Recent results from the Belle experiment

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Abstract

We report the recent results of a search for the decay $B^- \to \tau^- \bar{\nu}_\tau$, observations of new resonances X, Y and Z, and the first results from $\Upsilon(5S)$ data collected with the Belle detector at KEKB e^+e^- collider.

1 Belle detector and KEKB collider

The results reported in this paper were obtained using the data collected with the Belle detector [1] at the KEKB asymmetric-energy e^+e^- (3.5 on 8.0 GeV) collider [2] operating at the $\Upsilon(4S)$ resonance ($\sqrt{s} = 10.58\,\mathrm{GeV}$). The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), a mosaic of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an array of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L mesons and to identify muons (KLM).

Charged tracks are reconstructed in the CDC and their impact parameters are precisely determined using the SVD. Charged hardon identification is accomplished based on the combined information from the ACC, TOF and CDC dE/dx systems. Electron identification is based on a combination of dE/dx measurements, the ACC response and information about the shape, energy deposit and position of the associated shower in the ECL. Muons are identified by requiring an association between KLM hits and an extrapolated track. Photons are reconstructed in the ECL as showers that are not associated with charged tracks.

2 Search for $B^- \to \tau^- \bar{\nu}_\tau$

In the Standard Model (SM), the purely leptonic decay $B^+ \to \tau^+ \nu_\tau$ [3] proceeds via annihilation of b and $\bar{u}$ quarks into a W^- boson (Fig. 1). It provides a direct determination of the product of

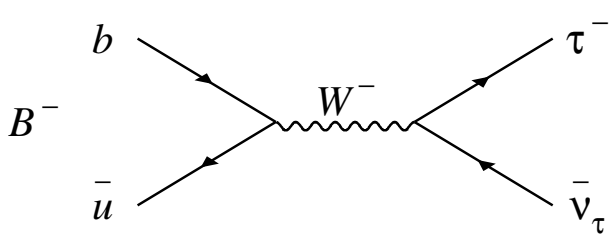

Figure 1: Purely leptonic B decay proceeds via quark annihilation into a W boson.

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the B meson decay constant f_B and the magnitude of the Cabibbo-Kobayashi-Maskawa matrix element $|V_{ub}|$. The branching fraction is given by

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}(1 - \frac{m_\tau^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B,$$

where G_F is the Fermi coupling constant, m_B and m_τ are the B and τ masses, and τ_B is the B^- lifetime [4]. The expected branching fraction is $(1.59 \pm 0.40) \times 10^{-4}$, obtained using $|V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$, determined with inclusive charmless semileptonic B decay data [5], $\tau_B = 1.643 \pm 0.010$ ps [5], and $f_B = 0.216 \pm 0.022$ GeV obtained from lattice QCD calculations [6]. Physics beyond the SM, such as supersymmetry or two-Higgs doublet models, could modify $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)$ through the introduction of a charged Higgs boson [7]. Purely leptonic B decays have not been observed in past experiments. The most stringent upper limit on $B^- \to \tau^- \bar{\nu}_\tau$ comes from the BABAR experiment: $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) < 2.6 \times 10^{-4}$ (90% C.L.) [8].

To reconstruct this decay mode, one B meson was fully reconstructed in the event (referred to hereafter as the tag side ($B_{\rm tag}$)), and the properties of the remaining particle(s) (referred to as the signal side ($B_{\rm sig}$)), are compared to those expected for signal and background. The method allows to suppress strongly the combinatorial background from both $B\bar{B}$ and continuum events.

In the events where a $B_{\rm tag}$ is reconstructed, decays of $B_{\rm sig}$ into a τ and a neutrino were searched for. Candidate events are required to have one or three charged track(s) on the signal side with total charge opposite to that of $B_{\rm tag}$. The τ lepton is identified in the five decay modes $\mu^- \bar{\nu}_\mu \nu_\tau$, $e^- \bar{\nu}_e \nu_\tau$, $\pi^- \nu_\tau$, $\pi^- \pi^0 \nu_\tau$ and $\pi^- \pi^+ \pi^- \nu_\tau$, which taken together correspond to 81% of all τ decays.

The most powerful variable for separating signal and background is the remaining energy in the ECL, denoted as $E_{\rm ECL}$ and defined as the sum of the energy deposits in the ECL that are not associated with either the $B_{\rm tag}$ or the π^0 candidate from the $\tau^- \to \pi^- \pi^0 \nu_\tau$ decay. For signal events, $E_{\rm ECL}$ must be either zero or a small value arising from beam background hits. Therefore, signal events peak at low $E_{\rm ECL}$. On the other hand background events are distributed toward higher $E_{\rm ECL}$ values due to the contribution of additional neutral clusters. Figure 2 shows the obtained $E_{\rm ECL}$ distribution when all τ decay modes are combined. One can see a significant excess of events in the $E_{\rm ECL}$ signal region below $E_{\rm ECL} < 0.25$ GeV. The number of signal events in the signal region deduced from the fit is $17.2^{+5.3}_{-4.7}$. The obtained branching fraction is $(1.79^{+0.56}_{-0.49}({\rm stat})\,^{+0.46}_{-0.51}({\rm syst})) \times 10^{-4}$. The significance of the observed signal is $3.5\,\sigma$.

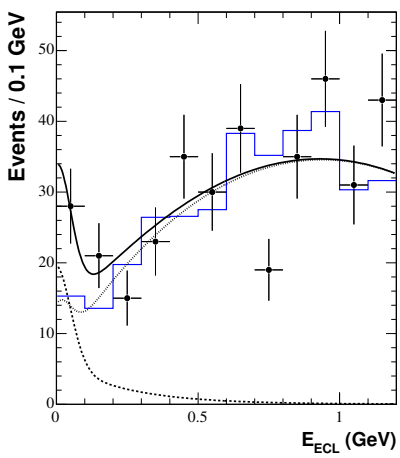

Figure 2: $E_{\rm ECL}$ distributions in the data. The data and background Monte Carlo (MC) samples are represented by the points with error bars and the solid histogram, respectively. The solid curve shows the result of the fit with the sum of signal shape (dashed) and background shape (dotted).

Using the measured branching fraction and the known values of G_F, m_B, m_τ, τ_B and $|V_{ub}|$, one obtains $f_B = 0.229^{+0.036}_{-0.031}(\text{stat})^{+0.034}_{-0.037}(\text{syst})$ GeV, which is the first determination of the B meson decay constant [9].

3 Observation of new resonances

Recently there has been a revival of interest in the possible existence of mesons with a more complex structure than the simple $q\bar{q}$ bound state of the original quark model. There are long-standing predictions of four-quark $q\bar{q}q\bar{q}$ meson-meson resonance states [10] and for $q\bar{q} - gluon$ hybrid states [11]. Searches for such particles in systems including a charmed-anticharmed quark pair ($c\bar{c}$) are particularly effective because, for at least some of these cases, the states are expected to have clean experimental signatures as well as relatively narrow widths, thereby reducing the possibility of overlap with standard $c\bar{c}$ mesons.

3.1 Observation of $X(3872)$

The Belle experiment discovered a new state, named $X(3872)$, as a narrow peak in the $\pi^+\pi^- J/\psi$ mass spectrum from exclusive $B \to K\pi^+\pi^- J/\psi$ decays [12]. This observation has been confirmed by other experiments [13]. The properties of the $X(3872)$ do not match well to any $c\bar{c}$ charmonium state [14]. This, together with the close proximity of the $X(3872)$ mass with the $m_{D^0}m_{D^{*0}}$ mass threshold, have led some authors to interpret the $X(3872)$ as a $D^0\bar{D}^{*0}$ resonant state [15].

To investigate further and determine its quantum numbers, the $X(3872)$ state was searched in various decay channels. It was observed in two decay modes: $X(3872) \to \gamma J/\psi$ from $B^+ \to K^+\gamma J/\psi$ and $X(3872) \to \pi^+\pi^-\pi^0 J/\psi$ from $B^+ \to K^+\pi^+\pi^-\pi^0 J/\psi$ decays [16]. Both decay modes favor the C-parity of $X(3872)$ to be $+1$.

Recently, the $X(3872)$ state has also been observed in the decay $X(3872) \to D^0\bar{D}^0\pi^0$ from $B \to D^0\bar{D}^0\pi^0 K$ decays [17] (Fig. 3). A 414 fb^{-1} data sample was used for this analysis. This observation, together with an angular analysis of $B^+ \to K^+\pi^+\pi^- J/\psi$ decays, gives evidence for $J^{PC}(X(3872)) = 1^{++}$.

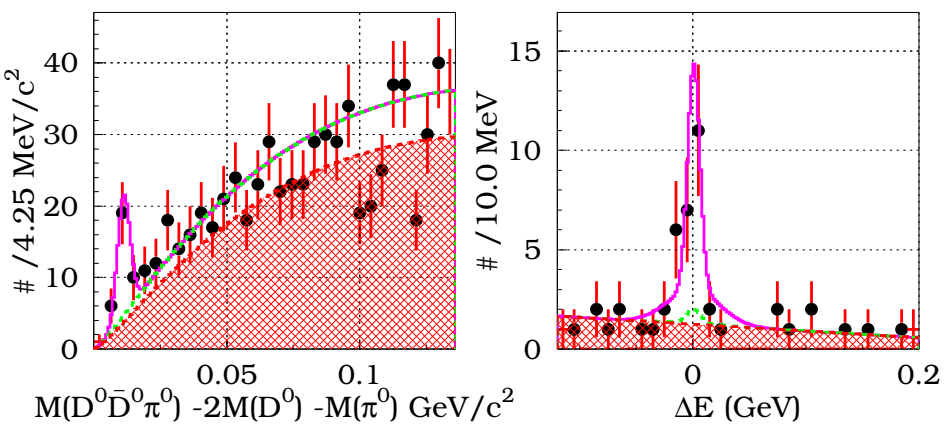

Figure 3: Projection of Q-value ($= M_{D^0\bar{D}^0\pi^0} - 2M_{D^0} - M_{\pi^0}$) ($\Delta E$) when ΔE (Q-value) is in the signal region corresponding to $|\Delta E| < 25$ MeV (6 MeV/c^2 < Q-value < 14 MeV/c^2). The dots with error bars are data, the hatched histogram corresponds to combinatorial background; the dashed line indicates the total background and the solid line is the combined fitting function.

3.2 Observation of $Y(3940)$

Another resonant state, denoted as $Y(3940)$, was observed in the $\omega J/\psi$ system produced in exclusive $B \to K\omega J/\psi$ decays [18]. The study was based on a 253 fb^{-1} data sample that contains 275 million $B\bar{B}$ pairs. To suppress events of the type $B \to K_X J/\psi, K_X \to K\omega$, the analysis was restricted to events in the region $M(K\omega) > 1.6$ GeV/c^2 (Fig. 4).

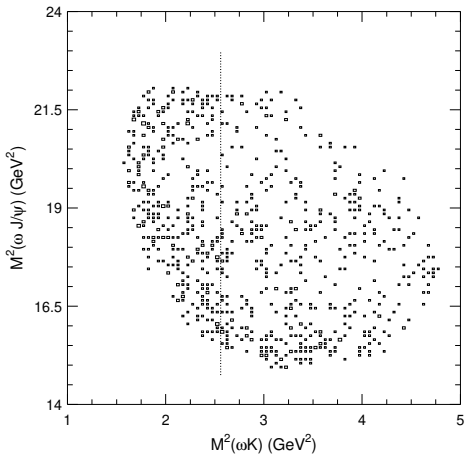

Figure 4: Dalitz-plot distribution for $B \to K\omega J/\psi$ candidate events. The dotted line indicates the boundary of the $M(K\omega) > 1.6$ GeV/c^2 selection requirement.

Figure 5 shows the result of fits in bins of the $\omega J/\psi$ invariant mass. An enhancement is evident around $M(\omega J/\psi) = 3940$ MeV/c^2. The fit yields a Breit-Wigner signal yield of 58 ± 11 events with mass $M = 3943 \pm 11$ MeV/c^2 and width $\Gamma = 87 \pm 22$ MeV/c^2 (statistical error only). The statistical significance of the signal is 8.1 σ.

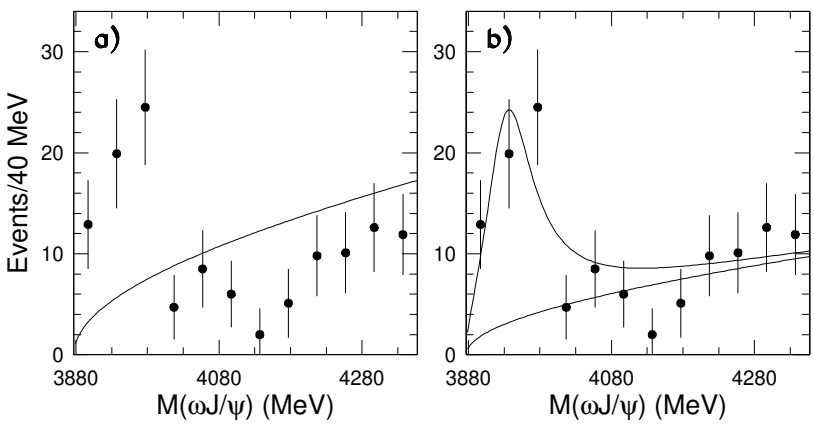

Figure 5: $B \to K\omega J/\psi$ signal yields *vs* $M(\omega J/\psi)$. The curve in a) indicates the result of a fit that includes only a phase-space-like threshold function. The curve in b) shows the result of a fit that includes an S-wave Breit-Wigner resonance term.

The product branching fraction was found to be:

$$\mathcal{B}(B \to KY(3940))\mathcal{B}(Y(3940) \to \omega J/\psi) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}.$$

Charmonium states above open charm threshold should dominantly decay to $D^{(*)}\bar{D}$ final states. But these decay modes were not observed for the $Y(3940)$ resonance. The properties of the observed enhancement are similar to those of some of the $c\bar{c} - gluon$ hybrid charmonium

states that were first predicted in 1978 [11] and are expected to be produced in B meson decays. It has been shown that a general property of these hybrid states is that their decays to $D^{(*)}\bar{D}^{(*)}$ meson pairs are forbidden or suppressed, and the relevant "open charm" threshold is $m_D + m_{D^{**}} \approx 4285$ MeV/c^2 [19], where D^{**} refers to the $J^P = (0,1,2)^+$ charmed mesons. However, the predicted masses are substantially higher than the measured value for $Y(3940)$.

3.3 Observation of $X(3940)$

A new charmonium-like state above the $D\bar{D}$ threshold, which was denoted as $X(3940)$, has been observed in the process $e^+e^- \to J/\psi X(3940)$ [20]. The analysis was based on a 375 fb^{-1} data sample. The signal was searched in the mass of the system recoiling against the reconstructed particles defined as

$$M_{\rm recoil}(X) = \sqrt{(E_{\rm CM} - E_X^*)^2 - p_X^{*2}},$$

where E_X^* and p_X^* are the center-of-mass (CM) energy and momentum. The $M_{\rm recoil}(J/\psi)$ is shown on Fig. 6. Here, a clean enhancement around 3.94 GeV/c^2 is seen. The significance of the $X(3940)$ signal is 5.0 σ. The fitted width of the $X(3940)$ state, $\Gamma = 39 \pm 26$ MeV/c^2, is consistent with zero within its large statistical error.

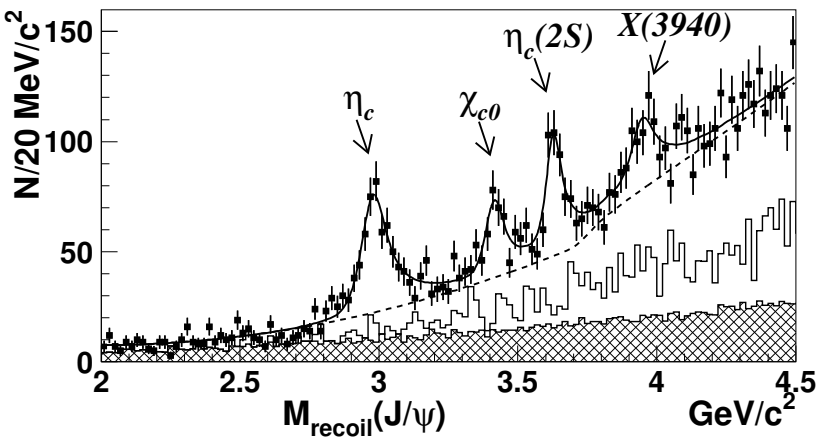

Figure 6: The distribution of $M_{\rm recoil}(J/\psi)$ in inclusive $e^+e^- \to J/\psi X$ events.

The new state has a mass above both the $D\bar{D}$ and $D^*\bar{D}$ thresholds. The search for $X(3940)$ decays into $D\bar{D}$ and $D^*\bar{D}$ was performed. Due to low charm meson reconstruction efficiency it is not feasible to reconstruct fully $X(3940) \to D^{(*)}\bar{D}$. To increase the efficiency only the prompt J/ψ meson and one D from the $X(3940)$ were reconstructed. $M_{\rm recoil}(J/\psi D)$ was constrained to the mass of either D or D^* and the $X(3940)$ signal was searched again in the spectrum of the mass recoiling against the J/ψ system. A clear peak has been seen in the case of $M_{\rm recoil}(J/\psi D) = M(D^*)$ with significance 5.0 σ, while no signal has been observed in the case of $M_{\rm recoil}(J/\psi D) = M(D)$ leading to the limit $\mathcal{B}(X(3940) \to D\bar{D}) < 41\%$ at 90% C.L. (Fig. 7).

The same study was done for the possible decay $X(3940) \to J/\psi\omega$ and no significant signal was observed, resulting in $\mathcal{B}(X(3940) \to J/\psi\omega) < 26\%$ at 90% C.L. This means that $Y(3940)$ and $X(3940)$ are different particles, since they have different decay modes and different decay widths. A possible interpretation of the $X(3940)$ could be $\eta_c(3S)$.

3.4 Observations of $Z(3930)$

A search for the χ'_{cJ} ($J = 0$ or 2) states and other C-even charmonium states in the mass region of $3.73 - 4.3$ GeV/c^2 produced via the process $\gamma\gamma \to D\bar{D}$ was performed using 395 fb^{-1} data

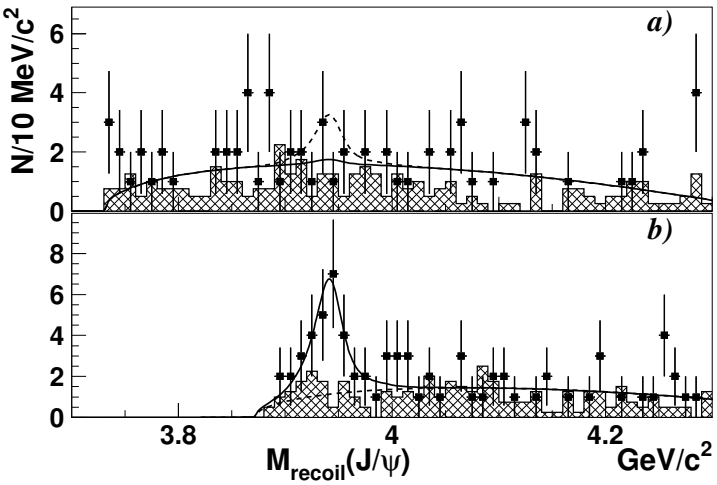

Figure 7: The $M_{\rm recoil}(J/\psi)$ distribution for events tagged and constrained as a) $e^+e^- \to J/\psi D\bar{D}$, and b) $e^+e^- \to J/\psi D^*\bar{D}$. The hatched histograms correspond to scaled D sidebands. The solid lines are the results of the fits. The dashed lines show: a) the 90% C.L. upper limit on the signal; b) the background contribution.

sample [21]. The two-photon process $e^+e^- \to e^+e^- D\bar{D}$ was studied in the "zero-tag" mode, where neither the final state electron nor positron is detected, and the $D\bar{D}$ system has very small transverse momentum: $P_t(D\bar{D}) < 0.05$ GeV/c. In Fig. 8a the $M(D\bar{D})$ invariant mass distribution is shown for the combined $D^0\bar{D}^0$ and D^+D^- channels.

The fit results for the peak near 3.93 GeV/c^2 for the resonance mass, width and total yield of the resonance are $M = 3929 \pm 5$ MeV/c^2, $\Gamma = 29 \pm 10$ MeV and 64 ± 18 events, respectively. The statistical significance of the peak is 5.3 σ.

Fig. 8b shows the event yields in the $3.91 - 3.95$ GeV/c^2 region versus $|\cos\theta^*|$. The curves show the expectations for cases of $J = 2$ (solid line) and $J = 0$ (dashed line). The data significantly favor a spin two assignment over spin zero. Using the number of observed events, the product of the two-photon decay width and $D\bar{D}$ branching fraction was determined to be

$$\Gamma_{\gamma\gamma}(Z(3930))\mathcal{B}(Z(3930) \to D\bar{D}) = 0.18 \pm 0.05 \pm 0.03 \text{ keV}.$$

The measured properties are consistent with expectations for the previously unseen χ'_{c2} charmonium state.

4 First results from $\Upsilon(5S)$ data

The possibility of studying B_s decays at very high luminosity e^+e^- colliders running at the energy of the $\Upsilon(5S)$ resonance has been discussed in several theoretical papers [22, 23, 24]. To test the experimental feasibility of B_s studies in $\Upsilon(5S)$ events, a sample of 1.86 fb^{-1} was collected by the Belle detector over three days in June 2005. Another data sample of 3.67 fb^{-1} taken at a CM energy 60 MeV below the $\Upsilon(4S)$ was used in this analysis to evaluate continuum contributions.

In the energy region of the $\Upsilon(5S)$, the hadronic events can be classified into three physics categories: $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$ continuum events, $b\bar{b}$ continuum events and $\Upsilon(5S)$ events. All $b\bar{b}$ events (including those from $\Upsilon(5S)$) are expected to hadronize in one of the following final states: $B\bar{B}, B\bar{B}^*, B^*\bar{B}, B^*\bar{B}^*, B\bar{B}\pi, B\bar{B}^*\pi, B^*\bar{B}\pi, B^*\bar{B}^*\pi, B\bar{B}\pi\pi, B_s^0\bar{B}_s^0, B_s^0\bar{B}_s^*, B_s^*\bar{B}^0$ or $B_s^*\bar{B}_s^*$. Here B denotes a B^0 or a B^+ meson and $\bar{B}$ denotes a $\bar{B}^0$ or a B^- meson. The excited states decay to their ground states via $B^* \to B\gamma$ and $B_s^* \to B_s^0\gamma$ [4].

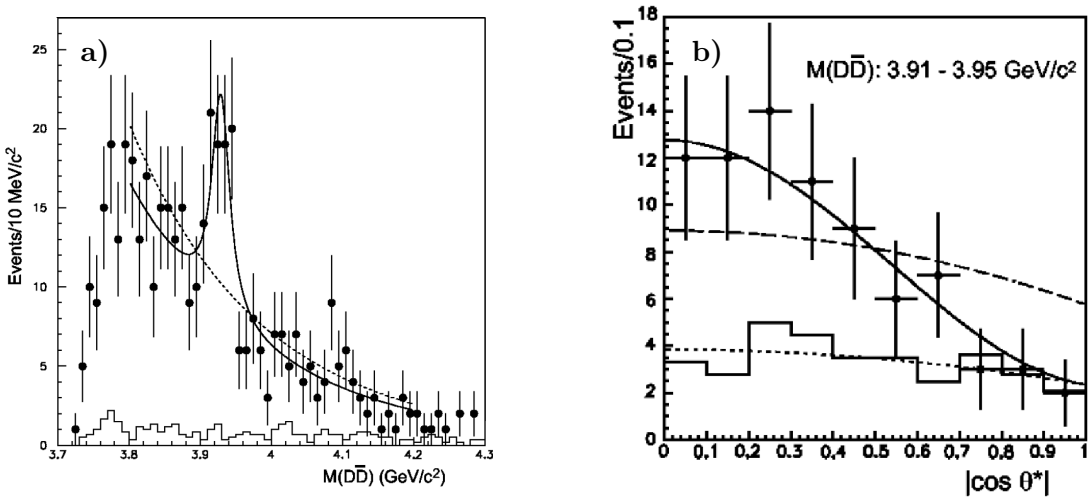

Figure 8: a) The $D\bar{D}$ invariant mass distribution. The curves show the fit with (solid) and without (dashed) a resonance component. The histogram shows the distribution of the events from the D-sidebands. b) The $|\cos\theta^*|$ distributions in the $(3.91 < M(D\bar{D}) < 3.95)$ GeV/c^2 region (points with error bars) and background scaled from the $M(D\bar{D})$ sidebands (solid histogram). The solid and dashed curves are expected distributions for the spin two (helicity two) and spin zero hypotheses, respectively, and contain the non-peaking background also shown separately by the dotted curve.

Using the numbers of hadronic events in the $\Upsilon(5S)$ and continuum data samples, the number of $b\bar{b}$ events was measured to be $N_{b\bar{b}}(\Upsilon(5S)) = (5.61 \pm 0.03(\text{stat}) \pm 0.29(\text{syst})) \times 10^5$. It corresponds to $N_{b\bar{b}}(\Upsilon(5S))/\text{fb}^{-1} = (3.02 \pm 0.15) \times 10^5$ [25], which is consistent with the CLEO measurement $N_{b\bar{b}}(\Upsilon(5S))/\text{fb}^{-1} = (3.10 \pm 0.52) \times 10^5$.

4.1 Inclusive $\Upsilon(5S) \to D_s X$ study

To measure the fraction f_s of $B_s^{(*)}\bar{B}_s^{(*)}$ events over the total number of $b\bar{b}$ events, the inclusive D_s production was studied. Finally, $b\bar{b}$ events from $\Upsilon(5S)$ data can decay either to $B_s\bar{B}_s + X$ or to $B\bar{B} + X$. The total inclusive branching fraction of D_s production can therefore be expressed as:

$$\mathcal{B}(\Upsilon(5S) \to D_s X)/2 = f_s \times \mathcal{B}(B_s \to D_s X) + (1 - f_s) \times \mathcal{B}(B \to D_s X),$$

where $\mathcal{B}(B_s \to D_s X)$ is theoretically predicted to be $(92 \pm 11)\%$ [26], and $\mathcal{B}(B \to D_s X) = (8.7 \pm 1.2)\%$ [4, 26] is well measured at the $\Upsilon(4S)$. The D_s was reconstructed in the cleanest mode $\phi\pi, \phi \to K^+K^-$. The D_s signal in the $\Upsilon(5S)$ and continuum data samples with $x(D_s) = p(D_s)/p_{\max}(D_s) < 0.5$ are shown in Fig. 9a. The normalized momentum distributions $x(D_s)$ are shown in Fig. 9b for the same data samples. The excess of events in the region $x(D_s) < 0.5$ corresponds to inclusive D_s production in $b\bar{b}$ events. Finally, the inclusive branching fraction $\mathcal{B}(\Upsilon(5S) \to D_s X)/2 = (23.6 \pm 1.2 \pm 3.6)\%$ was obtained. Using this result the value of f_s was measured to be $f_s = (17.9 \pm 1.4 \pm 4.1)\%$, consistent with CLEO result $f_s = (16.0 \pm 2.6 \pm 5.8)\%$. In the same way, but using D^0 instead of D_s, it was measured $\mathcal{B}(\Upsilon(5S) \to D^0 X)/2 = (53.8 \pm 2.0 \pm 3.4)\%$ and $f_s = (18.1 \pm 3.6 \pm 7.5)\%$ [25].

4.2 Fully reconstructed exclusive B_s

As mentioned above, the $\Upsilon(5S)$ meson can decay to the following B_s decay modes: $B_sB_s, B_s^*B_s, B_s^*B_s^*$, where $B_s^* \to B_s\gamma$. MC simulation shows that if the photon(s) is(are) lost, both ΔE and M_{bc} signal distributions are shifted, and the three types of $\Upsilon(5S)$ decays can be well distinguished by

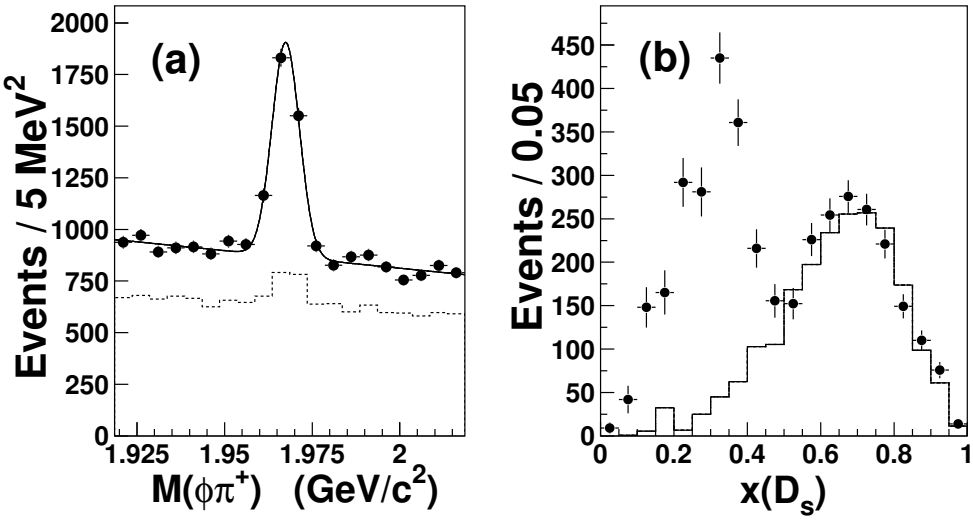

Figure 9: The D_s signal in the region $x(D_s) < 0.5$ (a) and the D_s normalized momentum $x(D_s)$ (b). The points with error bars are the $\Upsilon(5S)$ data, while the histograms show the normalized continuum.

reconstructing only B_s mesons without γ reconstruction (Fig. 10c). The B_s was reconstructed in the cleanest decay modes $B_s \to D_s^- \pi^+$ and $B_s \to D_s^{*-} \pi^+$ with $D_s^{*-} \to D_s^- \gamma$ and $D_s^- \to \phi \pi^-$. A clear signal was observed in the $B_s^* B_s^*$ channel, while no signal was observed in $B_s^* B_s$ and $B_s B_s$ (Fig. 10a and b). Taking into account the number of B_s mesons obtained from inclusive

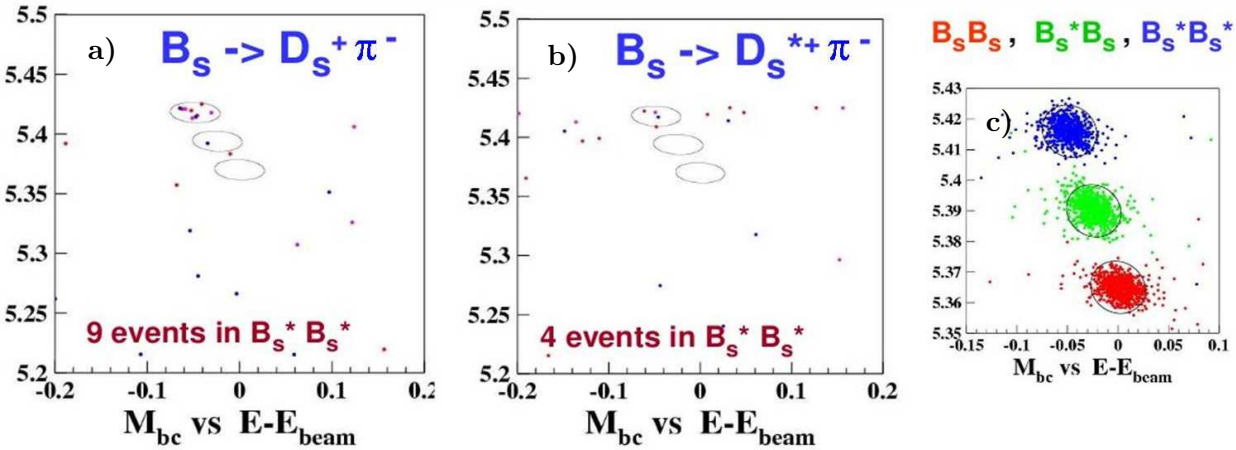

Figure 10: $M_{\rm bc}$ *vs* ΔE scatter plot for a) $B_s \to D_s^+ \pi^-$, b) $B_s \to D_s^{*+} \pi^-$ for the data, and c) signal MC events.

analysis, the branching fraction for the decay mode $B_s \to D_s^- \pi^+$ was measured to be:

$$\mathcal{B}(B_s \to D_s^- \pi^+) = (0.68 \pm 0.22 \pm 0.16)\%.$$

The fraction of $B_s^* B_s^*$ events over all $B_s^{(*)} B_s^{(*)}$ events was measured to be $N(B_s^* B_s^*)/N(B_s^{(*)} B_s^{(*)}) = (94^{+6}_{-9})$ [27]. The Potential models predict the dominance of $B_s^* B_s^*$ over $B_s^* B_s$ and $B_s B_s$ channels, but not as strong as what was observed.

Combining all studied decay modes, B_s^* and B_s masses were measured to be: $M(B_s^*) = 5418 \pm 1 \pm 3$ MeV/c^2 and $M(B_s) = 5370 \pm 1 \pm 3$ MeV/c^2 [27]. The obtained B_s mass is in agreement with the recent CDF measurement $M(B_s) = 5366.0 \pm 0.8$ MeV/c^2.

5 Summary

The first evidence for the decay $B \to \tau\nu$ has been reported by Belle. This is the first direct measurement of f_B.

Several new resonances have been observed by Belle: $X(3872)$, $Y(3940)$, $X(3940)$, $Z(3930)$. The first two can not be ascribed to the expected particle states. The possible explanations include $D^*\bar{D}$ molecules, $c\bar{c}$-gluon hybrids or tetraquarks.

Results from the $\Upsilon(5S)$ engineering run are very promising. Even with only a small amount of data some significant (preliminary) results were obtained.

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