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Recent Results from Belle in e^+e^- Annihilation at and near $\Upsilon(5S)$

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The past eight years have seen a tremendous number of interesting physics results obtained using data taken above the Υ(4S) by the Belle Collaboration, and in this talk, several of these results are summarized, with a focus on recent measurements of several cross-sections: $e^+e^- \to b\bar{b}$, $e^+e^- \to \pi^+\pi^-\Upsilon$(nS), and $e^+e^- \to \pi^+\pi^- h_b$(nP), as a function of $\sqrt{s}$ from approximately 10.6 to 11.0 GeV. In addition, results of the study of $e^+e^- \to (BB^*)^{\pm}\pi^{\mp}$ at Υ(5S) are described.

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1. Historical Introduction

Since 2008, when the Belle Collaboration collected the first large $\Upsilon(5S)$ data sample of 23.4fb^{-1} of e^+e^- annihilations was collected by the Belle detector at KEK, a number of interesting and surprising results have been observed. In this historical context-setting section, we briefly describe the sequence of measurements which sprung from this initial data sample and scan in the $\Upsilon(5S)$ to $\Upsilon(6S)$ region, and the much larger final $\Upsilon(5S)$ sample.

1.1 Anomalous rates for $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(nS)$

One of the first indications of the unusual nature of the $\Upsilon(5S)$ was the observation by the Belle Collaboration of very high rates for the process $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$, where $n = 1,2,3$ using their initial 24fb^{-1} sample of e^+e^- annihilations taken near the peak of the $\Upsilon(5S)$ resonance. The rates for transitions to lower bottomonia were observed to be two orders of magnitude *larger* than the rates for dipion transitions among the lower bottomonia (e.g. $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$) [1]).

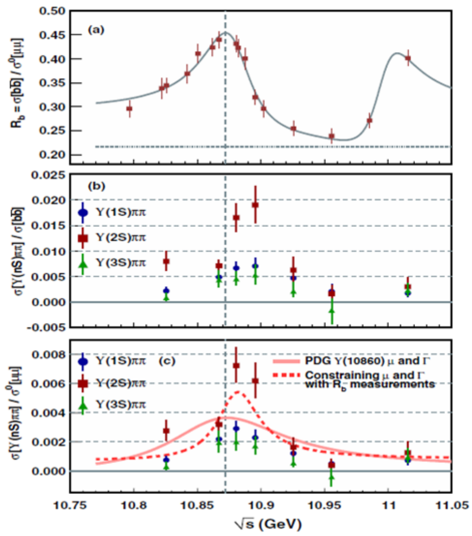

Figure 1: Ratios of $b\bar{b}, \Upsilon(nS)$, and $\mu^+\mu^-$ cross-sections, indicating a potential disagreement between the positions of the peak cross section for $b\bar{b}$ and that for $\pi^+\pi^-\Upsilon(nS)$ [2].

If the observed transitions were to be interpreted as direct dipion transitions from an S-wave vector $\Upsilon(5S)$, then such large transition rates are wholly inexplicable. These observations led immediately to a number of speculations, including the existence of a second state (denominated Y_b) that mixes with the conventional $\Upsilon(5S)$ bottomonium state [3].

These anomalous rates served as part of the motivation for the Belle Collaboration to take a large data sample at the $\Upsilon(5S)$ resonance, which they subsequently did in 2008-2009. This large data sample, finally totalling 121.4fb^{-1}, produced a number of very interesting results, two of which we describe in the coming subsections.

1.2 Discovery of $h_b(nP)$ in $\Upsilon(5S) \to \pi^+\pi^- h_b(nP)$

The anomalously large rates for $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ observed at energies near $\Upsilon(5S)$ indicated that something theoretically unexpected must be afoot in the region. Similar observations of unexpectedly high rates for production of lower vector quarkonia had earlier been seen in the charmonium system, and, furthermore, in 2010 the CLEO Collaboration presented results of the observation of similarly high rates of production of the singlet-P h_c state from data taken above open charm threshold [4]. Not only did this observation add to the array of unusually high-rate transitions to lower quarkonia from above open flavor threshold, but it represented something even more unexpected: a transition which requires the flip of a heavy quark spin, if the transition takes place between the initial triplet-S quarkonium state and the final singlet-P state. Such transitions ought to be significantly suppressed relative to triplet-to-triplet transitions - but CLEO observed similar rates for each process. The fact, however, that CLEO made this observation in their above-charm-threshold data immediately suggested the possibility of finally observing the previously unobserved h_b in a similar process.

Indeed Belle soon published results of the observation of both $h_b(1\mathrm{P})$ and $h_b(2\mathrm{P})$ in the process $e^+e^- \to \pi^+\pi^- h_b(\mathrm{nP})$ in the 121.4fb^{-1} data sample [5]. The two singlet-P states were discovered in the $\pi^+\pi^-$ missing mass spectrum in events passing a general hadronic selection. In Fig. 2 are shown the Belle observations of dipion transitions from $\Upsilon(5\mathrm{S})$ to all three sub-threshold $\Upsilon(\mathrm{nS})$ states, dipion transitions $(\Upsilon(2\mathrm{S},3\mathrm{S}) \to \pi^+\pi^-\Upsilon(1\mathrm{S})$ from $\Upsilon(2\mathrm{S},3\mathrm{S})$ produced via ISR, direct $\pi^+\pi^-$ transitions to $h_b(1\mathrm{P},2\mathrm{P})$ and evidence for a $\pi^+\pi^-$ transition to $\Upsilon(1\mathrm{D})$.

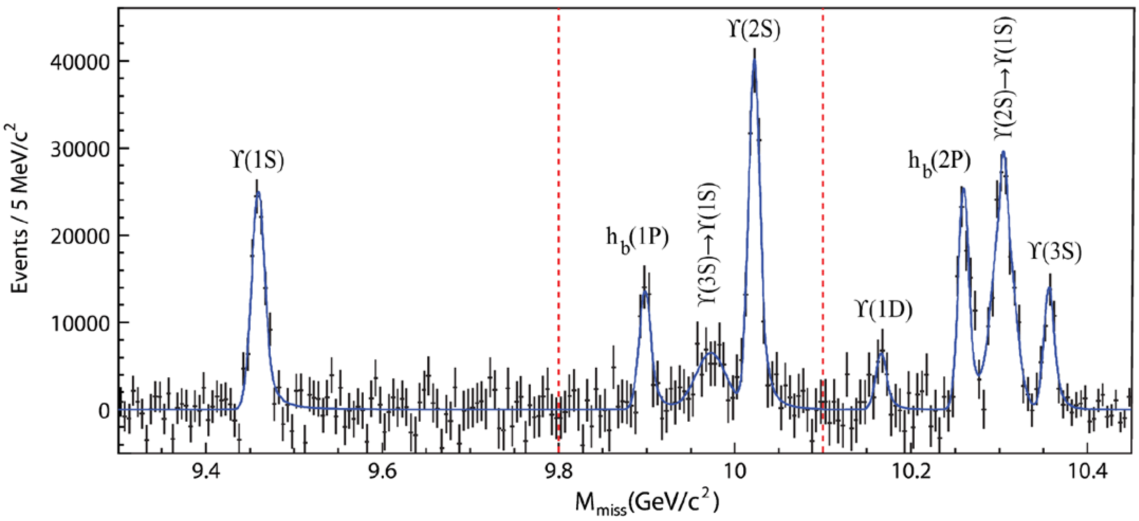

Figure 2: The background-subtracted $\pi^+\pi^-$ missing mass spectrum from Belle [5]. The peaks in this spectrum arise from $\Upsilon(5\mathrm{S}) \to \pi^+\pi^-\Upsilon(\mathrm{nS})$ with $n = 1,2,3$, $(\Upsilon(3\mathrm{S}),\Upsilon(2\mathrm{S})) \to \pi^+\pi^-\Upsilon(1\mathrm{S})$ arising from $\Upsilon(3\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ produced via ISR, and direct $\Upsilon(5\mathrm{S}) \to \pi^+\pi^-(h_b(1\mathrm{P}),h_b(2\mathrm{P}))$. The peak near 10.16 GeV$/c^2$ constitutes evidence for $\Upsilon(5\mathrm{S}) \to \pi^+\pi^-\Upsilon(1\mathrm{D})$.

As in the case of CLEO's observation in charmonium, the observation of $\Upsilon(5\mathrm{S}) \to \pi^+\pi^- h_b(\mathrm{nP})$ transitions requires - if the transition truly arises from direct emission of the pion pair from the vector state $\Upsilon(5\mathrm{S})$ - the spin-flip of a heavy b quark, and would be expected to be highly suppressed relative to the vector-to-vector transitions $\Upsilon(5\mathrm{S}) \to \pi^+\pi^-\Upsilon(\mathrm{nS})$. As is evident from Fig. 2, these transitions occur at similar rates - and thus questions about the mechanism of these transitions abound. Belle therefore set out next to study the dynamics of these decays by seeking possible resonant substructure in them to try to explain the lack of expected suppression of these rates - and this led to the next, even more unusual discovery.

1.3 Discovery of exotic charged states $Z_b(10610)$ and $Z_b(10650)$

If the large dipion transitions from $\Upsilon(5\mathrm{S})$ to below-threshold bottomonium states, both to triplet-S and singlet-P states, were to be explained, one likely possibility was that the two pions were not produced in a direct, three-body decay along with the bottomonium daughter, but that there was some sort of intermediate state produced in the decay. By studying either the invariant mass of a single pion with the daughter bottomonium state, or, equivalently, by examining the

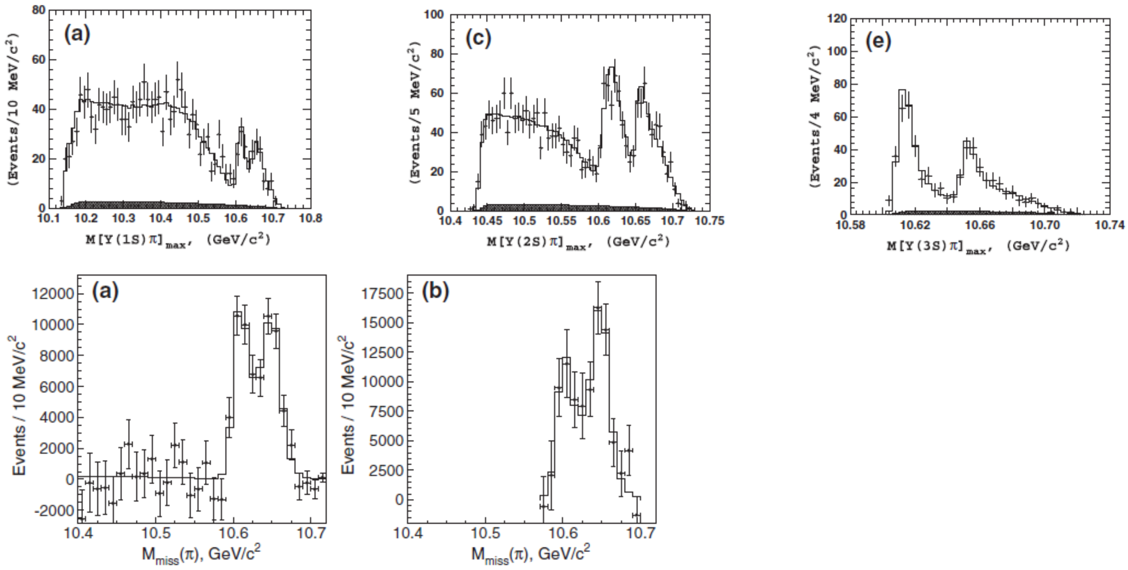

Figure 3: Distributions of (top) larger of the two invariant masses of a daughter pion and (left) Υ(1S), (center) Υ(2S), and (right)Υ(3S), and (bottom) single pion missing mass for events in which (left) h_b(1P) and (right) h_b(2P) are observed. The top row, invariant mass spectra involve fully reconstructed events, while the bottom row are sideband subtracted events in which only the two pions are reconstructed [6].

missing mass for one of the two pions in the event, such resonant substructure would possibly be observable.

Upon discovery of the h_b(nP) states, then, this is the study Belle undertook - and soon it was concluded that there were, in fact, intermediate resonances, dubbed $Z_b(10650)$ and $Z_b(10610)$, observable in the missing mass spectrum of single pions (See Fig. 3), both in events in which the lower vector bottomonia were produced, as well as the h_b(nP) states [6]. In fact, the h_b(nP) states were found to be produced ONLY when a Z_b intermediate state was involved; vector bottomonia were produced both in cases in which a Z_b resonance could be discerned from the single pion missing mass, and when one could not. Once the Z_b states were established, the requirement of a pion missing mass to lie in the Z_b mass regions enabled a cleaner selection of h_b(nP) states, and, eventually, the discovery of radiative transitions from the h_b(nP) to η_b(mS) states [7].

The Z_b states must be exotic - they cannot simply be a pair of quarks but, at a minimum, must involve four quarks. The mass of Z_b requires that two bottom quarks must be involved - and transitions from Υ(5S) to a single charged pion plus a Z_b indicate that the state itself is charged. The Z_b cannot be baryonic, as there is no second baryon produced in the transition - and therefore the simplest solution involves four quarks - though whether the Z_b are tetraquarks, or meson molecules is not immediately obvious. The molecular interpretation, however, is suggested by the fact that the Z_b states, sitting at approximately 10.61 and 10.65 GeV$/c^2$, are very near the thresholds, respectively, for the production of a B and B^*, and a pair of B^*. New results stemming from the investigation of the relation between the Z_b and these thresholds will be presented in a subsequent section.

2. Measurement of R_b and $e^+e^- \to \pi^+\pi^-\Upsilon(\mathrm{nS})$ Cross Sections

As noted in the first section, one of the interesting questions that arose from the smaller, 23.4fb^{-1} sample of data taken in the $\Upsilon(5\mathrm{S})$ region was the question of whether there were two peaking resonances, one of which transitioned to lower $\Upsilon(\mathrm{nS})$ states at a higher rate than a traditonal $\Upsilon(5\mathrm{S})$ could. Using a more comprehensive scan that was available in that earlier data sample, Belle studied the region again with a finer grained scan across the $\Upsilon(5\mathrm{S})$ region, extending even up to the vicinity of $\Upsilon(6S)$, near 11.0 GeV. The data sample used for these studies included both the large sample of 121.4fb^{-1} on the $\Upsilon(5\mathrm{S})$ peak, 16 points of $\sim$ 1fb^{-1} spread between 10.63 and 11.02 GeV, and 61 points in 5 MeV steps between 10.75 and 11.05 GeV.

This analysis utilized a selection requiring full reconstruction of $\pi^+\pi^-\Upsilon(\mathrm{nS})$ with $\Upsilon(\mathrm{nS})$ observed in the $\mu^+\mu^-$ decay mode to study the $e^+e^- \to \pi^+\pi^-\Upsilon(\mathrm{nS})$ cross section, and a hadronic selection with R_2, the ratio of the second to zeroth Fox-Wolfram moments, to be < 0.2, to suppress non-$b\bar{b}$ events to study the $b\bar{b}$ cross section. The resulting cross sections, normalized to the $e^+e^- \to \mu^+\mu^-$ cross section, are shown in Fig. 4 [8].

One of the most important distinctions observed in this analysis is the observation of a large interference between the resonant production of $b\bar{b}$ and the continuum $b\bar{b}$ as evidenced in the fit components shown in Fig. 4, and, by comparison, the complete lack of continuum production of $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, and $\Upsilon(3\mathrm{S})$. The intereference terms cause the $\Upsilon(5\mathrm{S})$- and $\Upsilon(6S)$-related peaks in the overall $b\bar{b}$ cross section to shift - and the degree of the shift is difficult to determine - since the non-resonant continuum $b\bar{b}$ contribution is almost certainly not flat (though that is the assumption made in this analysis). As a result of this lack of knowledge of the possibly complicated shape of the continuum $b\bar{b}$ cross section, it is advised that one should not take resonance parameters from measurements of R'_b, but only from the study of $e^+e^- \to \pi^+\pi^-\Upsilon(\mathrm{nS})$, which has no continuum cross section and thus no interference to distort the resonance curves.

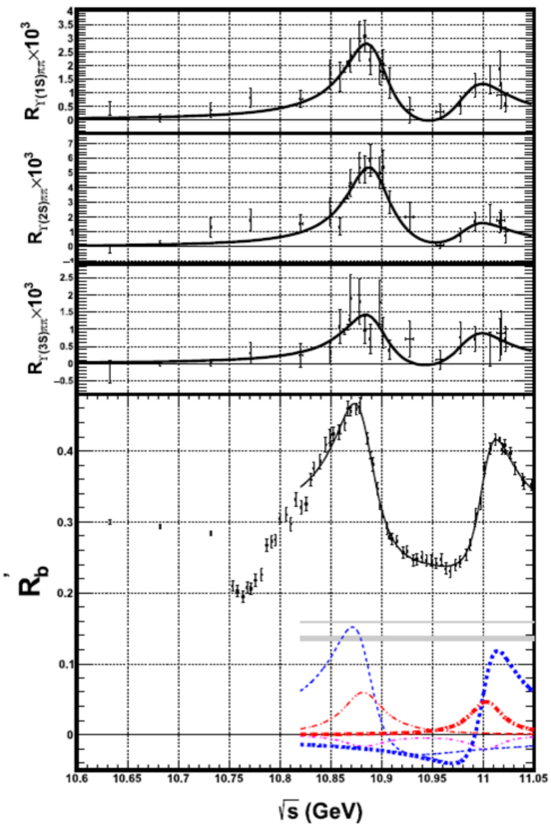

Figure 4: Ratios of $e^+e^- \to$ (from top to bottom) $\Upsilon(1\mathrm{S})$, $\Upsilon(2\mathrm{S})$, $\Upsilon(3\mathrm{S})$, and $b\bar{b}$ cross sections to that for $e^+e^- \to \mu^+\mu^-$ [8]. The ratio R'_b is the ratio $\sigma_{b\bar{b}}$ corrected to remove contributions in which bound bottomonium states are produced via Initial State Radiation.In the R'_b graph are included the fit components - the two gray curves are (assumed flat) continuum contributions, the dashed curves give resonant contributions for $\Upsilon(5\mathrm{S})$ and $\Upsilon(6S)$, the dot-dot-dash curves show interference cross terms with the continuum, and the dot-dash curve shows two-resonance cross terms.

3. Measurement of $e^+e^- \to \pi^+\pi^- h_b(\mathrm{nP})$ Cross Sections

Prior to this new observation, the $h_b(\mathrm{nP})$ states had only been observed using the 121.4fb^{-1} data sample taken on the $\Upsilon(5\mathrm{S})$ resonance. A natural extension of the work reported in the preveious section is the study, at the high luminosity $\sim 1\mathrm{fb}^{-1}$ scan points, of the $h_b(\mathrm{nP})$ cross sections of particular interest is the question of whether the $h_b(\mathrm{nP})$ are produced at all at the $\Upsilon(6S)$, and if there is any continuum contribution.

The analysis of these sixteen data points was performed using events that pass a general hadronic selection, and, additionally, include a $\pi^\pm$ having a missing mass in the range of $10.59\,\mathrm{GeV}/c^2 < M_{miss}(\pi^\pm) < 10.67\,\mathrm{GeV}/c^2$, thus privileging events with an intermediate Z_b. For such events, then, at each data point the missing mass against pairs of oppositely charged pions is computed, and fitted for yields of the two $h_b(\mathrm{nP})$ states. The fitted yields may then be plotted vs $\sqrt{s}$, and the resulting spectra are shown in Fig. 5. One may immediately conclude from these two spectra that the data a) are consistent with there being no continuum $h_b(1\mathrm{P})$ production, and b) reveal a healthy cross section at the $\Upsilon(6S)$ as well as at the $\Upsilon(5S)$. In addition, the production of $h_b(\mathrm{nP})$ at all these data points was found to be thoroughly saturated by processes involving an intermediate Z_b, just as was previously observed in the on-$\Upsilon(5\mathrm{S})$ data sample.

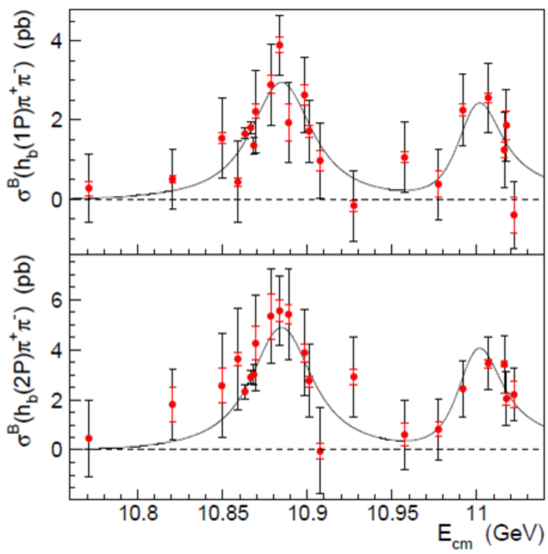

Figure 5: Cross sections for $e^+e^- \to \pi^+\pi^- h_b(\mathrm{nP})$ with (top) n=1 and (bottom) n=2. The data are represented by the points with error bars, while the fit results are indicated by the solid curves [10].

4. Measurement of $\Upsilon(5\mathrm{S}) \to (BB^*)^\pm\pi^\mp$ at $\Upsilon(5\mathrm{S})$

Finally, we return to the study of the Z_b states, which had been discovered to lie just above the BB^* and B^*B^* thresholds of approximately 10.61 and 10.65 GeV$/c^2$, respectively. This proximity lends credence to the possibility that the Z_b states are not conventional mesons, but are molecules of $B^{(*)}$ and B^*. In order to shed additional light on this question, Belle undertook an analysis, using partial reconstruction, of B and B^* mesons in events in which the missing mass against single charged pions in e^+e^- annihilation at $\Upsilon(5\mathrm{S})$ indicated the presence of a Z_b.

In events passing a hadronic event selection (again requiring a small value of R_2 to reject continuum $b\bar{b}$) B mesons were first reconstructed in a the final states $J/\psi K^{(*)}$ and $D^{(*)}\pi$. These B candidates were then combined with a single charged π, and then the missing mass against $B\pi$ was computed. Events of interest include $e^+e^- \to BB^*\pi$, which will produce a $B\pi$ missing mass peak at the nominal B^* mass M_{B^*}, as well as $e^+e^- \to B^*B^*\pi$, which will produce a $B\pi$ missing mass peak near $M_{B^*} + \Delta M_{B^*}$, where ΔM_{B^*} is the mass difference between B and B^*, due to the missed

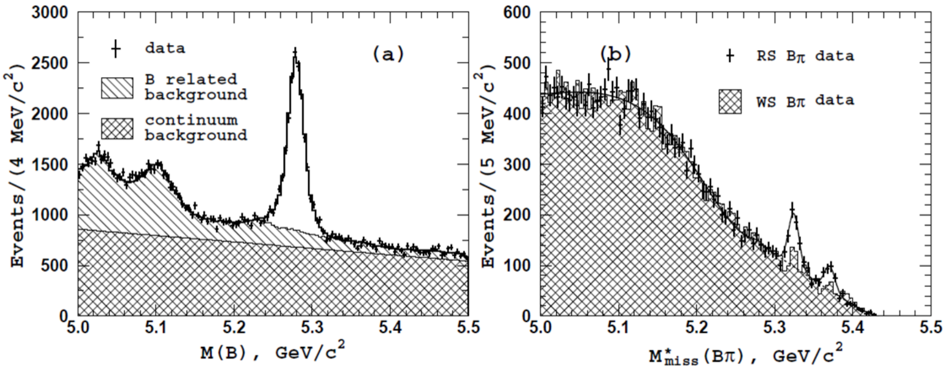

Figure 6: The (a) invariant mass of B candidates and (b) $B\pi$ missing mass. The open histogram indicates the signal events of interest - the shaded histograms, the continuum and B-related backgrounds [11].

photon in the $B^* \to B\gamma$ decay. The B candidate invariant mass and the $B\pi$ missing mass are shown in Fig. 6.

In order to study the composition of the observed excesses in the $B\pi$ missing mass distribution, the single charged π missing mass is calculated. In order to estimate backgrounds, a wrong-sign sample (where the charged pion missing mass is calculated for pions whose charge is the same as the tag B) is used. The single pion missing mass $M_{miss}(\pi)$ is shown for both the BB^* and B^*B^* selections in Fig. 7. Above the background we see in each plot an excess - in the case of BB^*, a clear excess at 10.61 GeV$/c^2$, and in the case of B^*B^*, a clear excess at 10.65 GeV$/c^2$. While there is not sufficient threshold for the lower Z_b state to decay to B^*B^*, and therefore no excess at 10.61 GeV$/c^2$ is expected in that plot, it is possible for the higher Z_b state to decay to BB^* - but no excess is seen in $M_{miss}(\pi)$ in those events. This observation therefore considerably bolsters the evidence for the molecular hypothesis.

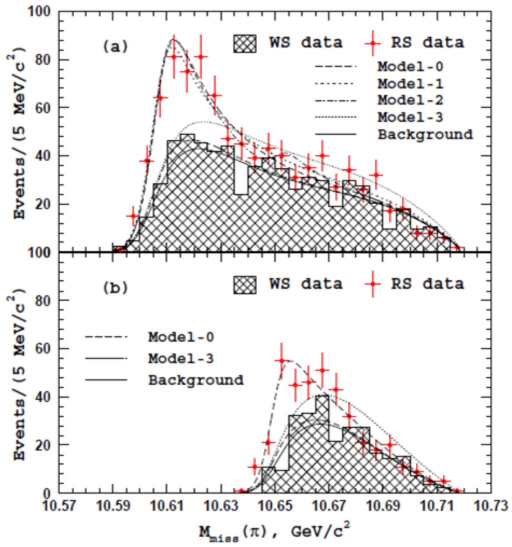

Figure 7: The distribution of single-pion missing mass $M_{miss}(\pi)$ for (a) $BB^*\pi$ and (b) $B^*B^*\pi$ candidate events. The shaded histogram indicates background estimated from wrong-sign events[11]

5. Summary

Over the course of the past eight years, the Belle Collaboration has made significant contributions to the understanding of the bottomonium system using its very large data sample at and near the $\Upsilon(5S)$ resonance. These contributions include the discovery of the long-awaited singlet-P mesons of bottomonium, $h_b(1\mathrm{P})$ and $h_b(2\mathrm{P})$, and their radiative transitions, the charged Z_b states whose interpretation as molecular bound states of B and B^* seems increasingly firmly established, and the important scans of various cross sections, both $b\bar{b}$, $\pi^+\pi^-\Upsilon(\mathrm{nS})$, and $\pi^+\pi^- h_b(\mathrm{nP})$, throughout the region from $\Upsilon(5\mathrm{S})$ to $\Upsilon(6S)$. The stage is set for Belle II as it begins to take data in the next several years, and, in addition to its primary mission of studying heavy flavor physics at $\Upsilon(4\mathrm{S})$, we can look forward to more interesting results in bottomonium spectroscopy.

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