Measurement of ψ' Production in e^+e^- Annihilations at 4.03 GeV

The BES Collaboration

Abstract

Using the BES detector operated at the Beijing Electron Positron Collider (BEPC), we have investigated the production mechanisms of the ψ' in e^+e^- annihilations at a center-of-mass energy of 4.03 GeV. The kinematic features of the ψ' signal are consistent with being exclusively produced from initial state radiation (ISR) with the emission of an energetic photon. Limits are placed on ψ' from decays of unknown charmonia or metastable hybrids that might be produced in e^+e^- annihilations at 4.03 GeV.

Preliminary Result

1 Introduction

In e^+e^- annihilations at a center of mass energy of 4.03 GeV the ψ' charmonium can be produced via

(1) initial state radiation (ISR) of photon by e^+ or e^-, followed by $e^+e^- \to \psi'$,

(2) $e^+e^- \to \pi^0\psi'$, where the π^0 can be produced in the hadronization of $c\overline{c}$ into $\psi'\pi^0$, or in two photon process where $\gamma\gamma$ couple to a π^0,

(3) decays of charmonium states more massive than ψ', and

(4) decays of possible metastable hybrids ($q\overline{q}g$) produced in e^+e^- annihilations at 4.03 GeV.

Reactions (1) is well described by QED and is expected to be dominant. Process (2) proceeds through two virtual photons or isospine violating hadronic interactions and is expected to be suppressed relative to (1). In principle, the ψ' can be produced in the decays of heavier charmonia that can be produced in e^+e^- annihilations at 4.03 GeV, process (3). However there is no such known charmonium that can be produced kinematically at this energy. Unless there is a new charmonium state, such as χ_c', produced in the e^+e^- annihilation at this 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 [2] to explain the ψ' anomaly [3] observed in $p\overline{p}$ collisions at the Tevatron. It is very interesting to search for these metastable hybrids via reaction (4), which experimentally can be probed by searching for excess ψ' in e^+e^- collisions.

In this paper, we report on a study of the production mechanisms of ψ' in e^+e^- collision using the BES data taken at 4.03 GeV at the BEPC e^+e^- collider. We search for processes (3) and (4) by measuring the excess of ψ' events above the QED prediction. The relatively low center of mass energy above the ψ' threshold should constrain reactions (1) — (4) to be low charged multiplicity events. Therefore ψ' containing events at this energy are expected to have very distinctive kinematic features and can be separated from other events.

The following sections describe the BES detector, identification of electrons and muons, the reconstruction of J/ψ and ψ', a study of the kinematic features and production rate of the ψ' and limits on the production of ψ' from reactions (3) and (4).

2 The BES detector and event selection

The BES detector has been detailed in [4]. Here we briefly describe detector elements crucial to this measurement.

Tracking is provided by a 10 superlayer main drift chamber (MDC) inside a 0.4 T magnetic field. Each superlayer contains four layers of sense wires measuring both the position and the ionization energy loss (dE/dx) of charged particles. The magnetic coil is surrounded by a time-of-flight counter array (TOF) and an electromagnetic calorimeter (ECAL) composed of streamer tubes and lead blocks with a z position resolution of 4 cm. The muon detector system lies outside of the ECAL and consists of four layers of streamer tubes, measuring 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 during the 1992, 1993 and 1994 runs. A data sample of 22.3 pb^{-1} was collected in $\mathrm{e}^+\mathrm{e}^-$ annihilations at a center-of-mass energy of 4.03 GeV. The BES trigger conditions, and the criteria for the selection of hadronic events have been described elsewhere [5].

3 Reconstruction of the ψ'

Additional selections are imposed on the BES hadronic events in this analysis. Charged tracks must satisfy:

(1) good charged tracks having more than 10 drift chamber hits used in track fit,

(2) $|\cos\theta| < 0.90$,

(3) $\mathrm{p_{xy}} > 0.050$ GeV/c and $\mathrm{p} < 2.0$ GeV/c,

(4) $\mathrm{d_0}$ <5 cm and $|\mathrm{z_0}| < 20$ cm,

(5) $|\cos\theta_\ell| < 0.90$,

where θ is the azimuthal angle of any charged track, p and $\mathrm{p_{xy}}$ are track momentum and its component on the xy plane, $\mathrm{d_0}$ and $\mathrm{z_0}$ are distances at closest approach on the xy plane and in the z direction, respectively, and θ_ℓ is the helicity angle of the ℓ^+ in the di-lepton rest frame. Events containing two (four) or more charged tracks are searched for J/ψ (ψ').

3.1 Selection of Electrons and Muons

Three detector components, the main drift chamber, the TOF, and the shower counters, are used for electron identification. The $\mathrm{dE}/\mathrm{d}x$ and TOF measurements of the charged tracks must be consistent with those of an electron. The E/p variable, where E is the total shower energy deposited by the charged track in the shower counters, is required to be within a range about 1.0. The range is extracted from a sample of radiative Bhabha events and depends on the momentum of the track. The efficiency for electron identification is about 85% above a momentum of 0.400 GeV/c.

Muons are identified using muon counter hits only. Generally an identified muon must match three hits in the muon chambers, among which at least one is a good muon hit. For tracks with transverse momenta ($\mathrm{p_{xy}}$) greater than 0.75 GeV/c, two good muon hits have to be matched. Above a transverse momentum of 0.95 GeV/c, all three muon hits need to be classified as good. 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 is determined to be 85% for p>0.8 GeV/c with a hadron fake rate of 4%.

3.2 Reconstruction of J/ψ and ψ'

The J/ψ is searched via its decay J/$\psi \to \mu^+\mu^-$. The invariant mass of oppositely charged muons with $\chi^2_+ + \chi^2_- < 9.0$ are calculated, where χ^2_+ and χ^2_- are the normalized chisquare of track fit of the negative and positive charged muons. The resulting distribution is shown in Figure 1, where a J/$\psi \to \mu^-\mu^+$ signal is observed. A fit is performed to the invariant mass with a signal Gaussian of a r.m.s. width of 61 MeV/c^2 as obtained from high statistics ψ' data above a 2nd order polynomial background. The fit estimates a total of 158$\pm$16 J/ψ events with a mass of 3098.2$\pm$7.2 MeV/c^2, agreeing well with the world average [1] of 3096.88$\pm$0.04 MeV/c^2.

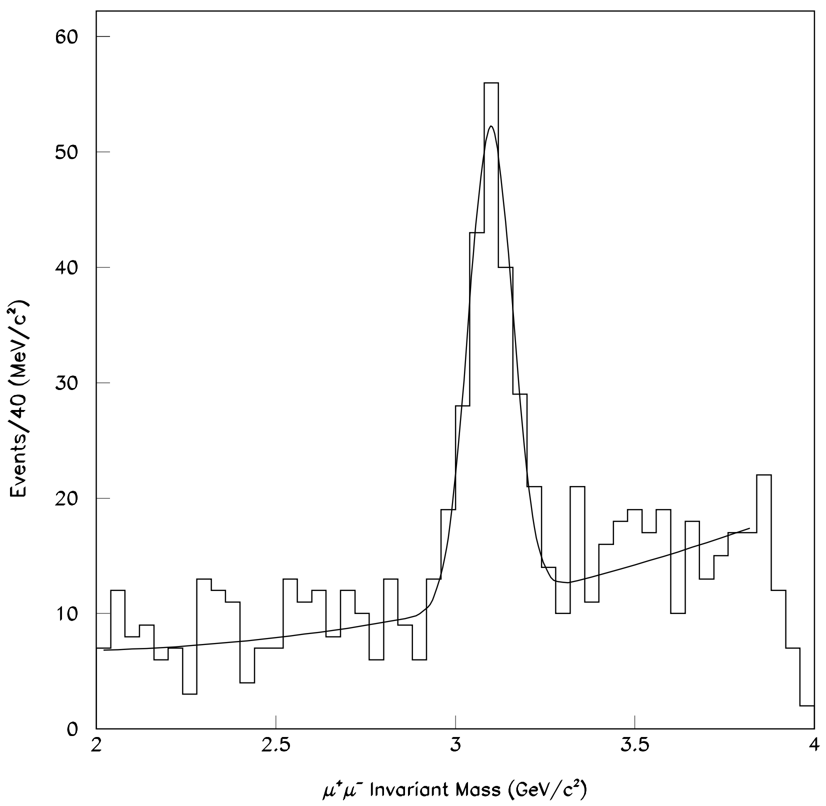

Figure 1: Invariant mass distribution of selected $\mu^+\mu^-$ pairs.

The ψ' is reconstructed in the decay $\psi' \to$ J/$\psi\pi^+\pi^-$, where J/$\psi \to \mu^+\mu^-$ or $\to e^+e^-$. The same joint track quality criterion required on the $\mu^+\mu^-$ is also applied to the e^+e^-. The J/ψ candidates, events with di-lepton invariant mass within $\pm$150 MeV/c^2 of the fitted J/ψ mass in Figure 1, are combined with a pair of oppositely charged tracks which are consistent with pions according to dE/dx and TOF measurements. The invariant mass differences between $\ell^+\ell^-\pi^+\pi^-$ and $\ell^+\ell^-$ are shown in Figure 2 for the two decay channels. The small mass difference between the ψ' and the J/ψ allows for a large cancellation of common measurement errors on the lepton momenta to reduce the mass resolution to ~6.5 MeV/c^2. Clear ψ' signals are reconstructed in both e and μ channels. We fit the distribution in Figure 2 to a signal Gaussian on a smooth polynomial background to find the center of the peak to be 588±1 MeV/c^2, in good agreement with the world average of 589.1±0.1 MeV/c^2.

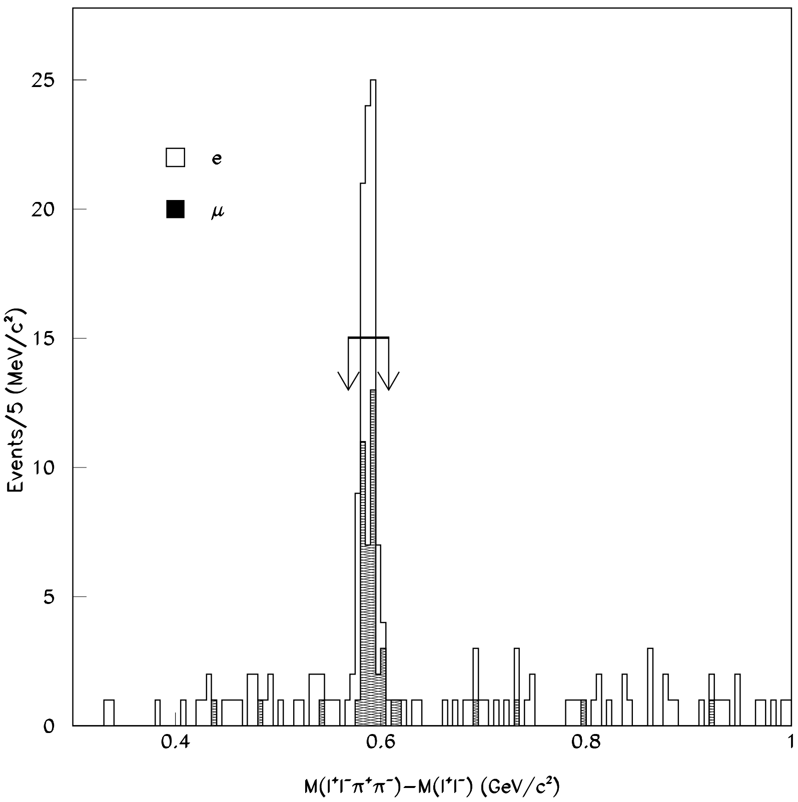

Figure 2: The invariant mass difference between $\ell^+\ell^-\pi^+\pi^-$ and $\ell^+\ell^-$, where ℓ = e (open histogram) or μ (hatched histogram).

To estimate the number of ψ' events, we define the region 568.5 - 607.5 MeV/c^2 as the ψ' signal area, as shown in Figure 2. For the muon mode, Monte Carlo simulation and studies of ψ' data show that there is no combinatorial background in the mode, and that events away from the ψ' signal region are genuine ψ' decays that are mis-reconstructed. We simply count the number of events in the signal region as the signal and find 37±6 ψ' events. A ±4% systematic error is assigned to the ψ' signal as estimated this way. For the electron mode, two background regions 450.0 - 555.5 MeV/c^2 and 620.5 - 750 MeV/c^2 are chosen to estimate the background events in the ψ' region. There are 56 events inside the signal area and 35 events in the background band. Correcting for the difference in areas, we estimate 50.2±7.5 ψ' events in the electron mode. Combining the μ and e modes, we reconstruct 87.2±9.6±4.0 ψ' events in Figure 2, where the first error is statistical and the second is the systematic error due to the method used for background estimate.

4 Kinematic distributions of the ψ' signal

4.1 Monte Carlo simulations

The reconstruction efficiencies for J/ψ and ψ' are estimated from a Monte Carlo simulation of the BES detector, subjected to the identical reconstruction procedure used in BES offline. The ISR $e^+e^- \to \gamma\psi'$ events are generated at a center-of-mass of 4.03 GeV, with the ψ' azimuthal angle distribution tuned to match that of the initial radiative Bhabha described in [6]. Other types of events are generated assuming a uniform angular distribution around the electron direction. The detection efficiencies for J/ψ and ψ' are calculated based on these different charmonium production mechanisms and are summaried in Table 1, where the errors are statistical only. The efficiencies do not vary among these models. The average of the estimated efficiencies are used for the calculation of production rates.

Table 1. Estimated reconstruction efficiencies of J/ψ and ψ'

Decay Mode	$e^+e^- \to \psi'\gamma$ ISR	$e^+e^- \to \psi'\pi^0$	Average
$J/\psi \to e^+e^-$	0.326±0.004	0.333±0.008	0.330±0.005
$J/\psi \to \mu^+\mu^-$	0.301±0.004	0.294±0.005	0.298±0.003
$\psi' \to J/\psi\pi^+\pi^-$ $J/\psi \to e^+e^-$	0.189±0.005	0.186±0.005	0.188±0.003
$\psi' \to J/\psi\pi^+\pi^-$ $J/\psi \to \mu^+\mu^-$	0.161±0.003	0.161±0.004	0.161±0.003

4.2 Kinematic features of the ψ'

Reactions in (1) - (4) have some unique distributions. Figure 3.a shows the $\cos\theta_{\psi'}$ distribution as predicted by QED for the ISR ψ' , where $\theta_{\psi'}$ is the angle between the ψ' and the positron direction. The ISR ψ's peak sharply in the forward and backward directions. For other interactions (2) — (4) this angular distribution is expected to be rather uniform.

Reaction (1) results in a simple two body final state, where the ψ' momenta, as shown in Figure 4.a, forms a narrow peak centered at 329 MeV/c with the width entirely due to experimental resolution. The momenta of ψ' particles from processes such as $e^+e^- \to \psi'\pi^0$ peak at a lower value of 303 MeV/c. This important difference in momentum provides a crucial separation between (1), the dominant source of ψ', and (3) and (4), the interesting physics that we wish to search for.

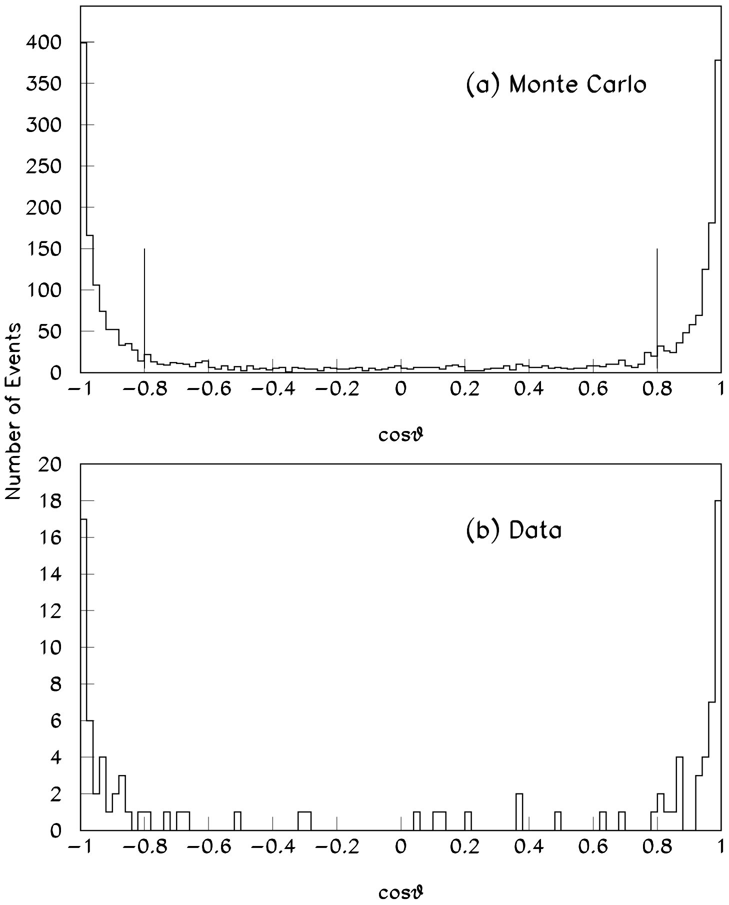

Figure 3: (a) Distribution of $\cos\theta$ of the ISR ψ' predicted by QED, and (b) $\cos\theta$ of ψ' candidates selected in the data.

For the electron channel, the ψ' momentum resolution suffers from radiative energy loss of the e's in the detector and is significantly worse than that of the ψ's reconstructed in the muon channel. To compensate for this energy loss, a 2-C kinematic fit is performed on the ψ' 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 $M_{\psi'}$ (3.686 GeV/c^2), respectively. This 2-C fit improves the momentum resolutions of the J/ψ and ψ', and enhances the separations between the various interactions based on the momenta of the charmonia. Monte Carlo simulation shows that the r.m.s. width of the ψ' momentum distribution is reduced by 17%. The improved momentum resolution for the electron channel is compatible with that of the muon channel. The combined r.m.s. width of the ψ' momentum is 28 MeV/c. Thereafter the ψ' reconstructed with e, μ data are treated together.

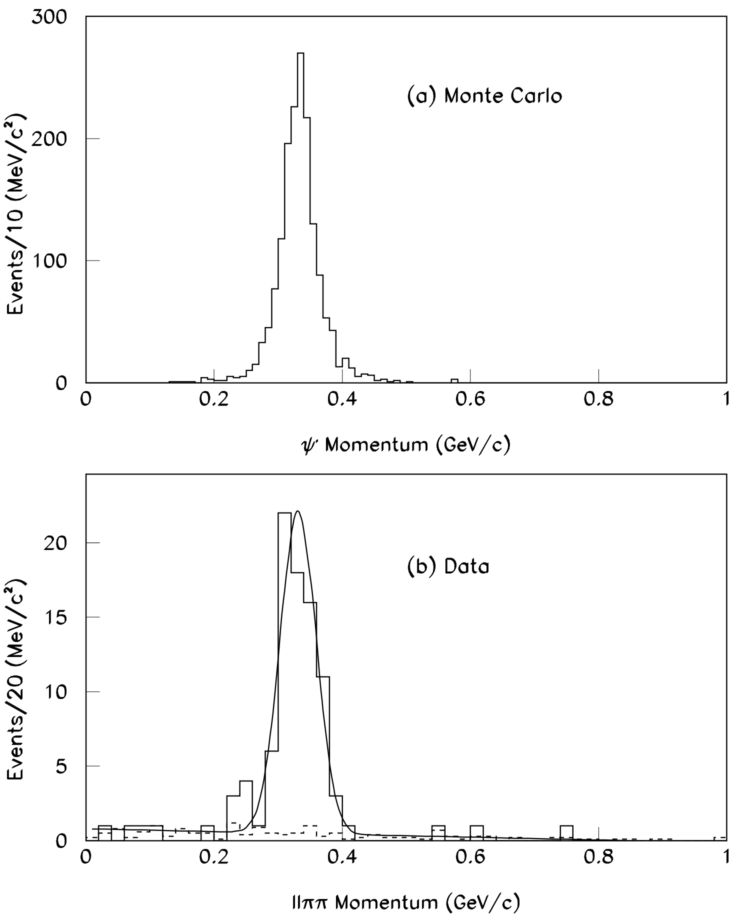

Figure 4: (a)Simulated momentum distribution of the ψ' produced in ISR, and (b) Momenta of reconstructed ψ' candidates (open histogram) and expected background shape (dashed histogram) extimated using J/ψ side bands. The fit is a Gaussian with a fixed width of 28 MeV/c, above a linear background distribution.

The $\cos\theta$ and $p_{\psi'}$ distributions of the events in the ψ' signal area are shown in Figure 3.b and Figure 4.b, respectively. The $\cos\theta_{psi'}$ distribution in Figure 3.b follows closely that of the ISR distribution. A fit is performed to the $p_{\psi'}$ spectrum in Figure 4.b which finds the peak of the Gaussian to be at 330.7$\pm$3.7 MeV/c, in excellent agreement with the expectation of 329 MeV/c a two body final state $e^+e^- \rightarrow \gamma\psi'$. These kinematic features show that the ψ' signal is consistent with being entirely produced via reaction (1).

5 J/ψ and ψ' production rates

5.1 Inclusive J/ψ, ψ' production rates

To determine their inclusive production rates, J/ψ and ψ' signals in Figures 1 and 2 are corrected for reconstruction efficiencies and the decay branching fractions of the mode studied. The branching fractions [1] Br($\psi' \to J/\psi \pi^+\pi^-$) = (32.4$\pm$2.6)%, Br(J/$\psi \to e^+e^-$) = (5.99$\pm$0.25)%, and Br(J/$\psi \to \mu^+\mu^-$) = (5.97$\pm$0.25)% have been used. We obtain

$$\sigma(e^+e^- \to J/\psi X) = 398\pm40\pm58 \text{ pb, and}$$
$$\sigma(e^+e^- \to \psi' X) = 571\pm63\pm71 \text{ pb}$$

in e^+e^- annihilations at 4.03 GeV. The latter is an average of e and μ channels. The second errors are systematic errors arising from uncertainties in the muon identification ($\pm$10%), determination of signal events ($\pm$4.7%), luminosity ($\pm$0.9 pb^{-1}), detection efficiency ($\pm$4%), and errors on the relevant J/ψ and ψ' branching ratios. An extra $\pm$5% systematic error is assigned to $\sigma(e^+e^- \to J/\psi X)$ to account for the tail which has been observed in the di-muon mass spectrum of the ψ' data.

Using Br($\psi' \to J/\psi X$) = 0.57$\pm$0.04, we expect 326$\pm$59 pb of $\sigma(e^+e^- \to J/\psi X)$ to be attributed to the decays of the ψ'. We have also searched directly for the initial state radiative reaction $e^+e^- \to \gamma J/\psi$ by demanding the di-muon momentum to be between 765 - 885 MeV/c which corresponds to a $\pm2\sigma$ window around the monochromatic J/ψ produced in this reaction. We find 10.3$\pm$4.3 J/ψ events, which translate into a cross section of $\sigma(e^+e^- \to \gamma J/\psi)$=33.3$\pm$13.9$\pm$4.2 pb, where the errors are statistical and systematic, respectively. Decays of ψ' and ISR production of J/ψ together contribute to (90^{+10}_{-18})% of the measured J/ψ production cross section.

5.2 Limit a new charmonium decaying into J/$\psi\pi^+\pi^-$

We have searched for a new $3D_2$ charmonium state with a mass of 3.836 GeV/c^2 which has been reported in the mode $\psi' \to J/\psi\pi^+\pi^-$ [7]. The selection is identical to that used in the ψ' reconstruction. This charmonium should be observed in Figure 2 around 736.4 MeV/c^2 if the production cross section and branching fraction are sufficiently large. We do not observe enhencement at this mass in Figure 2. The mass region 707.3 - 765.5 MeV/c^2 is considered as the signal region which corresponds to a $\pm3\sigma$ mass window surrounding the expected mass for the reported charmonium. The detection efficiency is identical to that of the ψ'. A total of 8 events fall within this mass region, translating into a 95% C. L. limit of $\sigma(e^+e^- \to 3D_2(3836) + \text{anything}) \cdot B(3D_2(3836) \to J/\psi\pi^+\pi^-) <38$ pb.

5.3 Limit on $X \to \gamma\psi'$

We assume in this analysis that the ψ' from possible unknown charmonium decays of the type $X \to \gamma\psi'$ also has a flat angular distribution in the lab frame. Candidate ψ' events must have exactly four charged tracks and are further selected by requiring $|\cos\theta_{\psi'}| <0.80$.

The cut rejects about 87% of the ISR ψ' events while having an efficiency of 80% for $X\rightarrow\gamma\psi'$. There is no momentum cut on the ψ' to maintain a constant detection efficiency for $X\rightarrow\gamma\psi'$ for all possible X masses. Background from ISR is estimated by assuming all ψ' events in the $|\cos\theta_{\psi'}|$ >0.80 region are entirely due to ISR, from which Figure 3 is used to estimate the ISR contribution to the region $|\cos\theta_{\psi'}|$ <0.80. The detection efficiency is obtained from a simulation of the detector and is found to be (13.4±0.4)%.

The result is shown in Table 2. A total of 19.3±4.7 ψ' events satisfy the selection criteria, with an expected ISR background of 12.6±1.7 events. A 95% C. L. limit of $\sigma(e^+e^- \rightarrow X + \text{anything})\cdot B(X \rightarrow \gamma\psi')$ <144 pb is set. In deriving this limit, we have included the systematic uncertainties due to lepton identification (±10%), the number of ψ' events (±4.7%), the total integrated luminosity used for the measurement (±4%), ψ' detection efficiency (±4%), and the Monte Carlo statistics (±1%).

5.4 Limit on ψ' from decays of possible metastable hybrids

A possible metastable hybrid $q\overline{q}g$ can decay into a ψ' plus at least a pion [2]. The ψ' momentum is lower than that of the ψ' from ISR. We require $|\cos\theta_{\psi'}|$ <0.80 and $p_{\psi/prime}$ <302.7 MeV/c, one standard deviation below the momentum of the ψ' from ISR. These cuts jointly reject about 95% of the ISR ψ's. The overall detection efficiency for $q\overline{q}g \rightarrow\psi'\pi^0$ is found to be (5.8±0.2)% . This efficiency is higher if an additional particle is present in the decay.

The results are listed in Table 2. We find 9.5±3.4 ψ' events after the selection, as shown in Figure 5, above an expected background of 3.5±0.7 from ISR. Correcting for detection efficiency and relevant branching ratios, we obtain $\sigma(e^+e^-\rightarrow q\overline{q}g)\cdot B(q\overline{q}g \rightarrow\psi' X) < 260$ pb at 95% C. L. We have included our estimates of the systematic errors in this limit.

Table 2. ψ' Events Reconstructed in Various Reactions

reactions	$N_{\psi'}$	estimated contrib. from ISR	efficiency	upper limits < (95% C. L.)
ISR	73.4±8.8		0.144±0.002	
$X \rightarrow \gamma\psi'$	19.3±4.7	12.6±1.7	0.134±0.004	144 pb
$q\overline{q}g \rightarrow\psi'$+ anything	9.5±3.4	3.5±0.7	0.058±0.002	260 pb

6 Summary

Using the BES data taken at the BEPC collider, we have investigated the production mechanisms and measured inclusive production rate of the ψ' in e^+e^- annihilations at a center-of-mass energy 4.03 GeV. About 90% of the J/ψ events at this energy are found to be from the cascade decays of the ψ'. The kinematic features of the ψ' signal are consistent with being exclusively produced from initial state radiation (ISR). We have set 95% C.

L. limits of $\sigma(e^+e^- \rightarrow X + \text{anything}) \cdot B(X \rightarrow \gamma\psi')$ <144 pb, where X is an unknown charmonium, and $\sigma(e^+e^-\rightarrow q\overline{q}g)\cdot$ B($q\overline{q}g \rightarrow \psi'$ + anything) $<$ 260 pb on the production of metastable hybrids which might be produced at 4.03 GeV.

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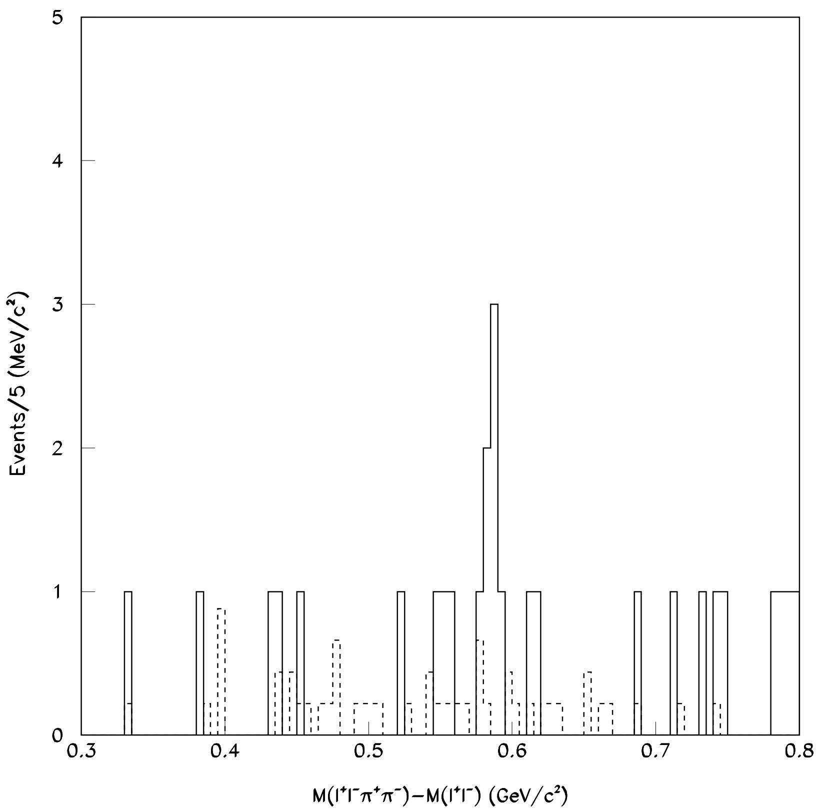

Figure 5: Distribution of M($\ell^+\ell^-\pi^+\pi^-$)−M($\ell^+\ell^-$) after applying initial state radiation rejection. The dashed histogram is an estimated background distribution from events outside of the J/ψ mass window.