High Transverse Momentum J/Ψ Production at the CERN Proton-Antiproton Collider.

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Abstract

We have studied high transverse momentum J/ψ production in $p \bar{p}$ interactions at $\sqrt{s} = 630$ GeV. The measured cross section times branching fraction for $J/\psi \rightarrow \mu^+ \mu^-$ production with $p_T > 5$ GeV/c and $|\eta| < 2.0$ is $7.5 \pm 0.7 \pm 1.2$ nb. The event topology is used to establish that there is J/ψ production from both the direct production of $c \bar{c}$ bound states and the decay of B hadrons. The inferred yield of J/ψ from beauty decays is compatible with our estimates of beauty production in other channels.

1) Introduction

Production of J/ψ 's in hadronic collisions has been extensively studied from threshold up to $\sqrt{s}=63$ GeV [1]. In low energy proton-antiproton interactions, the most important production mechanism is quark-antiquark annihilation [2]. At higher energies, J/ψ production from gluon-gluon fusion becomes progressively more important [3], and is predicted to occur partly via the radiative decay of χ states [4], as has been observed experimentally for π^- -Be and p-p interactions [5]. Both the above processes lead to low p_T J/ψ 's.

High transverse momentum J/ψ 's may be produced by higher order versions of the above processes. Of these, the reaction

$$\begin{aligned} g + g &\rightarrow \chi + g \\ &\rightarrow J/\psi + \gamma \end{aligned}$$

is expected to be dominant at collider energies [6, 7, 8], with small contributions coming from

$$g + g \rightarrow J/\psi + g$$

and other processes. We will refer to the above processes as direct charmonium production.

At collider energies, another possible source of J/ψ 's is the production and decay of B hadrons [9], via channels such as:

$$\begin{aligned} g + g &\rightarrow b + \bar{b} \\ &\rightarrow B_{\text{hadron}} + X \\ &\rightarrow J/\psi + X. \end{aligned}$$

Because of the large mass of the b quark and B hadrons, this source is expected to contribute mostly at large p_T . As the charmed quarks are not produced in the initial parton-parton interaction, we refer to this as indirect J/ψ production. Based on the measured cross section for beauty production [10] and the measured branching ratio for the decay of B mesons into J/ψ [11], we expect a significant number of J/ψ 's to be produced in this way.

2) Data taking, reduction and selection

The components of the UA1 detector and trigger used for dimuon studies are described in [10] and references therein. The data described here were taken in two collider running periods in 1984 and 1985 and correspond to an integrated luminosity of 556 nb^{-1} at a centre of mass energy of 630 GeV. Events satisfying either an inclusive single muon or a dimuon trigger were passed through a fast filter program to select events having at least one muon candidate with $p_T > 3 \text{ GeV}/c$, and the selected events were then fully reconstructed. Here and throughout this paper, p_T is the component of momentum transverse to the beam direction. Next, events containing at least two reconstructed muons were selected if they satisfied all the following criteria :

- (i) $p_T > 3 \text{ GeV}/c$ for at least one muon,
- (ii) $p_T > 0.75 \text{ GeV}/c$ for each muon,
- (iii) a fiducial cut for each muon,
- (iv) $p_T > 4 \text{ GeV}/c$ for the dimuon system,
- (v) $2 \text{ GeV}/c^2 < M_{\mu\mu} < 4 \text{ GeV}/c^2$, where $M_{\mu\mu}$ is the dimuon mass.

The p_T cuts are based on the experimental acceptance, which is described in section 4. The second and third criteria are designed to cut out a region at the edge of the muon chambers, close to the beam, where the background to the prompt muon signal is rapidly increasing. The selection yielded 480 unlike sign and 86 like sign candidate muon pairs, which were all scanned by physicists on a high resolution interactive graphics facility. Of these, 46 unlike sign events and 26 like sign events were rejected in the following categories : double interactions (13 events), muons resulting from cosmic rays (1 event), leakage of hadrons through cracks in the calorimeters (9 events), visible kaon decays (22 events) and incorrect association of central detector and muon chamber tracks (27 events). Information from the limited streamer chambers [12], not considered in the automatic selection, was used in the scanning to help resolve ambiguities. The final sample consists of 434 unlike sign and 60 like sign muon pairs.

The dimuon effective mass distributions for these samples are shown in figure 1, where a very strong J/ψ signal can be seen. There is also a possible indication of the ψ' , although the small spike near the ψ' mass is much narrower than the experimental resolution. The $\mu^+\mu^-$ mass distribution has been fitted with Gaussian distributions for the J/ψ and ψ' , plus a background linearly decreasing with mass. The mass of the ψ' was fixed at the world average value, $3.686 \text{ GeV}/c^2$ [13] and the widths of both Gaussians, which are dominated by the experimental resolution, were constrained to be equal. The fitted mass of $3.110 \pm 0.011 \text{ GeV}/c^2$ found for the J/ψ agrees well with the world average value of $3.097 \text{ GeV}/c^2$ [13]. The fitted width of $0.15 \pm 0.01 \text{ GeV}/c^2$ is consistent with that expected from the central detector resolution. The fitted numbers of J/ψ and ψ' events are 293 ± 22 and 22 ± 12 respectively.

We define the J/ψ signal region for further studies to be the mass interval $2.89 \rightarrow 3.33 \text{ GeV}/c^2$, corresponding to $\pm 1.5\sigma$ about the J/ψ mass, and containing 273 events.

Sources of background to the J/ψ signal are the Drell-Yan mechanism, open charm and beauty production followed by semi-leptonic decays, and decays in flight of pions and kaons. Background from hadronic shower leakage through the nine interaction lengths of material separating the muon chambers from the central detector is negligible. In order to correct for the background to the J/ψ signal, we define control bands of $2.0 \rightarrow 2.7$ and $3.8 \rightarrow 4.0$ GeV/c², containing 64 events. For the experimental data in figures 3 to 8, background distributions obtained from the events in the control bands have been subtracted. These are normalized to the fitted background in the J/ψ region. This leaves a J/ψ signal of 247 events in the selected mass interval, after subtracting a background of 26 events.

3) Monte Carlo calculations

A detailed simulation of the two J/ψ production models has been performed using the program ISAJET [14] in conjunction with the UA1 detector simulation.

ISAJET uses the Eichten et al. parameterization of the proton structure function [15], with the QCD scale factor, Λ , set to 0.2 GeV. Initial and final state radiative corrections are applied to the hard scatter using the approximation of Fox and Wolfram [16]. Final state partons are fragmented using the Field and Feynman independent fragmentation ansatz, in conjunction with the Peterson et al. parameterization of the beauty fragmentation function [17], taking $\epsilon_b=0.02$. All the simulated hadrons are allowed to decay with their measured branching fractions [13]. The decay kinematics are calculated according to V-A theory for semi-leptonic decays and according to phase space otherwise.

Beauty production was simulated as described in reference [18]. The branching fraction for B hadron decay into J/ψ was taken to be 1.1%, and the fractions of B hadrons decaying via two body and quasi-two body channels were taken to be 10% and 40% respectively, based on the measurements of reference [11]. χ production via the process gluon + gluon $\rightarrow \chi$ + gluon was simulated by using the parton-parton differential cross sections of Humpert [19] and the measured branching fractions for $\chi \rightarrow J/\psi + \gamma$ [13]. (The differential cross sections of Humpert agree in shape with those of Gastmans et al [20].) The shapes of the resulting p_T and rapidity distributions of the J/ψ before detector simulation agree closely with the published calculation [8]. The process gluon + gluon $\rightarrow \chi$, without additional gluons, does not give rise to high p_T J/ψ 's and was not considered. Direct J/ψ and ψ' production via gluon + gluon $\rightarrow J/\psi$ (ψ') + gluon are calculated to have small cross sections [8], and are expected to have similar event topologies to J/ψ coming from χ decay, and were therefore not simulated.

4) Acceptance and cross sections

The detector acceptance for $J/\psi \rightarrow \mu^+\mu^-$ is dominated by the ranging out of low momentum

muons in the calorimeter and muon absorber. In the central rapidity region, $|y| < 1$, this leads to an effective cut of between 2 and 3 GeV/c on the p_T of each muon. Thus only events with both muons on the same side of the beam, and hence with the J/ψ having $p_T > 5$ GeV/c, are detected. In the forward region, $1 < |y| < 2$, the acceptance extends down to a p_T of 4 GeV/c for the J/ψ . It is symmetric in y , and limited to $|y| < 2$ by the physical extent of the muon chambers. We therefore present cross section measurements for the region $|y| < 2$, $p_T > 5$ GeV/c over which we have continuous non-zero acceptance. Because of this, the acceptance does not depend on Monte Carlo extrapolation and is approximately independent of the model used for J/ψ production. The detector acceptance is plotted as a function of the p_T and of the rapidity of the J/ψ in figures 2a and 2b respectively.

The measured differential cross sections times muonic branching fraction of the J/ψ , $B \cdot d\sigma/dp_T$ and $B \cdot d\sigma/d|y|$, are shown, corrected for the experimental acceptance, in figures 3a and 3b respectively. The rapidity distribution is symmetric, and so has been folded in figure 3b to reduce the statistical error. The error bars do not include the overall normalization error of 15% arising from the uncertainty in the total integrated luminosity. The shapes are compared with Monte Carlo calculations, normalized to the observed cross section for $|y| < 2$ and $p_T > 5$ GeV/c. (The absolute magnitudes of the Monte Carlo cross sections are less certain and are discussed in section 7). The steep slope of the J/ψ p_T spectrum is better reproduced by the direct process Monte Carlo calculation than by the indirect one. Similarly, the rather flat rapidity spectrum is closer to that expected for direct charmonium production, although the acceptance does not extend to the high values of rapidity where the differences between the two processes are greatest. We have attempted to determine the relative contributions of direct and indirect processes by fitting the data in figures 3a and 3b to simple sums of direct and indirect Monte Carlo distributions. The slope of the calculated $d\sigma/dp_T$ distribution is sensitive to the definition of Q^2 used in calculating the running coupling constant α_s . We have used the variation in slope for different choices of Q^2 scale to estimate a systematic contribution to the error on the fitted fractions. The results for the fraction of direct production are $1.15 \pm 0.14 \pm 0.22$ and $0.85 \pm 0.43 \pm 0.21$ from the p_T and rapidity distributions respectively. The value obtained from the p_T spectrum exceeds unity, since the slope of the data is greater than that of either model. However, within the uncertainties, the data are consistent with either complete direct production or a moderate indirect contribution.

Taking the whole region $p_T > 5$ GeV/c and $|y| < 2$, we obtain an overall cross section times branching fraction of:

$$B \cdot \sigma(p \bar{p} \rightarrow J/\psi \rightarrow \mu^+ \mu^-) = 7.5 \pm 0.7 \pm 1.2 \quad \text{nb},$$

where the first error is statistical and the second is systematic. The systematic error comes mainly from the uncertainty in the integrated luminosity, but also contains small contributions from the residual model dependence of the acceptance and from uncertainties in the simulation of the ranging out of muons in the detector. For subsequent studies to separate the contributions of the two mechanisms, where we are much less sensitive to the J/ψ acceptance, we use the full event sample with $|y| < 2$, $p_T > 4$ GeV/c.

5) Event topology

Direct and indirect J/ψ production show a qualitative difference in the correlation of the J/ψ with other hadrons. J/ψ 's from B hadron decays will normally be accompanied both by the other decay products of the B hadron and by the other fragmentation products of the parent b quark. In contrast, J/ψ 's from the decay of χ 's are expected to be isolated, accompanied only by the photon from the χ decay, with no fragmentation products. In addition, for indirect production, the recoil jet has to balance the transverse momentum of both the J/ψ and the additional decay and fragmentation products of the parent parton. Hence on average, recoil jets are expected to have somewhat higher transverse energy (E_T) in the indirect process than in the direct one.

The isolation of the J/ψ is particularly well suited to evaluating the relative contributions of the direct and indirect processes. It is not very sensitive to the p_T of the hard scatter, the amount of gluon radiation, the spectator fragmentation, or the efficiency for reconstructing very low energy jets. We study the isolation of the J/ψ using the charged hadron tracks seen in the central detector, rather than the energy depositions measured in the calorimeter, for the following reasons:

- i) the momentum and angular resolution are far better in the central detector than in the calorimeters at the low momenta concerned (typically $p_T \approx 1$ GeV/c),
- ii) background from secondary (e.g. beam pipe) interactions is readily excluded, as it does not point to the primary vertex,
- iii) the photon, the only other decay product of the χ , is automatically excluded, and
- iv) the muons from the J/ψ decay are identified and easily excluded.

In order to reduce the background from soft tracks from the spectator system, unrelated to the hard scatter, we make a $p_T > 1$ GeV/c cut, based on Monte-Carlo studies. The results are insensitive to the choice of p_T threshold.

In figure 4, we plot the number of charged tracks with $p_T > 1$ GeV/c per J/ψ event, for intervals of $(\Delta R)^2$ around the J/ψ direction, where :

$$(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$$

and $\Delta\eta$ ($\Delta\phi$) is the separation in pseudorapidity (azimuth) between the track and the J/ψ direction. If these tracks are uniformly distributed in η and ϕ , and are uncorrelated with the J/ψ direction, then their distribution in $(\Delta R)^2$ will be flat. Figures 4a, 4b and 4c show the background-subtracted data and the Monte Carlo calculations for the direct and indirect processes respectively. Two features are visible. The broad enhancement centred around $(\Delta R)^2 = \pi^2$, seen most clearly for the indirect processes, is due to a jet recoiling against the J/ψ . It is smeared out by the lack of correlation with the J/ψ in rapidity, and cut off at high $(\Delta R)^2$ by rapidity acceptance limits. The enhancement at $(\Delta R)^2 \approx 0$ in the distribution for the indirect process is due to the fragments of the b

quark and the decay products of the B hadron, the latter being the more important. No corresponding enhancement is expected or seen in the direct process distribution. Evidently both direct and indirect processes are required to explain the data. The numbers of tracks found in a cone of $(\Delta R)^2 < 1.0$ are used to estimate the contributions of the two processes to the data. The contribution from the underlying event, (spectator system and initial state radiation), which is flat in $(\Delta R)^2$, is in each case computed from the interval $2 < (\Delta R)^2 < 5$ and then subtracted. This makes the results independent of the detailed Monte Carlo simulation of the underlying event. A linear interpolation between the two Monte Carlo predictions gives $0.79 \pm 0.08 \pm 0.12$ as the fraction of direct production. The systematic error has been estimated by varying the value of ϵ_b used for the b quark fragmentation function from 0.004 to 0.08, and by varying the fraction of two body plus quasi-two body decays of the B hadrons from 25% to 75%.

The scalar sum of the transverse momenta (Σp_T) of all charged tracks (except the muons from the J/ψ) in a cone of $\Delta R < 0.7$ about the J/ψ direction is plotted in figure 5. This is sensitive to the soft tracks in the event. A large peak near zero can be seen in the data, corresponding to very isolated J/ψ 's typical of direct production processes. There are a smaller number of non-isolated events with a large Σp_T in the cone, typical of production via b quarks. Linear interpolation in the mean value, $\langle \Sigma p_T \rangle$, yields $0.73 \pm 0.08 \pm 0.15$ for the fraction of direct processes. The systematic error term results from sensitivity to the simulation of the underlying event, as well as b quark fragmentation and B hadron decay.

In figure 6 we plot the distribution in E_T of the jet with the highest value of E_T in each event. The low E_T region is sensitive to the calorimeter energy scale, the simulation of gluon radiation and spectator fragmentation, and the reconstruction efficiency for low energy jets. We therefore consider only the region of high E_T (>15 GeV), dominated by the jet recoiling against the J/ψ , where we expect the above systematic effects to be smaller. In this region, the efficiency and resolution for jet detection and reconstruction are good. The distribution for the indirect process (fig 6c) contains a larger proportion of high E_T jets than both the direct process distribution (fig 6b) and the data (fig 6a). In order to be able to extract the fraction of each contributing process, we count jets with $E_T > 15$ GeV. This gives $0.65 \pm 0.19 \pm 0.20$ as the fraction of direct production, which is consistent with the preceding estimates. The second error reflects the sensitivity to the E_T threshold, resulting from the systematic effects discussed above.

6) Additional features

Several other features in the data offer the possibility of discrimination between direct and indirect J/ψ production processes, and are described below. Though each suffers from limited statistics due to either low acceptance or additional branching fractions, all are consistent with the fraction of direct processes determined from the event topology.

(i) ψ' production

Observation of a ψ' signal would be evidence for beauty production. The B meson has been measured to decay into ψ' with a branching fraction of $0.5 \pm 0.23\%$ [11], consistent with the theoretically expected ratio of ψ' to J/ψ [21]. On the other hand, direct production of ψ' is expected to be small [8]: the χ states are too light to decay into ψ' , and their radial excitations would decay into open charm states. We estimate the contribution of ψ' decays from the fit to the $\mu^+\mu^-$ mass spectrum, described in section 2, to be 22 ± 12 events, where the error is statistical only. We have also searched for the decay $\psi' \rightarrow J/\psi \pi^+\pi^-$, finding 17 ± 15 events. If the whole J/ψ sample were indirectly produced, then we would expect to observe 18 ± 8 $\psi' \rightarrow \mu^+\mu^-$ and 36 ± 17 $\psi' \rightarrow J/\psi \pi^+\pi^-$ events, where the error comes from the uncertainty in the $B \rightarrow \psi'$ branching fraction. These measurements do not significantly constrain the fraction of $B \rightarrow J/\psi$ in the data.

(ii) Trimuons

When the J/ψ is produced indirectly, an additional muon can come from the semi-leptonic decay of the recoiling beauty hadron. No additional muons are expected from the direct production process beyond those coming from K or π decay. Experimentally, we observe no additional muons either with $p_T > 2$ GeV/c or with $p > 4$ GeV/c and $p_T > 0.75$ GeV/c. The estimated background from π and K decay is 0.4 events. The Monte Carlo predicts 3.0 ± 1.0 extra muons if all the J/ψ come from B hadron decay.

(iii) Photons

We have searched for the photons correlated with the J/ψ which would be expected from χ decay. The granularity of the detector is such that we cannot unambiguously identify photons or π^0 's at low energies. For this study, neutral, localized energy depositions in the electromagnetic calorimeter, with E_T in the range 1 to 2.5 GeV, are treated as photon candidates: their separations $(\Delta R)^2$ from the J/ψ direction are plotted in figure 7. In figure 7a, a small excess at low $(\Delta R)^2$ is seen in the data, similar to the one predicted from the χ Monte Carlo in figure 7b. Using the same method as described for figure 4, we estimate the fraction of direct production to be $0.52 \pm 0.50 \pm 0.20$, where the error reflects the low statistics.

(iv) K^0 production

J/ψ 's coming from B hadron decays are expected to be accompanied by additional strange particles [9]. K^0_s decays into charged pions are reconstructed in the central detector with an efficiency of approximately 25%. As for charged tracks, we make a cut of $p_T > 1$ GeV/c to reduce the contribution of K^0 's from the spectator system. In figure 8, the number of K^0 's is plotted as a function of the separation $(\Delta R)^2$ from the J/ψ direction. A correlation between the K^0 and the J/ψ for $(\Delta R)^2 < 1$ is seen in figure 8c for the indirect process Monte Carlo, but not for the direct one in figure 8b. A weak correlation is seen in the data in figure 8a, leading to an estimate of $0.34 \pm 0.35 \pm 0.16$ for the fraction of direct J/ψ production, calculated as described for charged

tracks in section 5. We have also searched for exclusive B meson decays in the $J/\psi K^0$ and $J/\psi K^0 \pi^\pm$ decay channels, with inconclusive results due to the low acceptance for K^0 's and the consequent low statistics.

7) Cross sections for the direct and indirect channels

The estimates of the fractions of direct J/ψ production are summarized in table 1. The best measurement $0.79 \pm 0.08 \pm 0.12$ comes from the calculation based on the number of $p_T > 1$ GeV/c tracks close to the J/ψ (figure 4). This is consistent with the other values listed in table 1, and is the least subject to systematic error. We have not taken an overall mean because there are correlations between some of the measurements. For the J/ψ 's with $p_T > 5$ GeV/c this fraction translates to $0.76 \pm 0.08 \pm 0.12$. Using our measured overall J/ψ cross section for $|\eta| < 2$, $p_T > 5$ GeV/c, we obtain a cross section times muonic branching ratio for J/ψ production via direct processes of $5.7 \pm 0.8 \pm 1.3$ nb, and $1.8 \pm 0.6 \pm 0.9$ nb for J/ψ production via beauty hadrons.

The UA1 Monte Carlo calculation of beauty production predicts a value of 1.8 nb for the indirect J/ψ production cross section times branching ratio, where most of the cross section comes from lowest order QCD processes. This same Monte Carlo reproduces satisfactorily the observed single muon and $M_{\mu\mu} > 6$ GeV/c² dimuon cross sections measured at $\sqrt{s} = 630$ GeV [10, 18]. The absolute calculation of Glover et al.[8] gives compatible values in the range 1.0 - 1.7 nb. Both these calculations are consistent with our experimental measurement. Our J/ψ measurement thus corroborates the lowest order cross section for beauty production deduced from the measured UA1 cross section for dimuon production [10].

Lacking any experimental measurement with which to compare the normalization of our Monte Carlo calculation of χ production, we prefer to compare our data with the published calculation of the cross section for J/ψ production via the direct process [8], which gives the range 0.7 to 2.4 nb. It is evident that the predictions for direct production fall well below the measured cross sections. The same theoretical calculation applied at ISR energies, where direct production is the only significant process, underestimated the J/ψ cross section by a factor of 2-4 [8]. Multiplying the predicted direct cross sections at $\sqrt{s} = 630$ GeV by the factor needed to reproduce the ISR measurements would also give consistency with the collider data. The discrepancy could perhaps be explained by an underestimate of the gluon structure function of the proton at very low x, or by contributions from higher order QCD processes.

8) Conclusions

We have observed the production of J/ψ particles at high transverse momentum at the CERN SPS collider. The measured cross section times muonic branching fraction is $7.5 \pm 0.7 \pm 1.2$ nb at

$\sqrt{s} = 630$ GeV in the region $p_T > 5$ GeV/c, $|\eta| < 2$. Approximately one quarter of J/ψ 's are produced close to other high p_T particles, which we interpret as evidence for J/ψ production via the decay of beauty hadrons, with a cross section times muonic branching fraction of $1.8 \pm 0.6 \pm 0.9$ nb. This is consistent with our measurements of the beauty production cross section in other channels. The majority of J/ψ 's are produced in isolation from other high p_T hadrons, which we interpret as evidence for direct charmonium production, probably via χ states. The corresponding cross section times muonic branching fraction of $5.7 \pm 0.8 \pm 1.3$ nb is larger than theoretical expectations.

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Measurement	Figure	Fraction
$d\sigma/dp_T$ (for $p_T > 5$ GeV/c)	3a	$1.15 \pm 0.14 \pm 0.22$
$d\sigma/d y $ (for $p_T > 5$ GeV/c)	3b	$0.85 \pm 0.43 \pm 0.21$
$p_T > 1$ charged tracks in $(\Delta R)^2 < 1$ cone	4	$0.79 \pm 0.08 \pm 0.12$
Σp_T in $\Delta R < 0.7$ cone	5	$0.73 \pm 0.08 \pm 0.15$
$E_T > 15$ GeV jets	6	$0.65 \pm 0.19 \pm 0.20$
γ candidates in $(\Delta R)^2 < 0.5$ cone	7	$0.52 \pm 0.50 \pm 0.20$
$K^{0'}$ s with $p_T > 1$ in $(\Delta R)^2 < 1$ cone	8	$0.34 \pm 0.35 \pm 0.16$

Table 1 Summary of calculated fractions of $p + \bar{p} \rightarrow \chi \rightarrow J/\psi$
(for $p_T > 4$ GeV/c, unless stated otherwise).

Figure Captions

- Figure 1** The effective mass distribution for $\mu^+\mu^-$ pairs (open histogram) and for $\mu^+\mu^+$ plus $\mu^-\mu^-$ pairs (shaded histogram). The fitted curve is described in section 2; the dashed line represents the fitted non-resonant background.
- Figure 2** The acceptance for detecting $J/\psi \rightarrow \mu^+\mu^-$ as a function of: a) p_T , for $|\eta| < 2$, and b) $|\eta|$, for $p_T > 5$ GeV/c.
- Figure 3a** The differential cross section, $B.d\sigma/dp_T$, for $p + \bar{p} \rightarrow J/\psi \rightarrow \mu^+\mu^-$ in the region $|\eta| < 2$, corrected for acceptance. The dashed lines show the Monte Carlo calculations described in the text, normalized to the data for $p_T > 5$ GeV/c.
- Figure 3b** The differential cross section, $B.d\sigma/d|\eta|$, for $p + \bar{p} \rightarrow J/\psi \rightarrow \mu^+\mu^-$ in the region $p_T > 5$ GeV/c, corrected for acceptance. The dashed lines show the Monte Carlo calculations described in the text, normalized to the data for $p_T > 5$ GeV/c.
- Figure 4** Distribution in $(\Delta R)^2$ of charged tracks with $p_T > 1$ GeV/c, per J/ψ , with respect to the J/ψ direction: a) data, b) Monte Carlo calculation for direct processes, c) Monte Carlo calculation for indirect processes.
- Figure 5** Σp_T for charged tracks within a cone of $\Delta R < 0.7$ around the J/ψ direction: a) data, b) Monte Carlo for direct processes, c) Monte Carlo for indirect processes. Each plot is normalized to the observed data sample of 247 events after background subtraction.
- Figure 6** Transverse energy distribution of the highest transverse energy calorimeter jet: a) data, b) Monte Carlo for direct processes, c) Monte Carlo for indirect processes. For each plot, the total number of events before making the cut $E_T(\text{jet}) > 7$ GeV is normalized to the observed data sample of 247 events after background subtraction.
- Figure 7** Distribution in $(\Delta R)^2$ of photon candidates with respect to the J/ψ direction: a) data, b) direct Monte Carlo, c) indirect Monte Carlo. In each case, the total number of Monte Carlo J/ψ events is normalized to the observed data sample of 247 events after background subtraction.

Figure 8 Distribution in $(\Delta R)^2$ of $p_T > 1$ GeV/c K^0 candidates with respect to the J/ψ direction: a) data, b) direct Monte Carlo, c) indirect Monte Carlo. In each case, the total number of Monte Carlo J/ψ events is normalized to the observed data sample of 247 events after background subtraction.

Figure 1

Figure 2a

Figure 2b

Figure 3a

Figure 3b

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8