Strategy for detecting $b$ polarization effects

Jae Kwan Kim and Yeong Gyun Kim*,

Dept. of Physics, KAIST, Taejon 305-701, KOREA

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Abstract

We suggest a strategy for detecting $b$ polarization effects in $e^+e^-$ annihilation on $Z$ resonance. Using two types of inclusive leptonic samples with different $\Lambda_b$ fractions in $Z \rightarrow b\bar{b}$ events, the $b$ polarization effects may be detected without large uncertainties of $b$ fragmentation and $\Lambda_b$ decay model.

*ygkim@chep6.kaist.ac.kr
The standard model predicts that $b$ quarks are produced with a large longitudinal polarization in $e^+e^-$ collision on the $Z$ peak [1]. The measurable $b$ polarization effects are reduced by the fragmentation properties of $b$ quarks. All spin information is lost in the formation of both pseudoscalar and vector $B$ mesons. Only $b$-baryons are expected to retain some spin information [2].

Various methods which would be used to detect the $b$ polarization effects have been suggested by several authors [3,4]. Mele and Altarelli [3] have suggested that inclusive lepton energy spectrum in the semileptonic decays of $b$ hadrons could be used as a measure of $b$ quark polarization. In this method, a good control of fragmentation effects is crucial and this may be achieved by calibration on low energy data. Also one can use the $\Lambda_b$ sample of semileptonic events and compare it with the $B$-meson sample in order to control fragmentation effects. In latter case, a possible observed difference between the $\Lambda_b$ and the inclusive spectra could be blamed on the model dependent features of the exclusive decay and so a reliable model of $\Lambda_b$ exclusive decay is required.

In this Brief Report we suggest another possible strategy for detecting $b$ polarization effects, which would be almost free from the uncertainties of $b$-fragmentation and $\Lambda_b$ decay model. The main point of this strategy is that we study polarization effects in two types of ‘inclusive’ leptonic samples with different $\Lambda_b$ fractions.

First, we choose dilepton events in the $Z \rightarrow b\bar{b}$ events, in which both $B$ hadrons decay semileptonically. We can catalog these events into the “like-sign events” in which leptons have same charge and the “unlike-sign events” in which leptons have different charge. Clearly the existence of the like-sign events is a signal of $B - \bar{B}$ mixing [5]. In these events, one of the $B$ hadrons must be a $B_s$ or $B_d$ meson. However this is not the case in the unlike-sign events. So the fractions of $\Lambda_b$ would be different for each types of events and are given by

$$F_{\text{like}}(\Lambda_b) = \frac{f_{\Lambda_b}}{2(1 - \chi_B)} \quad \text{for ‘like sign events’},$$

$$F_{\text{unlike}}(\Lambda_b) = \frac{f_{\Lambda_b}(1 - \chi_B)}{[(1 - \chi_B)^2 + \chi_B^2]} \quad \text{for ‘unlike sign events’}$$

(1)
where $f_{\Lambda_b}$ is the branching ratio for $\Lambda_b$ production from $b$ quark and $\chi_B$ is $B$ hadron mixing parameter. We notice that the ratio $F_{\text{unlike}}(\Lambda_b)/F_{\text{like}}(\Lambda_b)$ is independent of $f_{\Lambda_b}$ and would be almost two with small value of $\chi_B$. The mixing parameter $\chi_B$ gives the probability that a hadron containing $b$ quark oscillates into a hadron containing $\bar{b}$ quark at the time of its decay and it has been measured at $\sqrt{s} = M_Z$ [5]. If we take the value $f_{\Lambda_b} = 0.1$ and $\chi_B = 0.12$, then we get $F_{\text{like}}(\Lambda_b) = 5.7\%$, $F_{\text{unlike}}(\Lambda_b) = 11.2\%$. So we have two types of inclusive leptonic samples with different $\Lambda_b$ fractions.

In the next step, we calculate the ratio $R_i^N(\hat{P})$ of the $N$-th moments of the lepton energy spectrum in the unlike-sign sample over the ones in the like-sign sample, 

$$ R_i^N(\hat{P}) = \frac{\langle x_i^N \rangle(\hat{P})}{\langle x_i^N \rangle(0.5\hat{P})} \quad (3) $$

where $x_i = 2E_i/\sqrt{s}$, $E_i$ is lepton energy in lab. frame, $\sqrt{s}$ is c.m. energy of $e^+e^-$ collision, and $\hat{P}$ is the effective polarization of the unlike-sign sample. Here, we assumed the ratio $F_{\text{like}}(\Lambda_b)/F_{\text{unlike}}(\Lambda_b)$ is 0.5 and this would be a good approximate value with the measured value of $\chi_B$ [5]. Then the effective polarization of the like-sign sample should be $0.5\hat{P}$.

In the collinear approximation, the observed leptonic spectrum in the laboratory is the convolution of the polarization-dependent ‘naive’ leptonic spectrum with $b$ fragmentation function. Then,

$$ R_i^N(\hat{P}) = \frac{\langle x_i^N \rangle(\hat{P})}{\langle x_i^N \rangle(0.5\hat{P})} = \frac{\langle x_b^N \rangle\langle x_i^N \rangle(\hat{P})}{\langle x_b^N \rangle\langle x_i^N \rangle(0.5\hat{P})} = \frac{\langle x_i^N \rangle(\hat{P})}{\langle x_i^N \rangle(0.5\hat{P})} \quad (4) $$

where $x_b = 2E_b/\sqrt{s}$, $x = E_i/E_b$ and $E_b$ is $b$ quark energy in lab. frame. (see ref. [3] for relevant definitions). Here, $b$-fragmentation effects are mostly cancelled and only the ratio of the moments of the ‘naive’ lepton spectrum in the unlike-sign sample over the like-sign sample is left. The inclusive $b \to c l \nu$ decay can be treated in the heavy-quark limit as a free-quark decay and there are no nonperturbative corrections of order $\Lambda_{QCD}/m_b$ [6]. So the above ratio can be predicted reliably. In fig.1, we present the ratio $R_i^N(\hat{P})$ for the first three moments. We used eq. (4) in ref [3] and we have taken $m_b=5$ GeV, $m_c=1.5$ GeV.

In the experiment of CERN $e^+e^-$ collider LEP, the energy(or momentum) of leptons is measured with high precision and already a number of $Z \to b\bar{b}$ events are avalible. So
the above ratio $R_i^N(\hat{P})$ could be measured with high precision and served as the indicator of existence of $b$ polarization.

In conclusion, we have suggested a possible method for detecting $b$ polarization effects in $e^+e^-$ collision on $Z$ resonance. We could get two types of inclusive leptonic samples with different $\Lambda_b$ fraction and calculated the ratio $R_i^N(\hat{P})$ for the first three moments. This ratio would be almost free from the uncertainties of $b$ fragmentation and $\Lambda_b$ decay model.

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FIGURES

FIG. 1. Prediction for the ratios $R^N_l(\hat{P})$ with $N=1, 2, 3$ versus the "effective" b polarization $\hat{P}$. 
Fig. 1

$R^N_1(\hat{P})$ vs $P$

- $N=1$
- $N=2$
- $N=3$