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Recent Results on New Resonances at Belle

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Abstract

The current generation of B-factories have given a major contributions in completing the spectrum of heavy quarkonia. New questions are raised above the thresholds, where many new states, the so called XYZ's were found. Insight into their nature can come from the investigation of EM and hadronic transitions between them. This review will cover Belle's recent progress in this sector, which exploits the record samples of data taken on the peaks of the $\Upsilon(2,4,5S)$ resonances: the discovery of two multiplets of charged bottomonia (Z_b's) and of four S=1 states (parabottomonia), the studies on η transitions and on D-wave resonances in both charmonium and bottomonium. Prospects for future studies are given.

Keywords: Bottomonium, Charmonium, Hyperfine splittings, Hadron Spectroscopy

1. Introduction

Since the observation of the conventional $\eta_c(2S)$ meson [1] and of the exotic X(3872) state [2], the B-factories have led to a renaissance of the studies on heavy quarkonia [3, 4]. In the last ten years, together with the filling of most missing slots in conventional charmonium and bottomonium spectra, we witnessed the observation of a plethora of unexpected narrow states both across and above the open flavor thresholds. With the generic name of XYZ states we refer to all those new states which do not fill in the usual $Q\bar{Q}$ framework and are challenging theorists and experimentalists. At the same time, it is important to stress that the improved measurements of conventional charmonium masses and decay modes allow to test effective theory predictions at next to leading order, whenever a perturbative approach is applicable, or to improve lattice QCD methods.

In this review, I will focus on the recent progress on a few selected topics:

- the discovery of the two triplets of charged bottomonia and of the triple hybrid cascade

$$\Upsilon(5S)\to Z_b \to h_b \to \eta_b$$

  which allowed to reach four parabottomonium states, in a way which was totally unpredicted by theory;
- the studies on hadronic transitions with the emission of one η meson: this process should be suppressed by the presence of a spin flipping term in the transition amplitude, but the transitions from $\Upsilon(4,5S)$ to narrow bottomonia do not seem to be affected;
- the studies on D-wave charmonia and bottomonia: very recently, Belle has announced the discovery of the $^3D_2$ state of charmonium in B decays and is currently exploring new pathways to the D states of bottomonium using dipion transitions from $\Upsilon(5S)$.

2. Charged bottomonia and parabottomonia

Until 2008, none of the spin singlet bottomonium states was known. The ground state, η_b was discovered by BaBar using the M1 radiative transitions from $\Upsilon(3S)$ [5] and $\Upsilon(2S)$[6] and later confirmed by CLEO [7] using $\Upsilon(3S)\to\gamma\eta_b$. The mass measured by BaBar and CLEO was significantly lower than the NLO NRQCD predictions [8] and agreed with lattice predictions [9], and earlier works based on potential models [10] or QCD sum rules [11]. The systematic error on the mass measurement is

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dominated by the parametrization of the PDF describing the background. In order to improve the mass measurement of the η_b, different paths for the study of this state had to be explored.

In 2010, using data taken at $\sqrt{s}$= 4170 MeV, CLEO announced the observation of the dipion transition to the P-wave spin singlet state $h_c(1P)$ [12], suggesting the idea that the dipion transitions could also be used to search for still unknown narrow quarkonia. CLEO also observed that such transition is comparable in intensity with the dipion transition to vector states. A similar search was therefore attempted using 120 fb^{-1} of data taken by Belle at the peak of $\Upsilon(5S)$.

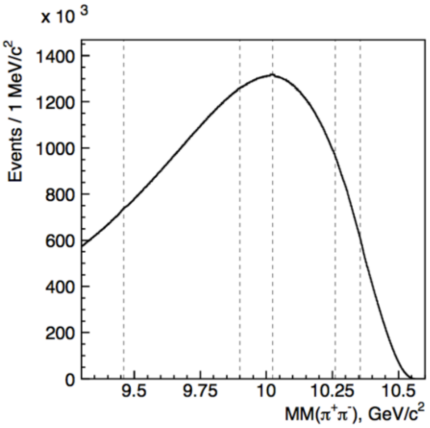

Figure 1: Distribution of missing mass recoiling against the dipion pair, MM($\pi^+\pi^-$), from Υ(5S), before the subtraction of combinatorial background. The vertical lines indicate the mass of the $\Upsilon(1,2,3S)$ and the $h_b(1,2P)$ states.

Despite a very large combinatorial background (see Figure 1), after the subtraction of a smooth polynomial background function, the distribution of the recoil mass $MM(\pi^+\pi^-)$ shows (see Figure 2) distinct peaks due to at least six dipion transitions:

- three large transitions to the narrow vector states $\Upsilon(1,2,3S)$; this process was already observed in exclusive mode by Belle, which devoted a special scan in December 2007 [13] to search for a potential bottomonium analogue of Y(4260). Results from the scan show that the $\Upsilon\pi\pi$ cross section peaks about 20 MeV above the $\Upsilon(5S)$ nominal CM energy;

- a peak at $\sqrt{s} = 10.160$ GeV, which corresponds to the first D-wave state of bottomonium, as observed by CLEO in 2004 using the quadruple photon transition $\Upsilon(3S) \to \chi_b(2P) \to \Upsilon(1D) \to \chi_b(1P) \to \Upsilon(1S)$ [14], and confirmed by BaBar, which produced the $\Upsilon(1D)$ via the same double photon cascade, but observed its decay to $\pi^+\pi^-\Upsilon(1S)$ [15];

- two peaks about 9900 and 10260 MeV/c^2, which are interpreted as the first observation of the spin singlet P wave states $h_b(1P)$ and $h_b(2P)$ [16], whose masses are summarized in Table 2. In both cases, the mass difference with respect to the spin averaged center of the $\chi_b(1,2P)$ states, defined as: $M_{cog} = \frac{5M(\chi_{b2})+3M(\chi_{b1})+M(\chi_{b0})}{9}$, is consistent with zero.

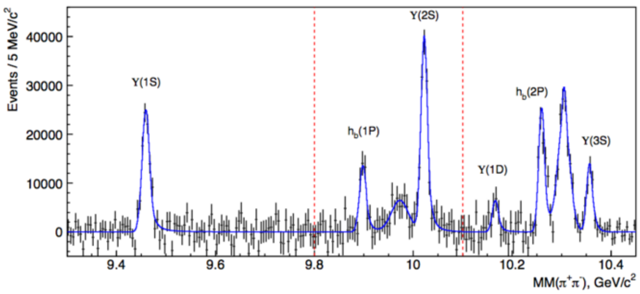

Figure 2: Residuals of the MM($\pi^+\pi^-$) from Υ(5S), after continuum subtraction. The two unlabeled peaks in the plot are due to the decays $\Upsilon(2,3S) \to \pi^+\pi^-\Upsilon(1S)$ of the $\Upsilon(2,3S)$'s produced either via ISR or via the transitions discussed in this paper.

Table 1: Yields of inclusive events from $\Upsilon(5S) \to \pi^+\pi^- + b\bar{b}$.

$b\bar{b}$	Yield, 10^3	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	18.2 σ
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	16.6 σ
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	8.5 σ
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	6.2 σ
$h_b(2P)$	$84.4 \pm 6.8^{+23}_{-10}$	12.4 σ
$\Upsilon(1D)$	22.0 ± 7.8	2.4 σ

The intensity of the transition who permitted the discovery of the h_b's, comparable to the one of the $\pi\pi$ transition to the $\Upsilon(1,2,3S)$ states, was totally unexpected by theory: in the QCD multipole expansion, while the $\pi\pi$ transition $1^{--} \to 1^{--}$ is described by a E1*E1 amplitude, the $1^{--} \to 1^{+-}$ is either modeled as M1*M1 or E1*M2. Such transitions should be suppressed by a O($1/m_b$) factor, and the absence of this suppression suggested the existence of an exotic mechanism.

Table 2: Belle measurements of the $h_b(nP)$ masses and of the P-wave hyperfine splittings $\Delta M_{HF} = M(h_b(nP)) - M_{cog}(nP)$, in MeV/c^2 (above) and of the Z_b masses, in MeV/c^2, and widths, in MeV.

$M(h_b(nP))$	$\Delta M_{HF}(nP)$
$9899.1 \pm 0.4 \pm 1.0$	$+0.8 \pm 1.1$
$10259.8 \pm 0.5 \pm 1.1$	$+0.5 \pm 1.2$
$M(Z_b)$	$\Gamma(Z_b)$
10608.1±1.7	15.5± 2.4
10653.3±1.7	14.0± 2.8

The anomaly was soon explained [17] by observing that also the single pion recoil in the h_b band, as well as the $\Upsilon\pi$ projection of the Dalitz plot, were featuring a double peak (see Figure 3), to indicate that the dipion transition occurs partially (in the case of Υ) or totally (in the case of h_b) in two steps, via two charged intermediate states, $Z_b^{\pm}(10610)$ and $Z_b^{\pm}(10650)$, lying in the close proximity of the $B\bar{B}^*$ and the $B^*\bar{B}^*$ thresholds. The study of the angular distributions allowed to assign $J^P = 1^+$ to both states. Given the proximity to the thresholds, a molecular interpretation is preferred, for the two states. Further studies, to establish the existence of a neutral partner, and to calculate the branching ratios to B meson pairs, are under way at Belle.

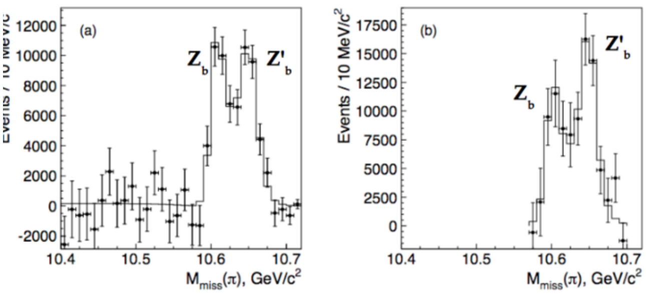

Figure 3: Residuals of MM($\pi^{\pm}$) from Υ(5S), in the $h_b(1P)$ band (a), and in the $h_b(2P)$ band (b), after continuum subtraction: the $Z_b = Z_b(10610)$ and $Z'_b = Z_b(10650)$ are shown

The discovery of the $h_b(1,2P)$ also opened a new pathway to the $\eta_b(1,2S)$ states, as the E1 transitions between these states are theoretically expected to occur with very large branching ratios [18]. Therefore, a search for these states in doubly inclusive transitions has been performed, studying the $\pi\pi$ recoil mass vs $\pi\pi\gamma$ recoil mass distribution [19]. Figure 4 shows the distribution of the variable:

$$\Delta M_{miss} = MM(\gamma\pi\pi) - MM(\pi\pi) + M(h_b)$$

in the h_b(1,2P) regions: the $\eta_b(1S)$ is observed with very high significance (15 and 9 σ) in both transitions. The mass value is barely consistent with BaBar and CLEO measurements (see Table 3), but with smaller systematic errors, and is closer to the NLO theoretical predictions from NRQCD.

Table 3: Experimental measurements of the S-wave hyperfine splitting $\Delta M_{HF} = M(\Upsilon(1S)) - M(\eta_b(1S))$ and theory predictions.

Experiment	ΔM_{HF},MeV/c^2	ref.
BaBar, from $\Upsilon(3S)$	$71.4^{+2.3}_{-3.1} \pm 2.7$	[5]
BaBar, from $\Upsilon(2S)$	$67.4^{+4.8}_{-4.6} \pm 2.0$	[6]
CLEO, from $\Upsilon(3S)$	$68.5 \pm 6.6 \pm 2.0$	[7]
Belle, from $\Upsilon(5S)$	57.9 ± 2.3	[19]
Potential Model	60	[10]
QCD Sum Rules	63^{+51}_{-29}	[11]
NRQCD	41 ± 14	[8]
Lattice QCD	60.3 ± 7.4	[9]

Belle has also made the first measurement of the $\eta_b(1S)$ width $\Gamma(\eta_b(1S)) = 10.8^{+4.0+4.5}_{-3.7-2.0}$ MeV. In addition, a strong evidence of the $\eta_b(2S)$ resonance (significance: 4.2σ) is found (Figure 5). All radiative branching fractions, and therefore the yields, are higher than theoretical expectations (see Table 4).

Table 4: Branching ratios of $h_b(1,2P) \to \eta_b(1,2S)$ transitions: Belle results vs theory expectations (from ref.[18]).

Transition	Belle	Theory
$1P \to 1S$	$(49.2 \pm 5.7^{+5.6}_{-3.3})$ %	41%
$2P \to 1S$	$(22.3 \pm 3.8^{+3.1}_{-3.3})$ %	13%
$2P \to 2S$	$(47.5 \pm 10.5^{+6.9}_{-7.7})$ %	19%

Very recently, an analysis by Seth's group of the data (about 9M events on $\Upsilon(2S)$ peak) taken by CLEO claimed the observation of $\eta_b(2S)$ [20] summing up 26 exclusive decay modes, in the $\Upsilon(2S)$ dataset. This result is largely inconsistent with Belle evidence: an independent search to verify this result in exclusive modes from $\Upsilon(2S)$ is underway using Belle data.

Using the new mass values for the η_b and h_b observed by Belle, it is possible to compute the mass splittings between spin averaged masses of S wave and P wave states (defined as $\bar{M} = (3M_{S=1} + M_{S=0})/4$) for charmonium and bottomonium systems. We obtain $\bar{M}_{1P}(c\bar{c}) - \bar{M}_{1S}(c\bar{c}) = 457.5 \pm 0.3$ MeV/c^2 and $\bar{M}_{1P}(b\bar{b}) - \bar{M}_{1S}(b\bar{b}) = 453.3 \pm 1.3$ MeV/c^2. Despite the large scale difference, the

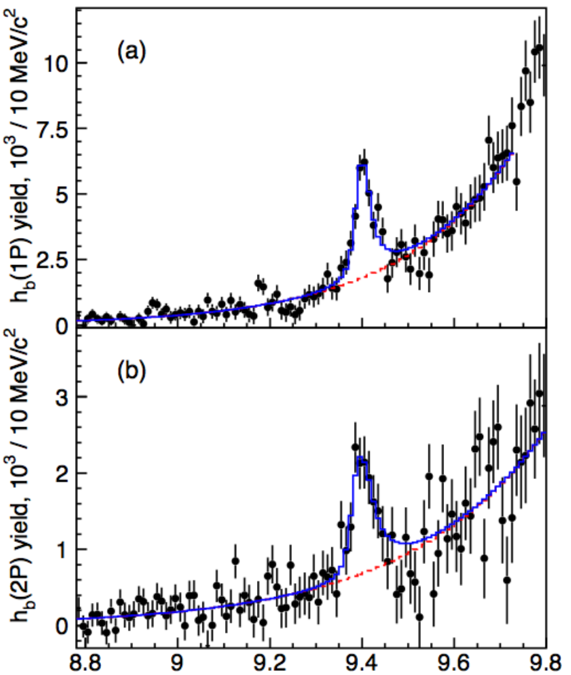

Figure 4: Observation of $h_b(1,2P) \to \eta_b(1S)$: residuals of ΔM_{miss} in the $h_b(1P)$ band (a) and $h_b(2P)$ band (b) from Υ(5S)

mass splittings differ by less than 1 percent.

The discovery of a $\pi^+\pi^-\gamma$ transition for the production of $\eta_b(1,2S)$ also opens a new path for the search of the decay $\eta_b \to \gamma\gamma$, which would be otherwise impossible to detect: the $\Upsilon(2,3S) \to 3\gamma$ exclusive mode is overwhelmed by QED backgrounds. For this process, a precise theory prediction at NNLL level is available from NRQCD [21].

3. Hadronic transitions with an η meson

The hadronic transitions between heavy quarkonia have been described within the framework of the QCD multipole expansion [22, 23], in analogy with EM transitions. In particular, the transition with emission of an η meson is described by an E1*M2 or a M1*M1 amplitude. Both terms imply a spin flip of the heavy quark , and a suppression of order $1/m_Q$ of the corresponding amplitude.

Belle has studied the η transitions between 5S, 2S and 1S vector states in the bottomonium system. The $\Upsilon(2S) \to \Upsilon(1S)$ transition has been measured detecting the η in $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ final states and the $\Upsilon(1S)$ in $e^+e^-, \mu^+\mu^-$ final states. Belle has recently improved the measurement of this BR [24]:

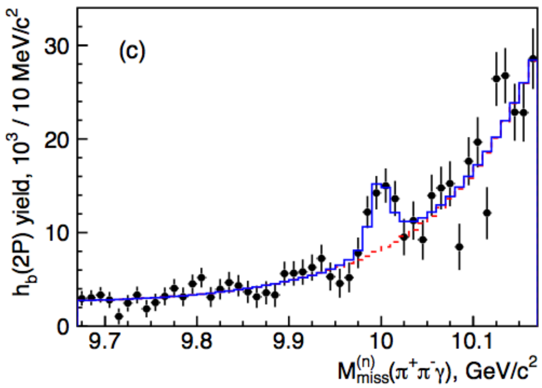

Figure 5: Strong evidence of $h_b(2P) \to \eta_b(2S)$: residuals of ΔM_{miss} in the $h_b(2P)$ band from Υ(5S)

the result of the global fit is consistent with previous measurements by CLEO [25] and BaBar [26], but closer to theory expectations [27, 28]. All results are summarized in Table 5.

Table 5: Branching ratios (in units of 10^{-4}) of $\Upsilon(2S) \to \eta\Upsilon(1S)$.

Experiment	BR*10^4	ref.
CLEO	$2.1^{+0.7}_{-0.6}$	[25]
BaBar	$2.39 \pm 0.31 \pm 0.14$	[26]
Belle	$3.41 \pm 0.28 \pm 0.35$	[24]

The search of a similar transition from $\Upsilon(3S)$ in BaBar did not yield any evidence [26]. Similarly, all attempts to detect the $\pi^0\Upsilon(1S)$ transition have given negative results.

Very recently, also the $\Upsilon(5S)$ transitions to $\Upsilon(1,2S)$ have been observed by Belle [29]. A few years ago, BaBar discovered [30] that the η transition to $\Upsilon(1S)$ is 2.5 times more frequent than the $\pi\pi$ transition, a fact that still challenges the QCDME expectations. It is therefore useful to compare the ratios $\eta/\pi\pi$ for all studied transitions, as summarized in Table 6.

Table 6: Branching ratios (in units of 10^{-4}) of $\Upsilon(mS) \to \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(mS) \to \eta\Upsilon(nS)$.

Transition	$\pi^+\pi^-$	η
$5S \to 1S$	$53 \pm 3 \pm 5$	7.3 ± 1.6
$5S \to 2S$	$78 \pm 6 \pm 11$	38 ± 4
$4S \to 1S$	0.81 ± 0.06	1.96 ± 0.11

The η transitions between h_b states and Υ states should be favored with respect to the ones already observed: it is therefore important to study the ratios $B(\Upsilon(5S) \to \eta\Upsilon(2S))/B(\Upsilon(5S) \to \eta h_b(1P))$ and $B(h_b(2P) \to \eta\Upsilon(1S))/B(\Upsilon(2S) \to \eta\Upsilon(1S))$.

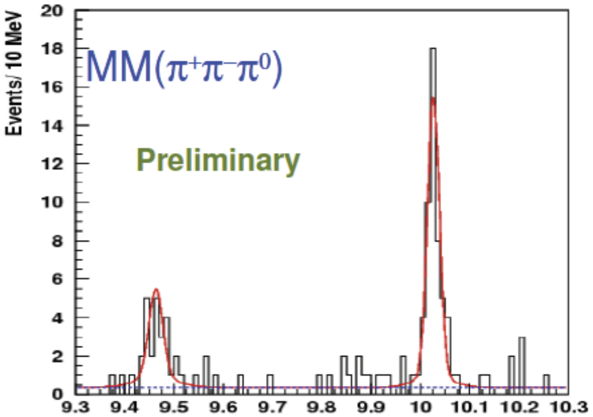

Figure 6: Observation of $\Upsilon(5S) \to \eta\Upsilon(1,2S)$ in η missing mass.

The η transitions from states above thresholds have been studied this year by Belle also in the charmonium system [31]. The process $e^+e^- \to \eta J/\psi$ was scanned using the full ISR data sample, 70% of which has been taken at the $\Upsilon(4S)$ peak. The $\eta \to \pi^+\pi^-\pi^0, \gamma\gamma$ decay modes were detected. The detection of the ISR photon was not required, to increase efficiency, given the low background level. Figure 7 shows the invariant mass of the $\eta J/\psi$ system: we observe clear peaks, consistent in masses and widths with the known vector states $\psi(4040)$ (6.5σ) and $\psi(4170)$ (7.6σ). A broader but not significant bump is visible in the 4.36 GeV region.

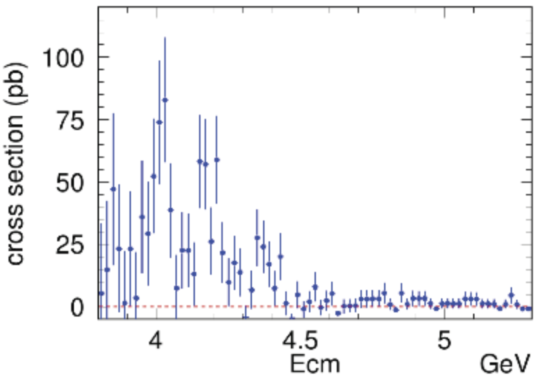

Figure 7: Cross section of $e^+e^- \to J/\psi\eta$ at Belle, using ISR.

A complete picture of the η transitions in the bottomonium and charmonium systems can be helpful to gain insights on the nature of the new states observed above the thresholds.

4. D wave quarkonia

In the charmonium system, the $\Psi(3770)$ is known since long to be a mixture of S-wave and a dominant D-wave: being above $\bar{D}D$ threshold it can decay to open charm and has a large width. The J=2 D-wave states, though, are expected to be quite narrow, because they are not allowed to decay to the same final state, as their quantum numbers, $J^{PC} = 2^{--}$ (spin triplet) and 2^{-+} (spin singlet) are not permitted to a $\bar{D}D$ pair, and the masses of these states are predicted to be below the $\bar{D}^*D$ threshold. Searches for these states in hadronic collisions were unsuccessful. The interpretation of X(3872) as the 2^{-+} $c\bar{c}$ state is not ruled out. Recently, the search for a tetraquark partner of X(3872) in B-decays at Belle yielded an unexpected outcome. At a mass M=3823.5±2.8 MeV, Belle has observed a peak [32] in the $M(\gamma\chi_{c1})$ distributions (see Figure 8), which can be interpreted as the long sought $\Psi(^3D_2)$ state, with $J^{PC} = 2^{--}$.

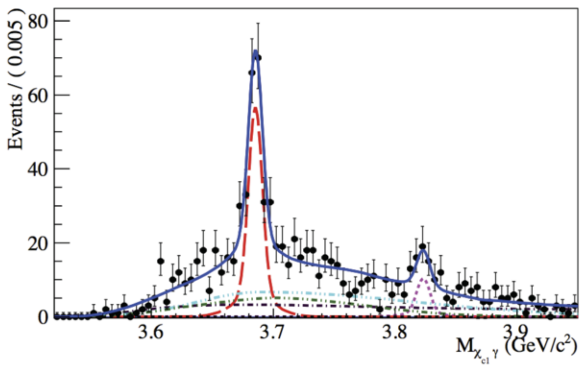

Figure 8: Discovery of $\Psi(^3D_2)$ in B decays to K $\gamma\chi_{c2}$

In the bottomonium system, the first D-wave state, (most likely the $J^{PC} = 2^{--}$) was observed by CLEO [14] in 2004 and confirmed by BaBar [15] in 2010, as described in Section 2: both observations are from $\Upsilon(3S)$ data. Belle has found inclusive evidence (2.4 σ significance) of $\pi\pi$ transitions from $\Upsilon(5S)$ to $\Upsilon(1D)$. The rate of dipion transitions to $\Upsilon(1D)$ can be compared with other transitions in Table 2. The most recent analysis from Belle, though, confirms such transition with much higher significance (9σ), using the exclusive transition: $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1D) \to \pi^+\pi^-\gamma\chi_b(1P) \to \pi^+\pi^-\gamma\gamma\Upsilon(1S)$, see Figure 9). Belle measures a rate of $(2.0 \pm 0.3 \pm 0.4) \times 10^{-4}$ for this triple cascade.

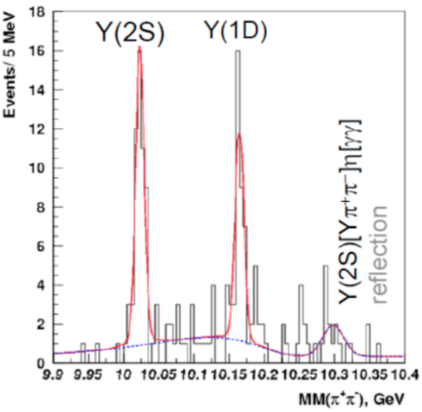

Figure 9: Observation of the exclusive process $\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1D)$ followed by the two photon cascade transition $\Upsilon(1D) \to \chi_b(1P) \to \Upsilon(1S)$

For the experimentalists, the next challenge will be the discovery of the other three D-wave states in bottomonium: in the near future, further studies on the $\Upsilon(3S)$ and $\Upsilon(5S)$ datasets can give Belle an opportunity to discover the missing states. From the comparison of bottomonium and charmonium splittings, we hope to get more clues to the understanding of all the XYZ's discovered in the threshold region.

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