Observation of Exclusive Charmonium Production and $\gamma\gamma \rightarrow \mu^+\mu^-$ 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 \( J/\psi \), \( \psi(2S) \), or \( \chi_{c0} \), 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 \( \vec{P} \), exchanges are significant, where \( \vec{P} \) 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 in \( ep \), collisions, and would appear as an enhancement in exclusive \( J/\psi \) 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 \( M_{\mu\mu} \in [3.0, 4.0] \text{ GeV}/c^2 \), directly [QED, Fig. 1(a)], or from photoproduced \( J/\psi(3097) \) or \( \psi(2S)(3686) \) [Fig. 1(b)] decay, and \( \chi_{c0}(3415) \rightarrow J/\psi + \gamma + \mu^+ \mu^- \gamma \) [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 \( \sqrt{s} = 10–14 \text{ TeV} \), 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 \( \sqrt{s} = 1.96 \text{ TeV} \) with an integrated luminosity \( L = 1.48 \text{ fb}^{-1} \) 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 \( p_T \geq 1 \text{ GeV}/c \) 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 \( p_T > 1.4 \text{ GeV}/c \) and no signal in BSC1 (\( 5.4 \leq |\eta| \leq 5.9 \)), 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 \( p_T > 1.4 \text{ GeV}/c \) and \( |\eta| < 0.6 \), accompanied by either (a) no other particles in the event or (b) only one additional EM shower with \( E_{\text{EM}} > 80 \text{ MeV} \) and \( |\eta| < 2.1 \). Condition (a) defines an exclusive dimuon event. The exclusivity efficiency \( \epsilon_{\text{exc}} \) 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 \( \epsilon_{\text{exc}} = 0.093 \) with negligible uncertainty. The product \( \epsilon_{\text{exc}} L = L_{\text{eff}} = 139 \pm 8 \text{ pb}^{-1} \) was the effective luminosity for single interactions.

![FIG. 1. Feynman diagrams for (a) \( \gamma\gamma \rightarrow \mu^+ \mu^- \), (b) \( \gamma p \rightarrow J/\psi(2S) \), and (c) \( p\bar{p} \rightarrow \chi_{c0} \), with the 2-gluon exchange forming a Pomeron.](image-url)
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 $J/\psi$ 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 ($\gamma \gamma \rightarrow \mu^+ \mu^-$), 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 $J/\psi$, $\chi_{c0}$ 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 $0.17 \pm 0.02$ (syst), and the probability that all the fragmentation products have $|\eta| > 7.4$ to be $0.14 \pm 0.02$ (syst). If a proton fragments, the decay products may not be detected through BSC inefficiency, estimated from data to be $0.08 \pm 0.01$. The fragmentation probability at the $p\bar{p}p(p^*)$ vertex was taken from the ratio of single diffractive fragmentation to elastic scattering at the Tevatron [18] to be $0.24 \pm 0.05$.

We compared the kinematics of the muons, e.g. $p_T(\mu^+ \mu^-)$ and $\Delta \phi_{\mu \mu}$, with simulations for the three classes: $J/\psi$, $\psi(2S)$ [19], and QED [17] with $M_{\mu \mu} \in [3.2, 3.6]$ and $[3.8, 4.0]$ GeV/c$^2$ to exclude the $J/\psi$ 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

![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 $J/\psi$ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the three shapes are predetermined, with only the normalizations and efficiencies to be applied to the events without background. The stated branching fraction $B$ are purely systematic except when both are given. The cross sections include a 6% luminosity uncertainty.

<table>
<thead>
<tr>
<th>Class</th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
<th>$\chi_{c0}(1P)$</th>
<th>$\gamma \gamma \rightarrow \mu^+ \mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptances:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detector (%)</td>
<td>18.8 ± 2.0</td>
<td>54 ± 3</td>
<td>19 ± 2</td>
<td>41.8 ± 1.5</td>
</tr>
<tr>
<td>Efficiencies:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu$-quality (%)</td>
<td>33.4 ± 1.7</td>
<td>45 ± 6</td>
<td>33 ± 2</td>
<td>41.8 ± 2.3</td>
</tr>
<tr>
<td>Photon (%)</td>
<td>...</td>
<td>...</td>
<td>83 ± 4</td>
<td>...</td>
</tr>
<tr>
<td>Events(fit)</td>
<td>286 ± 17</td>
<td>39 ± 7</td>
<td>65 ± 8</td>
<td>77 ± 9</td>
</tr>
<tr>
<td>Backgrounds:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fragmentation (%)</td>
<td>9 ± 2</td>
<td>9 ± 2</td>
<td>11 ± 2</td>
<td>8 ± 2</td>
</tr>
<tr>
<td>Nonexclusive (%)</td>
<td>3 ± 3</td>
<td>3 ± 3</td>
<td>3 ± 3</td>
<td>9 ± 5</td>
</tr>
<tr>
<td>$\chi_{c0}$ (%)</td>
<td>4.0 ± 1.6</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$B \rightarrow \mu^+ \mu^-$ (%)</td>
<td>5.93 ± 0.06</td>
<td>0.75 ± 0.08</td>
<td>0.076 ± 0.007</td>
<td>...</td>
</tr>
<tr>
<td>$\mathcal{B}_{\text{FKR}}(\text{pb})$</td>
<td>28.4 ± 2.0(stat) ± 6.0(syst)</td>
<td>1.02 ± 0.17(stat) ± 0.19(syst)</td>
<td>8.0 ± 0.9(stat) ± 0.9(syst)</td>
<td>27 ± 0.3(stat) ± 0.4(syst)</td>
</tr>
<tr>
<td>$\frac{d\mathcal{B}}{dE}\big</td>
<td>_{E=0}(\text{nb})$</td>
<td>3.92 ± 0.25(stat) ± 0.52(syst)</td>
<td>0.53 ± 0.09(stat) ± 0.10(syst)</td>
<td>76 ± 10(stat) ± 10(syst)</td>
</tr>
</tbody>
</table>
(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 \( p_T(\J/\psi) > 1.4 \text{ GeV}/c \) [Fig. 3(b)]. These could be due to nonexclusive background, some \( \chi_{c0} \) radiative decays with an undetected photon, or an Odderon component.

To measure \( \chi_{c0} \) production we required one EM shower with \( E_{\text{EM}}^\mu > 80 \text{ MeV} \) in addition to the two muons; if two adjacent towers had enough energy, they were combined. There are 65 events in the \( \J/\psi \) peak and eight continuum events; these are likely to be \( \gamma\gamma \to \mu^+\mu^- \) with a bremsstrahlung. We interpret the 65 events as \( \chi_{c0} \rightarrow \J/\psi + \gamma \) production and decay. The distribution of the mass formed from the \( \J/\psi \) and the EM shower energy, while broad, has a mean value equal to the \( \chi_{c0} \) mass. The \( E_{\text{EM}}^\mu \) spectrum is well fitted by an empirical function which extrapolates to only \( 3.6 \pm 1.3 \text{(syst)} \) \( \chi_{c0} \) candidates with showers below 80 MeV. The \( p_T(\J/\psi) \) and \( \Delta \phi_{\mu\mu} \) distributions for the events with an \( E_{\text{EM}}^\mu \) signal are consistent with all these \( \J/\psi \) being from \( \chi_{c0} \) 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 \( \J/\psi \) 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, \( \J/\psi \) and \( \psi(2S) \), and CHICMC [20] for \( \chi_{c0} \) 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 \( M_{\mu\mu} > 3 \text{ GeV}/c^2 \).

Figure 2 (inset) shows the subset of the Fig. 2 data above 3.15 GeV/c^2 (to exclude the \( \J/\psi \)), excluding the bin 3.65–3.75 GeV/c^2 which contains the \( \psi(2S) \) curve. The latter shows the product of the QED spectrum and acceptance \( \times \) efficiency, \( A_e \), 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 \( \pm \) 9\,(stat) events, and after correcting for backgrounds and efficiencies (Table 1), the measured cross section for QED events with \( |\eta(\mu^\pm)| < 0.6 \) and \( M_{\mu\mu} \in [3.0, 4.0] \text{ GeV}/c^2 \) is \( \sigma = 2.7 \pm 0.3 \text{(stat)} \pm 0.4 \text{(syst)} \text{ pb} \), in agreement with the QED prediction 2.18 \( \pm \) 0.01 pb [17].

For the prompt \( \J/\psi \) and \( \psi(2S) \) cross sections, we took the number of events from the Gaussian fits, subtracted backgrounds, and corrected for \( A_e \) to obtain \( B_{\J/\psi}^{\text{FKR}} \) for both muons in the fiducial kinematic region (see Table 1). To obtain \( \frac{d^2\sigma}{dy \, \J/\psi} \) from \( \sigma_{\J/\psi}^{\text{FKR}} \) we used the STARLIGHT MC program, which gives the ratio of these two cross sections for each resonance, and divided by the branching fractions \( B \). We found \( \frac{d^2\sigma}{dy \, \J/\psi} = 3.92 \pm 0.25 \text{(stat)} \pm 0.52 \text{(syst)} \text{ nb} \). This agrees with the predictions 2.7\( ^{+0.9}_{-0.2} \) nb [19] and 3.4 \( \pm \) 0.4 nb [22] among others [23,24]. We found \( \frac{d^2\sigma}{dy \, \psi(2S)} = 0.53 \pm 0.09 \text{(stat)} \pm 0.10 \text{(syst)} \text{ nb} \) 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 \( \chi_{c0} \) candidates for backgrounds and efficiencies, and applying the branching fraction \( B(\chi_{c0} \rightarrow \J/\psi + \gamma) = 0.0128 \pm 0.0011 \) [16], we found \( \frac{d^2\sigma}{dy \, \chi_{c0}} = 76 \pm 10 \text{(stat)} \pm 10 \text{(syst)} \text{ nb} \). The \( \chi_{c2}(3556) \) may be present, although it is strongly suppressed by the \( J_c = 0 \) rule [11] and is forbidden at 0° scattering angle. Exclusive \( gg \rightarrow \chi_{c1}(3511), \ J^{PC} = 1^{++} \) 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 \( \chi_{c1} \) and \( \chi_{c2} \) to be negligible. If several states \( \chi_i \) are present, \( \sum B_i \sigma_{i \J/\psi} = 8.0 \pm 0.9 \text{(stat)} \pm 0.9 \text{(syst)} \text{ pb} \). Theoretical predictions have large (often unstated) uncertainties, but are compatible with our measurement. Reference [11] predicted \( \frac{d^2\sigma}{dy \, \chi_{c0}} = 130 \text{ nb} \); however, the Particle Data Group (PDG) value [16] of the \( \chi_{c} \) 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, \( M_{\mu\mu} \in [3.2, 3.6] + [3.8, 4.0] \text{ GeV}/c^2 \), (b) \( \J/\psi \), and (c) \( \psi(2S) \). The MC predictions (with no background) are shown by the histograms, normalized to the data.
If the $J/\psi$ and $\psi(2S)$ cross sections were larger than expected for photoproduction, it would be evidence for Odderon exchange. Taking a theoretical value of $dJ/dy_{J/\psi} = 3.0 \pm 0.3$ nb for photoproduction, we give a 95% C.L. upper limit $dJ/dy_{J/\psi} < 2.3$ nb for Odderon exchange ($O^P \rightarrow J/\psi$). Bzdak et al. [29] predicted the ratio of Odderon: photon exchange in $J/\psi$ 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 $J/\psi$ and $\psi(2S)$, exclusive double Pomeron production of $\chi_{c0}$, and the QED process $\gamma\gamma \rightarrow \mu^+\mu^-$. The photoproduction process has previously been studied in ep collisions at HERA, with similar kinematics ($\sqrt{s} = 100$ GeV), and the cross sections are in agreement. We put an upper limit on an Odderon contribution to exclusive $J/\psi$ production. Our observation of exclusive $\chi_{c0}$ 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; $\theta$ is the polar angle and $\phi$ is the azimuthal angle. Transverse momentum is $p_T = \sqrt{p_x^2 + p_y^2}$, and transverse energy is $E_T = E \sin \theta$ where $E$ is the energy. Pseudorapidity is $\eta = -\ln(\tan(\theta/2))$, and for the charmonium states we use longitudinal rapidity $y = -\ln(E^+/p_T)$.


