Search for additional muons in hadronic production of J/ψ particles

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A sample of $J/\psi \rightarrow \mu^+\mu^-$ decays produced by a 225-GeV/c π^- beam on nuclear targets has been analyzed for extra muons. Muons observed in coincidence with J/ψ production could indicate either the production of charmed particles or the production of pairs of J/ψ particles. We find 90% confidence limits of $\sigma_{JD\bar{D}}/\sigma_J < 0.016$ for associated charm production and $\sigma_{JJ}/\sigma_J < 0.005$ for the production of J/ψ pairs.

I. INTRODUCTION

As part of our experimental program designed to study in detail production of high-mass dimuons by hadron beams, we have performed a sensitive search for additional muons accompanying J/ψ particles. The Okubo-Zweig-Iizuka (OZI) rule[1] which predicts the small width of the J/ψ particle (charm-anticharm bound state) can also be interpreted to imply the copious production of pairs of charmed particles ($C\bar{C}$) in association with the J/ψ.[2] However, arguments have been suggested in which the OZI-rule-allowed mechanism may be kinematically suppressed relative to the OZI-rule-forbidden mechanism.[3] Thus a search for evidence of associated charmed-particle production can help resolve this question. In particular, we have searched for multimuon events from associated charm production in processes of the type

$$\pi^- + \text{nucleus} \rightarrow \underbrace{J/\psi}_{\mu^+\mu^-} + (C + \underbrace{\bar{C}}_{\mu^\pm + \nu + X}) + \text{anything}.$$

II. APPARATUS

The experiment was performed using the Chicago cyclotron magnet spectrometer[4] (Fig. 1) at Fermilab. An incident 225-GeV/c π^- beam struck carbon, copper, and tungsten targets, each one absorption length thick. A 3-m-thick iron absorber was placed 1.7 m downstream of the target to shield the detector from hadrons. A triggering scintillation-counter hodoscope J (see Fig. 1) and a set of multiwire proportional chambers were located immediately downstream of this shield. The cylindrical spectrometer magnet which is 4.2 m in diameter and has a 1.29-m vertical gap gave a transverse-momentum kick of 1.1 GeV/c. Downstream of the magnet there were twelve planes of spark chambers, a trigger scintillation-counter hodoscope F, and a second iron absorber (2.5 m thick), followed by a scintillation-counter hodoscope P.

III. DATA

Details of the event-selection techniques used in the primary dimuon experiment have been reported elsewhere.[4,5] In a straightforward extension of the analysis of ~415 000 dimuon events, multimuon data consisting of 9103 three-muon events, 128 four-muon events, and 17 five-muon events were obtained. Figure 2 shows the mass distribution for all $\mu^+\mu^-$ combinations in the three-muon data sample. Multimuon events produced in association with the J/ψ are those containing at least one $\mu^+\mu^-$ combination per event with a mass of 2.7 to 3.5 GeV/c^2. This mass requirement is determined by the observed J/ψ mass resolution (full width at half maximum = 325 MeV/c^2). The observed numbers of 2, 3, and 4μ events containing a J/ψ are given in Table I.

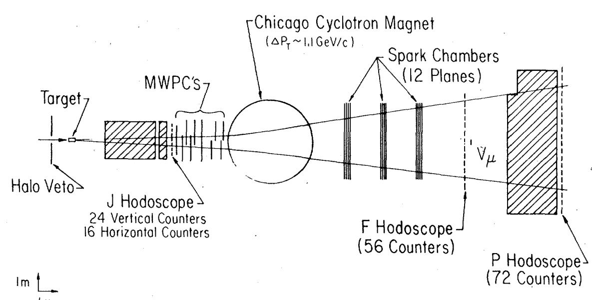

FIG. 1. Plan view of spectrometer.

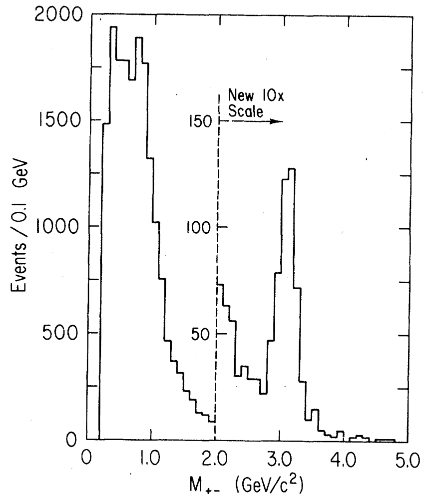

FIG. 2. Mass distribution, M_{+-}, for $\mu^+\mu^-$ pairs contained in three-muon events. Each $\mu^+\mu^-\mu^+$ event contributes twice.

IV. BACKGROUND

In order to determine the origin of the observed multimuon events, it is essential to understand possible conventional sources of the events. The obvious background sources are pions and kaons, produced along with J/ψ's, which decay in the drift space between the target and absorber. The number of muons arising from hadron decays can be calculated from measured π- and K-production spectra.[6] The detection efficiency for observing the extra muons from π and K decays was calculated using a Monte Carlo computer program which generated muons from π and K decays together with dimuons from J/ψ decays. The effective decay path (distance between the target and one absorption length into the first absorber) was 1.9 m and the minimum momentum required to penetrate both absorbers was about 8 GeV/c. The results of the background calculation, as given in Table I, indicate that the majority of the multimuon events originate from π and K decays. In addition, the observed charge ratio ($\mu^+\mu^-\mu^+/\mu^+\mu^-\mu^-$) for three-muon events with J/ψ mass combinations is 0.80±0.07, which agrees with the calculated value of 0.8±0.1 for incident π^- on a nuclear target. The errors on these background calculations are determined by uncertainties in the available π- and K-production measurements and in the acceptance for the lowest-energy muons. The errors on all observed numbers are statistical.

TABLE I. The number of events with $J/\psi \rightarrow \mu^+\mu^-$ is compared to events with $J/\psi \rightarrow \mu^+\mu^-$ + extra muons. Also shown are the predictions for the calculated number of events due to π and K decays.

	Observed data events	Predictions from π and K decays
J/ψ ($\rightarrow\mu^+\mu^-$)	65 900	
$J/\psi + \mu^\pm$	487	450 ± 135
$J/\psi + 2\mu$	11	7 ± 3

Confidence in our technique of calculating the π- and K-decay background can be obtained by comparing calculations of this background with two event samples: (1) low-mass pairs with extra muons, and (2) pairs of the same charge ($\mu^+\mu^+ + \mu^-\mu^-$). Since the OZI mechanism is not expected to enhance charm production in association with μ-pair events with masses below the J/ψ, the probability of a third muon due to hadron decay can be determined by attributing three-muon events with all $\mu^+\mu^-$ mass combinations below 2.0 GeV/c^2 to π and K decays. This leads to a probability of 0.011±0.004. Then, of the 65 900 J/ψ events, we expect 725±250 to contain a third muon in reasonable agreement with the 487 three-muon events observed. The charge ratio ($\mu^+\mu^-\mu^+/\mu^+\mu^-\mu^-$) observed for the low-mass three-muon data is 0.77±0.01, which is consistent with the charge ratios obtained earlier for the observed three-muon events with J/ψ masses and the predictions from the π and K calculations.

The "like-sign" dimuon events ($\mu^+\mu^+ + \mu^-\mu^-$) are predominantly the result of muonic decay of a pair of hadrons. (We expect a few percent of the like-sign pairs to originate from the observation of a single muon from a $\mu^+\mu^-$ pair and another muon from π or K decay.) Assuming hadronic decay accounts for all like-sign pairs above a mass of 1.5 GeV/c^2, we predict $\mu^+\mu^+/\mu^-\mu^-$ =0.5±0.15 and $(\mu^+\mu^+ + \mu^-\mu^-)/\mu^+\mu^-$ =0.07±0.03, which are to be compared with the observed values of $\mu^+\mu^+/\mu^-\mu^-$ =0.58±0.01 and $(\mu^+\mu^+ + \mu^-\mu^-)/\mu^+\mu^-$ =0.105±0.004. Thus, we find that our π- and K-decay calculations are consistent with both the observed low-mass multimuon events and the observed like-sign events. Therefore, our comparison with the number of observed J/ψ events with extra muons implies they can be accounted for on the basis of π and K decay.

The ratio of observed three-muon events to two-muon events for J/ψ production is shown as a function of the Feynman x of the J/ψ in Fig. 3. No difference is seen between the x distributions for J/ψ events with and without an extra muon, again consistent with the extra muon originating from π and K decay.

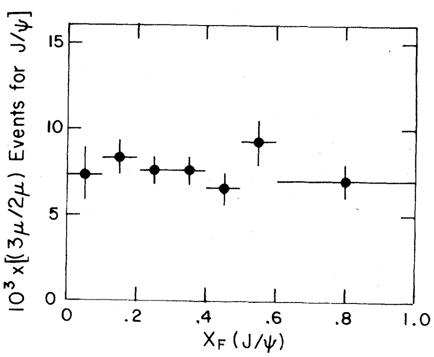

FIG. 3. The ratio of observed three-muon events to dimuon events for J/ψ production as a function of the Feynman x of the J/ψ.

V. MOMENTUM DISTRIBUTION OF ADDITIONAL MUONS

In Fig. 4 we plot the observed momentum spectra of the additional muon produced in association with J/ψ events. For comparison with the calculated momentum spectrum of muons resulting from π and K decays, we restrict ourselves to $p_\mu > 10$ GeV/c so as to avoid regions of rapidly varying acceptance for three-muon events. This requirement reduces the 487 three-muon events associated with the J/ψ to 390 events. Also shown in Fig. 4 are the expected momentum spectrum calculated from π- and K-production data and the observed momentum spectrum of the muons occurring in like-sign events. A good fit is found to the form $dN^{\pi,K}/dp_\mu \sim e^{-bp_\mu}$ for the calculated π and K decays where $b = 0.135 \pm 0.016$. There are 23 events observed with $p_\mu > 40$ GeV/c. The observed like-sign events predict 18 events while a calculation based on the π- and K-production data predicts 7 events.

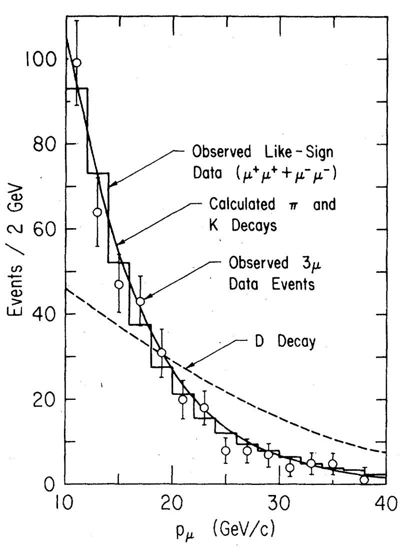

FIG. 4. The momentum spectrum for the extra muon (i.e., in addition to the $J/\psi \rightarrow \mu^+\mu^-$ pair) for three-muon events (data points) is compared to the spectra for calculated π- and K-decay muons (solid curve) for observed like-sign events (histogram) and for D decay muons (dashed curve). The momentum spectra of the like-sign events and predicted curves are normalized to the number of three-muon events ($J/\psi + \mu^{\pm}$) observed with $p_\mu > 10$ GeV/c.

To calculate the properties of muons from associated charm production ($J/\psi + C\bar{C}$) we take C to be the charmed D meson. We assume the D decays to be an equal mixture of $K\mu\nu$ and $K^*(892)\mu\nu$ (Ref. 7) with V–A coupling,[8] although as discussed below, other assumptions have been tried. A Monte Carlo calculation generates J/ψ particles with Feynman x and transverse momentum (p_T) according to observed $J/\psi \rightarrow \mu^+\mu^-$ data. The D is generated with $dN/dp_T \sim p_T e^{-2p_T}$ and with rapidity (y_D) such that the D to J/ψ rapidity gap is distributed as $\exp(-2|y_J - y_D|)$.[2] In addition, the total Feynman x, $x_{J/\psi} + x_D$, was required to be less than 0.7. The resulting muon momentum distribution (Fig. 4) decreases much more slowly with increasing momentum than the data and the expectations for π and K decays.

In the next section we set upper limits on associated charm production with the J/ψ using the observed and predicted momentum spectra for the third muon. This method takes full advantage of the information contained in our measurements without relying on the absolute number of background events predicted.

VI. RESULTS

To set upper limits for $J/\psi + D\bar{D}$ production, the momentum spectrum of the additional muon from three-muon events ($p_\mu > 10$ GeV/c) was fitted to a combination of the momentum spectra calculated for muons from π and K decays and D decays:

$$(1-\alpha)\frac{dN^{\pi+K}}{dp_\mu} + \alpha\frac{dN^D}{dp_\mu}.$$

The fit gives $\alpha = 0.0 \pm 0.2$ with a χ^2 of 15.4 for 22 degrees of freedom. We obtain 90% confidence limits by allowing α to increase until the probability of the resulting χ^2 is less than 10% ($\chi^2 = 30.8$); this gives α(90% C.L.) $= 0.18$. This corresponds to an upper limit of 70 three-muon events from $J/\psi + D\bar{D}$ production. Folding in the detection efficiency for observing the extra muon from D decay, we find an upper limit of 212 charmed meson events in our sample of 65 900 $J/\psi \rightarrow \mu^+\mu^-$ events. Taking a 10% branching ratio

TABLE II. Sensitivity of $\sigma_{JD\bar{D}}/\sigma_J$ upper limits to assumptions for D-meson production and decay.

Model	$\sigma_{JD\bar{D}}/\sigma_J$
Using assumptions discussed in text:	
$\Gamma(D \to K\mu\nu) = \Gamma(D \to K^*\mu\nu)$,	
p_T^D given by $dN/dp_T^2 \sim e^{-bp_T}$, $b = 2$ (GeV/c)$^{-1}$,	
$x_D + x_J \leq 0.7$,	
y_D correlated with y_J; $\exp(-2\lvert y_J - y_D\rvert)$	0.016
$D \to K\mu\nu$ only	0.014
$D \to K^*\mu\nu$ only	0.017
$b = 1$ (6)	0.015 (0.018)
$x_J + x_D \leq 0.5$ (1.0)	0.020 (0.010)
y_D and y_J uncorrelated,	
x_D and p_T^D distributions	
same as J/ψ's	0.035

for $D \to \mu + \nu + X$ (Ref. 7) gives $\sigma_{JD\bar{D}}/\sigma_J < 0.016$ (90% confidence limit). This limit can be recalculated for different intervals of the Feynman x of the J/ψ. The resulting 90% confidence limits are $\sigma_{JD\bar{D}}/\sigma_J < (0.033, 0.027, 0.040)$ for ($x_F = 0.0$–0.2, 0.2–0.4, 0.4–0.7).

The sensitivity of our upper limits to the details of D production and decay are given in Table II. The x_F distribution chosen for D production is the most sensitive parameter. This reflects the dependence of our acceptance on the minimum momentum required for the muon from D decay. In a model where the D is produced uncorrelated with the J/ψ, and with the same x_F as observed for the J/ψ, we find $\sigma_{JD\bar{D}}/\sigma_J < 0.035$ (90% confidence limit).

Another potential source of extra muons observed in association with $J/\psi \to \mu^+\mu^-$ is the production of a pair of J/ψ particles. Our four-muon data sample can be used to obtain an upper limit on double J/ψ production. We observe no four-muon events consistent with J/ψ pair production. In calculating the acceptance for such events, we assume the two J/ψ's are produced uncorrelated with x_F and p_T of observed $J/\psi \to \mu^+\mu^-$ events. Under this assumption we find $\sigma_{JJ}/\sigma_J < 0.005$ (90% C.L.).

Our results can be compared with two earlier Fermilab experiments. One used a broad-band neutron beam ($\langle E_n \rangle \simeq 300$ GeV).[9] The second experiment[10] used 225-GeV/c $\pi^\pm$ and proton beams in a different configuration of the apparatus used in this experiment.

These results are compared in Table III. Such a comparison is meaningful in that similar production models were used in the analysis of all three experiments. In conclusion, it appears that at Fermilab energies the OZI-rule-allowed mechanism can account for at most a few percent of the total hadronic production of J/ψ particles.

TABLE III. Comparison of experiments searching for extra muons in conjunction with hadronic J/ψ production.

	Beam	$J/\psi \to \mu\mu$	$\frac{\sigma_{JD\bar{D}}}{\sigma_J}$	$\frac{\sigma_{JJ}}{\sigma_J}$
This experiment	π^-	65 907	0.016	0.005
CP-II (Ref. 10)	π^-	434	0.041	0.079
	π^+	471	0.028	0.052
	protons	1 195	0.040	0.072
CFHI (Ref. 9)	neutrons	2 500	0.030	0.12

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