Observation of Exclusive Charmonium Production and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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In CDF we have observed the reactions $p + \bar{p} \rightarrow p + X + \bar{p}$, with X being a centrally produced J/ψ, $\psi(2S)$, or χ_{c0}, and $\gamma\gamma \rightarrow \mu^+\mu^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The event signature requires two oppositely charged central muons, and either no other particles or one additional photon detected. Exclusive vector meson production is as expected for elastic photoproduction, $\gamma + p \rightarrow J/\psi(\psi(2S)) + p$, observed here for the first time in hadron-hadron collisions. We also observe exclusive $\chi_{c0} \rightarrow J/\psi + \gamma$. The cross sections $\frac{d\sigma}{dy}|_{y=0}$ for J/ψ, $\psi(2S)$, and χ_{c0} are $3.92 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$ nb, $0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$ nb, and $76 \pm 10(\text{stat}) \pm 10(\text{syst})$ nb, respectively, and the continuum is consistent with QED. We put an upper limit on the cross section for Odderon exchange in exclusive J/ψ production.

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In central exclusive production processes, $p + \bar{p} \rightarrow p + X + \bar{p}$, the colliding hadrons emerge intact with small transverse momenta, p_T [1], and the produced state X is in the central region, with small rapidity $|y|$, and is fully measured. If regions of rapidity exceeding about 5 units are devoid of particles, only photon and Pomeron [2], $\mathbb{P}$, exchanges are significant, where $\mathbb{P}$ consists mostly of two gluons in a color singlet state with charge parity $C = +1$. Odderon, O, exchange, with 3 gluons in a $C = -1$ state [3–5], is allowed in $p\bar{p}$, but not ep, collisions, and would appear as an enhancement in exclusive J/ψ and $\psi(2S)$ production in $p\bar{p}$ compared to the expectation from pure photoproduction in ep. Using the CDF II detector at the Fermilab Tevatron, we previously observed [6] $p + \bar{p} \rightarrow p + e^+e^- + \bar{p}$ in agreement with QED, and found candidates [7] for $p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ consistent with QCD expectations [8]. In this Letter we report measurements of exclusive dimuon production, $X = \mu^+\mu^-$, with $M_{\mu\mu} \in [3.0, 4.0]$ GeV/c^2, directly [QED, Fig. 1(a)], or from photoproduced $J/\psi(3097)$ or $\psi(2S)(3686)$ [Fig. 1(b)] decay, and $\chi_{c0}(3415) \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^-\gamma$ [Fig. 1(c)]. Lower masses were excluded by muon range, and higher masses by trigger rate limitations. Exclusive photoproduction of vector mesons has been measured in ep collisions at HERA [9], but not previously observed in hadron-hadron collisions. The theoretical uncertainty on the QED cross section is <0.3%; this process is distinct from Drell-Yan production ($q\bar{q} \rightarrow \mu^+\mu^-$), which is negligible in this regime.

At the LHC, in pp collisions with $\sqrt{s} = 10$–14 TeV, central exclusive production of states such as $X = H$ and W^+W^-, where H is a Higgs boson, are allowed [10]. Apart from their intrinsic interest, our measurements confirm the viability of the proposed LHC studies. The $p + \chi_{c0} + \bar{p}$ [Fig. 1(c)] and $p + H + p$ [as in Fig. 1(c) but with a top quark loop] cross sections are related [11], and $p + \mu^+\mu^- + p$ can be used to calibrate forward proton spectrometers.

We used $\bar{p}p$ collision data at $\sqrt{s} = 1.96$ TeV with an integrated luminosity $L = 1.48$ fb^{-1} delivered to the CDF II detector. This is a general purpose detector described elsewhere [12]. Surrounding the collision region is a tracking system consisting of silicon microstrip detectors and a cylindrical drift chamber in a 1.4 Tesla solenoidal field. The tracking system has $\approx 100\%$ efficiency for reconstructing isolated tracks with $p_T \geq 1$ GeV/c and $|\eta| < 0.6$ [1]. A barrel of 216 time-of-flight counters outside the cylindrical drift chamber is surrounded by calorimeters with separate electromagnetic (EM) and hadronic sections covering the range $|\eta| < 3.6$. Drift chambers outside the calorimeters were used to measure muons with $|\eta| < 0.6$ [13]. The regions $3.6 < |\eta| < 5.2$ are covered by lead-liquid scintillator calorimeters [14]. Gas Cherenkov counters covering $3.7 < |\eta| < 4.7$ determined the luminosity with a 6% uncertainty [15]. We did not have detectors able to measure the forward p and $\bar{p}$, but beam shower scintillation counters (BSC1–BSC3), located along the beam pipe, detected products of $p(\bar{p})$ fragmentation, such as $p \rightarrow p\pi\pi$, with $|\eta| < 7.4$.

The level 1 trigger required at least one muon track with $p_T > 1.4$ GeV/c and no signal in BSC1 ($5.4 \lesssim |\eta| \lesssim 5.9$), and a higher level trigger required a second track with opposite charge. The offline event selection closely followed that described in Ref. [6], where we observed exclusive e^+e^- production. We required two oppositely charged muon tracks, each with $p_T > 1.4$ GeV/c and $|\eta| < 0.6$, accompanied by either (a) no other particles in the event or (b) only one additional EM shower with $E_T^{\text{EM}} > 80$ MeV and $|\eta| < 2.1$. Condition (a) defines an exclusive dimuon event. The exclusivity efficiency ε_{exc} is the probability that the exclusive requirement is not spoiled by another inelastic interaction in the same bunch crossing, or by noise in a detector element. This efficiency was measured [6] as the fraction of bunch crossing triggers that pass the exclusivity requirement (a). We found $\varepsilon_{\text{exc}} = 0.093$ with negligible uncertainty. The product $\varepsilon_{\text{exc}}L = L_{\text{eff}} = 139 \pm 8$ pb^{-1} was the effective luminosity for single interactions.

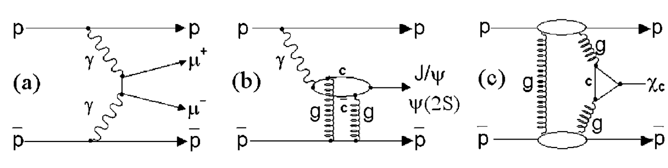

FIG. 1. Feynman diagrams for (a) $\gamma\gamma \rightarrow \mu^+\mu^-$, (b) $\gamma\mathbb{P} \rightarrow J/\psi(\psi(2S))$, and (c) $\mathbb{P}\mathbb{P} \rightarrow \chi_c$, with the 2-gluon exchange forming a Pomeron.

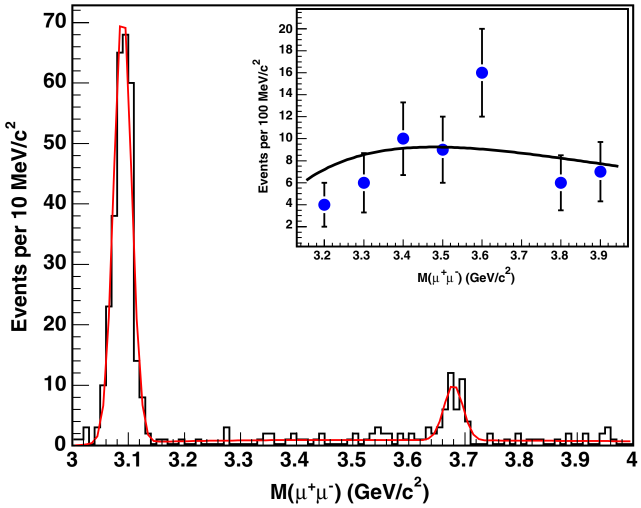

FIG. 2 (color online). Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower (histogram), together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65 < M_{\mu\mu} < 3.75$ GeV$/c^2$ [$\psi(2S)$] with the fit to the QED spectrum times acceptance (statistical uncertainties only).

After these selections, cosmic rays were the main background. They were all rejected, with no significant loss of real events, by timing requirements in the time-of-flight counters and by requiring the three-dimensional opening angle between the muon tracks to be $\Delta\theta_{3D}(\mu\mu) < 3.0$ rad. Within a fiducial kinematic region (FKR) [$|\eta(\mu)| < 0.6$, and $M_{\mu\mu} \in [3.0, 4.0]$ GeV$/c^2$], there are 402 events with no EM shower. The $M_{\mu\mu}$ spectrum is shown in Fig. 2. The J/ψ and $\psi(2S)$ are prominent, together with a continuum. The spectrum is well fitted by two Gaussians with expected masses and widths (dominated by the resolution) and a continuum whose shape is given by the product of the QED spectrum ($\gamma\gamma \to \mu^+\mu^-$), acceptance, and efficiency, as shown in Fig. 2 (inset). The numbers of events from the fit are given in Table I, with statistical uncertainties. The numbers given in Table I for backgrounds, acceptances, and efficiencies show systematic uncertainties estimated by varying parameters within acceptable bounds.

Backgrounds to exclusive $\mu^+\mu^-$ events are (see Table I) (a) proton fragmentation, if the products are not detected in the forward detectors, (b) for the J/ψ, χ_{c0} events with a photon that did not give an EM shower above 80 MeV, and (c) events with some other particle not detected. The probability of a p or $\bar{p}$ fragmenting at the $p\gamma p(p^*)$ vertex was calculated with the LPAIR Monte Carlo (MC) simulation [17] to be 0.17 ± 0.02(syst), and the probability that all the fragmentation products have $|\eta| > 7.4$ to be 0.14 ± 0.02(syst). If a proton fragments, the decay products may not be detected through BSC inefficiency, estimated from data to be 0.08 ± 0.01. The fragmention probability at the $p\mathbb{P}p(p^*)$ vertex was taken from the ratio of single diffractive fragmentation to elastic scattering at the Tevatron [18] to be 0.24 ± 0.05.

We compared the kinematics of the muons, e.g. $p_T(\mu^+\mu^-)$ and $\Delta\phi_{\mu\mu}$, with simulations for the three classes: J/ψ, $\psi(2S)$ [19], and QED [17] with $M_{\mu\mu} \in [3.2, 3.6]$ and $[3.8, 4.0]$ GeV$/c^2$ to exclude the J/ψ and $\psi(2S)$. The distributions agree well with the simulations; the few events that are outside expectations are taken to be nonexclusive background. Figure 3 shows the distributions of $p_T(\mu^+\mu^-)$. As expected, $\langle p_T\rangle$ is smaller for the QED process, and the data agree well with STARLIGHT [19], apart from two events with $p_T > 0.8$ GeV$/c$ where no events are expected. Comparing data with LPAIR we estimate that the nonexclusive background is $(9 \pm 5)\%$ of the observed

TABLE I. Numbers of events fitted to classes J/ψ, $\psi(2S)$, χ_{c0}, and QED. Backgrounds are given as percentages of the fit events, and efficiencies are to be applied to the events without background. The stated branching fraction $\mathcal{B}$ for the χ_{c0} is the product of the $\chi_{c0} \to J/\psi + \gamma$ and $J/\psi \to \mu^+\mu^-$ branching fractions [16]. For events (fit) the uncertainty is only statistical; all other uncertainties are purely systematic except when both are given. The cross sections include a 6% luminosity uncertainty.

Class	J/ψ	$\psi(2S)$	$\chi_{c0}(1P)$	$\gamma\gamma \to \mu^+\mu^-$
Acceptances:				
Detector (%)	18.8 ± 2.0	54 ± 3	19 ± 2	41.8 ± 1.5
Efficiencies:				
μ-quality (%)	33.4 ± 1.7	45 ± 6	33 ± 2	41.8 ± 2.3
Photon (%)	···	···	83 ± 4	···
Events(fit)	286 ± 17	39 ± 7	65 ± 8	77 ± 9
Backgrounds:				
Fragmention (%)	9 ± 2	9 ± 2	11 ± 2	8 ± 2
Nonexclusive (%)	3 ± 3	3 ± 3	3 ± 3	9 ± 5
χ_{c0} (%)	4.0 ± 1.6	···	···	···
$\mathcal{B} \to \mu^+\mu^-$ (%)	5.93 ± 0.06	0.75 ± 0.08	0.076 ± 0.007	···
$\mathcal{B}\sigma_{\rm FKR}$(pb)	28.4 ± 2.0(stat) ± 6.0(syst)	1.02 ± 0.17(stat) ± 0.19(syst)	8.0 ± 0.9(stat) ± 0.9(syst)	27 ± 0.3(stat) ± 0.4(syst)
$\frac{d\sigma}{dy}\|_{y=0}$(nb)	3.92 ± 0.25(stat) ± 0.52(syst)	0.53 ± 0.09(stat) ± 0.10(syst)	76 ± 10(stat) ± 10(syst)	···

(QED) events. The $\psi(2S)$ data are well fitted by the STARLIGHT photoproduction simulation [19]. The distribution of $p_T(J/\psi)$ is well fitted by STARLIGHT, apart from five events with $p_T(J/\psi) > 1.4$ GeV/c [Fig. 3(b)]. These could be due to nonexclusive background, some χ_{c0} radiative decays with an undetected photon, or an Odderon component.

To measure χ_{c0} production we required one EM shower with $E_T^{\rm EM} > 80$ MeV in addition to the two muons; if two adjacent towers had enough energy, they were combined. There are 65 events in the J/ψ peak and eight continuum events; these are likely to be $\gamma\gamma \to \mu^+\mu^-$ with a bremsstrahlung. We interpret the 65 events as $\chi_{c0} \to J/\psi + \gamma$ production and decay. The distribution of the mass formed from the J/ψ and the EM shower energy, while broad, has a mean value equal to the χ_{c0} mass. The $E_T^{\rm EM}$ spectrum is well fitted by an empirical function which extrapolates to only 3.6 ± 1.3(syst) χ_{c0} candidates with showers below 80 MeV. The $p_T(J/\psi)$ and $\Delta\phi_{\mu\mu}$ distributions for the events with an $E_T^{\rm EM}$ signal are consistent with all these J/ψ being from χ_{c0} decay, as simulated by CHICMC [20]. Additional photon inefficiency comes from conversion in material, $7 \pm 2\%$, and dead regions of the calorimeter, $5.0 \pm 2.5\%$, giving a total inefficiency $17 \pm 4\%$, which gives a background to exclusive J/ψ of $4.0 \pm 1.6\%$ (all errors systematic).

We calculated acceptances and efficiencies using the LPAIR [17] and STARLIGHT [19] MC generators for QED, J/ψ and $\psi(2S)$, and CHICMC [20] for χ_{c0} production. Generated events were passed through a GEANT-based [21] simulation of the CDF detector. The trigger efficiency for muons rose steeply between 1.4 GeV/c and 1.5 GeV/c, where it exceeded 90%. As we triggered on one muon, the trigger efficiency for events with two muons was >99% for $M_{\mu\mu} > 3$ GeV/c^2.

Figure 2 (inset) shows the subset of the Fig. 2 data above 3.15 GeV/c^2 (to exclude the J/ψ), excluding the bin 3.65–3.75 GeV/c^2 which contains the $\psi(2S)$. The curve shows the product of the QED spectrum and acceptance $\times$ efficiency, $A\varepsilon$, with only the normalization floating, from the 3-component fit to the full spectrum. The continuum data agrees with the QED expectation. The integral from 3 GeV/c^2 to 4 GeV/c^2 is 77 ± 9(stat) events, and after correcting for backgrounds and efficiencies (Table I), the measured cross section for QED events with $|\eta(\mu^\pm)| < 0.6$ and $M_{\mu\mu} \in [3.0, 4.0]$ GeV/c^2 is $\sigma = 2.7 \pm 0.3$(stat) $\pm$ 0.4(syst) pb, in agreement with the QED prediction 2.18 ± 0.01 pb [17].

For the prompt J/ψ and $\psi(2S)$ cross sections, we took the number of events from the Gaussian fits, subtracted backgrounds, and corrected for $A\varepsilon$ to obtain $\mathcal{B}\sigma_{\rm FKR}$ for both muons in the fiducial kinematic region (see Table I). To obtain $\frac{d\sigma}{dy}|_{y=0}$ from $\sigma_{\rm FKR}$ we used the STARLIGHT MC program, which gives the ratio of these two cross sections for each resonance, and divided by the branching fractions $\mathcal{B}$. We found $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.92 \pm 0.25$(stat) $\pm$ 0.52(syst) nb. This agrees with the predictions $2.7^{+0.6}_{-0.2}$ nb [19] and 3.4 ± 0.4 nb [22] among others [23,24]. We found $\frac{d\sigma}{dy}|_{y=0}(\psi(2S)) = 0.53 \pm 0.09$(stat) $\pm$ 0.10(syst) nb compared with a prediction [19] $0.46^{+0.11}_{-0.04}$ nb. The ratio $R = \frac{\psi(2S)}{J/\psi} = 0.14 \pm 0.05$ is in agreement with the HERA value [9] $R = 0.166 \pm 0.012$ at similar $\sqrt{s(\gamma p)}$.

After correcting the 65 χ_{c0} candidates for backgrounds and efficiencies, and applying the branching fraction $\mathcal{B}(\chi_{c0} \to J/\psi + \gamma) = 0.0128 \pm 0.0011$ [16], we found $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0}) = 76 \pm 10$(stat) $\pm$ 10(syst) nb. The $\chi_{c2}(3556)$ may be present, although it is strongly suppressed by the $J_z = 0$ rule [11] and is forbidden at 0° scattering angle. Exclusive $gg \to \chi_{c1}(3511)$, $J^{PC} = 1^{++}$ is forbidden by the Landau-Yang theorem, but may occur with off-shell gluons [25]. It is nevertheless forbidden by symmetry arguments [26] when both p and $\bar{p}$ scatter at 0°. Because of the limited $M(J/\psi + \gamma)$ resolution we cannot distinguish these states; we assume χ_{c1} and χ_{c2} to be negligible. If several states χ_{ci} are present, $\sum \mathcal{B}_i\sigma_{i,\rm FKR} = 8.0 \pm 0.9$(stat) $\pm$ 0.9(syst) pb. Theoretical predictions have large (often unstated) uncertainties, but are compatible with our measurement. Reference [11] predicted $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0}) = 130$ nb; however, the Particle Data Group (PDG) value [16] of the χ_c width has since been reduced by a factor 1.45, correcting their prediction to 90 nb. Yuan [27] predicted 160 nb (again the factor $\frac{1}{1.45}$ should be applied) and Bzdak [28] 45 nb.

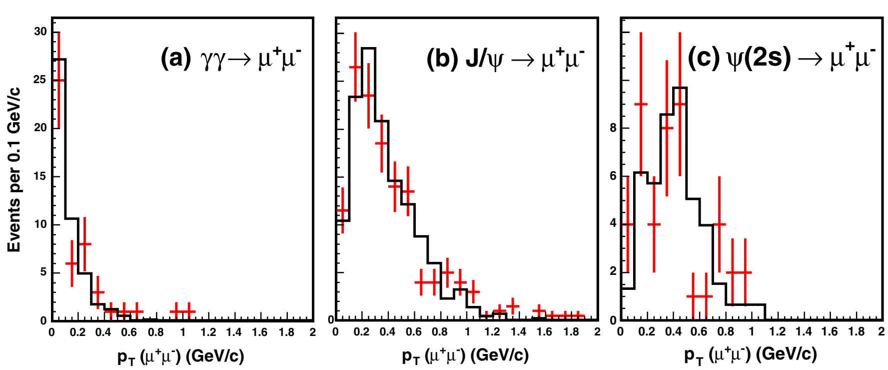

FIG. 3 (color online). p_T distribution of $\mu^+\mu^-$ (points with statistical error bars) for (a) QED, $M_{\mu\mu} \in [3.2, 3.6] + [3.8, 4.0]$ GeV/c^2, (b) J/ψ, and (c) $\psi(2S)$. The MC predictions (with no background) are shown by the histograms, normalized to the data.

If the J/ψ and $\psi(2S)$ cross sections were larger than expected for photoproduction, it would be evidence for Odderon exchange. Taking a theoretical value of $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.0 \pm 0.3$ nb for photoproduction, compatible with the predictions, we give a 95% C.L. upper limit $\frac{d\sigma}{dy}|_{y=0}(J/\psi) < 2.3$ nb for Odderon exchange ($O\mathbb{P} \rightarrow J/\psi$). Bzdak *et al.* [29] predicted the ratio of Odderon: photon exchange in J/ψ production to be 0.3–0.6, consistent with our limit.

In conclusion we have observed, for the first time in hadron-hadron collisions, exclusive photoproduction of J/ψ and $\psi(2S)$, exclusive double Pomeron production of χ_{c0}, and the QED process $\gamma\gamma \rightarrow \mu^+\mu^-$. The photoproduction process has previously been studied in ep collisions at HERA, with similar kinematics ($\sqrt{s(\gamma p)} \approx$ 100 GeV), and the cross sections are in agreement. We put an upper limit on an Odderon contribution to exclusive J/ψ production. Our observation of exclusive χ_{c0} production implies that exclusive Higgs boson production should occur at the LHC [10] and imposes constraints on the $p + p \rightarrow p + H + p$ cross section.

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*Deceased.

[1] A cylindrical coordinate system is used with the z axis along the proton beam direction; θ is the polar angle and ϕ is the azimuthal angle. Transverse momentum is $p_T = |p|\sin\theta$, and transverse energy is $E_T = E\sin\theta$ where E is the energy. Pseudorapidity is $\eta = -\ln(\tan\frac{\theta}{2})$, and for the charmonium states we use longitudinal rapidity $y = -\ln\frac{E+p_z}{E-p_z}$.

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