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Search for $\psi(2S)$ production in e^+e^- annihilations at 4.03 GeV

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A search is performed for the production of the $\psi(2S)$ in e^+e^- annihilation at a center-of-mass energy of 4.03 GeV using the BES detector operated at the Beijing Electron Positron Collider (BEPC). The kinematic features of the reconstructed $\psi(2S)$ signal are consistent with its being produced only in association with an energetic photon resulting from initial state radiation (ISR). Limits are placed on $\psi(2S)$ production from the decay of unknown charmonia or metastable hybrids that might be produced in e^+e^- annihilations at 4.03 GeV. Under the assumption that the observed cross section for $\psi(2S)$ production is due entirely to ISR, the partial width Γ_{ee} of the $\psi(2S)$ is measured to be 2.07 ± 0.32 keV. [S0556-2821(98)01309-5]

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I. INTRODUCTION

In e^+e^- annihilations at a center of mass energy of 4.03 GeV the $\psi(2S)$ can be produced via

(1) initial state radiation (ISR) of a photon by the e^+ or e^-, followed by $e^+e^-\to\psi(2S)$,
(2) $e^+e^-\to\pi^0\psi(2S)$, where the π^0 can be produced in the hadronization of $c\overline{c}$ into $\psi(2S)\pi^0$, or in a two photon process where $\gamma\gamma$ couples to a π^0,
(3) decays of charmonium states more massive than the $\psi(2S)$, and
(4) decays of possible metastable hybrids $(q\overline{q}g)$ produced in e^+e^- annihilations at 4.03 GeV.

Reaction (1) is well described by QED, and is expected to be dominant. Process (2) proceeds through two virtual photons, or an isospin-violating hadronic interaction, and is expected to be suppressed relative to (1) [1,2]. Unless there is a new charmonium state produced in e^+e^- annihilation at this

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energy, process (3) should be absent in the data. The possibility of the existence of metastable hybrids with mass $\sim$4 GeV has been proposed [3] to explain the $\psi(2S)$ anomaly observed in $p\overline{p}$ collisions at the Fermilab Tevatron [4]. It is of interest to search for these metastable hybrids via reaction (4); their existence might be revealed through an excess $\psi(2S)$ production in e^+e^- collisions.

In this paper, $\psi(2S)$ production in e^+e^- collisions at a center-of-mass energy of 4.03 GeV is reported using BES data taken at the Beijing Electron Positron Collider (BEPC). Evidence for processes (2), (3) and (4) is sought by measuring an excess of $\psi(2S)$ events above QED ISR production. Since the center of mass energy is not far above the $\psi(2S)$ threshold, reactions (1)–(4) should yield events of low charge multiplicity, when the $\psi(2S)$ is excluded. Therefore events containing $\psi(2S)$ at this energy are expected to have very distinctive kinematic features, and can be readily separated from other events.

The following sections describe the BES detector, the identification of electrons and muons, the reconstruction of the $\psi(2S)$, a study of the kinematic features and production rate of the $\psi(2S)$, limits on the production of $\psi(2S)$ due to reactions (3) and (4), and a determination of the partial width, Γ_{ee}, of the $\psi(2S)$.

II. THE BES DETECTOR AND EVENT SELECTION

The BES detector has been discussed in detail previously [5]. The detector elements crucial to the present measurement are now described briefly.

Charged particle tracking is provided by a 10 superlayer main drift chamber (MDC) operated inside a 0.4 T axial magnetic field. Each superlayer contains four layers of sense wires measuring both the position and the specific ionization (dE/dx) of charged particles. The magnet coil surrounds a time-of-flight (TOF) counter array and an electromagnetic calorimeter (ECAL) composed of proportional tubes and lead sheets. A muon detector system is outside the magnet coil; it consists of three double layers of streamer tubes, and measures the coordinates of muons in z and in $r\phi$ with resolutions of 5 cm and 3 cm, respectively.

This analysis is based on hadronic events recorded with the BES detector. A data sample of 22.3 pb^{-1} was collected in e^+e^- annihilations at a center-of-mass energy of 4.03 GeV.

III. RECONSTRUCTION OF THE $\psi(2S)$

Additional selection criteria are imposed on the BES hadronic events in this analysis. Each charged track must satisfy the following criteria:

(1) at least 10 drift chamber hits must be used on the fitted track, and the track fit must be of good quality;
(2) $|\cos\theta|<0.88$, where θ is the polar angle of the track;
(3) the momentum of the track must be less than 2.0 GeV/c, and its transverse momentum must be greater than 50 MeV/c;
(4) the distance of closest approach to the beam in the transverse plane must be less than 3 cm, and must occur along the beam direction within $\pm$20 cm (4.5σ) of the center of the detector;
(5) $|\cos\theta_l|<0.90$, where θ_l is the lepton helicity angle in the dilepton rest frame.

In addition, a particle species dependent correction for energy loss in the beam pipe is made for all charged tracks. A correction of -0.42% is also applied to the momentum of each charged track to compensate for a shift in the BES magnetic field.

Events containing four or more charged tracks are searched for $\psi(2S)$ production, where the $\psi(2S)$ is detected by means of the decay $\psi(2S)\to\pi\pi J/\psi$, $J/\psi\to e^+e^-$ or $\mu^+\mu^-$.

A. Selection of electrons and muons

Three detector components, the main drift chamber, the TOF counter array, and the shower counter, are used for electron identification. The dE/dx and TOF measurements for charged tracks must be consistent with those of an electron. A shower shape quantity using the weighted number of hits in each ECAL layer is formed. A momentum dependent cut on this quantity is chosen to identify electrons based on the fact that electrons have more hits in the ECAL than hadrons and the longitudinal shower development has a pattern which is different from that of hadrons. This selection is identical to the procedure used in [6]. The efficiency for electron identification is measured to be $(86\pm1)\%$ above a momentum of 1.2 GeV/c using $J/\psi\to e^+e^-$ events selected in the BES data collected at the $\psi(2S)$ energy.

Muons are identified based on their associated muon counter hits only. For a track with transverse momentum greater than 0.75 GeV/c, at least two good muon layer hits have to be matched to the track. Above a transverse momentum of 0.95 GeV/c, all three muon layers must have good associated hits. Here good hits are those that are within the projected ϕ angle range of the charged track, where this range is determined from studying a cosmic ray muon sample. The efficiency for muon identification, determined from reconstructed $\psi(2S)\to J/\psi\pi\pi$, $J/\psi\to\mu^+\mu^-$ decays, is measured to be $(77\pm1)\%$ for p$>$1.2 GeV/c.

B. Reconstruction of the $\psi(2S)$

The $\psi(2S)$ is reconstructed in the decay $\psi(2S)\to J/\psi\pi^+\pi^-$, where $J/\psi\to\mu^+\mu^-$ or e^+e^-. A J/ψ candidate, defined as an event with dilepton invariant mass between 2.5 and 3.25 GeV, is combined with a pair of oppositely charged tracks, where at least one track has been identified as a pion according to dE/dx and TOF measurements. An asymmetric cut on the l^+l^- mass is applied to include those $J/\psi\to e^+e^-$ events where the e^+ or e^- has radiated a hard photon, thus yielding a l^+l^- invariant mass which is significantly lower than the nominal J/ψ mass. The difference in invariant mass between $l^+l^-\pi^+\pi^-$ and l^+l^- is shown in Fig. 1 for the two decay modes. In this mass difference, the measurement uncertainties in the lepton momenta tend to cancel. This permits the inclusion of J/ψ tail events, thereby increasing the detection efficiency. From high statistics $\psi(2S)$ runs we determine the mass resolution to be $\sim$9.4 MeV/c^2 for $\psi(2S)$ events in this mass distribution. Clear $\psi(2S)$ signals are reconstructed in both the e and

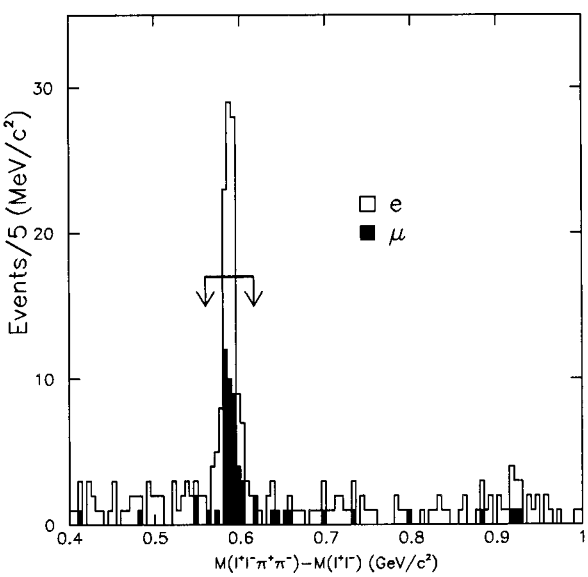

FIG. 1. The invariant mass difference between $l^+l^-\pi^+\pi^-$ and l^+l^-, where $l=e$ (histogram) or μ (hatched histogram). The arrows denote the $\psi(2S)$ signal region.

μ modes. The distribution in Fig. 1 is fit with a signal Gaussian on a smooth polynomial background; the fit value of the center is found to be 588 ± 1 MeV/c^2, in good agreement with the Particle Data Group (PDG) value of 589.1 ±0.1 MeV/c^2 [7].

In order to estimate the number of $\psi(2S)$ events, the range 560–616 MeV/c^2 is defined as the $\psi(2S)$ signal region, as shown by the arrows in Fig. 1. For the muon mode, Monte Carlo simulation and studies of data collected on the $\psi(2S)$ resonance show that there is no combinatorial background, and that events away from the $\psi(2S)$ signal region are genuine $\psi(2S)$ decays that are mis-reconstructed. All events in the signal region are interpreted as signal, and this yields 41.0 ± 6.4 $\psi(2S)$ events. A $\pm4\%$ systematic error is assigned to the $\psi(2S)$ signal. For the electron mode, two background regions, 409–541 MeV/c^2 and 635–767 MeV/c^2, are chosen to estimate the background contribution in the $\psi(2S)$ region. There are 80 events in the signal region, and 64 events in the background side-bands which imply 13.7 ± 1.7 background events in the signal region. After performing the background subtraction, it is estimated that there are 66.3 ± 9.0 $\psi(2S)$ events in the electron mode. Combining the μ and e modes, the distribution of Fig. 1 yields 107.3 $\pm11.0\pm4.3$ $\psi(2S)$ events, where the first error is statistical and the second is the systematic error resulting from the method used in estimating the background.

IV. KINEMATIC DISTRIBUTIONS FOR THE $\psi(2S)$ SIGNAL

A. Monte Carlo simulation

The reconstruction efficiencies for the $\psi(2S)$ are estimated using a Monte Carlo simulation of the BES detector, with the generated events being subjected to the same reconstruction procedure used in the BES data reconstruction. The ISR $e^+e^-\to\gamma\psi(2S)$ events are generated at a center-of-mass energy of 4.03 GeV, with the $\psi(2S)$ polar angle distributions as described in [1]. Other types of events are generated assuming a uniform angular distribution around the electron direction. The detection efficiencies for the $\psi(2S)$ are calculated based on different charmonium production mechanisms as outlined in (1)–(4), where the measured e/μ identification efficiencies have been used. The $\psi(2S)$ efficiencies are found not to vary significantly among these models. These efficiencies are used for the calculation of production rates in Sec. V. The small spread among these efficiencies is treated as a systematic error, and is included in the rate measurements.

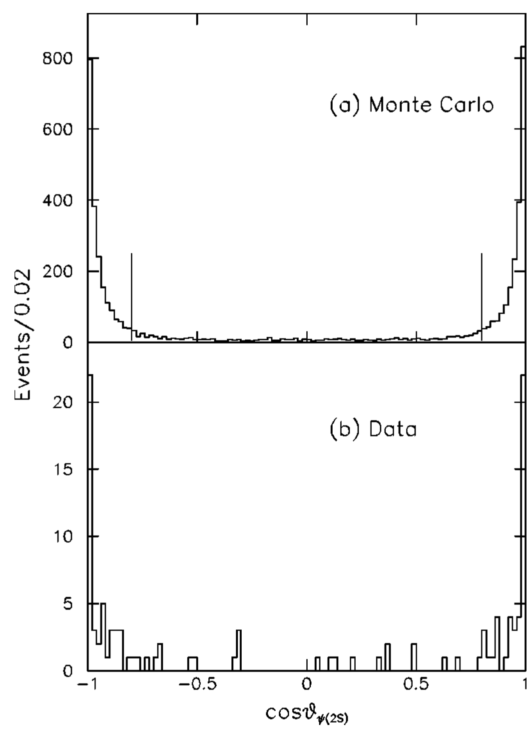

FIG. 2. Distribution in cos $\theta_{\psi(2S)}$ (a) for the ISR $\psi(2S)$ predicted by QED, and (b) for the $\psi(2S)$ candidates selected from the data.

B. Kinematic features of the $\psi(2S)$

The $\psi(2S)$ distributions from reactions in (1)–(4) have some unique kinematical features. Figure 2a shows the cos $\theta_{\psi(2S)}$ distribution as predicted by QED for the ISR $\psi(2S)$, where $\theta_{\psi(2S)}$ is the angle between directions of the $\psi(2S)$ and the positron. The ISR $\psi(2S)$ peak sharply in the forward and backward directions. For interactions (2)–(4) this angular distribution is expected to be rather uniform.

Reaction (1) results in a simple two body $\gamma\psi(2S)$ final state, where the $\psi(2S)$ momentum, as shown in Fig. 3a, peaks at 329 MeV/c with a width entirely due to the experimental resolution. The momenta of $\psi(2S)$ particles from processes such as $e^+e^-\to\psi(2S)\pi^0$ would peak at a value of 303 MeV/c. This important difference in momentum provides a crucial separation between (1), the dominant source of $\psi(2S)$, and (3) and (4), which involve the interesting physics that is being sought.

For the electron channel, the $\psi(2S)$ momentum resolution is degraded as a result of final state radiation, and is significantly worse than that of the $\psi(2S)$ reconstructed in the muon channel. To compensate for this energy loss, a 2-C kinematic fit is performed on the $\psi(2S)$ candidates for which the e^+e^- pairs and the $e^+e^-\pi^+\pi^-$ are constrained to $M_{J/\psi}$ (3.0969 GeV/c^2) and $M_{\psi(2S)}$ (3.686 GeV/c^2), respectively. This 2-C fit significantly improves the momentum resolution of the $\psi(2S)$, to the extent that the improved momentum resolution for the electron channel is compatible with that of the muon channel. The rms width of the combined $\psi(2S)$ momentum distribution is 26 MeV/c. Hereafter, the $\psi(2S)$ reconstructed using e and μ pairs are treated together.

The cos $\theta_{\psi(2S)}$ and $p_{\psi(2S)}$ distributions for the events in the $\psi(2S)$ signal region are shown in Fig. 2b and Fig. 3b, respectively. The cos $\theta_{\psi(2S)}$ distribution in Fig. 2b follows closely that of the ISR distribution in Fig. 2a. A Kolmogorov-Smirnov comparison between the ISR prediction of Fig. 2a, and the observed cos $\theta_{\psi(2S)}$ distribution of Fig. 2b, yields a probability of 75.2% that these distributions have the same shape. The fit performed to the $p_{\psi(2S)}$ spectrum in Fig. 3b yields a central value 336 ± 4 MeV/c for the Gaussian momentum distribution, in good agreement with the expectation of 329 MeV/c for the two body final state $e^+e^-\to\gamma\psi(2S)$. These kinematic features show that the $\psi(2S)$ signal is consistent with being produced entirely via reaction (1), the initial state radiation interaction.

V. THE PRODUCTION RATE OF THE $\psi(2S)$

A. Inclusive $\psi(2S)$ production rate

To determine the inclusive production rate, the $\psi(2S)$ signals in Fig. 1 are corrected for reconstruction efficiency, and the decay branching fractions of the mode studied. The branching fractions [7] $B(\psi(2S)\to J/\psi\pi^+\pi^-)=(32.4\pm2.6)\%$, $B(J/\psi\to e^+e^-)=(6.02\pm0.19)\%$, and $B(J/\psi\to\mu^+\mu^-)=(6.01\pm0.19)\%$ have been used. Monte Carlo simulations yield estimated detection efficiencies of $(18.9\pm0.1)\%$ and $(22.9\pm0.1)\%$ for $\psi(2S)\to J/\psi\pi^+\pi^-$, where $J/\psi\to\mu^+\mu^-$ and e^+e^-, respectively, and where the errors are statistical only. The corresponding cross section is

$$\sigma(e^+e^-\to\psi(2S)X)=592\pm61\pm68\text{ pb}$$

in e^+e^- annihilations at 4.03 GeV, averaged over the e and μ channels. The second errors are systematic, and arise from uncertainties in particle identification ($\pm3.1\%$), determination of number of signal events ($\pm4\%$), the absolute scale of the momentum measurement for the $\psi(2S)$ ($\pm2.7\%$), possible mode dependence of the $\psi(2S)$ detection efficiency ($\pm2.7\%$), luminosity uncertainty ($\pm0.9\text{ pb}^{-1}$), and errors on relevant J/ψ and $\psi(2S)$ branching fractions ($\pm8.6\%$). This result compares well with the value expected for process (1) which is 612 ± 60 pb, using the value 2.14 ± 0.21 keV for Γ_{ee} [7] of the $\psi(2S)$, the error being due to the uncertainty in Γ_{ee}.

B. Limit on a new charmonium decaying into $J/\psi\pi^+\pi^-$

A search has been made for a new $^3D_2$ charmonium state with a mass of 3.836 GeV/c^2 which has been reported in the decay mode $J/\psi\pi^+\pi^-$ [8]. The selection criteria are identical to those used in the $\psi(2S)$ reconstruction. This charmonium state should be observed in Fig. 1 at around 736.4 MeV/c^2 if the production cross section and branching fraction are sufficiently large. No enhancement is observed at this mass in Fig. 1. The mass region 718–755 MeV/c^2 is considered as the signal region, and corresponds to a $\pm2\sigma$ window at the mass of the reported charmonium state. The mass regions 635–699 MeV and 774–950 MeV are defined as background control regions, and events inside them are used to estimate the background in the signal region. A total of 9 and 47 events are found in the signal and background regions, respectively, leading to an estimate of $1.7^{+3.2}_{-1.7}$ excess events for a resonance at the reported $^3D_2$ mass. The detection efficiency is identical to that of the $\psi(2S)$. A 95% C.L. upper limit for $\sigma(e^+e^-\to{}^3D_2(3836)+\text{anything})\times B({}^3D_2(3836)\to J/\psi\pi^+\pi^-)$ is set at 12 pb in e^+e^- annihilations at 4.03 GeV.

TABLE I. Summary of $\psi(2S)$ cross section data.

Reaction	Number of $\psi(2S)$	Estimated ISR contrib.	Cross section or limit (pb) (95% C.L.)
ISR	107 ± 12	all	$592\pm61\pm68$
$^3D_2(3863)$	$1.7^{+3.2}_{-1.7}$	none	<12
$X\to\gamma\psi(2S)$	23.2 ± 5.8	16.9 ± 2.0	<107
$q\bar{q}g\to\psi(2S)X$	7.6 ± 3.0	5.0 ± 0.6	<117

C. Limit on $X\to\gamma\psi(2S)$

In this analysis it is assumed that the $\psi(2S)$ from unknown charmonium decays of the type $X\to\gamma\psi(2S)$ has a flat angular distribution in the lab frame. Candidate $\psi(2S)$ events are selected by requiring $|\cos\theta_{\psi(2S)}|<0.80$. Averaging over the e and μ modes, about 83% of the ISR $\psi(2S)$ events are rejected, and an efficiency of 80% for $X\to\gamma\psi(2S)$ is obtained. No momentum selection is made on the $\psi(2S)$ in order to maintain uniform detection efficiency for $X\to\gamma\psi(2S)$ for all possible X masses.

Background from ISR is estimated by assuming that all $\psi(2S)$ events in the $|\cos\theta_{\psi(2S)}|>0.80$ region are due to ISR; Fig. 2 is then used to estimate the ISR contribution to the region $|\cos\theta_{\psi(2S)}|<0.80$. The detection efficiency obtained from a simulation of the detector is found to be $(16.9\pm0.1)\%$, averaged over the e and μ modes.

The result is shown in Table I. A total of 23.2 ± 5.8 $\psi(2S)$ events satisfy the selection criteria, with an expected ISR background of 16.9 ± 2.0 events. A 95% C.L. upper limit for $\sigma(e^+e^-\to X+\text{anything})\times B(X\to\gamma\psi(2S))<107$ pb is set. In deriving this limit, the same systematic uncertainties described in Sec. V A have been taken into account.

D. Limit on $\psi(2S)$ from decays of metastable hybrids

A metastable hybrid, $q\bar{q}g$, would decay into a $\psi(2S)$ plus at least a pion [3]. The $\psi(2S)$ momentum is lower than that of the $\psi(2S)$ from ISR. In this search, it is required that $|\cos\theta_{\psi(2S)}|<0.80$ and $p_{\psi(2S)}<303$ MeV/c. The momentum cut is placed one standard deviation below the mean momentum of the ISR $\psi(2S)$. These cuts jointly reject about 95% of the ISR $\psi(2S)$. The overall detection efficiency for $q\bar{q}g\to\psi(2S)\pi^0$ is found to be $(7.6\pm0.1)\%$. This efficiency would be higher if an additional particle were present in the decay.

The results are listed in Table I. A total of 7.6 ± 3.0 $\psi(2S)$ events pass these cuts, with an expected background of 5.0 ± 0.6 from ISR, leading to an excess of $2.6^{+3.1}_{-2.6}$ $\psi(2S)$ events.

Correcting for detection efficiency and relevant branching fractions, the cross section $\sigma(e^+e^- \to q\overline{q}g) \times \mathrm{B}(q\overline{q}g \to \psi(2S)\mathrm{X})$ is found to be less than 117 pb at 95% C.L. Estimates of the systematic errors have been included in this limit.

E. Γ_{ee} of the $\psi(2S)$

After various possibilities have been considered, no evidence has been found for the production of $\psi(2S)$, other than by ISR. Assuming that the observed $\psi(2S)$ events are entirely due to the ISR production mechanism, Γ_{ee} of the $\psi(2S)$ can be extracted from the measured cross section. In the QED calculation, the ISR cross section is directly proportional to Γ_{ee} of the $\psi(2S)$. The value $\Gamma_{ee} = 2.07 \pm 0.32$ keV is determined, which is comparable in precision to the values 2.1 ± 0.3 keV and 2.0 ± 0.3 keV obtained by Mark I [9] and by DASP [10], respectively. The latter value has been corrected for radiative effects to 2.2 ± 0.3 keV by Alexander *et al.* [11], who then give the Mark I and DASP average, $\Gamma_{ee} = 2.14 \pm 0.21$ keV, which is the value reported in the PDG summary [7]. Combining this with the present measurement, a new world average of 2.12 ± 0.18 keV is obtained for Γ_{ee}. It should be noted that the value of Γ_{ee} obtained in this analysis corresponds to the left hand side of Eq. (9) of Ref. [11], i.e., it contains the factor $(1+\delta_{vp})$ representing the vacuum polarization corrections. All other QED corrections to second order have been explicitly included in the sampling function used to evaluate the luminosity contribution at mass value of the $\psi(2S)$.

VI. SUMMARY

Using BES data taken at the BEPC collider, a search has been performed for production of the $\psi(2S)$ in e^+e^- annihilations at a center-of-mass energy of 4.03 GeV. The kinematic features of the observed $\psi(2S)$ signal are consistent with its being exclusively produced from the initial state radiation process, for which the value $\sigma(e^+e^- \to \gamma\psi(2S)) = 592 \pm 61 \pm 68$ pb has been obtained. The following 95% C.L. upper limits have been obtained: $\sigma(e^+e^- \to {}^3D_2(3836) + \text{anything}) \times \mathrm{B}({}^3D_2(3836) \to J/\psi\pi^+\pi^-) > 12$pb, $\sigma(e^+e^- \to X + \text{anything}) \times \mathrm{B}(X \to \gamma\psi(2S)) < 107$ pb, where X is an unknown state, and $\sigma(e^+e^- \to q\overline{q}g) \times \mathrm{B}(q\overline{q}g \to \psi(2S) + \text{anything}) < 117$ pb for the production of metastable hybrids at 4.03 GeV. Using the measured ISR cross section, Γ_{ee} of the $\psi(2S)$ is determined to be 2.07 ± 0.32 keV.

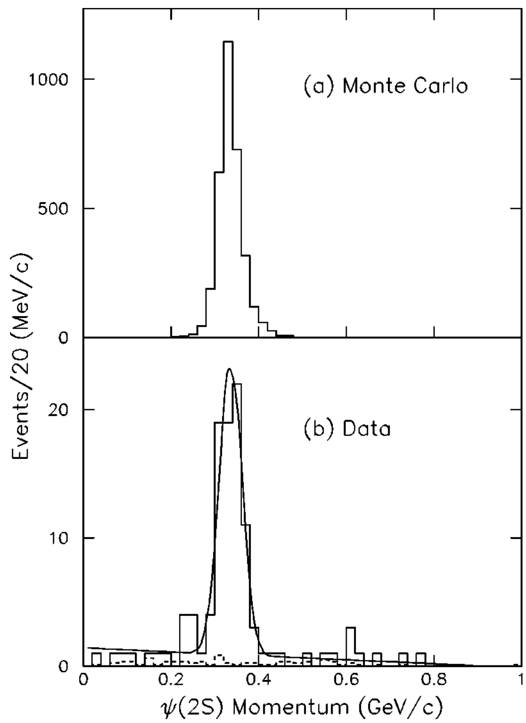

FIG. 3. (a) Simulated momentum distribution for $\psi(2S)$ produced via ISR; (b) the momentum distribution for reconstructed $\psi(2S)$ candidates (histogram), and the expected background distribution (dashed histogram) estimated using J/ψ side bands; the fit is to a Gaussian of rms deviation 26 MeV/c, above a linear background distribution.

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