Measurements of the Continuum R_{uds} and R Values in e^+e^- Annihilation in the Energy Region between 3.650 and 3.872 GeV

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We report measurements of the continuum R_{uds} near the center-of-mass energy of 3.70 GeV, the $R_{uds(c)+\psi(3770)}(s)$ and the $R_{\rm had}(s)$ values in e^+e^- annihilation at 68 energy points in the energy region between 3.650 and 3.872 GeV with the BES-II detector at the BEPC Collider. We obtain the R_{uds} for the continuum light hadron (containing u, d, and s quarks) production near the $D\bar{D}$ threshold to be $R_{\rm uds} = 2.141 \pm 0.025 \pm 0.085$.

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Precision measurement of the cross section $\sigma^0_{\rm had}(s)$ for a single photon exchange process in e^+e^- annihilation at the c.m. (center-of-mass) energy $\sqrt{s}$, which does not include the initial state radiative and vacuum polarization effects, is important for both testing the validity of the perturbative QCD (pQCD) calculation on the cross section and in calculation of the photon vacuum polarization. This cross section is defined as the lowest order cross section for inclusive hadron production in this Letter. It is often represented by a $R(s)$ ratio

$$R(s) = \frac{\sigma^0_{\rm had}(s)}{\sigma^0_{\mu^+\mu^-}(s)}, \tag{1}$$

where $\sigma^0_{\mu^+\mu^-}(s) = 4\pi\alpha^2(0)/3s$ is the lowest order QED cross section for muon pair production. The $\sigma^0_{\rm had}(s)$ still includes the final state photon radiation and all QCD corrections. It can be extracted from the observed cross section $\sigma^{\rm obs}_{\rm had}(s)$ for inclusive hadron production accounting for the initial state radiative corrections and the vacuum polarization corrections (see below).

In the lower energy region, precise measurements of the $R_{uds}(s)$, which is defined as the $R(s)$ ratio for the continuum light hadron (containing u, d, and s quarks) production in e^+e^- annihilation in this Letter, can be used to test the validity of the pQCD calculation [1,2] in this energy region. Moreover the $R_{\rm had}(s)$ values including the contributions from both the continuum hadrons and all 1^{--} resonances at all energies are needed to calculate the effects of vacuum polarization on the parameters of the standard model, such as the quantities $\alpha(M_Z^2)$, the QED running coupling constant evaluated at the mass of Z^0, and $\alpha_\mu = (g-2)/2$, the anomalous magnetic moment of the muon [3–5]. A large part of uncertainty in the calculation arises from the uncertainties in the measured inclusive hadronic cross sections in the open charm threshold region, in which many resonances overlap. To get credible measurements of the $R_{uds}(s)$ for tests of the pQCD calculation and various lowest order cross sections, i.e., the measurement of $R_{\rm had}(s)$, in this energy region, the overlapping effects have to be clarified clearly. Near the $D\bar{D}$ threshold region, say above the $\psi(2S)$ resonance and below the $D\bar{D}$ threshold, no direct measurement of the R_{uds} is currently available. The measurements of the $R(s)$ [6] in this region and in the region between 2.0 and 3.55 GeV [6], which were obtained from analyzing the data taken with the BES-II detector in the period from 1998 to 1999, cannot be used directly to test the validity, since those give the $R_{\rm had}(s)$ rather than the R_{uds}.

In this Letter, we report direct measurements of R_{uds} near the $D\bar{D}$ threshold region, measurements of $R_{uds(c)+\psi(3770)}(s)$ above the $D\bar{D}$ threshold and the $R_{\rm had}(s)$ values at 68 energy points in the region from 3.650 to 3.872 GeV. We here define the $R_{uds(c)+\psi(3770)}(s)$ to be the $R(s)$ ratio accounting for the contributions from both the continuum hadron production and the decays for $\psi(3770) \to$ hadrons. Combining the measurements of the $R_{uds(c)+\psi(3770)}(s)$ and the cross section for $D\bar{D}$ production [7] would give us some information about non-$D\bar{D}$ decays of $\psi(3770)$ [8–10] and improve our knowledge about the nature of $\psi(3770)$. The data samples used in the analysis were taken with the BES-II detector [11] at the BEPC Collider in December 2003.

The $\sigma^{\rm obs}_{\rm had}$ is determined by

$$\sigma^{\rm obs}_{\rm had}(s) = \frac{N^{\rm obs}_{\rm had}}{L\epsilon_{\rm had}\epsilon^{\rm trig}_{\rm had}}, \tag{2}$$

where $N^{\rm obs}_{\rm had}$ is the number of the observed hadronic events, L is the integrated luminosity, $\epsilon_{\rm had}$ is the efficiency for the detection of inclusive hadronic events, and $\epsilon^{\rm trig}_{\rm had}$ is the trigger efficiency for collecting hadronic events in online data acquisition system.

The hadronic events are required to have more than 2 good charged tracks satisfying selection criteria as described in Ref. [9]. To separate some beam-gas associated background events and cosmic rays background events from hadronic events we calculated the event vertex in the beam line direction. Figure 1 shows the distribution of the event vertex of the accepted events. Using a Gaussian function to describe the hadronic events plus a second order polynomial for the background to fit the distribution, we obtain the number, $N^{\rm zfit}_{\rm had}$, of the candidates for the hadronic events. This number of candidates for hadronic events contains contaminations from some background sources such as $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to (\gamma)e^+e^-$, $e^+e^- \to (\gamma)\mu^+\mu^-$, and two-photon processes. The number of background events N_b due to these processes can be estimated by means of a Monte Carlo simulation [9]. Subtracting N_b from $N^{\rm zfit}_{\rm had}$ yields the number of the observed hadronic events $N^{\rm obs}_{\rm had}$. The systematic uncertainty in measuring the produced hadronic events due to the hadronic event selection criteria is estimated to be $\sim$2.5% [9].

The integrated luminosities of the data sets are determined using large-angle Bhabha scattering events as described in Ref. [9]. The systematic uncertainty in the measured values of the luminosities is estimated to be $\sim$1.9% [9].

The detection efficiency for hadronic events is determined via a special Monte Carlo generator [12] in which the radiative corrections to α^2 order are taken into account. These generated events are simulated with the GEANT3-based Monte Carlo simulation. The systematic uncertainty in the efficiencies due to the generator is estimated to be $\sim$2.0% for reconstruction of the inclusive hadronic events from continuum hadrons, $\psi(3770)$ and $\psi(2S)$ decays, and to be $\sim$0.7% for reconstruction of the continuum hadronic events [9]. Figure 2(a) shows the Monte Carlo efficiencies for the detection of hadronic events produced at the different nominal c.m. energies, where the error is statistical.

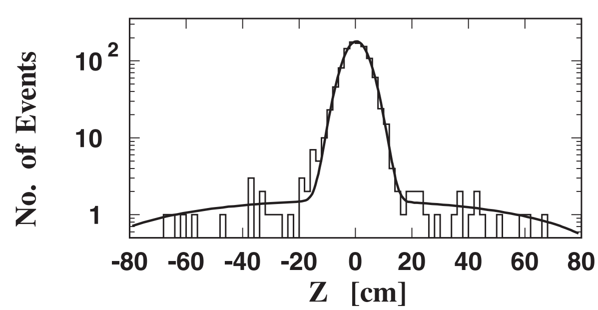

FIG. 1. The distribution of the event vertex in z.

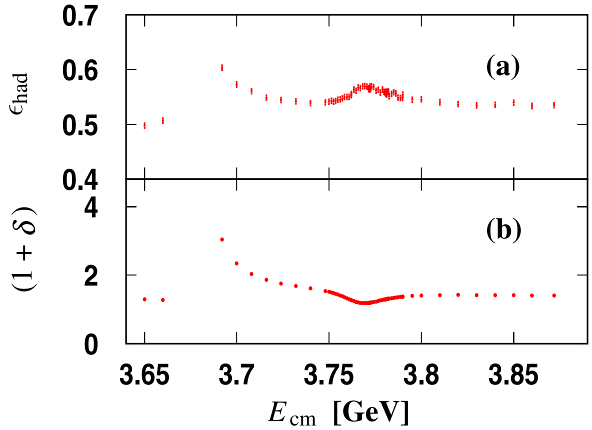

FIG. 2 (color online). (a) The efficiency versus the nominal c.m. energy; (b) the ISR factor versus the nominal c.m. energy (see text).

The trigger efficiencies are measured to be $\epsilon_{trig} = (100.0^{+0.0}_{-0.5})\%$ for both the $e^+e^- \to (\gamma)e^+e^-$ and $e^+e^- \to$ hadrons events [9].

To get the $\sigma^0_{had}(s)$, the $\sigma^{obs}_{had}(s)$ has to be corrected for the initial state radiative and vacuum polarization corrections. There is no correction for final state radiation needed, since the $\sigma^0_{had}(s)$ includes the final state photon radiation. The correction factor $[1+\delta(s)]$ is given by

$$[1+\delta(s)] = \frac{\sigma^{exp}(s)}{\sigma^0(s)}, \tag{3}$$

where $\sigma^{exp}(s)$ is the expected cross section and $\sigma^0(s)$ the lowest order cross section for inclusive hadronic event production. The $\sigma^{exp}(s)$ can be written as

$$\sigma^{exp}(s) = \int_0^{1-(4m_\pi^2/s)} dx \frac{\sigma^0[s(1-x)]}{|1-\prod[s(1-x)]|^2} F(x,s), \tag{4}$$

where $\sigma^0[s(1-x)]$ is the total lowest order cross section in the energy range from 0.28 GeV to $\sqrt{s}$, $F(x,s)$ is a sampling function [13], and $1/|1-\Pi[s(1-x)]|^2$ is the correction factor for the effects of vacuum polarization including both the leptonic and hadronic terms in QED [9,13]. Assuming that there are no other new structure and effects except the $\psi(3770)$ and continuum hadrons in the energy region from 3.729 to 3.872 GeV, we calculate the radiative correction factors. In the calculation of the cross sections, the $\psi(3770)$ and $\psi(2S)$ resonance parameters measured by the BES Collaboration [10] are used. Inserting the resonance parameters of other 1^{--} states [14] and the $R_{uds} = 2.218 \pm 0.091$ measured by the BES Collaboration [9] near 3.65 GeV in Eqs. (6)–(25) of Ref. [9] as the initial input, we obtain the radiative correction factors at the 68 energy points as shown in Fig. 2(b). The uncertainty in $[1+\delta(s)]$ is less than 1.5% [9].

The sum of the lowest order cross sections for continuum hadron and $\psi(3770)$ production is given by

$$\sigma^0_{uds(c)+\psi(3770)}(s) = \frac{\sigma^{obs}_{had}(s)}{[1+\delta(s)]} - \sum_i \sigma^0_{\mathrm{Res},i}(s), \tag{5}$$

in which $\sum_i \sigma^0_{\mathrm{Res},i}(s)$ is the contribution from the 1^{--} resonances [9] near the c.m. energy of 3.70 GeV except $\psi(3770)$. Equation (5) indicates

$$\sigma^0_{uds(c)+\psi(3770)}(s) = (R_{uds(c)} + R_{\psi(3770)})\sigma^0_{\mu^+\mu^-}(s), \tag{6}$$

where $R_{\psi(3770)}(s)$ is the $R(s)$ value due to the decays for $\psi(3770) \to$ hadrons. Dividing the $\sigma^0_{uds(c)+\psi(3770)}(s)$ by $\sigma^0_{\mu^+\mu^-}(s)$ yields $R_{uds(c)+\psi(3770)}(s)$ values as summarized in Table I, where $R_{uds(c)+\psi(3770)}(s)$ means $R_{uds}(s)$ or $R_{uds(c)}(s) + R_{\psi(3770)}(s)$; below the $D\bar{D}$ threshold $R_{uds(c)+\psi(3770)}(s)$ equals $R_{uds}(s)$; above the threshold $R_{uds(c)+\psi(3770)}(s) = R_{uds(c)}(s) + R_{\psi(3770)}(s)$ is the $R(s)$ value including both the continuum hadron production and the decays of $\psi(3770) \to$ hadrons. As mentioned above, calculating the effects of the vacuum polarization on $\alpha(M_Z^2)$ and a_μ^{SM} needs the $R_{had}(s)$ values, which can be obtained by dividing

$$\sigma^0_{had}(s) = \frac{\sigma^{obs}_{had}(s)}{[1+\delta(s)]} \tag{7}$$

by $\sigma^0_{\mu^+\mu^-}(s)$. Table I also lists the $R_{had}(s)$ values. The first errors in the measured $R_{uds(c)+\psi(3770)}(s)$ and $R_{had}(s)$ values listed in the table are statistical including the point-to-point systematic uncertainty arising from the statistical uncertainty in the measured luminosity and the uncertainty in the Monte Carlo efficiency, and the second ones are common systematic, arising from the uncertainties in luminosity ($\sim$1.9%), in selection of hadronic event ($\sim$2.5%), in Monte Carlo Modeling ($\sim$2.0%), in radiative correction ($\sim$1.5%) for measurements of $R(s)$ values off the $\psi(3770)$ resonance and in $\psi(3770)$ parameters ($\sim$2.7%) for those in the $\psi(3770)$ resonance region between 3.74 to 3.82 GeV. Adding these uncertainties in quadrature yields the total systematic uncertainties to be $\sim$4.0% and $\sim$4.9% for these outside the $\psi(3770)$ resonance and within $\psi(3770)$ resonance regions, respectively.

Weighting the first 8 $R_{uds(c)+\psi(3770)}(s)$ values below the $D\bar{D}$ threshold with the statistical error yields

$$R_{uds} = 2.141 \pm 0.025 \pm 0.085,$$

which can directly be compared to $R^{\mathrm{pQCD}}_{uds} = 2.15 \pm 0.03$ calculated by pQCD [4,15].

Figure 3 displays the $R_{uds(c)+\psi(3770)}(s)$ and/or $R_{had}(s)$ values from this measurements, together with those measured by the Mark I Collaboration [16], by the BES Collaboration from analysis of different data samples [6] and the continuum R^{pQCD}_{uds} calculated by pQCD [4,15], which is shown by two straight lines indicating $\pm 1\sigma$ error interval. There is one thing which we would like to point out. In the measurements of the $R(s)$ values, the measurements reported in Ref. [9] are the quantity $R_{uds(c)+\psi(3770)}(s)$

TABLE I. Summary of the $R_{uds(c)+\psi(3770)}(s)$ and $R_{\rm had}(s)$ values measured at 68 energy points.

c.m. energy	$R_{uds(c)+\psi(3770)}(s)$	$R_{\rm had}(s)$	c.m. energy	$R_{uds(c)+\psi(3770)}(s)$	$R_{\rm had}(s)$
3.6500	$2.157 \pm 0.035 \pm 0.086$	$2.186 \pm 0.035 \pm 0.087$	3.7726	$3.777 \pm 0.145 \pm 0.185$	$3.781 \pm 0.145 \pm 0.185$
3.6600	$2.131 \pm 0.105 \pm 0.085$	$2.185 \pm 0.105 \pm 0.087$	3.7730	$3.563 \pm 0.120 \pm 0.175$	$3.567 \pm 0.120 \pm 0.175$
3.6920	$2.034 \pm 0.092 \pm 0.081$	$2.803 \pm 0.092 \pm 0.112$	3.7742	$3.373 \pm 0.113 \pm 0.165$	$3.377 \pm 0.113 \pm 0.165$
3.7000	$2.079 \pm 0.079 \pm 0.083$	$2.240 \pm 0.079 \pm 0.089$	3.7754	$3.641 \pm 0.125 \pm 0.178$	$3.645 \pm 0.125 \pm 0.178$
3.7080	$2.197 \pm 0.083 \pm 0.088$	$2.270 \pm 0.083 \pm 0.091$	3.7766	$3.498 \pm 0.119 \pm 0.171$	$3.502 \pm 0.119 \pm 0.171$
3.7160	$2.177 \pm 0.086 \pm 0.087$	$2.224 \pm 0.086 \pm 0.089$	3.7778	$3.570 \pm 0.121 \pm 0.175$	$3.574 \pm 0.121 \pm 0.175$
3.7240	$2.125 \pm 0.086 \pm 0.085$	$2.164 \pm 0.086 \pm 0.086$	3.7790	$3.360 \pm 0.117 \pm 0.165$	$3.363 \pm 0.117 \pm 0.165$
3.7320	$2.156 \pm 0.086 \pm 0.086$	$2.170 \pm 0.086 \pm 0.087$	3.7798	$3.477 \pm 0.136 \pm 0.170$	$3.480 \pm 0.136 \pm 0.170$
3.7400	$2.190 \pm 0.099 \pm 0.088$	$2.200 \pm 0.099 \pm 0.088$	3.7802	$3.427 \pm 0.125 \pm 0.168$	$3.430 \pm 0.125 \pm 0.168$
3.7480	$2.371 \pm 0.106 \pm 0.116$	$2.380 \pm 0.106 \pm 0.116$	3.7804	$3.382 \pm 0.137 \pm 0.166$	$3.385 \pm 0.137 \pm 0.166$
3.7500	$2.517 \pm 0.085 \pm 0.123$	$2.525 \pm 0.085 \pm 0.123$	3.7808	$3.336 \pm 0.129 \pm 0.163$	$3.340 \pm 0.129 \pm 0.163$
3.7512	$2.637 \pm 0.090 \pm 0.129$	$2.644 \pm 0.090 \pm 0.129$	3.7810	$3.464 \pm 0.138 \pm 0.170$	$3.468 \pm 0.138 \pm 0.170$
3.7524	$2.615 \pm 0.095 \pm 0.128$	$2.622 \pm 0.095 \pm 0.128$	3.7812	$3.396 \pm 0.130 \pm 0.166$	$3.399 \pm 0.130 \pm 0.166$
3.7536	$2.652 \pm 0.093 \pm 0.130$	$2.659 \pm 0.093 \pm 0.130$	3.7814	$3.514 \pm 0.124 \pm 0.172$	$3.518 \pm 0.124 \pm 0.172$
3.7548	$2.733 \pm 0.093 \pm 0.134$	$2.739 \pm 0.093 \pm 0.134$	3.7816	$2.944 \pm 0.137 \pm 0.144$	$2.947 \pm 0.137 \pm 0.144$
3.7560	$2.585 \pm 0.090 \pm 0.127$	$2.591 \pm 0.090 \pm 0.127$	3.7818	$3.140 \pm 0.125 \pm 0.154$	$3.143 \pm 0.125 \pm 0.154$
3.7572	$2.942 \pm 0.107 \pm 0.144$	$2.948 \pm 0.107 \pm 0.144$	3.7822	$3.253 \pm 0.124 \pm 0.159$	$3.257 \pm 0.124 \pm 0.159$
3.7584	$3.025 \pm 0.108 \pm 0.148$	$3.031 \pm 0.108 \pm 0.148$	3.7826	$3.326 \pm 0.115 \pm 0.163$	$3.329 \pm 0.115 \pm 0.163$
3.7596	$3.076 \pm 0.102 \pm 0.151$	$3.082 \pm 0.102 \pm 0.151$	3.7838	$3.154 \pm 0.114 \pm 0.155$	$3.157 \pm 0.114 \pm 0.155$
3.7608	$3.138 \pm 0.089 \pm 0.154$	$3.143 \pm 0.089 \pm 0.154$	3.7850	$2.879 \pm 0.107 \pm 0.141$	$2.882 \pm 0.107 \pm 0.141$
3.7620	$2.992 \pm 0.110 \pm 0.147$	$2.998 \pm 0.110 \pm 0.147$	3.7862	$2.902 \pm 0.105 \pm 0.142$	$2.905 \pm 0.105 \pm 0.142$
3.7622	$3.207 \pm 0.114 \pm 0.157$	$3.213 \pm 0.114 \pm 0.157$	3.7874	$2.957 \pm 0.111 \pm 0.145$	$2.960 \pm 0.111 \pm 0.145$
3.7634	$3.345 \pm 0.122 \pm 0.164$	$3.350 \pm 0.122 \pm 0.164$	3.7886	$2.571 \pm 0.097 \pm 0.126$	$2.574 \pm 0.097 \pm 0.126$
3.7646	$3.585 \pm 0.126 \pm 0.176$	$3.590 \pm 0.126 \pm 0.176$	3.7898	$2.576 \pm 0.099 \pm 0.126$	$2.579 \pm 0.099 \pm 0.126$
3.7658	$3.381 \pm 0.119 \pm 0.166$	$3.386 \pm 0.119 \pm 0.166$	3.7900	$2.849 \pm 0.106 \pm 0.140$	$2.852 \pm 0.106 \pm 0.140$
3.7670	$3.760 \pm 0.130 \pm 0.184$	$3.764 \pm 0.130 \pm 0.184$	3.7950	$2.751 \pm 0.101 \pm 0.135$	$2.754 \pm 0.101 \pm 0.135$
3.7682	$3.451 \pm 0.124 \pm 0.169$	$3.455 \pm 0.124 \pm 0.169$	3.8000	$2.212 \pm 0.091 \pm 0.108$	$2.215 \pm 0.091 \pm 0.108$
3.7694	$3.611 \pm 0.125 \pm 0.177$	$3.615 \pm 0.125 \pm 0.177$	3.8100	$2.171 \pm 0.092 \pm 0.087$	$2.173 \pm 0.092 \pm 0.087$
3.7706	$3.580 \pm 0.123 \pm 0.175$	$3.584 \pm 0.123 \pm 0.175$	3.8200	$2.367 \pm 0.109 \pm 0.095$	$2.369 \pm 0.109 \pm 0.095$
3.7714	$3.538 \pm 0.139 \pm 0.173$	$3.543 \pm 0.139 \pm 0.173$	3.8300	$2.354 \pm 0.101 \pm 0.094$	$2.355 \pm 0.101 \pm 0.094$
3.7716	$3.634 \pm 0.146 \pm 0.178$	$3.638 \pm 0.146 \pm 0.178$	3.8400	$2.296 \pm 0.104 \pm 0.092$	$2.297 \pm 0.104 \pm 0.092$
3.7718	$3.939 \pm 0.133 \pm 0.193$	$3.943 \pm 0.133 \pm 0.193$	3.8500	$2.372 \pm 0.115 \pm 0.095$	$2.373 \pm 0.115 \pm 0.095$
3.7720	$3.636 \pm 0.134 \pm 0.178$	$3.640 \pm 0.134 \pm 0.178$	3.8600	$2.371 \pm 0.105 \pm 0.095$	$2.372 \pm 0.105 \pm 0.095$
3.7722	$3.652 \pm 0.143 \pm 0.179$	$3.656 \pm 0.143 \pm 0.179$	3.8720	$2.308 \pm 0.117 \pm 0.092$	$2.309 \pm 0.117 \pm 0.092$

which equals R_{uds} below the $D\bar{D}$ threshold and equals $R_{uds(c)}(s) + R_{\psi(3770)}(s)$ above the $D\bar{D}$ threshold; while the measurements reported from this Letter are the quantities R_{uds}, $R_{uds(c)+\psi(3770)}(s)$ and $R_{\rm had}(s)$, the other measurements are only the quantity $R_{\rm had}(s)$.

In summary, we measured the $R_{uds(c)+\psi(3770)}(s)$ and $R_{\rm had}(s)$ values in the energy region from 3.650 to 3.872 GeV with the systematic uncertainty of $\sim$4.0% for the continuum R_{uds} and the $R_{\rm had}(s)$ outside the $\psi(3770)$ resonance regions, and with the uncertainty of $\sim$4.9% for the $R_{uds(c)+\psi(3770)}(s)$ and the $R_{\rm had}(s)$ in the $\psi(3770)$ resonance region. These are improved measurements with respect to the earlier measurements [6,16] in both the accuracy and the number of energy points. These improved measurements of the $R_{\rm had}(s)$ are expected to provide an improvement in the precision of the calculated values of $\alpha(M_Z^2)$ [17] and $\alpha_\mu^{\rm SM}$ [5,17,18]. We obtained the continuum R_{uds} near the $D\bar{D}$ threshold region to be $R_{uds} = 2.141 \pm 0.025 \pm 0.085$, which is in excellent agreement with $R_{uds}^{\rm pQCD} = 2.15 \pm 0.03$ [4,15] predicted by pQCD in this energy region. This measured R_{uds} can directly be used

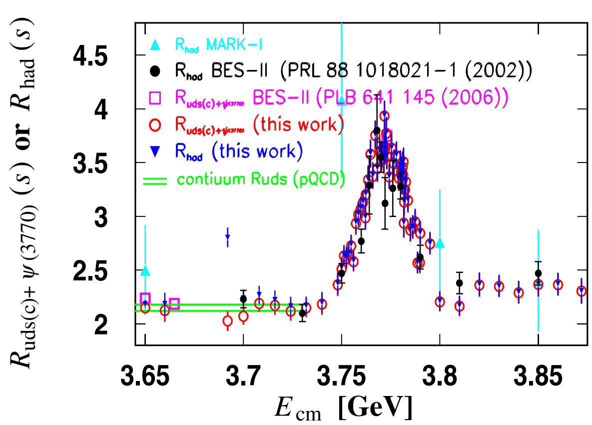

FIG. 3 (color online). The $R_{uds(c)+\psi(3770)}(s)$ or $R_{\rm had}(s)$ versus the c.m. energy (see text).

to evaluate the strong coupling constant $\alpha_s(s)$ at the energy scale of $\sim$3 GeV. In this analysis, we clarified the overlapping effects of different processes to the $R_{\rm had}(s)$. This is important for test of the validity of the pQCD calculation near the $D\bar{D}$ threshold region and for correctly using the data in the calculation of $\alpha(M_Z^2)$ and $\alpha_\mu^{\rm SM} = (g-2)/2$ with the help of the pQCD prediction.

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