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Production of Charmonium States in π^- Be Collisions at 515 GeV/c

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Abstract

We have studied the production of the charmonium states χ_{c1} and χ_{c2} in 515 GeV/c $\pi^- Be$ collisions in the Feynman-x range $0.1<x_F<0.8$. The χ_c states are observed through their radiative decays into J/ψ mesons. The resulting photons are reconstructed either as showers in the electromagnetic calorimeter or as e^+e^- pairs after conversion in the target and subsequent detection in the tracking system. The fraction of inclusive J/ψ production due to χ_{c1} and χ_{c2} decays is $0.443 \pm 0.041 \pm 0.035$. The ratio of the χ_{c1} to χ_{c2} cross section is $0.57 \pm 0.18 \pm 0.06$. Our results on J/ψ, ψ(2S), and χ_c production indicate that $0.454 \pm 0.044 \pm 0.042$ of the inclusive J/ψ's are produced directly.

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Studies of the production of charmonium states in hadron collisions provide important information on both perturbative and non-perturbative QCD. Recent advances in the understanding of quarkonium production have been stimulated by the unexpectedly large cross sections for J/ψ and $\psi(2S)$ direct production at large transverse momenta measured at the Fermilab Tevatron collider [1,2]. Three types of models have been used to describe charmonium formation [3]: the color-evaporation model [4,5]; the color-singlet model [6,7]; and the color-octet model [8,9]. In the color-evaporation model, the directly produced charmonium meson is not constrained to the same J^{PC} state as the $c\bar{c}$ pair produced in the hard scatter because of the emission of soft gluons during the meson's formation. In the color-singlet model, the charmonium meson retains the quantum numbers of the produced $c\bar{c}$ pair, and thus each J^{PC} state can only be directly produced via the corresponding hard scattering color-singlet sub-processes. The color-octet mechanism extends the color-singlet approach by taking into account the production of $c\bar{c}$ pairs in a color-octet configuration accompanied by a gluon. The color-octet state evolves into a color-singlet state via emission of a soft gluon. These models of charmonium formation lead to different expectations for the production rates of the charmonium states. This letter presents data on the production of these states in π^- nucleon collisions at a significantly higher $\sqrt{s}$ than previously available.

The experiment was carried out in the Fermilab Meson West beamline using a large-aperture, open-geometry spectrometer with the capability of studying high-mass muon pairs [10,11]. Data were collected with a 515 GeV/c beam incident on beryllium and copper targets. Only $\pi^- Be$ interactions, which represent 85% of the dimuon triggers, corresponding to an integrated luminosity of 7.5 pb^{-1} per nucleon, are discussed in this letter. The opposite-sign dimuon invariant mass distribution from this sample is shown in Fig. 1. A fit to this distribution yields $7750 \pm 90 \pm 60$ J/ψ mesons (here and elsewhere in this paper the first uncertainty is statistical and the second is systematic) with a FWHM mass resolution of 130 MeV/c^2 [12]. The J/ψ mass obtained from this fit is 3.0975 ± 0.0003 GeV/c^2. J/ψ candidates were defined as opposite sign dimuons with invariant mass between 2.9 GeV/c^2 and 3.3 GeV/c^2 coming from a primary vertex in the Be target, and having Feynman-x in the range $0.1<x_F<0.8$. The average x_F of the observed J/ψ's was 0.33.

We have examined events containing J/ψ's and γ's to search for radiative χ_c decays. Two independent methods were used to detect γ's in our spectrometer: (*i*) showers reconstructed in the electromagnetic liquid argon calorimeter (EMLAC), and (*ii*) converted γ's reconstructed as low-mass pairs of opposite-sign tracks in the charged particle tracking system.

In the first method, γ's were defined to be showers in the EMLAC with at least 20% of their energy in its front section and no associated charged track within a 1.5 cm radius around the shower location at the front face of the calorimeter. To further reduce background, only γ's with energy $>$10 GeV were considered. Acceptances and reconstruction efficiencies for χ_c decays were determined via GEANT-based Monte Carlo simulations. The generated x_F and p_T distributions for the charmonium states were based on our measured distributions for inclusive J/ψ's [10]. For events with accepted J/ψ's, the detection probabilities (including the 10 GeV γ energy cut) were 11.1% and 11.8% for γ's from χ_{c1} and χ_{c2} states, respectively.

The $J/\psi\gamma$ mass spectrum, shown in Fig. 2(a), was calculated by adding the nominal J/ψ mass to the mass difference between the $\mu^+\mu^-\gamma$ and $\mu^+\mu^-$ systems. The χ_c mass region was defined as 3.40 GeV/c^2 to 3.64 GeV/c^2. The initial background shape was obtained by combining γ's with J/ψ's from different events, normalized using the mass spectrum above the signal region. To make allowances for the presence of χ_c's in our data, γ's which originally formed a $J/\psi\gamma$ combination in the χ_c mass region were weighted by the probability that they were not from χ_c decays. This procedure was iterated, with the probability at each step based upon the observed signal to background ratio from the previous iteration [13]. A clear excess of combinations is observed above this background in the χ_c mass region. We interpret this excess as evidence for the production and radiative decay of the $\chi_{c1}(3510)$ and $\chi_{c2}(3555)$ states.

The χ_c yield was measured using an un-binned maximum-likelihood fit to the mass spectrum employing signal shapes obtained from the Monte Carlo simulation (centered at the nominal χ_c masses [14]) and the background shape. The numbers of χ_{c1}, χ_{c2}, and background combinations were allowed to vary while small contributions from χ_{c0} and $\psi(2S)$ were fixed at their expected values [15]. The fit assigned 196±45 and 183±48 combinations to the χ_{c1} and χ_{c2} states, respectively. The curves calculated using the fitted number of χ_c states and their simulated mass resolutions, shown in Fig. 2(b), describe the background subtracted mass spectrum very well. The average x_F of the observed $J/\psi\gamma$ combinations in the χ_c mass band is 0.31.

Correcting for detection probabilities and normalizing to the number of observed J/ψ's, we determine that the fraction of J/ψ's attributable to χ_{c1} and χ_{c2} decay (f_χ) is $0.429 \pm 0.047 \pm 0.046$. The main contributors to the systematic uncertainty are the sensitivity to the γ energy cut (8%), the background shape (5%), and the χ_c production model (3%). Using the Particle Data Group (PDG) branching ratios, the ratio of the χ_c cross sections ($\sigma_{\chi_c1}/\sigma_{\chi_c2}$) is $0.56 \pm 0.27 \pm 0.11$. The systematic uncertainty in this ratio due to detection efficiency is negligible, while the contribution due to sensitivity to the γ energy cut combined with the mass resolution and background shape uncertainties is 17%. There is an additional 10% uncertainty due to the branching ratios, and a 4% uncertainty due to the χ_c production model.

In the second method, we searched for J/ψ events with e^+e^- pairs resulting from γ conversions in the target region. Due to its small opening angle, a conversion pair appears as a single track (or two closely spaced tracks) in the silicon-strip detectors upstream of the dipole magnet. The dipole separates the particles by bending them primarily in the XZ-plane, and the particles are subsequently detected in wire chambers located downstream of the magnet. Pairs of oppositely charged tracks that have projected downstream segments within 0.5 cm of each other in both X and Y coordinates at the magnet center, and downstream YZ slopes agreeing within 0.005, were defined as γ conversion pairs.

The resultant $J/\psi\gamma$ mass distribution is shown in Fig. 3. Distinct peaks corresponding to the χ_{c1} and χ_{c2} are apparent. The background shape and the χ_c signals were evaluated via the methods used for the EMLAC analysis described above [15]. The maximum-likelihood fit gives 56±13 χ_{c1} combinations and 49±13 χ_{c2} combinations. The average x_F of the observed

$J/\psi\gamma$ combinations within the χ_{c1} and χ_{c2} mass bands is 0.37.

The detection probability for e^+e^- pairs from χ_c states was determined using the Monte Carlo simulation described previously. The conversion probability for each simulated γ was calculated from the materials in our apparatus and has an average of 7.2%. The detection probabilities for an e^+e^- pair (including the conversion probability) are 2.8% and 2.9% for χ_{c1} and χ_{c2} events, respectively. Correcting the number of χ_c's by these efficiencies and the relevant branching ratios gives: $f_\chi = 0.470 \pm 0.080 \pm 0.050$ and $\sigma_{\chi_c 1}/\sigma_{\chi_c 2} = 0.58 \pm 0.23 \pm 0.06$. The main contributors to the systematic uncertainty for f_χ are the reconstruction efficiency (8%), the background shape (3%), the γ conversion probability (3%), and the χ_c production model (3%). The main contributors to the systematic uncertainty for $\sigma_{\chi_c 1}/\sigma_{\chi_c 2}$ are the branching ratios (10%), the χ_c production model (4%), and the mass scale calibration (3%).

A combined fit of the results from both χ_c detection methods yields $f_\chi = 0.443 \pm 0.041 \pm 0.035$ for the fraction of the inclusive J/ψ cross section due to χ_{c1} and χ_{c2} decays, with $0.237 \pm 0.038 \pm 0.019$ due to χ_{c1}, and $0.206 \pm 0.036 \pm 0.016$ due to χ_{c2}. The combined fit gives $\sigma_{\chi_c 1}/\sigma_{\chi_c 2} = 0.57 \pm 0.18 \pm 0.06$. These measurements, and results obtained in previous experiments with incident π^- [16–19], are shown versus $\sqrt{s}$ in Fig. 4. There is no significant dependence of either quantity on $\sqrt{s}$, which is consistent with the color-evaporation model prediction. A comparable value for f_χ is also observed in fixed target experiments using proton beams [5] and at the Tevatron $p\bar{p}$ collider (for J/ψ's from sources other than b-quark decay) [1,2]. The insensitivity of f_χ to incident particle type is another successful prediction of the color-evaporation model.

Combining the fraction of J/ψ's from χ_c, the J/ψ's due to $\psi(2S)$ decay ($0.083 \pm 0.017 \pm 0.013$ as measured by this experiment [10]), and assuming 0.02 ± 0.02(sys) of the J/ψ's are from χ_{c0} decay [7], the remaining fraction of $0.454 \pm 0.044 \pm 0.042$ can be attributed to direct J/ψ production. The fraction of J/ψ's due to b-quark decay has been determined to be negligible (< 0.005) in this same data sample [20].

The cross sections for the individual charmonium states are given by $\sigma = f\sigma(J/\psi)/B$, where $\sigma(J/\psi)$ is the inclusive J/ψ cross section, f is the fraction of J/ψ's due to the given charmonium state, and B is the branching ratio for that state into J/ψ. $\sigma(J/\psi)$ was derived from our measurement of $B(J/\psi \to \mu^+\mu^-)\sigma(\pi^- Be \to J/\psi + X)/A = (12.9 \pm 0.2 \pm 1.6)$ nb/nucleon in the $x_F > 0$ range [10], assuming an A^α atomic mass dependence, where $\alpha = 0.90 \pm 0.02$ [7,21]. The cross sections for χ_{c1}, χ_{c2}, $\psi(2S)$, and direct J/ψ production are shown in Table I, together with the predictions of a color-singlet model [22]. While the observed fractions are accommodated by this model (when extreme values of K factors are included), the predicted direct and inclusive J/ψ yields are smaller than our measurements. The cross sections cannot be calculated using the color-evaporation model. However, expectations for the ratios of χ_c to direct J/ψ production are $\sigma(\chi_{c1})/\sigma(direct\ J/\psi) \approx 1.0$ and $\sigma(\chi_{c2})/\sigma(direct\ J/\psi) \approx 1.7$ [3,4] respectively, which are smaller than our measurements of $1.9 \pm 0.5 \pm 0.3$ and $3.4 \pm 0.9 \pm 0.5$. A color-octet model calculation of the inclusive forward J/ψ production cross section yields 240 to 280 nb, in excellent agreement with our measurement of $269 \pm 4 \pm 35$ nb [9]. The expected χ_c contributions are, however, smaller than those found in the data [9]. None of these three models reproduce all of the features observed by fixed target experiments. Our measurements at the highest π^- beam energy should thus contribute to the development of a more self-consistent description of charmonium production at both fixed target and Tevatron energies.

We dedicate this letter to the memories of our deceased colleagues Sy Margulies and Roman Sulyaev. We gratefully acknowledge the efforts of Fermilab's staff. This work was supported by the U.S. Department of Energy, the National Science Foundation, and the Russian Ministries of Science and Atomic Energy.

TABLES

TABLE I. Charmonium mesons detected in this experiment; the PDG branching ratios for the relevant modes B; the fractions of inclusive J/ψ production due to the charmonium states f; and the cross sections for $x_F > 0$ for π^-N interactions at 515 GeV/c compared with predictions of a color-singlet model. We have assumed that 0.02±0.02(sys) of J/ψ's are attributable to χ_{c0} decay.

Meson	Decay mode	B [14]	f	σ (nb) this exp.	σ (nb) theory [22]
inclusive J/ψ	$\mu^+\mu^-$	0.0597	1.0	$269 \pm 4 \pm 35$	133-180
χ_{c1}	$J/\psi\gamma$	0.273	$0.237 \pm 0.038 \pm 0.019$	$234 \pm 38 \pm 39$	79-158
χ_{c2}	$J/\psi\gamma$	0.135	$0.206 \pm 0.036 \pm 0.016$	$410 \pm 72 \pm 72$	315
ψ(2S) [10]	$J/\psi\pi^+\pi^-$	0.324	$0.083 \pm 0.017 \pm 0.013$		
ψ(2S)	J/ψX	0.57		$39 \pm 8 \pm 7$	14-25
direct J/ψ			$0.454 \pm 0.044 \pm 0.042$	$122 \pm 12 \pm 20$	59-77

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[13] The background shapes obtained without making this weighting correction result in a 4% (5%) decrease in the number of χ_c observed via showers in the EMLAC (via the converted γ method).

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[15] The contribution due to χ_{c0} decay was evaluated based upon a theoretical cross section estimate [22]. The contributions from $\psi(2S)$ decays into $J/\psi\pi^0\pi^0$, $J/\psi\eta$, and $\chi_c\gamma$ were determined from our measured $\psi(2S)$ cross section [10]. For the EMLAC analysis, the expected contributions are 9 and 20 combinations from χ_{c0} and $\psi(2S)$ decays, respectively. The corresponding numbers for the e^+e^- mode are 2 and 5 combinations.

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[22] Values are from Ref. [7]. Charmonium fractions are from Fig. 21 with the scale $\mu = M$ and the MRSD0' pdfs. Cross sections are determined using the inclusive J/ψ cross section from Fig. 22 for normalization. The larger values include the K factors described in Eq. 214 of Ref. [7].

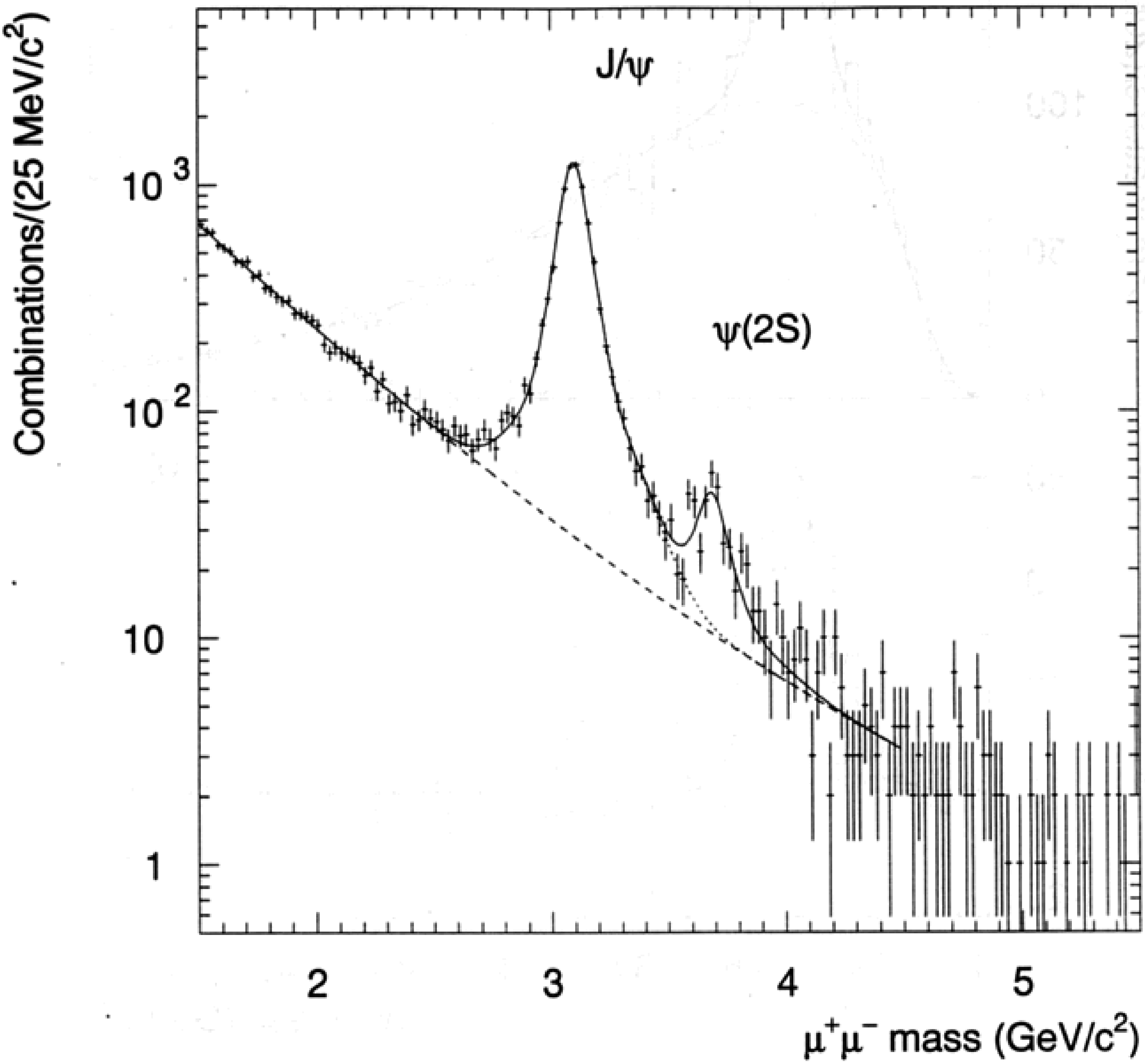

FIG. 1. Invariant mass distribution for $\mu^+\mu^-$ pairs in the J/ψ mass region. The solid curve is a fit to the data; the dotted curve shows the J/ψ contribution, and the dashed curve shows the background contribution.

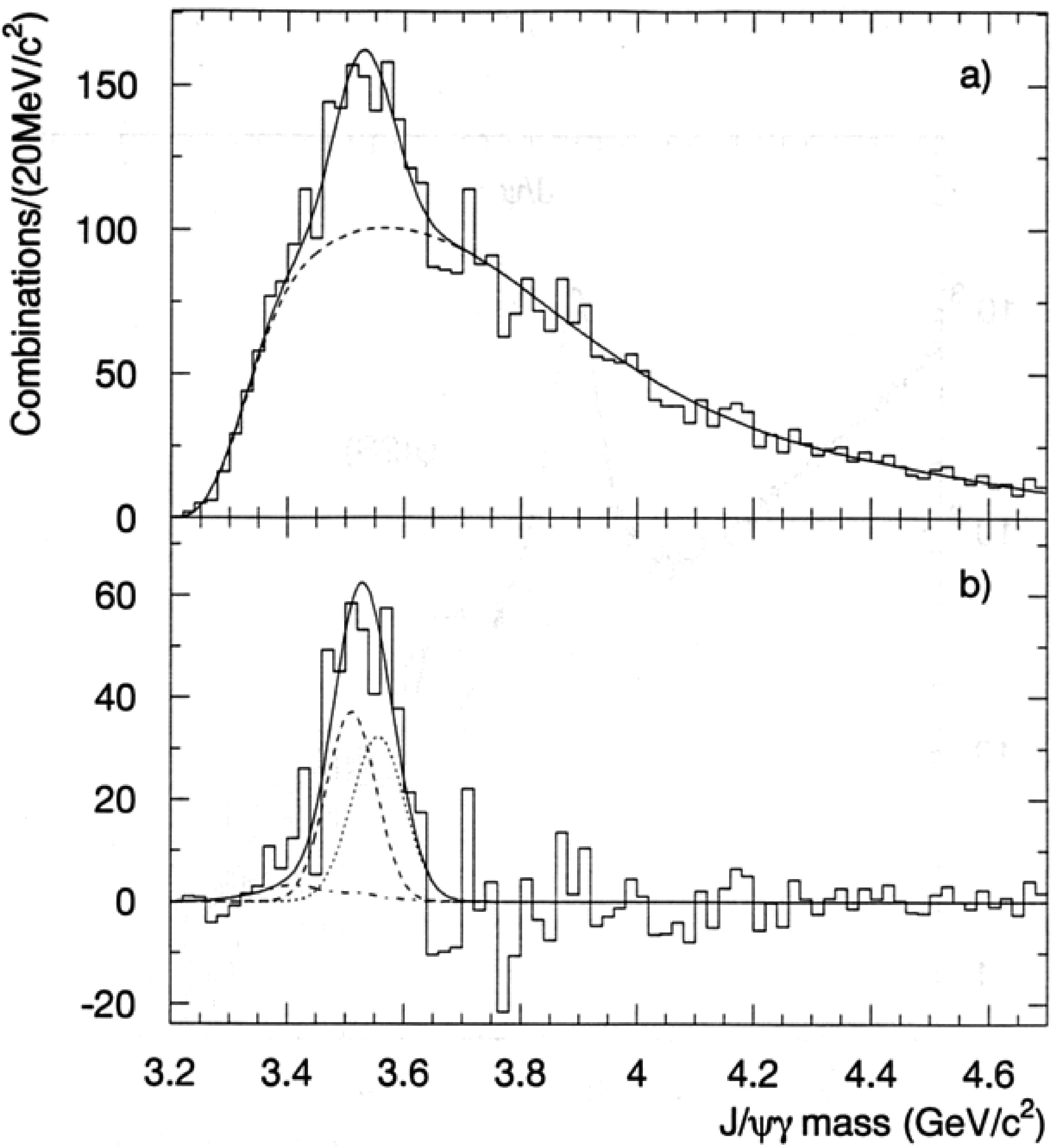

FIG. 2. $J/\psi\gamma$ invariant mass for γ's detected in the EMLAC: (a) the solid curve shows the fit to the signals and background, the dashed curve illustrates the background contribution; (b) the background subtracted data and signals (solid curve), and the estimated contributions from χ_{c0} and $\psi(2S)$ (dot-dash), χ_{c1}(dash), and χ_{c2}(dot).

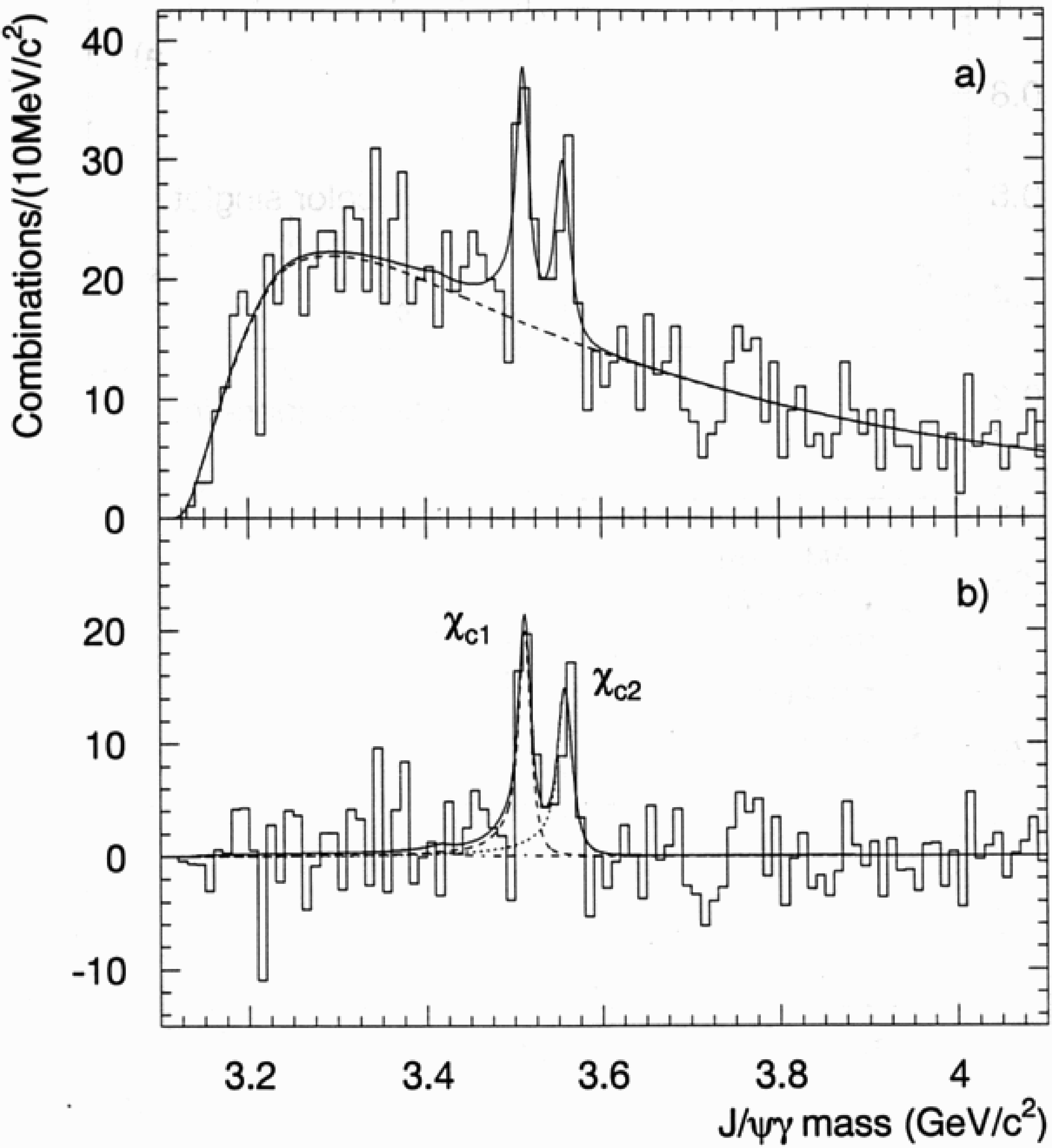

FIG. 3. $J/\psi\gamma$ invariant mass for γ's detected through conversions into e^+e^- pairs: (a) the solid curve shows the fit to the signals and background, the dashed curve shows the background contribution; (b) the background subtracted data and estimated contributions from χ_{c0} and $\psi(2S)$ (dot-dash), χ_{c1}(dash), and χ_{c2}(dot).

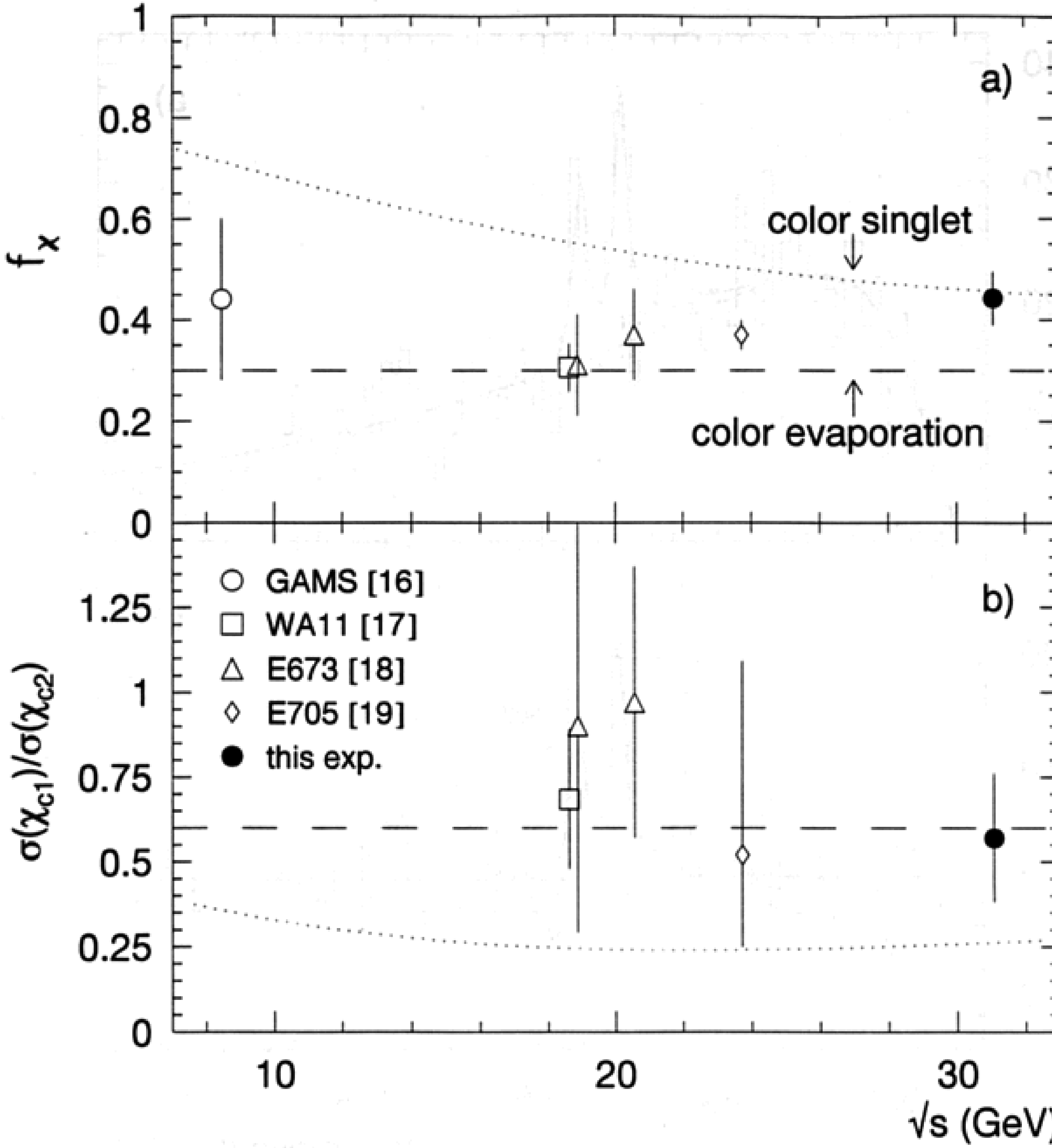

FIG. 4. Dependence of (a) the fraction of J/ψ's coming from χ_c decays, and (b) the ratio of χ_{c1} to χ_{c2} cross sections, on the π^--nucleon center of mass energy. The error bars represent statistical and systematic uncertainties added in quadrature. Dashed lines show predictions of a color-evaporation model[3,4], dotted curves show predictions of a color-singlet model by Schuler (without K factors)[20].