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Experimental study of J/ψ production in the two-photon process at TRISTAN

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Abstract

An experimental study was carried out for J/ψ production in a two-photon process using the VENUS detector at the TRISTAN e^+e^- collider. The study was based on 357 pb^{-1} data at an average e^+e^- center-of-mass energy of 58 GeV. No significant signal was observed, and the upper limit of the production cross section was obtained.

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1 Introduction

Charm-quark production in photon-photon collisions is expected to provide clear information concerning the hadronic structure of the photon, since the reaction requires a large momentum transfer in order to produce heavy charm quarks. The large momentum transfer is expected to suppress any non-perturbative effects of strong interactions. Experimental studies have been carried out extensively, based on this argument. Open-charm production from the two-photon process in e^+e^- collisions has been investigated by experiments at the e^+e^- colliders TRISTAN and LEP [1,2]. J/ψ production has also been studied in ep and γp collisions, both experimentally [3,4] and theoretically.

The resolved-photon process [5] has been observed in these measurements and has provided information on the photon structure function in medium-to-large x regions, where x denotes the momentum fraction carried by the parton content. However, the results are still insufficient for determining the photon structure at small x (< 0.1). In the small-x region, the parton content in the photon is expected to be dominated by gluons, not by quarks, and the higher order QCD contributions are expected to be significant. Thus, it is difficult to determine the structure function in this region with theoretical extrapolations. Further experimental information is necessary for a reliable determination.

To obtain some insight into the gluon content in a photon in the small-x region, we carried out an experimental study concerning the production of the J/ψ charmonium in the two-photon process at e^+e^- collisions. The leptonic-decay channel, $J/\psi \to e^+e^-$, was used to identify the production of J/ψ. Additional hadronic activity was required to eliminate the background from pure QED processes. In addition, we required that recoil beam electrons were not detected, so that two colliding photons should be nearly on the mass shell. The decay to muons was not used because the expected momenta of muons are too low to distinguish them from hadrons in our detector.

The J/ψ production in the two-photon process is expected to be dominated by a photon-gluon fusion process, $\gamma g \to J/\psi g$, where the incident gluon originates from a photon resolved into partons (the once-resolved process). It is noted that exclusive J/ψ production via the direct process in the collision of two real photons, $\gamma\gamma \to J/\psi$, is prohibited by the quantum number conservation by Yang's theorem [6]. The lowest-order diagram of this process is shown in Figure 1. Since the production is expected to be enhanced near to the threshold [7], the production cross section must be sensitive to the gluon density in the photon in a small and narrow x region. The region was estimated to be $0.03 < x < 0.1$ in our Monte-Carlo simulation at TRISTAN energies.

The contribution from other processes is expected to be small. The double-resolved photon process, where both incoming photons are resolved to partons, can hardly contribute to the heavy charm-quark production at our energies. Inclusive production in the direct process, $\gamma\gamma \to c\bar{c} \to J/\psi X$, is a higher-order process in QCD and is also suppressed. This is in contrast to the open-charm production in which the direct process takes an important role. One of the possible sources of non-resolved J/ψ production, $\gamma\gamma \to \chi_{c2} \to J/\psi\gamma$, has proved to be small by previous measurements [8]. Production from the decays of b-hadrons is small in our energy range. Meanwhile, J/ψ from the decay of ψ (2S) is included as a signal in the present measurement, because they are also due to the resolved photon process, $\gamma g \to \psi g \to J/\psi g X$.

2 Experimental apparatus

The study was based on the full data collected by the VENUS experiment at the TRISTAN e^+e^- collider, from 1987 to 1995. The data correspond to an integrated luminosity of 357 pb^{-1}. The center-of-mass energy is from 55 to 64 GeV for the e^+e^- system, with a luminosity-weighted average of 58 GeV. About 90% of the data were accumulated at 58 GeV. The VENUS detector is described in detail elsewhere [9]. In the present study, we used mainly the central drift chamber (CDC) [10] for tracking charged particles and the lead glass calorimeter array (LG) [11] for electron identification.

The CDC consisted of 20 axial and 9 stereo sampling layers. Charged particles produced in a polar-angle range of $|\cos\theta| < 0.75$ were sampled in all layers. Under an axial magnetic field of 0.75 T, produced by a superconducting solenoid, it provided momentum information with a resolution of $\sigma_p/p = \sqrt{1.3^2 + (0.8p_T)^2}\%$ in this region, where p_T is the transverse momentum measured with respect to the beam direction in units of GeV/c. Although the resolution became worse at smaller angles, the CDC was capable of reconstructing charged-particle tracks with good efficiency (better than 90%) down to $|\cos\theta| < 0.9$.

The LG was placed outside of the solenoid magnet and covered a polar-angle region of $|\cos\theta| < 0.80$. The energy resolution was $\sigma_E/E = 7.5\%$ for 1.5 GeV electrons. A pair of liquid argon calorimeters (LA) in the forward region were used together with the LG for selecting two-photon events.

A transition radiation detector (TRD) [12] was installed in 1990, in order to enhance the capability of electron identification. It was active for 75% of the data. It was placed between the CDC and the solenoid and covered a polar-angle region of $|\cos\theta| < 0.68$. The information from the TRD was used for estimating the background contributions in the present study.

The event trigger conditions [13,14] relevant to the present study were: "LG-total", where the total energy deposit in the LG was required to be larger than 3.0 GeV; and "LG-segment*2-tracks", where the detection of at least two tracks with $p_T > 0.6$ GeV/c was required in the CDC and the energy deposit in at least one segment of the LG was required to be larger than 0.6 GeV. We used only those events collected with these two triggers. The trigger efficiency was estimated to be better than 99% for the signal events within the detector acceptance.

3 Event Selection

3.1 Selection of e^+e^- inclusive events

From the collected data, we selected those events which satisfied the following criteria:

(1.1) $E_{\rm vis} < 20$ GeV, where $E_{\rm vis}$ is the sum of the momenta of CDC tracks and the energy deposits in the LG and the LA.

(1.2) A pair of oppositely charged tracks existed, where both tracks satisfied the following criteria a)-c). We refer these tracks as e^+ and e^- candidates.

- a) $|R_{\rm min}| < 1.0$ cm, $|Z_{\rm min}| < 6.0$ cm, and $|\cos\theta| < 0.80$, where $R_{\rm min}$ is the distance of the CDC track to the collision point in the projection onto the plane which is perpendicular to the beam direction (xy plane), and $Z_{\rm min}$ is the distance along the beam direction between the average collision point and the point which gives $R_{\rm min}$.
- b) $0.8 < p_T < 4.0$ GeV/c.
- c) $0.75 < E/p < 1.20$, where E is the energy deposit in the LG, and p is the momentum measured by the CDC. This is the condition for electron identification.

(1.3) One or more additional charged tracks with $|R_{\rm min}| < 2.0$ cm, $|Z_{\rm min}| < 6.0$ cm and $p_T > 0.1$ GeV/c existed within $|\cos\theta| < 0.90$. They are required to be isolated from both electron candidates with opening angles of more than 15°, where the angle is measured three-dimensionally at the closest approach in the xy plane to the collision point. We refer to these tracks as hadron candidates.

Criterion (1.1) sets an anti-tagging condition for recoil electrons. It also suppresses any background from e^+e^- annihilation processes and Bhabha scattering events. Figure 2 shows the E/p distribution for those tracks which satisfy criteria (1.1)-(1.2b) in events having at least three CDC tracks. We can see a peak around $E/p \sim 1.0$, corresponding to electrons.

After these selections, 200 events remained. Almost all of them are low-multiplicity events, and the number of events with only one hadron candidate amounts to about 65%.

3.2 Rejection of QED background

The main background in this analysis is considered to come from pure QED processes, such as $e^+e^- \to (e^+e^-)e^+e^-\gamma$. These events can satisfy the above selection criteria, if the γ is converted to an e^+e^- pair in the detector materials, and at least three of the produced four tracks are detected. The QED events have two distinct properties different from the signal events. First, e^+ and e^- tracks from a photon conversion have a small opening angle at the conversion point. Second, since the transverse momenta of colliding photons are small, the vector sum of the transverse momenta of observed charged tracks, $|\sum \vec{p}_T|$, is expected to be very small. On the other hand, $|\sum \vec{p}_T|$ can become large in the signal events, because neutral particles and those charged particles which escaped to the forward region may carry appreciable p_Ts.

In order to reduce the QED background, we applied the following three additional selection criteria. They also removed hadronic events in which the e^+ or e^- candidate came from a conversion of π^0 decay:

(2.1) Both e^+ and e^- candidates were required to be well isolated from any other oppositely charged tracks with an opening angle larger than 15°. A total of 94 events were rejected by this condition.

(2.2) A pair of oppositely-charged tracks were classified as a γ conversion candidate, if the opening angle was smaller than 15° or they were "kissing". The condition for the "kissing" is as follows: In the xy plane, the opening angle at the collision point is smaller than 90° and the distance between the tracks is smaller than 1.0 cm at the point where the two tracks go parallel; and the opening in the polar angle is smaller than 15°. Events were rejected if "all" hadron candidates belonged to the γ conversion candidates. We checked each hadron candidate with any other oppositely-charged and CDC-reconstructed tracks, and rejected 22 additional events.

(2.3) $|\sum \vec{p}_T|$ was required to be 0.2 GeV/c or larger. Then, 20 additional events were rejected.

Within the remaining 106 events after rejection (2.1), about three quarters of them included only one hadron candidate. Some ($\sim$ 10%) of those hadron candidates seem still to come from a γ conversion near the e^+ or e^- candidate. Especially for 24 events which included two hadron candidates, the distribution of the opening angle between both candidates, as shown in Figure 3, were concentrated in a small angle region, indicating that the sample is still dominated by the QED background. Figure 4 shows the $|\sum \vec{p}_T|$ distribution for the remaining events which survived criteria (2.1) and (2.2). The expectation for the signal events is overwritten with a dashed histogram, where the normalization is arbitrary. We can see that the event sample shows a concentration at small values, corresponding to the remaining QED background, whereas the signal events are expected to exhibit appreciably large values.

A total of 64 events survived all these selections. Figure 5 shows the invariant mass ($M_{e^+e^-}$) distribution for the candidate e^+e^- pairs. We took those events in a mass region of $2.95 < M_{e^+e^-} < 3.15$ GeV/c^2 as signal candidates. The mass range was chosen asymmetrically around the J/ψ mass (3097 MeV/c^2), in order to accept events in a tail due to the radiative energy loss of e^+ and e^-. We obtained six events as the signal candidates. However, these candidates are dominated by background, because there is no clear concentration around the J/ψ mass.

4 Background estimation

Among the remaining 64 events with the selections up to (2.3), 43 events included only one hadron candidate. A major part of them was expected to be the QED events in which either e^+ or e^- from the γ conversion escaped from the detection. Although no exact calculation is available for this higher-order QED process, it would be reasonable to expect the $M_{e^+e^-}^{-3}$ dependence of the cross section in a narrow mass region around the

J/ψ mass, in the same way as in the case of $e^+e^- \to e^+e^-l^+l^-$.

We estimated the total contribution of the QED events to the sample within the mass range of $2.0 < M_{e^+e^-} < 4.0$ GeV/c^2 (28 events observed), by using information from the TRD. Those events in which both e^+ and e^- candidates were identified as electrons again by the TRD were all counted as QED events, since the fraction of the signal events must be very small in this sample. Taking into account the smaller acceptance and the finite identification efficiency of the TRD, we estimated that 16.2 ± 6.5 events should be the QED events. Assuming the $M_{e^+e^-}^{-3}$ dependence, we estimated the contribution of the QED background to the 6 signal candidates to be 2.0 ± 0.8 events.

The contribution of open-charm production events, in which produced charm hadrons decay semi-electronically, was estimated by using a Monte-Carlo simulation [15]. We doubled the yield in order to take into account similar events from resolved-photon processes [1]. As a result, the contribution of these events was estimated to be 1.0 ± 0.2 in the mass region of $2.0 < M_{e^+e^-} < 4.0$ GeV/c^2, and 0.2 ± 0.04 event in the signal region. Most of these electron inclusive background events had only one electron, but included a misidentified hadron that resembled a pair of electron candidates. The contribution of the electronic and semi-electronic decays in light-quark production events was negligible, less than 0.01 events in the signal region.

Events including a recoiled electron beam with a large angle were also estimated to be 1.8 ± 0.3 events within $2.0 < M_{e^+e^-} < 4.0$ GeV/c^2, and 0.2 ± 0.04 event in the signal region. Here, we doubled the expected number of events from direct u- and c-quark production for this estimation.

The remaining background was due to hadronic events in which two hadrons at large angles were misidentified as electrons. We selected an event sample by excluding the E/p cut, and examined the TRD information for those tracks to which the E/p cut should be applied. As a result, we found that $4 \pm 1\%$ of the hadron tracks fell within $0.75 < E/p < 1.20$, yielding 8.4 ± 4.7 misidentification background events within $2.0 < M_{e^+e^-} < 4.0$ GeV/c^2. Approximating the $M_{e^+e^-}$ dependence with a polynomial function obtained by fitting the sample, we estimated the contribution of the misidentification background to be 0.8 ± 0.4 event in the signal region.

Adding the errors in quadrature, we estimated the total background contribution to be 27.4 ± 8.0 events for the 28 events observed within $2.0 < M_{e^+e^-} < 4.0$ GeV/c^2, and 3.2 ± 0.9 events for the 6 signal candidates. The background shape, estimated by the sum of the QED background and the misidentification background, is overwritten in Figure 5. It gives reasonable quantitative agreement with the measured invariant mass distribution outside nearby the J/ψ mass region. Therefore, we decided that the estimation in a signal mass region should be reliable.

5 Detection efficiency

We simulated the process $e^+e^- \to e^+e^-J/\psi X \to e^+e^-e^+e^-X$ using a Monte-Carlo method in order to compare our result with theoretical calculations based on different models on the gluon density in the photon. The differential cross section was calculated based on the photon-gluon-fusion mechanism and the color-singlet state of the $c\bar{c}$ system [16]. Events were generated at an e^+e^- center-of-mass energy of 58 GeV.

After simulating the $\gamma g \to J/\psi g$ reaction and J/ψ decay into e^+e^-, the produced gluon and a remnant part of the resolved photon were processed in the LUND jet fragmentation simulator [17], where the remnant part was replaced with a gluon and connected to the produced gluon with a string. The final-state particles were then put through a full detector simulator.

We generated simulation samples for three parametrizations on the gluon density function: DG [18], LAC1 [19], and GRV [20]. They differ mainly in the gluon distribution, which is affected largely by non-perturbative QCD effects. In Table 1, the estimated detection efficiency for the signal events is shown separately for each parametrization, where $\vec{p}_T$ of the gluon resolved from a photon is taken to be zero. The reason for the small efficiency values is that the J/ψ and decayed e^+ or e^- tend to go into the forward region. The J/ψ is strongly boosted due to the imbalance in momentum of the initial gluon and photon. In addition, the dominance of the J/ψ helicity-one cross section, $\sim 80\%$ of the total cross section in our simulation, forces the decay electron angles to be close to the direction of the incident photon [16].

The hatched histogram in Figure 5 is a result of the simulation with the LAC1 parametrization. The invariant mass resolution was estimated to be 46 MeV/c^2 in the vicinity of the J/ψ mass. The normalization is arbitrary.

The systematic error of the detection efficiency was estimated to be 15% due to the ambiguity in the efficiency of the electron identification by the E/p cut, and 7% due to the ambiguity of the amount of detector material and the nucleon absorption effect within the detector materials. In addition, there is an appreciable uncertainty in the event generation. We assumed $p_T = 0$ for the gluon from resolved photons for estimating the efficiencies in Table 1. However, it might be more reasonable to give a sizable p_T to them, since the successive interaction requires a large momentum transfer for producing a heavy charmonium. Indeed, it has been shown that an average p_T of 1.0 GeV/c gives reasonable agreement with the result from a photon remnant analysis at HERA [3]. A non-zero p_T of the gluons tends to push the direction of the decay electrons to larger angles. We found that the efficiency increases by about 10% if $\langle p_T \rangle = 1.0$ GeV/c is assumed in the simulation. Since no theoretical or experimental bases has yet been established, we take this variation as the uncertainty in the detection efficiency. Adding all these errors in quadrature, we estimate the systematic error of the detection efficiency to be 19% in total.

6 Results and discussion

Subtracting the estimated background from the 6 signal candidates, we obtain $2.8^{+3.7}_{-2.1}$ events in the signal region. This result is insignificant statistically, and leads to an upper limit of 8.7 events at the 95% confidence level (CL). This limit can be converted to an upper limit on the production cross section, based on the estimated detection efficiency, which depends on parametrization of the photon structure function. The obtained limits are listed in Table 2 separately for each parametrization model, where the estimated systematic error of the efficiency is included.

The obtained upper limit of the cross section is about 15 (44, 87) times the expectation value based on the LAC1 (DG, GRV) parametrization. However, these limits must be meaningful because large ambiguities exist in the theoretical bases for the predictions. Our simulation is based on the lowest-order diagram illustrated in Figure 1. Higher-order effects may significantly enhance the production of heavy charmonium states. Thus, the experimental cross section can be several-times larger than the prediction based on the leading-order QCD [4]. Besides, additional contributions of heavier ψ states would increase the expectation by about 20% [5]. Furthermore, the gluon density in the photon is quite uncertain in the small-x region relevant to the J/ψ production, as pointed out in section 1.

7 Conclusion

We carried out an experimental study of the J/ψ production in the two-photon process at e^+e^- collisions, for the first time. Using 357 pb^{-1} data at an average e^+e^- c.m. energy of 58 GeV, collected with the VENUS detector at TRISTAN, we obtained $2.8^{+3.7}_{-2.1}$ signal candidates. However, this number of events was statistically insignificant. The result can be converted to an upper limit on the production cross section of 51 pb at the 95% CL, using the detection efficiency estimated on the basis of the LAC1 parametrization for the photon structure function. Although the established limit is still one order of magnitude larger than the lowest-order expectations, the present result will give a useful constraint for future theoretical improvements, since there remain large theoretical ambiguities concerning the J/ψ production mechanism and the structure function in the relevant small-x region.

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Table 1
Comparison among the predictions based on the three parametrizations[15,16,17]. The total cross section of the J/ψ production (σ), the detection efficiency (ε) and the expected number of events (N) are listed. The result of the present experiment is also listed for comparison. The quoted errors are statistical for the experiment and systematic for the parametrizations.

	σ (pb)	ε(%)	N
DG	0.7	1.3 ± 0.2	0.2
LAC1	3.4	0.8 ± 0.2	0.6
GRV	0.4	1.5 ± 0.3	0.1
Experiment	–	–	$2.8^{+3.7}_{-2.1}$
			(< 8.7 in 95% CL)

Table 2
Obtained upper limit on the production cross sections at the 95% CL. The result depends on the structure function model, since the detection efficiency depends on it, as shown in Table 1.

	DG	LAC1	GRV
σ (pb)	< 31	< 51	< 27

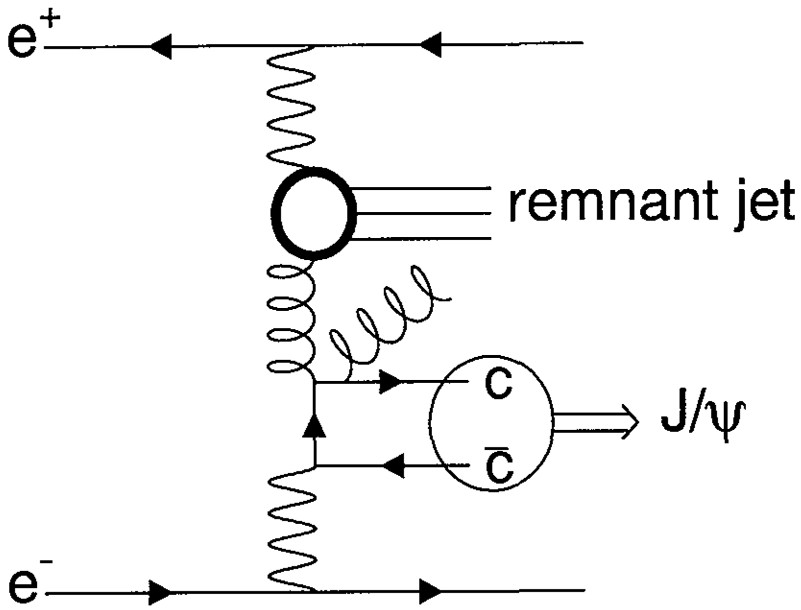

Fig. 1. Figure 1: Lowest-order Feynman diagram of the J/ψ production in the resolved photon process, $\gamma g \to J/\psi g$.

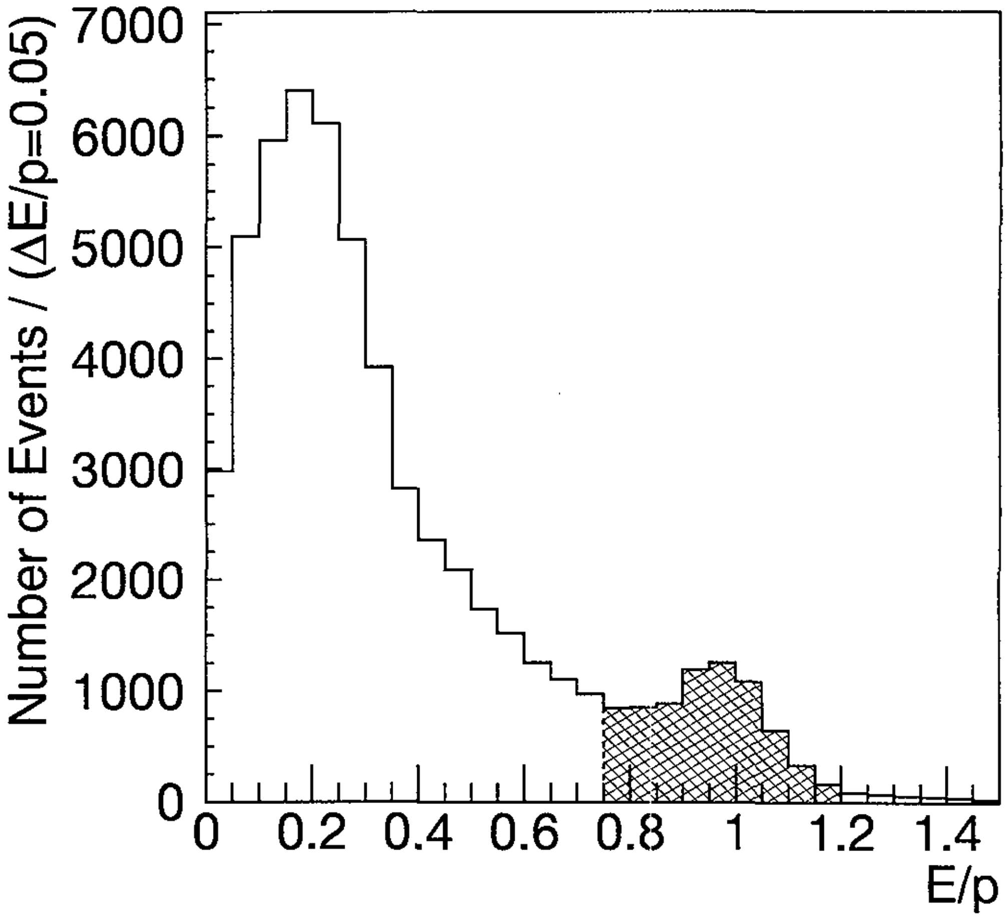

Fig. 2. Figure 2: E/p distribution of charged tracks in events satisfing criteria (1.1)-(1.2b) and having at least three CDC tracks. The tracks in the hatched region were regarded as electrons.

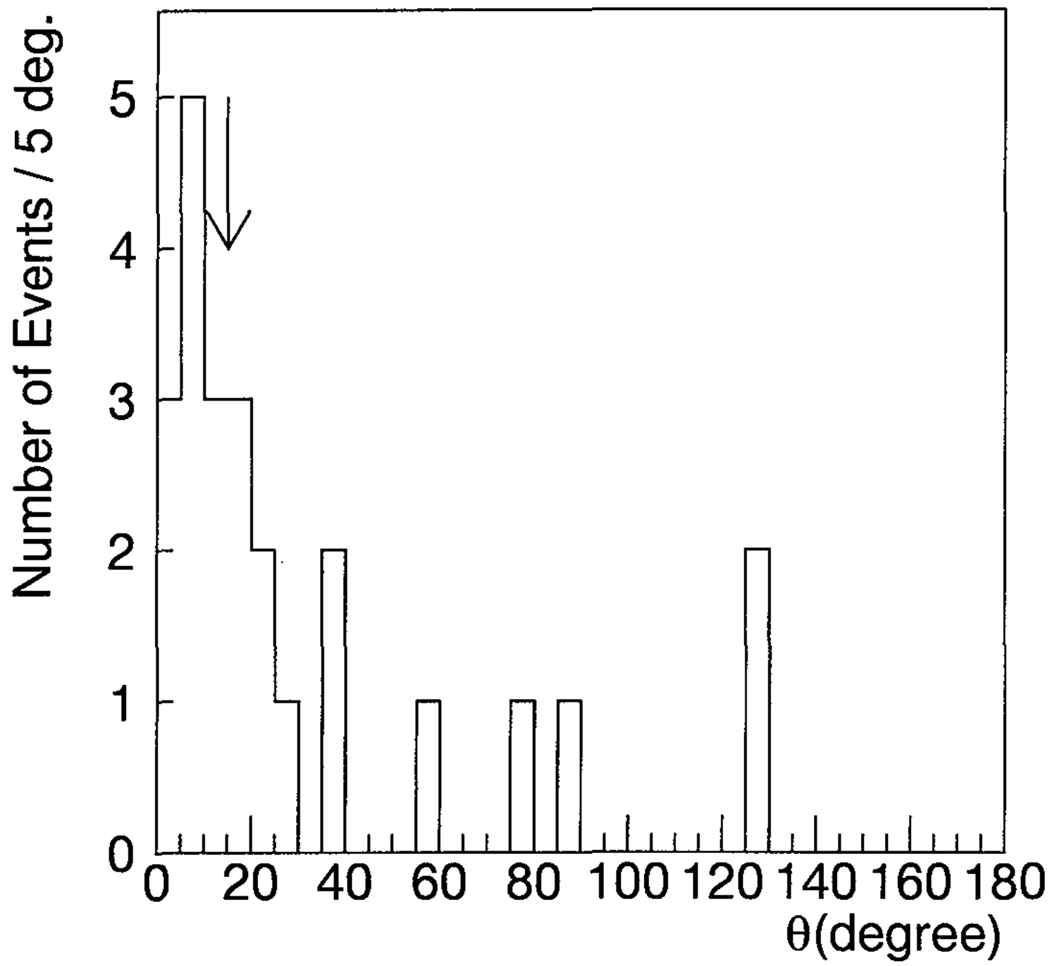

Fig. 3. Figure 3: Distribution of the opening angle between hadron candidates in those events which include only two hadron candidates. The arrow indicates 15°. For any pair of hadron candidates that consists smaller opening angle than this value, we considered that they were electrons which originated from gamma conversion, not hadrons.

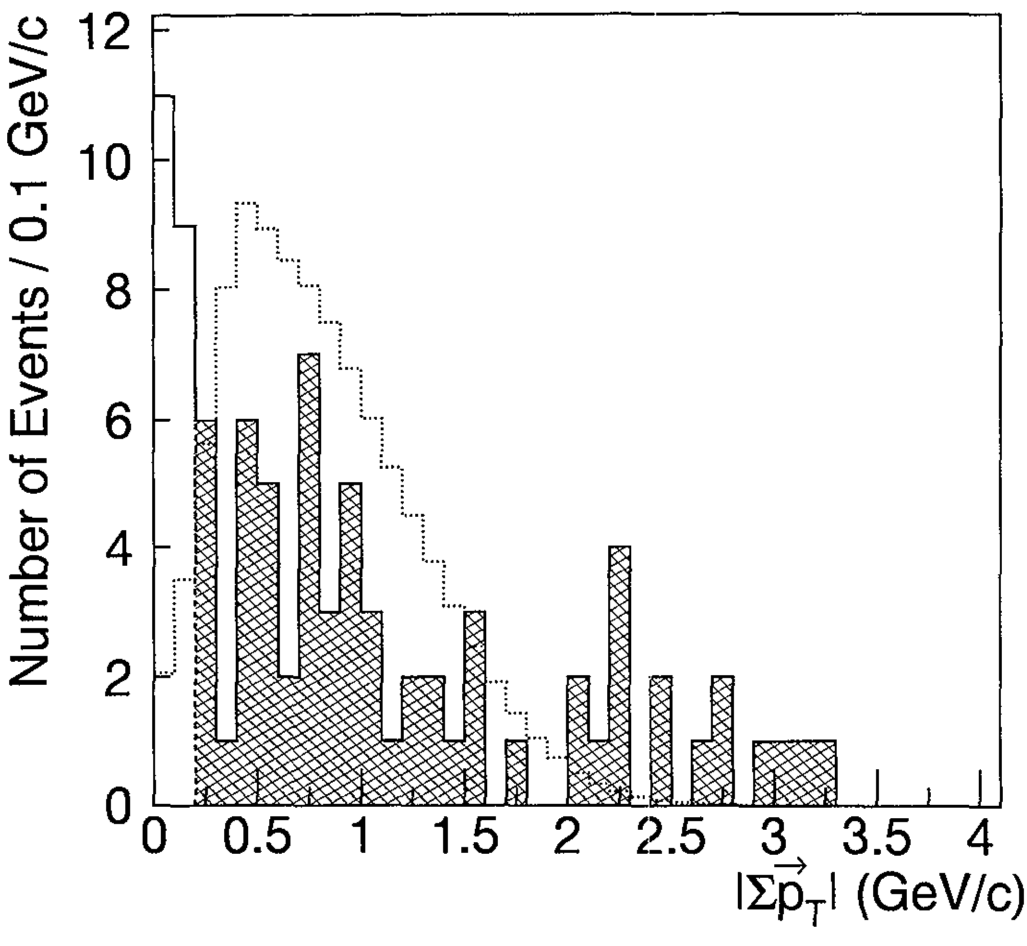

Fig. 4. Figure 4: Distribution of $|\sum \vec{p}_T|$ for events before the selection (2.3) (solid histogram). Events in the hatched region, $|\sum \vec{p}_T| > 0.2$ GeV/c, survived as not QED events. The dashed histogram shows the distribution of the simulated J/ψ-inclusive candidate events, where the normalization is arbitrary.

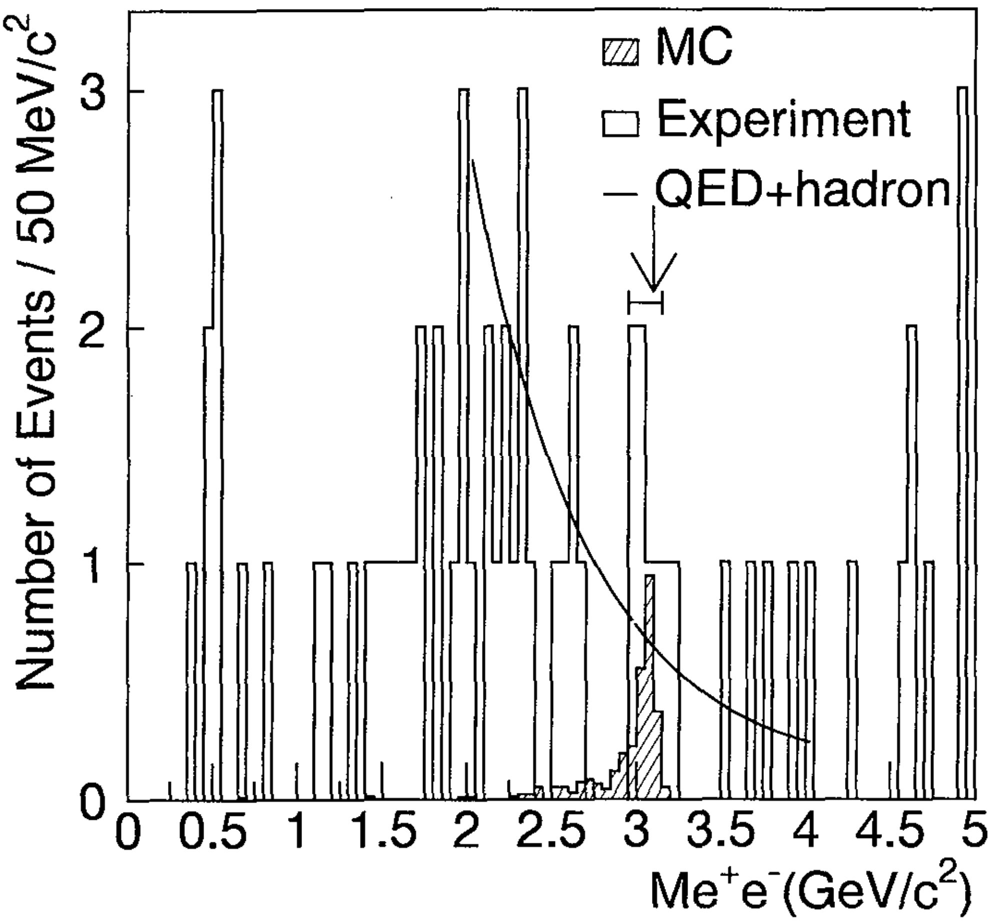

Fig. 5. Figure 5: Invariant mass distribution for the e^+e^- candidates in the final sample. The curve shows the estimated background, the QED background plus the misidentification background. The dashed histogram shows the J/ψ signal distribution; the normalization is arbitrary. The arrow indicates the nominal mass of J/ψ. The signal region is also indicated.