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Quarkonia Production at CDF and D0

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ABSTRACT

In this paper we present results on J/ψ, $\psi(2S)$, χ_c and Υ production at $\sqrt{s} = 1.8$ TeV. These results were obtained from data taken with the CDF and D0 detectors at Fermilab. We cover recently completed analyses of the 1992-95 collider run. Prospects for the near future are also discussed.

1. INTRODUCTION

The study of quarkonia has yielded valuable insight into the nature of strong interactions since the discovery of the J/ψ in 1974. As far as the strong interactions are concerned, heavy quarkonia are the next simplest particles (probes) after leptons and electroweak gauge bosons. In addition, the charmonium and bottomonium systems exhibit a rich spectrum of orbital and angular excitations and therefore they can potentially provide more information than leptons and electroweak gauge bosons. Quarkonia also provide a window in the boundary region between perturbative and non-perturbative QCD and they play a fundamental role in B physics studies. Their production has been recently the subject of a renewed experimental and theoretical interest. The reason is that recent high energy hadron collider experiments have measured the production cross sections for several $Q\bar{Q}$ states and they have been able to disentagle various production mechanisms in the $c\bar{c}$ system providing stringent tests of the production models. The data-theory comparison revealed dramatic discrepancies with production models available up to a couple of years ago (see Ref. [1] for a thorough review for these models and for references). These discrepancies have driven theorists to a better understanding of the underlying dynamics and to a more solid theoretical framework within which to operate. The data presented here have been collected with the CDF[2, 3] and D0 [4] detectors during the 1992-1995 Collider Run at Fermilab. This paper is organized as follows. In section 2 we describe results on charmonia physics from the CDF and D0 experiments; in section 3 we present results on Υ production from the CDF and D0 experiments and in section 4 we present conclusions and discuss the future prospects.

2. CHARMONIA PRODUCTION

In this section we will describe studies on the production of J/ψ's, $\psi(2S)$'s and χ_c's. In $p\bar{p}$ collisions, J/ψ's and $\psi(2S)$'s come from direct production or from the decay of b hadrons. J/ψ's can be additionally produced through radiative decays of χ_c mesons. Finally, the χ_c mesons are produced directly or from the decay of b hadrons.

2.1 *CDF RESULTS*

Using 15.4(17.8) pb^{-1} of data CDF measured the differential and integrated production cross sections for $J/\psi(\psi(2S))$. The two charmonium states are reconstructed in the dimuon channel in the kinematic range $P_T > 5$ GeV/c and $|\eta| < 0.6$ and the mesurements were based on 22,120$\pm$161 J/ψ's and 808$\pm$46 $\psi(2S)$'s. It was found that $\sigma(p\bar{p} \rightarrow J/\psi X) \cdot Br(J/\psi \rightarrow \mu^+\mu^-)$ =17.35 $\pm$ 0.14(stat)$^{+2.59}_{-2.79}$(sys) nb and $\sigma(p\bar{p} \rightarrow \psi(2S)X) \cdot Br(\psi(2S) \rightarrow \mu^+\mu^-) = 0.571$ $\pm$ 0.036(stat)$^{+0.082}_{-0.089}$(sys) nb. Using information from the Silicon Vertex Detector (SVX) to reconstruct the decay vertices of the charmonium states, CDF distinguishes between charmonia from B decays and from other production mechanisms. The SVX detector covers the luminous region of $|z| < 26$ cm along the beam line and only about 50-60% of the tracks found by the Central Tracking Chamber have SVX confirmation. Therefore, in order to decrease the statistical errors on the measurement of the fractions of charmonia coming from B decays, a larger data sample, of $\sim$110 pb^{-1}, was used for those studies. It was found that for the kinematic region $P_T > 5$ GeV/c and $|\eta| < 0.6$, (19.2$\pm$0.2(stat)$\pm$0.4(sys))% of J/ψ's and (23.3$\pm$1.8(stat)$\pm$0.5(sys))% of $\psi(2S)$'s come from the decay of b hadrons. Fig. 1 shows the fractions of J/ψ and $\psi(2S)$ from B decays as a function of P_T. In Fig. 2 the differential production cross section measurements from B decays are compared with the theoretical predictions. These cross sections are extracted by convoluting the differential B fraction with the differential J/ψ and $\psi(2S)$ cross sections. We see that the experimental measurements are a factor of 3-4 above the central value of the theoretical predictions. The CDF experiment has also found that $\frac{Br(B\to\psi(2S)X)\cdot Br(\psi(2S)\to\mu^+\mu^-)}{Br(B\to J/\psi X)\cdot Br(J/\psi\to\mu^+\mu^-)} = 0.033\pm0.003(\text{stat})\pm0.002(\text{sys})$.

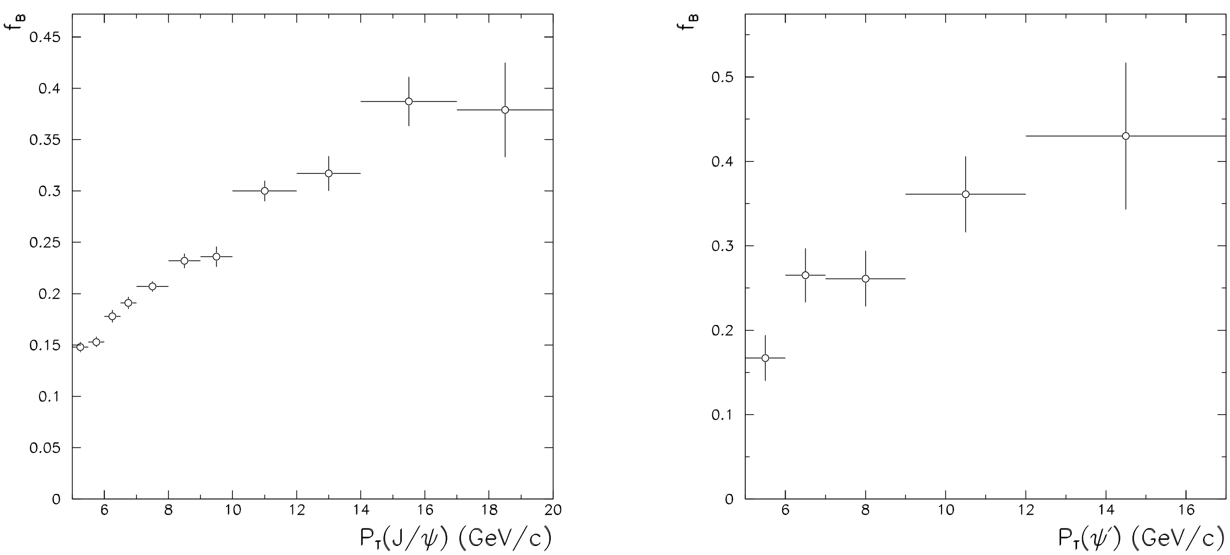

Figure 1: B fraction of J/ψ as a function of $P_T^{J/\psi}$ (left) and of $\psi(2S)$ as a function of $P_T^{\psi(2S)}$ (right).

During the past couple of years it was established that the observed CDF yield for J/ψ's and $\psi(2S)$'s not originating from B decays is much larger than the theoretical expectation from direct production models including contributions from charm fragmentation and gluon fragmentation from color-singlet diagrams [5, 6]. The disagreement with the theory is much more prominent in the $\psi(2S)$ state (a factor of ~ 50) and it has created intense theoretical interest [6–10]. It suggests that there are other important mechanisms for production of S wave states at large P_T beyond those that have already been calculated. This discrepancy triggered additional theoretical work [11, 12] and for the first time the color-octet fragmentation diagrams were considered as a possible solution for the J/ψ and $\psi(2S)$ anomalies [5, 11, 13, 14, 15]. CDF was able to test these theoretical assumptions for both the J/ψ and $\psi(2S)$ states. This became possible, especially for the J/ψ, since CDF measured the fraction of J/ψ's from χ_c decays.

CDF reconstructs the χ_c mesons through the decay chain $\chi_c\to J/\psi\gamma$, $J/\psi \to\mu^+\mu^-$. The photon is detected with two different methods, by using either calorimeter or tracking information. In the first analysis method the photon candidates were selected by demanding an electromagnetic energy deposition with at least 1 GeV at the calorimeter and a cluster in the electromagnetic strip chambers. With ~ 18 pb^{-1} of data $1,230 \pm 72$ χ_c's were reconstructed [16] and it was found that the fraction, $f_\chi^{J/\psi}$, of inclusive J/ψ's with $P_T^{J/\psi} > 4$ GeV/c and $|\eta^{J/\psi}| < 0.6$ coming from χ_c's is $f_\chi^{J/\psi} = 28.3 \pm 1.6(stat) \pm 6.8(syst)\%$. It was found as

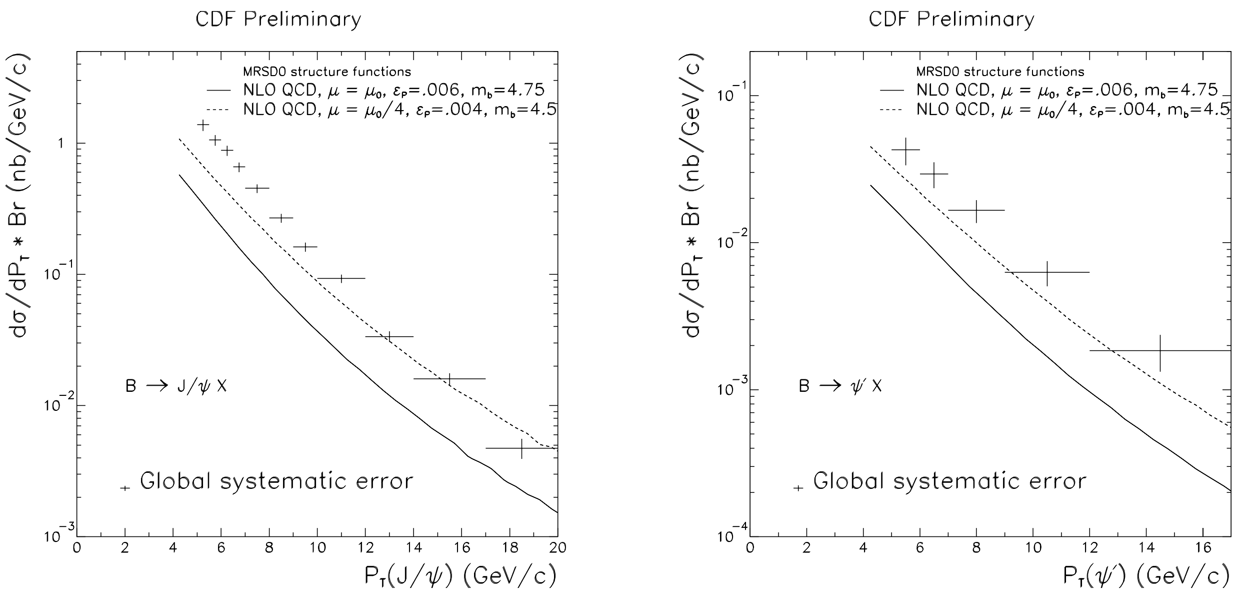

Figure 2: Differential cross sections from B production of J/ψ (left) and of $\psi(2S)$ (right) as a function of P_T, compared with theoretical expectation.

well that the fraction of J/ψ's from χ_c's not including contributions from $B \to J/\psi X$ and $B \to \chi_c X$ decays is $f(Nob)_{\chi}^{J/\psi} = 32.3 \pm 2.0(stat) \pm 8.5(syst)\%$. This implies that the production from χ_c's is not the dominant production mechanism of prompt J/ψ's, in disagreement with current theoretical predictions not including color-octet diagrams for the J/ψ production(see Fig. 3). The differential cross section of prompt J/ψ's from χ_c decays in Fig. 3 was obtained by parametrizing the fraction $f(Nob)_{\chi}^{J/\psi}$ as a function of $P_T^{J/\psi}$ with an exponential function and convoluting it with the differential prompt J/ψ cross section. The direct J/ψ cross section, that is prompt J/ψ's not from χ_c's, was obtained by subtraction. The curves are the color-singlet NLO theoretical calculation based on references [6, 7, 17]. In the second analysis method the χ_c signal is reconstructed through the detection of conversion photons. In $\sim$ 115 pb^{-1} of data, CDF sees 93.8 ± 11.8 χ_{c1}'s and 51.0 ± 9.8 χ_{c2}'s (see Fig. 3). Prompt χ_{c1}'s and χ_{c2}'s are isolated by imposing the requirement that the proper lifetime, λ, of the $J/\psi - \gamma$ system is less than 100 μm. It was found that for prompt events $\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})+\sigma(\chi_{c2})}=$ 0.47$\pm$0.08(stat)$\pm$0.02(syst.)

The differential, direct J/ψ and $\psi(2S)$ cross sections are shown in Fig 4. The open circles represent the data. The B and χ_c components have been removed from the J/ψ cross section and the B component has been removed from the $\psi(2S)$ cross section. The theory curves are from Ref. [14]. The J/ψ and $\psi(2S)$ curves are fit simultaneously and it is required that the ratio of the $^3S_1$ and $^1S_0$ amplitudes is the same for J/ψ and for $\psi(2S)$. Although the fit is above the J/ψ data at high P_T, the overall agreement with the data is good.

2.2 *D0 RESULTS*

D0 studied [18] J/ψ and $\psi(2S)$ production in the kinematic range $|\eta|$ <0.6 and P_T >

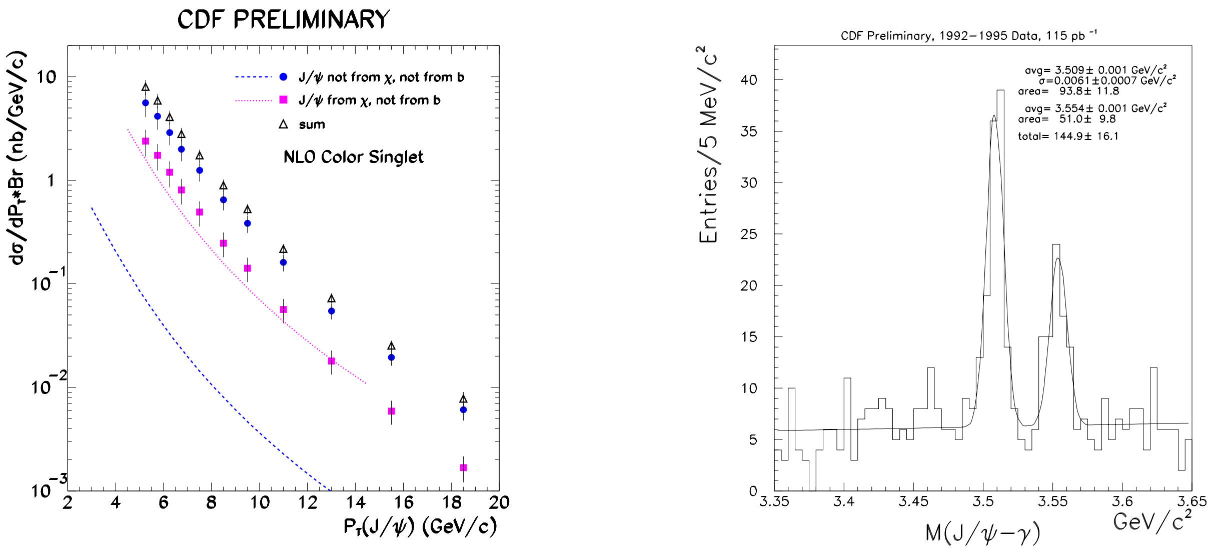

Figure 3: On the left, differential cross sections of prompt J/ψ as a function of $P_T^{J/\psi}$. On the right, the mass difference $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ for the J/ψ signal region and for $P_T^\gamma > 1$ GeV/c, where tracking information is used for the detection of the photon.

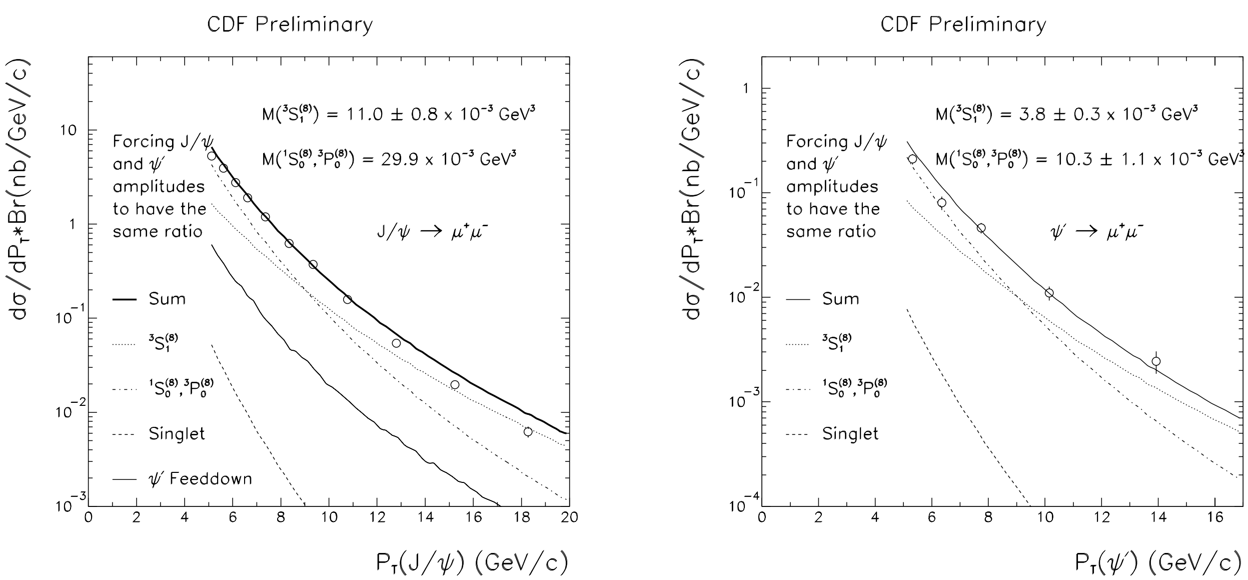

Figure 4: Differential cross sections of J/ψ as a function of $P_T^{J/\psi}$ (left) and of $\psi(2S)$ as a function of $P_T^{\psi(2S)}$ (right). The B contribution has been removed from both J/ψ and $\psi(2S)$ and the χ_c contribution has been removed from J/ψ. The ratio of the $^3S_1$ and $^1S_0$ amplitudes has been required to be the same for J/ψ and for $\psi(2S)$.

8 GeV/c using 6.6 pb^{-1} of data. The resulting dimuon invariant mass distribution is shown in Fig. 5. The dominant background contributions are expected to come from $b\bar{b}$, $c\bar{c}$ and π/K decays. Other mechanisms that yield dimuons in the J/ψ and $\psi(2S)$ mass region are Drell-Yan processes and decays of the ρ, ϕ and η mesons. To determine the contribution from J/ψ production, a maximum likelihood fit was performed using the dimuon invariant mass, the dimuon momentum transverse to the associated jet axis, and the isolation parameter of the most energetic muon. From the fit, the total number of dimuon events due to $J/\psi \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$ is $407 \pm 28(stat) \pm 55(sys)$. The detector resolution is not good enough to distinguish the J/ψ and $\psi(2S)$ states; on the other hand the decay $J/\psi \rightarrow \mu^+\mu^-$ has a branching ratio 7.8 times higher than the decay $\psi(2S) \rightarrow \mu^+\mu^-$ and the contribution of $\psi(2S)$ in the sample is expected to be small. The inclusive differential J/ψ cross section as a function of P_T is also shown in Fig. 5 along with the theoretical predictions. The integrated cross section is measured to be $\sigma(p\bar{p} \rightarrow J/\psi X) \cdot Br(J/\psi \rightarrow \mu^+\mu^-)$ =2.08 $\pm$ 0.17(stat) $\pm$ 0.46(sys) nb for $|\eta|$ <0.6 and P_T > 8 GeV/c. This systematic error does not include a 20% uncertainty due to the polarization of the J/ψ. By using a sample of 13 pb^{-1} of data and examining the distribution of the impact parameter of the muons relative to the event vertex in the transverse plane, D0 determined the fraction f_b of J/ψ events originating from B meson decays. By performing a simultaneous dimuon mass and impact parameter maximum likelihood fit in the region $|\eta|$ <0.6 and P_T > 8 GeV/c, f_b was measured to be $(35 \pm 9(stat) \pm 10(sys))\%$.

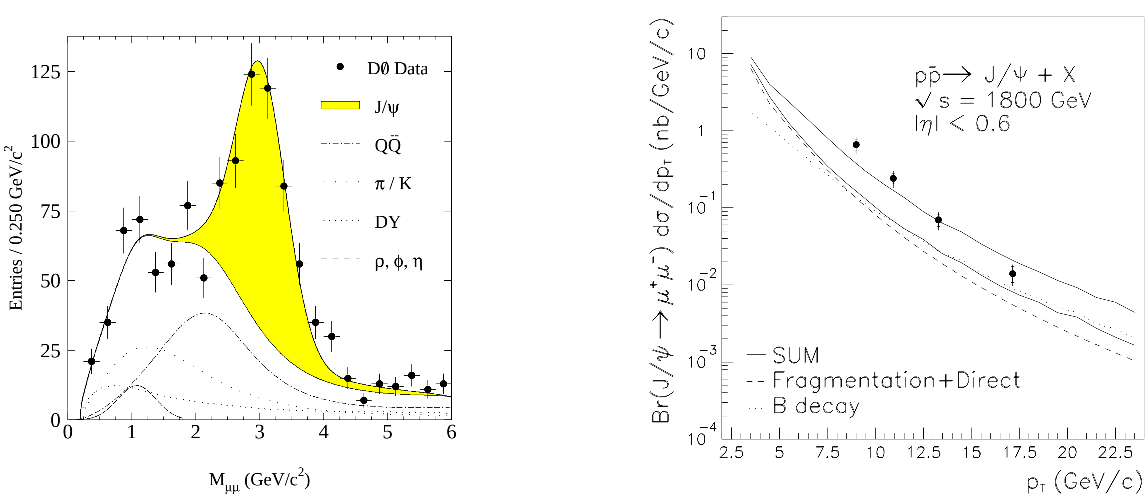

Figure 5: On the left, the dimuon invariant mass distribution in the range 0.2< $M^{\mu\mu}$ < 6 GeV/c^2 and for $|\eta^{\mu\mu}|$ <0.6. The hatched area indicates the J/ψ signal on top of the sum of the background contributions, which are also shown separately. On the right, the differential J/ψ production cross section as a function of P_T along with the theoretical predictions.

By fully reconstructing the decay chain $\chi_c \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$ D0 obtained $70 \pm 15(stat) \pm 12(sys)$ χ_c events and measured that the fraction of J/ψ events coming from χ_c decays is $f_{\chi_c} = (32 \pm 7(stat) \pm 7(sys))\%$ and that $(41 \pm 17)\%$ of J/ψ events do not originate from either B or χ_c decay. These results are consistent with the CDF findings and they also imply that χ_c mesons are not the dominant source of prompt J/ψ's.

D0 has also explored the forward rapidity region which is of particular importance since it is the region where the cross sections are most sensitive to the gluon distribution function of the colliding particles. By analyzing a dimuon data sample of 6.3 pb^{-1}, a signal of 567$\pm$57 events was observed in the region $P_T > 3$ GeV/c, 2.6< $|\eta|$ <3.4 and it was used to determine the differential cross section shown in Fig. 6, left. The data are compared with the expected contribution from B decays. Data from the dimuon analyses in the central and forward rapidity regions and for $P_T > 8$ GeV/c are combined to produce the plot in Fig. 6, right. Although there is no $|\eta|$ dependance in the production cross section in the central region, it is obvious that the cross section is lower at higher $|\eta|$.

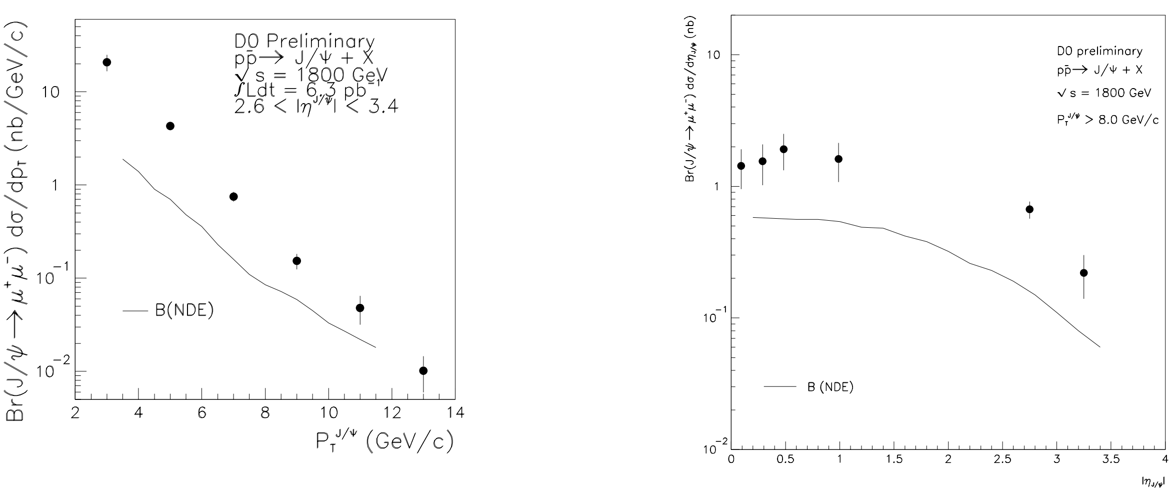

Figure 6: On the left, the D0 J/ψ cross section as a function of $P_T^{J/\psi}$ for 2.6< $|\eta^{\mu\mu}|$ <3.4. On the right, the D0 J/ψ cross section as a function of $|\eta^{J/\psi}|$

3. Υ PRODUCTION

It is expected that the Υ's resonances are produced directly or from the decay of higher mass χ_b states. The CDF and D0 experiments study Υ production by studying the reaction $p\bar{p} \rightarrow \Upsilon X \rightarrow \mu^+\mu^- X$. Since, as discussed above, the measurements of prompt J/ψ and $\psi(2S)$ production cross sections are higher than the theoretical predictions, it is of interest to carry out similar comparisons for the Υ particles.

3.1 *CDF RESULTS*

CDF measured [19] the differential and integrated production cross sections of the Υ(1S), Υ(2S) and Υ(3S) states using a data sample of 16.6 pb^{-1}. In the kinematic region $|y| < 0.4$ and P_T >0.0 GeV/c, 1,274 Υ(1S), 320 Υ(2S) and 196 Υ(3S) events were reconstructed (see Fig. 7). The differential cross section measurement for the Υ(1S) state is also shown in Fig. 7 along with the color-singlet theoretical calculation [14]. The theoretical calculation includes contributions from direct production and from $\chi_b(1P)$, $\chi_b(2P)$ decays. The integrated cross section results divided by the rapidity bin width are:

$$d\sigma/dy(\overline{p}p \rightarrow \Upsilon(1S), y = 0, 0 < P_t < 16 \text{ GeV/c}) \times Br = 753 \pm 29 \text{ (stat)} \pm 72 \text{ (sys) pb}$$
$$d\sigma/dy(\overline{p}p \rightarrow \Upsilon(2S), y = 0, 1 < P_t < 10 \text{ GeV/c}) \times Br = 183 \pm 18 \text{ (stat)} \pm 24 \text{ (sys) pb}$$
$$d\sigma/dy(\overline{p}p \rightarrow \Upsilon(3S), y = 0, 1 < P_t < 10 \text{ GeV/c}) \times Br = 101 \pm 15 \text{ (stat)} \pm 13 \text{ (sys) pb}$$

where Br stands for the branching ratio of the corresponding Υ state to $\mu^+\mu^-$. The ratios of the integrated cross section results were also computed in the range $1 < P_t < 10$ GeV/c and for $|y| < 0.4$. The results are $\sigma Br(\Upsilon(2S))/\sigma Br(\Upsilon(1S)) = 0.281 \pm 0.030 \text{ (stat)} \pm 0.038 \text{ (sys)}$ and $\sigma Br(\Upsilon(3S))/\sigma Br(\Upsilon(1S)) = 0.155 \pm 0.024 \text{ (stat)} \pm 0.021 \text{ (sys)}$. The rate of Υ production for all three states was found to be higher than color-singlet QCD calculations. Inclusion of color-octet production mechanisms seem to help explain some of the discrepancies [14].

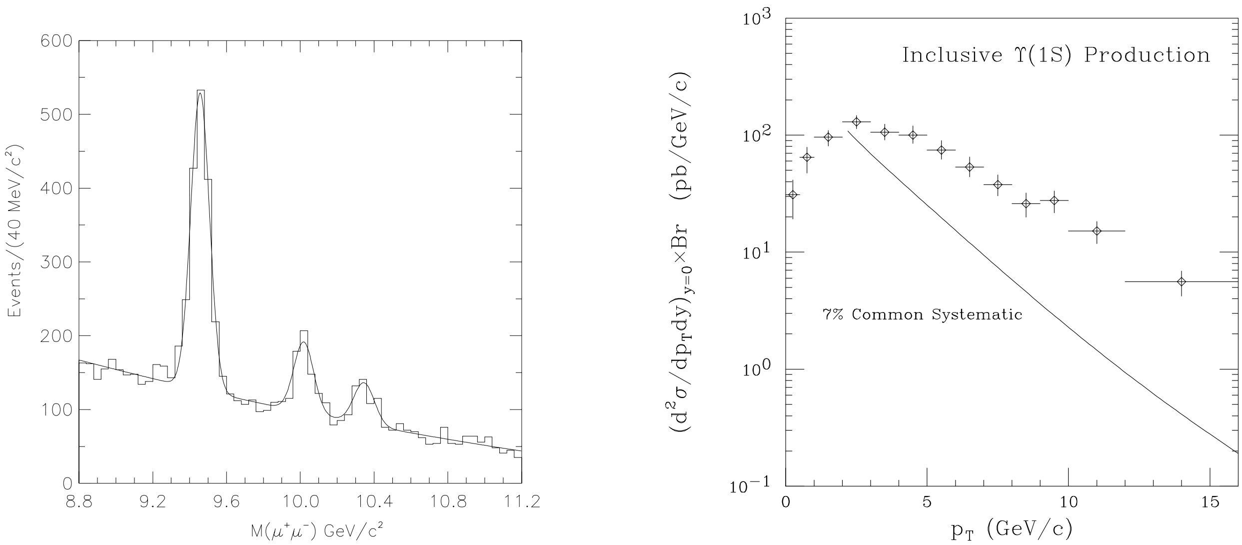

Figure 7: On the left, the CDF invariant mass distribution for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$. On the right, the differential cross section as a function of P_T for the $\Upsilon(1S)$ state. Both plots are for $|y|$ <0.4. The theoretical curve on the right corresponds to the color-singlet calculation of Ref. 14.

3.2 *D0 RESULTS*

D0 reconstructed Υ events from a data sample of 6.6 pb^{-1} and in the rapidity region $|y|$ <0.7[20]. Although the detector resolution is not good enough to separate the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states, 90 ± 11 Υ events were observed. The signal and background contributions were resolved using a simultaneous maximum likelihood fit to the dimuon invariant mass, to the energy in a halo about each muon and to the reconstructed time offset relative to the beam crossing. The differential and integrated cross section measurements are summed over the three resonances. The integrated cross section result divided by the rapidity bin width is $d\sigma/dy(\overline{p}p \rightarrow \Upsilon, y=0) \times Br(\Upsilon \rightarrow \mu^+\mu^-) = 768 \pm 81\,(\mathrm{stat}) \pm 142\,(\mathrm{sys})\,\mathrm{pb}$. For $P_T^{\Upsilon} > 5$ GeV/c, the measurement is roughly a factor of five larger than the $\mathcal{O}(\mathrm{a}_s^3)$ QCD prediction of Ref.[21].

4. CONCLUSIONS-PROSPECTS

In conclusion both CDF and D0 have studied charmonium and bottomonium production and have made measurements which are in disagreement with conventional theoretical expectations. The color-octet mechanism seems to help explain some of the discrepancies. Much more experimental and theoretical work is necessary though in order to show conclusively that heavy quarkonia production mechanisms are understood.

Currently, in 110 pb^{-1} of data, CDF has a sample of $\sim$ 500,000 J/ψ's in the rapidity region ($|\eta| < 1$), from which $\sim$ 244,000 are reconstructed at the SVX. It has also large samples of $\psi(2S)$'s in both the $\mu^+\mu^-$ and $J/\psi\pi^+\pi^-$ modes, χ_c's and Υ's. D0 has in addition a useful sample of J/ψ's and other quarkonia in the very forward rapidity region. The completion of the analysis of these data sets from the 1992-1995 Collider Run will shed, we hope, more light on the quarkonia production mechanisms. The increase of statistics will be particularly useful for the measurement of the spectra of the $\psi(2S)$, χ_{c1}, χ_{c2}, Υ(2S) and Υ(3S) states and for the rapidity dependence of the quarkonia cross sections. The measurement of the spin alignment of the J/ψ, $\psi(2S)$, χ_{c1} and χ_{c2} and the three Υ states will also produce very valuable information on the production mechanisms. The increase of statistics, combined with refinement in technique should also allow us to measure the production cross section of χ_b states and thus understand better the bottomonia production mechanisms.

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