bar{u}_c(p')\,[\,\gamma_\mu f_1(q^2) + P_\mu f_2(q^2) + q_\mu f_3(q^2)\,]\,u_b(p), \\ \langle \Lambda_c, p' | \bar{c}\gamma_\mu\gamma_5 b | \Lambda_b, p \rangle &= \bar{u}_c(p')\,[\,\gamma_\mu g_1(q^2) + P_\mu g_2(q^2) + q_\mu g(q^2)\,]\,\gamma_5 u_b(p), \\ \langle \Lambda_c, p' | \bar{c}b | \Lambda_b, p \rangle &= \bar{u}_c(p')\,[f_S(q^2)]\,u_b(p), \\ \langle \Lambda_c, p' | \bar{c}\gamma_5 b | \Lambda_b, p \rangle &= \bar{u}_c(p')\,[\gamma_5 g_P(q^2)]\,u_b(p), \\ \langle \Lambda_c, p' | \bar{c}\sigma_{\mu\nu} b | \Lambda_b, p \rangle &= \bar{u}_c(p')\,[\sigma_{\mu\nu} g_T(q^2)]\,u_b(p)\end{aligned}$$

where $P_\mu = p_\mu + p'_\mu$ and $q_\mu = p_\mu - p'_\mu$. The form factors in the Λ_b decay matrix elements can be related to a baryonic Isgur-Wise function[11]. HQET suggests the leading order relation $f_S = g_P = g_T = f_1$ which will be used in the numerical work. The momentum dependence of the form factors is taken from the quark model of Pervin *et al.*[12]

2. Results

The standard model predictions obtained in this work are tabulated in Table 1 and are in agreement with literature values. The ratios are determined largely by the relative phase space available in the light and τ lepton channels so for comparison the phase space only values are given in the Table also.

Ratio	Phase space	S.M.	Experiment
$R(D)$	0.28	0.32	0.440±0.058±0.042
$R(D^*)$	0.25	0.25	0.332±0.024±0.018
$R(\Lambda_c)$	0.26	0.31	

Table 1: Standard model (S.M.) values for the branching fraction ratios in B and Λ_b semileptonic decays. Values calculated using only phase space are given also. The experimental results are from BABAR[4].

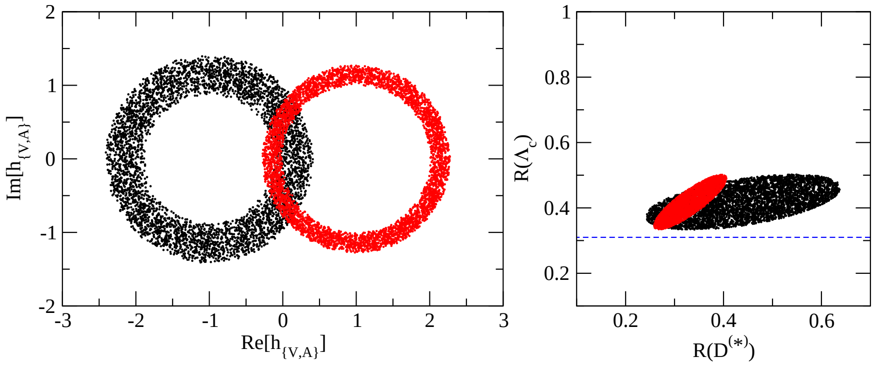

Figure 1: Left panel: Sample of parameters h_V (left circle) and h_A (right circle) giving ratios $R(D)$ and $R(D^*)$ in the 95% confidence interval. Right panel: The correlation of $R(\Lambda_c)$ with $R(D)$ (large elipse) and $R(D^*)$ (small elipse). The dashed line shows the standard model prediction.

The Hamiltonian contains more parameters than is convenient to deal with simultaneously. To visualize the effect of new interactions in the decay of Λ_b we will consider nonstandard model vector and axial vector terms, scalar and pseudoscalar terms and the tensor term separately.

A nonstandard model modification of the decay in the τ lepton channel due to vector and axial vector interactions amounts to a rescaling of the standard model contributions. We include both complex parameters h_V and h_A and fit simultaneously the ratios $R(D)$ and $R(D^*)$. A random sample of points in parameter space where the combined χ^2 is in the 95% confidence interval is shown in the left panel of Fig. 1, left circle for h_V and right circle for h_A. The right panel of Fig. 1 shows the correlation of $R(\Lambda_c)$ with $R(D)$and $R(D^*)$. Parameters that fit the B meson decay ratios predict a value in a narrow range around 0.42.

A nonstandard scalar interaction would contribute to $R(D)$ and a pseudoscalar interaction would contribute to $R(D^*)$. The parameters h_S and h_P can be adjusted independently to fit the experimental values. A sample of parameter values for ratios in the two-sigma allowed region are plotted in the left panel of Fig 2. As in [9], we observe that $R(D)$ is much more sensitive to a scalar interaction than $R(D^*)$ is to a pseudoscalar term.

The large black dotted region in Fig. 2 shows the correlation of $R(D)$ and $R(\Lambda_c)$ calculated with the standard model interactions plus a scalar term with h_S in the small circle in Fig. 2. The smaller region to the left (red) shows the effect of the nonstandard pseudoscalar interaction. If a scalar interaction accounts for the enhancement of $R(D)$ a similarly large effect in $R(\Lambda_c)$ would be expected.

A nonstandard model tensor interaction would contribute to both $R(D)$ and $R(D^*)$. Since there

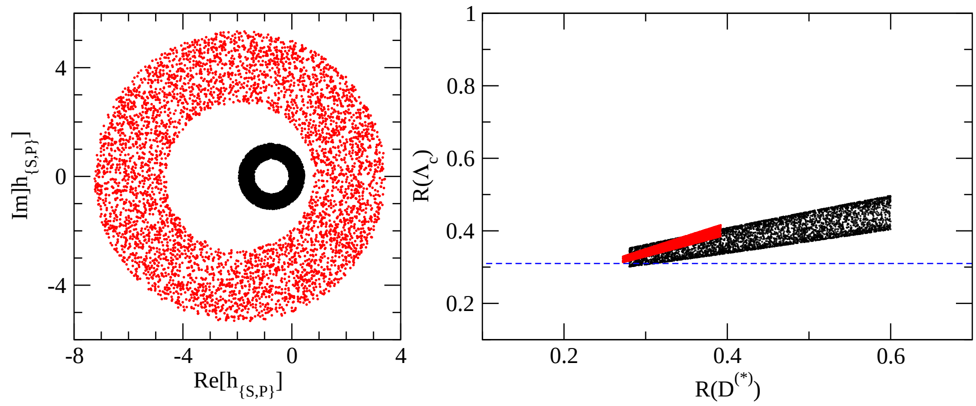

Figure 2: Left panel: Sample of parameters h_S (small circle) and h_P (large circle) giving ratios $R(D)$ and $R(D^*)$ in the 95% confidence interval. Right panel: The correlation of $R(\Lambda_c)$ with $R(D)$ (black) and $R(D^*)$ (red). The dashed line shows the standard model prediction.

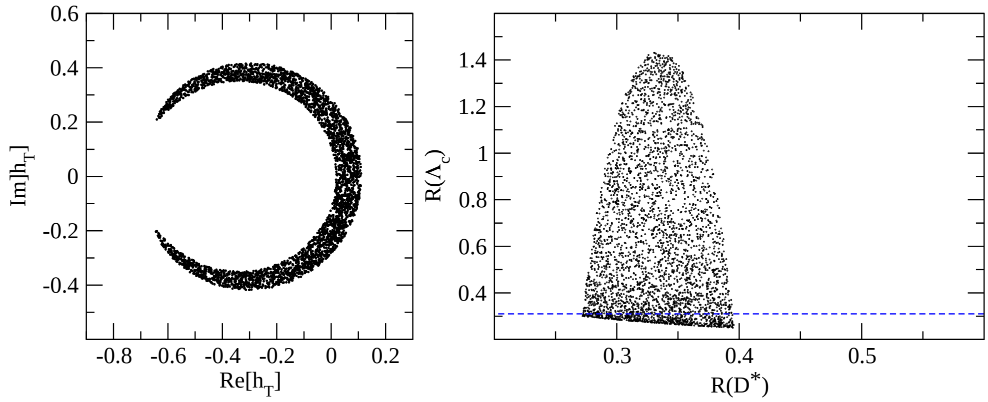

Figure 3: Left panel: Sample of parameters h_T giving ratios $R(D)$ and $R(D^*)$ in the 95% confidence interval. Right panel:The correlation of $R(\Lambda_c)$ with $R(D^*)$. The dashed line shows the standard model prediction.

is only one parameter there is some tension in trying to fit the experimental results simultaneously. The left panel of Fig. 3 shows a sample of points in the complex h_T plane where the combined χ^2 is in the 95% confidence interval. The allowed region agrees qualitatively with the results of [10] where the tensor interaction was considered also.

The right panel of Fig. 3 shows the expected values of $R(\Lambda_c)$ versus $R(D^*)$. The tensor contribution interferes with both the standard model vector and axial vector terms with contributions of different sign arising. Overall, however, the interference in Λ_b decay is opposite in sign to that in the meson decays. This leads to a large sensitivity of $R(\Lambda_c)$ to h_T. Different regions of parameter space can lead to either an enhancment or a decrease of $R(\Lambda_c)$ compared to its standard model value. Since the tensor interaction does not lead to a good simultaneous description of $R(D)$ and $R(D^*)$ it may be considered disfavoured as a possible nonstandard model explanation. However, if it does play a role, it would likely lead to a value of $R(\Lambda_c)$ quite different from the standard model result.

3. Summary and Discussion

In this work we present a phenomenological analysis of B meson and Λ_b semileptonic decay. There are indications from B decays that the τ decay channel is enhanced relative to the standard model prediction and various nonstandard model interactions have been suggested to explain this. These are fit to the B meson decay branching fraction ratios and the ratio $R(\Lambda_c)$ is calculated. If the nonstandard model interaction is scalar, pseudoscalar, vector or axial vector an enhancement of $R(\Lambda_c)$ comparable to that observed in B decays would be expected. For tensor interactions, a more complicated pattern of interference with the standard model can lead to either an increase or decrease of $R(\Lambda_c)$. In particular, a tensor term contributing to meson decay could lead to a very large enhancement of $R(\Lambda_c)$.

More experimental study of exclusive semileptonic Λ_b decay is warranted independent of the calculations presented here. Measurement of differential distributions would serve to constrain form factor models and test lattice QCD simulations. A determination of whether or not the τ mode branching ratio agrees with the standard model would be helpful in assessing the presence of new physics interactions.

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