Evidence for Simultaneous Production of J/ψ and Υ Mesons

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We report evidence for the simultaneous production of J/ψ and Υ mesons in 8.1 fb^{-1} of data collected at $\sqrt{s} = 1.96$ TeV by the D0 experiment at the Fermilab $p\bar{p}$ Tevatron Collider. Events with these characteristics are expected to be produced predominantly by gluon-gluon interactions. In this analysis, we extract the effective cross section characterizing the initial parton spatial distribution, $\sigma_{\mathrm{eff}} = 2.2 \pm 0.7(\mathrm{stat}) \pm 0.9(\mathrm{syst})$ mb.

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The importance of multiple parton interactions (MPI) in hadron-hadron collisions as a background to processes such as Higgs production or various new phenomena has been often underestimated in the past. For instance, in the associated production of Higgs and weak bosons, where the Higgs boson decays into $b\bar{b}$, the MPI background, in which one interaction produces the vector boson and another produces a pair of jets, may exceed the size of the Higgs signal even after the application of strict event selections [1]. Recent data [2–9] examining various double parton interactions have attracted considerable theoretical attention [1,10–14].

In this Letter, we measure for the first time the cross section for simultaneous production of J/ψ and Υ $(1S, 2S, 3S)$ mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The production of two quarkonium states can be used to probe the interplay of perturbative and nonperturbative phenomena in quantum chromodynamics (QCD) and to search for new bound states of hadronic matter such as tetraquarks [10,15]. Here we focus on double quarkonium production as a measure of the spatial distribution of partons in the nucleon.

Unlike other quarkonium processes such as double J/ψ production, or processes involving jets or vector bosons, the production of J/ψ and Υ mesons is expected to be dominated by double parton (DP) interactions involving the collisions of two independent pairs of partons within the colliding beam particles. The simultaneous production through single parton (SP) interactions is suppressed by additional powers of α_s and by the small size of the allowed color octet matrix elements [11]. The DP process is estimated in Ref. [13] to give the dominant contribution to the total $J/\psi + \Upsilon$ production at the Tevatron. In this analysis, we assume that there is no SP contribution [16]. Because of the dominance of gg interactions in producing heavy quarkonium states, the spatial distribution of gluons in a proton [17–19] is directly probed by the DP scattering rate, which represents simultaneous, independent parton interactions. In contrast, the DP studies involving vector bosons and jets probe the spatial distributions of quark-quark or quark-gluon initial states [2–6].

In $p\bar{p}$ collisions, there are three main production mechanisms for J/ψ mesons: prompt production; as a radiative decay product of promptly produced heavier charmonium states such as the $^3P_1$ state χ_{1c} and the $^3P_2$ state χ_{2c}; and nonprompt B hadron decays. A particle is considered produced promptly if it originates in the initial $p\bar{p}$ interaction or if it originates in either an electromagnetic or strong force mediated decay and thus the tracks appear to be produced at the $p\bar{p}$ interaction vertex. Υ mesons are only produced promptly, either directly or as decay products of higher mass states, such as χ_{1b} or χ_{2b}. Prompt heavy quarkonium production is described by three types of models: the color-singlet (CS) model [20]; the color evaporation model [21,22] with a subsequent soft color interaction model [23]; and the color-octet (CO) model [24,25].

In this Letter, we present the first measurement of the cross section of the simultaneous production of prompt

J/ψ and Υ mesons, as well as a measurement of the single prompt J/ψ production cross section. The Υ cross section was measured previously by D0 [26]. The measurements are based on a data sample collected by the D0 experiment at the Tevatron corresponding to an integrated luminosity of 8.1 ± 0.5 fb^{-1} [27]. Assuming that the simultaneous production of J/ψ and Υ mesons is caused solely by DP scattering, we extract the effective cross section ($\sigma_{\rm eff}$), a parameter related to an initial state parton spatial density distribution within a nucleon (see, e.g., Ref. [19]):

$$\sigma_{\rm eff}^{-1} = \int d^2\beta [F(\beta)]^2 \quad (1)$$

with $F(\beta) = \int f(\mathbf{b}) f(\mathbf{b} - \beta) d^2 b$, where β is the vector impact parameter of the two colliding hadrons, and $f(\mathbf{b})$ is a function describing the transverse spatial distribution of the partonic matter inside a hadron. The $f(\mathbf{b})$ may depend on the parton flavor.

The cross section for double parton scattering, $\sigma_{\rm DP}$, is related to $\sigma_{\rm eff}$ for the production of J/ψ and Υ mesons:

$$\sigma_{\rm eff} = \frac{\sigma(J/\psi)\sigma(\Upsilon)}{\sigma_{\rm DP}(J/\psi + \Upsilon)}. \quad (2)$$

Both the J/ψ and Υ mesons are fully reconstructed via their decay $J/\psi(\Upsilon) \to \mu^+\mu^-$, where the muons are required to have transverse momenta $p_T^\mu > 2$ GeV$/c$ and pseudorapidity $|\eta^\mu| < 2.0$ [28]. The cross sections measured with these kinematic requirements are referred to below as "fiducial cross sections."

The general purpose D0 detector is described in detail elsewhere [29,30]. The two subdetectors used to trigger and reconstruct muon final states are the muon and the central tracking systems. The central tracking system, used to reconstruct charged particle tracks, consists of the inner silicon microstrip tracker (SMT) [31] and outer central fiber tracker (CFT) detector both placed inside a 1.9 T solenoidal magnet. The solenoidal magnet is located inside the central calorimeter. The muon detectors [32] surrounding the calorimeters consist of three layers of drift tubes and three layers of scintillation counters, one inside the 1.8 T iron toroidal magnets and two outside. The luminosity is measured using plastic scintillation counters surrounding the beams at small polar angles [27].

We require events to pass at least one of a set of low-p_T dimuon triggers. The identification of muons starts with requiring hits at least in the muon detector layer in front of the toroids [33] and proceeds by matching the hits in the muon system to a charged particle track reconstructed by the central tracking system. The track is required to have at least one hit in the SMT and at least two hits in the CFT detectors. To suppress cosmic rays, the muon candidates must satisfy strict timing requirements. Their distance of the closest approach to the beam line has to be less than 0.5 cm and their matching tracks have to pass within 2 cm of the primary $p\bar{p}$ interaction vertex along the beam axis. We require two oppositely charged muons, isolated in the calorimeter and tracking detectors [33], with good matching of the tracks in the inner tracking and those in the muon detector, and masses within the ranges $2.4 < M_{\mu\mu} < 4.2$ GeV or $8 < M_{\mu\mu} < 12$ GeV for the J/ψ and Υ candidates, respectively. The mass windows are chosen to be large enough to provide an estimate of backgrounds on either side of the J/ψ or Υ mass peaks. Events that have a pair of such muons in each of the two invariant mass windows are identified as J/ψ and Υ simultaneous production candidates. Background events are mainly due to random combinations of muons from $\pi^\pm$, $K^\pm$ decays (decay background), continuous nonresonant $\mu^+\mu^-$ Drell-Yan (DY) production, and B hadron decays into $J/\psi + X$. In the case of $J/\psi + \Upsilon$ production, there is also a background where one muon pair results from a genuine J/ψ or Υ decay and the other pair is a nonresonant combination of muons $[J/\psi(\Upsilon) + \mu\mu]$.

In our single quarkonium sample, the backgrounds from $\pi^\pm$, $K^\pm$ decays and DY events are estimated simultaneously with the number of signal events by performing a fit to the $M_{\mu\mu}$ invariant mass distribution using a superposition of Gaussian functions for signal and a quadratic function for the background. The $\psi(2S)$ events are included in the fitted region but omitted for the single J/ψ cross section calculation, while all three Υ mass states $(1S, 2S, 3S)$ are included in the Υ cross section calculation. The number of single J/ψ events found in the fit is 6.9×10^6, while the number of single Υ events is 2.1×10^6.

The single J/ψ trigger efficiency is estimated using events with a reconstructed J/ψ which pass zero-bias (ZB) triggers requiring only a beam crossing, or minimum bias (MB) triggers which only require hits in the luminosity detectors, and that do or do not satisfy the dimuon trigger requirement. To estimate the trigger efficiency for the Υ selection, we use the $\Upsilon(1S)$ cross section previously measured by the D0 experiment [26], extrapolated to our fiducial region using events generated with the PYTHIA [34] Monte Carlo (MC) event generator and increased to include the $\Upsilon(2S, 3S)$ contributions. Using PYTHIA for the extrapolation introduces a negligible bias because the fiducial regions are similar and the D0 muon system acceptance outside both fiducial regions is low. The trigger efficiencies for single J/ψ mesons and for single Υ mesons in the fiducial region are 0.13 ± 0.03(syst) and 0.29 ± 0.05(syst), respectively, where the systematic uncertainties are dominated by the small size of the ZB and MB samples. The trigger efficiency for the $J/\psi + \Upsilon$ selection is estimated using the single J/ψ and Υ trigger efficiencies and MC samples of $J/\psi + \Upsilon$ events generated with the PYTHIA MC generator. The events are passed through a GEANT based [35] simulation of the D0 detector and overlaid with data ZB events to mimic event pileup, and processed with the same reconstruction software as data. We calculate the trigger efficiency for every possible pairing of muons in DP $J/\psi + \Upsilon$ MC events using the parametrizations of the dimuon trigger efficiencies as a function of $p_T^{J/\psi}$ and p_T^{Υ} and obtain an efficiency of $0.77 \pm 0.04(\mathrm{syst})$. The substantial increase in the trigger efficiency is due to the presence of four muons in the $J/\psi + \Upsilon$ events.

We use PYTHIA-generated single J/ψ and Υ events to estimate the combined geometric and kinematic acceptance and reconstruction efficiency. The generated and reconstructed events are selected using the same muon selection criteria. We correct the number of simulated reconstructed events for the different reconstruction efficiencies in data and MC events, calculated in (p_T^{μ}, η^{μ}) bins. The product of the acceptance and efficiency for single J/ψ events produced in the color singlet model is $0.19 \pm 0.01(\mathrm{syst})$. The product of the acceptance and efficiency for single Υ events is $0.43 \pm 0.05(\mathrm{syst})$. The systematic uncertainties are due to muon identification efficiency mismodeling and to the differences in the kinematic distributions between the data and simulated J/ψ or Υ events. The $\cos\theta^*$ distribution, where θ^* is the polar angle of the decay muon in the Collins-Soper frame [36], is sensitive to the J/ψ and Υ polarizations [37–41]. Data-to-MC reweighting factors based on the observed $\cos\theta^*$ distribution are used to recalculate the acceptance, and lead to $\lesssim 1\%$ difference with the default acceptance value for single J/ψ events and $\approx 11\%$ for single Υ events, which we take as systematic uncertainties.

The vertex of a B hadron decay into the $J/\psi + X$ final state is on average several hundred microns away from the $p\bar{p}$ interaction vertex, while prompt J/ψ production occurs directly at the interaction point. To identify promptly produced J/ψ mesons, we examine the decay length from the primary $p\bar{p}$ interaction vertex (in the plane transverse to the beam) to the J/ψ production vertex, defined as $c\tau = L_{xy} m_{J/\psi} / p_T^{J/\psi}$, where L_{xy} is calculated as the distance between the intersection of the muon tracks and the $p\bar{p}$ interaction vertex, $m_{J/\psi}$ is the world average J/ψ mass [42], and $p_T^{J/\psi}$ is the J/ψ transverse momentum.

The fraction of prompt J/ψ mesons in the data sample is estimated by performing a maximum likelihood fit of the $c\tau$ distribution. The fit uses templates for the prompt J/ψ signal events, taken from the single J/ψ MC sample, and for nonprompt J/ψ events, taken from the $b\bar{b}$ MC sample. Both are generated with PYTHIA. The prompt J/ψ fraction obtained from the fit is $0.83 \pm 0.03(\mathrm{syst})$. The systematic uncertainty is dominated by the uncertainty in the MC modeling of the $c\tau$. The fit result is shown in Fig. 1. By applying the selection $c\tau < 0.02 (> 0.03)$ cm, we verify that the $p_T^{J/\psi}$ spectra of the prompt (nonprompt) J/ψ events in data are well described by MC simulations in the prompt (B-decay) dominated regions.

The fiducial cross section of the prompt single J/ψ production is calculated using the number of J/ψ

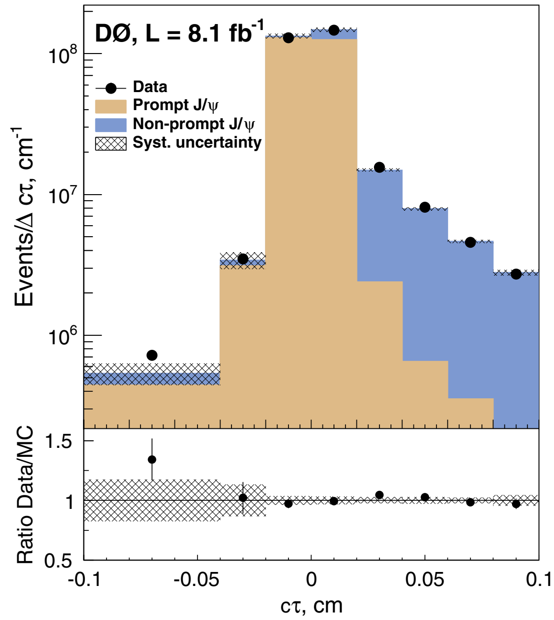

FIG. 1. The $c\tau$ distribution of background subtracted single J/ψ events after all selection criteria. The distributions for the signal and background templates are shown normalized to their respective fitted fractions with $\chi^2/\mathrm{Ndof} = 1.6$, $\mathrm{Ndof} = 6$. The shaded uncertainty band corresponds to the total systematic uncertainty on the sum of signal and background events.

candidates in data, the fraction of prompt J/ψ events, the trigger efficiency, the acceptance and selection efficiencies, as well as the integrated luminosity. The fiducial cross section is

$$\sigma(J/\psi) = 28 \pm 7(\mathrm{syst})\ \mathrm{nb}. \quad (3)$$

The systematic uncertainty in the single J/ψ cross section mainly arises from the trigger efficiency. The statistical uncertainty is negligible. The measured single J/ψ cross section is in agreement with the measurement by D0 [7] $[23.9 \pm 4.6(\mathrm{stat}) \pm 3.7(\mathrm{syst})\ \mathrm{nb}]$ in a similar fiducial region and with the measurement by CDF [43] if an interpolation to the CDF fiducial region is performed.

The cross section for single Υ production is extrapolated to our fiducial region from the previous D0 measurement [26]. Using the ratio of $\Upsilon(1S)$ to Υ (sum of $1S, 2S, 3S$ states) of $0.73 \pm 0.03(\mathrm{syst})$, estimated in Υ selection data, we obtain the Υ cross section (the statistical uncertainty is negligible):

$$\sigma(\Upsilon) = 2.1 \pm 0.3(\mathrm{syst})\ \mathrm{nb}. \quad (4)$$

The systematic uncertainty in $\sigma(\Upsilon)$ includes that from Ref. [26] as well as those from the $\Upsilon(1S)$ fraction and the extrapolation to the fiducial region.

In the data, 21 events pass the selection criteria for $J/\psi + \Upsilon$ pair production in the J/ψ mass window $2.88 < M_{\mu\mu} < 3.36\ \mathrm{GeV}/c^2$ and Υ mass window $9.1 < M_{\mu\mu} < 10.2\ \mathrm{GeV}/c^2$. Figure 2 shows the distribution of the two

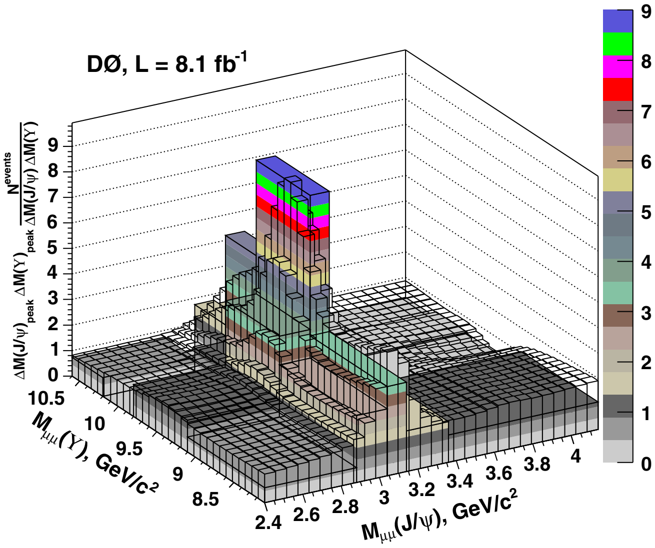

FIG. 2. Dimuon invariant mass distribution in data for two muon pairs, $M_{\mu\mu}(J/\psi)$, $M_{\mu\mu}(\Upsilon)$, divided by the bin area, after the selection criteria. Also shown is the two-dimensional fit surface. The factor $\Delta M(J/\psi)_{\text{peak}}\ \Delta M(\Upsilon)_{\text{peak}}$ is applied so that the height of the peak bin is the number of observed events in that bin.

dimuon masses $[M_{\mu\mu}(J/\psi,\Upsilon)]$ in these and surrounding mass regions. We estimate the accidental and $J/\psi(\Upsilon)+\mu\mu$ backgrounds using the same technique of combining the one-dimensional functional forms utilized in single J/ψ and Υ signal and background parametrizations as in Ref. [7]. We fit a two-dimensional distribution of the $M_{\mu\mu}(J/\psi,\Upsilon)$ with the resulting two-dimensional functional form and estimate the number of $J/\psi+\Upsilon$ events is $14.5\pm4.6(\text{stat})\pm 3.4(\text{syst})$. This corresponds to a prompt $J/\psi+\Upsilon$ signal of $12.0\pm3.8(\text{stat})\pm2.8(\text{syst})$ events. The probability of the observed number of events to have arisen from the background is 6.3×10^{-4}, corresponding to 3.2 standard deviation evidence for the production of prompt $J/\psi+\Upsilon$. The probability calculation includes the systematic uncertainties in the background estimates. The distribution of the azimuthal angle between the J/ψ and Υ candidates $\Delta\phi(J/\psi,\Upsilon)$ after the subtraction of backgrounds is shown in Fig. 3. The data distribution is consistent with the DP MC model, which is uniform [11], substantiating our assumption that the DP process is the dominant contribution to the selected $J/\psi+\Upsilon$ data sample.

We estimate the acceptance, reconstruction, and selection efficiencies for $J/\psi+\Upsilon$ events using MC DP samples. The product of the acceptance and the selection efficiency for the DP events is found to be $(A\varepsilon_s)=0.071\pm 0.007(\text{syst})$, where the systematic uncertainty is dominated by the uncertainty in the modeling of the J/ψ and Υ kinematics and muon identification efficiency for our sample with low p_T muons.

Using the numbers presented above, we obtain the cross section of the simultaneous production of J/ψ and Υ mesons:

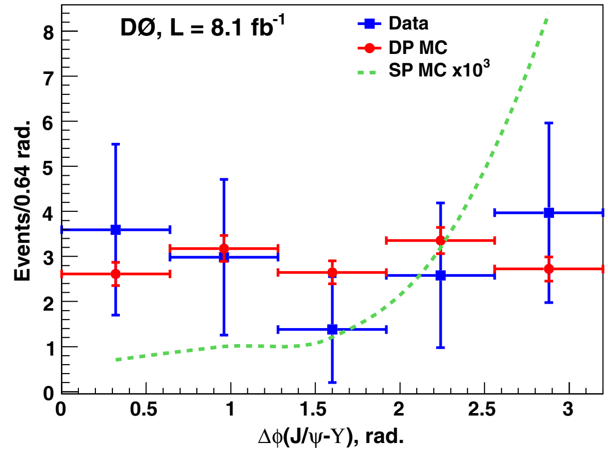

FIG. 3. The distribution of the azimuthal angle between the J/ψ and Υ candidates, $\Delta\phi(J/\psi,\Upsilon)$, in data after background subtraction, in DP MC [34], and SP MC [44] results. MC events are in arbitrary units.

$$\sigma_{\text{DP}}(J/\psi+\Upsilon)=27\pm9(\text{stat})\pm7(\text{syst})\ \text{fb}. \qquad (5)$$

From the measured cross sections of prompt single J/ψ, DP $J/\psi+\Upsilon$, and the estimate of the single Υ cross section, we calculate the effective cross section, σ_{eff}. The main sources of systematic uncertainty in the σ_{eff} measurement are the estimates of the trigger efficiency and combinatorial background. Based on Eq. (2) and upon the assumption [16] that $J/\psi+\Upsilon$ production has a negligible SP contribution, we obtain

$$\sigma_{\text{eff}}=2.2\pm0.7(\text{stat})\pm0.9(\text{syst})\ \text{mb}. \qquad (6)$$

The measured σ_{eff} agrees with the result reported by the AFS Collaboration in the 4-jet final state [45] ($\approx$5 mb) and D0 in the double J/ψ final state [7] $[4.8\pm0.5(\text{stat})\pm 2.5(\text{syst})$ mb]. However, it is lower than the CDF results in the 4-jet final state [46] $[12.1^{+10.7}_{-5.4}$ mb] and γ/π^0+3-jet final state [2] $[14.5\pm1.7(\text{stat})^{+1.7}_{-2.3}(\text{syst})$ mb]; the D0 [4] result in $\gamma+3$-jet events [4] $[12.7\pm0.2(\text{stat})\pm 1.3(\text{syst})$ mb]; both ATLAS [3] $[15\pm3(\text{stat})^{+5}_{-3}(\text{syst})$ mb] and CMS [5] $[20.7\pm0.8(\text{stat})\pm6.6(\text{syst})$ mb] results in the $W+2$-jet final state; and the LHCb [47] $[18.0\pm1.3(\text{stat})\pm1.2(\text{syst})$ mb] result in $\Upsilon+$ open charm events. The DP $J/\psi+\Upsilon$, double J/ψ, and 4-jet production are dominated by gg initial states, whereas the $\gamma(W)+$jets events are produced predominantly by $q\bar{q}'$, and qg processes. The values of σ_{eff} measured in different final state channels indicate that gluons occupy a smaller region of space within the proton than quarks. The pion cloud model [48] predicts a smaller average transverse size of the gluon distribution in a nucleon than that for quarks.

In conclusion, we have presented the first evidence of simultaneous production of prompt J/ψ and Υ $(1S,2S,3S)$ mesons with a significance of 3.2 standard deviations. The process is expected to be dominated by double parton scattering. The distribution of the azimuthal angle between the J/ψ and Υ candidates is consistent with the double parton scattering predictions. Under the assumption of it being entirely composed of double parton scattering, in the fiducial region of $p_T^\mu > 2$ GeV and $|\eta^\mu| < 2$ we measure the cross section $\sigma_{\rm DP}(J/\psi+\Upsilon)=27\pm9({\rm stat})\pm7({\rm syst})$ fb. We also measure the single J/ψ and estimate the single Υ $(1S, 2S, 3S)$ production cross sections in the same fiducial region as the $J/\psi + \Upsilon$ cross section and find the effective cross section for this gg dominated process to be $\sigma_{\rm eff} = 2.2 \pm 0.7({\rm stat}) \pm 0.9({\rm syst})$ mb, lower than the values found in the $q\bar{q}$ and qg dominated double parton processes. This suggests that the spatial region occupied by gluons within the proton is smaller than that occupied by quarks.

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