Measurement of the slope parameter of beauty baryon form factor

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Abstract

The slope of the form factor of $b$-baryons is estimated using $2.710^6$ hadronic $Z$ decays collected by the DELPHI experiment between 1992 and 1994. In a first step, charmed $\Lambda_c^+$ baryons are fully reconstructed in the $pK^-\pi^+$ mode. These $\Lambda_c^+$ baryons are then associated to an opposite sign lepton (electron or muon) in order to select $\Lambda_b \to \Lambda_c^- l^+ \bar{\nu}_l$ decays. Estimates of the neutrino energy and of the $\Lambda_b$ direction allow to reconstruct the distribution of the $w = v_{\Lambda_b} \cdot v_A$ variable of 29 selected events. From a binned $\chi^2$ fit to this $w$ distribution, the slope of $b$-baryon form factor is measured to be:

$$ \rho^2 = 1.81^{+0.70}_{-0.67} \text{ (stat.)} \pm 0.32 \text{ (syst.)} $$
1 Introduction

In the sector of the $b$ quark, mesons have been quite extensively studied at $T(4S)$ and LEP energies: masses, lifetimes and most of the branching ratios are now well measured. Recent publications also present results on the beauty mesons form factor [1]. On the other hand there is less information on beauty baryons, and this note provides a first estimate of the slope of the $b$-baryon form factor.

Section 2 summarises the form factor formalism and introduces the relevant variable $w$. The experimental analysis presented in the next sections is based on the study of $\Lambda_b$ semileptonic decays: $\Lambda_b \rightarrow \Lambda_b^+ l^- \nu_l$, with $l^- = \mu^-$ or $e^-$. Section 3 presents the $\Lambda_c^+$ reconstruction in the $pK^-\pi^+$ mode, followed by the description of $\Lambda_c$-lepton association. Section 4 presents the $w$ reconstruction algorithm and the results of the fit to the $w$ distribution. In Section 5, these results are summarised and compared to theoretical predictions and experimental results which are available on beauty mesons.

2 Beauty baryons form factor

A complete description of the form factor formalism and theoretical expectations can be found in ref. [2] [3] [4]. This section presents a brief summary of needed basics.

The current which describes the weak decay of a beauty particle to a charmed particle involves three form factors in the case of mesons (e.g. $B^0 \rightarrow D^{(*)}W^-$) and six form factors in the case of baryons (e.g. $\Lambda_b \rightarrow \Lambda_b^+ W^-$. In the limit of infinite $b$ and $c$ quarks masses, only one universal function $\xi(q^2)$ is needed, where $q^2$ is the squared four momentum transfer from the beauty particle to the charmed particle:

$$q^2 = (p_{\Lambda_b^+} - p_{\Lambda_b})^2$$

In this Heavy Quark Effective Theory (HQET) framework, the shape of this Isgur-Wise function $\xi(q^2)$ is not predicted, and a linear expansion is usually assumed:

$$\xi(q^2) = \xi(q_{max}^2) \left( 1 + a^2 \frac{q_{max}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c}} + O(1/m_{b,c}) \right)$$

This function can be rewritten using the four velocities of the $\Lambda_b$ and the $\Lambda_c$:

$$w = u_{\Lambda_b} \cdot v_{\Lambda_c} = \left( m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2 \right)/(2m_{\Lambda_b}m_{\Lambda_c})$$

$$\xi(w) = \xi(w \rightarrow 1) \left( 1 - \tilde{\beta}^2(w - 1) + O((w - 1)^3) \right)$$

As an example, $w$ values associated to the decay $\Lambda_b \rightarrow \Lambda_b^+ l^- \nu_l$ can range from 1 (highest transfer) to a value close to 1.44 (smallest transfer, $q^2 = 0$). In the absence of mass dependent corrections, the flavor independence of QCD implies that $\xi(w \rightarrow 1)$ is normalised to 1. Taking into account $\Lambda_{QCD}/m_c^2$ corrections and perturbative QCD effects [2]), we will use $\xi(w \rightarrow 1) = 0.91 \pm 0.04$.

$^1$Charge conjugation is implicitly assumed in this work and both $\Lambda_b^+ l^-$ and $\Lambda_b^- l^+$ are selected.
Theoretical predictions and experimental results available in the meson sector are:

\[\rho^2 = 0.9^{+0.6}_{-0.5} \quad \text{(lattice QCD [3])}\]
\[\rho^2 = 0.9^{+0.3}_{-0.0} \quad \text{(QCD sum rules [4])}\]
\[\rho^2 = 0.75^{+0.17}_{-0.10} \quad \text{(DELPHI, } B^0 \to D^{*+} \ell^- \bar{\nu}_\ell \text{ [5])}\]

To measure this slope in the baryonic channel, the semileptonic decay \(\Lambda_b \to \Lambda_c^+ \ell^- \bar{\nu}_\ell\) will be used (the semileptonic decay allows the extraction of \(V_{cb}\) with the smallest theoretical uncertainty in the mesonic channel [5]). The differential decay width of this process can be calculated from [2]:

\[
\frac{d\Gamma}{d\omega} = G K(\omega) \xi^2(\omega)
\]

\(G\) contains coupling factors such as \(G_F\) and \(V_{cb}\), and \(K(\omega)\) is a kinematical factor which depends on the nature of the involved particles:

\[
G(\omega) = \frac{2 G_F^2 |V_{cb}|^2 m_{\Lambda_c}^2}{3 (2\pi)^3}
\]

\[
K(\omega) = q^2 P \left( 2w + \frac{(m_{\Lambda_c}^2 + m_{\Lambda}^2 w - 2m_{\Lambda_c}m_{\Lambda})}{q^2} \right) \quad \text{with} \quad P = m_{\Lambda_c} \sqrt{w^2 - 1}
\]

From the experimental point of view, the reconstructed \(\omega\) distribution of \(N\) selected \(\Lambda_c\)-lepton events will be compared to the one predicted by the simulation. The \(G\) term will be accounted for through the normalisation of the simulated events to the number of real data events, and the \(K(\omega)\) factor will be automatically taken into account by the generation of the simulated events.

### 3 Event selection

#### 3.1 \(\Lambda_c^+ \to pK^-\pi^+\) selection

The \(\Lambda_c^+\) baryons are selected in the \(\Lambda_c^+ \to pK^-\pi^+\) mode using 92 to 94 data. The selection is briefly described below, and a more complete description can be found in [7].

After a standard hadronic event selection, triplets of charged tracks of total charge unity are selected. Each track is requested to have at least one hit in the microvertex detector. The momenta are required to be larger than 3 GeV/c (proton candidate), 2 GeV/c (kaon candidate) or 1 GeV/c (pion candidate), and the total momentum is required to be larger than 8 GeV/c. The mass of the \(\Lambda_c\) candidate should lie in the 2.1-2.5 GeV/c range. A secondary vertex is fitted with these three tracks, requiring a \(\chi^2\) probability larger than 0.001. A primary vertex is also fitted using a standard procedure starting from all tracks of the event. The \(\Lambda_c\) flight is computed as the difference between the secondary and the primary vertex. This flight is signed with respect to the momentum direction of the triplet and it is required to be positive.

HADSIGN flags are used to identify the proton and the kaon in 1992 and 1994 data. It was decided to use only RICH information to identify the proton and the kaon in 1993 data.
The expected number of reconstructed events from the simulation is then found to be $N_{\text{sim,exp}} = 69$, which is compatible with the number of reconstructed events obtained on real data ($N_{\text{real, recon}} = 72.7 \pm 16.1$).

A binned $\chi^2$ fit is then performed between the $w$ distribution obtained with reconstructed data events and the one predicted by the simulation. The comparison performed using the two physical bins leads to:

$$\hat{\rho}^2 = 1.81 \pm 0.70 \text{ (stat.)}$$

where the error is statistical only. The associated $\chi^2$ value is 0.15 for one degree of freedom. Performing the fit using the three bins gives $\hat{\rho}^2 = 1.60 \pm 0.62$ (stat.) with $\chi^2 = 1.2$ for two degrees of freedom. It can be seen on Figure 4 that the agreement between data and simulation is worse in the third bin corresponding to the unphysical $w$ values. This may be an indication that the $w$ resolution in the data is not well reproduced by the simulation at small $q^2$ values, or that there is a remaining contamination of $B \to \Lambda^+_c l^- X$ events. The two results are obviously compatible, and the first one will be kept as it corresponds to a better fit.

The systematic error on the first result has been estimated by varying all parameters (production cross sections, branching ratio $Br(\Lambda^+_c \to pK^-\pi^+)$, efficiencies) in turn and adding quadratically the variations of the slope parameter. This error is dominated by the uncertainties on the identification efficiencies. The final result is:

$$\hat{\rho}^2 = 1.81 \pm 0.70 \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

Taking into account the statistical error only, it can be stated that $\hat{\rho}^2 > 0$ with 95% confidence level. The systematic error slightly lowers the significance of the result, yet it is still 2.3 standard deviations above zero.

5 Conclusion

Using the $\Lambda_b \to \Lambda^+_c l^- \bar{\nu}_l$ decay, a first measurement of the slope of the form factor of the $\Lambda_b$ beauty baryon was obtained. Assuming a linear expansion of the Isgur-Wise function:

$$\xi(w) = \xi(w \to 1) \left( 1 - \hat{\rho}^2 (w - 1) + O((w - 1)^2) \right)$$

$\hat{\rho}^2$ was determined to be:

$$\hat{\rho}^2 = 1.81 \pm 0.70 \text{ (stat.)} \pm 0.32 \text{ (syst.)}$$

Figure 5 shows a comparison of this result to theoretical and experimental results available for beauty mesons. It can be seen on this figure that there is no obvious disagreement between all these results, yet a more precise measurement of the $\hat{\rho}^2$ of beauty baryons will of course be necessary to get further conclusions.

$^5$The slope $\hat{\rho}^2$ should not be the same for mesons and baryons, and the relation $\hat{\rho}^2_{\text{baryon}} \sim 2\hat{\rho}^2_{\text{meson}}$ can be inferred from crude considerations [11]
References


Figure 1: Mass distribution of $\Lambda_c$ candidates for right sign combinations ($\Lambda^\pm K^\mp$, full line) and wrong sign combinations ($\Lambda_c^\mp K^\pm$, black points). The fit is made with a Gaussian shape for the signal and a polynomial shape for the background.
Figure 2: Resolutions achieved in 1992-1993 and 1994 for the reconstruction of angular variables ($\theta$ and $\phi$) and for the $q^2$ variable.
Figure 3: Mass distribution of $\Lambda_c$ candidates for right sign combinations when $1 < w < 1.22$ (Figure 3-a), $1.22 < w < 1.44$ (Figure 3-b) and $w > 1.44$ (Figure 3-c). The fits are made with a Gaussian shape for the signal and a polynomial shape for the background.
Figure 4: $w$ distributions and fits. The dots represent real data, the histograms correspond to the fitted simulated distributions. Figure 4-a: 2 bins fit in the physical range ($w < 1.44$). Figure 4-b: fit over the whole $w$ range (the last bin contain all events with $w > 1.44$). The errors are statistical only.
Figure 5: Comparison of the available results: triangles represent theoretical estimations for mesons, squares show the experimental result on mesons and the result obtained here for baryons.