J/ψ and ψ' Production at the CERN $p\bar{p}$ Collider*UA1 Collaboration, CERN, Geneva, Switzerland*

Aachen¹ - Amsterdam (NIKHEF)² - Annecy (LAPP)³ - Birmingham⁴ - Boston⁵ -
CERN⁶ - Helsinki⁷ - Kiel⁸ - Imperial College, London⁹ -
Queen Mary Westfield College, London¹⁰ - Madrid (CIEMAT)¹¹ - MIT¹² -
Padua¹³ - Paris (College de France)¹⁴ - Rome¹⁵ - Rutherford Appleton Lab¹⁶ -
Saclay (CEN)¹⁷ - UCLA¹⁸ - Vienna¹⁹ Collaboration

C. Albajar⁶, M.G. Albrow¹⁶, O.C. Allkofer^{8*}, K. Ankoviak¹⁸, R. Apsimon¹⁶,
B. Aubert³, C. Bacci¹⁵, S. Bartha⁸, G. Bauer⁵, A. Bettini¹³, A. Bezaguet⁶,
P. Biddulph¹⁰, H. Bohn⁸, A. Böhrer¹, R. Bonino⁶, K. Bos², M. Botlo⁶,
D. Brockhausen⁸, C. Buchanan¹⁸, B. Buschbeck¹⁹, G. Busetto¹³, A. Caner¹³,
P. Casoli¹³, H. Castilla-Valdez¹⁸, F. Cavanna³, P. Cennini⁶, S. Centro¹³,
F. Ceradini¹⁵, G. Ciapetti¹⁵, S. Cittolin⁶, E. Clayton⁹, D. Cline¹⁸, J. Colas³,
R. Conte¹³, J.A. Coughlan¹⁶, D. Dau⁸, C. Daum², M. Della Negra⁶, M. Demoulin⁶,
D. Denegri¹⁷, H. Dibon¹⁹, A. DiCiaccio¹⁵, F.J. Diez Hedo⁶, L. Dobrzynski¹⁴,
J. Dorenbosch², J. D. Dowell⁴, D. Drijard⁶, K. Eggert⁶, E. Eisenhandler¹⁰, N. Ellis⁴,
H. Evans¹⁸, H. Faissner¹, M. Felcini⁵, I.F. Fensome⁴, A. Ferrando¹¹, L. Fortson¹⁸,
T. Fuess¹², J. Garvey⁴, A. Geiser¹, A. Givernaud⁶, A. Gonidec⁶, B. Gonzalez^{18*},
J. M. Gregory⁴, J. Gronberg¹⁸, D.J. Holthuijzen², W. Jank⁶, G. Jorat⁶, M.I. Josa¹¹,
P.I.P. Kalmus¹⁰, V. Karimäki⁷, I. Kenyon⁴, R. Kinnunen⁷, M. Krammer¹⁹,
F. Lacava¹⁵, S. Lammel¹, M. Landon¹⁰, Y. Lemoigne¹⁷, S. Levegrün⁸, D. Linglin³,
P. Lipa¹⁹, C. Markou⁹, M. Markytan¹⁹, M.A. Marquina⁶, R. Martinelli¹³, G. Maurin⁶,
S. McMahon⁹, J.-P. Mendiburu¹⁴, A. Meneguzzo¹³, J. P. Merlo¹⁷, T. Meyer⁶,
T. Moers¹, M. Mohammadi¹⁸, K. Morgan⁵, A. Morsch⁸, A. Moulin¹, Th. Muller⁶,
R. Munoz⁶, L. Naumann⁶, P. Nedelec¹⁴, M. Nikitas⁴, A. Nisati¹⁵, A. Norton⁶, V.
O'Dell¹⁶, S. Otwinowski⁵, G. Pancheri¹², M. Passaseo¹⁵, F. Pauss⁶, E. Petrollo¹⁵,
G. Piano Mortari¹⁵, E. Pietarinen⁷, M. Pimiä⁷, A. Placci⁶, L. Pontecorvo¹⁵,
J.-P. Porte⁶, R. Priem¹, R. Prosi⁸, E. Radermacher⁶, M. Rauschkolb⁸, H. Reithler¹,
J.-P. Revol^{6,12}, S. Robins¹⁰, D. Robinson¹⁰, T. Rodrigo⁶, J. Rohlf⁵, C. Rubbia⁶,
G. Sajot¹⁴, J.M. Salicio¹¹, D. Samyn⁶, D. Schinzel⁶, R. Schleichert¹, M. Schröder²,
C. Seez⁹, T. P. Shah^{6,16}, P. Sphicas⁶, D. Stork¹⁸, C. Stubenrauch⁶, K. Sumorok¹²,
F. Szoncs¹⁹, C. H. Tan¹², A. Taurok¹⁹, L. Taylor⁹, S. Tether¹², H. Teykal¹,
G. Thompson¹⁰, E. Torrente-Lujan¹¹, H. Tuchscherer¹, J. Tuominiemi⁷,
W. van de Guchte², A. van Dijk², M. Vargas¹⁸, S. Veneziano¹⁵, J.P. Vialle³,
T.S. Virdee^{6,9}, W. von Schlippe¹⁰, J. Vrana¹⁴, V. Vuillemin⁶, K. Wacker¹,
H. Wagner¹, X. Wu¹², C.-E. Wulz¹⁹, M. Yvert³, I. Zacharov⁶, L. Zanello¹⁵,
Y. Zolnierowski¹³ and P. Zotto⁶.

(to be submitted to Phys. Lett. B)

(* deceased)

Abstract

We have measured the production cross-section times branching ratio for $J/\psi \rightarrow \mu^+\mu^-$ in $p\bar{p}$ interactions at $\sqrt{s} = 630$ GeV in the kinematic range $|\eta| < 2.0$ and $p_T > 5$ GeV/c, $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow J/\psi) = 6.18 \pm 0.24 \pm 0.81$ nb. The data sample collected in 1988 and 1989 for an integrated luminosity of 4.7 pb^{-1} represents a fivefold improvement over the statistics in our earlier study of the J/ψ production process, and the p_T distribution which is measured extends to 28 GeV/c. Using event topology we show that the rate for the direct production of J/ψ , via radiative decays of χ states, is larger than that for production via B-hadrons. Production of ψ' is also studied using the decay modes $\psi' \rightarrow \mu^+\mu^-$ and $\psi' \rightarrow J/\psi\pi^+\pi^-$.

1) Introduction

At collider energies J/ψ production at high transverse momentum, p_T , is expected to be dominated by two processes as discussed in a previous publication [1]. The first process is gluon fusion [2, 3, 4] to χ states:

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

with a small contribution from $g g \rightarrow g J/\psi$. The second process is the production and decay of B-hadrons [5]; one such channel is:

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

In the case of the ψ' , production through a χ -state is not kinematically possible, whereas all the other channels described are open. Thus the ψ' production cross-section is expected to have a large contribution from the production and decay of B-hadrons.

In an earlier publication [1] we reported on evidence for J/ψ production through χ and beauty decays at the CERN $p\bar{p}$ collider based on 280 $J/\psi \rightarrow \mu^+\mu^-$ events. We were able to separate the two contributions statistically by making use of the event topology. The J/ψ production cross-section times muonic branching ratio was measured at centre-of-mass energy $\sqrt{s} = 630$ GeV to be $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow J/\psi) = 7.5 \pm 0.7 \pm 1.2$ nb for $p_T > 5$ GeV/c and $|\eta| < 2.0$. The beauty channel was found to account for $(24 \pm 8 \pm 12)\%$ of the J/ψ production. Here, we report on the analysis of a five-times-larger data sample of J/ψ and, in addition, of ψ' particles produced at $\sqrt{s} = 630$ GeV during the $p\bar{p}$ collider runs of 1988 and 1989.

2) Data taking and analysis

A description of the UA1 detector and the muon trigger has been presented in ref. [6] and material quoted therein. The data discussed here were recorded in two collider runs in 1988 and 1989, corresponding to an integrated luminosity of 4.7 pb^{-1} at $\sqrt{s} = 630$ GeV. For these runs the electromagnetic calorimeter was removed in preparation for the expected installation of a new Uranium-TMP calorimeter. Consequently, the path length available for decays of pions and kaons between the interaction point and the calorimeter was increased from 1.3 m to more than 1.5 m perpendicular to the beam direction. Studies have shown that energy measurements with the iron-scintillator calorimeter have a 12% uncertainty in the energy scale [7].

Two levels of single muon and dimuon triggers were used to select the events used in the present analysis. The first-level trigger, using the pattern of hit tubes in the muon drift chambers, requires at least one muon candidate with a typical cutoff of $p_T > 2.5$

GeV/c; the second-level trigger, using drift-time information in addition, requires two muons with a typical cutoff of $p_T > 1.5$ GeV/c for both muons or a single muon with $p_T > 4.5$ GeV/c. An event filter was applied to preselect events with two candidate muons prior to full event reconstruction. A selection was then made with the following cuts:

- (i) At least two muon chamber tracks are required to match with the extrapolation of tracks measured in the central detector (CD) within multiple scattering and measurement errors.
- (ii) The CD tracks must have $p_T > 3$ GeV/c for the first muon and $p_T > 2$ GeV/c for the second muon. The dimuon mass must lie in the range $2 < m_{\mu\mu} < 5$ GeV/c² and the transverse momentum of the dimuon system must have $p_{T\mu\mu} > 5$ GeV/c.
- (iii) The muon candidates, if both in the same muon chamber module, must be separated by at least 40 cm in both coordinates in the module plane in order to be accepted.

The final sample contains 2060 unlike-sign dimuon candidates.

During the running periods of 1988 and 1989 the collider luminosity was above 10^{30} cm⁻²s⁻¹ for long spells and it was therefore necessary to run the CD with reduced gas gain. In consequence the resolution of the measurements in the current-division coordinate (parallel to the magnetic field) was worsened. However, by using the information from the muon drift chambers and, where available, from the limited streamer chambers [8], the resolution in this direction was improved to ± 1 cm at the location of the outer wall of the CD. The mass resolution on the J/ ψ peak is similar to that obtained with the previous detector setup [1].

Figure 1a shows the mass distribution for the unlike-sign dimuon pairs. A fit was made to this spectrum using a Gaussian shape for the J/ ψ , and a background whose shape was taken from a Monte Carlo prediction for the dimuon mass distribution resulting from heavy-flavour production with semileptonic decays; the ψ' mass region (3.5–4.0 GeV/c²) was excluded from the fit. The resulting fit is shown as the solid curve in fig. 1a, and gives $1246 \pm 39 \pm 15$ J/ ψ , where the systematic error was obtained by varying the background shape. The fitted mass of the J/ ψ is 3.098 ± 0.005 GeV/c² and the fitted width of the Gaussian is 0.148 ± 0.004 GeV/c².

A possible excess of events is observed in fig. 1a in the region of the ψ' mass around 3.7 GeV/c². In order to remove contributions from the tail of badly measured J/ ψ events, a cut is applied to the fractional error on the mass measurement, $\Delta m_{\mu\mu}/m_{\mu\mu} < 5\%$. The resulting mass distribution is shown in fig. 1b. A small excess of events is still visible, when compared to the well understood shape of the background due to heavy flavour production. In order to get the best estimate of the

number of ψ' events produced in the $\mu^+ \mu^-$ channel, a fit was made using Gaussian shapes for the J/ψ and ψ' , and a background with the shape described above. The J/ψ and ψ' widths were constrained to be equal and contributed one of the free parameters to be fitted, while the J/ψ to ψ' mass ratio was fixed at the PDG value [9]. The resulting fit is shown as the solid curve in fig. 1b, and gives $778 \pm 30 \pm 9$ J/ψ and $29 \pm 10 \pm 5$ ψ' . We use this result in section 7 where we discuss ψ' production. However, in order to maximize the J/ψ statistics, we do not impose the $\Delta m_{\mu\mu}/m_{\mu\mu} < 5\%$ cut for the J/ψ analysis discussed below.

In the following analysis we define the J/ψ signal region to be the mass interval 2.7–3.5 GeV/c², containing 1473 events (fig. 1a). In addition to the J/ψ signal there are backgrounds from open charm and beauty production followed by semi-leptonic decays, Drell-Yan production, as well as decays of kaons and pions in flight. Hadronic shower leakage through the 8 or more interaction lengths of material in the detector before the muon chambers is negligible. A pair of guard bands is used to select a sample of background events; these bands are 2.0–2.6 GeV/c² and 3.9–4.5 GeV/c². According to the results of the fit to fig. 1a, the numbers of background events in the signal and guard band regions are in the ratio 0.7 : 1.0. In all the distributions shown below for the data, a guard band subtraction has been applied. The plots therefore show the properties of the J/ψ events in the signal region.

3) Monte Carlo Calculations

The detailed simulation of the production and decay processes for the χ and beauty channels was based on the ISAJET Monte Carlo program [10] using EHLQ (set I) structure functions. The output was processed through a full simulation of the detector and subsequently the same reconstruction package as used for the data.

Beauty production was simulated as described in ref. [11]. The branching fractions for B-hadron decays to J/ψ and ψ' were taken to be $(1.12 \pm 0.18)\%$ and $(0.46 \pm 0.20)\%$ respectively [9], and the fractions of B-hadrons decaying to two-body and quasi two-body channels were taken to be 10% and 40%, based on measurements at e^+e^- machines [12]. The decay $\psi' \rightarrow J/\psi \pi^+ \pi^-$, discussed in section 7 below, was simulated with a p-wave amplitude which reproduces the experimentally observed two-pion mass spectrum [13]. The following branching fractions were used $BR(J/\psi \rightarrow \mu^+ \mu^-) = (6.9 \pm 0.9)\%$, $BR(\psi' \rightarrow \mu^+ \mu^-) = (0.77 \pm 0.17)\%$ and $BR(\psi' \rightarrow J/\psi \pi^+ \pi^-) = (32.4 \pm 3.2)\%$.

The production of J/ψ in χ decays via the process $g g \rightarrow g \chi$ was simulated by implementing the parton-parton differential cross-sections of Humpert [14] and the measured branching fractions for $\chi \rightarrow J/\psi \gamma$ [9] in the ISAJET program. We have checked that the shapes of these differential cross-sections agree with the predictions of

Gastmans et al. [15]. In addition we note that the resulting shapes of the p_T and $|\eta|$ distributions for the J/ψ are in agreement with the predictions of Glover et al. [4]. The reaction $g g \rightarrow \chi$, without additional gluons, does not give rise to J/ψ with high p_T and has not been considered. Direct J/ψ and ψ' production via $g g \rightarrow g J/\psi$ (ψ') are expected to have low cross-sections [4], and should possess event topologies similar to those for J/ψ coming from χ decay, and hence have not been 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 the iron absorber. In the central region of rapidity $|\eta| < 1.0$, this imposes an effective cut of about 2 GeV/c on the muon transverse momentum. Also, the trigger requires that at least one of the muons has $p_T > 2.5$ GeV/c. Motivated by these facts, the muons have been selected with $p_T > 3$ GeV/c for the first muon and $p_T > 2$ GeV/c for the second muon. Consequently only events with both muons on the same side of the beam and hence with a J/ψ transverse momentum of greater than about 4–5 GeV/c can be detected. The geometry of the muon chambers restricts the acceptance in the forward region to rapidity $|\eta| < 2.0$. We therefore present J/ψ cross-sections restricted to the kinematic range $|\eta| < 2.0$ and $p_T > 5.0$ GeV/c, where the acceptance is sufficiently large that its calculation with Monte Carlo samples is reliable. Over this kinematic region, the beauty and χ production mechanisms do not lead to very different shapes in rapidity so that the calculation of the acceptance from Monte Carlo samples is nearly model independent. We use a mixture of 69% χ and 31% beauty production for our acceptance calculations based on the measurements described in section 5 below.

After correction for the experimental acceptance, the measured J/ψ differential cross-section times the muonic branching fraction $BR d\sigma/dp_T$ is shown in fig. 2. The error bars include an overall 8% contribution arising from the uncertainty in the integrated luminosity and a 10% uncertainty on the acceptance. In fig. 2 we also show the Monte Carlo predictions for the two production processes and for the 69%–31% mixture, where all the curves are normalized to the data for $|\eta| < 2.0$ and $p_T > 5.0$ GeV/c. It is clear that the data show a steeper p_T distribution than any of the Monte Carlo curves. Since beauty production as a function of p_T is well understood [17], we conclude that our Monte-Carlo prediction for the p_T slope of the χ process does not agree with the data. The shape of the prediction is affected by theoretical uncertainties due to the choice of the gluon structure functions and of the Q^2 scale. It is not obvious however that a better choice will be enough to restore agreement with the data.

Taking the whole of the kinematic interval $p_T > 5.0$ GeV/c and $|\eta| < 2.0$, we obtain an overall cross-section times branching fraction of $BR(J/\psi \rightarrow \mu^+ \mu^-) \sigma(p\bar{p} \rightarrow J/\psi) =$

$6.18 \pm 0.24 \pm 0.81$ nb where the first error is statistical and the second is systematic. The systematic error comes from the uncertainty in the integrated luminosity, the trigger and reconstruction efficiency, and from the acceptance calculation for low- p_T muons.

5) Event topology

As pointed out in ref. [1], the difference between the beauty and χ production processes lies in the correlation of hadrons with the J/ψ direction. The J/ψ from beauty decays will normally be accompanied both by the other decay products of the B-hadron and by the other fragmentation products of the original b-quark. By contrast, the J/ψ from the decay of χ are expected to be isolated apart from a photon from the χ decay, with no fragmentation products. Furthermore, because the recoil jet in the beauty production process has to balance the transverse momenta of the J/ψ and its accompanying hadrons, the recoil jet will have on average higher transverse energy (E_T) than when the J/ψ comes from χ decay. In the following, we examine these different features of the data in turn, making a comparison with the Monte Carlo samples for the two production processes so as to extract the fractional contributions of the two processes.

The isolation of the J/ψ is particularly suitable for evaluating the fractions. It is not very sensitive to the details of the hard scattering process, the amount of gluon radiation, the spectator fragmentation or the efficiency of reconstructing low energy jets. We study the isolation of the J/ψ using the charged hadron tracks in the CD, rather than the energy deposition measured in the calorimeter, for the following reasons: (i) The photon from χ decay and the muon do not contribute. (ii) The momentum and angular resolution of the CD is better than that of the calorimeter for the low momentum of the particles involved (typically $p_T \sim 1$ GeV/c). (iii) Tracks originating from secondary interactions or from additional primary interactions are readily excluded. Monte Carlo studies show that soft hadrons from the underlying event can be eliminated by demanding that the tracks have $p_T > 1.0$ GeV/c, so this cut is also imposed.

In fig. 3 the number of charged tracks with $p_T > 1.0$ GeV/c per J/ψ event is plotted in intervals of the variable $(\Delta R)^2$ around the J/ψ direction. The definition of this variable is $(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2$, where $\Delta\eta$ ($\Delta\phi$) is the separation in pseudorapidity (azimuth) between the track and the J/ψ direction. If the tracks were uniformly distributed in pseudorapidity and azimuth, and uncorrelated with the J/ψ direction, then their distribution in $(\Delta R)^2$ would be flat. Figures 3a, 3b and 3c show the distributions for the data after background subtraction, and for the Monte Carlo predictions of the beauty and χ processes respectively. Two features are clear: A broad enhancement around $(\Delta R)^2 = \pi^2$ is due to the jet recoiling against the J/ψ , back-to-back in azimuth; it

is smeared out by the difference in the rapidities of the J/ψ and the recoil jet. The enhancement near $(\Delta R)^2 = 0$ in the beauty process is due to the fragments of the b -quark and the other decay products of the B -hadron, with the latter being more important. It is apparent that both production processes are required in order to reproduce the observed distribution. The number of tracks in the cone $(\Delta R)^2 < 1.0$ is used to estimate the contributions to the data. In each case the track count coming from the underlying event is first subtracted. Because the track distribution in the underlying event is flat, this number is computed from the track count in the region $2.0 < (\Delta R)^2 < 5.0$. A linear interpolation between the two Monte Carlo predictions gives $F = 0.31 \pm 0.02 \pm 0.12$ as the fraction of J/ψ from the beauty process. Here the systematic error has been estimated by varying the value of the Peterson et al.[16] fragmentation parameter ϵ_b from 0.004 to 0.080 and by varying the fraction of two-body plus quasi two-body decays of the B -hadrons from 25% to 75%.

We have also measured the beauty fraction using the distribution of the scalar sum of the transverse momenta of charged tracks in a cone of $\Delta R < 0.7$ about the J/ψ direction ($F = 0.32 \pm 0.05 \pm 0.15$) and the distribution in E_T of the jet with the highest E_T in each event ($F = 0.52 \pm 0.05 \pm 0.20$). A study of K_S^0 production correlated with the J/ψ direction gives $F = 0.50 \pm 0.32 \pm 0.16$. Since the systematic errors are partially correlated, we do not combine the results from the different methods, but take only the one from the number of charged tracks with $p_T > 1.0$ GeV/c around the J/ψ direction which we believe to be the most reliable: $F = 0.31 \pm 0.02 \pm 0.12$. The other results are compatible with this value.

When the J/ψ comes from beauty production an additional muon can result from the semi-leptonic decay of the recoiling B -hadron. On the other hand no extra muon is expected from the χ process. Enlarging the J/ψ sample by removing the $p_{T\mu\mu} > 5$ GeV/c requirement, we observe 5 events in the signal region with an additional muon having $p_T > 2$ GeV/c, and 3 events in the guard bands. If all the J/ψ had originated from B -hadron decays, we would expect to see about 15 events in the signal region with additional muons from semileptonic B -hadron decays. The observed number of events is thus consistent with the above measured beauty fraction.

6) Cross-sections for the beauty and direct processes

Using the measured overall cross-section for J/ψ production for $|\eta| < 2.0$ and $p_T > 5$ GeV/c, $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow J/\psi) = 6.18 \pm 0.24 \pm 0.81$ nb, and the measured beauty fraction $F = 0.31 \pm 0.02 \pm 0.12$ we obtain the cross-section times muonic branching ratio $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow b \rightarrow J/\psi) = 1.92 \pm 0.15 \pm 0.79$ nb for inclusive J/ψ production from beauty decays. We estimate by Monte Carlo simulation that $(25 \pm 10)\%$ of this cross-section is due to the decay chain $b \rightarrow \psi' \rightarrow J/\psi$. For

comparison, Glover et al. calculate cross-sections in the range $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow b \rightarrow J/\psi) = 1.5\text{--}2.3$ nb [4]. Using $BR(J/\psi \rightarrow \mu^+\mu^-) = (6.9 \pm 0.9)\%$, our measurement corresponds to $\sigma(p\bar{p} \rightarrow b \rightarrow J/\psi) = 28 \pm 2 \pm 12$ nb for the same cuts on p_T and y . A cross-section for b-quark production is derived from this measurement in a separate paper [17].

The cross-section times branching fraction for direct J/ψ production with $p_T > 5$ GeV/c and $|y| < 2.0$ (including J/ψ from radiative χ decays) is similarly calculated from our measurements to be $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow J/\psi) = 4.26 \pm 0.21 \pm 0.89$ nb. For this process, using a K-factor of 2 in order to reproduce measurements from the ISR, Glover et al. [4] predict 2.8–4.2 nb, depending on the choice of the structure functions.

7) The ψ' signal

Two processes are responsible for ψ' production. The first of these is:

$$g g \rightarrow g \psi'.$$

The second process is the production and decay of B-hadrons [5]; one such channel is:

$$\begin{aligned} g g &\rightarrow b \bar{b} \\ &\rightarrow \text{B-hadron} + X \\ &\rightarrow \psi' + X. \end{aligned}$$

The branching ratio for producing ψ' in beauty decays is about 40% of the one for decays to J/ψ [9], whilst the direct ψ' production cross-section is calculated to be lower by an order of magnitude compared to the corresponding cross-section for J/ψ [18]. Therefore the beauty production mechanism is expected to account for a large fraction of ψ' production given the beauty fraction of $(31 \pm 2 \pm 12)\%$ presented above for J/ψ production.

From the fit to the invariant mass distribution of fig. 1b, we got an estimate of the number of $\psi' \rightarrow \mu^+\mu^-$ decays, $29 \pm 10 \pm 5$, compared to $778 \pm 30 \pm 9$ $J/\psi \rightarrow \mu^+\mu^-$ decays. We then estimate a production cross-section times muonic branching fraction for ψ' of $BR(\psi' \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow \psi') = 0.18 \pm 0.06 \pm 0.04$ nb for $|y| < 2.0$ and $p_T > 5.0$ GeV/c. Taking $BR(\psi' \rightarrow \mu^+\mu^-) = 0.77 \pm 0.17\%$, this corresponds to $\sigma(p\bar{p} \rightarrow \psi') = 23 \pm 8 \pm 8$ nb for the same p_T and $|y|$ cuts.

A second estimate of ψ' production has been obtained from a search for the decay sequence:

$$\begin{aligned} \psi' &\rightarrow J/\psi \pi^+ \pi^- \\ &\rightarrow \mu^+ \mu^- \end{aligned}$$

In the search we have used the mass-difference parameter $\Delta m = m(J/\psi \pi^+ \pi^-) - m(J/\psi)$ which has the advantage that uncertainties in the J/ψ mass measurement cancel. Any ψ'

events give a peak in the Δm distribution centred at $0.589 \text{ GeV}/c^2$. Figure 4 shows the Δm distributions for unlike-sign (fig. 4a) and like-sign (fig. 4b) pion combinations with the J/ψ , where we have enlarged the J/ψ sample by removing the $p_{T\mu\mu} > 5 \text{ GeV}/c$ requirement; the ψ' candidate is required to have $p_T > 5 \text{ GeV}/c$. The following cuts have been applied for entries to fig. 4: (i) the pion momenta must exceed $0.5 \text{ GeV}/c$, (ii) the separation of the pions with respect to the J/ψ direction must satisfy $\Delta R < 1.0$, the invariant mass of the two-pion system must be more than $0.35 \text{ GeV}/c^2$, and (iii) the cosine of the decay angle of the J/ψ in the rest frame of the ψ' must be less than -0.1 . The decay angle and momentum cuts suppress the background coming from low-momentum pions in the underlying event. The full lines shown in fig. 4 are Monte-Carlo predictions for the combinatorial background surviving the above cuts, when the J/ψ is produced in B-hadron decays (see section 3).

There is a peak in fig. 4a at $\Delta m = 0.58 \pm 0.03 \text{ GeV}/c^2$ indicating the presence of a ψ' signal. To estimate the number of ψ' events in the peak we use two background shapes: The Monte-Carlo shape (full line fig. 4a) or the like-sign distribution (fig. 4b). In both cases the background is normalized to the data in the control region above the ψ' peak, $\Delta m > 0.70 \text{ GeV}/c^2$. The dashed line in fig. 4b gives the shape of the unlike-sign Monte-Carlo combinatorial background for comparison with the like-sign background; the difference is small. Gaussian fits to fig. 4a using the two different background shapes lead to the best estimate of the number of ψ' events : $25 \pm 5 \pm 4$, where the first error is statistical and the second error is the systematic error due to the background uncertainty.

A Monte Carlo simulation of the production of ψ' in beauty decays followed by $\psi' \rightarrow J/\psi \pi^+ \pi^-$ has been performed to estimate of the acceptance corresponding to the cuts of fig. 4. From the observed number of events, we obtain $BR(J/\psi \rightarrow \mu^+ \mu^-)BR(\psi' \rightarrow J/\psi \pi^+ \pi^-)\sigma(p\bar{p} \rightarrow \psi') = 0.82 \pm 0.16 \pm 0.20 \text{ nb}$ for $|\eta| < 2.0$ and $p_T > 5.0 \text{ GeV}/c$. Using the branching ratios given in section 3, this corresponds to $\sigma(p\bar{p} \rightarrow \psi') = 37 \pm 8 \pm 11 \text{ nb}$ for the same p_T and $|\eta|$ cuts, which is consistent with the result given above from the $\psi' \rightarrow \mu^+ \mu^-$ channel. We average the two results to obtain $\sigma(p\bar{p} \rightarrow \psi') = 28 \pm 9 \text{ nb}$, where statistical and systematic errors have been combined in quadrature.

It is interesting to compare the cross-section $\sigma(p\bar{p} \rightarrow \psi') = 28 \pm 9 \text{ nb}$ (expected to be mainly due to beauty decays) with the cross-section for inclusive J/ψ production from beauty decays $\sigma(p\bar{p} \rightarrow b \rightarrow J/\psi) = 28 \pm 2 \pm 12 \text{ nb}$, where both cross-sections are for $p_T (J/\psi \text{ or } \psi') > 5 \text{ GeV}/c$ and $|\eta| < 2.0$. Allowing for the higher average p_T of the ψ' compared to the J/ψ in beauty decays, one would expect the ratio of these cross-sections to be 0.44 ± 0.23 assuming no direct ψ' production, compared to 1.0 ± 0.5 measured. The quoted error on the expectation comes from the uncertainty on the branching ratios for J/ψ and ψ' production in beauty decays. Given that a small

contribution ($\sigma(p\bar{p} \rightarrow \psi') \approx 4 \text{ nb}$ [18]) is also expected from directly produced ψ' , the relative production rates of ψ' and J/ψ are consistent within the large statistical and systematic errors, although the measured value is somewhat higher than predicted.

8) Conclusions

We have measured the cross-section for the production of J/ψ particles at the CERN $p\bar{p}$ collider. The measured cross-section times muonic branching fraction for J/ψ production at $\sqrt{s} = 630 \text{ GeV}$ in the range $p_T > 5 \text{ GeV}/c$ and $|\eta| < 2.0$ is $BR(J/\psi \rightarrow \mu^+\mu^-)\sigma(p\bar{p} \rightarrow J/\psi) = 6.18 \pm 0.24 \pm 0.81 \text{ nb}$.

The evidence from the correlation of hadrons, including K_S^0 's, with the J/ψ direction and from the recoil-jet E_T distribution indicates that a fraction of the J/ψ production is from the fragmentation and decay of b-quarks. The fraction of the J/ψ production due to the beauty process is estimated to be $F = 0.31 \pm 0.02 \pm 0.12$.

The transverse momentum distribution has been measured in the range 5–28 GeV/c . The data show a steeper p_T distribution than the Monte Carlo prediction for the measured mixture of production processes 69%(χ)–31% (beauty).

The cross-sections inferred for production via beauty decays and for direct charmonium production are in reasonable agreement with QCD predictions. However, it is worth noting that the predictions for the direct charmonium production process with which we compare our data include a K -factor of 2 which is also needed to reproduce data from the ISR.

Production of ψ' is observed in the decay channel $\psi' \rightarrow J/\psi \pi^+ \pi^-$. Consistent results are observed in the $\psi' \rightarrow \mu^+ \mu^-$ channel. The observed production rate for ψ' is consistent within errors with the expectation for ψ' production from beauty decays alone.

Acknowledgements

We are grateful to the management and staff of CERN and of all participating Institutions for the vigorous support of this experiment. The following funding agencies have contributed to this programme:

Fonds zur Förderung der Wissenschaftlichen Forschung, Austria;
Valtion luonnontieteellinen toimikunta, Suomen Akatemia, Finland;
Institut National de Physique Nucléaire et de Physique des Particules, and
Institut de Recherche Fondamentale (CEA), France;
Bundesministerium für Forschung und Technologie, Fed. Rep. Germany;
Istituto Nazionale di Fisica Nucleare, Italy;
Science and Engineering Research Council, United Kingdom;
Stichting Voor Fundamenteel Onderzoek der Materie, The Netherlands;
Centro de Investigaciones Energetica, Medioambientales y Tecnológicas
(CIEMAT), Spain;
Department of Energy, United States of America.

Thanks are due to the following people who have worked with the Collaboration in the preparation for and data collection on the runs described here: L. Baumard, F. Bernasconi, D. Brozzi, V. Cecconi, L. Dumps, G. Fetchenhauer, G. Gallay, S. Lazic, J.C. Michelon, S. Pavlon and L. Pollet.

References

- [1] C. Albajar et al., (UA1 Collab.), Phys. Lett. **B200** (1988) 380.
- [2] R. Baier and R. Rückl, Nucl. Phys. **B208** (1982) 381.
- [3] F. Halzen et al., Phys. Rev. **D30** (1984) 700.
- [4] E. W. N. Glover, A. D. Martin and W.J. Stirling, Z. Phys. **C38** (1988) 473.
- [5] F. Fritzsche, Phys. Lett. **B86** (1979) 164; **B86** (1979) 343.
- [6] C. Albajar et al., (UA1 Collab.), Z. Phys. **C38** (1990) 1.
- [7] UA1 technical note TN 89-29 (unpublished).
- [8] G. Bauer et al., Nucl. Instrum. Methods **A253** (1987) 179.
- [9] Review of Particle Properties, Phys. Lett. **B204** (1988) 1.
- [10] F. Paige and S.D. Protopopescu, ISAJET Monte Carlo, BNL 38034 (1986).
- [11] C. Albajar et al., (UA1 Collab.), Z. Phys. **C37** (1988) 489.
- [12] H. Albrecht et al., Phys. Lett. **B199** (1987) 451.
M. S. Alam et al., Phys. Rev. **D34** (1986) 3279.
C. Bebek et al., Phys. Rev. **D36** (1987) 1289.
- [13] G. S. Abrams, Proc. Int. Symp. on Lepton and Photon Interactions at High Energies (1975), Ed. W. T. Kirk.
M. Oreglia et al., Phys. Rev. Lett. **45** (1980) 959.
- [14] B. Humpert, Phys. Lett. **B184** (1987) 105.
- [15] R. Gastmans, W. Troost and T. T. Wu, Phys. Lett. **B184** (1987) 257.
- [16] C. Peterson et al., Phys. Rev. **D27** (1983) 105.
- [17] C. Albajar et al., (UA1 Collab.), preprint CERN-PPE/90-155.
- [18] Based on ref. [4] and a private communication from N. Glover.

Figure Captions.

Figure 1: The effective mass distribution for unlike-sign muon pairs: (a) before cutting on $\Delta m/m$, and (b) after cutting on $\Delta m/m$. Results of fitting to the data are shown (see text).

Figure 2: The differential cross-section $BR(J/\psi \rightarrow \mu^+\mu^-)d\sigma/dp_T$, for $p\bar{p} \rightarrow J/\psi$ in the region $|\eta| < 2.0$. The curves show the Monte Carlo predictions described in the text and normalized to the data for $p_T > 5.0$ GeV/c: χ decays (dashed line), beauty decays (dotted line), 69%–31% mixture of χ and beauty decays (solid line).

Figure 3: The distribution in $(\Delta R)^2$ of charged tracks with $p_T > 1.0$ GeV/c per J/ψ event for: (a) the data, (b) the beauty process Monte Carlo, and (c) the χ process Monte Carlo.

Figure 4: The mass-difference spectrum $\Delta m = m(J/\psi \pi \pi) - m(J/\psi)$ (a) for pairs of unlike-sign pions, (b) for pairs of like-sign pions. The full lines are Monte-Carlo predictions for the expected distributions without ψ' production. The dashed line is the Monte-Carlo unlike sign distribution superimposed to the like-sign distribution for comparison.

FIG. 1

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 4