SEARCH FOR BOTTOM COUNTERPARTS OF $X(3872)$ AND $Y(4260)$ VIA $\pi^+\pi^-\Upsilon$

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The $X(3872)$ and $Y(4260)$, both discovered in $\pi^+\pi^-J/\psi$ mode, are rather unusual: $X_c \equiv X(3872)$ is very narrow, while $Y_c \equiv Y(4260)$ has large $Y_c \rightarrow \pi^+\pi^-J/\psi$ width. Many models for their composition have been suggested, but perhaps discovering their bottom counterparts could shed much light on the issue. The narrow state, $X_b$, may be searched for at the Tevatron via $p\bar{p} \rightarrow \pi^+\pi^-\Upsilon + X$, with the LHC much more promising. The state $Y_b$ can be searched for at B factories via radiative return $e^+e^- \rightarrow \gamma_{\text{ISR}} + \pi^+\pi^-\Upsilon$ on $\Upsilon(5S)$, or by $e^+e^- \rightarrow \pi^+\pi^-\Upsilon$ direct scan.

1. INTRODUCTION

After laying dormant for two decades, charmonium physics is experiencing a renaissance largely due to the unprecedented luminosities achieved at the B factories. We now have\(^{1}\) an $X$ and a $Y$ and a $Z$ of 3940 MeV states produced via various mechanisms. But two states stand out especially: the $X(3872)$ and the $Y(4260)$, both observed in the $\pi^+\pi^-J/\psi$ channel.

The $X_c \equiv X(3872)$ was discovered\(^{2}\) by Belle. A very narrow state with $\Gamma < 2.3$ MeV (consistent with experimental resolution) was observed in $\pi^+\pi^-J/\psi$ recoiling against $K^+$ from $B^+$ decay. Owing to this narrowness, it was quickly confirmed by CDF\(^{3}\) and D0 in $p\bar{p} \rightarrow \pi^+\pi^-J/\psi + X$. The mass of $X_c$ is just at the $D^0\bar{D}^{*0}$ threshold, which may be related to its narrowness. Theoretical interpretations for $X_c$ has ranged from $D^0\bar{D}^{*0}$ molecule, 4 quark state, to charmonium hybrid.

The $Y_c \equiv Y(4260)$ was discovered\(^{4}\) by BaBar in initial state radiation (ISR, or “radiative return”) $e^+e^- \rightarrow \gamma_{\text{ISR}} + \pi^+\pi^-J/\psi$ events, hence has $J^{PC} = 1^{--}$. It has a normal hadronic width of $\sim 90$ MeV. However, $\Gamma_{ee} = \frac{\Gamma e^-}{\Gamma_{e^-}} \sim 5.5$ eV implies (cf. $\sim 0.5$ eV for $\psi(3770)$) a rather large $Y_c \rightarrow \pi^+\pi^-J/\psi$ rate. These properties were confirmed\(^{5}\) by CLEO-c via $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ energy scan. Theoretical interpretations for $Y_c$ range from hybrid, 4 quark state, meson molecule or baryonium, to conventional $\psi(4S)$.

So, what about bottomonium? Clearly, the analogous $X_b$, $Y_b$ states should be searched for in the $\pi^+\pi^-\Upsilon$ channel.\(^{6}\) We point out that the narrow state $X_b$ can be searched for at the Tevatron and the LHC. The $1^{-+}$ state $Y_b$ can be searched for at the B factories, and future Super B factory, either by ISR search on the $\Upsilon(5S)$, or by direct scan at $\Upsilon(5S)$ energies and beyond.

2. Tevatron/LHC: $X_b \rightarrow \pi^+\pi^-\Upsilon$

What is the $X_b$ mass? It could be at the $B\bar{B}$ threshold of 10640 MeV, but it could also be lower, e.g. 10560 MeV, by coupled channel arguments. The mass itself is to be probed to shed light on the hadronic structure.

For $X_b$ production, we no longer have the analogy of $B \rightarrow KX$, and since the preferred $J^{PC}$ is $1^{+-}$, we have to resort to hadronic machines. Fortunately, prompt $X(3872)$ production, similar to $\psi'$, dominates.

The current projection\(^{7}\) is for roughly 3000 reconstructed $X(3872)$ per fb\(^{-1}\). From 40 pb\(^{-1}\) data one can\(^{8}\) reconstruct $\sim 3 \times 10^5$ $J/\psi$. In comparison, from 77 pb\(^{-1}\) data, $\sim 4400$ $\Upsilon$ is reconstructed.\(^{9}\) The leptonic
branching fraction has been taken into account. We estimate that \( \sim 180 \) reconstructed \( X_b \to \pi^+\pi^-\Upsilon \) events may be possible for 8 fb\(^{-1}\). More conservatively, we take the ratio of the peak cross sections for reconstructed \( \Upsilon \) and \( J/\psi \to \mu\mu \) events, which is \( \sim 1/800 \), and reach an estimate of \( \sim 30 \) \( X_b \to \pi^+\pi^-\Upsilon(\to \mu\mu) \) events. However, the relative BRs and production fractions for \( X_b \) vs \( X_c \) are unknown, which is in fact to be probed in the search. We can only conclude that \( X_b \) might be accessible.

What needs to be done at the Tevatron Run II is to benchmark the \( \Upsilon(2S) \to \pi^+\pi^-\Upsilon \) process, then look for a higher mass “bump”, much like the case for \( X(3872) \).

The LHC is much more promising. For \( \Upsilon \) production, a study using PYTHIA fits to the results of \( \Upsilon \) production at the Tevatron, then extends to the LHC. The peak cross section increases by over two orders of magnitude, and \( B(\Upsilon \to \mu^+\mu^-) \sigma(pp \to \Upsilon + X) / d \tau \) at LHC is roughly 1/10 that of \( B(J/\psi \to \mu^+\mu^-) \sigma(p\bar{p} \to J/\psi + X) / d \tau \) at the Tevatron. Thus, one expects over 1000 \( X_b \to \pi^+\pi^-\Upsilon(\to \mu\mu) \) events per fb\(^{-1}\), and discovery at the LHC seems assured, if the \( X_b \) exists.

The homework for ATLAS, CMS and LHCb is the same as at the Tevatron: benchmark \( \Upsilon(2S) \to \pi^+\pi^-\Upsilon \), then look for higher mass narrow state(s). It is highly desirable to improve cross section calculations.

Note that the forward production of \( b\bar{b} \) pairs should be enhanced, although even less is known compared to central production. To take advantage of this, and because of the interest in heavy flavor physics and CP studies, the dedicated LHCb experiment has forward design with the luxury of RICH and ECAL detectors, i.e. much better hadron identification and photon detection than ATLAS and CMS. Thus, though discovery of \( X_b \) may be an open competition between the three LHC experiments, LHCb may have the best capability in exploiting this new bottomonium spectroscopy, such as narrow states in \( \omega\Upsilon \) and \( K^+K^-\Upsilon \). Of course, charmonium spectroscopy can also be studied.

3. \( \Upsilon_b \to \pi^+\pi^-\Upsilon \) in \( e^+e^- \to (\gamma)\Upsilon_b \)

With 211 fb\(^{-1} \) data, BaBar discovered\(^4 \) the \( Y(4260) \) in radiative return \( e^+e^- \to \gamma\text{ISR} + \pi^+\pi^- J/\psi \). From 125 reconstructed \( Y(4260) \to \pi^+\pi^- J/\psi \) events,

\[
\Gamma_{\Upsilon_c \to ee} B_{\Upsilon_c \to \pi^+\pi^- J/\psi} \sim 5.5 \text{ eV}, \tag{1}
\]

is inferred, while \( \Gamma_{\Upsilon_c} \simeq 88 \text{ MeV} \). This gives \( B_{\Upsilon_c \to ee} B_{\Upsilon_c \to \pi^+\pi^- J/\psi} \sim 7 \times 10^{-8} \), which is larger than the case for \( \psi(4040) \) and \( \psi(4160) \). But since \( Y_c(4260) \) falls at a dip in the cross section for \( e^+e^- \to \text{hadrons} \), barring subtle interference effects, presumably \( \Gamma_{\Upsilon_c \to ee} \ll \Gamma_{\psi(4160)\to ee} \sim 770 \text{ eV} \). Hence, the partial width \( \Gamma_{\Upsilon_c \to \pi^+\pi^- J/\psi} \) should be a few MeV or higher, much larger than typical charmonia.

Stimulated by this, CLEO-c made a scan\(^5 \) for \( \sqrt{s} = 3.97 \) to 4.26 GeV, which covers the \( \psi(4040) \), \( \psi(4160) \) and \( Y_c(4260) \), and 15 decay channels were studied. With just 0.013 fb\(^{-1} \) around 4260 MeV, CLEO-c confirmed the BaBar signal, finding \( \sigma(e^+e^- \to \pi^+\pi^- J/\psi) \simeq 58 \text{ pb} \), which is consistent with Eq. (1). CLEO-c also found signals in \( \pi^0\pi^0 J/\psi \) and \( K^+K^- J/\psi \) channels.

What is noteworthy is that, with accumulated data that is only 1/16000 that of the ISR data, CLEO-c reconstructed 35 \( \pi^+\pi^- J/\psi \) events with low background, while the ISR approach gave 125 events after accounting for background. For \( \Upsilon_b \) search, therefore, one should consider both ISR return and direct scan, i.e. try both \( e^+e^- \to \gamma\text{ISR} \pi^+\pi^- \Upsilon \) and \( e^+e^- \to \pi^+\pi^- \Upsilon \) processes, and weigh the benefits against cost. It should be clear that a \( \sim 100 \text{ MeV} \) width precludes hadronic machines as an effective search tool because of high background.

It is interesting to note that, motivated by \( B_s \) physics, Belle has now accumulated\(^11 \) \( \sim 24 \text{ fb}^{-1} \) data on the \( \Upsilon(5S) \). The study not
only demonstrated the capability to accumulate $\sim 1$ fb$^{-1}$ per day on $\Upsilon(5S)$, a scan of 5 energy points of 0.03 fb$^{-1}$ each around the $\Upsilon(5S)$, altogether done within a day, demonstrates the relative ease in changing energies. So, one not only has significant amount of data at hand to probe for $Y_b$ lighter than 10870 MeV, direct scan can be contemplated.

So what is the target mass range for $Y_b$? And what cross sections can one expect for the two advocated processes? We can only make guestimates, using the CLEO-c favored $Q\bar{Q}g$ hybrid picture as a guide.

Lattice studies have put the lowest $b\bar{b}g$ hybrid at around$^{12}$ 10700–11000 MeV. The $1^{--}$ quantum number is possible, but many other quantum numbers are possible, including exotic ones such as $1^{--}$. The $1^{--}$ can mix with standard $s$-wave mesons and may not be the lightest, but it is clearly the most accessible. Lattice studies tend to give lightest $c\bar{c}g$ hybrid mass around 4400 MeV. If $Y_b(4260)$ is indeed dominantly a hybrid, by analogy the lattice range for the $b\bar{b}g$ hybrid should be scaled down to 10600–10900 MeV. This would make $\Upsilon(5S)$, at 10865 MeV, an excellent place to conduct $e^+e^-\rightarrow\gamma_{\text{ISR}}Y_b\rightarrow\gamma_{\text{ISR}}\pi^+\pi^-\Upsilon$ search. We take 10600, 10700 and 10800 MeV as nominal $M_{Y_b}$ values for purpose of illustration.

We caution, however, that even with lattice studies of hybrids, there are uncertainties due to difference in numerical approach, scale uncertainty, as well as treatment of dynamic quarks. For example, some studies$^{13}$ find the lowest $b\bar{b}g$ hybrid mass to be $\sim 10900$–11000 MeV, while giving the right mass for $c\bar{c}g$ hybrid that is consistent with $Y_c(4260)$. If $Y_b$ is heavier than 10900 MeV, then it cannot be accessed by $\Upsilon(5S)$ data, and a direct scan would be necessary.

For other properties of $Y_b$, a width of order 100 MeV seems reasonable, while the product branching fraction similar to Eq. (1) can also be assumed, although $\Gamma_{\Upsilon\rightarrow e^+e^-}\frac{B_{Y_b\rightarrow\pi^+\pi^-J/\psi}}{M_{Y_b}}$ could be smaller or larger than Eq. (1).

The ISR cross section is well known. In the narrow width approximation, and leading order in $\alpha$, one has$^{14}$

$$\sigma_{\text{ISR}} \approx 36 \frac{\Gamma_{\Upsilon\rightarrow e^+e^-}\frac{B_{Y_b\rightarrow\pi^+\pi^-\Upsilon}}{M_{Y_b}}}{x-1+x/2} \mu\text{b},$$

(2)

where $x = 1 - M_{Y_b}^2/s$ is the energy fraction carried away by the ISR photon (usually not observed) in the CM frame. The cross sections for our representative values of $M_{Y_b} = 10600, 10700$ and 10800 MeV are given in Table 1.

Radiative return cross section is $O(\alpha)$ suppressed, but one might enjoy a longer run on the $\Upsilon(5S)$ for reasons of $B_s$ physics. One could also gain in $1/E_\gamma$ enhancement when $Y_b$ is closer to $\Upsilon(5S)$, but the narrow width approximation may start to be questionable. Since we do not know the width for $Y_b$, we just use Table 1 as a rough guide. With 24 fb$^{-1}$ on $\Upsilon(5S)$, assuming $\Gamma_{\Upsilon\rightarrow e^+e^-}\frac{B_{Y_b\rightarrow\pi^+\pi^-\Upsilon}}{M_{Y_b}}$ is similar Eq. (1), even for $M_{Y_b} \sim 10600$ MeV one expects close to 600 $\pi^+\pi^-\ell^+\ell^-$ events, where $\ell = e, \mu$ and $m_{\ell\ell}$ reconstruct to $M_\Upsilon$. $Y_b$ mass closer to $\Upsilon(5S)$ would give more events. Thus, even for $\Gamma_{\Upsilon\rightarrow e^+e^-}\frac{B_{Y_b\rightarrow\pi^+\pi^-\Upsilon}}{M_{Y_b}}$ as low as 1 eV, one can get similar significance for $Y_b$ as the BaBar discovery of $Y(4260)$, where 125 events were obtained from 211 fb$^{-1}$ data on the $\Upsilon(4S)$. It seems that ISR return on $\Upsilon(5S)$ would definitely find the corresponding $Y_b$ if it is lighter than 10865 MeV in mass.

The ISR return from $\Upsilon(5S)$ does not cover the full range of lattice predictions for the $b\bar{b}g$ hybrid. One may have to directly

| Process                | 10600 | 10700 | 10800 |
|------------------------|-------|-------|-------|
| $e^+e^-\rightarrow\gamma_{\text{ISR}}\pi^+\pi^-\Upsilon$ | 0.4 pb | 0.6 pb | 1.6 pb |
| $e^+e^-\rightarrow\pi^+\pi^-\Upsilon$             | 9.1 pb | 9.0 pb | 8.8 pb |

Table 1. Cross section for radiative return from $\Upsilon(5S)$, and for direct $e^+e^-\rightarrow\pi^+\pi^-\Upsilon$ scan, for $M_{Y_b} = 10600, 10700$ and 10800 MeV. The branching ratio product is taken as the same as Eq. (1).
scan for \( e^+e^- \to Y_b \to \pi^+\pi^-\Upsilon \) if \( Y_b \) turns out to be heavier than \( \Upsilon(5S) \). Let us estimate the cross section involved. This is a standard resonance cross section, hence
\[
\sigma(s) \simeq \frac{12\pi B_{\ell\ell} B_{s^{-\pi-\Upsilon}}}{s} \sim \frac{1027}{M_{Y_b}^2} \text{ pb} \sim 9 \text{ pb},
\]
where \( s = M_{Y_b}^2 \) is in GeV\(^2\) units, and we have taken \( B_{\ell\ell} B_{s^{-\pi-\Upsilon}} \) to be the same as for \( Y_c(4260) \). The cross sections for the three mass values are given in Table 1, but can be easily extended above as it varies slowly.

With just 0.013 fb\(^{-1}\) of data on the \( Y_c(4260) \), CLEO-c was able to observe\(^5\) a clean signal of 37 \( \pi^+\pi^-J/\psi \to \pi^+\pi^-\ell^+\ell^- \) events with little background. If Eq. (1) holds approximately for \( Y_b \to \pi^+\pi^-\Upsilon \), what is the integrated luminosity needed to achieve the same for \( Y_b \)? The 1/s drop in cross section costs a factor of 0.16, while \( \Gamma_{\ell\ell} \) costs a factor of 0.4. With background and trigger issues, the efficiency could be lower. Thus, even if Eq. (1) holds for the \( Y_b \), one would probably need \( \sim 0.3 \) fb\(^{-1}\) data or more to reach a similar number of events as the CLEO-c scan for \( Y_c \). After all, CLEO-c knew the target mass. Without knowing more precisely the \( Y_b \) mass range, it seems difficult to pursue a scan search over a wide range. Maybe at the future Super B factory, the issue could be more easily covered.

4. Discussion and Conclusion

Let us offer a few remarks.

Only narrow states are accessible at hadronic machines, so \( X_b \) should be pursued, and higher energy machines have the advantage. But heavy ion environment would be too difficult because of pion combinatorics. Since \( 1^{++} \) and many other quantum numbers are difficult to access at \( e^+e^- \) machines, LHCb should be prepared for other narrow states as well. Also, LHCb has the capability to explore a more diverse program, such as \( K^+K^-\Upsilon, \omega\Upsilon \) etc., as well as \( J^{PC} \) determination. Thus, LHCb may well enjoy the bonanza in bottomonium spectroscopy that the B factories have enjoyed for charmonium.

For \( Y_b \), Belle should exploit their \( \Upsilon(5S) \) data for ISR return search. It would probably be a difficult decision for BaBar to make to run on \( \Upsilon(5S) \) to compete. However, at 0.3 fb\(^{-1}\) per scan point, the scan search for \( Y_b \) above the \( \Upsilon(5S) \) may have to await the end of the B factory era, the Super B factory era, or a strong stimulus that focuses the target mass range. On the other hand, if the \( Y_b \) is found by ISR return study on \( \Upsilon(5S) \), a dedicated direct production study would be much profitable to learn about more detailed properties, such as \( K^+K^-\Upsilon \) and \( \pi^0\pi^0\Upsilon \) decay channels.

In conclusion, we think that the bottom counterparts of \( X(3872) \) and \( Y(4260) \), called the \( X_b \) and \( Y_b \), could possibly be discovered in the near future.

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