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Double $c\bar{c}$ and $D^{(*)}\bar{D}^{(*)}$ production at Belle

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Abstract. We present a new study of double $c\bar{c}$ production in the e^+e^- continuum. We report a study of many double charmonium final states in e^+e^- annihilation. The $e^+e^- \to J/\psi c\bar{c}$ cross-section is measured with reduced model dependence. The cross-section of the coherent $D^{(*)}\bar{D}^{(*)}$ pair production in the e^+e^- continuum is measured for the first time.

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1 Charmonium production

The mechanism of charmonium production in various processes remains a puzzle after many years. Theoretically, the $e^+e^- \to J/\psi gg$ process was considered to be the leading mechanism with a cross-section as high as 1 pb; the color-octet $e^+e^- \to J/\psi g$ contribution could be also significant. In contrast, none of these processes were observed experimentally sofar, while the process $e^+e^- \to J/\psi c\bar{c}$ was measured by Belle with unexpectedly large cross-section [1]. In this paper we present an updated study of charmonium production with additional $c\bar{c}$ pair using a data sample of $101.8\,\mathrm{fb}^{-1}$ collected at the $\Upsilon(4S)$ resonance and nearby continuum.

In the published Belle paper [1] a significant peak was observed around the η_c mass in the spectrum of the mass recoiling against the J/ψ, defined as $M_{\mathrm{recoil}}(J/\psi) \equiv ((E_{\mathrm{CMS}} - E_{J/\psi})^2 - p^{\,2}_{J/\psi})^{1/2}$. The measured cross-section for the $e^+e^- \to J/\psi\,\eta_c$ process was an order-of-magnitude larger than theoretical predictions [2]. In an attempt to explain at least partially this discrepancy, it is suggested in [3] that processes proceeding via two virtual photons may be important and that the observed $e^+e^- \to J/\psi\,\eta_c$ signal might also include double J/ψ events. Given the arguments in [3], it is important to check for any momentum scale bias that may confuse the interpretation of the peaks in the recoil mass spectrum. We use $e^+e^- \to \psi(2S)\gamma$, $\psi(2S) \to J/\psi\pi^+\pi^-$ events for calibration of the recoil mass scale and find that shifts in the recoil mass are less than $3\,\mathrm{MeV}/c^2$.

The spectrum of recoil masses against the J/ψ in the updated data sample is shown in Fig. 1: a clear peak is observed around the η_c nominal mass, and a smaller peak is seen around the χ_{c0} nominal mass; the large peak at $\sim 3.63\,\mathrm{GeV}/c^2$ is interpreted as the $\eta_c(2S)$. In this paper we extend our analysis by including all the known charmonum states in the fit to the spectrum of recoil mass against the reconstructed J/ψ. The fit results, listed in Table 1, give negative yields for the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$. We performed another fit with all these contributions fixed at zero; the result of the latter fit is shown as the solid line in Fig. 1. The dotted line in Fig. 1 corresponds to the case where the contributions of the J/ψ, χ_{c1}, χ_{c2} and $\psi(2S)$ are set at their 90% confidence level upper limit values. The dashed line is the background function.

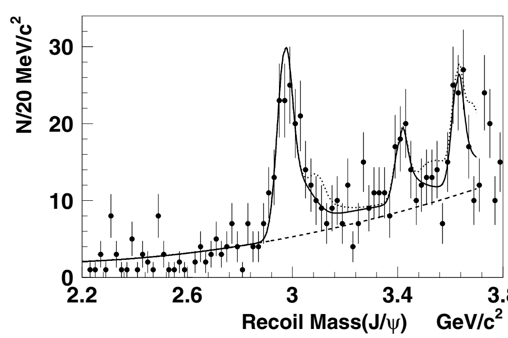

Fig. 1. The distribution of recoil mass against the J/ψ

The $\psi(2S)$ recoil mass spectrum is studied in a similar way. It demonstrates the similar behaviour, but only the $\eta_c(2S)$ peak is found to be significant; only hints for η_c and χ_{c0} signals are seen. A search for $e^+e^- \to \chi_{c1(2)}\,(c\bar{c})_{res}$ is also performed: the $J/\psi\gamma$ mass distribution for the region of recoil masses from 2.8 to $3.7\,\mathrm{GeV}/c^2$ is studied. Fit to this ditribution finds $2.3^{+3.0}_{-2.3}$ χ_{c1} and $0.7^{+2.0}_{-1.4}$ χ_{c2} candidates. After correction for the reconstruction efficiencies we calculate the cross-sections and upper limits for many double charmonium final states produced in e^+e^- annihilation. The results are listed in Table 2.

In the published Belle paper [1] the $e^+e^- \to J/\psi c\bar{c}$ cross-section was calculated with method relied on the

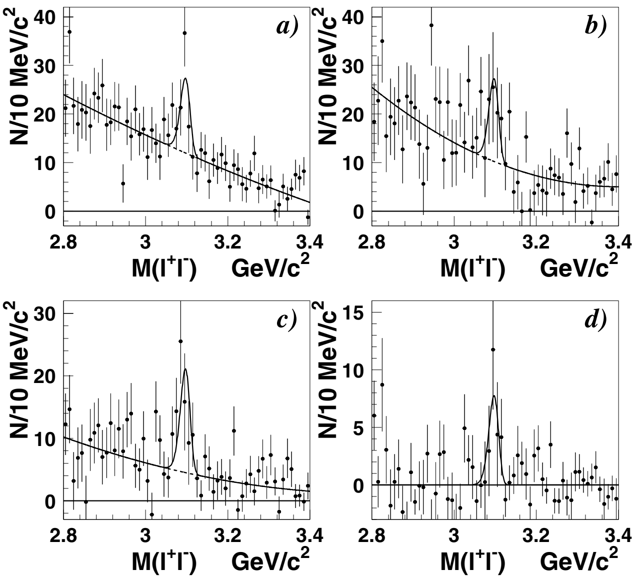

Fig. 2. Charm meson signals in bins of $\ell^+\ell^-$ mass: **a** $D^0 \to K^-\pi^+$; **b** $D^0 \to K^-3\pi^\pm$; **c** $D^+ \to K^-2\pi^+$; **d** $D_s^+ \to K^-K^+\pi^+$. The curves represent the fit described in the text

Table 1. Summary of the signal yields, charmonium masses and significances for $e^+e^- \to J/\psi, (c\bar{c})_{res}$

	N	M [GeV/c^2]	σ
η_c	175 ± 23	2.972 ± 0.007	9.9
J/ψ	-9 ± 17	fixed	—
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	—
$\eta_c(2S)$	107 ± 24	3.630 ± 0.008	4.4
$\psi(2S)$	-38 ± 21	fixed	—

Table 2. Summary of double charmonium production cross-sections and upper limits (at 90% CL):
$\sigma(e^+e^- \to (c\bar{c})_{res_1} (c\bar{c})_{res_2}) \times \mathcal{B}((c\bar{c})_{res_2} \to \geq 4\,\text{charged})$ (fb)

	J/ψ	χ_{c1}	χ_{c2}	$\psi(2S)$
η_c	$46 \pm 6^{+7}_{-9}$	< 18	< 20	$18 \pm 8 \pm 7$
J/ψ	< 8	< 18	< 20	< 64
χ_{c0}	$16 \pm 5 \pm 4$	< 18	< 20	$17 \pm 8 \pm 7$
χ_{c1}	< 8	< 18	< 20	< 24
χ_{c2}	< 8	< 18	< 20	< 24
$\eta_c(2S)$	$25 \pm 6 \pm 6$	< 18	< 20	$31 \pm 9 \pm 10$
$\psi(2S)$	< 16	< 18	< 20	< 18

LUND fragmentation model. In the present study we reconstruct as many ground state charm hadrons as possible to reduce the model dependence: $D^0 \to K^-\pi^+(K^-3\pi^\pm)$, $D^+ \to K^-2\pi^+$, $D_s^+ \to K^+K^-\pi^+$ and $\Lambda_c \to pK^-\pi^+$ decay modes are used. To extract the number of charmed hadrons produced conjointly with J/ψ the charmed hadron signals are fitted in bins of dilepton mass. The latter distributions are fitted by a sum of J/ψ signal and second order polynomial functions. Fits are shown in Fig. 2 and the results are listed in Table 3. The number of $e^+e^- \to J/\psi\, c\bar{c}$ events is calculated as a sum over the D^0, D^+, D_s^+, Λ_c and $(c\bar{c})_{res}$ yields corrected for the efficiency. Taking into account the total number of reconstructed J/ψ we finally calculate $\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} = 0.82 \pm 0.15 \pm 0.14$

Table 3. Summary of the signal yields and significances for $e^+e^- \to J/\psi D(\Lambda_c)X$

mode	N_{events}	σ
$D^0 \to K^-\pi^+$	49.6 ± 13.3	3.7
$D^0 \to K^-3\pi^\pm$	53.0 ± 21.2	2.5
$D^+ \to K^-2\pi^+$	56.2 ± 15.4	3.6
$D_s^+ \to K^+K^-\pi^+$	23.8 ± 9.4	2.6
$\Lambda_c \to K^-p\pi^+$	3.0 ± 4.2	—

2 $e^+e^- \to D^{(*)+}D^{(*)-}$ study

The processes $e^+e^- \to D^{(*)}\overline{D}^{(*)}$, with no extra fragmentation particles in the final state, have not previously been observed at energies $\sqrt{s} \gg 2M_D$. A calculation [4] predicts cross-sections of about $5\,\text{pb}^{-1}$ for $e^+e^- \to D\overline{D}^*$ and $e^+e^- \to D_T^*\overline{D}_L^*$ at $\sqrt{s} \sim 10.6\,\text{GeV}$ (the subscripts indicate transverse [T] and longitudinal [L] polarization of the D^*); the cross-section for $e^+e^- \to D\overline{D}$ is expected to be suppressed by a factor of $\sim 10^{-3}$.

The analysis is based on $88.9\,\text{fb}^{-1}$ of data at the $\Upsilon(4S)$ resonance and nearby continuum. The present study is limited to final states that contain charged $D^{(*)}$ mesons only. The D^{*+} mesons are reconstructed in the $D^0\pi^+$ decay mode, D mesons are reconstructed in the $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^-\pi^+\pi^+$ modes.

We use partial reconstruction of the event to increasce the statistics. For the signal a peak in the $M_{recoil}(D^*)$ distribution around the nominal mass of the recoiling $D^{(*)-}$ is expected. For the $e^+e^- \to D^+D^{*-}$ and $e^+e^- \to D^{*+}D^{*-}$ processes we reconstruct the first $D^{(*)+}$ fully, while the recoiling D^{*-} is required to decay into $\bar{D}^0\pi^-_{slow}$. The reconstructed π^-_{slow} provides an extra information allowing to reduce the background to a negligible level: We calculate the difference between the recoil masses against the $D^{(*)+}\pi^-_{slow}$ and $D^{(*)+}$, $\Delta M_{\text{recoil}} \equiv M_{\text{recoil}}(D^{(*)+}) - M_{\text{recoil}}(D^{(*)+}\pi^-_{slow})$. The ΔM_{recoil} distribtion peaks around the nominal $D^{*+} - D^0$ mass difference with a resolution of $\sigma_{\Delta M_{\text{recoil}}} \sim 1\,\text{MeV}/c^2$.

The $M_{\text{recoil}}(D^{*+})$ and $M_{\text{recoil}}(D^+)$ distributions are shown in Figs. 3a and 3b, respectively. Clear signals are seen around the nominal D^{*-} mass in both cases. The hatched histograms show the M_{recoil} distributions for events in the ΔM_{recoil} sidebands.

The backgrounds in the region of $M_{\text{recoil}} < 2.1\,\text{GeV}/c^2$, are negligible for both processes. To provide a numerical

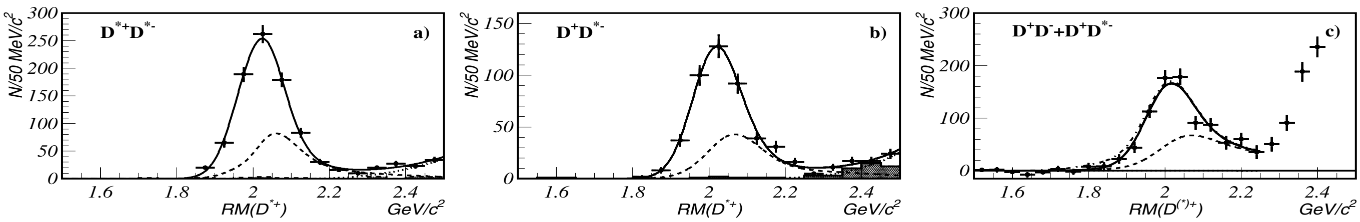

Fig. 3. a-b The distributions of the recoil mass against **a** D^{*+}, **b** D^{+} and **c** D^{+} without $\Delta M_{\rm recoil}$ cut. Lines represent the fits described in the text

estimate, we divide the background sources into three categories: (I) fake reconstructed D^{*+} or D^{+}; (II) $e^+e^- \to D^{(*)+}D^{(*)}n\pi$, where the π^-_{slow} is not produced from D^{*-} decays; (III) $e^+e^- \to D^{(*)+}D^{*-}n\pi$, where $n \geq 1$.

First we consider the backgrounds for the process $e^+e^- \to D^{*+}D^{*-}$. To estimate background (I) and (II) we count the entries in the D^{*+} mass sidebands ($2.016 < M_{D^0\pi^+} < 2.02\,\mathrm{GeV}/c^2$) and $\Delta M_{\rm recoil}$ sidebands. The number of events is found to be consistent with MC predictions. Backgrounds (I) and (II) are estimated to be smaller than 3 and 9 events at 90% CL, respectively. To estimate the residual background (III) contribution we perform a fit to the $M_{\rm recoil}(D^{*+})$ distribution. The fit results are shown in Fig. 3a as the solid line. The dotted line represents the expected background (III) distribution. The contribution from background (III) is estimated from this fit to be less than 2 events. The backgrounds for the $e^+e^- \to D^+D^{*-}$ process are studied in a similar way. Backgrounds (I), (II) and (III) for the $e^+e^- \to D^+D^{*-}$ process are estimated to be smaller than 7, 4 and 2 events at 90% CL, respectively. From the above study we estimate the total background in the $M_{\rm recoil} < 2.1\,\mathrm{GeV}/c^2$ interval to be of order of 1% of the signal. We consider all events in the interval $M_{\rm recoil} < 2.1\,\mathrm{GeV}/c^2$ as signal and include the possible background contribution in the systematic error.

Since the reconstruction efficiency depends on the production and $D^{*\pm}$ helicity angles, we perform an angular analysis before computing cross-sections. A scatter plot of the helicity angles for the two D^*-mesons is fitted by a sum of three functions corresponding to the $D^*_T D^*_T$, $D^*_T D^*_L$ and $D^*_L D^*_L$ final states, obtained from MC. The fit finds the fractions of $D^*_T D^*_T$, $D^*_T D^*_L$ and $D^*_L D^*_L$ final states to be $(1.5 \pm 3.6)\%$, $(97.2 \pm 4.8)\%$ and $(1.3 \pm 4.7)\%$, respectively. The fraction of the $D^+D^{*-}_L$ in $e^+e^- \to D^+D^{*-}$final state is found to be equal to $(95.8 \pm 5.6)\%$.

The production angle distributions for D^{*+} from e^+e^- $D^{(*)}D^{(*)}$ and D^+ from $e^+e^- \to D^*D$ processes are obtained from the region of recoil masses $M_{\rm recoil} < 2.1\,\mathrm{GeV}/c^2$. The reconstruction efficiency is estimated from the MC. To calculate the total cross-sections, the signal yields are corrected on the fraction of events with initial state radiation that lie outside of the interval $M_{\rm recoil} < 2.1\,\mathrm{GeV}/c^2$. The efficiency corrected signal yields are found to be 58000 ± 3400 and 64000 ± 4800 for the $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$ processes respectively. We find cross-sections of $0.65 \pm 0.04 \pm 0.07\,\mathrm{pb}$ and $0.71 \pm 0.05 \pm 0.09\,\mathrm{pb}$ for $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$, respectively.

We search for the process $e^+e^- \to D^+D^-$ by studying the mass of the system recoiling against the reconstruted D^+ (M_{recoil}). In the $e^+e^- \to D^{*+}D^{*-}$ and $e^+e^- \to D^+D^{*-}$ analyses, backgrounds are strongly suppressed by the tight $\Delta M_{\rm recoil}$ cut, which is not applicable for $e^+e^- \to D^+D^-$. Figure 1c shows the distribution of $M_{\rm recoil}(D^+)$ after sutraction of the D^+ meson mass sideband. To extract the $e^+e^- \to D^+D^-$ and $e^+e^- \to D^+D^{*-}$ yields we fit this distribution with the sum of two signal functions corresponding to D^- and D^{*-} peaks and a background function. The latter is a threshold function, convolved with the detector resolution. The fit finds -13 ± 24 events in the D^+ peak and 935 ± 42 in the D^{*+} peak. The fit function is shown in the Fig. 3c as the solid line and the dotted line represents the case where the contribution of $e^+e^- \to D^+D^-$ is set at the value corresponding to the 90% confidence level upper limit. For the $e^+e^- \to D^+D^-$ cross-section we set an upper limit of $0.04\,\mathrm{pb}$ at the 90% confidence level.

3 Summary

We have studied many double charmonium final states produced in e^+e^- annihilation. The ratio

$$\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X)$$

has been calculated with better accuracy. We also measured cross-section of $e^+e^- \to D^{(*)+}D^{(*)-}$ processes for the first time.

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