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STUDY OF χ_{c2} PRODUCTION IN PHOTON-PHOTON COLLISIONS*

TPC/Two-Gamma Collaboration

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ABSTRACT

Two-photon production of the charmonium state χ_c has been studied by the TPC/Two-Gamma experiment at the SLAC e^+e^- collider PEP. We observe evidence of the χ_{c2} state in the channel $\gamma\gamma \to \chi_{c2}$, $\chi_{c2} \to \gamma J/\psi$, $J/\psi \to l^+l^-$ and obtain a value of $\Gamma_{\gamma\gamma}(\chi_{c2}) = 3.4 \pm 1.7 \pm 0.9$ keV. This is the first observation of the two-photon production of a χ_c state. Comparison is made with previous experimental results and QCD predictions for $\Gamma_{\gamma\gamma}(\chi_{c2})$.

The two-photon decay widths, $\Gamma_{\gamma\gamma}$, of the $C = +1$ charmonium states such as the χ_{c2} provide valuable information in understanding the nature of heavy quarkonia. In potential models, the χ_{c2} is assumed to be a $c\bar{c}$ bound state, $^3P_2$ in spectroscopic notation. Predictions for $\Gamma_{\gamma\gamma}$ have been made in relativistic potential models[1,2] and in dispersion-relation models based upon QCD sum rules.[3] These calculations lead to a rather wide range of values $0.4 < \Gamma_{\gamma\gamma}(\chi_{c2}) < 2.0$ keV. A precise experimental measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ would set a constraint on these models. Furthermore, since the ratio of partial widths into two gluons and into two photons, $\Gamma_{gg}(\chi_{c2})/\Gamma_{\gamma\gamma}(\chi_{c2})$, is related to the strong coupling constant α_s,[4] the experimental determination of this ratio offers a method to test the validity of perturbative QCD predictions.

Experimental measurements of two-photon decay widths for charmonium states are difficult due to their lack of dominant decay modes. The two-photon decay of the χ_{c2} state has been directly observed in production from radiative ψ' decay[5] and in $p\bar{p}$ annihilation.[6,7] Since the decay branching rate to two photons is small, about 0.1%, these results have large uncertainties. Two-photon reactions at e^+e^- colliders provide another method for measuring $\Gamma_{\gamma\gamma}$. The TPC/Two-Gamma[8] and CLEO[9] collaborations have used four-hadron final states, such as $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$, to search for the χ_{c2}, but the substantial background from the continuum makes observing the expected few signal events difficult, and only upper limits on $\Gamma_{\gamma\gamma}(\chi_{c2})$ have been obtained.

The VENUS Collaboration[10] has reported a search for the two-photon production of χ_{c2} in the decay channel $\chi_{c2} \to \gamma J/\psi$, $J/\psi \to l^+l^-$, where l is either an electron or a muon. Again, only an upper limit on $\Gamma_{\gamma\gamma}(\chi_{c2})$ has been reported. The overall decay branching ratio to the sum of two lepton flavors, $(1.65 \pm 0.15)\%$,[11] is comparable to each of the four-hadron decays mentioned above, and has a smaller uncertainty. The competing backgrounds for this decay channel are pure QED processes of order α^5. Therefore, the signal-to-background ratio for this channel should be better than that for the four-hadron decay channels.

In this letter we report another study of the "untagged" two-photon process $e^+e^- \rightarrow e^+e^-\chi_{c2}$, $\chi_{c2} \rightarrow \gamma J/\psi$, $J/\psi \rightarrow l^+l^-$, where $l = e$ or μ. In this mode, the scattered electron and positron emerge at very small angles with respect to the beam axis, and the two virtual photons radiated by the scattered electron and positron have masses squared, q_1^2 and q_2^2, close to zero; *i.e.*, the photons are quasi-real. This situation is not only strongly favored by QED,[12] it is also enforced by the total transverse momentum cut to be described. One expects such a measurement to be far more sensitive to χ_{c2} than to either χ_{c1} or χ_{c0}. While the branching ratio of χ_{c1} to $\gamma J/\psi$ is twice that of χ_{c2},[11] the Landau-Yang theorem[13] prohibits the production of a spin-one particle by two real photons; for virtual photon i, the cross section for formation of a spin-one state of mass M is suppressed by $\sim -q_i^2/M^2$.[14] Hence the two-photon untagged production of the χ_{c1} is expected to be very small. For χ_{c0} on the other hand, the production cross section is expected[15] to be of the same order as that for χ_{c2}, but the decay branching ratio of χ_{c0} to $\gamma J/\psi$ is only 5% that of χ_{c2}.[11]

The data were collected with the TPC/Two-Gamma facility at the SLAC e^+e^- storage ring PEP. The integrated luminosity was 140 pb^{-1} at an e^+e^- center of mass energy of 29 GeV. The TPC/Two-Gamma facility has been described elsewhere,[16] but here we will summarize detector features relevant to this analysis. The Time Projection Chamber (TPC), operating within a solenoidal magnetic field, was used to measure charged particle momenta and separately identify electrons, pions, kaons, and protons by measuring their energy loss, dE/dx. The muon system, consisting of iron absorber with interleaved proportional chambers, gave muon identification capability for a total solid angle coverage of 98% of 4π. A hexagonal barrel calorimeter (HEX) and two pole-tip calorimeters (PTC) provided electromagnetic shower detection for polar angles above 260 mrad. The measured energy resolution, σ_E/E, is about 22% for 350 MeV HEX photons and 27% for PTC photons of similar energy. Particles were also measured by detectors in the forward-backward directions at polar angles between 25 and 180 mrad.

In this study, events were selected with two oppositely-charged particles and just one photon; the recoil e^+ and e^- were undetected. The charged particles had to be in the TPC fiducial volume and had to extrapolate to within 5 cm of the beam axis and to within 10 cm of the interaction point along the beam axis. The charged particle momenta were required to be larger than 0.8 GeV/c and, in order to eliminate annihilation events, were also required to be less than 4 GeV/c. The charged particle pair had to be identified as either e^+e^- or $\mu^+\mu^-$. Particle identification for electrons was based on a χ^2 fit of the measured truncated mean dE/dx and momentum to the expected relation between dE/dx and velocity. Identification of muons was based on hits in successive layers in the muon chambers. The muon detection efficiency as a function of momentum and angle was determined using muon tracks from the two-photon process $\gamma\gamma \rightarrow \mu^+\mu^-$. For the expected distribution of muon momenta (0.8 to 3.0 GeV/c) and directions resulting from the χ_{c2} decay, the average efficiency was about 90%. The probability of fake muons from hadron punch-through and decay was estimated, using pions and kaons from the two-photon processes $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$, to be less than 1% for the muon momenta characteristic of the χ_{c2} decays. Final-state photons were required to have measured energies of at least 200 MeV in the HEX or PTC and to be not associated with any charged tracks. To ensure that only untagged events with two tracks and one photon were included, a total missing transverse momentum $p_T < 0.25$ GeV/c was required. This cut suppressed backgrounds from processes such as $e^+e^- \rightarrow e^+e^-l^+l^-$ with a spurious photon, and $e^+e^- \rightarrow e^+e^-J/\psi+$ hadrons. After applying the selection criteria, 40 events remained.

The mass M_{+-} of the charged particle pair is histogrammed in Figure 1. A $J/\psi(3097)$ signal is apparent despite the background. Figure 2 shows the distribution of the invariant mass difference $(M_{+-\gamma} - M_{+-})$ for all 40 events. Here $M_{+-\gamma}$ is the invariant mass of all three particles. The solid curve is the expected shape of $(M_{+-\gamma} - M_{+-})$ from a Monte Carlo calculation normalized to the 6.2 χ_{c2} events found in our analysis. The resolution for M_{+-} and $M_{+-\gamma}$ were estimated to be 0.06 and 0.13 GeV/c^2, respectively. To reduce background from $l^+l^-\gamma$, we further rejected events with an $(M_{+-\gamma} - M_{+-})$ invariant mass difference outside the mass region from 0.25 to 0.75 GeV/c^2, values suggested by the Monte Carlo curve. Using this cut, 15 of the 40 events were rejected. Figure 3 shows the M_{+-}

distribution of the surviving 25 events; the 9 events (3 $e^+e^-\gamma$ events and 6 $\mu^+\mu^-\gamma$ events) having M_{+-} within ± 0.15 GeV/c^2 of the J/ψ mass are the χ_{c2} candidates.

A considerable number of events without J/ψ content is seen in Fig. 3. We believe these events are due mainly to the QED process, $e^+e^- \rightarrow e^+e^-l^+l^-\gamma$. Smaller contributions to the non-J/ψ background might arise from misidentifying hadronic or higher-order QED $\gamma\gamma$ processes, or from accidental calorimeter energy simulating a γ. There are no readily available calculations of the QED backgrounds.[17] Hence the number of non-J/ψ background events was estimated by fitting the distribution of M_{+-} outside of the J/ψ mass region with an exponential function, shown as the dashed curve in Fig. 3. This background was estimated to be 2.4 events in the J/ψ mass region with a systematic uncertainty of 0.7 events. After subtracting this background, we have an estimated 6.6 ± 3.0 $J/\psi\gamma$ events. Possible background sources with real J/ψ's include $\gamma\gamma \rightarrow b\bar{b}$, $b\bar{b} \rightarrow J/\psi + X$,[18] where the hadronic system X is mistaken for a single photon; and $\gamma\gamma \rightarrow \chi_{c0}(\chi_{c1}) \rightarrow J/\psi + \gamma$. Since the $\gamma\gamma \rightarrow b\bar{b}$ rate is low and the branching ratio for $B \rightarrow J/\psi + X$ is only about 1%,[11] we expect that this background after event selection is negligible. In support of this, no events with the exclusive final state $J/\psi + \pi^0$, the state most likely to be misidentified as $J/\psi + \gamma$, were found in our untagged data. The contribution from the χ_{c0} and χ_{c1} was estimated to be $(7 \pm 6)\%$ of the χ_{c2} events.[19] This leaves a total of 6.2 ± 3.0 events for the χ_{c2} signal, with a total of 2.8 ± 0.8 (systematic) events from all backgrounds.

As an alternative to cutting on the invariant mass difference $(M_{+-\gamma} - M_{+-})$, kinematic fitting was used on the same selected sample of 40 events in order to check the number (6.6 ± 3.0) of $J/\psi\gamma$ events (χ_{c2} plus χ_{c0} plus χ_{c1}) obtained above. All 40 events were kinematically fitted to an untagged $J/\psi\gamma$ final state. In the fit, the charged lepton pair was constrained to have the J/ψ mass (3.097 GeV/c^2), and the untagged recoil electrons were constrained to lie within a very small scattering angle of the beam axis; *i.e.*, the undetected p_x and p_y were required to be peaked at zero, with a small rms deviation suggested by a Monte Carlo calculation to be described below. Fourteen events (4 $e^+e^-\gamma$ events and 10 $\mu^+\mu^-\gamma$ events) "passed" this fit with a confidence level of at least 2%. Their invariant mass difference $M_{J/\psi\gamma} - M_{J/\psi}$, as determined from kinematically fitted quantities, is shown in Fig. 4(a). An enhancement at a mass difference consistent with $M_{\chi_{c2}} - M_{J/\psi}(0.459\ GeV/c^2)$ is seen, along with one other peak at 0.2 to 0.3 GeV/c^2. The solid curve shown is a Monte Carlo calculation for the expected spectrum of this constrained mass difference from χ_{c2} decay, normalized to 6.2 events; it implies an rms resolution of 0.06 GeV/c^2. A fitting efficiency of about 97% was determined as the fraction of Monte Carlo χ_{c2} events which passed the fit, with the requirement of at least a 2% confidence level.

To estimate the background from $l^+l^-\gamma$ in the kinematical fit, the remaining 26 events were fitted to an untagged $l^+l^-\gamma$ final state. In this fit, the undetected p_x and p_y were again constrained to be zero with the same error as in the previous fit, but no constraint on the lepton pair mass was applied. All of these events passed the fit with at least a 2% confidence level. Figure 4(b) shows that the resulting distribution of the fitted invariant mass difference $M_{+-\gamma} - M_{+-}$ peaks at 0.2 to $0.3 GeV/c^2$, similar to the lower peak in Fig. 4(a). Thus that peak is readily ascribable to QED background, with still lower mass differences having been eliminated by the event selection cuts. If we assume that the background from $l^+l^-\gamma$ in Fig. 4(a) has a distribution that is the same as the histogram in Fig. 4(b), and that the signal is a Gaussian with a mean mass corresponding to the χ_{c2}, then a likelihood fit[20] yields a total χ_{c2} signal of 7.0 ± 3.2 events. Since the estimated fitting efficiency (about 97%) is the same as the Monte Carlo-estimated survival rate (about 97%) for the method using an invariant mass difference cut, this result is consistent with the preceding 6.6 ± 3.0 events. A similar fit using the χ_{c0} mass instead yields 2.4 ± 3.1 events, but with an unacceptable chi-squared, supporting the expectation[19] that our method would not be sensitive to χ_{c0} production. In what follows, we will use the result from the first method, with its small correction for possible χ_{c0} and χ_{c1} contributions.

To determine the experimental acceptance, events were generated in a Monte Carlo program that used the QED luminosity function for transversely polarized virtual photons[12] and assumed the χ_{c2} was produced in a pure helicity-2 state[21] with a vector meson-dominated form factor, $F(q_1^2, q_2^2) \propto \sqrt{\Gamma_{\gamma\gamma}}/((1 - q_1^2/m_{J/\psi}^2) \times (1 - q_2^2/m_{J/\psi}^2))$. The decay angular distributions for χ_{c2} and J/ψ were assumed to be from a pure $E1$ transition for a helicity-2 state $\chi_{c2} \to \gamma J/\psi$.[1,22] Using angular distributions appropriate for mixed helicity states gave relatively small differences in acceptance, resulting in the assignment of an 8% systematic error for the decay model selection. Generated events were processed through a detector simulation program which included the effects of resolution, energy loss, bremsstrahlung, pair creation, multiple scattering, nuclear interactions in the detector materials, and a trigger simulation. The output was then passed through the same selection programs as the data. The trigger efficiency was about 28%. Overall acceptance for the $e^+e^-\gamma$ final state was about 2.7%, as compared to 6.0% for $\mu^+\mu^-\gamma$, since the efficiency for unambiguous electron identification in the TPC was lower than that for muon identification by the muon chambers. A calculated yield of $1.8 \times \Gamma_{\gamma\gamma}(\chi_{c2})$ [keV] events in our data was obtained. Thus the 6.2 ± 3.0 events implies $\Gamma_{\gamma\gamma}(\chi_{c2}) = 3.4 \pm 1.7$ keV.

A systematic error of 20% for the acceptance was derived from the uncertainty in trigger simulations (7%), the uncertainty due to detector simulation and kinematic cuts (15%), possible errors in particle identification (8%), and the Monte Carlo model selection (8%). The uncertainty in the integrated luminosity was 7%, while that from the background subtraction was 13%. Uncertainties in decay branching ratios, $Br(\chi_{c2} \rightarrow \gamma J/\psi)Br(J/\psi \rightarrow l^+l^-)$, contributed 9%.[11] These uncertainties were added in quadrature for a total systematic error of 26%. The two-photon width of the χ_{c2} state is therefore measured to be $\Gamma_{\gamma\gamma}(\chi_{c2}) = 3.4 \pm 1.7 \pm 0.9$ keV.

The present result is consistent with observations of $\chi_{c2} \rightarrow \gamma\gamma$, which gave the $\Gamma_{\gamma\gamma}(\chi_{c2})$ values (1.8 ± 0.8)keV[5,11] and $(2.0^{+1.0}_{-0.8})$ keV.[6,11] This result is also in agreement with the VENUS result from the same two-photon process, an upper limit of 4.2 keV at the 95% C.L.,[10] and with our previous result from purely hadronic decay channels in two-photon processes, an upper limit of 4.2 keV at the 95% C.L.[8] However, it does not seem to be in good agreement with the CLEO measurement, an upper limit of 1.0 keV at the 95% C.L.,[9] nor with the FNAL E-760 measurement of $0.304 \pm 0.084 \pm 0.049$ keV.[7] The measurement is consistent with theoretical predictions, but is not precise enough to distinguish among various models.

In conclusion, we have studied the production of χ_{c2} in two-photon collisions using the decay channel $\chi_{c2} \rightarrow \gamma J/\psi$, $J/\psi \rightarrow l^+l^-$. We have presented evidence for exclusive production of the charmonium state χ_{c2}, which is the first observation of any χ_c state in two-photon collisions. The two-photon decay width has been measured to be $\Gamma_{\gamma\gamma}(\chi_{c2}) = 3.4 \pm 1.7 \pm 0.9$ keV.

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15. Assuming the spatial wave function for the scalar meson χ_{c0} and tensor meson χ_{c2} to be similar, one can obtain from Ref. 2 and Ref. 4 a simple relation between their $\gamma\gamma$ decay rates, $\Gamma_{\gamma\gamma}(\chi_{c0})/\Gamma_{\gamma\gamma}(\chi_{c2}) = 2.8 \times (1 + 5.5\alpha_s/\pi) \approx 4.2$. Since the two-photon cross section for producing a particle of (even) spin J is proportional to the product $(2J+1) \times \Gamma_{\gamma\gamma}$, the ratio of χ_{c0} to χ_{c2} cross sections is expected to be ≈ 0.84.

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19. The ratio of the number of χ_{c0} or χ_{c1} events to χ_{c2} events is the product of the ratio of the acceptances, the ratio of decay branching ratios, and the ratio of the two-photon cross sections. Monte Carlo simulations predict that

the acceptance for χ_{c2} is almost equal to that for χ_{c0}, so (using Ref. 15) the ratio of χ_{c0} to χ_{c2} events is about $1 \times 0.05 \times 0.84 = 0.042$. For χ_{c1}, a Monte Carlo calculation based upon the model described in Ref. 14 finds that the cross section averaged over our low-q_i^2 acceptance (in the untagged configuration) is only $\approx 1/80$ of the χ_{c2} cross section. With its two-times larger decay branching ratio, the number of χ_{c1} events should then be about 1/40 times that of χ_{c2}. Therefore, the total number of events from χ_{c0} and χ_{c1} is about 7% of the χ_{c2} events. Since this estimate has large ambiguities, an 80% relative error is assigned to the ratio.

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Figure Captions

Figure 1. The distribution of the invariant mass of the charged lepton pair for the 40 selected events.

Figure 2. The distribution of the invariant mass difference $M_{+-\gamma} - M_{+-}$ for the 40 selected events. The arrows show the cuts used. The curve is the estimate from the χ_{c2} Monte Carlo calculation normalized to the 6.2 events found in our analysis.

Figure 3. The distribution of the lepton pair mass M_{+-} for the 25 events remaining after the cut on $M_{+-\gamma} - M_{+-}$. The dashed curve shows a fit to the non-J/ψ background using an exponential function. The solid curve additionally includes the results of a Monte Carlo calculation normalized to 6.6 J/ψ events, in which 6.2 events are from χ_{c2} decay, 0.25 events from χ_{c0}, and 0.15 events from χ_{c1}.

Figure 4. (a) The mass difference $M_{J/\psi\gamma} - M_{J/\psi}(3.097)$ spectrum for events surviving the untagged $J/\psi\gamma$ kinematic fit. The curve shows the expectation from the χ_{c2} Monte Carlo calculation normalized to 6.2 events. (b) The mass difference $M_{+-\gamma} - M_{+-}$ spectrum based upon an untagged $l^+l^-\gamma$ kinematic fit for those events failing the fit in (a).

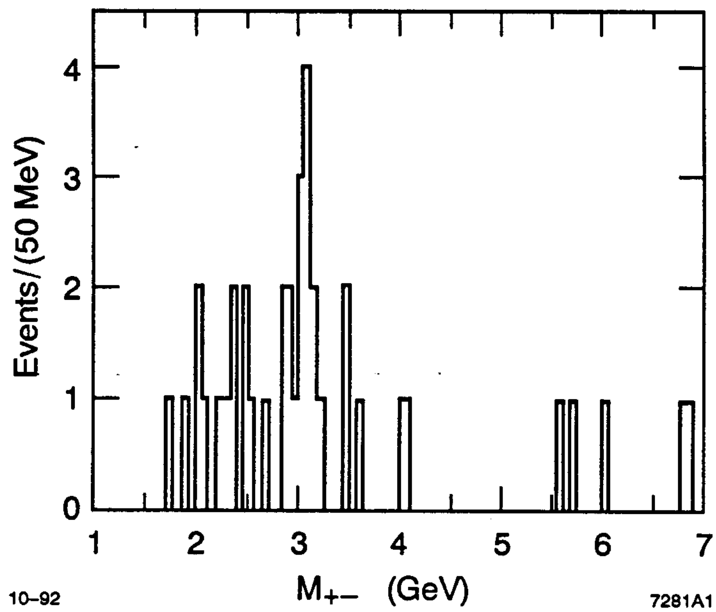


Fig. 1

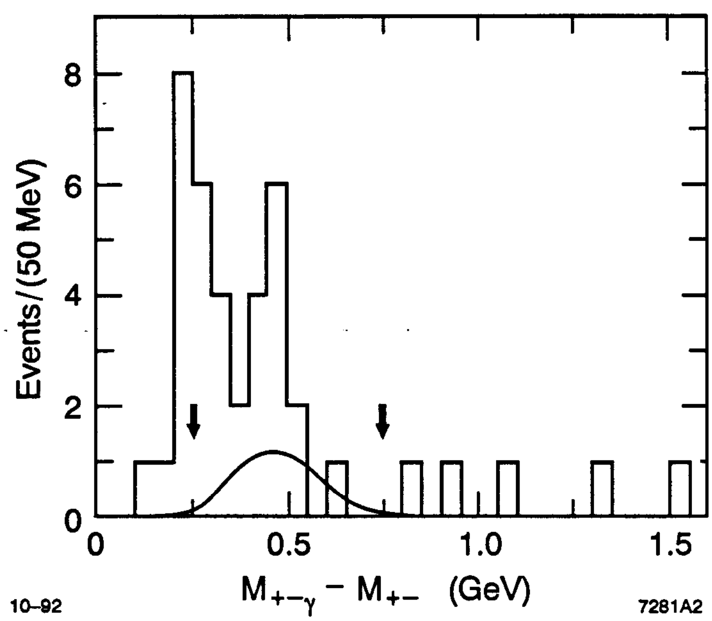


Fig. 2

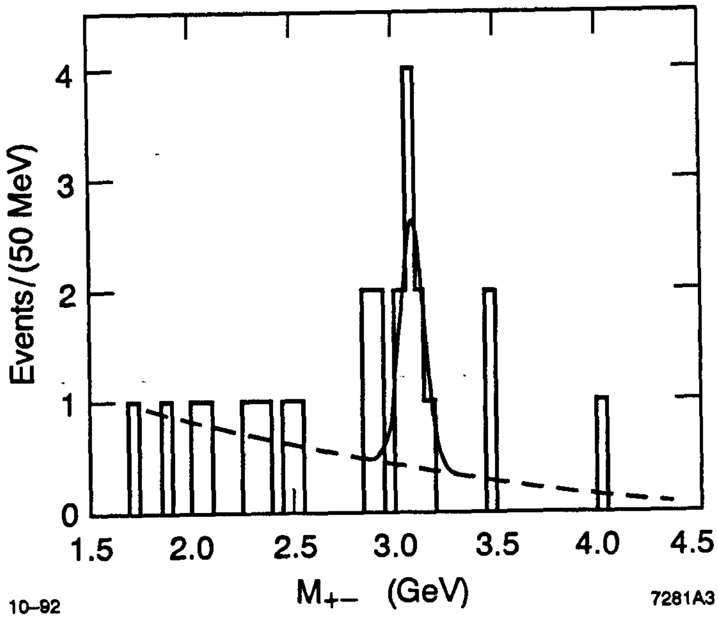
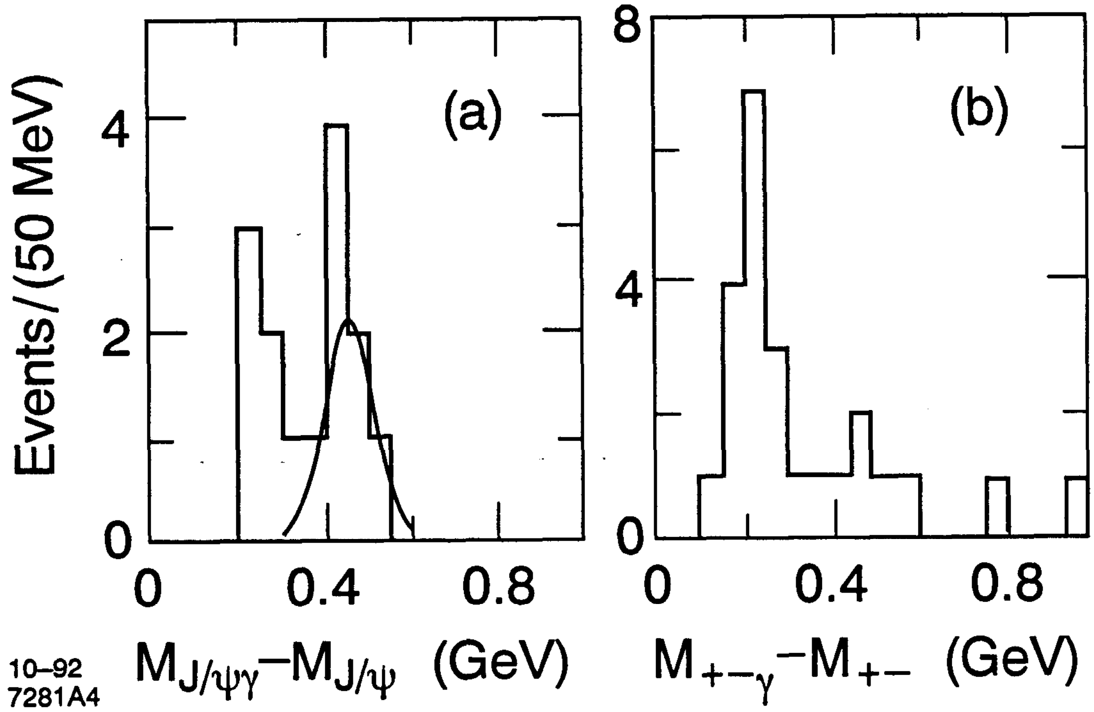


Fig. 3



Events/(50 MeV)
(a)
(b)
0
2
4
0
4
8
0
0.4
0.8
0
0.4
0.8
10–92
7281A4
$M_{J/\psi\gamma} - M_{J/\psi}$ (GeV)
$M_{+-\gamma} - M_{+-}$ (GeV)

Fig. 4