PROCEEDINGS OF SCIENCE

Search for new Bottomonium(-like) States in $e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi)$ at Belle

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A search for new bottomonium(-like) states in $e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi)$ reactions in energy scan data between the $\Upsilon(4S)$ and $\Upsilon(6S)$ resonances has been performed. An inclusive lepton approach is used for tagging semileptonically decaying B mesons recorded by the Belle detector. Preliminary evidence for B production in $\Upsilon(6S)$ decays has been found.

XLIX International Winter Meeting on Nuclear Physics
24-28 January 2011
BORMIO, Italy

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PoS(Bormio 2011)016

1. Introduction

The physics of charm and bottom quarks has aroused interest of both experimentalists and theoreticians since their discoveries [1][2][3] in the 70's. Significant effort was put in the investigation of the underlying flavour physics using the B-factories, namely BaBar at the PEP-II collider at SLAC laboratory in California and BELLE at the KEKB collider in Tsukuba, Japan. The B-factories have yielded a large number of results, including the first observation of CP violation outside the Kaon-system and measurements of the Cabibbo-Kobayashi-Maskawa (CKM) parameters, which contain information on the strength of flavor-changing weak decays. Overconstraining measurements of the unitarity triangle, which is determined by the CKM parameters, may reveal physics beyond the Standard Model.
But even within the Standard Model there are questions which need to be answered. Several charmonium and bottomonium states predicted by the Standard Model have not been seen yet (see Fig.3). QCD also predicts non-mesonic exotic states like hybrids, glueballs, tetraquarks and hadronic molecules (see Fig.4), but none of them have been unambigiously discovered yet.

2. The X(3872) Resonance

The $X(3872)$ is a narrow resonance discovered by the BELLE collaboration in 2003 [4]. The invariant mass distribution for $J/\psi\ \pi^+\pi^-$ in exclusively reconstructed $B^\pm \to J/\psi\ \pi^+\pi^-\ K^\pm$ events has a peak at about 3872 MeV, implying the $X(3872)$ is produced via $B^\pm \to X\ K^\pm$ and is then decaying into $J/\psi\ \pi^+\pi^-$. The upper limit on its width is very narrow, meaning the lifetime of the X is much longer than expected. The situation that the X mass and its narrow width do not agree well with quark model expectations has led to speculation that the X could be a novel charmomium state such as a hybrid, a tetraquark or a molecule. Soon after the discovery of the $X(3872)$, people noticed a curious fact: its mass is extremely close to the sum of D^0 and $\bar{D}^{*0}$ mass. Several theoretical studies investigated the possibility that $X(3872)$ is a weekly bound molecule of the charmed mesons D^0 and $\bar{D}^{*0}$ [5][6][7]

$$|X(3872)\rangle = \frac{1}{\sqrt{2}}\Big(|D^0\bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle\Big) \quad , \tag{2.1}$$

with quantum numbers $J^{PC} = 1^{++}$. Since the mass of this constituents is slighty higher than the mass of $X(3872)$, the difference in mass could be the binding energy which holds $D^0\bar{D}^{*0}$ together.

2.1 Searching for a bottom counterpart of $X(3872)$

Since the $X(3872)$ has rather unusual properties and its nature is not unambiguously identified yet, a discovery of a bottom counterpart X_b should shed more light on the issue. A search for states with $J^P = 1^+$ at electron-positron colliders is nontrivial since the initial state quantum numbers are always $J^P = 1^-$. The analogue state $X(3872)$ can be 1^+ since it is produced in a weak, parity violating B decay (Eq. (2.2))

$$\underset{0^-}{B^0} \to \underbrace{\underset{1^+}{X(3872)} + \underset{0^-}{K^0}}_{L=1} \tag{2.2}$$

The production of X_b in e^+e^- collisions would need additional pions to conserve parity and charge conjugation symmetry:

$$\begin{aligned} \underbrace{e^+e^-}_{1^{--}} &\not\to \underbrace{X_b}_{1^{++}} \\ &\to \underbrace{\underbrace{\underset{1^{++}}{X_b} + \underset{0^{-+}}{\pi^0} + \underset{1^{--}}{\gamma}}_{L=1}}_{1^{--}} \end{aligned} \tag{2.3}$$

The analysis with the π^0 (2.3) needs an additional γ to conserve charge conjugation symmetry. If the X_b would be a weakly bound B meson molecule of the form

$$|X_b\rangle = \frac{1}{\sqrt{2}}\left(|B^0\bar{B}^{*0}\rangle + |B^{*0}\bar{B}^0\rangle\right) \tag{2.4}$$

(equivalent to the $X(3872)$ in the charm sector), it should decay into $B^0\bar{B}^{*0}$ or $B^{*0}\bar{B}^0$ if the width of the state would allow this decay. A search in

$$e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi) \tag{2.5}$$

might reveal such new states like the X_b.

3. Analysis and Results

This analysis was done with data from an energy scan, where the beam energies were varied in a way that different center of mass energies between the $\Upsilon(4S)$ and $\Upsilon(6S)$ masses were achieved. Energy scans are usually not performed with a large integrated luminosity, therefore one should consider an inclusive approach for such a related corresponding analysis. B mesons have a relatively large semileptonical branching fraction of $\Gamma_{\text{sl}} = 10.33\%$. Demanding both, B and $\bar{B}$ meson to decay semileptonically, results in a final branching fraction of $\Gamma_{\text{slf}} = 10.33\%^2 = 1.07\%$. A highly inclusive analysis such as this provides large statistics thanks to the large branching ratios and efficiencies at the cost of limited information about the dynamics of each event.

The inclusive analysis presented here is based on the selection of pairs of leptons from semileptonic B meson decays (see Fig.5).

3.1 Dilepton Event Selection

If an event contains two or more lepton candidates, the analysis proceeds considering only the two leptons with the highest momentum in the center of mass system $|\vec{p}_{cms}|$. The CMS momentum of each lepton is required to meet

$$1.1\ GeV < \left|\vec{p}_{cms}\right| < 2.3\ GeV \quad . \tag{3.1}$$

These cuts were optimized for dilepton analysis from B decays in $\Upsilon(4S) \to B\bar{B}$ events in [9]. The lower cut reduces contributions from cascade or secondary (charm) decays, the upper cut reduces continuum contributions.

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In order to gain cleaner results just $e\mu$ pairs are considered, this cuts out all leptons from leptonic $J^{PC} = 1^{--}$ state decays (J/Ψ, Ψ',...).

Analyzing the dilepton yield as a function of center of mass energy ($\sqrt{s}$) of the scan point indicates the B meson production rate. To be able to compare results from different scan points, the dilepton yield of each scan point has to be normalized by the scan point's integrated luminosity (see Tab.3),

$$N = \frac{\tilde{N}}{\int \mathscr{L} dt [pb^{-1}]} \qquad , \tag{3.2}$$

with N being the normalized dilepton yield and $\tilde{N}$ being the total dilepton yield in the scan point's data. Since the momentum cuts remain unchanged with increasing $\sqrt{s}$, a correction factor is introduced to account for the rising lepton energies inside the center of mass frame. The correction factor calculation is based on Monte Carlo simulations of semileptonically decaying $B-\bar{B}$ pairs at five different center of mass energies. The total number of created dileptons from B decays in relation to the number of dileptons after the momentum cuts lets us calculate the correction factor Ξ to account for the rising momenta of the leptons. The Ξ values for the data points are normalized to the $\Upsilon(4S)$ value of $\Xi_{\Upsilon(4S)} = 1$.

$\sqrt{s}$ [GeV]	$\frac{\text{total counts}}{\text{counts after cuts}}$	normalized Ξ
$\Upsilon(4S)(10.5779)$	1.725	1
10.7985	1.960	1.136
$\Upsilon(5S)(10.871)$	2.018	1.170
10.9575	2.106	1.221
$\Upsilon(6S)(11.0175)$	2.177	1.262

Table 1: MC results for the correction factor Ξ.

In order to obtain values for all scan points and to reduce statistical errors, a linear fit was performed, leading to the final values for Ξ (Tab.2).

$\sqrt{s}$ [GeV]	Ξ	$\sqrt{s}$ [GeV]	Ξ
$\Upsilon(4S)(10.5779)$	1	10.8975	1.189
10.8275	1.147	10.9275	1.207
$\Upsilon(5S)(10.871)$	1.173	10.9575	1.224
10.8825	1.180	$\Upsilon(6S)(11.0175)$	1.260

Table 2: Final values for the correction factor Ξ.

The luminosity-normalized dilepton count rate, which indicates $B_{(s)}\bar{B}_{(s)}$ production, can be seen in Fig.1 and Fig.2.

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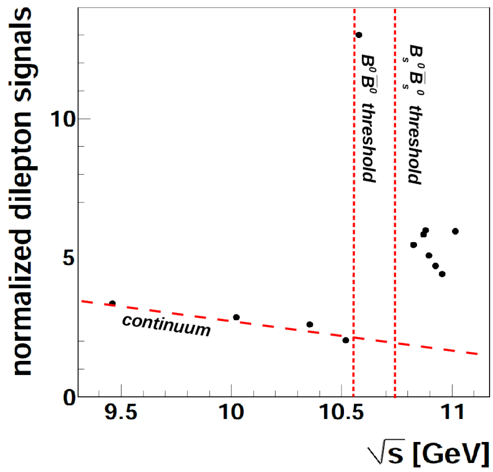

Figure 1: The normalized dilepton yield including correction factor as a function of $\sqrt{s}$. The datapoints below the $B^0\bar{B}^0$ threshold correspond to continuum dilepton yield from $\Upsilon(1S), \Upsilon(2S)$, $\Upsilon(3S)$ and off-resonance data (no correction factor applied).

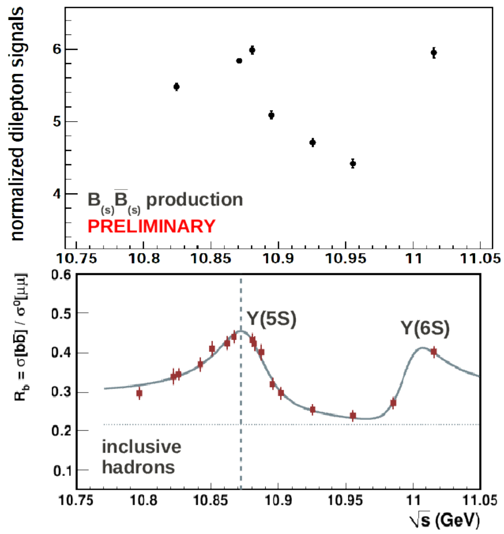

Figure 2: Same as Fig.1, but zoomed into the $\Upsilon(5S, 6S)$ region: The upper plot shows the normalized dilepton yield including the correction factor as a function of $\sqrt{s}$. The lower plot shows the corresponding $\Upsilon(5S)$ and $\Upsilon(6S)$ lineshapes measured in inclusive hadron production by Belle [10].

Fig.2 shows a good agreement with the inclusive hadron production data from [10]. A clear enhancement of $B_{(s)}$ production at $\Upsilon(5S)$ energies can be seen, it also shows preliminary evidence for $B_{(s)}\bar{B}_{(s)}$ production in $\Upsilon(6S)$ decays. Note that the error bars just present the statistical error, no systematical error studies were accomplished so far. Also the $\sqrt{s}$ scale was not corrected to the $\Upsilon(1S)$ mass.

3.2 $B^{(*)}\bar{B}^{(*)}\pi^0$ analysis

The analysis of $B^{(*)}\bar{B}^{(*)}\pi^0$ events is more complicated since there are many π^0 candidates in one event due to two reasons:

1. Large photon background produces up to 20 fake pion candidates per one event and
2. subsequent resonance decays (e.g. $\omega^0 \to \pi^+\pi^-\pi^0$) generate low energetic real pions, which cannot be easily distinguished from primary pions from direct e^+e^- production.

What one could do is to calculate momentum constraints for primary pions by using the available phase space. Then one could analyze the π^0 recoil mass under the condition that the dilepton from the B decays has been found, and if there would be a new state X_b decaying into B mesons with a significant branching fraction, it's mass might be seen in the π^0 recoil mass spectrum. A preliminary study was performed in [11].

4. Summary and Outlook

This work covered the search for new bottomonium(-like) states in the $e^+e^- \to B^{(*)}\bar{B}^{(*)}(\pi)$ channel in order to find a bottom counter part of the $X(3872)$. Energy scan data between $\Upsilon(4S)$ and $\Upsilon(6S)$ collected at the Belle experiment was used for the analysis. Dileptons from semileptonically decaying $B\bar{B}$ pairs were tagged as an indication for B meson production. The dilepton yield was normalized with the integrated luminosity, corrected for the changing kinematic conditions and plotted as a function of $\sqrt{s}$. The analysis gives first evidence for B meson production in $\Upsilon(6S)$ decays and proves that this inclusive dilepton approach for tagging B production is a powerful tool to examine Υ spectroscopy in low integrated luminosity environments such as energy scans.
At Belle-II energy scans could be done with larger integrated luminosities and one could use a more powerful semiexclusive analysis with the exclusive construction of one B meson, using recoil mass methods for examining the other side B decay.

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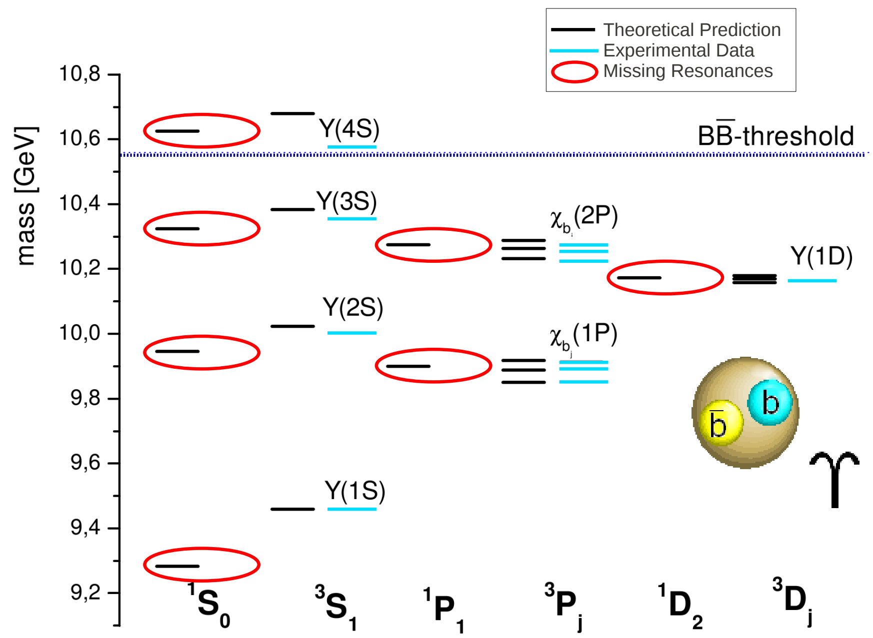

Figure 3: Theoretically predicted bottomonium spectrum - several resonances have not been experimentally discovered yet.

Figure 4: Exotics predicted by QCD.

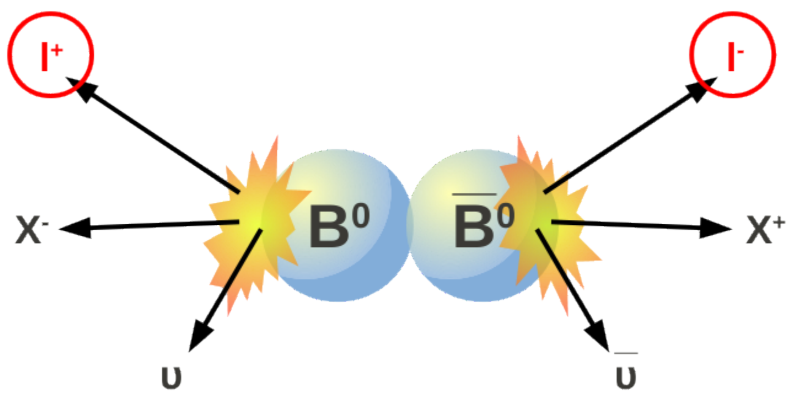

Figure 5: Scheme of semileptonically decaying $B/\bar{B}$ mesons, the leptons are used for tagging B meson production.

energy [GeV]	$\int \mathscr{L}$ **dt** [pb^{-1}]
$\Upsilon(1S)$ (9.4600)	2360
	3351
$\Upsilon(2S)$ (10.0218)	6517
$\Upsilon(3S)$ (10.3547)	1813
10.5183	8080
$\Upsilon(4S)$ (10.5779)	22153
10.8255	1676.51
$\Upsilon(5S)$ (10.871)	21513
10.8805	1830.90
10.8955	1410.47
10.9255	1138.65
10.9555	1009.18
11.0155	855.34

Table 3: Integrated luminosity of the used scan points