

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

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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 proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV using the Run II Collider Detector at Fermilab. The event signature requires two oppositely charged muons, each with pseudorapidity $|\eta| < 0.6$, with $M_{\mu\mu} \in [3.0, 4.0]$ GeV/c² and either no other particles, or one additional photon, detected. The J/ψ and the $\psi(2S)$ are prominent, on a continuum consistent with the QED process $\gamma\gamma \rightarrow \mu^+\mu^-$. Events with a J/ψ and an associated photon candidate are consistent with exclusive χ_{c0} production through double pomeron exchange. The exclusive

vector meson production is as expected for elastic photoproduction, $\gamma + p \rightarrow J/\psi(\psi(2S)) + p$, which is observed here for the first time in hadron-hadron collisions. The cross sections $\frac{d\sigma}{dy}|_{y=0}$ for $p + \bar{p} \rightarrow p + X + \bar{p}$ with $X = J/\psi, \psi(2S)$ or χ_{c0} are 3.92 ± 0.62 nb, 0.53 ± 0.14 nb, and 76 ± 14 nb respectively. The cross section for the continuum, with $|\eta(\mu^\pm)| < 0.6$, $M_{\mu\mu} \in [3.0, 4.0]$ GeV/c², is $\int \frac{d\sigma}{dM.d\eta_1.d\eta_2} = 2.7 \pm 0.5$ pb, consistent with QED predictions. We put an upper limit on the cross section for odderon exchange in exclusive J/ψ production: $\frac{d\sigma}{dy}|_{y=0}(J/\psi_{OP}) < 2.3$ nb at 95% C.L.

PACS numbers:

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 rapidity in the range $-2 \lesssim |y| \lesssim +2$, and is fully measured. If regions of rapidity exceeding about 5 units are devoid of particles (“rapidity gaps”), only photon and pomeron, \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 [2–4], is allowed but has not yet been observed. A comparison of exclusive J/ψ and $\psi(2S)$ production in hadron-hadron and ep collisions is sensitive to odderon exchange. Using the CDF II detector at the Fermilab Tevatron, we previously observed [5] $p + \bar{p} \rightarrow p + e^+e^- + \bar{p}$ in agreement with QED, and found candidates [6] for $p + \bar{p} \rightarrow p + \gamma\gamma + \bar{p}$ consistent with QCD expectations [7]. We have also observed exclusive dijets [8]. In this paper we report measurements of exclusive dimuon production, $X = \mu^+\mu^-$, directly or from J/ψ or $\psi(2S)$ decay, and $\chi_{c0} \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- \gamma$.

Exclusive $\mu^+\mu^-$ production, either direct ($\gamma\gamma \rightarrow \mu^+\mu^-$) (Fig. 1a), or via photoproduction of vector mesons ($\gamma\mathbb{P} \rightarrow V \rightarrow \mu^+\mu^-$) (Fig. 1b), has not previously been observed in hadron-hadron collisions. At the Large Hadron Collider, LHC, in pp collisions with $\sqrt{s} = 14$ TeV, central exclusive production of massive states $X = Z, H, W^+W^-, ZZ$, or $\tilde{l}^+\tilde{l}^-$, where H is a Higgs boson and \tilde{l} is a slepton are allowed [9]. Apart from their intrinsic interest, our measurements confirm the viability of the proposed LHC studies. In particular the $p + \chi_{c0} + \bar{p}$ (Fig. 1c) and $p + H + p$ (as in Fig. 1c but with a top quark loop) cross sections are related [10], and $p + \mu^+\mu^- + p$ can be used to calibrate forward proton spectrometers.

We consider here $M_{\mu\mu} \in [3.0, 4.0]$ GeV/c²; this region includes the $J/\psi(3097)$ and $\psi(2S)(3686)$ resonances [11], and a continuum from the QED process $\gamma\gamma \rightarrow \mu^+\mu^-$. The theoretical uncertainty on the QED cross section is $< 0.3\%$. This process is distinct from Drell-Yan ($q\bar{q} \rightarrow \mu^+\mu^-$), which is negligible in this regime. Exclusive vector mesons, V , can be produced by photoproduction, $\gamma\mathbb{P} \rightarrow J/\psi(\psi(2S))$, which has been measured at HERA [12] in ep collisions. In hadron-hadron collisions it can provide a probe of diffraction and Vp elastic scat-

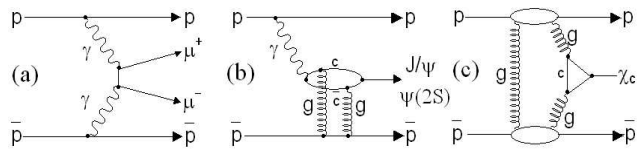


FIG. 1: Feynman diagrams for (a) $\gamma\gamma \rightarrow \mu^+\mu^-$, (b) $\gamma\mathbb{P} \rightarrow J/\psi(\psi(2S))$, and (c) $\mathbb{P}\mathbb{P} \rightarrow \chi_c$, with the 2-gluon exchange forming a pomeron.

tering [3]. We also observe exclusive $\chi_{c0}(3415)$ production, a “double pomeron exchange” process: $\mathbb{P}\mathbb{P} \rightarrow \chi_{c0}$, followed by $\chi_{c0} \rightarrow J/\psi + \gamma$. This is a background to exclusive J/ψ production if the photon is not detected. We do not have detectors able to measure the forward p and \bar{p} , but beam shower scintillation counters (BSC1-BSC3), located along the beampipe, detect products of $p(\bar{p})$ dissociations.

We use $\bar{p}p$ collision data at $\sqrt{s} = 1.96$ TeV corresponding to an integrated luminosity $L = 1.48$ fb⁻¹ delivered to the CDF II detector. This is a general purpose detector described elsewhere [13]; here we give a brief summary of the detector components used in this analysis. Surrounding the collision region is a tracking system consisting of silicon microstrip detectors and a cylindrical drift chamber (COT) 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 $|\eta| < 0.6$. A barrel of 216 time-of-flight counters (ToF) outside the COT is surrounded by calorimeters with separate electromagnetic (EM) and hadronic sections covering the range $|\eta| < 3.6$. Drift chambers outside the calorimeters are used to measure muons with $|\eta| < 0.6$ [14]. The regions $3.6 < |\eta| < 5.2$ are covered by lead-liquid scintillator calorimeters (mini-plugs [15]), and the BSC cover $5.4 < |\eta| < 7.4$. Gas Čerenkov counters covering $3.7 < |\eta| < 4.7$ determine the luminosity with a 6% uncertainty by counting inelastic interactions [16].

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 follows closely that described in Ref. [5], where we observed exclusive e^+e^- production. We require 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

*Deceased

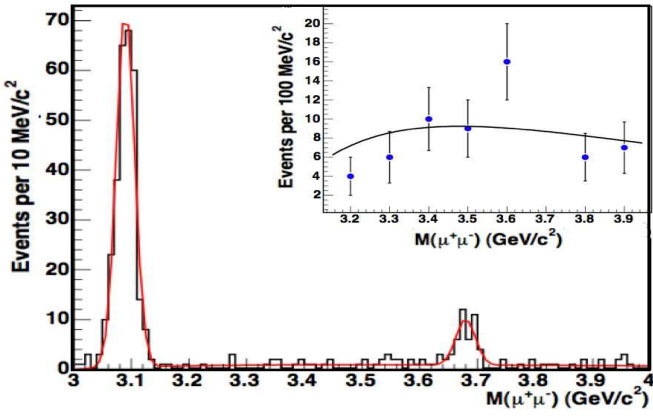


FIG. 2: Mass $M_{\mu\mu}$ distribution of 402 exclusive events, with no EM shower, (histogram) together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalizations floating. Inset: Data above the J/ψ and excluding $3.65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

$E_T^{EM} > 80$ 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 depends on the individual bunch-by-bunch luminosities, and is measured [5] as the fraction of bunch crossing triggers that pass the exclusivity requirement (a). We find $\varepsilon_{\text{exc}} = 0.093$. The product $\varepsilon_{\text{exc}} \times L = L_{\text{eff}} = 139 \pm 8 \text{ pb}^{-1}$ is the effective luminosity for single interactions.

After these selections, cosmic rays are the main background. They are essentially all rejected, with no significant loss of real events, by timing requirements in the ToF counters and by requiring the 3D opening angle between the muon tracks to be $\Delta\theta_{3D}(\mu\mu) < 3.0$ rad. Within a fiducial kinematic region (FKR): $[p_T(\mu) > 1.4 \text{ GeV}/c, |\eta(\mu)| < 0.6, \text{ and } M_{\mu\mu} \in [3.0, 4.0] \text{ GeV}/c^2]$, 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 ($\gamma\gamma \rightarrow \mu^+\mu^-$), acceptance, and efficiency, as shown in Fig. 2(inset). The numbers of events from the fit are given in Table I, along with statistical uncertainties. The QED component has an additional systematic uncertainty from the fit shape. The numbers given in Table I for backgrounds, acceptances, and efficiencies include systematic uncertainties estimated by varying parameters within acceptable bounds.

Backgrounds to exclusive $\mu^+\mu^-$ events are (see Table I) (a) proton dissociation, if the products are not detected

TABLE I: Numbers of events fitted to classes $J/\psi, \psi(2S)$, QED and χ_{c0} . 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 $\chi_{c0} \rightarrow J/\psi + \gamma$ and $J/\psi \rightarrow \mu^+\mu^-$ branching fractions [11]. The cross sections include a 6% luminosity uncertainty.

Class	J/ψ	$\psi(2S)$	$\gamma\gamma \rightarrow \mu^+\mu^-$	$\chi_{c0}(1P)$
Acceptances:				
Detector(%)	18.8 ± 2.0	54 ± 3	41.8 ± 1.5	19 ± 2
Efficiencies:				
μ -quality(%)	33.4 ± 1.7	45 ± 6	41.8 ± 2.3	33 ± 2
Photon(%)	-	-	-	83 ± 4
Events(fit)	286 ± 17	39 ± 7	77 ± 10	65 ± 8
Backgrounds:				
Dissoc.(%)	9 ± 2	9 ± 2	8 ± 2	11 ± 2
Non-excl.(%)	3 ± 3	3 ± 3	9 ± 5	3 ± 3
χ_{c0} (%)	4.0 ± 1.6	-	-	-
Events(corr.)	243 ± 21	34 ± 7	65 ± 10	56 ± 8
\mathcal{B}_{FKR} (pb)	28.4 ± 4.5	1.02 ± 0.26	2.7 ± 0.5	8.0 ± 1.3
$\mathcal{B} \rightarrow \mu^+\mu^-$ (%)	5.93 ± 0.06	0.75 ± 0.08	-	0.076
				± 0.007
$\frac{d\sigma}{dy} _{y=0}$ (nb)	3.92 ± 0.62	0.53 ± 0.14	-	76 ± 14

in the forward detectors, (b) for the $J/\psi, \chi_{c0}$ events with a photon that did not give an EM tower above the 80 MeV threshold, and (c) events with some other particle not detected. The probability of a proton (p or \bar{p}) dissociating at the $p\gamma p(p^*)$ vertex was calculated with the LPAIR Monte Carlo (MC) simulation [17] to be 0.17, and the probability that all the fragmentation products have $|\eta| > 7.4$ to be 0.14. If a proton dissociates, the decay products may not be detected through BSC inefficiency, estimated from data to be 0.08 ± 0.01 . The dissociation probability at the $pPp(p^*)$ vertex is taken from the ratio of single diffractive dissociation to elastic scattering at the Tevatron [18] to be 0.24 ± 0.05 . We assume the dissociation products are detected with the same probability in photon- and pomeron-induced fragmentation. The resulting dissociation backgrounds are given in Table I.

We compare the kinematics of the muons, specifically $p_T(\mu^+\mu^-)$ and $\Delta\phi_{\mu\mu}$, with simulations for the three classes: $J/\psi, \psi(2S)$ [19], and QED [17] with $M_{\mu\mu} \in [3.2, 3.6] \& [3.8, 4.0] \text{ GeV}/c^2$ 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 non-exclusive 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, apart from two events with $p_T > 0.8$ GeV/c where no events are expected. Choosing cuts in $p_T(\mu^+\mu^-)$ and $\Delta\phi_{\mu\mu}$ that are 98%(96%) efficient for the

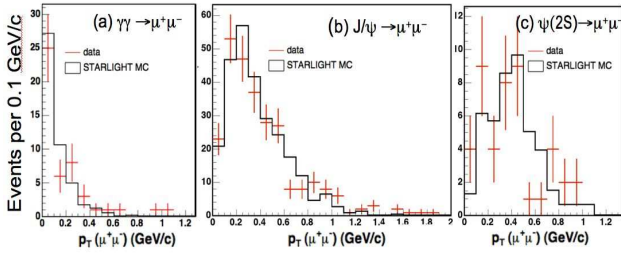


FIG. 3: p_T distribution of $\mu^+\mu^-$ (points with statistical error bars) for (a) QED, $M_{\mu\mu} \in [3.2, 3.6] + [3.8, 4.0]$ GeV/c^2 , (b) J/ψ , and (c) $\psi(2S)$. The MC predictions (with no background) are shown by the histograms, normalized to the data.

LPAIR events we find the fraction of data events exceeding these cuts, and conclude that the non-exclusive background is $(9 \pm 5)\%$ of the observed(QED) events. The $\psi(2S)$ data are well fitted by the STARLIGHT photoproduction simulation[17, 19]. The distribution of $p_T(J/\psi)$ is well fitted by STARLIGHT, apart from six events with $p_T(J/\psi) > 1.4$ GeV/c (Fig. 3b). These could be due to non-exclusive background, some χ_{c0} radiative decays with an undetected photon, or an odderon component.

To measure χ_{c0} production we require one EM shower with $E_T^{EM} > 80$ MeV in addition to the two muons; if two adjacent towers have enough energy they are combined. The fit to the dimuon spectrum has 65 events in the J/ψ component, only one $\psi(2S)$ and eight continuum events. We interpret the 65 events as $\chi_{c0} \rightarrow J/\psi + \gamma$ production and decay. The distribution of the mass formed from the J/ψ and the EM tower energy, while broad, has a mean value equal to the χ_{c0} mass. The E_T^{EM} spectrum is well fitted by an empirical function $A \times E_T^{2.5} \times e^{-12.5 \cdot E_T}$ (E_T in GeV), which extrapolates to only three χ_{c0} candidates under the 80 MeV cut. The $p_T(J/\psi)$ and $\Delta\phi_{\mu\mu}$ distributions for the events with an E_T^{EM} signal are consistent with all these J/ψ being from χ_{c0} decay, as simulated by the CHICMC simulation [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 $4.0 \pm 1.6\%$.

We calculate acceptances and efficiencies for QED 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 are passed through a GEANT-based [21] simulation of the CDF detector. The level 1 trigger efficiency for muons rises steeply between 1.4 GeV/c and 1.5 GeV/c , where it exceeds 90%. As we triggered on a single muon, the trigger efficiency for events with two muons is $> 99\%$ for $M_{\mu\mu} > 3$ GeV/c^2 . We parametrize the detector acceptance \times reconstruction efficiency as $A\varepsilon = 0.6 - 0.5 \times e^{-3.22(M_{\mu\mu} - 3.05)}$ ($M_{\mu\mu}$ in GeV/c^2).

Figure 2(inset) shows the subset of 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 high point at 3.6 GeV/c^2 may contain a small, ≈ 2 event, contamination of $\psi(2S)$.) 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 coarser binning enables one to see that the continuum data is in agreement with the QED expectation. The integral from 3 GeV/c^2 to 4 GeV/c^2 is 77 ± 10 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 $\sigma = 2.7 \pm 0.5$ pb, in agreement with the QED prediction 2.18 ± 0.01 pb [17].

For the prompt J/ψ cross section we take the number of events from the Gaussian fit, subtract backgrounds and correct for $A\varepsilon$ (see Table I). We obtain $\mathcal{B} \times \sigma_{FKR}(J/\psi) = 28.1 \pm 4.4$ pb, for both muons in the fiducial kinematic region. We divide by the branching fraction to $\mu^+\mu^-$ (\mathcal{B}) and use the STARLIGHT MC to convert this (by a factor 8.18 ± 0.15) to $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.92 \pm 0.62$ nb. This agrees with the predictions $2.7_{-0.2}^{+0.6}$ nb [19] and 3.4 ± 0.4 nb [22] among others [23, 24]. We find $\frac{d\sigma}{dy}|_{y=0}(\psi(2S)) = 0.53 \pm 0.14$ nb (Table I) compared with a prediction [19] $0.46_{-0.04}^{+0.11}$ nb. The ratio $R = \frac{\psi(2S)}{J/\psi} = 0.14 \pm 0.05$ is in agreement with the HERA value [12] $R = 0.166 \pm 0.012$ at similar $\sqrt{s}(\gamma p)$.

After correcting the 65 χ_{c0} candidates for backgrounds and efficiencies, including a $17 \pm 4\%$ loss due to photon conversion and inefficiency, and applying the branching fraction $\mathcal{B}(\chi_{c0} \rightarrow J/\psi + \gamma) = 0.0128 \pm 0.0011$ [11] we find $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0}) = 76 \pm 14$ nb. The $\chi_{c2}(3556)$ may be present, although it is strongly suppressed by the $J_z = 0$ rule [10] 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 χ_{c1} and χ_{c2} to be negligible. If several states χ_{ci} are present, $\sum \mathcal{B}_i \sigma_{i,FKR} = 8.0 \pm 1.3$ pb. Theoretical predictions for $\frac{d\sigma}{dy}|_{y=0}(\chi_{c0})$ [10, 27, 28] have large uncertainties, but are compatible with our measurement.

If the J/ψ and $\psi(2S)$ cross sections were larger than expected for photoproduction, it would be evidence for odderon exchange. If we assume a theoretical value of $\frac{d\sigma}{dy}|_{y=0}(J/\psi) = 3.0 \pm 0.3$ nb for photoproduction ($\gamma P \rightarrow J/\psi$), compatible with the predictions, we can place a 95% C.L. upper limit $\frac{d\sigma}{dy}|_{y=0}(J/\psi) < 2.3$ nb for odderon exchange ($OIP \rightarrow J/\psi$).

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 QED 2-photon process $\gamma\gamma \rightarrow e^+e^-$ has previously been observed in e^+e^- , ep and nuclear collisions, and recently by CDF [5] in $p\bar{p}$ collisions. 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 [9] and imposes constraints on the $p+p \rightarrow p+H+p$ cross section.

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- [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. For the charmonium states we use longitudinal rapidity $y = -\ln \frac{E+p_z}{E-p_z}$.
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