Evidence for the $B_s$ meson in the $\Upsilon(5S)$ data

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Abstract. Employing exclusive and inclusive reconstruction techniques, evidence for the $B_s$ meson is established in 0.42 fb$^{-1}$ of data collected at the $\Upsilon(5S)$ resonance with the CLEO III detector. It is found that at the energy of the $\Upsilon(5S)$ resonance the $B_s$ meson production proceeds predominantly through the creation of $B_s^*\bar{B}_s^*$ pairs and the ratio of the $B_s^*(\bar{B}_s^*)$ production to the total $b\bar{b}$ quark pair production is $(21\pm3\pm9)\%$ (model dependent). All results are preliminary.

1. Introduction

A physics case is being made for a Super $B$ factory at an asymmetric $e^+e^-$ collider with a design luminosity of $5 \times 10^{35}$ cm$^{-2}$s$^{-1}$, for example, in [1]. While the rich physics accessible at the $\Upsilon(4S)$ resonance is in the focus of such a program, the option of additional running at the $\Upsilon(5S)$ resonance at the design luminosity promises a large sample of $B_s$ mesons produced in a clean $e^+e^-$ environment subject to kinematic constraints similar to those enjoyed in the $B$ meson reconstruction at the $\Upsilon(4S)$ resonance. References [1] and [2] discuss measurements that such a sample could make possible. Knowledge of the $B_s$ production rate and mechanism at the $\Upsilon(5S)$ energy are clearly essential for assessing the potential of the $B_s$ physics at such an $e^+e^-$ collider.

The $\Upsilon(5S)$ was discovered at the Cornell Electron Storage Ring (CESR) [3] (Figure 1). The $\Upsilon(5S)$ is massive enough to decay into a variety of $B_s^{(*)}\bar{B}_s^{(*)}(\pi)(\pi)$ channels, as well as the following three channels with $B_s$ mesons: $B_s\bar{B}_s$, $B_s\bar{B}_s^*$ (or $B_s^*\bar{B}_s$) and $B_s^*\bar{B}_s^*$. Little is known about the $B_s$ production at the $\Upsilon(5S)$ resonance at this moment. The CLEO I.V detector collected around 120 pb$^{-1}$ of data at the $\Upsilon(5S)$ resonance, but no conclusive evidence for the $B_s$ meson in this data sample was found. Theoretical models (e.g., Unitarized Quark Model in [4]) predict that the $\Upsilon(5S)$ should decay predominantly to the $B_s^*\bar{B}_s^*$ states with the $B_s^*\bar{B}_s^*$ state produced about a third of the time. The $e^+e^- \rightarrow \Upsilon(5S)$ cross section is predicted to be about 0.35 nb, which is consistent with the early CLEO data.

In 2003, a data sample of 0.42 fb$^{-1}$ of $e^+e^-$ annihilation at the $\Upsilon(5S)$ energy provided by CESR was recorded by the CLEO III detector [5]. Two experimental approaches are employed in the searches for the $B_s$ meson in this data sample: an exclusive approach and an inclusive one. Below, we will first overview basic selection criteria used in the reconstruction and, after that, the two approaches will be described and the preliminary results given.

2. Basic event selection requirements

All tracks and showers are required to satisfy a set of standard quality criteria. Charged pions or kaons are identified using the specific ionization information ($dE/dx$) in the drift chamber.
Figure 1. The $e^+e^-$ hadronic cross section in the region of the Υ resonances. The insert plot shows the position of the Υ(5S) resonance.

and the information from the Ring Imaging Cherenkov Detector (RICH), if it is available. Identification of electrons is based on a likelihood function constructed from the ratio of the energy deposited in the calorimeter to the track momentum measured by the drift chamber, and the information from the $dE/dx$ and RICH systems. Bremsstrahlung photons from electrons are recovered using showers in the crystal calorimeter that are not matched to the electron track but that line up with the track momentum. Muons are identified using the information from three layers of muon counters located behind layers of iron. Neutral pion candidates are formed from pairs of showers in the crystal calorimeter with the invariant mass within $[-3.5\sigma;+3.0\sigma]$ from the π⁰ mass. $K_S^0$ candidates are built from pairs of oppositely charged pions constrained by a vertex fit and with the invariant mass within 12 MeV/$c^2$ from the $K_S^0$ mass. The basic reconstructed objects described in this section are used in the reconstruction of $B_s$ decays in what follows.

3. Exclusive approach

Exclusive $B$ meson reconstruction techniques used at the Υ(4S) resonance are employed to reconstruct $B_s$ mesons at the Υ(5S) resonance. The search is performed on the plane of the following two variables: (1) $M_{bc} \equiv \sqrt{E_{\text{beam}}^2 - p_{\text{candidate}}^2}$ and (2) $\Delta E \equiv E_{\text{beam}} - E_{\text{candidate}}$. Event shape variables, describing the distribution of track and shower momenta over the solid angle in the detector [6], are used to suppress the dominant continuum background in the same way as it is done at the Υ(4S).

The Υ(5S) resonance can decay into the following three channels with the $B_s$ mesons: (1) $B_s\bar{B}_s$, (2) $B_s^*\bar{B}_s$ (or $B_s\bar{B}_s^*$) and (3) $B_s^*\bar{B}_s^*$. Case 1 is analogous to the $B$ meson reconstruction at the Υ(4S) resonance, when $M_{bc}$ peaks at the $B$ meson mass and $\Delta E$ at zero. We assume that $B_s^*$ decay to $B_s$ via emission of a 47 MeV photon 100% of the time ($M(B_s^*) - M(B_s) = (47.0 \pm 2.6)$ MeV/$c^2$ [7]). In Cases 2 and 3, the photon from $B_s^*$ is not reconstructed, which leads to a smearing of the $B_s^*$ momentum, but not a significant one, as the photon carries only a small fraction of the total $B_s^*$ momentum. In Case (3), because the soft photon is not reconstructed, $E_{B_s}$ is approximately 47 MeV lower than $E_{\text{beam}}$, therefore $M_{bc}$ peaks approximately 47 MeV/$c^2$ higher than $M_{B_s}$, i.e., at the mass of $M_{B_s^*}$, and $\Delta E$ peaks at $(M_{B_s^*} - M_{B_s}) \approx 47.0$ MeV. Similarly, in Case (2) the beam constrained mass peaks at $\frac{1}{2}(M_{B_s} + M_{B_s^*})$ and $\Delta E$ peaks at $\frac{1}{2}(M_{B_s^*} - M_{B_s})$. For these reasons, fully reconstructed $B_s$ mesons populate different regions on the $M_{bc} - \Delta E$ plane for the three cases, which allows the identification of the states in which $B_s^{(*)}$ mesons are produced.

Among experimental challenges in this analysis are backgrounds. The amount of the
The inclusive approach [8] exploits the fact that $D_s$ mesons are produced more copiously in the $B_s$ decays compared to $B$ decays: $B(D_s \rightarrow D_s X) = (94\pm 30)\%$ and $B(B \rightarrow D_s X) = (10.5 \pm 2.6)\%$ [7]. Establishing higher production rate of $D_s$ meson per an $\Upsilon(5S)$ decay compared to the same rate per an $\Upsilon(4S)$ decay would be evidence for $B_s$ at the $\Upsilon(5S)$. The analysis involves three steps described below.

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**Figure 2.** The signal $M_{bc} - \Delta E$ plane in the data for $B_s$ modes with $J/\psi$ (left) and $D_s^{(*)}$ (right). The absolute $M_{bc}$ and $\Delta E$ scales are subject to systematic uncertainties in the beam energy. Preliminary.
Firstly, $D_s$ yields are measured in bins of $x \equiv |\vec{p}_{Ds}|/E_{beam}$ in the continuum, $\Upsilon(4S)$ and $\Upsilon(5S)$ data. In this analysis, the $D_s$ is reconstructed in $\phi\pi^+$ modes with $\phi \rightarrow K^+K^−$. The $D_s$ reconstruction efficiency in this mode is about 30% independent of the $D_s$ momentum.

Secondly, $B(\Upsilon(4S) \rightarrow D_sX)$ and $B(\Upsilon(5S) \rightarrow D_sX)$ are measured by subtracting scaled and normalized $D_s$ yields in the continuum data from the $D_s$ yields in the $\Upsilon(4S)$ and $\Upsilon(5S)$ data. CLEO finds $B(\Upsilon(4S) \rightarrow D_sX) = (22.3 \pm 0.7 \text{(stat)} \pm 5.9 \text{(syst)})\%$ (which is in good agreement with $B(B \rightarrow D_sX) = (10.5 \pm 2.6)\%$ in [7]) and $B(\Upsilon(5S) \rightarrow D_sX) = (55.0 \pm 5.2 \text{(stat)} \pm 17.8 \text{(syst)})\%$. Figure 3 shows excess in the $D_s$ production at the $\Upsilon(5S)$ over that at the $\Upsilon(4S)$. This excess is interpreted as evidence for the $B_s$ meson in the $\Upsilon(5S)$ data.

Finally, using $B(B \rightarrow D_sX)$ and $B(B_s \rightarrow D_sX)$ and model dependent estimate for $B(B_s \rightarrow D_sX)$ in [8], CLEO measures: $B(\Upsilon(5S) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}) = (21 \pm 3 \text{(stat)} \pm 9 \text{(syst)})\%$, for the inclusive $B_s^{(*)}$ production rate, where the largest contributors to the systematic uncertainty are the uncertainty associated with the continuum subtraction and the uncertainty in $B(D_s \rightarrow \phi\pi^+)$. 

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure3.png}
\caption{The enhancement of $D_s$ yield at the $\Upsilon(5S)$ resonance compared to the $\Upsilon(4S)$ resonance. Preliminary.}
\end{figure}

5. Conclusion
Using 0.42 fb$^{-1}$ of data collected with the CLEO III detector at the $\Upsilon(5S)$ resonance, we have established evidence for the $B_s$ meson using exclusive and inclusive reconstruction techniques. It is found that at the $\Upsilon(5S)$ energy the production of the $B_s^{(*)}\bar{B}_s^{(*)}$ state is favored over the production of the $B_s\bar{B}_s$ or $B_s\bar{B}_s^{(*)}$ states, and the ratio of $B_s^{(*)}\bar{B}_s^{(*)}$ pair production to the total $b\bar{b}$ quark production is $(21 \pm 3 \text{(stat)} \pm 9 \text{(syst)})\%$. All results are preliminary.

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