Exclusive Charmonium Production at CDF

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We have observed the reactions $p\bar{p} \to pX\bar{p}$, with X being a centrally produced J/ψ, $\psi(2S)$, or χ_{c0}, and $\gamma\gamma \to \mu^+\mu^-$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The required event topology consists of 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, $\gamma p \to J/\psi(\psi(2S))p$, observed here for the first time in hadron-hadron collisions. We also observe exclusive $\chi_{c0} \to J/\psi + \gamma$ decays. The cross sections $\frac{d\sigma}{dy}|_{y=0}$ for J/ψ, $\psi(2S)$, and χ_{c0} are (3.92 ± 0.25(stat) ± 0.52(syst)) nb, (0.53 ± 0.09(stat) ± 0.10(syst)) nb, and (76 ± 10(stat) ± 10(syst)) nb, respectively, and the continuum is consistent with QED.

1 Introduction

In central exclusive production processes, $p + \bar{p} \to p + X + \bar{p}$ the colliding hadrons emerge intact with small transverse momenta, 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 [1], $I\!P$, exchanges are significant, where $I\!P$ consists mostly of two gluons in a colour singlet state with charge parity $C = 1$ state [2].

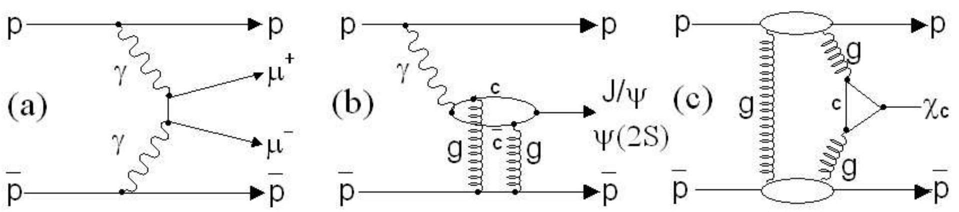

Figure 1: Feynman diagrams for (a) $\gamma\gamma \to \mu^+\mu^-$, (b) $\gamma I\!P \to J/\psi(\psi(2S))$, and (c) $I\!P I\!P \to \chi_c$, with the 2-gluon exchange forming a Pomeron.

In these proceedings we report measurements of exclusive dimuon production, $X \to \mu^+\mu^-$, with 3.0 GeV/c^2 $\leq M \leq$ 4.0 GeV/c^2, directly [QED, Figure 1(a)], or from photoproduced J/ψ or $\psi(2S)$ [Figure 1(b)] decay, and $\chi_{c0} \to J/\psi + \gamma \to \mu^+\mu^-\gamma$ [Figure 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 [3], 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, which is negligible in this regime.

2 The CDF Detector

We used $p\bar{p}$ collision data at $\sqrt{s} = 1.96\,\text{TeV}$ corresponding to an integrated luminosity L = 1.48 fb^{-1} delivered to the CDF-II detector. This is a general purpose detector described in more detail elsewhere [4]. 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 100% efficiency for reconstructing isolated tracks with $p_T \geq 1\,\text{GeV/c}$ and pseudorapidity $|\eta| < 0.6$.

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 $|\eta| < 0.6$ [5]. The regions $3.6 < |\eta| < 5.2$ are covered by lead-liquid scintillator calorimeters [6]. Gas Cherenkov counters covering $3.7 < |\eta| < 4.7$ determined the luminosity with a 6% uncertainty [7]. 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, can detect products of $p(\bar{p})$ fragmentation over the range $|\eta| < 7.4$.

The Event Selection

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 [8] 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 $E_T^{EM} > 80\,\text{MeV}$ 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 as the fraction of bunch crossing triggers that pass the exclusivity requirement (a). We found $\varepsilon_{exc} = 0.093$ with negligible uncertainty. The product $\varepsilon_{exc}L = L_{eff} = (139 \pm 8)\,\text{pb}^{-1}$ is the effective luminosity for single interactions.

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 $\Delta\theta_{3D} < 3.0\,\text{rad}$. Within a Fiducial Kinematic Region (FKR) [$|\eta(\mu)| < 0.6$ and $3.0\,\text{GeV}/c^2 \leq M_{\mu\mu} \leq 4.0\text{GeV}/c^2$], there are 402 events with no EM shower. The $M_{\mu\mu}$ spectrum is shown in Figure 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 Figure 2(inset).

Backgrounds to exclusive $\mu^+\mu^-$ events are (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

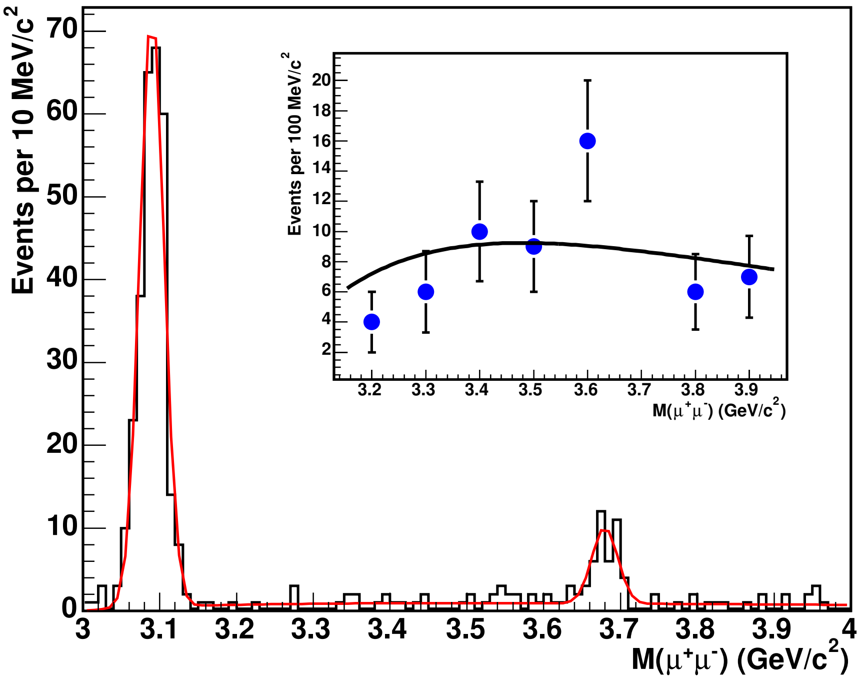

Figure 2: Mass distribution of 402 exclusive events, with no EM shower (histogram, together with a fit to two Gaussians for the J/ψ and $\psi(2S)$, and a QED continuum. All three shapes are predetermined, with only the normalisations floating. Inset - Data above the J/ψ and excluding $3.65 \leq M_{\mu^+\mu^-}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

Carlo (MC) simulation [9] 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 fragmentation probability at the $pIPp(p^*)$ vertex was taken from the ratio of single diffractive fragmentation to elastic scattering at the Tevatron [10] 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 J/ψ, $\psi(2S)$ [11], and QED [9] with $3.2 \leq M_{\mu\mu} \leq 3.6$ and $3.8 \leq M_{\mu\mu} \leq 4.0\,\mathrm{GeV/c^2}$ 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. As expected, $\langle p_T \rangle$ is smaller for the QED process, and the data agree well with STARLIGHT [11], apart from two events with $p_T > 0.8\,\mathrm{GeV/c}$ where no events are expected. Comparing data with LPAIR we estimate that the nonexclusive background is $9 \pm 5\%$ of the observed (QED) events. The $\psi(2S)$data are well fitted by the STARLIGHT photoproduction simulation [11]. The distribution of $p_T(J/\psi)$ is well fitted by STARLIGHT, apart from five events with p_T >1.4 GeV/c. 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 $E_T^{EM} > 80$ MeV in addition to two muons. 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^{EM} spectrum is well fitted by an empirical function which extrapolates to only 3.6 $\pm$ 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 anE_T^{EM} signal are consistent with all these J/ψ being from χ_{c0} decay, as simulated by the CHICMC Monte Carlo [12]. 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).

Figure 2 (inset) shows the subset of the 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, Aε, 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 2 is 77 $\pm$ 9(stat) events, and after correcting for backgrounds and efficiencies, the measured cross section for QED events with $|\eta|(\mu^\pm) < 0.6$ and $3.0 \leq M_{\mu\mu} \leq$ GeV/c^2 is $\sigma = 2.7 \pm 0.3(stat) \pm 0.4$ pb, in agreement with the QED prediction 2.18 $\pm$ 0.01 pb [9].

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 Aε to obtain $BR.\sigma_{FKR}$ for both muons in the fiducial kinematic region. To obtain $\frac{d\sigma}{dy}|_{y=0}$ from σ_{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 BR. We found $\frac{d\sigma}{dy}_{y=0}(J/\psi) = 3.93 \pm 0.25(\text{stat}) \pm 0.52(\text{syst})$ nb. This agrees with the predictions $2.76^{+0.6}_{-0.2}$nb [11] and 3.4 $\pm$ 0.4 nb [13] among others [14, 15]. We found $\frac{d\sigma}{dy}_{y=0}(\psi(2S)) = 0.53 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$ nb compared with a prediction [11] $0.46^{+0.11}_{-0.04}$. The ratio $\text{R} = \frac{\psi(2S)}{J/\psi} = 0.14 \pm 0.05$ is in agreement with the HERA value [3] $\text{R} = 0.166 \pm 0.012$ at similar $\sqrt{(\gamma p)}$.

After correcting the 65 χ_{c0} candidates for backgrounds and efficiencies, and applying the branching fraction $BR(\chi_{c0} \to J/\psi + \gamma) = 0.128 \pm 0.0011$ [16], we found $\frac{d\sigma}{dy}_{y=0}(\chi_{c0}) = 76 \pm$ 10(stat) $\pm$ 10(syst) nb. Reference [17] 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 been reduced by a factor 1.45 correcting this prediction to 90 nb. Yuan [18] predicted 160 nb (again the factor 1.45 should be applied) and Bzdak [19] 45 nb.

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 $\gamma\gamma \to \mu^+\mu^-$. The photoproduction process has previously been studied in *ep* collisions at HERA, with similar kinematics ($\sqrt{s(\gamma p)}$ ~100 GeV), and t the cross sections are in agreement. Our observation of exclusive χ_{c0} production implies that exclusive Higgs boson production should occur at the LHC [20] and imposes constraints on the $p + \bar{p} \to p + H + \bar{p}$ cross section.

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