**MEASUREMENT OF THE INCLUSIVE J/ψ PRODUCTION CROSS-SECTIONS
IN $\bar{p}p$ AND pp COLLISIONS AT $\sqrt{s} = 24.3$ GeV**

UA6 Collaboration

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ABSTRACT

The inclusive cross-section times branching ratio for $J/\psi \rightarrow e^+e^-$ has been measured in the forward region in the UA6 experiment for $\bar{p}p$ and pp collisions at $\sqrt{s} = 24.3$ GeV. The ratio of the pp to $\bar{p}p$ cross-sections is found to be $0.76 \pm 0.14 \pm 0.06$. This demonstrates that gluon–gluon fusion dominates over quark–antiquark annihilation in the formation of the $c\bar{c}$ state.

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1. INTRODUCTION

The cross-section for J/ψ production in hadron-hadron collisions is expected to depend on the gluon content and, at Super Proton Synchrotron (SPS) energies, to a lesser extent on the quark content of the hadrons. It is therefore sensitive to the quark and gluon distribution functions at a scale $Q^2 \approx m_{J/\psi}^2$. In the UA6 experiment, the cross-sections for inclusive J/ψ production are measured at $\sqrt{s} = 24.3$ GeV with either the proton beam or the antiproton beam, stored in the SPS Collider, interacting with an internal hydrogen-jet target. The J/ψ is observed through its e^+e^- decay mode. An integrated luminosity of 541 nb^{-1} in $\bar{p}p$ collisions was collected during 1985, and 1497 nb^{-1} in pp collisions during 1986.

2. APPARATUS

The experiment (fig. 1) is located in a straight section of the CERN SPS tunnel. A hydrogen-jet target provides a collimated stream of clusters of hydrogen molecules with a density of 4×10^{14} protons per cubic centimetre. The width of the jet at the beam position is 4 mm and its length is 8 mm. This gives an instantaneous luminosity of $5.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ for a circulating beam of 4×10^{10} particles in the SPS ring, which is typical of stored antiprotons. The luminosity is monitored with four silicon detectors [1] by counting protons recoiling near 90° from elastic scattering in the laboratory frame.

The apparatus consists of a double-arm magnetic spectrometer with a vertical field and a bending power of 2.3 T·m. Each arm includes five multiwire proportional chambers (MWPCs), two in front of the magnet and three behind it, a transition radiation detector (TRD), and an electromagnetic calorimeter. Each MWPC has three anode planes with wires at 90° and $\pm 30^\circ$ from the vertical. For the front chambers, the wire spacing is 2 mm; for the rear chambers it is 3 mm. The TRD is made of a lithium-foil radiator immersed in a helium atmosphere, followed by a He-Xe-CO₂ MWPC [2]. The calorimeter is of the gas-proportional-tube sampling type [3]. It consists of 30 lead plates, 4 mm thick, interleaved with alternating layers of vertical and horizontal proportional tubes operating at a gas multiplication of about 1000. Each tube is 1 cm in the transverse direction and has a thickness of 0.5 cm. The calorimeter is divided into three identical modules (A, B, and C), each of which is 8 radiation lengths or 0.25 nuclear interaction length thick. Test-beam results with electrons show linear energy response from 10 to 100 GeV. These results also show an energy resolution of $\sigma_E = 0.33 \sqrt{E} \text{ (GeV)}^{1/2}$ and a spatial resolution (r.m.s.) that improves from 4.8 mm at 3 GeV to 1.7 mm at 70 GeV. The absolute energy scale of the calorimeter is established by adjusting the reconstructed π^0 and η masses. Each arm covers opening angles from 20 to 100 mrad in the laboratory frame and about 70° in azimuth for a total acceptance of 1.8 sr per arm.

A hodoscope of seven horizontal scintillation counters is located between the first and second modules of the calorimeter. Signals from the phototubes at each end of a counter are summed and discriminated with increasing thresholds as the distance from the counter to the beam decreases. The two electrons from J/ψ decay are found predominantly one in each arm.

The trigger therefore consisted of any coincidence between a counter in the top arm and a counter in the bottom arm.

3. DATA ANALYSIS

Charged-particle track reconstruction is performed using projection algorithms based on the information given by the three MWPCs behind the magnet. The centre of the jet is used as the projection point in the side view, and projection points in the top view are the positions of energy clusters in the calorimeter. Assuming that the centre of the jet is the vertex of the J/ψ decay, the resolution on the invariant mass of the electron pair is $140 \text{ MeV}/c^2$.

The J/ψ candidates are the pairs of tracks, one in each arm and with momenta $10 < p < 100 \text{ GeV}/c$, which are associated with energy clusters in at least the first two modules of the calorimeter (AB and ABC cluster types). The cuts applied to the data were studied with a sample of electrons which had been identified using the TRD.

Cuts on the differences between vertical and horizontal projections of the impact position of the track and the associated cluster position in module A provide good background suppression. Cuts are set at 2 standard deviations for the matching of both vertical and horizontal positions, i.e. $|\text{vertical-position match}| < 4.5 \text{ mm}$ and $|\text{horizontal-position match}| < 3.5 \text{ mm}$, resulting in an efficiency of 90% per electron.

In each calorimeter module, the energies of the vertical and horizontal clusters associated with the track are summed, taking into account the sharing with other clusters. The sum over the three modules then gives the calorimeter energy associated with the spectrometer track. Spectrometer and calorimeter information is used to get a normal energy-match distribution (ESD). The parameter ESD is the difference between the track momentum and the associated calorimeter energy divided by the estimated resolution on the difference :

$$\text{ESD} = \frac{p_{\text{spect}} - E_{\text{cal}}}{\sqrt{\sigma_p^2 + \sigma_E^2}} .$$

The resolution of the spectrometer $\sigma_p = 1.44 \times 10^{-3} p^2 (\text{GeV}/c)^{-1}$ worsened, owing to the high multiplicity of hit wires, to $\sigma_p = 2.10 \times 10^{-3} p^2 (\text{GeV}/c)^{-1}$ per electron. A cut on ESD set at 2 standard deviations leads to an efficiency of 95% per electron and provides good electron-hadron discrimination, as well as a rejection of the background of charged particles that do not come from the jet.

Further hadron rejection is obtained by making a cut on the ratio of the energy deposited in module A to the total energy of the cluster in the calorimeter, E_A/E_{tot} . An efficiency of 95% per electron is obtained with the cut $E_A/E_{\text{tot}} > 0.35$.

The direction of an electron is given by the spectrometer, whereas its momentum is a weighted average of the momentum measured in the spectrometer and the energy deposited in the calorimeter, according to their respective resolution.

The measured chamber efficiency is 97% per plane. Overall reconstruction efficiency is determined by a hybrid Monte Carlo method, injecting generated $J/\psi \rightarrow e^+e^-$ into real data and

analysing them in the same way as the normal data. About 6% of the electrons are lost owing to the requirement of having AB and ABC types of clusters, and less than 1% of the surviving electrons are lost because of the track momentum restriction to $10 < p < 100 \text{ GeV}/c$. The measured overall reconstruction efficiency amounts to 55% per J/ψ . About 5% of the events, in which more than 1500 wires were hit, were truncated during data acquisition; these events were subsequently rejected during reconstruction.

The geometrical acceptance is estimated, as a function of centre-of-mass rapidity and p_T , with J/ψ 's generated uniformly in (y, p_T) by Monte Carlo and distributed within bins of 0.05 unit in rapidity and 0.1 GeV/c in p_T . The accepted rapidity region is $-0.5 < y < 1.2$.

Triggering conditions were monitored on a run-by-run basis, since discriminator thresholds and photomultiplier gains varied. The trigger efficiency is estimated for each trigger condition as a function of the centre-of-mass rapidity and p_T . The average efficiency of the trigger was around 55%.

A J/ψ is defined as an e^+e^- pair having an invariant mass between 2.8 and 3.3 GeV/c^2 . This restriction causes a 10% loss of real detected J/ψ , as shown by the hybrid Monte Carlo simulation in which bremsstrahlung has been included. The hybrid Monte Carlo simulation also shows that the combinatorial background of the unlike-sign mass spectrum is well reproduced by the like-sign mass spectrum. This is also confirmed by a sample of electron pairs triggered by the TRD: below the J/ψ peak, the like- and unlike-sign mass spectra agree in shape and magnitude. The number of J/ψ candidates is therefore obtained by subtracting the like-sign from the unlike-sign invariant mass spectra in the mass region between 2.8 and 3.3 GeV/c^2 (fig. 2). Within the rapidity window $0 < y < 1$, where the acceptance is significant, the number of J/ψ candidates extracted is (87 ± 10) from an integrated luminosity of 540.7 nb^{-1} in the $\bar{p}p$ run, and (146 ± 14) from 1496.9 nb^{-1} in the pp run.

Each J/ψ candidate is corrected by its geometric acceptance and trigger efficiency according to its measured rapidity and p_T . The average geometrical acceptance over the (y, p_T) region covered by the experiment is about 15%.

Agreement between the data and hybrid Monte Carlo is found for the shape of the J/ψ mass spectrum, for the distribution of the rear chamber wire multiplicity for J/ψ events, and for the distribution of the Gottfried–Jackson angle for accepted e^+e^- pairs decaying isotropically from a J/ψ . In all cases, an acceptable agreement was found for both pp and $\bar{p}p$ data.

The total systematic uncertainty on $\sigma \cdot \text{BR}(J/\psi \rightarrow e^+e^-)$ is 7%. This uncertainty is the quadratic combination of the following contributions: 4% error in the luminosity monitoring; 2% error in the Monte Carlo evaluation of the geometric acceptance and the trigger efficiency; 4% error in the track reconstruction efficiency owing to the 1% uncertainty in the average MWPC plane efficiency; 3% error introduced by the cuts for selecting electrons; 1% error due to the truncation, during data acquisition, of events in which more than 1500 wires were hit in

the MWPCs. Other contributions, e.g. uncertainty in the absolute position of the calorimeter, have been found to be negligible.

4. CROSS-SECTION MEASUREMENT AND COMPARISONS

The product of the cross-section for inclusive J/ψ production integrated over rapidity from 0 to 1 and the branching ratio into e^+e^- is $(5.1 \pm 0.7 \pm 0.4)$ nb for $\bar{p}p$ and $(3.9 \pm 0.5 \pm 0.3)$ nb for pp . The average p_T is (0.9 ± 0.2) GeV/c in $\bar{p}p$ and (1.1 ± 0.2) GeV/c in pp . The data have been extrapolated to the full forward hemisphere, using the Bourquin–Gaillard parametrization [4]. The results are $(5.9 \pm 0.8 \pm 0.4)$ nb for $\bar{p}p$ and $(4.5 \pm 0.5 \pm 0.3)$ nb for pp .

In the mass region between 4 and 8 GeV/ c^2 , a predominance of unlike-sign pairs over like-sign pairs is observed. This excess amounts to (4 ± 2) pairs for the $\bar{p}p$ run and (8 ± 3) pairs for the pp run. This allows a crude estimate to be made of the inclusive production of Drell–Yan pairs within this mass range: $(71 \pm 36 \pm 21)$ pb and $(51 \pm 21 \pm 15)$ pb for the $\bar{p}p$ and pp production, respectively. The latter estimate agrees with the value of 45 nb expected from the CFS parametrization [5] for Drell–Yan production under the conditions of our experiment. In the mass window between 2.8 and 3.3 GeV/ c^2 used for extracting the J/ψ cross-sections, at most three Drell–Yan pairs are expected in the pp data, but they have not been subtracted from the J/ψ signal.

Our $\sigma \cdot \text{BR}(J/\psi \rightarrow e^+e^-)$ values in the forward hemisphere are compared with results from other experiments: fig. 3 [6–10]; fig. 4 [6, 11–15]; fig. 5 [11, 13, 16]; we obtain good agreement with them.

For the ratio of $\sigma(pp \rightarrow J/\psi + X)$ to $\sigma(\bar{p}p \rightarrow J/\psi + X)$ in the forward hemisphere at $\sqrt{s} = 24.3$ GeV, the UA6 measurement gives $0.76 \pm 0.14 \pm 0.06$. Our result is compared (fig. 6) with other available experimental data [11, 13] and with the predictions of a simple QCD model of open-charm production [17], which mixes quark–antiquark annihilation and gluon–gluon fusion mechanisms and uses the parametrization of the Duke–Owens set 1 of the structure functions [18]. At our energy the prediction for this ratio is 0.75, in excellent agreement with our measurement: $\sigma(q\bar{q})/\sigma(gg)$ is about 0.19 for pp and about 0.58 for $\bar{p}p$. As shown in fig. 6, the gluon contribution is essential: the near equality of the J/ψ cross-sections in $\bar{p}p$ and pp interactions demonstrates that $q\bar{q}$ annihilation is not a dominant mechanism in J/ψ production.

5. CONCLUSION

We have observed a clear J/ψ signal in $\bar{p}p$ and pp collisions at $\sqrt{s} = 24.3$ GeV. The cross-sections times e^+e^- branching ratio for inclusive J/ψ production in the rapidity region $0 < y < 1$ are $(5.1 \pm 0.7 \pm 0.4)$ nb for $\bar{p}p$ and $(3.9 \pm 0.5 \pm 0.3)$ nb for pp . They are compatible with other experiments. Our measured ratio $\sigma(pp \rightarrow J/\psi + X)/\sigma(\bar{p}p \rightarrow J/\psi + X) = 0.76 \pm 0.14 \pm 0.06$ is in good agreement with a naïve open-charm QCD production estimate. It suggests that the gluon contribution dominates in J/ψ hadroproduction.

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Figure captions

- Fig. 1** Layout of the UA6 experiment in the SPS tunnel.
- Fig. 2** Invariant mass distributions for unlike-sign pairs (solid line) and like-sign pairs (hatched area).
- Fig. 3** Comparison of pp differential cross-sections times e^+e^- branching ratio for inclusive J/ψ production at $y = 0$ versus $\sqrt{s}$.
- Fig. 4** Comparison of pp cross-sections times e^+e^- branching ratio for inclusive J/ψ production in the forward hemisphere versus $\sqrt{s}$.
- Fig. 5** Comparison of $\bar{p}p$ cross-sections times e^+e^- branching ratio for inclusive J/ψ production in the forward hemisphere versus $\sqrt{s}$.
- Fig. 6** Ratio $\sigma(pp \rightarrow J/\psi + X)/\sigma(\bar{p}p \rightarrow J/\psi + X)$. The solid line shows the result of a simple open-charm model [17] with both the gluon-gluon and the quark-antiquark fusion contributions. The dashed line represents the quark-antiquark contribution alone.

Fig. 1

Fig. 2

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