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Observation and studies of double J/ψ production at the Tevatron

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We present the observation of doubly-produced J/ψ mesons with the D0 detector at Fermilab in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The production cross section for both singly and doubly-produced J/ψ mesons is measured using a sample with an integrated luminosity of 8.1 fb^{-1}. For the first time, the double J/ψ production cross section is separated into contributions due to single and double parton scatterings. Using these measurements, we determine the effective cross section $\sigma_{\rm eff}$, a parameter characterizing an effective spatial area of the parton-parton interactions and related to the parton spatial density inside the nucleon.

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Heavy quarkonium is a well established probe of both quantum chromodynamics (QCD) and possible new bound states of hadronic matter, e.g., tetraquarks [1, 2]. Production of multiple quarkonium states provides insight into the parton structure of the nucleon and parton-to-hadron fragmentation effects. In $p\bar{p}$ collisions, there are three main production mechanisms for J/ψ mesons: prompt production (i.e. directly at the interaction point) of J/ψ, and prompt production of heavier charmonium states, such as the $^3P_1$ state χ_{1c} and the $^3P_2$ state χ_{2c} decaying to $J/\psi+\gamma$, and non-prompt B hadron decays. The first observation of J/ψ meson pair production was made in 1982 by the NA3 Collaboration [3, 4]. The LHCb Collaboration has measured the double J/ψ production cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV [5]. At Tevatron and LHC energies this cross section is dominated by gluon fusion, $gg \to J/\psi J/\psi$ [1, 6].

The interest in this channel originates from the different mechanisms that can generate simultaneous double J/ψ (DJ) meson production in single parton (SP) and double parton (DP) scatterings in a single hadron-hadron collision. A number of discussions of early experimental results [7, 8] and more recent LHCb results [6, 9], show that the fraction of DP events at the Tevatron and especially at the LHC can be quite substantial. Since the initial state is dominated by gg scattering, the fraction of DP scatterings representing simultaneous, independent parton interactions, should significantly depend on the spatial distribution of gluons in a proton [10]. Other DP studies involving vector bosons and jets probe the spatial distributions in processes with quark-quark or quark-gluon initial states [11–15]. The measurement of the SP production cross section provides unique information to constrain parametrizations of the gluon parton distribution function (PDF) at low parton momentum fraction and energy scale, where the gluon PDF has large uncertainty [16]. The production of J/ψ mesons may proceed via two modes, color singlet and color octet [1, 8, 17, 18]. Predictions carried out using nonrelativistic QCD (NRQCD) show that the color singlet process in SP scattering contributes $\approx 90\%$ for the region of transverse momenta, $p_T^{J/\psi} \geq 4$ GeV/c, relevant for this measurement [8, 17].

In this Letter, we present first observation of double J/ψ production at the Tevatron and measurements of single and double J/ψ production cross sections. For the first time, the latter is split into measurements of the SP and DP production cross sections. This allows us to extract the effective cross section ($\sigma_{\rm eff}$), a parameter

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related to an initial state parton spatial density distribution within a nucleon (see, e.g., [6]):

$$\sigma_{\rm eff} = \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma_{\rm DP}(J/\psi J/\psi)}. \qquad (1)$$

The factor of 1/2 corresponds to the two indistinguishable processes of single J/ψ production [19, 20].

The measurements are based on the data sample collected by the D0 experiment at the Tevatron in proton-antiproton ($p\bar{p}$) collisions at the center-of-mass energy $\sqrt{s} = 1.96$ GeV, and corresponds to an integrated luminosity of 8.1 ± 0.5 fb^{-1} [21].

All cross section measurements are performed for prompt J/ψ mesons with $p_T^{J/\psi}> 4$ GeV/c and $|\eta^{J/\psi}|< 2$, where $\eta^{J/\psi}$ is the J/ψ pseudorapidity [22]. The J/ψ mesons are fully reconstructed via their decay $J/\psi \to \mu^+\mu^-$. The muons are required to have transverse momenta $p_T^{\mu} > 2$ GeV/c if their absolute pseudorapidities are $|\eta^{\mu}| < 1.35$ or total momenta $|p^{\mu}| > 4$ GeV/c if $1.35 < |\eta^{\mu}| < 2$. The cross sections measured with these kinematic requirements are refered below as fiducial cross sections.

The D0 detector is a general purpose detector described in detail elsewhere [23]. The sub-detectors used in this analysis to select events at the trigger level and to reconstruct muons are the muon and the central tracking systems. The central tracking system, used to reconstruct charged particle tracks, consists of the silicon microstrip tracker (SMT) [24] and a central fiber tracker (CFT) detector both placed inside a 1.9 T solenoidal magnet. The solenoidal magnet is located inside the central calorimeter, which is surrounded by the muon detector [25]. The muon detector consists of three layers of drift tubes and three layers of plastic scintillators, one inside surrounding 1.9 T toroidal magnets and two outside. The luminosity of colliding beams is measured using plastic scintillator arrays installed in front of the two end calorimeter cryostats [21].

Muons are identified as having either hits in all three layers of the muon detector or just in one layer in front of the toroids [26]. They are also required to be matched to a track reconstructed by the central tracking system as having at least one hit in the SMT and at least two hits in the CFT detectors. The muon candidates must satisfy timing requirements to suppress cosmic rays. Their distance of closest approach to the beam line has to be less than 0.5 cm and their matching tracks have to pass within 2 cm along the beam (z) axis of the event interaction vertex. The $p\bar{p}$ interaction vertex should be within 60 cm of the center of the detector along beam axis. Events that have two such muons with opposite electric charge that satisfy an invariant mass requirement of $2.85 < M_{\mu\mu} < 3.35$ GeV/c^2 are identified as single J/ψ candidates. Events having two such pairs of muons are identified as DJ candidates. Background events are mainly due to random combinations of muons from $\pi^{\pm}$, $K^{\pm}$ decays (accidental background), continuous non-resonant $\mu^+\mu^-$ production in Drell-Yan (DY) events, and B hadron decays into $J/\psi + X$.

To properly normalize the cross section measurements and to reduce the backgrounds, we require events to pass at least one of the low-p_T di-muon triggers. The single J/ψ trigger efficiency is estimated using events which pass zero-bias triggers (which only require a beam crossing) or minimum bias triggers (which only require hits in the luminosity detectors), and that also pass the di-muon trigger. The efficiency is found to be $0.124 \pm 0.024(\text{stat}) \pm 0.012(\text{syst})$.

To measure the trigger efficiency for double J/ψ selection, we use DP and SP events generated in Monte Carlo (MC). The double J/ψ DP events are generated with the PYTHIA [27] MC event generator, while the double J/ψ SP events are generated with HERWIG++ [28]. Events passed through a GEANT based [29] simulation of the D0 detector and overlaid with data zero-bias events are then processed with the same reconstruction code as data. We calculate the trigger efficiency for every possible pairing of muons in DP and SP MC events, and obtain efficiencies of $\varepsilon_{\rm tr}^{\rm DP} = 0.48 \pm 0.07$ and $\varepsilon_{\rm tr}^{\rm SP} = 0.51 \pm 0.07$.

The number of single J/ψ events after selections is about 7.4×10^6. The background from $\pi^{\pm}$, $K^{\pm}$ decays and DY events, in our single J/ψ selection is estimated as a function of $p_T^{J/\psi}$and $\eta^{J/\psi}$. In each ($p_T^{J/\psi}$, $\eta^{J/\psi}$) bin, we perform a simultaneous fit of signal using a double Gaussian function and background with a linear dependence in a mass window of $2.3 < M_{\mu\mu} < 4.2$ GeV/c^2. We then calculate the background in the selection mass window of $2.85 < M_{\mu\mu} < 3.35$ GeV/c^2. Averaging the contributions over all ($p_T^{J/\psi}$, $\eta^{J/\psi}$) bins, we estimate the background fraction to be 0.126 ± 0.013. The uncertainty is derived from variation of the fit parameters in the signal and background models.

We use PYTHIA generated single J/ψ events to estimate the combined geometric and kinematic acceptance and reconstruction efficiency of the selection criteria, calculated as the ratio of the number of reconstructed events to the number of input events. The generated events are selected at the particle and reconstruction levels using the same J/ψ and muon selection criteria in transverse momenta and rapidity. The number of reconstructed events is corrected for the different reconstruction efficiency in data and MC, calculated in ($p_T^{J/\psi}$, $\eta^{J/\psi}$) bins. The product of the acceptance and efficiency for single J/ψ events produced in the color singlet model is found to be $0.221 \pm 0.002(\text{stat}) \pm 0.023(\text{syst})$. The systematic uncertainty is due to differences in the kinematic distributions between the simulated and data J/ψ events, muon identification efficiency mismodeling, and differences between the color singlet and color octet models. The $\cos\theta^*$ distribution, where θ^* is the polar angle of the decay muon in the Collins-Soper frame [30], is sensitive to the J/ψ polarization [31–33]. Small data-to-MC reweighting factors based on the observed $\cos\theta^*$ are used to re-calculate the acceptance, and lead to $\lesssim 1\%$ difference with the default acceptance value.

Due to the long lifetimes of B hadrons, their decay vertex into the $J/\psi + X$ final state is usually several hundred microns away from the $p\bar{p}$ interaction vertex, while prompt J/ψ production occurs directly at the interaction point. To distinguish prompt from non-prompt J/ψ mesons, we examine the decay length from the primary $p\bar{p}$ interaction vertex to the J/ψ production vertex, defined as $c\tau = L_{xy} m^{J/\psi}_{\rm pdg}/p_T^{J/\psi}$, where L_{xy} is the decay length of J/ψ meson calculated as the distance between the intersection of the muon tracks and the hard scattering vertex in the plane transverse to the beam, and $m^{J/\psi}_{\rm pdg}$ is the world average J/ψ mass [34].

To estimate the fraction of prompt J/ψ mesons in the data sample, we perform a maximum likelihood fit of the $c\tau$ distribution using templates for the prompt J/ψ signal events, taken from the single J/ψ MC sample, and for non-prompt J/ψ events, taken from the $b\bar{b}$ MC sample. The latter are generated with PYTHIA [27]. The prompt J/ψ fraction obtained from the fit is 0.814 ± 0.009. The fit result is shown in Fig. 1. We verify that the $p_T^{J/\psi}$ spectra of the prompt signal (non-prompt background) events in data are well described by MC in the signal (background) dominated regions by applying the selection $c\tau < 0.02$ ($>$ 0.03) cm.

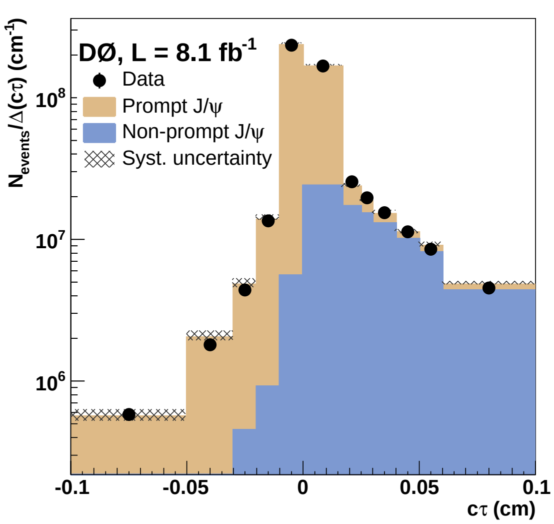

FIG. 1: (color online) The $c\tau$ distribution of background subtracted single J/ψ events after all selection criteria. The distributions for the signal and background templates are shown normalized to their respective fitted fractions. The uncertainty band corresponds to the total systematic uncertainty on the sum of signal and background events.

The fiducial cross section of the prompt single J/ψ production is calculated using the number of J/ψ candidates in data, the fraction of prompt events, the dimuon trigger efficiency, the acceptance and selection efficiency, as well as the integrated luminosity. It is found to be

$$\sigma(J/\psi) = 23.9 \pm 4.6({\rm stat}) \pm 3.7({\rm syst})\ {\rm nb}. \quad (2)$$

The uncertainties mainly arise from the trigger efficiency and acceptance calculations.

This value is compared to that calculated in the "k_T factorization" approach [6] with the unintegrated gluon density "A0" set [16]:

$$\sigma_{\rm k_T}(J/\psi) = 23.0 \pm 8.5\ {\rm nb}. \quad (3)$$

In this calculation, the J/ψ meson is produced either directly or through the radiative $\chi_{1(2)} \to J/\psi + \gamma$ process [6]. The uncertainty is determined by variations of the PDF model (to "A+"and "A- ") and scale variations by a factor of 2 with respect to the default choice $\mu_R = \mu_F = \hat{s}/4$.

In total, 242 events remain after DJ selection criteria and 902 events are found in the wider mass window $2.3 < M_{\mu\mu} < 4.2$ GeV/c^2. Fig. 2 shows the distribution of the two dimon masses ($M^{(1),(2)}_{\mu\mu}$) in these events.

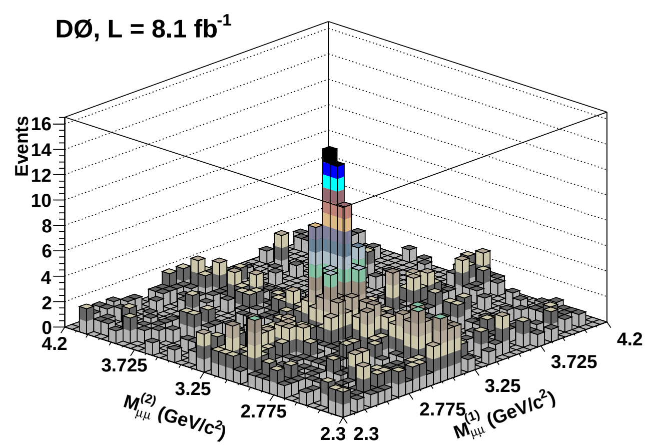

FIG. 2: (color online) Dimuon invariant mass distribution in data for two muon pairs $M^{(1)}_{\mu\mu}$, $M^{(2)}_{\mu\mu}$ after the DJ selection criteria.

In analogy with the single J/ψ event selection, we estimate the accidental, DY backgrounds and fraction of prompt DJ events. First, we reduce the non-prompt and background events by requiring $c\tau < 0.03$ cm for both J/ψ candidates, with about 94% efficiency for signal events (see Fig. 1). This cut selects $N_{\rm d} = 138$ events in data. To estimate the accidental and DY backgrounds in the selected data, we perform a maximum likelihood fit to the data, in the two-dimensional (2D) ($M^{(1)}_{\mu\mu}$, $M^{(2)}_{\mu\mu}$) plane (similar to Fig. 2) using a 2D Gaussian function for the DJ mass peak and a 2D linear function (plane) for the background. We use the fitted parameters of the plane to estimate the background in the selection window $2.85 < M_{\mu\mu} < 3.35$ GeV/c^2 for both J/ψ meson candidates and compute the fraction of the accidental+DY backgrounds in the DJ events to be $f_{\rm acc,DY} = 0.132 \pm 0.025$.

To estimate the fraction of the prompt double J/ψ events, we use a template fit to the 2D $c\tau$ distribution in DJ data. The $c\tau$ template for double prompt mesons is obtained from the signal MC sample. The double non-prompt template is created from the $b\bar{b}$ MC sample, in which B hadron decays produce two J/ψ mesons. We also create a prompt+non-prompt template by randomly choosing $c\tau$ values from the prompt and non-prompt templates. The prompt fraction of DJ events in our selection is found to be $f_{\rm prompt} = 0.604 \pm 0.086$, while the non-prompt and prompt+non-prompt events contribute 0.303 ± 0.065 and 0.093 ± 0.057, respectively. The main source of systematic uncertainty for the prompt fraction is the template fitting, and the uncertainty related with the subtraction of the accidental and DY backgrounds from the data.

We measure the acceptances, reconstruction, and selection efficiencies separately for double J/ψ events on SP and DP samples using a mixture of 90% color singlet and 10% color octet samples, as predicted by NRQCD [17] for our kinematic selection criteria. The code for the predictions is implemented in the MC model DJpsiFDC [35]. We use PYTHIA for showering and fragmentation of the $gg \to J/\psi J/\psi$ final state. Products of the acceptances and the selection efficiencies are found to be $(A\varepsilon_s)^{\rm SP} = 0.109 \pm 0.002({\rm stat}) \pm 0.005({\rm syst})$ for the SP and $(A\varepsilon_s)^{\rm DP} = 0.099 \pm 0.006({\rm stat}) \pm 0.005({\rm syst})$ for the DP events, where the systematic uncertainties arise from uncertainties in the modeling of the J/ψ kinematics, muon identification efficiencies and the possible non-zero J/ψ polarization effects.

In this analysis, we measure the DJ production cross section for the DP and SP scatterings separately. To discriminate between the two mechanisms, we exploit the distribution of the pseudorapidity difference between the two J/ψ candidates, $|\Delta\eta(J/\psi, J/\psi)|$ [6, 9]. We use the DP and SP templates produced by MC to obtain the DP and SP fractions from a maximum likelihood fit to the $|\Delta\eta(J/\psi, J/\psi)|$ distribution in DJ data. Contributions from the accidental and DY backgrounds, non-prompt and prompt+non-prompt double J/ψ events are subtracted from data. The fit result is shown in Fig. 3. In the region $|\Delta\eta(J/\psi, J/\psi)| \gtrsim 2$, the data are dominated by DP events, as predicted in Ref. [6]. A possible contribution from pseudo-diffractive gluon-gluon scattering should give a negligible contribution [6]. To estimate the systematic uncertainties of the DP and SP fractions, we vary the subtraction of accidental+DY, non-prompt and prompt+non-prompt backgrounds within their uncertainties. To conservatively estimate systematic uncertainty related to the prompt+non-prompt background, it is assumed to be either 100% SP- or DP-like. We also create a data-like DP template combining two J/ψ meson candidates from two events randomly selected from the single J/ψ data sample, emulating two independent scatterings each with a single J/ψ final state. This template is corrected for the accidental, DY and non-prompt backgrounds in data. We extract the DP and SP fractions from the fit to the DJ data sample. These results are averaged over those obtained with the two SP and two DP models. We find the fractions to be $f^{\rm DP} = 0.30 \pm 0.10$ and $f^{\rm SP} = 0.70 \pm 0.11$. The main sources of the uncertainties on DP (SP) fractions are the background subtraction, 28% (13%), the model dependence, 19% (7.6%), and the template fit, 6.2% (3.2%). The uncertainty due to the model dependence is estimated by varying the DP (PYTHIA and data-like) and SP (HERWIG++ and DJpsiFDC) models. We verify that we do not introduce a bias by determining the prompt, SP, and DP fractions in data by doing two successive fits of the $c\tau$ and $|\Delta\eta(J/\psi, J/\psi)|$ distributions. For this purpose, we perform a simultaneous 2D fit for the non-prompt, SP, and DP fractions using templates as functions of inclusive $c\tau$ and $|\Delta\eta(J/\psi, J/\psi)|$ to the data corrected for the accidental, DY and prompt+non-prompt backgrounds. The fractions of prompt DP and SP events determined by this procedure are in agreement within uncertainties with the central result obtained by the two successive fits.

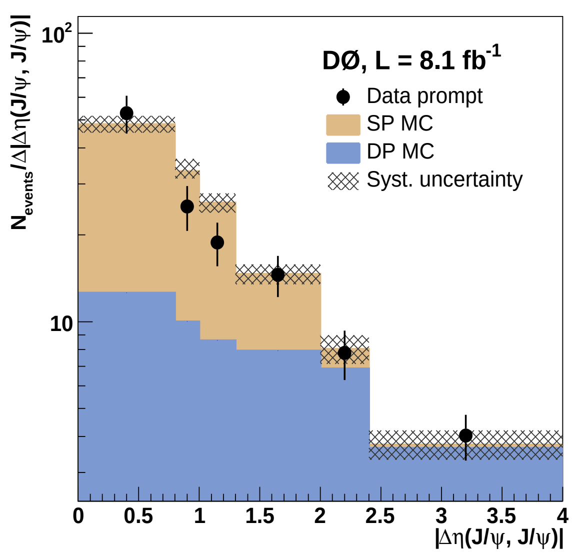

FIG. 3: (color online) The $|\Delta\eta(J/\psi, J/\psi)|$ distribution of background subtracted double J/ψ events after all selection criteria. The distributions for the SP and DP templates are shown normalized to their respective fitted fractions. The uncertainty band corresponds to the total systematic uncertainty on the sum of SP and DP events.

The fiducial prompt DJ cross section is calculated according to

$$\sigma(J/\psi J/\psi)=\frac{N_{\rm d} f_{\rm prompt}(1-f_{\rm acc,DY})}{L}\sum_{i={\rm DP,SP}}\frac{f^i}{(A\varepsilon_{\rm s})^i\varepsilon^i_{tr}}, \quad (4)$$

where $N_{\rm d}$ is the number of data events in the DJ selection, $f_{\rm prompt}$ is the fraction of prompt DJ events, f^i is the fraction of DP or SP events, $\varepsilon^i_{\rm tr}$ is the trigger efficiency, $(A\varepsilon_s)^i$ is the product of acceptance and selection and reconstruction efficiency, and L is the integrated luminosity.

Using the numbers presented above, we obtain

$$\sigma(J/\psi J/\psi) = 169 \pm 15({\rm stat}) \pm 38({\rm syst})\ {\rm fb}. \quad (5)$$

In the same way, we calculate the cross sections of DP and SP events individually

$$\sigma_{\rm DP}(J/\psi J/\psi) = 57 \pm 6({\rm stat}) \pm 23({\rm syst})\ {\rm fb}, \quad (6)$$

$$\sigma_{\rm SP}(J/\psi J/\psi) = 112 \pm 10({\rm stat}) \pm 30({\rm syst})\ {\rm fb}. \quad (7)$$

The prediction for the SP cross section made in the "k_T factorization" approach [6] is

$$\sigma_{\rm k_T}(J/\psi J/\psi) = 55.1^{+28.5}_{-15.6}({\rm PDF})^{+31.0}_{-17.0}({\rm scale})\ {\rm fb}. \quad (8)$$

The choice of the gluon density as well as the renormalization and factorization scales are the same as for the prediction shown in Eq. 3.

We also compare the SP prediction obtained with NRQCD [17] using renormalization and factorization scales of $\mu_R = \mu_F = ((p_T^{J/\psi})^2 + m_c^2)^{1/2}$ and $m_c = 1.5$ GeV/c^2

$$\sigma_{\rm NRQCD}(J/\psi J/\psi) = 51.9\ {\rm fb}. \quad (9)$$

to our result.

The measured SP cross section is larger than the theoretical predictions, but is compatible with the prediction from "k_T factorization" within 1.2 standard deviations, if the theoretical uncertainties are combined with the experimental ones. The discrepancy may be caused by the gluon PDF, higher order corrections, or non-perturbative $g \to c\bar{c}$ fragmentation processes [34, 36, 37].

The DP production cross section predicted by the "k_T factorization" approach according to Eq. 1, and using the fixed effective cross section $\sigma^0_{\rm eff} = 15$ mb [6], is

$$\sigma^{\rm DP}_{\rm k_T}(J/\psi J/\psi) = 17.6 \pm 13.0\ {\rm fb}, \quad (10)$$

Using the measured cross sections of prompt single J/ψ and DP production, we calculate the effective cross section, $\sigma_{\rm eff}$ (see Eq. 1). The main sources of systematic uncertainty in the $\sigma_{\rm eff}$ measurement are trigger efficiency and the fraction of DP events. By substituting the measured single J/ψ and double J/ψ DP cross sections (Eqs. 2 and 6) into Eq. 1, we obtain

$$\sigma_{\rm eff} = 5.0 \pm 0.5({\rm stat}) \pm 2.7({\rm syst})\ {\rm mb}. \quad (11)$$

In conclusion, we have observed double J/ψ production at the Tevatron and measured its cross section. We show that this production is caused by single and double parton scatterings. The measured SP cross section may indicate a need for a higher gluon PDF at small parton momenta and small energy scale, and higher order corrections to the theoretical predictions. The measured $\sigma_{\rm eff}$ agrees with the result reported by the AFS Collaboration (≈ 5 mb [38]), and is in agreement with the $\sigma_{\rm eff}$ obtained by CDF [12] in the 4-jet final state ($12.1^{+10.7}_{-5.4}$ mb). However, it is lower than the result obtained by CDF [13] ($14.5 \pm 1.7({\rm stat})^{+1.7}_{-2.3}({\rm syst})$), the latest D0 [14] result ($12.7 \pm 0.2({\rm stat}) \pm 1.3({\rm syst})$) in $\gamma + 3$-jet events, and by ATLAS [15] ($15 \pm 3({\rm stat})^{+5}_{-3}({\rm syst})$) in the W+2-jet final state. We note that initial state in the DP double J/ψ production is very similar to 4-jet production at low p_T which is dominated by gluons, while $\gamma(W)$+jets events are produced in quark interactions, $q\bar{q}$, qg, and $q\bar{q}'$. The measured $\sigma_{\rm eff}$ may indicate a smaller average distance between gluons than between quarks or between a quark and a gluon, in the transverse space. This result is in a qualitative agreement with the pion cloud model predicting a smaller nucleon's average gluonic transverse size than that for singlet quarks [39].

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